# THE

# CRYSTAL AND MOLECULAR STRUCTURES

# OF SOME

# BIOINORGANIC COMPOUNDS

A thesis submitted to the
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by

MINO RODOLFO CAIRA B.Sc.(Hons.) M.Sc.

Department of Physical Chemistry,
University of Cape Town,
Rondebosch, Cape Province,
Republic of South Africa.

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# PUBLICATIONS

Sections of this work have been published. Those papers which have not yet appeared have been accepted for publication and are in press.

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4. "The Crystal Structure of a Five-Coordinate Copper(II) Macrocyclic Complex: Chloro (2,7,12-trimethyl-3,7,11,17 - tetraazabicyclo[11.3.1]heptadeca-1(17),2,11,13,15 - pentaene) Copper(II) Nitrate Dihydrate".
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6. "Crystal Structure of the Bis-(5,5'-diethylbarbiturato) bispyridine Complex of Copper(II)".
   M.R. CAIRA, G.V. FAZAKERLEY, P.W. LINDER and
   L.R. NASSIMBENI.
   *Acta.Cryst.* B29, 2898 (1973).

7. "*Trans*- (Dithiocyanato)(bispyridine)Platinum(II)".
   M.R. CAIRA and L.R. NASSIMBENI.
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8. "Crystal Structure of the Dimeric 6-Mercaptopurine Copper(I) Chloride Complex".
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9. "Crystal and Molecular Structure of the Polymeric 8-Mercaptopurine Copper(I) Chloride Complex".
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# CHAPTER I

# INTRODUCTION

## I.1 BIOINORGANIC CHEMISTRY [1,2]

The ubiquity and manifold functions of metal ions in biological systems[3] have prompted extensive study of their interaction with biomolecules. Each essential metal ion has its own set of *in vivo* functions, the optimum concentration of the element for each of these functions being controlled within fine limits. At the same time, many thousands of biomolecular ligands compete for these ions. To establish the *in vivo* role of metal ions interacting with specific substrates, it is necessary to understand how they react *in vitro* with a host of potential ligands. These ligands include amino acids, purines, pyrimidines and vitamins. The new discipline of bioinorganic chemistry is intent on updating biochemistry by placing more emphasis on metal-dependent reactions. In practical terms, the results of such study have been a better understanding and a positive treatment of metal-dependent conditions in humans and a more rational approach to the design and synthesis of metal-containing drugs. Since the discovery, in the 1950's, of the antiviral properties of metal complexes, more cancers have been found to be virus dependent. Metallotherapy is now established as a powerful probe in the fight against cancer.

One obvious prerequisite for the understanding of the mode of action of drugs at the molecular level is a knowledge of the detailed molecular structure of the drug in question.[4,5] An important approach to the problem of obtaining more detailed information regarding the structures and reactions of ligand binding-sites is to design and perform systematic model studies, both in solution and in the crystalline state. A vast body of chemical information has been acquired by spectroscopic and kinetics studies in solution. In the case of crystalline metal-biomolecular complexes (for example metalloenzymes and metalloproteins), X-ray diffraction analyses have provided information about the geometry of the metal coordination sphere. Since X-ray studies are performed on isolated solids, the possibility exists that the molecules under consideration may assume other conformations at biological interphases. Speculation as to the mechanism of *in vivo* action by extrapolation from the solid to the solution situation must therefore be cautiously exercised. In many instances however[6,7], molecular orbital calculations predict that the conformations established by X-ray diffraction are the most stable and probably best represent the structures of the molecules. This is especially true in the case of low molecular-weight metal complexes which generally have a rigid structure with few variable conformational parameters.

In this thesis are presented the results of X-ray structural studies of seven metal-containing crystalline compounds. In some cases, the ligands associated with the metals are themselves biologically active; in other cases, the compound as an entity, rather than any constituent, is of direct or indirect biological significance. Detailed motivations for the individual structural analyses are described in the separate introductions in the body of this work. The compounds studied are generally dissimilar and present different facets of metal-ligand interaction. For this reason, the paragraphs which follow serve to introduce each compound by reviewing the pertinent areas of metal-binding.

## I.2 MODELS FOR METAL-BIOMOLECULAR INTERACTION [2,3,8]

Relatively few complete X-ray structural analyses of metalloproteins have been achieved due to both the practical difficulties involved in crystallizing such molecules and their complexity. For this reason much of the current knowledge has been obtained by studies of the coordination chemistry of low molecular-weight systems. Although a simple molecular analogue may mimic a biopolymer in its enzymatic activity only to a small extent, study of the former permits one to obtain highly accurate data, especially in the case of metal complexes. Since copper ions occur in five of the seven compounds presented here, the emphasis will be placed on some *in vivo* aspects of copper ion activity.

Among the functions of copper proteins [9] are electron transfer interactions, the transport of oxygen molecules and the transport and storage of copper ions. Some of the better known copper proteins involved in electron transfer reactions are ascorbate oxidase, cytochrome c oxidase and tyrosinase. These contain eight, two and one gram atoms respectively of copper per mole of protein. Oxygen transport in the blood of certain invertebrates is effected by the copper protein haemocyanin. The main copper protein in the blood plasma of mammals is ceruloplasmin, the true function of which is still uncertain. Many coordination compounds are regarded as model systems for copper-protein interaction. Applying the (a) and (b) type (or "hard" and "soft") classification of metal ions [10], it is observed that those metal ions with intermediate character are best suited for interaction with proteins; this is mainly due to the fact that the principal ligand atoms in proteins are oxygen and nitrogen. Amino acid chelates of copper(II) (e.g. NaCu(II)(glycylglycylglycine).$H_2O$), are of particular interest in this regard. X-ray analyses have revealed a wide variety of stereochemistries in this series of model compounds. That they are realistic models is confirmed by the fact that in some cases, the metal chelate (e.g. Cu(II)(L-histidine)(L-threonine).$H_2O$) was first isolated and crystallized from human blood plasma. In the examples quoted, the donor atoms have been oxygen and nitrogen, but the presence of sulphur atoms in proteins could in principle permit metal-sulphur binding. Thiol groups in non-haem iron proteins are known to be ligands for iron-binding. The interaction of thiol groups with copper ions is less well understood but some inferences have been drawn from X-ray analyses of low molecular-weight copper-thiourea and copper-thiocarbamate complexes. A structural analysis of diethyldisulphide-copper(I) chloride has revealed that copper(I) interacts with disulphide sulphur atoms; the latter are present in almost every protein molecule. A third group of compounds representative of copper-protein interaction are the binuclear complexes which have the pair of cupric ions bridged *via* carboxylate oxygen atoms.

The participation of metal ions in the biological functions of nucleotides and nucleic acids has been given much attention in recent years[11,12,13]. Several phenomena involving metal ions have prompted these investigations. Metal ions are essential to the function of DNA. Copper ions take part in the reversible unwinding and rewinding of the double-helix DNA strands and are thus involved in the passing on of the genetic information. The ability of some metal ions to react preferentially with some bases rather than others is of practical use in the study of nucleotide sequence in polynucleotides. Copper(II) ions, for example, display this selective ability in that they lack affinity for uracil but show a preference for guanine. Metal ions influence the thermal denaturation of nucleic acids. For example, copper(II), cadmium(II) and mercury(II) ions bind preferentially to the heterocyclic bases and disrupt the hydrogen bonding. On the other hand, the double-helical conformation is stabilized by the ions $Na^+$, $Mn^{2+}$ and $Co^{2+}$, which appear to bind to the sugar-phosphate chain.

The nucleosides as monomers are of great importance in many metabolic processes, most of which are also mediated by metal ions. Consequently, the coordination of divalent metal ions to nucleic acid components has been the subject of several investigations. X-ray studies of metal complexes of purine bases[14] have contributed to the understanding of metal-nucleic acid interaction through the establishment of the binding-sites in these ligands. In this connection, the structures of two complexes of copper with the less common thiolated purines are presented in Chapter VII. Selective metal-binding was anticipated in view of the "soft" nature of the sulphur donor atom in these heterocyclic ligands. Moreover, these complexes are of biological interest because one of the criteria for determining whether a metal complex will have carcinostatic activity is that ligands with sulphur donors are likely to be most effective.[15]

There is current interest in the interaction between metal ions and relatively simple metabolites such as Vitamins. Vitamin $B_1$ (thiamine), the beriberi drug, which consists of a substituted pyrimidine and a substituted thiazole ring joined by a methylene bridge, has been shown to be implicated in numerous reactions involving metal ions.[16,17,18]

The general metal requirements noted in many thiamine-dependent enzyme systems[19] as well as the catalytic hydrogen wave produced by cobalt-ammonia buffer solutions of thiamine during polarography[20] lend support for metal-thiamine interaction of some kind. In addition, *in vivo* studies have indicated the possibility of metal-thiamine complex formation. For example, it has been shown that thiamine affects cadmium uptake and metabolism, and has a mitigating effect on cadmium poisoning. As part of a study aiming to clarify the cause of the inhibitory effect of uranyl ion, $UO_2^+$, on neural transmission, the physico-chemical and structural properties of a uranium-thiamine complex have recently been investigated.[17] A chemical model for enzyme-catalysed acetylcholine hydrolysis is the thiamine-acetylcholine interaction.[16] It has been suggested that copper(II) ions inhibit the formation of the thiamine-acetylcholine complex. Accordingly, a thiamine-copper(II) complex has been synthesised and its crystal structure forms part of Chapter III of this thesis.

When the structure of vitamin $B_1$ was unravelled [21], it was the first instance that a thiazole nucleus had been found in a natural product. Since then, many synthetic metal complexes of thiazole (regarded by some as a thiamine analogue), have been studied with the aim of establishing metal-binding sites and relating these to the chemistry of the vitamin[22,23,24]. The substituted thiazole moiety occurring in vitamin $B_1$ is itself biologically active [25] and the crystal structure of a cobalt(II) complex of this ligand is also presented in Chapter III.

## 1.3 BIOINORGANIC DRUGS AND CANCER CHEMOTHERAPY

The involvement of metal ions in some types of cancer is well known[26]. Prior to the discovery (1969) of anti-tumour platinum compounds, relatively little systematic research into anticancer drugs was attempted. In some of the studies, miscellaneous metal compounds including simple oxides, halides, cyanides and amines were tested by subcutaneous injection of their saline solutions into animals bearing implanted carcinomas . Generally, little therapeutic activity was detected. Later, use of the oil-soluble butylphthalate complexes of copper, nickel and cobalt was claimed to be beneficial in seven out of twenty cases of leukaemia treated. Amine complexes of cobalt(II) and chromium(II) have been studied and evaluated against certain tumours. Some naturally-occurring cobalt-containing molecules such as vitamin $B_{12}$ (cyanocobalamin) and cobalt protoporphyrin have found occasional use in the treatment of specific tumours.

Some copper complexes have been successfully applied in this area. Chelates of copper(II) with dimethylglyoxime and with thiosemicarbazones are highly active as anti-tumour agents. The activity and toxicity of the organic substance kethoxal bis-thiosemicarbazone, KTS, have been shown to be directly proportional to the dietary intake of copper(II) ions for rats bearing the Walker 256 carcinosarcoma. The copper chelate, CuKTS, was synthesised and also showed activity. The crystal structure analysis of this chelate revealed certain features which may account for its cytostatic action[27].

A relationship between metal chelation, carcinogens and anticancer agents has been postulated[26]. The majority of non-metallic carcinogens are potential chelating agents and this suggests that their action may be due to their interactions with essential metals. Inhibition of enzymes by removal of the metal from specific cellular locations is one possible mechanism. Further, some metals are themselves known to cause some cancers. Cell permeation by metals is best effected when the metal is in a chelated form and therefore a carcinogenic chelate may introduce an abnormal metal into a cell. The concentration of abnormal metal under carcinogenic conditions may be higher and the perturbation of cell metabolism could result in transformation to a neoplastic cell. Anticancer agents capable of binding metals may inactivate the abnormal more than the normal metal in the cell. Some of these speculations, based on general observations, seem unlikely in view of more recent studies. Many anticancer agents have now been shown to react directly with nucleic acids and inhibit DNA synthesis and this appears to be the normal mode of action.

Cancer research studies which indicated that viruses are associated with many types of cancer prompted the synthesis of metal complexes which might be successfully used in the alteration of these viruses with the consequent destruction or diminution of their activity[28]. Of the twenty-six complexes prepared, five of them displayed anticancer activity. These were platinum, palladium and bismuth complexes with such ligands as thioguanine, butylthiopurine and 6-mercaptopurine. The presence in the complex of a ligand which is itself carcinostatic (e.g. 6-mercaptopurine) is significant. The reasons for the marked anticancer activity of the complexes are still not understood. It has been suggested that the transfer of metal ion from the ligand to the viruses associated with cancer is a mechanism for releasing the anticancer drug in the locality of the tumour. Current studies are aimed at establishing the relationship between metal-ligand bond type and carcinostatic activity. Metal complexes containing carcinostatic ligands are interesting from this point of view. In this connection, mention may again be made of the copper complex of 6-mercaptopurine whose structure is described in Chapter VII.

Transplanted, carcinogen-initiated and viral-induced cancers all respond to treatment with simple platinum complexes[29]. Most of the systematic anticancer work carried out till now has involved complexes of this series. Generally, these are neutral platinum-amine-halide molecules. The simplest theory of their mode of activity is that the site of their action is inside the cancer cells at the nuclear DNA. It is postulated that, in the case of the active complex *cis*-diamino dichloro platinum(II), the chloride ions are lost to form a purine-Pt-purine cross-link between nitrogens of two neighbouring purines. An *intra* strand link is formed if these purines are part of the same DNA chain and the synthesis of new DNA polymers is inhibited. Interatomic distances in the platinum complex, established by X-ray diffraction, fit the hypothesis very well.

The crystal structure of a simple Platinum(II) complex is presented in Chapter VI. It is obviously necessary to establish accurate bond lengths in platinum complexes as these are crucial in postulating theories concerning their mode of action at the molecular level.

## 1.4 PHARMACOLOGICAL ASPECTS OF DRUG-METAL BINDING

Although many drugs are chelating agents, this does not necessarily imply that they function by direct interaction with some receptor metal[30]. However, chelation can be regarded as one means by which a poisonous drug may be removed from the systemic circulation. The best known application of chelating agents in medicine is the treatment of heavy metal poisoning in humans. A drug, often administered orally, sequesters the polluting metal ion and by complexation with it, renders it inactive. In therapy of this kind, the chelating agent should ideally diminish the absorption of metal into the systemic circulation and also facilitate the excretion of excess metal that has been absorbed. Examples of this application are the use of dimercaprol for arsenical poisoning and that of ferrichrome in the treatment of poisoning by ferric ions. Unfortunately, some chelating agents can also bind trace metals which are required for normal body function. For example, ethylenediamine tetraacetic acid (containing oxygen and nitrogen donor atoms), often used as an antidote for iron, lead or cadmium poisoning, also removes large amounts of zinc from the body fluids. The drug D-penicillamine (containing sulphur, nitrogen and oxygen donors), commonly used to treat copper poisoning and Wilson's disease, also acts as a pyridoxal antimetabolite, thus producing undesirable side effects. However, from the finding that albumin, the copper transport protein in human blood, possesses a copper specific site constructed from three amino acids, a drug surpassing D-penicillamine has been designed and synthesised[31]. This is the tripeptide glycylglycyl-L-histidine methyl ester whose structure mimics the copper specific site in albumin. This is an interesting application of the principle of copying *in vivo* processes to treat diseases. Specificity may not always be desirable, however. One theory regarding the action of tetracycline antibiotics is in terms of removing metal ions in general from bacteria and thus starving them.

Distinct from the *in vivo* application of metal-drug binding is the detection and identification of poisonous drugs extracted from human tissue by the toxicologist. Here, use is often made of the metal-binding properties of drug molecules[32]. The addition of metal ions to the acid ether extract or to the alkaline chloroform extract of the drug often produces characteristic colours which are generally due to the formation of a metal-drug complex. The use of ferric chloride for the identification of phenolic drugs is well known. The formation of variously-coloured crystals by the reaction of gold chloride with the phenothiazine drugs is used to differentiate members of this series. In the same way, alkaloids can be distinguished by their reactions with a number of metal salts (e.g. lead iodide, mercuric chloride, platinum iodide). Spot tests for strychnine are based on colour reactions with potassium dichromate, gold chloride and platinum chloride. Although these procedures are routinely followed, in many cases the molecular structure of the metal-drug complex is unknown.

A standard technique for the clinical identification of barbiturates is the 'copper-pyridine' test[32,33]. Addition of copper-pyridine reagent to a barbiturate produces a violet-coloured complex. Members of a series of barbiturates may be more easily distinguished by comparison of the infrared spectra of these complexes rather than by comparison of the spectra of the parent barbiturates. Indirect evidence for the molecular structures of these compounds has appeared but the copper binding site in the barbiturate ligand was not established unambiguously[33,34].In Chapter V of this thesis, the first X-ray structural elucidation of a copper complex of this series is presented. Since this analysis has been carried out, a series of metal-barbiturate complexes has been synthesised and studied by infrared and X-ray methods[35].

## 1.5 METAL ION BINDING BY SYNTHETIC MACROCYCLES

Natural macrocyclic compounds include porphyrins, corrins and phthalocyanines. Ligands of this type have a cyclic structure characterised by central donor atoms and exterior flexible frameworks. The tetradentate system of nitrogen donors in porphyrins is capable of binding heavy metals, in particular iron, giving rise to the haematin compounds. The important haem-containing compounds in the body are haemoglobin, myoglobin, the enzymes catalase and peroxidase, and the cytochromes. Vitamin $B_{12}$, used in the treatment of pernicious anaemia, contains a cobalt ion tightly bound by a corrin ring. Although metal complexes of natural macrocycles have been known for more than fifty years, it is only during the last decade that a large number of synthetic macrocycles capable of binding cations have been prepared and investigated[36]. The study of these synthetic complexes has yielded observations that are of direct use in accounting for the behaviour of certain natural systems. These novel complexes contain central hydrophilic cavities ringed with either electronegative or electropositive binding atoms and exterior frameworks which exhibit hydrophobic tendencies. These hydrophobic exteriors render ionic substances soluble in non-aqueous solvents and in membrane media. This property accounts in part for the action of the macrocyclic antibiotic valinomycin, which actively transports complexed $K^+$ ions across mitochondrial membranes.

An extensive literature exists on the selective complexation and transport of alkali metal ions by such macrocycles ("ionophores")[37,38] as valinomycin and monactin.

In addition to their high thermodynamic stability, macrocyclic complexes are selective with respect to the cations they bind. The latter property is a function of ring size, number and kind of donor atoms and substituents. By altering these structural features, ligands with a wide variety of properties are obtained. Apart from their value in assessing factors which determine metal selectivity and specificity in biological reactions, macrocycles are ideally suited for processes requiring cation separation. One obvious application, previously mentioned (1.4), is the selective removal of metal ions when present in toxic amounts in biological systems including man. On the other hand, metal-macrocyclic complexes could prove useful in diet supplementation of trace elements because of their favourable membrane permeability properties.

In principle, macrocycles may be synthesised by the condensation of two suitable organic molecules. An interesting aspect of this reaction is that the macrocycle often does not form readily (or does not form at all) *via* such a condensation; however, ring-closure may be effected in the presence of metal ions and consequently, the metal-macrocyclic complex is the product. The term "template effect" has been proposed [39] to describe the organizational role of the metal ion in such reactions.

Interest in macrocyclic complexes as bioinorganic models has led to several structural analyses by X-ray diffraction[36]. Relatively few X-ray studies have been performed on copper-containing macrocyclic complexes. The crystal structure of a copper(II) complex of a tetradentate macrocycle is presented in Chapter IV.

# CHAPTER II

# GENERAL EXPERIMENTAL AND COMPUTATIONAL PROCEDURES

What follows is a general summary of the methods employed for the chemical characterisation of the compounds studied, their preliminary analyses and X-ray data collection. Details of these procedures for each individual structure are provided in the appropriate sections.

## II.1 CHARACTERISATION OF THE COMPOUNDS

Generally, the stoichiometric composition of any one crystalline compound was determined by microanalytical estimates of its carbon, hydrogen and nitrogen content. In one case, the metal content was determined by atomic absorption spectrophotometry, while in another, a gravimetric procedure was employed.

## II.2 PRELIMINARY X-RAY ANALYSES[40,41,42]

Unit cell dimensions and the diffraction geometry of the crystals were obtained by single-crystal rotation, oscillation, Weissenberg and precession photographic methods. In general, analysis of zero and upper layer Weissenberg photographs obtained with a crystal oscillating about each of its principal axes sufficed to establish the space group symmetry. Nickel-filtered CuK$_\alpha$ radiation ($\lambda$ = 1.5418 Å) was used with a non-integrating Stoe (Heidelberg) goniometer and a camera of radius 2.865 cm. The X-ray generators, operating at 20 mA and 40 kV were

Philips PW 1120 and PW 1008 models. X-ray films (Kodirex) were processed in the normal way with Kodak X-ray developer and fixer solutions.

Taking into account the optimum crystal size[43], suitable specimens were selected, checked for reflection quality and mounted on glass fibres for intensity data collection.

## II.3 DIFFRACTOMETER DATA COLLECTION

The mounted specimens together with spare crystals were sent to Dr. G. Gafner at the National Physical Research Laboratory, C.S.I.R. (Pretoria) where the intensities of the reflections were measured on a Philips PW 1100 computer-controlled four-circle diffractometer. In cases where mounted crystals had undergone decomposition or had fractured, they were replaced by fresh crystals cut into cubes or ground into spheres in order to minimise absorption effects. A Philips PW 1130 3 kw X-ray generator, operating at 50 kV and 20 mA, provided MoK$_\alpha$ radiation which was monochromated ($\lambda$ = 0.7107 Å) by a flat graphite (002) crystal. Lattice constants were obtained at room temperature by a least-squares fit of the $\chi$, $\phi$ and 2$\Theta$ angles of 25 reflections accurately centred on the diffractometer. For all data collections except one, the $\omega$-2$\Theta$ scan mode was employed. The $\omega$-scan technique was used for the fourth compound in the series studied[44]. For any one crystal, the intensities of three suitable reference reflections were measured (usually

structure factor calculation), SINGEN and PHASE (direct methods of phase determination), LOADAT (atomic parameter loading program), FC (structure factor calculation), FOURR (calculation of three-dimensional Patterson, electron-density and E maps), CRYLSQ (least-squares refinement of atomic parameters), PEKPIK (location of peaks in maps), BONDAT (generation of bonded atom positions), BONDLA (bond lengths and angles calculation), LSQPL (least-squares line and plane program), LISTFC (listing of observed and calculated structure factors).

For the calculation of torsion angles, it was convenient to use the program XANADU[47]. A useful feature of this program is the two-dimensional mapping of an array of atomic positions viewed normal to the mean plane through the atoms.

All illustrations of molecules were obtained with the programs PLUTO[48] (atoms represented by spheres of arbitrary radii) and ORTEP[49] (atoms represented by thermal ellipsoids drawn at the 50% probability level).

In all cases, the agreement between observed ($F_o$) and calculated ($F_c$) structure factors is expressed by the conventional residual factor[50] defined by

$$R = \frac{\Sigma \left| \, |F_o| - |F_c| \, \right|}{\Sigma |F_o|} .$$

Unless otherwise stated, the van der Waals radii quoted are those of Pauling[51].

# CHAPTER III

# METAL COMPLEXES WITH VITAMIN $B_1$ AND A RELATED THIAZOLE AS LIGANDS : THE CRYSTAL STRUCTURE OF THE THIAMINE HYDROCHLORIDE COPPER(II) COMPLEX AND THAT OF THE COMPLEX DIBROMOBIS-[5(2-HYDROXYETHYL)-4-METHYLTHIAZOLE]COBALT(II)

## III.1 INTRODUCTION

### Vitamin $B_1$

Vitamin $B_1$ (thiamine) is a required dietary constituent for all animals other than ruminants. In man, its deficiency is the cause of beriberi[52]. Thiamine itself is the chloride salt of an organic cation. The doubly charged acid form, thiamine hydrochloride, has the structural formula and ring-numbering scheme shown in Fig. III.1.1.

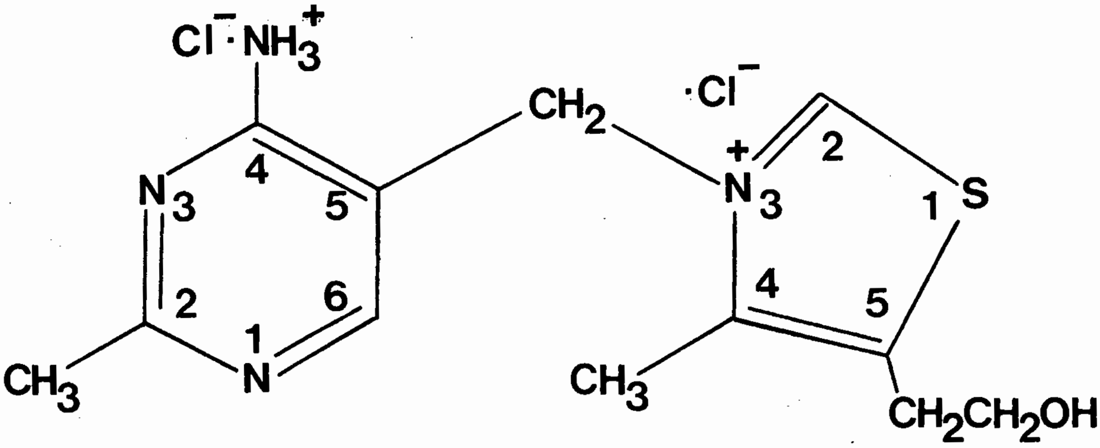

Fig. III.1.1

The molecular structure of this species was elucidated by classical chemical methods in 1936 as 3-(4-amino-2-methyl-5-pyrimidylmethyl)-5-(β-hydroxyethyl)-4-methylthiazolium chloride hydrochloride. The substance is colourless, decomposes at 248°C and is soluble in water (1 g per ml) and other polar solvents.

Thiamine deficiency (more frequently encountered in Eastern countries) is characterised by degenerative changes in the nervous system, including multiple peripheral neuritis. In the body, the circulating form of the vitamin is thiamine or its monophosphate derivative. The coenzyme form of the vitamin is the pyrophosphate. In mammalian metabolism, the vitamin is involved in the following reactions: (a) the decarboxylation of α-keto acids to aldehydes or acyloins (b) oxidative decarboxylation of α-keto acids to acids, and (c) the transformation of α-keto acids to acyl phosphates. These reactions have been extensively studied and a thiazolium zwitterion has been postulated as the likely active intermediate. In this species, a positive charge resides on the quaternary nitrogen atom and atom C(2) of the thiazole ring is negatively charged (obtained by base-catalysed proton removal from C(2)). Such a species is capable of condensing with carbonyl functions. Generally, thiamine-requiring enzymes catalyse reactions in which C-C bonds adjacent to carbonyl groups are cleaved ('α-type cleavage'). The major carbohydrate metabolic cycles are all dependent on such cleavage and are therefore thiamine-dependent.

## Thiamine- Metal ion interaction

Carboxylase, the enzyme system, contains one molecular equivalent of thiamine pyrophosphate (i.e. co-carboxylase) for each molecule of protein and five atoms of magnesium. For some time it has been assumed, in the case of pyrophosphate-containing coenzymes in which metal ion cofactor requirements can be demonstrated, that the metal ion links the coenzyme *via* its pyrophosphate residue to the enzyme. This mechanism had been proposed for thiamine pyrophosphate but a subsequent investigation[19] led to the proposal that the nitrogen atom N(1) of the pyrimidine portion of the vitamin might be involved in metal-nitrogen binding. Work during the last few years has been directed towards confirming such binding. There are several potential metal-binding sites in the thiamine molecule viz. the pyrimidine ring nitrogens and the amino nitrogen and the sulphur and oxygen atoms of the thiazole moiety.

Interaction between uranyl ions and thiamine has been studied[17]. Uranyl ion influences neural transmission and is used for the negative staining technique in electron microscopy. Thiamine is involved in the biosynthesis of acetylcholine and is largely diffused at the level of neural membranes stained with uranyl ion. Any interaction between thiamine and uranium is therefore of interest. The product obtained by the reaction of thiamine hydrochloride with a uranium salt has been isolated and its structure has been elucidated by X-ray methods.

Recent work[18] has shown that the vitamin affects the *in vivo* uptake of cadmium and its metabolism and that it has a mitigating effect on cadmium poisoning. A product formed by the reaction of thiamine hydrochloride and cadmium nitrate has been the subject of a recent X-ray analysis.

Following the proposal of metal-pyrimidine nitrogen bonding, zinc(II) and cobalt(II) halides were reacted[53] with thiamine and with N-substituted thiazolium salts in order to establish the possible sites of chelation. It is significant that in all of the metal complexes of thiamine whose solid-state structures have been elucidated by X-ray diffraction, there is no evidence of direct metal-vitamin interaction. The compounds are better formulated as "complex salts" consisting of cationic vitamin and anionic metal-halide units associated by electrostatic forces.

## Thiamine-Copper(II) interaction : Motivation for structural analysis

Work on thiamine-copper(II) interaction was initiated by observations related to the non-enzymatic hydrolysis of acetylcholine in the presence of both metal and vitamin [54]. The chemical mediator acetylcholine, $CH_3CO_2CH_2CH_2N^+(CH_3)_3$, is involved in the transmission of impulses throughout the cholinergic nervous system. The transmission of the impulse through the synapse is due to the liberation of acetylcholine which then transmits the impulse to the next nerve segment [55]. To ensure an orderly flow of impulses from nerve to nerve or from nerve to muscle or gland, the acetylcholine must be destroyed after its reaction with the receptor site and subsequent dissociation. This is effected by the enzyme acetylcholinesterase which catalyses the hydrolysis of acetylcholine to acetic acid and choline. The latter species may subsequently combine to regenerate the mediator. Physical data related to the non-enzymatic hydrolytic reaction of acetylcholine in the presence of both thiamine and copper(II) ions revealed that a 1:1 thiamine - Cu(II) complex was formed in aqueous solution [54]. The formation of a thiamine-acetylcholine complex has been shown to occur [56]. The thiamine-acetylcholine interaction is a chemical model for acetylcholinesterase-catalysed acetylcholine hydrolysis.

It was deduced that Cu(II) ions evidently inhibit the formation of the thiamine - acetylcholine complex. In order to investigate the role of Cu(II) ions in this scheme, a thiamine hydrochloride-Cu(II) complex was synthesised and its physico-chemical properties were examined by X-ray powder diffraction, UV, fluorescence, IR and NMR spectroscopy[16]. The IR and NMR spectra were used chiefly to ascertain the metal interaction site in the thiamine ligand. It was concluded that the copper atom is bonded to a pyrimidine ring nitrogen atom in the complex.

The three-dimensional X-ray crystal structure of this copper complex is presented here. As previous X-ray analyses had not revealed direct metal-binding in complexes of thiamine, it was considered of interest to elucidate the structure of the copper complex in view of the conclusions reached from the spectral studies.

With regard to thiamine-copper interaction, it has also recently been shown[57] that the metal specifically promotes reactions involving the thiazole ring, either by breaking the ring to form thiamine disulphide or by linking with the amino group to form thiochrome.

## Thiazoles as Thiamine analogues

Metal complexes of thiazole and its derivatives have been studied as model compounds for metal-thiamine interaction[22,23,24]. Further, as mentioned above, decarboxylation reactions effected by thiamine are postulated to occur *via* the zwitterion which formally involves electrostatic charges in the thiazolium ring of the vitamin molecule. Possible metal-binding sites in simple thiazoles are the ring nitrogen and sulphur atoms.

## Thiazole-Cobalt interaction :
## Motivation for structural analysis

With these points in mind, it was considered of interest to establish the structure of a suitable crystalline metal complex of thiazole. The ligand chosen for this study has the structural formula and numbering scheme shown in Fig. III.1.2. Its chemical name is 4-methyl-5(2-hydroxyethyl) thiazole but for the sake of abbreviation it will hereafter be referred to as MHET.

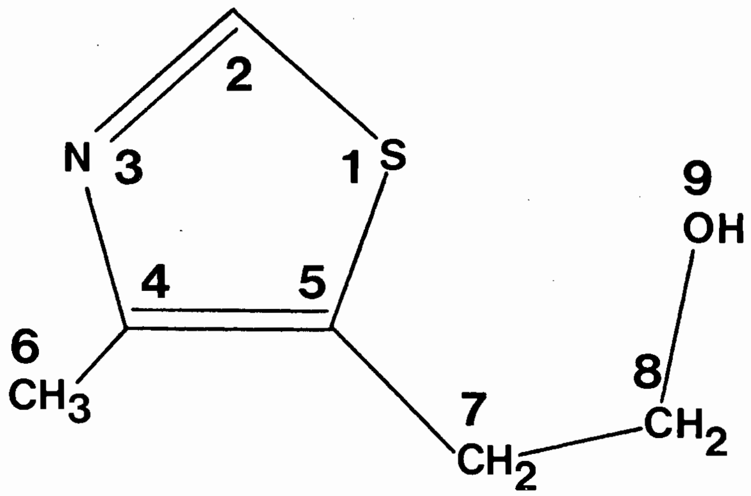

Fig. III.1.2

Comparison with the structure of thiamine hydrochloride (Fig. III.1.1) shows that this ligand is the neutral counterpart of the (charged) thiazolium moiety of the vitamin. Insofar as thiazoles may be regarded as thiamine analogues, this ligand serves as a rather good structural model. In addition, MHET is itself a biologically active molecule. A growth-stimulating effect of MHET on thiamine-deficient rats has been observed [25]. The addition of highly-purified MHET to a sub-optimal thiamine diet of rats resulted in an increased weight gain in these animals. In low concentration, the MHET had an activity comparable to that of thiamine. The likelihood of actual *in vivo* conversion of MHET to the vitamin was not supported by the experimental data. Several mechanisms for the observed activity were put forward, including the possibility that both MHET and thiamine can participate about equally well in some metabolic action.

In addition to sulphur and nitrogen donor atoms, the oxygen atom of the ethylhydroxy side-chain is also a potential donor in metal ion - MHET interaction. The choice of cobalt(II) as the metal ion was governed mainly by the quality of the crystalline products obtained by the reaction of a series of metals with this ligand [58]. In view of the potential binding-sites in MHET, four feasible structures were anticipated. These are N-,S- and O- metal-bonded possibilities (where the ligand is monodentate) and a six-membered chelate ring involving the bidentate S and O system. The X-ray analysis was undertaken in order to resolve the question of the metal-interaction site.

It was concurrently found that copper(II) ions also form a suitably crystalline complex and the latter structure was elucidated by a colleague [59] shortly after the X-ray analysis of the cobalt complex.

## III.2 THE CRYSTAL STRUCTURE OF THE THIAMINE HYDROCHLORIDE COPPER(II) COMPLEX;$(C_{12}H_{18}N_4OS)^{2+}(CuCl_4)^{2-}$

### Crystal preparation and chemical analysis

Single crystals of the compound were synthesised by the method of Marzotto et al[16]. 1.5g of thiamine.HCl(4.5mmoles) was mixed with 1.36g of $CuCl_2.2H_2O$(9mmoles) dissolved in 50 ml of methanol at room temperature. After two hours, chloroform (20 ml) was added to the reaction mixture. On standing for a few days, yellow-orange crystals separated.

These were filtered and dried under vacuum. The longer crystals were tabular and hexagonal in cross-section. Microanalytical data (Table III.2.1) are in accordance with the formulation of a 1:1 adduct of thiamine hydrochloride and copper(II) chloride.

TABLE III.2.1

| | %C | %H | %N |
|---|---|---|---|
| Calculated: | 30.57 | 3.82 | 11.87 |
| Found : | 30.4 | 3.8 | 11.9 |

### Density determination

The crystal density was determined as 1.72g $cm^{-3}$ by flotation in a mixture of chlorobenzene and methyl iodide. With the known unit cell volume, the number of adduct molecules in the cell was calculated as 4.

### Space group assignment

From Weissenberg photographs,the conditions for non-extinction of reflections were found to be $h0l$ $l$=2n and $0k0$

$k=2n$ which uniquely determine[60] the monoclinic space group $P2_1/c$.

Diffractometer data

A single crystal selected for intensity measurements was ground into a rough sphere of average radius 0.2 mm. Crystal data are listed in Table III.2.2.

TABLE III.2.2 CRYSTAL DATA

| | |
|---|---|
| Molecular formula | $(C_{12}H_{18}N_4OS)^{2+}(CuCl_4)^{2-}$ |
| Molecular weight | 471.8 g $\text{mole}^{-1}$ |
| Space group | $P2_1/c$ (Monoclinic, 2nd setting) |
| a = 9.488(5) Å | |
| b = 16.871(7) Å | $D_m = 1.72$ g $\text{cm}^{-3}$ |
| c = 12.940(5) Å | $D_c = 1.70$ g $\text{cm}^{-3}$ for Z = 4 |
| $\beta = 117.2(2)^\circ$ | $\mu(\text{MoK}\alpha) = 19.2\ \text{cm}^{-1}$ |
| V = 1841.85 $Å^3$ | F(000) = 956 |

For data collection the $\omega$-$2\theta$ scan mode was employed with a scan width of $1^\circ\theta$ and a speed of $0.04^\circ\theta\ \text{sec}^{-1}$. In the $2\theta$ range from $6^\circ$ to $40^\circ$, 1808 reflections were measured; 201 reflections including systematic absences had $I_{rel}<1.65\sigma(I_{rel})$ and they were excluded from the analysis. The remaining 1607 independent reflections constituted the observed data.

Throughout the data collection, three reference reflections were recorded after every 68 measured reflections; their intensities remained constant to within 2% of their respective mean values.

The value of $\mu R$ for the spherical crystal was 0.38 and the absorption correction factor A* varied[61] only between 1.80 and 1.79; this variation was considered negligible and no corrections for absorption were made.

## Solution and refinement of the structure

The position of the copper atom was readily deduced from a three-dimensional Patterson vector map (program CENTROSY).

An electron-density map based on the copper atom at this position revealed four large peaks surrounding the metal at distances ranging from 2.0 to 2.4 Å. The disposition of these peaks and their relative heights suggested the presence of a tetrachlorocuprate ion in the structure. Structure factor calculations including these five atoms yielded a conventional R factor of 0.46.

The remaining 18 non-hydrogen atoms of the vitamin residue were revealed in a subsequent electron-density map.

With unit weights assigned to all reflections, five cycles of least-squares refinement (program ORFLS) with isotropic temperature factors yielded an R of 0.08. Anisotropic temperature factors were introduced and three cycles of refinement reduced R to 0.05. The function minimised in the least-squares process was $\Sigma(|F_o|-|F_c|)^2$.

The atomic scattering factors used were those obtained from the Hartree-Fock-Slater model[62]. The copper atom was treated as $Cu^0$ and the anomalous dispersion correction ($\Delta f' = 0.3$ for MoKα radiation) was applied to the scattering curve[63].

In the last cycle of refinement, the average e.s.d. in the positional and thermal parameters was 50 times the average parameter shift which indicated satisfactory convergence. All of the hydrogen atoms were located in subsequent difference electron-density maps and they were assigned the anisotropic temperature factors of the atoms to which they were bonded.

After the final cycle of refinement in which the hydrogen atomic positions were varied, the average e.s.d. in these parameters was 20 times the average parameter shift and the residual index was 0.029. As a check of the correctness of the proposed model, a final difference electron-density map was prepared. This map was practically featureless. The final positional and thermal parameters for the non-hydrogen atoms are listed in Table III.2.3; hydrogen atom positions appear in Table III.2.4. Observed and calculated structure factors are listed in Table III.2.5.

## TABLE III.2.3

### NON-HYDROGEN ATOMS

### FRACTIONAL ATOMIC COORDINATES (x$10^4$) AND THEIR E.S.D'S AND ANISOTROPIC TEMPERATURE FACTORS

Thermal parameters are of the form

$$T = \exp\,[-(\beta_{11}h^2 + \beta_{22}k^2 + \beta_{33}l^2 + 2\beta_{12}hk + 2\beta_{23}kl + 2\beta_{31}lh)\mathrm{x}10^4].$$

| | $x$ | $y$ | $z$ | $\beta_{11}$ | $\beta_{22}$ | $\beta_{33}$ | $\beta_{12}$ | $\beta_{23}$ | $\beta_{31}$ |
|---|---|---|---|---|---|---|---|---|---|
| Cu | 845(1) | 2200(0) | 756(1) | 33 (2) | 18(0.4) | 42(1) | 5(1) | 19(1) | 7(1) |
| Cl(1) | 2406(2) | 1267(1) | 1981(1) | 45 (3) | 28(1) | 56(2) | 15(2) | 21(2) | 20(1) |
| Cl(2) | 2393(2) | 2542(1) | -102(1) | 64 (3) | 17(1) | 55(2) | -2(1) | 41(2) | 1(1) |
| Cl(3) | -49(2) | 3409(1) | 922(1) | 68 (4) | 18(1) | 58(2) | 7(1) | 41(2) | 0(1) |
| Cl(4) | -1473(2) | 1567(1) | 64(1) | 39 (3) | 21(1) | 50(2) | -3(1) | 12(2) | 7(1) |
| S (1) | -3458(2) | 3764(1) | 991(1) | 83 (4) | 16(1) | 61(2) | 12(2) | 48(3) | 7(1) |
| C (2) | -3039(6) | 2855(3) | 1551(5) | 54(11) | 18(3) | 47(6) | -0(5) | 32(7) | -2(4) |
| C (4) | -4598(5) | 3314(3) | 2320(4) | 17(10) | 17(3) | 26(6) | 45(4) | -2(6) | -5(4) |
| C (5) | -4603(6) | 3946(3) | 1691(4) | 31(10) | 17(3) | 29(6) | 4(4) | 4(6) | -9(4) |
| C (6) | -5424(7) | 3242(4) | 3062(5) | 68(12) | 31(3) | 46(7) | 10(5) | 32(7) | -2(4) |
| C (7) | -5455(7) | 4728(3) | 1497(5) | 66(12) | 17(3) | 41(7) | 6(5) | 12(8) | -7(4) |
| C (8) | -7187(6) | 4668(4) | 570(5) | 48(13) | 20(3) | 54(8) | 5(5) | 27(8) | 7(4) |
| C(10) | -3448(7) | 1929(3) | 2861(5) | 48(11) | 15(3) | 27(6) | -2(5) | 11(7) | -1(3) |
| C(12) | -1407(6) | 108(3) | 1732(4) | 59(13) | 12(3) | 26(6) | 1(5) | 16(7) | 6(3) |
| C(14) | -3629(6) | 811(3) | 1471(4) | 51(12) | 13(3) | 22(6) | -1(5) | 21(7) | 5(3) |
| C(15) | -2731(6) | 1300(3) | 2458(4) | 37(11) | 9(3) | 21(6) | -0(4) | 5(7) | 0(3) |
| C(16) | -1138(6) | 1147(3) | 3024(5) | 56(13) | 13(3) | 22(6) | -6(5) | 4(7) | -3(3) |
| C(17) | -611(8) | -501(4) | 1367(6) | 67(11) | 21(3) | 63(7) | 12(5) | 29(7) | -13(4) |
| N (3) | -3701(4) | 2691(2) | 2230(3) | 36 (8) | 15(2) | 19(4) | 1(4) | 12(5) | -3(3) |
| N(11) | -511(5) | 566(3) | 2657(4) | 33 (9) | 16(2) | 29(5) | 1(4) | 1(6) | -4(3) |
| N(13) | -2949(4) | 203(2) | 1170(3) | 25 (9) | 14(2) | 22(4) | 1(4) | 4(5) | -3(3) |
| N(18) | -5172(5) | 909(3) | 819(4) | 20(10) | 26(3) | 35(5) | 4(4) | 1(6) | -2(3) |
| O (9) | -7300(4) | 4431(2) | -525(3) | 66 (8) | 26(2) | 34(4) | 1(3) | 2(4) | -7(2) |

## TABLE III.2.4

## HYDROGEN ATOMS

## FRACTIONAL ATOMIC COORDINATES ($\times 10^3$) AND THEIR E.S.D.'s

| | $x$ | $y$ | $z$ |
|---|---|---|---|
| H(23) | -775(8) | 433(4) | 81(5) |
| H(24) | -769(7) | 521(4) | 49(5) |
| H(25) | -543(7) | 489(4) | 226(6) |
| H(26) | -494(7) | 519(4) | 132(5) |
| H(27) | -588(8) | 369(4) | 316(6) |
| H(28) | -620(8) | 287(4) | 294(6) |
| H(29) | -479(8) | 305(4) | 394(6) |
| H(30) | -253(7) | 247(4) | 123(5) |
| H(31) | -443(7) | 174(4) | 283(5) |
| H(32) | -273(7) | 204(4) | 368(6) |
| H(33) | -51(7) | 147(4) | 370(5) |
| H(34) | 36(7) | 50(4) | 292(5) |
| H(35) | -64(8) | -95(4) | 154(6) |
| H(36) | -106(7) | -56(4) | 43(6) |
| H(37) | 46(8) | -33(4) | 139(6) |
| H(38) | -575(7) | 63(4) | 23(6) |
| H(39) | -583(7) | 127(4) | 89(5) |
| H(40) | -727(8) | 388(4) | -46(6) |

# TABLE III.2.5

| h | k | $F_o$ | $F_c$ |
|---|---|---|---|
| | | ℓ = 0 | |
| 0 | 4 | 297 | -283 |
| 0 | 6 | 84 | -85 |
| 0 | 8 | 888 | 904 |
| 0 | 10 | 653 | -651 |
| 0 | 12 | 315 | -321 |
| 0 | 14 | 177 | 180 |
| 0 | 16 | 227 | -215 |
| 1 | 16 | 506 | -492 |
| 1 | 15 | 233 | 228 |
| 1 | 14 | 555 | 548 |
| 1 | 13 | 151 | 132 |
| 1 | 12 | 51 | -51 |
| 1 | 11 | 222 | 203 |
| 1 | 10 | 569 | -565 |
| 1 | 9 | 209 | -210 |
| 1 | 8 | 162 | -154 |
| 1 | 7 | 454 | 473 |
| 1 | 6 | 250 | 241 |
| 1 | 5 | 1295 | -1317 |
| 1 | 4 | 483 | 489 |
| 1 | 3 | 699 | 687 |
| 1 | 2 | 815 | -763 |
| 2 | 0 | 237 | -177 |
| 2 | 1 | 1348 | -1324 |
| 2 | 2 | 47 | -40 |
| 2 | 3 | 961 | 941 |
| 2 | 4 | 224 | -194 |
| 2 | 5 | 915 | -904 |
| 2 | 6 | 493 | 479 |
| 2 | 7 | 906 | 879 |
| 2 | 8 | 1030 | -1048 |
| 2 | 9 | 313 | 184 |
| 2 | 10 | 277 | 277 |
| 2 | 11 | 639 | -635 |
| 2 | 12 | 273 | 275 |
| 2 | 13 | 549 | 543 |
| 2 | 14 | 226 | 222 |
| 2 | 15 | 72 | -79 |
| 3 | 15 | 731 | -704 |
| 3 | 14 | 145 | 149 |
| 3 | 13 | 388 | 400 |
| 3 | 12 | 461 | -442 |
| 3 | 11 | 621 | -614 |
| 3 | 10 | 132 | -121 |
| 3 | 9 | 575 | 600 |
| 3 | 8 | 104 | -91 |
| 3 | 7 | 413 | -399 |
| 3 | 6 | 108 | -99 |
| 3 | 5 | 480 | -458 |
| 3 | 3 | 1028 | 991 |
| 3 | 2 | 38 | -32 |
| 3 | 1 | 328 | 286 |
| 3 | 0 | 524 | 510 |
| 4 | 0 | 517 | 477 |
| 4 | 1 | 242 | -240 |
| 4 | 2 | 390 | 366 |
| 4 | 3 | 677 | 642 |
| 4 | 4 | 227 | -222 |
| 4 | 5 | 240 | -250 |
| 4 | 7 | 183 | -176 |
| 4 | 8 | 106 | 116 |
| 4 | 9 | 189 | 185 |
| 4 | 10 | 535 | -521 |
| 4 | 11 | 131 | 138 |
| 4 | 12 | 283 | 291 |
| 4 | 13 | 222 | 221 |
| 4 | 14 | 435 | -449 |
| 5 | 12 | 545 | 539 |
| 5 | 11 | 73 | -82 |
| 5 | 10 | 455 | -464 |
| 5 | 9 | 598 | -593 |
| 5 | 7 | 368 | 365 |
| 5 | 6 | 332 | 341 |
| 5 | 5 | 160 | -148 |
| 5 | 4 | 583 | -578 |
| 5 | 2 | 71 | 79 |
| 5 | 1 | 1562 | -1578 |
| 5 | 0 | 921 | -893 |
| 6 | 0 | 906 | -904 |
| 6 | 1 | 173 | -175 |
| 6 | 2 | 513 | 519 |
| 6 | 3 | 61 | 72 |
| 6 | 4 | 903 | -905 |
| 6 | 5 | 388 | 370 |
| 6 | 6 | 875 | 880 |
| 6 | 7 | 133 | 133 |
| 6 | 8 | 274 | -286 |
| 6 | 9 | 204 | -214 |
| 7 | 8 | 174 | -180 |
| 7 | 7 | 268 | -259 |
| 7 | 6 | 961 | 962 |
| 7 | 5 | 100 | 99 |
| 7 | 4 | 386 | -377 |
| 7 | 3 | 207 | -224 |
| 7 | 2 | 493 | 509 |
| 7 | 1 | 845 | 863 |
| 7 | 0 | 282 | -277 |
| 8 | 0 | 492 | 461 |
| 8 | 1 | 629 | 635 |
| 8 | 2 | 148 | -157 |
| | | ℓ = 1 | |
| -8 | 5 | 222 | -230 |
| -8 | 4 | 108 | 79 |
| -8 | 3 | 292 | 300 |
| -8 | 2 | 838 | -856 |
| -8 | 1 | 346 | -347 |
| -7 | 1 | 225 | -239 |
| -7 | 2 | 294 | 285 |
| -7 | 3 | 97 | 61 |
| -7 | 5 | 473 | -468 |
| -7 | 6 | 89 | 66 |
| -7 | 7 | 728 | 726 |
| -7 | 8 | 111 | -108 |
| -7 | 9 | 215 | -229 |
| -6 | 11 | 320 | 313 |
| -6 | 10 | 644 | 645 |
| -6 | 9 | 269 | -279 |
| -6 | 8 | 417 | 407 |
| -6 | 7 | 666 | 674 |
| -6 | 6 | 238 | -229 |
| -6 | 5 | 238 | -231 |
| -6 | 4 | 352 | -350 |
| -6 | 3 | 553 | 546 |
| -6 | 2 | 986 | 993 |
| -5 | 1 | 102 | -92 |
| -5 | 2 | 696 | 691 |
| -5 | 3 | 193 | 176 |
| -5 | 4 | 743 | -754 |
| -5 | 5 | 625 | -611 |
| -5 | 6 | 311 | 295 |
| -5 | 7 | 280 | 277 |
| -5 | 8 | 63 | -59 |
| -5 | 11 | 441 | 439 |
| -5 | 12 | 403 | -409 |
| -5 | 13 | 430 | -426 |
| -4 | 14 | 555 | 541 |
| -4 | 13 | 497 | -497 |
| -4 | 12 | 320 | -315 |
| -4 | 11 | 82 | 72 |
| -4 | 10 | 90 | 91 |
| -4 | 9 | 716 | 721 |
| -4 | 8 | 367 | -353 |
| -4 | 6 | 905 | 897 |
| -4 | 5 | 289 | -281 |
| -4 | 4 | 1167 | -1157 |
| -4 | 3 | 235 | 218 |
| -4 | 2 | 397 | 404 |
| -4 | 1 | 816 | -763 |
| -3 | 1 | 1373 | -1351 |
| -3 | 2 | 845 | 837 |
| -3 | 3 | 1107 | 1066 |
| -3 | 4 | 311 | -317 |
| -3 | 5 | 531 | 539 |
| -3 | 6 | 635 | 630 |
| -3 | 7 | 863 | -866 |
| -3 | 8 | 772 | -775 |
| -3 | 9 | 650 | 643 |
| -3 | 10 | 976 | 967 |
| -3 | 11 | 91 | 91 |
| -3 | 12 | 580 | -585 |
| -3 | 13 | 72 | 60 |
| -3 | 14 | 223 | 214 |
| -3 | 15 | 147 | -146 |
| -2 | 16 | 115 | 109 |
| -2 | 13 | 78 | 58 |
| -2 | 11 | 316 | -316 |
| -2 | 10 | 422 | 414 |
| -2 | 9 | 491 | 536 |
| -2 | 7 | 1524 | -1537 |
| -2 | 6 | 556 | 562 |
| -2 | 5 | 689 | 691 |
| -2 | 3 | 247 | 202 |
| -2 | 2 | 744 | 700 |
| -2 | 1 | 189 | 170 |
| -1 | 2 | 509 | -490 |
| -1 | 3 | 1064 | -1048 |
| -1 | 4 | 303 | -289 |
| -1 | 5 | 363 | 370 |
| -1 | 6 | 648 | -646 |
| -1 | 7 | 600 | -596 |
| -1 | 8 | 528 | -505 |
| -1 | 9 | 1226 | 1257 |
| -1 | 10 | 56 | -57 |
| -1 | 11 | 1197 | -1214 |
| -1 | 12 | 51 | 62 |
| -1 | 13 | 49 | 56 |
| -1 | 14 | 370 | -366 |
| -1 | 16 | 192 | 173 |
| 0 | 16 | 309 | -284 |
| 0 | 15 | 57 | -58 |
| 0 | 14 | 234 | 249 |
| 0 | 13 | 519 | 508 |
| 0 | 12 | 96 | 121 |
| 0 | 11 | 89 | -86 |
| 0 | 10 | 434 | -440 |
| 0 | 9 | 478 | 477 |
| 0 | 8 | 496 | 513 |
| 0 | 7 | 579 | -405 |
| 0 | 5 | 627 | 636 |
| 0 | 4 | 902 | -902 |
| 0 | 3 | 342 | -334 |
| 1 | 1 | 539 | 531 |
| 1 | 2 | 709 | -708 |
| 1 | 3 | 684 | 660 |
| 1 | 4 | 829 | 796 |
| 1 | 5 | 981 | 969 |
| 1 | 7 | 375 | -389 |
| 1 | 8 | 1238 | 1262 |
| 1 | 9 | 256 | 248 |
| 1 | 10 | 1172 | -1158 |
| 1 | 11 | 125 | -144 |
| 1 | 14 | 408 | 412 |
| 2 | 15 | 98 | 85 |
| 2 | 14 | 149 | -139 |
| 2 | 13 | 171 | -180 |
| 2 | 12 | 307 | 312 |
| 2 | 11 | 419 | -417 |
| 2 | 10 | 336 | -333 |
| 2 | 9 | 523 | 900 |
| 2 | 8 | 1391 | 1413 |
| 2 | 7 | 805 | -789 |
| 2 | 6 | 1635 | -1669 |
| 2 | 5 | 404 | -375 |
| 2 | 4 | 458 | -434 |
| 2 | 3 | 390 | 359 |
| 2 | 2 | 1475 | 1425 |
| 2 | 1 | 456 | 440 |
| 3 | 1 | 300 | -286 |
| 3 | 2 | 334 | -330 |
| 3 | 3 | 1286 | 1242 |
| 3 | 5 | 440 | -458 |
| 3 | 6 | 1281 | -1287 |
| 3 | 7 | 190 | -189 |
| 3 | 8 | 576 | 572 |
| 3 | 9 | 48 | -42 |
| 3 | 10 | 220 | -218 |
| 3 | 11 | 243 | 238 |
| 3 | 12 | 228 | 221 |
| 3 | 13 | 519 | -525 |
| 3 | 16 | 79 | -86 |
| 4 | 13 | 814 | -807 |
| 4 | 12 | 543 | 539 |
| 4 | 11 | 432 | 435 |
| 4 | 10 | 820 | -823 |
| 4 | 8 | 398 | 404 |
| 4 | 7 | 374 | 357 |
| 4 | 6 | 157 | 151 |
| 4 | 5 | 1125 | -1120 |
| 4 | 4 | 432 | 414 |
| 4 | 3 | 593 | 587 |
| 4 | 2 | 569 | -573 |
| 4 | 1 | 179 | -178 |
| 5 | 1 | 349 | -335 |
| 5 | 2 | 151 | -141 |
| 5 | 3 | 833 | 840 |
| 5 | 4 | 210 | 207 |
| 5 | 5 | 501 | -506 |
| 5 | 6 | 111 | 120 |
| 5 | 7 | 191 | 205 |
| 5 | 8 | 92 | -71 |
| 5 | 9 | 459 | -444 |
| 5 | 10 | 365 | 371 |
| 5 | 11 | 86 | 91 |
| 6 | 10 | 360 | 372 |
| 6 | 9 | 783 | -785 |
| 6 | 8 | 598 | -594 |
| 6 | 7 | 161 | -139 |
| 6 | 6 | 243 | -247 |
| 6 | 5 | 390 | -373 |
| 6 | 4 | 304 | -300 |
| 6 | 3 | 528 | 535 |
| 6 | 2 | 312 | 308 |
| 6 | 1 | 220 | -230 |
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| -3 | 2 | 173 | 176 |
| -3 | 3 | 942 | 920 |
| -3 | 4 | 180 | -166 |
| -3 | 5 | 87 | -85 |
| -3 | 6 | 374 | -390 |
| -3 | 7 | 339 | -322 |
| -2 | 6 | 444 | 445 |
| -2 | 4 | 458 | -450 |
| -2 | 3 | 364 | 381 |
| -2 | 2 | 83 | -72 |
| -2 | 1 | 221 | -221 |
| -1 | 1 | 80 | 62 |
| -1 | 2 | 158 | 164 |
| -1 | 3 | 83 | 74 |
| -1 | 5 | 419 | -420 |
| 0 | 1 | 139 | 162 |
| | | ℓ = 12 | |
| -6 | 0 | 61 | 66 |
| -6 | 1 | 342 | -328 |
| -5 | 3 | 270 | -199 |
| -5 | 2 | 429 | 437 |
| -5 | 1 | 89 | -62 |
| -5 | 0 | 188 | -198 |
| -4 | 0 | 272 | -274 |
| -4 | 1 | 244 | 208 |
| -4 | 2 | 75 | -13 |
| -4 | 3 | 341 | -330 |
| -3 | 3 | 228 | -270 |
| -3 | 1 | 104 | 114 |
| -3 | 0 | 390 | -388 |
| -2 | 0 | 132 | 125 |
| -2 | 1 | 326 | 224 |

## III.3 DESCRIPTION OF THE STRUCTURE AND DISCUSSION

Intramolecular bond lengths and bond angles are listed in Tables III.3.1 and III.3.2 respectively. Least-squares planes are listed in Table III.3.3.

The molecular structure viewed down the unit cell *a* axis is shown in Fig. III.3.1. The atomic nomenclature in the vitamin residue is the same as that used for thiamine hydrochloride[64]. This system is crystallographically more convenient than the organic nomenclature.

The asymmetric unit consists of a tetrachlorocuprate anion and a thiaminium cation so that the compound is better formulated as (protonated thiamine)$^{2+}$($CuCl_4$)$^{2-}$. The copper atom is tetrahedrally surrounded by four chlorine atoms at an average Cu-Cl distance of 2.25 Å, but the deviation of the Cl-Cu-Cl bond angles from ideal tetrahedral geometry is considerable. Four of these angles are roughly equal (mean 99°) and the remaining two are approximately 136 and 131°. This flattening of the tetrachlorocuprate tetrahedron has been observed in several other structures[65,66,67,68]. In the crystal structure of the ionic compound[68] $[(C_2H_5)_3NH]_2CuCl_4$ the average Cu-Cl distance is 2.24 Å. Four of the Cl-Cu-Cl angles average about 98° while the remaining two are 136.75 (0.10)° and 132.91 (0.10)°.

Bond lengths and angles in the vitamin residue compare very favourably with those found in the structure

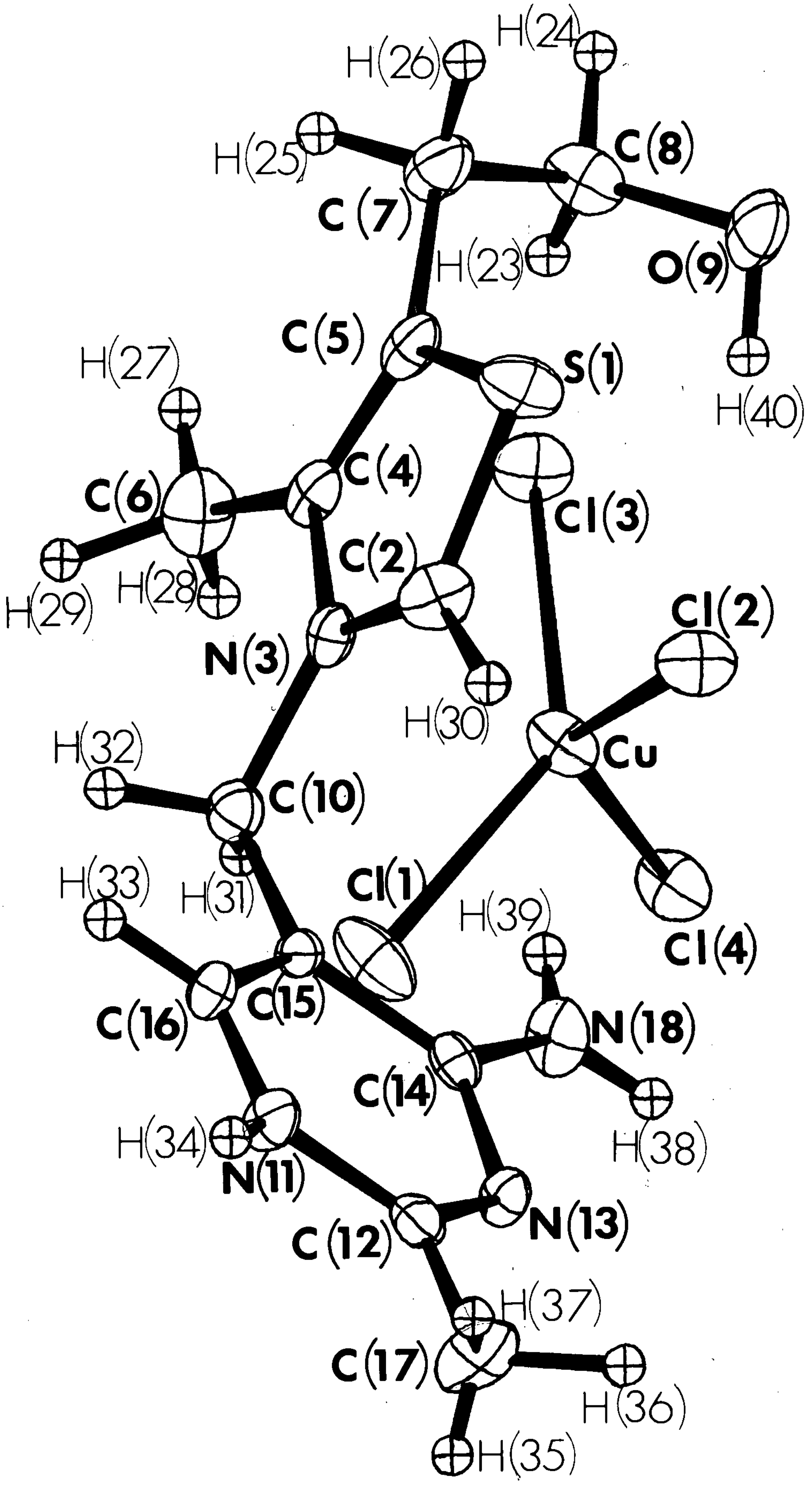

H(24)
H(26)
H(25)
C(8)
C (7)
O(9)
H(23)
C(5)
S(1)
H(40)
H(27)
C(4)
C(6)
Cl(3)
C(2)
H(28)
H(29)
Cl(2)
N(3)
H(30)
Cu
H(32)
C(10)
H(33)
H(31)
Cl(1)
H(39)
Cl(4)
C(16)
C(15)
N(18)
C(14)
H(38)
H(34)
N(11)
N(13)
C (12)
H(37)
C(17)
H(36)
H(35)

FIG. III.3.1

## TABLE III.3.1

## INTRAMOLECULAR BOND LENGTHS AND THEIR E.D.S.'s (Å)

(For bond distances involving H atoms, the e.s.d.'s are 0.1 Å)

| | | | |
|---|---|---|---|
| Cu—Cl(1) | 2.245(4) | | |
| Cu—Cl(2) | 2.283(3) | | |
| Cu—Cl(3) | 2.257(2) | | |
| Cu—Cl(4) | 2.231(3) | | |
| S(1)—C(2) | 1.664(6) | | |
| S(1)—C(5) | 1.731(7) | C(8)—H(23) | 0.9 |
| C(2)—N(3) | 1.323(9) | C(8)—H(24) | 1.0 |
| N(3)—C(4) | 1.391(7) | C(7)—H(25) | 1.0 |
| C(4)—C(5) | 1.339(8) | C(7)—H(26) | 1.0 |
| C(4)—C(6) | 1.50(1) | C(6)—H(27) | 0.9 |
| C(5)—C(7) | 1.508(8) | C(6)—H(28) | 0.9 |
| C(7)—C(8) | 1.533(8) | C(6)—H(29) | 1.1 |
| C(8)—O(9) | 1.427(8) | C(2)—H(30) | 1.0 |
| N(3)—C(10) | 1.482(7) | O(9)—H(40) | 0.9 |
| C(10)-C(15) | 1.478(9) | C(10)-H(31) | 1.0 |
| N(11)-C(12) | 1.349(7) | C(10)-H(32) | 1.0 |
| C(12)-N(13) | 1.313(7) | C(16)-H(33) | 1.0 |
| N(13)-C(14) | 1.360(7) | N(11)-H(34) | 0.7 |
| C(14)-C(15) | 1.430(7) | C(17)-H(35) | 0.8 |
| C(15)-C(16) | 1.369(7) | C(17)-H(36) | 1.1 |
| N(11)-C(16) | 1.342(8) | C(17)-H(37) | 1.0 |
| C(12)-C(17) | 1.48(1) | N(18)-H(38) | 0.9 |
| C(14)-N(18) | 1.323(7) | N(18)-H(39) | 0.9 |

## TABLE III.3.2

## INTRAMOLECULAR BOND ANGLES AND THEIR E.S.D.'s (DEGREES)

| | | | |
|---|---|---|---|
| Cl(1)-Cu-Cl(2) | 99.07(7) | C(4)—C(5)—C(7) | 130.5(6) |
| Cl(1)-Cu-Cl(4) | 99.09(7) | C(5)—C(7)—C(8) | 111.9(5) |
| Cl(2)-Cu-Cl(3) | 99.88(7) | C(7)—C(8)—O(9) | 111.3(6) |
| Cl(3)-Cu-Cl(4) | 97.26(7) | N(3)—C(10)-C(15) | 114.3(6) |
| Cl(1)-Cu-Cl(3) | 136.20(7) | | |
| Cl(2)-Cu-Cl(4) | 131.40(7) | C(12)-N(11)-C(16) | 122.1(4) |
| | | N(11)-C(12)-N(13) | 120.8(5) |
| C(2)-S(1)-C(5) | 91.0(3) | N(11)-C(12)-C(17) | 118.4(5) |
| S(1)-C(2)-N(3) | 113.0(4) | N(13)-C(12)-C(17) | 120.8(4) |
| C(2)-N(3)-C(4) | 113.1(4) | C(12)-N(13)-C(14) | 119.2(4) |
| C(2)-N(3)-C(10) | 122.8(5) | N(13)-C(14)-C(15) | 121.6(4) |
| C(4)-N(3)-C(10) | 124.1(5) | N(13)-C(14)-N(18) | 116.3(4) |
| N(3)-C(4)-C(5) | 112.6(6) | C(15)-C(14)-N(18) | 122.1(5) |
| N(3)-C(4)-C(6) | 120.8(5) | C(14)-C(15)-C(16) | 115.5(5) |
| C(5)-C(4)-C(6) | 126.6(5) | C(10)-C(15)-C(16) | 121.4(4) |
| S(1)-C(5)-C(4) | 110.4(4) | C(10)-C(15)-C(14) | 123.2(4) |
| S(1)-C(5)-C(7) | 119.1(5) | N(11)-C(16)-C(15) | 120.6(4) |

of thiamine hydrochloride. An important feature is the site of protonation in the pyrimidine ring. As in the parent vitamin, the atom N(11) opposite the amino group is protonated. The region around N(13), the other possible site of hydrogen attachment, was scanned in difference electron-density maps, but this revealed no peaks confirming that all of the hydrogen atoms had been correctly located. A plausible explanation for the preferred N(11) protonation site in the case of the parent hydrochloride has been offered[64] in terms of qualitative resonance theory. Distances for C-H and N-H bonds in the copper adduct are within the expected ranges.

Least-squares planes for the pyrimidine and thiazolium rings were calculated (Table III.3.3). In the pyrimidine ring, the greatest deviation from the least-squares plane is that of N(13), 0.03 Å. The standard deviation of the six atoms defining the plane is 0.02 Å from the least-squares plane. The thiazolium ring is planar; the standard deviation of the five atoms from this plane is 0.003 Å and the maximum deviation, that of atom C(5) is 0.0038 Å. The acute angle between the pyrimidine and thiazolium ring planes is 89.3°. Dihedral angles between these planes for related structures are 76° for thiamine hydrochloride, and 90° for thiamine monophosphate[69]. Flexibility in the orientations of these ring planes in related structures has been pointed out. In addition, the structural relationship[70] between the pyrimidine amino group and the thiazolium dimethylene side chain is "*cis*" in the copper adduct as is the case in thiamine monophosphate

# TABLE III.3.3

## LEAST-SQUARES PLANES

The equations of the planes are expressed in orthogonalized space as $PI+QJ+RK=S$.

Plane I: through the atoms of the pyrimidine ring

Equation: $0.47455I+0.63898J-0.6054K= -2.2231$

| Atoms included in calculation | Dist. from plane | Atoms not included in calculation | Dist. from plane |
|---|---|---|---|
| C(15) | -0.007Å | C(10) | -0.047Å |
| C(16) | -0.009 | H(33) | -0.039 |
| N(11) | 0.006 | H(34) | 0.069 |
| C(12) | 0.013 | C(17) | 0.071 |
| N(13) | -0.030 | | |
| C(14) | 0.026 | N(18) | 0.074 |

Plane II: through the atoms of the thiazolium ring

Equation: $0.50087I+0.35636J+ 0.78876K= 1.22196$

| Atoms included in calculation | Dist. from plane | Atoms not included in calculation | Dist. from plane |
|---|---|---|---|
| N(3) | -0.0002Å | C(10) | 0.048Å |
| C(4) | 0.0031 | C(6) | 0.021 |
| C(5) | -0.0038 | C(7) | -0.056 |
| S(1) | 0.0030 | | |
| C(2) | -0.002 | H(30) | -0.186 |

and in thiamine hydrochloride. In the latter structure, the rings are oriented so that the pyrimidine amino group can readily interact with atom C(2) of the thiazolium ring. The non-bonded distance C(2).... N(18) is 3.50 Å while in the copper adduct, this distance is 3.74 Å.

An extensive hydrogen bonded network exists in the structure. These are interactions of the types N-H...Cl, N-H...O, O-H...Cl and C-H...Cl. Relevant interatomic distances and angles are listed in Table III.3.4. For each entry in this table, the interatomic distance between the hydrogen and the acceptor atom has a value equal to or below that for which a hydrogen bond may be said to exist[71], but it must be noted that the average error in these distances is fairly large (0.1 Å).

TABLE III.3.4 INTERATOMIC DISTANCES (Å) AND ANGLES (°) FOR HYDROGEN BONDS, N-H...Cl, O-H...Cl AND C-H...Cl INTERACTIONS

Symmetry operations : The atoms without superscripts refer to the basic asymmetric unit whose coordinates (x,y,z) are given in Tables III.2.3 and III.2.4.

(i) x + 1, ½ - y, ½ + z

(ii) x - 1, y, z

(iii) x, ½ - y, ½ + z.

| | | | | | |
|---|---|---|---|---|---|
| H(34)..O(9$^{i}$) | 2.2(1) | N(11)..O(9$^{i}$) | 2.87(1) | ∠N-H..O | 148(7)° |
| H(39)..Cl(1$^{ii}$) | 2.6(1) | N(18)..Cl(1$^{ii}$) | 3.33(1) | ∠N-H..Cl | 133(7)° |
| H(39)..Cl(2$^{ii}$) | 2.7(1) | N(18)..Cl(2$^{ii}$) | 3.44(1) | ∠N-H..Cl | 144(6)° |
| H(40)..Cl(2$^{ii}$) | 2.35(7) | O(9)...Cl(2$^{ii}$) | 3.27(1) | ∠O-H..Cl | 166(7)° |
| H(23)..Cl(3$^{ii}$) | 2.7(1) | C(8)...Cl(3$^{ii}$) | 3.64(1) | ∠C-H..Cl | 164(7)° |
| H(30)..Cl(4) | 2.64(8) | C(2)...Cl(4) | 3.64(1) | ∠C-H..Cl | 171(4)° |
| H(31)..Cl(1$^{ii}$) | 2.8(1) | C(10)..Cl(1$^{ii}$) | 3.73(1) | ∠C-H..Cl | 162(5)° |
| H(33)..Cl(3$^{iii}$) | 2.7(1) | C(16)..Cl(3$^{iii}$) | 3.49(1) | ∠C-H..Cl | 137(5)° |

All of the interactions recorded above are represented by dashed lines in Fig. III.3.2. In this figure, the superscripted atoms are symmetry-related to the corresponding atoms of the asymmetric unit. The two $CuCl_4{}^{2-}$ units drawn are equivalent by translation along the x-direction; atom Cl($3^{iii}$) is a chlorine of a third $CuCl_4{}^{2-}$ unit close to the thiamine cation.

There are two N-H..Cl interactions, one N-H..O intermolecular hydrogen bond, one O-H..Cl and four C-H..Cl interactions. Atom H(39) of the pyrimidine amino group is engaged in interactions with two chlorine atoms giving rise to a system similar to the bifurcated hydrogen bond (involving the same atom types) observed in glycine hemihydrochloride[72]. The intermolecular N-H..O hydrogen bond with the distance N(11)...O($9^{i}$) of 2.87(1) Å was also detected in the structure of bis (protonated thiamine)$^{2+}$ $(UO_2Cl_4)^{2-}$. The relevant hydrogen was not located in the latter analysis but the non-bonded N(11)...O(9) distance was 2.77 Å.

A common feature of the copper compound and thiamine hydrochloride is the apparent formation of C-H...Cl hydrogen bonds. In the parent hydrochloride, these bonds involve H(33) and H(30) with H...$Cl^-$ distances of 2.5 and 2.6 Å respectively. Four H..Cl distances less than the normal van der Waals sum of 3.0 Å are observed in the copper compound and these involve atoms H(33), H(30), H(31) and H(23). These interactions, especially those involving methylene hydrogens, are probably very weak since each hydrogen is interacting with a Cl of a $CuCl_4{}^{2-}$ unit and not with a

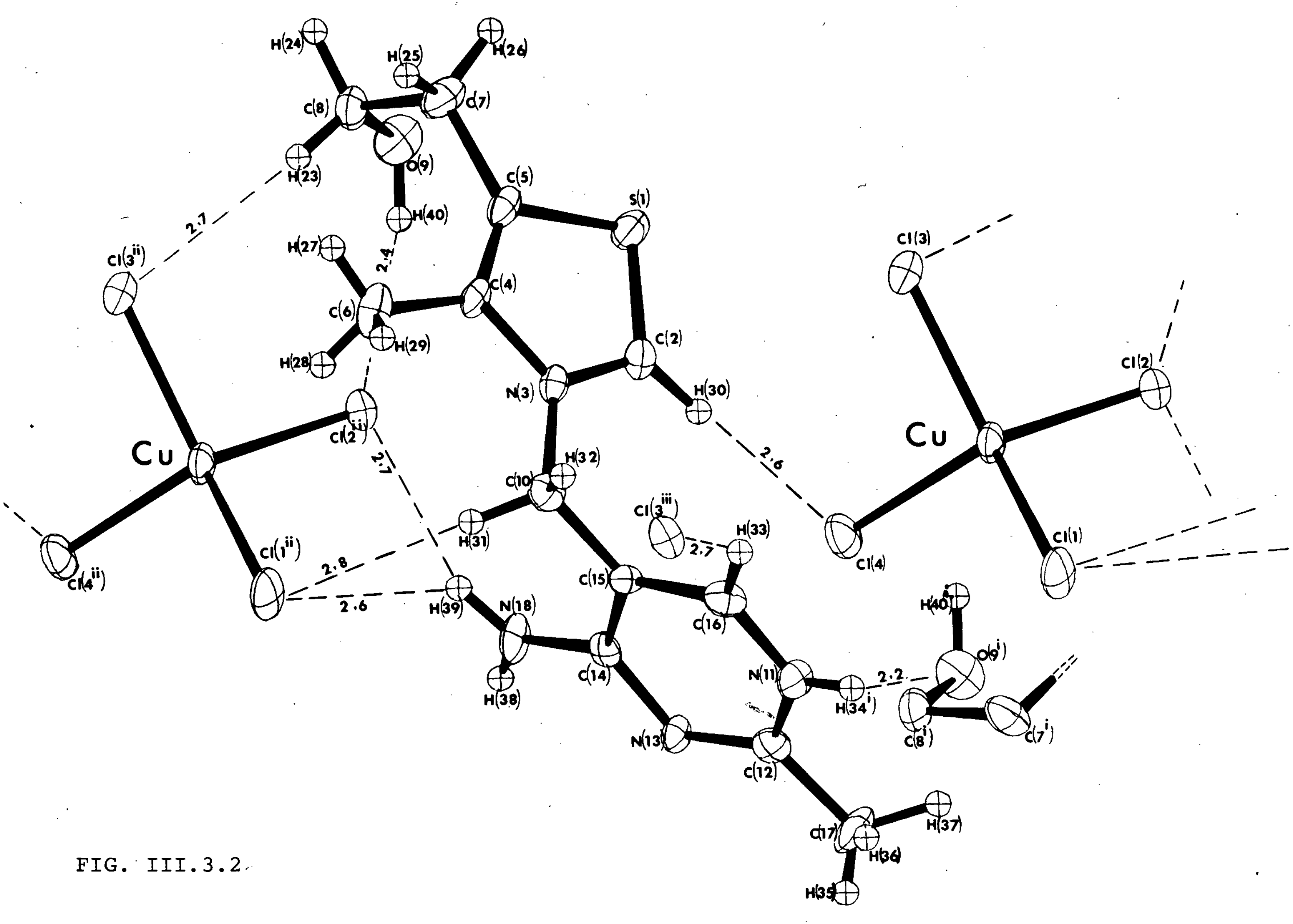

H(24)
H(25)
H(26)
C(8)
C(7)
O(9)
H(23)
C(5)
S(1)
H(40)
2.7
H(27)
2.4
Cl(3ii)
C(4)
C(6)
H(29)
C(2)
H(28)
H(30)
N(3)
Cu
Cl(2ii)
Cl(3)
Cl(2)
Cu
2.7
H(32)
2.6
C(10)
Cl(3iii)
H(33)
H(31)
Cl(1ii)
2.7
Cl(4)
Cl(1)
Cl(4ii)
2.8
C(15)
H(39)
N(18)
C(16)
H(40i)
2.6
O(9i)
C(14)
N(11)
2.2
H(34i)
H(38)
C(8i)
C(7i)
N(13)
C(12)
H(37)
C(17)
H(36)
H(35)

FIG. III.3.2

full charge of a free $Cl^-$ ion as in the case of thiamine hydrochloride. For the same reason, the N-H...Cl interactions are probably much weaker than those found in the parent vitamin. In the structure of $[(C_2H_5)_3NH]_2CuCl_4$ however[68], an analogous N-H...Cl hydrogen bond involving a Cl atom of the tetrachlorocuprate anion and the organic cation is reported with a N...Cl distance of 3.11 Å.

## Copper Coordination

For copper(II) ions, direct binding to a ring nitrogen of the thiamine pyrimidine ring was postulated[16]. It should be noted that several of the spectral studies were performed in solution. A methanolic solution of the copper complex was used for the UV spectrum. The fluorescence spectrum was obtained from an aqueous solution of the complex and the NMR analysis included spectra measured in $D_2O$. However, the X-ray powder pattern and the infrared spectrum were obtained from the complex in the solid-state. The solid-state X-ray analysis presented here shows that there is no direct bonding between copper ions and thiamine. This finding does not preclude the possibility of such binding in solution. From data for the analogous cobalt compound, $(\text{thiamine})^{2+}(CoCl_4)^{2-}$, obtained by spectroscopic and magnetic measurements[53], it was predicted that the formation of a "complex salt" of the type $(L)^{2+}(MX_4)^{2-}$ is a strong possibility where a "built-in" cation exists within the molecule L. It was also pointed out that the existence of the ionic forms can only be proven by a rather detailed study because the 1:1 stoichiometry of metal-thiamine adducts does not rule out metal-nitrogen or metal-sulphur interaction. In the crystal structure[17] of bis(protonated thiamine)tetrachlorodioxouranium(VI), two protonated vitamin residues are associated with one octahedral $(UO_2Cl_4)^{2-}$ ion. It has also been clearly shown[18] that cadmium does not coordinate to thiamine in the compound [(protonated thiaminium)tetrachlorocadmate monohydrate]. It therefore appears that when sufficient anion (e.g. chloride) is present in acid solutions, the metal-halide anion forms preferentially. This observation does not, however, preclude coordination of thiamine under different experimental conditions. (e.g. higher pH, different anions).

The geometry of the tetrachlorocuprate ion in the adduct is that of a flattened tetrahedron. The structure is intermediate between a tetrahedral and square planar form, far on the tetrahedral side. This feature has been observed in other ionic compounds[65,66,67,68] containing $CuCl_4{}^{2-}$. A comparison of bond lengths and angles in several structures containing the tetrachlorocuprate anion is provided in Table III.3.5. (See overleaf). All results were obtained by X-ray methods. A theoretical treatment[73] starting with an ionic model and taking into account the polarization of the $Cl^-$ ions and their perturbation on the 3d orbitals of the cupric ion leads to calculated Cl-Cu-Cl bond angles ($122.4^o$ and $103.4^o$) in general agreement with those observed.

## TABLE III.3.5 COMPARISON OF BOND LENGTHS AND ANGLES IN $CuCl_4^{2-}$ IONS IN DIFFERENT STRUCTURES

| Associated cation (s) | $[(C_2H_5)_3NH]_2^+$ | $(C_{12}H_{18}N_4OS)^{2+}$ | $(C_{12}H_{14}N_2)^{2+}$ | $(C_{13}H_{19}N_2OS)_2^+$ |
|---|---|---|---|---|
| Reference | 68 | present study | 66 | 67 |
| Cu-Cl distances (Å) | 2.237(2)<br>2.239(2)<br>2.247(2)<br>2.240(2) | 2.245(4)<br>2.283(3)<br>2.257(2)<br>2.231(3) | 2.244(1)<br>2.249(1)<br>* | 2.259(3)<br>2.220(2)<br>* |
| Cl-Cu-Cl angles (°) | 98.53(0.10)<br>99.62(0.09)<br>99.09(0.10)<br>96.60(0.09)<br>132.91(0.10)<br>136.75(0.10) | 99.07(7)<br>99.09(7)<br>99.88(7)<br>97.26(7)<br>131.40(7)<br>136.20(7) | 99.23(6)<br>100.66(4)<br>101.85(6)<br>129.18(5) | 94.56(6)<br>98.59(6)<br>96.64(5)<br>143.53(5) |

* Anion situated on a two-fold axis

A more recent molecular-orbital calculation[74] of the stable charge separation in the ground state of tetrahedral $CuCl_4^{2-}$ has yielded the model $Cu^{+0.92}\ 4Cl^{-0.73}$, but such charge separation was not taken into account in the assignment of scattering factors in the present analysis. Such a refinement would presumably affect atomic thermal parameters significantly, but not bond distances and angles in the ion.

### Thiamine Conformation

The relative ring orientation in the thiamine moiety in thiamine-containing compounds has undoubtedly been the structural feature which has received closest attention. The reason for the significance of the molecular conformation of thiamine is that its biological action may be correlated with this parameter.

Since the two rings in the molecule, pyrimidine and thiazolium, are joined through a methylene bridge carbon, the relative ring orientation is provided in terms of the torsion angles about the bonds from the methylene carbon to the rings. Figure III.3.3 shows the structural formula and numbering scheme of the thiamine molecular skeleton.

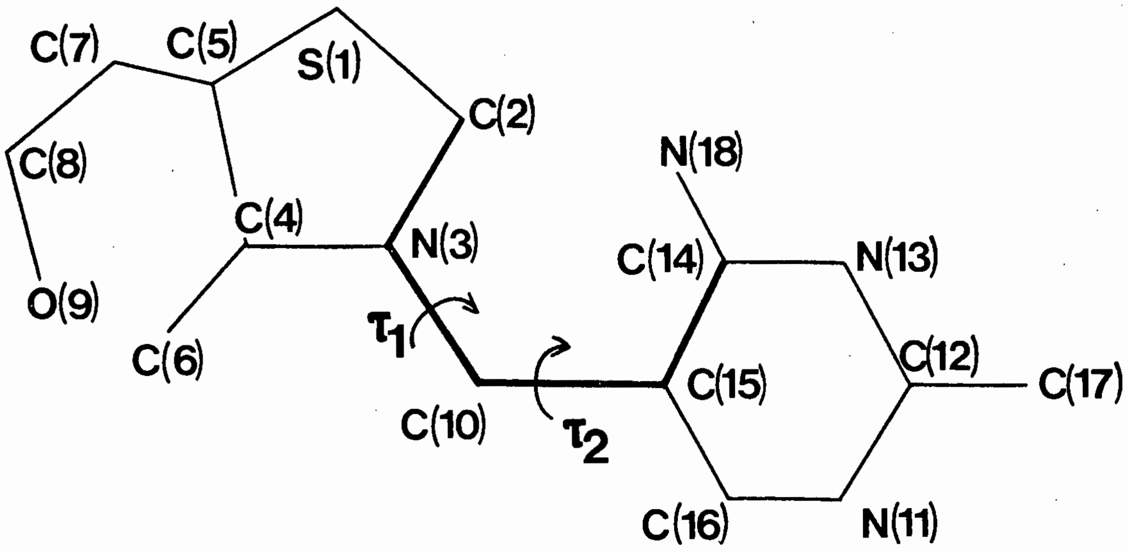


Fig. III.3.3

The conformation of this system is completely specified by the two torsion angles $\tau_1$ and $\tau_2$ defined by C(2) N(3) C(10) C(15) and N(3) C(10) C(15) C(14) respectively. Bonds linking the five atoms involved are drawn in bold in the figure. These torsion angles have been calculated for the thiamine residue as it occurs in the crystal structures of several related compounds, including the copper(II)-thiamine hydrochloride complex. If the two rings are themselves planar, combination of these torsion angles $\tau_1$ and $\tau_2$, yields a resultant dihedral angle i.e. the angle between the normals to the pyrimidine and thiazolium rings. As a result of rotating the rings, atoms C(2) and N(18) may be made to approach one another. Table III.3.6 lists the relevant data which was calculated from the published coordinates and cell parameters of the various structures.

TABLE III.3.6 COMPARISON OF TORSION AND DIHEDRAL ANGLES (°) AND RELEVANT NON-BONDED SEPARATIONS (Å) IN RELATED THIAMINE RESIDUES

| Structure | Thiamine pyrophosphate | | Bis(protonated thiamine) tetrachloro-dioxouranium(VI) | Thiamine Hydrochloride | Copper(II)-Thiamine Hydrochloride Complex |
|---|---|---|---|---|---|
| Reference | 75 | | 17 | 64 | present study |
| $\tau_1$ (°) | 8.3 | -15.4 | 5.4 | -9.0 | -14.1 |
| $\tau_2$ (°) | -55.5 | -82.3 | -83.7 | -76.1 | -82.6 |
| Dihedral angle (°) | 70.0 | 85.0 | 74.4 | 76.0 | 89.3 |
| Non-bonded C(2)..N(18) distance (Å) | 2.48 | 3.95 | 3.49 | 3.50 | 3.74 |

It is clear that the conformation of the thiamine moiety in the copper(II)-thiamine hydrochloride complex is very close to that of the second molecule in thiamine pyrophosphate, and quite similar to that observed in the parent vitamin, thiamine hydrochloride. (In the thiamine pyrophosphate structure, two independent thiamine conformers constitute the asymmetric unit).

To date,two basic conformations of thiamine have been observed. In the first (exemplified by all of the compounds listed above), the thiazolium ring is roughly coplanar with the N(3)-C(10)-C(15) plane (reflected in $\tau_1$), while the pyrimidine ring is almost perpendicular to this plane (reflected in $\tau_2$). The second conformation, in which the thiazolium ring is almost perpendicular to the N(3)-C(10)-C(15) plane,has been observed in 2-(α-hydroxyethyl) thiamine [76] and in (protonated thiaminium)tetrachlorocadmate monohydrate [18]. In both conformations however, the five- and six-membered rings are nearly perpendicular to one another. The first conformation is more interesting from a biological point of view because this involves the close approach of atoms C(2) and N(18). The close proximity of the amino group to the active site C(2) on the thiazolium ring lends support to the proposed mechanism of the catalytic action of thiamine and its conversion to thiochrome. The latter reaction is the rapid oxidative ring closure of thiamine in basic solution [64]. Thiamine is converted to a yellow form at pH 11.6 and spectroscopic evidence has indicated the formation of a bond between C(2) and N(18) to produce a tricyclic compound. As for the catalytic activity, it has been suggested that the pyrimidine amino group facilitates proton removal from C(2) in such processes. The apparent formation of C(2)-H....$Cl^-$ hydrogen bonds in both thiamine hydrochloride and the copper(II) compound is further evidence of the acidic nature of the hydrogen involved.

When the thiamine residue is viewed down the bond from the methylene bridge carbon to the thiazolium ring nitrogen, such that the ring is viewed edge-on, the C-C bond of the dimethylene side-chain is nearly perpendicular to the ring plane. From this position, the pyrimidine ring is seen in projection, with the amino group directed either to the left or to the right i.e. either on the same side (*cis*) as the dimethylene side-chain or on the opposite side (*trans*). In all of the structures tabulated above, including the copper(II) complex, the *cis* configuration has been observed. The only example of a *trans* configuration occurs in the crystal structure of thiamine pyrophosphate hydrochloride[70].

The similarity in the relative ring orientations in the various thiamine structures does seem to indicate an inherent stability in this geometry. Recently[77], semiempirical calculations of the electronic structure and preferred conformations of thiamine and thiamine pyrophosphate have been performed. The conformational analysis involved the rotation (defined by torsion angles $\phi$C-N and $\phi$C-C) of the two aromatic rings with respect to the bridge methylene group. The conformational stability maps predict two basic conformations of similar energy: the first is in the area with $\phi$C-N ~ 0°, $\phi$C-C ~ 0° and the second, in the area with $\phi$C-N ~ 60°, $\phi$C-C ~ 320°. Surprisingly, no sharp local minima are indicated near the two conformations observed in the crystal structures of the various thiamine derivatives. It seems unlikely however, that crystal packing forces alone are responsible for the conformations consistently observed, though it is possible that such forces determine the *cis* or *trans* arrangement of the substituents.

## III.4 THE CRYSTAL STRUCTURE OF THE COMPLEX DIBROMOBIS-[5-(2-HYDROXYETHYL)-4-METHYLTHIAZOLE]COBALT(II); $Co(C_6H_9NOS)_2Br_2$

### Crystal preparation and chemical analysis

The title compound was one of several cobalt(II) complexes of thiamine hydrochloride and related thiazoles recently synthesised[58] at this university.

Fresh single crystals were prepared in the following manner: solutions of anhydrous cobalt(II) bromide and 5-(2-hydroxyethyl)-4-methylthiazole in dry methanol were mixed in a 1:6 molar ratio and gently heated.

The mixture was evaporated to a small volume and a small amount of 1-propanol was added. Dark blue needles with approximately square cross-section grew from solution. These were filtered, washed with 1-propanol and dried under vacuum. By microanalysis (Table III.4.1) the crystals were shown to have the composition Co[5-(2-hydroxyethyl)-4-methylthiazole]$_2$Br$_2$.

TABLE III.4.1

| | %C | %H | %N |
|---|---|---|---|
| Calculated: | 28.5 | 3.6 | 5.5 |
| Found : | 28.7 | 3.7 | 5.6 |

### Density determination

A density of 1.84 g cm$^{-3}$ was recorded by flotation of the crystals in a chlorobenzene-methyl iodide mixture. This indicated a unit cell content of four molecules of the complex.

## Space group assignment

Reflections of the type *h0l* $l$=2n+1 and 0*k*0 $k$=2n+1 were absent on Weissenberg photographs. From these conditions, the space group $P2_1/c$ (Monoclinic) is uniquely determined[60].

## Diffractometer data

Intensity measurements were recorded from a single crystal cut to a cube of side 0.4 mm. Crystal data are listed in Table III.4.2.

TABLE III.4.2 CRYSTAL DATA

| | |
|---|---|
| Molecular formula | $Co(C_6H_9NOS)_2Br_2$ |
| Molecular weight | 504.9 g mole$^{-1}$ |
| Space group | $P2_1/c$ (Monoclinic,2nd setting) |
| a = 16.993(8) Å | |
| b = 7.794(5) Å | $D_m$ = 1.84 g cm$^{-3}$ |
| c = 14.807(7) Å | $D_c$ = 1.85 g cm$^{-3}$ for Z = 4 |
| $\beta$ = 112.1(2)° | $\mu$(MoK$\alpha$) = 58.6 cm$^{-1}$ |
| V = 1817.18 Å$^3$ | F(000) = 996 |

Diffraction intensities were collected by the $\omega$-2$\theta$ scan technique using a speed of 0.04°$\theta$sec$^{-1}$ and a scan width of 1.2°$\theta$. A total of 2433 reflections up to 2$\theta$=44° were recorded; 737 of these including systematic absences had $I_{rel}<1.65\sigma(I_{rel})$ and were excluded from the analysis. The remaining 1696 independent reflections constituted the observed data set. The intensities of three reference reflections (monitored every hour) remained constant to within 3% of their respective mean values. With cobalt and bromine atoms in the crystal, the absorption coefficient is rather large. For the crystal selected, $\mu R$ ranged from 1.2 to 1.6 with corresponding A* values of 6.86 and 12.3 at $\theta=0^{\circ}$. At $\theta=20^{\circ}$, the minimum and maximum values[78] of A* were 6.35 and 10.6. That is, the value of A* over the $\theta$-range covered was quite severely affected by the crystal size. Although no absorption corrections were made, anomalous dispersion corrections were applied to the heavy atom scattering curves.

## Solution and refinement of the structure

A Patterson map (X-RAY 72 program system[46]) showed only a single broad peak on the Harker-section 0, $\frac{1}{2}-2y$, $\frac{1}{2}$ despite the presence of four heavy atoms (cobalt, sulphur and two bromine atoms) in general positions. This implied near equality of the y-coordinates of two or more of the heavy atoms. In addition there were nine prominent peaks, some of them multiple, in the section $2x, \frac{1}{2}, \frac{1}{2}+2z$ which led to several possible solutions for the heavy atom coordinates. In order to gain familiarity with other techniques, it was decided to use direct methods to solve the structure. Subroutines of the X-RAY 72 program system (NORMSF, SINGEN, PHASE) were used. E values for the reflections were calculated from the normalized structure factors. Three suitable origin-defining reflections were chosen and assigned the following phases:

| $h$ | $k$ | $l$ | $\|E\|$ | sign |
|---|---|---|---|---|
| -5 | 2 | 1 | 3.69 | + |
| 6 | 3 | 1 | 3.40 | - |
| 2 | 1 | 4 | 2.95 | - |

With these defined phases, 235 reflections with $E>1.5$ were phased from 50 generators. An E map based on these reflections revealed the heavy atoms. The initial y-coordinates of the cobalt and the two bromine atoms were 0.64, 0.81 and

0.80 respectively, which correlated with the results obtained from the Patterson analysis. An electron-density map phased on the three heavy atoms revealed most of the light atoms. A subsequent difference electron-density map yielded the positions of the remaining atoms of the side-chains in the substituted thiazoles. After three cycles of full-matrix least-squares refinement with isotropic temperature factors assigned to all the atoms, R was 0.11. On introducing anisotropic temperature factors, three further cycles of refinement reduced R to 0.067 and at this stage a difference electron-density map was prepared in order to locate the hydrogen atoms. All of the hydrogens (except one of a hydroxylic oxygen) were located in this map; they were assigned the isotropic temperature factors of the atoms to which they were bonded and their positions were refined. In the last cycle, the average shift:error ratio was 0.04 in the case of heavy atoms and 0.15 for the hydrogen atom parameters. The function minimised was $\Sigma(|F_o|-|F_c|)^2$ and the terminal R value was 0.061 with unit weights applied throughout. As a check of the correctness of the structure, a final difference synthesis with all atoms subtracted was computed. This map showed no prominent peaks. Scattering factors for Br, C, N, O and S were those of Cromer and Mann[79], for H, those of Stewart et al[80]., and for cobalt, those of Hanson et al[62]. Anomalous dispersion corrections[63] for MoKα radiation were applied to the Co and Br scattering curves.

In retrospect, the ambiguity in the Patterson analysis arose because of the non-crystallographic two-fold molecular symmetry. Since the *b* cell axis is very nearly parallel with the bisector of the Br(1)-Co-Br(2) angle (and the Br atoms therefore have similar y-coordinates), the individual Co-Br(1) and Co-Br(2) vector peaks become indistinguishable in the Patterson map due to the latter's symmetry. Each Co-Br vector peak is distinct but the symmetry operation x, y, z → $\bar{x}$, y, $\bar{z}$ in the Patterson space group, P2/m, causes each peak to be reflected into the other. In addition, a large peak in the Harker section 2x, ½, ½ + 2z, which was originally assumed to represent an interaction between a heavy atom and its symmetry related image, was in fact due to the sum of the vector interactions Br(2)-S(1) and Br(1)-S(11).

The final atomic coordinates and thermal parameters for the heavy atoms and hydrogen atoms are listed in Tables III.4.3 and III.4.4 respectively. Observed and calculated structure factors appear in Table III.4.5.

# TABLE III.4.3

## NON-HYDROGEN ATOMS

## FRACTIONAL ATOMIC COORDINATES ($\times 10^4$) AND THEIR E.S.D.'s AND ANISOTROPIC TEMPERATURE FACTORS

Thermal parameters are of the form

$$T = \exp[-2\pi^2(U_{11}h^2a^{*2} + U_{22}k^2b^{*2} + U_{33}l^2c^{*2} + 2U_{12}hka^*b^* + 2U_{13}hla^*c^* + 2U_{23}klb^*c^*)\times 10^3].$$

| | $x$ | $y$ | $z$ | $U_{11}$ | $U_{22}$ | $U_{33}$ | $U_{12}$ | $U_{13}$ | $U_{23}$ |
|---|---|---|---|---|---|---|---|---|---|
| Co | 2458 (1) | 6371 (2) | 668 (1) | 37 (1) | 27 (1) | 32 (1) | 4 (1) | 13 (1) | 0 (1) |
| Br(1) | 1655 (1) | 8217 (2) | 1284 (1) | 62 (1) | 49 (1) | 64 (1) | 24 (1) | 35 (1) | 3 (1) |
| Br(2) | 3383 (1) | 7996 (2) | 115 (1) | 52 (1) | 41 (1) | 64 (1) | -6 (1) | 28 (1) | 6 (1) |
| N (3) | 3162 (7) | 4827 (14) | 1798 (7) | 27 (7) | 30 (7) | 28 (7) | -5 (5) | 5 (5) | -6 (5) |
| C (2) | 3275 (9) | 5184 (18) | 2692 (10) | 40 (9) | 34 (8) | 41 (9) | 4 (7) | 13 (7) | 4 (7) |
| S (1) | 3893 (3) | 3785 (5) | 3527 (3) | 54 (3) | 54 (3) | 32 (2) | 17 (2) | 15 (2) | 8 (2) |
| C (4) | 3593 (8) | 3344 (17) | 1741 (9) | 26 (8) | 23 (7) | 37 (8) | -1 (6) | 9 (6) | 0 (6) |
| C (5) | 4026 (9) | 2635 (18) | 2604 (10) | 39 (9) | 29 (8) | 49 (9) | 7 (7) | 22 (8) | 10 (7) |
| C (6) | 3566 (11) | 2784 (19) | 791 (11) | 81 (12) | 29 (8) | 45 (9) | 9 (8) | 26 (9) | -7 (7) |
| C (7) | 4546 (9) | 995 (21) | 2809 (11) | 33 (9) | 50 (10) | 58 (10) | 4 (8) | 15 (7) | 6 (8) |
| C (8) | 4175 (12) | -428 (23) | 3141 (17) | 60 (13) | 46 (11) | 125 (17) | 13 (9) | 57 (12) | 19 (12) |
| O (9) | 4183 (15) | -47 (23) | 4072 (17) | 262 (26) | 91 (13) | 231 (24) | 56 (15) | 196 (22) | 70 (15) |
| N(31) | 1759 (7) | 4799 (14) | -439 (7) | 39 (8) | 38 (7) | 21 (6) | -1 (6) | 11 (5) | -0 (5) |
| C(21) | 1874 (9) | 4780 (18) | -1260 (10) | 31 (9) | 36 (8) | 38 (9) | -4 (7) | 7 (7) | 1 (7) |
| S(11) | 1441 (2) | 3102 (5) | -1990 (3) | 46 (2) | 52 (2) | 31 (2) | -7 (2) | 17 (2) | -5 (2) |
| C(41) | 1287 (8) | 3386 (18) | -368 (10) | 32 (8) | 32 (8) | 40 (8) | 4 (7) | 17 (7) | 6 (7) |
| C(51) | 1065 (8) | 2361 (19) | -1145 (10) | 27 (8) | 47 (9) | 34 (8) | 7 (7) | 10 (6) | -4 (7) |
| C(61) | 1080 (12) | 3210 (22) | 497 (12) | 89 (14) | 54 (11) | 63 (11) | -22 (10) | 47 (10) | -10 (9) |
| C(71) | 553 (10) | 686 (20) | -1288 (12) | 41 (10) | 43 (10) | 42 (9) | -7 (8) | 12 (8) | -7 (8) |
| C(81) | 876 (11) | -770 (23) | -1722 (13) | 46 (12) | 45 (10) | 59 (12) | 1 (9) | 10 (8) | -0 (9) |
| O(91) | 766 (9) | -315 (18) | -2666 (9) | 127 (12) | 73 (9) | 69 (9) | -31 (9) | 57 (9) | -24 (7) |

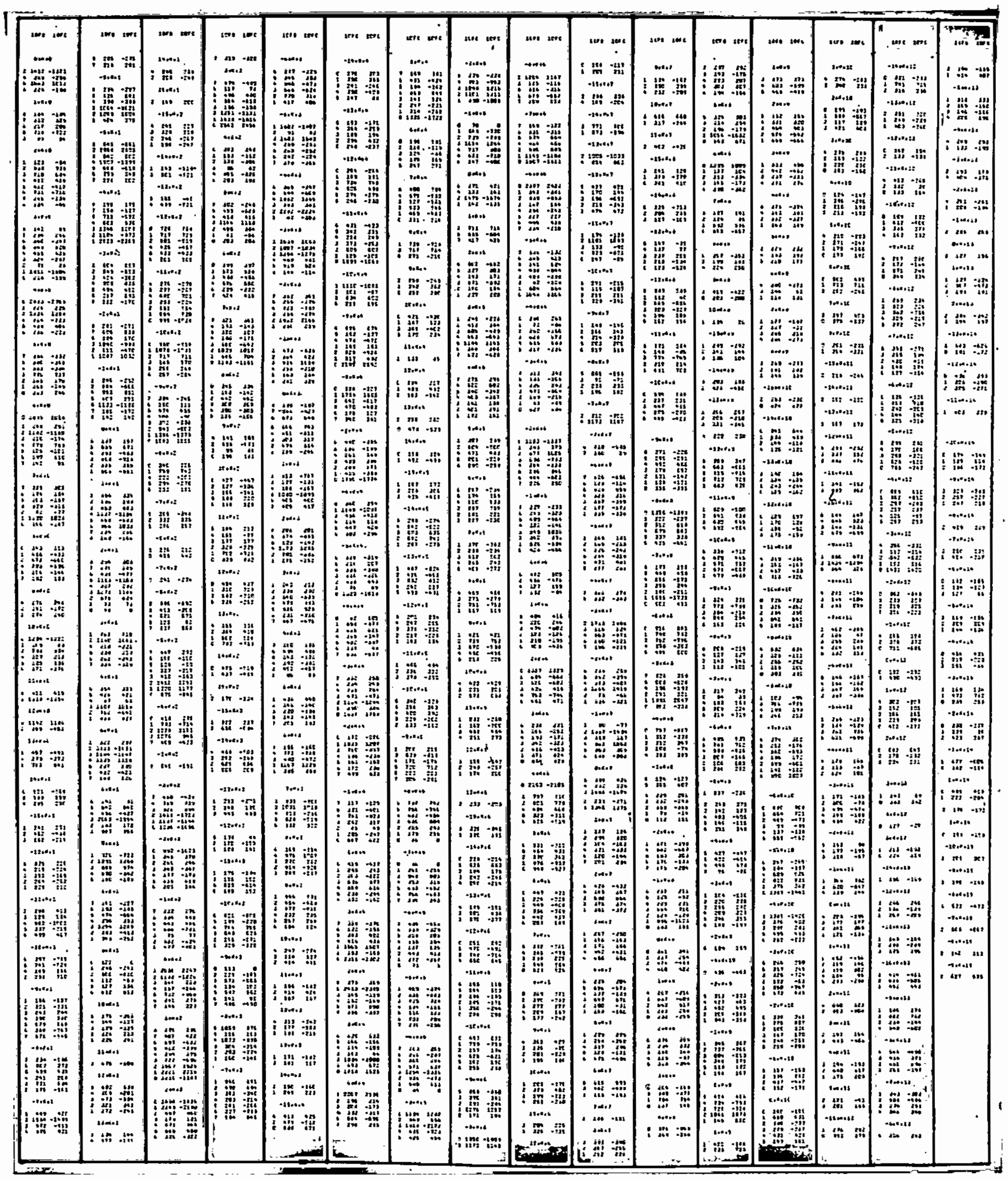
## TABLE III.4.4

### HYDROGEN ATOMS

### FRACTIONAL ATOMIC COORDINATES (x10$^3$) AND THEIR E.S.D.'s AND ISOTROPIC TEMPERATURE FACTORS (x10$^3$)

| | *x* | *y* | *z* | *Uiso* |
|---|---|---|---|---|
| H (2) | 308 (8) | 634(17) | 285 (9) | 43 |
| H (61) | 305 (9) | 211(19) | 47(10) | 57 |
| H (62) | 359 (9) | 327(19) | 35(10) | 57 |
| H (63) | 377 (9) | 193(19) | 81(10) | 57 |
| H (71) | 460 (7) | 70(17) | 215 (9) | 44 |
| H (72) | 489 (8) | 113(17) | 323 (9) | 44 |
| H (81) | 363 (9) | -66(21) | 311(11) | 73 |
| H (82) | 456 (9) | -209(21) | 352(11) | 73 |
| H (21) | 214 (7) | 605(16) | -134 (8) | 35 |
| H(611) | 95 (9) | 397(20) | 68(10) | 57 |
| H(612) | 71 (9) | 258(19) | 46(10) | 57 |
| H(613) | 159 (9) | 293(19) | 110(10) | 57 |
| H(711) | 54 (8) | 25(18) | -64(10) | 48 |
| H(712) | -4 (9) | 98(18) | -179(10) | 48 |
| H(811) | 127(10) | -76(21) | -124(11) | 48 |
| H(812) | 52 (8) | -183(19) | -164 (9) | 48 |
| H (91) | 107(10) | -123(23) | -307(12) | 78 |

# TABLE III.4.5



## III.5 DESCRIPTION OF THE STRUCTURE AND DISCUSSION

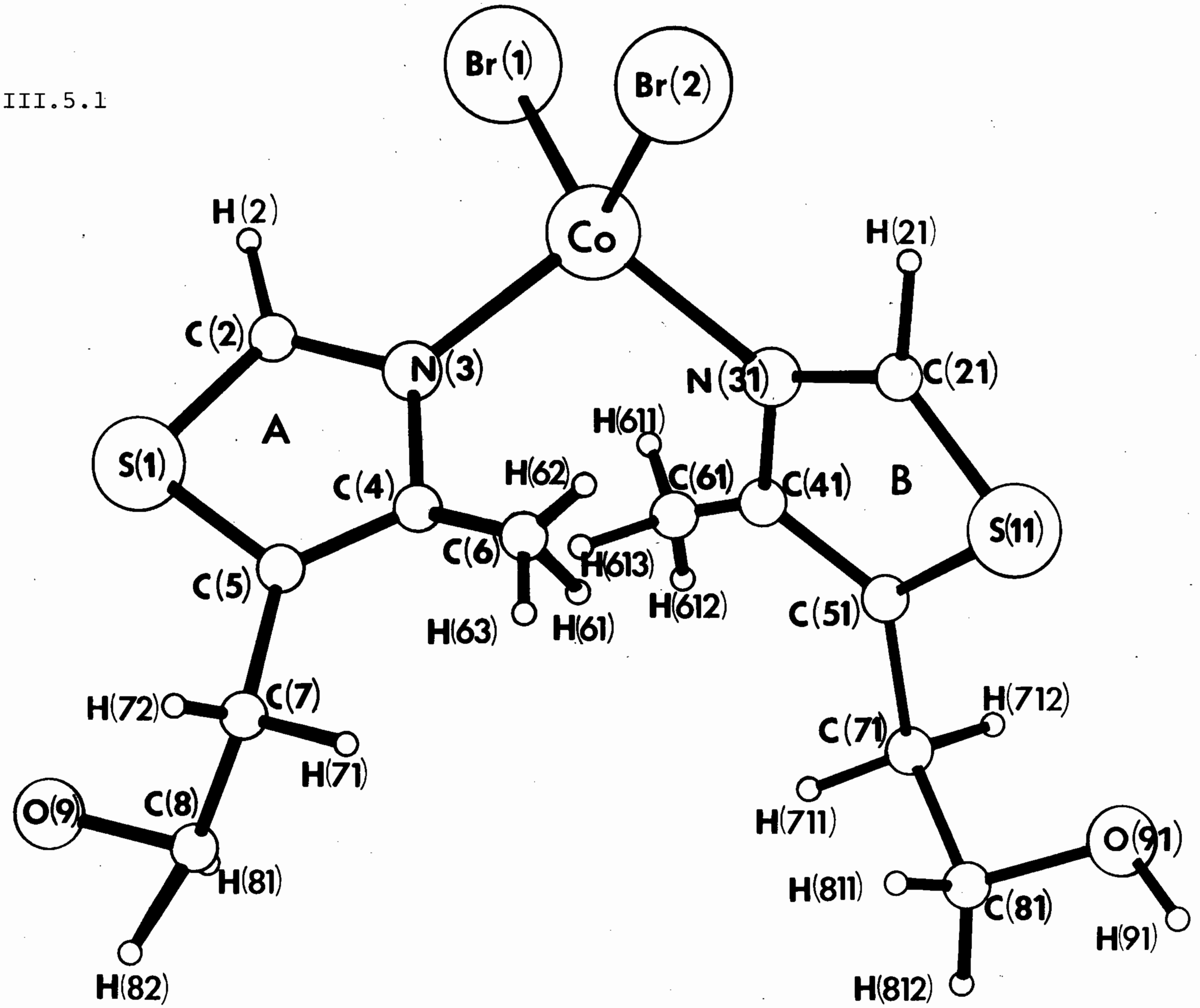
Interatomic distances and bond angles in the complex are listed in Tables III.5.1 and III.5.2 respectively. Relevant least-squares planes are presented in Table III.5.3.

The molecular structure and atomic nomenclature are shown in Figure III.5.1 which views the molecule approximately parallel to $a^*$. The atomic nomenclature is standard in the case of one MHET ligand (labelled A). For ligand B, chemically equivalent atoms are similarly labelled but suffixed with the number 1. All hydrogen atoms which were located have been labelled in the figure.

The cobalt atom has a tetrahedral environment, the ligands being two bromine and two nitrogen atoms. The bromine atoms are at an average distance of 2.39 Å from the cobalt atom while the nitrogen atoms of the substituted thiazole ligands are bound to the metal at an average Co-N distance of 2.04 Å. The tetrahedral geometry about the metal atom is fairly regular, the largest deviation from the ideal being that of angle Br(1)-Co-N(31), 115.2(4)°.

Although the atomic positions for the members of the asymmetric unit (i.e. one complex molecule) are general, the overall molecular symmetry is approximately two-fold, the rotation axis being the bisector of the Br(1)-Co-Br(2) angle. This is evident from Fig. III.5.2 which views the molecule down the cell *b*-axis, the latter lying almost

FIG. III.5.1


Br(1)
Br(2)
Co
H(2)
H(21)
C(2)
N(3)
N(31)
C(21)
A
S(1)
H(611)
C(4)
H(62)
C(61)
C(41)
B
C(6)
H(613)
S(11)
C(5)
H(612)
C(51)
H(63)
H(61)
H(72)
C(7)
H(712)
C(71)
H(71)
H(711)
O(9)
C(8)
O(91)
H(81)
H(811)
C(81)
H(91)
H(82)
H(812)

## TABLE III.5.1

## INTRAMOLECULAR BOND LENGTHS AND THEIR E.S.D.'s (Å)

(For bond distances involving H atoms, the e.s.d.'s are 0.1 Å)

| | | | |
|---|---|---|---|
| Co—Br(1) | 2.388(3) | | |
| Co—Br(2) | 2.391(3) | | |
| Co—N(3) | 2.04(1) | | |
| Co—N(31) | 2.03(1) | | |
| N(3)—C(2) | 1.29(2) | | |
| N(31)-C(21) | 1.30(2) | C(2)—H(2) | 1.0 |
| C(2)—S(1) | 1.69(1) | C(6)—H(61) | 1.0 |
| C(21)-S(11) | 1.68(1) | C(6)—H(62) | 0.8 |
| S(1)—C(5) | 1.72(2) | C(6)—H(63) | 0.7 |
| S(11)-C(51) | 1.71(2) | C(7)—H(71) | 1.0 |
| C(5)—C(4) | 1.33(2) | C(7)—H(72) | 0.7 |
| C(51)-C(41) | 1.33(2) | C(8)—H(81) | 1.0 |
| C(4)—N(3) | 1.39(2) | C(8)—H(82) | 1.1 |
| C(41)-N(31) | 1.39(2) | C(21)-H(21) | 1.1 |
| C(4)—C(6) | 1.46(2) | C(61)-H(611) | 0.7 |
| C(41)-C(6) | 1.46(3) | C(61)-H(612) | 0.8 |
| C(5)—C(7) | 1.52(2) | C(61)-H(613) | 1.0 |
| C(51)-C(71) | 1.54(2) | C(71)-H(711) | 1.0 |
| C(7)—C(8) | 1.45(3) | C(71)-H(712) | 1.0 |
| C(71)-C(81) | 1.51(3) | C(81)-H(811) | 0.8 |
| C(8)—O(9) | 1.41(4) | C(81)-H(812) | 1.1 |
| C(81)-O(91) | 1.38(2) | O(91)-H(91) | 1.2 |

## TABLE III.5.2

## INTRAMOLECULAR BOND ANGLES AND THEIR E.S.D.'s (DEGREES)

| | | | |
|---|---|---|---|
| Br(1)-Co—Br(2) | 110.8(1) | S(1)—C(5)—C(4) | 111(1) |
| Br(1)-Co—N(3) | 106.6(4) | S(11)-C(51)-C(41) | 112(1) |
| Br(1)-Co—N(31) | 115.2(4) | C(5)—C(4)—N(3) | 114(1) |
| Br(2)-Co—N(3) | 109.6(3) | C(51)-C(41)-N(31) | 113(1) |
| Br(2)-Co—N(31) | 107.6(4) | N(3)—C(4)—C(6) | 119(1) |
| N(3)—Co—N(31) | 106.9(4) | N(31)-C(41)-C(61) | 119(1) |
| Co—N(3)—C(4) | 126.9(9) | C(5)—C(4)—C(6) | 127(1) |
| Co—N(31)-C(41) | 126.5(9) | C(51)-C(41)-C(61) | 128(1) |
| Co—N(3)—C(2) | 121.8(9) | C(4)—C(5)—C(7) | 128(1) |
| Co—N(31)-C(21) | 120.9(9) | C(41)-C(51)-C(71) | 126(1) |
| C(2)—N(3)—C(4) | 111(1) | S(1)—C(5)—C(7) | 121(1) |
| C(21)-N(31)-C(41) | 111(1) | S(11)-C(51)-C(71) | 122(1) |
| N(3)—C(2)—S(1) | 115(1) | C(5)—C(7)—C(8) | 115(2) |
| N(31)-C(21)-S(11) | 115(1) | C(51)-C(71)-C(81) | 115(2) |
| C(2)—S(1)—C(5) | 89.2(7) | C(7)—C(8)—O(9) | 109(2) |
| C(21)-S(11)-C(51) | 89.1(8) | C(71)-C(81)-O(91) | 108(1) |

## TABLE III.5.3

## LEAST-SQUARES PLANES

The equations of the planes are expressed in orthogonalized space as $PI+QJ+RK=S$

Plane I: through atoms N(3),C(2),S(1),C(5),C(4) of thiazole ring A.

Equation: $0.83166I+0.54836J+0.08743K=5.91525$

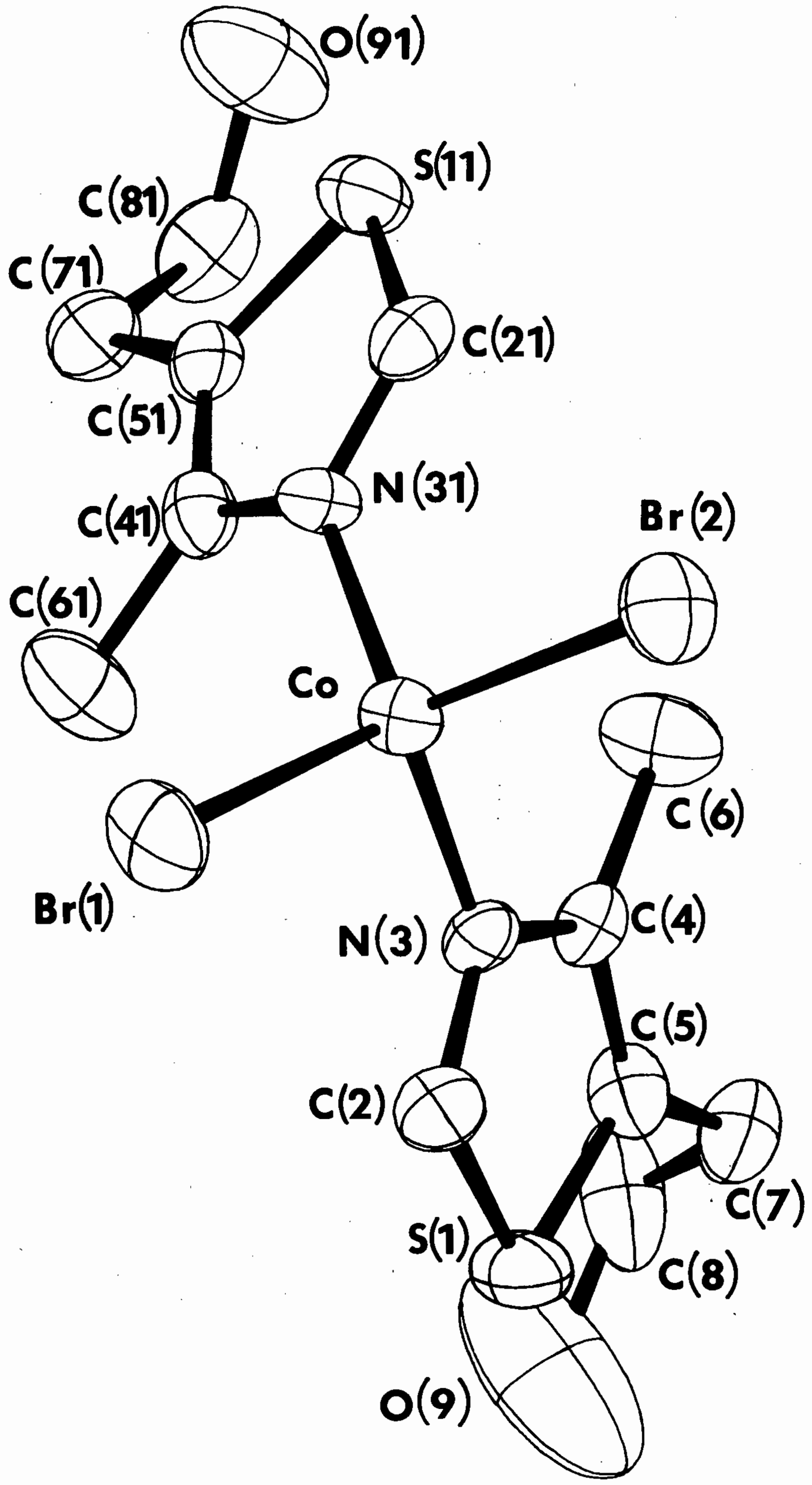
| Atoms included in calculation | Dist. from plane | Atoms not included in calculation | Dist. from plane |
|---|---|---|---|
| N(3) | -0.002Å | Co | 0.053Å |
| C(2) | 0.006 | H(2) | 0.113 |
| S(1) | -0.006 | | |
| C(5) | -0.007 | C(7) | -0.030 |
| C(4) | 0.005 | C(6) | 0.043 |

Plane II: through atoms N(31),C(21),S(11),C(51),C(41) of thiazole ring B.

Equation: $0.73313I-0.52282J+0.43494K=0.15164$

| Atoms included in calculation | Dist. from plane | Atoms not included in calculation | Dist. from plane |
|---|---|---|---|
| N(31) | 0.001Å | Co | 0.44Å |
| C(21) | -0.003 | H(21) | -0.20 |
| S(11) | 0.004 | | |
| C(51) | -0.004 | C(71) | 0.014 |
| C(41) | 0.003 | C(61) | -0.021 |

FIG. III.5.2


O(91)
S(11)
C(81)
C(71)
C(21)
C(51)
N(31)
C(41)
Br(2)
C(61)
Co
C(6)
Br(1)
N(3)
C(4)
C(5)
C(2)
C(7)
S(1)
C(8)
O(9)

parallel with the bisector. This pseudo-symmetry is displayed with respect to both the ring orientations and the configurations of the ethylhydroxy side chains. Equivalent bond lengths and angles in the independent A and B ligands are in good general agreement and are within the expected ranges.

Least-squares planes were calculated for the ring atoms of the MHET ligands, both of which are accurately planar. The root-mean-square deviations of the atoms from the respective planes are 0.006 and 0.003 Å.

Interatomic distances less than the van der Waals sum have been found for certain atom pairs and these are of interest (Table III.5.4).

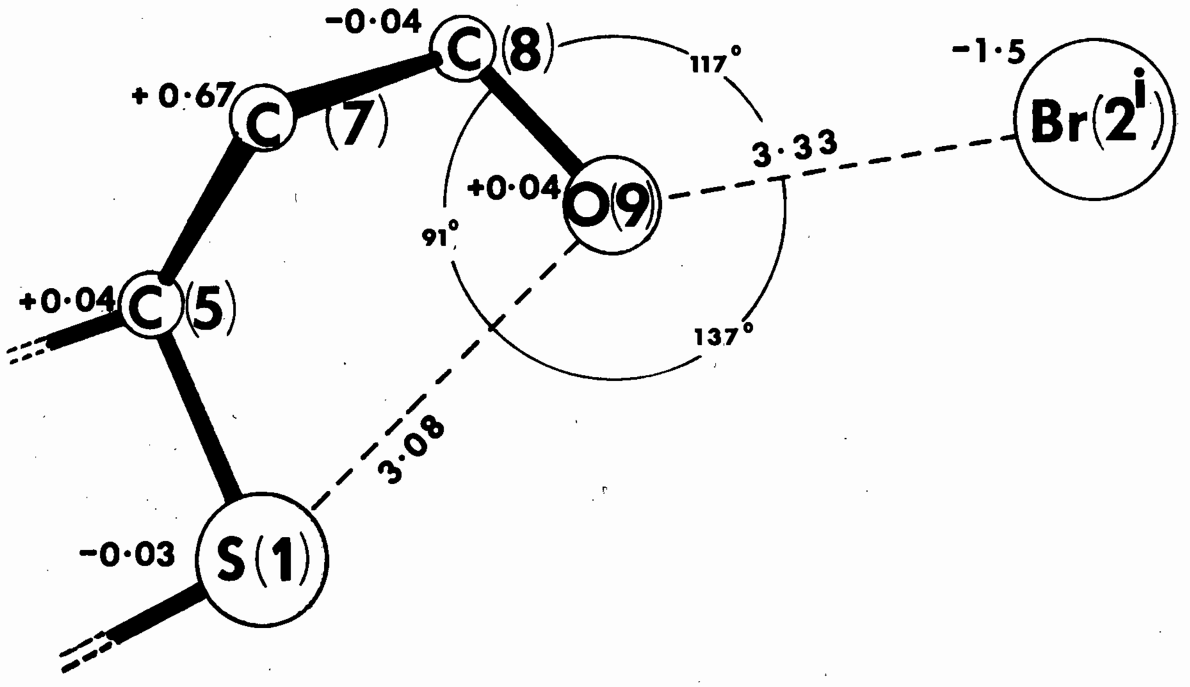
TABLE III.5.4 CLOSE INTRAMOLECULAR AND INTERMOLECULAR APPROACHES (Å)

Symmetry code: (i) $x, \frac{1}{2} - y, \frac{1}{2} + z$

(ii) $x, \frac{1}{2} - y, -\frac{1}{2} + z$

| | | | |
|---|---|---|---|
| S(1)....O(9) | 3.08(2) | | |
| S(11)...O(91) | 2.92(1) | C(2)....Br(1) | 3.63(1) |
| O(9)....Br($2^{i}$) | 3.33(3) | C(21)...Br(2) | 3.62(1) |
| O(91)...Br($1^{ii}$) | 3.40(2) | | |

The van der Waals sum for S and O atoms is 3.25 Å. The short S...O distances observed arise from the near *cis*-configurations of the side chains. This is shown in Fig. III.5.3. For ring A, the torsion angle defined by S(1)-C(5)-C(7)-C(8) is 68°, numerically equal to that defined by C(5)-C(7)-C(8)-O(9) and the directions of torsion result in atoms S(1), C(5),C(8) and O(9) being almost coplanar, with atom C(7) 0.67 Å out of the plane. The corresponding torsion angles in ring B are 41° and 66° respectively, resulting in a similar *cis*-configuration, with atom C(71) a distance of 0.55 Å from the plane through atoms S(11), C(51), C(81) and O(91). In Fig. III.5.3 which illustrates the geometry, the figures to the left of each atom are their normal distances in Å from the least-squares planes through S(1), C(5), C(8), O(9) and S(11), C(51), C(81) and O(91) respectively. An analogous short S...O intramolecular contact has been observed in the crystal structure of 2,7-dimethylthiachromine-8-ethanol dihydrate[81]. The other short contacts observed in the cobalt complex are intermolecular and involve O and Br atoms. (Fig. III.5.4). In one case, O(9) and $Br(2^{i})$ are separated by 3.33 Å (van der Waals sum = 3.35 Å), while in the other, the $O(91)...Br(1^{ii})$ distance is 3.40 Å. Although atom H(91) bonded to O(91) was located in the analysis, the hydroxylic hydrogen of atom O(9) was not found. The latter failure can be attributed to the fact that atom O(9) has the largest thermal vibration of all the atoms in the structure (Table III.4.3). The short intermolecular $H(91)...Br(1^{ii})$ distance of 2.2(2) Å and the $O(91) - H(91)...Br(1^{ii})$ angle of 175(14)° indicate hydrogen bonding between these atoms. Atom O(91) is thus involved in two interactions viz. an intramolecular S...O coulombic interaction and an O-H...Br hydrogen bond. The similar geometry for atoms O(9) and $Br(2^{i})$ suggests analogous H...Br interaction. In Fig.III.5.4,


-0·04
C(8)
117°
-1·5
Br(2$^{i}$)
+0·67
C (7)
3·33
+0·04
O(9)
91°
+0·04
C(5)
137°
3·08
-0·03
S(1)

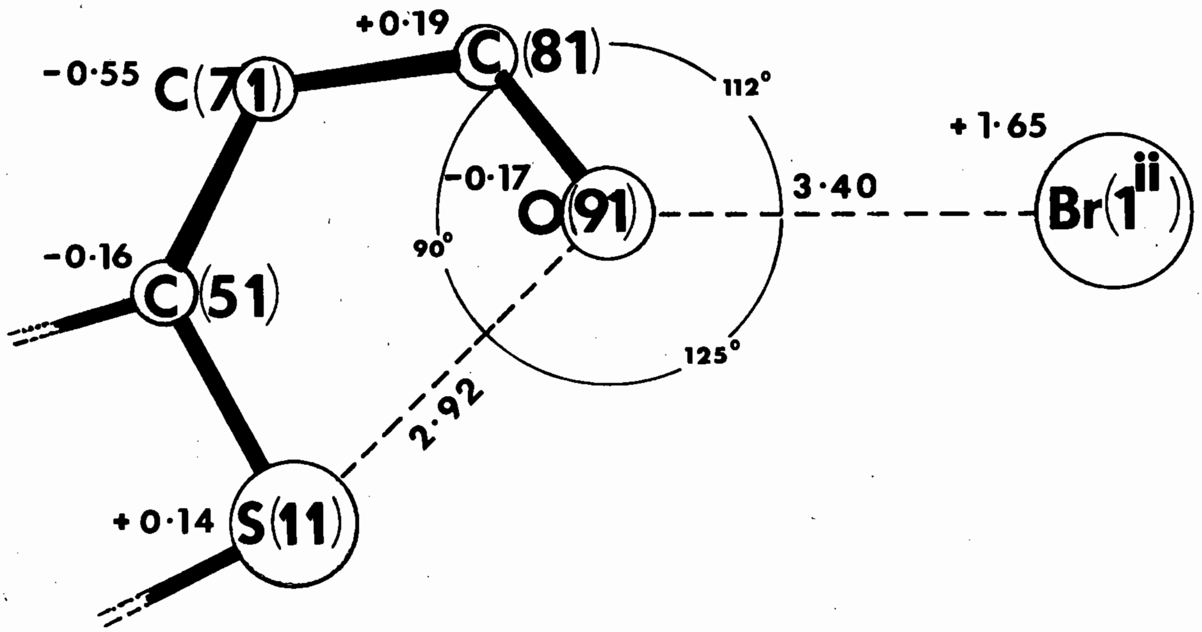
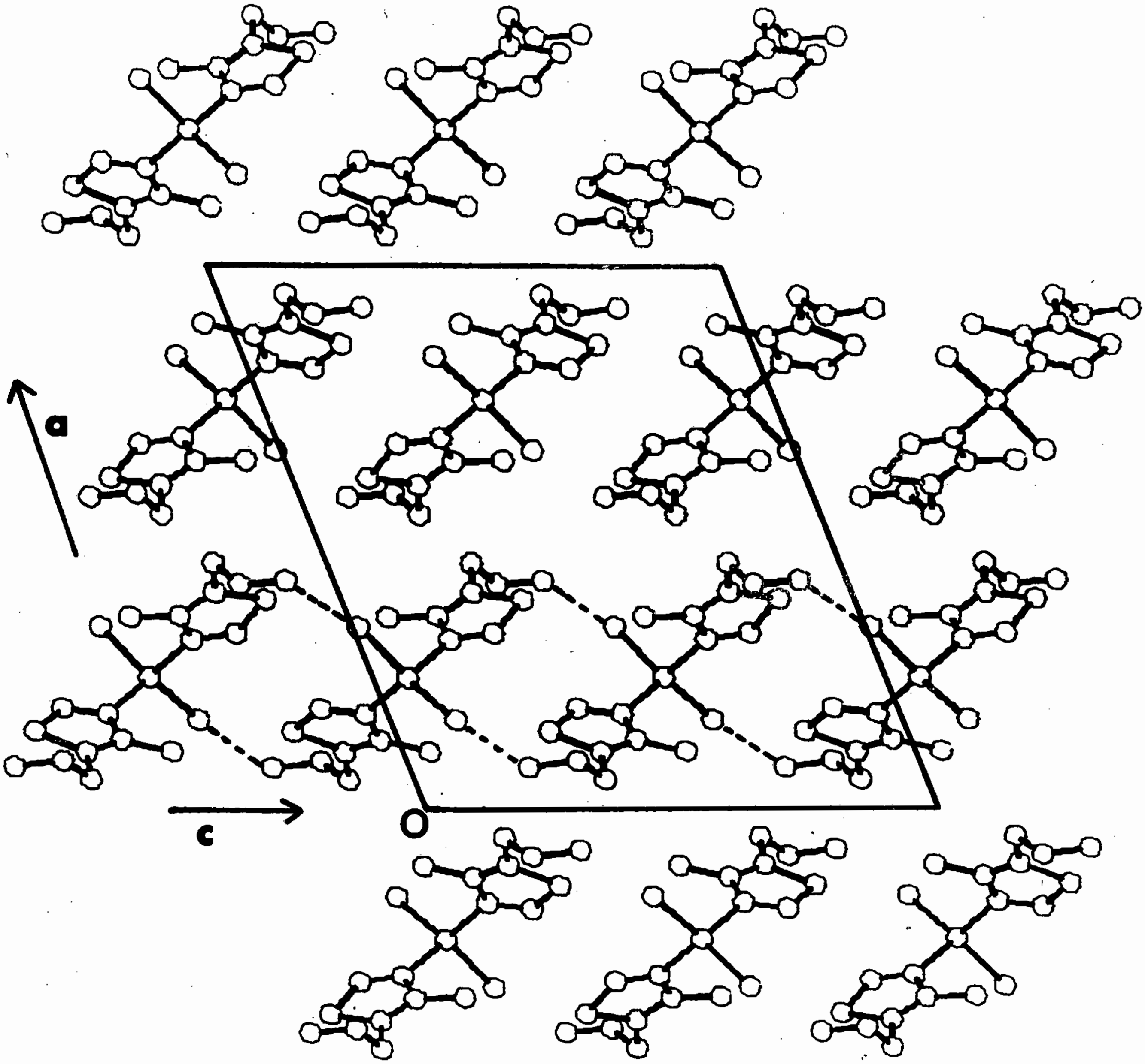

+0·19
C(81)
-0·55
C(71)
112°
+1·65
-0·17
O(91)
3·40
Br(1$^{ii}$)
90°
-0·16
C(51)
125°
2·92
+0·14
S(11)

FIG. III.5.3

FIG. III.5.4



the [010] projection of the structure, short O....Br contacts for a row of molecules are represented by dashed lines.

Further possible hydrogen bonding sites are the ring methine groups, as observed in the structure of N-benzyl-4-methylthiazolium bromide [82], involving C-H....$Br^-$ interactions. It should be mentioned that hydrogen bonding involving the C-H group is a controversial topic. While C-H...Cl and C-H..Br interactions have been observed in many structures and have been referred to as 'hydrogen bonds', short C....O distances have been refuted as evidence for C-H...O hydrogen bonding [83]. In the cobalt complex, the distances H(2)....Br(1) and H(21)....Br(2) are 3.1(1) and 2.8(1) Å respectively, indicating some interaction. (The H...Br van der Waals sum is 3.15 Å). However, the respective C(2)...Br(1) and C(21)...Br(2) distances are 3.63(1) and 3.62(1) Å, both of which just exceed the sum of the C-H hydrogen bond radius [82] of 1.64 Å and the acceptor radius of a bromine atom, 1.95 Å. Weak C-H...Br interaction is therefore suggested by these distances and by the favourable ring orientations. As a result of the dispositions of the rings, the relevant angles C(2)-H(2)...Br(1) and C(21)-H(21)...Br(2) are 120(8)° and 127(7)° respectively.

## Cobalt-thiazole binding

Evidence for the metal-binding site in simple thiazoles has generally been gleaned from spectroscopic studies [22,23,24,53]. Data obtained for nineteen complexes of 4- and 2,4- dialkyl-substituted thiazoles with divalent zinc, cobalt, nickel and platinum was used to predict that metal-nitrogen (as opposed to metal-sulphur) coordination occurs in this series[24]. For cobalt(II) complexes, the normal tetrahedral species was anticipated. The results showed that, while ambidentate (S and N) behaviour might have been expected with class b metal ions (e.g. $Pt^{2+}$), both class a ("hard") and b ("soft") metal ions only N-bond to thiazole. This finding was explained by the fact that the important resonance structures for thiazoles place a formal positive charge on the sulphur atom, which would inhibit π-donation from the ligand. On the basis of previous infrared studies[84], coordination involving both S and N to nickel in nickel(II) bromide-benzothiazole was predicted, but this has been refuted[24]. A spectroscopic study of the interaction of zinc and cobalt ions with N-alkylated thiazoles showed that complex salts formed in preference to the S-bonded complexes[53].

The X-ray analysis of the analogous copper complex[59] containing MHET has revealed an unusual structure. Again the metal is N-bonded, but the substance is ionic, consisting of a distorted tetrahedral anion $[Br_3Cu(MHET)]^-$ and an uncoordinated N-protonated MHET cation. Common structural features of the cobalt and copper complexes are the presence of short S...O intramolecular contacts and of C(2)-H...Br interactions. Close S...O approaches lying between the single S-O bond length of approximately 1.67 Å and the van der Waals sum of 3.25 Å have been observed in many crystal structures[85].

## III.6 GENERAL CONCLUSIONS

Splitting of thiamine into pyrimidine and thiazolium fragments and subsequent study of their metal derivatives seems a reasonable experimental approach for simulating metal-thiamine interaction. However, in the case where thiamine itself is employed as a ligand, the use of metal halides in these reactions generally leads to the formation of complex salts. Metal salts containing different anions[86] (e.g. nitrate) may permit the formation of a coordination complex through the nucleophilic sites of thiamine.

Metal-thiazole N-bonding observed in the cobalt(II) complex of MHET is a possibility that can be eliminated in thiamine, (MHET regarded as a thiamine analogue), for the quaternary nitrogen in the thiazolium portion of thiamine can be neglected as a cation binding-site. As there is no evidence precluding coordination through oxygen (or sulphur and oxygen), a more realistic approach would be the synthesis and study of metal complexes of N-substituted derivatives of MHET.

# CHAPTER IV

# THE CRYSTAL STRUCTURE OF A TETRADENTATE MACROCYCLIC COMPLEX : CHLORO(2,7,12-TRIMETHYL-3,7,11,17-TETRAAZABICYCLO[11.3.1]HEPTADECA-1(17),2,11,13,15-PENTAENE)COPPER(II) NITRATE DIHYDRATE

## IV.1 INTRODUCTION

### Synthetic Macrocyclic Complexes as Bioinorganic Models

Macrocyclic compounds are now established as an important class of ligand in chemical and biochemical systems. In particular, the favourable disposition of donor atoms for firm metal-binding as compared with acyclic ligands enables them to influence more strongly the metal ion which they chelate, and their rigidity enables their chemistry to be more easily interpreted. Flexible macrocycles readily fold when presented with metal ions that are too large for them to encompass [87], the critical ring size occurring at different values for different sets of donor atoms.

The study of synthetic macrocyclic complexes as bioinorganic models has yielded observations that have a direct bearing on aspects such as metal binding to enzymes, oxidation-reduction properties of porphyrins and protein and vitamin analogues. The unusual stability and inherent inertness of macrocyclic complexes has led to the term [87] "multiple juxtapositional fixedness" (MJF). This describes the inertness occurring when some minimum number of donor atoms is so arranged with respect to the metal atom that the normal mechanism for stepwise dissociation of the ligand is thwarted. Thus, MJF may be of importance in metal binding to enzymes, because the donor atoms may be so arranged in space that they cannot be removed from a metal ion in a stepwise fashion without greatly altering the protein conformation. An entatic state has been suggested for metal ions in active sites on enzymes. The binding of metals may be viewed in terms of MJF and entasis, considered as opposing factors.

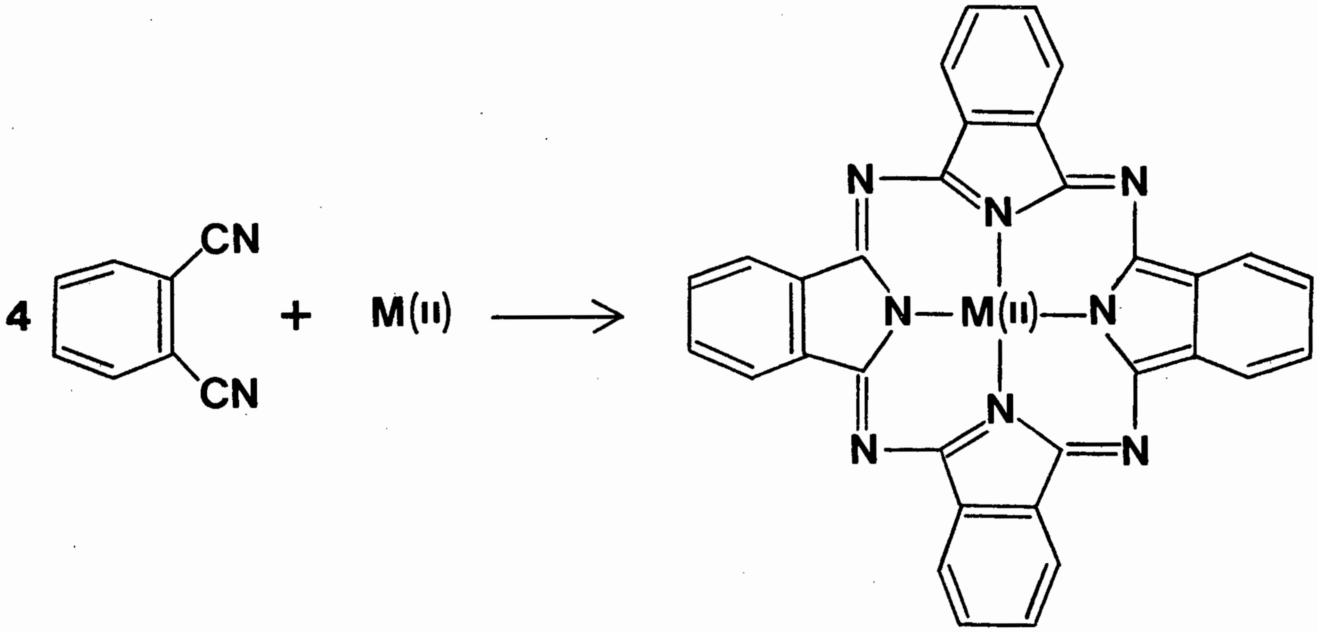
Some macrocyclic iron complexes serve as biochemical models. Certain five-coordinate high-spin iron complexes share structural characteristics with deoxyhaemoglobin. The latter compound contains five-coordinate high-spin Fe(II) surrounded by a tetradentate macrocycle having four nitrogen donors.

The active site in the Vitamin $B_{12}$ coenzyme consists of a cobalt(III) ion in a tetradentate nitrogen-donor macrocycle with a Co- alkyl bond and a base in axial sites. The characteristics of macrocycles which lead to the stability of the unusual cobalt-carbon bond have been investigated. Stable Co-C bonds have been produced in synthetic macrocyclic cobalt complexes.

## Synthetic Macrocyclic Schiff Base Ligands

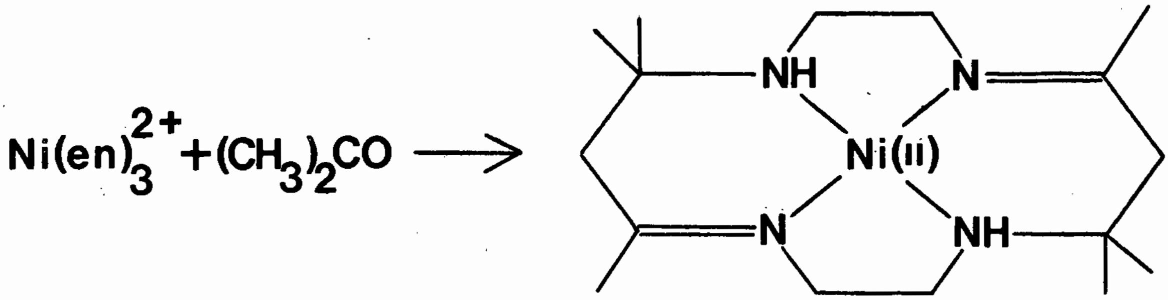
The discovery that monocarbonyl compounds condense with diamines to produce cyclic compounds[88] has been a major contribution to the new synthetic macrocyclic chemistry. The cyclic products are Schiff base ligands, containing nitrogen donor atoms capable of binding metal ions to form macrocyclic complexes. In certain cases where reaction of the organic components should in principle (but does not in practice) yield a cyclic product, the cyclisation may be effected in the presence of metal ions; consequently the product is the metal complex of the macrocyclic ligand. The metal ions are therefore able to act as a molecular organizer, leading to the formation of a large molecule from small molecules. A large negative entropy of activation is associated with many synthetic reactions and the metal ion must compensate for this factor by the coordinate bond energy. This action constitutes a kind of "template (or organizational) effect" by metal ions[39].

For the reaction A + B + M(metal ion) → [(macrocycle)M], the formation of a macrocyclic ligand complex is due to the template effect exerted by the metal ion since the reaction does not proceed in the absence of metal ion. The term applied to such a role is a "kinetic template effect". If the effect of addition of metal ion upon the equilibrium reaction A+B ⇄ AB is to displace the equilibrium to the right hand side by forming a complex [(AB)M], the metal ion is said to exert a "thermodynamic template effect". These concepts may be illustrated by the following examples. Phthalonitrile forms a phthalocyanine metal complex when heated with a metal salt, though it does not do so in the absence of it (Reaction IV.1.1).



....... IV.1.1

This reaction demonstrates a kinetic template effect. A macrocyclic ligand complex may be synthesised by the condensation of tris(ethylenediamino)nickel with acetone (Reaction IV.1.2) .



....... IV.1.2

Because this same macrocyclic ligand has been found to form by the condensation of acetone with a protonic acid salt of ethylenediamine, even in the absence of metal ion, the above reaction is considered as a thermodynamic template effect.

## Metal Complexes of CR, a tetradentate macrocycle

The nomenclature of macrocyclic ligands is generally cumbersome and abbreviations for common ligand structures are frequently given in the literature. Thus, the tetradentate macrocycle 2,12-dimethyl-3,7,11,17-tetraazabicyclo [11.3.1] heptadeca-1(17),2,11,13,15-pentaene, $C_{15}H_{22}N_4$, whose metal complexes have been studied [89], is generally referred to as CR. The structural formula and ring numbering scheme of CR are shown in Fig. IV.1.1.

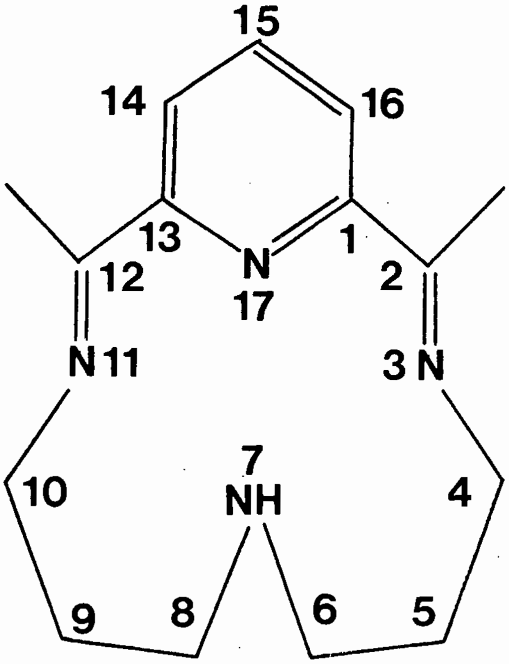


Fig. IV 1.1

The copper compound presented in this chapter is a complex of a derivative of CR. Recently, metal complexes of CR have acquired significance as possible bioinorganic models [90]. Ligands of this type leave one or more vacant coordination sites for further ligating groups. The enzyme carbonic anhydrase, which catalyses the hydration of carbonyl compounds, depends for its activity on a zinc ion (which may be replaced by cobalt). An ionizing group, supposedly a water molecule, with a $pK_a$ of around 7 is associated with the metal ion. The X-ray structural analysis of the enzyme has shown the existence of a water molecule at the active site. However, a criticism of the postulate has been that the $pK_a$ of a water molecule bound to a free hydrated zinc ion (as in $Zn(OH_2)_6^{2+}$) is 10.0. The macrocyclic complex $ZnCR^{2+}$ was synthesised and potentiometric titration of its aqueous solution showed neutralization of one molecule of the complex with one hydroxide ion, corresponding to a $pK_a$ of around 8. Ionization of zinc-bound water was inferred and it was deduced that the zinc ion in $ZnCR^{2+}$ polarizes water in the inner coordination sphere more strongly than in $Zn(OH_2)_6^{2+}$. It was therefore reasonable to admit the possibility that zinc-bound water could in fact attain a $pK_a$ as low as 7, particularly if the coordination number of the zinc in the enzyme is four. Study of these macrocyclic complexes of CR and related compounds may therefore yield results of chemical and indirectly, of biochemical interest. Complexes of CR (e.g. $[Co(CR)Cl_2]^+$), capable of forming cobalt-alkyls have been studied in connection with cyanocobalamin models[87].

## Derivatives of the ligand CR; Motivation for Structural Analysis

In a recent publication[91], the mechanism of formation of complexes of CR and related ligands (Fig. IV.1.2), was discussed.

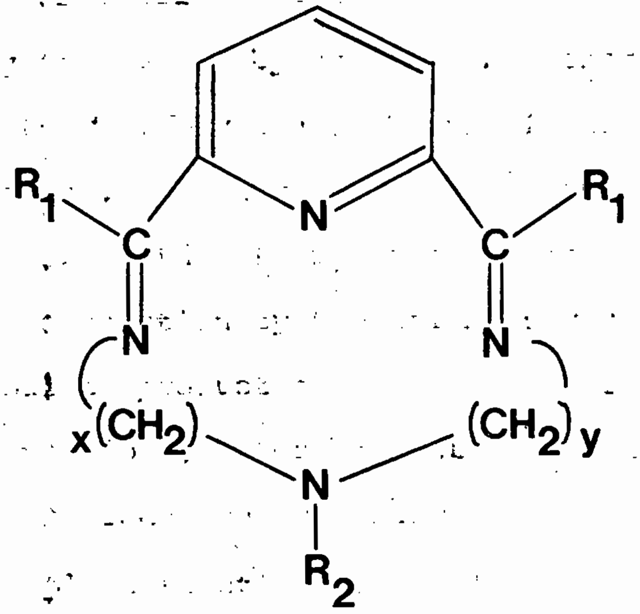
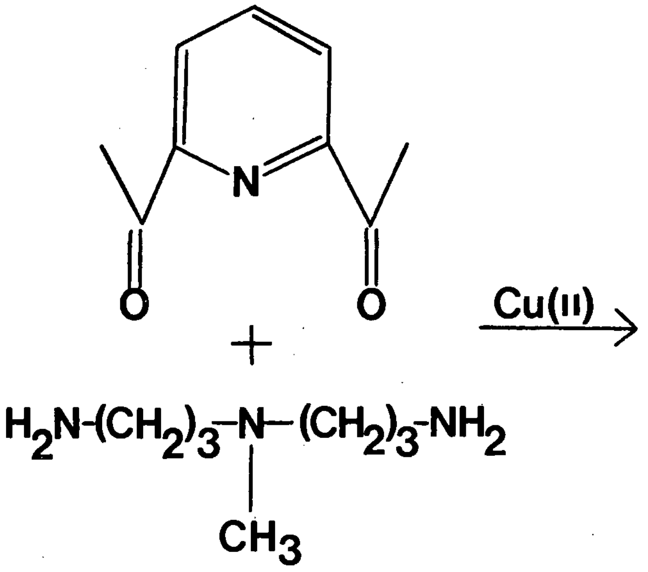
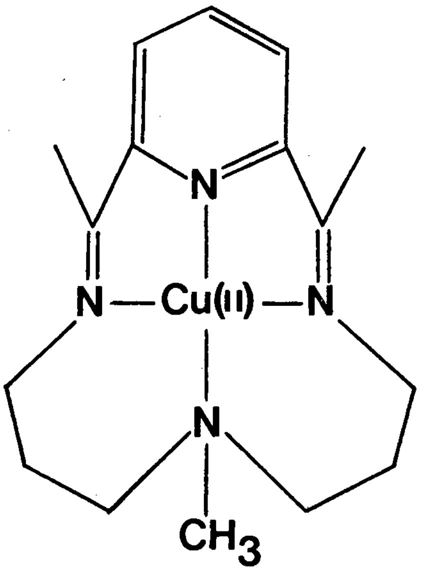


Fig. IV.1.2

The nomenclature for the ligands is given in Table IV.1.1.





....... IV.1.3

A macrocyclic cation (Cu N-MeCR)$^{2+}$ is produced in this reaction. Anions (from the metal salt) have not been included in the reaction scheme, but the possibility of their binding to the metal is not precluded. X-ray structural data is limited to two nickel complexes [92,93], of CR. In view of the potential of macrocyclic complexes of CR and its derivatives as bioinorganic models, it was decided to elucidate the structure of the complex Cu(N-MeCR)(Cl)($NO_3$).$2H_2O$. The choice of the salt used was determined by the ease of obtaining crystals, as opposed to the amorphous particles obtained with most other counterions.

## IV.2 THE CRYSTAL STRUCTURE OF CHLORO(2,7,12-TRIMETHYL-3,7,11,17-TETRAAZABICYCLO[11.3.1]HEPTADECA-1(17),2,11,13,15-PENTAENE)COPPER(II) NITRATE DIHYDRATE; $Cu(C_{16}H_{24}N_4)(Cl)(NO_3).2H_2O$.

### Crystal preparation and chemical analysis

The crystals were prepared by Dr. P.R. Woolley at the University Chemical Laboratory, Cambridge.

The tetradentate ligand 2,12-dimethyl-3,7,11,17-tetraazabicyclo[11.3.1]heptadeca-1(17),2,11,13,15-pentaene, $C_{15}H_{22}N_4$, commonly referred to[89] as CR differs from the ligand used in this study by the presence of an N-methyl group at N(7) in the latter molecule. The ligand in the copper complex is therefore referred to as N-MeCR($C_{16}H_{24}N_4$) and its synthesis and that of the complex Cu(N-MeCR)Cl($ClO_4$) have recently been described[91]. The latter formulation was verified by microanalysis.

With this complex as starting material, the replacement of perchlorate with chloride ions was effected by passing the material down an Amberlite column. To the resulting solution, two equivalents of $NaNO_3$ were added and the mixture allowed to evaporate until dark green crystals formed. These were dried at room temperature, as they returned to powder on warming. Their exact composition with respect to the anions was uncertain but the X-ray analysis described below showed that the complex is a mixed salt containing both chloride and nitrate ions as well as water molecules of crystallisation.

### Density determination

A crystal density of 1.48 g cm$^{-3}$ was recorded by allowing single crystals to settle in a graduated density-gradient column[94] containing an equilibrated mixture of carbon tetrachloride and m-xylene.

The number of molecules in the unit cell was calculated as four.

### Space group assignment

A survey of the reflections on Weissenberg photographs showed no systematic absences. Odd layer-lines on the *b*-axis rotation photograph were extremely weak and this information proved useful in the structural elucidation. The space group P1 or P$\bar{1}$ (Triclinic) was indicated[95].

### Diffractometer data

Crystal instability was detected during data collection. The first crystal selected for intensity measurements fractured in the X-ray beam. A second specimen cut into a rough cube of dimensions 0.38 x 0.43 x 0.25 mm was finally used with the X-ray generator operating at 0.75kW (half the original power). Crystal data are listed in Table IV.2.1.

TABLE IV.2.1 CRYSTAL DATA

| | |
|---|---|
| Molecular formula | $Cu(C_{16}H_{24}N_4)(Cl)(NO_3).2H_2O$ |
| Molecular weight | 469.0 g mole$^{-1}$ |
| Space group | P$\bar{1}$ (Triclinic) |
| a = 15.90(5) Å | |
| b = 14.47(5) Å | |
| c = 10.39(5) Å | |
| $\alpha$ = 103.4(2)° | $D_m$ = 1.48 g cm$^{-3}$ |
| $\beta$ = 88.6(2)° | $D_c$ = 1.47 g cm$^{-3}$ for Z = 4 |
| $\gamma$ = 114.4(2)° | $\mu$(MoK$\alpha$) = 12.2 cm$^{-1}$ |
| V = 2112.7 Å$^3$ | F(000) = 980 |

The errors in the cell dimensions are large and are due to the mosaic spread of the crystal. A $2\Theta$ range from $6^{\circ}$ to $38^{\circ}$ was explored by the $\omega$-$2\Theta$ scan technique (scan speed $0.1^{\circ}\Theta\sec^{-1}$, scan width $1.4^{\circ}\Theta$) and a total of 3381 reflections were counted. Of these, 1789 had $I_{rel}<1.65\sigma(I_{rel})$. Treatment of these 'less-thans' is discussed below. For the minimum $\mu R$ value of 0.25, the A* value was 1.5 with no variation over the $\Theta$-range covered. For the maximum $\mu R$ of 0.36, A* was 1.8, which remained constant over the $\Theta$-range covered[78]. Absorption corrections were considered negligible. Three reference reflections were monitored after every 240 measured reflections and their intensities showed a rather high variation (up to 8%) due to crystal decomposition. This resulted in intensity data of rather poor quality.

## Solution and refinement of the structure

The structure was solved in the space group $P\bar{1}$.

From the observation of weak odd layer-lines on the *b*-axis rotation photograph, it was deduced that the structure was approximately repeated with a period one half of the true repeat along the *b*-axis. With four molecules and hence four copper atoms in the cell, a plausible set of positions for these atoms is therefore

1. $x,y,z$ 2. $x,\frac{1}{2}+y,z$ 3. $-x,-y,-z$ and 4. $-x,-\frac{1}{2}-y,-z$.

A three-dimensional Patterson map was prepared using all the reflections (X-RAY 72 program system[46]) and was analysed on the basis of such a model. The latter was consistent with the presence of a vector peak of height just less than the origin height at the position $0,\frac{1}{2},0$ in the map. A likely conclusion was that most of the atoms of one molecule were related to those of the second molecule of the asymmetric unit simply by the addition of 0.5 to their y-coordinates. This would therefore necessitate finding a set of coordinates for only one copper atom, the others being generated by the symmetry operations listed above. Further analysis of the vector map yielded four inversion peaks (2x,2y,2z) of the expected height and hence four different sets of coordinates for the copper atom. Electron-density maps were prepared with each of the four assignments. One of these maps clearly revealed an arrangement resembling the macrocyclic ligand centred around the copper atom as well as a large peak above the macrocyclic plane at 2.5 Å from the metal.

In all, 27 peaks were located in chemically feasible positions in the two separate molecules comprising the asymmetric unit. Structure factors based on these assignments yielded an R value of 0.40. All of the remaining atoms including nitrate ions and water molecules of crystallisation were located in subsequent electron-density maps. The positions and isotropic temperature factors of the 56 non-hydrogen atoms of the asymmetric unit were refined by full-matrix least-squares methods. After four cycles of refinement, R was 0.17. Attempts to refine the carbon and nitrogen temperature factors anisotropically resulted in many of the component temperature coefficients calculating 'non-positive definite'. Despite resetting of these matrix elements between cycles, they would not refine to reasonable positive values. This failure was attributed to the inferior quality of the reflection data. Several cycles of refinement with anisotropic temperature factors assigned to the copper and chlorine atoms and isotropic temperature factors assigned to all other atoms yielded an average shift:error ratio of 0.14 indicating satisfactory convergence of all parameters. Since corresponding atoms of the two molecules of the asymmetric unit had coordinates differing only by about 0.5 in y, information concerning the differences between the individual molecules was contained in the reflections whose intensities were less than the threshold value. Inclusion of some of these reflections was obviously necessary in order to resolve fine structure. With the option that reflections would be included if they calculated greater than the observed value, 598 (i.e. 33%) of the 'less-thans' contributed in the final cycle of refinement.

The function minimised was $\Sigma(|F_o|-|F_c|)^2$ and the terminal value of R was 0.108 based on 2190 reflections each assigned unit weight. A final difference electron-density map showed smeared peaks due to the anisotropic motion of the light atoms. No attempt was made to locate hydrogen atoms. First, these were not of vital interest to the chemical problem and secondly, the inferior quality of the data did not permit this degree of refinement.

All of the scattering factors employed were those of the Hartree-Fock-Slater model[62]. Anomalous dispersion corrections[63] were applied to the Cu and Cl scattering curves.

Final positional and thermal parameters are presented in Table IV.2.2. Observed and calculated structure factors are listed in Table IV.2.3. The 'less-than' reflections are labelled with an asterisk.

# TABLE IV.2.2

## FRACTIONAL ATOMIC COORDINATES ($\times 10^4$) AND THEIR E.S.D.'s AND THERMAL PARAMETERS

Anisotropic temperature factors refer to the expression

$$T = \exp[-2\pi^2(U_{11}h^2a^{*2} + U_{22}k^2b^{*2} + U_{33}l^2c^{*2} + 2U_{12}hka^*b^* + 2U_{13}hla^*c^* + 2U_{23}klb^*c^*)\times 10^3]$$

| | $x$ | $y$ | $z$ | $U_{11}$ | $U_{22}$ | $U_{33}$ | $U_{12}$ | $U_{13}$ | $U_{23}$ |
|---|---|---|---|---|---|---|---|---|---|
| CuA | 2395(2) | 3925(2) | 3522(3) | 42(2) | 52(2) | 43(2) | 25(2) | 3(1) | 10(2) |
| ClA | 2147(5) | 2396(5) | 4454(7) | 88(5) | 54(4) | 58(5) | 36(4) | 7(4) | 14(4) |
| CuB | 2393(2) | 8923(2) | 3523(3) | 46(2) | 52(2) | 37(2) | 27(2) | 5(1) | 9(1) |
| ClB | 2160(5) | 7400(5) | 4452(6) | 95(5) | 56(4) | 51(4) | 41(4) | 7(4) | 25(3) |

| | $x$ | $y$ | $z$ | $U_{iso}$ ($\times 10^3$) |
|---|---|---|---|---|
| N(1)A | 3676(13) | 4728(15) | 3571(19) | 48(6) |
| N(2)A | 2610(12) | 4967(14) | 5266(18) | 41(5) |
| N(3)A | 1066(13) | 3641(14) | 3083(19) | 50(6) |
| N(4)A | 2654(13) | 3293(14) | 1768(18) | 43(5) |
| C(1)A | 4088(16) | 5531(18) | 4564(23) | 44(6) |
| C(2)A | 3444(15) | 5641(17) | 5620(22) | 41(6) |
| C(3)A | 1866(17) | 4851(19) | 6185(25) | 59(7) |
| C(4)A | 947(20) | 4623(22) | 5400(29) | 73(9) |
| C(5)A | 547(19) | 3572(21) | 4307(27) | 65(8) |
| C(6)A | 574(19) | 2563(22) | 2147(29) | 71(9) |
| C(7)A | 1000(19) | 2438(21) | 842(28) | 67(8) |
| C(8)A | 1954(20) | 2315(22) | 842(29) | 72(9) |
| C(9)A | 3511(16) | 3636(17) | 1478(22) | 42(6) |
| C(10)A | 4140(15) | 4557(17) | 2541(22) | 41(6) |
| C(11)A | 5079(17) | 5135(19) | 2425(24) | 49(7) |
| C(12)A | 5499(18) | 5955(20) | 3605(26) | 58(8) |
| C(13)A | 5027(17) | 6179(18) | 4685(24) | 50(7) |
| C(14)A | 3741(17) | 6428(18) | 6939(24) | 54(7) |
| C(15)A | 3924(17) | 3216(19) | 270(25) | 48(7) |
| C(16)A | 1033(19) | 4482(21) | 2507(27) | 67(8) |

TABLE IV.2.2 (cont'd)

| | | | | |
|---|---|---|---|---|
| N(5)A | 2981(18) | 5045(18) | -361(24) | 68(7) |
| O(1)A | 3747(19) | 5570(20) | 200(26) | 122(9) |
| O(2)A | 2883(16) | 4313(18) | -1375(24) | 104(7) |
| O(3)A | 2305(23) | 5105(24) | 2(31) | 152(11) |
| O(4)A | 3743(13) | 1880(14) | 2765(18) | 74(6) |
| O(5)A | 1744(17) | 2227(19) | 7434(27) | 105(8) |
| N(1)B | 3721(11) | 9771(12) | 3585(15) | 24(4) |
| N(2)B | 2618(12) | 9966(14) | 5280(18) | 40(5) |
| N(3)B | 1076(13) | 8634(15) | 3080(19) | 51(5) |
| N(4)B | 2669(13) | 8296(14) | 1730(18) | 46(5) |
| C(1)B | 4123(15) | 10583(17) | 4642(22) | 38(6) |
| C(2)B | 3430(15) | 10610(17) | 5624(21) | 37(6) |
| C(3)B | 1843(16) | 9848(18) | 6195(23) | 46(7) |
| C(4)B | 946(18) | 9630(20) | 5416(26) | 59(7) |
| C(5)B | 580(18) | 8632(20) | 4348(26) | 62(8) |
| C(6)B | 604(18) | 7577(20) | 2179(27) | 62(8) |
| C(7)B | 993(19) | 7453(21) | 785(28) | 68(8) |
| C(8)B | 1914(18) | 7300(20) | 886(26) | 59(7) |
| C(9)B | 3480(17) | 8621(18) | 1487(23) | 46(6) |
| C(10)B | 4121(15) | 9522(16) | 2478(21) | 38(6) |
| C(11)B | 5087(16) | 10151(18) | 2518(24) | 47(7) |
| C(12)B | 5553(18) | 10962(20) | 3557(26) | 57(7) |
| C(13)B | 5090(16) | 11203(18) | 4675(23) | 48(6) |
| C(14)B | 3791(18) | 11434(19) | 6884(26) | 59(6) |
| C(15)B | 3897(23) | 8163(26) | 287(34) | 72(11) |
| C(16)B | 1045(19) | 9472(21) | 2467(27) | 68(8) |
| N(5)B | 2941(23) | 10014(23) | -393(31) | 98(9) |
| O(1)B | 3687(19) | 10527(20) | 189(26) | 119(8) |
| O(2)B | 2893(17) | 9300(19) | -1342(25) | 113(8) |
| O(3)B | 2276(25) | 10054(26) | -36(34) | 168(12) |
| O(4)B | 3714(13) | 6877(14) | 2789(19) | 76(6) |
| O(5)B | 1752(18) | 7246(19) | 7437(27) | 104(8) |

# TABLE IV.2.3

| | 10FO | 10FC |
|---|---|---|
| H,0,0 | | |
| 3 | 67 | -159 |
| 4 | 297 | 375 |
| 5 | 613 | 548 |
| 6 | 1161 | -1239 |
| 7 | 1147 | -1151 |
| 8 | 739 | 772 |
| 9 | 0* | 88 |
| 10 | 133 | -192 |
| 11 | 172 | -73 |
| 12 | 186 | 194 |
| 13 | 132 | 34 |
| H,1,0 | | |
| 12 | 43* | 4 |
| 11 | 24* | 4 |
| 10 | 0* | -13 |
| 9 | 54* | -8 |
| 8 | 56* | -32 |
| 7 | 35* | 26 |
| 6 | 0* | -22 |
| 5 | 46* | -4 |
| 4 | 28* | -11 |
| 3 | 41* | -9 |
| 2 | 0* | -11 |
| -3 | 0* | -14 |
| -4 | 29* | -38 |
| -5 | 41* | 29 |
| -6 | 44* | 16 |
| -7 | 0* | -5 |
| -8 | 44* | 3 |
| -9 | 43* | -6 |
| -10 | 54* | 29 |
| -11 | 47* | 22 |
| -12 | 28* | -8 |
| -13 | 26* | -4 |
| H,2,0 | | |
| -14 | 266 | -217 |
| -13 | 275 | -324 |
| -12 | 422 | 441 |
| -11 | 391 | 346 |
| -10 | 338 | -343 |
| -9 | 525 | -503 |
| -8 | 716 | 762 |
| -7 | 1149 | 1134 |
| -6 | 109 | 114 |
| -5 | 2359 | -2219 |
| -4 | 28* | -75 |
| -3 | 1160 | 1301 |
| -2 | 774 | -708 |
| 0 | 635 | 473 |
| 1 | 444 | 346 |
| 2 | 563 | 492 |
| 3 | 181 | -154 |
| 4 | 202 | 306 |
| 5 | 721 | 724 |
| 6 | 373 | -425 |
| 7 | 355 | -351 |
| 8 | 0* | 10 |
| 9 | 271 | 302 |
| 10 | 148 | 166 |
| 11 | 220 | -248 |
| 12 | 55* | 61 |
| H,3,0 | | |
| 11 | 35* | 51 |
| 10 | 69* | -16 |
| 9 | 63* | -29 |
| 8 | 40* | 33 |
| 7 | 54* | -23 |
| 6 | 3* | 21 |
| 5 | 11* | 29 |
| 4 | 6* | -36 |
| 3 | 18* | 22 |
| 2 | 17* | 3 |
| 1 | 3* | 20 |
| 0 | 8* | -4 |
| -1 | 24* | -10 |
| -2 | 34* | 3 |
| -3 | 35* | 5 |
| -4 | 3* | 11 |
| -5 | 38* | -1 |
| -6 | 19* | 13 |
| -7 | 34* | -20 |
| -8 | 4* | 17 |
| -9 | 40* | -6 |
| -10 | 55* | -24 |
| -11 | 34* | -9 |
| -12 | 31* | 19 |
| -13 | 0* | -2 |
| -14 | 52* | -5 |
| H,4,0 | | |
| -14 | 53* | -74 |
| -13 | 262 | -294 |
| -12 | 237 | -269 |
| -11 | 173 | 299 |
| -10 | 653 | 695 |
| -9 | 266 | -391 |
| -8 | 494 | -487 |
| -7 | 35* | 130 |
| -6 | 338 | 510 |
| -5 | 69 | 39 |
| -4 | 228 | 143 |
| -3 | 323 | -190 |
| -2 | 435 | -426 |
| -1 | 343 | -367 |
| 0 | 497 | 471 |
| 1 | 1202 | 1090 |
| 2 | 297 | 213 |
| 3 | 532 | -554 |
| 4 | 618 | -592 |
| 5 | 373 | 394 |
| 6 | 427 | 418 |
| 7 | 60* | -131 |
| 8 | 578 | -601 |
| 9 | 333 | -152 |
| 10 | 372 | 384 |
| H,5,0 | | |
| 9 | 50* | -14 |
| 8 | 46* | 64 |
| 7 | 52* | -40 |
| 6 | 46* | 27 |
| 5 | 40* | 12 |
| 4 | 34* | -29 |
| 3 | 37* | 14 |
| 2 | 40 | 0 |
| 1 | 0* | 3 |
| 0 | 0* | 11 |
| -1 | 23* | -25 |
| -2 | 20* | -8 |
| -3 | 19* | -14 |
| -4 | 0* | 8 |
| -5 | 15* | -15 |
| -6 | 35* | -14 |
| -7 | 26* | 26 |
| -8 | 47* | -6 |
| -9 | 23* | -6 |
| -10 | 55* | 17 |
| -11 | 40* | 14 |
| -12 | 37* | 12 |
| -13 | 29* | -11 |
| -14 | 43* | -30 |
| H,6,0 | | |
| -14 | 168 | 155 |
| -13 | 110 | -42 |
| -12 | 432 | -368 |
| -11 | 24* | 25 |
| -10 | 529 | 533 |
| -9 | 219 | -226 |
| -8 | 341 | -318 |
| -7 | 41* | 121 |
| -6 | 419 | 439 |
| -5 | 99 | 55 |
| -4 | 484 | -423 |
| -3 | 150 | -127 |
| -2 | 543 | 499 |
| -1 | 461 | 541 |
| 0 | 315 | -417 |
| 1 | 1137 | -1134 |
| 2 | 190 | 220 |
| 3 | 838 | 841 |
| 4 | 57* | -127 |
| 5 | 680 | -532 |
| 6 | 54* | -8 |
| 7 | 379 | 275 |
| 8 | 331 | 314 |
| H,7,0 | | |
| 7 | 32* | -20 |
| 6 | 29* | 15 |
| 5 | 50* | -9 |
| 4 | 0* | -4 |
| 3 | 32* | -29 |
| 2 | 23* | 2 |
| 1 | 3* | 0 |
| 0 | 20* | -8 |
| -1 | 0* | 5 |
| -2 | 3* | -13 |
| -3 | 20* | 12 |
| -4 | 29* | 11 |
| -5 | 0* | 8 |
| -6 | 0* | 14 |
| -7 | 3* | 6 |
| -8 | 3* | 10 |
| -9 | 35* | -21 |

| | 10FO | 10FC |
|---|---|---|
| -10 | 46* | -3 |
| -11 | 31* | 0 |
| -12 | 0* | -11 |
| -13 | 29* | 14 |
| -14 | 31* | -39 |
| H,8,0 | | |
| -14 | 257 | 262 |
| -13 | 255 | 243 |
| -12 | 225 | -287 |
| -11 | 644 | -627 |
| -10 | 55* | 152 |
| -9 | 753 | 789 |
| -8 | 315 | 193 |
| -7 | 435 | -478 |
| -6 | 394 | -121 |
| -5 | 514 | 559 |
| -4 | 1033 | 427 |
| -3 | 927 | -1042 |
| -2 | 426 | -814 |
| -1 | 187 | 312 |
| 0 | 673 | 735 |
| 1 | 335 | 322 |
| 2 | 297 | -276 |
| 3 | 89 | -56 |
| 4 | 561 | 532 |
| 5 | 205 | -269 |
| 6 | 176 | -81 |
| H,9,0 | | |
| 5 | 9* | 21 |
| 4 | 0* | -13 |
| 3 | 0* | 10 |
| 2 | 46* | 8 |
| 1 | 53* | 26 |
| 0 | 7* | 17 |
| -1 | 3* | -14 |
| -2 | 0* | 1 |
| -3 | 7* | 12 |
| -4 | 3* | -2 |
| -5 | 28* | 7 |
| -6 | 34* | -21 |
| -7 | 0* | -6 |
| -8 | 3* | 4 |
| -9 | 0* | -24 |
| -10 | 3* | 20 |
| -11 | 0* | -2 |
| -12 | 44* | 7 |
| -13 | 0* | -5 |
| H,10,0 | | |
| -12 | 251 | 312 |
| -11 | 142 | 96 |
| -10 | 436 | -462 |
| -9 | 425 | -398 |
| -8 | 543 | 670 |
| -7 | 317 | 301 |
| -6 | 269 | -245 |
| -5 | 109 | -12 |
| -4 | 569 | 517 |
| -3 | 233 | -317 |
| -2 | 196 | -290 |
| -1 | 255 | -290 |
| 0 | 50* | 21 |
| 1 | 21* | -14 |
| 2 | 384 | -329 |
| 3 | 99 | 19 |
| H,11,0 | | |
| 1 | 43 | 22 |
| 0 | 49* | -16 |
| -1 | 58* | -23 |
| -2 | 0* | 10 |
| -3 | 38* | -11 |
| -4 | 49* | -6 |
| -5 | 15* | 9 |
| -6 | 60* | -12 |
| -7 | 43* | 10 |
| -8 | 0* | -4 |
| -9 | 47* | -8 |
| -10 | 0* | 11 |
| -11 | 0* | -1 |
| H,12,0 | | |
| -10 | 49 | -117 |
| -9 | 308 | -274 |
| -8 | 43 | 135 |
| -7 | 340 | 288 |
| -6 | 303 | -394 |
| -5 | 396 | -254 |
| -4 | 502 | 563 |
| -3 | 445 | 319 |
| -2 | 113 | -123 |
| H,-12,1 | | |
| 10 | 557 | 522 |
| 9 | 34* | -91 |
| 8 | 396 | -397 |
| 7 | 122 | -124 |
| 6 | 386 | 368 |
| 5 | 52* | -128 |
| 4 | 555 | -588 |
| 3 | 164 | -126 |
| 2 | 265 | 324 |
| 1 | 350 | 334 |
| H,-11,1 | | |
| -2 | 0* | -3 |
| -1 | 17* | 4 |
| 0 | 0* | -4 |
| 1 | 47* | 11 |
| 2 | 26* | 11 |
| 3 | 26* | 7 |
| 4 | 39* | 14 |
| 5 | 43* | -12 |
| 6 | 29* | 6 |
| 7 | 43 | 9 |
| 8 | 0* | -10 |
| 9 | 59* | 8 |
| 10 | 15* | -14 |
| 11 | 63* | -7 |
| 12 | 86 | 26 |
| H,-10,1 | | |
| 13 | 153 | -143 |
| 12 | 61* | 39 |
| 11 | 41* | 59 |
| 10 | 386 | 316 |
| 9 | 286 | -336 |
| 8 | 363 | -355 |
| 7 | 122 | 145 |
| 6 | 69 | 97 |
| 5 | 151 | -66 |
| 4 | 52* | 39 |
| 3 | 350 | 316 |
| 2 | 291 | 293 |
| 1 | 176 | 153 |
| 0 | 266 | -269 |
| -1 | 0* | -48 |
| -2 | 158 | 140 |
| -3 | 289 | -347 |
| H,-9,1 | | |
| -5 | 3* | -6 |
| -4 | 3* | 21 |
| -3 | 47* | -24 |
| -2 | 58* | 16 |
| -1 | 3* | -10 |
| 0 | 55* | -7 |
| 1 | 3* | -4 |
| 2 | 34* | 4 |
| 3 | 43* | -1 |
| 4 | 29* | -25 |
| 5 | 49* | -3 |
| 6 | 37* | -4 |
| 7 | 4* | -7 |
| 8 | 24* | 19 |
| 9 | 12* | 19 |
| 10 | 0* | -10 |
| 11 | 7* | 7 |
| 12 | 63* | 17 |
| 13 | 52* | -6 |
| H,-8,1 | | |
| 14 | 257 | -298 |
| 13 | 334 | -190 |
| 12 | 503 | 610 |
| 11 | 303 | 335 |
| 10 | 539 | -585 |
| 9 | 280 | -283 |
| 8 | 69 | 130 |
| 7 | 408 | 468 |
| 6 | 217 | 196 |
| 5 | 701 | -890 |
| 4 | 29* | -22 |
| 3 | 603 | 539 |
| 2 | 3* | -58 |
| 1 | 225 | -193 |
| 0 | 465 | -490 |
| -1 | 469 | 481 |
| -2 | 222 | 186 |
| -3 | 379 | -431 |
| -4 | 49 | -29 |
| -5 | 213 | 194 |
| -6 | 157 | 149 |
| H,-7,1 | | |
| -7 | 61* | 28 |
| -6 | 12* | -11 |

| | 10FO | 10FC |
|---|---|---|
| -5 | 0* | 0 |
| -4 | 60* | 35 |
| -3 | 54* | -42 |
| -2 | 0* | 8 |
| -1 | 29* | 32 |
| 0 | 14* | -22 |
| 1 | 0* | 3 |
| 2 | 29* | 4 |
| 3 | 34* | 14 |
| 4 | 43* | 8 |
| 5 | 0* | -3 |
| 6 | 0* | -17 |
| 7 | 38* | -19 |
| 8 | 0* | 6 |
| 9 | 21* | -15 |
| 10 | 40* | -28 |
| 11 | 57* | 8 |
| 12 | 64* | 25 |
| 13 | 0* | 0 |
| 14 | 43* | 5 |
| H,-6,1 | | |
| 14 | 0* | 14 |
| 13 | 447 | 426 |
| 12 | 158 | 153 |
| 11 | 496 | -501 |
| 10 | 347 | -393 |
| 9 | 477 | 574 |
| 8 | 363 | 407 |
| 7 | 739 | -753 |
| 6 | 413 | -375 |
| 5 | 430 | 347 |
| 4 | 1075 | 1018 |
| 3 | 38* | -193 |
| 2 | 710 | -795 |
| 1 | 410 | -332 |
| 0 | 1068 | 1136 |
| -1 | 78 | -109 |
| -2 | 1092 | -1210 |
| -3 | 207 | -132 |
| -4 | 633 | 686 |
| -5 | 312 | 335 |
| -6 | 496 | -495 |
| -7 | 334 | -333 |
| -8 | 366 | 363 |
| -9 | 360 | 331 |
| H,-5,1 | | |
| -8 | 44* | -23 |
| -7 | 61* | -5 |
| -6 | 60* | 1 |
| -5 | 0* | 12 |
| -4 | 35* | -18 |
| -3 | 0* | 19 |
| -2 | 0* | -18 |
| -1 | 23* | 30 |
| 0 | 19* | 2 |
| 1 | 19* | -5 |
| 2 | 20* | 39 |
| 3 | 23* | -25 |
| 4 | 0* | 11 |
| 5 | 34* | 11 |
| 6 | 34* | -16 |
| 7 | 11* | 25 |
| 8 | 50* | -4 |
| 9 | 39* | 43 |
| 10 | 41* | -7 |
| 11 | 60* | -21 |
| 12 | 60* | 26 |
| 13 | 46* | -27 |
| 14 | 38* | 16 |
| H,-4,1 | | |
| 14 | 236 | 209 |
| 13 | 408 | 420 |
| 12 | 52* | -88 |
| 11 | 422 | -416 |
| 10 | 24* | 43 |
| 9 | 532 | -473 |
| 8 | 543 | -562 |
| 7 | 422 | -516 |
| 6 | 252 | 284 |
| 5 | 308 | -329 |
| 4 | 517 | 334 |
| 3 | 1371 | -1243 |
| 2 | 650 | 636 |
| 1 | 1276 | 1408 |
| 0 | 404 | 368 |
| -1 | 496 | -1071 |
| -2 | 32* | -31 |
| -3 | 604 | 644 |
| -4 | 628 | 643 |
| -5 | 935 | -953 |
| -6 | 124 | -159 |
| -7 | 638 | 667 |
| -8 | 231 | 182 |
| -9 | 523 | -513 |
| -10 | 173 | -97 |
| H,-3,1 | | |
| -11 | 43* | -2 |
| -10 | 3* | 1 |
| -9 | 3* | 17 |
| -8 | 63* | 21 |
| -7 | 13* | -36 |
| -6 | 47* | -9 |
| -5 | 34* | 40 |
| -4 | 3* | -31 |
| -3 | 13* | -29 |
| -2 | 23* | -18 |
| -1 | 26* | -2 |
| 0 | 3* | 7 |
| 1 | 26* | -29 |
| 2 | 29* | 0 |
| 3 | 47 | 25 |
| 4 | 34* | -11 |
| 5 | 15* | -5 |
| 6 | 31* | -21 |
| 7 | 46* | 19 |
| 8 | 64 | -25 |
| 9 | 35* | 6 |
| 10 | 57* | -54 |
| 11 | 3* | 16 |
| 12 | 26* | 91 |
| 13 | 54* | -16 |
| 14 | 57* | -10 |
| H,-2,1 | | |
| 14 | 3* | 44 |
| 12 | 673 | -676 |
| 11 | 54* | -95 |
| 10 | 399 | 494 |
| 9 | 0* | 73 |
| 8 | 1357 | -1295 |
| 7 | 203 | 231 |
| 6 | 1207 | 1110 |
| 5 | 1277 | 1380 |
| 4 | 796 | 605 |
| 3 | 531 | -507 |
| 2 | 1379 | 1249 |
| 1 | 379 | 311 |
| 0 | 1834 | -1797 |
| -1 | 1196 | -1157 |
| -2 | 513 | -499 |
| -3 | 419 | 392 |
| -4 | 44* | 98 |
| -5 | 870 | -798 |
| -6 | 684 | 252 |
| -7 | 219 | 235 |
| -8 | 265 | -273 |
| -9 | 308 | -297 |
| -10 | 376 | 343 |
| -11 | 70* | 37 |
| -12 | 228 | -299 |
| H,-1,1 | | |
| -12 | 73* | 6 |
| -11 | 29* | 20 |
| -10 | 61 | -32 |
| -9 | 41* | 9 |
| -8 | 0* | 36 |
| -7 | 29* | -21 |
| -6 | 14* | 28 |
| -5 | 24* | -18 |
| -4 | 24* | 30 |
| -1 | 9* | 9 |
| -2 | 5* | -5 |
| 2 | 0* | -25 |
| 3 | 0* | 27 |
| 4 | 20* | 9 |
| 5 | 1* | 27 |
| 6 | 59 | 11 |
| 7 | 47* | -39 |
| 8 | 0* | 10 |
| 9 | 34* | 41 |
| 10 | 29* | -32 |
| 11 | 31* | -17 |
| 12 | 60* | 2 |
| 13 | 35* | 6 |
| H,0,1 | | |
| 13 | 216 | -171 |
| 12 | 0* | -66 |
| 11 | 449 | 437 |
| 10 | 6* | -50 |
| 9 | 707 | -726 |
| 8 | 0* | 111 |
| 7 | 1762 | 1719 |
| 6 | 198 | -181 |
| 5 | 1190 | -1137 |

| | 10FO | 10FC |
|---|---|---|
| H,0,1 | | |
| 4 | 1138 | -961 |
| 3 | 756 | 739 |
| 2 | 114 | 52 |
| -2 | 364 | 336 |
| -3 | 872 | 859 |
| -4 | 442 | -465 |
| -5 | 361 | 314 |
| -6 | 1184 | 1234 |
| -7 | 650 | -565 |
| -8 | 753 | -794 |
| -9 | 0* | 69 |
| -10 | 596 | 634 |
| -11 | 0* | 27 |
| -12 | 401 | -361 |
| -13 | 26* | 61 |
| H,1,1 | | |
| -13 | 45* | -25 |
| -12 | 64* | -11 |
| -11 | 32* | 30 |
| -10 | 0* | -35 |
| -9 | 26* | 31 |
| -8 | 0* | -4 |
| -7 | 61 | -33 |
| -6 | 0* | 37 |
| -5 | 38* | -31 |
| -4 | 0* | 13 |
| -3 | 21* | -13 |
| -2 | 11* | -26 |
| 1 | 26* | 35 |
| 2 | 26* | -24 |
| 3 | 29* | 0 |
| 4 | 24* | -3 |
| 5 | 0* | -19 |
| 6 | 63 | 31 |
| 7 | 23* | -4 |
| 8 | 41* | 4 |
| 9 | 41* | -3 |
| 10 | 6* | 2 |
| 11 | 38* | -26 |
| 12 | 54* | 21 |
| H,2,1 | | |
| 11 | 67* | -69 |
| 10 | 399 | -375 |
| 9 | 29* | 57 |
| 8 | 502 | 511 |
| 7 | 55* | 54 |
| 6 | 557 | -552 |
| 5 | 106 | -147 |
| 4 | 1190 | 1076 |
| 3 | 127 | 133 |
| 2 | 1458 | -1417 |
| 1 | 451 | 393 |
| 0 | 1133 | 1101 |
| -1 | 237 | 368 |
| -2 | 862 | -885 |
| -3 | 61 | 46 |
| -4 | 468 | 282 |
| -5 | 721 | 793 |
| -6 | 511 | -414 |
| -7 | 1061 | -1093 |
| -8 | 292 | 245 |
| -9 | 451 | 652 |
| -10 | 23* | 62 |
| -11 | 777 | -729 |
| -12 | 199 | -229 |
| -13 | 471 | 464 |
| -14 | 200 | 292 |
| H,3,1 | | |
| -14 | 0* | -6 |
| -13 | 64* | -4 |
| -12 | 53* | -15 |
| -11 | 55* | 6 |
| -10 | 9* | -18 |
| -9 | 53* | 3 |
| -8 | 26* | 4 |
| -7 | 12* | 13 |
| -6 | 20* | -2 |
| -5 | 3* | 30 |
| -4 | 31* | -4 |
| -3 | 17* | -5 |
| -2 | 14* | 13 |
| -1 | 4* | -14 |
| 0 | 3* | 0 |
| 1 | 32* | 11 |
| 2 | 26* | -4 |
| 3 | 28* | -4 |
| 4 | 17* | -1 |
| 5 | 63 | 49 |
| 6 | 23* | -32 |
| 7 | 12* | 1 |
| 8 | 34* | 6 |
| 9 | 54* | -15 |
| 10 | 31* | 45 |
| 11 | 54* | -31 |
| H,4,1 | | |
| 10 | 64* | 41 |
| 9 | 239 | 263 |
| 8 | 265 | 261 |
| 7 | 327 | -220 |
| 6 | 563 | -596 |
| 5 | 261 | 181 |
| 4 | 219 | 273 |
| 3 | 537 | -590 |
| 2 | 519 | 404 |
| 1 | 105 | 122 |
| 0 | 637 | 591 |
| -1 | 161 | -160 |
| -2 | 546 | -447 |
| -3 | 433 | 861 |
| -4 | 24* | 91 |
| -5 | 277 | -253 |
| -6 | 162 | -107 |
| -7 | 734 | -559 |
| -8 | 597 | 593 |
| -9 | 272 | 256 |
| -10 | 519 | -556 |
| -11 | 124 | -80 |
| -12 | 340 | 297 |
| -13 | 67* | -33 |
| -14 | 35* | -44 |
| H,5,1 | | |
| -14 | 48 | 44 |
| -13 | 57* | -15 |
| -12 | 28* | -4 |
| -11 | 0* | 14 |
| -10 | 37* | -21 |
| -9 | 0* | -1 |
| -8 | 20* | 25 |
| -7 | 26* | -28 |
| -6 | 37* | -36 |
| -5 | 17* | 23 |
| -4 | 24* | 10 |
| -3 | 21* | 26 |
| -2 | 16* | 9 |
| -1 | 37* | -30 |
| 0 | 0* | -2 |
| 1 | 43* | 29 |
| 2 | 43* | 29 |
| 3 | 31* | 12 |
| 4 | 80 | -38 |
| 5 | 9* | 20 |
| 6 | 30 | -32 |
| 7 | 34* | 24 |
| 8 | 0* | -1 |
| 9 | 23* | -23 |
| H,6,1 | | |
| 8 | 356 | -249 |
| 7 | 159 | -122 |
| 6 | 326 | 257 |
| 5 | 721 | 753 |
| 4 | 243 | -225 |
| 3 | 592 | -547 |
| 2 | 424 | 372 |
| 1 | 238 | 287 |
| 0 | 213 | -116 |
| -1 | 892 | -856 |
| -2 | 330 | -429 |
| -3 | 519 | 515 |
| -4 | 874 | 535 |
| -5 | 835 | -783 |
| -6 | 255 | -266 |
| -7 | 662 | 632 |
| -8 | 64 | -15 |
| -9 | 34* | 13 |
| -10 | 525 | -492 |
| -11 | 57* | 44 |
| -12 | 534 | 567 |
| -13 | 210 | -281 |
| -14 | 141 | 71 |
| H,7,1 | | |
| -14 | 52* | 26 |
| -13 | 61* | -33 |
| -12 | 0* | 16 |
| -11 | 52* | 5 |
| -10 | 20* | -11 |
| -9 | 52* | 8 |
| -8 | 43* | -5 |
| -7 | 0* | 13 |
| -6 | 44* | 16 |
| -5 | 37* | -23 |
| -4 | 0* | -13 |

| | 10FO | 10FC |
|---|---|---|
| -3 | 12* | 6 |
| -2 | 3* | -24 |
| -1 | 3* | 4 |
| 0 | 0* | -19 |
| 1 | 3* | 5 |
| 2 | 17* | 1 |
| 3 | 3* | -6 |
| 4 | 63* | 13 |
| 5 | 89 | 46 |
| 6 | 38* | -27 |
| 7 | 44* | 25 |
| H,8,1 | | |
| 5 | 196 | -197 |
| 4 | 739 | -743 |
| 3 | 434 | 400 |
| 2 | 271 | 237 |
| 1 | 323 | -295 |
| 0 | 451 | -472 |
| -1 | 139 | 47 |
| -2 | 1095 | 1040 |
| -3 | 229 | 392 |
| -4 | 624 | -749 |
| -5 | 161 | -233 |
| -6 | 659 | 597 |
| -7 | 434 | 484 |
| -8 | 1027 | -875 |
| -9 | 54* | -97 |
| -10 | 513 | 472 |
| -11 | 461 | 421 |
| -12 | 358 | -311 |
| -13 | 444 | -490 |
| H,9,1 | | |
| -13 | 32* | 12 |
| -12 | 73* | -1 |
| -11 | 17* | -13 |
| -10 | 3* | -11 |
| -9 | 29* | 16 |
| -8 | 37* | 9 |
| -7 | 47* | -5 |
| -6 | 34* | -9 |
| -5 | 11* | 15 |
| -4 | 52* | -8 |
| -3 | 72* | 34 |
| -2 | 0* | -3 |
| -1 | 41* | -4 |
| 0 | 48* | -20 |
| 1 | 47* | -18 |
| 2 | 61* | 19 |
| 3 | 0* | -20 |
| 4 | 21* | -11 |
| H,10,1 | | |
| 2 | 73* | 138 |
| 1 | 274 | -273 |
| 0 | 98 | 108 |
| -1 | 336 | 339 |
| -2 | 166 | -98 |
| -3 | 236 | -195 |
| -4 | 237 | -281 |
| -5 | 342 | 372 |
| -6 | 144 | 166 |
| -7 | 611 | -594 |
| -8 | 159 | -176 |
| -9 | 551 | 523 |
| -10 | 95 | 99 |
| -11 | 366 | -348 |
| -12 | 401 | -412 |
| H,11,1 | | |
| -11 | 54* | 26 |
| -10 | 65* | -36 |
| -9 | 37* | 7 |
| -8 | 12* | 0 |
| -7 | 0* | -25 |
| -6 | 44* | 23 |
| -5 | 0* | 4 |
| -4 | 0* | 4 |
| -3 | 31* | 13 |
| -2 | 16* | -13 |
| -1 | 14* | 20 |
| 0 | 50* | -3 |
| H,12,1 | | |
| -3 | 228 | -263 |
| -4 | 216 | 172 |
| -5 | 133 | 146 |
| -6 | 136 | -192 |
| -7 | 32* | -68 |
| -8 | 57* | 66 |
| H,-13,2 | | |
| 6 | 53* | 4 |
| 5 | 0* | 1 |
| H,-12,2 | | |
| 1 | 172 | -146 |
| 2 | 522 | -473 |
| 3 | 159 | -219 |
| 4 | 358 | 328 |
| 5 | 331 | 328 |
| 6 | 473 | -443 |
| 7 | 33 | -40 |
| 8 | 349 | 392 |
| 9 | 432 | 465 |
| 10 | 726 | -715 |
| H,-11,2 | | |
| 12 | 18* | -17 |
| 11 | 38* | 4 |
| 10 | 6* | -1 |
| 9 | 12* | 4 |
| 8 | 56* | -14 |
| 7 | 35* | -13 |
| 6 | 38* | 0 |
| 5 | 0* | 2 |
| 4 | 24* | 13 |
| 3 | 21* | -2 |
| 2 | 23* | -4 |
| 1 | 52* | -6 |
| 0 | 64* | -8 |
| -1 | 17* | 12 |
| -2 | 37* | 4 |
| H,-10,2 | | |
| -4 | 59* | -12 |
| -3 | 329 | 292 |
| -2 | 41* | 56 |
| -1 | 338 | -152 |
| 0 | 63* | 43 |
| 1 | 43* | 27 |
| 2 | 87 | 45 |
| 3 | 199 | -188 |
| 4 | 40* | -23 |
| 5 | 32* | 71 |
| 6 | 28* | 4 |
| 7 | 191 | -291 |
| 8 | 112 | -110 |
| 9 | 216 | 239 |
| 10 | 124 | 139 |
| 11 | 23* | -41 |
| 12 | 254 | -216 |
| 13 | 132 | 185 |
| H,-9,2 | | |
| 13 | 29* | -8 |
| 12 | 61* | -8 |
| 11 | 55* | -10 |
| 10 | 35* | -15 |
| 9 | 47* | 0 |
| 8 | 26* | 32 |
| 7 | 17* | 12 |
| 6 | 37* | -7 |
| 5 | 35* | 6 |
| 4 | 0* | -9 |
| 3 | 37* | 18 |
| 2 | 60 | -8 |
| 1 | 52* | -1 |
| 0 | 33* | 19 |
| -1 | 0* | -19 |
| -2 | 28* | 15 |
| -3 | 29* | 12 |
| -4 | 32* | -11 |
| -5 | 52* | 53 |
| H,-8,2 | | |
| -6 | 104 | 143 |
| -5 | 162 | -166 |
| -4 | 92 | -67 |
| -3 | 133 | 172 |
| -2 | 221 | 253 |
| -1 | 311 | -330 |
| 0 | 133 | -146 |
| 1 | 275 | 263 |
| 2 | 323 | 299 |
| 3 | 294 | -339 |
| 4 | 165 | -280 |
| 5 | 101 | 132 |
| 6 | 249 | 283 |
| 7 | 262 | -259 |
| 8 | 467 | -469 |
| 9 | 167 | 170 |
| 10 | 615 | 610 |
| 11 | 53* | 61 |
| 12 | 671 | -655 |

| | 10FO | 10FC |
|---|---|---|
| 13 | 20* | 15 |
| 14 | 344 | 344 |
| H,-7,2 | | |
| 14 | 64* | -4 |
| 13 | 44* | -4 |
| 12 | 28* | 1 |
| 11 | 42 | 21 |
| 10 | 0* | -12 |
| 9 | 20* | 27 |
| 8 | 31* | -12 |
| 7 | 54* | -27 |
| 6 | 50* | 22 |
| 5 | 21* | 9 |
| 4 | 0* | -13 |
| 3 | 34* | 23 |
| 2 | 60 | -8 |
| 1 | 29* | -8 |
| 0 | 43* | -12 |
| -1 | 31* | -13 |
| -2 | 20* | 31 |
| -3 | 3* | -21 |
| -4 | 32* | -31 |
| -5 | 29* | 27 |
| -6 | 47* | -23 |
| -7 | 32* | 11 |
| -8 | 55* | 22 |
| H,-6,2 | | |
| -9 | 57* | 38 |
| -8 | 310 | -306 |
| -7 | 50* | -45 |
| -6 | 361 | 371 |
| -5 | 78 | 90 |
| -4 | 431 | -407 |
| -3 | 431 | -448 |
| -2 | 441 | 635 |
| -1 | 464 | 520 |
| 0 | 572 | -631 |
| 1 | 708 | -763 |
| 2 | 60 | -29 |
| 3 | 1915 | 1899 |
| 4 | 49* | -30 |
| 5 | 721 | -996 |
| 6 | 379 | 432 |
| 7 | 1186 | 1192 |
| 8 | 950 | -936 |
| 9 | 768 | -795 |
| 10 | 298 | -223 |
| 11 | 575 | 588 |
| 12 | 15* | 55 |
| 13 | 394 | -414 |
| 14 | 230 | -189 |
| H,-5,2 | | |
| 14 | 54* | -1 |
| 13 | 46* | -5 |
| 12 | 23* | -16 |
| 11 | 6* | -7 |
| 10 | 37* | -21 |
| 9 | 43* | 25 |
| 8 | 20* | 15 |
| 7 | 23* | -17 |
| 6 | 34* | 9 |
| 5 | 9* | 1 |
| 4 | 47* | -21 |
| 3 | 0* | 15 |
| 2 | 23* | 5 |
| 1 | 3* | -41 |
| 0 | 3* | -13 |
| -1 | 32* | 23 |
| -2 | 21* | -4 |
| -3 | 20* | 5 |
| -4 | 50* | 46 |
| -5 | 43* | -12 |
| -6 | 15* | 4 |
| -7 | 58* | -1 |
| -8 | 8* | 16 |
| -9 | 55* | 7 |
| -10 | 29* | -10 |
| H,-4,2 | | |
| -13 | 26* | -55 |
| -9 | 412 | 348 |
| -8 | 251 | 279 |
| -7 | 396 | -371 |
| -6 | 725 | -626 |
| -5 | 867 | 977 |
| -4 | 549 | 712 |
| -3 | 587 | -545 |
| -2 | 457 | -359 |
| -1 | 203 | -135 |
| 0 | 1996 | 1627 |
| 1 | 153 | 53 |
| 2 | 4574 | -4369 |
| 3 | 2354 | 1951 |
| 4 | 477 | 437 |
| 5 | 643 | -473 |
| 6 | 844 | -547 |
| 7 | 44* | -51 |
| 8 | 1155 | 1094 |
| 9 | 561 | 493 |
| 10 | 571 | -566 |
| 11 | 349 | 349 |
| 12 | 57* | 76 |
| 13 | 122 | -114 |
| 14 | 223 | -197 |
| H,-3,2 | | |
| 13 | 67* | -12 |
| 12 | 21* | -5 |
| 11 | 46* | 4 |
| 10 | 53* | 46 |
| 9 | 47* | -12 |
| 8 | 47* | 1 |
| 7 | 32* | -15 |
| 6 | 26* | 31 |
| 5 | 3* | 15 |
| 4 | 3* | -20 |
| 3 | 37* | -2 |
| 2 | 35* | 1 |
| 1 | 31* | -18 |
| 0 | 3* | -1 |
| -1 | 17* | 19 |
| -2 | 54 | 91 |
| -3 | 34* | -30 |
| -4 | 20* | -15 |
| -5 | 20* | 21 |
| -6 | 0* | 2 |
| -7 | 29* | 15 |
| -8 | 67 | -29 |
| -9 | 43* | -31 |
| -10 | 43* | 3 |
| -11 | 26* | 4 |
| H,-2,2 | | |
| -12 | 213 | 157 |
| -11 | 41* | 40 |
| -10 | 491 | -575 |
| -9 | 192 | -192 |
| -8 | 369 | 420 |
| -7 | 360 | 395 |
| -6 | 353 | -309 |
| -5 | 355 | -364 |
| -4 | 116 | 72 |
| -3 | 896 | 910 |
| -2 | 1239 | -1108 |
| -1 | 271 | -357 |
| 0 | 1596 | 1516 |
| 1 | 1539 | 1918 |
| 2 | 1764 | -1746 |
| 3 | 693 | 599 |
| 4 | 933 | 753 |
| 5 | 593 | 371 |
| 6 | 1092 | -1099 |
| 7 | 824 | -758 |
| 8 | 566 | 596 |
| 9 | 64 | 113 |
| 10 | 390 | -389 |
| 11 | 265 | -236 |
| 12 | 243 | 226 |
| 13 | 470 | 483 |
| H,-1,2 | | |
| 13 | 91 | -96 |
| 12 | 37* | 9 |
| 11 | 32* | 33 |
| 10 | 0* | -25 |
| 9 | 52* | 15 |
| 8 | 0* | 0 |
| 7 | 69 | -25 |
| 6 | 40* | 39 |
| 5 | 40* | -43 |
| 4 | 44* | -2 |
| 3 | 41* | -14 |
| 2 | 28* | 7 |
| 1 | 32* | -10 |
| 0 | 31* | 2 |
| -1 | 44 | 24 |
| -2 | 37* | -25 |
| -3 | 31* | 24 |
| -4 | 34* | 21 |
| -5 | 0* | -2 |
| -6 | 63 | -43 |
| -7 | 0* | -17 |
| -8 | 0* | 17 |
| -9 | 72 | 22 |
| -10 | 29* | -21 |
| -11 | 0* | 5 |

| | 10FO | 10FC |
|---|---|---|
| -12 | 61* | 3 |
| H,0,2 | | |
| -13 | 75* | -93 |
| -12 | 350 | 377 |
| -11 | 114 | 45 |
| -10 | 234 | -235 |
| -9 | 243 | -272 |
| -8 | 47* | -12 |
| -7 | 500 | 584 |
| -6 | 471 | -371 |
| -5 | 608 | -731 |
| -4 | 361 | 450 |
| -3 | 1210 | 1320 |
| -2 | 644 | -669 |
| -1 | 818 | -969 |
| 0 | 294 | 366 |
| 1 | 695 | 761 |
| 2 | 339 | -420 |
| 3 | 1034 | -1041 |
| 4 | 494 | 324 |
| 5 | 985 | 1013 |
| 6 | 317 | 328 |
| 7 | 752 | -445 |
| 8 | 441 | -401 |
| 9 | 384 | 431 |
| 10 | 691 | 563 |
| 11 | 153 | -156 |
| 12 | 514 | -462 |
| H,1,2 | | |
| 12 | 74* | 16 |
| 11 | 43 | 39 |
| 10 | 80 | -54 |
| 9 | 18* | 45 |
| 8 | 26* | -27 |
| 7 | 37* | -29 |
| 6 | 8* | 21 |
| 5 | 0* | -3 |
| 4 | 38* | -7 |
| 3 | 31* | -4 |
| 2 | 29* | 0 |
| 1 | 41* | 7 |
| 0 | 34* | 5 |
| -1 | 17* | 25 |
| -2 | 18* | -23 |
| -3 | 37* | 27 |
| -4 | 32* | 12 |
| -5 | 55 | -45 |
| -6 | 47* | 13 |
| -7 | 23* | 18 |
| -8 | 28* | -30 |
| -9 | 35* | -12 |
| -10 | 46* | 4 |
| -11 | 43* | 13 |
| -12 | 64* | 30 |
| -13 | 89 | -20 |
| H,2,2 | | |
| -13 | 171 | -229 |
| -12 | 43* | -34 |
| -11 | 465 | 428 |
| -10 | 438 | 437 |
| -9 | 548 | -623 |
| -8 | 402 | -935 |
| -7 | 476 | 506 |
| -6 | 539 | 657 |
| -5 | 169 | -53 |
| -4 | 1158 | -1263 |
| -3 | 209 | 286 |
| -2 | 893 | 919 |
| -1 | 223 | -127 |
| 0 | 413 | -402 |
| 1 | 568 | -682 |
| 2 | 260 | 251 |
| 3 | 859 | 802 |
| 4 | 521 | -381 |
| 5 | 413 | -434 |
| 6 | 490 | 570 |
| 7 | 463 | 446 |
| 8 | 169 | -135 |
| 9 | 392 | -336 |
| 10 | 165 | -215 |
| 11 | 349 | 447 |
| H,3,2 | | |
| 10 | 54* | -19 |
| 9 | 7* | 21 |
| 8 | 57* | -6 |
| 7 | 29* | 4 |
| 6 | 3* | -7 |
| 5 | 0* | 33 |
| 4 | 23* | -7 |
| 3 | 0* | -6 |
| 2 | 23* | 25 |
| 1 | 32* | 10 |
| 0 | 39* | 10 |
| -1 | 37* | -13 |
| -2 | 29* | 8 |
| -3 | 96* | 18 |
| -4 | 20* | -21 |
| -5 | 6* | -28 |
| -6 | 46* | -37 |
| -7 | 60 | 32 |
| -8 | 21* | 10 |
| -9 | 37* | 3 |
| -10 | 12* | 22 |
| -11 | 43* | -37 |
| -12 | 61* | 50 |
| -13 | 47* | -15 |
| -14 | 57* | -10 |
| H,4,2 | | |
| -14 | 69* | 76 |
| -13 | 441 | 455 |
| -12 | 454 | -430 |
| -11 | 190 | -187 |
| -10 | 449 | 429 |
| -9 | 829 | 790 |
| -8 | 202 | -227 |
| -7 | 736 | -684 |
| -6 | 115 | -27 |
| -5 | 618 | 637 |
| -4 | 343 | -297 |
| -3 | 245 | -257 |
| -2 | 323 | -326 |
| -1 | 1548 | 1559 |
| 0 | 144 | 139 |
| 1 | 649 | -659 |
| 2 | 302 | -451 |
| 3 | 229 | -293 |
| 4 | 52* | 110 |
| 5 | 237 | -237 |
| 6 | 384 | -480 |
| 7 | 520 | 596 |
| 8 | 0* | -85 |
| 9 | 60* | 88 |
| H,5,2 | | |
| 8 | 73* | 4 |
| 7 | 32* | -34 |
| 6 | 0* | 13 |
| 5 | 63* | 7 |
| 4 | 17* | -7 |
| 3 | 0* | -10 |
| 2 | 29* | -23 |
| 1 | 21* | -1 |
| 0 | 44* | 5 |
| -1 | 0* | -17 |
| -2 | 0* | 4 |
| -3 | 46* | -19 |
| -4 | 39* | -6 |
| -5 | 29* | 21 |
| -6 | 0* | -10 |
| -7 | 41* | 25 |
| -8 | 52* | -19 |
| -9 | 21* | 6 |
| -10 | 0* | 3 |
| -11 | 55* | 8 |
| -12 | 0* | 10 |
| -13 | 47* | -12 |
| -14 | 46* | -6 |
| H,6,2 | | |
| -14 | 463 | -500 |
| -13 | 457 | 444 |
| -12 | 46* | -2 |
| -11 | 449 | -426 |
| -10 | 119 | -195 |
| -9 | 217 | 192 |
| -8 | 254 | 209 |
| -7 | 209 | -162 |
| -6 | 722 | -673 |
| -5 | 646 | 690 |
| -4 | 419 | 444 |
| -3 | 418 | -461 |
| -2 | 792 | -791 |
| -1 | 1262 | 1121 |
| 0 | 407 | 417 |
| 1 | 74 | -49 |
| 2 | 205 | -121 |
| 3 | 364 | 381 |
| 4 | 653 | 649 |
| 5 | 278 | -250 |
| 6 | 684 | -705 |
| 7 | 193 | 227 |

| | 10FO | 10FC |
|---|---|---|
| H,7,2 | | |
| 6 | 29* | 16 |
| 5 | 9* | -23 |
| 4 | 8* | 4 |
| 3 | 26* | -18 |
| 2 | 0* | 23 |
| 1 | 0* | 33 |
| 0 | 28* | -6 |
| -1 | 34* | -1 |
| -2 | 0* | 29 |
| -3 | 3* | -2 |
| -4 | 29* | 21 |
| -5 | 43* | -28 |
| -6 | 39* | -17 |
| -7 | 0* | 28 |
| -8 | 0* | 9 |
| -9 | 37* | 5 |
| -10 | 24* | -28 |
| -11 | 31* | 17 |
| -12 | 57* | -5 |
| -13 | 26* | 23 |
| H,8,2 | | |
| -13 | 35* | 10 |
| -12 | 555 | 567 |
| -11 | 55* | 77 |
| -10 | 434 | -437 |
| -9 | 164 | -167 |
| -8 | 418 | 457 |
| -7 | 374 | 401 |
| -6 | 744 | -794 |
| -5 | 653 | -581 |
| -4 | 617 | 420 |
| -3 | 343 | 345 |
| -2 | 947 | -944 |
| -1 | 316 | -259 |
| 0 | 360 | 375 |
| 1 | 573 | 530 |
| 2 | 358 | -393 |
| 3 | 574 | -526 |
| 4 | 353 | 340 |
| 5 | 312 | 263 |
| H,9,2 | | |
| 3 | 6* | -6 |
| 2 | 43* | 1 |
| 1 | 49* | 28 |
| 0 | 31* | -6 |
| -1 | 0* | -6 |
| -2 | 44* | 20 |
| -3 | 18* | -36 |
| -4 | 0* | 5 |
| -5 | 0* | -14 |
| -6 | 28* | 0 |
| -7 | 54* | 4 |
| -8 | 0* | -10 |
| -9 | 52* | 4 |
| -10 | 54* | 6 |
| -11 | 0* | -2 |
| -12 | 29* | 4 |
| H,10,2 | | |
| -11 | 462 | 485 |
| -10 | 240 | 197 |
| -9 | 491 | -495 |
| -8 | 301 | -263 |
| -7 | 516 | 511 |
| -6 | 315 | 309 |
| -5 | 401 | -347 |
| -4 | 361 | -391 |
| -3 | 263 | 280 |
| -2 | 292 | 223 |
| -1 | 141 | -131 |
| 0 | 272 | -295 |
| 1 | 197 | 197 |
| H,11,2 | | |
| -1 | 41* | -5 |
| -2 | 29* | 27 |
| -3 | 8* | -54 |
| -4 | 44* | 14 |
| -5 | 32* | -16 |
| -6 | 57* | 1 |
| -7 | 38* | 37 |
| -8 | 35* | -7 |
| -9 | 31* | 10 |
| -10 | 57* | -7 |
| H,-13,3 | | |
| 5 | 44* | 4 |
| 6 | 3* | 23 |
| 7 | 26* | -4 |
| H,-12,3 | | |
| 9 | 274 | -295 |
| 8 | 98 | -62 |
| 7 | 524 | 519 |
| 6 | 135 | 159 |
| 5 | 459 | -424 |
| 4 | 38* | -84 |
| 3 | 286 | 232 |
| 2 | 327 | 356 |
| 1 | 341 | -324 |
| H,-11,3 | | |
| -2 | 0* | -29 |
| -1 | 19* | 41 |
| 0 | 0* | -6 |
| 1 | 23* | -21 |
| 2 | 36* | 12 |
| 3 | 21* | -6 |
| 4 | 14* | 21 |
| 5 | 41* | 2 |
| 6 | 57* | -21 |
| 7 | 44* | -7 |
| 8 | 31* | 13 |
| 9 | 60* | 12 |
| 10 | 55* | -8 |
| 11 | 0* | 7 |
| H,-10,3 | | |
| 12 | 151 | 179 |
| 11 | 87 | 8 |
| 10 | 239 | -218 |
| 9 | 112 | 96 |
| 8 | 109 | 66 |
| 7 | 57* | -7 |
| 6 | 174 | -217 |
| 5 | 177 | 194 |
| 4 | 191 | 241 |
| 3 | 19* | 43 |
| 2 | 601 | -629 |
| 1 | 130 | -132 |
| 0 | 646 | -491 |
| -1 | 222 | 259 |
| -2 | 321 | -247 |
| -3 | 363 | -313 |
| -4 | 190 | 151 |
| H,-9,3 | | |
| -5 | 37* | -5 |
| -4 | 41* | 0 |
| -3 | 35* | 3 |
| -2 | 0* | 0 |
| -1 | 43* | -3 |
| 0 | 3* | 4 |
| 1 | 29* | -25 |
| 2 | 11* | 28 |
| 3 | 21* | -22 |
| 4 | 11* | -36 |
| 5 | 3* | 31 |
| 6 | 20* | -8 |
| 7 | 11* | 4 |
| 8 | 44* | -1 |
| 9 | 35* | -27 |
| 10 | 23* | 22 |
| 11 | 12* | -21 |
| 12 | 32* | 19 |
| 13 | 46* | 0 |
| H,-8,3 | | |
| 13 | 341 | 393 |
| 12 | 167 | 235 |
| 11 | 521 | -459 |
| 10 | 41* | -92 |
| 9 | 623 | 621 |
| 8 | 497 | 512 |
| 7 | 194 | 132 |
| 6 | 1069 | -991 |
| 5 | 431 | 392 |
| 4 | 116 | 211 |
| 3 | 114 | -392 |
| 2 | 519 | -510 |
| 1 | 174 | 178 |
| 0 | 219 | 200 |
| -1 | 32* | 27 |
| -2 | 334 | -350 |
| -3 | 332 | 341 |
| -4 | 94 | 137 |
| -5 | 229 | -332 |
| -6 | 262 | -269 |
| H,-7,3 | | |
| -7 | 44* | -2 |
| -6 | 26* | -6 |
| -5 | 5* | 25 |

| | 10FO | 10FC |
|---|---|---|
| -4 | 21* | -1 |
| -3 | 20* | -40 |
| -2 | 35* | 17 |
| -1 | 29* | 22 |
| 0 | 0* | 22 |
| 1 | 37* | -7 |
| 2 | 24* | 2 |
| 3 | 31* | 10 |
| 4 | 0* | 4 |
| 5 | 31* | 1 |
| 6 | 46* | -3 |
| 7 | 78 | -21 |
| 8 | 29* | 19 |
| 9 | 17* | -4 |
| 10 | 0* | 10 |
| 11 | 46* | -4 |
| 12 | 40* | 38 |
| 13 | 44* | -13 |
| H,-6,3 | | |
| 13 | 210 | 238 |
| 12 | 367 | -325 |
| 11 | 228 | -240 |
| 10 | 467 | 932 |
| 9 | 138 | 192 |
| 8 | 1051 | -1033 |
| 7 | 914 | -930 |
| 6 | 142 | 82 |
| 5 | 1296 | 1294 |
| 4 | 945 | -870 |
| 3 | 1269 | -1382 |
| 2 | 608 | 579 |
| 1 | 1541 | 1547 |
| 0 | 499 | 626 |
| -1 | 669 | -699 |
| -2 | 578 | -679 |
| -3 | 731 | 739 |
| -4 | 34* | -36 |
| -5 | 272 | -255 |
| -6 | 35* | -36 |
| -7 | 335 | 347 |
| -8 | 80 | -89 |
| H,-5,3 | | |
| -9 | 35* | -7 |
| -8 | 0* | 24 |
| -7 | 49* | -22 |
| -6 | 70 | -17 |
| -5 | 31* | 7 |
| -4 | 0* | -14 |
| -3 | 0* | 6 |
| -2 | 32* | -25 |
| -1 | 0* | 11 |
| 0 | 35* | 4 |
| 1 | 0* | -15 |
| 2 | 40* | 40 |
| 3 | 0* | -21 |
| 4 | 0* | -7 |
| 5 | 69 | -24 |
| 6 | 18* | 21 |
| 7 | 11* | -7 |
| 8 | 9* | -7 |
| 9 | 32* | -3 |
| 10 | 43* | -7 |
| 11 | 49* | -15 |
| 12 | 83 | 36 |
| 13 | 46* | -3 |
| H,-4,3 | | |
| 13 | 326 | -273 |
| 12 | 372 | -319 |
| 11 | 294 | 271 |
| 10 | 407 | 424 |
| 9 | 617 | -769 |
| 8 | 0* | -67 |
| 7 | 415 | 433 |
| 6 | 517 | 468 |
| 5 | 259 | -262 |
| 4 | 234 | -302 |
| 3 | 952 | 927 |
| 2 | 1006 | 963 |
| 1 | 1339 | -1023 |
| 0 | 413 | -504 |
| -1 | 89 | -165 |
| -2 | 825 | 973 |
| -3 | 217 | 330 |
| -4 | 1314 | -1415 |
| -5 | 139 | -225 |
| -6 | 595 | 636 |
| -7 | 252 | 298 |
| -8 | 493 | -523 |
| -9 | 259 | -242 |
| -10 | 361 | 340 |
| H,-3,3 | | |
| -11 | 21* | 24 |
| -10 | 67* | -5 |
| -9 | 17* | -24 |
| -8 | 74 | 44 |
| -7 | 43* | -10 |
| -6 | 61 | 39 |
| -5 | 0* | 15 |
| -4 | 44* | -40 |
| -3 | 40* | 9 |
| -2 | 18* | -31 |
| -1 | 35* | -12 |
| 0 | 26* | 23 |
| 1 | 32* | -17 |
| 2 | 18* | 11 |
| 3 | 43* | 6 |
| 4 | 37* | 37 |
| 5 | 3* | -1 |
| 6 | 26* | 2 |
| 7 | 3* | -6 |
| 8 | 29* | -10 |
| 9 | 21* | -3 |
| 10 | 17* | -11 |
| 11 | 41* | -5 |
| 12 | 31* | 4 |
| 13 | 32* | 30 |
| H,-2,3 | | |
| 13 | 225 | -210 |
| 12 | 286 | 263 |
| 11 | 419 | 412 |
| 10 | 147 | -151 |
| 9 | 587 | -591 |
| 8 | 3* | -19 |
| 7 | 469 | 579 |
| 6 | 67 | -126 |
| 5 | 405 | -534 |
| 4 | 219 | 416 |
| 3 | 479 | -468 |
| 2 | 72 | -58 |
| 1 | 467 | 760 |
| 0 | 737 | 794 |
| -1 | 722 | -562 |
| -2 | 797 | -540 |
| -3 | 693 | -630 |
| -4 | 41* | -62 |
| -5 | 818 | 822 |
| -6 | 95 | 128 |
| -7 | 591 | -585 |
| -8 | 239 | -305 |
| -9 | 551 | 579 |
| -10 | 415 | 483 |
| -11 | 194 | -224 |
| H,-1,3 | | |
| -12 | 0* | 4 |
| -11 | 0* | -4 |
| -10 | 40* | 14 |
| -9 | 6* | -17 |
| -8 | 26* | 5 |
| -7 | 17* | 16 |
| -6 | 34* | 21 |
| -5 | 32* | 4 |
| -4 | 12* | 15 |
| -3 | 39* | -27 |
| -2 | 60 | 24 |
| -1 | 35* | -8 |
| 0 | 56 | -20 |
| 1 | 38* | 26 |
| 2 | 15* | -3 |
| 3 | 0* | -17 |
| 4 | 43* | -7 |
| 5 | 6* | 11 |
| 6 | 43* | 23 |
| 7 | 32* | -23 |
| 8 | 24* | 23 |
| 9 | 0* | -11 |
| 10 | 0* | -6 |
| 11 | 0* | 7 |
| 12 | 44* | -40 |
| H,0,3 | | |
| 12 | 181 | 195 |
| 11 | 149 | -110 |
| 10 | 429 | -398 |
| 9 | 212 | 152 |
| 8 | 838 | 757 |
| 7 | 179 | -235 |
| 6 | 981 | -1121 |
| 5 | 511 | 463 |
| 4 | 613 | 607 |
| 3 | 548 | -471 |
| 2 | 921 | -975 |
| 1 | 733 | -711 |
| 0 | 931 | 912 |
| -1 | 55 | 169 |

| | 10FO | 10FC |
|---|---|---|
| H,0,3 | | |
| -2 | 358 | -237 |
| -3 | 693 | -621 |
| -4 | 945 | -916 |
| -5 | 961 | 929 |
| -6 | 220 | 232 |
| -7 | 909 | -379 |
| -8 | 353 | 354 |
| -9 | 473 | 419 |
| -10 | 161 | -137 |
| -11 | 197 | -137 |
| -12 | 197 | -223 |
| H,1,3 | | |
| -13 | 0* | 3 |
| -12 | 26* | -27 |
| -11 | 38* | 28 |
| -10 | 24* | -17 |
| -9 | 41* | -40 |
| -8 | 29* | 27 |
| -7 | 28* | 2 |
| -6 | 41* | -9 |
| -5 | 12* | 12 |
| -4 | 34* | 15 |
| -3 | 44* | -25 |
| -2 | 35* | -1 |
| -1 | 24* | -3 |
| 0 | 43* | 3 |
| 1 | 20* | 3 |
| 2 | 32* | -9 |
| 3 | 37* | -20 |
| 4 | 43* | 4 |
| 5 | 44* | 4 |
| 6 | 52* | 35 |
| 7 | 18* | -22 |
| 8 | 63* | 33 |
| 9 | 55* | -29 |
| 10 | 6* | 7 |
| 11 | 21* | 20 |
| H,2,3 | | |
| 10 | 69* | 63 |
| 9 | 81 | 59 |
| 8 | 205 | -210 |
| 7 | 704 | -749 |
| 6 | 50* | 63 |
| 5 | 907 | 980 |
| 4 | 226 | -231 |
| 3 | 393 | -518 |
| 2 | 312 | 173 |
| 1 | 1423 | 1472 |
| 0 | 306 | 537 |
| -1 | 1826 | -1950 |
| -2 | 1623 | -1459 |
| -3 | 835 | 1127 |
| -4 | 1412 | 1523 |
| -5 | 177 | -235 |
| -6 | 196 | -227 |
| -7 | 263 | -256 |
| -8 | 731 | 749 |
| -9 | 309 | 364 |
| -10 | 1022 | -1077 |
| -11 | 40* | -24 |
| -12 | 55* | 53 |
| -13 | 83 | -58 |
| H,3,3 | | |
| -13 | 47* | 20 |
| -12 | 53* | -31 |
| -11 | 67* | 39 |
| -10 | 43* | -17 |
| -9 | 11* | 4 |
| -8 | 67 | -12 |
| -7 | 23* | -20 |
| -6 | 58 | 19 |
| -5 | 17* | -23 |
| -4 | 28* | 23 |
| -3 | 46* | 42 |
| -2 | 8* | 21 |
| -1 | 47* | -30 |
| 0 | 57 | 29 |
| 1 | 0* | 3 |
| 2 | 19* | 30 |
| 3 | 15* | -40 |
| 4 | 0* | -17 |
| 5 | 38* | 5 |
| 6 | 63* | 0 |
| 7 | 44* | -41 |
| 8 | 69* | 32 |
| 9 | 43* | -37 |
| 10 | 32* | 7 |
| H,4,3 | | |
| 9 | 46* | 46 |
| 8 | 139 | -127 |
| 7 | 181 | -294 |
| 6 | 791 | 690 |
| 5 | 243 | 187 |
| 4 | 44* | 28 |
| 3 | 75 | -110 |
| 2 | 119 | -118 |
| 1 | 158 | 218 |
| 0 | 883 | -780 |
| -1 | 967 | -938 |
| -2 | 983 | 574 |
| -3 | 182 | 353 |
| -4 | 566 | -481 |
| -5 | 768 | -820 |
| -6 | 1011 | 1079 |
| -7 | 197 | 399 |
| -8 | 490 | -589 |
| -9 | 710 | -611 |
| -10 | 76 | 95 |
| -11 | 832 | 825 |
| -12 | 34* | -19 |
| -13 | 350 | -389 |
| H,5,3 | | |
| -13 | 0* | -12 |
| -12 | 26* | 20 |
| -11 | 40* | -2 |
| -10 | 44* | 5 |
| -9 | 0* | -8 |
| -8 | 50* | -9 |
| -7 | 0* | 1 |
| -6 | 3* | 12 |
| -5 | 5* | -15 |
| -4 | 35* | -3 |
| -3 | 28* | -24 |
| -2 | 38* | 29 |
| -1 | 12* | -32 |
| 0 | 44* | 9 |
| 1 | 35* | -9 |
| 2 | 17* | 40 |
| 3 | 44* | 3 |
| 4 | 0* | -17 |
| 5 | 31* | 35 |
| 6 | 0* | 7 |
| 7 | 18* | -4 |
| 8 | 63* | 39 |
| H,6,3 | | |
| 6 | 499 | 575 |
| 5 | 329 | -313 |
| 4 | 630 | -644 |
| 3 | 795 | 207 |
| 2 | 502 | 422 |
| 1 | 231 | -206 |
| 0 | 468 | -441 |
| -1 | 372 | -402 |
| -2 | 566 | 574 |
| -3 | 308 | 316 |
| -4 | 358 | -296 |
| -5 | 304 | 265 |
| -6 | 387 | 426 |
| -7 | 394 | -376 |
| -8 | 169 | -145 |
| -9 | 122 | 42 |
| -10 | 420 | 471 |
| -11 | 161 | -159 |
| -12 | 627 | -604 |
| -13 | 67* | 7 |
| H,7,3 | | |
| -13 | 61* | 0 |
| -12 | 61* | -4 |
| -11 | 47* | -11 |
| -10 | 32* | 38 |
| -9 | 0* | -38 |
| -8 | 73 | 43 |
| -7 | 29* | -34 |
| -6 | 0* | -5 |
| -5 | 67 | 10 |
| -4 | 28* | -18 |
| -3 | 57* | 7 |
| -2 | 0* | -3 |
| -1 | 44* | -27 |
| 0 | 47* | 14 |
| 1 | 23* | -28 |
| 2 | 18* | 14 |
| 3 | 0* | -23 |
| 4 | 44* | -12 |
| 5 | 46 | 25 |
| H,8,3 | | |
| 4 | 231 | 191 |
| 3 | 298 | 276 |
| 2 | 233 | -219 |

# TABLE IV.2.3 (continued)

[illegible]

## IV.3 DESCRIPTION OF THE STRUCTURE AND DISCUSSION

Intramolecular bond lengths and angles for the independent macrocycles A and B are listed in Tables IV.3.1 and IV.3.2 respectively. Least-squares planes are listed in Table IV.3.3.

Two independent macrocycles and their associated ions comprise the asymmetric unit. Bond lengths in the complexed macrocycles, $(Cl.Cu.N\text{-}MeCR)^+$, are shown in Fig. IV.3.1. For clarity, the nitrate ions and water molecules have been omitted in this figure. For the purpose of general description, the structures of the two assemblages (labelled A and B), may be considered identical, every atom of macrocycle B being effectively generated from the corresponding A atom by the addition of 0.5 to y. In addition, two water molecules of crystallisation are associated with each macrocycle.

The copper atom is five coordinate; four of the donor atoms are the nitrogens of the macrocycle and the fifth is a chloride ion at the apex of a distorted square pyramid. The Cu-Cl distances of 2.50(1) and 2.49(1) Å are slightly longer than the analogous bond lengths (2.431 Å) found in bis-(6-hydroxypurine)copper(II) chloride trihydrate[96]. The closest approach of a water oxygen to the copper atom is 4.2 Å.

Chemically equivalent bond lengths in the independent ligands are generally in fair agreement although some equivalent angles differ considerably, especially in the vicinity of the

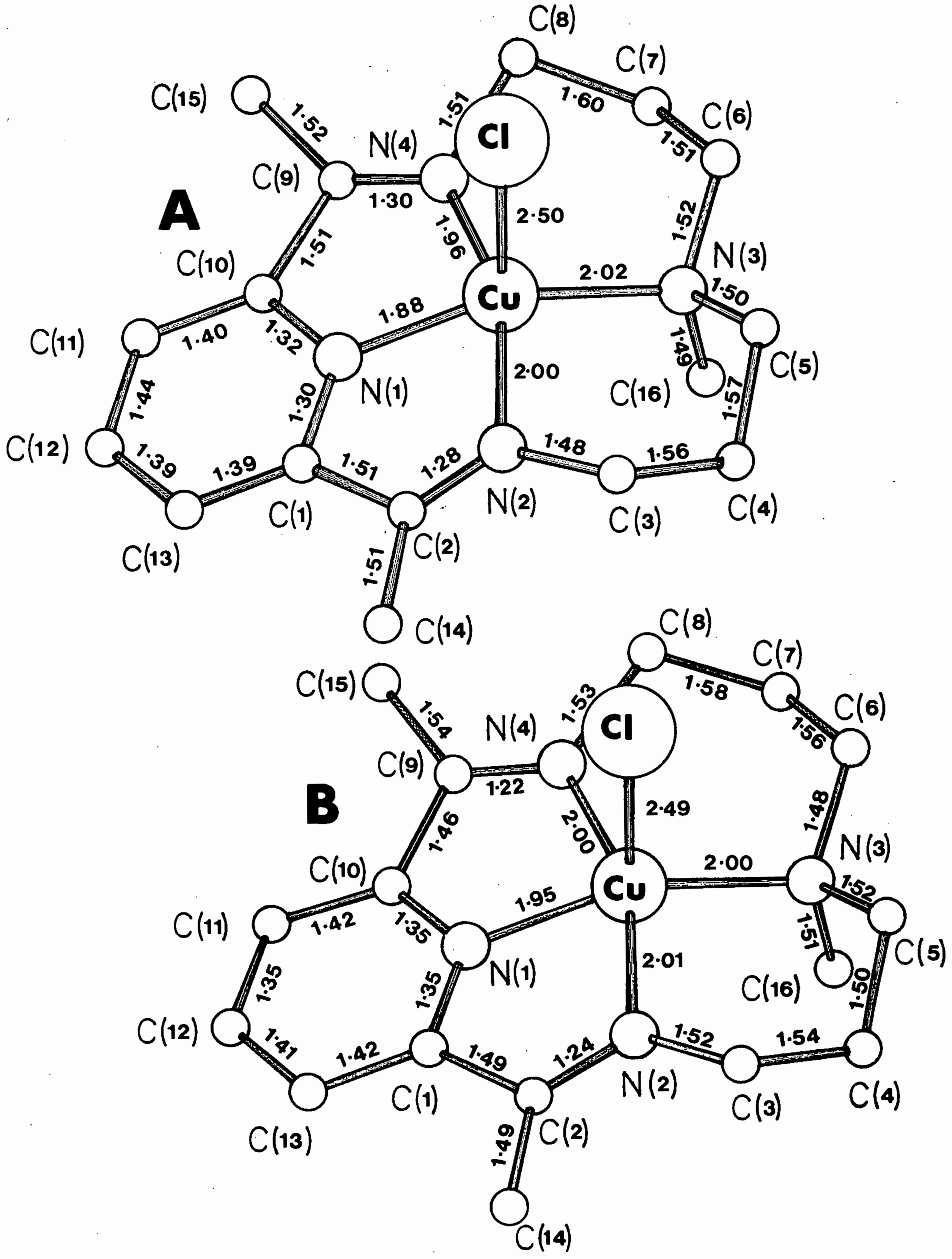

A
C(8)
C(7)
C(6)
C(15)
N(4)
Cl
C(9)
C(10)
C(11)
C(12)
C(13)
C(1)
N(1)
Cu
N(2)
C(2)
C(14)
C(3)
C(4)
C(5)
C(16)
N(3)
1·52
1·51
1·60
1·51
1·30
1·96
2·50
1·52
1·51
2·02
1·50
1·49
1·88
1·40
1·32
1·44
1·30
2·00
1·57
1·39
1·39
1·51
1·28
1·48
1·56
1·51
B
C(8)
C(7)
C(6)
C(15)
N(4)
Cl
C(9)
C(10)
C(11)
C(12)
C(13)
C(1)
N(1)
Cu
N(2)
C(2)
C(14)
C(3)
C(4)
C(5)
C(16)
N(3)
1·54
1·53
1·58
1·56
1·22
2·00
2·49
1·48
1·46
2·00
1·52
1·51
1·95
1·42
1·35
1·35
1·35
2·01
1·50
1·41
1·42
1·49
1·24
1·52
1·54
1·49

FIG. IV.3.1

## TABLE IV.3.1

## INTERATOMIC DISTANCES AND THEIR E.S.D's (Å) IN THE INDEPENDENT MACROCYCLES A AND B

| | | | |
|---|---|---|---|
| CuA—ClA | 2.50(1) | CuB—ClB | 2.49(1) |
| CuA—N(1)A | 1.88(2) | CuB—N(1)B | 1.95(2) |
| CuA—N(2)A | 2.00(2) | CuB—N(2)B | 2.01(2) |
| CuA—N(3)A | 2.02(2) | CuB—N(3)B | 2.00(2) |
| CuA—N(4)A | 1.96(2) | CuB—N(4)B | 2.00(2) |
| N(1)A—C(1)A | 1.30(3) | N(1)B—C(1)B | 1.35(2) |
| N(1)A—C(10)A | 1.32(3) | N(1)B—C(10)B | 1.35(3) |
| C(1)A—C(13)A | 1.39(3) | C(1)B—C(13)B | 1.42(3) |
| C(10)A-C(11)A | 1.40(3) | C(10)B-C(11)B | 1.42(3) |
| C(11)A-C(12)A | 1.44(3) | C(11)B-C(12)B | 1.35(3) |
| C(12)A-C(13)A | 1.39(4) | C(12)B-C(13)B | 1.41(4) |
| C(1)A—C(2)A | 1.51(3) | C(1)B—C(2)B | 1.49(3) |
| C(10)A-C(9)A | 1.51(3) | C(10)B-C(9)B | 1.46(3) |
| C(2)A—C(14)A | 1.51(3) | C(2)B—C(14)B | 1.49(3) |
| C(9)A—C(15)A | 1.52(4) | C(9)B—C(15)B | 1.54(4) |
| N(4)A—C(9)A | 1.30(3) | N(4)B—C(9)B | 1.22(3) |
| N(2)A—C(2)A | 1.28(3) | N(2)B—C(2)B | 1.24(3) |
| N(2)A—C(3)A | 1.48(3) | N(2)B—C(3)B | 1.52(3) |
| N(4)A—C(8)A | 1.51(3) | N(4)B—C(8)B | 1.53(3) |
| C(3)A—C(4)A | 1.56(4) | C(3)B—C(4)B | 1.54(4) |
| C(7)A—C(8)A | 1.60(5) | C(7)B—C(8)B | 1.58(5) |
| C(4)A—C(5)A | 1.57(4) | C(4)B—C(5)B | 1.50(3) |
| C(6)A—C(7)A | 1.51(4) | C(6)B—C(7)B | 1.56(4) |
| C(5)A—N(3)A | 1.50(3) | C(5)B—N(3)B | 1.52(3) |
| C(6)A—N(3)A | 1.52(3) | C(6)B—N(3)B | 1.48(3) |
| N(3)A—C(16)A | 1.49(4) | N(3)B—C(16)B | 1.51(4) |
| N(5)A—O(1)A | 1.21(3) | N(5)B—O(1)B | 1.19(4) |
| N(5)A—O(2)A | 1.27(3) | N(5)B—O(2)B | 1.23(4) |
| N(5)A—O(3)A | 1.16(5) | N(5)B—O(3)B | 1.13(6) |

## TABLE IV.3.2

## BOND ANGLES AND THEIR E.S.D.'s (DEGREES) IN THE INDEPENDENT MACROCYCLES A AND B

| | | | |
|---|---|---|---|
| N(1)A—CuA——N(2)A | 79.4(8) | N(1)B—CuB——N(2)B | 78.4(7) |
| N(2)A—CuA——N(3)A | 98.0(8) | N(2)B—CuB——N(3)B | 98.8(8) |
| N(3)A—CuA——N(4)A | 98.2(8) | N(3)B—CuB——N(4)B | 98.3(8) |
| N(4)A—CuA——N(1)A | 79.6(8) | N(4)B—CuB——N(1)B | 79.6(7) |
| N(1)A—CuA——N(3)A | 152.0(9) | N(1)B—CuB——N(3)B | 151.6(9) |
| N(2)A—CuA——N(4)A | 158.5(7) | N(2)B—CuB——N(4)B | 157.5(7) |
| N(1)A—CuA——ClA | 108.2(8) | N(1)B—CuB——ClB | 108.0(6) |
| N(2)A—CuA——ClA | 96.6(7) | N(2)B—CuB——ClB | 96.3(7) |
| N(3)A—CuA——ClA | 100.1(7) | N(3)B—CuB——ClB | 100.4(7) |
| N(4)A—CuA——ClA | 94.4(7) | N(4)B—CuB——ClB | 94.9(7) |
| CuA——N(1)A—C(1)A | 120(2) | CuB——N(1)B—C(1)B | 118(1) |
| CuA——N(1)A—C(10)A | 120(1) | CuB——N(1)B—C(10)B | 115(1) |
| CuA——N(2)A—C(2)A | 117(2) | CuB——N(2)B—C(2)B | 117(2) |
| CuA——N(2)A—C(3)A | 121(1) | CuB——N(2)B—C(3)B | 120(1) |
| CuA——N(4)A—C(8)A | 124(2) | CuB——N(4)B—C(8)B | 119(2) |
| CuA——N(4)A—C(9)A | 117(1) | CuB——N(4)B—C(9)B | 117(1) |
| N(1)A—C(1)A—C(2)A | 113(2) | N(1)B—C(1)B—C(2)B | 110(2) |
| C(1)A—C(2)A—N(2)A | 112(2) | C(1)B—C(2)B—N(2)B | 116(2) |
| C(2)A—N(2)A—C(3)A | 122(2) | C(2)B—N(2)B—C(3)B | 123(2) |
| N(2)A—C(3)A—C(4)A | 110(2) | N(2)B—C(3)B—C(4)B | 110(2) |
| C(3)A—C(4)A—C(5)A | 115(3) | C(3)B—C(4)B—C(5)B | 115(3) |
| C(4)A—C(5)A—N(3)A | 112(2) | C(4)B—C(5)B—N(3)B | 117(2) |
| CuA——N(3)A—C(5)A | 110(2) | CuB——N(3)B—C(5)B | 109(2) |
| CuA——N(3)A—C(6)A | 110(2) | CuB——N(3)B—C(6)B | 110(2) |
| C(5)A—N(3)A—C(6)A | 104(2) | C(5)B—N(3)B—C(6)B | 108(2) |
| CuA——N(3)A—C(16)A | 110(1) | CuB——N(3)B—C(16)B | 110(1) |
| C(6)A—N(3)A—C(16)A | 112(2) | C(6)B—N(3)B—C(16)B | 112(2) |
| C(5)A—N(3)A—C(16)A | 111(2) | C(5)B—N(3)B—C(16)B | 110(2) |
| N(3)A—C(6)A—C(7)A | 114(2) | N(3)B—C(6)B—C(7)B | 115(2) |
| C(6)A—C(7)A—C(8)A | 118(3) | C(6)B—C(7)B—C(8)B | 110(2) |
| C(7)A—C(8)A—N(4)A | 107(2) | C(7)B—C(8)B—N(4)B | 110(2) |
| C(8)A—N(4)A—C(9)A | 118(2) | C(8)B—N(4)B—C(9)B | 123(2) |
| N(4)A—C(9)A—C(10)A | 112(2) | N(4)B—C(9)B—C(10)B | 116(2) |
| C(9)A—C(10)A-N(1)A | 110(2) | C(9)B—C(10)B-N(1)B | 113(2) |
| N(1)A—C(10)A-C(11)A | 126(2) | N(1)B—C(10)B-C(11)B | 114(2) |
| C(10)A-C(11)A-C(12)A | 111(2) | C(10)B-C(11)B-C(12)B | 122(2) |
| C(11)A-C(12)A-C(13)A | 125(2) | C(11)B-C(12)B-C(13)B | 120(2) |
| C(12)A-C(13)A-C(1)A | 115(2) | C(12)B-C(13)B-C(1)B | 118(2) |
| C(13)A-C(1)A—N(1)A | 124(2) | C(13)B-C(1)B—N(1)B | 118(2) |
| C(1)A—N(1)A—C(10)A | 120(2) | C(1)B—N(1)B—C(10)B | 127(2) |
| C(13)A-C(1)A—C(2)A | 123(2) | C(13)B-C(1)B—C(2)B | 132(2) |
| C(9)A—C(10)A-C(11)A | 124(2) | C(9)B—C(10)B-C(11)B | 132(2) |
| C(1)A—C(2)A—C(14)A | 125(2) | C(1)B—C(2)B—C(14)B | 116(2) |
| C(10)A-C(9)A—C(15)A | 119(2) | C(10)B-C(9)B—C(15)B | 117(2) |
| N(2)A—C(2)A—C(14)A | 124(2) | N(2)B—C(2)B—C(14)B | 128(2) |
| N(4)A—C(9)A—C(15)A | 129(2) | N(4)B—C(9)B—C(15)B | 127(2) |
| O(1)A—N(5)A—O(2)A | 118(3) | O(1)B—N(5)B—O(2)B | 116(4) |
| O(2)A—N(5)A—O(3)A | 116(2) | O(2)B—N(5)B—O(3)B | 119(3) |
| O(1)A—N(5)A—O(3)A | 125(3) | O(1)B—N(5)B—O(3)B | 125(3) |

## TABLE IV.3.3

## LEAST-SQUARES PLANES

The equations of the planes are expressed in orthogonalized space as $PI+QJ+RK=S$

Plane I: through atoms N(1)A,N(2)A,N(3)A and N(4)A

Equation: $-0.25384I+0.75711J-0.60195K=2.28132$

| Atoms included in calculation | Dist. from plane, Å | Atoms not included in calculation | Dist. from plane, Å |
|---|---|---|---|
| N(1)A | .181 | CuA | -.325 |
| N(2)A | -.147 | ClA | -2.819 |
| N(3)A | .117 | | |
| N(4)A | -.150 | | |

Plane II: through atoms N(1)B,N(2)B,N(3)B and N(4)B

Equation: $-0.26660I+0.75738J-0.59607K=8.87094$

| Atoms included in calculation | Dist. from plane, Å | Atoms not included in calculation | Dist. from plane, Å |
|---|---|---|---|
| N(1)B | .184 | CuB | -.332 |
| N(2)B | -.153 | ClB | -2.823 |
| N(3)B | .122 | | |
| N(4)B | -.153 | | |

Plane III: through atoms N(1)A,C(1)A,C(13)A,C(12)A,C(11)A and C(10)A of the pyridine ring in ligand A.

Equation: $-0.53257I+0.60879J-0.58800K=0.75632$

| Atoms included in calculation | Dist. from plane, Å | Atoms not included in calculation | Dist. from plane, Å |
|---|---|---|---|
| N(1)A | -.029 | CuA | .055 |
| C(1)A | .032 | C(2)A | .059 |
| C(13)A | -.006 | | |
| C(12)A | -.019 | | |
| C(11)A | .020 | | |
| C(10)A | .002 | C(9)A | .016 |

Plane IV: through atoms N(1)B,C(1)B,C(13)B,C(12)B,C(11)B and C(10)B of the pyridine ring in ligand B .

Equation: $-0.52307I+0.61392J-0.59118K=7.24490$

| Atoms included in calculation | Dist. from plane, Å | Atoms not included in calculation | Dist. from plane, Å |
|---|---|---|---|
| N(1)B | -.025 | CuB | .028 |
| C(1)B | .021 | C(2)B | .016 |
| C(13)B | -.008 | | |
| C(12)B | .000 | | |
| C(11)B | -.003 | | |
| C(10)B | .016 | C(9)B | .013 |

pyridine rings. Both pyridine rings are essentially planar as is evident from data listed in Table IV.3.3. There is close agreement between equivalent angles in the copper coordination spheres. The 'square-pyramid' is considerably distorted, the N-Cu-N angles (ideally 90°) ranging from 78° to 99°. A least-squares plane calculation through the four donor nitrogens shows that the diagonal atom pair N(1), N(3) is below the plane, while the pair N(2), N(4) is above the plane. In each macrocycle, the copper ion lies about 0.3 Å out of this plane towards the coordinated chloride ion.

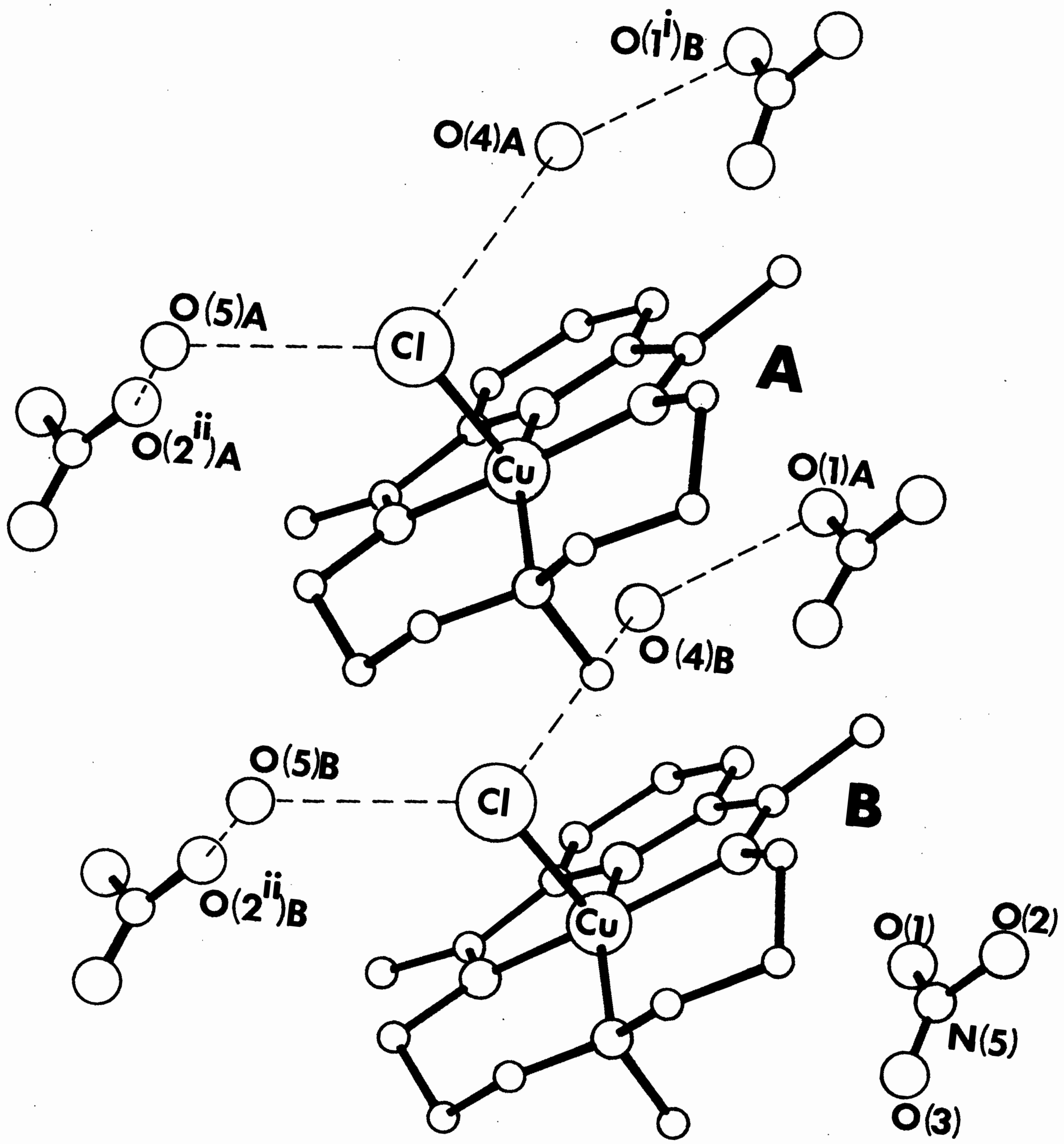
The macrocyclic planes are interleaved by two water oxygen atoms O(4) and O(5). Fig. IV.3.2 shows this arrangement and includes the nitrate ions. Although hydrogen atoms were not located in the analysis, hydrogen bonding (represented by dashed lines in Fig. IV.3.2) may be inferred from relevant short contacts. Each water oxygen is hydrogen bonded to the chloride ion and to an oxygen of the nitrate ion. Relevant data are listed in Table IV.3.4.

TABLE IV.3.4 SHORT CONTACTS AND HYDROGEN BOND DATA

Symmetry code: (i) x, y-1, z
(ii) x, y , z+1

| | | | |
|---|---|---|---|
| ClA ..... O(4)A | 3.29(2) Å | O(4)A .. ClA .. O(5)A | 126.0(8)° |
| ClA ..... O(5)A | 3.19(3) | | |
| ClB ..... O(4)B | 3.22(2) | O(4)B .. ClB .. O(5)B | 126.3(8) |
| ClB ..... O(5)B | 3.19(3) | | |
| O(4)A.... O($1^{i}$)B | 2.91(2) | O(4)B .. O(1)A | 2.92(3) Å |
| O(5)A ... O($2^{ii}$)A | 2.79(2) | O(5)B .. O($2^{ii}$)B | 2.77(3) |

FIG. IV.3.2



Each chlorine atom is therefore involved in two hydrogen bonds; the O...Cl...O angles are approximately 126° in both A and B. Two of the O...O contacts involving water and nitrate oxygen atoms are just less than the van der Waals diameter of 2.8 Å while the other two just exceed this value.

## Copper Coordination

The geometry of pentacoordinate complexes has been the subject of a recent review[97]. From general observations of such structures, it was pointed out that due consideration should be given to the possibility of such a structure possessing a geometry intermediate between the trigonal bipyramidal and square pyramidal forms. This intermediate geometry is observed in the copper complex, $(Cl.Cu.N\text{-}MeCR)^+$. Tension in the macrocyclic N-MeCR ring tends to bring about distortion of a notional square-planar configuration, resulting in (i) a reduction of the angles N(2)-Cu-N(1) and N(4)-Cu-N(1) and (ii) the movement of N(3) out of the plane of the other donors. (Fig. IV.3.1). Molecular models suggest that this latter movement encourages twisting about the Schiff base double bonds, resulting in an overall geometry which approaches trigonal bipyramidal (with N(2) and N(4) axial) rather than square pyramidal (with apical Cl). Opposing the distortion from square-planar geometry is the tendency of copper(II) toward short, strong equatorial bonds (attributable to the electronic nature of the $d^9$ ion).

The copper complex may be compared with two analogous low-spin metal complexes whose X-ray structures have been reported. These are the complex[92] Ni(II)CR.Br and the reduced complex[93] Ni(II)CRH.Br. Considering the three structures, the angle N(1)-M-N(3) (where M represents the metal atom in each case) may be taken as a crude measure of the balance between the tension in the ligand, tending towards distortion away from square-planar, and the metal's coordination inflexibility tending towards the square pyramidal configuration. (The angle N(2)-M-N(4) is distorted from 180° by strong covalent bonds in the ligand and variations in this angle are smaller and less informative). The angle N(1)-M-N(3) is expected to lie between 180° (square pyramid) and 120° (trigonal bipyramid). In fact its value is 152° in $(Cl.Cu.N\text{-}MeCR)^+$ and 164° and 172° in $(Br.Ni.CR)^+$ and $(Br.Ni.CRH)^+$ respectively. The difference between copper and nickel in these examples may perhaps be attributable to the extra $d_{x^2-y^2}$ "hole" of low-spin Ni(II), and that between CR and CRH presumably due to the greater flexibility and slightly larger ring of CRH. In both nickel compounds the pyridine N-Ni bond distance is shorter than the others by 0.1 Å. Here, a similar effect is observed, with a shortening between 0.05 and 0.1 Å.

The copper ion lies about 0.3 Å out of the plane of the four donor nitrogen atoms, towards the chloride ion. The analogous displacement in the complex bis-(6-hydroxypurine) copper(II) chloride trihydrate is 0.29 Å. Another common feature of these copper complexes is the presence of hydrogen bonds emanating from the chlorine to two water molecules. A crystal structure analysis[98] of a copper complex containing dodeca(dimethylamido)cyclohexaphosphonitrile as a macrocyclic ligand has shown this substance to be ionic with the formulation $[N_6P_6(NMe_2)_{12}CuCl]^+CuCl_2^-$. The cupric ion is also five-coordinate, being bonded to four nitrogen atoms and a chlorine atom. The latter can be regarded as occupying either the apical position of a distorted square pyramid, since the N-Cu-N angle is large (160.9°), or an equatorial position of a distorted trigonal bipyramid. The ligand is quite unrelated to ligands of the CR type, being completely saturated and containing phosphorus atoms.

Since the geometry of the macrocyclic ion $(Cl.Cu.N\text{-}MeCR)^+$ is almost midway between square pyramidal and trigonal bipyramidal, the question of whether there is room for a sixth ligand (e.g. a water molecule) in aqueous solution is not conclusively solved. Inspection of the molecular model shows that the area of copper ion available for such interaction is not large. However, in the crystal, hydrogen bonding involving the water molecules is probably the overriding factor in determining the location of these potential ligands. The preparation and study of a complex of $(Cu\ N\text{-}MeCR)^{2+}$, using for example axial thiocyanate ligands, may confirm the possibility of six-coordination in this system[99]. A five-coordinate system is not an unrealistic biological model. The crystal structure[100] of the biologically-active iron protoporphyrin, α-chlorohemin, shows that the iron atom is bonded to four nitrogen atoms and a chlorine atom. The iron atom lies out of the plane of the four nitrogens toward the chlorine atom.

# CHAPTER V

## THE CRYSTAL STRUCTURE OF A COPPER-BARBITURATE COMPLEX: BIS-(5,5'-DIETHYLBARBITURATO)(BISPYRIDINE)COPPER(II)

## V.1 INTRODUCTION

### The Barbiturate drugs

The series of drugs derived from barbituric acid, $C_4H_4N_2O_3$, are most frequently employed as sedatives and hypnotics[101,102], but structural variation of the substituents $R_1$ and $R_2$ in barbiturates (Fig. V.1.1) produces compounds with a wide range of properties and differing effects on the central nervous system.

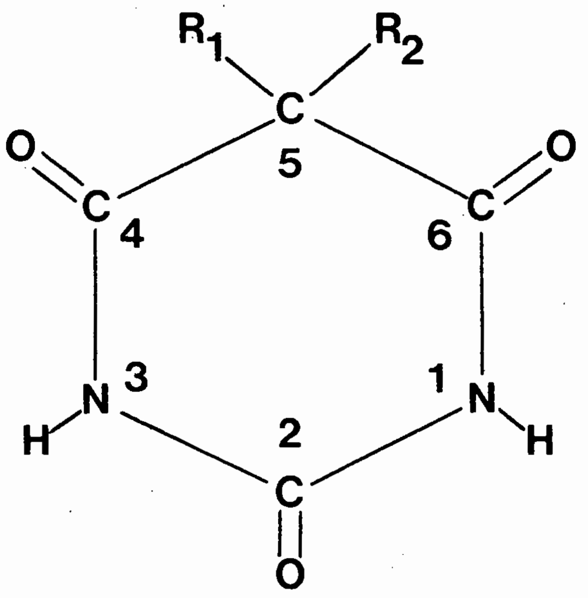


Fig. V.1.1

Barbiturates are very weak acids with dissociation constants of the order $10^{-7}$ - $10^{-8}$. At physiological pH, disubstituted (but not monosubstituted) barbiturates are in the undissociated form to an appreciable extent. Only in the undissociated state are these drugs able to penetrate the blood-brain barrier and affect the central nervous system.

As a class of drugs, the barbiturates are characterised by the fact that their action is dependent on neither structural specificity nor on stereospecificity. This behaviour, atypical of substances which block enzyme systems, implies that the barbiturates exert their actions by virtue of their physical properties. The activity of hypnotics is greatly modified by structural change, primarily as a result of alteration of their lipid solubility. The latter property of barbiturates may be altered in three ways:

(a) substitution of suitable groups in the 5-position

(b) methylation of the ring-nitrogen atoms and

(c) substitution of sulphur for oxygen atoms. Increase in the chain length of alkyl substituents or introduction of aryl or aralkyl groups causes the relative nonpolarity and lipid solubility of hypnotics to increase. This is followed by an increase in hypnotic activity until the total number of carbon atoms of both groups substituted in the 5-position of barbiturates reaches eight. Further chain-lengthening produces compounds which are either inactive or act as convulsants. The hydrophobic nature of the compounds (resulting from chain-lengthening) does improve blood-brain barrier penetration, but at the same time, their solubility in water is decreased. This may reach a point where they are unable to enter the biophase. Methylation of ring-nitrogen atoms leads to weaker acids with a concomitant increase in lipid solubility. Replacement of oxygen by sulphur atoms yields thiobarbiturates which enter the central nervous system more rapidly than do their oxygen analogues, because they are more lipid-soluble.

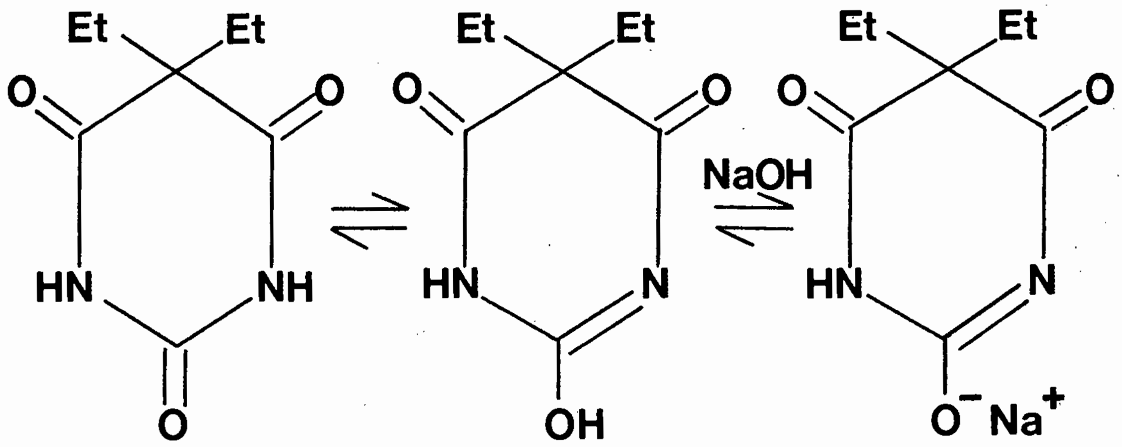
The properties of barbital will be emphasised below, as the anion of this molecule was used as a metal-complexing ligand in this study. In addition, barbital is the most commonly used barbiturate.

## Barbital

The discovery of the hypnotic properties of 5,5'-diethylbarbituric acid (barbital or Veronal) led to the extensive development of the barbiturates as a class of drugs. In this compound, $R_1 = R_2 = C_2H_5$- in Fig. V.1.1. Barbital is chemically the simplest hypnotic barbiturate. Structural requirements for hypnotic activity are (a) disubstitution at the 5-position either by ethyl or by larger nonpolar groups and (b) a minimum capacity for hydrogen bonding. (Hydrogen bonding potential is lost on methylation of both imide groups and replacement of the three carbonyl oxygen atoms by sulphur).

Drug active barbiturates are commonly polymorphous in their crystal structures; several polymorphs of barbital have been characterised and the X-ray crystal structures of two of these have been elucidated[103]. In both polymorphs, the molecules of barbital are in the trioxopyrimidine tautomeric form, as drawn in Fig. V.1.1.

Salts of barbital are readily formed by treatment with bases, but only the sodium,calcium and magnesium salts have been used therapeutically. The sodium salts of substituted barbituric acids are the most water-soluble and hence most commonly employed. The formation of the salt sodium barbital is formally represented by reaction V.1.1 which involves initial enolisation of the keto form.



....... V.1.1

The X-ray crystal structure of sodium barbital has been reported[104]; this study showed the anionic charge to be associated with the two oxygen atoms flanking the deprotonated nitrogen atom in the salt. A similar charge distribution has been found in the anion of calcium barbital trihydrate[105].

Barbital is also capable of forming molecular complexes. Several X-ray crystal structures of such compounds (e.g. 1:1 urea-barbital[106], 1:1 imidazole-barbital[107], 1:2 caffeine-barbital[108]) have appeared in the literature.

## Metal Complexes of Barbiturates

The complex whose structure is presented here was the first of the copper-pyridine barbiturate series to be analysed. When the analysis was undertaken, a parallel study involving variations in metal, base and barbiturate components was initiated[35]. The results obtained from the latter work are in agreement with the findings of this investigation. This will be evident from the discussion below. For some time it has been known that barbiturates are capable of forming coloured complex compounds with a series of heavy metals and organic bases[33]. With divalent metal cations M(II) in the presence of neutral bases L, such as pyridines, picolines and lutidines, complexes with the formula $M(II)(barb)_2L_2$ are formed with barbiturate anions (barb). From the observation[109] that copper-pyridine complexes of barbiturates are generally violet- or lilac-coloured, which is atypical of salts of divalent copper, it was correctly assumed that the copper atom is directly bonded to one or more atoms of the drug molecule in complexes of this type. For the series with the stoichiometric composition $Cu(II)(barb)_2(pyridine)_2$, it was suggested that the copper atom is six-coordinate with one of two possible structures. In the first, the barbiturate atom grouping $-N{=}\overset{|}{C}-O$ is bidentate through N and O forming a four-membered chelate with copper. In the second, each barbiturate ligand is again bidentate with both donors being carbonyl oxygen atoms. The nitrogen atoms of the pyridines complete the octahedron in each case. Later studies[33] emphasised the use of these complexes in the toxicological identification of the barbiturate drugs. It was shown that the infrared spectra of the series Cu(II)(barb)$_2$(pyridine)$_2$, containing different drugs, serve as a convenient means of distinguishing the barbiturates recovered during toxicological examination of organs and body fluids. In addition, a proposed mechanism for the formation of such compounds led to the formulation of a four-coordinate species, with the barbiturate behaving as a monodentate oxygen-donor ligand. More recent work[34] led to a similar proposal for the barbiturate binding site.

The X-ray crystal structure determinations[110] of the complexes M(II)(barbital)$_2$(imidazole)$_2$, M = Co, Zn, revealed that the metal atom is tetrahedrally coordinated by the deprotonated nitrogen atoms from the two barbital anions and by nitrogen atoms from two imidazole molecules. Complexes in which the base is imidazole had not been previously described, but this ligand was chosen because the metal-binding site might be more illustrative of possible barbiturate binding to metalloenzymes. More recently[111] it was shown that in the complex Ni(II)(barbital)$_2$(imidazole)$_2$, which has octahedral stereochemistry, the barbiturate binds as a bidentate ligand through oxygen and nitrogen atoms of the group $-N=\overset{|}{C}-O$, to form four-membered rings with the metal atoms. While the Ni-N bond distance was 2.072(2) Å, the Ni-O distance was long, 2.237(2) Å, indicating that the oxygen atom is not tightly bound to the nickel atom.

## Motivation for Structural Analysis

A standard procedure[32,33] for the clinical identification of barbiturates is the 'copper-pyridine' test. Addition of a few drops of copper-pyridine reagent (10% copper sulphate solution, pyridine and water in the ratio 4:1:5 by volume) to as little as 10 mg of barbiturate produces a violet colour due to the formation of a complex of stoichiometry $Cu(barb)_2(pyridine)_2$. In view of the clinical significance of this series of compounds and the conflicting theories as to their molecular structure, it was thought to be of interest to undertake an X-ray analysis of a member of the series in order to establish unequivocally the barbiturate metal-binding site. Further, since the mode of action of barbiturates in the central nervous system is still not understood[101], a knowledge of the binding-sites may play an important role in postulates of their mechanism of action.

The ligand chosen for the study, 5,5'-diethylbarbituric acid (barbital), is an important hypnotic and is representative of this class of drugs.

## V.2 THE CRYSTAL STRUCTURE OF THE BIS-(5,5'-DIETHYLBARBITURATO) (BISPYRIDINE)COMPLEX OF COPPER(II); $Cu(C_8H_{11}N_2O_3)_2(C_5H_5N)_2$

### Crystal preparation and chemical analysis

Initially, the preparative method of Levi and Hubley[33] was used in order to synthesise crystals of the compound. This involved the addition of 50 ml of a 0.005 M solution of 5,5'-diethylbarbituric acid in 1:1 aqueous pyridine to an equal volume of a 0.08 M aqueous copper sulphate solution containing 25% by volume of pyridine. The expected purple-coloured precipitate formed but the product was not crystalline. Suitable single crystals were obtained by modifying the above method.

Dilute aqueous solutions of copper(II) chloride dihydrate, pyridine and the sodium salt of the parent acid (sodium barbital) were mixed in the molar ratio 1:2:2. From the resultant mauve solution, single crystals grew as purple prisms with hexagonal cross-sections.

The infrared spectrum of this material was identical to that of the product reported by Levi and Hubley. Microanalysis (Table V.2.1) confirmed that the crystals had the composition Cu(II)(5,5'-diethylbarbiturato)$_2$(pyridine)$_2$ as proposed by these authors.

The copper content was estimated by igniting an accurately weighed sample of the crystals to constant weight (copper(II)oxide).

TABLE V.2.1

| | %C | %H | %N | %Cu |
|---|---|---|---|---|
| Calculated: | 53.11 | 5.45 | 14.30 | 10.81 |
| Found : | 52.4 | 5.2 | 14.0 | 10.9 |

## Density determination

A crystal density of 1.41 g cm$^{-3}$ was found by allowing crystalline specimens to settle in a density-gradient column[94] containing the components m-xylene (S.G. 0.86) and carbon tetrachloride (S.G. 1.60). The column was calibrated with aqueous caesium chloride solutions and the gradient was accurately linear over the range of measurement.

The number of complex molecules per unit cell was calculated as two.

## Space group assignment

Weissenberg and precession photographs revealed the systematic absence of reflections of the types $h0l$ $l$=2n+1 and $0k0$ $k$=2n+1. These conditions enabled the space group $P2_1/c$ (Monoclinic) to be unambiguously assigned[60].

## Diffractometer data

Careful cleavage of a large single crystal with a razor blade yielded a roughly cubic specimen with dimensions 0.225 x 0.25 x 0.35 mm. This was mounted with the rotation axis parallel to the longest side and oriented on the diffractometer. Relevant crystal parameters appear in Table V.2.2.

TABLE V.2.2 CRYSTAL DATA

| | |
|---|---|
| Molecular formula | $Cu(C_8H_{11}N_2O_3)_2(C_5H_5N)_2$ |
| Molecular weight | 587.5 g mole$^{-1}$ |
| Space group | $P2_1/c$ (Monoclinic, 2nd setting) |
| a = 11.235(5) Å | |
| b = 9.958(4) Å | $D_m$ = 1.41 g cm$^{-3}$ |
| c = 12.624(5) Å | $D_c$ = 1.415 g cm$^{-3}$ for Z = 2 |
| $\beta$ = 102.6(2)° | $\mu$(MoK$\alpha$) = 8.74 cm$^{-1}$ |
| V = 1378.54 Å$^3$ | F(000) = 614 |

Intensities were measured by the $\omega$-scan mode specified by a scan width of $0.9^\circ\theta$ and a speed of $0.03^\circ\theta\,\mathrm{sec}^{-1}$. In the range $6^\circ \leqslant 2\theta \leqslant 40^\circ$, the counts for 1462 reflections were recorded. Of these, 101 were systematically absent, 116 had $I_{rel}<2\sigma(I_{rel})$ and 9 other reflections were redundant due to space group equivalence. Thus 226 reflections were considered unobserved and only the remaining 1236 unique reflections were employed in the structural determination. The intensities of three standard reflections, measured every hour, remained constant to within 2% of their respective mean values.

For the crystal selected, $\mu R$ varied between 0.10 and 0.15 and the maximum variation[78] in the corresponding A* values was between 1.18 and 1.28 for the $\theta$-range explored. This variation was deemed too small to warrant absorption corrections which were therefore neglected.

## Solution and refinement of the structure

If in a unit cell having space group symmetry $P2_1/c$ there are only two atoms of a particular kind, these must lie in one pair of centres of symmetry. The copper atoms were therefore assigned the positions 0,0,0 and 0,½,½ and a three-dimensional Patterson synthesis was computed. The symmetry (P2/m) of the vector map caused every peak to be mirrored across the *ac* plane. Selection of unique peaks was facilitated by the recognition of ring fragments belonging to the pyridine and barbiturate ligands. Nine atomic positions were assigned in this way and a subsequent electron-density map revealed all of the non-hydrogen atoms. The conventional R factor was 0.292 before least-squares refinement of the twenty atoms. After six cycles of refinement with isotropic temperature factors followed by three cycles with the atoms vibrating anisotropically (program ORFLS)[45],R was 0.06. All of the hydrogen atoms were located in a difference electron-density map and they were included in the calculations. They were assigned the anisotropic temperature factors of the atoms to which they were bonded and only their positions were allowed to vary.

In the final cycle of refinement, the average $\Delta/\sigma$ was 0.02 for the heavy atom parameters and 0.1 in the case of hydrogen atoms indicating satisfactory convergence. Throughout the refinement, each reflection was assigned unit weight and the function minimised was $\Sigma(|F_o|-|F_c|)^2$. Atomic scattering factors were those obtained from the Hartree-Fock-Slater model[62].

The copper atom was treated as $Cu^o$ and the anomalous dispersion correction[63] ($\Delta f'$=0.3 for MoKα) was applied to the scattering curve. At the end of the refinement, the residual index was 0.036. No prominent peaks were detected in a difference electron-density map calculated with the final atomic parameters.

The positional and thermal parameters for the non-hydrogen atoms are presented in Table V.2.3 and the hydrogen atom positions are listed in Table V.2.4. Observed and calculated structure factors appear in Table V.2.5.

## TABLE V.2.3

## NON-HYDROGEN ATOMS

## FRACTIONAL ATOMIC COORDINATES ($\times 10^4$) AND THEIR E.S.D.'s AND ANISOTROPIC TEMPERATURE FACTORS

Thermal parameters are of the form

$$T = \exp[-(\beta_{11}h^2 + \beta_{22}k^2 + \beta_{33}l^2 + 2\beta_{12}hk + 2\beta_{23}kl + 2\beta_{31}lh)\times 10^4]$$

| | $x$ | $y$ | $z$ | $\beta_{11}$ | $\beta_{22}$ | $\beta_{33}$ | $\beta_{12}$ | $\beta_{23}$ | $\beta_{31}$ |
|---|---|---|---|---|---|---|---|---|---|
| Cu | 0 | 0 | 0 | 22(1) | 47(1) | 18(1) | -9(1) | 3(1) | -2(1) |
| C(1) | 1304(6) | 1941(7) | -770(6) | 40(6) | 75(8) | 31(6) | -6(6) | 6(5) | 7(6) |
| C(2) | 3180(6) | 3176(6) | -3(5) | 50(7) | 47(8) | 36(5) | 5(6) | 9(5) | 3(5) |
| C(3) | 2087(5) | 1705(6) | 1153(5) | 31(6) | 50(8) | 27(6) | -2(5) | 7(5) | -12(5) |
| C(4) | 3038(6) | 2791(7) | 1138(5) | 47(6) | 86(9) | 25(5) | -32(6) | -9(4) | -1(5) |
| C(5) | 2640(8) | 4097(8) | 1641(6) | 149(11) | 85(10) | 45(6) | -59(9) | 28(7) | -25(6) |
| C(6) | 1416(8) | 4656(8) | 1126(7) | 132(10) | 68(10) | 117(9) | 5(8) | 71(8) | -39(8) |
| C(7) | 4278(7) | 2313(10) | 1796(6) | 63(7) | 181(14) | 50(6) | -49(9) | -22(6) | 43(8) |
| C(8) | 4743(7) | 1066(10) | 1362(8) | 51(8) | 146(13) | 150(10) | 18(8) | 6(7) | 78(10) |
| C(9) | -1009(6) | 2023(7) | 1264(6) | 49(7) | 96(10) | 41(6) | 0(6) | 10(5) | -6(6) |
| C(10) | -1813(7) | 2989(8) | 1503(6) | 63(8) | 111(10) | 54(6) | 8(7) | 24(6) | -20(7) |
| C(11) | -2854(7) | 3253(7) | 748(7) | 63(8) | 74(9) | 98(8) | 11(7) | 41(7) | 0(7) |
| C(12) | -3070(6) | 2569(8) | -226(7) | 44(7) | 78(9) | 77(7) | 8(7) | 6(5) | 16(7) |
| C(13) | -2230(6) | 1644(7) | -427(5) | 46(7) | 70(9) | 47(6) | -2(7) | 7(5) | -6(6) |
| N(1) | 1294(4) | 1390(5) | 226(4) | 25(5) | 57(6) | 20(4) | -16(4) | 2(4) | -7(4) |
| N(2) | 2234(5) | 2819(5) | -844(4) | 43(5) | 94(7) | 15(4) | -31(5) | -1(4) | 10(4) |
| N(3) | -1217(4) | 1366(5) | 323(4) | 32(5) | 61(6) | 33(4) | 1(5) | 6(4) | -13(5) |
| O(1) | 530(4) | 1638(5) | -1562(4) | 56(4) | 136(7) | 19(3) | -41(5) | -15(3) | -5(4) |
| O(2) | 4040(4) | 3789(5) | -171(4) | 47(5) | 104(6) | 58(4) | -46(5) | 13(3) | 28(4) |
| O(3) | 2031(4) | 1162(4) | 2009(3) | 67(5) | 78(5) | 14(3) | -16(4) | 11(3) | 5(4) |

## TABLE V.2.4

## HYDROGEN ATOMS

## FRACTIONAL ATOMIC COORDINATES (x$10^3$) AND THEIR E.S.D's

| | $x$ | $y$ | $z$ |
|---|---|---|---|
| H(2) | 231(5) | 316(7) | -154(5) |
| H(51) | 269(7) | 385(8) | 236(6) |
| H(52) | 336(7) | 472(7) | 170(6) |
| H(71) | 414(6) | 216(8) | 257(6) |
| H(72) | 480(6) | 312(8) | 184(6) |
| H(61) | 73(7) | 401(8) | 125(7) |
| H(62) | 124(7) | 556(7) | 159(7) |
| H(63) | 132(7) | 464(7) | 29(7) |
| H(81) | 478(8) | 116(8) | 71(7) |
| H(82) | 549(7) | 79(8) | 184(7) |
| H(83) | 424(7) | 25(8) | 155(7) |
| H(9) | -26(6) | 170(7) | 184(5) |
| H(10) | -156(6) | 341(7) | 223(6) |
| H(11) | -334(6) | 382(7) | 94(6) |
| H(12) | -381(6) | 275(7) | -77(6) |
| H(13) | -237(6) | 108(7) | -114(5) |

# TABLE V.2.5

| k | l | $F_o$ | $F_c$ |
|---|---|---|---|
| | h = -10 | | |
| -3 | 4 | 138 | -148 |
| -3 | 3 | 277 | 270 |
| -3 | 2 | 63 | -69 |
| -3 | 1 | 314 | 325 |
| -3 | 0 | 171 | 185 |
| -2 | 0 | 85 | 80 |
| -2 | 1 | 248 | 258 |
| -2 | 2 | 132 | 148 |
| -2 | 3 | 79 | 84 |
| -2 | 4 | 379 | 383 |
| -2 | 6 | 246 | 246 |
| -1 | 6 | 81 | -85 |
| -1 | 5 | 210 | 212 |
| -1 | 3 | 116 | 116 |
| -1 | 2 | 147 | 149 |
| -1 | 1 | 186 | 194 |
| -1 | 0 | 179 | -186 |
| 0 | 0 | 472 | 490 |
| 0 | 2 | 407 | 409 |
| 0 | 4 | 244 | 243 |
| 0 | 6 | 268 | 269 |
| | h = -9 | | |
| -5 | 0 | 85 | -81 |
| -5 | 1 | 162 | 171 |
| -5 | 2 | 103 | -110 |
| -5 | 3 | 56 | 43 |
| -4 | 6 | 194 | 187 |
| -4 | 5 | 104 | 106 |
| -4 | 4 | 95 | 73 |
| -4 | 3 | 79 | -83 |
| -4 | 2 | 153 | 149 |
| -4 | 1 | 38 | -34 |
| -4 | 0 | 251 | 265 |
| -3 | 0 | 36 | 51 |
| -3 | 1 | 127 | 132 |
| -3 | 2 | 170 | 173 |
| -3 | 3 | 220 | 229 |
| -3 | 4 | 201 | 205 |
| -3 | 5 | 320 | 309 |
| -3 | 6 | 125 | 130 |
| -3 | 7 | 209 | 203 |
| -2 | 8 | 149 | 144 |
| -2 | 7 | 85 | -82 |
| -2 | 6 | 272 | 271 |
| -2 | 5 | 103 | -106 |
| -2 | 4 | 324 | 316 |
| -2 | 3 | 75 | -75 |
| -2 | 2 | 301 | 293 |
| -2 | 1 | 85 | 92 |
| -2 | 0 | 123 | 170 |
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| -4 | 1 | 85 | 49 |
| -4 | 2 | 260 | 264 |
| -4 | 4 | 63 | 19 |
| -4 | 5 | 68 | 50 |
| -4 | 7 | 107 | 93 |
| -4 | 8 | 304 | 302 |
| -4 | 9 | 53 | -53 |
| -4 | 10 | 274 | 287 |
| -3 | 11 | 375 | 375 |
| -3 | 10 | 57 | -47 |
| -3 | 9 | 374 | 376 |
| -3 | 7 | 288 | 298 |
| -3 | 6 | 309 | 273 |
| -3 | 5 | 374 | 377 |
| -3 | 4 | 150 | 137 |
| -3 | 3 | 806 | 794 |
| -3 | 2 | 358 | 354 |
| -3 | 1 | 37 | 46 |
| -2 | 0 | 952 | -1005 |
| -2 | 1 | 49 | 43 |
| -2 | 2 | 43 | 35 |
| -2 | 3 | 46 | -53 |
| -2 | 4 | 672 | 648 |
| -2 | 5 | 307 | 298 |
| -2 | 6 | 407 | 394 |
| -2 | 7 | 162 | 153 |
| -2 | 8 | 303 | 305 |
| -2 | 9 | 94 | 81 |
| -2 | 10 | 238 | 234 |
| -2 | 11 | 387 | 401 |
| -1 | 11 | 152 | 146 |
| -1 | 10 | 215 | 223 |
| -1 | 5 | 614 | 587 |
| -1 | 6 | 200 | -185 |
| -1 | 7 | 295 | 289 |
| -1 | 8 | 31 | 17 |
| -1 | 9 | 287 | 264 |
| -1 | 4 | 583 | -560 |
| -1 | 2 | 798 | 798 |
| -1 | 3 | 408 | 378 |
| 0 | 4 | 61 | 49 |
| 0 | 2 | 1424 | 1546 |
| 0 | 6 | 952 | 956 |
| 0 | 8 | 489 | 468 |
| 0 | 10 | 380 | 388 |
| | h = 1 | | |
| -9 | 1 | 197 | 192 |
| -9 | 2 | 46 | -32 |
| -9 | 3 | 362 | 354 |
| -8 | 6 | 135 | 128 |
| -8 | 5 | 62 | -74 |
| -8 | 4 | 372 | 374 |
| -8 | 3 | 89 | -99 |
| -8 | 2 | 170 | 177 |
| -8 | 0 | 150 | 156 |
| -7 | 0 | 87 | -73 |
| -7 | 1 | 361 | 366 |
| -7 | 2 | 139 | 144 |
| -7 | 3 | 298 | 292 |
| -7 | 4 | 87 | -73 |
| -7 | 5 | 385 | 388 |
| -7 | 6 | 158 | -161 |
| -7 | 7 | 277 | 275 |
| -6 | 8 | 304 | 320 |
| -6 | 7 | 56 | -63 |
| -6 | 6 | 404 | 399 |
| -6 | 5 | 66 | -52 |
| -6 | 4 | 109 | 105 |
| -6 | 3 | 118 | 121 |
| -6 | 2 | 512 | 508 |
| -6 | 1 | 111 | -123 |
| -6 | 0 | 692 | 685 |
| -5 | 1 | 437 | 431 |
| -5 | 3 | 116 | 122 |
| -5 | 4 | 277 | -272 |
| -5 | 5 | 155 | 165 |
| -5 | 6 | 371 | -376 |
| -5 | 7 | 269 | 279 |
| -5 | 8 | 126 | -123 |
| -5 | 9 | 215 | 237 |
| -4 | 10 | 176 | 191 |
| -4 | 9 | 42 | 44 |
| -4 | 8 | 262 | 265 |
| -4 | 7 | 85 | 80 |
| -4 | 6 | 286 | 294 |
| -4 | 5 | 56 | 43 |
| -4 | 4 | 106 | 112 |
| -4 | 3 | 156 | 149 |
| -4 | 2 | 587 | 586 |
| -4 | 1 | 45 | -53 |
| -4 | 0 | 277 | 278 |
| -3 | 0 | 407 | 387 |
| -3 | 1 | 54 | 66 |
| -3 | 2 | 94 | -75 |
| -3 | 3 | 603 | 585 |
| -3 | 4 | 265 | 247 |
| -3 | 5 | 415 | 406 |
| -3 | 6 | 582 | 564 |
| -3 | 7 | 243 | 247 |
| -3 | 9 | 229 | 219 |
| -3 | 10 | 45 | -46 |
| -2 | 11 | 172 | 182 |
| -2 | 10 | 515 | 523 |
| -2 | 8 | 362 | 360 |
| -2 | 7 | 196 | -188 |
| -2 | 6 | 508 | 496 |
| -2 | 5 | 208 | 205 |
| -2 | 4 | 666 | 641 |
| -2 | 3 | 529 | -516 |
| -2 | 2 | 43 | 67 |
| -2 | 1 | 447 | -424 |
| -2 | 0 | 468 | 442 |
| -1 | 1 | 866 | 884 |
| -1 | 2 | 447 | -412 |
| -1 | 3 | 838 | 839 |
| -1 | 4 | 93 | 81 |
| -1 | 5 | 533 | 521 |
| -1 | 6 | 158 | 154 |
| -1 | 7 | 390 | 382 |
| -1 | 8 | 97 | 101 |
| -1 | 9 | 353 | 354 |
| -1 | 10 | 542 | 556 |
| -1 | 11 | 127 | 121 |
| 0 | 10 | 44 | -63 |
| 0 | 8 | 294 | 295 |
| 0 | 6 | 266 | 245 |
| 0 | 4 | 603 | 586 |
| 0 | 2 | 317 | 323 |
| | h = 2 | | |
| -9 | 1 | 228 | 223 |
| -9 | 0 | 59 | 61 |
| -8 | 0 | 334 | 323 |
| -8 | 1 | 109 | -100 |
| -8 | 2 | 288 | 292 |
| -8 | 4 | 198 | 193 |
| -8 | 5 | 198 | 203 |
| -7 | 7 | 223 | 223 |
| -7 | 6 | 53 | 56 |
| -7 | 5 | 269 | 273 |
| -7 | 4 | 214 | -208 |
| -7 | 3 | 345 | 351 |
| -7 | 2 | 84 | -77 |
| -7 | 1 | 60 | 65 |
| -7 | 0 | 113 | 110 |
| -6 | 0 | 311 | 308 |
| -6 | 2 | 128 | 141 |
| -6 | 3 | 59 | -61 |
| -6 | 4 | 176 | 177 |
| -6 | 5 | 197 | -195 |
| -6 | 6 | 354 | 347 |
| -6 | 7 | 50 | -50 |
| -6 | 8 | 206 | 202 |
| -5 | 9 | 194 | 196 |
| -5 | 7 | 250 | 247 |
| -5 | 5 | 350 | 354 |
| -5 | 4 | 162 | 153 |
| -5 | 3 | 288 | 292 |
| -5 | 2 | 423 | 428 |
| -5 | 1 | 755 | 731 |
| -4 | 0 | 364 | 361 |
| -4 | 1 | 126 | -124 |
| -4 | 2 | 379 | 367 |
| -4 | 3 | 70 | 70 |
| -4 | 4 | 536 | 515 |
| -4 | 5 | 123 | -124 |
| -4 | 6 | 469 | 486 |
| -4 | 7 | 147 | -147 |
| -4 | 8 | 135 | 133 |
| -4 | 9 | 59 | -51 |
| -4 | 10 | 337 | 342 |
| -3 | 10 | 132 | 122 |
| -3 | 9 | 308 | 316 |
| -3 | 7 | 88 | 91 |
| -3 | 6 | 193 | -188 |
| -3 | 5 | 431 | 431 |
| -3 | 4 | 129 | -140 |
| -3 | 3 | 555 | 545 |
| -3 | 2 | 573 | -548 |
| -3 | 1 | 264 | 257 |
| -3 | 0 | 100 | 95 |
| -2 | 0 | 1018 | 1039 |
| -2 | 1 | 459 | 429 |
| -2 | 2 | 341 | 328 |
| -2 | 3 | 207 | 280 |
| -2 | 4 | 403 | 399 |
| -2 | 5 | 446 | 415 |
| -2 | 6 | 252 | 252 |
| -2 | 7 | 185 | 177 |
| -2 | 8 | 392 | 393 |
| -2 | 9 | 202 | 203 |
| -2 | 10 | 360 | 370 |
| -1 | 11 | 202 | 200 |
| -1 | 10 | 48 | -42 |
| -1 | 9 | 267 | 269 |
| -1 | 8 | 184 | -186 |
| -1 | 7 | 517 | 519 |
| -1 | 6 | 75 | -78 |
| -1 | 5 | 311 | 287 |
| -1 | 4 | 255 | 232 |
| -1 | 3 | 541 | 511 |
| -1 | 2 | 174 | -162 |
| -1 | 1 | 903 | 913 |
| -1 | 0 | 208 | -195 |
| 0 | 2 | 665 | 631 |
| 0 | 4 | 315 | 317 |
| 0 | 6 | 426 | 418 |
| 0 | 8 | 448 | 458 |
| 0 | 10 | 76 | -71 |
| | h = 3 | | |
| -9 | 0 | 106 | 100 |
| -9 | 1 | 142 | 140 |
| -8 | 4 | 110 | 102 |
| -8 | 3 | 74 | 69 |
| -8 | 2 | 177 | 173 |
| -8 | 0 | 200 | 199 |
| -7 | 0 | 68 | 68 |
| -7 | 1 | 242 | 245 |
| -7 | 2 | 91 | -91 |
| -7 | 3 | 163 | 162 |
| -7 | 5 | 62 | 65 |
| -7 | 6 | 132 | 121 |
| -6 | 6 | 261 | 250 |
| -6 | 5 | 84 | 82 |
| -6 | 4 | 301 | 301 |
| -6 | 3 | 78 | 90 |
| -6 | 2 | 296 | 297 |
| -6 | 1 | 282 | 278 |
| -6 | 0 | 193 | 198 |
| -5 | 0 | 182 | -178 |
| -5 | 1 | 583 | 570 |
| -5 | 2 | 54 | -55 |
| -5 | 3 | 468 | 456 |
| -5 | 5 | 414 | 414 |
| -5 | 7 | 264 | 236 |
| [illegible] | [illegible] | [illegible] | [illegible] |
| -4 | 8 | 232 | 235 |
| -4 | 6 | 229 | 224 |
| -4 | 5 | 135 | -132 |
| -4 | 4 | 629 | 619 |
| -4 | 3 | 55 | 56 |
| -4 | 2 | 214 | 208 |
| -4 | 1 | 77 | -75 |
| -4 | 0 | 763 | 741 |
| -3 | 0 | 46 | 51 |
| -3 | 1 | 736 | 719 |
| -3 | 2 | 105 | 81 |
| -3 | 3 | 395 | 378 |
| -3 | 4 | 234 | -224 |
| -3 | 5 | 458 | 460 |
| -3 | 6 | 200 | -175 |
| -3 | 7 | 299 | 303 |
| -3 | 8 | 301 | 306 |
| -3 | 9 | 433 | 445 |
| -2 | 9 | 235 | -235 |
| -2 | 8 | 132 | 129 |
| -2 | 6 | 408 | 404 |
| -2 | 5 | 38 | -27 |
| -2 | 4 | 198 | 211 |
| -2 | 3 | 368 | -355 |
| -2 | 2 | 203 | 215 |
| -2 | 1 | 485 | -459 |
| -2 | 0 | 356 | 352 |
| -0 | 1 | 276 | 258 |
| -1 | 1 | 267 | 275 |
| -1 | 2 | 61 | -54 |
| -1 | 3 | 484 | 467 |
| -1 | 4 | 593 | 555 |
| -1 | 5 | 221 | 220 |
| -1 | 6 | 183 | 169 |
| -1 | 7 | 306 | 314 |
| -1 | 8 | 366 | -378 |
| -1 | 9 | 142 | 139 |
| -1 | 10 | 322 | -313 |
| 0 | 10 | 430 | 427 |
| 0 | 8 | 629 | 643 |
| 0 | 6 | 564 | 557 |
| 0 | 4 | 567 | 567 |
| 0 | 2 | 979 | 961 |
| | h = 4 | | |
| -8 | 0 | 120 | 127 |
| -8 | 1 | 70 | 77 |
| -8 | 2 | 73 | 66 |
| -8 | 3 | 202 | -201 |
| -7 | 5 | 146 | 146 |
| -7 | 4 | 262 | 264 |
| -7 | 1 | 266 | 261 |
| -7 | 0 | 163 | 165 |
| -6 | 0 | 220 | 214 |
| -6 | 1 | 65 | -77 |
| -6 | 2 | 461 | 452 |
| -6 | 3 | 136 | 129 |
| -6 | 4 | 355 | 347 |
| -6 | 5 | 225 | 220 |
| -6 | 6 | 166 | 165 |
| -6 | 7 | 92 | -77 |
| -5 | 8 | 184 | 188 |
| -5 | 7 | 234 | 232 |
| -5 | 5 | 263 | 269 |
| -5 | 3 | 490 | 483 |
| -5 | 2 | 118 | -118 |
| -5 | 1 | 294 | 283 |
| -5 | 0 | 90 | -79 |
| -4 | 0 | 436 | 427 |
| -4 | 1 | 74 | 75 |
| -4 | 2 | 468 | 466 |
| -4 | 4 | 613 | 611 |
| -4 | 6 | 345 | 335 |
| -4 | 7 | 167 | 176 |
| -4 | 8 | 321 | 323 |
| -3 | 9 | 143 | 150 |
| -3 | 8 | 200 | -105 |
| -3 | 7 | 158 | 152 |
| -3 | 6 | 110 | -103 |
| -3 | 5 | 433 | 436 |
| -3 | 4 | 197 | -185 |
| -3 | 3 | 318 | 312 |
| -3 | 2 | 189 | 199 |
| -3 | 1 | 162 | 163 |
| -3 | 0 | 114 | -102 |
| -2 | 0 | 363 | 363 |
| -2 | 1 | 39 | -23 |
| -2 | 2 | 376 | 375 |
| -2 | 3 | 100 | 107 |
| -2 | 4 | 625 | 606 |
| -2 | 5 | 270 | -260 |
| -2 | 6 | 386 | 378 |
| -2 | 7 | 264 | -274 |
| -2 | 8 | 193 | 210 |
| -2 | 9 | 400 | -410 |
| -1 | 9 | 362 | 368 |
| -1 | 8 | 39 | -36 |
| -1 | 7 | 434 | 441 |
| -1 | 6 | 55 | 53 |
| -1 | 5 | 227 | 234 |
| -1 | 4 | 240 | -233 |
| -1 | 3 | 372 | 364 |
| -1 | 2 | 141 | -129 |
| -1 | 1 | 929 | 904 |
| -1 | 0 | 368 | -350 |
| 0 | 2 | 329 | 346 |
| 0 | 4 | 296 | -283 |
| 0 | 6 | 270 | 259 |
| 0 | 8 | 192 | 200 |
| 0 | 10 | 172 | 182 |
| | h = 5 | | |
| -8 | 2 | 222 | 217 |
| -8 | 1 | 41 | 22 |
| -8 | 0 | 242 | 244 |
| -7 | 0 | 160 | -163 |
| -7 | 1 | 229 | 224 |
| -7 | 2 | 88 | -82 |
| -7 | 3 | 141 | 133 |
| -6 | 6 | 147 | 155 |
| -6 | 5 | 146 | 167 |
| -6 | 3 | 201 | 194 |
| [illegible] | [illegible] | [illegible] | [illegible] |
| -6 | 1 | 55 | -58 |
| -6 | 0 | 247 | 256 |
| -5 | 1 | 427 | 425 |
| -5 | 2 | 72 | 72 |
| -5 | 3 | 415 | 420 |
| -5 | 4 | 209 | 217 |
| -5 | 5 | 219 | 213 |
| -5 | 6 | 179 | 166 |
| -5 | 7 | 374 | 376 |
| -4 | 8 | 101 | 90 |
| -4 | 6 | 257 | 252 |
| -4 | 5 | 151 | -150 |
| -4 | 4 | 347 | 337 |
| -4 | 3 | 56 | -50 |
| -4 | 2 | 406 | 398 |
| -4 | 0 | 248 | 252 |
| -3 | 0 | 37 | -36 |
| -3 | 1 | 424 | 415 |
| -3 | 3 | 578 | 567 |
| -3 | 4 | 99 | -116 |
| -3 | 5 | 504 | 513 |
| -3 | 6 | 113 | -118 |
| -3 | 7 | 306 | 302 |
| -3 | 8 | 212 | -206 |
| -2 | 8 | 350 | 370 |
| -2 | 6 | 374 | 376 |
| -2 | 5 | 34 | -41 |
| -2 | 4 | 462 | 445 |
| -2 | 3 | 196 | -192 |
| -2 | 2 | 618 | 599 |
| -2 | 1 | 211 | 208 |
| -2 | 0 | 543 | 531 |
| -1 | 0 | 321 | 304 |
| -1 | 1 | 292 | 278 |
| -1 | 2 | 476 | -450 |
| -1 | 3 | 81 | 19 |
| -1 | 4 | 622 | -592 |
| -1 | 5 | 213 | 226 |
| -1 | 6 | 172 | 184 |
| -1 | 7 | 244 | 243 |
| -1 | 8 | 70 | -84 |
| -1 | 9 | 304 | 312 |
| 0 | 8 | 100 | 95 |
| 0 | 6 | 226 | 234 |
| 0 | 4 | 433 | 447 |
| 0 | 2 | 35 | 23 |
| | h = 6 | | |
| -7 | 3 | 315 | 314 |
| -7 | 2 | 101 | -117 |
| -7 | 1 | 320 | 322 |
| -7 | 0 | 73 | -80 |
| -6 | 0 | 299 | 286 |
| -6 | 1 | 152 | -156 |
| -6 | 2 | 104 | 86 |
| -6 | 3 | 73 | -64 |
| -6 | 4 | 73 | 76 |
| -5 | 6 | 83 | -92 |
| -5 | 5 | 143 | 146 |
| -4 | 3 | 175 | 181 |
| -5 | 4 | 222 | 228 |
| -5 | 3 | 83 | 76 |
| -5 | 2 | 62 | 52 |
| -5 | 1 | 54 | 54 |
| -5 | 0 | 113 | -123 |
| -4 | 0 | 446 | 436 |
| -4 | 1 | 120 | 116 |
| -4 | 2 | 578 | 568 |
| -4 | 4 | 401 | 395 |
| -4 | 5 | 84 | -89 |
| -4 | 6 | 385 | 393 |
| -4 | 7 | 275 | -274 |
| -3 | 7 | 274 | 267 |
| -3 | 6 | 79 | 85 |
| -3 | 5 | 427 | 423 |
| -3 | 4 | 37 | 30 |
| -3 | 3 | 405 | 400 |
| -3 | 2 | 73 | -62 |
| -3 | 1 | 507 | 493 |
| -2 | 0 | 423 | 426 |
| -2 | 1 | 31 | -23 |
| -2 | 2 | 267 | 265 |
| -2 | 3 | 371 | -371 |
| -2 | 4 | 354 | 346 |
| -2 | 6 | 207 | 204 |
| -2 | 7 | 103 | 109 |
| -2 | 8 | 117 | 114 |
| -1 | 7 | 245 | 244 |
| -1 | 5 | 271 | 271 |
| -1 | 3 | 330 | 342 |
| -1 | 2 | 83 | 81 |
| -1 | 1 | 246 | 259 |
| -1 | 0 | 185 | 181 |
| 0 | 2 | 505 | 505 |
| 0 | 4 | 244 | 243 |
| 0 | 6 | 96 | 98 |
| 0 | 8 | 479 | 502 |
| | h = 7 | | |
| -7 | 0 | 94 | 98 |
| -6 | 3 | 329 | -322 |
| -6 | 2 | 342 | 345 |
| -6 | 1 | 128 | -128 |
| -6 | 0 | 226 | 214 |
| -5 | 0 | 184 | -178 |
| -5 | 1 | 279 | 273 |
| -5 | 3 | 137 | 129 |
| -5 | 4 | 108 | -104 |
| -4 | 5 | 68 | 53 |
| -4 | 4 | 88 | 87 |
| -4 | 3 | 275 | 278 |
| -4 | 2 | 85 | 75 |
| -4 | 1 | 37 | 23 |
| -4 | 0 | 397 | 385 |
| -3 | 1 | 445 | 454 |
| -3 | 2 | 121 | -112 |
| -3 | 3 | 165 | 161 |
| -3 | 4 | 74 | 70 |
| -3 | 5 | 225 | 236 |
| -3 | 6 | 54 | -45 |
| -2 | 6 | 168 | 164 |
| -2 | 5 | 102 | 114 |
| -2 | 4 | 297 | 300 |
| -2 | 3 | 194 | -188 |
| [illegible] | [illegible] | [illegible] | [illegible] |
| -2 | 1 | 96 | 95 |
| -2 | 0 | 302 | 305 |
| -1 | 0 | 108 | 92 |
| -1 | 1 | 138 | 139 |
| -1 | 2 | 91 | 73 |
| -1 | 3 | 454 | 466 |
| -1 | 4 | 91 | -76 |
| -1 | 5 | 328 | 325 |
| -1 | 6 | 86 | 91 |
| -1 | 7 | 244 | 244 |
| 0 | 6 | 301 | 300 |
| 0 | 4 | 328 | 321 |
| 0 | 2 | 446 | 439 |
| | h = 8 | | |
| -4 | 0 | 223 | 215 |
| -5 | 3 | 313 | 309 |
| -5 | 2 | 204 | -205 |
| -5 | 1 | 300 | 305 |
| -5 | 0 | 44 | -37 |
| -4 | 0 | 126 | 123 |
| -4 | 1 | 293 | -288 |
| -4 | 2 | 108 | -108 |
| -4 | 4 | 94 | 97 |
| -3 | 5 | 240 | 243 |
| -3 | 4 | 114 | 111 |
| -3 | 2 | 301 | 312 |
| -3 | 1 | 64 | -58 |
| -2 | 0 | 523 | 522 |
| -2 | 2 | 314 | 314 |
| -2 | 3 | 157 | 158 |
| -2 | 4 | 219 | 230 |
| -2 | 5 | 55 | -60 |
| -1 | 5 | 203 | 194 |
| -1 | 4 | 99 | 94 |
| -1 | 1 | 519 | 526 |
| -1 | 3 | 502 | 504 |
| -1 | 2 | 72 | -63 |
| 0 | 2 | 593 | 590 |
| 0 | 4 | 350 | 362 |
| 0 | 6 | 257 | 160 |
| | h = 9 | | |
| -4 | 2 | 260 | 261 |
| -4 | 1 | 210 | -217 |
| -4 | 0 | 271 | 265 |
| -3 | 3 | 143 | 139 |
| -2 | 3 | 194 | 190 |
| -2 | 1 | 279 | 283 |
| -2 | 0 | 122 | 120 |
| -1 | 1 | 483 | 493 |
| -1 | 2 | 81 | 79 |
| -1 | 3 | 312 | 316 |
| -1 | 4 | 160 | -158 |
| 0 | 4 | 278 | 285 |
| 0 | 2 | 469 | 474 |
| | h = 10 | | |
| -3 | 0 | 184 | -185 |
| -2 | 0 | 84 | 80 |
| -1 | 1 | 193 | 189 |
| -1 | 0 | 188 | 186 |
| 0 | 2 | 328 | 328 |

## V.3 DESCRIPTION OF THE STRUCTURE AND DISCUSSION

Intramolecular bond lengths and angles appear in Tables V.3.1 and V.3.2 respectively. Distances and angles in the copper coordination sphere are listed in Table V.3.3. Relevant least-squares planes are presented in Table V.3.4.

The molecular structure is shown in Fig. V.3.1, in which superscripted atoms are centrosymmetrically related to the corresponding atoms without superscripts. Numbering in the barbiturate ligand is not standard, the copper atom being coordinated to deprotonated nitrogen atoms labelled N(1) and N($1^i$). The four nitrogen donor atoms are arranged in a square-planar configuration about the metal with bond angles N(1)-Cu-N(3) and N(1)-Cu-N($3^i$), 90.5(2)° and 89.5(2)° respectively. The distance Cu-N(3), 2.032(5) Å may be compared with the analogous bond length of 1.989(6) Å observed in the complex [112] *trans*-bis[(chloroacetato)-(α-picoline)] copper(II). Since this complex was analysed, two other copper complexes of barbiturates have been studied. The Cu-N(1) distance, 1.983(5) Å involving the barbiturate nitrogen compares favourably with distances [113] of 1.980(5) Å and 2.06(2) Å observed in bis-(5,5'-diethylbarbiturato)-bis-(picoline)copper(II) dihydrate and bis-[5-allyl-5-(2-bromoallyl) barbiturato]bispyridine copper(II) dihydrate respectively.

Two exocyclic barbiturate oxygen atoms O(1) and O($1^i$) are at a distance of 2.723(5) Å from the copper atom,

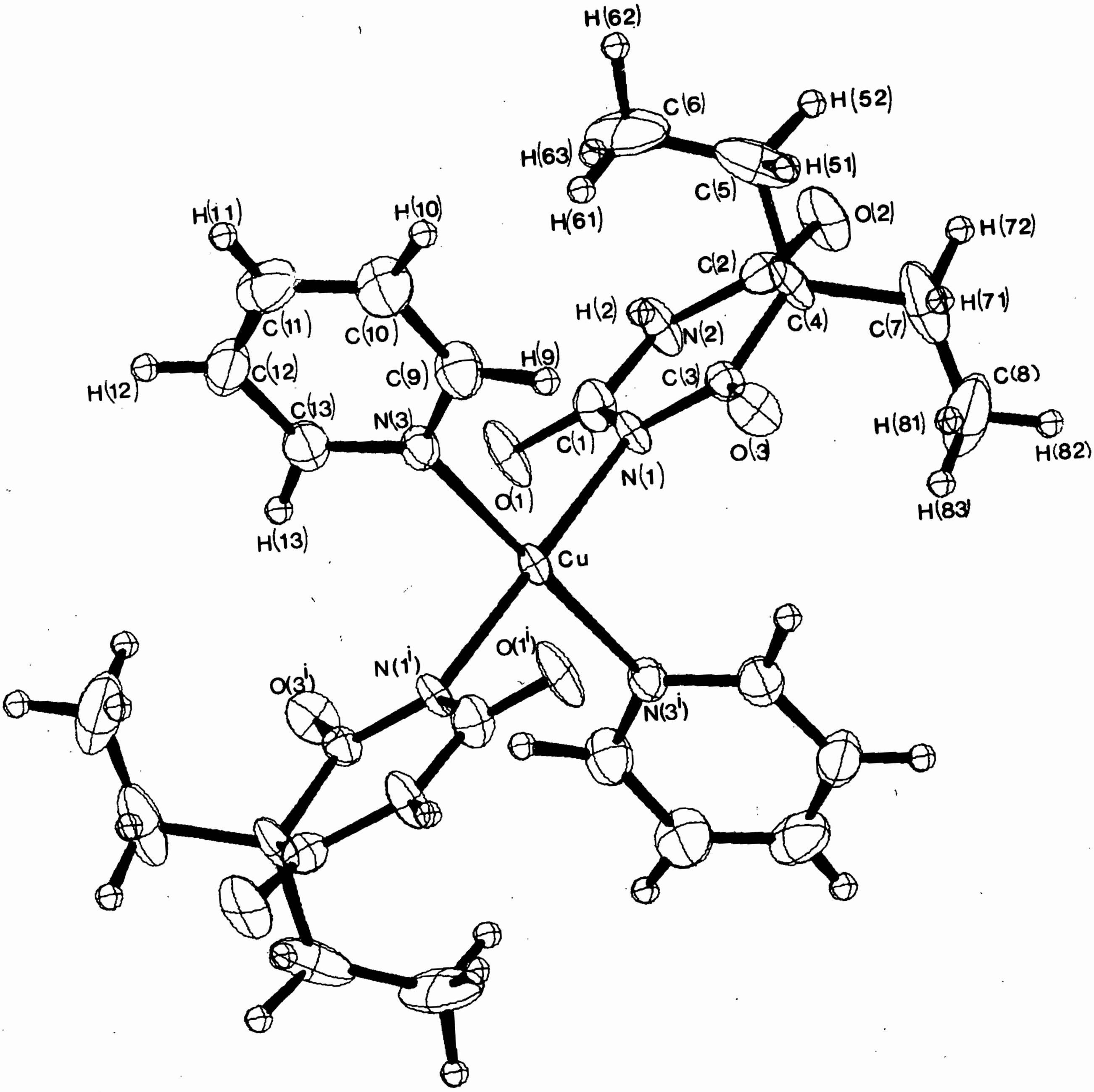

H(62)
C(6)
H(52)
H(63)
H(51)
C(5)
H(61)
O(2)
H(72)
H(11)
H(10)
C(2)
H(2)
H(71)
C(11)
C(10)
N(2)
C(4)
C(7)
H(9)
H(12)
C(12)
C(9)
C(3)
C(8)
C(13)
N(3)
H(81)
C(1)
O(3)
H(82)
N(1)
O(1)
H(83)
H(13)
Cu
O(1$^i$)
N(1$^i$)
O(3$^i$)
N(3$^i$)

FIG. V.3.1

## TABLE V.3.1

## INTRAMOLECULAR BOND LENGTHS AND THEIR E.S.D.'s (Å)

| | | | |
|---|---|---|---|
| Cu—N(1) | 1.983(5) | C(11)-C(12) | 1.38(1) |
| Cu—N(3) | 2.032(5) | C(12)-C(13) | 1.38(1) |
| C(1)—N(1) | 1.374(9) | N(2)—H(2) | 0.97(6) |
| C(3)—N(1) | 1.345(8) | C(9)—H(9) | 1.04(6) |
| C(1)—N(2) | 1.381(9) | C(10)-H(10) | 1.00(7) |
| C(2)—N(2) | 1.376(8) | C(11)-H(11) | 0.86(7) |
| C(9)—N(3) | 1.332(9) | C(12)-H(12) | 0.97(6) |
| C(13)-N(3) | 1.342(8) | C(13)-H(13) | 1.04(7) |
| C(1)—O(1) | 1.212(8) | C(5)—H(51) | 0.93(7) |
| C(2)—O(2) | 1.200(9) | C(5)—H(52) | 1.01(8) |
| C(3)—O(3) | 1.222(8) | C(7)—H(71) | 1.03(8) |
| C(2)—C(4) | 1.532(9) | C(7)—H(72) | 0.98(8) |
| C(3)—C(4) | 1.523(9) | C(6)—H(61) | 1.04(8) |
| C(4)—C(5) | 1.56(1) | C(6)—H(62) | 1.11(8) |
| C(5)—C(6) | 1.49(1) | C(6)—H(63) | 1.04(8) |
| C(4)—C(7) | 1.53(1) | C(8)—H(81) | 0.84(9) |
| C(7)—C(8) | 1.50(1) | C(8)—H(82) | 0.96(7) |
| C(9)—C(10) | 1.40(1) | C(8)—H(83) | 1.04(8) |
| C(10)-C(11) | 1.36(1) | | |

## TABLE V.3.2

## INTRAMOLECULAR BOND ANGLES AND THEIR E.S.D.'s (DEGREES)

| | | | |
|---|---|---|---|
| N(1)-Cu—N(1$^{i}$) | 180.0 | N(1)—C(3)—O(3) | 121.0(6) |
| N(3)-Cu—N(3$^{i}$) | 180.0 | C(4)—C(3)—O(3) | 119.8(5) |
| N(3)-Cu—N(1) | 90.5(2) | N(1)—C(3)—C(4) | 119.2(6) |
| N(1)-Cu—N(3$^{i}$) | 89.5(2) | C(2)—C(4)—C(3) | 114.0(5) |
| Cu—N(1)-C(3) | 127.9(4) | C(5)—C(4)—C(7) | 110.3(6) |
| Cu—N(1)-C(1) | 107.4(4) | C(4)—C(5)—C(6) | 116.9(6) |
| C(1)-N(1)-C(3) | 124.6(5) | C(4)—C(7)—C(8) | 114.0(6) |
| C(1)-N(2)-C(2) | 125.5(6) | Cu—N(3)—C(9) | 120.8(4) |

being situated above and below the plane of the four nitrogen donors. They are thus involved in off-the-z-axis coordination (Fig. V.3.2). "Out-of-the-plane" bonding in axial complexes of the copper(II) ion is well-known[114]. In the complex[115] diacetato-diamine copper(II), which also exhibits off-the-z-axis coordination, the Cu...O separation is 2.77 Å. Similarly, in *trans*-bis[(chloroacetato)-(α-picoline)]copper(II), the distance Cu...O is 2.707 Å. If the barbital ligand were bonded to copper in a symmetrical manner, the angles Cu-N(1)-C(1) and Cu-N(1)-C(3) would be equal and approximately 120°. The Cu...O(1) interaction is reflected in the closing of the angle Cu-N(1)-C(1) to 107.4(4)° and the opening of angle Cu-N(1)-C(3) to 127.9(4)°. Atoms O(3) and O($3^i$), exocyclic barbiturate oxygen atoms, lie at a distance of 3.234(7) Å from the copper atom, just less than the van der Waals sum of Cu and O (3.4 Å).

The bond lengths in the pyridine moiety are within the expected ranges. The greatest deviation from the least-squares plane through the six ring atoms is that of atom C(13), 0.011 Å (Table V.3.4).

Comparison of the crystal structures of barbital[103] and sodium barbital[104] shows that, on deprotonation of barbital to yield the anion, the internal ring angle (Fig. V.3.1) C(1)-N(1)-C(3) closes from 126.4° in barbital to 119.2° in its ion. The three carbon to oxygen bond lengths in the barbital molecule average 1.21 Å and indicate the presence of the trioxopyrimidine (i.e. keto) tautomeric form. In the barbital anion, the two bond lengths in the CO groups flanking the deprotonated nitrogen atom are

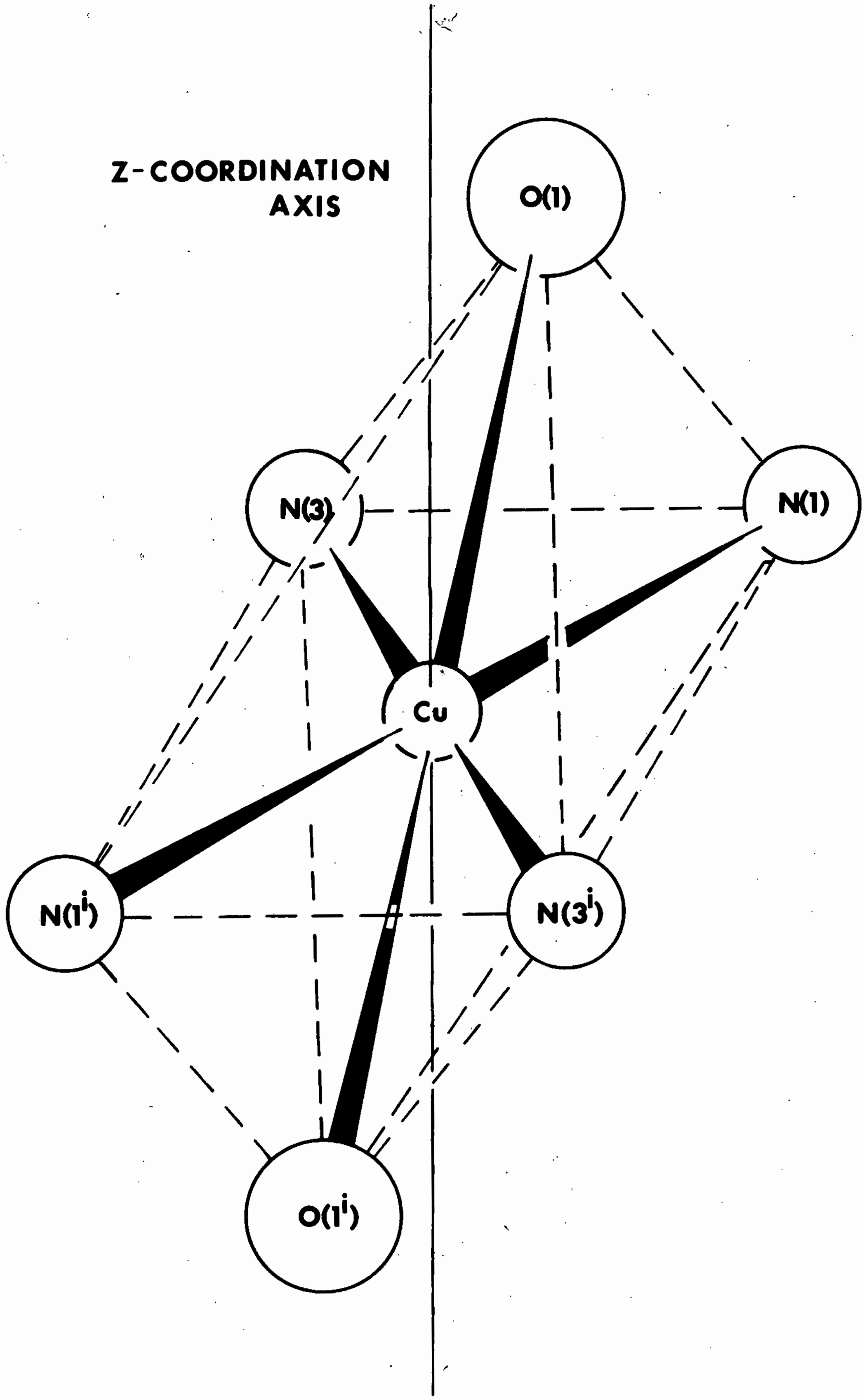


FIG. V.3.2

## TABLE V.3.4

## LEAST-SQUARES PLANES

The equations of the planes are expressed in orthogonalized space as $PI+QJ+RK=S$.

Plane I: through atoms Cu,N(1),N(3),N($1^i$),N($3^i$)

Equation: $0.04272I-0.23816J+0.97028K=0.00$

Plane II: through the six pyrimidine ring atoms, C(3),N(1),C(1), N(2),C(2) and C(4)

Equation: $-0.63299I+0.76268J+0.13278K=0.24309$

| Atoms included in calculation | Dist.from plane, Å | Atoms not included in calculation | Dist.from plane, Å |
|---|---|---|---|
| C(3) | -0.043 | O(3) | -0.127 |
| N(1) | -0.031 | | |
| C(1) | 0.044 | O(1) | 0.097 |
| N(2) | 0.024 | | |
| C(2) | -0.094 | O(2) | -0.296 |
| C(4) | 0.100 | | |

Angle of intersection of planes I and II: 85.42°.

Plane III: through the six pyridine ring atoms, C(9),C(10),C(11), C(12),C(13),N(3)

Equation: $0.58073I+0.71496J-0.38934K= -0.02245$

| Atoms included in calculation | Dist.from plane, Å | Atoms not included in calculation | Dist.from plane, Å |
|---|---|---|---|
| C(9) | -0.003 | H(9) | -0.114 |
| C(10) | 0.007 | H(10) | 0.002 |
| C(11) | -0.002 | H(11) | -0.037 |
| C(12) | -0.007 | H(12) | -0.015 |
| C(13) | 0.011 | H(13) | -0.031 |
| N(3) | -0.006 | Cu | 0.022 |

Angle of intersection of planes I and III: 58.45°

Angle of intersection of planes II and III: 82.76°.

Plane IV: through the trioxopyrimidine ring atoms C(3),N(1), C(1),N(2),C(2),C(4),O(1),O(2),O(3).

Equation: $-0.59364I+0.78876J+0.15955K=0.36558$

| Atoms included in calculation | Dist.from plane, Å |
|---|---|
| C(3) | -0.004 |
| N(1) | -0.056 |
| C(1) | 0.012 |
| N(2) | 0.055 |
| C(2) | 0.007 |
| C(4) | 0.210 |

Table V.3.4 (cont'd)

| Atoms included in calculation | Dist. from plane, Å |
|---|---|
| O(1) | 0.006 |
| O(2) | -0.146 |
| O(3) | -0.085 |

Angle of intersection of planes II and IV: 3.11°

Angle of intersection of planes I and IV: 86.70°.

Plane V: through atoms C(5),C(6),C(7),C(8) of the diethyl group and atom C(4)

Equation: $-0.58613I-0.54894J+0.59592K= -2.48933$

| Atoms included in calculation | Dist. from plane, Å |
|---|---|
| C(4) | -0.018 |
| C(5) | -0.020 |
| C(6) | 0.020 |
| C(7) | 0.016 |
| C(8) | 0.003 |

Angle of intersection of planes II and V: 88.2°.

significantly longer, 1.24 Å (while the third CO group has a bond length of 1.216 Å). These geometrical changes were taken as evidence for the distribution of the negative charge in the barbital ion between the two flanking carbonyl oxygen atoms. In the copper complex, the internal ring angle C(1)-N(1)-C(3) is 124.6(5)°, close to that found in the neutral barbital molecule; this is expected for trigonal coordination of the nitrogen atom N(1). The flanking carbonyl bond lengths are about 1.21(1) Å and 1.22(1) Å which are similar to those found in the parent barbital molecule. The third carbonyl in the copper complex has a length of 1.20(1) Å. Thus, the barbiturate ring in the copper complex may be regarded as possessing a charge distribution similar to that of the parent barbital molecule.

The conformation of the trioxopyrimidine ring is shown in Fig. V.3.3, in which the dashed line is a trace of the least-squares plane through the six ring atoms. The exocyclic oxygen atoms have been included in the figure. The vertical scale is approximately three times the horizontal scale, but slight puckering of the ring is evident. This is expected in view of the fact that atom C(4), which is $sp^3$ hybridized, cannot contribute to conjugation in the ring. The square plane of coordination and the trioxopyrimidine ring are almost perpendicular (angle of intersection 86.7°). Atom C(4) and the diethyl groups form a hydrocarbon chain in the all-*trans* configuration, with the chain axis almost at right angles (88.2°) to the pyrimidine ring plane.

From the analysis of the complex[110]

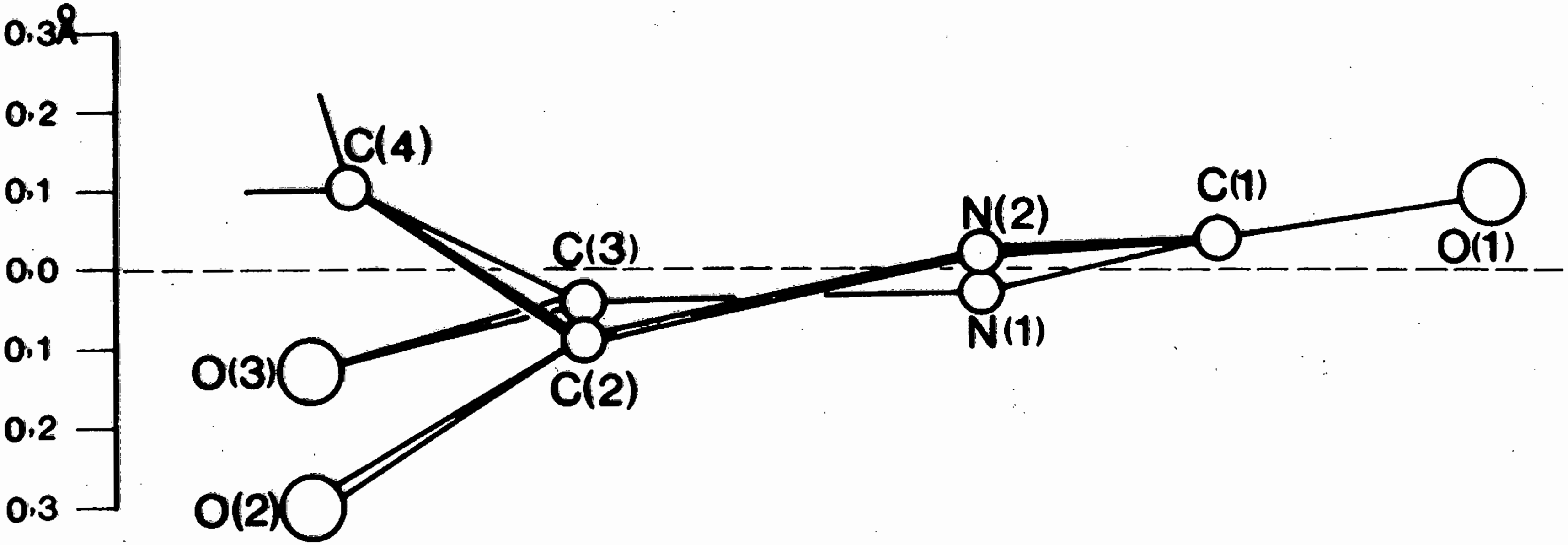
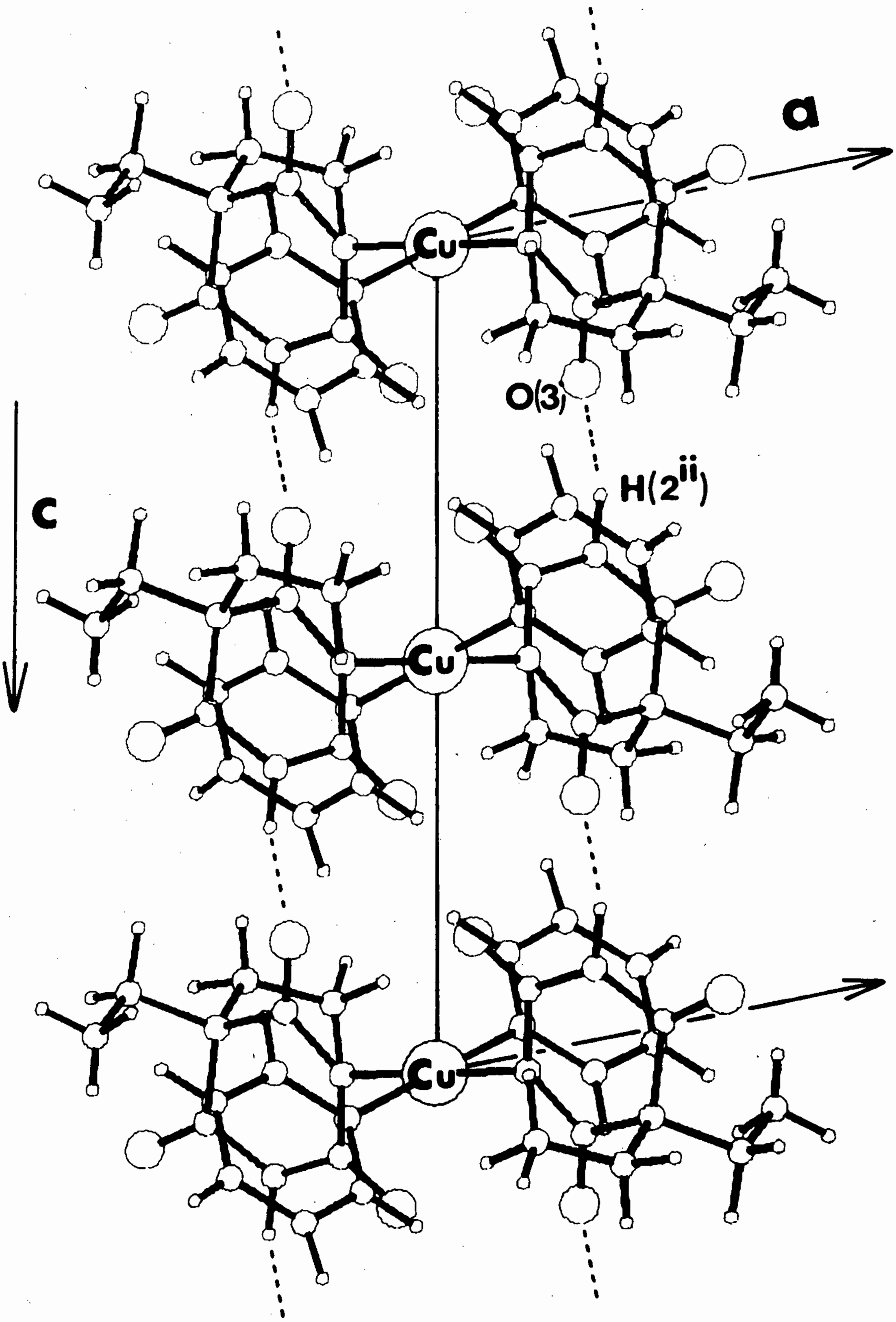


FIG. V.3.3

$Zn(II)(barb)_2(imidazole)_2$, it was concluded that the configuration of the barbiturate and imidazole ligands is stabilized by attractive C-H...O interactions involving carbon atoms of imidazole and carbonyl oxygen atoms of barbital at a C...O distance of 3.02 Å. The H...O distance was reported as 2.37(3) Å. In imidazole, the methine group involved is flanked by basic ring nitrogens which may enhance the acidity of the hydrogen atoms and favour a C-H...O interaction. In the present study, interaction of this type was precluded by the relatively long C...O separations between the relevant rings. One author strongly maintains that a short C...O separation should not be taken as evidence of a C-H...O interaction[83] because the latter does not occur.

The crystal structure of the copper complex is stabilized by intermolecular hydrogen bonding of the type C=O...H-N (represented by dashed lines in Fig. V.3.4, the [010] projection). There is only one crystallographically distinct hydrogen bond, $O(3)...H(2^{ii})-N(2^{ii})$, and this links barbital moieties of adjacent molecules along the cell Z-direction. The symmetry superscript (ii) refers to the transformation x, ½ - y, ½ + z for an atom at x, y, z. Data characterising the hydrogen bond are as follows: $O(3)...H(2^{ii})$ 1.91 Å (van der Waals sum 2.6 Å), $O(3)...N(2^{ii})$ 2.856 Å and angle $O(3)...H(2^{ii})-N(2^{ii})$ 166°. These are in good agreement with the corresponding values in hydrogen bonded systems involving donor ring-NH groups and acceptor carbonyl oxygen atoms[83].

FIG. V.3.4



## Off-the -z-axis coordination

Out-of-the-plane bonding in axial complexes of the copper(II) ion has been observed in many cases[114]. Structures have been determined involving potential ligand atoms positioned both out of the xy plane and off-the-z-axis or in some complexes, the structures involve a mixture of off- and along-the-z-axis ligands.

Crystallographic data[35,114] for some (effectively) six-coordinate complexes is provided in Table V.3.5. The distance $R_S$ is the mean Cu-L distance in the square-planar $CuL_4$ chromophore and $R_L$ is the distance from the Cu atom to the out-of-the-plane ligand atom.

TABLE V.3.5 COPPER-OXYGEN BOND LENGTHS $R_S$ AND $R_L$, (Å) INVOLVING OFF-THE-Z-AXIS LIGANDS

| No. | Complex | $R_S$ | $R_L$ |
|---|---|---|---|
| 1 | $Cu(NH_3)_2(CH_3CO_2)_2$ | 2.07 | 2.77 |
| 2 | $Cu(pyrazine)(NO_3)_2$ | 2.01 | 2.49 |
| 3 | $Cu(\alpha\text{-pic})_2(NO_3)_2$ | 1.99 | 2.53 |
| 4 | $Cu(\alpha\text{-pic})_2(ClCH_2CO_2)_2$ | 1.98 | 2.71 |
| 5 | $Cu(bipy)_1(ONO)_2$ | 1.986 | 2.49 |
| 6 | $Cu(\beta\text{-pic})_2(barb)_2.2H_2O$ | 2.00 | 2.86 |
| 7 | $Cu(py)_2(brallobarb)_2.2H_2O$ | 2.00 | 2.75 |
| 8 | $Cu(py)_2(barb)_2$, present study | 2.00 | 2.72 |

Taking all eight complexes into account, the mean $R_L - R_S$ value is 0.66 Å. Considering the normal to the $CuL_4$ chromophore as the 'tetragonal' axis, Z, the angle between the 'out-of-plane' Cu-O direction and the Z-axis is a measure of the distortion from true tetragonal stereochemistry. For compounds 4 and 8, which have similar parameters, these angles are 36.1° and 35.7° respectively.

Consideration of orbital overlap shows that there is some justification for considering the out-of-the-plane ligands as bonding. If the copper(II) ion in an elongated tetragonal octahedral stereochemistry is considered to have a prolate ellipsoidal shape, then the observed values of $R_L$ will reflect the asymmetry of the effective ionic radius in the direction of the out-of-the-plane bonds. The lack of spherical symmetry of the $d^9$ electronic configuration of the copper(II) ion has been demonstrated[116].

## The barbiturate binding-site

One postulated mechanism[33] for the formation of complexes of the type $Cu(barbiturate)_2(pyridine)_2$ involves three steps: (a) enolisation and partial ionization of the barbiturate to yield an anion with the negative charge formally residing on the carbonyl oxygen flanked by imine nitrogens (b) the formation of a positively charged copper-pyridine complex ion, $[Cu(py)_2]^{2+}$ and (c) interaction of the ionic species derived from (b) with two barbiturate anions to yield a four-coordinate complex in which the barbiturate donor atoms are oxygens. Infrared absorption data were obtained for a series of compounds with different barbiturates and it was suggested that a Cu-O-C linkage exists in such complexes. Comparison of the crystal structures of 5,5'-diethylbarbituric acid (barbital)[103] and sodium 5,5'-diethylbarbiturate (sodium barbital)[104] indicates that on deprotonation of the former to yield the barbital ion (present in the latter compound), the greatest part of the formal negative charge on the ion is distributed almost equally between the oxygen atoms flanking the deprotonated nitrogen atom. This observation would tend to confirm the suggestion of binding to copper *via* an oxygen atom of the barbital ion. However, since the present study and subsequent analyses[35] of copper-barbiturate complexes have shown conclusively that the barbiturate donor is a nitrogen atom, delocalisation of the transient negative charge on the nitrogen atom (possibly occurring in solution) and distribution to the oxygen atoms may permit a more stable configuration in the structure of sodium barbital than would localisation of the charge on the nitrogen atom. Steric hindrance by the exocyclic oxygen atoms might disfavour nitrogen-sodium coordination. In the crystal of sodium barbital, each oxygen atom is coordinated to one or more sodium ions, while the deprotonated nitrogen atom is not situated in the immediate coordination shell about the sodium ion. These speculations require further experiment in order to confirm any plausible mechanism for the complexation process. Kinetics studies and the use of radioactively-labelled barbiturates may resolve this question.

# CHAPTER VI

# ANTICANCER DRUGS OF THE TYPE $PtA_2X_2$ : THE CRYSTAL STRUCTURE OF TRANS-(DITHIOCYANATO)(BISPYRIDINE)PLATINUM(II)

## VI.1 INTRODUCTION

### The antitumour activity of platinum drugs

In 1969, four compounds (*cis*-[Pt$(NH_3)_2Cl_2$], *cis*-[Pt$(NH_3)_2Cl_4$], [Pt(en)$Cl_4$], [Pt(en)$Cl_2$], en = ethylenediamine), were tested against a specific tumour in mice and were found to be effective in inhibiting the tumour growth[117]. The most potent of these original compounds was *cis*-[Pt$(NH_3)_2Cl_2$] which is known to have a wide spectrum of activity and is still undergoing extensive human clinical trials. Since the discovery of the therapeutic properties of these compounds, a vast number of platinum ( and other metal) complexes have been synthesised and tested for anticancer activity. Generally, compounds are screened on an empirical basis and when a potential drug is discovered, a systematic screening of related molecules can lead to a knowledge of the factors required for maximum therapeutic effect.

### Factors affecting activity in the platinum series

It has been found that of the *cis*- and *trans*-isomers of $PtA_2X_2$ ($A_2$ is two monodentate or one bidentate amine ligand and $X_2$ is two monodentate or one bidentate anionic ligand), only the *cis*-isomer displays anticancer activity[26]. A feature of this series of compounds is that the *trans*-isomers are consistently more reactive than their *cis*-analogues. The *trans*-isomers are therefore likely to react more quickly and with a host of body constituents. Compared with the *cis*-compounds they will be less specific in their action. Only *cis*-compounds have the potential to form chelates and this observation has led to one of the simplest theories connecting chelation and cancer. This is discussed below.

In the molecule $PtA_2X_2$, anionic ligands X will largely determine the overall reactivity of the complex while the nature of the amine A, should modify this by steric, electronic and basic properties. Compounds with ligands of intermediate leaving ability ($X = Cl^-, Br^-$) show considerable antitumour activity. With bidentate anions (e.g. oxalate and malonate), several active complexes have been synthesised, but their mode of action is not properly understood. It has been found that if a chloro complex is active the corresponding malonate (and usually oxalate) also shows a good response against the S.180 tumour system. Apart from alkylamines, alicyclic and heterocyclic amines have been incorporated into $PtA_2X_2$. Generally, aromatic amines have not shown promise but active complexes have been obtained with alicyclic amines (cyclopropylamine to cyclooctylamine). There is at present no obvious explanation for the variation of activity with amine structure.

The structures of platinum (II) and (IV) compounds found to have antitumour activity are illustrated in Fig. V1.1.1.

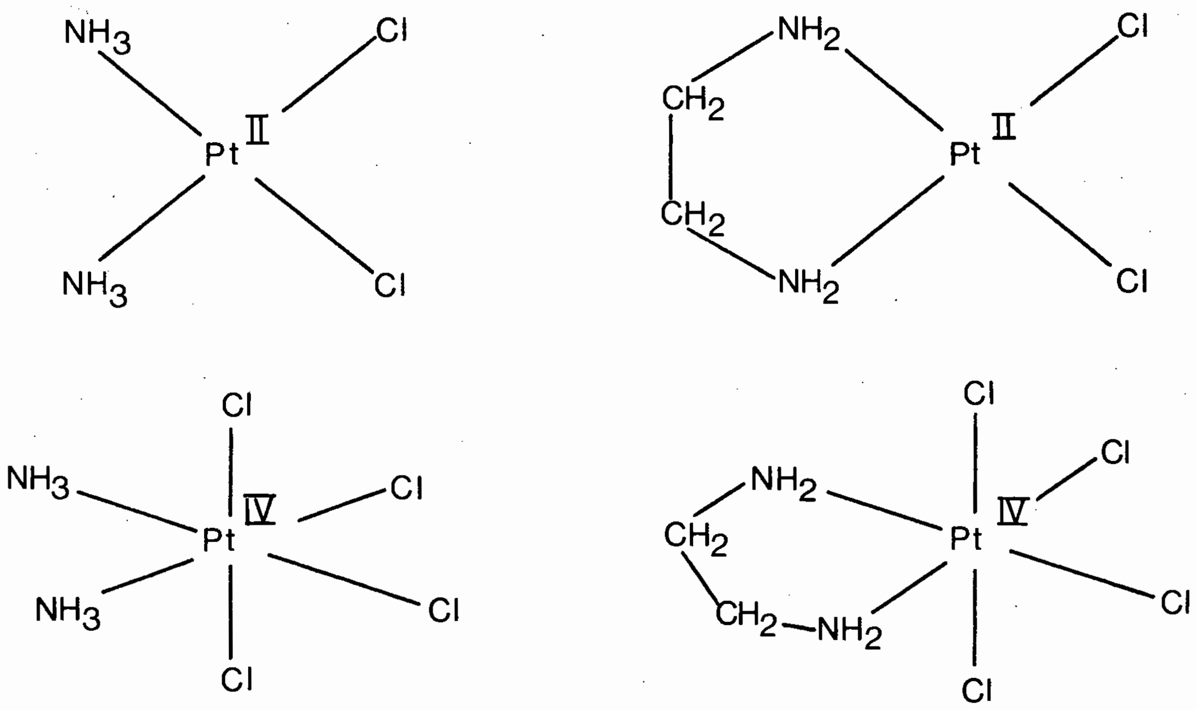


Fig. Vl.1.1

The simplest theory concerning the mode of action of these drugs[118] is that the site of their action is inside the cancer cells at the nuclear DNA. It is suggested that the two *cis*-chloride ions are lost, allowing the Pt atom to form a purine - Pt-purine cross-link between nitrogen atoms of two neighbouring DNA purines. The formation of an *intra* strand link (if the purines are parts of the same DNA chain) or an *inter* strand link (if the Pt bridges adjacent DNA chains) constitutes an anomalous bond or "DNA lesion". Normally, such lesions inhibit the synthesis of new DNA polymers by the cancer cell. The interatomic Cl...Cl distance in the *cis*-dichloroplatinum(II) complexes is 3.3 Å, which is the distance required for *intra* chain bridging (e.g. between amino groups of adenine or guanine).

The efficacy of the platinum drugs against human cancers will only have been assessed within several years, due mainly to the thorough screening tests involved. A wide variety of *in vivo* screens (i.e. different tumour lines) are employed in order to estimate the relative activity of a drug. At present, no particular screen is sufficiently sensitive to all known drugs to be used as a universal screen. Some commonly used transplantable tumours in mice include Sarcoma 180, Leukaemia L.1210, and Ehrlich ascites. In rats of various strains, the Walker carcinoma and Yoshida sarcoma are the common tumours.

## Motivation for structural analysis

Recent work[119] at this university has involved the synthesis and physico-chemical study of complexes of the type $PtA_2X_2$ with a view to establishing what structural features enhance or diminish the anticancer activities of such drugs. Anionic ligands include thiocyanate and halide ions; the amines include pyridines and anilines. During the course of this work, two complexes with the stoichiometry $Pt(pyridine)_2(SCN)_2$ were synthesised. It was not possible to establish which compound was the *cis*- and which the *trans*-isomer from infrared studies. In addition, the thiocyanate ion is known to be ambidentate forming M-NCS or M-SCN bonds with metals M. Of the two isomers prepared, one had formed crystals of good quality and it was chosen for X-ray structural analysis. It was also hoped that the structural elucidation would facilitate the interpretation of the infrared spectra.

## VI.2 THE CRYSTAL STRUCTURE OF TRANS-(DITHIOCYANATO) (BISPYRIDINE) PLATINUM(II); $Pt(C_5H_5N)_2(SCN)_2$

### Crystal preparation and chemical analysis

Aqueous solutions of $K_2PtCl_4$ and KSCN were mixed in a 1:4 molar ratio[119].

After heating the mixture on a steambath, pyridine (2 mole) was added dropwise and a yellow product separated from solution. After filtration, the product was recrystallised from acetone containing an excess of pyridine.

Orange-yellow needles with approximately square cross-section were isolated and microanalytical data (Table VI.2.1) indicated the stoichiometric composition $Pt(SCN)_2(pyridine)_2$.

TABLE VI.2.1

| | %C | %H | %N |
|---|---|---|---|
| Calculated: | 30.70 | 2.13 | 11.94 |
| Found : | 30.50 | 2.11 | 11.95 |

### Density determination

A nomogram for the solvent system methylene iodide-m-xylene was constructed[94] and a crystal density of 2.15 g $cm^{-3}$ was registered by flotation of single crystals in 10 ml of the mixture. This value was consistent with one complex molecule per unit cell.

### Space group assignment

Weissenberg photographs, taken with the crystal oscillating about the three principal axes, showed no systematic absences indicating that the crystal space group was either

P1 or P$\bar{1}$ (Triclinic)[95].

Diffractometer data

Consideration of the linear absorption coefficient (Table VI.2.2) showed that it was necessary to use a very small crystal in order to reduce absorption effects. An optimum radius[43] of 0.2 mm was calculated. For data collection, a single needle was cut into a cube of side 0.25 mm and was mounted on the diffractometer. Relevant crystal data are listed in Table VI.2.2.

TABLE VI.2.2 CRYSTAL DATA

| | |
|---|---|
| Molecular formula | $Pt(C_5H_5N)_2(SCN)_2$ |
| Molecular weight | 469.0 g mole$^{-1}$ |
| Space group | P$\bar{1}$ (Triclinic) |
| a = 5.377(5) Å | |
| b = 10.568(5) Å | |
| c = 6.820(5) Å | |
| $\alpha$ = 96.8(1)° | $D_m$ = 2.15 g cm$^{-3}$ |
| $\beta$ = 107.2(1)° | $D_c$ = 2.17 g cm$^{-3}$ for Z = 1 |
| $\gamma$ = 99.7(1)° | $\mu$(MoK$\alpha$) = 104.5 cm$^{-1}$ |
| V = 358.94 Å$^3$ | F(000) = 220 |

Intensities were measured with the diffractometer operating in the $\omega$-2$\theta$ scan mode (scan speed 0.05°$\theta$sec$^{-1}$, scan width 1.6°$\theta$). In the 2$\theta$ range from 6° to 50°, 1259 reflections were recorded; all of these had $I_{rel} > 1.65\sigma(I_{rel})$ and were therefore classified as observed data. Crystal stability was confirmed by the observation that the intensities of three reference reflections (measured every hour) remained constant to within 2% of their respective mean values. The approximate $\mu R$ range was from 1.3 to 1.8 with corresponding A* values[78] of 7.96 and 16.3 at $\Theta=0^{\circ}$ and 6.92 and 12.2 at $\Theta=25^{\circ}$. That is, A* varied considerably with crystal size. Although no absorption corrections were applied, anomalous dispersion corrections were applied to the heavy atom scattering curves.

<u>Solution of the structure and refinement</u>

With one Pt atom per molecule and one molecule per unit cell, the Pt atom may be placed arbitrarily at 0,0,0. In such a case, the space group $P\bar{1}$ would demand a centre of molecular symmetry, that is, the *trans*-isomer, whereas the acentric space group P1 would permit only the *cis*-isomer in the crystal. Initially, the space group P1 was assumed and with the Pt atom fixed at the origin, structure factors and an electron-density map were computed (X-RAY 72 program system[46]).

The pyridine ring was clearly revealed in this map but there was some doubt concerning the position of the thiocyanate ion. Using the pyridine ring atom positions as input, an electron-density map was prepared assuming space group P1. This map revealed a second set of peaks related to the pyridine ring atoms by a centre of symmetry and thus confirmed that the space group was $P\bar{1}$. The thiocyanate group was easily located in the corresponding map based on the space group $P\bar{1}$. The relative peak heights clearly indicated that the SCN group was bound to the Platinum atom through the sulphur rather than the nitrogen atom.

After two cycles of isotropic and four cycles of anisotropic full-matrix least-squares refinement including all atoms, R was 0.037. In order to facilitate hydrogen atom location, theoretical positions (at 1.08 Å from their parent atoms) were calculated (program XANADU) and these were compared with the positions of the peaks found in a final difference electron-density map. All of the hydrogen atoms were clearly revealed in this map and they were included in the refinement process, only their positions being allowed to vary. Each hydrogen atom was assigned the isotropic temperature factor of its bonded parent atom and this parameter was held invariant. After three cycles of refinement, all positional and thermal parameters had settled. The average shift:error ratio was 0.004 for the non-hydrogen atoms and 0.024 for the hydrogen atoms. A final difference electron-density map showed only slight ripples in the vicinity of the Platinum atom. The terminal R value was 0.035 with unit weights applied to each reflection. In the refinement process, the function $\Sigma(|F_o|-|F_c|)^2$ was minimised.

Atomic scattering factors for Pt, S, C and N were those of Cromer and Mann[79], and for H, those of Stewart et al[80]. Anomalous dispersion corrections[63](MoKα) were applied to the Pt and S scattering curves. Tables VI.2.3 and VI.2.4 list the final positional and thermal parameters of the heavy atoms and the hydrogen atoms respectively. Observed and calculated structure factors appear in Table VI.2.5.

## TABLE VI.2.4

## HYDROGEN ATOMS

## FRACTIONAL ATOMIC COORDINATES ($\times 10^2$) AND THEIR E.S.D.'s AND ISOTROPIC TEMPERATURE FACTORS ($\times 10^2$)

|  | $x$ | $y$ | $z$ | $U_{iso}$ (Å$^2$) |
|---|---|---|---|---|
| H(1) | 27(2) | -22(1) | -4(2) | 3.9 |
| H(2) | 32(2) | -40(1) | 10(2) | 4.5 |
| H(3) | 10(2) | -47(1) | 35(2) | 4.6 |
| H(4) | -15(2) | -32(1) | 46(2) | 5.1 |
| H(5) | -16(2) | -15(1) | 32(2) | 3.6 |

# TABLE VI.2.5

| | 10FO | 10FC |
|---|---|---|
| H,0,0 | | |
| 2 | 707 | 721 |
| 3 | 460 | 459 |
| 4 | 266 | 269 |
| 5 | 265 | 260 |
| H,1,0 | | |
| 5 | 249 | 246 |
| 4 | 235 | 252 |
| 3 | 371 | 366 |
| 2 | 761 | 742 |
| 1 | 566 | 579 |
| -1 | 653 | 655 |
| -2 | 343 | 354 |
| -3 | 705 | 727 |
| -4 | 271 | 279 |
| -5 | 263 | 265 |
| -6 | 179 | 156 |
| H,2,0 | | |
| -6 | 262 | 151 |
| -5 | 158 | 171 |
| -4 | 318 | 321 |
| -3 | 513 | 512 |
| -2 | 444 | 452 |
| -1 | 747 | 760 |
| 0 | 403 | 356 |
| 1 | 288 | 292 |
| 2 | 551 | 577 |
| 3 | 380 | 402 |
| 4 | 261 | 276 |
| 5 | 225 | 234 |
| H,3,0 | | |
| 5 | 212 | 225 |
| 4 | 319 | 335 |
| 3 | 287 | 303 |
| 2 | 601 | 629 |
| 1 | 998 | 954 |
| 0 | 705 | 651 |
| -1 | 661 | 680 |
| -2 | 338 | 390 |
| -3 | 334 | 353 |
| -4 | 328 | 330 |
| -5 | 192 | 187 |
| -6 | 205 | 179 |
| H,4,0 | | |
| -6 | 212 | 147 |
| -5 | 244 | 231 |
| -4 | 393 | 394 |
| -3 | 436 | 450 |
| -2 | 410 | 428 |
| -1 | 779 | 769 |
| 0 | 330 | 314 |
| 1 | 545 | 546 |
| 2 | 448 | 456 |
| 3 | 216 | 220 |
| 4 | 259 | 274 |
| 5 | 163 | 166 |
| H,5,0 | | |
| 4 | 266 | 266 |
| 3 | 237 | 236 |
| 2 | 399 | 405 |
| 1 | 646 | 645 |
| 0 | 837 | 809 |
| -1 | 708 | 710 |
| -2 | 841 | 866 |
| -3 | 327 | 338 |
| -4 | 468 | 414 |
| -5 | 227 | 225 |
| H,6,0 | | |
| -5 | 235 | 226 |
| -4 | 365 | 388 |
| -3 | 343 | 362 |
| -2 | 554 | 576 |
| -1 | 503 | 536 |
| 0 | 479 | 461 |
| 1 | 719 | 725 |
| 2 | 350 | 359 |
| 3 | 305 | 314 |
| 4 | 264 | 258 |
| H,7,0 | | |
| 4 | 164 | 171 |
| 3 | 338 | 346 |
| 2 | 215 | 217 |
| 1 | 989 | 950 |
| 0 | 430 | 426 |
| -1 | 441 | 442 |
| -2 | 662 | 689 |
| -3 | 348 | 371 |
| -4 | 309 | 308 |
| -5 | 242 | 236 |
| H,8,0 | | |
| -5 | 267 | 265 |
| -4 | 189 | 195 |
| -3 | 238 | 252 |
| -2 | 415 | 434 |
| -1 | 274 | 282 |
| 0 | 542 | 542 |
| 1 | 251 | 297 |
| 2 | 237 | 265 |
| 3 | 274 | 282 |
| H,9,0 | | |
| 3 | 232 | 239 |
| 2 | 246 | 253 |
| 1 | 295 | 303 |
| 0 | 384 | 389 |
| -1 | 235 | 239 |
| -2 | 209 | 227 |
| -3 | 323 | 376 |
| -4 | 204 | 209 |
| -5 | 229 | 226 |
| H,10,0 | | |
| -4 | 222 | 221 |
| -3 | 395 | 365 |
| -2 | 344 | 363 |
| -1 | 310 | 320 |
| 0 | 358 | 371 |
| 1 | 224 | 238 |
| 2 | 239 | 246 |
| H,11,0 | | |
| 1 | 149 | 188 |
| 0 | 340 | 355 |
| -1 | 320 | 331 |
| -2 | 270 | 276 |
| -3 | 302 | 308 |
| H,12,0 | | |
| -1 | 328 | 337 |
| 0 | 217 | 233 |
| H,-12,1 | | |
| 2 | 287 | 296 |
| 1 | 261 | 261 |
| 0 | 393 | 390 |
| H,-11,1 | | |
| -1 | 262 | 255 |
| 0 | 380 | 379 |
| 1 | 244 | 236 |
| 2 | 371 | 376 |
| 3 | 267 | 266 |
| H,-10,1 | | |
| 4 | 227 | 228 |
| 3 | 305 | 312 |
| 2 | 419 | 426 |
| 1 | 351 | 342 |
| 0 | 329 | 316 |
| -1 | 356 | 363 |
| -2 | 183 | 188 |
| H,-9,1 | | |
| -3 | 203 | 194 |
| -2 | 257 | 260 |
| -1 | 432 | 421 |
| 0 | 403 | 387 |
| 1 | 339 | 326 |
| 2 | 463 | 476 |
| 3 | 311 | 326 |
| 4 | 292 | 298 |
| H,-8,1 | | |
| 5 | 203 | 193 |
| 4 | 311 | 295 |
| 3 | 131 | 137 |
| 2 | 369 | 366 |
| 1 | 402 | 385 |
| 0 | 370 | 362 |
| -1 | 530 | 517 |
| -2 | 266 | 268 |
| -3 | 286 | 279 |
| -4 | 257 | 247 |
| H,-7,1 | | |
| -4 | 237 | 242 |
| -3 | 276 | 275 |
| -2 | 364 | 346 |
| -1 | 508 | 497 |
| 0 | 233 | 237 |
| 1 | 660 | 647 |
| 2 | 388 | 388 |
| 3 | 266 | 262 |
| 4 | 277 | 273 |
| 5 | 158 | 146 |
| H,-6,1 | | |
| 5 | 187 | 170 |
| 4 | 400 | 386 |
| 3 | 501 | 496 |
| 2 | 457 | 448 |
| 1 | 679 | 634 |
| 0 | 441 | 402 |
| -1 | 444 | 433 |
| -2 | 552 | 554 |
| -3 | 208 | 212 |
| -4 | 292 | 287 |
| H,-5,1 | | |
| -6 | 214 | 208 |
| -4 | 256 | 251 |
| -3 | 321 | 314 |
| -2 | 605 | 613 |
| -1 | 588 | 566 |
| 0 | 847 | 755 |
| 1 | 835 | 786 |
| 2 | 369 | 356 |
| 3 | 512 | 499 |
| 4 | 346 | 335 |
| 5 | 227 | 213 |
| H,-4,1 | | |
| 5 | 239 | 229 |
| 4 | 282 | 275 |
| 3 | 859 | 838 |
| 2 | 493 | 475 |
| 1 | 740 | 730 |
| 0 | 954 | 843 |
| -1 | 465 | 386 |
| -2 | 566 | 578 |
| -3 | 308 | 322 |
| -4 | 190 | 188 |
| -5 | 218 | 208 |
| H,-3,1 | | |
| -5 | 265 | 248 |
| -4 | 224 | 226 |
| -3 | 403 | 422 |
| -2 | 454 | 459 |
| -1 | 409 | 386 |
| 0 | 915 | 790 |
| 1 | 447 | 413 |
| 2 | 524 | 506 |
| 3 | 491 | 479 |
| 4 | 282 | 280 |
| 5 | 221 | 231 |
| H,-2,1 | | |
| 5 | 226 | 231 |
| 4 | 144 | 167 |
| 3 | 429 | 432 |
| 2 | 461 | 446 |
| 1 | 631 | 572 |
| 0 | 534 | 409 |
| -1 | 694 | 611 |
| -2 | 624 | 627 |
| -3 | 584 | 608 |
| -4 | 297 | 308 |
| -5 | 235 | 233 |
| H,-1,1 | | |
| -6 | 209 | 206 |
| -5 | 242 | 240 |
| -4 | 291 | 305 |
| -3 | 531 | 548 |
| -2 | 576 | 562 |
| -1 | 492 | 469 |
| 0 | 745 | 654 |
| 1 | 100 | 86 |
| 2 | 629 | 670 |
| 3 | 373 | 395 |
| 4 | 231 | 231 |
| 5 | 238 | 248 |
| H,0,1 | | |
| 5 | 216 | 222 |
| 4 | 365 | 360 |
| 3 | 234 | 252 |
| 2 | 648 | 675 |
| 1 | 350 | 391 |
| 0 | 747 | 608 |
| -1 | 1050 | 1119 |
| -2 | 283 | 282 |
| -3 | 559 | 562 |
| -4 | 317 | 328 |
| -5 | 242 | 247 |
| -6 | 226 | 202 |
| H,1,1 | | |
| -6 | 179 | 161 |
| -5 | 167 | 167 |
| -4 | 451 | 418 |
| -3 | 436 | 464 |
| -2 | 377 | 414 |
| -1 | 1071 | 1164 |
| 0 | 780 | 793 |
| 1 | 1291 | 1312 |
| 2 | 720 | 731 |
| 3 | 321 | 324 |
| 4 | 310 | 313 |
| 5 | 140 | 163 |
| H,2,1 | | |
| 5 | 146 | 147 |
| 4 | 290 | 309 |
| 3 | 328 | 332 |
| 2 | 368 | 366 |
| 1 | 671 | 641 |
| 0 | 430 | 410 |
| -1 | 669 | 698 |
| -2 | 795 | 833 |
| -3 | 365 | 412 |
| -4 | 447 | 462 |
| -5 | 184 | 200 |
| -6 | 173 | 158 |
| H,3,1 | | |
| -6 | 157 | 160 |
| -5 | 249 | 260 |
| -4 | 423 | 380 |
| -3 | 326 | 353 |
| -2 | 674 | 608 |
| -1 | 716 | 724 |
| 0 | 418 | 402 |
| 1 | 590 | 536 |
| 2 | 279 | 289 |
| 3 | 280 | 289 |
| 4 | 297 | 301 |
| 5 | 130 | 133 |
| H,4,1 | | |
| 4 | 243 | 246 |
| 3 | 322 | 329 |
| 2 | 263 | 268 |
| 1 | 649 | 633 |
| 0 | 439 | 427 |
| -1 | 388 | 393 |
| -2 | 471 | 513 |
| -3 | 257 | 284 |
| -4 | 317 | 341 |
| -5 | 262 | 266 |
| -6 | 180 | 170 |
| H,5,1 | | |
| -6 | 184 | 180 |
| -5 | 301 | 303 |
| -4 | 330 | 340 |
| -3 | 372 | 392 |
| -2 | 609 | 633 |
| -1 | 366 | 368 |
| 0 | 538 | 533 |
| 1 | 434 | 431 |
| 2 | 240 | 233 |
| 3 | 306 | 364 |
| 4 | 164 | 164 |
| H,6,1 | | |
| 4 | 102 | 113 |
| 3 | 318 | 326 |
| 2 | 261 | 265 |
| 1 | 454 | 453 |
| 0 | 537 | 599 |
| -1 | 373 | 378 |
| -2 | 492 | 404 |
| -3 | 414 | 432 |
| -4 | 272 | 284 |
| -5 | 278 | 276 |
| -6 | 157 | 140 |
| H,7,1 | | |
| -5 | 225 | 216 |
| -4 | 227 | 239 |
| -3 | 449 | 463 |
| -2 | 458 | 469 |
| -1 | 338 | 343 |
| 0 | 567 | 574 |
| 1 | 285 | 287 |
| 2 | 363 | 384 |
| 3 | 279 | 282 |
| H,8,1 | | |
| 3 | 172 | 181 |
| 2 | 304 | 316 |
| 1 | 232 | 217 |
| 0 | 448 | 462 |
| -1 | 513 | 525 |
| -2 | 345 | 357 |
| -3 | 425 | 438 |
| -4 | 235 | 226 |
| -5 | 232 | 221 |
| H,9,1 | | |
| -5 | 200 | 196 |
| -4 | 277 | 281 |
| -3 | 278 | 288 |
| -2 | 176 | 189 |
| -1 | 367 | 378 |
| 0 | 299 | 306 |
| 1 | 261 | 272 |
| 2 | 241 | 246 |
| H,10,1 | | |
| 2 | 245 | 252 |
| 1 | 190 | 195 |
| 0 | 200 | 210 |
| -1 | 238 | 249 |
| -2 | 226 | 238 |
| -3 | 254 | 269 |
| -4 | 259 | 258 |
| H,11,1 | | |
| -2 | 259 | 266 |
| -1 | 356 | 366 |
| 0 | 186 | 193 |
| 1 | 227 | 224 |
| H,12,1 | | |
| -1 | 271 | 277 |
| -2 | 254 | 261 |
| H,-12,2 | | |
| 0 | 298 | 302 |
| 1 | 228 | 233 |
| 2 | 330 | 342 |
| H,-11,2 | | |
| 3 | 236 | 242 |
| 2 | 357 | 369 |
| 1 | 385 | 397 |
| 0 | 264 | 285 |
| -1 | 422 | 428 |
| -2 | 205 | 204 |
| H,-10,2 | | |
| -2 | 289 | 300 |
| -1 | 340 | 343 |
| 0 | 296 | 253 |
| 1 | 421 | 424 |
| 2 | 328 | 331 |
| 3 | 260 | 259 |
| 4 | 276 | 262 |
| H,-9,2 | | |
| 4 | 321 | 320 |
| 3 | 307 | 312 |
| 2 | 343 | 341 |
| 1 | 439 | 436 |
| 0 | 319 | 334 |
| -1 | 369 | 365 |
| -2 | 353 | 363 |
| -3 | 183 | 180 |
| H,-8,2 | | |
| -4 | 165 | 188 |
| -3 | 174 | 176 |
| -2 | 341 | 345 |
| -1 | 417 | 415 |
| 0 | 391 | 376 |
| 1 | 595 | 578 |
| 2 | 271 | 267 |
| 3 | 386 | 345 |
| 4 | 346 | 329 |
| H,-7,2 | | |
| 5 | 165 | 169 |
| 4 | 169 | 156 |
| 3 | 338 | 329 |
| 2 | 242 | 233 |
| 1 | 576 | 546 |
| 0 | 604 | 560 |
| -1 | 315 | 303 |
| -2 | 527 | 549 |
| -3 | 295 | 304 |
| -4 | 288 | 289 |
| H,-6,2 | | |
| -4 | 212 | 218 |
| -3 | 397 | 413 |
| -2 | 838 | 841 |
| -1 | 336 | 315 |
| 0 | 648 | 592 |
| 1 | 404 | 371 |
| 2 | 419 | 396 |
| 3 | 447 | 430 |
| 4 | 174 | 169 |
| 5 | 170 | 184 |
| H,-5,2 | | |
| 5 | 269 | 250 |
| 4 | 271 | 262 |
| 3 | 495 | 476 |
| 2 | 470 | 445 |
| 1 | 384 | 350 |
| 0 | 777 | 693 |
| -1 | 631 | 491 |
| -2 | 421 | 416 |
| -3 | 454 | 460 |
| -4 | 216 | 217 |
| -5 | 240 | 234 |
| H,-4,2 | | |
| -5 | 189 | 186 |
| -4 | 259 | 258 |
| -3 | 497 | 496 |
| -2 | 458 | 443 |
| -1 | 699 | 645 |
| 0 | 1049 | 921 |
| 1 | 673 | 626 |
| 2 | 635 | 659 |
| 3 | 365 | 350 |
| 4 | 261 | 254 |
| 5 | 249 | 241 |
| H,-3,2 | | |
| 5 | 215 | 227 |
| 4 | 257 | 276 |
| 3 | 377 | 376 |
| 2 | 689 | 659 |
| 1 | 598 | 565 |
| 0 | 651 | 578 |
| -1 | 798 | 739 |
| -2 | 210 | 207 |
| -3 | 407 | 409 |
| -4 | 269 | 263 |
| -5 | 193 | 182 |
| H,-2,2 | | |
| -6 | 180 | 153 |
| -5 | 134 | 190 |
| -4 | 392 | 382 |
| -3 | 427 | 417 |
| -2 | 405 | 385 |
| -1 | 676 | 635 |
| 0 | 566 | 511 |
| 1 | 472 | 456 |
| 2 | 638 | 642 |
| 3 | 287 | 276 |
| 4 | 262 | 278 |
| 5 | 219 | 217 |
| H,-1,2 | | |
| 5 | 120 | 117 |
| 4 | 285 | 296 |
| 3 | 177 | 173 |
| 2 | 582 | 592 |
| 1 | 534 | 555 |
| 0 | 454 | 475 |
| -1 | 503 | 482 |
| -2 | 643 | 616 |
| -3 | 530 | 513 |
| -4 | 400 | 391 |
| -5 | 208 | 202 |
| -6 | 166 | 169 |
| H,0,2 | | |
| -6 | 256 | 217 |
| -5 | 235 | 241 |
| -4 | 460 | 444 |
| -3 | 389 | 362 |
| -2 | 564 | 576 |
| -1 | 858 | 812 |
| 0 | 127 | 137 |
| 1 | 576 | 613 |
| 2 | 211 | 220 |
| 3 | 277 | 266 |
| 4 | 300 | 307 |
| 5 | 105 | 112 |
| H,1,2 | | |
| 5 | 138 | 133 |
| 4 | 237 | 246 |
| 3 | 322 | 325 |
| 2 | 246 | 245 |
| 1 | 747 | 759 |
| 0 | 658 | 669 |
| -1 | 394 | 419 |
| -2 | 639 | 737 |
| -3 | 250 | 290 |
| -4 | 449 | 461 |
| -5 | 300 | 285 |
| -6 | 167 | 160 |
| H,2,2 | | |
| -6 | 111 | 111 |
| -5 | 235 | 261 |
| -4 | 261 | 288 |
| -3 | 409 | 435 |
| -2 | 695 | 685 |
| -1 | 384 | 392 |
| 0 | 755 | 746 |
| 1 | 768 | 764 |
| 2 | 533 | 532 |
| 3 | 416 | 425 |
| 4 | 217 | 222 |
| H,3,2 | | |
| 4 | 183 | 186 |
| 3 | 386 | 393 |
| 2 | 283 | 281 |
| 1 | 450 | 448 |
| 0 | 698 | 693 |
| -1 | 596 | 596 |
| -2 | 646 | 661 |
| -3 | 486 | 499 |
| -4 | 262 | 274 |
| -5 | 276 | 275 |
| -6 | 162 | 164 |
| H,4,2 | | |
| -6 | 186 | 180 |
| -5 | 262 | 262 |
| -4 | 277 | 286 |
| -3 | 377 | 400 |
| -2 | 469 | 490 |
| -1 | 379 | 388 |
| 0 | 676 | 675 |
| 1 | 318 | 319 |
| 2 | 265 | 267 |
| 3 | 273 | 269 |
| 4 | 133 | 133 |
| H,5,2 | | |
| 4 | 116 | 113 |
| 3 | 240 | 243 |
| 2 | 329 | 328 |
| 1 | 253 | 251 |
| 0 | 456 | 459 |
| -1 | 331 | 343 |
| -2 | 291 | 312 |
| -3 | 427 | 446 |
| -4 | 261 | 267 |
| -5 | 276 | 267 |
| -6 | 205 | 195 |
| H,6,2 | | |
| -6 | 211 | 195 |
| -5 | 286 | 294 |
| -4 | 313 | 317 |
| -3 | 446 | 450 |
| -2 | 341 | 346 |
| -1 | 455 | 456 |
| 0 | 436 | 433 |
| 1 | 210 | 210 |
| 2 | 319 | 311 |
| 3 | 158 | 156 |
| H,7,2 | | |
| 3 | 119 | 121 |
| 2 | 360 | 350 |
| 1 | 280 | 279 |
| 0 | 335 | 336 |
| -1 | 452 | 462 |
| -2 | 286 | 292 |
| -3 | 386 | 353 |
| -4 | 300 | 296 |
| -5 | 183 | 177 |
| H,8,2 | | |
| -5 | 162 | 153 |
| -4 | 271 | 266 |
| -3 | 288 | 292 |
| -2 | 321 | 326 |
| -1 | 466 | 476 |
| 0 | 209 | 214 |
| 1 | 315 | 322 |
| 2 | 247 | 242 |
| H,9,2 | | |
| 2 | 169 | 175 |
| 1 | 288 | 294 |
| 0 | 291 | 298 |
| -1 | 389 | 367 |
| -2 | 340 | 352 |
| -3 | 191 | 209 |
| -4 | 285 | 286 |
| -5 | 186 | 193 |
| H,10,2 | | |
| -4 | 253 | 245 |
| -3 | 231 | 235 |
| -2 | 240 | 245 |
| -1 | 198 | 210 |
| 0 | 184 | 194 |
| 1 | 245 | 247 |
| H,11,2 | | |
| 0 | 121 | 131 |
| -1 | 186 | 180 |
| -2 | 256 | 262 |
| -3 | 210 | 202 |
| H,-12,3 | | |
| 1 | 347 | 347 |
| 0 | 201 | 201 |
| H,-11,3 | | |
| -2 | 340 | 355 |
| -1 | 319 | 321 |
| 0 | 293 | 301 |
| 1 | 410 | 422 |
| 2 | 204 | 206 |
| H,-10,3 | | |
| 3 | 322 | 319 |
| 2 | 294 | 301 |
| 1 | 419 | 423 |
| 0 | 440 | 441 |
| -1 | 262 | 269 |
| -2 | 359 | 377 |
| H,-9,3 | | |
| -3 | 316 | 326 |
| -2 | 371 | 388 |
| -1 | 303 | 306 |
| 0 | 391 | 388 |
| 1 | 371 | 369 |
| 2 | 266 | 275 |
| 3 | 344 | 340 |
| H,-8,3 | | |
| 4 | 200 | 193 |
| 3 | 416 | 406 |
| 2 | 282 | 301 |
| 1 | 335 | 334 |
| 0 | 520 | 574 |
| -1 | 314 | 313 |
| -2 | 335 | 342 |
| -3 | 231 | 224 |
| -4 | 142 | 149 |
| H,-7,3 | | |
| -4 | 192 | 192 |
| -3 | 320 | 319 |
| -2 | 259 | 259 |
| -1 | 310 | 297 |
| 0 | 645 | 621 |
| 1 | 309 | 300 |
| 2 | 450 | 449 |
| 3 | 317 | 315 |
| 4 | 205 | 202 |
| H,-6,3 | | |
| 4 | 154 | 144 |
| 3 | 233 | 226 |
| 2 | 522 | 505 |
| 1 | 383 | 383 |
| 0 | 534 | 594 |
| -1 | 605 | 581 |
| -2 | 371 | 359 |
| -3 | 516 | 522 |
| -4 | 257 | 262 |
| -5 | 189 | 189 |
| H,-5,3 | | |
| -5 | 187 | 181 |
| -4 | 330 | 328 |
| -3 | 425 | 422 |
| -2 | 427 | 410 |
| -1 | 721 | 682 |
| 0 | 453 | 428 |
| 1 | 348 | 325 |
| 2 | 466 | 469 |
| 3 | 255 | 233 |
| 4 | 259 | 246 |
| H,-4,3 | | |
| 4 | 304 | 305 |
| 3 | 222 | 216 |
| 2 | 429 | 417 |
| 1 | 532 | 508 |
| 0 | 499 | 463 |
| -1 | 718 | 675 |
| -2 | 437 | 417 |
| -3 | 390 | 378 |
| -4 | 370 | 373 |
| -5 | 209 | 202 |
| H,-3,3 | | |
| -5 | 216 | 204 |
| -4 | 367 | 358 |
| -3 | 336 | 323 |
| -2 | 570 | 548 |
| -1 | 723 | 688 |
| 0 | 451 | 465 |
| 1 | 759 | 760 |
| 2 | 466 | 469 |
| 3 | 299 | 306 |
| 4 | 259 | 263 |
| H,-2,3 | | |
| 4 | 302 | 310 |
| 3 | 307 | 317 |
| 2 | 388 | 414 |
| 1 | 570 | 581 |
| 0 | 478 | 472 |
| -1 | 447 | 442 |
| -2 | 478 | 481 |
| -3 | 264 | 267 |
| -4 | 387 | 340 |
| -5 | 248 | 236 |
| -6 | 159 | 161 |
| H,-1,3 | | |
| -6 | 138 | 132 |
| -5 | 241 | 227 |
| -4 | 331 | 322 |
| -3 | 387 | 382 |
| -2 | 540 | 555 |
| -1 | 454 | 462 |
| 0 | 336 | 336 |
| 1 | 601 | 626 |
| 2 | 222 | 229 |
| 3 | 311 | 317 |
| 4 | 203 | 221 |
| H,0,3 | | |
| 3 | 385 | 389 |
| 2 | 267 | 225 |
| 1 | 802 | 817 |
| 0 | 614 | 639 |
| -1 | 451 | 470 |
| -2 | 727 | 774 |
| -3 | 364 | 370 |
| -4 | 310 | 304 |
| -5 | 286 | 264 |
| -6 | 192 | 174 |
| H,1,3 | | |
| -6 | 219 | 206 |
| -5 | 383 | 382 |
| -4 | 318 | 341 |
| -3 | 498 | 493 |
| -2 | 628 | 670 |
| -1 | 338 | 346 |
| 0 | 710 | 762 |
| 1 | 216 | 228 |
| 2 | 241 | 245 |
| 3 | 253 | 254 |
| 4 | 135 | 128 |
| H,2,3 | | |
| 4 | 112 | 113 |
| 3 | 247 | 240 |
| 2 | 371 | 370 |
| 1 | 374 | 377 |
| 0 | 632 | 649 |
| -1 | 452 | 473 |
| -2 | 331 | 342 |
| -3 | 634 | 682 |
| -4 | 272 | 305 |
| -5 | 265 | 276 |
| -6 | 176 | 176 |
| H,3,3 | | |
| -6 | 194 | 182 |
| -5 | 169 | 172 |
| -4 | 263 | 266 |
| -3 | 395 | 420 |
| -2 | 397 | 406 |
| -1 | 465 | 406 |
| 0 | 462 | 489 |
| 1 | 334 | 329 |
| 2 | 464 | 453 |
| 3 | 309 | 303 |
| 4 | 162 | 161 |
| H,4,3 | | |
| 3 | 167 | 167 |
| 2 | 338 | 333 |
| 1 | 270 | 269 |
| 0 | 474 | 476 |
| -1 | 672 | 645 |
| -2 | 376 | 377 |
| -3 | 387 | 460 |
| -4 | 294 | 295 |
| -5 | 211 | 212 |
| -6 | 178 | 174 |
| H,5,3 | | |
| -6 | 188 | 171 |
| -5 | 204 | 205 |
| -4 | 302 | 307 |
| -3 | 347 | 347 |
| -2 | 276 | 241 |
| -1 | 463 | 465 |
| 0 | 302 | 303 |
| 1 | 329 | 323 |
| 2 | 288 | 287 |
| 3 | 117 | 113 |
| H,6,3 | | |
| 3 | 104 | 106 |
| 2 | 228 | 226 |
| 1 | 267 | 261 |
| 0 | 136 | 136 |
| -1 | 357 | 364 |
| -2 | 310 | 317 |
| -3 | 282 | 286 |
| -4 | 331 | 326 |
| -5 | 225 | 216 |
| H,7,3 | | |
| -5 | 222 | 212 |
| -4 | 361 | 321 |
| -3 | 265 | 279 |
| -2 | 364 | 352 |
| -1 | 367 | 360 |
| 0 | 207 | 202 |
| 1 | 317 | 315 |
| 2 | 149 | 132 |
| H,8,3 | | |
| 2 | 131 | 135 |
| 1 | 287 | 272 |
| 0 | 247 | 237 |
| -1 | 240 | 237 |
| -2 | 376 | 364 |
| -3 | 224 | 221 |
| -4 | 231 | 233 |
| -5 | 202 | 179 |
| H,9,3 | | |
| -4 | 183 | 169 |
| -3 | 215 | 207 |
| -2 | 206 | 200 |
| -1 | 221 | 221 |
| 0 | 282 | 277 |
| 1 | 131 | 136 |
| H,10,3 | | |
| 0 | 248 | 245 |
| -1 | 227 | 213 |
| -2 | 214 | 216 |
| -3 | 244 | 236 |
| -4 | 136 | 136 |
| H,11,3 | | |
| -2 | 209 | 210 |
| H,-11,4 | | |
| 1 | 226 | 233 |
| 0 | 369 | 383 |
| -1 | 207 | 209 |
| H,-10,4 | | |
| -2 | 266 | 269 |
| -1 | 328 | 335 |
| 0 | 434 | 448 |
| 1 | 273 | 270 |
| 2 | 314 | 322 |
| H,-9,4 | | |
| 3 | 284 | 284 |
| 2 | 370 | 379 |
| 1 | 326 | 329 |
| 0 | 403 | 404 |
| -1 | 377 | 383 |
| -2 | 272 | 278 |
| -3 | 320 | 333 |
| H,-8,4 | | |
| -4 | 222 | 231 |
| -3 | 321 | 334 |
| -2 | 351 | 357 |
| -1 | 454 | 458 |
| 0 | 413 | 413 |
| 1 | 229 | 241 |
| 2 | 386 | 392 |
| 3 | 209 | 210 |
| H,-7,4 | | |
| 3 | 178 | 175 |
| 2 | 384 | 387 |
| 1 | 345 | 344 |
| 0 | 330 | 326 |
| -1 | 483 | 478 |
| -2 | 176 | 182 |
| -3 | 260 | 260 |
| -4 | 229 | 225 |
| H,-6,4 | | |
| -4 | 316 | 310 |
| -3 | 249 | 265 |
| -2 | 289 | 281 |
| -1 | 427 | 415 |
| 0 | 228 | 222 |
| 1 | 489 | 488 |
| 2 | 367 | 365 |
| 3 | 206 | 203 |
| 4 | 290 | 243 |
| H,-5,4 | | |
| 4 | 213 | 206 |
| 3 | 239 | 242 |
| 2 | 309 | 306 |
| 1 | 809 | 805 |
| 0 | 378 | 363 |
| -1 | 553 | 532 |
| -2 | 591 | 577 |
| -3 | 318 | 316 |
| -4 | 336 | 330 |
| -5 | 191 | 183 |
| H,-4,4 | | |
| -5 | 268 | 263 |
| -4 | 331 | 319 |
| -3 | 335 | 324 |
| -2 | 869 | 852 |
| -1 | 457 | 460 |
| 0 | 461 | 429 |
| 1 | 449 | 437 |
| 2 | 180 | 189 |
| 3 | 267 | 275 |
| 4 | 196 | 196 |
| H,-3,4 | | |
| 4 | 172 | 164 |
| 3 | 271 | 276 |
| 2 | 242 | 246 |
| 1 | 441 | 446 |
| 0 | 821 | 826 |
| -1 | 359 | 355 |
| -2 | 588 | 565 |
| -3 | 365 | 369 |
| -4 | 314 | 306 |
| -5 | 300 | 272 |
| H,-2,4 | | |
| -5 | 274 | 260 |
| -4 | 265 | 259 |
| -3 | 393 | 399 |
| -2 | 467 | 477 |
| -1 | 416 | 426 |
| 0 | 551 | 576 |
| 1 | 426 | 447 |
| 2 | 321 | 326 |
| 3 | 340 | 347 |
| 4 | 166 | 165 |
| H,-1,4 | | |
| 4 | 133 | 130 |
| 3 | 327 | 333 |
| 2 | 274 | 272 |
| 1 | 325 | 337 |
| 0 | 454 | 487 |
| -1 | 257 | 283 |
| -2 | 345 | 374 |
| -3 | 389 | 390 |
| -4 | 273 | 273 |
| -5 | 249 | 237 |
| -6 | 192 | 160 |
| H,0,4 | | |
| -6 | 144 | 165 |
| -5 | 210 | 206 |
| -4 | 209 | 220 |
| -3 | 392 | 425 |
| -2 | 386 | 414 |
| -1 | 331 | 353 |
| 0 | 511 | 533 |
| 1 | 186 | 177 |
| 2 | 364 | 364 |
| 3 | 206 | 207 |
| 4 | 109 | 108 |
| H,1,4 | | |
| 4 | 159 | 140 |
| 3 | 183 | 151 |
| 2 | 349 | 356 |
| 1 | 260 | 266 |
| 0 | 440 | 452 |
| -1 | 588 | 614 |
| -2 | 265 | 283 |
| -3 | 409 | 435 |
| -4 | 238 | 256 |
| -5 | 235 | 239 |
| -6 | 222 | 201 |
| H,2,4 | | |
| -6 | 213 | 204 |
| -5 | 235 | 253 |
| -4 | 413 | 442 |
| -3 | 403 | 436 |
| -2 | 332 | 364 |
| -1 | 499 | 523 |
| 0 | 294 | 308 |
| 1 | 322 | 326 |
| 2 | 262 | 248 |
| 3 | 102 | 101 |
| H,3,4 | | |
| 3 | 139 | 136 |
| 2 | 290 | 287 |
| 1 | 318 | 310 |
| 0 | 263 | 276 |
| -1 | 400 | 415 |
| -2 | 409 | 417 |
| -3 | 321 | 345 |
| -4 | 338 | 345 |
| -5 | 199 | 195 |
| -6 | 166 | 166 |
| H,4,4 | | |
| -6 | 159 | 153 |
| -5 | 202 | 195 |
| -4 | 246 | 240 |
| -3 | 242 | 248 |
| -2 | 339 | 337 |
| -1 | 405 | 408 |
| 0 | 295 | 235 |
| 1 | 337 | 323 |
| 2 | 226 | 221 |
| 3 | 166 | 174 |
| H,5,4 | | |
| 2 | 159 | 153 |
| 1 | 331 | 327 |
| 0 | 292 | 265 |
| -1 | 332 | 340 |
| -2 | 363 | 350 |
| -3 | 238 | 236 |
| -4 | 277 | 268 |
| -5 | 190 | 194 |
| H,6,4 | | |
| -5 | 215 | 197 |
| -4 | 237 | 234 |
| -3 | 235 | 235 |
| -2 | 327 | 327 |
| -1 | 229 | 226 |
| 0 | 286 | 284 |
| 1 | 272 | 265 |
| 2 | 129 | 129 |
| H,7,4 | | |
| 1 | 184 | 170 |
| 0 | 240 | 231 |
| -1 | 179 | 140 |
| -2 | 313 | 298 |
| -3 | 256 | 247 |
| -4 | 237 | 224 |
| H,8,4 | | |
| -4 | 211 | 190 |
| -3 | 284 | 273 |
| -2 | 278 | 263 |
| -1 | 187 | 181 |
| 0 | 275 | 263 |
| 1 | 136 | 123 |
| H,7,4 | | |
| -5 | 245 | 210 |
| H,-10,5 | | |
| -1 | 362 | 345 |
| -2 | 217 | 236 |
| H,-9,5 | | |
| -2 | 292 | 300 |
| H,-10,5 | | |
| 0 | 228 | 236 |
| H,9,4 | | |
| -1 | 222 | 211 |
| -2 | 184 | 178 |
| -3 | 241 | 224 |
| H,10,4 | | |
| -2 | 160 | 145 |
| H,9,4 | | |
| -4 | 170 | 146 |
| 0 | 200 | 188 |
| H,-9,5 | | |
| -1 | 370 | 378 |
| 0 | 300 | 299 |
| 1 | 338 | 347 |
| 2 | 298 | 304 |
| H,-8,5 | | |
| 2 | 304 | 307 |
| 1 | 361 | 375 |
| 0 | 263 | 271 |
| -1 | 393 | 409 |
| -2 | 345 | 351 |
| -3 | 251 | 256 |
| H,-7,5 | | |
| -4 | 254 | 260 |
| -3 | 249 | 247 |
| -2 | 389 | 406 |
| -1 | 437 | 445 |
| 0 | 304 | 310 |
| 1 | 417 | 426 |
| 2 | 170 | 177 |
| 3 | 204 | 212 |
| H,-6,5 | | |
| 3 | 241 | 244 |
| 2 | 169 | 180 |
| 1 | 376 | 387 |
| 0 | 321 | 339 |
| -1 | 184 | 191 |
| -2 | 342 | 353 |
| -3 | 200 | 209 |
| -4 | 270 | 265 |
| H,-5,5 | | |
| -5 | 231 | 258 |
| -4 | 211 | 206 |
| -3 | 307 | 304 |
| -2 | 381 | 385 |
| -1 | 193 | 196 |
| 0 | 320 | 337 |
| 1 | 282 | 243 |
| 2 | 216 | 217 |
| 3 | 266 | 270 |
| H,-4,5 | | |
| 3 | 259 | 265 |
| 2 | 248 | 244 |
| 1 | 276 | 279 |
| 0 | 512 | 521 |
| -1 | 396 | 395 |
| -2 | 426 | 431 |
| -3 | 374 | 363 |
| -4 | 213 | 209 |
| -5 | 245 | 216 |
| H,-3,5 | | |
| -5 | 254 | 243 |
| -4 | 277 | 274 |
| -3 | 414 | 411 |
| -2 | 361 | 362 |
| -1 | 398 | 397 |
| 0 | 482 | 493 |
| 1 | 248 | 255 |
| 2 | 279 | 264 |
| 3 | 165 | 160 |
| H,-2,5 | | |
| 3 | 200 | 182 |
| 2 | 249 | 256 |
| 1 | 264 | 266 |
| 0 | 370 | 390 |
| -1 | 429 | 451 |
| -2 | 330 | 336 |
| -3 | 400 | 408 |
| -4 | 294 | 292 |
| -5 | 233 | 214 |
| H,-1,5 | | |
| -5 | 200 | 185 |
| -4 | 288 | 281 |
| -3 | 325 | 347 |
| -2 | 293 | 319 |
| -1 | 397 | 417 |
| 0 | 386 | 397 |
| 1 | 266 | 269 |
| 2 | 356 | 348 |
| 3 | 169 | 173 |
| H,0,5 | | |
| 3 | 109 | 109 |
| 2 | 289 | 285 |
| 1 | 249 | 240 |
| 0 | 196 | 228 |
| -1 | 382 | 399 |
| -2 | 246 | 243 |
| -3 | 325 | 343 |
| -4 | 261 | 277 |
| -5 | 187 | 187 |
| H,1,5 | | |
| -5 | 164 | 161 |
| -4 | 253 | 241 |
| -3 | 209 | 213 |
| -2 | 306 | 314 |
| -1 | 423 | 429 |
| 0 | 177 | 178 |
| 1 | 336 | 325 |
| 2 | 174 | 174 |
| 3 | 133 | 130 |
| H,2,5 | | |
| 3 | 148 | 136 |
| 2 | 159 | 152 |
| 1 | 328 | 318 |
| 0 | 295 | 292 |
| -1 | 286 | 296 |
| -2 | 362 | 366 |
| -3 | 195 | 204 |
| -4 | 302 | 302 |
| -5 | 215 | 217 |
| H,3,5 | | |
| -5 | 243 | 238 |
| -4 | 244 | 301 |
| -3 | 342 | 352 |
| -2 | 390 | 396 |
| -1 | 270 | 275 |
| 0 | 268 | 262 |
| 1 | 270 | 264 |
| 2 | 134 | 133 |
| H,4,5 | | |
| 2 | 131 | 125 |
| 1 | 227 | 218 |
| 0 | 255 | 260 |
| -1 | 287 | 258 |
| -2 | 343 | 343 |
| -3 | 278 | 273 |
| -4 | 222 | 213 |
| -5 | 221 | 201 |
| H,5,5 | | |
| -5 | 198 | 187 |
| -4 | 190 | 183 |
| -3 | 208 | 206 |
| -2 | 247 | 250 |
| -1 | 187 | 192 |
| 0 | 288 | 267 |
| 1 | 175 | 170 |
| H,6,5 | | |
| 1 | 189 | 183 |
| 0 | 267 | 245 |
| -1 | 202 | 191 |
| -2 | 218 | 214 |
| -3 | 245 | 235 |
| -4 | 174 | 166 |
| -5 | 183 | 162 |
| H,7,5 | | |
| -4 | 166 | 160 |
| -3 | 234 | 217 |
| -2 | 179 | 176 |
| -1 | 191 | 180 |
| 0 | 203 | 195 |
| H,8,5 | | |
| -1 | 223 | 198 |
| -2 | 159 | 143 |
| -3 | 230 | 216 |
| -4 | 203 | 173 |
| H,-9,6 | | |
| 0 | 267 | 275 |
| -1 | 243 | 248 |
| H,-8,6 | | |
| -2 | 300 | 313 |
| -1 | 245 | 260 |
| 0 | 285 | 295 |
| 1 | 317 | 321 |
| H,-7,6 | | |
| 2 | 193 | 190 |
| 1 | 243 | 266 |
| 0 | 365 | 372 |
| -1 | 258 | 262 |
| -2 | 337 | 347 |
| -3 | 226 | 239 |
| H,-6,6 | | |
| -4 | 210 | 202 |
| -3 | 308 | 311 |
| -2 | 300 | 306 |
| -1 | 284 | 294 |
| 0 | 426 | 449 |
| 1 | 218 | 228 |
| 2 | 220 | 241 |
| H,-5,6 | | |
| 2 | 263 | 263 |
| 1 | 166 | 170 |
| 0 | 249 | 246 |
| -1 | 236 | 247 |
| -2 | 191 | 207 |
| -3 | 341 | 338 |
| -4 | 210 | 216 |
| H,-4,6 | | |
| -4 | 226 | 216 |
| -3 | 249 | 206 |
| -2 | 227 | 237 |
| -1 | 316 | 329 |
| 0 | 217 | 226 |
| 1 | 143 | 144 |
| 2 | 237 | 241 |
| H,-3,6 | | |
| 2 | 243 | 232 |
| 1 | 276 | 277 |
| 0 | 279 | 249 |
| -1 | 406 | 413 |
| -2 | 259 | 265 |
| -3 | 256 | 259 |
| -4 | 263 | 245 |
| -5 | 179 | 148 |
| H,-2,6 | | |
| -5 | 210 | 193 |
| -4 | 293 | 299 |
| -3 | 277 | 281 |
| -2 | 318 | 319 |
| -1 | 349 | 356 |
| 0 | 246 | 247 |
| 1 | 288 | 282 |
| 2 | 223 | 212 |
| H,-1,6 | | |
| 2 | 192 | 186 |
| 1 | 285 | 272 |
| 0 | 249 | 239 |
| -1 | 341 | 343 |
| -2 | 332 | 331 |
| -3 | 259 | 273 |
| -4 | 261 | 267 |
| -5 | 137 | 147 |
| H,0,6 | | |
| -5 | 179 | 172 |
| -4 | 230 | 238 |
| -3 | 232 | 231 |
| -2 | 312 | 310 |
| -1 | 280 | 235 |
| 0 | 209 | 202 |
| 1 | 319 | 306 |
| 2 | 129 | 131 |
| H,1,6 | | |
| 2 | 100 | 94 |
| 1 | 262 | 158 |
| 0 | 224 | 220 |
| -1 | 176 | 140 |
| -2 | 346 | 339 |
| -3 | 207 | 209 |
| -4 | 217 | 219 |
| -5 | 197 | 194 |
| H,2,6 | | |
| -5 | 222 | 202 |
| -4 | 177 | 164 |
| -3 | 218 | 206 |
| -2 | 243 | 241 |
| -1 | 179 | 174 |
| 0 | 286 | 272 |
| 1 | 153 | 150 |
| 2 | 140 | 114 |
| H,3,6 | | |
| 1 | 175 | 158 |
| 0 | 243 | 224 |
| -1 | 192 | 192 |
| -2 | 189 | 196 |
| -3 | 279 | 256 |
| -4 | 263 | 183 |
| -5 | 167 | 170 |
| H,4,6 | | |
| -5 | 161 | 147 |
| -4 | 211 | 201 |
| -3 | 284 | 275 |
| -2 | 266 | 260 |
| -1 | 244 | 223 |
| 0 | 221 | 213 |
| 1 | 125 | 119 |
| H,5,6 | | |
| 0 | 197 | 185 |
| -1 | 234 | 215 |
| -2 | 187 | 184 |
| -3 | 221 | 205 |
| -4 | 183 | 163 |
| H,6,6 | | |
| -4 | 187 | 162 |
| -3 | 182 | 171 |
| -2 | 142 | 129 |
| -1 | 182 | 172 |
| H,7,6 | | |
| -2 | 152 | 145 |
| -3 | 156 | 146 |
| H,-7,7 | | |
| -2 | 211 | 216 |
| -1 | 243 | 253 |
| 0 | 263 | 266 |
| H,-6,7 | | |
| 0 | 223 | 238 |
| -1 | 313 | 321 |
| -2 | 173 | 184 |
| -3 | 223 | 232 |
| H,-5,7 | | |
| -3 | 226 | 233 |
| -2 | 235 | 233 |
| -1 | 298 | 316 |
| 0 | 196 | 214 |
| 1 | 243 | 260 |
| H,-4,7 | | |
| 1 | 208 | 196 |
| 0 | 111 | 121 |
| -1 | 227 | 237 |
| -2 | 263 | 263 |
| -3 | 209 | 211 |
| -4 | 240 | 231 |
| H,-3,7 | | |
| -4 | 211 | 195 |
| -3 | 174 | 173 |
| -2 | 251 | 248 |
| -1 | 218 | 221 |
| 0 | 164 | 167 |
| 1 | 196 | 186 |
| H,-2,7 | | |
| 1 | 243 | 223 |
| 0 | 247 | 235 |
| -1 | 199 | 201 |
| -2 | 255 | 262 |
| -3 | 193 | 192 |
| -4 | 180 | 190 |
| H,-1,7 | | |
| -4 | 216 | 204 |
| -3 | 252 | 244 |
| -2 | 270 | 269 |
| -1 | 221 | 206 |
| 0 | 222 | 212 |
| 1 | 204 | 195 |
| H,0,7 | | |
| 1 | 171 | 160 |
| 0 | 263 | 245 |
| -1 | 194 | 187 |
| -2 | 267 | 260 |
| -3 | 226 | 221 |
| -4 | 146 | 179 |
| H,1,7 | | |
| -4 | 147 | 147 |
| -3 | 229 | 219 |
| -2 | 204 | 193 |
| -1 | 178 | 166 |
| 0 | 245 | 223 |
| H,2,7 | | |
| 0 | 164 | 153 |
| -1 | 232 | 203 |
| -2 | 156 | 149 |
| -3 | 225 | 212 |
| -4 | 164 | 156 |
| H,3,7 | | |
| -4 | 187 | 170 |
| -3 | 171 | 164 |
| -2 | 134 | 124 |
| -1 | 185 | 166 |
| 0 | 146 | 129 |
| H,4,7 | | |
| -1 | 173 | 145 |
| -2 | 167 | 152 |
| -3 | 183 | 161 |
| H,-3,8 | | |
| -2 | 212 | 207 |
| H,-2,8 | | |
| -2 | 155 | 154 |
| -1 | 166 | 151 |
| H,-1,8 | | |
| -1 | 171 | 147 |
| -2 | 161 | 149 |
| H,0,8 | | |
| -2 | 173 | 164 |

## VI.3 DESCRIPTION OF THE STRUCTURE AND DISCUSSION

Intramolecular bond lengths and angles appear in Tables VI.3.1 and VI.3.2 respectively. Relevant least-squares planes are listed in Table VI.3.3.

The molecule is in the *trans*-configuration (Fig. VI.3.1), the atom Pt being the centre of molecular symmetry. Superscripted atoms are centrosymmetrically related to the corresponding atoms without superscripts. The metal is bonded to two nitrogen atoms of the pyridine ligands and to the sulphur atoms of the two thiocyanate ions. The Pt-N(1) distance, 2.041(9) Å is somewhat shorter than Pt-N distances (2.15, 2.16, 2.11, 2.20, 2.33, 2.25 Å, all ± 0.03 Å) observed in cyclopropane complexes of platinum[120] containing also pyridine as a ligand, but it is similar to analogous bond lengths of 2.10(6) and 2.05(5) Å observed[121] in dichloro(pyridinium propylide)pyridine platinum(II). Recent studies of mixed thiocyanate complexes of platinum(II) containing acetylenic phosphines [122,123] have provided values of Pt-S distances for S-bonded thiocyanate ligands. Values of 2.327(5), 2.408(4) and 2.374(8) Å compare favourably with the Pt-S distance, 2.322(5) Å, observed in the present study. Deviation of the SCN group from strict linearity is evident from the angle S-C(6)-N(2), 177(1)°. Analogous angles of 171(2), 177(1), 179.3(16), and 178.6(13)° were reported for the

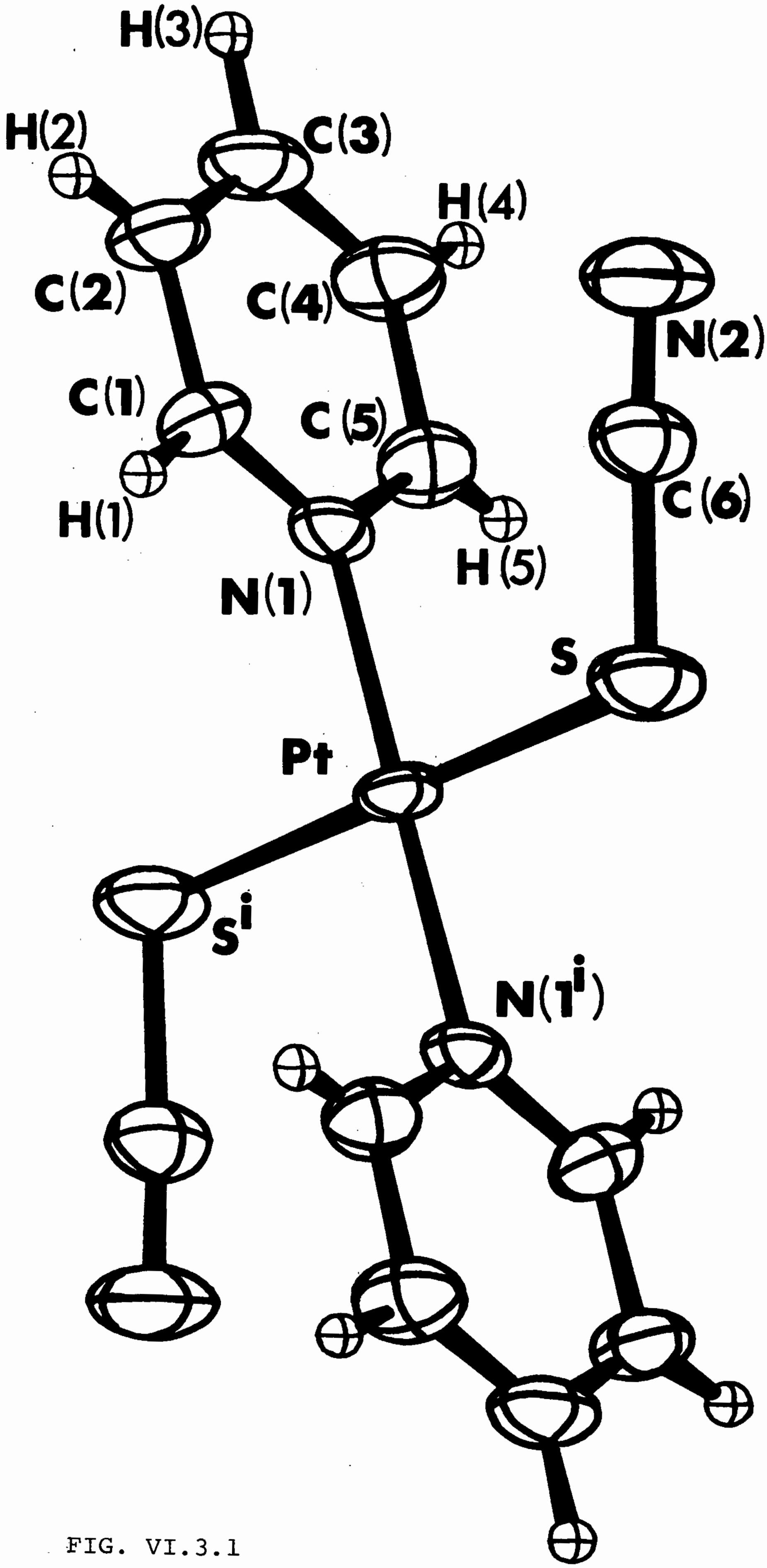


FIG. VI.3.1

## TABLE VI.3.1

## INTRAMOLECULAR BOND LENGTHS AND THEIR E.S.D.'s (Å)

| | | | |
|---|---|---|---|
| Pt-N(1) | 2.041(9) | S——C(6) | 1.69(1) |
| Pt-S | 2.322(5) | C(6)-N(2) | 1.14(2) |
| N(1)-C(1) | 1.34(2) | C(1)-H(1) | 1.0(1) |
| C(1)-C(2) | 1.39(2) | C(2)-H(2) | 0.9(1) |
| C(2)-C(3) | 1.37(2) | C(3)-H(3) | 1.0(1) |
| C(3)-C(4) | 1.36(2) | C(4)-H(4) | 1.0(1) |
| C(4)-C(5) | 1.39(2) | C(5)-H(5) | 0.8(1) |
| C(5)-N(1) | 1.32(2) | | |

## TABLE VI.3.2

## INTRAMOLECULAR BOND ANGLES AND THEIR E.S.D.'s (DEGREES)

| | | | |
|---|---|---|---|
| N(1)-Pt——$N(1^i)$ | 180.0 | Pt——N(1)-C(5) | 120.8(8) |
| S——Pt——$S^i$ | 180.0 | C(1)-N(1)-C(5) | 120(1) |
| S——Pt——N(1) | 95.3(2) | N(1)-C(1)-C(2) | 121(1) |
| $S^i$——Pt——N(1) | 84.7(2) | C(1)-C(2)-C(3) | 119(1) |
| Pt——S——C(6) | 105.4(4) | C(2)-C(3)-C(4) | 119(1) |
| S——C(6)-N(2) | 177(1) | C(3)-C(4)-C(5) | 120(1) |
| Pt——N(1)-C(1) | 118.8(9) | C(4)-C(5)-N(1) | 121(1) |

## TABLE VI.3.3

## LEAST-SQUARES PLANES

The equations of the planes are expressed in orthogonalized space as $PI+QJ+RK=S$.

Plane I: through atoms Pt,N(1),N($1^{i}$),S and $S^{i}$.

Equation: $-0.83668I+0.22172J+0.50081K=0.00000$

Plane II: through atoms N(1),C(2),C(3),C(4) and C(5) of the pyridine ring.

Equation: $0.55231I+0.49655J+0.66962K=0.11557$

| Atoms included in calculation | Dist. from plane, Å | Atoms not included in calculation | Dist. from plane, Å |
|---|---|---|---|
| N(1) | 0.005 | Pt | -0.116 |
| C(1) | -0.010 | H(1) | -0.080 |
| C(2) | 0.007 | H(2) | 0.013 |
| C(3) | 0.002 | H(3) | -0.022 |
| C(4) | -0.006 | H(4) | 0.027 |
| C(5) | 0.003 | H(5) | 0.002 |

Plane III: through atoms Pt, S and C(6).

Equation: $-0.82550I+0.14221J+0.54619K=0.00000$

Angles of intersection:
planes I and II : 89.0°
planes I and III: 5.3°
planes II and III : 88.8°

mixed thiocyanate complexes. The deviation in the angle S-Pt-N(1), 95.3°, from the ideal value of 90° can be explained by steric repulsion between the thiocyanate ligand and the pyridine ring. As a consequence of the inclinations of the various least-squares planes (Table VI.3.3), the thiocyanate ion is almost symmetrically located with respect to the plane of the pyridine ring.

## Thiocyanate coordination

In both organic and inorganic compounds, the thiocyanate ion is capable of forming bonds through either the nitrogen or the sulphur atom. Structural investigations have shown that in metal complexes containing the $SCN^-$ ion, the metal-ligand bond angle is around 180° for N-bonded SCN and around 100° for S-bonded SCN. In the present study, the Pt-S-C(6) bond angle is 105.4(4)°. From the angles involved, it is clear that the ambidentate nature of the thiocyanate ion permits N-bonding through $\sigma$-orbitals and S-bonding through $\pi$-orbitals. A molecular-orbital study of the ion[124] led to the following calculated charge distribution: $q_S = 0.48$, $q_C = 0.01$, $q_N = 0.51$. With the charge being almost equally distributed over the terminal atoms, the bidentate nature of the $SCN^-$ ion is clearly explained. In both isomers[125] of $Pt(NH_3)_2(SCN)_2$, the thiocyanate ion is S-bonded to platinum. However, the bidentate nature of the ion is well exemplified in certain dinuclear complexes of platinum(II)[122,123]. Here two platinum atoms in the same molecule are bridged by two

S-C≡N ions to form an eight-membered ring $\{Pt_2(SCN)_2\}$, in which both Pt-S and Pt-N bonds occur. Again the Pt-N-C angles are close to 180° while the Pt-S-C angles are close to 100°.

The question of S- or N-bonding by the $SCN^-$ ion for a given metal has been the subject of several recent papers[122,126,127]. The factors influencing the preferential bonding of N- or S- sites of the ion to a species $ML_2{}^{2+}$ are the nature of the metal ion and that of the species L, steric effects and the polarity of the solvents used in the synthesis of neutral complexes. $Pt^{2+}$ is an intrinsically "soft" ion and in the absence of other effects, it might be expected to favour Pt-SCN bonding. The nature of other ligands present can affect the mode of bonding. For example the ion is S-bonded in $Pt(NH_3)_2(SCN)_2$ but N-bonded in $Pt(P(C_2H_5)_3)_2(NCS)_2$. This has been explained in terms of the good π-bonding properties of the phosphine ligand which would favour M-NCS bonding. In this connection, it has been reported[127] that $Pd^{2+}$ (also a "soft" ion) forms the complexes $Pd(NH_3)_2(SCN)_2$ and $Pd(pyridine)_2(NCS)_2$, i.e. with S- and N- bonding respectively. The π-bonding properties of pyridine are intermediate between those of $P(C_2H_5)_3$, (strong π-bonding) and $NH_3$, (no π-bonding) and this intermediate character could account for the occurrence of N-bonding in $Pd(pyridine)_2(NCS)_2$ and S-bonding in $Pt(pyridine)_2(SCN)_2$ of the present study. Steric factors at Pd(II) in the complexes $Pd(pyridine)_2(NCS)_2$ and $Pd(\gamma\text{-picoline})_2(SCN)_2$ are identical yet N- and S-bonded thiocyanate occur respectively. Only small electronic effects appear to be required to alter the nature of $SCN^-$ bonding to these systems.

## Infrared Spectra

Two complexes with the formula $Pt(py)_2(SCN)_2$ were prepared and their infrared spectra were determined[119] as Nujol mulls between CsI plates using a Beckman I.R. 12 spectrophotometer. Assignment of the infrared frequencies is still in progress but preliminary results are presented here.

Square planar complexes of general formula $MX_2L_2$ can exist in either the *cis*- or *trans*- configuration. The *trans*-compounds (symmetry group $D_{2h}$) are expected to exhibit one infrared active frequency for each type of stretching mode $\nu(M-X)$ and $\nu(M-L)$, whereas for *cis*-compounds (symmetry group $C_{2v}$), the theory requires two bands each for $\nu(M-X)$ and $\nu(M-L)$ respectively[128]. The spectra of *cis*- and *trans*-$Pt(py)_2(SCN)_2$ (the latter isomer was investigated in the present X-ray analysis) show a distinctively different pattern, especially in the 500-200 $cm^{-1}$ region. A schematic representation of the regions studied thus far is given in Fig. VI.3.2.

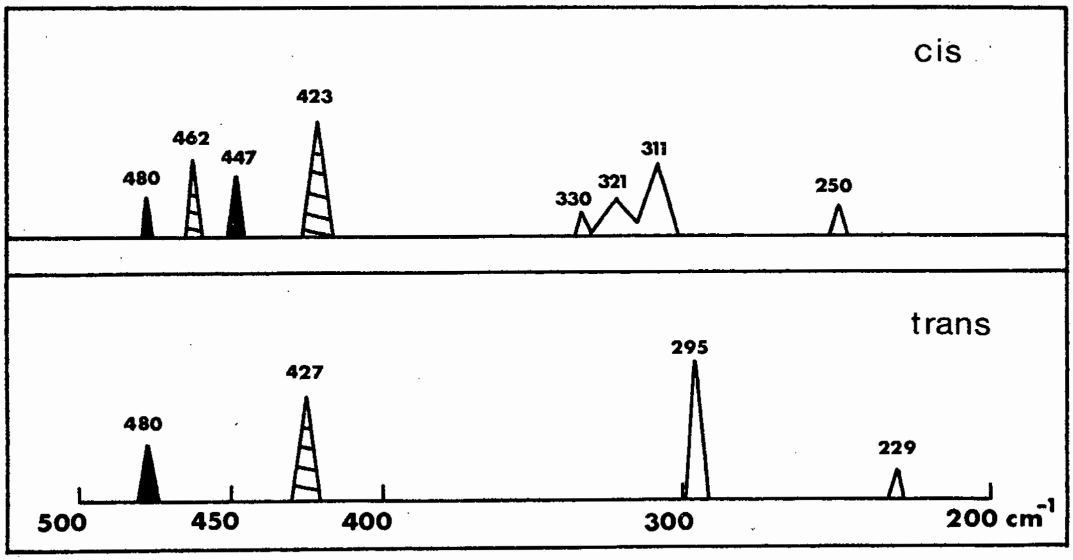


Fig. VI.3.2

The *cis*-compound shows four bands (423, 447, 462 and 480 $cm^{-1}$) of which two (447 and 480 $cm^{-1}$) have been tentatively assigned to a ν(Pt-N-py) vibration on the grounds of significant shifts on labelling the pyridine nitrogen with $N^{15}$. The other two bands (423 and 462 $cm^{-1}$) shift to lower wave numbers on labelling the thiocyanate group with $N^{15}$ and are normally assigned[129] to a bending frequency δ(N≡C-S).

The *trans*-compound shows only two bands in the region concerned (480 and 427 $cm^{-1}$). Only the higher one shifts on labelling the pyridine nitrogen, whereas the band at 427 $cm^{-1}$ shifts as expected on labelling the nitrogen of the thiocyanate group.

Both isomers exhibit a large band above 2000 $cm^{-1}$ which has previously been assigned to a C≡N stretch of the SCN group[130,131]. The bands appear at 2124 and 2119 $cm^{-1}$ for the *cis*- and *trans*- isomers respectively, and shift considerably to lower wavenumbers (both by 28 $cm^{-1}$) on labelling the thiocyanate group with $N^{15}$.

A *cis*- conformation was tentatively assumed from the presence of extra peaks in the spectrum of the *cis*-compound; the unambiguous results of this study confirm this, since the *trans*- complex does yield a less complex spectrum. The region below 200 $cm^{-1}$ has yet to be studied.

## General conclusions

With regard to the anticancer properties of compounds of the type $PtA_2X_2$, it is clear from the foregoing discussion that a *cis*-configuration is required for the complex to display such activity. The complex studied here is in the *trans*- configuration and it is unlikely to have any therapeutic value. The procedure adopted for the synthesis of the complex (section VI.2) was that for obtaining the *cis*-isomer but it seems probable that isomerisation to the *trans*-isomer occurred during subsequent redissolving and recrystallisation from an acetone-pyridine mixture. Together with the infrared data, the results of this X-ray study are anticipated to be of value in the interpretation of spectra of similar potential anticancer drugs which are currently being synthesised[119]. The *cis*-isomer of $Pt(py)_2(SCN)_2$ is undergoing screening tests for possible anticancer activity.

# CHAPTER VII

## CRYSTALLOGRAPHIC STUDIES OF COPPER-MERCAPTOPURINE COMPLEXES : THE X-RAY CRYSTAL STRUCTURE OF THE DIMERIC 6-MERCAPTOPURINE COPPER(I)CHLORIDE COMPLEX AND THAT OF THE POLYMERIC 8-MERCAPTOPURINE COPPER(I) CHLORIDE COMPLEX

## VII.1 INTRODUCTION

### Nucleic acid - Metal ion interaction

Metal complexation is a significant phenomenon in the biochemistry of nucleic acids[132], because it is known that the processes of DNA replication, transcription and translation are mediated by metal ions.

In addition to the DNA template and deoxynucleotide triphosphates, the DNA polymerase reaction (synthesis of new DNA molecules with the nucleotide sequence of the existing DNA) requires the presence of divalent metal ions, usually Mg(II). The latter are involved in the cleavage and formation of phosphate bonds. The reaction proceeds when Mg(II) is replaced by Mn(II) ions, but, whereas the former can differentiate between certain nucleotides, the latter cannot. Studies of metal binding to nucleotides are required in order to clarify this selective mechanism which is not at present understood.

The copying ('transcription') of the DNA code in polyribonucleotide form, as mRNA, is effected by the RNA polymerase enzymes. As well as DNA template and ribonucleoside triphosphates, metal ions participate in this process. The ions Mg(II), Mn(II) and Co(II) show such activity.

In the translation process, a given amino acid is incorporated into protein by a specific codon. The selection of an acid from several amino acids can be determined by the concentration of divalent metal ions present.

The effect of metal ions on native double-stranded DNA has been studied[133].In distilled water, the DNA strands unwind; this unwinding is prevented by electrolyte in low (~ $2 \times 10^{-3}M$) concentration. By neutralizing the negative charges of the phosphate groups of the double-helix, metal ions (e.g. $Na^+$, $Mn^{2+}$, $Mg^{2+}$, $Co^{2+}$) reduce electrostatic repulsion between phosphate oxygen atoms and stabilize the double-helical conformation. This stabilization is reflected in an increase in the DNA 'melting temperature', $T_m$ (the mean temperature at which thermal denaturation occurs). While ions such as magnesium(II) increase $T_m$, copper(II) ions, for example, decrease $T_m$, that is, destabilize the DNA. The difference in behaviour can be attributed to the different binding tendencies of these metal ions. Whereas Mg(II) ions bind to the sugar-phosphate backbone (thus stabilizing the ordered structure by the counter ion effect), Cu(II) ions bind to both the phosphate groups and to the heterocyclic bases. Copper-binding to the pyrimidine and purine derivatives in the nucleic acids disrupts hydrogen bonding between the bases and results in a destabilization of the double-helix.

If a solution of DNA is heated in the absence of metal ions, the single strands dissociate and the complementary bases are unable to pair up to regenerate the double-helix. Reversible unwinding and rewinding of

DNA has been achieved in the following manner: a Cu(II) DNA solution is heated until unwinding occurs; the solution is cooled and solid electrolyte (e.g. $Na^+$) is added to regenerate the double-helix. The finding that the double-helix is actually reconstituted implies that the copper ions in the denatured state form cross-links between adjacent bases of the DNA strands. Addition of a metal complexing agent (e.g. EDTA) also causes DNA rewinding by removal of Cu(II) ions.

As an aid to the interpretation of these phenomena, it is important to establish which sites on the heterocyclic bases are capable of metal-binding. The purines and their derivatives possess a variety of potential donor atoms and metal-coordination in these systems has been given much attention recently. X-ray crystallographic studies of both purines and their metal complexes have been reported[14,134]. Although these complexes display a wide variety of structural features, the copper-coordination to purines is dominated by the tendency to form dinuclear metal complexes in which two nitrogen atoms (one from each of the heterocyclic rings) are utilised.

## The relevance of thiolated purines

Until fairly recently, relatively little attention has been devoted to metal complexes of the less common thiolated purines. There are several reasons for the current interest in this group of compounds. Thionucleosides have been found as minor constituents in transfer ribonucleic acids (tRNA)[135] ; they may therefore participate in metal ion - nucleic acid interaction. Transfer ribonucleic acids act as adaptor molecules in protein biosynthesis and contain about ten percent of "rare" nucleosides such as 4-thiouridine and dihydrouridine.

Some mercaptopurines are known to have anti-tumour and other inhibitory properties and recently, certain metal complexes containing 6-mercaptopurine, thioguanine and butylthiopurine as ligands have themselves proved successful as anticancer agents.

## The antineoplastic drug, 6-mercaptopurine

The structural formula and ring-numbering system in 6-mercaptopurine ('6-purinethiol'), $C_5H_4N_4S$, is shown in Fig. VII.1.1.

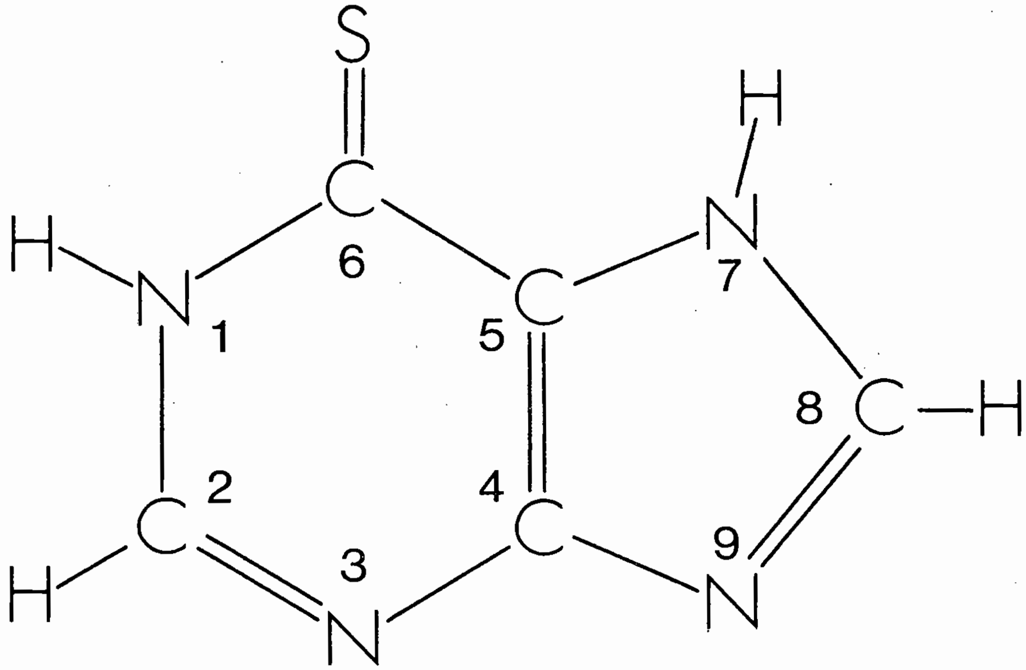


Fig. VII.1.1

The thione tautomeric form (drawn in the figure) is that which exists in the solid state of the substance[136,137]. This drug has probably been studied at the molecular level more than any other[138]. It is of great interest as an antimetabolite and particularly, as an anti-tumour agent, being active against childhood leukaemia (but less so against acute adult leukaemia). The drug is thought to enter the synthesis of nucleic acids at an early stage, probably as a competitor to hypoxanthine in the conversion of inosinic acid to nucleic acid. The parent compound and its anabolites are known to interact with over twenty enzymes. The selective cytotoxicity of 6-mercaptopurine is not firmly established, but it may depend on several mechanisms (e.g. incorporation into DNA, or interference with the synthesis or functioning of coenzyme A). Current hypotheses for the mechanism of action of drugs such as 6-mercaptopurine centre around either sequestering polluting metal ions or deactivating the metalloenzymes which are necessary for the rapid growth of malignant cells[31].

Certain types of cancer are caused by viruses. These viruses contain proteins and nucleic acid units, some atoms of which are excellent coordinating agents for metal ions. The possibility of altering the virus *via* metal-chelation so as to diminish or eliminate its viral activity has been investigated[26,28]. The introduction of simple hydrated metals into living organisms is not effective in this regard because of the many binding-sites available in proteins, amino acids and other species present in the animal system. However, introduction of metal ion in the form of a moderately stable coordination complex may lead to displacement of the ligands by the virus and consequent metal-virus complexation. Release of the biologically active ligand might further inhibit cell growth. The following complexes have been shown to possess anticancer activity[28]: $Na_2[Pt(mp)_2Cl_4].2H_2O$, $Na_2[Pd(mp)_2Cl_2].H_2O$ and $Na_2[Bi(O)(mp)_3].3H_2O$, (mp = 6-mercaptopurine). The platinum and palladium complexes are extremely active against Adenocarcinoma 755 and Sarcoma 180. A comparison of the activities of the ligands compared with the metal complexes containing these ligands indicated that the complexes might exhibit a somewhat greater anticancer activity than do the parent compounds.

## Motivation for Structural Analyses

In section VII.2, the crystal structure of a copper complex containing the ligand 6-mercaptopurine is presented. The isomeric complex with 8-mercaptopurine as a ligand has also been studied and its structure is presented in section VII.4. Both complexes are of interest in connection with metal ion - thionucleoside interaction and it was considered of interest to establish the binding-sites in the ligands. In addition, 6-mercaptopurine and certain of its metal complexes are potent anticancer drugs. Many copper chelates are known to have cytostatic properties[26]. The successful use of the copper complex of kethoxal bis-thiosemicarbazone (KTS) as an anti-tumour agent indicates the potential of copper complexes containing S- and N- donor ligands in cancer chemotherapy [27].

X-ray structural data for mercaptopurines and their metal complexes is very limited. A structural analysis of bis(6-mercapto-9-benzylpurine)-palladium(II)-dimethylacetamide has shown[139] that the 6-mercaptopurine ligand can behave as a bidentate complexing agent with Pd(II) ions, binding to the metal through atoms N(7) and S.

As the copper complexes were prepared under similar experimental conditions (acid solution, 1 : 1 metal : ligand), it was also thought to be of interest to make a direct comparison of the modes of copper-mercaptopurine binding for the two isomers.

## VII.2 THE CRYSTAL STRUCTURE OF THE DIMERIC 6-MERCAPTOPURINE COPPER(I)CHLORIDE COMPLEX;

## $[Cu(C_5H_5N_4S)Cl_2.H_2O]_2$

### Crystal preparation and chemical analysis

Suitable single crystals of the complex were isolated from a slowly-evaporating mixture of solutions of 6-mercaptopurine and copper(II) chloride dihydrate in 20% aqueous HCl in a 1:1 ligand-metal ratio. Deep-red needles formed after several weeks. The crystal faces were badly developed and grew dull on exposure to air for prolonged periods. Microanalytical data (Table VII.2.1) suggested the stoichiometric composition Cu(6-mercaptopurine)$Cl_2.H_2O$.

Measurement of the magnetic moment of the complex yielded a value of $\mu$=0.21 B.M. indicating that reduction of the metal to Cu(I) had occurred. The correct formulation for the complex is therefore: (protonated 6-mercaptopurine)Cu(I)$Cl_2.H_2O$.

TABLE VII.2.1

| | %C | %H | %N |
|---|---|---|---|
| Calculated: | 19.64 | 2.29 | 18.33 |
| Found : | 19.9 | 2.4 | 18.2 |

### Density determination

The crystal density was measured by flotation in a mixture of chlorobenzene and methylene iodide. A value of 2.03 g $cm^{-3}$ was recorded and was consistent with the presence of two formula units in the crystal unit cell.

## Space group assignment

Preliminary X-ray photographs showed that the crystals belonged to the triclinic system, space group P1 or P$\bar{1}$[95].

## Diffractometer data

A single crystal cut to a block of dimensions 0.3 x 0.3 x 0.2 mm was used for intensity measurements. Relevant crystal data are listed in Table VII.2.2.

TABLE VII.2.2 CRYSTAL DATA

| | |
|---|---|
| Molecular formula | $[Cu(C_5H_5N_4S)Cl_2.H_2O]_2$ |
| Molecular weight | 611.0 g mole$^{-1}$ |
| Space group | P1 (Triclinic) |
| a = 10.067(5) Å | |
| b = 7.697(5) Å | |
| c = 6.771(5) Å | |
| $\alpha$ = 89.7(2)° | $D_m$ = 2.03 g cm$^{-3}$ |
| $\beta$ = 105.6(2)° | $D_c$ = 2.04 g cm$^{-3}$ for Z = 1 |
| $\gamma$ = 100.4(2)° | $\mu$(MoK$\alpha$) = 28.2 cm$^{-1}$ |
| V = 496.45 Å$^3$ | F(000) = 304 |

The $\omega$-2$\theta$ scan technique was employed (scan speed 0.06°$\theta$sec$^{-1}$, scan width 1.8°$\theta$) to measure 1740 reflections in the 2$\theta$ range from 6° to 50°. Three reference reflections were monitored every hour. Two of these were constant to within 4% of their respective mean values but the third showed a maximum deviation of 9% from the mean value indicating crystal decomposition. As the variation was not systematic, corrections for this factor were not possible. Of the reflections recorded, 156 had $I_{rel} < 1.65\sigma(I_{rel})$ but most of these were allowed to contribute in the structural refinement. For the crystal selected, the maximum $\mu R$ was 0.6 and A*, the absorption correction factor, varied[78] from 2.69 to 2.63 in the $\Theta$-range scanned. The minimum $\mu R$ was 0.4 with a corresponding A* variation between 1.95 and 1.93. However, no absorption corrections were applied to the data.

Solution of the structure and refinement

From intensity statistics, (subroutine NORMSF of the X-RAY 72 program system), a centric space group was indicated. At this stage of the analysis, the number of formula units (and hence the number of copper atoms) in the cell was calculated as two. This information strongly suggested that the crystal space group was $P\bar{1}$; however, several attempts to solve the structure failed. It was subsequently realized that in a structure containing heavy atoms, results from intensity statistics are not strictly valid, a centre being effectively chosen between the heavy atoms in the unit cell. The acentric space group P1 was chosen, this choice being vindicated by the successful structural solution.

The six largest vector peaks in a three-dimensional Patterson map (X-RAY 72 program system)[46] had heights corresponding to doubly-weighted copper-sulphur and copper-chlorine interactions. This suggested that the heavy atom positions were possibly related by a centre (or pseudocentre) of symmetry. On the assumption that the structure was acentric, one copper atom was fixed at the origin and the second was assigned a position from the Patterson analysis. An electron-density map phased on the two copper atoms revealed the chlorine and sulphur atoms in tetrahedral coordination to the metal atoms. Structure factors based on the positions of the eight Cu, S and Cl atoms yielded a conventional R factor of 0.33 and all the atoms of the independent mercaptopurine ligands were revealed in a subsequent electron-density map. Five cycles of full-matrix least-squares refinement of all the atoms (including hydrate oxygens) with isotropic temperature factors reduced R to 0.141. Failure of the light atoms to refine anisotropically was attributed to the inferior quality of the reflection data. After several cycles of refinement with anisotropic temperature factors assigned to the heavy atoms only, R was 0.055. The ten hydrogen atoms of the ligands were clearly revealed in a difference electron-density map. Theoretical positions (at 1.08 Å from their parent atoms) were calculated for the hydrogens. The final cycles of refinement were carried out with constraints on the H atom positions as previously calculated and assigning them the isotropic temperature factors of their bonded atoms. In the last cycle of refinement the $\Delta/\sigma$ ratio was 0.3 and a final difference map showed evidence of anisotropic motion of the light atoms but no prominent peaks. With the option that reflections would be included if they calculated greater than the observed value, 1704 reflections contributed in the final cycle and the terminal R value was 0.051 with unit weights applied throughout. The function minimised was $\Sigma(|F_o|-|F_c|)^2$. The hydrogens of the water molecules could not be located and determination of the absolute configuration of the structure was not attempted.

Scattering factors for the heavy atoms were those of Cromer and Mann;[79] for hydrogen, those of Stewart et al.[80]

Anomalous dispersion corrections[63] were applied to the Cu,Cl and S scattering curves. Positional and anisotropic thermal parameters for the heavy atoms appear in Table VII.2.3. The positions and isotropic temperature factors of the C, N and O atoms are listed in Table VII.2.4. Theoretical hydrogen atom positions are given in Table VII.2.5.

In Table VII.2.6, observed and calculated structure factors, the columns list (from left to right) the running index h, 10 $F_o$, 10 $F_c$ and the phase angle, $\alpha$, expressed in millicycles.

# TABLE VII.2.3

## HEAVY ATOMS

## FRACTIONAL ATOMIC COORDINATES (x10$^4$) AND THEIR E.S.D.'s AND ANISOTROPIC TEMPERATURE FACTORS

Temperature factors are of the form

$$T = \exp[-2\pi^2(U_{11}h^2a^{*2} + U_{22}k^2b^{*2} + U_{33}l^2c^{*2} + 2U_{12}hka^*b^* + 2U_{13}hla^*c^* + 2U_{23}klb^*c^*)\text{x}10^3]$$

| | $x$ | $y$ | $z$ | $U_{11}$ | $U_{22}$ | $U_{33}$ | $U_{12}$ | $U_{13}$ | $U_{23}$ |
|---|---|---|---|---|---|---|---|---|---|
| CuA | 10000 | 0 | 0 | 23(2) | 50(2) | 25(2) | 17(1) | -7(1) | -17(1) |
| Cl(1)A | 10222(6) | 1495(9) | 3173(9) | 25(3) | 37(3) | 22(3) | 16(2) | -4(2) | -21(2) |
| Cl(2)A | 12179(5) | -255(8) | -17(9) | 16(2) | 28(3) | 19(3) | 5(2) | 5(2) | -6(2) |
| SA | 8130(5) | 243(7) | -2612(9) | 12(2) | 23(3) | 19(3) | 9(2) | 2(2) | -9(2) |
| CuB | 6940(2) | -3067(3) | -1818(3) | 21(2) | 45(2) | 32(2) | 15(1) | -6(1) | -18(1) |
| Cl(1)B | 6719(6) | -4562(9) | -4939(10) | 25(3) | 37(3) | 17(3) | 16(2) | -16(2) | -15(2) |
| Cl(2)B | 4754(6) | -2852(9) | -1775(9) | 20(2) | 35(3) | 20(3) | 5(2) | -2(2) | -3(2) |
| SB | 8808(6) | -3310(8) | 842(9) | 18(3) | 28(3) | 16(3) | 6(2) | -5(2) | -9(2) |

## TABLE VII.2.5

## HYDROGEN ATOMS : THEORETICAL ATOMIC COORDINATES $(x10^3)$

| | $x$ | $y$ | $z$ |
|---|---|---|---|
| H(1)A | 832 | 163 | 140 |
| H(2)A | 694 | 315 | 277 |
| H(7)A | 522 | 34 | -600 |
| H(8)A | 277 | 100 | -632 |
| H(9)A | 282 | 294 | -306 |
| H(1)B | 851 | -503 | -297 |
| H(2)B | 1001 | -632 | -433 |
| H(7)B | 1182 | -312 | 402 |
| H(8)B | 1411 | -443 | 468 |
| H(9)B | 1427 | -564 | 131 |

# TABLE VII.2.6

H,0,0

| | | | |
|---|---|---|---|
| 2 | 327 | 297 | 209 |
| 3 | 326 | 334 | 49 |
| 4 | 508 | 515 | 482 |
| 5 | 129 | 149 | 271 |
| 6 | 669 | 460 | 87 |
| 7 | 119 | 136 | 939 |
| 8 | 131 | 137 | 763 |
| 9 | 353 | 359 | 199 |
| 10 | 222 | 218 | 979 |
| 11 | 46 | 53 | 454 |

H,1,0

| | | | |
|---|---|---|---|
| 11 | 170 | 170 | 178 |
| 10 | 37 | 39 | 222 |
| 9 | 82 | 69 | 23 |
| 8 | 30 | 31 | 216 |
| 7 | 116 | 120 | 829 |
| 6 | 34 | 42 | 967 |
| 5 | 659 | 653 | 89 |
| 4 | 428 | 419 | 246 |
| 3 | 183 | 157 | 699 |
| 2 | 416 | 399 | 71 |
| 1 | 19 | 21 | 129 |
| -1 | 328 | 369 | 12 |
| -2 | 320 | 357 | 166 |
| -3 | 110 | 112 | 762 |
| -4 | 768 | 816 | 967 |
| -5 | 939 | 942 | 104 |
| -6 | 13* | 23 | 91 |
| -7 | 179 | 186 | 919 |
| -8 | 321 | 329 | 76 |
| -9 | 189 | 197 | 273 |
| -10 | 376 | 381 | 488 |
| -11 | 243 | 243 | 98 |

H,2,0

| | | | |
|---|---|---|---|
| -11 | 82 | 88 | 925 |
| -10 | 19* | 29 | 208 |
| -9 | 389 | 397 | 85 |
| -8 | 57 | 61 | 453 |
| -7 | 200 | 219 | 807 |
| -6 | 443 | 472 | 123 |
| -5 | 719 | 777 | 961 |
| -4 | 28 | 39 | 795 |
| -3 | 551 | 602 | 159 |
| -2 | 132 | 121 | 949 |
| -1 | 375 | 353 | 837 |
| 0 | 752 | 719 | 191 |
| 1 | 934 | 886 | 40 |
| 2 | 119 | 117 | 941 |
| 3 | 12* | 9 | 190 |
| 4 | 360 | 367 | 107 |
| 5 | 405 | 397 | 926 |
| 6 | 75 | 69 | 843 |
| 7 | 26 | 39 | 163 |
| 8 | 19* | 20 | 231 |
| 9 | 8* | 22 | 948 |
| 10 | 291 | 290 | 171 |

H,3,0

| | | | |
|---|---|---|---|
| 9 | 40 | 40 | 166 |
| 8 | 119 | 119 | 781 |
| 7 | 10* | 27 | 896 |
| 6 | 182 | 196 | 159 |
| 5 | 119 | 111 | 761 |
| 4 | 196 | 206 | 967 |
| 3 | 358 | 398 | 89 |
| 2 | 4* | 12 | 78 |
| 1 | 273 | 251 | 897 |
| 0 | 280 | 278 | 58 |
| -1 | 322 | 289 | 201 |
| -2 | 202 | 183 | 898 |
| -3 | 69 | 69 | 29 |
| -4 | 313 | 358 | 151 |
| -5 | 315 | 393 | 805 |
| -6 | 190 | 157 | 994 |
| -7 | 256 | 256 | 129 |
| -8 | 28 | 31 | 175 |
| -9 | 323 | 326 | 929 |
| -10 | 271 | 257 | 61 |
| -11 | 169 | 166 | 239 |

H,4,0

| | | | |
|---|---|---|---|
| -11 | 80 | 94 | 118 |
| -10 | 189 | 191 | 917 |
| -9 | 16* | 19 | 851 |
| -8 | 189 | 189 | 123 |
| -7 | 298 | 271 | 946 |
| -6 | 193 | 201 | 805 |
| -5 | 43 | 56 | 217 |
| -4 | 313 | 362 | 3 |
| -3 | 121 | 126 | 889 |
| -2 | 131 | 119 | 243 |
| -1 | 118 | 116 | 42 |
| 0 | 425 | 409 | 885 |
| 1 | 19* | 26 | 883 |
| 2 | 31 | 33 | 201 |
| 3 | 76 | 76 | 945 |
| 4 | 156 | 182 | 762 |
| 5 | 185 | 179 | 111 |
| 6 | 371 | 374 | 981 |
| 7 | 159 | 153 | 819 |
| 8 | 122 | 125 | 139 |
| 9 | 122 | 118 | 19 |

H,5,0

| | | | |
|---|---|---|---|
| 8 | 31* | 92 | 117 |
| 7 | 29* | 25 | 120 |
| 6 | 50 | 53 | 671 |
| 5 | 309 | 301 | 982 |
| 4 | 39 | 29 | 25 |
| 3 | 125 | 120 | 235 |
| 2 | 178 | 163 | 962 |
| 1 | 403 | 440 | 72 |
| 0 | 81 | 86 | 188 |
| -1 | 378 | 353 | 907 |
| -2 | 152 | 138 | 43 |
| -3 | 206 | 195 | 180 |
| -4 | 320 | 339 | 653 |
| -5 | 378 | 426 | 6 |
| -6 | 61 | 65 | 210 |
| -7 | 63 | 58 | 815 |
| -8 | 156 | 159 | 951 |
| -9 | 19* | 9 | 166 |
| -10 | 108 | 123 | 769 |

H,6,0

| | | | |
|---|---|---|---|
| -9 | 285 | 294 | 961 |
| -8 | 90 | 102 | 816 |
| -7 | 92 | 99 | 179 |
| -6 | 21* | 27 | 790 |
| -5 | 252 | 265 | 849 |
| -4 | 28 | 36 | 817 |
| -3 | 298 | 288 | 45 |
| -2 | 25 | 24 | 790 |
| -1 | 19* | 12 | 880 |
| 0 | 269 | 261 | 77 |
| 1 | 467 | 453 | 437 |
| 2 | 88 | 89 | 773 |
| 3 | 50 | 56 | 478 |
| 4 | 42 | 46 | 451 |

H,6,0

| | | | |
|---|---|---|---|
| 5 | 91 | 99 | 763 |
| 6 | 207 | 207 | 193 |
| 7 | 65 | 69 | 39 |

H,7,0

| | | | |
|---|---|---|---|
| 5 | 192 | 192 | 189 |
| 4 | 50 | 55 | 797 |
| 3 | 68 | 70 | 18 |
| 2 | 181 | 160 | 136 |
| 1 | 21* | 31 | 939 |
| 0 | 309 | 293 | 924 |
| -1 | 102 | 95 | 128 |
| -2 | 49 | 38 | 162 |
| -3 | 222 | 205 | 869 |
| -4 | 408 | 400 | 52 |
| -5 | 100 | 103 | 206 |
| -6 | 137 | 150 | 831 |
| -7 | 139 | 191 | 26 |
| -8 | 50 | 51 | 127 |

H,8,0

| | | | |
|---|---|---|---|
| -7 | 88 | 137 | 824 |
| -6 | 79 | 77 | 212 |
| -5 | 227 | 225 | 52 |
| -4 | 293 | 279 | 892 |
| -3 | 92 | 98 | 182 |
| -2 | 113 | 111 | 125 |
| -1 | 81 | 67 | 992 |
| 0 | 43 | 43 | 773 |
| 1 | 215 | 219 | 120 |
| 2 | 43 | 41 | 930 |
| 3 | 25* | 19 | 990 |

H,9,0

| | | | |
|---|---|---|---|
| -1 | 49 | 59 | 875 |
| -2 | 38 | 47 | 906 |
| -3 | 109 | 106 | 93 |
| -4 | 26* | 26 | 195 |

H,-9,1

| | | | |
|---|---|---|---|
| 1 | 125 | 131 | 160 |
| 2 | 113 | 110 | 43 |
| 3 | 169 | 152 | 621 |

H,-8,1

| | | | |
|---|---|---|---|
| 6 | 42 | 52 | 779 |
| 5 | 191 | 136 | 497 |
| 4 | 185 | 166 | 42 |
| 3 | 131 | 120 | 153 |
| 2 | 33 | 25 | 842 |
| 1 | 65 | 59 | 4 |
| 0 | 89 | 78 | 166 |
| -1 | 60 | 52 | 863 |
| -2 | 187 | 188 | 990 |
| -3 | 103 | 105 | 111 |

H,-7,1

| | | | |
|---|---|---|---|
| -5 | 63 | 68 | 206 |
| -4 | 132 | 130 | 136 |
| -3 | 0* | 3 | 83 |
| -2 | 125 | 129 | 771 |
| -1 | 99 | 90 | 189 |
| 0 | 161 | 143 | 959 |
| 1 | 224 | 213 | 828 |
| 2 | 227 | 213 | 190 |
| 3 | 203 | 187 | 33 |
| 4 | 232 | 272 | 885 |
| 5 | 25 | 40 | 772 |
| 6 | 50 | 51 | 88 |
| 7 | 62 | 63 | 977 |
| 8 | 38 | 37 | 228 |

H,-6,1

| | | | |
|---|---|---|---|
| 9 | 223 | 220 | 976 |
| 8 | 58 | 56 | 118 |
| 7 | 63 | 58 | 750 |
| 6 | 223 | 249 | 918 |
| 5 | 56 | 60 | 39 |
| 4 | 32 | 24 | 217 |
| 3 | 196 | 179 | 895 |
| 2 | 60 | 63 | 963 |
| 1 | 38 | 51 | 400 |
| 0 | 19* | 10 | 821 |
| -1 | 208 | 202 | 13 |
| -2 | 29 | 20 | 165 |
| -3 | 139 | 139 | 761 |
| -4 | 35 | 11 | 889 |
| -5 | 101 | 94 | 136 |
| -6 | 66 | 61 | 806 |
| -7 | 139 | 196 | 903 |

H,-5,1

| | | | |
|---|---|---|---|
| -8 | 67 | 73 | 908 |
| -7 | 30 | 37 | 89 |
| -6 | 70 | 77 | 119 |
| -5 | 80 | 90 | 698 |
| -4 | 247 | 277 | 795 |
| -3 | 128 | 120 | 193 |
| -2 | 189 | 173 | 985 |
| -1 | 190 | 125 | 833 |
| 0 | 67 | 59 | 131 |
| 1 | 15* | 23 | 811 |
| 2 | 25 | 18 | 793 |
| 3 | 138 | 192 | 235 |
| 4 | 352 | 409 | 70 |
| 5 | 185 | 202 | 923 |
| 6 | 103 | 101 | 758 |
| 7 | 126 | 127 | 108 |
| 8 | 361 | 358 | 963 |
| 9 | 208 | 208 | 830 |
| 10 | 21* | 11 | 72 |

H,-4,1

| | | | |
|---|---|---|---|
| 10 | 216 | 212 | 995 |
| 9 | 292 | 292 | 147 |
| 8 | 233 | 227 | 798 |
| 7 | 18* | 19 | 76 |
| 6 | 129 | 139 | 159 |
| 5 | 218 | 221 | 751 |
| 4 | 450 | 409 | 919 |
| 3 | 219 | 245 | 88 |
| 2 | 142 | 116 | 220 |
| 1 | 75 | 60 | 855 |
| 0 | 509 | 461 | 42 |
| -1 | 294 | 275 | 209 |
| -2 | 496 | 477 | 645 |
| -3 | 115 | 126 | 967 |
| -4 | 135 | 139 | 162 |
| -5 | 181 | 192 | 269 |
| -6 | 258 | 259 | 969 |
| -7 | 15* | 27 | 809 |
| -8 | 90 | 86 | 231 |
| -9 | 20* | 21 | 167 |

H,-3,1

| | | | |
|---|---|---|---|
| -10 | 46 | 51 | 867 |
| -9 | 46 | 37 | 809 |

H,-3,1

| | | | |
|---|---|---|---|
| -8 | 222 | 227 | 83 |
| -7 | 64 | 62 | 950 |
| -6 | 326 | 327 | 803 |
| -5 | 48 | 49 | 65 |
| -4 | 96 | 101 | 39 |
| -3 | 92 | 119 | 233 |
| -2 | 387 | 382 | 183 |
| -1 | 443 | 410 | 19 |
| 0 | 329 | 305 | 673 |
| 1 | 227 | 210 | 233 |
| 2 | 318 | 328 | 70 |
| 3 | 626 | 639 | 916 |
| 4 | 76 | 92 | 809 |
| 5 | 391 | 397 | 109 |
| 6 | 246 | 246 | 969 |
| 7 | 80 | 78 | 823 |
| 8 | 430 | 420 | 152 |
| 9 | 499 | 483 | 499 |
| 10 | 166 | 158 | 642 |

H,-2,1

| | | | |
|---|---|---|---|
| 11 | 13* | 22 | 823 |
| 10 | 232 | 229 | 207 |
| 9 | 113 | 115 | 840 |
| 8 | 405 | 403 | 10 |
| 7 | 110 | 106 | 145 |
| 6 | 167 | 152 | 416 |
| 5 | 710 | 682 | 956 |
| 4 | 409 | 434 | 111 |
| 3 | 10* | 20 | 436 |
| 2 | 149 | 137 | 938 |
| 1 | 719 | 651 | 65 |
| 0 | 203 | 210 | 206 |
| -1 | 1821 | 1708 | 873 |
| -2 | 329 | 333 | 45 |
| -3 | 276 | 285 | 196 |
| -4 | 37 | 54 | 434 |
| -5 | 509 | 509 | 999 |
| -6 | 132 | 139 | 102 |
| -7 | 281 | 279 | 788 |
| -8 | 129 | 127 | 965 |
| -9 | 255 | 254 | 116 |
| -10 | 170 | 163 | 228 |

H,-1,1

| | | | |
|---|---|---|---|
| -11 | 195 | 138 | 762 |
| -10 | 38 | 51 | 96 |
| -9 | 258 | 257 | 946 |
| -8 | 101 | 99 | 820 |
| -7 | 289 | 285 | 133 |
| -6 | 376 | 383 | 973 |
| -5 | 389 | 388 | 835 |
| -4 | 511 | 523 | 170 |
| -3 | 518 | 534 | 35 |
| -2 | 105 | 83 | 859 |
| -1 | 377 | 437 | 233 |
| 0 | 290 | 309 | 83 |
| 1 | 236 | 202 | 912 |
| 2 | 769 | 711 | 763 |
| 3 | 767 | 733 | 112 |
| 4 | 694 | 674 | 956 |
| 5 | 220 | 209 | 809 |
| 6 | 116 | 128 | 114 |
| 7 | 20 | 12 | 215 |
| 8 | 35 | 34 | 761 |
| 9 | 117 | 117 | 168 |

H,0,1

| | | | |
|---|---|---|---|
| 9 | 367 | 352 | 40 |

H,-1,1

| | | | |
|---|---|---|---|
| 10 | 273 | 260 | 94 |
| 11 | 23* | 22 | 916 |

H,0,1

| | | | |
|---|---|---|---|
| 10 | 69 | 75 | 452 |
| 9 | 361 | 335 | 403 |
| 3 | 300 | 293 | 471 |
| 2 | 169 | 161 | 96 |
| 1 | 191 | 180 | 243 |
| 0 | 752 | 756 | 417 |
| -1 | 681 | 800 | 69 |
| -2 | 131 | 174 | 186 |
| -3 | 427 | 429 | 862 |
| -4 | 633 | 658 | 25 |
| -5 | 188 | 192 | 188 |
| -6 | 355 | 361 | 823 |
| -7 | 368 | 366 | 997 |
| -8 | 427 | 437 | 166 |
| -9 | 235 | 240 | 779 |
| -10 | 301 | 286 | 957 |
| -11 | 47 | 87 | 98 |

H,1,1

| | | | |
|---|---|---|---|
| -11 | 139 | 125 | 909 |
| -10 | 143 | 140 | 797 |
| -9 | 111 | 115 | 119 |
| -8 | 213 | 209 | 3 |
| -7 | 88 | 102 | 773 |
| -6 | 136 | 137 | 195 |
| -5 | 321 | 399 | 29 |
| -4 | 79 | 69 | 939 |
| -3 | 440 | 480 | 222 |
| -2 | 433 | 463 | 69 |
| -1 | 233 | 250 | 916 |
| 0 | 173 | 160 | 795 |
| 1 | 299 | 293 | 109 |
| 2 | 553 | 469 | 954 |
| 3 | 178 | 169 | 828 |
| 4 | 291 | 268 | 153 |
| 5 | 461 | 460 | 8 |
| 6 | 21 | 27 | 12 |
| 7 | 29 | 33 | 449 |
| 8 | 29 | 29 | 949 |
| 9 | 315 | 306 | 878 |
| 10 | 60 | 63 | 759 |

H,2,1

| | | | |
|---|---|---|---|
| 10 | 237 | 225 | 79 |
| 9 | 77 | 73 | 756 |
| 8 | 205 | 196 | 486 |
| 7 | 17* | 32 | 212 |
| 6 | 63 | 52 | 186 |
| 5 | 600 | 592 | 850 |
| 4 | 395 | 395 | 487 |
| 3 | 11* | 18 | 197 |
| 2 | 9* | 13 | 760 |
| 1 | 179 | 181 | 435 |
| 0 | 253 | 231 | 127 |
| -1 | 450 | 446 | 759 |
| -2 | 168 | 161 | 419 |
| -3 | 358 | 377 | 82 |
| -4 | 41 | 30 | 132 |
| -5 | 348 | 379 | 675 |
| -6 | 106 | 115 | 69 |
| -7 | 388 | 409 | 182 |
| -8 | 111 | 327 | 628 |
| -9 | 216 | 213 | 490 |
| -10 | 21* | 31 | 209 |
| -11 | 71 | 72 | 298 |

H,3,1

| | | | |
|---|---|---|---|
| -11 | 36 | 49 | 91 |
| -10 | 22* | 23 | 943 |
| -9 | 151 | 159 | 806 |
| -8 | 46 | 49 | 189 |
| -7 | 191 | 203 | 31 |
| -6 | 460 | 494 | 875 |
| -5 | 237 | 258 | 228 |
| -4 | 19 | 30 | 200 |
| -3 | 49 | 77 | 922 |
| -2 | 348 | 298 | 768 |
| -1 | 186 | 169 | 129 |
| 0 | 1046 | 981 | 955 |
| 1 | 228 | 219 | 817 |
| 2 | 296 | 239 | 179 |
| 3 | 286 | 270 | 989 |
| 4 | 441 | 426 | 840 |
| 5 | 117 | 111 | 184 |
| 6 | 229 | 206 | 38 |
| 7 | 83 | 67 | 940 |
| 8 | 27 | 32 | 109 |
| 9 | 299 | 268 | 91 |

H,4,1

| | | | |
|---|---|---|---|
| 8 | 36 | 33 | 86 |
| 7 | 105 | 99 | 228 |
| 6 | 128 | 130 | 886 |
| 5 | 479 | 483 | 28 |
| 4 | 95 | 104 | 763 |
| 3 | 36 | 33 | 600 |
| 2 | 167 | 176 | 39 |
| 1 | 226 | 208 | 150 |
| 0 | 419 | 561 | 807 |
| -1 | 541 | 516 | 452 |
| -2 | 445 | 419 | 119 |
| -3 | 274 | 259 | 762 |
| -4 | 547 | 568 | 914 |
| -5 | 237 | 257 | 46 |
| -6 | 109 | 111 | 209 |
| -7 | 37 | 39 | 887 |
| -8 | 316 | 339 | 39 |
| -9 | 15* | 17 | 441 |
| -10 | 313 | 313 | 825 |
| -11 | 70 | 70 | 969 |

H,5,1

| | | | |
|---|---|---|---|
| -10 | 102 | 99 | 175 |
| -9 | 100 | 101 | 42 |
| -8 | 152 | 140 | 898 |
| -7 | 72 | 80 | 762 |
| -6 | 315 | 350 | 70 |
| -5 | 524 | 563 | 917 |
| -4 | 89 | 88 | 213 |
| -3 | 302 | 304 | 113 |
| -2 | 207 | 198 | 980 |
| -1 | 212 | 193 | 785 |
| 0 | 215 | 211 | 130 |
| 1 | 443 | 421 | 997 |
| 2 | 35 | 23 | 985 |
| 3 | 299 | 288 | 188 |
| 4 | 389 | 386 | 50 |
| 5 | 237 | 233 | 680 |
| 6 | 29 | 45 | 799 |
| 7 | 32 | 36 | 78 |

H,6,1

| | | | |
|---|---|---|---|
| 6 | 138 | 147 | 107 |
| 5 | 94 | 99 | 201 |
| 4 | 107 | 116 | 865 |
| 3 | 93 | 95 | 979 |
| 2 | 130 | 125 | 173 |
| 1 | 19* | 25 | 19 |
| 0 | 403 | 392 | 492 |
| -1 | 250 | 247 | 158 |
| -2 | 315 | 294 | 806 |
| -3 | 230 | 219 | 973 |
| -4 | 309 | 300 | 92 |
| -5 | 707 | 707 | 759 |
| -6 | 249 | 264 | 922 |
| -7 | 277 | 291 | 78 |
| -8 | 294 | 310 | 213 |
| -9 | 255 | 247 | 866 |
| -10 | 156 | 161 | 999 |

H,7,1

| | | | |
|---|---|---|---|
| -9 | 16* | 21 | 771 |
| -8 | 224 | 225 | 92 |
| -7 | 29* | 20 | 73 |
| -6 | 187 | 194 | 761 |
| -5 | 39 | 44 | 170 |
| -4 | 152 | 150 | 953 |
| -3 | 165 | 159 | 794 |
| -2 | 195 | 195 | 181 |
| -1 | 169 | 166 | 21 |
| 0 | 112 | 108 | 829 |
| 1 | 23* | 4 | 233 |
| 2 | 81 | 76 | 93 |
| 3 | 190 | 196 | 896 |
| 4 | 21* | 44 | 163 |
| 5 | 116 | 125 | 82 |

H,8,1

| | | | |
|---|---|---|---|
| 3 | 29* | 38 | 89 |
| 2 | 92 | 98 | 877 |
| 1 | 107 | 112 | 39 |
| 0 | 89 | 75 | 157 |
| -1 | 48 | 63 | 888 |
| -2 | 66 | 58 | 948 |
| -3 | 65 | 61 | 139 |
| -4 | 82 | 76 | 796 |
| -5 | 188 | 183 | 939 |
| -6 | 122 | 122 | 137 |
| -7 | 151 | 159 | 239 |

H,9,1

| | | | |
|---|---|---|---|
| -4 | 50 | 46 | 110 |
| -3 | 39 | 49 | 959 |
| -2 | 85 | 87 | 845 |
| -1 | 69 | 63 | 238 |

H,-8,2

| | | | |
|---|---|---|---|
| -3 | 31 | 34 | 89 |
| -2 | 59 | 69 | 912 |
| -1 | 4* | 24 | 176 |
| 0 | 32 | 36 | 200 |
| 1 | 31 | 33 | 37 |
| 2 | 69 | 57 | 799 |
| 3 | 33 | 15 | 83 |
| 4 | 31 | 31 | 900 |
| 5 | 188 | 215 | 792 |

H,-7,2

| | | | |
|---|---|---|---|
| 7 | 219 | 213 | 633 |
| 6 | 191 | 196 | 986 |
| 5 | 21* | 20 | 149 |
| 4 | 102 | 105 | 799 |
| 3 | 299 | 269 | 937 |
| 2 | 30 | 25 | 107 |
| 1 | 76 | 78 | 782 |
| 0 | 14* | 21 | 178 |

H,-7,2

| | | | |
|---|---|---|---|
| -1 | 16* | 16 | 901 |
| -2 | 47 | 25 | 149 |
| -3 | 71 | 73 | 836 |
| -4 | 92 | 92 | 29 |
| -5 | 159 | 172 | 175 |

H,-6,2

| | | | |
|---|---|---|---|
| -7 | 111 | 120 | 893 |
| -6 | 78 | 87 | 143 |
| -5 | 103 | 103 | 33 |
| -4 | 13* | 17 | 209 |
| -3 | 166 | 180 | 221 |
| -2 | 124 | 129 | 109 |
| -1 | 269 | 272 | 411 |
| 0 | 145 | 149 | 236 |
| 1 | 115 | 116 | 109 |
| 2 | 175 | 155 | 464 |
| 3 | 354 | 343 | 386 |
| 4 | 15* | 25 | 889 |
| 5 | 185 | 193 | 999 |
| 6 | 113 | 113 | 832 |
| 7 | 10* | 15 | 863 |
| 8 | 300 | 293 | 41 |

H,-5,2

| | | | |
|---|---|---|---|
| 9 | 22* | 34 | 238 |
| 8 | 302 | 293 | 865 |
| 7 | 412 | 396 | 18 |
| 6 | 195 | 197 | 176 |
| 5 | 27 | 13 | 602 |
| 4 | 308 | 309 | 989 |
| 3 | 177 | 173 | 129 |
| 2 | 158 | 167 | 790 |
| 1 | 295 | 243 | 942 |
| 0 | 333 | 341 | 101 |
| -1 | 32 | 31 | 171 |
| -2 | 206 | 203 | 883 |
| -3 | 348 | 370 | 62 |
| -4 | 131 | 139 | 768 |
| -5 | 39 | 37 | 954 |
| -6 | 18* | 29 | 75 |
| -7 | 103 | 101 | 180 |
| -8 | 19* | 30 | 877 |

H,-4,2

| | | | |
|---|---|---|---|
| -9 | 10* | 17 | 10 |
| -8 | 42 | 47 | 99 |
| -7 | 97 | 110 | 969 |
| -6 | 212 | 212 | 972 |
| -5 | 156 | 140 | 175 |
| -4 | 338 | 339 | 60 |
| -3 | 67 | 62 | 950 |
| -2 | 682 | 697 | 293 |
| -1 | 258 | 254 | 80 |
| 0 | 327 | 340 | 929 |
| 1 | 209 | 232 | 787 |
| 2 | 326 | 315 | 132 |
| 3 | 279 | 280 | 980 |
| 4 | 319 | 292 | 827 |
| 5 | 397 | 385 | 144 |
| 6 | 129 | 127 | 29 |
| 7 | 187 | 173 | 862 |
| 8 | 68 | 64 | 239 |
| 9 | 282 | 279 | 75 |

H,-3,2

| | | | |
|---|---|---|---|
| 10 | 111 | 103 | 759 |
| 9 | 228 | 211 | 909 |
| 8 | 107 | 101 | 34 |
| 7 | 219 | 218 | 202 |
| 6 | 182 | 191 | 860 |
| 5 | 149 | 161 | 999 |
| 4 | 383 | 356 | 176 |
| 3 | 315 | 293 | 831 |
| 2 | 507 | 469 | 982 |
| 1 | 757 | 738 | 139 |
| 0 | 136 | 155 | 421 |
| -1 | 43 | 126 | 998 |
| -2 | 397 | 415 | 107 |
| -3 | 361 | 369 | 299 |
| -4 | 217 | 221 | 913 |
| -5 | 394 | 397 | 42 |
| -6 | 48 | 47 | 150 |
| -7 | 74 | 70 | 796 |
| -8 | 229 | 225 | 6 |
| -9 | 209 | 200 | 173 |
| -10 | 75 | 66 | 802 |

H,-2,2

| | | | |
|---|---|---|---|
| -11 | 100 | 101 | 835 |
| -10 | 252 | 257 | 159 |
| -9 | 341 | 333 | 49 |
| -8 | 102 | 96 | 889 |
| -7 | 25 | 36 | 72 |
| -6 | 109 | 101 | 65 |
| -5 | 269 | 269 | 895 |
| -4 | 490 | 509 | 299 |
| -3 | 259 | 275 | 59 |
| -2 | 286 | 302 | 940 |
| -1 | 169 | 209 | 813 |
| 0 | 270 | 271 | 133 |
| 1 | 75 | 80 | 946 |
| 2 | 65 | 55 | 889 |
| 3 | 165 | 142 | 205 |
| 4 | 231 | 232 | 33 |
| 5 | 52 | 49 | 871 |
| 6 | 299 | 299 | 231 |
| 7 | 117 | 126 | 47 |
| 8 | 356 | 394 | 911 |
| 9 | 47 | 59 | 839 |
| 10 | 11* | 20 | 886 |

H,-1,2

| | | | |
|---|---|---|---|
| 10 | 81 | 79 | 923 |
| 9 | 63 | 49 | 122 |
| 8 | 275 | 266 | 246 |
| 7 | 19* | 29 | 108 |
| 6 | 210 | 207 | 83 |
| 5 | 87 | 85 | 157 |
| 4 | 532 | 513 | 673 |
| 3 | 372 | 391 | 35 |
| 2 | 60 | 65 | 179 |
| 1 | 429 | 560 | 813 |
| 0 | 380 | 366 | 986 |
| -1 | 50 | 43 | 196 |
| -2 | 39 | 68 | 236 |
| -3 | 259 | 276 | 926 |
| -4 | 430 | 457 | 99 |
| -5 | 205 | 210 | 775 |
| -6 | 79 | 82 | 880 |
| -7 | 69 | 77 | 493 |
| -8 | 227 | 230 | 182 |
| -9 | 32 | 27 | 883 |
| -10 | 37 | 30 | 852 |
| -11 | 25* | 35 | 172 |

H,0,2

| | | | |
|---|---|---|---|
| -11 | 19* | 22 | 874 |
| -10 | 111 | 119 | 851 |
| -9 | 311 | 317 | 206 |

H,0,2

| | | | |
|---|---|---|---|
| -8 | 408 | 417 | 53 |
| -7 | 32 | 31 | 952 |
| -6 | 192 | 197 | 758 |
| -5 | 58 | 78 | 168 |
| -4 | 378 | 403 | 949 |
| -3 | 29 | 20 | 854 |
| -2 | 167 | 165 | 145 |
| -1 | 362 | 338 | 971 |
| 0 | 203 | 190 | 811 |
| 1 | 393 | 370 | 172 |
| 2 | 318 | 310 | 6 |
| 3 | 386 | 389 | 460 |
| 4 | 523 | 494 | 220 |
| 5 | 213 | 218 | 69 |
| 6 | 119 | 122 | 924 |
| 7 | 73 | 68 | 755 |
| 8 | 276 | 269 | 119 |
| 9 | 392 | 396 | 952 |
| 10 | 107 | 97 | 794 |

H,1,2

| | | | |
|---|---|---|---|
| 9 | 220 | 221 | 790 |
| 8 | 428 | 430 | 959 |
| 7 | 239 | 228 | 117 |
| 6 | 96 | 98 | 216 |
| 5 | 352 | 347 | 905 |
| 4 | 458 | 432 | 64 |
| 3 | 184 | 162 | 172 |
| 2 | 344 | 317 | 672 |
| 1 | 779 | 716 | 28 |
| 0 | 42 | 38 | 75 |
| -1 | 1070 | 1059 | 822 |
| -2 | 383 | 362 | 982 |
| -3 | 91 | 132 | 159 |
| -4 | 238 | 236 | 778 |
| -5 | 113 | 141 | 943 |
| -6 | 49 | 51 | 196 |
| -7 | 269 | 275 | 242 |
| -8 | 185 | 169 | 886 |
| -9 | 138 | 127 | 46 |
| -10 | 51 | 57 | 112 |
| -11 | 40 | 46 | 935 |

H,2,2

| | | | |
|---|---|---|---|
| -11 | 182 | 179 | 187 |
| -10 | 111 | 102 | 82 |
| -9 | 358 | 365 | 906 |
| -8 | 130 | 133 | 755 |
| -7 | 163 | 168 | 93 |
| -6 | 329 | 392 | 417 |
| -5 | 421 | 451 | 787 |
| -4 | 653 | 697 | 124 |
| -3 | 758 | 787 | 483 |
| -2 | 390 | 330 | 832 |
| -1 | 320 | 274 | 169 |
| 0 | 625 | 592 | 16 |
| 1 | 131 | 116 | 886 |
| 2 | 457 | 426 | 213 |
| 3 | 449 | 452 | 79 |
| 4 | 623 | 620 | 900 |
| 5 | 82 | 78 | 786 |
| 6 | 406 | 395 | 98 |
| 7 | 46 | 50 | 906 |
| 8 | 76 | 86 | 808 |
| 9 | 153 | 148 | 140 |

H,3,2

| | | | |
|---|---|---|---|
| 8 | 190 | 189 | 196 |
| 7 | 74 | 91 | 833 |
| 6 | 63 | 56 | 936 |
| 5 | 199 | 211 | 122 |
| 4 | 109 | 105 | 238 |
| 3 | 441 | 425 | 421 |
| 2 | 668 | 636 | 57 |
| 1 | 305 | 313 | 208 |
| 0 | 431 | 409 | 666 |
| -1 | 445 | 440 | 19 |
| -2 | 332 | 284 | 178 |
| -3 | 61 | 55 | 234 |
| -4 | 515 | 548 | 478 |
| -5 | 220 | 235 | 199 |
| -6 | 292 | 323 | 778 |
| -7 | 372 | 400 | 442 |
| -8 | 369 | 379 | 99 |
| -9 | 39 | 46 | 138 |
| -10 | 46 | 79 | 406 |
| -11 | 52 | 46 | 0 |

H,4,2

| | | | |
|---|---|---|---|
| -11 | 97 | 99 | 850 |
| -10 | 75 | 79 | 205 |
| -9 | 486 | 491 | 86 |
| -8 | 327 | 329 | 954 |
| -7 | 27 | 38 | 874 |
| -6 | 29 | 25 | 763 |
| -5 | 340 | 353 | 970 |
| -4 | 49 | 80 | 855 |
| -3 | 728 | 702 | 179 |
| -2 | 438 | 424 | 25 |
| -1 | 373 | 352 | 862 |
| 0 | 298 | 279 | 228 |
| 1 | 313 | 319 | 49 |
| 2 | 241 | 221 | 889 |
| 3 | 42 | 45 | 629 |
| 4 | 135 | 137 | 88 |
| 5 | 221 | 229 | 969 |
| 6 | 347 | 341 | 793 |
| 7 | 182 | 183 | 153 |
| 8 | 18* | 14 | 829 |

H,5,2

| | | | |
|---|---|---|---|
| 7 | 69 | 55 | 50 |
| 6 | 89 | 62 | 161 |
| 5 | 177 | 171 | 790 |
| 4 | 177 | 163 | 950 |
| 3 | 114 | 117 | 76 |
| 2 | 312 | 317 | 765 |
| 1 | 126 | 112 | 897 |
| 0 | 55 | 57 | 78 |
| -1 | 26 | 19 | 969 |
| -2 | 109 | 105 | 895 |
| -3 | 338 | 334 | 35 |
| -4 | 375 | 362 | 175 |
| -5 | 73 | 30 | 229 |
| -6 | 35 | 30 | 126 |
| -7 | 409 | 436 | 132 |
| -8 | 155 | 157 | 760 |
| -9 | 721 | 712 | 959 |
| -10 | 101 | 95 | 119 |
| -11 | 47 | 39 | 139 |

H,6,2

| | | | |
|---|---|---|---|
| -10 | 44 | 33 | 977 |
| -9 | 113 | 117 | 815 |
| -8 | 249 | 260 | 125 |
| -7 | 170 | 160 | 495 |
| -6 | 135 | 145 | 799 |
| -5 | 60 | 57 | 193 |
| -4 | 100 | 100 | 77 |
| -3 | 107 | 103 | 872 |
| -2 | 0* | 7 | 118 |

H,6,2

| | | | |
|---|---|---|---|
| -1 | 81 | 71 | 29 |
| 0 | 222 | 215 | 901 |
| 1 | 136 | 137 | 752 |
| 2 | 78 | 90 | 157 |
| 3 | 58 | 57 | 973 |
| 4 | 168 | 173 | 776 |
| 5 | 39 | 36 | 199 |

H,7,2

| | | | |
|---|---|---|---|
| 4 | 33 | 37 | 36 |
| 3 | 76 | 69 | 780 |
| 2 | 73 | 74 | 972 |
| 1 | 100 | 103 | 109 |
| 0 | 228 | 234 | 763 |
| -1 | 178 | 175 | 892 |
| -2 | 210 | 200 | 72 |
| -3 | 183 | 178 | 215 |
| -4 | 0* | 3 | 129 |
| -5 | 0* | 8 | 968 |
| -6 | 97 | 105 | 199 |
| -7 | 50 | 63 | 428 |
| -8 | 237 | 249 | 997 |
| -9 | 52 | 54 | 224 |

H,8,2

| | | | |
|---|---|---|---|
| -7 | 28* | 39 | 253 |
| -6 | 59 | 60 | 11 |
| -5 | 208 | 205 | 641 |
| -4 | 105 | 110 | 197 |
| -3 | 239 | 235 | 61 |
| -2 | 55 | 47 | 942 |
| -1 | 268 | 260 | 737 |
| 0 | 89 | 78 | 112 |
| 1 | 116 | 110 | 926 |
| 2 | 0* | 26 | 96 |

H,-8,3

| | | | |
|---|---|---|---|
| 4 | 87 | 91 | 869 |
| 3 | 19* | 29 | 133 |
| 2 | 116 | 113 | 199 |
| 1 | 7* | 20 | 939 |
| 0 | 105 | 98 | 972 |
| -1 | 115 | 122 | 105 |
| -2 | 101 | 121 | 775 |

H,-7,3

| | | | |
|---|---|---|---|
| -5 | 113 | 117 | 117 |
| -4 | 197 | 230 | 991 |
| -3 | 35 | 21 | 160 |
| -2 | 41 | 56 | 161 |
| -1 | 179 | 190 | 976 |
| 0 | 55 | 59 | 808 |
| 1 | 37 | 36 | 137 |
| 2 | 119 | 134 | 999 |
| 3 | 92 | 88 | 856 |
| 4 | 131 | 125 | 212 |
| 5 | 210 | 203 | 49 |
| 6 | 192 | 178 | 871 |

H,-6,3

| | | | |
|---|---|---|---|
| 7 | 78 | 80 | 88 |
| 6 | 34 | 39 | 207 |
| 5 | 35 | 39 | 864 |
| 4 | 302 | 288 | 57 |
| 3 | 57 | 47 | 221 |
| 2 | 26 | 16 | 58 |
| 1 | 181 | 205 | 496 |
| 0 | 269 | 281 | 165 |
| -1 | 48 | 42 | 240 |
| -2 | 76 | 73 | 922 |
| -3 | 238 | 267 | 112 |
| -4 | 89 | 109 | 765 |
| -5 | 169 | 158 | 928 |
| -6 | 118 | 120 | 96 |
| -7 | 45 | 44 | 248 |

H,-5,3

| | | | |
|---|---|---|---|
| -8 | 58 | 72 | 779 |
| -7 | 16* | 23 | 789 |
| -6 | 127 | 133 | 402 |
| -5 | 17* | 27 | 875 |
| -4 | 274 | 294 | 119 |
| -3 | 137 | 149 | 984 |
| -2 | 42 | 106 | 759 |
| -1 | 187 | 200 | 175 |
| 0 | 366 | 405 | 6 |
| 1 | 69 | 49 | 869 |
| 2 | 48 | 52 | 227 |
| 3 | 207 | 198 | 40 |
| 4 | 0* | 15 | 179 |
| 5 | 290 | 294 | 231 |
| 6 | 237 | 229 | 73 |
| 7 | 39 | 37 | 488 |
| 8 | 108 | 95 | 771 |

H,-4,3

| | | | |
|---|---|---|---|
| 8 | 26 | 31 | 766 |
| 7 | 232 | 217 | 789 |
| 6 | 76 | 81 | 932 |
| 5 | 255 | 299 | 100 |
| 4 | 120 | 119 | 233 |
| 3 | 50 | 40 | 423 |
| 2 | 108 | 99 | 94 |
| 1 | 209 | 219 | 229 |
| 0 | 60 | 71 | 856 |
| -1 | 109 | 107 | 17 |
| -2 | 31 | 31 | 849 |
| -3 | 19* | 18 | 957 |
| -4 | 107 | 115 | 496 |
| -5 | 330 | 338 | 121 |
| -6 | 26 | 29 | 752 |
| -7 | 70 | 67 | 421 |
| -8 | 38 | 31 | 179 |
| -9 | 23* | 19 | 49 |

H,-3,3

| | | | |
|---|---|---|---|
| -10 | 48 | 49 | 768 |
| -9 | 142 | 159 | 46 |
| -8 | 102 | 113 | 401 |
| -7 | 76 | 75 | 805 |
| -6 | 152 | 156 | 193 |
| -5 | 227 | 232 | 982 |
| -4 | 38 | 52 | 771 |
| -3 | 48 | 49 | 223 |
| -2 | 79 | 73 | 39 |
| -1 | 159 | 172 | 843 |
| 0 | 429 | 448 | 172 |
| 1 | 181 | 172 | 57 |
| 2 | 213 | 193 | 433 |
| 3 | 317 | 301 | 242 |
| 4 | 145 | 138 | 58 |
| 5 | 260 | 240 | 946 |
| 6 | 90 | 93 | 229 |
| 7 | 116 | 105 | 106 |
| 8 | 128 | 119 | 2 |
| 9 | 68 | 70 | 777 |

H,-2,3

| | | | |
|---|---|---|---|
| 8 | 336 | 349 | 829 |
| 7 | 383 | 368 | 981 |
| 6 | 191 | 195 | 136 |
| 5 | 15* | 15 | 959 |
| 4 | 290 | 275 | 942 |
| 3 | 222 | 197 | 88 |
| 2 | 73 | 73 | 233 |
| 1 | 327 | 314 | 873 |
| 0 | 507 | 501 | 47 |
| -1 | 17 | 14 | 443 |
| -2 | 139 | 150 | 815 |
| -3 | 26 | 26 | 954 |
| -4 | 158 | 169 | 159 |
| -5 | 195 | 209 | 875 |
| -6 | 12* | 24 | 152 |
| -7 | 49 | 69 | 166 |
| -8 | 59 | 57 | 782 |
| -9 | 269 | 276 | 923 |
| -10 | 209 | 199 | 77 |

H,-1,3

| | | | |
|---|---|---|---|
| -11 | 17* | 23 | 793 |
| -10 | 87 | 69 | 903 |
| -9 | 80 | 77 | 235 |
| -8 | 59 | 68 | 89 |
| -7 | 6* | 35 | 220 |
| -6 | 11* | 23 | 756 |
| -5 | 338 | 359 | 145 |
| -4 | 310 | 346 | 21 |
| -3 | 180 | 198 | 862 |
| -2 | 459 | 462 | 192 |
| -1 | 235 | 222 | 35 |
| 0 | 679 | 637 | 896 |
| 1 | 60 | 42 | 69 |
| 2 | 236 | 239 | 93 |
| 3 | 473 | 442 | 443 |
| 4 | 129 | 120 | 785 |
| 5 | 400 | 399 | 120 |
| 6 | 358 | 355 | 477 |
| 7 | 286 | 269 | 832 |
| 8 | 20* | 29 | 79 |
| 9 | 269 | 261 | 31 |

H,0,3

| | | | |
|---|---|---|---|
| 9 | 191 | 177 | 848 |
| 8 | 200 | 237 | 6 |
| 7 | 175 | 166 | 169 |
| 6 | 187 | 178 | 895 |
| 5 | 550 | 535 | 964 |
| 4 | 406 | 395 | 133 |
| 3 | 327 | 317 | 765 |
| 2 | 458 | 444 | 434 |
| 1 | 894 | 857 | 85 |
| 0 | 335 | 319 | 298 |
| -1 | 449 | 431 | 888 |
| -2 | 75 | 86 | 59 |
| -3 | 184 | 191 | 166 |
| -4 | 509 | 547 | 458 |
| -5 | 658 | 698 | 992 |
| -6 | 111 | 117 | 173 |
| -7 | 97 | 100 | 750 |
| -8 | 210 | 206 | 961 |
| -9 | 261 | 257 | 117 |
| -10 | 706 | 709 | 789 |
| -11 | 60 | 60 | 952 |

H,1,3

| | | | |
|---|---|---|---|
| -11 | 70 | 74 | 770 |
| -10 | 176 | 178 | 91 |
| -9 | 401 | 390 | 469 |
| -8 | 159 | 159 | 633 |
| -7 | 62 | 69 | 293 |
| -6 | 271 | 278 | 15 |
| -5 | 272 | 299 | 439 |
| -4 | 427 | 452 | 190 |
| -3 | 589 | 586 | 40 |
| -2 | 180 | 191 | 900 |
| -1 | 47 | 38 | 149 |
| 0 | 562 | 576 | 83 |
| 1 | 659 | 610 | 927 |
| 2 | 42 | 63 | 450 |
| 3 | 139 | 130 | 115 |
| 4 | 175 | 190 | 991 |
| 5 | 118 | 124 | 826 |
| 6 | 309 | 323 | 171 |
| 7 | 242 | 242 | 11 |
| 8 | 129 | 122 | 860 |
| 9 | 85 | 79 | 178 |

H,2,3

| | | | |
|---|---|---|---|
| 8 | 117 | 122 | 177 |
| 7 | 82 | 74 | 839 |
| 6 | 290 | 292 | 16 |
| 5 | 526 | 516 | 167 |
| 4 | 163 | 155 | 835 |
| 3 | 90 | 96 | 993 |
| 2 | 287 | 286 | 136 |
| 1 | 625 | 566 | 773 |
| 0 | 257 | 258 | 916 |
| -1 | 531 | 489 | 85 |
| -2 | 26 | 11 | 119 |
| -3 | 223 | 215 | 887 |
| -4 | 807 | 839 | 49 |
| -5 | 198 | 222 | 190 |
| -6 | 45 | 40 | 895 |
| -7 | 61 | 59 | 46 |
| -8 | 220 | 221 | 137 |
| -9 | 129 | 119 | 861 |
| -10 | 403 | 390 | 956 |
| -11 | 75 | 66 | 179 |

H,3,3

| | | | |
|---|---|---|---|
| -11 | 18* | 29 | 98 |
| -10 | 50 | 39 | 898 |
| -9 | 292 | 276 | 197 |
| -8 | 451 | 471 | 2 |
| -7 | 175 | 181 | 830 |
| -6 | 186 | 190 | 220 |
| -5 | 400 | 412 | 52 |
| -4 | 253 | 251 | 909 |
| -3 | 115 | 119 | 226 |
| -2 | 132 | 116 | 107 |
| -1 | 61 | 49 | 916 |
| 0 | 46 | 38 | 237 |
| 1 | 562 | 590 | 128 |
| 2 | 157 | 156 | 949 |
| 3 | 127 | 128 | 829 |
| 4 | 173 | 165 | 163 |
| 5 | 61 | 90 | 92 |
| 6 | 73 | 63 | 912 |
| 7 | 61 | 50 | 159 |

H,4,3

| | | | |
|---|---|---|---|
| 7 | 97 | 105 | 66 |
| 6 | 278 | 273 | 191 |
| 5 | 115 | 115 | 861 |
| 4 | 47 | 42 | 989 |
| 3 | 99 | 111 | 128 |
| 2 | 61 | 69 | 840 |
| 1 | 258 | 264 | 982 |
| 0 | 259 | 252 | 117 |

TABLE VII.2.6 (continued)

| | | | |
|---|---|---|---|
| H,4,3 | | | |
| -1 | 229 | 209 | 745 |
| -2 | 125 | 109 | 937 |
| -3 | 123 | 136 | 81 |
| -4 | 239 | 240 | 236 |
| -5 | 50 | 47 | 891 |
| -6 | 47 | 48 | 72 |
| -7 | 15* | 32 | 91 |
| -8 | 44 | 43 | 836 |
| -9 | 251 | 237 | 997 |
| -10 | 195 | 196 | 185 |
| -11 | 180 | 159 | 925 |
| H,5,3 | | | |
| -10 | 63 | 53 | 91 |
| -9 | 266 | 263 | 858 |
| -8 | 128 | 133 | 203 |
| -7 | 24 | 30 | 928 |
| -6 | 43 | 43 | 781 |
| -5 | 41 | 43 | 793 |
| -4 | 375 | 363 | 78 |
| -3 | 423 | 406 | 935 |
| -2 | 168 | 165 | 769 |
| -1 | 176 | 176 | 125 |
| 0 | 281 | 277 | 968 |
| 1 | 131 | 131 | 825 |
| 2 | 55 | 64 | 173 |
| 3 | 119 | 120 | 52 |
| 4 | 259 | 248 | 899 |
| 5 | 17* | 20 | 26 |
| 6 | 146 | 156 | 63 |
| H,6,3 | | | |
| 4 | 120 | 133 | 201 |
| 3 | 125 | 134 | 683 |
| 2 | 371 | 381 | 18 |
| 1 | 168 | 174 | 139 |
| 0 | 121 | 124 | 787 |
| -1 | 19* | 14 | 861 |
| -2 | 111 | 102 | 182 |
| -3 | 19* | 19 | 153 |
| -4 | 446 | 445 | 926 |
| -5 | 15* | 3 | 239 |
| -6 | 152 | 152 | 202 |
| -7 | 116 | 118 | 873 |
| -8 | 112 | 107 | 11 |
| -9 | 38 | 43 | 62 |
| -10 | 43 | 43 | 769 |
| H,7,3 | | | |
| -8 | 307 | 303 | 493 |
| -7 | 54 | 50 | 225 |
| -6 | 57 | 55 | 110 |
| -5 | 199 | 200 | 931 |
| -4 | 71 | 66 | 830 |
| -3 | 270 | 267 | 116 |
| -2 | 408 | 393 | 974 |
| -1 | 153 | 154 | 806 |
| 0 | 219 | 207 | 171 |
| 1 | 330 | 338 | 12 |
| 2 | 55 | 54 | 845 |
| 3 | 99 | 88 | 199 |
| H,8,3 | | | |
| 0 | 26* | 39 | 47 |
| -1 | 86 | 84 | 105 |
| -2 | 24* | 31 | 766 |
| -3 | 241 | 238 | 966 |
| -4 | 309 | 306 | 116 |
| -5 | 74 | 70 | 227 |
| -6 | 25* | 30 | 901 |
| H,-7,4 | | | |
| 4 | 196 | 197 | 98 |
| 3 | 65 | 61 | 790 |
| 2 | 19* | 25 | 849 |
| 1 | 31 | 37 | 97 |
| 0 | 36 | 24 | 100 |
| -1 | 152 | 151 | 475 |
| -2 | 75 | 75 | 42 |
| -3 | 99 | 115 | 147 |
| -4 | 0* | 31 | 488 |
| H,-6,4 | | | |
| -6 | 190 | 139 | 1000 |
| -5 | 19* | 31 | 61 |
| -4 | 53 | 55 | 242 |
| -3 | 50 | 44 | 87 |
| -2 | 25 | 33 | 826 |
| -1 | 69 | 79 | 210 |
| 0 | 132 | 151 | 118 |
| 1 | 120 | 127 | 941 |
| 2 | 58 | 64 | 296 |
| 3 | 68 | 62 | 111 |
| 4 | 435 | 428 | 989 |
| 5 | 31 | 21 | 865 |
| 6 | 128 | 121 | 165 |
| H,-5,4 | | | |
| 7 | 77 | 69 | 899 |
| 6 | 17* | 19 | 869 |
| 5 | 147 | 158 | 133 |
| 4 | 155 | 190 | 814 |
| 3 | 80 | 68 | 929 |
| 2 | 129 | 135 | 106 |
| 1 | 51 | 64 | 899 |
| 0 | 107 | 104 | 934 |
| -1 | 219 | 255 | 28 |
| -2 | 27 | 46 | 235 |
| -3 | 133 | 138 | 699 |
| -4 | 31 | 20 | 149 |
| -5 | 21* | 4 | 192 |
| -6 | 75 | 79 | 889 |
| -7 | 43 | 61 | 18 |
| -8 | 71 | 66 | 186 |
| H,-4,4 | | | |
| -9 | 56 | 53 | 164 |
| -8 | 74 | 71 | 57 |
| -7 | 63 | 58 | 809 |
| -6 | 86 | 95 | 209 |
| -5 | 127 | 132 | 25 |
| -4 | 18* | 13 | 433 |
| -3 | 37 | 37 | 665 |
| -2 | 47 | 57 | 122 |
| -1 | 291 | 319 | 928 |
| 0 | 123 | 132 | 219 |
| 1 | 109 | 109 | 119 |
| 2 | 94 | 89 | 936 |
| 3 | 121 | 119 | 837 |
| 4 | 160 | 155 | 187 |
| 5 | 277 | 279 | 13 |
| 6 | 247 | 238 | 847 |
| 7 | 138 | 148 | 192 |
| H,-3,4 | | | |
| 8 | 171 | 180 | 695 |
| 7 | 96 | 94 | 50 |
| 6 | 22* | 12 | 20 |
| H,-3,4 | | | |
| 5 | 183 | 180 | 438 |
| 4 | 416 | 407 | 499 |
| 3 | 153 | 148 | 132 |
| 2 | 129 | 116 | 819 |
| 1 | 256 | 251 | 956 |
| 0 | 225 | 225 | 87 |
| -1 | 207 | 227 | 769 |
| -2 | 89 | 79 | 911 |
| -3 | 92 | 104 | 58 |
| -4 | 15* | 39 | 136 |
| -5 | 216 | 220 | 899 |
| -6 | 239 | 240 | 13 |
| -7 | 72 | 75 | 205 |
| -8 | 55 | 50 | 902 |
| -9 | 13* | 21 | 857 |
| H,-2,4 | | | |
| -10 | 207 | 193 | 983 |
| -9 | 87 | 67 | 631 |
| -8 | 94 | 94 | 223 |
| -7 | 19* | 19 | 99 |
| -6 | 345 | 352 | 857 |
| -5 | 168 | 180 | 241 |
| -4 | 292 | 318 | 59 |
| -3 | 35 | 35 | 961 |
| -2 | 13* | 10 | 919 |
| -1 | 463 | 467 | 123 |
| 0 | 609 | 467 | 963 |
| 1 | 80 | 79 | 781 |
| 2 | 49 | 46 | 232 |
| 3 | 368 | 357 | 2 |
| 4 | 321 | 307 | 836 |
| 5 | 440 | 427 | 200 |
| 6 | 272 | 267 | 40 |
| 7 | 32 | 39 | 891 |
| 8 | 16* | 19 | 2 |
| H,-1,4 | | | |
| 8 | 97 | 102 | 91 |
| 7 | 56 | 65 | 173 |
| 6 | 49 | 49 | 868 |
| 5 | 345 | 359 | 31 |
| 4 | 326 | 324 | 189 |
| 3 | 192 | 127 | 822 |
| 2 | 92 | 69 | 949 |
| 1 | 255 | 253 | 131 |
| 0 | 203 | 187 | 803 |
| -1 | 334 | 334 | 966 |
| -2 | 270 | 266 | 87 |
| -3 | 209 | 211 | 249 |
| -4 | 329 | 346 | 907 |
| -5 | 409 | 425 | 68 |
| -6 | 38 | 32 | 782 |
| -7 | 33 | 50 | 985 |
| -8 | 195 | 195 | 72 |
| -9 | 42 | 40 | 49 |
| -10 | 223 | 202 | 895 |
| -11 | 133 | 120 | 963 |
| H,0,4 | | | |
| -11 | 167 | 152 | 816 |
| -10 | 42 | 55 | 105 |
| -9 | 211 | 193 | 9 |
| -8 | 93 | 99 | 870 |
| -7 | 237 | 239 | 219 |
| -6 | 239 | 295 | 63 |
| -5 | 472 | 470 | 918 |
| -4 | 111 | 123 | 788 |
| -3 | 155 | 168 | 126 |
| -2 | 263 | 258 | 943 |
| -1 | 53 | 37 | 826 |
| 0 | 739 | 696 | 199 |
| 1 | 286 | 284 | 9 |
| 2 | 156 | 148 | 843 |
| 3 | 35 | 21 | 849 |
| 4 | 517 | 500 | 32 |
| 5 | 248 | 248 | 871 |
| 6 | 191 | 186 | 213 |
| 7 | 89 | 82 | 50 |
| 8 | 21* | 16 | 895 |
| H,1,4 | | | |
| 7 | 20* | 24 | 223 |
| 6 | 22* | 52 | 90 |
| 5 | 14* | 20 | 33 |
| 4 | 118 | 94 | 917 |
| 3 | 156 | 193 | 38 |
| 2 | 43 | 45 | 83 |
| 1 | 60 | 67 | 805 |
| 0 | 569 | 536 | 993 |
| -1 | 21 | 46 | 153 |
| -2 | 304 | 295 | 797 |
| -3 | 28 | 27 | 82 |
| -4 | 193 | 195 | 101 |
| -5 | 37 | 52 | 832 |
| -6 | 170 | 181 | 949 |
| -7 | 196 | 193 | 92 |
| -8 | 310 | 303 | 213 |
| -9 | 273 | 282 | 671 |
| -10 | 209 | 187 | 20 |
| -11 | 69 | 69 | 195 |
| H,2,4 | | | |
| -11 | 159 | 138 | 59 |
| -10 | 117 | 92 | 853 |
| -9 | 17* | 28 | 697 |
| -8 | 46 | 35 | 151 |
| -7 | 145 | 150 | 952 |
| -6 | 93 | 93 | 761 |
| -5 | 289 | 309 | 97 |
| -4 | 165 | 174 | 951 |
| -3 | 261 | 292 | 811 |
| -2 | 79 | 69 | 101 |
| -1 | 285 | 286 | 984 |
| 0 | 309 | 307 | 868 |
| 1 | 52 | 60 | 132 |
| 2 | 80 | 69 | 81 |
| 3 | 67 | 62 | 907 |
| 4 | 78 | 80 | 291 |
| 5 | 456 | 450 | 73 |
| 6 | 239 | 239 | 429 |
| 7 | 707 | 208 | 799 |
| H,3,4 | | | |
| 6 | 49 | 69 | 212 |
| 5 | 279 | 307 | 429 |
| 4 | 177 | 185 | 92 |
| 3 | 168 | 169 | 210 |
| 2 | 200 | 204 | 904 |
| 1 | 299 | 309 | 32 |
| 0 | 15* | 17 | 128 |
| -1 | 292 | 284 | 862 |
| -2 | 55 | 48 | 476 |
| -3 | 30 | 29 | 57 |
| -4 | 443 | 433 | 611 |
| -5 | 426 | 428 | 942 |
| -6 | 135 | 138 | 122 |
| -7 | 68 | 63 | 853 |
| -8 | 15* | 22 | 136 |
| -9 | 171 | 169 | 62 |
| -10 | 208 | 200 | 231 |
| H,3,4 | | | |
| -11 | 28 | 25 | 758 |
| H,4,4 | | | |
| -11 | 91 | 91 | 786 |
| -10 | 124 | 119 | 1 |
| -9 | 197 | 174 | 883 |
| -8 | 50 | 27 | 222 |
| -7 | 52 | 53 | 169 |
| -6 | 79 | 69 | 948 |
| -5 | 417 | 422 | 794 |
| -4 | 273 | 266 | 139 |
| -3 | 138 | 141 | 983 |
| -2 | 75 | 66 | 859 |
| -1 | 122 | 119 | 214 |
| 0 | 416 | 435 | 26 |
| 1 | 513 | 521 | 689 |
| 2 | 60 | 60 | 173 |
| 3 | 39 | 39 | 69 |
| 4 | 293 | 299 | 931 |
| 5 | 32 | 19 | 869 |
| H,5,4 | | | |
| 4 | 51 | 57 | 804 |
| 3 | 116 | 118 | 929 |
| 2 | 79 | 62 | 83 |
| 1 | 146 | 146 | 239 |
| 0 | 380 | 395 | 889 |
| -1 | 428 | 412 | 38 |
| -2 | 60 | 69 | 194 |
| -3 | 412 | 394 | 849 |
| -4 | 467 | 460 | 970 |
| -5 | 137 | 144 | 118 |
| -6 | 66 | 71 | 829 |
| -7 | 159 | 162 | 972 |
| -8 | 142 | 139 | 96 |
| -9 | 241 | 234 | 773 |
| -10 | 343 | 319 | 908 |
| H,6,4 | | | |
| -9 | 145 | 150 | 49 |
| -8 | 245 | 229 | 996 |
| -7 | 206 | 203 | 768 |
| -6 | 150 | 145 | 179 |
| -5 | 428 | 431 | 991 |
| -4 | 136 | 148 | 857 |
| -3 | 268 | 267 | 183 |
| -2 | 28 | 37 | 182 |
| -1 | 59 | 59 | 869 |
| 0 | 104 | 106 | 248 |
| 1 | 440 | 446 | 76 |
| 2 | 48 | 51 | 964 |
| 3 | 153 | 151 | 785 |
| H,7,4 | | | |
| 1 | 191 | 191 | 932 |
| 0 | 253 | 259 | 75 |
| -1 | 95 | 104 | 248 |
| -2 | 39 | 49 | 871 |
| -3 | 170 | 160 | 35 |
| -4 | 78 | 64 | 161 |
| -5 | 36 | 29 | 886 |
| -6 | 207 | 197 | 21 |
| -7 | 210 | 214 | 164 |
| H,-7,5 | | | |
| -2 | 86 | 113 | 860 |
| -1 | 60 | 50 | 796 |
| 0 | 17* | 34 | 430 |
| 1 | 56 | 68 | 941 |
| H,-6,5 | | | |
| 4 | 180 | 171 | 897 |
| 3 | 142 | 138 | 55 |
| 2 | 22* | 19 | 945 |
| 1 | 95 | 95 | 806 |
| 0 | 87 | 94 | 994 |
| -1 | 34 | 63 | 16 |
| -2 | 133 | 196 | 821 |
| -3 | 23* | 24 | 79 |
| -4 | 91 | 90 | 162 |
| -5 | 11* | 12 | 897 |
| H,-5,5 | | | |
| -7 | 107 | 123 | 877 |
| -6 | 84 | 87 | 786 |
| -5 | 55 | 73 | 68 |
| -4 | 19* | 90 | 931 |
| -3 | 47 | 65 | 798 |
| -2 | 20* | 24 | 130 |
| -1 | 199 | 195 | 953 |
| 0 | 81 | 88 | 812 |
| 1 | 82 | 85 | 192 |
| 2 | 159 | 159 | 1 |
| 3 | 197 | 186 | 659 |
| 4 | 15* | 21 | 869 |
| 5 | 103 | 110 | 52 |
| H,-4,5 | | | |
| 6 | 159 | 157 | 760 |
| 5 | 142 | 131 | 918 |
| 4 | 393 | 381 | 65 |
| 3 | 45 | 73 | 219 |
| 2 | 79 | 80 | 880 |
| 1 | 65 | 67 | 73 |
| 0 | 119 | 115 | 189 |
| -1 | 287 | 298 | 893 |
| -2 | 250 | 279 | 996 |
| -3 | 113 | 122 | 122 |
| -4 | 89 | 82 | 775 |
| -5 | 163 | 172 | 931 |
| -6 | 50 | 63 | 129 |
| -7 | 110 | 109 | 199 |
| -8 | 21* | 42 | 893 |
| H,-3,5 | | | |
| -9 | 66 | 72 | 980 |
| -8 | 105 | 100 | 191 |
| -7 | 96 | 92 | 103 |
| -6 | 182 | 180 | 947 |
| -5 | 72 | 79 | 752 |
| -4 | 255 | 270 | 129 |
| -3 | 129 | 131 | 948 |
| -2 | 19* | 5 | 859 |
| -1 | 24 | 30 | 123 |
| 0 | 205 | 197 | 4 |
| 1 | 123 | 122 | 980 |
| 2 | 319 | 329 | 209 |
| 3 | 279 | 267 | 60 |
| 4 | 149 | 151 | 685 |
| 5 | 61 | 63 | 771 |
| 6 | 118 | 123 | 65 |
| H,-2,5 | | | |
| 6 | 117 | 117 | 978 |
| 5 | 188 | 187 | 89 |
| 4 | 145 | 139 | 791 |
| 3 | 275 | 258 | 969 |
| H,-2,5 | | | |
| 2 | 37 | 28 | 147 |
| 1 | 272 | 270 | 201 |
| 0 | 88 | 93 | 922 |
| -1 | 425 | 425 | 12 |
| -2 | 139 | 140 | 167 |
| -3 | 56 | 58 | 902 |
| -4 | 52 | 58 | 79 |
| -5 | 157 | 165 | 155 |
| -6 | 170 | 167 | 801 |
| -7 | 75 | 69 | 918 |
| -8 | 233 | 229 | 97 |
| -9 | 164 | 154 | 740 |
| -10 | 79 | 53 | 652 |
| H,-1,5 | | | |
| -10 | 123 | 140 | 241 |
| -9 | 236 | 219 | 82 |
| -8 | 57 | 59 | 20 |
| -7 | 25 | 37 | 157 |
| -6 | 15* | 24 | 843 |
| -5 | 67 | 62 | 938 |
| -4 | 110 | 116 | 793 |
| -3 | 346 | 355 | 148 |
| -2 | 29 | 19 | 969 |
| -1 | 307 | 295 | 863 |
| 0 | 35 | 37 | 221 |
| 1 | 100 | 96 | 11 |
| 2 | 191 | 180 | 898 |
| 3 | 212 | 197 | 761 |
| 4 | 59 | 62 | 91 |
| 5 | 82 | 92 | 949 |
| 6 | 41 | 43 | 218 |
| 7 | 90 | 42 | 223 |
| H,0,5 | | | |
| 6 | 74 | 72 | 212 |
| 5 | 219 | 220 | 801 |
| 4 | 509 | 502 | 953 |
| 3 | 36 | 37 | 32 |
| 2 | 50 | 65 | 185 |
| 1 | 125 | 119 | 927 |
| 0 | 119 | 126 | 96 |
| -1 | 185 | 183 | 226 |
| -2 | 123 | 131 | 861 |
| -3 | 28 | 32 | 198 |
| -4 | 288 | 293 | 180 |
| -5 | 102 | 102 | 830 |
| -6 | 186 | 195 | 958 |
| -7 | 132 | 129 | 135 |
| -8 | 224 | 214 | 819 |
| -9 | 16* | 18 | 838 |
| -10 | 13* | 29 | 788 |
| H,1,5 | | | |
| -11 | 148 | 150 | 112 |
| -10 | 117 | 110 | 913 |
| -9 | 35 | 39 | 138 |
| -8 | 142 | 139 | 161 |
| -7 | 129 | 124 | 993 |
| -6 | 257 | 260 | 805 |
| -5 | 277 | 292 | 197 |
| -4 | 194 | 191 | 973 |
| -3 | 60 | 60 | 412 |
| -2 | 66 | 67 | 766 |
| -1 | 199 | 195 | 58 |
| 0 | 337 | 349 | 908 |
| 1 | 51 | 58 | 827 |
| 2 | 73 | 83 | 136 |
| 3 | 266 | 271 | 957 |
| 4 | 219 | 237 | 791 |
| 5 | 156 | 157 | 179 |
| 6 | 91 | 109 | 28 |
| H,2,5 | | | |
| 6 | 122 | 108 | 839 |
| 5 | 417 | 440 | 984 |
| 4 | 205 | 225 | 151 |
| 3 | 129 | 125 | 819 |
| 2 | 81 | 92 | 930 |
| 1 | 346 | 359 | 92 |
| 0 | 345 | 343 | 757 |
| -1 | 419 | 424 | 909 |
| -2 | 379 | 362 | 63 |
| -3 | 340 | 330 | 212 |
| -4 | 187 | 199 | 899 |
| -5 | 399 | 400 | 19 |
| -6 | 192 | 194 | 158 |
| -7 | 19* | 42 | 777 |
| -8 | 159 | 148 | 991 |
| -9 | 97 | 89 | 122 |
| -10 | 131 | 105 | 291 |
| -11 | 110 | 107 | 840 |
| H,3,5 | | | |
| -10 | 100 | 97 | 172 |
| -9 | 203 | 186 | 967 |
| -8 | 60 | 76 | 900 |
| -7 | 191 | 186 | 198 |
| -6 | 249 | 239 | 2 |
| -5 | 338 | 334 | 867 |
| -4 | 159 | 192 | 296 |
| -3 | 273 | 274 | 56 |
| -2 | 341 | 344 | 907 |
| -1 | 192 | 190 | 769 |
| 0 | 386 | 387 | 94 |
| 1 | 49 | 119 | 998 |
| 2 | 109 | 109 | 792 |
| 3 | 256 | 271 | 197 |
| 4 | 334 | 343 | 987 |
| 5 | 180 | 189 | 845 |
| H,4,5 | | | |
| 4 | 50 | 61 | 789 |
| 3 | 46 | 52 | 949 |
| 2 | 334 | 337 | 143 |
| 1 | 49 | 100 | 771 |
| 0 | 475 | 476 | 996 |
| -1 | 245 | 251 | 110 |
| -2 | 339 | 336 | 752 |
| -3 | 71 | 65 | 618 |
| -4 | 436 | 430 | 60 |
| -5 | 29 | 32 | 199 |
| -6 | 275 | 284 | 868 |
| -7 | 252 | 238 | 39 |
| -8 | 415 | 408 | 145 |
| -9 | 129 | 116 | 812 |
| -10 | 160 | 149 | 927 |
| H,5,5 | | | |
| -9 | 44 | 42 | 201 |
| -8 | 249 | 294 | 39 |
| -7 | 67 | 65 | 944 |
| -6 | 159 | 149 | 203 |
| -5 | 111 | 102 | 35 |
| -4 | 42 | 108 | 903 |
| -3 | 235 | 244 | 753 |
| -2 | 181 | 176 | 109 |
| -1 | 191 | 204 | 942 |
| 0 | 68 | 81 | 769 |
| 1 | 19* | 39 | 117 |
| H,5,5 | | | |
| 2 | 23* | 45 | 957 |
| 3 | 127 | 149 | 837 |
| H,6,5 | | | |
| 1 | 86 | 96 | 994 |
| 0 | 35 | 17 | 998 |
| -1 | 21* | 29 | 176 |
| -2 | 90 | 86 | 899 |
| -3 | 185 | 168 | 111 |
| -4 | 92 | 89 | 771 |
| -5 | 199 | 192 | 893 |
| -6 | 107 | 111 | 76 |
| -7 | 271 | 260 | 231 |
| -8 | 133 | 133 | 822 |
| H,7,5 | | | |
| -5 | 212 | 207 | 233 |
| -4 | 9* | 21 | 226 |
| -3 | 18* | 15 | 839 |
| -2 | 118 | 119 | 839 |
| H,-6,6 | | | |
| -2 | 107 | 112 | 238 |
| -1 | 81 | 81 | 49 |
| 0 | 18* | 31 | 799 |
| H,-5,6 | | | |
| 3 | 23* | 29 | 909 |
| 2 | 110 | 92 | 951 |
| 1 | 261 | 264 | 84 |
| 0 | 159 | 159 | 757 |
| -1 | 47 | 45 | 872 |
| -2 | 0* | 7 | 792 |
| -3 | 94 | 112 | 209 |
| -4 | 0* | 14 | 116 |
| -5 | 149 | 148 | 995 |
| H,-4,6 | | | |
| -7 | 72 | 64 | 189 |
| -6 | 42 | 63 | 53 |
| -5 | 90 | 63 | 249 |
| -4 | 120 | 101 | 232 |
| -3 | 49 | 59 | 37 |
| -2 | 125 | 195 | 873 |
| -1 | 15* | 29 | 974 |
| 0 | 166 | 169 | 65 |
| 1 | 108 | 110 | 942 |
| 2 | 77 | 76 | 809 |
| 3 | 119 | 117 | 177 |
| 4 | 84 | 81 | 967 |
| H,-3,6 | | | |
| 4 | 72 | 63 | 883 |
| 3 | 21* | 38 | 88 |
| 2 | 219 | 205 | 133 |
| 1 | 182 | 180 | 762 |
| 0 | 40 | 36 | 860 |
| -1 | 7* | 10 | 219 |
| -2 | 119 | 119 | 226 |
| -3 | 85 | 101 | 866 |
| -4 | 220 | 228 | 36 |
| -5 | 98 | 94 | 140 |
| -6 | 49 | 56 | 926 |
| -7 | 48 | 59 | 56 |
| -8 | 71 | 66 | 112 |
| H,-2,6 | | | |
| -9 | 180 | 161 | 196 |
| -8 | 71 | 74 | 17 |
| -7 | 62 | 71 | 918 |
| -6 | 67 | 62 | 213 |
| -5 | 185 | 197 | 57 |
| -4 | 18* | 29 | 89 |
| -3 | 25 | 9 | 121 |
| -2 | 89 | 94 | 101 |
| -1 | 63 | 68 | 948 |
| 0 | 51 | 82 | 806 |
| 1 | 198 | 197 | 109 |
| 2 | 59 | 53 | 922 |
| 3 | 363 | 359 | 832 |
| 4 | 105 | 106 | 165 |
| 5 | 8* | 42 | 965 |
| H,-1,6 | | | |
| 5 | 70 | 86 | 916 |
| 4 | 243 | 257 | 39 |
| 3 | 39 | 43 | 121 |
| 2 | 125 | 121 | 833 |
| 1 | 156 | 163 | 2 |
| 0 | 115 | 110 | 109 |
| -1 | 167 | 166 | 792 |
| -2 | 181 | 168 | 938 |
| -3 | 82 | 81 | 36 |
| -4 | 123 | 126 | 209 |
| -5 | 74 | 79 | 810 |
| -6 | 180 | 196 | 77 |
| -7 | 79 | 82 | 141 |
| -8 | 44 | 56 | 891 |
| -9 | 115 | 84 | 18 |
| H,0,6 | | | |
| -9 | 109 | 104 | 873 |
| -8 | 143 | 147 | 168 |
| -7 | 50 | 62 | 991 |
| -6 | 259 | 277 | 898 |
| -5 | 0* | 10 | 191 |
| -4 | 417 | 425 | 86 |
| -3 | 310 | 309 | 937 |
| -2 | 152 | 148 | 790 |
| -1 | 108 | 112 | 190 |
| 0 | 388 | 385 | 969 |
| 1 | 88 | 78 | 837 |
| 2 | 191 | 150 | 199 |
| 3 | 258 | 276 | 19 |
| 4 | 289 | 302 | 850 |
| 5 | 58 | 81 | 217 |
| H,1,6 | | | |
| 4 | 29* | 30 | 287 |
| 3 | 196 | 167 | 859 |
| 2 | 294 | 305 | 16 |
| 1 | 336 | 345 | 162 |
| 0 | 79 | 80 | 403 |
| -1 | 337 | 327 | 967 |
| -2 | 92 | 96 | 182 |
| -3 | 45 | 43 | 775 |
| -4 | 181 | 186 | 912 |
| -5 | 32 | 25 | 923 |
| -6 | 57 | 57 | 779 |
| -7 | 116 | 116 | 866 |
| -8 | 273 | 259 | 26 |
| -9 | 74 | 58 | 93 |
| -10 | 88 | 73 | 633 |
| H,2,6 | | | |
| -10 | 17* | 21 | 835 |
| H,2,6 | | | |
| -9 | 425 | 392 | 91 |
| -8 | 331 | 337 | 943 |
| -7 | 21* | 43 | 776 |
| -6 | 115 | 113 | 77 |
| -5 | 291 | 297 | 992 |
| -4 | 253 | 245 | 249 |
| -3 | 496 | 494 | 125 |
| -2 | 150 | 157 | 993 |
| -1 | 266 | 259 | 821 |
| 0 | 219 | 224 | 150 |
| 1 | 345 | 344 | 8 |
| 2 | 119 | 110 | 868 |
| 3 | 97 | 97 | 217 |
| 4 | 131 | 141 | 31 |
| H,3,6 | | | |
| 3 | 35 | 47 | 113 |
| 2 | 244 | 259 | 198 |
| 1 | 112 | 121 | 857 |
| 0 | 5* | 15 | 803 |
| -1 | 13* | 13 | 960 |
| -2 | 0* | 10 | 758 |
| -3 | 131 | 136 | 983 |
| -4 | 335 | 329 | 121 |
| -5 | 58 | 52 | 807 |
| -6 | 20* | 42 | 12 |
| -7 | 201 | 199 | 40 |
| -8 | 113 | 105 | 206 |
| -9 | 125 | 119 | 939 |
| H,4,6 | | | |
| -9 | 205 | 186 | 217 |
| -8 | 296 | 278 | 102 |
| -7 | 32 | 35 | 982 |
| -6 | 86 | 87 | 231 |
| -5 | 82 | 82 | 139 |
| -4 | 163 | 149 | 975 |
| -3 | 157 | 141 | 789 |
| -2 | 59 | 61 | 165 |
| -1 | 20* | 21 | 186 |
| 0 | 86 | 98 | 885 |
| 1 | 196 | 166 | 166 |
| 2 | 85 | 69 | 93 |
| H,5,6 | | | |
| 0 | 117 | 135 | 140 |
| -1 | 147 | 163 | 839 |
| -2 | 89 | 86 | 21 |
| -3 | 225 | 219 | 174 |
| -4 | 4* | 1 | 107 |
| -5 | 19* | 34 | 229 |
| -6 | 176 | 176 | 102 |
| -7 | 21* | 9 | 887 |
| H,6,6 | | | |
| -5 | 113 | 123 | 781 |
| -4 | 23* | 29 | 32 |
| -3 | 188 | 195 | 3 |
| H,-4,7 | | | |
| 0 | 126 | 119 | 994 |
| -1 | 23* | 23 | 124 |
| -2 | 20* | 12 | 22 |
| -3 | 61 | 63 | 966 |
| -4 | 36 | 33 | 91 |
| H,-3,7 | | | |
| -6 | 0* | 33 | 981 |
| -5 | 117 | 108 | 93 |
| -4 | 66 | 69 | 919 |
| -3 | 56 | 62 | 817 |
| -2 | 29* | 27 | 208 |
| -1 | 119 | 109 | 999 |
| 0 | 78 | 87 | 912 |
| 1 | 33 | 33 | 192 |
| 2 | 41 | 42 | 96 |
| H,-2,7 | | | |
| 2 | 119 | 120 | 896 |
| 1 | 207 | 207 | 27 |
| 0 | 203 | 196 | 197 |
| -1 | 199 | 231 | 844 |
| -2 | 73 | 75 | 10 |
| -3 | 19* | 38 | 111 |
| -4 | 126 | 136 | 819 |
| -5 | 293 | 296 | 965 |
| -6 | 51 | 38 | 112 |
| -7 | 113 | 129 | 792 |
| H,-1,7 | | | |
| -8 | 22* | 27 | 875 |
| -7 | 45 | 45 | 98 |
| -6 | 17* | 32 | 975 |
| -5 | 22* | 7 | 934 |
| -4 | 121 | 109 | 162 |
| -3 | 89 | 83 | 0 |
| -2 | 43 | 82 | 826 |
| -1 | 209 | 204 | 189 |
| 0 | 301 | 304 | 35 |
| 1 | 131 | 129 | 895 |
| 2 | 49 | 60 | 200 |
| H,0,7 | | | |
| 2 | 129 | 119 | 73 |
| 1 | 224 | 225 | 224 |
| 0 | 169 | 163 | 877 |
| -1 | 131 | 136 | 16 |
| -2 | 79 | 68 | 219 |
| -3 | 61 | 55 | 776 |
| -4 | 363 | 366 | 0 |
| -5 | 260 | 255 | 173 |
| -6 | 75 | 88 | 899 |
| -7 | 18* | 19 | 972 |
| -8 | 59 | 38 | 92 |
| H,1,7 | | | |
| -8 | 106 | 102 | 956 |
| -7 | 169 | 169 | 824 |
| -6 | 93 | 90 | 189 |
| -5 | 209 | 203 | 991 |
| -4 | 0* | 14 | 27 |
| -3 | 126 | 108 | 184 |
| -2 | 39 | 42 | 991 |
| -1 | 127 | 116 | 669 |
| 0 | 197 | 182 | 229 |
| 1 | 246 | 257 | 67 |
| 2 | 28 | 34 | 687 |
| H,2,7 | | | |
| 1 | 195 | 103 | 927 |
| 0 | 152 | 169 | 58 |
| -1 | 35 | 61 | 827 |
| -2 | 69 | 64 | 912 |
| -3 | 69 | 63 | 987 |
| -4 | 151 | 154 | 162 |
| -5 | 61 | 56 | 698 |
| H,2,7 | | | |
| -8 | 23* | 7 | 950 |
| -7 | 16* | 30 | 13 |
| -6 | 57 | 45 | 761 |
| H,3,7 | | | |
| -7 | 196 | 192 | 975 |
| -6 | 39 | 46 | 961 |
| -5 | 22* | 22 | 185 |
| -4 | 276 | 266 | 37 |
| -3 | 111 | 112 | 909 |
| -2 | 76 | 89 | 210 |
| -1 | 80 | 61 | 19 |
| 0 | 149 | 158 | 903 |
| H,4,7 | | | |
| -2 | 79 | 75 | 129 |
| -3 | 129 | 108 | 747 |
| -4 | 208 | 218 | 877 |
| -5 | 89 | 95 | 2 |
| -6 | 0* | 24 | 143 |
| H,0,8 | | | |
| -4 | 29 | 35 | 760 |
| -3 | 91 | 96 | 772 |
| -2 | 31 | 40 | 245 |
| H,1,8 | | | |
| -3 | 10* | 11 | 881 |

## VII.3 DESCRIPTION OF THE STRUCTURE

Intramolecular bond lengths and angles for the independent units A and B of the dimer are provided in Tables VII.3.1 and VII.3.2 respectively. Relevant least-squares planes are listed in Table VII.3.3.

The molecular structure is shown in Fig. VII.3.1. It consists of protonated 6-mercaptopurine ligands complexed with copper(I) chloride *via* Cu-S bonds of normal length (mean 2.25 Å). Two of these crystallographically independent units (labelled A and B in the figure) are associated by longer Cu-S distances (mean 2.74 Å) to form sulphur-bridged dimers. In Fig. VII.3.1, hydrogen atoms have been omitted for clarity. The numbering system in the mercaptopurine ligands is standard[137] and interatomic distances are included in the figure. Although the structure possesses no crystallographic symmetry, the midpoint of the line joining the copper atoms is very nearly a centre of molecular symmetry (which accounts for the doubling of copper-chlorine and copper-sulphur vector peaks in the Patterson map). This pseudo-symmetry is also reflected in the fact that the two independent mercaptopurine moieties are almost coplanar.

A least-squares plane calculation (Table VII.3.3) shows that the four-membered ring of alternating Cu and S

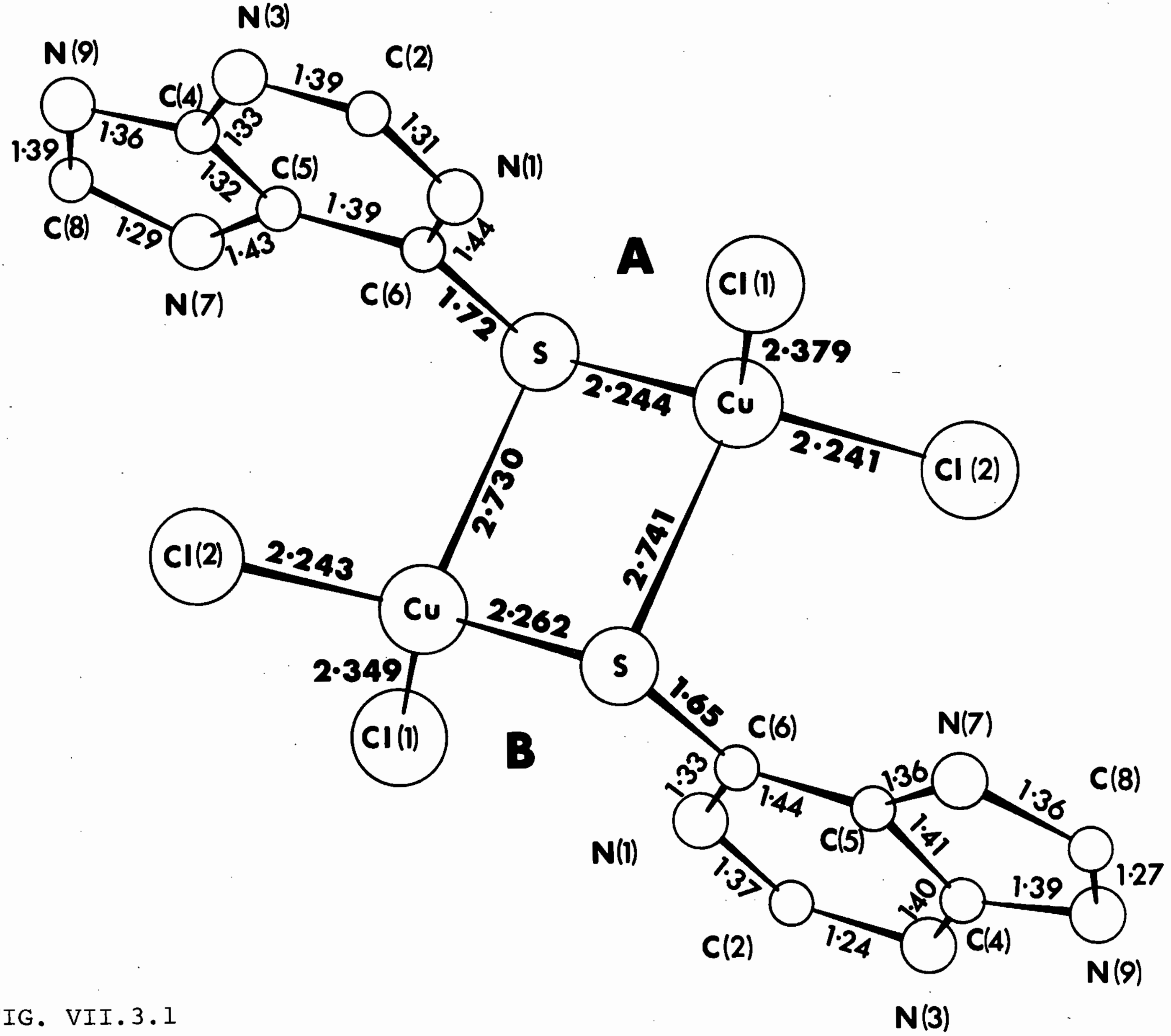

N(3)
N(9)
C(2)
C(4)
1·39
1·36
1·33
1·31
1·39
1·32
C(5)
N(1)
1·39
C(8)
1·29
1·43
1·44
N(7)
C(6)
A
1·72
S
Cl(1)
2·379
2·244
Cu
2·241
Cl(2)
2·730
2·741
Cl(2)
2·243
Cu
2·262
S
2·349
1·65
Cl(1)
B
C(6)
N(7)
1·36
C(8)
1·33
1·44
1·36
C(5)
1·41
N(1)
1·27
1·37
1·40
1·39
C(2)
1·24
C(4)
N(9)
N(3)

FIG. VII.3.1

## TABLE VII.3.1

### INTRAMOLECULAR BOND LENGTHS AND THEIR E.S.D.'s (Å) FOR THE INDEPENDENT UNITS A AND B OF THE DIMER

| | | | |
|---|---|---|---|
| CuA—Cl(1)A | 2.379(7) | CuB—Cl(1)B | 2.349(7) |
| CuA—Cl(2)A | 2.241(6) | CuB—Cl(2)B | 2.243(7) |
| CuA—SA | 2.244(5) | CuB—SB | 2.262(6) |
| CuA—SB | 2.741(6) | CuB—SA | 2.730(6) |
| C(6)A-SA | 1.72(2) | C(6)B-SB | 1.65(3) |
| N(1)A-C(2)A | 1.31(4) | N(1)B-C(2)B | 1.37(3) |
| C(2)A-N(3)A | 1.39(3) | C(2)B-N(3)B | 1.24(3) |
| N(3)A-C(4)A | 1.33(3) | N(3)B-C(4)B | 1.40(3) |
| C(4)A-C(5)A | 1.32(4) | C(4)B-C(5)B | 1.41(3) |
| C(5)A-C(6)A | 1.39(3) | C(5)B-C(6)B | 1.44(3) |
| C(6)A-N(1)A | 1.44(3) | C(6)B-N(1)B | 1.33(3) |
| C(5)A-N(7)A | 1.43(3) | C(5)B-N(7)B | 1.36(2) |
| N(7)A-C(8)A | 1.29(3) | N(7)B-C(8)B | 1.36(3) |
| C(8)A-N(9)A | 1.39(3) | C(8)B-N(9)B | 1.27(4) |
| N(9)A-C(4)A | 1.36(3) | N(9)B-C(4)B | 1.39(3) |

## TABLE VII.3.2

### INTRAMOLECULAR BOND ANGLES AND THEIR E.S.D.'s IN THE DIMER

| | | | |
|---|---|---|---|
| Cl(1)A-CuA-Cl(2)A | 106.1(2) | Cl(1)B-CuB—Cl(2)B | 106.1(2) |
| Cl(1)A-CuA—SA | 117.1(2) | Cl(1)B-CuB—SB | 117.5(3) |
| Cl(2)A-CuA—SA | 130.2(2) | Cl(2)B-CuB—SB | 129.0(3) |
| Cl(2)A-CuA—SB | 104.3(2) | Cl(2)B-CuB—SA | 105.0(2) |
| Cl(1)A-CuA—SB | 98.7(2) | Cl(1)B-CuB—SA | 99.7(2) |
| SA—CuA—SB | 92.9(2) | SB—CuB—SA | 92.8(2) |
| CuA—SA—CuB | 87.5(2) | CuA—SB—CuB | 86.8(2) |
| CuA—SA—C(6)A | 109.4(7) | CuB—SB—C(6)B | 106.4(8) |
| CuB—SA—C(6)A | 92.9(7) | CuA—SB—C(6)B | 92.9(8) |
| SA—C(6)A-N(1)A | 121(1) | SB—C(6)B-N(1)B | 127(2) |
| SA—C(6)A-C(5)A | 128(2) | SB—C(6)B-C(5)B | 124(2) |
| N(1)A—C(6)A-C(5)A | 111(2) | N(1)B—C(6)B-C(5)B | 109(2) |
| C(6)A—N(1)A-C(2)A | 125(2) | C(6)B—N(1)B-C(2)B | 126(2) |
| N(1)A—C(2)A-N(3)A | 122(2) | N(1)B—C(2)B-N(3)B | 128(2) |
| C(2)A—N(3)A-C(4)A | 112(2) | C(2)B—N(3)B-C(4)B | 111(2) |
| N(3)A—C(4)A-C(5)A | 129(2) | N(3)B—C(4)B-C(5)B | 124(2) |
| C(4)A—C(5)A-C(6)A | 121(2) | C(4)B—C(5)B-C(6)B | 121(2) |
| C(6)A—C(5)A-N(7)A | 129(2) | C(6)B—C(5)B-N(7)B | 134(2) |
| C(4)A—C(5)A-N(7)A | 110(2) | C(4)B—C(5)B-N(7)B | 104(2) |
| C(5)A—N(7)A-C(8)A | 104(2) | C(5)B—N(7)B-C(8)B | 110(2) |
| N(7)A—C(8)A-N(9)A | 112(2) | N(7)B—C(8)B-N(9)B | 110(2) |
| C(8)A—N(9)A-C(4)A | 106(2) | C(8)B—N(9)B-C(4)B | 109(2) |
| N(9)A—C(4)A-C(5)A | 107(2) | N(9)B—C(4)B-C(5)B | 107(2) |
| N(9)A—C(4)A-N(3)A | 123(2) | N(9)B—C(4)B-N(3)B | 129(2) |

## TABLE VII.3.3

## LEAST-SQUARES PLANES

The equations of the planes are expressed in orthogonalized space as $PI+QJ+RK=S$

Plane I: through atoms CuA, SA, CuB and SB

Equation: $0.68316I-0.40118J-0.61020K=6.87083$

| Atoms included in calculation | Dist. from plane, Å | Atoms not included in calculation | Dist. from plane, Å |
|---|---|---|---|
| CuA | 0.007 | | |
| SA | -0.007 | C(6)A | -1.63 |
| CuB | 0.007 | | |
| SB | -0.007 | C(6)B | 1.57 |

Plane II: through atoms SA, N(1)A, C(2)A, N(3)A, C(4)A, C(5)A, C(6)A, N(7)A, C(8)A and N(9)A of the mercaptopurine ligand A.

Equation: $0.32081I+0.88387J-0.34037K=3.48986$

| Atoms included in calculation | Dist. from plane, Å | Atoms not included in calculation | Dist. from plane, Å |
|---|---|---|---|
| SA | 0.023 | CuA | -0.260 |
| N(1)A | -0.054 | Cl(1)A | -0.128 |
| C(2)A | -0.013 | Cl(2)A | 0.286 |
| N(3)A | 0.047 | OA | 0.228 |
| C(4)A | -0.020 | | |
| C(5)A | -0.018 | | |
| C(6)A | 0.031 | | |
| N(7)A | 0.019 | | |
| C(8)A | -0.057 | | |
| N(9)A | 0.043 | | |

Angle of intersection of planes I and II: 85.9°.

Plane III: through atoms SB, N(1)B, C(2)B, N(3)B, C(4)B, C(5)B, C(6)B, N(7)B, C(8)B and N(9)B of the mercaptopurine ligand B.

Equation: $0.31437I+0.87814J-0.36061K=0.43470$

| Atoms included in calculation | Dist. from plane, Å | Atoms not included in calculation | Dist. from plane, Å |
|---|---|---|---|
| SB | 0.010 | CuB | 0.351 |
| N(1)B | -0.019 | Cl(1)B | 0.247 |
| C(2)B | 0.005 | Cl(2)B | -0.217 |
| N(3)B | 0.033 | OB | 0.024 |
| C(4)B | -0.043 | | |
| C(5)B | -0.031 | | |
| C(6)B | 0.005 | | |
| N(7)B | 0.046 | | |
| C(8)B | -0.036 | | |
| N(9)B | 0.030 | | |

Angles of intersection: planes I and III: 85.3°

planes II and III: 1.3°.

atoms is accurately planar with atoms C(6)A, 1.63 Å above and C(6)B, 1.57 Å below the plane. The coordination geometry around the copper and bridging sulphur atoms is illustrated in Fig. VII.3.2. The short Cu-S bond lengths of 2.244(5) and 2.262(6) Å fall within the range of Cu-S distances found in copper(I)-thiourea complexes[140,141] (2.23 - 2.36 Å). The longer Cu-S distances of 2.730(6) and 2.741(6) Å are evidence of weaker sulphur-bridged bonds, reminiscent of the commonly observed[142] asymmetry in copper-bridging Cl - Cu bond distances. The relatively small angles within the ring are evidence of strain in the structure and this results in considerable distortion from tetrahedral geometry around the copper atoms. The Cu....Cu internuclear distance of 3.456(3) Å is similar to the analogous separation of 3.479(2) Å observed in a trinuclear copper complex of adenine which contains chlorine bridges of the asymmetric type[142]. The relatively short S....S separation (3.63 Å) does not necessarily imply any interaction as the effective van der Waals radius for sulphur can vary[136] from 1.65 to 1.85 Å. The resultant flattening of the tetrahedron and its orientation are such that the copper atom and its bonded chlorines lie close to the plane of the mercaptopurine ligand with the Cu A - SB bond approximately normal to this plane (Table VII.3.3). The four independent Cu-Cl distances fall into two classes: two of them (2.241(6) and 2.243(7) Å) are of normal length while the other two are somewhat longer (2.349(7) and 2.379(7) Å). The Pauling covalent radii sum[51] for a single copper-chlorine

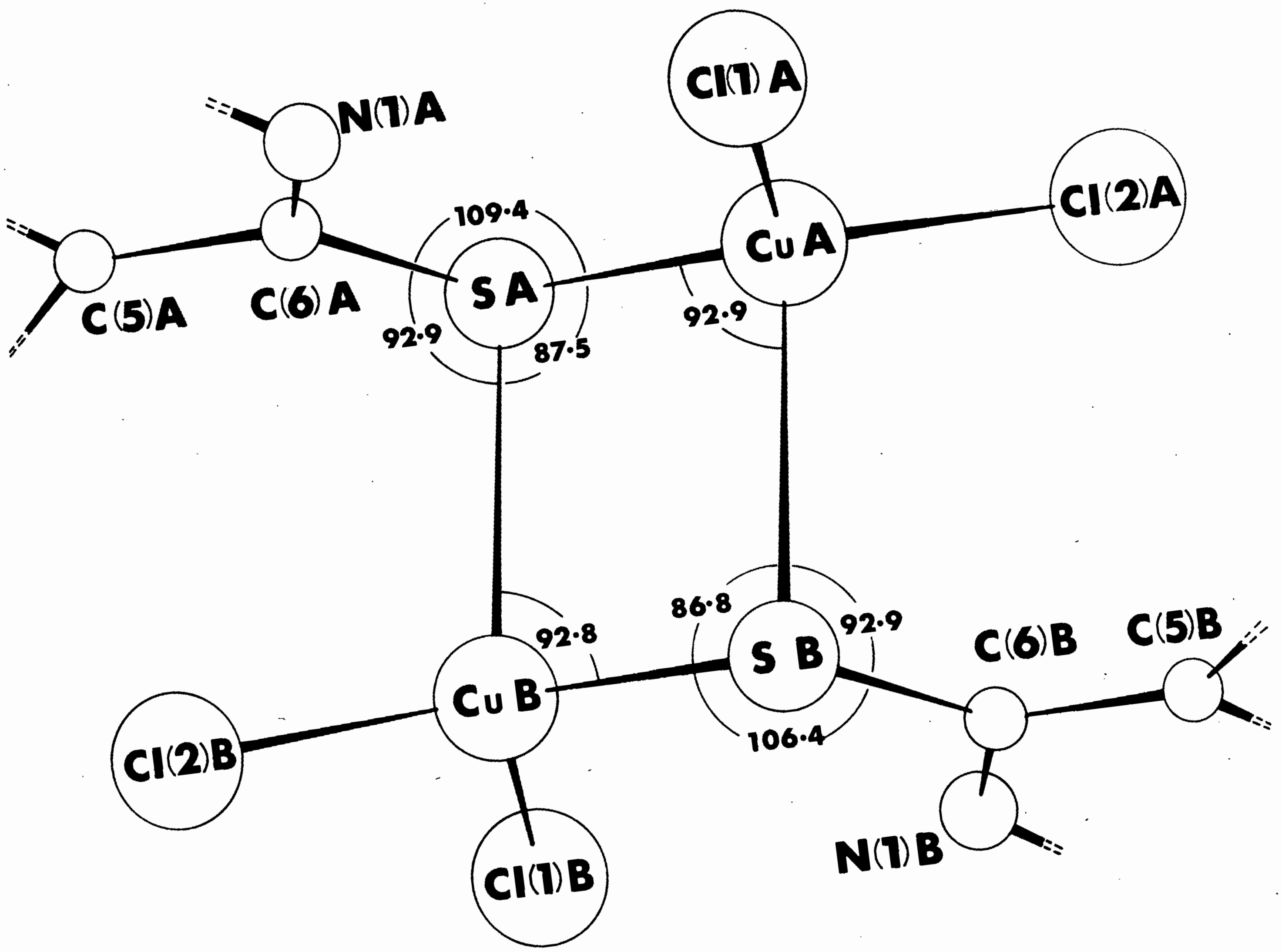

Cl(1) A
N(1) A
Cl(2)A
109·4
Cu A
C(6) A
S A
C(5)A
92·9
92·9
87·5
86·8
92·9
C(6)B
C(5)B
92·8
S B
Cu B
Cl(2)B
106·4
N(1)B
Cl(1)B

FIG. VII.3.2

bond is 2.41 Å. A Cu-Cl distance of 2.406(5) Å has been reported[141] for tetrahedral copper(I) bonded to three sulphur atoms and one chlorine atom.

There are significant differences in chemically equivalent bond lengths and angles in the two complexed mercaptopurine ligands. Comparison with the parent 6-mercaptopurine monohydrate structure[136,137] again shows significant differences in the values of these parameters. However, many factors contribute to such differences (e.g. the presence of metal and halogen atoms, ligand protonation, hydrogen bonding scheme). In 6-mercaptopurine monohydrate[136,137], the carbon-sulphur bond has a mean length of 1.68 Å and this was taken as evidence for the presence of the thione (C=S) tautomer in the crystal. From the C(6)-S distances of 1.72(2) and 1.65(3) Å in ligands A and B respectively of the copper complex, it appears that the thione form is retained on complexation. (C-S single bonds in thiols fall in the range 1.81 ± 0.01 Å)[143]. The angles C(6)-S-Cu of 109.4(7)° and 106.4(8)° for units A and B respectively compare favourably with the analogous angles[144] of 109.8° and 108.6° observed in chlorobis - (2-thiouracil)copper(I) dimethylformamide solvate.

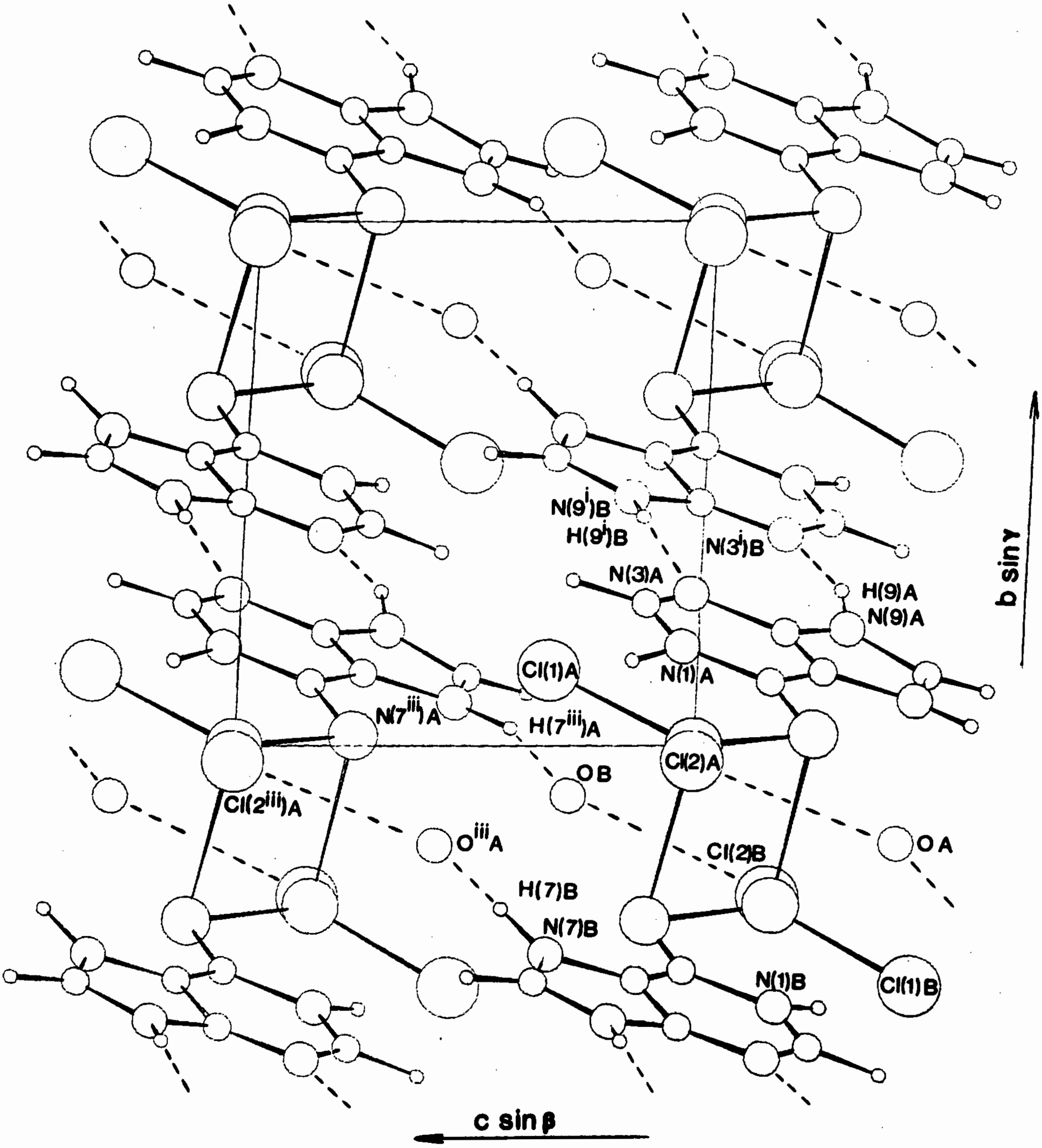
## Ligand protonation and hydrogen bonding

From difference electron-density maps, atom N(9) was clearly indicated as the protonation site in both ligands A and B. This permits hydrogen bonding of the type N(9)A-H(9)A...N($3^i$)B and N($9^i$)B-H($9^i$)B...N(3)A

In Fig. VII.3.3, the unit cell is viewed down the *a*-axis and hydrogen bonds of the type N-H...N (as well as N-H...O and HO-H...Cl) are represented by dashed lines. Hydrogen bonding of the type N-H...N links molecules of trichloroadeninium zinc(II) in pairs[145]. In contrast, dimers of the copper complex are linked by pairs of such bonds to form infinite chains. The angle of intersection of adjacent hydrogen bonded purine planes is about 1° (Table VII.3.3) and the independent N...N distances are 2.93(3) and 2.94(3) Å compared with 2.952 Å for the analogous distance observed in the zinc-adenine complex[145].

Each hydrate oxygen atom participates in two analogous hydrogen bonds; one is the N(7)-H(7) ... O interaction and the second is of the type HO-H... Cl(2). These bonds link the infinite chains of base-paired dimers as shown in Fig. VII.3.3. Atom H(1) of each of the mercaptopurine rings, A and B, is involved in an intramolecular hydrogen bond, N(1)-H(1)... Cl(1) with N ... Cl distances of about 3.1 Å. These and other interactions including short C-H ... Cl contacts involving C(2) of each ligand are also listed. The only hydrogen atoms which are not engaged in any interactions are H(8)A and H(8)B.

FIG. VII.3.3


N(9$^{i}$)B
H(9$^{i}$)B
N(3$^{i}$)B
N(3)A
H(9)A
N(9)A
Cl(1)A
N(1)A
N(7$^{iii}$)A
H(7$^{iii}$)A
Cl(2)A
OB
Cl(2$^{iii}$)A
O$^{iii}$A
Cl(2)B
OA
H(7)B
N(7)B
N(1)B
Cl(1)B
c sin β
b sin γ

## VII.4 THE CRYSTAL STRUCTURE OF THE POLYMERIC 8-MERCAPTOPURINE COPPER(I) CHLORIDE COMPLEX; $[Cu(C_5H_5N_4S)Cl_2]_\infty$

### Crystal preparation and chemical analysis

Heated solutions of 8-mercaptopurine and copper(II) chloride dihydrate in 1 M HCl were mixed in the ligand-metal molar ratio 1:1. On cooling the resulting brown solution, long orange needles of the complex grew within 60 minutes. The fomulation Cu(8-mercaptopurine)$Cl_2$ was consistent with microanalytical data (Table VII.4.1).

Measurement of the magnetic moment of the complex yielded a value of $\mu$ = 0.24 B.M. indicating a diamagnetic species. Reduction of the metal to Cu(I) had evidently occurred during synthesis.

The correct formulation for the complex is therefore (protonated 8-mercaptopurine)Cu(I)$Cl_2$. The copper content of the crystals was determined by atomic absorption spectrophotometry.

TABLE VII.4.1

| | %C | %H | %N | %Cu |
|---|---|---|---|---|
| Calculated: | 20.87 | 1.74 | 19.48 | 22.09 |
| Found : | 21.10 | 1.75 | 19.40 | 23.36 |

### Density determination

A nomogram was prepared[94] for the solvent system methylene iodide - m-xylene and a density of 2.04 g $cm^{-3}$ was recorded by flotation of single crystals in a total volume of 9 ml of solvent mixture. The number of formula units per unit cell was calculated as four.

Space group assignment

A survey of the X-ray photographic data showed that reflections of the type *h*0*l* *l*=2n+1 and 0*k*0 *k*=2n+1 were systematically absent, characteristic[60] of the monoclinic space group $P2_1/c$.

Diffractometer data

For intensity data collection a single crystal was cut into a block of dimensions 0.2 x 0.2 x 0.1 mm. Crystal data are listed in Table VII.4.2.

TABLE VII.4.2 CRYSTAL DATA

| | |
|---|---|
| Molecular formula | $Cu(C_5H_5N_4S)Cl_2$ |
| Molecular weight | 287.5 g $mole^{-1}$ |
| Space group | $P2_1/c$ (Monoclinic, 2nd setting) |
| a = 9.464(5) Å | |
| b = 6.119(3) Å | $D_m$ = 2.04 g $cm^{-3}$ |
| c = 19.690(10) Å | $D_c$ = 2.03 g $cm^{-3}$ for Z = 4 |
| β = 124.78(5)° | μ(MoKα) = 31.5 $cm^{-1}$ |
| V = 936.57 $Å^3$ | F(000) = 568 |

With the diffractometer operating in the ω-2θ scan mode (scan width 1.0°θ, scan speed 0.03°θ $sec^{-1}$) a total of 1776 reflections were counted in the range $6^\circ<2\theta<50^\circ$. Of these, 164 reflections were systematically absent while of the remaining 1612 observations, 1253 had $I_{rel}>1.65\sigma(I_{rel})$ and were considered 'observed'. Treatment of the 'less-thans' is discussed below.

The intensities of three reflections (monitored after every 52 measured reflections) remained constant to within 3% of their respective mean values during data collection. The approximate range of $\mu R$ values for the crystal selected was between 0.3 and 0.4 with corresponding A* values[78] of 1.65 and 1.95 at $\theta = 0^{\circ}$ and 1.64 and 1.93 at $\theta = 25^{\circ}$. No absorption corrections were applied to the reflection data.

Solution of the structure and refinement

The position of the copper atom was deduced from a three-dimensional Patterson map (X-RAY 72 program system)[46]. In the Harker section 0, ½-2y,½ two peaks were found; the larger peak was assumed to be due to a Cu-Cu vector interaction. The x and z coordinates were assigned from the highest peak in the Harker plane 2x, ½, ½ + 2z. The positional assignment for Cu was confirmed by the presence of an inversion peak 2x, 2y, 2z in the required position. Structure factors calculated with the copper atom alone yielded an R factor of 0.53 and a subsequent electron-density map revealed the remaining heavy atoms. The latter were tetrahedrally arranged at an average distance of 2.4 Å from the metal atom. All of the atoms of the mercaptopurine ligand were located in an electron-density map phased on the four heavy atoms. With the sulphur atom in the 8-position of the purine ring, the ligand has mirror symmetry and ambiguity with respect to carbon and nitrogen locations can arise. Correct atomic assignments were facilitated by the relative peak heights in the map. The average ratio of nitrogen:carbon peak heights in the pyrimidine ring was actually 1.5.

After three cycles of full-matrix least-squares calculations with individual isotropic temperature factors, R was 0.093. Four cycles with all the atoms vibrating anisotropically reduced R to 0.056 and a difference electron-density map was prepared in order to locate hydrogen atoms. Theoretical positions for all possible sites of hydrogen attachment in the purine ring were calculated (program XANADU). Comparison with the peak positions found in the difference map enabled all five hydrogens to be located unambiguously. They were assigned the isotropic temperature factors of their bonded atoms and only their positions were refined.

In the last cycle of refinement, the average shift: error ratio was 0.006. 'Less-than' reflections were included in the refinement if they calculated greater than the observed value. The function minimised was $\Sigma(|F_o|-|F_c|)^2$ and the final R was 0.050 based on 1408 contributing reflections each assigned unit weight.

Atomic scattering factors for the non-hydrogen atoms were those of Cromer and Mann[79]; for hydrogen atoms, those of Stewart et al.[80] were employed. Anomalous dispersion corrections[63] were applied to the Cu, Cl and S scattering curves.

The final atomic coordinates and thermal parameters for the non-hydrogen atoms are listed in Table VII.4.3 while those for the hydrogens are listed in Table VII.4.4.

Observed and calculated structure factors appear in Table VII.4.5. In this list, reflections with observed intensities below the threshold value are labelled with an asterisk.

# TABLE VII.4.3

## NON-HYDROGEN ATOMS

## FRACTIONAL ATOMIC COORDINATES ($\times 10^4$) AND THEIR E.S.D.'s AND ANISOTROPIC TEMPERATURE FACTORS

Thermal parameters are of the form

$$T = \exp[-2\pi^2(U_{11}h^2a^{*2} + U_{22}k^2b^{*2} + U_{33}l^2c^{*2} + 2U_{12}hka^*b^* + 2U_{13}hla^*c^* + 2U_{23}klb^*c^*)\times 10^3]$$

| | $x$ | $y$ | $z$ | $U_{11}$ | $U_{22}$ | $U_{33}$ | $U_{12}$ | $U_{13}$ | $U_{23}$ |
|---|---|---|---|---|---|---|---|---|---|
| Cu | 1039 (1) | 520 (2) | 8347(1) | 40(1) | 33(1) | 36(1) | -1(0) | 31(1) | -1(0) |
| Cl(1) | 620 (2) | -709 (3) | 9311(1) | 29(1) | 25(1) | 27(1) | 4(1) | 20(1) | 8(1) |
| Cl(2) | 3523 (2) | 2904 (3) | 8948(1) | 27(1) | 30(1) | 27(1) | -8(1) | 20(1) | -10(1) |
| S | 1250 (2) | -2098 (3) | 7579(1) | 28(1) | 21(1) | 25(1) | -7(1) | 21(1) | -3(1) |
| N (1) | 3521 (8) | 1907(11) | 5511(4) | 25(3) | 35(4) | 20(3) | 1(3) | 17(3) | 3(3) |
| C (2) | 4086(10) | 3439(13) | 6076(5) | 24(4) | 27(4) | 28(4) | -5(3) | 14(3) | 3(4) |
| N (3) | 3890 (7) | 3452(10) | 6691(4) | 20(3) | 26(3) | 24(3) | -6(3) | 13(3) | -3(3) |
| C (4) | 3071 (8) | 1675(11) | 6695(4) | 7(3) | 20(3) | 18(3) | -1(3) | 5(3) | 2(3) |
| C (5) | 2442 (8) | -27(11) | 6113(4) | 15(3) | 18(3) | 16(3) | 1(3) | 10(3) | 1(3) |
| C (6) | 2692 (9) | 99(12) | 5498(4) | 19(4) | 26(4) | 22(4) | -3(3) | 12(3) | -4(3) |
| N (7) | 1710 (8) | -1509(10) | 6350(4) | 27(3) | 19(3) | 25(3) | -7(3) | 19(3) | -7(3) |
| C (8) | 1856 (8) | -767(11) | 7033(4) | 18(3) | 11(3) | 19(3) | -2(3) | 13(3) | -4(3) |
| N (9) | 2668 (7) | 1207 (9) | 7236(3) | 21(3) | 17(3) | 15(3) | -3(2) | 11(3) | -4(2) |

## TABLE VII.4.4

## HYDROGEN ATOMS

## FRACTIONAL ATOMIC COORDINATES (x$10^3$) AND THEIR E.S.D.'s AND ISOTROPIC TEMPERATURE FACTORS (x$10^3$)

| | *x* | *y* | *z* | *Uiso* |
|---|---|---|---|---|
| H(1) | 347(10) | 207(13) | 508(5) | 24 |
| H(2) | 451(10) | 446(14) | 602(5) | 27 |
| H(6) | 232 (9) | -105(13) | 508(5) | 23 |
| H(7) | 132(10) | -272(14) | 615(5) | 22 |
| H(9) | 305 (9) | 195(12) | 771(5) | 18 |

# TABLE VII.4.5

TABLE VII.4.5 (continued)

| | 10FO | 10FC |
|---|---|---|
| 6,K,1 | | |
| 5 | 198 | -223 |
| 4 | 33* | 8 |
| 7,K,1 | | |
| 2 | 248 | 255 |
| 3 | 285 | -304 |
| 4 | 115 | 112 |
| 8,K,1 | | |
| 3 | 166 | -174 |
| 2 | 122 | -25 |
| 1 | 186 | -209 |
| -9,K,2 | | |
| 2 | 178 | 179 |
| 1 | 317 | 328 |
| -8,K,2 | | |
| 0 | 221 | 233 |
| -9,K,2 | | |
| 0 | 217 | -249 |
| -8,K,2 | | |
| 1 | 77* | 42 |
| -7,K,2 | | |
| 4 | 17* | -9 |
| 3 | 413 | 429 |
| -6,K,2 | | |
| 4 | 51* | -38 |
| 5 | 156 | -145 |
| -5,K,2 | | |
| 6 | 119 | 117 |
| 5 | 235 | -265 |
| -4,K,2 | | |
| 6 | 99 | 129 |
| -3,K,2 | | |
| 6 | 83* | 85 |
| -2,K,2 | | |
| 6 | 45* | -50 |
| 7 | 76* | -96 |
| -1,K,2 | | |
| 7 | 152 | 156 |
| 6 | 249 | 255 |
| 0,K,2 | | |
| 6 | 53* | 15 |
| 7 | 122 | 109 |
| 1,K,2 | | |
| 7 | 176 | 139 |
| 6 | 375 | -298 |
| 2,K,2 | | |
| 6 | 195 | -193 |
| 3,K,2 | | |
| 6 | 299 | -282 |
| 4,K,2 | | |
| 5 | 103 | -116 |
| 6 | 142 | -120 |
| 5,K,2 | | |
| 5 | 3* | 15 |
| 4 | 187 | -172 |
| 6,K,2 | | |
| 3 | 209 | -191 |
| 4 | 67* | -5 |
| 5 | 88* | -70 |
| 7,K,2 | | |
| 4 | 36* | -95 |
| 3 | 36* | 8 |
| 2 | 46* | 59 |
| 1 | 80* | -119 |
| 0 | 409 | -400 |
| 8,K,2 | | |
| 0 | 567 | -554 |
| 1 | 139 | 197 |
| 2 | 119 | 41 |
| -9,K,3 | | |
| 1 | 206 | -202 |
| 2 | 251 | 263 |
| 3 | 207 | -216 |
| -8,K,3 | | |
| 4 | 251 | 219 |
| 3 | 77* | 78 |
| 2 | 265 | 256 |
| -7,K,3 | | |
| 4 | 124 | 132 |
| 5 | 46* | -39 |
| -6,K,3 | | |
| 5 | 22* | 33 |
| -5,K,3 | | |
| 5 | 237 | -292 |
| 6 | 212 | -190 |
| -4,K,3 | | |
| 6 | 296 | -191 |
| -3,K,3 | | |
| 6 | 419 | -436 |
| 7 | 76* | -69 |
| -2,K,3 | | |
| 7 | 26* | -23 |
| 6 | 389 | -385 |
| -1,K,3 | | |
| 6 | 70* | 12 |
| 7 | 102 | -59 |
| 0,K,3 | | |
| 7 | 59* | 23 |
| 6 | 51* | 63 |
| 1,K,3 | | |
| 6 | 296 | 259 |
| 7 | 378 | 325 |
| 2,K,3 | | |
| 6 | 181 | 209 |
| 3,K,3 | | |
| 5 | 306 | -322 |
| 6 | 73* | -109 |
| 4,K,3 | | |
| 6 | 76* | 79 |
| 5 | 178 | -183 |
| 5,K,3 | | |
| 4 | 194 | 180 |
| 5 | 199 | 141 |
| 6,K,3 | | |
| 4 | 26* | 76 |
| 3 | 79* | -123 |
| 7,K,3 | | |
| 1 | 56* | 12 |
| 2 | 79* | -19 |
| 3 | 193 | -196 |
| 8,K,3 | | |
| 1 | 178 | -164 |
| -10,K,4 | | |
| 0 | 223 | 206 |
| 1 | 190 | -176 |
| -9,K,4 | | |
| 3 | 159 | 197 |
| 2 | 136 | -198 |
| 1 | 125 | -132 |
| 0 | 57* | 21 |
| -8,K,4 | | |
| 2 | 359 | -386 |
| 3 | 153 | 193 |
| 4 | 43* | 5 |
| -7,K,4 | | |
| 5 | 169 | 175 |
| 4 | 82* | 91 |
| -6,K,4 | | |
| 5 | 379 | 405 |
| 4 | 47* | 109 |
| -5,K,4 | | |
| 4 | 83* | 92 |
| 5 | 401 | 499 |
| -4,K,4 | | |
| 4 | 57* | 18 |
| -3,K,4 | | |
| 7 | 53* | -59 |
| 6 | 71* | 56 |
| -2,K,4 | | |
| 6 | 175 | 170 |
| 7 | 19* | -75 |
| -1,K,4 | | |
| 7 | 221 | -219 |
| 6 | 199 | 199 |
| 0,K,4 | | |
| 6 | 73* | -85 |
| 7 | 155 | -198 |
| 1,K,4 | | |
| 6 | 20* | 20 |
| 2,K,4 | | |
| 6 | 101 | 85 |
| 3,K,4 | | |
| 6 | 33* | 26 |
| 5 | 101 | 132 |
| 4,K,4 | | |
| 5 | 133 | 118 |
| 5,K,4 | | |
| 5 | 158 | 100 |
| 4 | 128 | -85 |
| 6,K,4 | | |
| 2 | 389 | 386 |
| 3 | 142 | 132 |
| 4 | 116 | 127 |
| 7,K,4 | | |
| 3 | 158 | 193 |
| 2 | 99 | 57 |
| 1 | 59* | -57 |
| 0 | 591 | 577 |
| 8,K,4 | | |
| 0 | 175 | 160 |
| -10,K,5 | | |
| 2 | 169 | -171 |
| 1 | 170 | 171 |
| -9,K,5 | | |
| 1 | 102 | 129 |
| 2 | 191 | -166 |
| 3 | 119 | 199 |
| -8,K,5 | | |
| 4 | 189 | 173 |
| 3 | 203 | -199 |
| -7,K,5 | | |
| 4 | 271 | 279 |
| 5 | 115 | -17 |
| -6,K,5 | | |
| 6 | 240 | 256 |
| 5 | 226 | 236 |
| -5,K,5 | | |
| 5 | 296 | 299 |
| 6 | 251 | 231 |
| -4,K,5 | | |
| 6 | 475 | -445 |
| -3,K,5 | | |
| 6 | 407 | 387 |
| -2,K,5 | | |
| 7 | 183 | 156 |
| 6 | 150 | -190 |
| -1,K,5 | | |
| 6 | 175 | -170 |
| 7 | 197 | 205 |
| 0,K,5 | | |
| 7 | 89* | -71 |
| 6 | 520 | -479 |
| 1,K,5 | | |
| 6 | 418 | -593 |
| 2,K,5 | | |
| 6 | 0* | -39 |
| 3,K,5 | | |
| 5 | 243 | 220 |
| 4 | 0* | 86 |
| 4,K,5 | | |
| 5 | 128 | -96 |
| 4 | 142 | 198 |
| 5,K,5 | | |
| 3 | 93 | 86 |
| 4 | 79* | -101 |
| 5 | 139 | -180 |
| 6,K,5 | | |
| 4 | 217 | 209 |
| 3 | 111 | -116 |
| 2 | 79* | 15 |
| 1 | 169 | 181 |
| 7,K,5 | | |
| 1 | 76* | 75 |
| 2 | 26* | -11 |
| -10,K,6 | | |
| 0 | 421 | 418 |
| 1 | 365 | 359 |
| 2 | 76* | 123 |
| -9,K,6 | | |
| 3 | 76* | 12 |
| 2 | 334 | 306 |
| 1 | 138 | -138 |
| 0 | 392 | 399 |
| -8,K,6 | | |
| 3 | 216 | -228 |
| 4 | 69* | -119 |
| -7,K,6 | | |
| 5 | 127 | -151 |
| 4 | 0* | 93 |
| -6,K,6 | | |
| 5 | 105 | -70 |
| 6 | 73* | 39 |
| -5,K,6 | | |
| 6 | 76* | 100 |
| 5 | 155 | 165 |
| -4,K,6 | | |
| 6 | 229 | 228 |
| -3,K,6 | | |
| 6 | 223 | 210 |
| -2,K,6 | | |
| 6 | 77* | 28 |
| 7 | 149 | 162 |
| -1,K,6 | | |
| 7 | 161 | 130 |
| 6 | 0* | -26 |
| 0,K,6 | | |
| 6 | 127 | 98 |
| 1,K,6 | | |
| 6 | 43* | 49 |
| 2,K,6 | | |
| 6 | 34* | 69 |
| 3,K,6 | | |
| 4 | 85* | 90 |
| 5 | 415 | -377 |
| 4,K,6 | | |
| 4 | 130 | 100 |
| 5 | 191 | -72 |
| 5,K,6 | | |
| 4 | 79* | 38 |
| 3 | 0* | 16 |
| 2 | 277 | -260 |
| 6,K,6 | | |
| 0 | 82* | -93 |
| 1 | 127 | 118 |
| 2 | 209 | 211 |
| 3 | 45* | 11 |
| 7,K,6 | | |
| 1 | 211 | 235 |
| 0 | 114 | 49 |
| -10,K,7 | | |
| 2 | 62* | -18 |
| 1 | 237 | 222 |
| -9,K,7 | | |
| 1 | 410 | 413 |
| 2 | 327 | 337 |
| 3 | 161 | 147 |
| 4 | 113 | -119 |
| -8,K,7 | | |
| 5 | 39* | -18 |
| 4 | 111 | -83 |
| 3 | 54* | -32 |
| -7,K,7 | | |
| 4 | 99 | -83 |
| 5 | 288 | -329 |
| -6,K,7 | | |
| 6 | 192 | -92 |
| 5 | 249 | -260 |
| -5,K,7 | | |
| 5 | 90 | 93 |
| 6 | 336 | -329 |
| -4,K,7 | | |
| 6 | 303 | -269 |
| -3,K,7 | | |
| 6 | 283 | 283 |
| -2,K,7 | | |
| 6 | 190 | 179 |
| -1,K,7 | | |
| 6 | 268 | 230 |
| 0,K,7 | | |
| 6 | 58* | 606 |
| 1,K,7 | | |
| 5 | 73* | 81 |
| 6 | 63* | 25 |
| 2,K,7 | | |
| 6 | 237 | -231 |
| 5 | 279 | -252 |
| 3,K,7 | | |
| 4 | 435 | -408 |
| 5 | 109 | 57 |
| 4,K,7 | | |
| 5 | 130 | 137 |
| 4 | 206 | -185 |
| 3 | 150 | -126 |
| 5,K,7 | | |
| 1 | 77* | -120 |
| 2 | 327 | -317 |
| 3 | 79* | -92 |
| 4 | 263 | -217 |
| 6,K,7 | | |
| 3 | 119 | -118 |
| 2 | 50* | 8 |
| 1 | 102 | -95 |
| -10,K,8 | | |
| 0 | 161 | -210 |
| 1 | 68* | -34 |
| 2 | 68* | -67 |
| -9,K,8 | | |
| 4 | 149 | 170 |
| 3 | 181 | 131 |
| 2 | 183 | -169 |
| 1 | 60* | -62 |
| 0 | 506 | 509 |
| -8,K,8 | | |
| 3 | 300 | 292 |
| 4 | 157 | 131 |
| 5 | 125 | 115 |
| -7,K,8 | | |
| 5 | 197 | 222 |
| 4 | 63* | -98 |
| -6,K,8 | | |
| 5 | 67* | 81 |
| 6 | 239 | -205 |
| -5,K,8 | | |
| 5 | 299 | -293 |
| -4,K,8 | | |
| 6 | 73* | -12 |
| -3,K,8 | | |
| 6 | 71* | -67 |
| -2,K,8 | | |
| 6 | 152 | 147 |
| -1,K,8 | | |
| 6 | 311 | 337 |
| 0,K,8 | | |
| 6 | 228 | 233 |
| 1,K,8 | | |
| 6 | 114 | 92 |
| 5 | 240 | 216 |
| 2,K,8 | | |
| 5 | 169 | 152 |
| 3,K,8 | | |
| 5 | 73* | -52 |
| 4 | 77* | 71 |
| 4,K,8 | | |
| 3 | 229 | -229 |
| 4 | 79* | -52 |
| 5,K,8 | | |
| 3 | 234 | -242 |
| 2 | 15* | -48 |
| 1 | 303 | -262 |
| 0 | 304 | 316 |
| 6,K,8 | | |
| 0 | 53* | -15 |
| 1 | 367 | -379 |
| 2 | 87* | 4 |
| -10,K,9 | | |
| 3 | 178 | -162 |
| 2 | 129 | -111 |
| 1 | 212 | -179 |
| -9,K,9 | | |
| 1 | 264 | -267 |
| 2 | 263 | -269 |
| 3 | 163 | -199 |
| 4 | 147 | 161 |
| -8,K,9 | | |
| 5 | 63* | -30 |
| 4 | 54* | 79 |
| 3 | 67* | -15 |
| -7,K,9 | | |
| 4 | 375 | 347 |
| 5 | 169 | 207 |
| -6,K,9 | | |
| 6 | 206 | 183 |
| 5 | 122 | -105 |
| -5,K,9 | | |
| 5 | 91 | -71 |
| 6 | 381 | 387 |
| -4,K,9 | | |
| 6 | 79* | 11 |
| -3,K,9 | | |
| 6 | 212 | -184 |
| -2,K,9 | | |
| 6 | 197 | -176 |
| -1,K,9 | | |
| 6 | 249 | -257 |
| 0,K,9 | | |
| 6 | 79* | -3 |
| 5 | 138 | 133 |
| 1,K,9 | | |
| 5 | 396 | 389 |
| 6 | 79* | 64 |
| 2,K,9 | | |
| 5 | 180 | 173 |
| 4 | 218 | 204 |
| 3,K,9 | | |
| 3 | 42* | 27 |
| 4 | 130 | -127 |
| 5 | 66* | 71 |
| 4,K,9 | | |
| 4 | 71* | -85 |
| 3 | 82* | 111 |
| 2 | 70* | 94 |
| 1 | 102 | 114 |
| 5,K,9 | | |
| 1 | 76* | 50 |
| 2 | 119 | -77 |
| 3 | 189 | 234 |
| -11,K,10 | | |
| 1 | 136 | -79 |
| 0 | 29* | -96 |
| -10,K,10 | | |
| 0 | 910 | -911 |
| 1 | 59* | -8 |
| -10,K,10 | | |
| 2 | 43* | 49 |
| 3 | 262 | -308 |
| -9,K,10 | | |
| 4 | 45* | -49 |
| 3 | 449 | -433 |
| 2 | 56* | -39 |
| 1 | 90* | 36 |
| -8,K,10 | | |
| 3 | 73* | -29 |
| 4 | 153 | -160 |
| 5 | 119 | -121 |
| -7,K,10 | | |
| 6 | 59* | 28 |
| 4 | 297 | -319 |
| -6,K,10 | | |
| 5 | 181 | 136 |
| 6 | 161 | -173 |
| -5,K,10 | | |
| 6 | 156 | -159 |
| 5 | 209 | 169 |
| -4,K,10 | | |
| 5 | 427 | 430 |
| 6 | 269 | -261 |
| -3,K,10 | | |
| 6 | 231 | -221 |
| 5 | 136 | 136 |
| -2,K,10 | | |
| 5 | 175 | -153 |
| 6 | 51* | 38 |
| -1,K,10 | | |
| 6 | 59* | -56 |
| 5 | 149 | -149 |
| 0,K,10 | | |
| 5 | 215 | -212 |
| 6 | 74* | -19 |
| 1,K,10 | | |
| 5 | 79* | -9 |
| 2,K,10 | | |
| 4 | 59* | 37 |
| 5 | 189 | 177 |
| 3,K,10 | | |
| 4 | 127 | 116 |
| 3 | 136 | 149 |
| 4,K,10 | | |
| 0 | 68 | 19 |
| 1 | 79* | -9 |
| 2 | 150 | -192 |
| 3 | 67* | 39 |
| 5,K,10 | | |
| 2 | 79* | 46 |
| 1 | 249 | 213 |
| 0 | 63* | 30 |
| -11,K,11 | | |
| 1 | 234 | 206 |
| -10,K,11 | | |
| 3 | 142 | -110 |
| 2 | 153 | -169 |
| 1 | 133 | 122 |
| -9,K,11 | | |
| 1 | 193 | -203 |
| 2 | 269 | -259 |
| 3 | 24* | -2 |
| 4 | 419 | -396 |
| -8,K,11 | | |
| 5 | 180 | -169 |
| 4 | 522 | -501 |
| 3 | 67* | 92 |
| -7,K,11 | | |
| 4 | 280 | -299 |
| 5 | 37* | -24 |
| -6,K,11 | | |
| 5 | 142 | -161 |
| -5,K,11 | | |
| 5 | 291 | -298 |
| 6 | 76* | 22 |
| -4,K,11 | | |
| 4 | 121 | 119 |
| 5 | 62* | 83 |
| -3,K,11 | | |
| 5 | 74* | 61 |
| 6 | 90* | 43 |
| -2,K,11 | | |
| 4 | 359 | 327 |
| 5 | 40* | 459 |
| -1,K,11 | | |
| 5 | 77* | 190 |
| 6 | 170 | 139 |
| 0,K,11 | | |
| 5 | 169 | -174 |
| 1,K,11 | | |
| 4 | 342 | -337 |
| 1,K,11 | | |
| 6 | 258 | -243 |
| 2,K,11 | | |
| 5 | 62* | 68 |
| 4 | 69* | 8 |
| 3 | 103 | -195 |
| 3,K,11 | | |
| 1 | 471 | -478 |
| 2 | 59* | -68 |
| 3 | 22* | -67 |
| 4 | 359 | 362 |
| 4,K,11 | | |
| 3 | 33* | -39 |
| 2 | 113 | 73 |
| 1 | 328 | -329 |
| 5,K,11 | | |
| 1 | 26* | -61 |
| -11,K,12 | | |
| 1 | 181 | 167 |
| 0 | 77* | -17 |
| -10,K,12 | | |
| 0 | 549 | 549 |
| 1 | 433 | -441 |
| 2 | 73* | -30 |
| 3 | 166 | 149 |
| -9,K,12 | | |
| 4 | 167 | 147 |
| 3 | 319 | -313 |
| 2 | 263 | 261 |
| 1 | 169 | -146 |
| -8,K,12 | | |
| 3 | 630 | -605 |
| 4 | 149 | 152 |
| 5 | 407 | -379 |
| -7,K,12 | | |
| 5 | 333 | -363 |
| 4 | 51* | 4 |
| -6,K,12 | | |
| 5 | 155 | -172 |
| -5,K,12 | | |
| 6 | 73* | 89 |
| 5 | 0* | 28 |
| -4,K,12 | | |
| 5 | 76* | -20 |
| 6 | 20* | -47 |
| -3,K,12 | | |
| 6 | 139 | -103 |
| 5 | 211 | 230 |
| -2,K,12 | | |
| 5 | 286 | 261 |
| 6 | 212 | -203 |
| -1,K,12 | | |
| 5 | 193 | 179 |
| 0,K,12 | | |
| 4 | 93 | 93 |
| 5 | 223 | 238 |
| 1,K,12 | | |
| 5 | 29* | 13 |
| 4 | 63* | 59 |
| 2,K,12 | | |
| 2 | 279 | 278 |
| 3 | 197 | -169 |
| 4 | 180 | -162 |
| 3,K,12 | | |
| 3 | 173 | -199 |
| 2 | 80* | -97 |
| 1 | 166 | 193 |
| 0 | 310 | -291 |
| 4,K,12 | | |
| 0 | 243 | -299 |
| 1 | 125 | -103 |
| 2 | 141 | -193 |
| -11,K,13 | | |
| 1 | 192 | -201 |
| -10,K,13 | | |
| 3 | 195 | 217 |
| 2 | 252 | 228 |
| 1 | 277 | -285 |
| -9,K,13 | | |
| 1 | 200 | 207 |
| 2 | 71* | 98 |
| 3 | 128 | -94 |
| 4 | 170 | 168 |
| -8,K,13 | | |
| 4 | 158 | 188 |
| 3 | 127 | 139 |
| -7,K,13 | | |
| 4 | 421 | -416 |
| 5 | 60* | 109 |
| -6,K,13 | | |
| 5 | 220 | 236 |
| 4 | 667 | -710 |
| -5,K,13 | | |
| 5 | 142 | -150 |
| -4,K,13 | | |
| 4 | 212 | 191 |
| 5 | 65* | -70 |
| -3,K,13 | | |
| 5 | 37* | 15 |
| 4 | 111 | -19 |
| -2,K,13 | | |
| 5 | 479 | -469 |
| -1,K,13 | | |
| 4 | 288 | 269 |
| 5 | 139 | -141 |
| 0,K,13 | | |
| 5 | 178 | 162 |
| 4 | 566 | 558 |
| 1,K,13 | | |
| 3 | 211 | 262 |
| 4 | 272 | 236 |
| 2,K,13 | | |
| 4 | 80* | -45 |
| 3 | 152 | -139 |
| 2 | 156 | 145 |
| 1 | 229 | 293 |
| 3,K,13 | | |
| 1 | 96 | 67 |
| 2 | 127 | -91 |
| 3 | 70* | 12 |
| 4,K,13 | | |
| 1 | 0* | -52 |
| -11,K,14 | | |
| 1 | 331 | 328 |
| 0 | 189 | -196 |
| -10,K,14 | | |
| 0 | 279 | -259 |
| 1 | 195 | 185 |
| 2 | 193 | -176 |
| 3 | 156 | 166 |
| -9,K,14 | | |
| 4 | 169 | -139 |
| 3 | 434 | 437 |
| 2 | 178 | 191 |
| 1 | 209 | 200 |
| 0 | 639 | -694 |
| -8,K,14 | | |
| 3 | 153 | 159 |
| 4 | 73* | -99 |
| -7,K,14 | | |
| 5 | 0* | -33 |
| 4 | 266 | 285 |
| -6,K,14 | | |
| 4 | 158 | 159 |
| 5 | 279 | -271 |
| -5,K,14 | | |
| 5 | 389 | -421 |
| 4 | 110 | 139 |
| -4,K,14 | | |
| 4 | 31* | -71 |
| 5 | 458 | -455 |
| -3,K,14 | | |
| 5 | 47* | -106 |
| 4 | 65* | -18 |
| -2,K,14 | | |
| 4 | 121 | 112 |
| 5 | 113 | -108 |
| -1,K,14 | | |
| 5 | 46* | 72 |
| 4 | 299 | -323 |
| 0,K,14 | | |
| 3 | 20* | 189 |
| 4 | 263 | -256 |
| 1,K,14 | | |
| 4 | 60* | 86 |
| 3 | 333 | 335 |
| 2 | 59* | 62 |
| 2,K,14 | | |
| 0 | 455 | 435 |
| 1 | 134 | -158 |
| 2 | 195 | 137 |
| 3 | 429 | 436 |
| 3,K,14 | | |
| 2 | 79* | 80 |
| 1 | 183 | 141 |
| 0 | 173 | 101 |
| -11,K,15 | | |
| 1 | 239 | -219 |
| -10,K,15 | | |
| 3 | 218 | -205 |
| 2 | 39* | 43 |
| 1 | 449 | -497 |
| -9,K,15 | | |
| 1 | 302 | -309 |
| 2 | 313 | 285 |
| 3 | 257 | -223 |
| 4 | 119 | -93 |
| -8,K,15 | | |
| 3 | 60* | 51 |
| 2 | 353 | 346 |
| -7,K,15 | | |
| 3 | 132 | 141 |
| 4 | 187 | 199 |
| 5 | 255 | -275 |
| -6,K,15 | | |
| 5 | 79* | 42 |
| 4 | 149 | 211 |
| -5,K,15 | | |
| 4 | 45* | 115 |
| 5 | 180 | 230 |
| -4,K,15 | | |
| 5 | 37* | 43 |
| 4 | 359 | -356 |
| -3,K,15 | | |
| 4 | 471 | -496 |
| 5 | 111 | 109 |
| -2,K,15 | | |
| 5 | 79* | 45 |
| 4 | 416 | -398 |
| -1,K,15 | | |
| 3 | 96 | 99 |
| 4 | 279 | -365 |
| 5 | 0* | -12 |
| 0,K,15 | | |
| 4 | 87* | -147 |
| 3 | 39* | -41 |
| 2 | 116 | 120 |
| 1,K,15 | | |
| 1 | 71* | -135 |
| 2 | 102 | -66 |
| 3 | 111 | -63 |
| 2,K,15 | | |
| 2 | 65* | 76 |
| 1 | 83* | 1 |
| -11,K,16 | | |
| 1 | 212 | -221 |
| 0 | 93* | -49 |
| -10,K,16 | | |
| 0 | 71* | -63 |
| 1 | 128 | 108 |
| 2 | 229 | -230 |
| -9,K,16 | | |
| 3 | 65* | 28 |
| 2 | 707 | -699 |
| 1 | 209 | -216 |
| 0 | 172 | -175 |
| -8,K,16 | | |
| 2 | 395 | -386 |
| 3 | 71* | -6 |
| 4 | 36* | 19 |
| -7,K,16 | | |
| 4 | 73* | 50 |
| 3 | 53* | 48 |
| -6,K,16 | | |
| 3 | 322 | 339 |
| 4 | 60* | -88 |
| 5 | 172 | 207 |
| -5,K,16 | | |
| 5 | 164 | 149 |
| 4 | 139 | -163 |
| -4,K,16 | | |
| 4 | 220 | 239 |
| 5 | 0* | 12 |
| -3,K,16 | | |
| 5 | 328 | -332 |
| 4 | 235 | 235 |
| 3 | 0* | -9 |
| -2,K,16 | | |
| 3 | 415 | -433 |
| 4 | 88* | -77 |
| -1,K,16 | | |
| 4 | 132 | 92 |
| 3 | 436 | -421 |
| 2 | 264 | -272 |
| 0,K,16 | | |
| 0 | 98* | 19 |
| 1 | 15* | 70 |
| 2 | 0* | -55 |
| 3 | 155 | -151 |
| 4 | 59* | 14 |
| 1,K,16 | | |
| 3 | 229 | -197 |
| 2 | 59* | 19 |
| 1 | 223 | 217 |
| 0 | 40* | 40 |
| 2,K,16 | | |
| 0 | 170 | -149 |
| 1 | 138 | 30 |
| -10,K,17 | | |
| 2 | 119 | -74 |
| 1 | 297 | 290 |
| -9,K,17 | | |
| 1 | 44* | -25 |
| -9,K,17 | | |
| 2 | 89 | -94 |
| 3 | 121 | 128 |
| -8,K,17 | | |
| 4 | 136 | -145 |
| 3 | 339 | -324 |
| 2 | 0* | 31 |
| 1 | 362 | -361 |
| -7,K,17 | | |
| 2 | 201 | -199 |
| 3 | 499 | -493 |
| 4 | 134 | 156 |
| -6,K,17 | | |
| 4 | 42* | 19 |
| 3 | 48* | -42 |
| -5,K,17 | | |
| 3 | 317 | -301 |
| 4 | 82* | -73 |
| -4,K,17 | | |
| 4 | 297 | 292 |
| 3 | 28* | -23 |
| -3,K,17 | | |
| 3 | 410 | 419 |
| 4 | 50* | -43 |
| -2,K,17 | | |
| 4 | 70* | -96 |
| 3 | 161 | 149 |
| 2 | 40* | -63 |
| -1,K,17 | | |
| 1 | 326 | 323 |
| 2 | 506 | -489 |
| 3 | 229 | 229 |
| 4 | 33* | -8 |
| 0,K,17 | | |
| 3 | 85* | 6 |
| 2 | 320 | -307 |
| 1 | 150 | 130 |
| 1,K,17 | | |
| 1 | 0* | 49 |
| 2 | 166 | -153 |
| -10,K,18 | | |
| 0 | 62* | 113 |
| 1 | 172 | 153 |
| 2 | 528 | 509 |
| -9,K,18 | | |
| 3 | 65* | -30 |
| 2 | 252 | 270 |
| 1 | 62* | 55 |
| 0 | 327 | 327 |
| -8,K,18 | | |
| 0 | 154 | 136 |
| 1 | 288 | -298 |
| 2 | 262 | 272 |
| 3 | 239 | 297 |
| -7,K,18 | | |
| 4 | 67* | -85 |
| 3 | 71* | -69 |
| 2 | 76* | -92 |
| 1 | 107 | -109 |
| -6,K,18 | | |
| 2 | 754 | -771 |
| 3 | 36* | 22 |
| 4 | 174 | 169 |
| -5,K,18 | | |
| 4 | 65* | -29 |
| 3 | 133 | 158 |
| 2 | 565 | -551 |
| -4,K,18 | | |
| 2 | 252 | -256 |
| 3 | 133 | -119 |
| 4 | 65* | 64 |
| -3,K,18 | | |
| 4 | 33* | 37 |
| 3 | 62* | 67 |
| 2 | 308 | -309 |
| -2,K,18 | | |
| 0 | 915 | -907 |
| 1 | 67* | -98 |
| 2 | 212 | 199 |
| 3 | 48* | 95 |
| 4 | 68* | -105 |
| -1,K,18 | | |
| 3 | 129 | -80 |
| 2 | 302 | 276 |
| 1 | 316 | 283 |
| 0 | 166 | -169 |
| 0,K,18 | | |
| 0 | 483 | 456 |
| 1 | 279 | -261 |
| 2 | 166 | 150 |
| -10,K,19 | | |
| 1 | 328 | 326 |
| -9,K,19 | | |
| 1 | 302 | 293 |
| 2 | 119 | 107 |
| 3 | 300 | 282 |
| -8,K,19 | | |
| 3 | 325 | 329 |
| 2 | 209 | 179 |
| 1 | 331 | 301 |
| -7,K,19 | | |
| 1 | 324 | 317 |
| 2 | 62* | -96 |
| 3 | 126 | 76 |
| 4 | 82* | 52 |
| -6,K,19 | | |
| 4 | 108 | 117 |
| 3 | 65* | 119 |
| 2 | 159 | -173 |
| 1 | 3* | 3 |
| -5,K,19 | | |
| 1 | 368 | -349 |
| 2 | 42* | -46 |
| 3 | 206 | -159 |
| 4 | 141 | -93 |
| -4,K,19 | | |
| 4 | 91* | 67 |
| 3 | 382 | -356 |
| 2 | 70* | -51 |
| 1 | 577 | -542 |
| -3,K,19 | | |
| 1 | 385 | -342 |
| 2 | 63* | 27 |
| 3 | 229 | -196 |
| -2,K,19 | | |
| 3 | 89* | -110 |
| 2 | 79* | 100 |
| 1 | 156 | -146 |
| -1,K,19 | | |
| 1 | 82* | -76 |
| 2 | 108 | 90 |
| 0,K,19 | | |
| 1 | 91* | -50 |
| -10,K,20 | | |
| 0 | 29* | 17 |
| 1 | 161 | -190 |
| -9,K,20 | | |
| 2 | 60* | -53 |
| 1 | 459 | 463 |
| 0 | 410 | 395 |
| -8,K,20 | | |
| 0 | 662 | 650 |
| 1 | 195 | 161 |
| 2 | 67* | -38 |
| 3 | 240 | 231 |
| -7,K,20 | | |
| 3 | 73* | 83 |
| 2 | 536 | 521 |
| 1 | 193 | 198 |
| 0 | 46* | 37 |
| -6,K,20 | | |
| 0 | 269 | 271 |
| 1 | 361 | 368 |
| 2 | 339 | 319 |
| 3 | 155 | -196 |
| -5,K,20 | | |
| 3 | 73* | 77 |
| 2 | 136 | 198 |
| 1 | 299 | -307 |
| 0 | 170 | 150 |
| -4,K,20 | | |
| 0 | 512 | -492 |
| 1 | 176 | -165 |
| 2 | 132 | 137 |
| 3 | 68* | 27 |
| -3,K,20 | | |
| 3 | 73* | -19 |
| 2 | 44* | -447 |
| 1 | 60* | -11 |
| 0 | 280 | -274 |
| -2,K,20 | | |
| 0 | 322 | -296 |
| 1 | 229 | -208 |
| 2 | 455 | -419 |
| -1,K,20 | | |
| 1 | 44* | 78 |
| 0 | 206 | -197 |

## VII.5 DESCRIPTION OF THE STRUCTURE

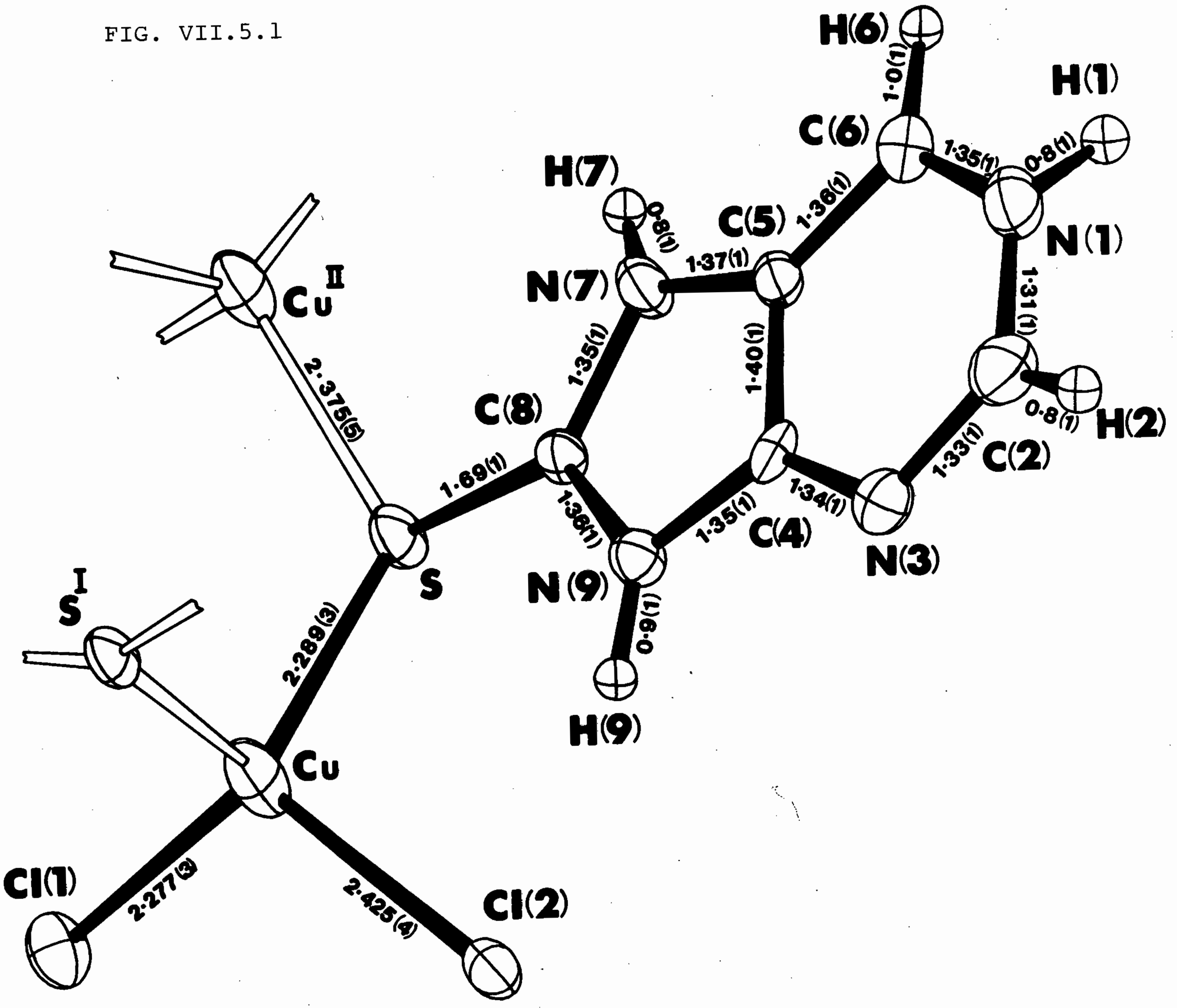
Interatomic distances and bond angles in the polymer chain are listed in Tables VII.5.1 and VII.5.2. Least-squares planes are listed in Table VII.5.3.

The molecular configuration is shown in Fig.VII.5.1. Atoms of the asymmetric unit are linked by shaded bonds and symmetry superscripts refer to the transformations listed in Table VII.5.4. The structure is polymeric, consisting of infinite columns of 8-mercaptopurine units which are bonded to copper chloride *via* their sulphur atoms. The chain of -S-Cu-S-Cu- bonds forms a helix around the two-fold crystallographic screw axis. The latter feature is quite an unusual one but a similar spiralling chain of Cu and S atoms has been observed in the crystal structure of bis(thiourea)copper(I)chloride[140]. The nature of the bonds involving sulphur atoms is somewhat different from that observed in the present study however.

The two unique Cu-S bond lengths (2.289(3) and 2.375(5) Å) differ by nearly 0.1 Å. Analogous bond lengths in bis(thiourea)copper(I)chloride vary from 2.254(5) to 2.309(5) Å. The Cu-Cl bond lengths (2.277(3) and 2.425(4) Å) also differ considerably showing a similar trend to that observed in the 6-mercaptopurine copper(I) chloride structure discussed in section VII.3.

A least-squares plane calculation (Table VII.5.3)

FIG. VII.5.1


H(6)
H(1)
C(6)
1·0(1)
1·35(1)
0·8(1)
1·36(1)
H(7)
C(5)
N(1)
0·8(1)
1·37(1)
Cu^II
N(7)
1·31(1)
1·40(1)
1·35(1)
2·375(5)
C(8)
0·8(1)
H(2)
C(2)
1·33(1)
1·69(1)
1·34(1)
1·36(1)
1·35(1)
C(4)
N(3)
S
N(9)
S^I
2·289(3)
0·9(1)
H(9)
Cu
Cl(1)
2·277(3)
2·425(4)
Cl(2)

## TABLE VII.5.1

## INTERATOMIC DISTANCES* AND THEIR E.S.D.'s (Å)

| | | | |
|---|---|---|---|
| Cu—Cl(1) | 2.277(3) | N(1)-C(2) | 1.31(1) |
| Cu—Cl(2) | 2.425(4) | C(2)-N(3) | 1.33(1) |
| Cu—S | 2.289(3) | N(3)-C(4) | 1.34(1) |
| $Cu^{II}$-S | 2.375(5) | C(5)-C(6) | 1.36(1) |
| S—C(8) | 1.69(1) | N(1)-C(6) | 1.35(1) |
| N(9)-C(8) | 1.36(1) | N(1)-H(1) | 0.8(1) |
| N(7)-C(8) | 1.35(1) | C(2)-H(2) | 0.8(1) |
| N(7)-C(5) | 1.37(1) | C(6)-H(6) | 1.0(1) |
| C(5)-C(4) | 1.40(1) | N(7)-H(7) | 0.8(1) |
| C(4)-N(9) | 1.35(1) | N(9)-H(9) | 0.9(1) |

## TABLE VII.5.2

## BOND ANGLES* AND THEIR E.S.D.'s (DEGREES) IN THE POLYMER CHAIN

| | | | |
|---|---|---|---|
| Cl(1)-Cu-Cl(2) | 111.9(1) | N(3)-C(4)-C(5) | 125.2(8) |
| Cl(1)-Cu-S | 116.3(1) | C(4)-C(5)-C(6) | 118.4(7) |
| Cl(2)-Cu-S | 108.5(1) | C(5)-C(6)-N(1) | 115.0(7) |
| $S^{I}$-Cu-Cl(1) | 109.1(1) | N(3)-C(4)-N(9) | 127.0(7) |
| $S^{I}$-Cu-Cl(2) | 102.2(1) | C(6)-C(5)-N(7) | 135.7(7) |
| $S^{I}$-Cu-S | 107.9(1) | C(5)-C(4)-N(9) | 107.9(7) |
| Cu-S-C(8) | 105.8(3) | C(4)-N(9)-C(8) | 108.7(7) |
| $Cu^{II}$-S-C(8) | 107.4(2) | N(9)-C(8)-N(7) | 108.1(8) |
| $Cu^{II}$-S-Cu | 123.5(1) | N(9)-C(8)-S | 125.4(6) |
| C(2)-N(1)-C(6) | 123.7(9) | N(7)-C(8)-S | 126.4(5) |
| N(1)-C(2)-N(3) | 125.2(9) | C(8)-N(7)-C(5) | 109.3(6) |
| C(2)-N(3)-C(4) | 112.5(7) | N(7)-C(5)-C(4) | 105.9(8) |

* Superscripts refer to the symmetry code in Table VII.5.4.

## TABLE VII.5.3

## LEAST-SQUARES PLANES

The equations of the planes are expressed in orthogonalized space as $PI+QJ+RK=S$.

Plane I: through atoms N(1),C(2),N(3),C(4),C(5),C(6),N(7),C(8), N(9) and S of the ligand.

Equation: $0.67360I-0.46929J+0.57099K=2.60268$

| Atoms included in calculation | Dist. from plane, Å | Atoms not included in calculation | Dist. from plane, Å |
|---|---|---|---|
| N(1) | .015 | H(1) | -.138 |
| C(2) | .029 | H(2) | -.002 |
| N(3) | .003 | Cu | -.696 |
| C(4) | -.008 | Cl(1) | -.449 |
| C(5) | -.018 | Cl(2) | .303 |
| C(6) | .003 | H(6) | .028 |
| N(7) | -.019 | H(7) | .045 |
| C(8) | -.025 | | |
| N(9) | -.040 | H(9) | .069 |
| S | .062 | | |

Plane II: through atoms N(1),C(2),N(3),C(4),C(5) and C(6) of the pyrimidine ring.

Equation: $0.66231I-0.47901J+ 0.57611K=2.68871$

| Atoms included in calculation | Dist. from plane, Å | Atoms not included in calculation | Dist. from plane, Å |
|---|---|---|---|
| N(1) | -.005 | H(1) | -.167 |
| C(2) | .006 | H(2) | -.037 |
| N(3) | -.005 | | |
| C(4) | .003 | N(9) | -.011 |
| C(5) | -.002 | N(7) | .019 |
| C(6) | .003 | H(6) | .030 |

Plane III: through atoms C(4),C(5),N(7),C(8) and N(9) of the imidazole ring.

Equation: $0.66777I-0.46918J+0.57788K=2.68573$

| Atoms included in calculation | Dist. from plane, Å | Atoms not included in calculation | Dist. from plane, Å |
|---|---|---|---|
| C(4) | .010 | N(3) | .017 |
| C(5) | -.007 | C(6) | .002 |
| N(7) | .001 | H(7) | .063 |
| C(8) | .006 | S | .106 |
| N(9) | -.010 | H(9) | .105 |

shows that the 8-mercaptopurine ligand is essentially planar. The greatest deviation from the plane is that of the sulphur atom, 0.062 Å. The C(8)-S distance of 1.69(1) Å indicates that this is a double carbon-sulphur bond[136,137] which would require S-Cu bonding *via* in-plane $sp^2$ orbitals on the sulphur atom. The bonding around S seems nearer tetrahedral however (C(8)-S-Cu 105.8(3)° and C(8)-S-$Cu^{II}$ 107.4(2)°) with the angle Cu-S-$Cu^{II}$ 123.5(1)° the exception. The latter value may be explained by Cu ... $Cu^{II}$ repulsions.

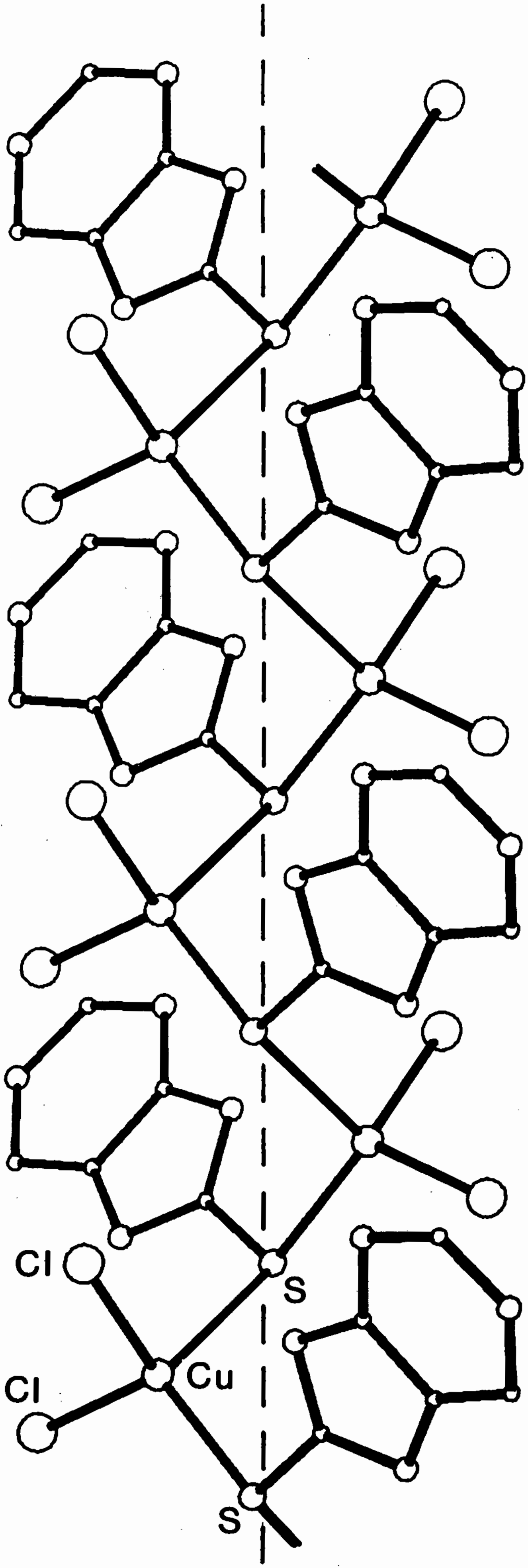
As the crystal structure of 8-mercaptopurine has not been reported, bond lengths and angles in the complexed ligand cannot be compared with those in the parent compound. In addition, the ligand is protonated in the complex. The bond lengths and bond angles do, however, fall within the expected ranges for purine derivatives[134].

In Fig. VII.5.2, a single column of the polymer is drawn with the two-fold screw axis (parallel to *b*) represented by a dashed line. This figure emphasises that the 8-mercaptopurine ligands are bridged (*via* their sulphur atoms) by $CuCl_2$ units.

## Hydrogen bonding in the complex

All data pertaining to hydrogen bonding and short contacts are presented in Table VII.5.4.

FIG. VII.5.2



## TABLE VII.5.4

## HYDROGEN BONDING AND SHORT CONTACTS, DISTANCES IN Å, ANGLES IN DEGREES

Hydrogen bond data

| | | | |
|---|---|---|---|
| N(1) ... Cl(2)$^{IV}$ | 3.082(9) | N(1)-H(1) ... Cl(2)$^{IV}$ | 172(8) |
| H(1) ... Cl(2)$^{IV}$ | 2.3(1) | | |
| N(7) ... Cl(1)$^{II}$ | 3.144(7) | N(7)-H(7) ... Cl(1)$^{II}$ | 156(10) |
| H(7) ... Cl(1)$^{II}$ | 2.37(8) | | |
| N(9) ... Cl(2) | 3.159(8) | N(9)-H(9) ... Cl(2) | 161(8) |
| H(9) ... Cl(2) | 2.29(9) | | |

Short contacts

| | | | |
|---|---|---|---|
| C(6) ... Cl(1)$^{III}$ | 3.360(8) | C(6)-H(6) ... Cl(1)$^{III}$ | 153(8) |
| H(6) ... Cl(1)$^{III}$ | 2.46(7) | | |

Roman numeral superscripts refer to the following coordinate transformations:

| | | | |
|---|---|---|---|
| I | $-x, \frac{1}{2} + y, \frac{1}{2} - z + 1$ | II | $-x, \frac{1}{2} + y - 1, \frac{1}{2} - z + 1$ |
| III | $x, \frac{1}{2} - y - 1, \frac{1}{2} + z - 1$ | IV | $x, \frac{1}{2} - y, \frac{1}{2} + z$ |

There are two distinct N-H...Cl hydrogen bonds within a polymer chain involving the imidazole nitrogen atoms N(7) and N(9). A third N-H...Cl hydrogen bond involves N(1). The latter interactions and short C-H...Cl interactions form cross-links between adjacent polymer chains. All of the N-H...Cl hydrogen bonds are represented by dashed lines in Fig.VII.5.3, the [010] projection of the structure.

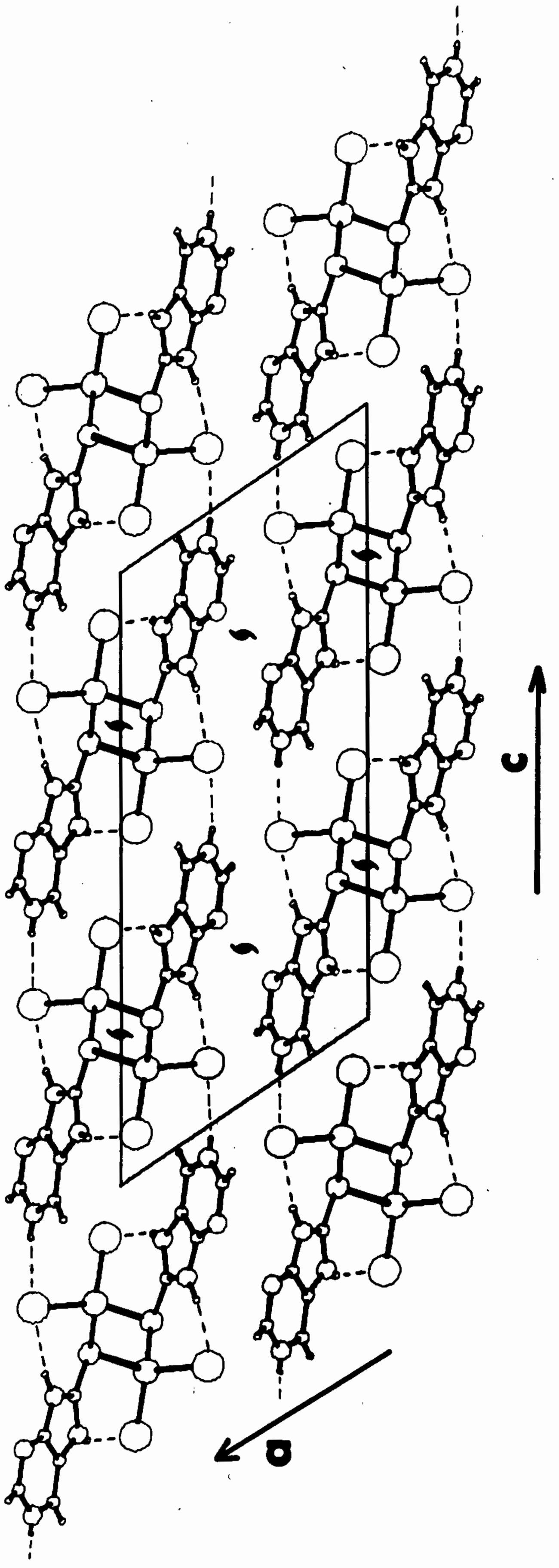


FIG. VII.5.3

## VII.6 DISCUSSION

### Common structural features in the mercaptopurine complexes

The mercaptopurine-copper(I) chloride complexes share certain common structural features and these are discussed in turn. The abbreviation MP for mercaptopurine is used where convenient.

The formula units, (protonated MP)Cu(I)$Cl_2$ are associated in the solid state; in the case of 6-MP, a dimer is formed while with 8-MP, polymerisation occurs. This association presumably arises in order to satisfy the normal quadrivalency of the Cu(I) ion. Formation of -S-Cu-S- linkages in both cases is not unexpected when considered in the light of the HSAB principle[10]. The Cu(I) ion is a class b ("soft") species, forming its most stable complexes with ligand atoms of the same class, for example sulphur. On this basis, Cu-S rather than Cu-N bonds should preferentially form. In bis(6-mercapto-9-benzylpurine)palladium(II)-dimethylacetamide, the coordination geometry of the Pd(II) ion is square-planar (typical of this species) with two chelating ligands contributing both sulphur and N(7) donor atoms[139]. Five-membered rings are thus formed with an average S-Pd-N(7) angle of 88°. The preferred geometry of the Cu(I) ion being tetrahedral, it may be argued that in

containing bridging halogen atoms was postulated. It was also suggested that reduction to copper(I) occurs after coordination of the ligand to the metal.

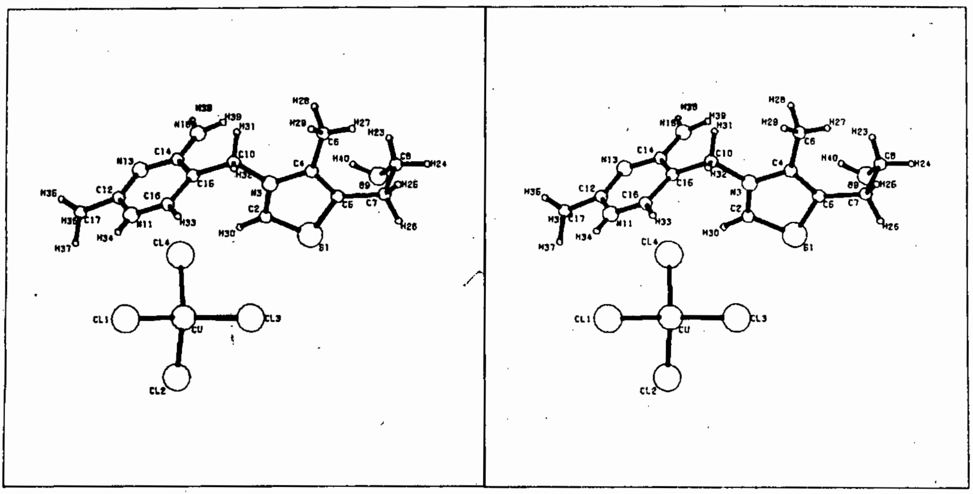
Retention of the thione tautomeric form C=S on coordination of sulphur to copper has been observed in complexes other than those studied here. In chlorobis-(2-thiouracil)copper(I)dimethylformamide solvate[144], the ligand again binds to copper *via* the sulphur atom of the C=S group. Although the reported carbon-sulphur distance (1.69(1) Å) again indicates a double bond, the coordination geometry appears to be tetrahedral (mean C=S-Cu angle, 109.8°) rather than the expected trigonal. Similar features are observed in copper-thiourea complexes[140,141].

## General conclusions

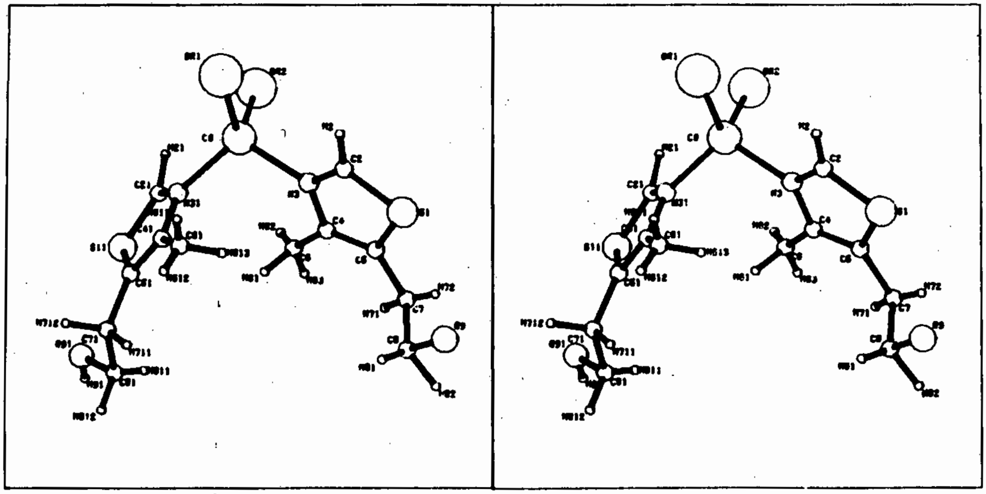
These crystallographic studies have shown that the sulphur atom in both 6- and 8- MP is the sole donor atom in their copper(I) complexes. In addition, the X-ray analyses have provided interesting structural data regarding -S-Cu-S- catenation, protonation of the ligands and consequent hydrogen bonding in the crystalline state. Further studies may be directed towards the synthesis of mercaptopurine derivatives which more closely resemble thionucleosides. This may be achieved by blocking various sites on the molecule with cyclic substituents. Coupled with the X-ray method, the determination of equilibrium constants and spectroscopic studies should provide a better understanding of the role of metal ions in nucleic acid chemistry, in particular with regard to the functional mechanism of tRNA. The relationship between metal-ligand bond type and carcinostatic activity requires further research in order to explain the antineoplastic properties of metal complexes.

# STEREOSCOPIC ILLUSTRATIONS

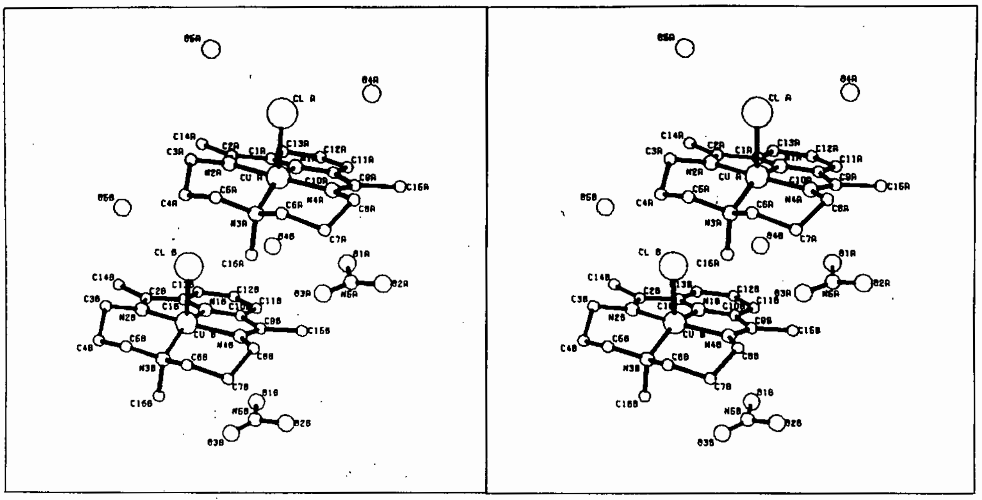
The drawings which follow have been prepared with the computer program[48] PLUTO. They are designed to be viewed with the STEREOPTICON 707 viewer, provided on the inside of the back cover of this thesis.



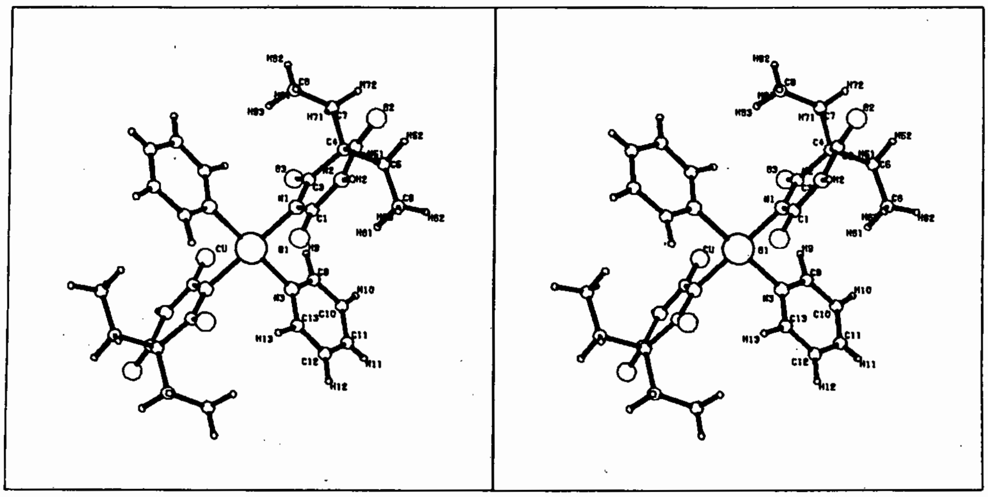
The Thiamine Hydrochloride Copper(II) Complex



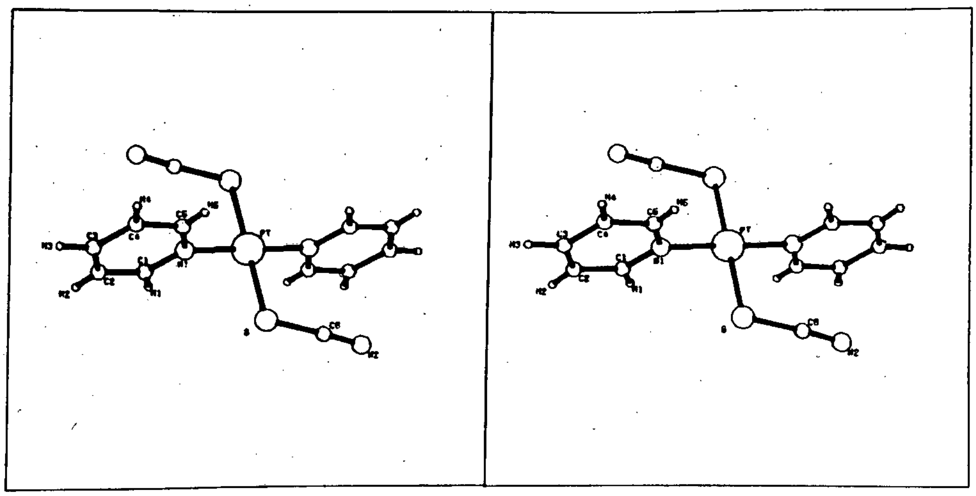
Dibromobis-[5-(2-hydroxyethyl)-4-methylthiazole]Cobalt(II)



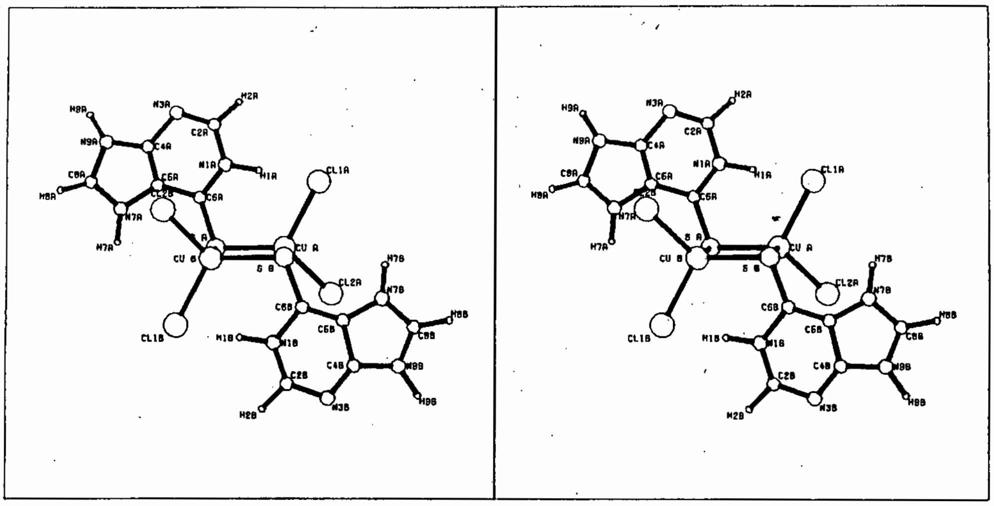
**Chloro(2,7,12-trimethyl-3,7,11,17-tetraazabicyclo[11.3.1] heptadeca-1(17),2,11,13,15-pentaene) Copper(II) Nitrate Dihydrate**



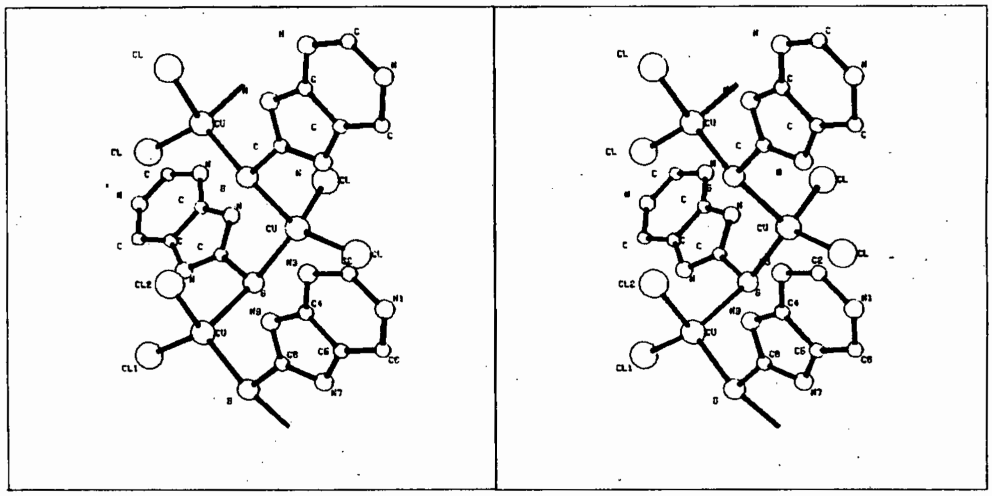
Bis- (5,5'- diethylbarbiturato) (bispyridine) Copper (II)



Trans- (Dithiocyanato) (bispyridine) Platinum(II)



**The Dimeric 6–Mercaptopurine Copper(I)Chloride Complex**



**The Polymeric 8–Mercaptopurine Copper(I)Chloride Complex**

# REFERENCES

1. EICHORN, G.L. (Editor).(1973). *Inorganic Biochemistry.* Vol. I. Amsterdam : Elsevier Scientific Publishing Company.

2. EICHORN, G.L. (Editor).(1973). *Inorganic Biochemistry.* Vol. II. Amsterdam : Elsevier Scientific Publishing Company.

3. WILLIAMS, D.R. (1971). *The Metals of Life.* London : Van Nostrand.

4. BURGER, A. (Editor).(1970). *Medicinal Chemistry.* Part I. New York : Wiley Interscience.

5. BURGER, A. (Editor).(1970). *Medicinal Chemistry.* Part II. New York : Wiley Interscience.

6. PURCELL, W.P., SINGER, J.A., SUNDARAM, K. & PARKS, G.L. in Ref. 4. p 164.

7. RICH, A. & DAVIDSON, N. (Editors). (1968). *Structural Chemistry and Molecular Biology.* San Francisco : Freeman.

8. BERGMANN, E.D. & PULLMAN, B. (Editors). (1972). *The Purines - Theory and Experiment (The Jerusalem Symposia on Quantum Chemistry and Biochemistry, IV).* Jerusalem : The Israel Academy of Sciences and Humanities.

9. ÖSTERBERG, R. (1974). *Coord.Chem.Rev. 12,* 309.

10. ANGELICI, R.J. in Ref.1. p 67.

11. EICHORN, G.L. in Ref. 2. p 1191.

12. PHILIPS, R. (1966). *Chem.Rev. 66,* 501.

13. SUNDARALINGAM, M. & CARRABINE, J.A. (1971). *J.Mol.Biol. 61,* 287.

14. SLETTEN, E. in Ref. 8. p 160.

15. AKBAR ALI, M. & LIVINGSTONE, S.E. (1974). *Coord.Chem.Rev. 13,* 101.

16. MARZOTTO, A., NICOLINI, M., SIGNOR, A. & GALZIGNA, L. (1970). *Atti Accad.Peloritana Pericolanti, Classe Sci. Fis.Mat.Nat. 50,* 79.

17. CLEMENTE, D.A., BANDOLI, G., BENETOLLO, F. & MARZOTTO, A. (1974). *J.Cryst.Mol.Struct. 4,* 1.

18. FRANKLIN, K., RICHARDSON, M.F., (Brock University, Ontario) & THOMPSON, D.M. (South Carolina, U.S.A.). (1974). private communication.

19. SCHELLENBERGER, A. (1967). *Angew.Chem. 6*, 1024.

20. GUDBJARNASON, S. (1970). *Methods Enzymol. A*, 93.

21. WILLIAMS, R.R. (1937). *Ind.and Eng.Chem. 29*, 980.

22. HUGHES, M.N. & RUTT, K.J. (1971). *Inorg.Chem. 10(2)*, 414.

23. HUGHES, M.N. & RUTT, K.J. (1970). *J.Chem.Soc. A. 18*, 3015.

24. WEAVER, J.A., HAMBRIGHT, P., TALBERT, P.T., KANG, E. & THORPE, A.N. (1970). *Inorg.Chem. 9(2)*, 268.

25. LEAVER, F.W. & WOODY, B.R. (1964). *Proc.Soc.Exptl.Biol. Med. 117*, 359.

26. CLEARE, M.J. (1974). *Coord.Chem.Rev. 12*, 349.

27. TAYLOR, M.R., GLUSKER, J.P., GABE, E.J. & MINKIN, J.A. (1974). *Bioinorg.Chem. 3(3)*, 189.

28. KIRSCHNER, S., WEI, Y., FRANCIS, D. & BERGMAN, J.G. (1966). *J.Medicinal Chem. 9*, 369.

29. THOMSON, A.J., WILLIAMS, R.J.P. & RESLOVA, S. (1972). *Struct.Bond. 11*, (Biochemistry), 1.

30. CAMMARATA, A. & MARTIN, A.N. in Ref. 4.p 151.

31. WILLIAMS, D.R. (1974). *Educ.Chem. 11(5)*, 166.

32. THIENES, C.H. & HALEY, T.J. (1972). *Clinical Toxicology.* London : Henry Kimpton.

33. LEVI, L. & HUBLEY, C.E. (1956). *Anal.Chem. 28*, 1591.

34. CRACIUNESCU, D., POPA, E. & FRUMA, A. (1970). *Israel Journal of Chemistry, 8*, 93.

35. NASSIMBENI, L.R. & RODGERS, A.L. (1974). *Acta Cryst. B30*, 2593.

36. CHRISTENSEN, J.J., EATOUGH, D.J. & IZATT, R.M. (1974). *Chem.Rev. 74(3)* , 351.

37. IZATT, R.M., EATOUGH, D.J. & CHRISTENSEN, J.J. (1973). *Struct.Bond. 16*, 161.

38. PRESSMAN, B.C. in Ref. 1. p 203.

39. OCHIAI, E. (1968). *Coord.Chem.Rev. 3*, 49.

40. *International Tables for X-ray Crystallography* (1969). Vol. I. Birmingham : Kynoch Press.

41. *International Tables for X-ray Crystallography* (1967). Vol. II. Birmingham : Kynoch Press.

42. *International Tables for X-ray Crystallography* (1968). Vol. III. Birmingham : Kynoch Press.

43. BUERGER, M.J. (1942). *X-Ray Crystallography,* p 179. New York : John Wiley and Sons.

44. STOUT, G.H. & JENSEN, L.H. (1968). *X-ray Structure Determination,* p 179. London : Macmillan.

45. BUSING, W.R., MARTIN, K.O. & LEVY, H.A. (1963). ORFLS. Report ORNL-TM-305, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

46. X-RAY (1972). Program system, version of June 1972, Technical Report TR-192 of the Computer Science Center, Univ. of Maryland.

47. ROBERTS, P. & SHELDRICK, G. (Cambridge). To be published.

48. MOTHERWELL, W.D.S. (Cambridge). Unpublished.

49. JOHNSON, C.K. (1965). ORTEP. Report ORNL-3794. Oak Ridge National Laboratory, Oak Ridge, Tennessee.

50. BUERGER, M.J. (1967). *Crystal Structure Analysis,* p 586. New York : John Wiley and Sons.

51. PAULING, L. (1960). *The Nature of the Chemical Bond.* Ithaca : Cornell University Press.

52. DOUGHERTY, H.W. & POLLAK, P.I. in Ref. 5. p 798.

53. TALBERT, P.T., WEAVER, J.A. & HAMBRIGHT, P. (1970). *J.Inorg.Nucl.Chem. 32,* 2147.

54. MARZOTTO, A. & GALZIGNA, L. (1970). 3rd National Congress of Inorganic Chemistry, Bressanone, Italy. Abstract C45.

55. BRAND, E.D. & WESTFALL, T.C. in Ref. 5.p 1190.

56. GALZIGNA, L. (1970). *Internat.J.Vit.Res. 40,* 44.

57. KOBAYASHI, K. (1972). *Vitamins, 45,* 239.

58. FAZAKERLEY, G.V. & RUSSELL, J.C. (1975). *J.Inorg.Nucl. Chem.* in press.

59. THACKERAY, M.M. & NASSIMBENI, L.R. (1974). *Acta Cryst. B30,* 2469.

60. Ref. 40. p 99.

61. Ref. 41. p 302.

62. HANSON, H.P., HERMAN, F., LEA, J.D. & SKILLMAN, S. (1964). *Acta Cryst. 17,* 1040.

63. Ref. 42. p 213.

64. KRAUT, J. & REED, H.J. (1962). *Acta Cryst. 15,* 747.

65. HELMHOLZ, L. & KRUH, R.F. (1952). *J.Amer.Chem.Soc. 74,* 1176.

66. RUSSELL, J.H. & WALLWORK, S.C. (1969). *Acta Cryst. B25,* 1691.

67. BONAMARTINI, A.C., NARDELLI, M., PALMIERI, C. & PELIZZI, C. (1971). *Acta Cryst. B27,* 1775.

68. LAMOTTE-BRASSEUR, J., DUPONT, L. & DIDEBERG, O. (1973). *Acta Cryst. B29,* 241.

69. KARLE, I.L. & BRITTS, K. (1966). *Acta Cryst. 20,* 118.

70. PLETCHER, J. & SAX, M. (1972). *J.Amer.Chem.Soc. 94,* 3998.

71. HAMILTON, W.C. in Ref. 7. p 466.

72. HAHN, T. & BUERGER, M.J. (1957). *Z.Kristallogr. 108,* 419.

73. FELSENFELD, G. (1956). *Proc.Roy.Soc. A, 236,* 506.

74. ROS, P., VAN DER AVOIRD, A. & SCHUIT, G.C.A. (1967). *Coord.Chem.Rev. 2,* 77.

75. CARLISLE, C.H. & COOK, D.S. (1969). *Acta Cryst. B25,* 1359.

76. SAX, M., PULSINELLI, P. & PLETCHER, J. (1974). *J.Amer. Chem.Soc. 96,* 155.

77. JORDAN, F. (1974). *J.Amer.Chem.Soc. 96,* 3623.

78. Ref.41. p 295.

79. CROMER, D.T. & MANN, J. (1968). *Acta Cryst. A24,* 321.

80. STEWART, R.F., DAVIDSON, E.R. & SIMPSON, W.T. (1965). *J.Phys.Chem. 42,* 3175.

81. PLETCHER, J., SAX, M., YOO, C.S., CHU, J. & POWER, L. (1974). private communication.

82. POWER, L., PLETCHER, J. & SAX, M. (1970). *Acta Cryst. B26,* 143.

83. DONOHUE, J. in Ref. 7. p 459.

84. DUFF, E.J., HUGHES, M.N. & RUTT, K.J. (1968). *J.Chem. Soc. A. 3*, 2354.

85. LYNCH, T.R., MELLOR, I.P. & NYBURGH, S.C. (1971). *Acta Cryst. B27*, 1948.

86. MARZOTTO, A. (1973). *J.Inorg.Nucl.Chem. 35*, 3403.

87. BUSCH, D.H., FARMERY, K., GOEDKEN, V., KATOVIC, V., MELNYK, A.C., SPERATI, C.R. & TOKEL, N. (1971). (Ohio State Univ., Columbus, Ohio). *Advan.Chem.Ser.No. 100*, 44.

88. CURTIS, N.F. (1968). *Coord.Chem.Rev. 3*, 3.

89. KARN, J.L. & BUSCH, D.H. (1966). *Nature*, Lond. *211*, 160.

90. PRINCE, R.H. & WOOLLEY, P.R. (1972). *Nature (Physical Science)*, *240*, 117.

91. PRINCE, R.H., STOTTER, D.A. & WOOLLEY, P.R. (1974). *Inorg.Chim.Acta. 9*, 51.

92. FLEISCHER, E.B. & HAWKINSON, S.W. (1968). *Inorg.Chem. 7*, 2312.

93. DEWAR, R. & FLEISCHER, E. (1969). *Nature*, Lond. *222*, 372.

94. Ref. 42. p 17.

95. Ref. 40. p 74.

96. SLETTEN, E. (1970). *Acta Cryst. B26*, 1609.

97. HOSKINS, B.F. & WHILLANS, F.D. (1972-73). *Coord.Chem.Rev. 9*, 365.

98. MARSH, W.C., PADDOCK, N.L., STEWART, C.J. & TROTTER, J. (1970). *Chem.Comm.*, 1190.

99. WOOLLEY, P.R. private communication.

100. KOENIG, D.F. (1965). *Acta Cryst. 18*, 663.

101. MAUTNER, H.G. & CLEMSON, H.C. in Ref. 5.p 1365.

102. DORAN, W.J. (1959). *Medicinal Chemistry*. Vol. IV. New York : John Wiley.

103. CRAVEN, B.M., VIZZINI, E.A. & RODRIGUES, M.M. (1969). *Acta Cryst. B25*, 1978.

104. BERKING, B. & CRAVEN, B.M. (1971). *Acta Cryst. B27*, 1107.

105. BERKING, B. (1972). *Acta Cryst. B28*, 98.

106. GARTLAND, G.L. & CRAVEN, B.M. (1974). *Acta Cryst. B30*, 980.

107. HSU, I. & CRAVEN, B.M. (1974). *Acta Cryst. B30*, 988.

108. CRAVEN, B.M. & GARTLAND, G.L. (1970). *J.Pharm.Sci. 59(11)*, 1666.

109. FIALKOV, Y.A. & RAPAPORT, L.I. (1955). *J.Gen.Chem.* (U.S.S.R.) *25*,1855.

110. WANG, B.C. & CRAVEN, B.M. (1971). *Chem.Comm.*, 290.

111. WANG, B.C., WALKER, W.R. & LI, N.C. (1973). *J.Coord. Chem. 3*, 179.

112. DAVEY, G. & STEPHENS, F.S. (1971). *J.Chem.Soc. A*, 1917.

113. FAZAKERLEY, G.V., LINDER, P.W., NASSIMBENI, L.R. & RODGERS, A.L. (1974). *Cryst.Struct.Comm. 3*, 463.

114. HATHAWAY, B.J. (1973). *Struct.Bond. 14*, (Inorganic Chemistry), 49.

115. SIMINOV, Y.A., ABLOV, A.V. & MALINOVSKII, T.I. (1963). *Kristallografiya. 8*, 270.

116. HATHAWAY, B.J. & BILLING, D.E. (1970). *Coord.Chem.Rev. 5*, 143.

117. ROSENBERG, B., VAN CAMP, L., TROSKO, J.E. & MANSOUR, V.H. (1969). *Nature*. Lond. *222*, 385.

118. WILLIAMS, D.R. (1972). *Inorg.Chim.Acta.Rev. 6*, 123.

119. THORNTON, D.A. & ENGELTER, C. (1975). To be published.

120. McGINNETY, J.A. (1973). *J.Organometallic Chem. 59*, 429.

121. KEETON, M., MASON, R. & RUSSELL, D.R. (1971). *J.Organometallic Chem. 33*, 259.

122. WONG, Y.S., JACOBSON, S., CHIEH, P.C. & CARTY, A.J. (1974). *Inorganic Chem. 13(2)*, 284.

123. GREGORY, U.A., JARVIS, J.A.J., KILBOURN, B.T. & OWSTON, G. (1970). *J.Chem.Soc. A*, 2770.

124. DI SIPIO, L., OLEARI, L. & DE MICHELIS, G. (1966). *Coord.Chem.Rev.* *1*, 7.

125. BLEIDELIS, Ya.Ya. & BOKII, G.B. (1957). *Kristallografiya.* *2*, 281.

126. NORBURY, A.H. (1971). *J.Chem.Soc. A*, 1089.

127. BASOLO, F., BADDLEY, W.H. & BURMEISTER, J.L. (1964). *Inorg.Chem.* *3*, 1203.

128. CLARK, J.H. & WILLIAMS, C.S. (1965). *Inorg.Chem.* *4*, 350.

129. CLARK, J.H. & WILLIAMS, C.S. (1966). *Spectrochim.Acta*, *22*, 1081.

130. MITCHELL, P.C.H. & WILLIAMS, R.J.P. (1960). *J.Chem.Soc.* *2*, 1912.

131. NAKAMOTO, K. (1963). *Infrared Spectra of Inorganic and Coordination Compounds.* p 173. New York : John Wiley and Sons.

132. EICHORN, G.L. in Ref. 2. p 1210.

133. THOMAS, R. (1954). *Trans.Faraday Soc.* *50*, 304.

134. RINGERTZ, H.G. in Ref. 8. p 61.

135. LANCELOT, G. & HÉLÈNE, C. in Ref. 8. p 342.

136. SLETTEN, E., SLETTEN, J. & JENSEN, L.H. (1969). *Acta Cryst.* *B25*, 1330.

137. BROWN, G.M. (1969). *Acta Cryst.* *B25*, 1338.

138. MONTGOMERY, J.A., JOHNSTON, T.P. & SHEALY, Y.F. in Ref. 4. p 680.

139. HEITNER, H.I., LIPPARD, S.J. & SUNSHINE, H.R. (1972). *J.Amer.Chem.Soc.* *94(25)*, 8936.

140. SPOFFORD, W.A. III & AMMA, E.L. (1960). *Acta Cryst.* *B26*, 1474.

141. GIRLING, R.L. & AMMA, E.L. (1971). *Inorg.Chem.* *10(2)*, 335.

142. DE MEESTER, P., GOODGAME, D.M.L., PRICE, K.A. & SKAPSKI, A.C. (1970). *Chem.Comm.*, 1573.

143. Ref. 42. p 276.

144. HUNT, G.W. & AMMA, E.L. (1973). *Chem.Comm.*, 869.

145. TAYLOR, M.R. (1973). *Acta Cryst. B29*, 884.

146. SLETTEN, E. (1971). *Chem.Comm.*, 558.

147. EVANS, I.P. & WILKINSON, G. (1974). *J.Chem.Soc. Dalton. 9*, 946.

Toward light source

KEEP

this line parallel to the bottom of stereo picture.

Fold

# HOW TO USE

1. Place viewer open-ended towards light. Avoid shadows on both pictures to achieve equal illumination both sides.

2. Align bottom edge of stereo pictures to parallel line between lenses. (Some defects of vision may necessitate a slight twist off the parallel.)

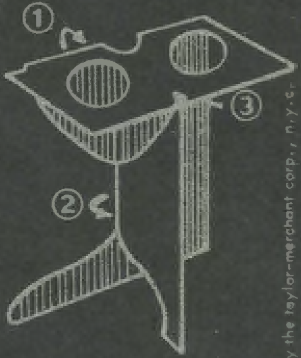
3. If you wear glasses, use them while viewing.

4. In some cases, focusing may be improved by raising or lowering the viewer.

5. Give your eyes fair amount of time to fuse the stereo pictures; only 8% of people cannot see stereo.

Fold

# HOW TO ASSEMBLE



1. Fold lens panel.
2. Fold support panel.
3. Lock support to lens panel.

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# STEREOPTICON 707