THE NEUTRON SENSITIVITIES OF GEIGER-MÜLLER COUNTERS

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PAPER 1 : "A High Flux Associated Particle Neutron Source"
(Nucl. Inst. and Meth., 1981)

PAPER 2 : "An Associated Particle Neutron Source for Dosimetry Applications"
(Proc. 4th Symp. on Neutron Dosimetry, 1981)

PAPER 3 : "The Neutron Sensitivity of a G-M Counter between 0.5 and 8 MeV"
(Proc. 4th Symp. on Neutron Dosimetry, 1981)

PAPER 4 : "Absolute Measurement of the Neutron Sensitivity of a ZP1320 Geiger-Müller Counter Using the Associated Particle Technique"
(Health Phys., 1982)

PAPER 5 : "The Neutron Sensitivity of a Geiger-Müller Counter between 0.5 and 8 MeV"
(Health Phys., 1983)

PAPER 6 : "The k_u-Values of a ZP1300 Geiger-Müller Counter between 0.7 and 7.5 MeV"
(Proc. 5th Symp. on Neutron Dosimetry, 1984)

APPENDIX A : Proof of Publication

APPENDIX B : Associated Particle Kinematics

APPENDIX C : Neutron Time-of-Flight Kinematics

APPENDIX D : NE213 Neutron Detection Efficiencies

APPENDIX E : Linear Least Squares Fitting

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2. ORGANISATION OF PRESENTATION

Six published works are presented here all of which relate to the determination of the neutron sensitivities (k_u-values) of two types of Geiger-Müller (G-M) counters, viz. types ZP1320 and ZP1300. The six papers are listed below in the chronological order of which they were submitted for publication :

1. C.M. Bartle, F.D. Brooks, D.T.L. Jones, W.R. McMurray and R. Verbruggen, "A High Flux Associated Particle Neutron Source", Nucl. Inst. and Meth. 180 (1981) 165

2. D.T.L. Jones, C.M. Bartle, W.R. McMurray and F.D. Brooks, "An Associated Particle Neutron Source for Dosimetry Applications", Proc. 4th Symp. on Neutron Dosimetry", Neuherberg/Munich, FRG, EUR 7448 EN (1981) Vol. I, p. 465 (Luxembourg : Commission of the European Communities)

3. D.T.L. Jones, "The Neutron Sensitivity of a GM Counter between 1 and 8 MeV", Proc. 4th Symp. on Neutron Dosimetry, Neuherberg/Munich, FRG, EUR 7448 EN (1981) Vol. II, p. 409 (Luxembourg : Commission of the European Communities)

4. D.T.L. Jones, C.M. Bartle, J.H. Hough and W.R. McMurray, "Absolute Measurement of the Neutron Sensitivity of a ZP1320 Geiger-Müller Counter using the Associated Particle Technique", Health Phys. 43 (1982) 715

5. D.T.L. Jones and W.R. McMurray, "The Neutron Sensitivity of a Geiger-Müller Counter between 0.5 and 8 MeV", Health Phys. 45 (1983) 659

6. D.T.L. Jones and W.R. McMurray, "The k_u-Values of a ZP1300 Geiger-Müller Counter between 0.7 and 7.5 MeV", Proc. 5th Symp. on Neutron Dosimetry, Neuherberg/Munich, FRG (1984) (Luxembourg : Commission of the European Communities) - to be published.

For the sake of uniformity, preprints of the papers are presented. The presentation is organised as follows: Following a comment on the relevance of the project and the abstract a summary of the work done is given. For the sake of clarity this section also includes elaborations of some of the important techniques, experimental methods and calculations which were used and which were not fully documented in the papers; the preprints of the papers themselves then follow and finally there is a series of appendices which consist of proof that the papers presented were published and sample outputs of some of the computer programmes which were written for the project. Only those programmes which include significant mathematical content are included in this section. In the summary (Section 5) only important additional references which have not been quoted in the papers are given.

3. RELEVANCE OF THE PROJECT

The 200 MeV cyclotron facility at the South African National Accelerator Centre (NAC) (Re81, Re83, Bo84) at Faure will be used for basic and applied research, radionuclide production and radiotherapy and radiobiology with charged particles and fast neutrons. The medical facilities (Jo82) will probably come into full use in 1985-6. Neutron radiobiology and neutron therapy will utilize a significant proportion of the accelerator beam time which will be available for medical use. The neutron therapy treatment system (Jo79, Jo83) includes an isocentric gantry incorporating a variable collimator. Neutrons will be produced by the reaction of 66 MeV protons on a beryllium target producing a broad spectrum of neutrons with an average energy of about 25 MeV. The physical characteristics of the treatment system will be very similar to those of an 8 MV linear accelerator (Jo84).

As part of the preliminary neutron dosimetry research and development programme at the NAC several projects (Jo79a, Jo80, Jo81) in addition to the present one, have been undertaken in order to : (i) establish dosmetric methods and techniques which could be applied (either directly or with modification) to measurements in the clinical neutron beam when it becomes available; and (ii) undertake original research, the results of which would be important to all workers in the field of neutron dosimetry as applied to biology and medicine. The present work falls in the latter category, but nevertheless some of the techniques will be used, possibly with adaptation, in dosimetry measurements in the NAC neutron therapy beam.

References

Bo84 A.H. Botha and H.N. Jungwirth, 1984, "The Status of the South African National Accelerator Centre", Proc. 10th Int. Conf. on Cyclotrons and their Applications, East Lansing, Michigan. (To be published.)

Jo79 D.T.L. Jones, 1979, "Neutron Therapy at the South African National Accelerator Centre", Proc. XII International Conference on Medical and Biological Engineering/V International Conference on Medical Physics, Jerusalem, Israel.

Jo79a D.T.L. Jones, F.D. Brooks, S. Wynchank and I.J. van Heerden, 1979, "Differential Dose Measurements with T(d,n) and Cf-252 Neutron Sources", Proc. XII International Conference on Medical and Biological Engineering/V International Conference on Medical Physics, Jerusalem, Israel.

Jo80 D.T.L. Jones, 1980, "Angular Distribution of Gamma-Rays from D(d,n) and T(d,n) Neutron Sources Used for the Calibration of Dosimeters", SUNI Annual Research Report, SUNI-65, p. 86.

Jo81 D.T.L. Jones and F.D. Brooks, 1981, "A New Type of Recoil Spectrometer for Neutron Energy Spectra Measurements", Proc. 4th Symposium on Neutron Dosimetry, Neuherberg/Munich, EUR 7448 EN, Vol. I, p. 479 (Luxembourg : Commission of the European Communities).

Jo82 D.T.L. Jones, 1982, "Proposed Medical Applications of the National Accelerator Centre Facilities", S.A.J. Sc. 78 149.

Jo83 D.T.L. Jones, 1983, "Neutron and Charged Particle Therapy Facilities at the National Accelerator Centre", Workshop on Heavy Particles in Biology and Medicine, Darmstadt, FRG.

Jo84 D.T.L. Jones, 1984, "Progress with the 200 MeV Cyclotron Facility at the National Accelerator Centre", Proc. 5th Symposium on Neutron Dosimetry, Neuherberg/Munich, FRG (Luxembourg : Commission of the European Communities). (To be published.)

Re81 D. Reitmann, 1981, "Spotlight on the Beam", Nuclear Active, 25, 29.

Re83 D. Reitmann, 1983, "Nasionale Versnellersentrum Vorder", Scientiae, 24, No. 4, 9.

4. ABSTRACT

Neutron beams are always accompanied by gamma rays. Because neutrons and gamma rays have different biological effects, it is essential that the neutron and gamma dose components be determined when neutron beams are used for radiotherapy and radiobiology. Since gamma ray dosimeters almost always also respond to neutrons, it is generally not possible to use two different devices to measure the separate dose components. The separate doses are usually determined by making measurements with two instruments which have different sensitivities to the two types of radiation and deducing the separate components from these measurements. One instrument usually has approximately equal sensitivity to both neutrons and gamma rays while the other has a low sensitivity to neutrons. The latter instrument is often a Geiger-Müller (G-M) counter. Although its neutron sensitivity (k_u) is low, it must be measured for accurate dose determinations. Previous measurements of the neutron sensitivities of such counters have not always been in good agreement.

In the present work the neutron sensitivities of two types of G-M counters, viz. ZP1320 and ZP1300 have been measured at neutron energies between 0.72 and 7.42 MeV. An absolute measurement of the neutron sensitivity of the ZP1320 counter was made at 3 MeV using the associated particle technique while the neutron sensitivities of both counters were measured at several energies using the pulsed beam time-of-flight technique. For the latter measurements a NE213 scintillation counter was used to measure the neutron flux. The detection efficiencies of this counter were calculated and the validity of the calculations were confirmed by measurements using the associated particle technique. The neutron sensitivities obtained in the present work are in reasonable agreement with most previous measurements.

All available data for similar types of counters were fitted with a function of the form $k_u(E) = a\,E^b$. The values of the fitting parameters were :

ZP1320 (0.72 to 7.42 MeV) : $a = 0.10 \pm 0.01$, $b = 1.32 \pm 0.05$

and ZP1300 (0.57 to 15.65 MeV) : $a = 0.25 \pm 0.01$, $b = 0.78 \pm 0.03$

5. SUMMARY

5.1. MIXED FIELD DOSIMETRY

From the radiotherapeutic and dosimetric point of view neutrons and photons (x-rays and gamma rays) are physically very similar. They are both indirectly ionizing radiations, with near-exponential attenuation characteristics in extended media. Many of the dosimetric techniques used with photons can be used with neutrons. However, there are two important differences between these two types of radiation which have important implications. Firstly, photons interact primarily with atomic electrons whereas neutrons interact primarily with atomic nuclei. In the energy range of interest for radiotherapy neutron interactions in tissue take place predominantly with hydrogen nuclei. Hydrogen content is therefore the most important factor in the choice of materials used in neutron dosimetry, whereas mean atomic number is the most important factor in photon dosimetry.

Secondly, neutron beams are always accompanied by gamma rays. Fast neutrons can only be produced in a nuclear reaction. A charged particle beam from an accelerator is incident on a target, usually a solid or a gas. A nuclear interaction occurs between the nuclei in the target and the incident charged particles, producing neutrons in all directions. Bulky shields and collimators are required to confine a neutron beam to a given direction and cross sectional area. Unfortunately neutron production is always accompanied by the production of gamma rays, which are produced either in the primary nuclear reaction or when the neutrons themselves interact with nuclei in the target, collimator, shielding and other structures which the beam may strike. Furthermore as a neutron beam penetrates tissue or any other absorbing medium, nuclear interactions occur which produce further gamma rays. Indeed, in tissue or in a phantom, the proportion of gamma rays in the beam increases with depth of penetration. The gamma dose component in a mixed beam depends critically on the neutron producing reaction, target construction, particle energies, field size and on the materials and design of the shielding and the collimator. Gamma rays account typically for 5 - 10% of the total dose in air, increasing to the order of 20% and higher at depths in tissue of 20 cm or so.

The RBE for neutrons in mammalian tissue is typically about 3. Because of their very different biological effects, it is therefore extremely important in both neutron radiobiology and in neutron radiotherapy to know, with some precision, what proportion of the dose in the beam is due to neutrons and what proportion is due to gamma rays.

Most instruments which are used in photon dosimetry have some response to neutrons and therefore separate measurements of the two dose components cannot be made. Dosimeters which contain little or no hydrogen have a much lower neutron than photon sensitivity. Some dosimeters have an almost equal sensitivity to neutrons and photons. In this category tissue-equivalent (TE) ionization chambers are the most notable example and they are the instruments of choice with which to measure the total dose in a neutron field.

Ionization chambers which have a wall of TE conducting plastic (A150) and are flushed with methane-based TE gas are almost always used. Both A150 plastic and TE gas have hydrogen concentrations which match that of tissue and therefore these ionization chambers are closely tissue equivalent to neutrons. For practical reasons the concentrations of carbon and oxygen in these substances differ from their concentrations in tissue but the perturbations are small (less than 5%) and suitable corrections can be applied to the dose measurements. Since A150 and TE gas have mean atomic numbers which match that of tissue TE ionization chambers are also tissue equivalent to photons.

To determine the neutron and gamma doses separately, two dosimeters with different relative sensitivities to the two types of radiation are used. Usually a dosimeter (t) which has approximately the same sensitivity to neutrons and gamma rays (usually a TE ionization chamber) is used, together with a dosimeter (u) with a low neutron sensitivity. The instruments are normally calibrated in either a Co-60 or a Cs-137 standard field.

The equations describing the responses of the two counters are :

$$R_t = k_t D_N + h_t D_G$$

$$R_u = k_u D_N + h_u D_G$$

D_N and D_G are the neutron and gamma doses respectively.

R_t and R_u are the responses of the two dosimeters relative to their sensitivity to the calibration gamma rays.

k_t and k_u are the sensitivities of each dosimeter to neutrons relative to its sensitivity to the calibration gamma rays.

h_t and h_u are the sensitivities of each dosimeter to the gamma rays in the mixed field relative to its sensitivity to the calibration gamma rays.

The above equations can be solved to give :

$$D_N = \frac{h_u R_t - h_t R_u}{h_u k_t - h_t k_u}$$

$$D_G = \frac{k_t R_u - k_u R_t}{h_u k_t - h_t k_u}$$

h_t and h_u are normally taken to be unity; they would be exactly unity if the gamma radiation in the neutron beam had the same energy as the calibration gamma rays or if the photon responses of the two dosimeters were energy-independent.

Assuming $h_t = h_u = 1$, the above equations reduce to :

$$D_N = \frac{R_t - R_u}{k_t - k_u}$$

$$D_G = \frac{k_t R_u - k_u R_t}{k_t - k_u}$$

k_t is approximately equal to one if the dosimeter t is almost equally sensitive to neutrons and gamma rays.

The "neutron-insensitive" instruments (u) which have been most often used in mixed field dosimetry have been non-hydrogenous ionization chambers (e.g. Mg/Ar, C/CO_2) and G-M counters. It can be shown that the uncertainty in the measurement of the gamma dose component depends on the magnitude of the neutron sensitivity of the "neutron-insensitive" dosimeter; a lower neutron sensitivity results in a lower uncertainty in the determination of the gamma dose (Go74). G-M counters are therefore often the instruments of choice in mixed field dosimetry since their neutron sensitivities are much less than those of non-hydrogenous ionization chambers (typically by about an order of magnitude).

In addition, G-M counters come close to meeting the additional ICRU requirements for an ideal neutron-insensitive counter, viz. one which is also :

(i) Insensitive to orientation in the field, and

(ii) has a linear response independent of photon energy.

k_u-values are not easy to calculate for G-M counters and a separate measurement has to be made of k_u. Unfortunately these measurements have not always been in good agreement, but this can to some extent be ascribed to differences in the neutron beams, in the shielding and collimation, in the precise details of the construction of the G-M counters and even possibly in the measuring techniques.

Reference

Go74 L.J. Goodman, 1974, "Uncertainty Analysis for Dosimetry in a Mixed Field of Neutrons and Photons", Proc. 2nd Symp. on Neutron Dosimetry in Biology and Medicine, Neuherberg/Munich, FRG, EUR 5273 d-e-f, p. 227 (Luxembourg : Commission of the European Communities).

5.1.1. The present work

The present work consisted of several distinct projects. The main projects and the papers in which they are described are listed below :

1. The development and testing of an associated particle neutron source. (Papers 1 and 2)
2. The use of the associated particle neutron source to measure
    - (i) the k_u-value of a type ZP1320/PTFE G-M counter at 3 MeV (Papers 2 and 4) and
    - (ii) the neutron detection efficiency of a NE213 scintillation counter (Paper 2). Such a counter was used as the neutron flux monitor in projects 3 and 4 below.
3. The measurement of the k_u-values of a ZP1320/PTFE G-M counter between 0.72 and 7.42 MeV using the pulsed beam time-of-flight technique (Papers 3 and 5).
4. The measurement of the k_u-values of a ZP1300/PTFE G-M counter between 0.72 and 7.42 MeV using the pulsed beam time-of-flight technique (Paper 6).

There is of course some duplication between the different papers included here. However, each paper does include some unique information relevant to the project as a whole.

G-M counters with PTFE outer sleeves were chosen for the present work in place of the perspex sleeves which were often used in earlier measurements because PTFE does not contain hydrogen. The neutron sensitivity of the counter is dependent on the energy and number of the recoil protons produced in the sleeve. Both of these quantities increase with neutron energy and therefore one expects an enhancement of k_u with increasing energy if the sleeves contain hydrogen and if the energy of the recoil protons is high enough to penetrate the walls of the G-M tube.

Obviously the enhancement of k_u due to recoil proton penetration of the G-M tube depends on the wall material and thickness, and on the details of the construction of the filter assembly and the outer sleeve. Although PTFE eliminates recoil proton production there is some evidence that there is greater production of gamma rays in the PTFE which more than compensates for the lack of recoil protons. Technical drawings of the G-M counter assemblies were supplied by the manufacturers but reproduction is not permitted.

5.2. THE ASSOCIATED PARTICLE METHOD

The associated particle method can provide an electronically collimated monoenergetic neutron beam of absolutely known flux. In a two-body nuclear reaction such as D(d,n)He-3 (the one used in the present application of this method), the neutron energy, angle of emission and flux are fixed by detecting the neutrons and the associated recoil He-3 ions in time coincidence. The pulse from the He-3 particle detector identifies the time of emission of the associated neutron from the target and can thus be used as the "START" signal for a time-to-amplitude converter. The "STOP" signal is generated by the detection of the associated neutron. Much of the attraction of this technique is a consequence of the low background resulting from this coincidence requirement. The characteristics of the associated particle neutron source which was developed are fully described in Papers 1 and 2.

A computer programme NAPKIN was written to determine the appropriate kinematic relationships for the experiments performed. Relativistic kinematics (Ba61) were used. Examples of both printed and graphical outputs are given in APPENDIX B. The graphs show the behaviour, as a function of neutron emission angle and deuteron energy, of various quantities relevant to the D(d,n)He-3 reaction. From these graphs it is easy to select approximate operating conditions for providing the desired neutron beam. Once the approximate conditions are chosen detailed calculations can be performed (as shown in the print-out example), to establish the precise kinematic relationships.

In the present project the D(d,n)He-3 associated particle source has been used to measure the k_u-value of a ZP1320/PTFE G-M counter at 3.0 MeV and to measure the neutron detection efficiency of a 5 x 5 cm NE213 scintillation counter at 3.00, 4.01 and 7.03 MeV.

In principle the associated particle method can be used to calibrate any neutron detector which provides a pulse output. Preliminary measurements have been made using U-235, Np-237 and U-238 pulse fission counters. The range of neutron energies obtainable can be extended by using the T(p,n)He-3 and T(d,n)He-4 reactions.

Reference

Ba61 A.M. Baldin, V.I. Gol'danski and I.L. Rozenthal, 1961, "Kinematics of Nuclear Reactions" (Pergamon Press)

5.2.1. The k_u-value of a ZP1320/PTFE G-M counter at 3 MeV

The associated particle neutron source was used to determine the k_u-value of a type ZP1320 (alternatively designated MX164 or 18550) G-M counter at 3 MeV. The method is fully described in Papers 2 and 4. Although intrinsically a very accurate method it was found to be most time consuming and tedious. The statistical accuracy of the measurement was severely limited by the available accelerator time. For the single k_u-value measured using this technique nearly 100 hours of accelerator beam time was necessary. The counter used in the measurement was nearly 25 times more sensitive to Co-60 radiation than the other counter (ZP1300) used in the present project. In view of the prohibitive requirements on accelerator beam time it was decided to abandon the associated particle method of measuring k_u in favour of the more practical pulsed beam time-of-flight method.

5.2.2. The neutron detection efficiencies of NE213 scintillators

A NE213 scintillation counter was used to measure the neutron flux in the k_u measurements using the time-of-flight technique. In order to determine the flux it is essential to know the neutron detection efficiency of the counter. A computer code, DETEFF (Ref. Th71, Paper 5), was used to calculate the detection efficiencies of the counter used. However, previous experience had shown that different computer codes and methods of calculation did not always agree well and it was therefore essential to experimentally determine the validity of the DETEFF calculations. The measurements are described in Paper 2. The validity of the calculations were confirmed by the measurements. Numerical values of the results obtained have not been published and they are given in Table I overleaf, where they are compared with the DETEFF calculations.

TABLE I - Neutron detection efficiencies for 5 x 5 cm NE213 scintillator

NEUTRON ENERGY (MeV)	NE213 DETECTION EFFICIENCY	
	Measured	DETEFF calculation
3.00	0.33 ± 0.02	0.322
4.01	0.28 ± 0.01	0.280
7.03	0.22 ± 0.01	0.228

Precise knowledge of the pulse height bias is required in any determination of neutron flux with a scintillation counter (or of the neutron detection efficiency). In the measurements described in Paper 2 the pulse height bias was set at 60 keVee (equivalent electron energy). This was accomplished by using a Am-241 source which emits a 60 keV gamma and the bias was set on the corresponding peak in the pulse height spectrum. In the time-of-flight measurements (Section 5.3) a smaller scintillator was used and the bias level was set each time at 50 keVee. Compton electron spectra were recorded with Am-241, Cs-137 and Na-22 gamma ray sources in order to obtain the pulse height versus energy calibration using the energy of the Compton edges. Since the efficiency of the detector varies most rapidly near the operating bias it was necessary to check the bias setting at regular intervals during the running of the experiment to ensure accurate determination of the neutron fluxes.

5.3. THE PULSED BEAM TIME-OF-FLIGHT TECHNIQUE

The so-called pulsed beam neutron time-of-flight technique is a method of determining the energy of neutrons emitted from a source by measuring their velocity. The time elapsed for a neutron originating at the target to reach the detector is measured. In a (p,n) reaction, for example, a pulsed beam of protons (i.e. protons produced in short bursts of duration typically about 1 ns) strikes a target and causes bursts of neutrons to be emitted.

The neutrons in general will be of different energies and consequently of different velocities. They therefore take different times (t) to reach the detector placed at a given distance (d) from the target. Thus the spectrum of neutrons emitted at any angle with respect to the incident charged particle beam direction may be determined by measurement of the times-of flight of these neutrons. Two signals are used to define the times-of-flight: one is taken from the neutron detector; the other is an electrical pulse produced when a pulse of protons passes through a small coil immediately upstream of the target. These two signals are then fed into the START and STOP inputs respectively of a time-to-amplitude converter (TAC). The electronic circuit employed for the G-M counters' time-of-flight measurements is shown in Fig. 1, Paper 3.

The spectrum obtained when the TAC output is analysed by a multichannel analyser is an amplitude spectrum giving the frequency distribution of the neutrons (and any other radiation to which the detector responds) as a function of time. In order to obtain the time versus channel number calibration a zero time position is established with reference to the prompt gamma ray peak (which is due to gamma rays produced in the target) and the time scale is determined by changing the delays in the START and STOP inputs of the TAC by known amounts. Neutron energies (E_n) can then be calculated using the following formula :

$$E_n(\mathrm{MeV}) = \left[\frac{72.3\ d(\mathrm{m})}{t(\mathrm{ns})}\right]^2 \qquad \text{(non-relativistic)}$$

A computer programme TOFKIN was written, using relativistic kinematics formulae (Ba61, section 5.2), to determine the energies of neutrons produced in nuclear reactions. An example of the programme print-out is given in APPENDIX C.

The energies of the accelerated charged particles produced by the Van de Graaff accelerator used in the present work are measured by means of a nuclear magnetic resonance probe in the field of the 90 degree analysing magnet. The calibration of the probe was confirmed from time to time by measuring the threshold (1.811 MeV) of the $^7Li(p,n)^7Be$ reaction. This ensured that the incident beam energies were accurately known.

Gas targets were used for all the time-of-flight measurements. The target cells were 3 cm long and had a 2.5 micron thick havar entrance window. The gas pressure was kept at about 0.8 kPa for all the measurements. Since the incident charged particles lose energy as they traverse both the entrance window and the gas it was necessary to calculate the mean charged particle energy in order that the energies of the emitted neutrons could be precisely determined. The energies lost by protons and deuterons in the havar window were derived from published measurements (Po70, Fo78). A computer programme ENLOSS, which used an empirical approximation (Za74), was used to calculate the mean energy loss of the charged particles in the gas. The results of the calculations are given in Table I, Paper 5.

The measurements made using the time-of-flight technique consisted of determining the k_u-values for the ZP1320/PTFE and ZP1300/PTFE G-M counters at neutron energies of 0.72, 1.82, 2.86, 3.88, 4.55, 5.66, 6.70 and 7.42 MeV. For all the measurements the same NE213 scintillation counter (always operated at a bias of 50 keVee) was used to measure the neutron flux. The results presented in the papers are the means of several measurements made at different times.

References

Fo78	F. Foroughi, B. Vuilleumier and E. Bovet, 1978, "Stopping Power and Multiple Scattering of Havar and Kapton for Low Energy Protons", Nucl. Inst. and Meth. <u>159</u>, 513
Po70	L.E. Porter, L.C. McIntyre and W. Haeberli, 1970, "Stopping Power of Havar for 2.5 to 7.0 MeV Deuterons", Nucl. Inst. and Meth. <u>89</u>, 237
Za74	C.S. Zaidins, 1974, "A Method for Energy-Loss and Range Calculations Based on Empirical Approximations", Nucl. Inst. and Meth. <u>120</u>, 125

5.3.1. The neutron fluences

A vital aspect of the measurement of the k_u-values of the G-M counters by the time-of-flight method, was the simultaneous determination of the neutron fluences. As described in Papers 3 and 5, these were very carefully measured with a NE213 scintillation counter. The importance of the accurate determination of the pulse height bias has been described in Section 5.2.2.

The DETEFF calculation for the efficiencies of the NE213 scintillator, which was used in the determination of the neutron fluences in all the time-of-flight experiments, is presented graphically in APPENDIX D. Relevant numerical values are given in Table I, Paper 5.

Scintillators containing hydrogen generally afford the most efficient and convenient method of detecting fast neutrons since the neutrons can produce recoil protons (via n-p scattering) in the scintillator itself. Unfortunately, however, these organic scintillators also detect gamma rays which produce Compton electrons in the scintillator. It is essential for accurate neutron fluence measurements to eliminate these gamma ray-induced events from the accumulated spectra.

The usual method of accomplishing this is to use pulse shape discrimination (PSD) techniques. It is well known that the scintillation decay of organic scintillators generally consists of an intense fast (nanosecond) component followed by a less intense longer lived (microsecond) tail. In some scintillators, such as NE213, the shape of the pulse depends on the nature of the particle causing the event. The difference lies in the ratio of the amount of light in the slow and the fast components of the scintillations produced by the different ionizing radiations and results in different scintillation decay times with different radiations. In the commercial PSD module used in the present work, the different decay times are exploited to provide particle identification and subsequent discrimination between neutron- and gamma ray-induced events in NE213. PSD was used in both the time-of-flight experiments and in the measurements of the NE213 neutron detection efficiencies using the associated particle method.

The performance of the pulse shape discriminator used is illustrated in Fig. 3, Paper 3 and in Fig. 3, Paper 6. In the former figure the elimination by PSD of both the prompt gamma ray peak and the time-uncorrelated gamma ray background is convincingly demonstrated.

5.3.2. The k_u-values of ZP1320/PTFE and ZP1300/PTFE G-M counters between 0.72 and 7.42 MeV

The experimental details and calculation procedures are fully described in Papers 3 and 5. Briefly, time-of-flight spectra were measured with the G-M counters at different flight paths in order to ensure that the gamma ray and neutron peaks were well resolved. Some overlapping occurred between the two peaks and spectra were therefore also measured at some energies with the target cells evacuated in order to obtain the line shape of the gamma ray peak. After suitable normalisation this peak shape was subtracted from the composite spectra to give the neutron yield. A constant background level was fitted by the method of least squares to each spectrum prior to the subtraction.

A suite of computer programmes was written to determine the neutron yields from the raw spectra. The programmes basically provided the means to normalise and subtract spectra, fit backgrounds and smooth the raw data, if necessary. The Savitsky filter (Sa64) was used in the smoothing process, but this facility was seldom required.

At the neutron fluence rates which were used in the present work activation of the G-M counters did not cause any problems. Although G-M counters are very sensitive to thermal neutrons, since the present measurements were made in air the thermal neutron component in the beam was very small. No differences could be detected in the neutron responses of either G-M counter when the counters were shielded with cadmium.

Tabulations of the k_u-values obtained for the ZP1320 and ZP1300 counters are given in Table I, Paper 5 and Table I, Paper 6 respectively. The results are plotted together with other published measurements with similar counters in Fig. 2, Paper 5 and Fig. 5, Paper 6 respectively.

Reference

Sa64 A. Savitsky and M.J.E. Golay, 1964, "Smoothing and Differentiation of Data by Simplified Least Squares Procedures", Anal. Chem. 36, 1627.

5.4. INTERCOMPARISON OF DATA

5.4.1. ZP1320 measurements

All published measurements of the k_u-values of ZP1320/PTFE G-M counters are given in Table I, Paper 4 (the present measurement at 3 MeV using the associated particle method and the measurements of Lewis and Hunt (Le78) at 4.2 and 5.5 MeV using the spectral difference method) and in Table I, Paper 5 (the 8 present measurements using the time-of-flight technique). All the foregoing data are plotted in Fig. 2, Paper 5. As can be seen from the figure existing data are in excellent agreement. All these data were obtained with the axis of the G-M counter parallel to the neutron beam direction.

The only other measurements have been made with a ZP1320/Perspex counter. For completeness details of these measurements are given in Table II below.

TABLE II k_u-values for ZP1320/Perspex counters

NEUTRON ENERGY (MeV)	k_u	ORIENTATION (degrees)	MEASURING TECHNIQUE	REF.
4.2	0.54 ± 0.06	0	SD	Le78
5.5	0.60 ± 0.06	0	SD	Le78
14.7	1.02 ± 0.10	0	AP	Le77
14.7	1.30 ± 0.20	90	AP	Le77

SD : Spectral Difference, AP : Associated Particle
The references are given in Paper 5.

The measurements at 4.2 and 5.5. MeV are lower than those measured at these energies by the same authors with the perspex sleeve replaced by a PTFE sleeve (Table I, Paper 4). This is indicative of the enhanced production of gamma rays in PTFE at these energies.

5.4.2. ZP1300 measurements

All published measurements of the k_u-values of ZP1300 G-M counters are given in Table I, Paper 6. Included in the table are the 8 present measurements using the time-of-flight technique. All the data indicated with an asterisk in the table (i.e. all positive k_u-values for ZP1300/PTFE counters above 0.57 MeV) are plotted in Fig. 5, Paper 6. As can be seen existing measurements made with this type of counter are not in very good agreement.

5.4.3. Functional relationships

In an effort to describe the data in terms of a functional relationship the ZP1320/PTFE data plotted in Fig. 2, Paper 5 and the ZP1300/PTFE data plotted in Fig. 5, Paper 6 have been fitted with a function of the form $k_u(E) = a\,E^b$. The data were fitted with other functions e.g. straight lines and polynomials, but were found to be best fit by the function described above.

The data were transformed to logarithmic co-ordinates and were fitted with the straight line : $\log k_u = \log a + b \log E$. A general linear least squares programme LINFIT was written for the data analysis. The formulae used in the programme are available in most standard data reduction and statistics text books (e.g. Be69, So69, Da71).

An example of the printed and plotted programme output is given in APPENDIX E. The example given in fact represents the fit to the ZP1320/PTFE data. This information has not yet been published. The values of the parameters a and b obtained were :

$$a = 0.10 \pm 0.01 \quad \text{and} \quad b = 1.32 \pm 0.05$$

The energy range of the data is from 0.72 to 7.42 MeV.

The fit to all the ZP1300/PTFE data is plotted in Fig. 5, Paper 6. The values of various parameters for different sets of data are given in

Table II, Paper 6. The values of a and b for all available data (the energy range is 0.57 to 15.65 MeV) are :

$$a = 0.25 \pm 0.01 \quad \text{and} \quad b = 0.78 \pm 0.03$$

References

Be69 P.R. Bevington, 1969, "Data Reduction and Error Analysis for the Physical Sciences" (New York : McGraw Hill Book Co.)

Da71 C. Daniel and F.S. Wood, 1971, "Fitting Equations to Data" (New York : Wiley-Interscience)

So69 R.R. Sokal and F.J. Rohlf, 1969, "Biometry : The Principles and Practice of Statistics in Biological Research" (San Francisco : W.H. Freeman and Co.)

6. DISCUSSION

The results of the present work are highly satisfactory: the most extensive measurements of the k_u-values for the ZP1300 and ZP1320 G-M counters in the energy range between 0.7 and 7.5 MeV have been made; the work represents a significant contribution to knowledge in the field of neutron dosimetry.

The functional relationship $k_u(E) = a\,E^b$ can be used to describe the energy dependence of the k_u-values for both counters with reasonable confidence in the energy range where measurements have been made. However, some caution must be exercised in using the values of the parameters which have been obtained here to calculate the neutron sensitivities of nominally similar counters since slight differences in construction may modify their responses.

In addition, the energy spectrum of the neutron field in which the sensitivities are measured may play a role. The present measurements and those which have been used here for intercomparisons have nearly all been made with monoenergetic neutron sources. The only exceptions are the two measurements made in d(16 MeV)/Be neutron fields (refs. Ho79 and Ho84, Paper 6) where the neutrons are distributed over a broad spectrum of energies ranging from 0 to about 18 MeV. The k_u-values are quoted at the average energy of the neutrons. Such broad spectra are characteristic of cyclotron-produced neutron sources used in radiotherapy.

It is recommended that the k_u-value for every G-M counter be measured in the neutron beam in which it is to be used for mixed field dosimetry. The present description of the energy dependences of the k_u-values for ZP1300/PTFE and ZP1320/PTFE G-M counters can be used as a guide and for normalisation and extrapolation purposes in the energy ranges over which the data have been fitted.

The associated particle method and the pulsed beam time-of-flight technique have been demonstrated to be highly satisfactory methods for measuring k_u-values for monoenergetic neutrons. The associated particle method has the notable advantage of yielding absolute results (no independent measurement of the neutron fluence is required) and is therefore intrinsically very accurate; the coincidence requirement precludes the detection of gamma rays;

and the method can be used to calibrate any neutron dosimeter which provides a pulse output. The disadvantage of the method lies in the high demand on accelerator beam time and it is not considered practical for measurements at a series of different neutron energies. A possible experimental programme could, however, involve an absolute k_u determination at a single energy using the associated particle method, and then a set of relative measurements using a different and quicker technique.

The pulsed beam time-of-flight technique which has been developed in this work is a practical and relatively quick way of measuring k_u-values for G-M counters and is not too demanding on accelerator time. Its accuracy is limited by the precision with which the neutron fluences can be determined. Although G-M counters respond to both neutrons and gamma rays the time-of-flight technique is particularly suitable for k_u determinations since the neutron and gamma components are separated by the differences in their times-of-flight. The separation of the two can be increased by operating at longer flight paths at the expense, however, of fluence rates.

The associated particle method has been used to provide monoenergetic neutron beams with energies in excess of 100 MeV at other centres. This technique could therefore in principle be used to determine k_u-values for G-M counters at neutron energies of interest in neutron therapy at the NAC (up to about 70 MeV). The pulsed beam time-of-flight facilities at the NAC will provide a most suitable means for measuring the k_u-values for the G-M counters which will be used in mixed field dosimetry. Flight paths of up to 100 m will be available and the orders-of-magnitude increase in neutron intensity will compensate for the long flight path which will be necessary to make measurements with good resolution. Spectrum unfolding techniques will have to be used to determine the k_u-values over selected energy intervals since the spectrum of neutrons for the p(66 MeV)/Be source reaction is a broad distribution extending up to about 70 MeV.

PAPER 1

"A High Flux Associated Particle Neutron Source"

(Nucl. Inst. and Meth. 180 (1981) 165)

A HIGH FLUX ASSOCIATED PARTICLE NEUTRON SOURCE

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Abstract:

An associated particle system for neutron production using the $^2H(d,n)^3He$ reaction is described. The system employs a thin-walled scattering chamber, an assembly to rotate a deuterated polyethylene target and a magnetic analyzer for recoil particle separation in high flux applications. Neutron beam intensities of up to 1000 s^{-1} are routinely obtainable.

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1. INTRODUCTION

Measurements using neutrons produced with the $^2H(d,n)^3He$ reaction often are improved in precision by detecting the associated ^3He ions1-4). A monoenergetic neutron beam of absolutely determined flux is defined by detecting the neutrons in time coincidence with the ^3He ions. The ^3He ions are usually detected in a surface barrier detector which subtends a small solid angle at the target. The profile of the neutron beam is determined by the size of both the deuteron beam and the collimator in front of the surface barrier detector, although other factors such as multiple scattering and kinematic effects also play a role in determining the neutron beam profile.

As an example, if the collimator subtends an angle of 0.4 msr at the target and the deuteron beam spot size is 1.5 mm in diameter, a tagged neutron beam $3-4^\circ$ wide (FWHM) can be achieved for deuterons in the 2-5 MeV range. In a typical application, the cross sections of neutron induced reactions on nuclei incorporated in organic or inorganic scintillators are measured5-7). In this type of experiment the scintillator physically encompasses the electronically defined neutron beam and serves as both target and detector. Reaction cross sections are then deduced from the ratio of the coincidence rate (between events in the scintillator and ^3He detector) and the ^3He detection rate.

In many experiments of this type a neutron rate of about 50 s^{-1} is sufficient to give the required statistical accuracy in the measurement after a few hours of data accumulation. In these experiments the background count rate in the scintillator is typically a few kHz and a higher tagged neutron flux is avoided to minimize pile-up effects. However, there are applications, e.g. in scattering and polarization studies and with detectors having low neutron detection efficiencies, where increased neutron intensity is desirable.

Increased neutron beam intensity is achieved by increasing the incident deuteron beam current or the target thickness. However, limitations are imposed by the amount of current which the target can withstand and by the count rate (mainly due to elastically scattered deuterons) which the surface barrier detector can tolerate without deterioration.

An experimental system is described here in which a relatively intense monoenergetic neutron beam has been produced by means of improved target fabrication and by optimization of the ^{3}He detection system.

2. TARGET CHAMBER AND COMPONENTS

A thin-walled, 34 cm diameter aluminium scattering chamber, constructed at the Southern Universities Nuclear Institute, while having similar features to some earlier chambers[2-4]), incorporates a number of improvements. Cross sectional drawings of the chamber are shown in fig. 1, and an overall view is shown in plate 1. The wall of the chamber is made of aluminium sheet 1.5 mm thick and is essentially transparent to MeV neutrons.

A deuterated polyethylene target is used and is mounted on an annular ring with an internal diameter of 25 mm. It is rotated by a motor mounted outside the chamber. The axis of rotation of the target does not coincide with the axis of the deuteron beam which thus sweeps out a circular path on the foil.

The rotary motion is transmitted to the target by means of a ferrofluidic rotary feedthrough* and a bevel gear and pinion drive mechanism. The target is rotated at 5 Hz and by periodically moving the target vertically (i.e. exposing a new path) its lifetime can be considerably extended.

The deuteron beam is collimated to 1.5 mm in diameter before entering the chamber. After passing through the target it is stopped 2 m downstream in a shielded beam dump.

3. TARGET PREPARATION AND PERFORMANCE.

Self-supporting deuterated polyethylene foils, even when rotated at high speeds, typically have a lifetime of only a few minutes for incident beam currents of the order of 2 μA. The foils can however be strengthened considerably by evaporating thin layers of carbon onto both sides of the polyethylene as proposed by a number of workers[9-11]). It has been found that these target sandwiches with thicknesses in the 200-400 μg cm^{-2} range rotated at 5 Hz can withstand 2.5 μA of 5 MeV deuterons for long periods. The deuterated

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* Type SB-253-B-N-026. Manufactured by the Ferrofluidics Corp., Burlington, Massachusetts 01803, U.S.A.

polyethylene foil is prepared from the powdered form* using a procedure described previously[8]. One carbon layer is evaporated onto the foil using a carbon arc (arc voltage 150 V) while it is still attached to the glass slide on which it was formed. After floating the foil off the slide in a water bath, the other carbon layer is evaporated onto the reverse side.

Plate 2 is an electron microscope photograph of the cross section of a typical target. In this example, the deuterated polyethylene layer is approximately 1.2 μm thick (corresponding to an areal density of 120 μg cm^{-2}) and the carbon layers sandwiching the target are approximately 0.25 μm thick. The thickness of the deuterated polyethylene layer, which was nominally 400 μg cm^{-2} (based on the mass of polyethylene dissolved in the solvent) was found on examination to vary between 100 μg cm^{-2} and 300 μg cm^{-2} over the 2.5 cm diameter foil.

Typical yield characteristics of a target sandwich are shown in fig. 2. It can be seen from the figure that, after an initial rapid fall off, the yield remains fairly constant for a long period. This type of behaviour has been observed previously with such targets[9].

4. MAGNETIC ANALYSIS OF THE RECOIL IONS

When incident deuteron beams of more than 2 μA are used with thick targets ($\gtrsim$ 200 μg cm^{-2}), the high flux of elastically scattered deuterons causes damage to the solid

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* Available from Merck Sharp and Dohme, Pointe-Claire/Dorval, Quebec, Canada.

state detector as well as producing severe pile up effects which limits the resolution of the ^{3}He events. A simple electromagnetic analyzer has been employed to partially screen the detector from these elastically scattered deuterons. The magnetic analyzer attached to a port positioned at 25° relative to the deuteron beam direction is shown in plate 1. A schematic figure of the magnetic analyzer attachment is given in fig. 3.

The magnet has polepieces with circular cross section 10 cm in diameter and provides a field of 0.6 T. For 5 MeV incident deuterons this is sufficient to separate the elastically scattered deuterons and the 5.3 MeV ^{3}He recoil particles by approximately 3 mm at the exit of the field region.

The ^{3}He detector is a 30 μm thick silicon surface barrier transmission detector. This detector is of sufficient thickness to stop up to 5.5 MeV ^{3}He particles, while only absorbing a small part of the energy of the elastically scattered deuterons. Correct selection of the surface barrier detector thickness ensures that the elastically scattered particle events do not obscure the ^{3}He events[2-4]).

Fig. 4 shows typical charged particle spectra without (fig. 4(A)) and with (fig. 4(B)) magnetic analysis. As can be seen from the figure, the magnetic analysis greatly improves the quality of the spectrum. In particular the resolution of the ^{3}He group is superior due to the reduction in the number of pile up events.

5. THE NEUTRON BEAM CHARACTERISTICS

The direction and angular spread of the neutron beam are known from the kinematic conditions, ^{3}He acceptance angle and deuteron beam spot size. However, it is important that the neutron beam profile be measured firstly in order to assess effects such as multiple scattering of deuterons and ^{3}He ions in the target, and secondly to check the alignment of the apparatus.

In order to accomplish this a small cylindrical plastic scintillator (NE 102A) which subtends 1° at the neutron source is scanned across the beam in both the horizontal and vertical planes. Typically a coincidence timing resolution of 1 ns (FWHM) was obtained.

Measured horizontal and vertical neutron beam profiles are shown in fig. 5 for the calculated kinematic conditions: $E_d = 5$ MeV; $\theta_{He} = 25^\circ$; $E_n = 3$ MeV; $\theta_n = 104.6^\circ$. Magnetic analysis was used for these measurements. As can be seen from the figure the angular width is 3° in both the vertical and horizontal planes while the centre of the neutron beam coincides almost exactly with the direction given by the kinematic calculations.

6. CONCLUSION

An associated particle system for electronic collimation of a neutron beam from the ^{2}H(d,n)^{3}He reaction is described. Using deuterated polyethylene foils sandwiched between carbon layers and magnetic analysis of the emitted recoil particles a relatively intense neutron beam compared with that obtained from earlier systems can be achieved, while retaining good ^{3}He particle resolution. Using targets 400 μg cm^{-2} thick and with deuteron beam currents of 2.5 μA it was possible to achieve ^{3}He rates (and therefore neutron rates) of up to 1000 s^{-1}.

The authors are indebted to the South African Council for Scientific and Industrial Research and the Atomic Energy Board for financial assistance.

FIGURE CAPTIONS

Fig. 1: Schematic diagram of the scattering chamber. The surface barrier detector usually positioned on the rotatable circular table is not shown.

Fig. 2: The ^{3}He yield as a function of time for a 200 μg cm^{-2} thick "sandwiched" deuterated polyethylene target bombarded with 2.5 μA of 5 MeV deuterons. The ^{3}He particles are detected at 25° in a solid angle of 0.4 msr. Local variations in yield (continuous line) are due to variations in the beam current. The target was rotating at 5 Hz while the deuteron beam was displaced 6 mm from the axis of rotation.

Fig. 3: Plan of the magnetic analyzer attached to the target chamber. Crosses indicate the magnetic field region.

Fig. 4: Charged particle spectra obtained with a 30 μm thick silicon surface barrier transmission detector positioned at 25° to the 5 MeV incident deuteron beam. Spectrum (A) was obtained without magnetic analysis while for spectrum (B) magnetic analysis of the recoil charged particles was employed. The spectra are recorded for approximately the same number of elastically scattered deuterons.

Fig. 5: Horizontal and vertical neutron beam profiles

measured at $E_d = 5$ MeV, $\theta_{He} = 25^{o}$ with a magnetically analysed charged particle beam. The charged particle detector subtended an angle of 0.4 msr at the target and the deuteron beam spot size was 1.5 mm in diameter.

Plate 1: A view of the target chamber and magnetic analyzer.

Plate 2: An electron microscope photograph of a sectioned edge of a deuterated polyethylene target sandwiched between two carbon layers. The horizontal scale shown is in units of micrometers.

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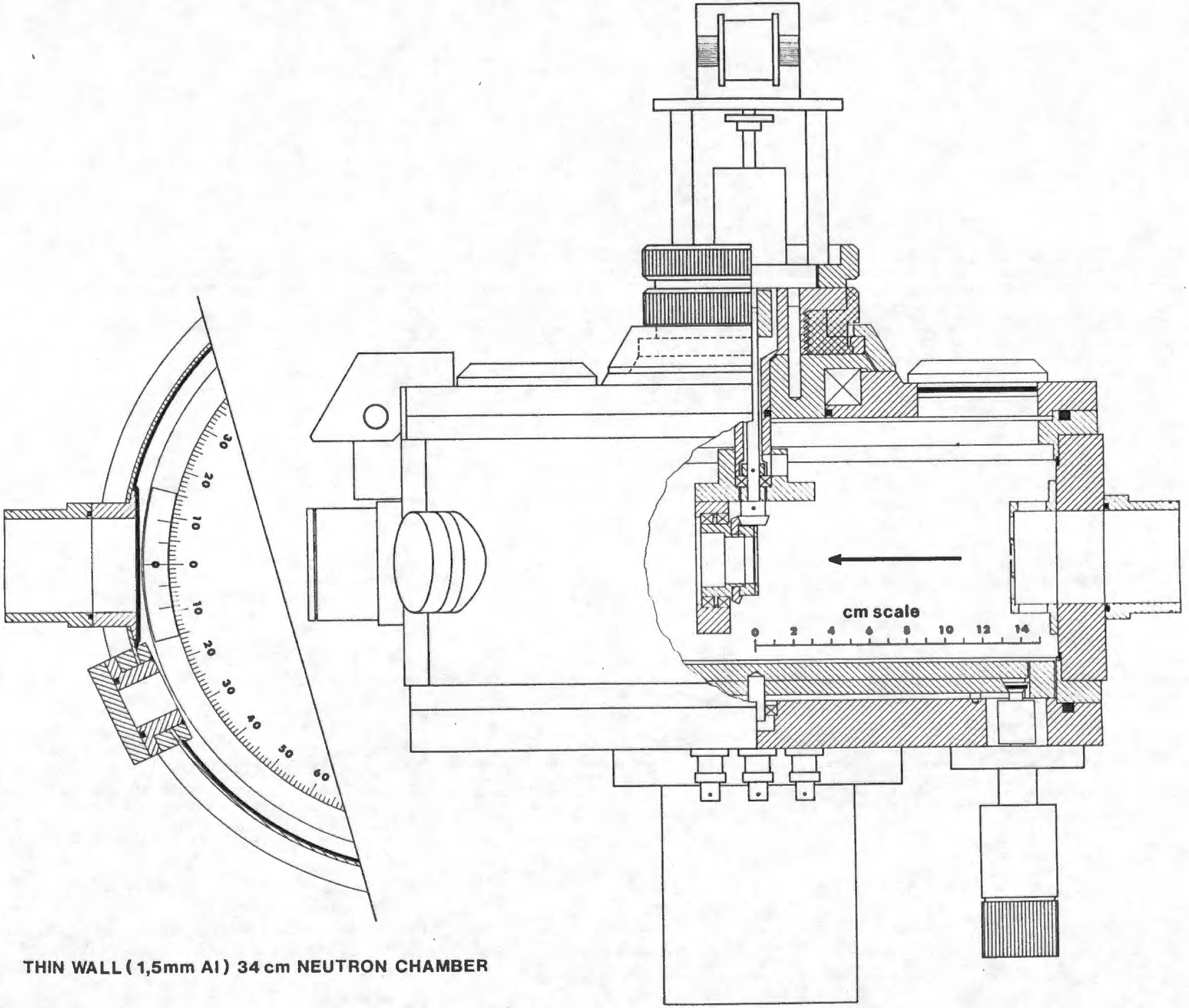
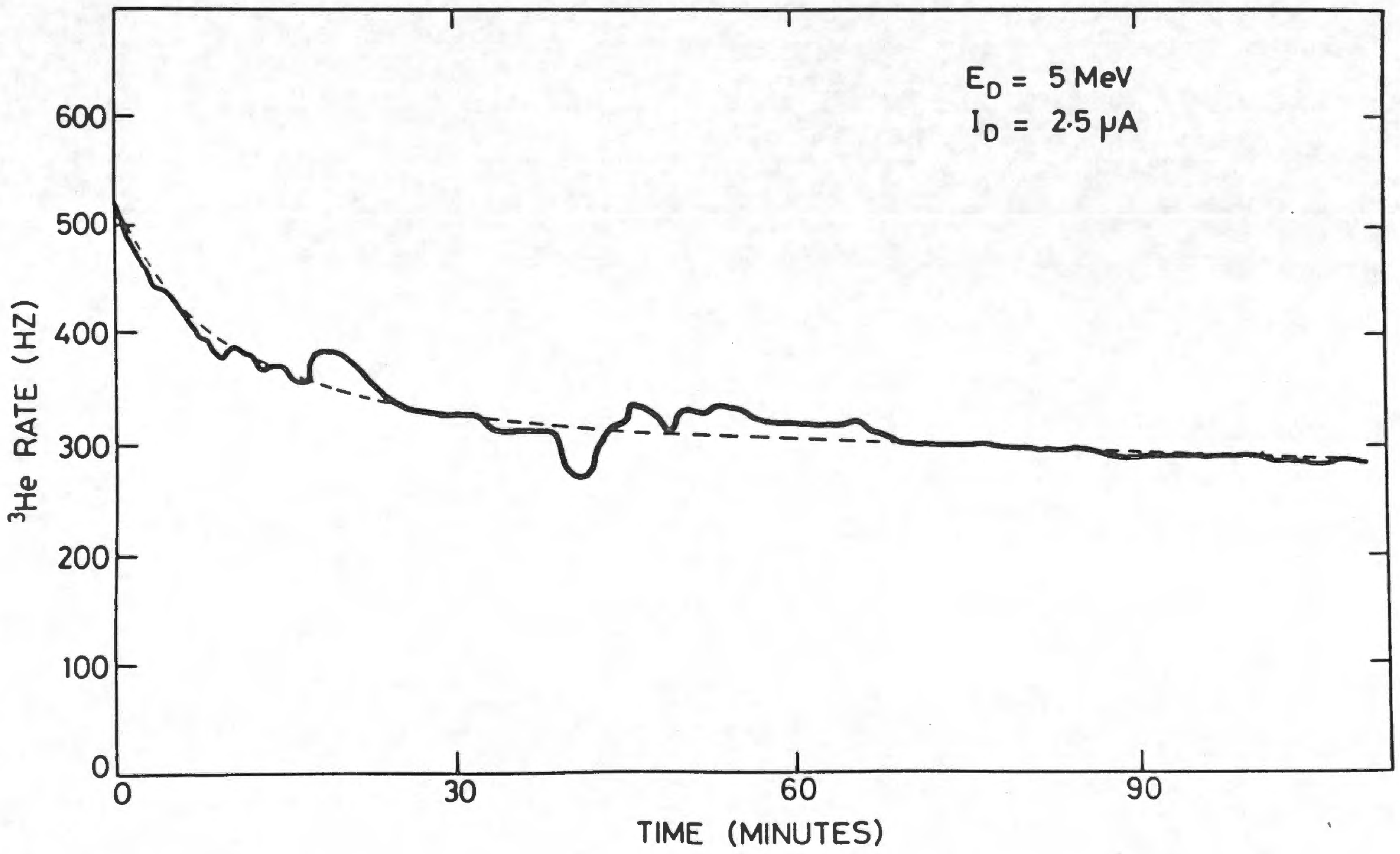
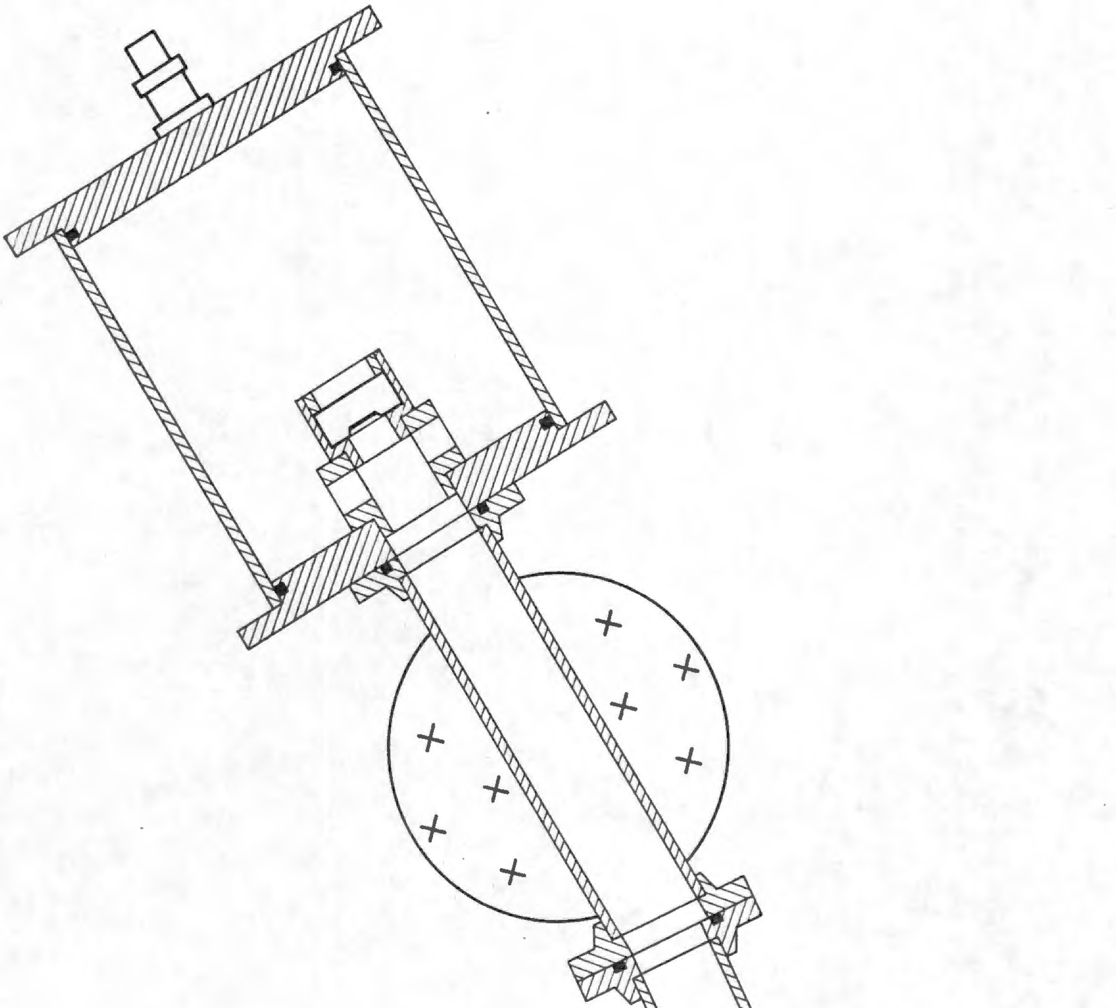
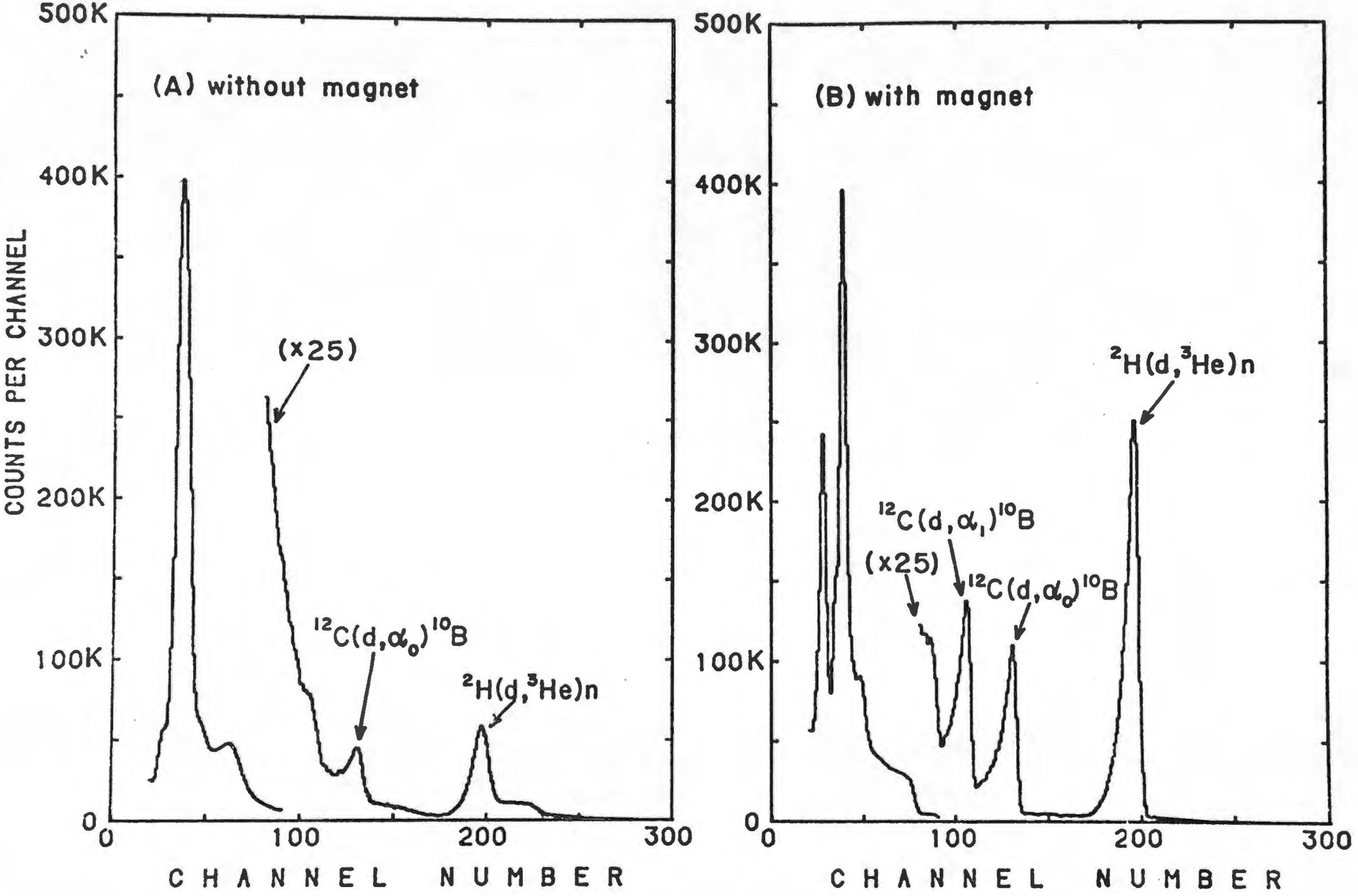


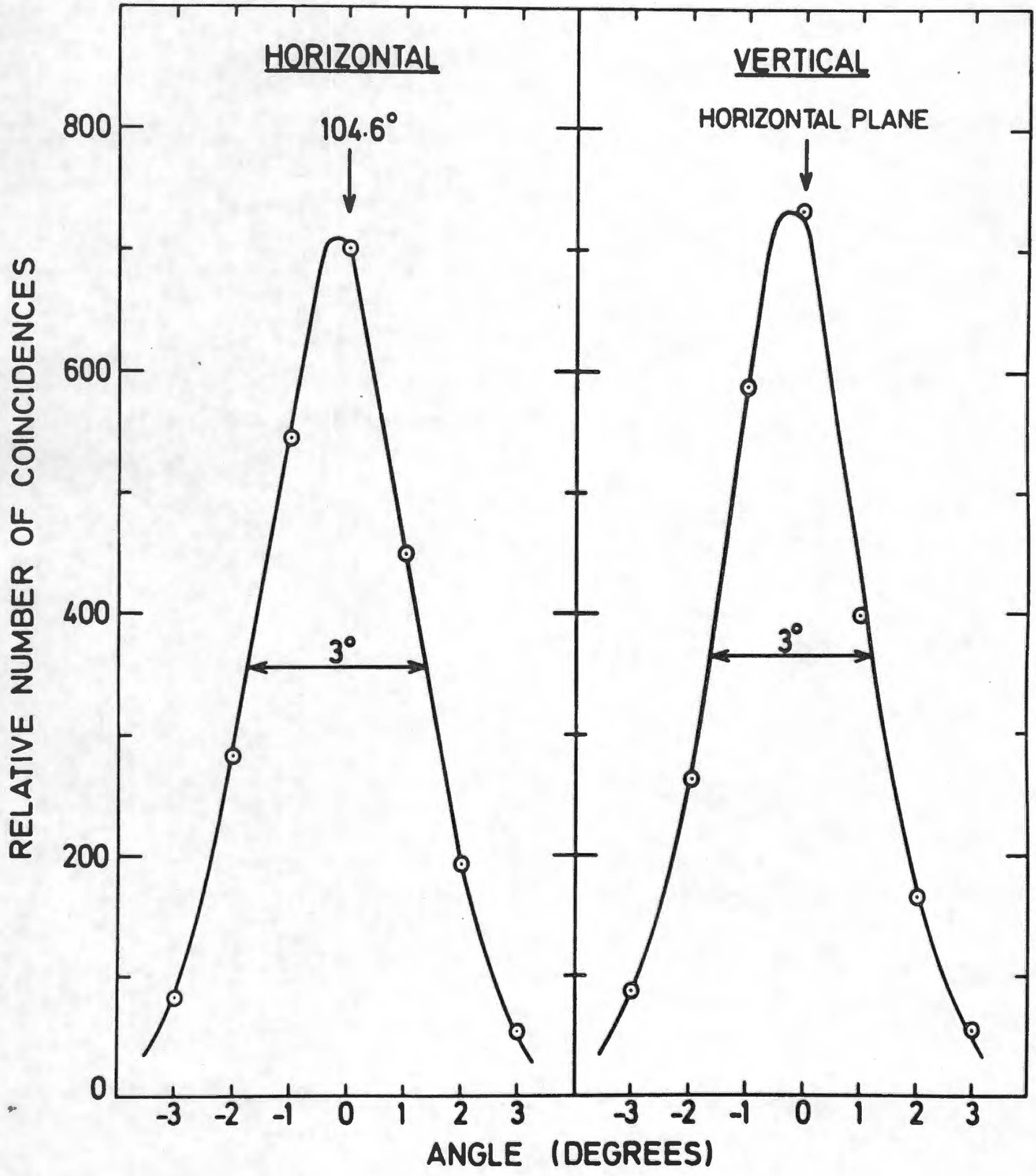
THIN WALL (1,5mm Al) 34 cm NEUTRON CHAMBER


E_D = 5 MeV
I_D = 2.5 μA
^{3}He RATE (HZ)
0
100
200
300
400
500
600
0
30
60
90
TIME (MINUTES)


20
30



COUNTS PER CHANNEL
500K
400K
300K
200K
100K
0
(A) without magnet
(x25)
$^{12}C(d,\alpha_0)^{10}B$
$^{2}H(d,^{3}He)n$
0
100
200
300
CHANNEL NUMBER
(B) with magnet
$^{12}C(d,\alpha_1)^{10}B$
(x25)
$^{12}C(d,\alpha_0)^{10}B$
$^{2}H(d,^{3}He)n$
CHANNEL NUMBER

HORIZONTAL
VERTICAL
104.6°
HORIZONTAL PLANE
3°
3°
RELATIVE NUMBER OF COINCIDENCES
800
600
400
200
0
-3
-2
-1
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1
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-3
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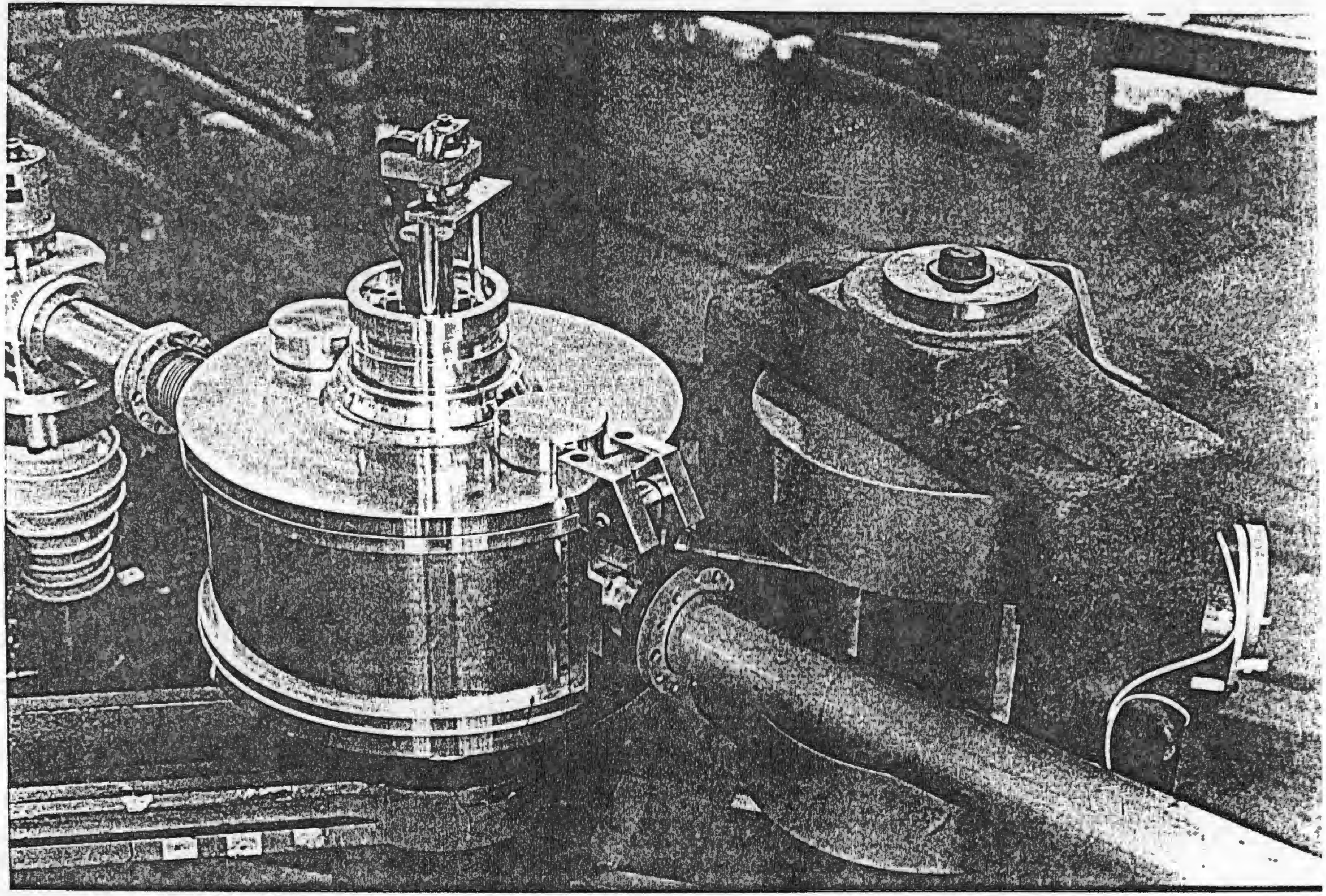
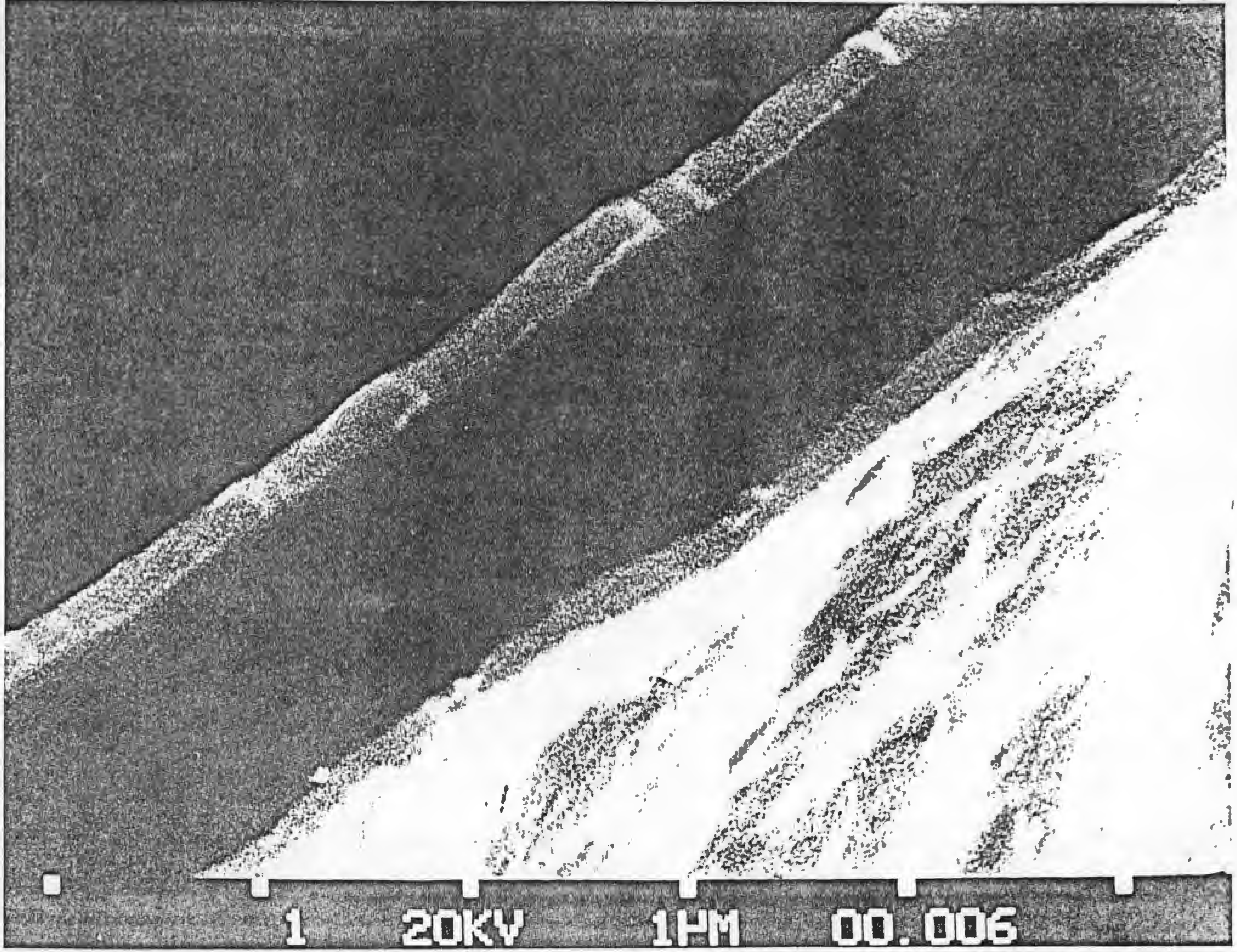
2
3
ANGLE (DEGREES)

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PAPER 2

"An Associated Particle Neutron Source for Dosimetry Applications"

(Proc. 4th Symp. on Neutron Dosimetry, 1981)

AN ASSOCIATED PARTICLE NEUTRON SOURCE FOR DOSIMETRY APPLICATIONS

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ABSTRACT

A high flux associated particle neutron source has been developed for neutron dosimetry applications. The $D(d,n)^3He$ reaction has been used with a deuterated polyethylene target to produce monoenergetic collimated neutrons of absolutely determined flux in the 2 to 8 MeV range. Neutron rates of up to 1000 s^{-1} have been achieved. The source has been used to measure the neutron detection efficiency of a NE213 scintillator and the k_u-value of a ZP1320 GM counter.

INTRODUCTION

The main problems associated with neutron experiments in the MeV region are collimating the neutrons, measuring their energy and determining their flux. One of the best means of overcoming these problems is to use the so-called associated particle technique(1).

In a two-body nuclear reaction such as $D(d,n)^3He$ there is a definite relationship, defined by the kinematics of the reaction, between the energies and angles of the two emergent particles. In the associated particle method one fixes the neutron energy and angle and determines the neutron flux by detecting the associated ^3He ions at a particular angle and in a physically defined solid angle. There will then be a corresponding solid angle of neutrons as shown in fig. 1.

By requiring a time coincidence between the neutrons and the associated ^3He ions one obtains a monoenergetic collimated neutron beam. Since there is a one to one correspondence between a ^3He ion and a neutron in the collimated beam, in principle an absolute determination of the neutron flux is possible by simply counting the number of ^3He ions.

In many applications neutron rates of 100 s^{-1} are adequate. Indeed a higher tagged neutron flux is avoided to minimize pile up effects. However, there are applications e.g. with detectors having low neutron detection efficiencies where increased neutron intensity is desirable.

To increase the neutron flux the deuteron beam current or the target thickness must be increased. However, limitations are imposed by the current which the target can withstand and by the count rate (mainly due to elastically scattered deuterons) which the surface barrier detector usually used to detect the ^3He's can tolerate without physical deterioration or degradation of the ^3He resolution.

The source we have developed provides a relatively intense monoenergetic neutron beam by means of improved target fabrication and by optimization of ^3He detection system. The source has been used to calibrate a NE213 scintillator and a ZP1320 GM counter.

APPARATUS

An aluminium scattering chamber, 34 cm in diameter and with 1.5 mm thick walls, has been constructed. The walls are essentially transparent to MeV neutrons.

A self-supporting deuterated polyethylene target$^{(2)}$ was used and was rotated eccentrically about the deuteron beam axis by a motor mounted outside the chamber. The target was rotated at 5 Hz and by periodically moving it vertically (i.e. exposing a new path) its lifetime was considerably extended.

The ^{3}He detector was a 30 μm thick totally depleted silicon surface barrier transmission detector. This thickness is just sufficient to stop 5.5 MeV ^{3}He ions while only absorbing a fraction of the energy of the elastically scattered deuterons. Careful selection of the kinematic conditions for each measurement ensured that events due to elastic scattering did not obscure ^{3}He events. The ^{3}He detector was mounted on a rotating table within the chamber. The required ^{3}He angle could be set accurately from outside the chamber.

The neutron detector was mounted outside the chamber on a rotating arm. The deuteron beam was collimated to 1.5 mm in diameter before entering the chamber. After passing through the target it was stopped 2 m downstream in a shielded beam dump.

Standard fast electronics were used in the measurements. The neutron detector provided the START pulse for a time-to-amplitude converter while the ^{3}He detector provided the STOP pulse. The number of counts in the peak in the time spectrum then gave the number of real coincidences.

In order to measure the neutron beam profile a small cylindrical plastic scintillator (NE102A) which subtended 1° at the neutron source was scanned across the beam in both the horizontal and the vertical planes. Typically a coincidence timing resolution of 1 ns (FWHM) was obtained. Measured horizontal and vertical neutron beam profiles are shown in fig. 2. Magnetic analysis (see below) was used for these measurements. The angular width is 3° (FWHM) in both the vertical and horizontal planes while the centre of the neutron beam coincides almost exactly with the direction given by the kinematic calculations.

IMPROVEMENTS TO THE EXPERIMENTAL ARRANGEMENT

Because of inefficient heat dissipation self-supporting deuterated polyethylene foils, even when rotated at high speed rupture very easily for deuteron beam currents of the order of 2 μA. The foils have been strengthened considerably by evaporating thin layers (~ 0.25 μm) onto both sides of the polyethylene. It was found that such target sandwiches with thicknesses between 200 and 400 $\mu g.cm^{-2}$ rotated at 5 Hz could withstand 2.5 μA of 5 MeV deuterons for periods of days.

Typical yield characteristics of a target sandwich are shown in fig. 3. It can be seen from the figure that, after an initial rapid fall off, the yield remains fairly constant for a long period. This type of behaviour has been observed previously with such targets(3).

When incident deuteron beams of more than 2 μA are used with thick targets ($\geqslant 200\ \mu g.cm^{-2}$), the high flux of elastically scattered deuterons causes damage to the surface barrier detector as well as producing severe pile-up effects which limits the resolution of the ^{3}He events. A simple electromagnetic analyser, attached to a port at 25° relative to the deuteron beam direction, has been employed to partially screen the detector from these elastically scattered deuterons.

Fig. 4 shows typical charged particle spectra without (fig. 4(A)) and with (fig. 4(B)) magnetic analysis. As can be seen from the figure, the magnetic analysis greatly improves the quality of the spectrum. In particular the resolution of the ^{3}He group is superior due to the reduction in the number of pile-up events.

Using targets 400 μg.cm^{-2} thick and with deuteron beam currents of 2.5 μA it has been possible to achieve ^{3}He rates (and therefore neutron rates) of up to 1000 s^{-1} while retaining unambiguous ^{3}He particle resolution and with no distortion of the neutron beam profile (see fig. 2).

APPLICATIONS

1. The neutron detection efficiency of a NE213 scintillator

NE213 scintillation counters are used for several dosimetry applications in our laboratory, e.g. to measure neutron flux(4) and neutron energy spectra(5). Such measurements require knowledge of the detection efficiency of the scintillator. The computer code DETEFF(6), which is a modified version of the earlier Kurz code(7), is usually used to calculate the efficiencies.

We have compared the calculations with measurements made with a 5 cm x 5 cm NE213 scintillator using the associated particle source. The scintillator was mounted on a RCA 8850 photomultiplier tube and on the axis of the neutron beam which it completely encompassed. The electronic circuit included a pulse shape discriminator to eliminate gamma ray induced events. The detector was biased at 60 keVee and measurements were made at neutron energies of 3.00, 4.01 and 7.03 MeV. The high flux capability of the source was not required because of the relatively high efficiency of the scintillator.

The central efficiency was calculated as the ratio of coincidences to detected ^{3}He's. The results obtained are shown in fig. 5. The overall uncertainty in each measurement is estimated to be 5%. Also plotted in fig. 5 is the DETEFF calculation. Care must be taken in comparing the measurements and the calculations since no corrections for attenuation and multiple scattering were applied to the measurements and the calculations assume that the whole scintillator is illuminated by the neutron flux. However, these effects are small and allowing for them, the present measurements are in good agreement with the calculations to which a 10% error is ascribed(6).

2. The neutron sensitivity of a GM counter at E_n = 3 MeV

GM counters are often used to determine the gamma dose fraction in mixed neutron radiation fields. Although their neutron sensitivity is small it has to be determined for accurate dose specification. The high flux capability of the associated particle source has been used to measure the neutron sensitivity of a ZP1320 (MX164)+ GM counter at 3 MeV.

The counter was scanned horizontally across the diameter of the neutron beam (which enveloped the counter) and the ratio of coincidences to detected ^{3}He's was determined at each position. A typical coincidence time spectrum is shown in fig. 6. The high gamma sensitivity of the GM counter is mainly responsible for the random background caused by gamma rays produced in the target and by the deuteron beam striking the collimator.

The measured profile is shown in fig. 7. The errors are statistical and only corrections for dead time losses have been made to the data points. Because of the cylindrical symmetry of both the GM counter and the neutron beam the average efficiency of the counter could be calculated by numerical integration of the profile(8).

The efficiency at 3 MeV was found to be :

$$\varepsilon = (2.86 \pm 0.57) \times 10^{-4} \text{ counts.neutron}^{-1}$$

The k_u-value relative to Co^{60} was calculated as follows :

$$k_u = \frac{\varepsilon}{D_g} \frac{A}{K}$$

+ Alrad Instruments, U.K. - AEA Winfrith design

where D_g is the dose sensitivity to Co^{60} (rad^{-1})
A is the cross sectional area of the counter (cm^2)
K is the neutron kerma factor in ICRU tissue ($rad.cm^2$)

The result obtained was k_u (3 MeV) = 0.0039 ± 0.0008

The measuring technique is difficult and time consuming. In spite of the fact that several days of accelerator time were necessary to obtain the profile shown in fig. 7, the statistical accuracy is poor. It appears therefore that the advantage of absolute flux determination is outweighed by the statistical disadvantages. However, the k_u-value obtained agreed well with other results obtained in this energy region using a similar counter(4,9).

The authors are indebted to Dr J.H. Hough for his assistance with this measurement.

CONCLUSION

An associated particle neutron source based on the $D(d,n)\,^3He$ reaction has been developed and is capable of providing collimated monoenergetic neutron beams of absolutely known flux in the 2 to 8 MeV range. Neutron fluences of up to 1000 s^{-1} are routinely obtainable. The source has been successfully used to measure the neutron detection efficiencies of a NE213 scintillator and a ZP1320 GM tube. In principle the source can be used to calibrate other dosimeters which provide a pulse output.

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FIGURE CAPTIONS

Fig. 1 : Schematic diagram of the experimental arrangement.

Fig. 2 : Horizontal and vertical neutron beam profiles measured at $E_d = 5$ MeV, $\theta_\tau = 25^o$ with a magnetically analysed charged particle beam. The charged particle detector subtended and angle of 0.4 msr at the target and the deuteron beam spot size was 1.5 mm in diameter.

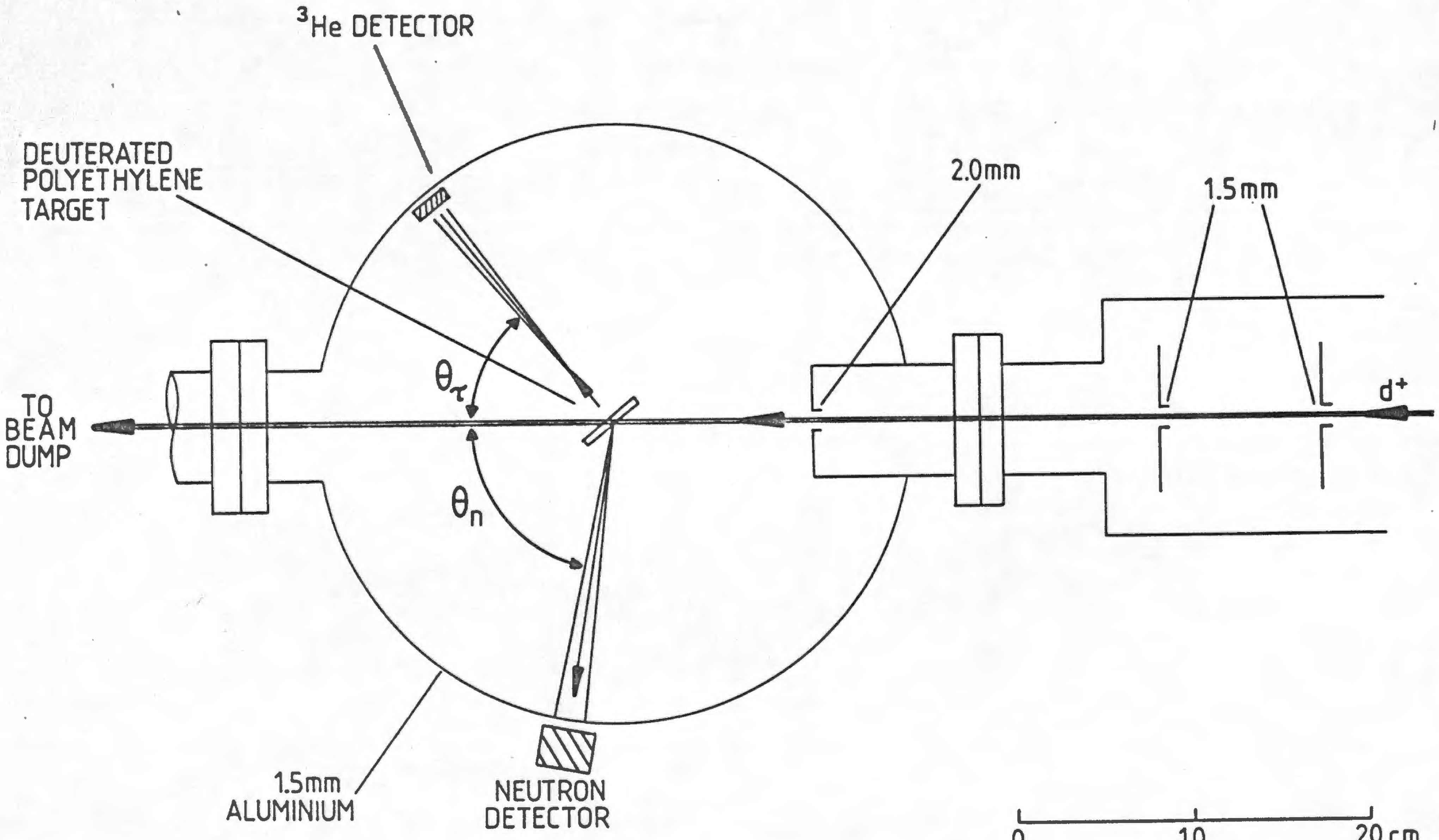
Fig. 3 : The ^3He yield as a function of time for a 200 $\mu g.cm^{-2}$ thick "sandwiched" deuterated polyethylene target bombarded with 2.5 μA of 5 MeV deuterons. The ^3He particles are detected at 25^o in a solid angle of 0.4 msr. Local variations in yield (continuous line) are due to variations in the beam current. The target was rotating at 5 Hz while the deuteron beam was displaced 6 mm from the axis of rotation.

Fig. 4 : Charged particle spectra obtained with a 30 μm thick silicon surface barrier transmission detector positioned at 25^o to the 5 MeV incident deuteron beam. Spectrum (A) was obtained without magnetic analysis while for spectrum (B) magnetic analysis of the recoil charged particles was employed. The spectra are recorded for approximately the same number of elastically scattered deuterons.

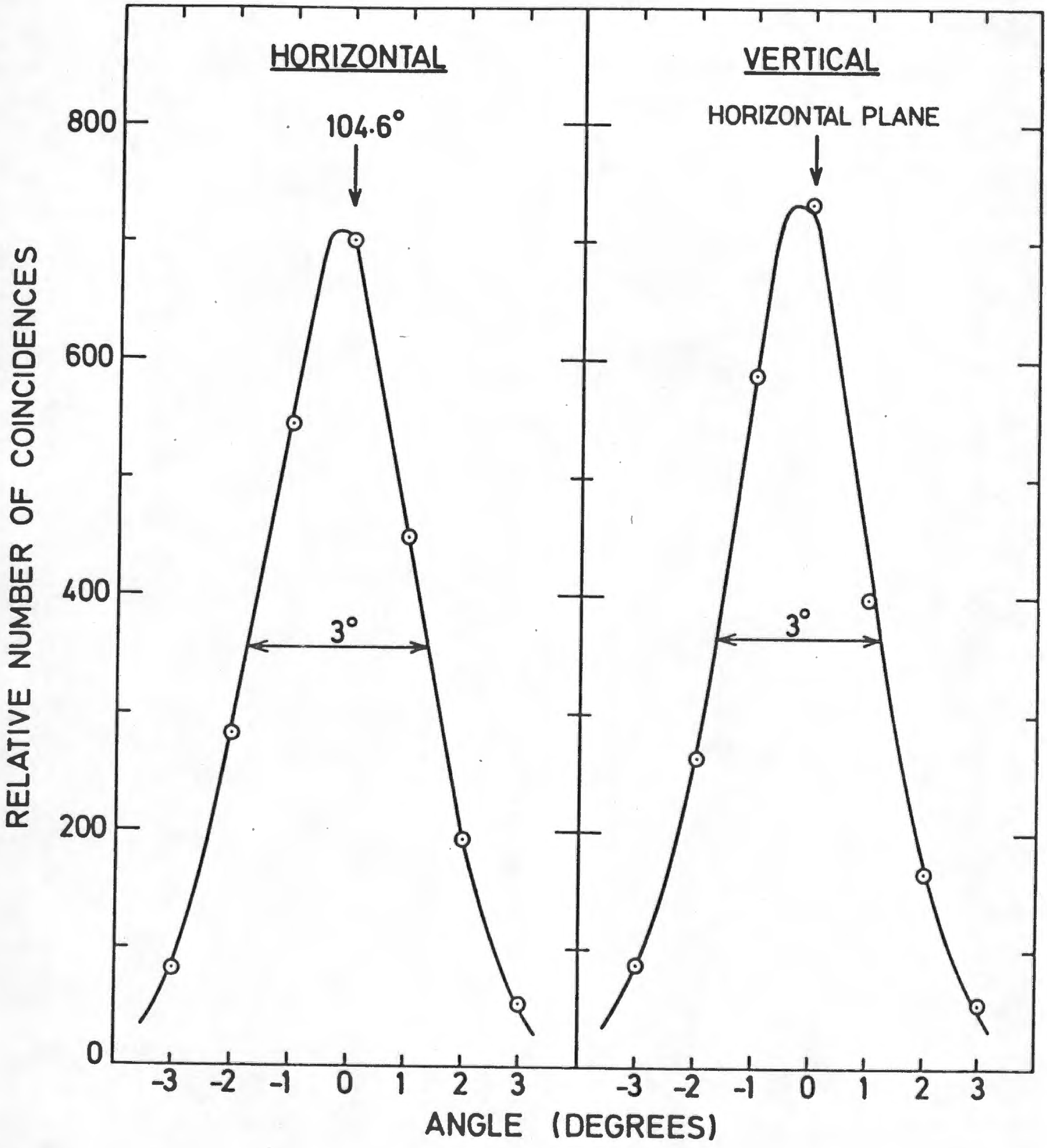
Fig. 5 : Measured central efficiency of 5.08 cm x 5.08 cm NE213 scintillator. The curve was calculated by the computer programme DETEFF(6).

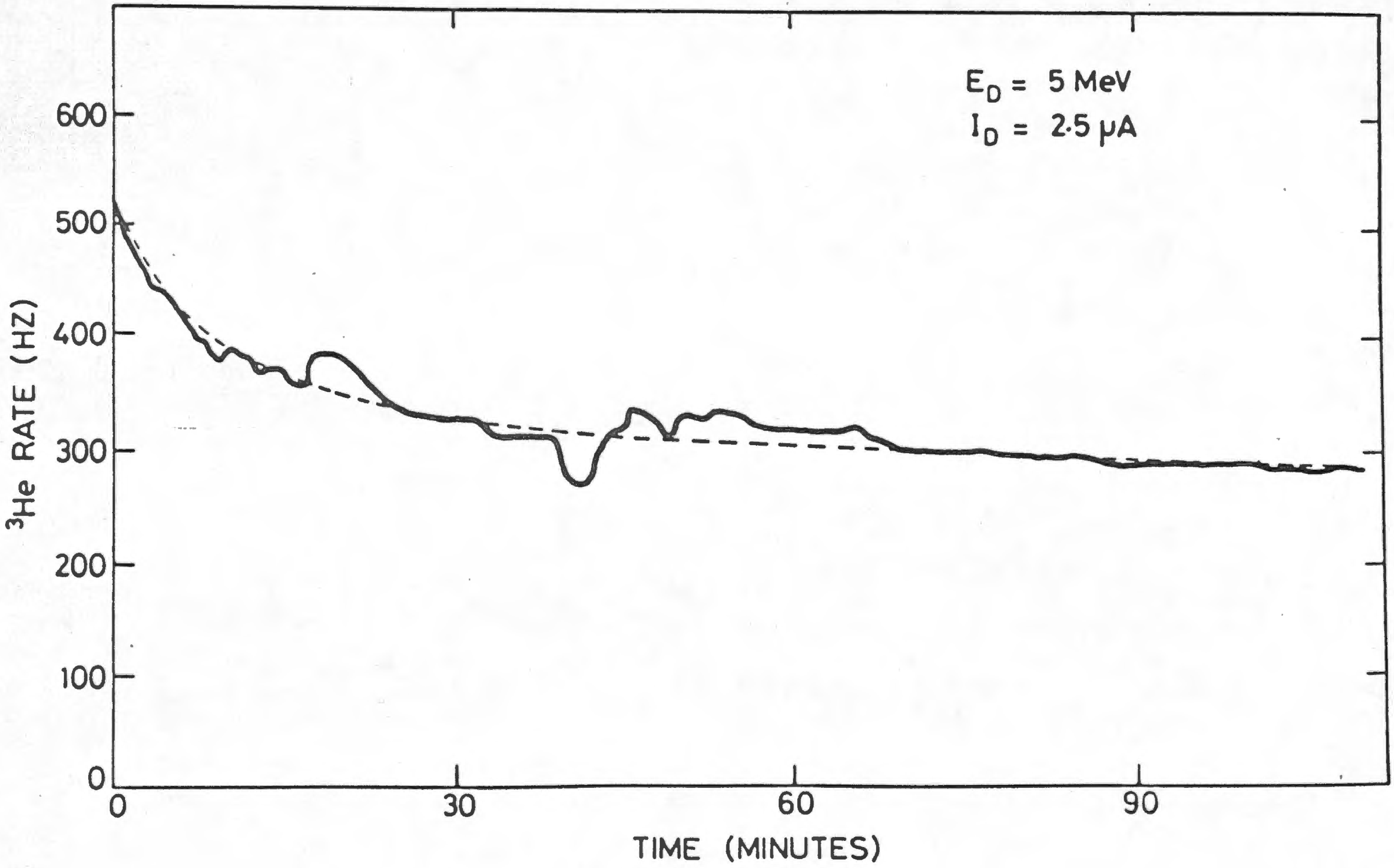
Fig. 6 : Coincidence time spectrum measured with ZP1320 GM counter on the neutron beam axis.

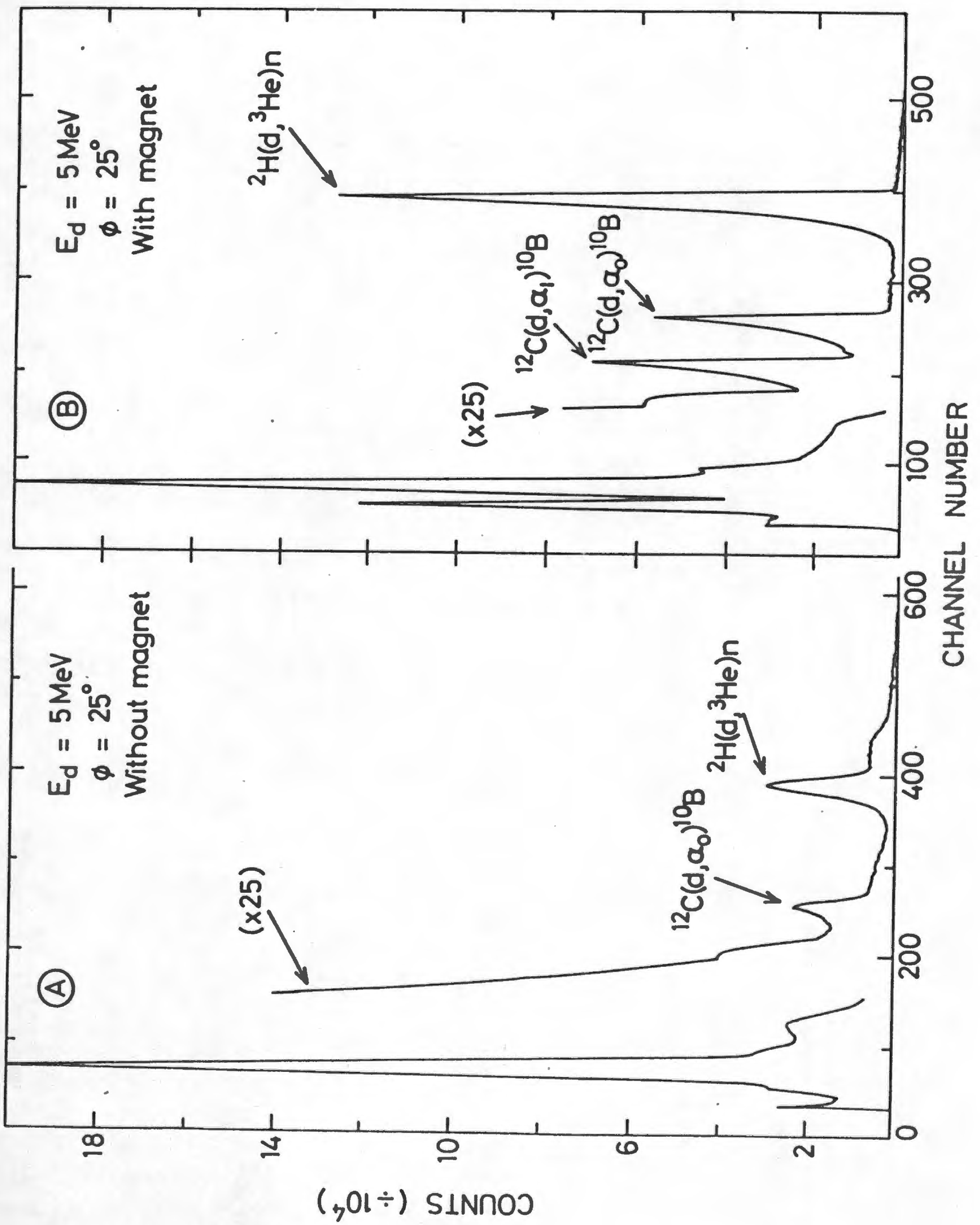
Fig. 7 : The neutron beam profile measured with ZP1320 GM counter for $E_d = 5$ MeV, $\theta_\tau = 25^o$. On the linear scale 3.5 mm corresponds to a rotation of 1^o and zero corresponds to $\theta_n = 104.6^o$

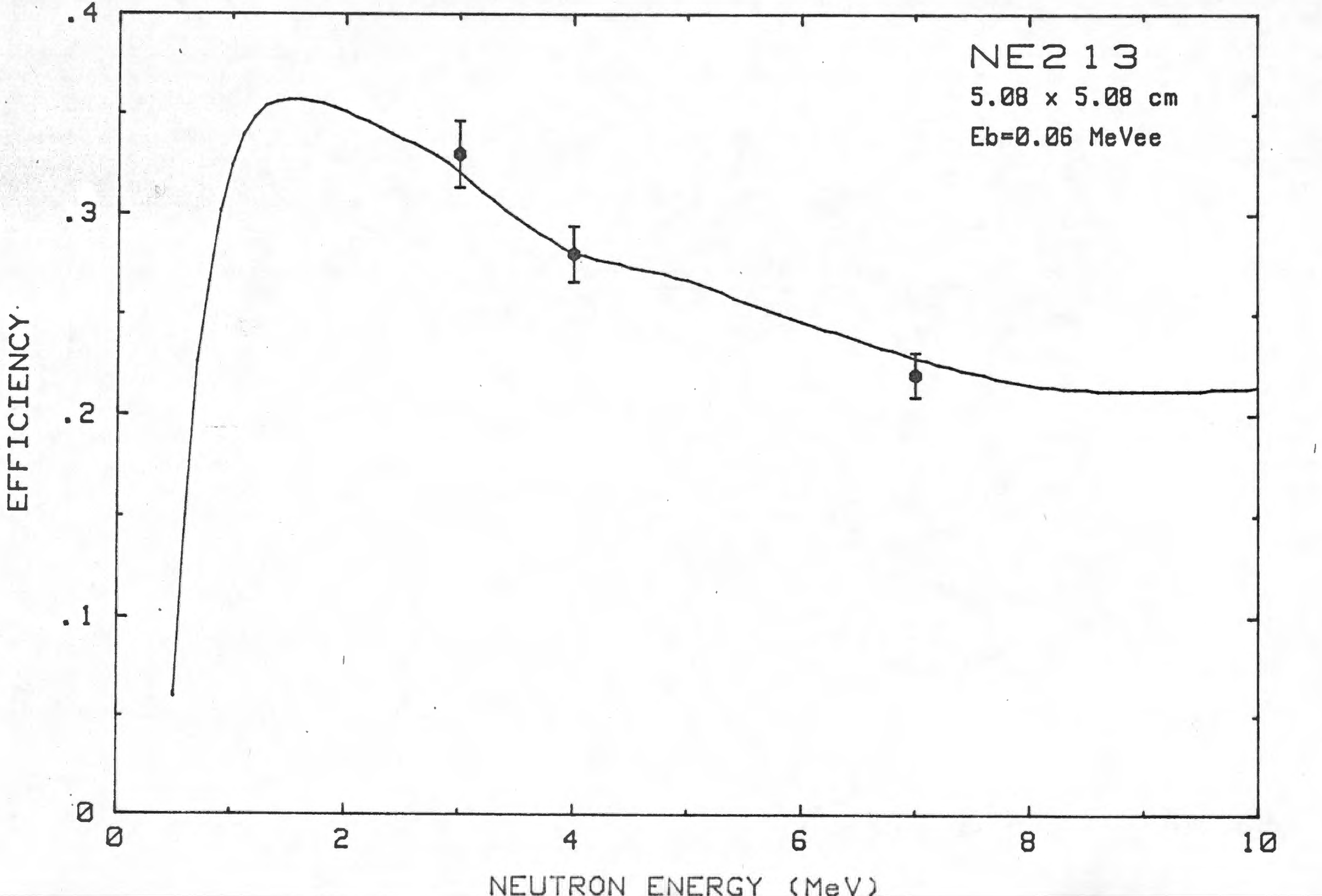


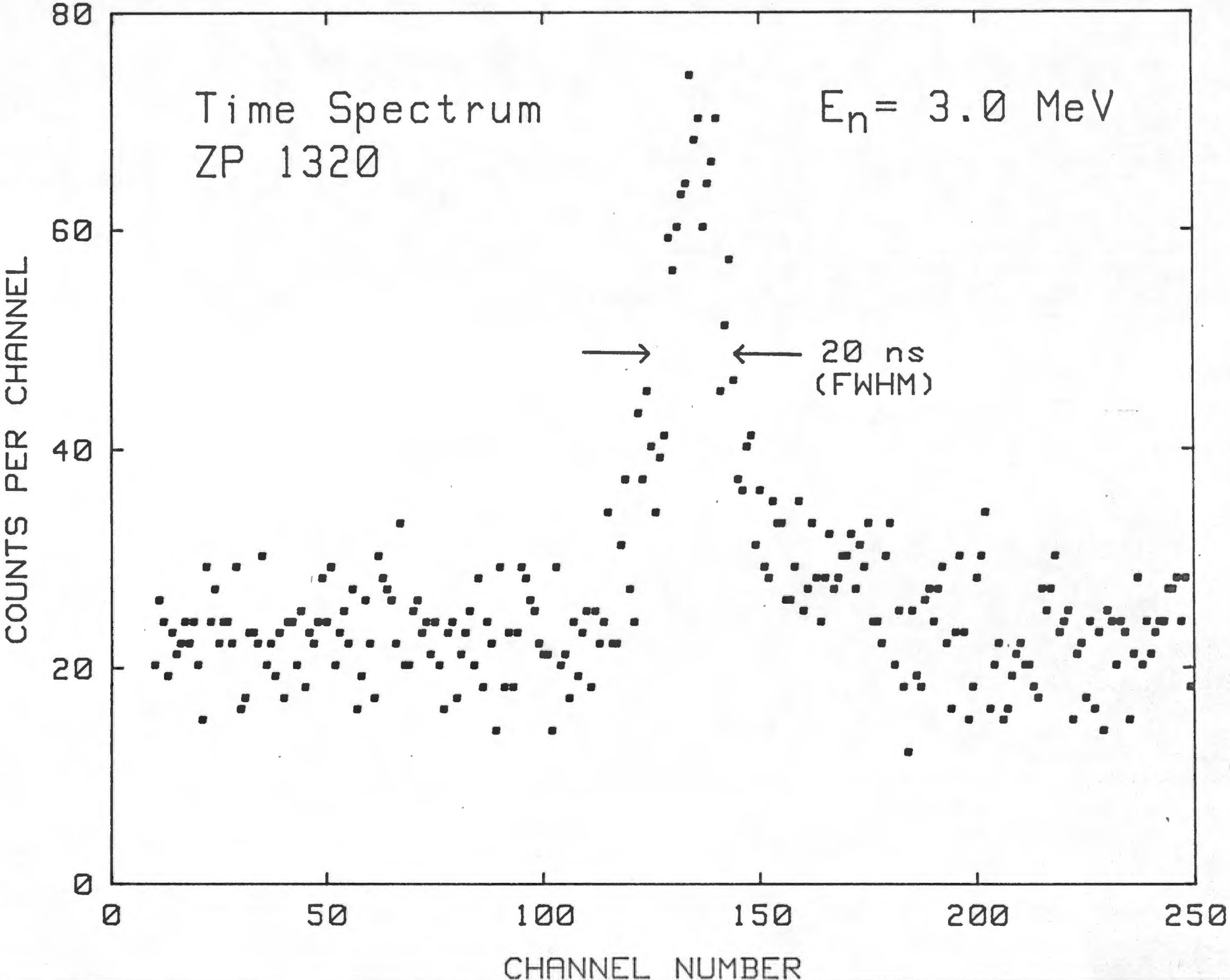
^{3}He DETECTOR
DEUTERATED POLYETHYLENE TARGET
2.0mm
1.5mm
d^+
θ_τ
TO BEAM DUMP
θ_n
1.5mm ALUMINIUM
NEUTRON DETECTOR
0
10
20 cm

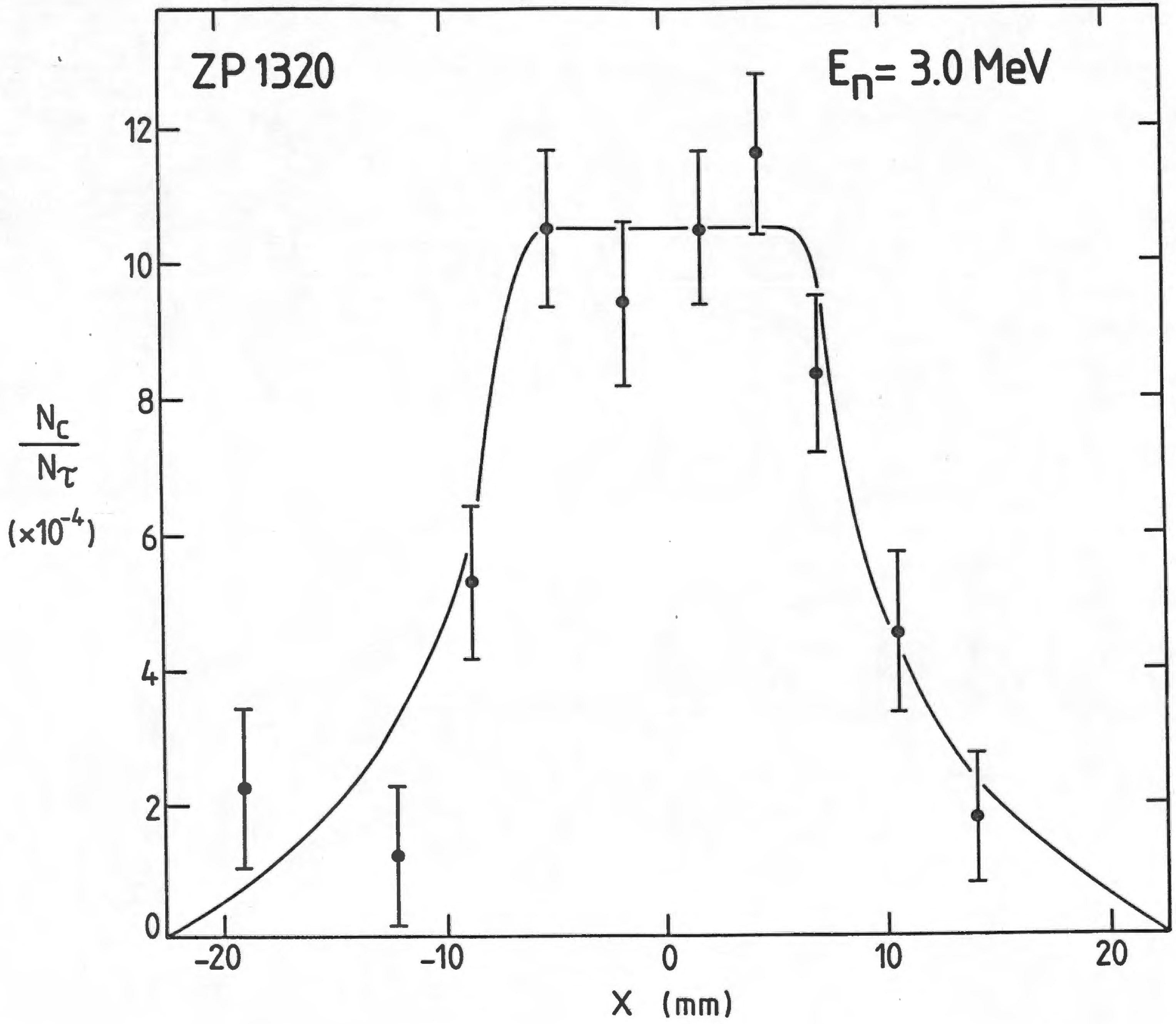

HORIZONTAL
VERTICAL
104.6°
HORIZONTAL PLANE
3°
3°
RELATIVE NUMBER OF COINCIDENCES
800
600
400
200
0
-3
-2
-1
0
1
2
3
-3
-2
-1
0
1
2
3
ANGLE (DEGREES)


E_D = 5 MeV
I_D = 2.5 μA
^{3}He RATE (HZ)
600
500
400
300
200
100
0
0
30
60
90
TIME (MINUTES)


A
E_d = 5 MeV
φ = 25°
Without magnet
(x25)
12C(d,α0)10B
2H(d,3He)n
B
E_d = 5 MeV
φ = 25°
With magnet
(x25)
12C(d,α1)10B
12C(d,α0)10B
2H(d,3He)n
COUNTS (÷10⁴)
18
14
10
6
2
0
200
400
600
100
300
500
CHANNEL NUMBER


NE213
5.08 x 5.08 cm
Eb=0.06 MeVee
EFFICIENCY
.4
.3
.2
.1
0
0
2
4
6
8
10
NEUTRON ENERGY (MeV)


Time Spectrum
ZP 1320
E_n= 3.0 MeV
20 ns
(FWHM)
COUNTS PER CHANNEL
0
20
40
60
80
CHANNEL NUMBER
0
50
100
150
200
250


ZP 1320
$E_n = 3.0$ MeV
$\frac{N_c}{N_\tau}$
$(\times 10^{-4})$
0
2
4
6
8
10
12
-20
-10
0
10
20
X (mm)

PAPER 3

"The Neutron Sensitivity of a GM counter between 0.5 and 8 MeV"

(Proc. 4th Symp. on Neutron Dosimetry, 1981)

THE NEUTRON SENSITIVITY OF A GM COUNTER BETWEEN 0·5 AND 8 MeV

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ABSTRACT

The pulsed beam time-of-flight method has been used to determine the k_u-values of a ZP1320 GM counter in the 0·5 to 8 MeV region. The neutron fluence was carefully determined by simultaneous measurement of the time-of-flight spectra with a NE213 scintillation counter. The results obtained are in good agreement with other measurements in this energy region using a similar counter.

INTRODUCTION

Since fast neutron beams can only be produced in nuclear reactions they are always contaminated with gamma rays which are produced by interactions of the primary charged particle beam in the target and by the resultant neutrons interacting with the surroundings. To completely specify such a mixed radiation field it is necessary to determine the neutron and gamma dose contributions since their biological effectiveness is markedly different.

The classical method is to measure the total (neutron + gamma) dose with a tissue-equivalent ionization chamber and the gamma dose with a "neutron-insensitive" photon dosimeter. A Geiger-Müller counter comes close to meeting the requirements(1) of such a dosimeter, viz. one which is

(1) Insensitive to neutrons
(2) Insensitive to orientation in the field and
(3) Has a linear response independent of photon energy.

Unfortunately, however, GM counters are not completely insensitive to neutrons. Although their sensitivity is low (and less than C-CO_2 or Mg-Ar ionization chambers which are also used in mixed field dosimetry) it has to be determined for accurate dose specifications. The neutron sensitivity is usually expressed as k_u, the ratio of the neutron response to the response to the gamma rays used for the calibration.

Various techniques have been used to determine k_u- values of photon dosimeters, for example the lead attenuation method(2,3), the spectral difference method(4,5) and the associated particle(6,7) and pulsed beam time-of-flight(8,9) techniques. The measurements which have been made with similar devices have not always been in good agreement, probably because of the inherent difficulties in measuring such low neutron efficiencies and because the response of each instrument is dependent on the precise details of its construction.

In the present work the k_U-values of an energy compensated GM counter have been measured by the pulsed beam time-of-flight technique using monoenergetic neutron beams between 0.5 and 8 MeV. The neutron flux was measured simultaneously with an NE213 scintillation counter.

THE GM COUNTER

A type ZP1320 (MX164)[+] GM counter was used. The counter was supplied with an energy compensating filter assembly with a PTFE outer sleeve and the device was enclosed in a perforated metal shield.

A GM tube has intrinsically poor fast timing characteristics. The standard counter was modified so that the output was taken directly from the cathode strap across a 50 Ω load resistor, while the high voltage was applied to the anode. The timing resolution improves with increased applied voltage and the counter was therefore operated near the top end of the plateau. Timing resolution of about 20 ns (FWHM) was obtained both in a γ-γ coincidence measurement with an organic scintillator and in the pulsed beam time-of-flight measurements.

The counter was calibrated with a Co^{60} source. The measured dose sensitivity was 31.3×10^6 counts.rad^{-1}. The dead time of the counter was 46 μs and at the count rates encountered in the present experiment (≤15 Hz) dead time losses in both the counter and the electronics were negligible.

EXPERIMENTAL METHOD

Measurements were made using the 6 MV van de Graaff accelerator of the Southern Universities Nuclear Institute. Pulsed (2 MHz) beams of protons and deuterons were incident on gas targets of tritium and deuterium respectively producing monoenergetic neutrons from the $T(p,n)^3He$ and $D(d,n)^3He$ reactions. The incident particle energies

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[+] Alrad Instruments, U.K. - AEA Winfrith design were below the reaction threshold for ^{3}He breakup (8.34 MeV and 4.45 MeV at 0^o respectively), thus ensuring that strictly monoenergetic beams were used.

The target cells were 3 cm long with a gold beam stop and had a 2.5 μm thick havar entrance window. The gas pressure was kept at approximately 0.8 kPa for all the measurements. Target currents were typically about 1 μA. Standard fast electronics was used to obtain the time-of-flight spectra. A simplified block diagram of the electronic circuit is given in Fig. 1.

The GM counter was placed at -5^o to the accelerator beam direction with its axis parallel to the neutron beam apart from one measurement at E_n = 1.82 MeV when the axis was perpindicular to the neutron beam.

Depending on neutron energy flight paths of between 0.8 and 2.5 MeV were required to give good separation between the monoenergetic neutron peak and the prompt gamma peak in the time spectra. However, these peaks were not completely resolved because of their low energy "tail". Spectra were therefore measured at some energies with the target evacuated in order to obtain the line shape of the gamma peak which was then used to strip the neutron peaks from the composite spectra. A flat background was fitted to each spectrum by least squares prior to stripping.

Fig. 2 shows spectra measured at a flight path of 1.23 m for the $T(p,n)^3He$ reaction at E_p = 3.65 MeV with the target filled (upper curve) and evacuated (lower curve). The horizontal lines are the background fits.

MEASUREMENT OF NEUTRON FLUX

The neutron flux was determined by simultaneous measurement of the time-of-flight spectra with a 2.54 cm diameter x 2.54 cm long NE213 scintillator mounted on a RCA 8850 photomultiplier tube. This detector was placed at $+5^o$ to the accelerator beam direction. The electronic circuit used to measure the spectra was similar to that shown in Fig. 1. A pulse shape discriminator (PSD)+(10) was incorporated in the circuit to eliminate gamma-induced events. Typical time spectra are shown in Fig. 3. These were obtained with the T(p,n) He reaction at E_n = 3.65 MeV and a flight path of 5.77 m. The PSD was inoperative (upper curve) and operative (lower curve) showing the elimination of the prompt gamma ray peak and the time-uncorrelated gamma ray background.

For the flux measurements a flight path of 5.77 m was used for all energies except for E_n = 0.72 MeV when the flight path was 1.99 m. The long flight path was necessary to ensure that dead time losses in the counting system were kept to a minimum. These were carefully monitored and were seldom more than about 5%.

The computer code DETEFF(11) was used to calculate the neutron detection efficiency of the scintillation counter. Following the authors' recommendation an error of 10% was ascribed to the calculation at each energy point.

RESULTS

k_u at energy E relative to Co^{60} was calculated as follows :

$$k_u(E) = A_g(E) \left[\frac{A_s(E)}{\varepsilon_s(E)} \quad \frac{1}{\pi r_s^2} \quad \frac{d_s^2}{d_g^2} \right]^{-1} \frac{1}{D_g} \quad \frac{1}{K(E)}$$

The subscripts g and s refer to the GM and scintillation counters respectively.

A	is the number of counts in the monoenergetic neutron peak in the time spectrum
ε	is the efficiency of the scintillator
r,d	are the radii and flight paths of the detectors (cm)
D	is the dose sensitivity to Co^{60} radiation of the GM tube (rad^{-1})
K	is the neutron kerma factor in ICRU tissue ($rad.cm^2$)

+ Link Systems, U.K.

In Fig. 4 the present k_u- values are shown together with measurements made in this energy range with a similar counter by Jones et al(7) using the associated particle technique and Lewis and Hunt(5) using the spectral difference method.

The uncertainties in the present measurements include statistical errors but are mainly due to the 10% error ascribed to the calculated efficiency of the NE213 scintillation counter.

The measurement made at 1.82 MeV with the counter axis perpindicular to the neutron beam direction is about 20% higher than the measurement made with the axis parallel to the beam direction. This increase is of the same order as found by Lewis and Young(6) with a similar counter at 14.7 MeV using the associated particle technique.

CONCLUSION

The pulsed beam time-of-flight technique is a relatively simple method of measuring k_u- values of a GM counter with reasonable accuracy in this energy range. This technique is particularly amenable to this type of measurement since the gamma and neutron contributions can be well separated in the time spectra by operating at sufficiently long flight paths where the only limiting factor may be the time required to collect data with sufficient statistical accuracy. The accuracy of the present results are limited by the precision with which the neutron flux can be determined, but agree well with previous measurements.

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FIGURE CAPTIONS

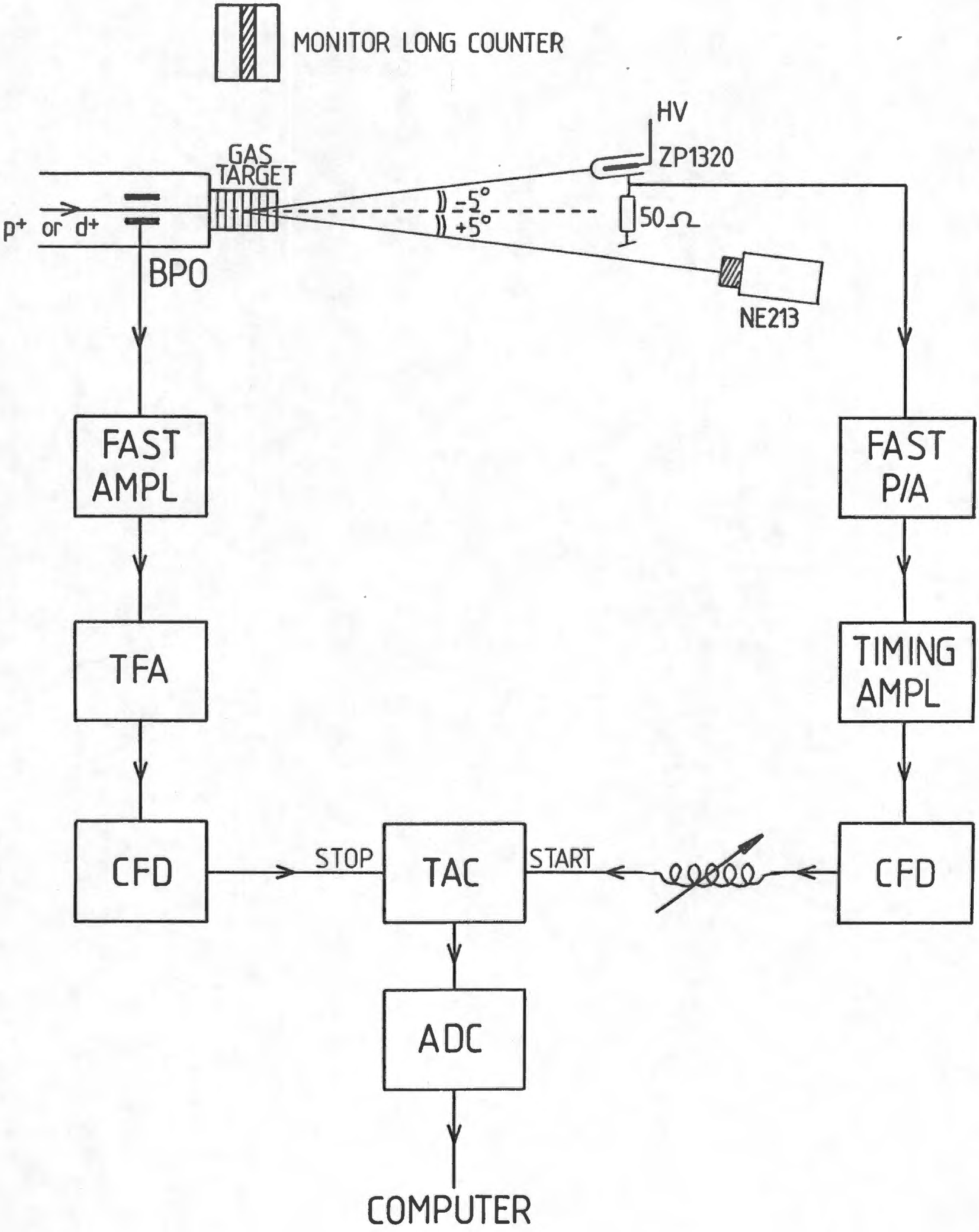
Fig. 1. Simplified block diagram of the experimental arrangement for the measurement of time-of-flight spectra with ZP1320 GM counter.

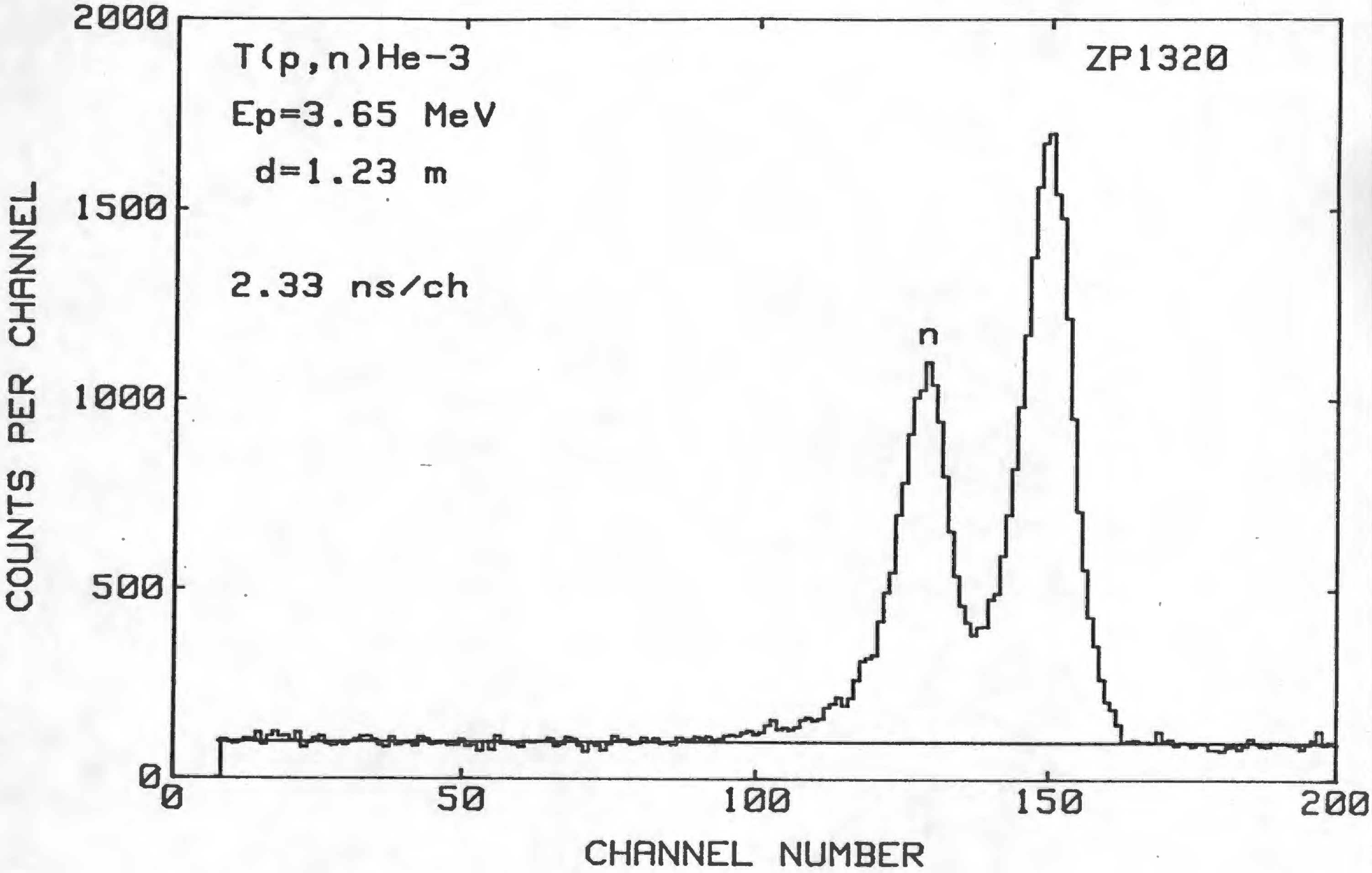
BPO : beam pick-off
TFA : timing filter amplifier
CFD : constant fraction discriminator
TAC : time-to-amplitude converter
ADC : analogue-to-digital converter

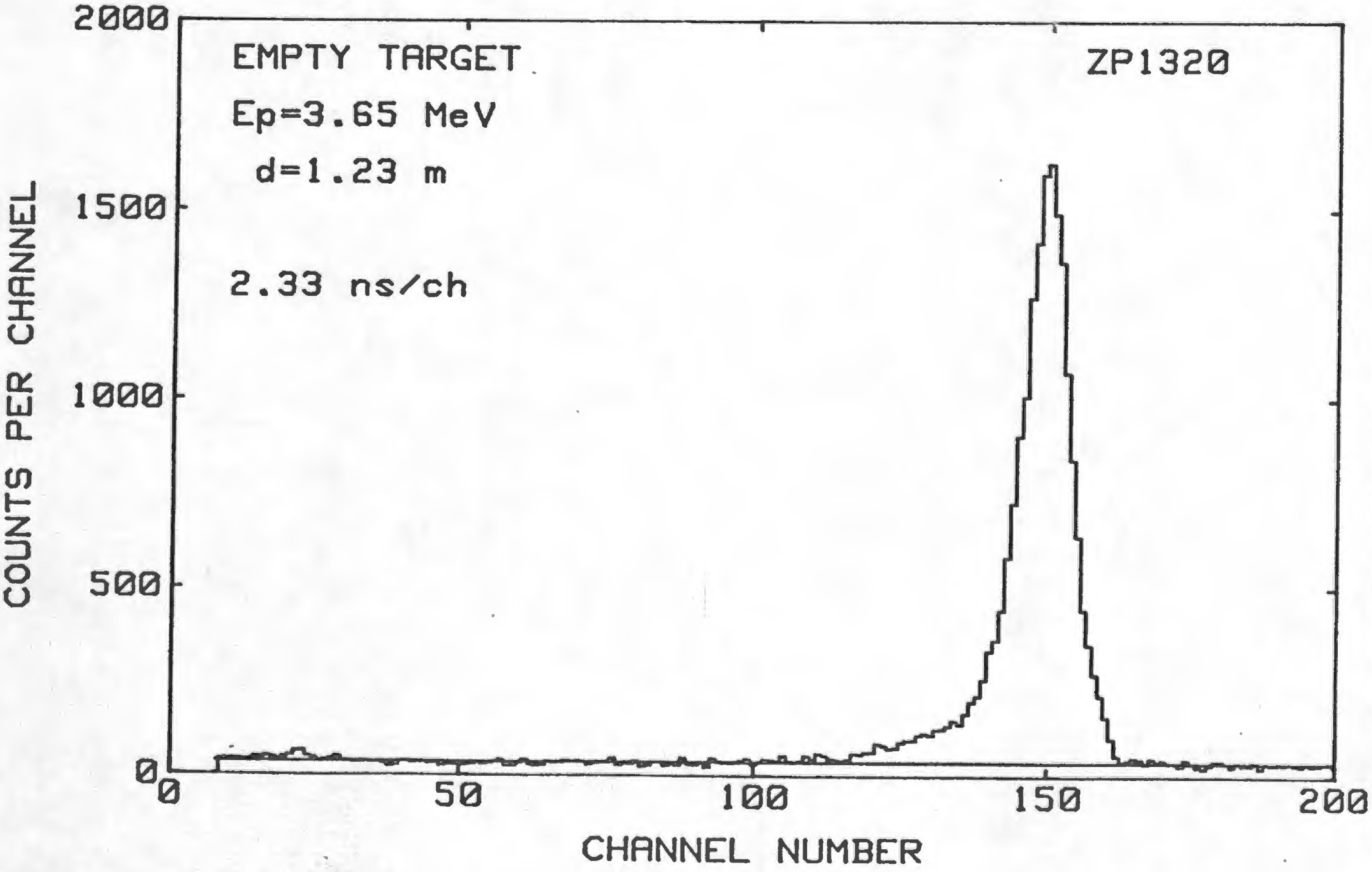
Fig. 2. Time-of-flight spectra of T(p,n)^{3}He reaction measured with ZP1320 GM counter. The horizontal lines are least squares fits to the background. The mean energy of the neutron peak is 2.86 MeV. The spectra were recorded for the same integrated charge on the target.

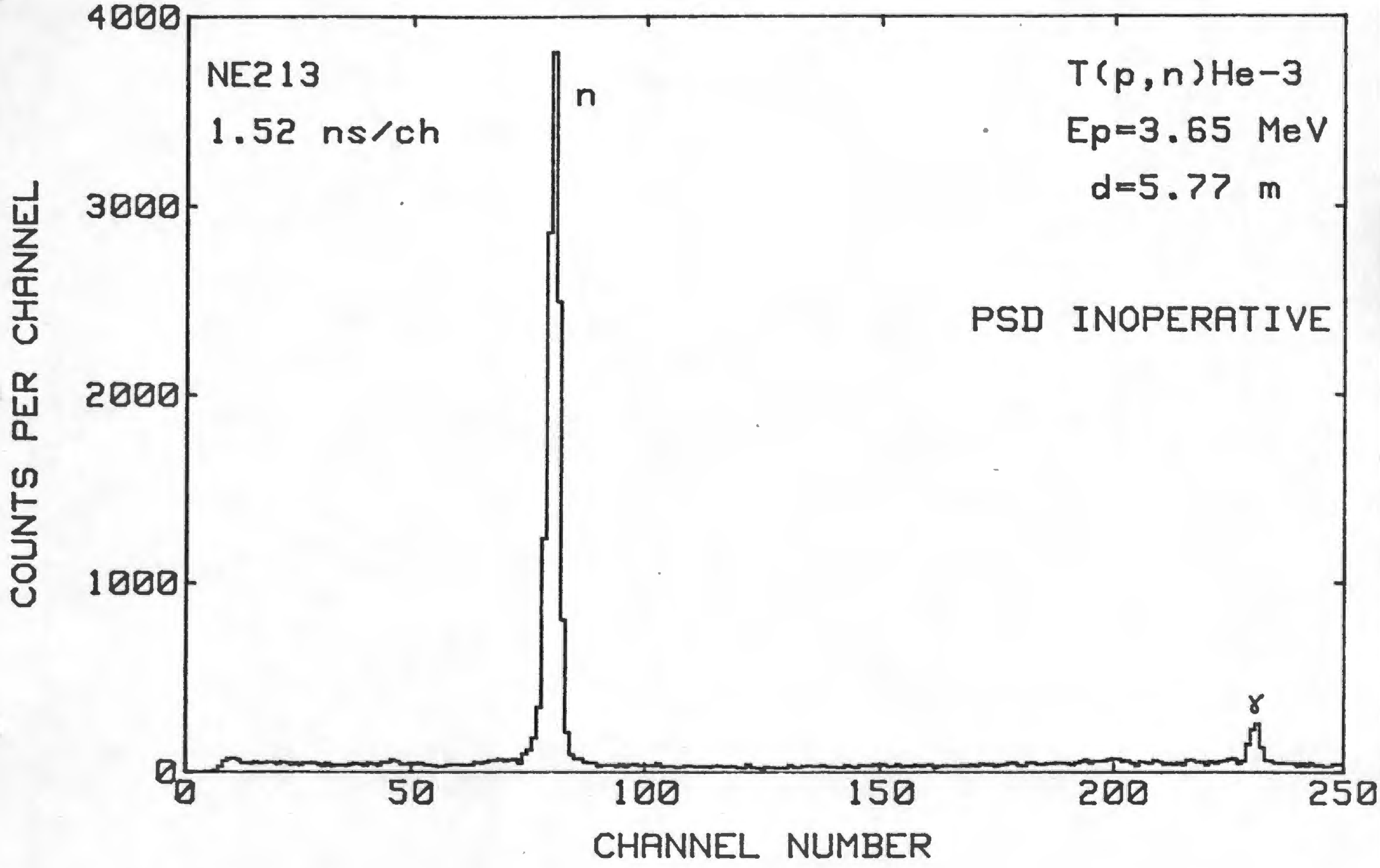
Fig. 3. Time-of-flight spectra of T(p,n)^{3}He reaction measured with NE213 scintillation counter. The mean energy of the neutron peak is 2.86 MeV. The spectra were recorded for the same integrated charge on the target.

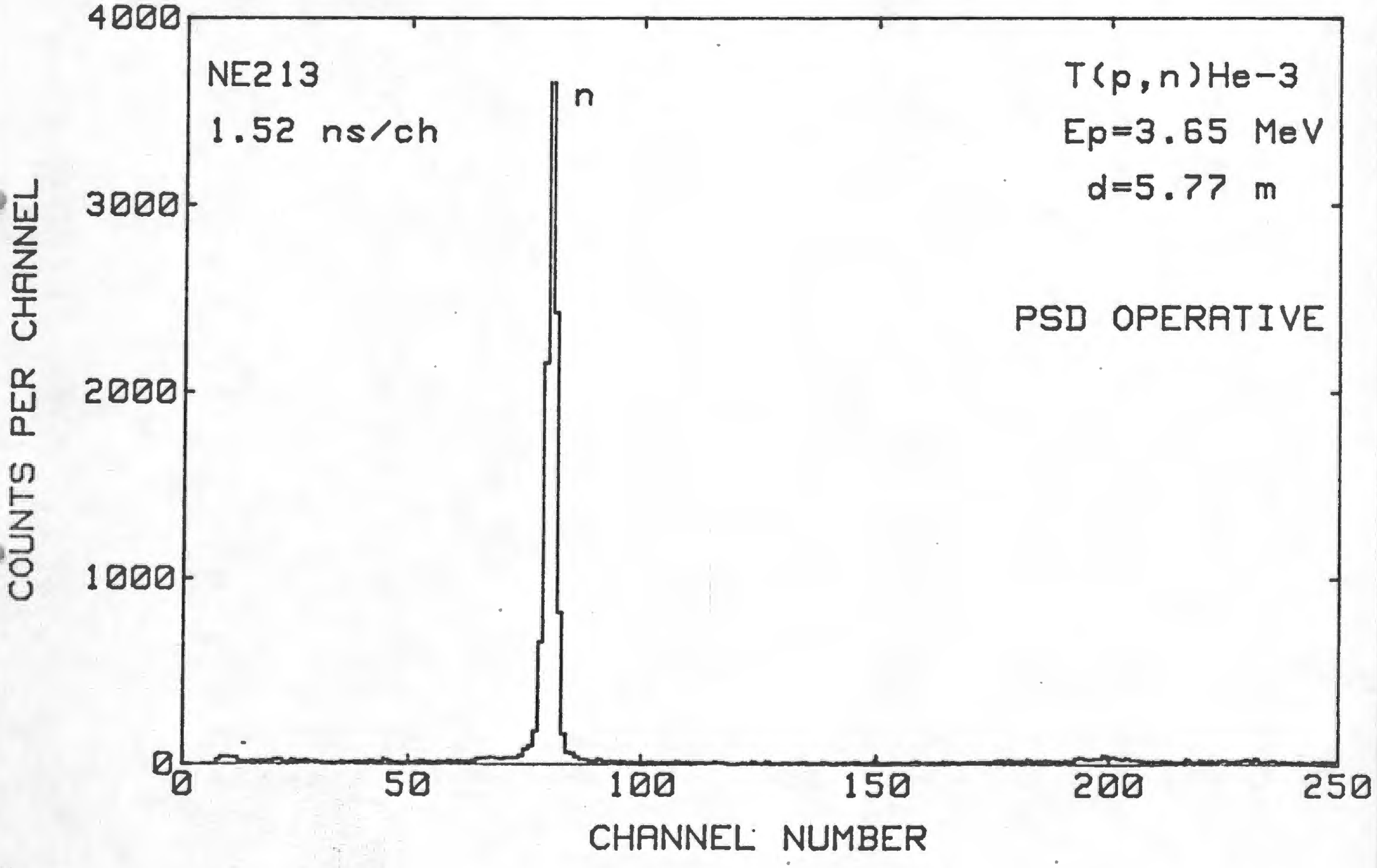
Fig. 4. k_u-values for the ZP1320 GM counter obtained in the present experiment. All the measurements were made with the axis of the counter parallel to the neutron beam except for one measurement at E_n = 1.82 MeV. Also plotted are measurements made with a similar counter by Lewis and Hunt(5) and Jones et al(7).

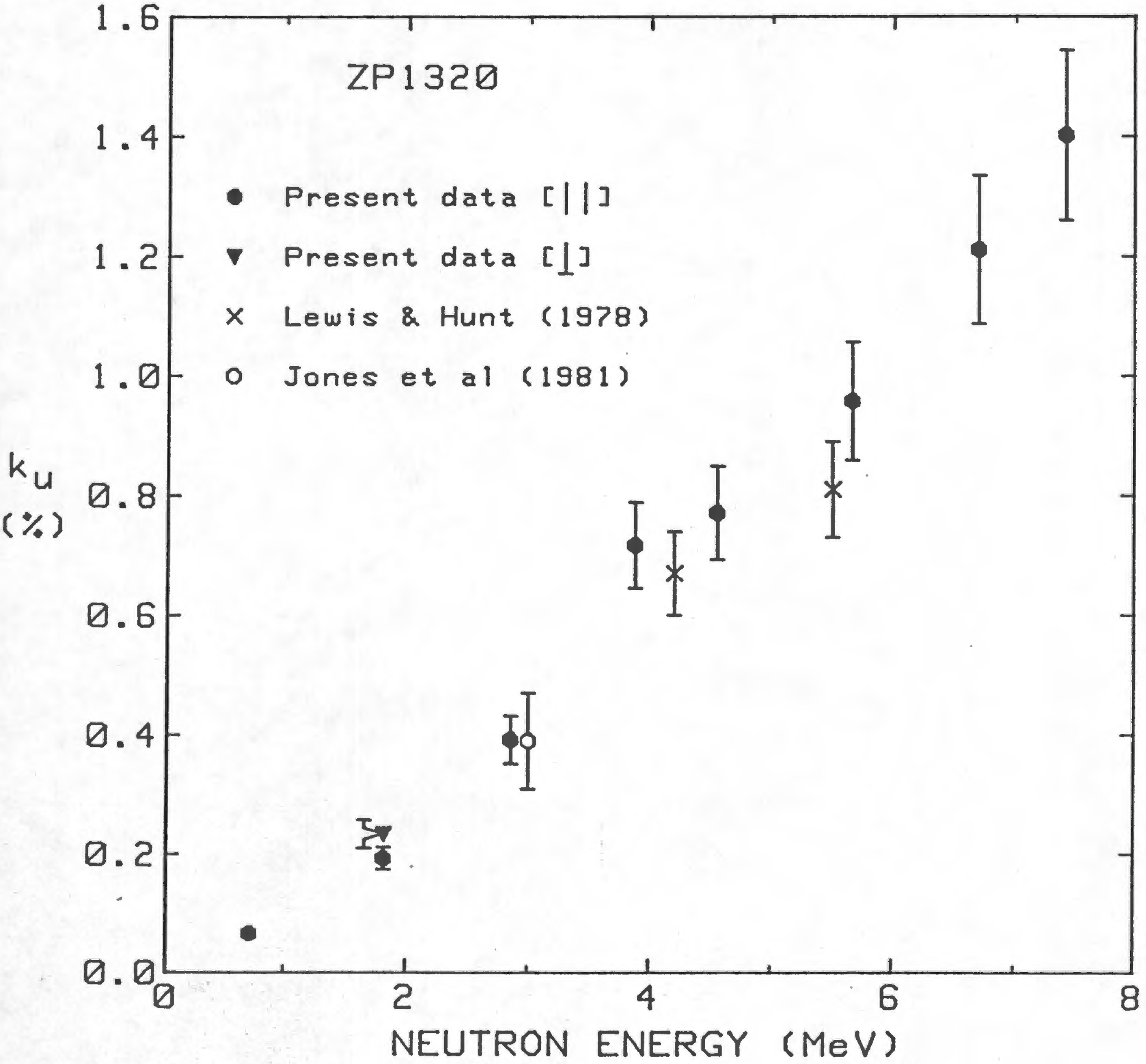

MONITOR LONG COUNTER
HV
ZP1320
GAS TARGET
-5°
+5°
50 Ω
p+ or d+
BPO
NE213
FAST AMPL
FAST P/A
TFA
TIMING AMPL
CFD
STOP
TAC
START
CFD
ADC
COMPUTER


T(p,n)He-3
ZP1320
Ep=3.65 MeV
d=1.23 m
2.33 ns/ch
n
COUNTS PER CHANNEL
CHANNEL NUMBER
0
500
1000
1500
2000
0
50
100
150
200


EMPTY TARGET
ZP1320
Ep=3.65 MeV
d=1.23 m
2.33 ns/ch
COUNTS PER CHANNEL
CHANNEL NUMBER
0
500
1000
1500
2000
0
50
100
150
200


4000
3000
2000
1000
0
COUNTS PER CHANNEL
0
50
100
150
200
250
CHANNEL NUMBER
NE213
1.52 ns/ch
n
γ
T(p,n)He-3
Ep=3.65 MeV
d=5.77 m
PSD INOPERATIVE


4000
3000
2000
1000
0
COUNTS PER CHANNEL
0
50
100
150
200
250
CHANNEL NUMBER
NE213
1.52 ns/ch
n
T(p,n)He-3
Ep=3.65 MeV
d=5.77 m
PSD OPERATIVE


ZP1320
● Present data [||]
▼ Present data [⊥]
× Lewis & Hunt (1978)
○ Jones et al (1981)
k_u (%)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
0
2
4
6
8
NEUTRON ENERGY (MeV)

PAPER 4

"Absolute Measurement of the Neutron Sensitivity of a ZP1320 Geiger-Müller Counter Using the Associated Particle Technique"

(Health Phys. 43 (1982) 715)

ABSOLUTE MEASUREMENT OF THE NEUTRON SENSITIVITY OF A ZP1320 GEIGER-MÜLLER COUNTER USING THE ASSOCIATED PARTICLE TECHNIQUE

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Abstract Because of their low neutron sensitivity Geiger-Müller counters are often used in mixed field dosimetry to determine the photon dose fraction. The associated particle technique has been used to determine absolutely the neutron sensitivity of an energy compensated ZP1320 Geiger-Müller counter at 3 MeV. The measurement is consistent with previous measurements using this type of counter.

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Introduction

Fast neutron beams are always accompanied by gamma rays. The gamma contamination of neutron beams used for radiotherapy and radiobiology, although typically of the order of a few percent, is an important factor since the biological effectiveness of gamma rays differs markedly from that of neutrons. Because of their low neutron detection efficiency, energy compensated Geiger-Müller (GM) counters (Wa61) are often the instruments of choice for the determination of the gamma dose component in mixed radiation fields (ICRU77).

For accurate dose specification it is necessary to determine the sensitivity of these counters to neutrons. This is usually expressed as k_u, the ratio of the neutron response to the response to the gamma rays used for the calibration (ICRU77). Several groups have determined the neutron sensitivities of different types of GM counters using a variety of techniques (At75, Gu80, Ho79, Kl78, Ku75, Le77, Le78). The measurements which have been made with similar counters have not always been in good agreement, probably because of the inherent difficulties in measuring such low neutron responses and because the response of each counter is dependent on the precise details of its construction.

In the present work we have measured absolutely the k_u-value of an energy compensated ZP1320 GM counter at 3 MeV using the associated particle technique.

Measurement of k_u

The high flux associated particle neutron source (Ba81) at the Southern Universities Nuclear Institute was used to provide an electronically collimated cone of 3 MeV neutrons of known flux. An aluminium scattering chamber, 340 mm in diameter and with 15 mm thick walls was used. The neutrons were produced in the $D(d,n)^3He$ reaction by bombarding a rotating deuterated polyethylene target, sandwiched between two carbon layers, with a 1.5 mm diameter deuteron beam. The associated ^3He ions were detected in a totally depleted silicon surface barrier transmission detector. A simple magnetic analyser was employed to partially screen the surface barrier detector from the high flux of elastically scattered neutrons. The ^3He peak was unambiguously resolved in the energy loss charged particle spectrum (Ba81).

A type ZP1320/PTFE[+] (also known as 18550 or MX164) GM counter was used. The counter was fitted with an energy compensating tin and lead filter and a PTFE outer sleeve. In order to improve the timing characteristics of the counter the output was taken directly from the cathode strap across a 50 ohm load resistor while the high voltage was applied to the anode. The counter was operated at 750 V, near the top end of the plateau. Typically a timing resolution of 20 ns (FWHM) was obtained. The counter was placed just outside the scattering chamber on a rotating arm with the axis of the counter aligned with the neutron cone axis. Hevimet was used to shield the counter from the deuteron beam collimators in order to reduce the gamma background. The experimental arrangement is shown schematically in fig. 1.

Standard fast electronics were used with the GM counter and the surface barrier detector to provide the START and STOP pulses respectively to a time-to-pulse height converter. A typical coincidence time spectrum is shown in fig. 2. The random background is a result of the high sensitivity of the counter to the gamma rays produced in the target and in the surroundings.

[+] Alrad Instruments Ltd., Newbury, Berkshire, England - AEA Winfrith design

The number of counts in the peak in the time spectrum gives the number of real coincidences N_C. The number of counts N_τ in the associated ^{3}He peak in the surface barrier detector spectrum, which was recorded simultaneously, is equal to the effective number of neutrons in the cone. The variation of the ratio $\varepsilon' = N_C/N_\tau$ with position on the neutron cone was measured by scanning the GM counter horizontally across the cone (which enveloped the counter).

Results

The measured horizontal neutron cone profile scan is shown in fig. 3. The errors shown are statistical and corrections for dead time effects have been made to the data points.

Because of the cylindrical symmetry of both the GM counter and the neutron cone (Ba81), the efficiency of the counter can be calculated by numerical integration of the profile.

The efficiency is given by (Fo80) :

$$\varepsilon = \frac{2\pi}{A}\int_0^{R+r} \varepsilon'(x)\, x\, dx$$

where A and R are the cross sectional area and radius of the GM counter respectively.

r is the radius of the neutron cone at the effective centre of the GM counter

x is the displacement of the GM counter axis from the neutron cone axis

and $\varepsilon' = N_c/N_\tau$ (see above)

The efficiency at 3 MeV was found to be :

$$\varepsilon\ (3\ \text{MeV}) = (2.86 \pm 0.57) \times 10^{-4}$$

The k_u value relative to ^{60}Co was calculated as follows :

$$k_u\ (E) = \frac{\varepsilon(E)}{D_G}\ \frac{A}{K(E)}$$

where D_G is the dose sensitivity to ^{60}Co (31.3×10^8 Gy^{-1})

and K is the neutron kerma factor in ICRU muscle at 3 MeV

(.367 x 10^{-10} Gy.cm^2 (ICRU77))

The result obtained was :

$$k_u\ (3\ \text{MeV}) = 0.0039 \pm 0.0008$$

Previous measurements with the ZP1320/PTFE GM counter have been made by Lewis and Hunt (Le78) using the so-called spectral difference method. Their results are compared with the present measurement in Table 1. Since k_u for GM counters increases with neutron energy in this energy range (Mi79, Jo81) the present measurement is not inconsistent with the earlier work.

Conclusion

The associated particle technique has been used for the measurement of the k_u-value of a ZP1320/PTFE Geiger-Müller counter. The result obtained is consistent with previous measurements made with this type of counter using an independent technique.

The advantage of using the present method lies in the fact that the neutron flux is known absolutely and it is therefore intrinsically more accurate than other techniques which have been used for this type of measurement. However, because of the extremely low neutron sensitivity of GM counters the measurements are very time consuming and their statistical accuracy is therefore limited by the available accelerator time. The method can in principle be used for calibrating any dosimeter which provides pulse output, such as pulse fission counters.

The authors are indebted to the technical staff of the Southern Universities Nuclear Institute for their assistance during the experiment.

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Le78 Lewis V.E. and Hunt J.B., 1978, "Fast Neutron Sensitivities of Geiger-Mueller Gamma Dosemeters", Phys. Med. Biol. 23, No. 5, 888

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Table Captions

Table 1: k_u-values for ZP1320/PTFE GM counter

Figure Captions

Fig. 1 : Schematic diagram of the experimental arrangement. The magnetic analyser attachment is not drawn to scale. The kinematic conditions were:

E_d = 5.0 MeV, θ_τ = 25.0°, E_τ = 5.27 MeV, θ_n = 104.6° (nominal)

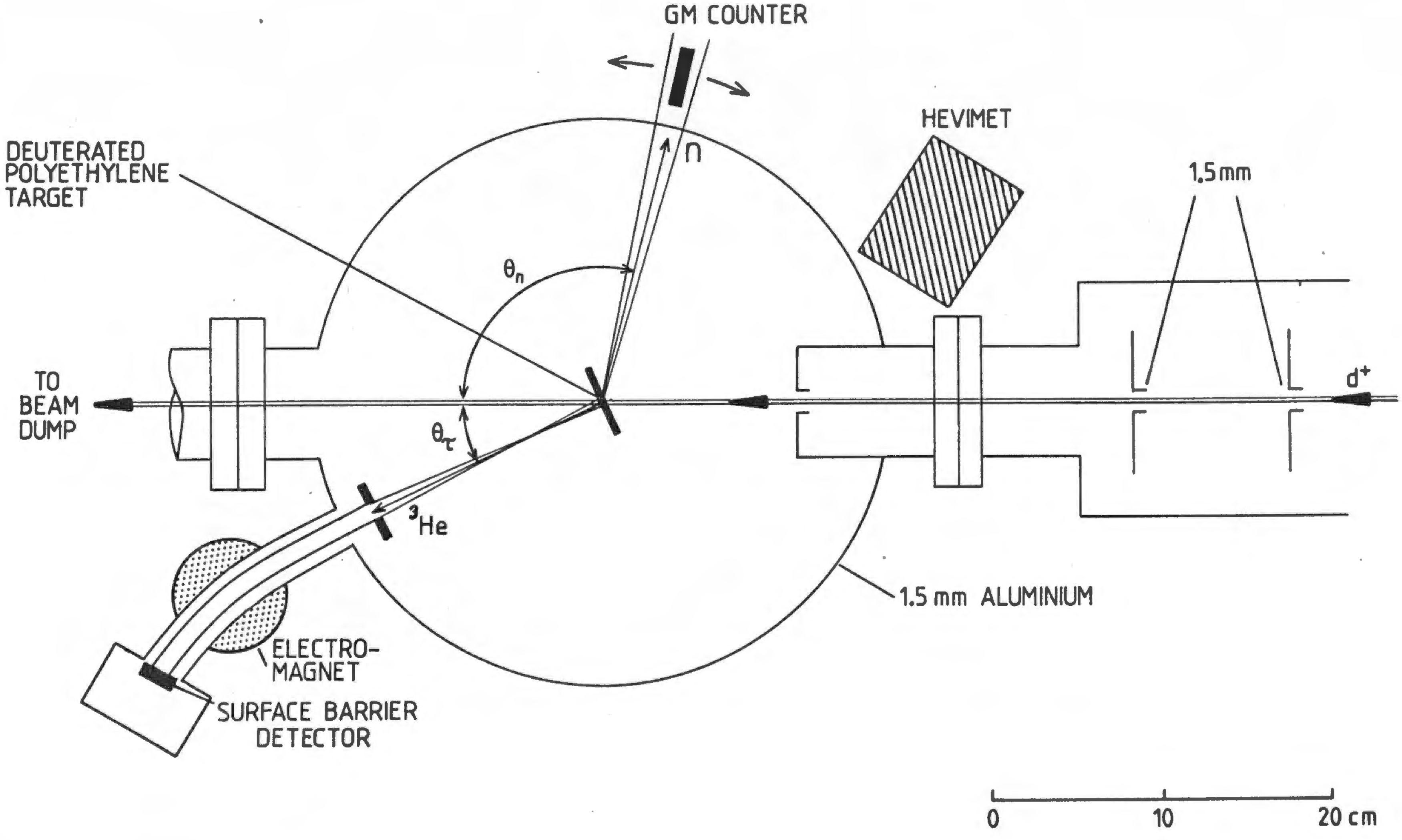
E_n = 3.0 MeV.

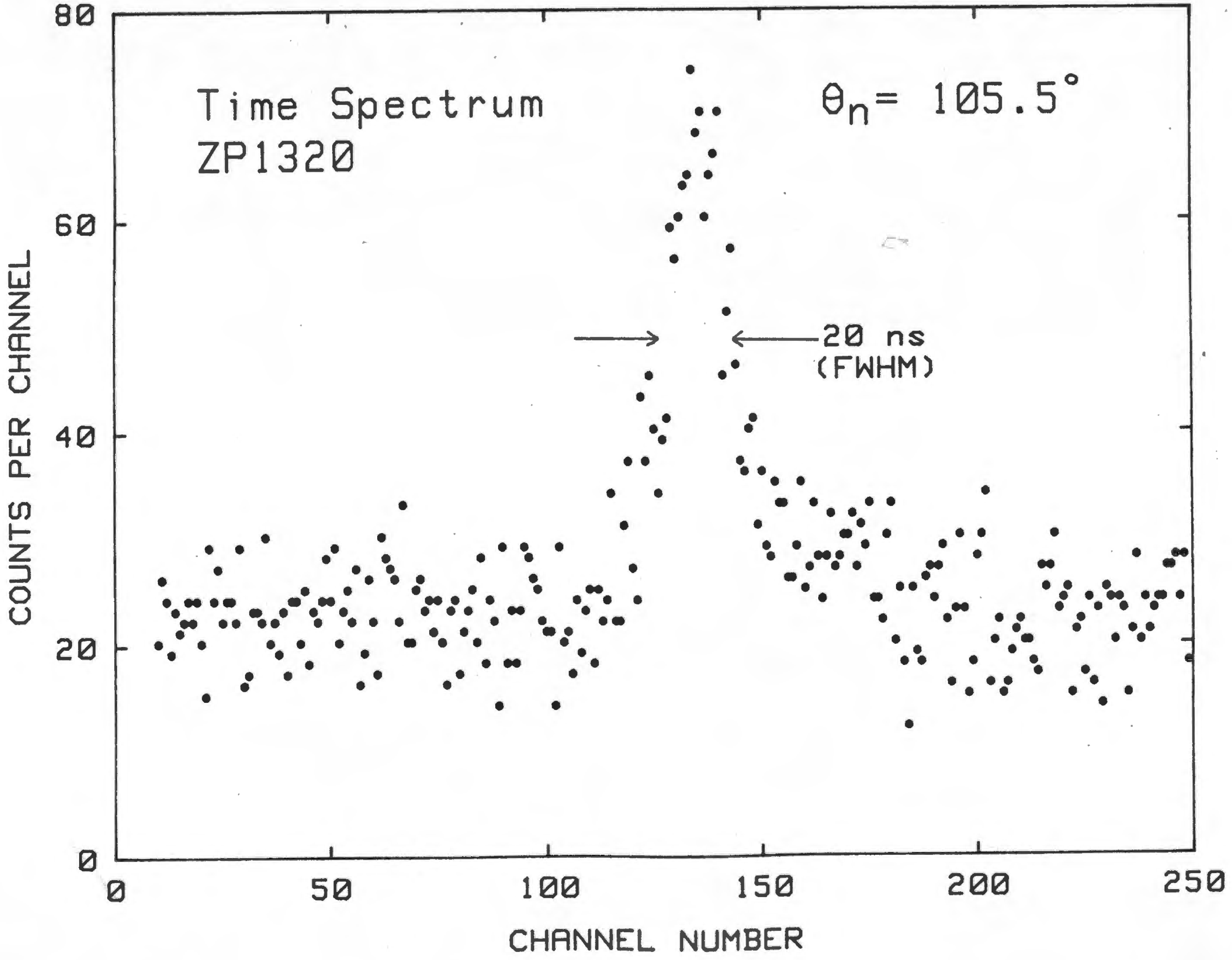
Fig. 2 : Coincidence time spectrum measured with the GM counter positioned at an angle of 105.5° to the deuteron beam direction.

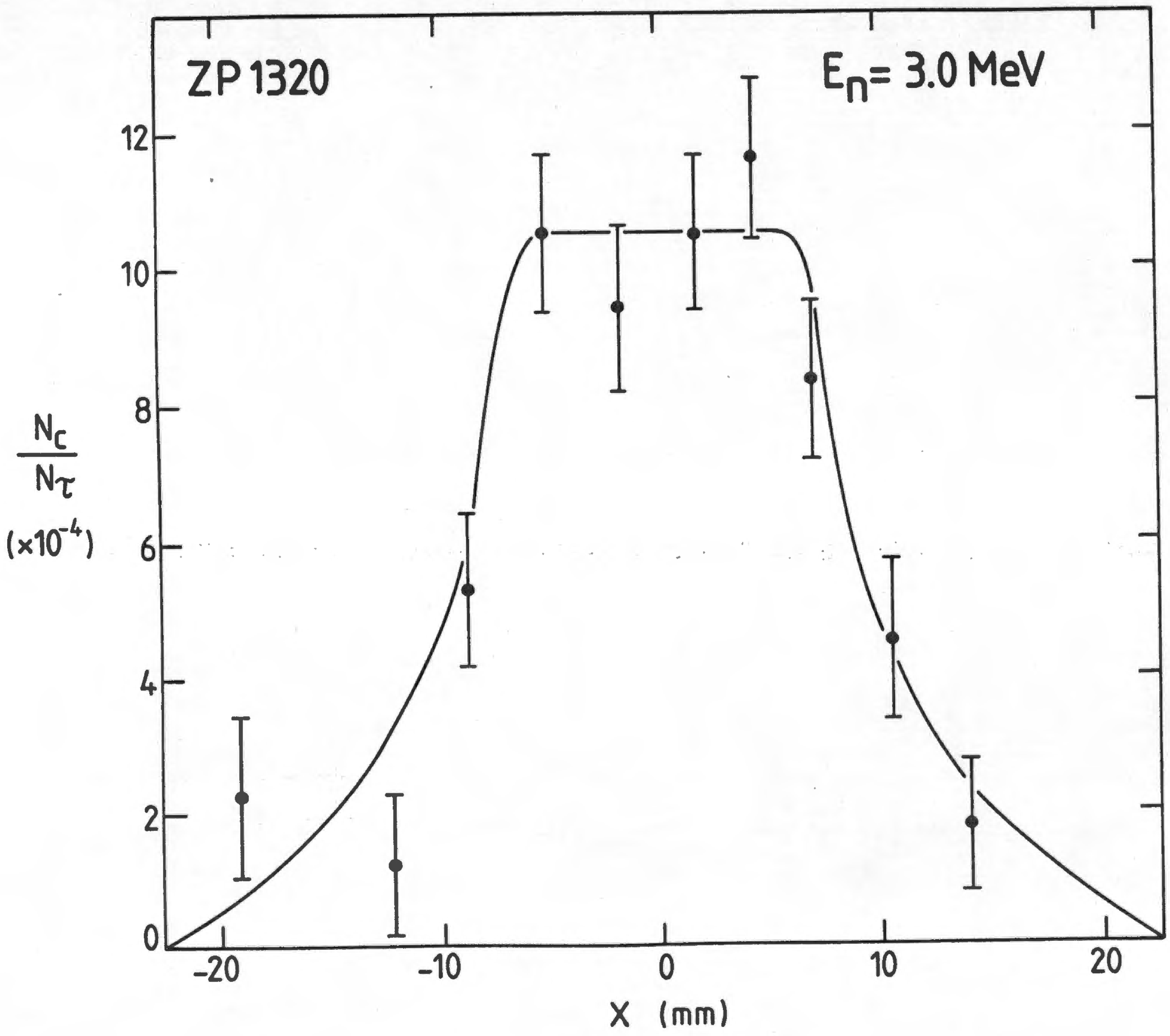
Fig. 3 : Variation of N_c/N_τ with displacement x between the GM counter and the neutron cone axes. The line is a smooth curve drawn through the data points.

TABLE 1

REFERENCE	E_n (MeV)	k_u (%)
Present work	3.0	0.39 ± 0.08
Le78	4.2	0.67 ± 0.07
Le78	5.5	0.81 ± 0.08


GM COUNTER
HEVIMET
1.5mm
DEUTERATED POLYETHYLENE TARGET
n
θ_n
d^+
TO BEAM DUMP
θ_τ
^3He
1.5 mm ALUMINIUM
ELECTRO-MAGNET
SURFACE BARRIER DETECTOR
0
10
20 cm


Time Spectrum
ZP1320
$\theta_n = 105.5°$
20 ns
(FWHM)
COUNTS PER CHANNEL
CHANNEL NUMBER
0
20
40
60
80
0
50
100
150
200
250


ZP 1320
$E_n = 3.0$ MeV
$\frac{N_c}{N_\tau}$ $(\times 10^{-4})$
0
2
4
6
8
10
12
-20
-10
0
10
20
X (mm)

PAPER 5

"The Neutron Sensitivity of a Geiger-Müller Counter between 0.5 and 8 MeV"

(Health Phys. 45 (1983) 659)

THE NEUTRON SENSITIVITY OF A GEIGER-MüLLER COUNTER BETWEEN 0.5 AND 8 MeV

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Abstract

Geiger-Müller counters are often used in mixed field dosimetry to determine the photon dose fraction. For accurate dose specification their neutron sensitivities must be known. The pulsed beam time-of-flight method was used to determine the neutron sensitivities of an energy-compensated type ZP1320/PTFE Geiger-Müller counter in the 0.5 to 8 MeV region. The flux of monoenergetic neutrons from the $T(p,n)^3He$ and $D(d,n)^3He$ reactions which were used in these measurements, was determined from time-of-flight spectra with an NE213 scintillation counter of known efficiency.

INTRODUCTION

Since fast neutron beams can only be produced in nuclear reactions, they are always contaminated with gamma rays which are produced by interactions of the primary charged particle beam in the target and by the resultant neutrons interacting with the surroundings. To completely specify such a mixed radiation field it is necessary to determine the neutron and gamma dose contributions since their biological effectiveness is markedly different.

The classical method is to measure the total (neutron + gamma) dose with a tissue-equivalent ionization chamber and the gamma dose with a "neutron-insensitive" photon detector. A Geiger-Müller (GM) counter comes close to meeting the requirements (ICRU77) of such a detector, viz., one which is

(1) Insensitive to neutrons
(2) Insensitive to orientation in the field and
(3) Has a linear response independent of photon energy.

Unfortunately, however, GM counters are not completely insensitive to neutrons. Although their sensitivity is low (and less than C-CO_2 or Mg-Ar ionization chambers which are also used in mixed field dosimetry), it has to be determined for accurate dose specifications. The neutron sensitivity is usually expressed as k_u, the ratio of the neutron response to the response to the gamma rays used for the calibration.

Various techniques have been used to determine k_u-values of photon detectors, for example the lead-attenuation method (At75, Ho79) the spectral-difference method (Ku75, Le78) and the associated-particle (Le77, Jo82) and pulsed beam time-of-flight (K178, Gu80) techniques. The measurements which have been made with similar devices have not always been in good agreement. However, the sensitivity of the same GM counter has recently been measured by independent groups using the four different experimental techniques mentioned above (Mi82). The results obtained were consistent and appear to indicate that discrepancies in k_u measurements made with GM counters can largely be ascribed to differences in the construction of the counters rather than to differences in the experimental methods.

In the present work we have used a relatively straightforward method of measuring the k_u-values of an energy-compensated GM counter using monoenergetic neutron beams between 0.5 and 8 MeV. The pulsed-beam time-of-flight technique was used to separate the photon and neutron components in the mixed field. The neutron flux was measured simultaneously with an NE213[+] scintillation counter of known efficiency which minimises normalisation uncertainties.

THE GM COUNTER

A type ZP1320/PTFE* (also known as 18550 or MX164) GM counter was used. The counter was supplied with an energy-compensating tin and lead filter assembly and a PTFE outer sleeve and the device was enclosed in a perforated metal shield.

A GM tube has intrinsically poor fast timing characteristics. The standard counter was modified so that the output was taken directly from the cathode strap across a 50 Ω load resistor, while the high voltage was applied to the anode. The timing resolution was found to improve with increased applied voltage and the counter was therefore operated near the top end of the plateau. Timing resolution of about 20 ns (FWHM) was obtained in a γ-γ coincidence measurement with a fast-response organic scintillator.

[+] Nuclear Enterprises Ltd., Sighthill, Edinburgh, Scotland.

* Alrad Instruments Ltd., Newbury, England - AEA Winfrith design.

The GM counter was calibrated with a Co^{60} source. The measured dose sensitivity was 31.3×10^8 Gy^{-1}. The dead time of the counter was 46 μs and at the count rates encountered in the present experiment (<15 Hz) dead time losses in both the counter and the electronics were negligible.

EXPERIMENTAL METHOD

Measurements were made using the 6 MV van de Graaff accelerator of the Southern Universities Nuclear Institute. Pulsed (2 MHz) beams of protons and deuterons were incident on gas targets of tritium and deuterium respectively producing monoenergetic neutrons from the $T(p,n)^3He$ and $D(d,n)^3He$ reactions. The incident particle energies for these measurements were below the reaction threshold for ^3He breakup (8.34 MeV and 4.45 MeV at 0^o respectively), thus ensuring that strictly monoenergetic beams were used.

The target cells were 3 cm long with a gold or platinum beam stop and had a 2.5 μm thick havar$^+$ entrance window. The gas pressure was kept at approximately 0.8 kPa for all the measurements. The beam energies quoted in the text are the mean incident particle energies in the target cell after correction for energy loss in the gas and the entrance foil. Target currents were typically about 1 μA. Standard fast electronic modules were used to obtain the time-of-flight spectra.

The GM counter was placed at -5^o to the accelerator beam direction with its axis parallel to the neutron beam. A previous measurement (Le77) has shown that the sensitivity of this type of GM counter is increased when the axis is perpendicular to the neutron beam. Depending on the neutron energy, flight paths of between 0.8 and 2.5 m were required to give good separation between the monoenergetic neutron peak and the prompt gamma peak in the time spectra. However, these peaks were not completely resolved because of their low energy "tail". Spectra were

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[+] Foil containing Fe(17.9%), Co(42.5%), Cr(20.0%), Ni(13.0%), W(2.8%) and traces of Mo, Mn, C and Be.

therefore measured at some energies with the target evacuated in order to obtain the line shape of the gamma peak which was then used to strip the neutron peaks from the composite spectra. A flat background was fitted to each spectrum by least squares prior to stripping.

Fig. 1 shows spectra measured at a flight path of 1.23 m for the $T(p,n)^3He$ reaction at $E_p = 3.65$ MeV with the target filled (upper curve) and evacuated (lower curve). The horizontal lines are the background fits.

MEASUREMENT OF NEUTRON FLUX

The neutron flux was determined by simultaneous measurement of the time-of-flight spectra with a 2.54 cm diameter x 2.54 cm long NE213 scintillator mounted on a RCA 8850 photomultiplier tube. This detector was placed at $+5^{\circ}$ to the accelerator beam direction with the GM counter positioned along the -5° line. A pulse shape discriminator* (Ad78) was incorporated in the circuit to eliminate gamma-induced events. A flight path of 5.77 m was used for the flux measurements at all energies except for $E_n = 0.72$ MeV when the flight path was 1.99 m. The long flight path was necessary to achieve lower counting rates to minimise the corrections for dead time losses in the counting system. These were seldom more than about 5%.

The computer code DETEFF (Th71) was used to calculate the absolute neutron detection efficiency of the scintillation counter. Following the authors' recommendation an error of 10% was ascribed to the calculation at each energy point.

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* Link Systems, High Wycombe, England.

RESULTS

The neutron sensitivity k_u at energy E relative to Co^{60} was calculated as follows:

$$k_u(E) = A_g(E) \left[\frac{A_s(E)}{\varepsilon_s(E)} \quad \frac{1}{\pi r_s^2} \quad \frac{d_s^2}{d_g^2} \right]^{-1} \frac{1}{D_g} \quad \frac{1}{K(E)}$$

The subscripts g and s refer to the GM and scintillation counters respectively.

A	is the number of counts in the monoenergetic neutron peak in the time spectrum
ε	is the efficiency of the scintillator
r,d	are the radii and flight paths of the detectors (cm)
D	is the dose sensitivity to Co^{60} radiation of the GM tube (Gy^{-1})
K	is the neutron kerma factor in ICRU muscle ($Gy.cm^2$) (ICRU77).

The experimental details and the results obtained are given in Table 1. In fig. 2 these results are shown together with measurements made in this energy range with a similar counter by Jones et al. (Jo82) using the associated-particle technique and Lewis and Hunt (Le78) using the spectral-difference method. The present work shows that for this type of GM counter the energy dependence is clearly non-linear over the energy range 0.5 to 8 MeV.

The uncertainties in the present measurements include statistical errors but are mainly due to the 10% error ascribed to the calculated efficiency of the NE213 scintillation counter.

CONCLUSION

The pulsed beam time-of-flight technique is a straightforward method of measuring k_u-values of a GM counter with reasonable accuracy in this energy range. This technique is particularly applicable to this type of measurement since the gamma and neutron contributions can be separated in the time spectra by operating at sufficiently long flight paths where a limiting factor is the time required to collect data with sufficient statistical accuracy. The accuracy of the present results is not limited by statistics but by the precision with which the neutron flux can be determined. The technique should be applicable to all types of GM counters. Although monoenergetic neutron beams were used in this work the technique could be used with broad spectrum neutron sources, such as are often used in therapy, if suitable pulsed beam time-of-flight facilities are available.

The authors are indebted to the technical staff of the Southern Universities Nuclear Institute, and to Mr. B.R. Simpson and Mr. D.M. Whittal of the University of Cape Town for their assistance during the running of the experiment and to the Hospitals Department of the Cape Provincial Administration as well as the Council for Scientific and Industrial Research and Atomic Energy Board for financial support.

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TABLE CAPTIONS

Table 1. Experimental details and measured k_u-values for ZP1320 GM counter.

E_o is the accelerator beam energy.

ΔE_o is the mean energy loss in the target.

$\overline{E}_o$ is the mean incident particle energy ($= E_o - \Delta E_o$).

E_n is the mean neutron energy at 5°.

d_g and d_s are the flight paths of the GM and scintillation counters respectively.

ε_s is the calculated efficiency of the scintillation counter (Th71).

K is the neutron kerma factor in ICRU muscle (ICRU77).

k_u is the neutron sensitivity of the ZP1320 GM counter relative to Co^{60}.

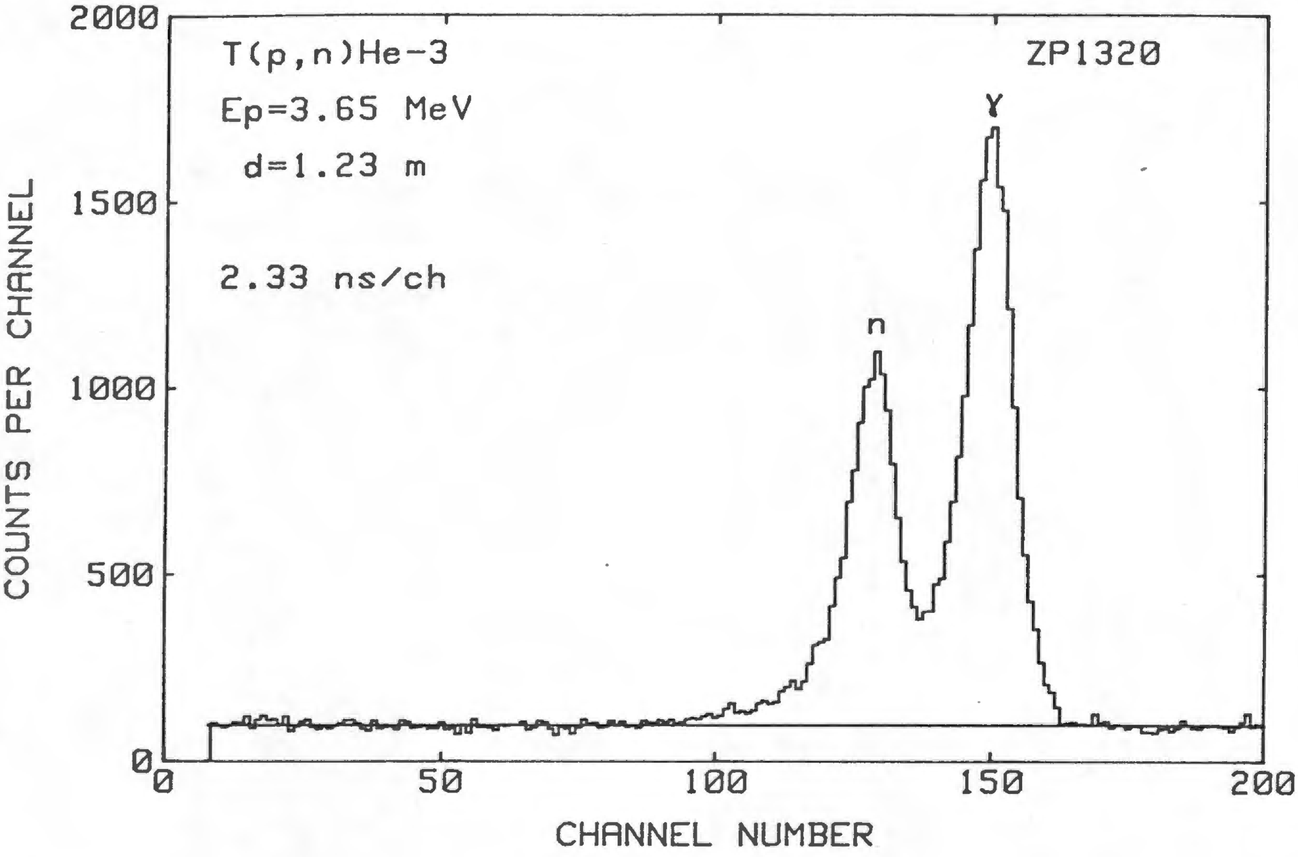
FIGURE CAPTIONS

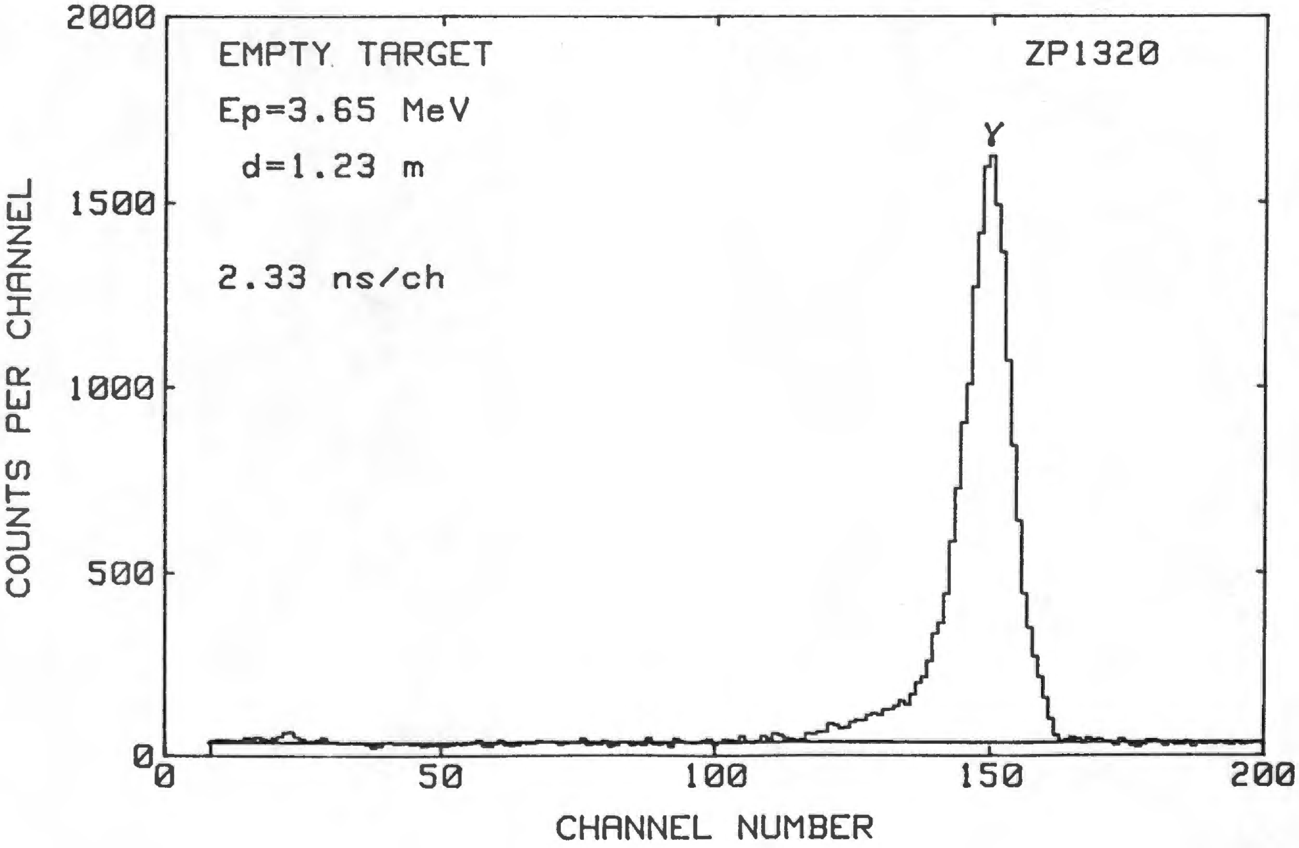
Fig. 1 Time-of-flight spectra of $T(p,n)^3He$ reaction measured with the ZP1320 GM counter. The horizontal lines are least squares fits to the background. The mean energy of the neutron peak is 2.86 MeV. The spectra were recorded for the same integrated charge on the target.

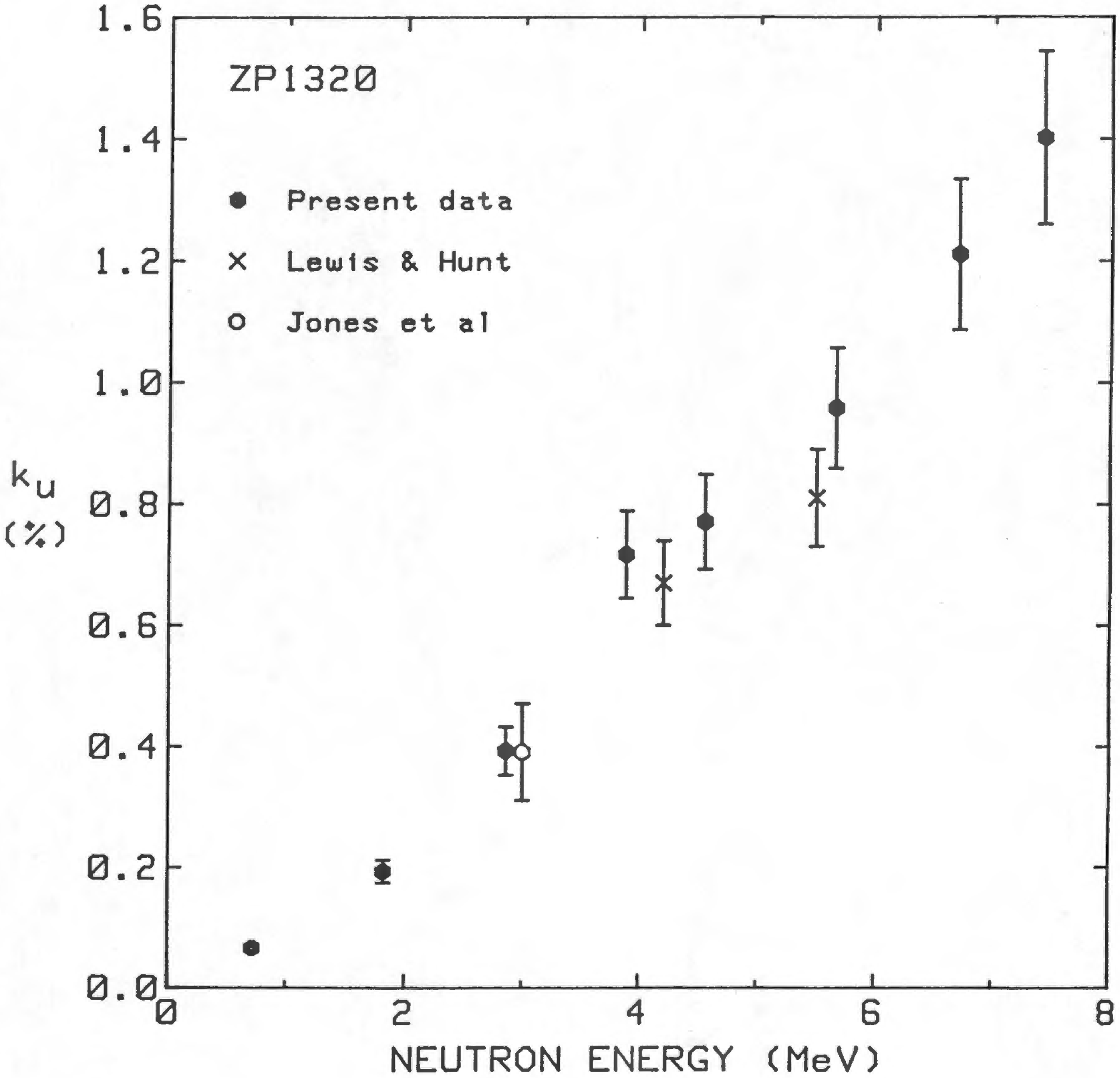
Fig. 2 k_u-values for the ZP1320 GM counter obtained in the present experiment. Also plotted are measurements made with a similar counter by Lewis and Hunt (Le78) and Jones et al. (Jo82). All the measurements were made with the axis of the counter parallel to the neutron beam.

TABLE 1

INCIDENT PARTICLE	TARGET	E_o	ΔE_o	$\overline{E}_o$	$E_n(5^0)$	d_g	d_s	ε_s	K (x 10^{-10})	k_u
		MeV	MeV	MeV	MeV	m	m		Gy.cm^2	%
p^+	T	1.82	0.28	1.54	0.72	0.80	1.99	0.179	0.192	0.066 ± 0.007
		2.80	0.19	2.61	1.82	1.23	5.77	0.226	0.299	0.193 ± 0.019
		3.80	0.15	3.65	2.86	1.23	5.77	0.200	0.357	0.392 ± 0.040
		4.80	0.13	4.67	3.88	1.67	5.77	0.173	0.419	0.717 ± 0.072
d^+	D	1.79	0.42	1.37	4.55	1.67	5.77	0.162	0.431	0.771 ± 0.078
		2.76	0.34	2.42	5.66	2.00	5.77	0.146	0.457	0.958 ± 0.099
		3.76	0.31	3.45	6.70	2.50	5.77	0.133	0.488	1.211 ± 0.124
		4.41	0.23	4.18	7.42	2.50	5.77	0.126	0.511	1.402 ± 0.142


T(p,n)He-3
Ep=3.65 MeV
d=1.23 m
2.33 ns/ch
ZP1320
n
γ
COUNTS PER CHANNEL
CHANNEL NUMBER
0
500
1000
1500
2000
0
50
100
150
200


EMPTY TARGET
Ep=3.65 MeV
d=1.23 m
2.33 ns/ch
ZP1320
γ
COUNTS PER CHANNEL
CHANNEL NUMBER
0
500
1000
1500
2000
0
50
100
150
200


ZP1320
● Present data
× Lewis & Hunt
○ Jones et al
k_u (%)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
0
2
4
6
8
NEUTRON ENERGY (MeV)

PAPER 6

"The k_u-Values of a ZP1300 Geiger-Müller Counter between 0.7 and 7.5 MeV"

(Proc. 5th Symp. on Neutron Dosimetry, 1984)

THE k_u - VALUES OF A ZP1300 GEIGER-MULLER COUNTER BETWEEN 0.7 AND 7.5 MEV

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ABSTRACT

The pulsed beam time-of-flight method has been used to determine the k_u-values of an energy compensated type ZP1300/PTFE Geiger-Müller counter in the 0.5 to 7.5 MeV region. Monoenergetic neutrons from the $T(p,n)^3He$ and $D(d,n)^3He$ reactions were used in the measurements. The neutron flux was determined by simultaneous measurement of the time-of-flight spectra with a NE213 scintillation counter of known efficiency. The k_u-values obtained are in good agreement with previous data in this energy region using similar counters. All published values obtained with ZP1300/PTFE counters have been fitted with a function of the form $k_u(E_n) = a\, E_n{}^b$ where $a = 0.25 \pm 0.01$ and $b = 0.78 \pm 0.03$.

INTRODUCTION

The usual method of determining the neutron and gamma dose components in a mixed neutron-gamma radiation field is to make measurements both with a tissue-equivalent ionization chamber (which has approximately the same response to neutrons as to gamma-rays) and with a relatively neutron insensitive device. The latter is usually a non-hydrogenous ionization chamber or a Geiger-Müller counter. Since Geiger-Müller counters are usually less sensitive to neutrons than are non-hydrogenous ionization chambers they are often the instruments of choice in mixed field dosimetry.

Since the biological effectiveness of gamma-rays is typically approximately one-third that of neutrons the effective RBE of the mixed field can only be determined if the separate neutron and gamma dose components are known. Unfortunately Geiger-Müller counters do respond to neutrons and their sensitivity to neutrons must be known if the separate dose components are to be determined with any precision.

The responses of a tissue-equivalent detector (t) and a "neutron insensitive" detector (u) in a mixed neutron-gamma field are respectively given by (ICRU77):

$$R_t = h_t D_g + k_t D_n$$

and

$$R_u = h_u D_g + k_u D_n$$

where D_n and D_g are the absorbed neutron and gamma doses in tissue respectively, k_t and k_u are the ratios of the sensitivities of each detector to neutrons to its sensitivity to the gamma-rays used for the calibration, and h_t and h_u are the ratios of the sensitivities of each detector to the gamma-rays in the mixed field to its sensitivity to the gamma-rays used for the calibration.

The Geiger-Müller counter which has most often been employed in the high dose rate neutron fields which are used in biomedical applications is the ZP1300/PTFE counter. Previous measurements of their neutron sensitivities have not always been in good agreement. In the present work the neutron sensitivity of a counter of this type has been determined by the pulsed beam time-of-flight technique using monoenergetic neutron beams of energies between 0.72 and 7.42 MeV.

THE GEIGER-MüLLER COUNTER

The ZP1300/PTFE Geiger-Müller counter* (also known as the 18529 or the MX163) was fitted with an energy compensating filter assembly with a PTFE outer sleeve and the device was enclosed in a perforated metal shield. The filter consisted of 1.05 mm of tin and 0.55 mm of lead which produced a reasonably flat response to gamma-rays from about 60 keV to 1.5 MeV. The PTFE outer shield was used in preference to a perspex one which had been used in earlier versions of the counter (Le77) because the hydrogen in perspex can enhance the k_u-values for higher energy neutrons via the production of recoil protons which can penetrate the counter wall if they have sufficient energy (Le78).

In order to improve the intrinsically poor timing characteristics of the counter the output was taken directly from the cathode strap across a 50 ohm load resistor while the high voltage was applied to the anode. The timing resolution improves with applied voltage and for this reasons the counter was operated near the top end of the plateau at 750 volts. Timing resolution of about 10 ns (FWHM) was obtained.

The counter was calibrated with a ^{60}Co source. The measured dose sensitivity was 1.27×10^8 Gy^{-1} in ICRU muscle. The dead time of the counter was 13 μs which was determined by the two-source method (Pr58). At the count rates encountered in the present experiment (< 3 Hz) dead time losses in both the counter and the electronics were negligible.

EXPERIMENTAL METHOD

The experimental technique has been described previously (Jo81, Jo83) and will only be briefly outlined here. Pulsed beams of deuterons and protons were incident on gas targets of tritium and deuterium respectively producing monoenergetic neutrons from the T(p,n)^{3}He and D(d,n)^{3}He reactions. The incident particle energies were kept below the reaction threshold for ^{3}He breakup, thus ensuring that strictly monoenergetic beams were used.

---

* Supplied by Alrad Instruments Ltd., Newbury, England.

The Geiger-Müller counter was placed at -5° to the incident charged particle beam direction with its anode wire parallel to the neutron beam direction. With this particular type of counter the neutron response appears to be practically independent of the orientation of the counter (Le78, Gu80).

At the flight paths employed (0.8 to 2.5 m) the neutron and prompt gamma-ray peaks were very well resolved in the time-of-flight spectra. However, the low energy "tail" of the gamma peak still contributed a small amount to the counts in the neutron peak. Spectra were therefore measured at some energies with the target cells evacuated in order to obtain the line shape of the gamma peak. This peak shape was then subtracted from the composite spectra to give the neutron yield. A flat background was fitted by least squares to each spectrum prior to the subtraction.

Fig 1 shows the time-of-flight spectrum measured with the ZP1320/PTFE counter at a flight path of 2 m for the $D(d,n)^3He$ reaction at E_d = 2.42 MeV with the target filled. The dashed line is the background fit. Fig 2 shows the spectrum measured for the same conditions as in Fig 1 but with the target cell evacuated.

The neutron flux was determined by simultaneous measurement of the time-of-flight spectra with a NE213* scintillation counter placed at +5° to the incident charged particle beam direction. A pulse shape discriminator+ (PSD) (Ad78) was used to eliminate gamma-ray induced events in the counter. In Fig 3 the performance of the pulse shape discriminator is illustrated. A typical NE213 time-of-flight spectrum with the PSD operative is shown in Fig 4. This was obtained with the $D(d,n)^3He$ reaction at E_d = 2.42 MeV and a flight path of 5.77 m and was measured simultaneously with the ZP1320 spectrum shown in Fig 1. Also indicated is the position where the prompt gamma peak would have appeared if PSD had not been employed.

The computer code DETEFF (Th71) was used to calculate the neutron detection efficiency of the scintillation counter. Following the author's recommendation an error of 10% was ascribed to the calculation at each energy point. In a separate experiment (Jo81a) the detection efficiency of this particular counter was measured in order to verify the validity of the calculations.

* Nuclear Enterprises Ltd., Sighthill, Scotland.

\+ Link Systems Ltd., High Wycombe, England.

RESULTS

The neutron sensitivity k_u at energy E relative to ^{60}Co was calculated as follows:

$$k_u(E) = A_g(E) \left[\frac{A_s(E)}{\varepsilon_s(E)} \quad \frac{1}{\pi r_s^2} \quad \frac{d_s^2}{d_g^2} \right]^{-1} . \frac{1}{D_g} \frac{1}{K(E)} \qquad (1)$$

The subscripts g and s refer to the Geiger-Müller and scintillation counters respectively.

A = the number of counts in the neutron peak in the time-of-flight spectrum,

ε = the neutron detection efficiency of the scintillator,

r,d = the radii and flight paths of the detectors respectively (cm),

D = the dose sensitivity to ^{60}Co radiation of the Geiger-Müller counter (Gy^{-1}), and

K = the neutron kerma factor in ICRU muscle ($Gy.cm^2$) (ICRU77).

The results obtained in this work are given in Table I together with all other known k_u measurements using similar counters. The uncertainties in the present data include only statistical errors and the 10% error ascribed to the calculated efficiency of the NE213 scintillation counter. All the measurements listed in Table I were made with counters having tin and lead energy-compensating shields except for datum number 16 where the counter only had a tin shield. All measurements were made relative to ^{60}Co except for datum number 1 where ^{226}Ra was used. Dashes in the table indicate that the relevant experimental details are not known.

All the ZP1300/PTFE data indicated with an asterisk in Table I have been fitted by the method of least squares with a function of the form $k_u(E_n) = a(E_n)^b$ by transforming the data to a logarithmic coordinate system. The data and the fitted line are shown in Fig 5. The values obtained for the parameters are $a = 0.25 \pm 0.01$ and $b = 0.78 \pm 0.03$. The correlation coefficient (R) was 0.96.

For comparison Table II gives the results of fitting different sets of data with the function described above.

CONCLUSIONS

The k_u-values for a ZP1300/PTFE Geiger-Müller counter have been determined for neutron energies between 0.72 and 7.42 MeV. The results obtained agree reasonably well with previous data acquired with similar counters. A parametric fit to all known ZP1300/PTFE k_u-values from 0.5 to 15.5 MeV indicates that the function $k_u(E_n) = (0.25)\ E_n^{(0.78)}$ can be used with moderate confidence to predict k_u-values in this latter energy range.

Acknowledgements - The authors are indebted to the technical staff of the Van de Graaff Group, National Accelerator Centre, and to Mr B R Simpson and Mr D M Whittal of the University of Cape Town for their assistance during the running of the experiment and to the Hospitals Department of the Cape Provincial Administration as well as the Council for Scientific and Industrial Research and the Nuclear Development Corporation for financial support.

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TABLE CAPTIONS

Table I : All known k_u-values obtained with ZP1300 G-M counters. Dashes indicate that the relevant experimental details are not known. Orientation refers to the angle between the anode wire and the neutron beam direction. The various measuring techniques are:

AP : Associated Particle
SD : Spectral Difference
TF : Time-of-Flight
VF : Variable Filtration

The data points indicated with an asterisk are plotted in Fig 5.

Table II : Comparison of fitting parameters obtained for different sets of k_u data for the function $\log k_u(E) = \log a + b \log E$. R is the correlation coefficient.

FIGURE CAPTIONS

Fig 1 Time-of-flight spectrum of $D(d,n)^3He$ reaction measured with the ZP1300/PTFE G-M counter. The horizontal dashed line is a least squares fit to the background. The neutron energy is 5.66 MeV.

Fig 2 Time-of-flight spectrum measured under the same conditions as Fig 1 except that the target cell was evacuated. The spectrum has been normalised to the same gamma peak intensity as in the spectrum shown in Fig 1.

Fig 3 Illustration of the performance of the pulse shape discriminator used with the NE213 scintillation counter. The neutron energy was 2.86 MeV and the pulse height bias (E_b) was set at 0.05 MeV equivalent electron energy.

Fig 4 Time-of-flight spectrum of the $D(d,n)^3He$ reaction measured with the NE213 scintillation counter. The neutron energy is 5.66 MeV and the PSD was operative. Also indicated is the position of the prompt gamma peak which would have appeared if PSD had not been employed.

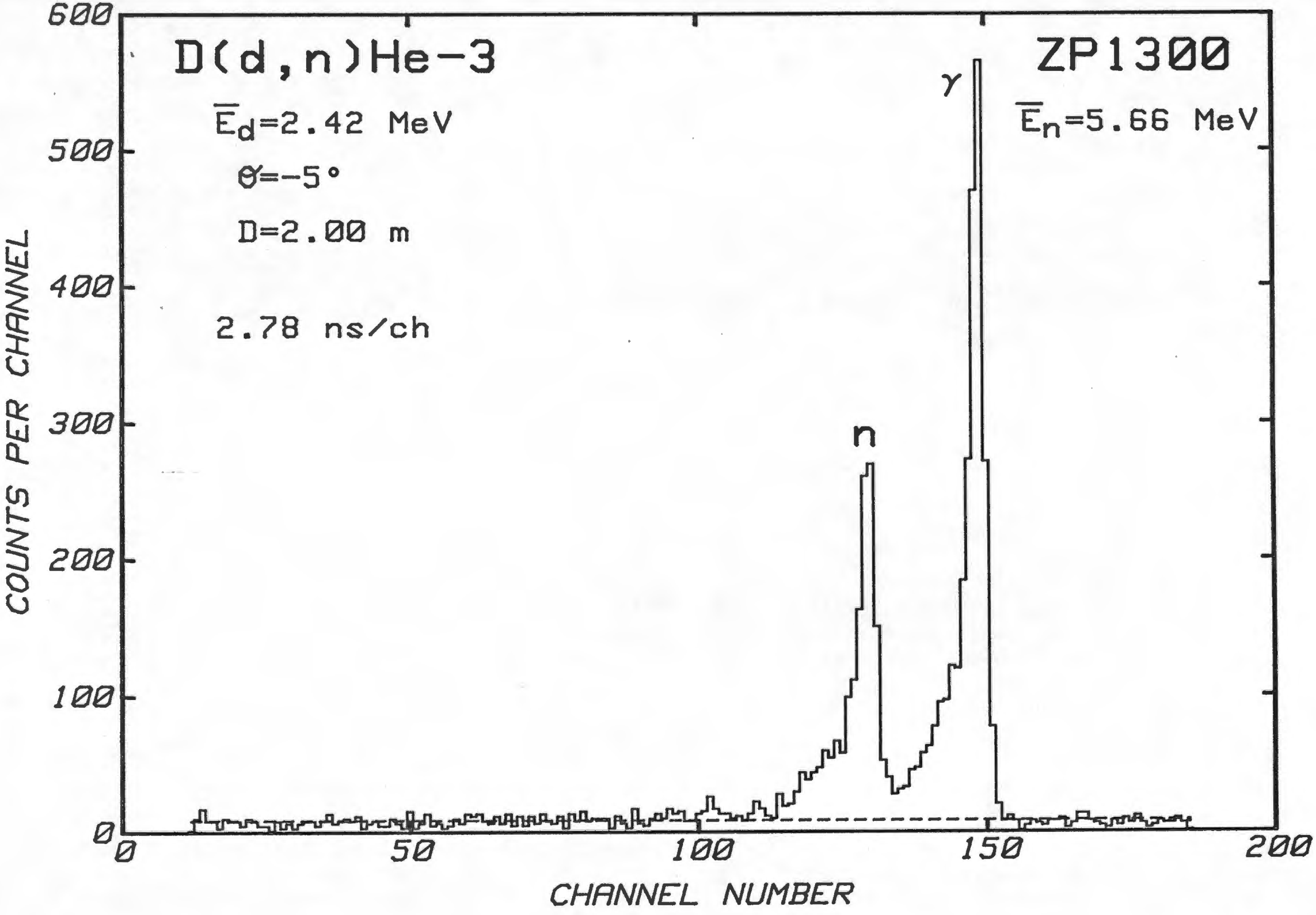
Fig 5 k_u-values for ZP1300/PTFE G-M counters above 0.57 MeV. All the data indicated with an asterisk in Table I have been plotted and used to determine the straight line fit. The dashed curves are the 90% confidence limits for this line. The values of the fitting parameters are given in Table II.

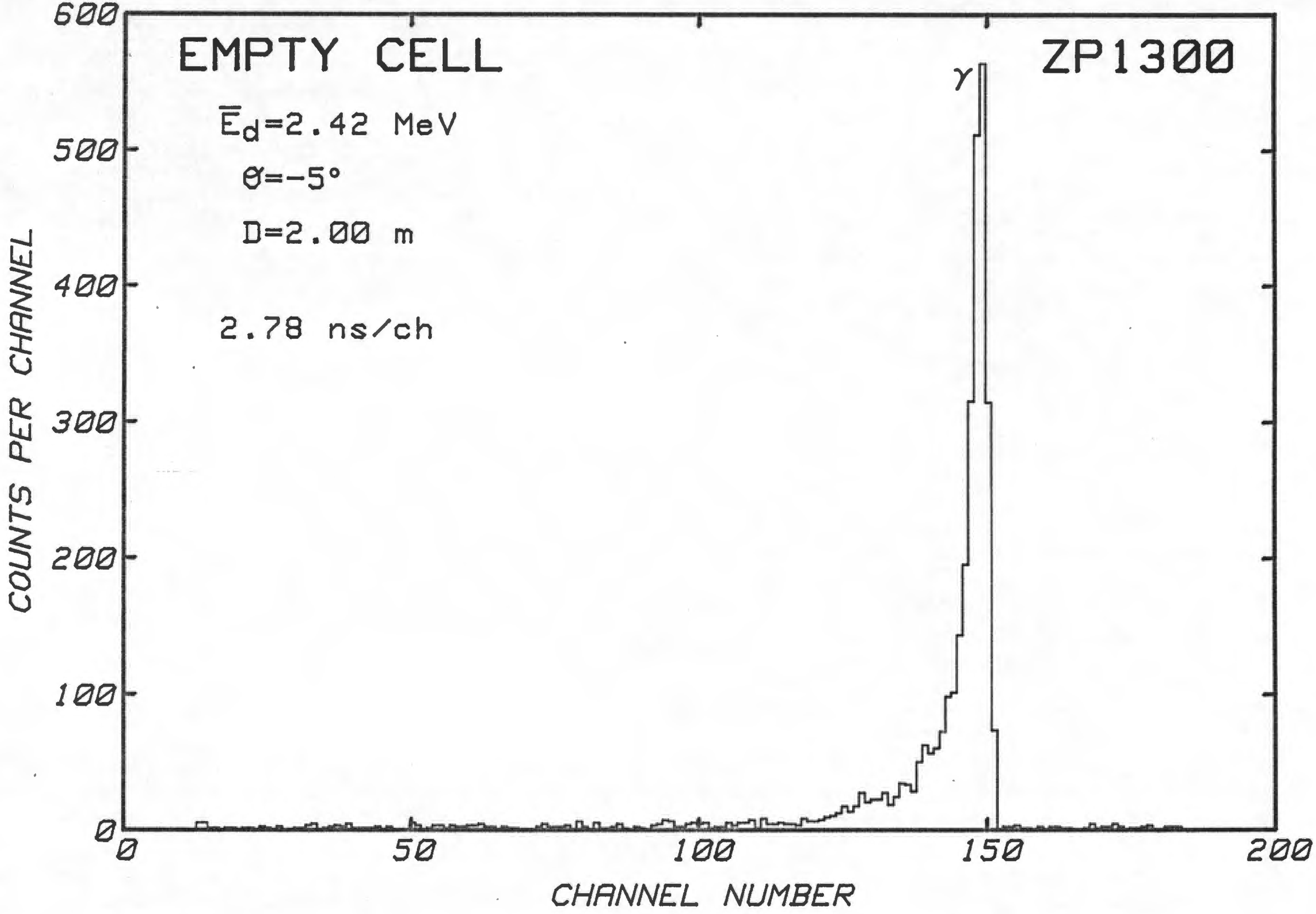
k_u-VALUES FOR ZP1300 GEIGER-MüLLER COUNTERS

DATUM	$\bar{E}_n$ (MeV)	k_u (%)	ORIENTATION (deg.)	SLEEVE	MEASURING TECHNIQUE	REF.
1	15.4	∿0.4 ± 0.1	-	PTFE	-	Co74
2 *	14.0	3.2	-	PTFE	VF	At77
3	14.7	2.55 ± 0.25	0	Perspex	AP	Le77
4	14.7	2.15 ± 0.20	90	Perspex	AP	
5 *	4.2	0.63 ± 0.07	0	PTFE	SD	Le78
6 *	5.5	0.80 ± 0.08	0	PTFE	SD	
7 *	14.7	1.65 ± 0.16	0	PTFE	SD	
8 *	14.7	1.60 ± 0.16	90	PTFE	SD	
9	14.8	<0.6	90	Perspex	VF	Zo78
10	13.2	4.9	-	Perspex	VF	He78
11	8.0	0.73 ± 0.07	90	Perspex	VF	Ho79
12 *	8.0	0.68 ± 0.14	90	PTFE	VF	
13	14.1	1.72 ± 0.25	-	-	-	Mi79
14	14.7	1.33 ± 0.20	-	-	AP	
15	15.5	1.71	-	-	TF	
16	15.5	1.48	-	-	TF	
17	0.25	0.24 ± 0.06	90	PTFE	TF	Gu80
18 *	0.57	0.12 ± 0.02	90	PTFE	TF	
19 *	4.2	0.87 ± 0.09	0	PTFE	TF	
20 *	5.0	1.03 ± 0.13	90	PTFE	TF	
21 *	15.5	1.93 ± 0.27	90	PTFE	TF	
22	0.57	-0.16 ± 0.25	90	PTFE	SD	Mi82
23 *	0.57	0.122 ± 0.018	90	PTFE	TF	
24	0.79	-0.07 ± 0.23	90	PTFE	VF	
25 *	5.0	1.31 ± 0.15	90	PTFE	SD	
26 *	5.0	1.03 ± 0.13	90	PTFE	TF	
27 *	5.5	1.18 ± 0.27	90	PTFE	VF	
28 *	14.65	1.85 ± 0.20	90	PTFE	AP	
29 *	15.5	1.93 ± 0.27	90	PTFE	TF	
30 *	14.1	1.82 ± 0.14	90	PTFE	VF	
31 *	8.0	1.41 ± 0.10	90	PTFE	VF	Ho84
32 *	0.72	0.19 ± 0.03	0	PTFE	TF	Present work
33 *	1.82	0.31 ± 0.04	0	PTFE	TF	
34 *	2.86	0.54 ± 0.06	0	PTFE	TF	
35 *	3.88	0.80 ± 0.09	0	PTFE	TF	
36 *	4.55	0.94 ± 0.10	0	PTFE	TF	
37 *	5.66	1.21 ± 0.13	0	PTFE	TF	
38 *	6.70	1.30 ± 0.16	0	PTFE	TF	
39 *	7.42	1.44 ± 0.17	0	PTFE	TF	

FIT OF $\ell og\ k_u(E) = \ell og\ a + b\ \ell og\ E$ TO ZP1300/PTFE DATA

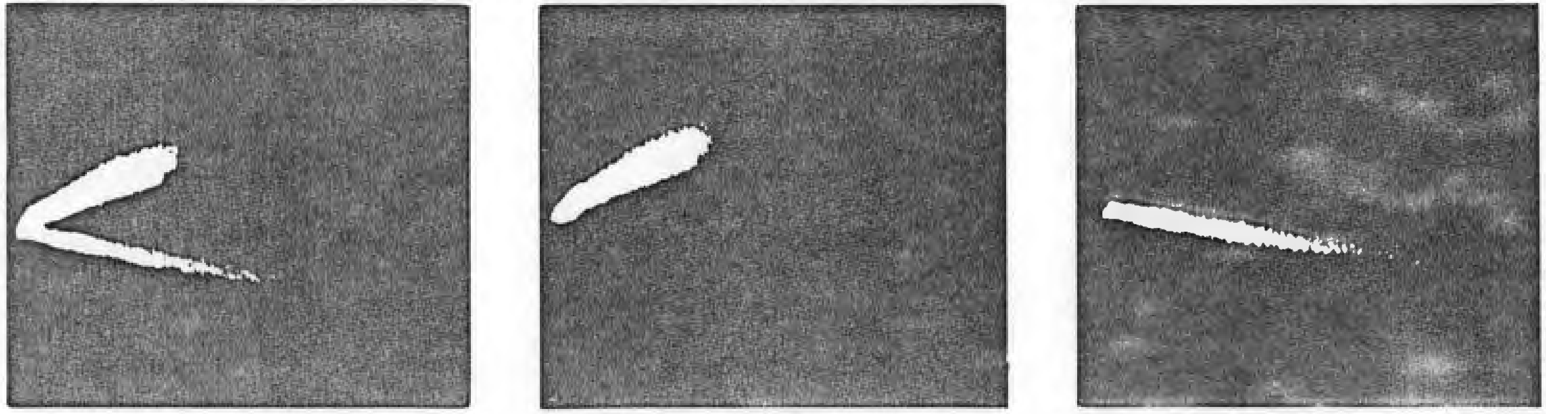
REFERENCE	ENERGY RANGE (MeV)	a	b	R	REDUCED χ^2
Present work	0.72 - 7.42	0.21 ± 0.02	0.96 ± 0.07	0.99	0.90
Gu80	0.57 - 5.0	0.21 ± 0.03	0.99 ± 0.09	1.00	0.00
Gu80	0.57 - 15.5	0.23 ± 0.03	0.85 ± 0.07	0.98	2.69
All data	0.57 - 15.65	0.25 ± 0.01	0.78 ± 0.03	0.96	2.95


D(d,n)He-3
$\overline{E}_d$=2.42 MeV
θ=−5°
D=2.00 m
2.78 ns/ch
ZP1300
$\overline{E}_n$=5.66 MeV
γ
n
COUNTS PER CHANNEL
0
100
200
300
400
500
600
CHANNEL NUMBER
0
50
100
150
200

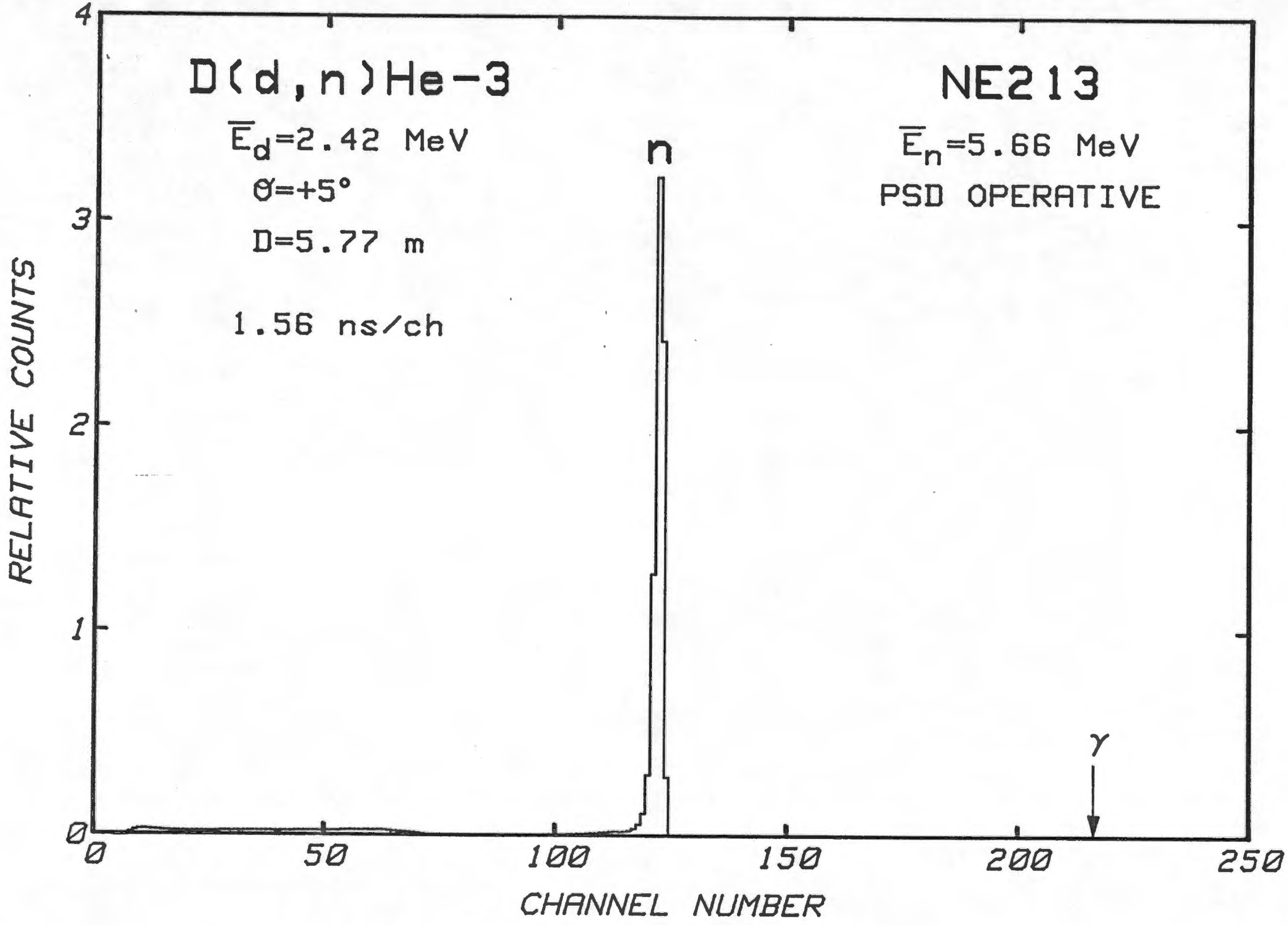

EMPTY CELL
ZP1300
$\overline{E}_d$=2.42 MeV
θ=−5°
D=2.00 m
2.78 ns/ch
γ
COUNTS PER CHANNEL
0
100
200
300
400
500
600
CHANNEL NUMBER
0
50
100
150
200

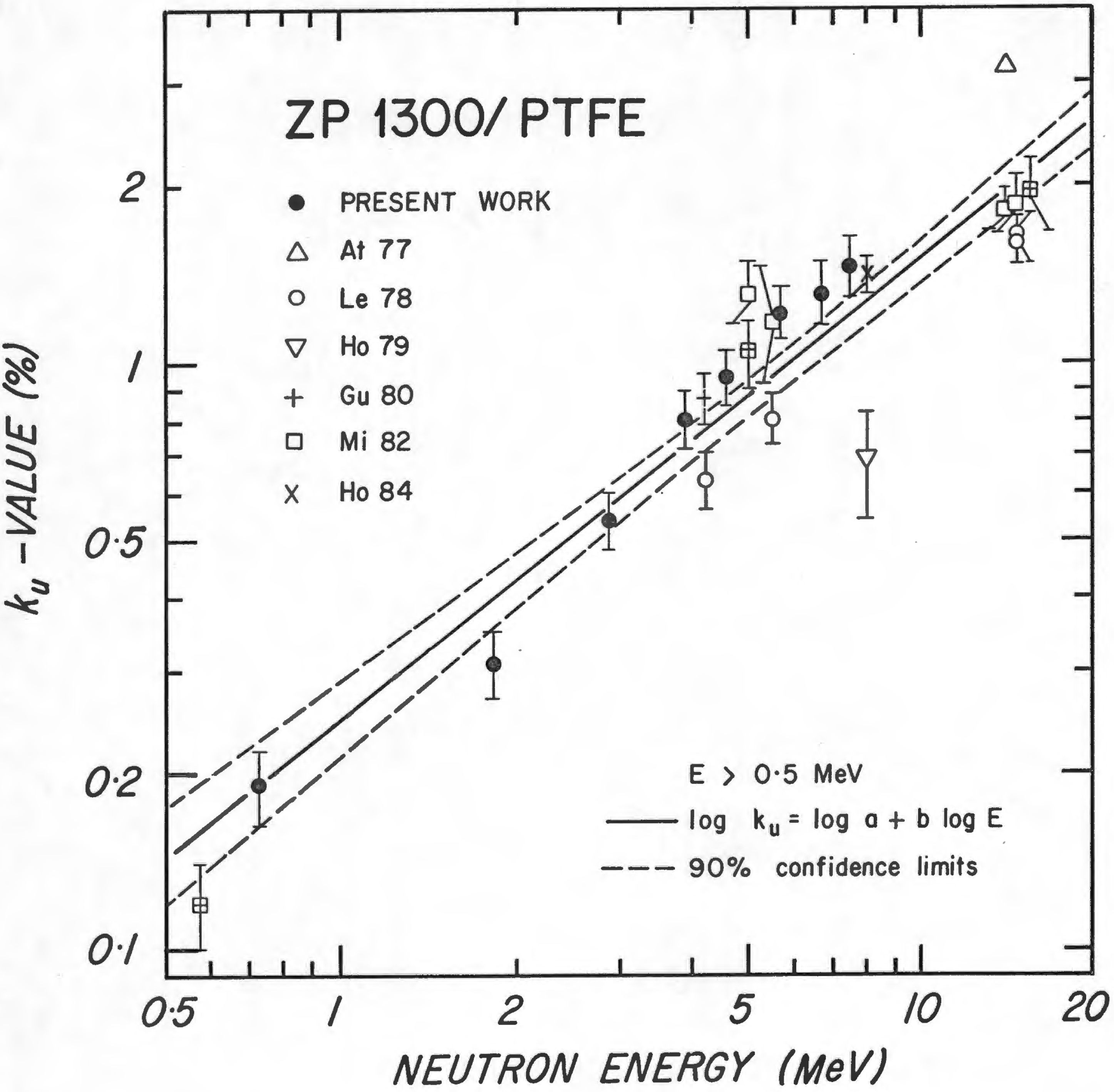
NE213 (2.54 cm x 2.54 cm)

E_n = 2.86 MeV E_b = 0.05 MeVee



NEUTRONS + GAMMAS NEUTRONS GAMMAS


D(d,n)He-3
$\overline{E}_d$=2.42 MeV
θ=+5°
D=5.77 m
1.56 ns/ch
NE213
$\overline{E}_n$=5.66 MeV
PSD OPERATIVE
n
γ
RELATIVE COUNTS
0
1
2
3
4
0
50
100
150
200
250
CHANNEL NUMBER


ZP 1300/ PTFE
● PRESENT WORK
△ At 77
○ Le 78
▽ Ho 79
+ Gu 80
□ Mi 82
X Ho 84
E > 0·5 MeV
—— log k_u = log a + b log E
– – – 90% confidence limits
k_u -VALUE (%)
2
1
0·5
0·2
0·1
0·5
1
2
5
10
20
NEUTRON ENERGY (MeV)

APPENDIX A

Proof of Publication

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A HIGH FLUX ASSOCIATED PARTICLE NEUTRON SOURCE

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An associated particle system for neutron production using the $^2H(d,n)^3He$ reaction is described. The system employs a thin-walled scattering chamber, an assembly to rotate a deuterated polyethylene target and a magnetic analyzer for recoil particle separation in high flux applications. Neutron beam intensities of up to 1000 s^{-1} are routinely obtainable.

1. Introduction

Measurements using neutrons produced with the $^2H(d,n)^3He$ reaction often are improved in precision by detecting the associated ^3He ions [1–4]. A monoenergetic neutron beam of absolutely determined flux is defined by detecting the neutrons in time coincidence with the ^3He ions. The ^3He ions are usually detected in a surface barrier detector which subtends a small solid angle at the target. The profile of the neutron beam is determined by the size of both the deuteron beam and the collimator in front of the surface barrier detector, although other factors such as multiple scattering and kinematic effects also play a role in determining the neutron beam profile.

As an example, if the collimator subtends an angle of 0.4 msr at the target and the deuteron beam spot size is 1.5 mm in diameter, a tagged neutron beam 3–4° wide (fwhm) can be achieved for deuterons in the 2–5 MeV range. In a typical application, the cross sections of neutron induced reactions on nuclei incorporated in organic or inorganic scintillators are measured [5–7]. In this type of experiment the scintillator physically encompasses the electronically defined neutron beam and serves as both target and detector. Reaction cross sections are then deduced from the ratio of the coincidence rate (between events in the scintillator and ^3He detector) and the ^3He detection rate.

In many experiments of this type a neutron rate of about 50 s^{-1} is sufficient to give the required statistical accuracy in the measurement after a few hours of data accumulation. In these experiments the background count rate in the scintillator is typically a few kHz and a higher tagged neutron flux is avoided to minimize pile-up effects. However, there are applications, e.g. in scattering and polarization studies and with detectors having low neutron detection efficiencies, where increased neutron intensity is desirable.

Increased neutron beam intensity is achieved by increasing the incident deuteron beam current or the target thickness. However, limitations are imposed by the amount of current which the target can withstand and by the count rate (mainly due to elastically scattered deuterons) which the surface barrier detector can tolerate without deterioration.

An experimental system is described here in which a relatively intense monoenergetic neutron beam has been produced by means of improved target fabrication and by optimization of the ^3He detection system.

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Radiation protection aspects

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edited by

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ABSOLUTE MEASUREMENT OF THE NEUTRON SENSITIVITY OF A ZP1320 GEIGER–MÜLLER COUNTER USING THE ASSOCIATED-PARTICLE TECHNIQUE

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(*Received* 22 *October* 1981; *accepted* 25 *November* 1981)

Abstract—Because of their low neutron sensitivity Geiger–Müller counters are often used in mixed-field dosimetry to determine the photon dose fraction. The associated-particle technique has been used to determine absolutely the neutron sensitivity of an energy-compensated ZP1320 Geiger–Müller counter at 3 MeV. The measurement is consistent with previous measurements using this type of counter.

INTRODUCTION

FAST neutron beams are always accompanied by γ rays. The γ contamination of neutron beams used for radiotherapy and radiobiology, although typically of the order of a few percent, is an important factor since the biological effectiveness of γ rays differs markedly from that of neutrons. Because of their low neutron detection efficiency, energy-compensated Geiger–Müller (GM) counters (Wa61) are often the instruments of choice for the determination of the γ dose component in mixed radiation fields (ICRU77).

For accurate dose specification it is necessary to determine the sensitivity of these counters to neutrons. This is usually expressed as k_u, the ratio of the neutron response to the response to the γ rays used for the calibration (ICRU77). Several groups have determined the neutron sensitivities of different types of GM counters (Gu80; Ho79; Kl78; Le77; Le78) and non-hydrogenous ion chambers (At75, Ku75) using a variety of techniques. The measurements which have been made with similar counters have not always been in good agreement, probably because of the inherent difficulties in measuring such low neutron responses and because the response of each counter is

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THE NEUTRON SENSITIVITY OF A GEIGER–MÜLLER COUNTER BETWEEN 0.5 AND 8 MeV

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(*Received* 17 *May* 1982; *accepted* 18 *August* 1982)

Abstract—Geiger–Müller counters are often used in mixed-field dosimetry to determine the photon dose fraction. For accurate dose specification, their neutron sensitivities must be known. The pulsed beam time-of-flight method was used to determine the neutron sensitivities of an energy-compensated type ZP1320/PTFE Geiger–Müller counter in the 0.5–8-MeV region. The flux of monoenergetic neutrons from the T(p, n)^{3}He and D(d, n)^{3}He reactions, which were used in these measurements, was determined from time-of-flight spectra with an NE213 scintillation counter of known efficiency.

INTRODUCTION

GEIGER–MÜLLER (GM) counters are often used to measure the γ dose component in a neutron field. Although the GM sensitivity to neutrons is low it has to be determined for accurate specification of the radiation field. The neutron sensitivity of a GM counter is usually expressed as k_u, the ratio of the neutron response to the response to the γ-rays used for the calibration.

Various techniques have been used to determine k_u values of photon detectors, for example the lead-attenuation method (At75; Ho79) the spectral-difference method (Ku75; Le78) and the associated-particle (Le77; Jo82) and pulsed-beam time-of-flight (Kl78; Gu80) techniques. The measurements which have been made with similar devices have not always been in good agreement. However, the sensitivity of the same GM counter has recently been measured by independent groups using the four different experimental techniques mentioned above (Mi82). The results obtained were consistent and appear to indicate that discrepancies in k_u measurements made with GM counters can largely be ascribed to differences in the construction of the counters rather than to differences in the experimental methods.

In the present work we have used a relatively straightforward method of measuring the k_u values of an energy-compensated GM counter using monoenergetic neutron beams between 0.5 and 8 MeV. The pulsed-beam time-of-flight technique was used to separate the photon and neutron components in the mixed field. The neutron flux was measured simultaneously with an NE213* scintillation counter of known efficiency which minimizes normalization uncertainties.

A type ZP1320/PTFE† (also known as 18550 or MX164) GM counter was used. The counter was supplied with an energy-compensating tin and lead filter assembly and a PTFE outer sleeve and the device was enclosed in a perforated metal shield. A GM tube has intrinsically poor fast-timing characteristics. The standard counter was modified so that the output was taken directly from the cathode strap across a 50 Ω load resistor, while the high voltage was applied to the

---

*Nuclear Enterprises Ltd., Sighthill, Edinburgh, Scotland.

†Alrad Instruments Ltd., Newbury, England—AEA Winfrith design.

5TH SYMPOSIUM ON NEUTRON DOSIMETRY

September 17-21, 1984

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Development of Hydrogen Proportional Counte
Spectrometry for Radiological Protection

JAKES, J., H. SCHRAUBE, H., Prague, CSSR
Microdosimetric Experiments at a Light and Heavy
Water Moderated Cf-Fission Neutron Source

MORSTIN, K., KAWECKA, B., BOOZ, J.,
Jülich, Germany
Again on the Dose Distributions in the ICRU
Sphere

SIEBERT, B.R.L., HOLLNAGEL, R., JAHR, R.,
Braunschweig, Germany
An Improved Operational Quantity for Neutron
Radiation Protection Monitoring

17.25 COFFEE BREAK

POSTER SESSION II Spectrometry and Detector Response

Chairman
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17.35 BREDE, H.J., G. DIETZE, G., SCHLEGEL-BICKMANN,
D., KUDO, K., Braunschweig, Germany
Neutron Spectral Fluence and Tissue Kerma in
Collimated Neutron Beams from Be + d

KOESTER, L., WAGNER, F.M., FITZEK, TH.,
SCHRAUBE, H., Garching, Germany
Neutron Fluence and Kerma in a Fission Beam

POSTER SESSION II Continuation

SPURNY, F., VOTOCKOVA, I., Praha, CSSR
Dosimetric Characteristics of Reactor Neutron
Beams for Radiobiological Applications

ERTEK, C., Vienna, Austria
Tools and Results of the Real P-80-Project

GULDBAKKE, S., JAHR, R., Braunschweig, Germany
Neutron Response of Ion Chamber Photon
Dosemeters for Neutron Energies Between
0.144 MeV and 15.5 MeV

→ JONES, D.T.L., MCMURRAY, W.R., Faure, SOUTH
AFRICA
The k_u-Values of a ZP1300 Geiger-Müller
Counter Between 0.7 and 7.5 MeV

NAGARAJAN, P.S., BHATIA, D.P., Bombay, India
Computed Responses of Cavity Chambers for 14 MeV
Neutrons

SPURNY, F., MEDIONI, R., Praha, CSSR
Comparison of Dose Determinations in 3 and
15 MeV Neutron Beams

APPENDIX B

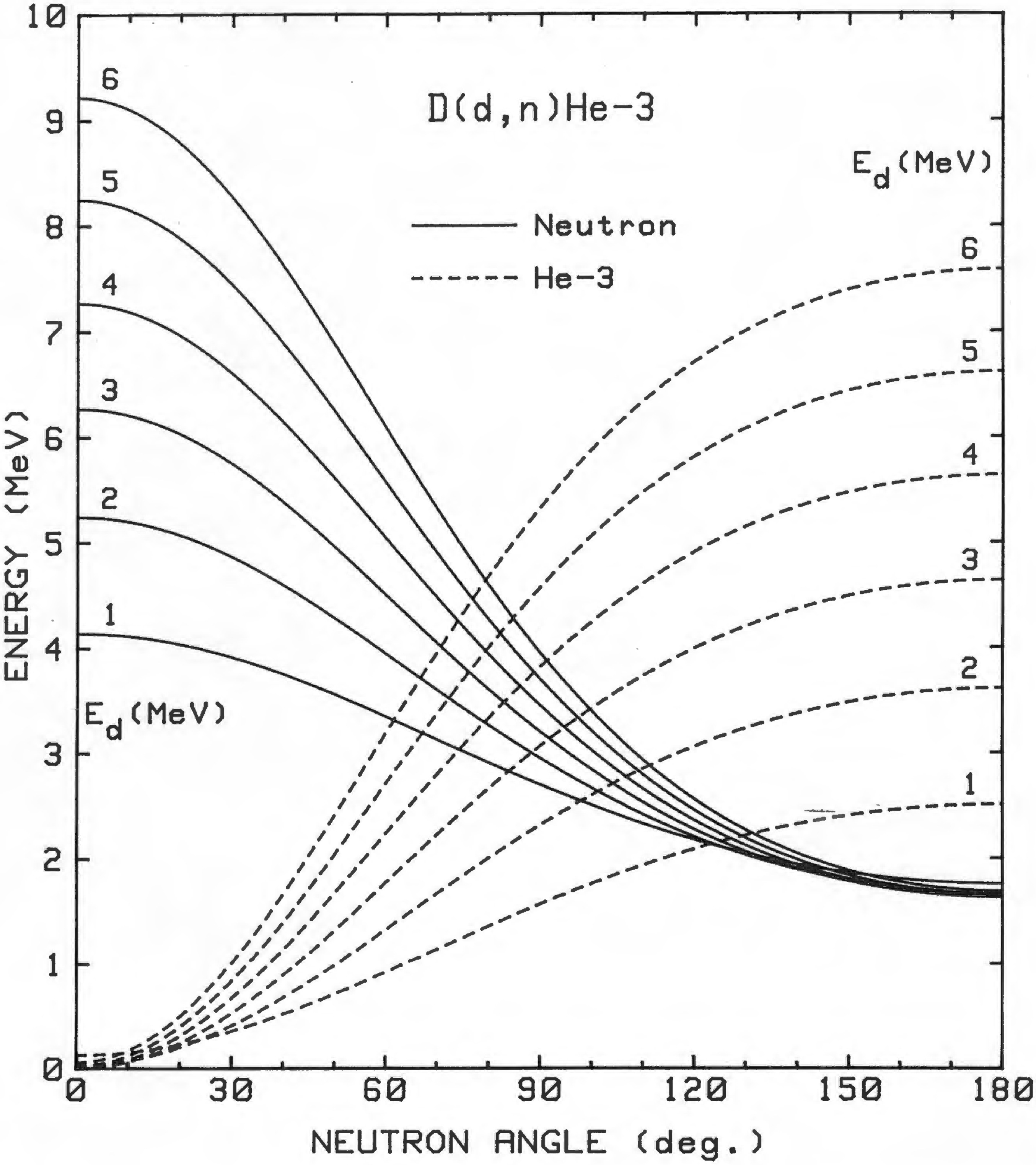
Associated Particle Kinematics

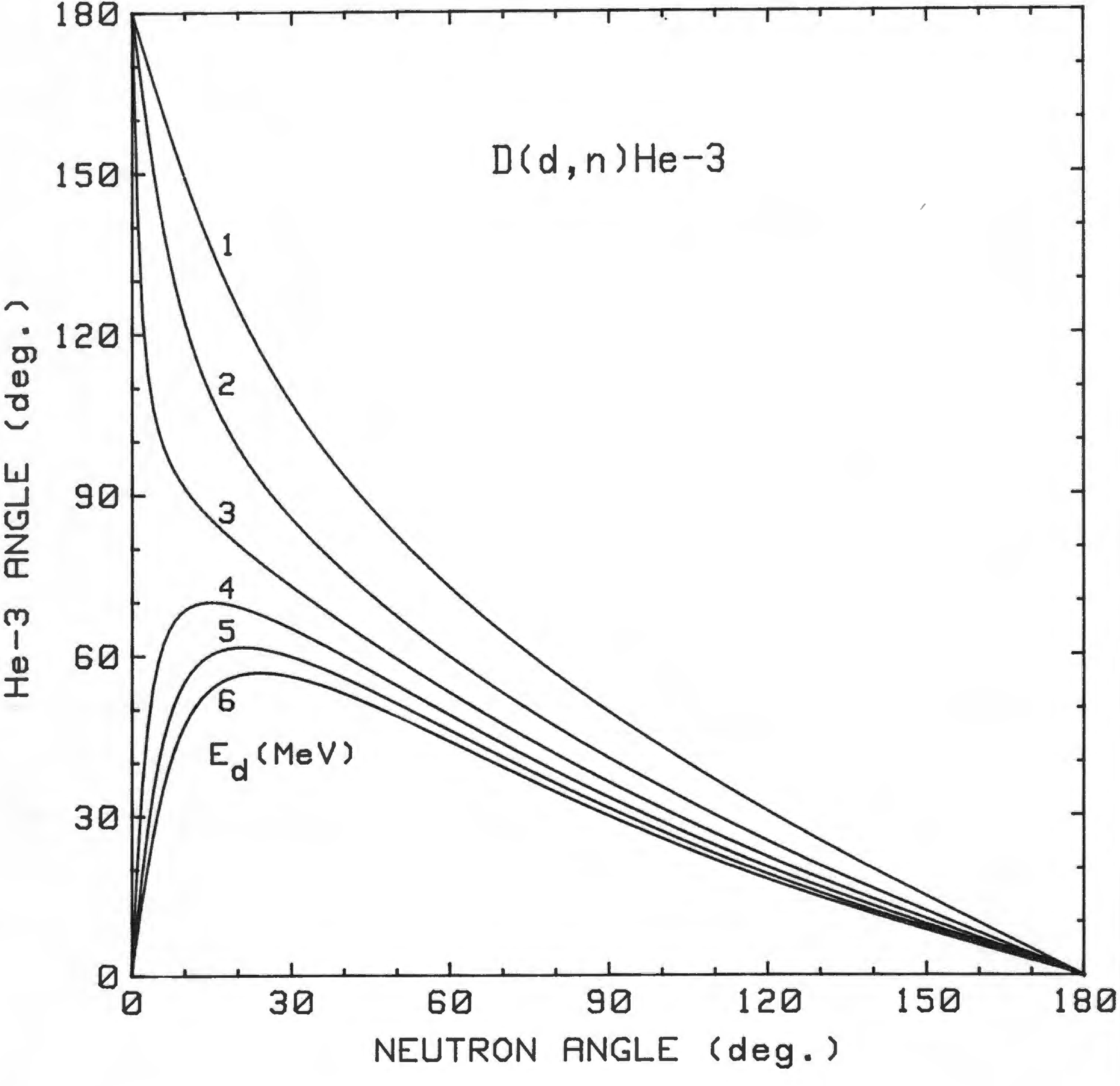
Programme NAPKIN

```
_________________PROGRAM NAPKIN  DTLJ/80_________________


                        ----- D(d,n)He-3 -----


PARTICLE MASSES (AMU) :

                        Incident (1) =  2.0141022

                        Target   (2) =  2.0141022

                        Detected (3) =  3.0160297

                        Recoil   (4) =  1.0086652

GROUND STATE Q-VALUE =  3.269022034  MeV

LEVEL ENERGIES (MeV) :

                        1 :    0.000


INCIDENT ENERGIES (1) (MeV) :  5  to  5  step  0

DETECTED ANGLES   (3) (deg) :  0  to  180  step  2.5
```

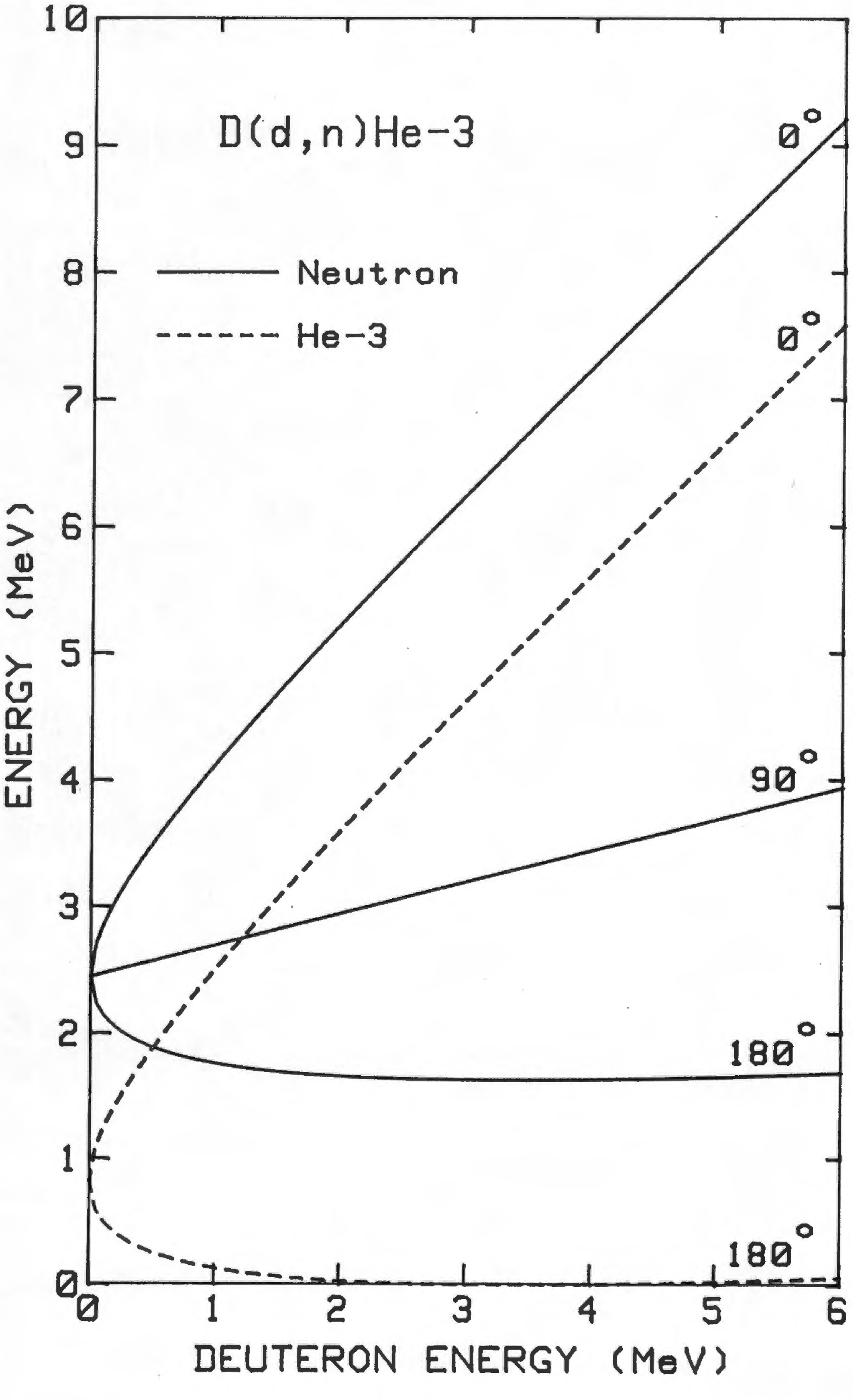
```
                                                                          D(d.n)He-3

                                                                    Ex =  0.000 MeV

                                                                    Ei =  5.000 MeV

                     ---S O L U T I O N  1---           ---S O L U T I O N  2---
 Theta3          E3         E4        Theta4         E3          E4         Theta4
 (deg)          (MeV)      (MeV)       (deg)        (MeV)       (MeV)        (deg)

   0.0          6.61       1.66       180.0          .03         8.24          .0
   2.5          6.60       1.67       171.4          .03         8.24          .2
   5.0          6.56       1.71       162.9          .03         8.24          .5
   7.5          6.48       1.78       154.5          .03         8.24          .7
  10.0          6.39       1.88       146.4          .03         8.24         1.0
  12.5          6.26       2.01       138.6          .03         8.24         1.3
  15.0          6.11       2.16       131.2          .03         8.24         1.5
  17.5          5.93       2.34       124.1          .03         8.24         1.8
  20.0          5.73       2.54       117.3          .03         8.24         2.1
  22.5          5.51       2.76       110.8          .03         8.24         2.4
  25.0          5.27       3.00       104.6          .03         8.24         2.7
  27.5          5.01       3.26        98.6          .04         8.23         3.0
  30.0          4.73       3.54        92.9          .04         8.23         3.4
  32.5          4.44       3.83        87.4          .04         8.23         3.7
  35.0          4.13       4.14        82.1          .04         8.23         4.1
  37.5          3.82       4.45        76.8          .05         8.22         4.6
  40.0          3.49       4.78        71.7          .05         8.22         5.0
  42.5          3.16       5.10        66.7          .06         8.21         5.6
  45.0          2.83       5.44        61.8          .06         8.21         6.2
  47.5          2.50       5.77        56.9          .07         8.20         6.8
  50.0          2.16       6.11        51.9          .08         8.19         7.6
  52.5          1.83       6.44        46.9          .10         8.17         8.6
  55.0          1.49       6.77        41.6          .12         8.15         9.9
  57.5          1.16       7.11        36.0          .15         8.11        11.6
  60.0           .80       7.47        29.3          .22         8.05        14.4

Ei =  5  MeV IS ABOVE THRESHOLD ,BUT TOO LOW FOR REACTION ANGLE OF 62.5 deg.
```

The calculations refer to the kinematic conditions pertaining in Fig. 5, Paper 1 and Figs. 2 and 7, Paper 2.


D(d,n)He-3
Neutron
He-3
Ed (MeV)
1
2
3
4
5
6
Ed (MeV)
6
5
4
3
2
1
ENERGY (MeV)
0
1
2
3
4
5
6
7
8
9
10
NEUTRON ANGLE (deg.)
0
30
60
90
120
150
180



D(d,n)He-3
1
2
3
4
5
6
E_d (MeV)
He-3 ANGLE (deg.)
180
150
120
90
60
30
0
NEUTRON ANGLE (deg.)
0
30
60
90
120
150
180


D(d,n)He-3
Neutron
He-3
0°
0°
90°
180°
180°
ENERGY (MeV)
DEUTERON ENERGY (MeV)
0
1
2
3
4
5
6
7
8
9
10
0
1
2
3
4
5
6

APPENDIX C

Neutron Time of Flight Kinematics

Programme TOFKIN

```
          ________________PROGRAM TOFKIN  DTLJ/80________________



                         ----- D(d.n)He-3 -----


PARTICLE MASSES (AMU) :

                           Incident (1) =  2.0141022

                           Target   (2) =  2.0141022

                           Detected (3) =  1.0086652

                           Recoil   (4) =  3.0160297

GROUND STATE Q-VALUE =  3.26902203  MeV

LEVEL ENERGIES (MeV) :

                             1 :    0.000


INCIDENT ENERGIES (1) (MeV) :  2.42  to  2.42  step  0

DETECTED ANGLES   (3) (deg) :  0  to  180  step  5
```

D(d.n)He-3

D = 5.77 m Cal = 1.5600 ns/ch Ex = 0.000 MeV

Gampeak at ch. 216.0 T=0 at ch. 228.3 E1 = 2.420 MeV

Theta3 (deg)	E3 (MeV)	T1 (ns/m)	T (ns)	Cn (chan)	The3cm (deg)	S
0.0	5.68	30.481	175.9	115.6	.0	.590
5.0	5.66	30.515	176.1	115.5	6.5	.591
10.0	5.63	30.619	176.7	115.1	13.0	.595
15.0	5.56	30.793	177.7	114.4	19.5	.601
20.0	5.47	31.036	179.1	113.5	25.9	.609
25.0	5.36	31.349	180.9	112.4	32.3	.620
30.0	5.23	31.732	183.1	111.0	38.7	.633
35.0	5.09	32.185	185.7	109.3	45.0	.649
40.0	4.92	32.709	188.7	107.4	51.2	.668
45.0	4.75	33.302	192.2	105.2	57.3	.690
50.0	4.56	33.965	196.0	102.7	63.4	.715
55.0	4.37	34.696	200.2	100.0	69.3	.743
60.0	4.18	35.494	204.8	97.1	75.1	.775
65.0	3.98	36.356	209.8	93.9	80.9	.811
70.0	3.78	37.280	215.1	90.4	86.4	.850
75.0	3.59	38.261	220.8	86.8	91.9	.894
80.0	3.40	39.294	226.7	83.0	97.3	.942
85.0	3.22	40.374	233.0	79.0	102.5	.993
90.0	3.05	41.494	239.4	74.9	107.5	1.049
95.0	2.89	42.644	246.1	70.6	112.5	1.109
100.0	2.73	43.817	252.8	66.3	117.3	1.172
105.0	2.59	45.001	259.7	61.9	121.9	1.239
110.0	2.46	46.187	266.5	57.5	126.4	1.309
115.0	2.34	47.362	273.3	53.2	130.8	1.381
120.0	2.23	48.515	279.9	48.9	135.1	1.454
125.0	2.13	49.633	286.4	44.8	139.3	1.528
130.0	2.04	50.705	292.6	40.8	143.3	1.602
135.0	1.96	51.717	298.4	37.1	147.3	1.673
140.0	1.89	52.659	303.8	33.6	151.2	1.742
145.0	1.83	53.518	308.8	30.4	154.9	1.807
150.0	1.78	54.286	313.2	27.6	158.7	1.866
155.0	1.74	54.952	317.1	25.1	162.3	1.918
160.0	1.70	55.508	320.3	23.0	165.9	1.963
165.0	1.67	55.948	322.8	21.4	169.5	1.999
170.0	1.66	56.267	324.7	20.2	173.0	2.025
175.0	1.64	56.459	325.8	19.5	176.5	2.041
180.0	1.64	56.524	326.1	19.3	180.0	2.047

Ecm3 = 3.36 MeV

The calculations refer to the kinematic conditions pertaining to Fig. 4, Paper 6.

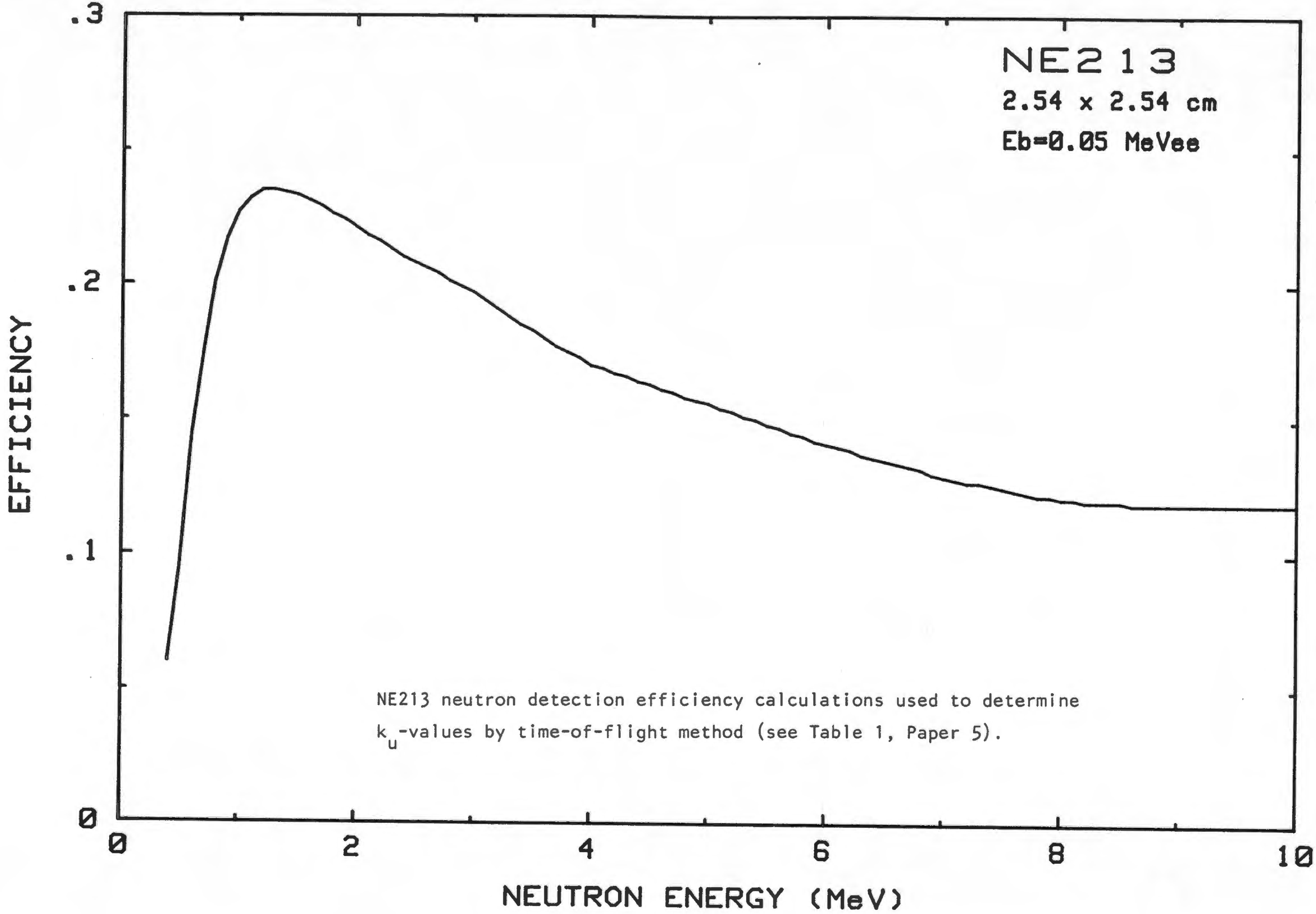
APPENDIX D

NE213 Neutron Detection Efficiencies

Programme DETEFF[*]

---

[*] S.T. Thorton and J.R. Smith, Nucl. Inst. and Meth. 96 (1971) 551



NE213 neutron detection efficiency calculations used to determine k_u-values by time-of-flight method (see Table 1, Paper 5).

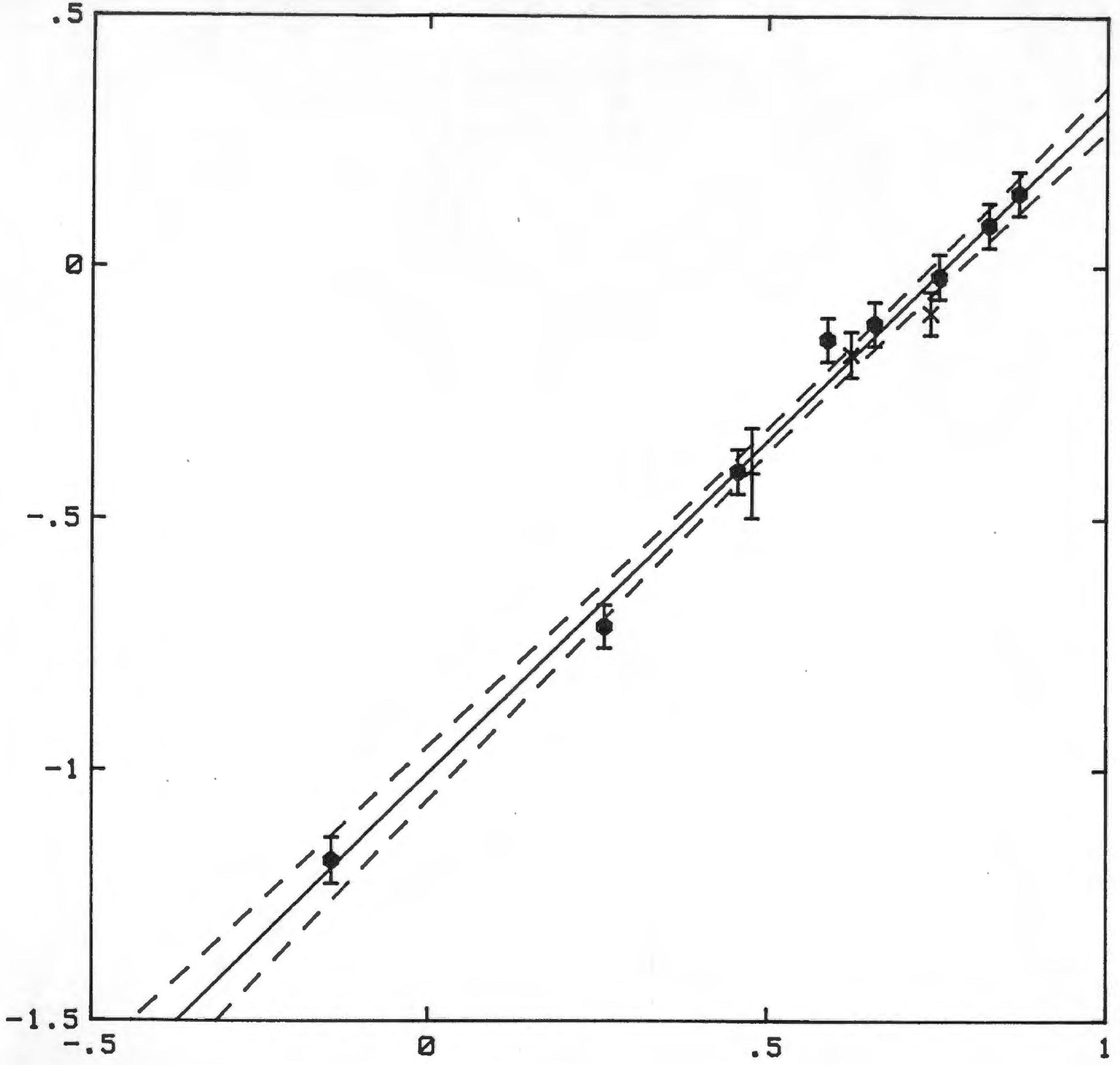
APPENDIX E

Linear Least Squares Fitting

Programme LINFIT

```
ZP1320 DATA            The data are those shown in Fig. 2, Paper 5.

File : 164TEF

Fit to equation    y = a*x^b               transformed to    Logy = Loga + b*Logx

Errors are instrumental [=DeltaY]


                                  RESULTS OF FIT
                                  --------------


                           a =      .098   +-     .007

                           b =     1.322   +-     .049


          R          Chisq          Var          Sigma          Xav          Yav
        .9946        .8833        .0019          .0430        .5651       -.2604



                                   ORIGINAL DATA

 POINT          X          Y       Dy/Wt        FIT       DIFF       -95%       +95%

   1          .720       .066       .007       .064      -.002       .053       .077
   2         1.820       .193       .019       .217       .024       .196       .240
   3         2.860       .392       .040       .394       .002       .367       .424
   4         3.880       .717       .072       .590      -.127       .551       .632
   5         4.550       .771       .078       .728      -.043       .678       .782
   6         5.660       .958       .099       .972       .014       .896      1.055
   7         6.700      1.211       .124      1.215       .004      1.108      1.333
   8         7.420      1.402       .142      1.391      -.011      1.258      1.537
   9         3.000       .390       .080       .420       .030       .391       .451
  10         4.200       .670       .070       .655      -.015       .612       .702
  11         5.500       .810       .080       .936       .126       .864      1.014


                                  TRANSFORMED DATA

 POINT          X          Y       Dy/Wt        FIT       DIFF       -95%       +95%

   1         -.143     -1.180       .046     -1.196      -.016     -1.276     -1.116
   2          .260      -.714       .043      -.664       .051      -.707      -.620
   3          .456      -.407       .044      -.404       .003      -.436      -.373
   4          .589      -.144       .044      -.229      -.085      -.259      -.200
   5          .658      -.113       .044      -.138      -.025      -.169      -.107
   6          .753      -.019       .045      -.012       .006      -.048       .023
   7          .826       .083       .044       .085       .001       .044       .125
   8          .870       .147       .044       .143      -.004       .100       .187
   9          .477      -.409       .089      -.377       .032      -.408      -.346
  10          .623      -.174       .045      -.184      -.010      -.214      -.154
  11          .740      -.092       .043      -.029       .063      -.063       .006
```

ZP1320 DATA



File : 164TEF

Logy = Loga + b*Logx

Errors : Instrumental

a = .098 +- .007

b = 1.322 +- .049

R = .9946

------- 95% conf. limits

Bars are weighting factors

● : NAC DATA - TOF

+ : NAC DATA - APM

x : NPL DATA

The data are those shown in Fig. 2, Paper 5.