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STRANGE PARTICLE PRODUCTION IN pp AND pn REACTIONS

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ABSTRACT

A statistical model of particle production valid for a wide range of Feynman's x is developed and applied to describe strange particle production in hadronic collisions. Predictions of relative abundances of multiply strange hadrons are made which compare well with the available fragmentary data.

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Multihadron production at $P_\perp < 1$ GeV/c shows many characteristic features which suggest the presence of a statistical mechanism [1]. However, there are many features of these reactions, like the quantum number dependence of particle production in the fragmentation region which cannot be described within a simple statistical model. In this paper we will present a new type of statistical model of particle production, capable of combining some crucial aspects of both statistical and fragmentation models.

The physics of our approach is, in spirit, related to the reaction picture proposed by Pokorski and Van Hove [2]. In their approach to nondiffractive particle production in pp-collisions the valence quarks of one nucleon penetrate the other nucleon rather freely without much interaction, while the remaining energy and momentum in the gluon field remains dominant in the central reaction region. This region, therefore, should exhibit zero net baryon and charge number whereas in the maximum rapidity region we would expect to see the quantum numbers of the incoming particles, that is the baryon number is found mainly in the projectile (and target) fragmentation regions.

To describe different particle multiplicities, including the rapidity distribution of the baryon number, it is necessary in a statistical model to find for the baryochemical potential μ_B, controlling the baryon number, a distribution between the central and projectile rapidity regions. In this paper we explore the consequences of a linear relationship

$$|x| m_N = \mu_B \tag{1}$$

suggested by the above considerations. For $x = \pm 1$ (projectile/target region) we have $\mu_B \to m_N$, where $m_N = 940$ MeV is the nucleon's mass. For

$x = 0$ (central region) we have $\mu_B = 0$, which corresponds to zero baryon density. In order to obtain particle spectra having origin between these extreme cases, we consider x in eq.(1) as the usual Feynman x-variable which is the fraction of the maximum momentum that a particle could carry. Further assumptions of our work are:

1) existence of highly excited matter consisting of individual hadrons,
2) local thermal equilibrium among hadrons [1],
3) baryochemical equilibrium between strange and nonstrange hadrons, and
4) relative strangeness and charge (i.e. quark isospin) equilibration concerning the flavour content of individual hadrons.

We record that as consequence of the hypothesis eq.(1), we furthermore tacitly assume that all this is true even in a small interval of the values of x. While this is a very daring step, it is only the experimental data which can justify our approach. At present we lack understanding of why this or even the assumption 2) should be true. A further point of caution is that our model may for $x \to \pm 1$ be inconsistent, as in such a case it is hard to imagine that any of our assumptions remain valid. Hence we only compare with data obtained at $|x| \leq 0.7$.

In order to calculate, in particular, strange particle abundances, we consider here an extension of our previous work on relative strange particle abundances [3] by incorporating aside from baryon number (B) and strangeness (S) conservation now also electric charge conservation (Q). Thus in order to calculate particle abundances we start from the following grand canonical partition function (in the Boltzmann approximation):

$$\ell n\, Z_{(1)}^{\text{strange}}\left(V,T,\lambda_S,\lambda_B,\lambda_Q\right) = Z_{K^o}\left[\lambda_S+\lambda_S^{-1}\right] + Z_{Y^o}\left[\lambda_S\lambda_B + \lambda_S^{-1}\lambda_B^{-1}\right]$$
$$+ Z_{K^\pm}\left[\lambda_S\lambda_Q^{-1} + \lambda_S^{-1}\lambda_Q\right] + Z_{\Sigma^-}\left[\lambda_S\lambda_B\lambda_Q^{-1} + \lambda_S^{-1}\lambda_B^{-1}\lambda_Q\right]$$
$$+ Z_{\Sigma^+}\left[\lambda_S\lambda_B\lambda_Q + \lambda_S^{-1}\lambda_B^{-1}\lambda_Q^{-1}\right] \quad . \qquad (2)$$

Particles with higher strangeness than $|S| = 1$ are similarly added to eq.(2) when needed to evaluate their abundance (see eq.(9)). They do not influence significantly [4] the actual values of the fugacities λ_S, λ_B and λ_Q, introduced to control the strangeness, baryon and electric charge number of the hadronic matter system. It is important to appreciate that by counting also the electric charge we indeed now follow the flow of up and down quarks in hadronic reactions. We recall that usually one substitutes for the fugacities, their chemical potentials:

$$\lambda_C = e^{\frac{\mu_C}{T}} \text{ with } C = S,\ B,\ Q. \qquad (3a)$$

Introduction of fugacities implies relative chemical equilibrium [5]. The quantities

$$Z_i = g_i\ C_i\left(\frac{m_i}{T}\right)^2 K_2\left(\frac{m_i}{T}\right) \qquad (3b)$$

are the one particle relativistic Boltzmann partition functions for noninteracting particles of mass m_i, degeneracy g_i at temperature T. One should notice that only for a fully equilibrated state we expect the constant C_i to be equal to $C = \frac{VT^3}{2\pi^2}$. However, depending on the reaction channel, absolute strangeness abundance may substantially differ from this value. If quark gluon plasma is formed for more than $2\cdot 10^{-23}$ sec., we will have an overabundance of strangeness [6], while if the reaction proceeds via individual hadronic reactions, we may have less strangeness then expected. When studying the relative yields, we can eliminate the unknown absolute normalization C_i, i.e. our ignorance concerning the reaction channel (and mechanism), if we consider particle abundance ratios which are expected to deviate similarly from equilibrium.

Using the partition function (2) we can calculate the mean strangeness which must be set equal to zero in view of the fact that strangeness is a conserved quantity in hadronic reactions. This generates a constraint [3] among the variables λ_B, λ_Q, λ_S and T which reads

$$\lambda_S = \left[\frac{Z_{K^0} + Z_{Y^0}\,\lambda_B^{-1} + Z_{\Sigma^+}\,\lambda_B^{-1}\lambda_Q^{-1} + \left[Z_{K^\pm} + Z_{\Sigma^-}\lambda_B^{-1}\right]\lambda_Q}{Z_{K^0} + Z_{Y^0}\,\lambda_B + Z_{\Sigma^+}\,\lambda_B\lambda_Q + \left[Z_{K^\pm} + Z_{\Sigma^-}\lambda_B\right]\lambda_Q^{-1}} \right]^{\frac{1}{2}} \tag{4}$$

Note that expression (4) is independent of the normalization C. From eq.(2) we find for the singly strange particles

$$\frac{\langle n_{K^+} \rangle}{\langle n_{K^-} \rangle} = \lambda_Q^2\,\lambda_S^{-2} \tag{5a}$$

$$\frac{\langle n_{\bar\Lambda} + n_{\bar\Sigma^0} \rangle}{\langle n_\Lambda + n_{\Sigma^0} \rangle} = \lambda_B^{-2}\cdot\lambda_S^{-2} \tag{5b}$$

$$\frac{\langle n_{\bar\Sigma^{\mp}} \rangle}{\langle n_{\Sigma^{\mp}} \rangle} = \lambda_B^{-2}\,\lambda_Q^{-2}\,\lambda_S^{-2} \tag{5c}$$

etc. The factors λ_i on the right hand side of eq.(5) describe the charge, baryon number and strangeness content of the ratios.

To confront our model with experiment, we first need to use the measured π^+/π^- ratio [7, 8, 9, 10]

$$\frac{\pi^+}{\pi^-} \cong \lambda_Q^2 \qquad (6a)$$

to fix the x-dependence of the charge fugacity λ_Q which can be satisfactorily represented [11] for pp reactions by the functional form

$$\frac{\pi^+}{\pi^-} = e^{2x} \qquad (6b)$$

in the region $0.2 \leq x \leq 0.7$. Our assumption 1 implies, together with eq.(3a) that the baryon fugacity is

$$\lambda_B^2 = e^{2\,x\,m_N/T} = \begin{cases} e^{10.7x} & T = 175 \text{ MeV} \\ e^{12.5x} & T = 150 \text{ MeV} \end{cases} \qquad (7)$$

where as indicated above, the temperature parameter T was chosen to be 175 MeV for pp-collisions and 150 MeV for pN reactions (see below) in agreement with values deducable from mean transversal momenta of mesons [7]. With λ_Q as given by eq.(6), λ_B^2 by eq.(7) and λ_S as given by eq.(4) we can now proceed to explore the consequences arising from our hypothesis eq.(1). Fig.1a shows good agreement of the so calculated and measured K^+/K^- ratio in pp reactions where we have included experimental data with $0.2 \leq P_\perp \leq 1.5$ GeV/c and $23.3 \leq \sqrt{S} \leq 53$ GeV. It is very important to observe that the presented results depend strongly on the functional form

$\lambda_S(\lambda_Q, \lambda_B)$, eq.(4). Thus the agreement between our predictions and experiment is when strange particles are considered a nontrivial consequence of our assumptions, hypothesis eq.(1) *and* imposed strangeness conservation.

In the case of p nucleus reactions [12, 13] it turns out that

$$\frac{\pi^+}{\pi^-} \cong \lambda_Q^2 = e^{2.2x} \tag{8}$$

and T = 150 MeV is a better parameterisation of the data in the range $0.1 \leq x \leq 0.6$. Indeed, the need to consider smaller temperatures in p-N reactions justifies the 10% increase in the exponent of eq.(8) in the same manner as we have recorded it already in eq.(7) for the baryon number fugacity. We subsequently again find satisfactory agreement with the measured K^+/K^- [12-14] as well as $\bar{\Lambda}/\Lambda$ [15] ratios, as shown in Figs. 1b and 1c. Also the double ratio $(\bar{P}/p)/(\pi^-/\pi^+)$ which is equal to λ_B^{-2} and therefore provides an independent consistency check for the assumed relation, eq.(1), gives a satisfactory agreement with data (Fig.1d). One should note that these comparisons indicate the validity of the linear relationship expressed in eq.(1). Taking any other power of x would destroy the visible (e.g. Fig.1d) exponential behaviour of this double ratio as a function of x.

A further comment deals with our choice of temperature, based on measured transverse momenta. We have here, for simplicity, decided to take x-independent value of T. However, as the chemical potential is x-dependent so should be T, and that in such a particular way that for any fixed x both μ and T are the associated critical values forming the boundary in the μ-T plane which separates the domains of quasi-gluon plasma from hadronic gas phase [1d, 5]. However, as long as the considered values of x are not too large, e.g. $x < 0.6$, the x-dependence of T turns out to be slow and unimportant. However, these comments suggest not only a certain improvement of our model, but furthermore point out that $<p_\perp>$ are particular functions of x related to the phase diagram of hadronic matter. We must here admit that our calculation will not provide individual x-dependences of the particle abundances. This is because there is a substantial kinématical effect to be expected in the absolute normalisation in the factor C, eq.(3b). Aside from the (slow) x dependence of temperature, there is very likely a substantial effect on the volume. Hence, it is only the ratio which is independent of the kinematics of the hadronic collision.

However, a challenging test of our appraoch comes when we confront it with the measured multistrange anti-to particle ratios [14]. To this end we need to add to eq.(2) the following terms describing double and triple strange hadrons:

$$\begin{aligned} \ln Z^{\text{Strange}}_{(2,3)}(V,T,\lambda_B,\lambda_S,\lambda_Q) &= Z_{\Sigma^0}[\lambda_B\lambda_S^2 + \lambda_B^{-1}\lambda_S^{-2}] \\ &+ Z_{\Sigma^-}[\lambda_B\lambda_S^2\lambda_Q^{-1} + \lambda_B^{-1}\lambda_S^{-2}\lambda_Q] \\ &+ Z_{\Omega^-}[\lambda_B\lambda_S^3\lambda_Q^{-1} + \lambda_B^{-1}\lambda_S^{-3}\lambda_Q]. \end{aligned} \quad (9)$$

The calculation of the mean particle numbers proceed straightforwardly as in the case of simple stangeness carrying particles [4]. The result of this proposed model for the particle ratio in comparison with data of M. Bourquin et al [14] at $x = 0.48$ is shown in Fig.2, where our prediction is indicated by a full circle. As a function of strangeness

(S = 1,2,3), we are able to describe the systematics of this experiment quite well and in particular the increase of the ratio with S. It would be very interesting to confront as function of x our prediction, shown in Fig.3, for the same ratios of multiply strange hadrons.

An extension of our model to N-N collisions seems possible but requires an input π^+/π^- ratio or other independent means of estimating λ_Q^2.

In our opinion it is quite remarkable that we are able to describe the (strange) particle production data as function of x with our very simple model, eq.(1). Even more striking is the resulting explanation of the data of Bourquin et al [14] for multiply strange hadrons. This indeed indicates that our initial hypothesis, eq.(1) is correctly establishing a relationship between a statistical quantity μ_B and a kinematical variable x. This allows us to obtain a realistic estimation of particle abundances in different kinematic regions for very high energy pp, p-N and in future perhaps NN reactions.

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FIGURE CAPTIONS

FIGURE 1 : Particle abundance ratios as function of x in pp and pN collisions. Drawn lines are our calculated results with $T^{(pp)} = 175$ MeV and $\lambda_Q^{(pp)} = e^{2x}$ or $\lambda_Q^{(pN)} = e^{2.2x}$ and $T^{(pN)} = 150$ MeV

(a) K^+/K^-(pp): ref.8 (Δ): ref.9 (●): ref.11 (0).
Data averaged over range of transverse momenta and $\sqrt{s}$.

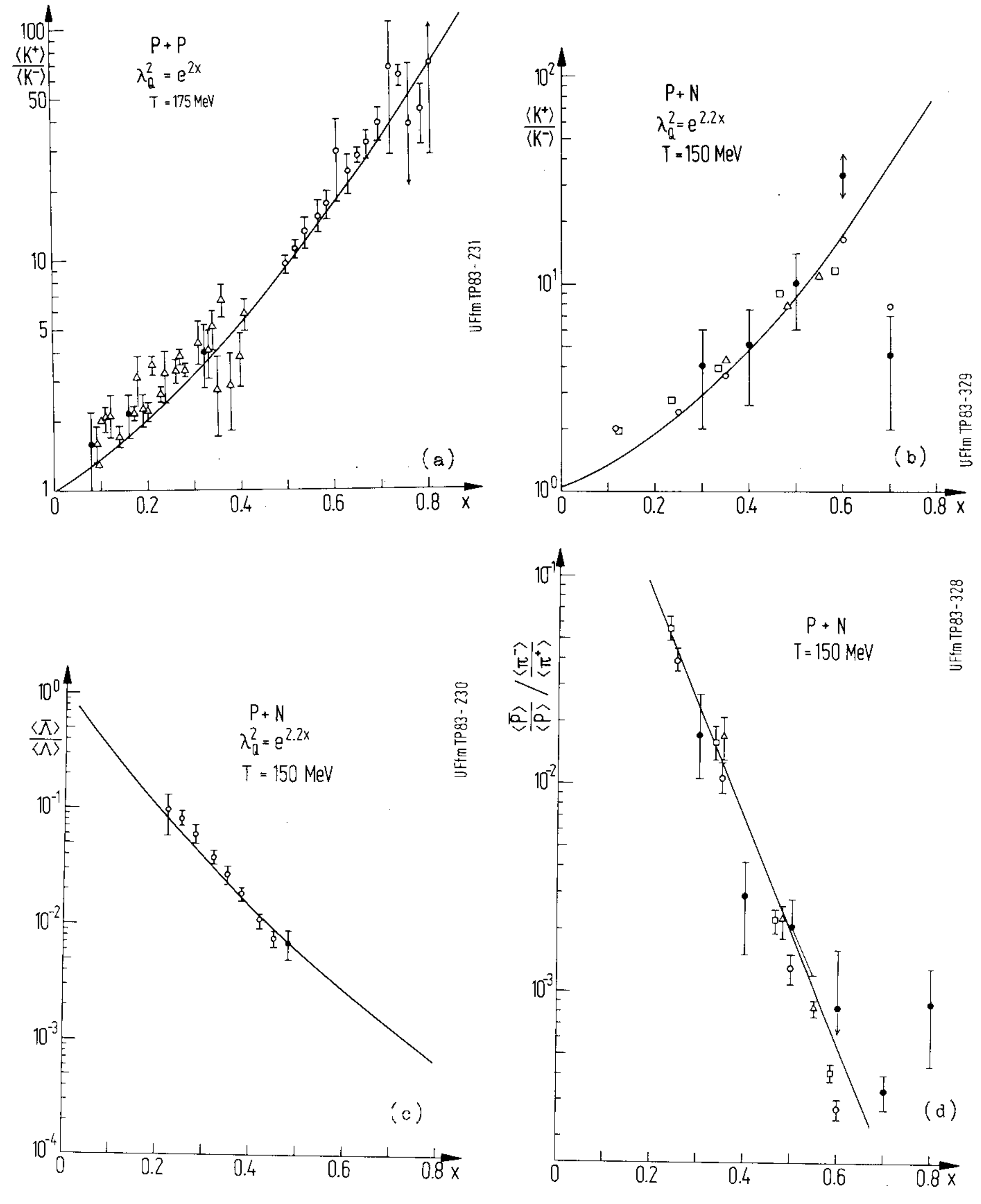
(b) K^+/K^-(pBe): ref.13 (o, at $P_{proj} = 200$ GeV/c); ref.13 (□ at $P_{proj} = 300$ GeV/c); ref.15 (Δ, pBe0 at $P_{proj} = 210$ GeV/c); ref.14 (●, pA different A, $P_{proj} = 100$ GeV/c).

(c) $(\overline{\Lambda} + \overline{\Sigma}^0)/(\Lambda + \Sigma^0)$(pBe), ref.15.

(d) double ratio $(\overline{p}/p) : (\pi^-/\pi^+)$ Ref.13, 14, 15.

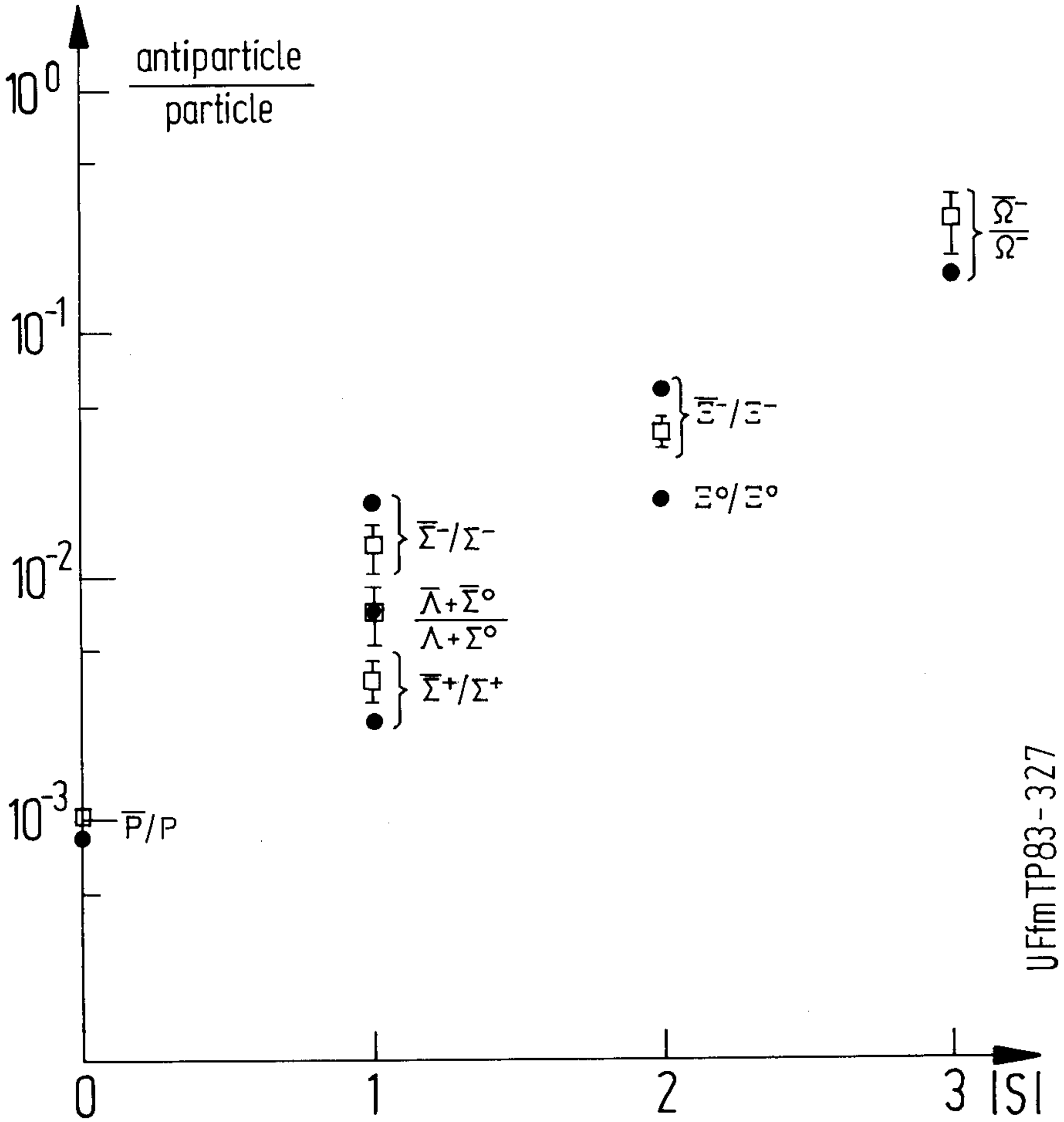
FIGURE 2 : Antibaryon to baryon ratio for p-Be collision as function of strangeness S for x = 0.48, Ref.14. Our calculated points are indicated by a full circle. (T = 150 MeV, $\lambda_Q = e^{2.2x}$).

FIGURE 3 : Multistrange antibaryon to baryon ratios for p-A collision as function of x.



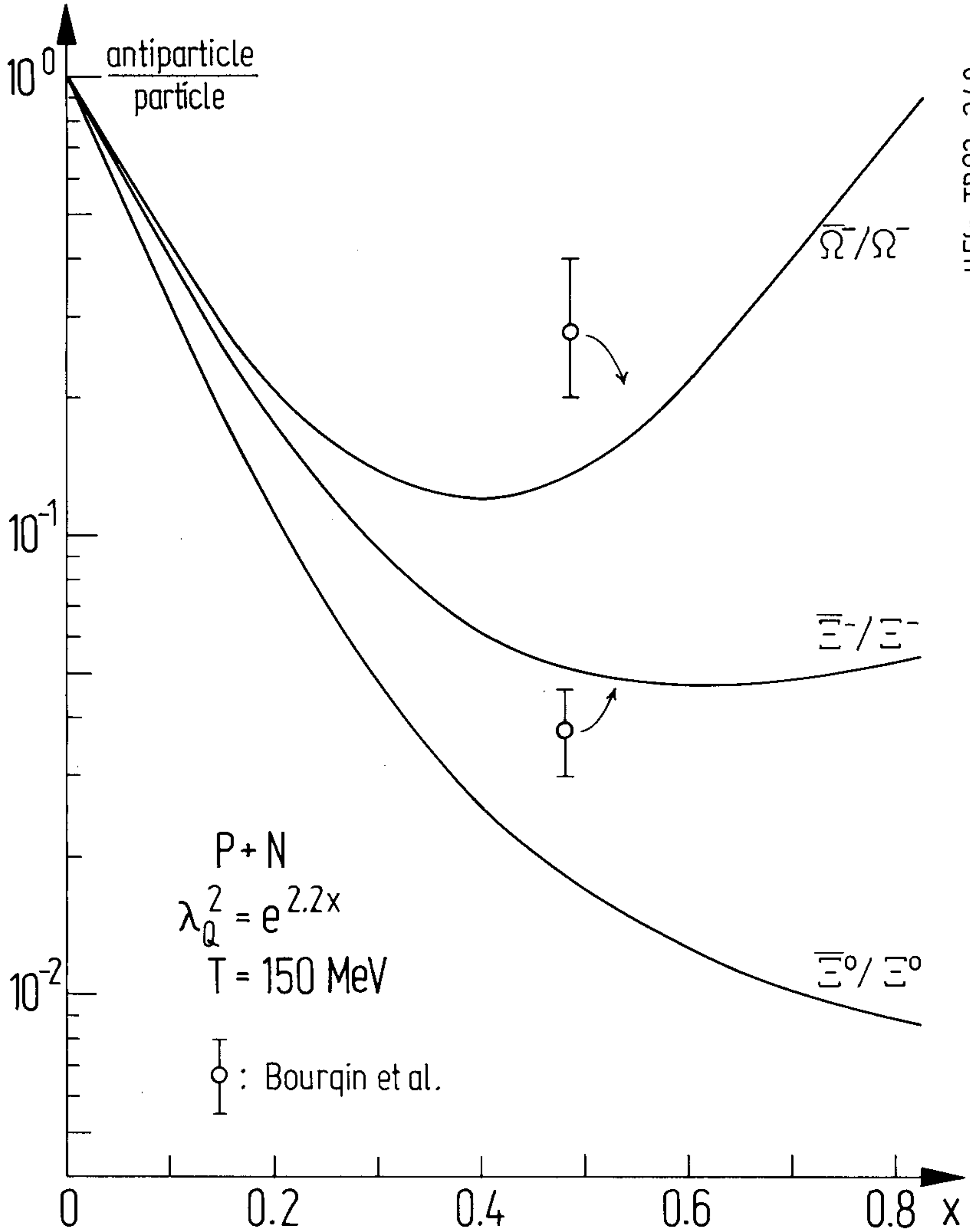
P + P
$\lambda_Q^2 = e^{2x}$
T = 175 MeV
(a)
UFfm TP83-231
P + N
$\lambda_Q^2 = e^{2.2x}$
T = 150 MeV
(b)
UFfm TP83-329
P + N
$\lambda_Q^2 = e^{2.2x}$
T = 150 MeV
(c)
UFfm TP83-230
P + N
T = 150 MeV
(d)
UFfm TP83-328

FIG 1



antiparticle / particle
10^0
10^{-1}
10^{-2}
10^{-3}
$\overline{P}/P$
$\overline{\Sigma}^-/\Sigma^-$
$\frac{\overline{\Lambda}+\overline{\Sigma}^0}{\Lambda+\Sigma^0}$
$\overline{\Sigma}^+/\Sigma^+$
$\overline{\Xi}^-/\Xi^-$
Ξ^0/Ξ^0
$\frac{\overline{\Omega}^-}{\Omega^-}$
0
1
2
3 |S|
UFfmTP83-327

FIG 2



UFfm TP83-348

FIG 3