SUBTHRESHOLD PRODUCTION OF ANTIPROTONS ON NUCLEI

BY B. N. KALINKIN, A. V. CHERBU AND V. L. SHMONIN

Laboratory of Theoretical Physics, Joint Institute for Nuclear Research, Dubna*

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The "gathering" model for cumulative processes is applied to interpret the subthreshold production of antiprotons by nuclei. The comparison with the available experimental data is rather good. The results indicate the importance of the space-time factors in the hadron collective interactions at high energies.

1. *Introduction*

A possible effect of the hadron collective interaction in nuclear matter (like the cumulative meson production) is the antiproton production in collisions of relativistic protons with the nucleus in the subthreshold energy region.

The threshold energy of the antiproton production in a nucleon-nucleon collision equals

$$E_{\rm p}^{\rm thr} = 6.58\ {\rm GeV} \tag{1}$$

(the kinetic energy $T_{\rm p}^{\rm thr} = 5.64$ GeV). However, experiments reveal antiproton production up to energies $T_{\rm p} \approx 3$ GeV.

At first this effect was studied within a model allowing for the nucleon Fermi-motion in a target-nucleus. Rough estimations [1, 2] for the yield of antiprotons and pions have produced the ratio $\varphi = I(\tilde{p})/I(\pi)$ which is in qualitative agreement with experiment (normalization to experiment has been used).

This interpretation, unfortunately, meets certain difficulties. For instance, it is known that the model of the Fermi-motion fails to describe a similar phenomenon, cumulative meson production on nuclei.

Further, the antiproton production requires large (in magnitude) relative momenta between nuclear nucleons, i. e. rather short relative distances. Then, it is not clear why the nucleons do not interact collectively with the initial particle.

* Address: Joint Institute for Nuclear Research, Head Post Office, P. O. Box 79, Moscow, USSR.

Also, the very concept of the two-particle wave function is doubtful at distances where nucleons should lose their individuality.

More arguments can be given as well in favour of a large uncertainty over such a formulation of the problem. And finally, the traditional question arises whether the aforementioned interpretation is unique.

2. *The "gathering" model and antiproton production*

We consider the antiproton production by nuclei in the subthreshold energy region using the ideas of the "gathering model" as a variant realizing processes of the cumulative type. This model was formulated in Ref. [4].

Here we shall use a modification of the model suitable for analysing this case.

Figure 1 represents schematically the process resulting in antiproton production. An incident proton colliding with the nucleus of radius $R = r_0 A^{1/3}$; $r_0 = 1.2$ fm and density $\varrho = 3/4\pi r_0^3$ produces, with a certain probability, a compound system together

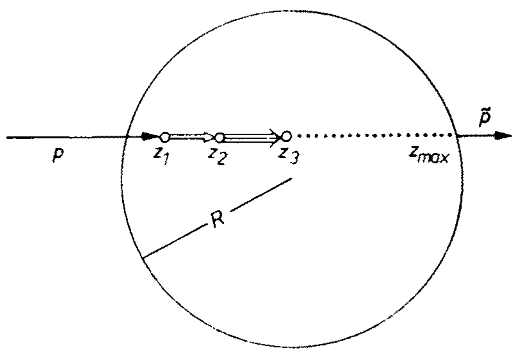

Fig. 1. The scheme of the gathering process resulting in antiproton production

with a nucleon near the point z_1. Moving further through the nucleus this system can increase its mass in subsequent collisions with nucleons at points z_2, z_3 and so on by means of the same process. Since the threshold of antiproton production depends on the number n of "gathered" nucleons of the target

$$[E_p^{(n)}]^{\text{thr}} = \frac{(n+3)^2 m^2 - (n^2+1)m^2}{2nm} = \frac{m}{n}(3n+4) \tag{2}$$

(m is the nucleon mass), with increasing n the process can occur at E_p rather smaller than the value (1). Asymptotically $[E_p^{(n)}]^{\text{thr}}_{n\to\infty} \to 3\,m$. The decay resulting from the gathering of the compound system is accompanied, with some probability, by the production of a proton-antiproton pair (in the scheme — near the point z_3). However, only those antiprotons are detected which could pass the distance $z_3 \to z_{\max}$ in nuclear matter without annihilation.

Let us consider these phases step by step.

To begin, we examine the first step, the probability of gathering of n nucleons by a primary particle into the compound system. Obviously, it decreases with increasing n.

In Ref. [4] it is shown that the probability of gathering of n nucleons by a primary hadron into the compound system is proportional to the expression

$$W^{(n)} = \frac{\pi}{2} \frac{(\sigma\varrho)^n}{\prod_{j=1,\dots,n} (\sigma\varrho+a_j)} \left\{ 2R^2 + \sum_{k=1}^{n} C_k^{(n)} \frac{\gamma[2; 2(\sigma\varrho+a_k)R]}{(\sigma\varrho+a_k)^2} \right\}, \tag{3}$$

where $\gamma\,[2; x]$ is the incomplete γ-function, $a_1 \equiv 0$ and

$$C_{k\neq 1}^{(n)} = \prod_{\substack{\lambda=1,\dots,n \\ \lambda\neq k}} (\sigma\varrho+a_\lambda) \Big[\prod_{\substack{\zeta=1,\dots,n \\ \zeta\neq k}} (a_k-a_\zeta) \Big]^{-1},$$

$$C_{k=1}^{(n)} = [(-1)^{n+1} \sum_{k=2}^{n} C_k^{(n)} - 1]. \tag{4}$$

The $W^{(n)}$ is a function of two parameters evaluated by comparing the model with the experimental data on cumulative meson production:

$$\sigma = 0.25 \cdot \sigma_{\mathrm{NN}}^{\mathrm{in}} \tag{5}$$

i. e. the partial cross section of the compound system production, and

$$\tau_0 c = 5, \tag{6}$$

the parameter which defines the magnitude of a_n in (2)

$$a_n = \frac{1}{\tau_0 c} \frac{(n'^2+1)m^2+2n'mE_{\mathrm{p}}}{(E_{\mathrm{p}}^2-m^2)^{1/2}}, \qquad n' = n-1, \qquad n \geqslant 2. \tag{7}$$

The a_n determine the possibility of the decay of the system (and other reasons for leaving the considered channel) at intermediate steps of the gathering mechanism.

To a first approximation, it is reasonable to employ $W^{(n)}$ at the same values of parameters (5) and (6) since the energies E_{p} are almost in the same interval and in both cases (cumulative meson production and antiproton production) the whole excitation energy is released in practice through the production of a small number of particles (one and two, resp.).

In Fig. 2 the $W^{(n)}$ is shown as a function of n (the target nucleus Cu), the energy values are given below (see (13)). It is seen that with increasing order of the cumulation ("gathering") the $W^{(n)}$ sharply decreases in magnitude.

At the next step, the gathered system, being strongly excited, should suffer from the decay which can give rise to the production of the proton-antiproton pair (under the kinematical conditions). Let us briefly discuss the probability $w(\tilde{p}, \Omega)$ of the production of antiprotons with a momentum $\tilde{p}$. As in the final state there are many particles, "gathered" nucleons plus a produced pair, and in principle, "soft" pions, then to determine the function $w(\tilde{p}, \Omega)$ a thermodynamical model is useful. The most important fact is that this model gives a correct composition of the produced particles (and some other characteristics): above the threshold the ratio of integral yields of antiprotons and pions is 10^{-4}–10^{-5}

that is consistent with experiment [5]. This fact will be used for normalization of the function $\varphi = I(\tilde{p})/I(\pi)$ (the normalization of this function to φ_{exp}, $T_{\text{p}} > T^{\text{thp}}_{\text{p.NN}}$).

Also it is to be considered that measurements are carried out only at definite values of the antiproton momenta, i. e. we should analyse the distribution over momenta.

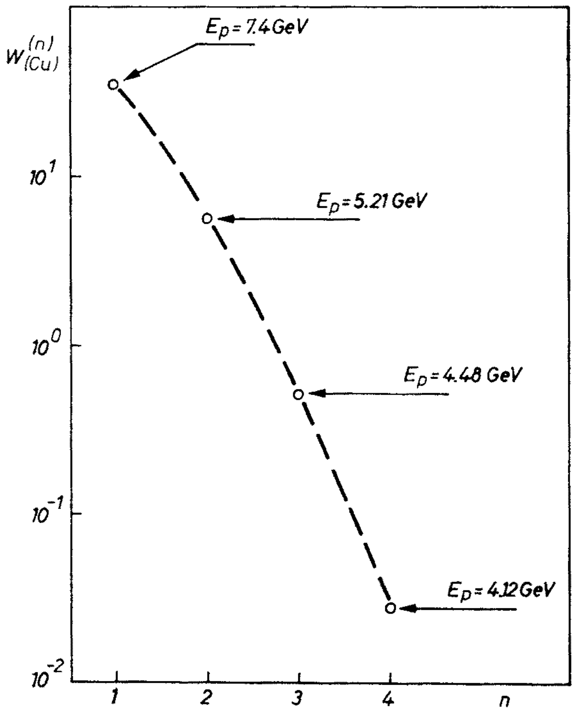

Fig. 2. The probability $W^{(n)}$(Cu)

By the thermodynamical model, antiprotons in the c. m. system are nonrelativistic with the following distribution

$$dw_0 \sim \tilde{p}_0^2 d\tilde{p}_0 \exp(-\tilde{p}_0^2/2mT),$$
$$T \approx (0.9 \div 1.0) \cdot \mu_\pi, \tag{8}$$

the angular distribution in c. m. s. is assumed isotropic. In the lab. frame

$$w(\tilde{p} \cos \Theta) = \frac{\tilde{p}^2 \cdot \tilde{E}_0}{\tilde{p}_0^2 \cdot \tilde{E}} w(\tilde{p}_0, \cos \Theta_0). \tag{9}$$

Measurements [2] were performed for the angle of emission $\Theta \approx 0°$. Then we have

$$w(\tilde{p}) = \frac{\tilde{p}^2}{\sqrt{\tilde{p}^2 + m^2}} \sqrt{\tilde{p}_0^2 + m^2} \exp\left(-\frac{\tilde{p}_0^2}{2mT}\right) \tag{10}$$

with

$$\tilde{p} = (\tilde{p}_0 + V_{(n)} \tilde{E}_0) \cdot \gamma_{(n)}. \tag{11}$$

The values of the velocity $V_{(n)}$ and Lorentz factor $\gamma_{(n)}$ are defined by the kinematics of the "gathering" mechanism.

At this point, a remark should be made. To simplify the calculations, it is convenient to consider the process at energies E_p (or T_p) not exactly equal to (2) but sufficient for the antiproton emission in each order of cumulation with the momenta $\tilde{p}_0 \approx \langle \tilde{p}_0 \rangle \approx 0.45$ GeV/c. These energies can be easily obtained provided the mean kinetic energy of a produced pair is

$$\bar{T}_{\tilde{p},p} \approx 2\bar{T}_{\tilde{p}} \approx 0.2 \text{ GeV}. \tag{12}$$

Then, instead of (2) we have:

$$E_p^{(n)} = [2m^2(3n+4) + 2\bar{T}_{\tilde{p},p} \cdot (n+3) \cdot m + \bar{T}^2_{\tilde{p},p}] \frac{1}{2nm}$$

$$\approx \frac{1}{n} [m(3n+4) + (n+3) \cdot \bar{T}_{\tilde{p},p}]. \tag{13}$$

It is just these values of energy $E_p^{(n)}$ that will be used in what follows. This removes uncertainties caused by the threshold phenomena and guarantees the production of antiprotons with the momenta fixed experimentally.

The energy $E_p^{(n)}$ (13) is related to kinematic characteristics $V_p^{(n)}$ and $\gamma_{(n)}$ as follows

$$V_{(n)} = \frac{\sqrt{E_p^{(n)} - m^2}}{E_p^{(n)} + nm}, \tag{14}$$

$$\gamma_{(n)} = \frac{E_p^{(n)} + nm}{\sqrt{m^2(n^2+1) + 2nmE_p^{(n)}}}. \tag{15}$$

And finally, a few words on the last phase of the process, the passing of antiprotons through the nucleus. To a first approximation we neglect the rescattering of antiprotons and pions assuming that it does not influence sensitively the yield ratio φ in the momentum range considered. We take into account a possible annihilation of antiprotons only roughly. Note also that the cumulative process at the parameters σ and τ_0 we have chosen has a voluminal character (see Ref. [4]). Therefore, the factor of "survival" of antiprotons in matter should be proportional, to a first approximation, to the thickness of the nuclear layer at the backward surface transparent with respect to annihilation.

The thickness of the transparent layer is approximately equal to the mean free (with respect to annihilation) path of an antiproton. Therefore, we put the factor of "survival" in the following form

$$\eta(\tilde{p}) \sim 1/\varrho\sigma_{an}(\tilde{p}). \tag{16}$$

The data on the antiproton annihilation cross section in interaction [7] can be represented as

$$\sigma_{an}(\tilde{p}) \approx (63 \pm 2) \cdot \tilde{p}^{-(0.64 \pm 0.02)} \text{mb}. \tag{17}$$

3. *Comparison with experiment*

The model we have presented gives the following approximate expression of the relative yield of antiprotons

$$\varphi \approx A \cdot W^{(n)} \cdot w_{(n)}(\tilde{p}) \cdot \eta(\tilde{p}). \tag{18}$$

In the subthreshold energy range, i. e. for $n \geqslant 2$, first the energies $E_p^{(n)}$ (and $T_p^{(n)}$) (13) were calculated, then $V_{(n)}$ and $\gamma_{(n)}$. Taking the momenta $\tilde{p}$ the same as in the experiment [2] at energies T_p near $T_p^{(n)}$, we calculated the functions $w_{(n)}(\tilde{p})$ and $\eta(\tilde{p})$.

The results of calculation and relevant experimental data are shown in Fig. 3. The φ_{theor} is normalized to the φ_{exp} at the point $T_p \approx 6.0$ GeV and $\tilde{p} \approx 2.0$ GeV/c so that

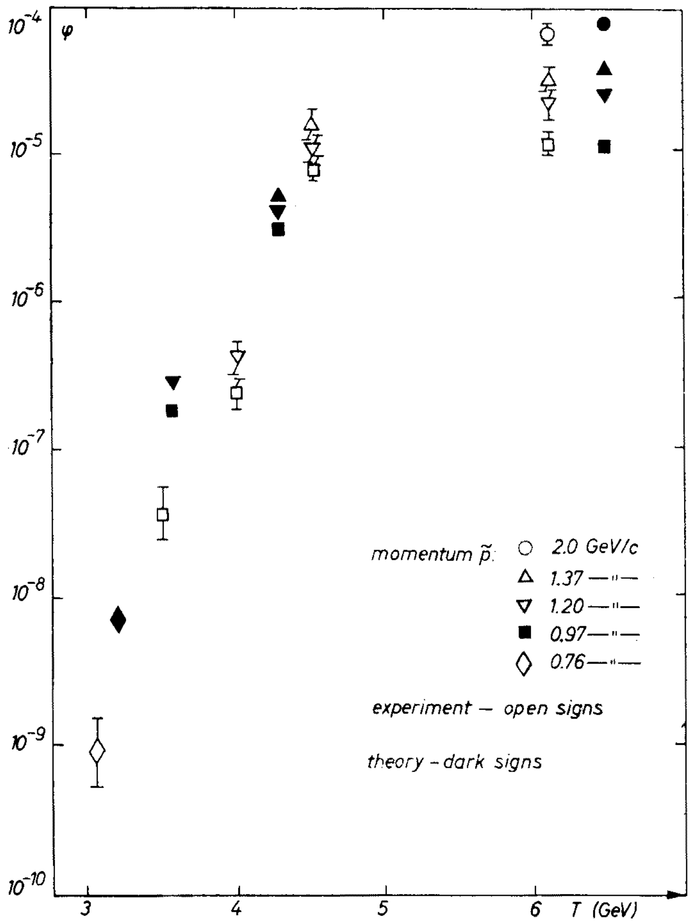

Fig. 3. The ratio $\varphi(T_p)$ for the Cu target [2]

$\varphi_{\text{theor}} \approx \varphi_{\text{exp}}$ above the threshold $T_p > 5.64$ GeV. It should be emphasized once more that this normalization is sound in magnitude as it gives the correct description of the qualitative composition within the thermodynamical model.

Fig. 3 demonstrates the rather good agreement of the model with experiment: the rate of the decrease of φ with decreasing T_p, and the spread of points corresponding to different values of momenta at T_p = const do not contradict the experimental data.

Figure 4 shows the antiproton spectra at small angles at $T_p \approx 6.0$ GeV: points are from the experiment [1] with a carbon target, the solid curve is the calculation by the model for the gathering of two nucleons ($n = 2$). The value $T_p = 6$ GeV somewhat exceeds

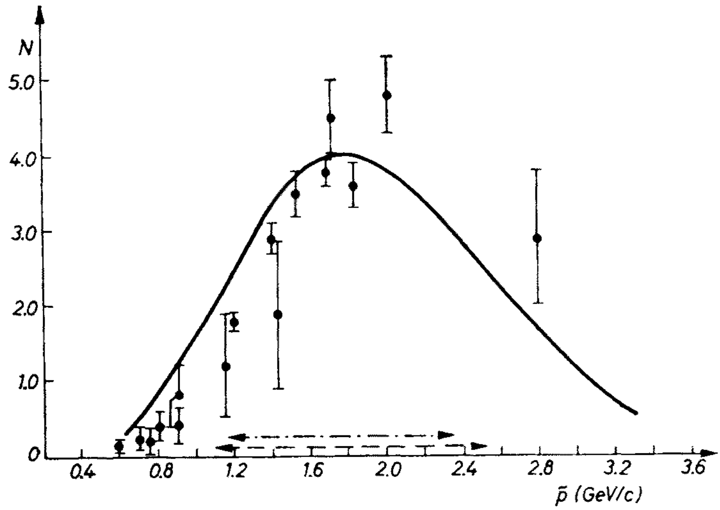

Fig. 4. The spectrum of antiprotons at $T_p \approx 6$ GeV emitted from the C^{12} [1] nucleus. The solid curve represents the model calculation ($n = 2$, the normalization is made to experimental points near the distribution maximum)

the production threshold energy production in NN-collision. However, simple calculations give a substantially more narrow distribution. In Fig. 4 the interval where the distribution is nonzero is marked by lines: the dashed line corresponds to the case when the recoil momentum at the antiproton emission is taken by the three-nucleon system, the dash-dotted line — the recoil momentum is taken by one of the nucleons. It is seen that the cumulation of energy by the gathering model ($n = 2$) is preferable also when T_p slightly exceeds $(T_p^{thr})_{NN}$ but differs from it a little.

4. *Conclusions*

Clearly, the approximations we have used in our calculations are rough. In subsequent, more correct calculations many of them can be removed, if not, they can be improved considerably.

However, even with this calculation, we may state that the gathering model correctly describes the main property of the phenomenon. So, we complete the paper with the following comments:

i) the model avoids serious difficulties inherent in other approaches (e. g. in the model of Fermi-motion) which require detailed information about the behaviour of two, three-, and so on nucleon systems at short relative distances. Strictly speaking it is doubtful whether in this case the corresponding problem can be posed at all (e. g. the use of the notion of the two-nucleon function at these distances).

ii) The model rests on the obvious, this is that any physical process is realized within a finite space-time interval.

iii) The results of calculation have been found at those values of parameters which allow the description of the cumulative meson production. Also at this point, the resemblance is observed of both processes as the ones which take place near the limiting values of kinematical variables. This justifies the validity of the model as a whole.

Thus, we conclude that the effect of the subthreshold production of antiprotons also shows that the problems of relativistic nuclear physics certainly require the consideration of space-time factors.

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