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CUMULATIVE EFFECTS IN PROCESSES INVOLVING A DEUTERON

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It is shown that a space-time formulation of the phenomenological model of cumulative processes based on the scheme of "gathering" of hadrons into a unique compound system can be used successfully for interpreting meson production and elastic scattering in processes involving even such a loose nucleus as a deuteron.

1. *Introduction*

In paper [1] we proposed a phenomenological model for the space-time evolution of the cumulative meson production in a nucleon-nucleus interaction. It is briefly called the "gathering" model since that name reflects its main ideas. An initial hadron moving in dense nuclear matter can, with a certain probability, compose, with a nuclear nucleon, a compound system with mass increasing in subsequent collisions. Also increasing is the number of nucleons captured by it, that is their "gathering". Note that we consider both the formation of the compound system and further increasing its mass in the channel with $K \approx 1$ (K is the coefficient of inelasticity). Therefore, the occurring cumulative process is specified by variables somewhat larger than their kinematic limit for the N,N-collision.

Here we briefly analyse the processes involving a deuteron with cumulative effects: meson-production and large-angle elastic (p, d)-scattering. The case with a deuteron is to be examined separately because unlike the complex nuclei, it is not an object with uniform density and a sharp boundary, even to a rough approximation. Therefore, in this case it is a complicated problem to apply directly the method from Ref. [1] developed for (p, A)-interaction.

Nevertheless, keeping with the ideas of the gathering model, some reasonable estimates can be made in this case, as well.

To begin with, let us consider the two types of experiments on meson production in reactions involving a deuteron:

$$(\mathrm{p, d}) \rightarrow \pi^-(180^\circ)+X, \tag{1}$$

$$(\mathrm{d}, A) \rightarrow \pi(0^\circ)+X. \tag{2}$$

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2. *Cumulative meson production in process (1)*

The invariant cross section of (1) is

$$\mathscr{R}_d = 2E_\pi \frac{d^3\sigma}{dp_\pi^3} = \sigma \cdot 2F(x), \tag{3}$$

where $F(x)$ is a scale-invariant function defined in [2], $x = p_\pi/p_\pi^{max}$, σ the cross section of the compound-system formation by an initial proton, both nucleons of the deuteron being included.

The latter cross section can be written as

$$\sigma = \sigma_{p,d}^{in} \cdot W, \tag{4}$$

where $\sigma_{p,d}^{in}$ is the cross section of inelastic (p, d) interaction and W is the probability for all the three nucleons to be gathered in a unique system. Then the invariant density is

$$\varrho_d = \frac{\mathscr{R}_d}{\sigma_{p,d}} = W \cdot 2F(x). \tag{5}$$

The probability W depends, obviously, on the nucleon distribution in a deuteron over relative distances i. e. $|\psi_d|^2$, on the possibility for the system to leave the considered channel between gathering acts and on the orientation of the deuteron axis relative to the axis of the p, d-collision.

The function $\psi_d = u_d(r)/r\sqrt{4\pi}$ is taken to be the deuteron wave function in the S-state with the hard core radius r_c proposed in Ref. [3], which eliminates the short-distance contribution. Its radial dependence is shown in Fig. 1.

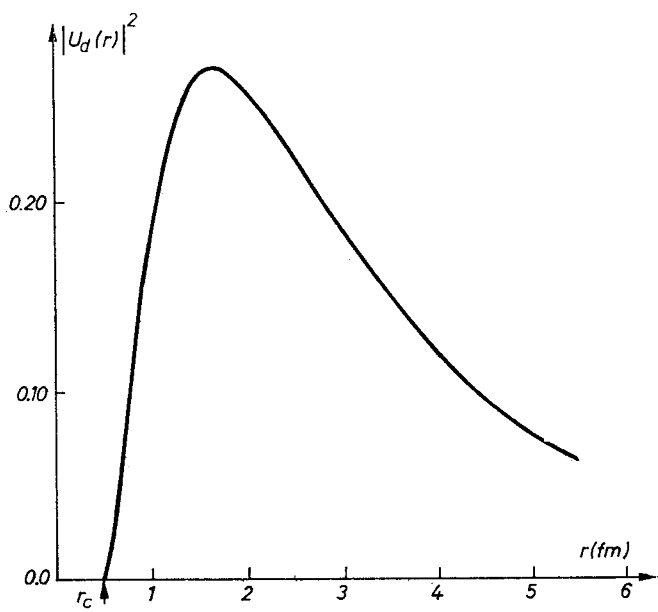

Fig. 1. The function $|u_d(r)|^2$ for the deuteron S-state with hard core $r_c = 0.484$ fm [3]

In the cylindrical system of coordinates appropriate for the given geometry of collision (Fig. 2) the function W can be written in the form

$$W(b^{\max}, a) = 2(2\pi) \int_0^{b^{\max}} bdb \int_{z_{\min}}^{\infty} |\psi_d(b, z)|^2 e^{-az} dz, \tag{6}$$

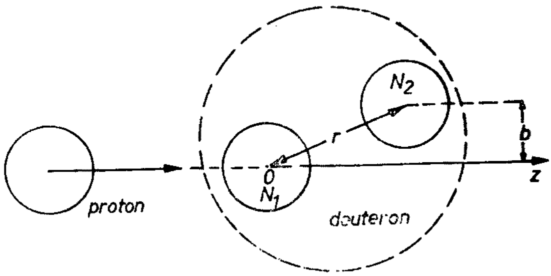

Fig. 2. The scheme of "gathering" of nucleons in p, d-collisions

where b is the impact parameter, $\exp(-az)$ is the factor for states, capable of emitting the cumulative pion, to "die out" in time (for details see Ref. [1]). The coefficient 2 means the independence of the results of the deuteron nucleon index. The more detailed form of W is

$$W(b^{\max}, a) = \int_0^{b^{\max}} bdb \int_{z_{\min}}^{\infty} \frac{u_d^2(\sqrt{b^2+z^2})}{b^2+z^2} e^{-az} dz, \tag{7}$$

$$z_{\min} = \begin{cases} \sqrt{r_c^2 - b^2} = \sqrt{\Delta} & \text{if} \quad \Delta > 0, \\ 0 & \text{if} \quad \Delta \leqslant 0, \end{cases} \tag{8}$$

where

$$u_d(r) = e^{-\alpha r}[1 - e^{-\delta(r-r_c)}] \sum_{l=1}^{8} C_l \cdot \exp[-(l-1)\mu r],$$

$$\mu = 0.7082, \quad \alpha = 0.2317, \quad r_c = 0.484, \quad \delta = 5.4. \tag{9}$$

(The coefficients C_l are given in [3]).

According to (5) and (7) the density ϱ_d is a function of two parameters, "a" and "$b^{\max}$", as in the case of the (p, A)-interaction. Therefore, we naturally choose them to be the same as for the (p, A)-process [1]. Then

$$a = 0.418. \tag{10}$$

The parameter $b^{\max}$ can be estimated by using the partial cross section σ [1]

$$\sigma = 0.25\sigma_{NN}^{in}. \tag{11}$$

Taking the quasiclassical approximation to σ_{NN}^{in}

$$\sigma_{NN}^{in} \simeq \kappa \cdot \pi(\langle r_N \rangle + \langle r_N \rangle)^2 \approx \kappa \cdot 4\pi \langle r_N \rangle^2, \tag{12}$$

where $\kappa < 1$ is a coefficient of proportionality (say, specifying the degree of "transparency" of the hadron matter) and $\langle r_N \rangle$ is the nucleon mean radius, we obtain for σ

$$\sigma(K \to 1) \simeq \kappa \cdot \pi (b^{max})^2. \tag{13}$$

Then formulae (11), (12) and (13) produce the following value

$$b^{max} \approx \langle r_N \rangle \approx 0.8 \text{ fm}. \tag{14}$$

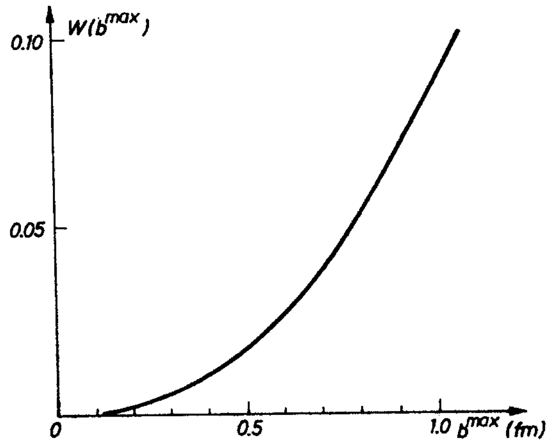

Fig. 3. The probability $W(b^{max}, a = 0.418)$ as a function of b^{max}

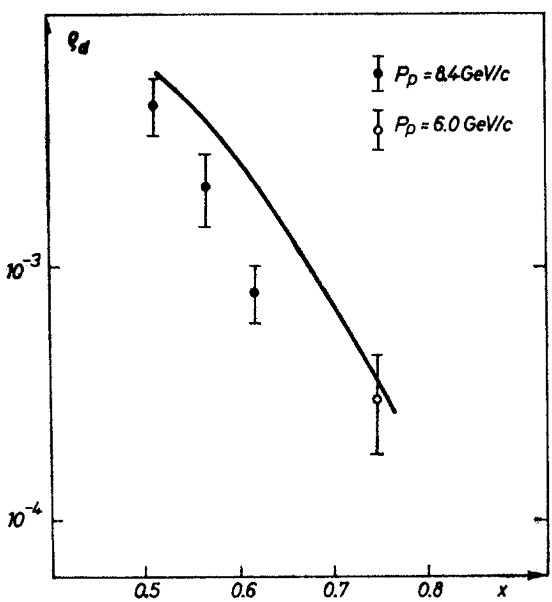

Fig. 4. The invariant density $\varrho_d(x)$

This value limits the range of varying the impact parameter in (p, d)-collisions, which produce the compound system. The probability $W(b^{max}, a = 0.418)$ as a function of b^{max} is plotted in Fig. 3 which gives the following value for $b^{max} \approx 0.8$:

$$W \approx 0.05. \tag{15}$$

That is, the probability for a deuteron to be kinematically a unique object in this collision is about 5%. Consequently, the invariant density is

$$\varrho_d \simeq 0.1 \cdot F(x). \tag{16}$$

In Fig. 4 we compare the theoretical curve for (16) with the experimental data on ϱ_d at $P_p = 8.4$; 6.0 (GeV/c) [4] (x was calculated within the kinematics of p, d-collision).

As the calculations are approximate, the agreement with experiment can be considered to be good.

3. *Cumulative production in the process* (2)

This process has been studied in Ref. [2]. In contrast to process (1), the production probability was measured for mesons emitted in the forward direction with an energy somewhat larger than that per one nucleon of deuteron. In that paper it has been shown that the ratio of the cross sections of pion production by deuterons to the one by protons at the same energy release does not depend on x and E_d and equals

$$\alpha \approx 0.06 \pm 0.007. \tag{17}$$

This result permits the following simple interpretation (see the above consideration for (p, d)-process (1)): the part of cases (17), when the deuteron is kinematically a unique object, is almost equal to the probability (15) having the same meaning.

4. *A comment on backward elastic* (*p, d*)-*scattering*

We think that the cumulative processes could help in solving the problem on backward elastic (p, d)-scattering at $T_p \approx 1$ GeV. For backward elastic p, d-scattering, the experimental information and its comparison with different theoretical models are given in the review paper [5].

Apparently, one may believe in one of the conclusions of Ref. [5]: "... there are arguments in favour of that the correct consideration of the nucleon-exchange diagram and of the process through excitation of the isobar (3/2, 3/2) is sufficient to describe backward (p, d)-scattering in a wide energy interval from 100 to 700 MeV".

However, in the region $0.7 \text{ GeV} \leqslant T_p \leqslant 2 \div 3 \text{ GeV}$ things are not so clear. The main difficulty characteristic of most approaches presented in the review [5] is the necessity to appeal to the behaviour of the two-body system at very small separations. For instance, according to the data from [5] at $T_p \approx 1$ GeV the direct scattering requires the Fourier component of the deuteron function equal 10 fm^{-1}, while the pickup mechanism gives 2.5 fm^{-1}.

However, it has already been mentioned that under these conditions the very concept of a two-particle function can be considered questionable.

It may well happen that the cumulation mechanism we have presented in this paper and Ref. [1] can be observed not only in production but also in scattering processes. If so, one should consider the decay of a "gathered" compound system into the initial channel.

To test the idea, we make only rough estimations. To this end, we use the following arguments.

Recent investigations on the large-angle elastic p, p-scattering (beyond the diffractional cone) at T_p of several GeV have provided interesting results. As has been shown [6–8], a scattering of this type can be caused by the statistical mechanism. Such an interpretation raises serious problems. Unexpectedly, it well reproduces the empirical cross section found in paper [6]:

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{cms}} \approx \frac{\sigma^{c}}{4\pi} \exp\left[-3.3(\sqrt{S}-2m_{N})\right] \tag{18}$$

with

$$\sigma^{c} \simeq \frac{\sigma_{NN}^{in}}{z^{2}\gamma_{\text{cms}}^{2}}, \qquad z \simeq 1.18. \tag{19}$$

The thermodynamical model produces the exponential factor because of competing processes of the inelastic type. The difference $\sqrt{S}-2m_N$ is the energy for production of new particles and the factor $3.3 \approx 1/2\mu_\pi$ corresponds to the effective temperature of decay of the system in the elastic channel.

The cross section of formation of the compound system, σ^c, is not defined by any thermodynamical model (as in the standard nonrelativistic physics) and is obtained from some additional considerations. A particular form of σ^c in (19) has been found in paper [6] from the condition that for the production of the compound system, at a given impact parameter, the interaction should involve, during the collision, the whole system.

Thus, an inspection of Eq. (18) shows how it can be extended to p, d-scattering within the cumulative gathering model.

First, the argument of the exponential function should be transformed as follows

$$\sqrt{S}-2m_{N} \rightarrow \sqrt{S_{(2)}}-(m_{N}+m_{d}) \simeq \sqrt{S_{(2)}}-3m_{N}, \tag{20}$$

$S_{(2)}$ being calculated within the kinematics of a p, d-collision:

$$S_{(2)} = m_{N}^{2}+m_{d}^{2}+2m_{d}\cdot E_{p} \simeq 5m_{N}^{2}+4m_{N}E_{p}. \tag{21}$$

Second, the cross section for production of the compound system should be modified through inserting the probability W of the gathering of nucleons of the deuteron by the initial proton, i. e.

$$\frac{\sigma_{NN}^{in}}{z^{2}\gamma^{2}} \rightarrow \frac{\sigma_{NN}^{in}}{z^{2}\gamma^{2}} W(b^{\max}). \tag{22}$$

To evaluate $W(b^{max})$, we again apply the quasiclassical approximation. In analogy with the estimate (15) we get

$$b^{max} \simeq \frac{2\langle r_N \rangle}{z\gamma}. \tag{23}$$

Third, it should be taken into account that the decaying system has two protons, each of them being able to scatter in a backward direction.

Therefore, the differential cross section in the c. m. s. acquires the form

$$\left[\frac{d\sigma(\mathrm{p, d})}{d\Omega}\right]_{cms} \simeq \frac{\sigma_{NN}^{in}}{2\pi z^2 \gamma^2} W\left(\frac{2\langle r_N \rangle}{z\gamma}\right) \exp\left[-3.3(\sqrt{S_{(2)}} - 3m_N)\right]. \tag{24}$$

The results of estimation $\left[\frac{d\sigma}{d\Omega}(\mathrm{p, d})\right]_{lab.s.}^{backward}$, 0.7 GeV $\leq T_p \leq$ 2.4 GeV, ($\langle r_N \rangle$ = 0.8 fm, W from Fig. 3) and relevant experimental data are presented in Fig. 5. As is seen, the calculated cross section is close to the experimental one both in magnitude and

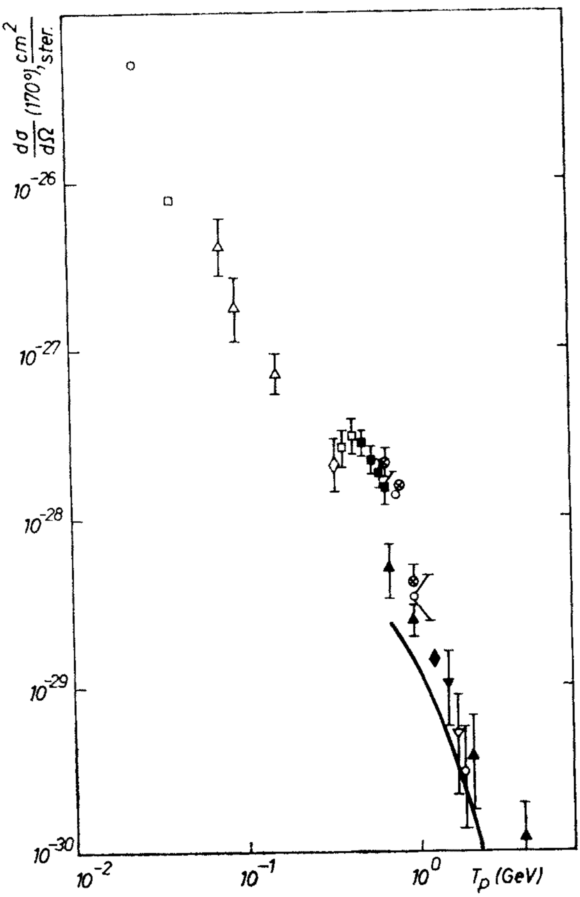

Fig. 5. Backward elastic p, d-scattering [5] and its estimation by the "gathering" model (solid line)

in energy dependence, however, being smaller by a factor of 1.5–2.0. The latter is not surprising since (in addition to the rough calculation) there is a strong argument in favour of that the result should be treated as a lower limit. Indeed, we have considered the simplest, but not unique, of decaying channels of the compound system which can provide the elastic p, d-scattering. For instance, at first the system may decay into three nucleons. Its phase volume is larger than that we have considered. Then the pair of nucleons (n, p) may form, with a certain probability, the deuteron. This probability is small as the deuteron is a loosely bound system.

As a result, the channel gives a contribution of the order of the direct decay into p and d. This additional possibility lifts slightly the curve in Fig. 5.

Thus, our interpretation of the backward elastic p, d-scattering at energies T_p of an order of 1 GeV differs in principle from approaches reviewed in [5]. It is based on the consideration of the space-time development of a process and does not depend on the detailed information of the behaviour of the deuteron system in the ultrasmall volume (just in order to exclude ultrashort distances, we have used a wave function with a hard core).

5. *Conclusion*

The space-time description of the cumulation mechanism allows the processes of elastic and inelastic types to be treated uniquely. An approach of this kind makes it possible to avoid some serious difficulties inherent in traditional models.

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