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CONFINEMENT FORCES IN FAST BACKWARD NUCLEON PRODUCTION OFF NUCLEI

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A new mechanism for production of fast backward nucleons from nuclear target at high energies is suggested, which is closely connected with the idea of "long range" colour forces acting between colour objects. This mechanism does not pretend to explain the whole effect observed in experiments, but plays an important role in production of nucleons with backward momenta $p_L \gtrsim 0.5$ GeV/c.

Let us consider first the simplest case of $hd \to hp_B n$ with the proton produced backward in the deuteron rest frame. The incident hadron may exchange colour (say, by gluon exchange) consecutively with both deuteron nucleons and become white again (see figs.1,2). As a result, the deuteron turns into a state with "hidden colour", and confining forces can give one of the nucleons a momentum directed backward.

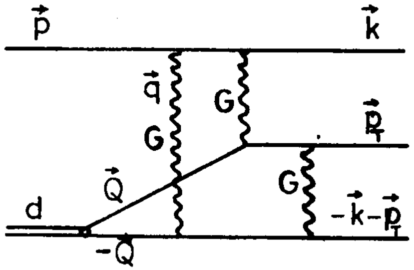
To do consideration more definite we make use of the colour flux tube model[1-4], realizing the idea of confinement. It can be argued that the tension κ of the octet tube and the probability W of breaking the tube by quark pair production are $\sqrt{3}$ times those of the triplet tube. Thus we shall use the values $\kappa = 1.5$ GeV fm^{-1} and $W = 2\sqrt{3}$ fm^{-2}.

In the collision of the incident hadron with the second nucleon (the proton) the colour charge is transmitted to this nucleon. The colour flux tube is stretched now between the deuteron nucleons and gives the last of them a momentum directed backward. In the course of the collision of these two colour nucleons they can exchange colour and become white as is shown in Fig.1. The space-time development of this process is shown in Fig.2.

It is easy to calculate the longitudinal momentum of the proton produced in the backward direction as a function of the initial distance L between the two nucleons:

$$p_L(L) = \frac{1}{2}\sqrt{\kappa L}\left(\frac{2m_N + \kappa L}{\sqrt{m_N + \kappa L}} - \sqrt{\kappa L}\right) \qquad (1)$$

(It is assumed here that the incident hadron has a momentum $p_h \gg \kappa L$). Figure 3 shows graphically this dependence. It is seen that high backward momenta p_L emerge from deuteron configurations with large longitudinal distances between the nucleons. As $L \to \infty$, p_L tends to its maximal value $3m_N/4$ allowed by kinematics. This is contrasted with the spectator mechanism[5], where short distances (large relative momenta) are important.



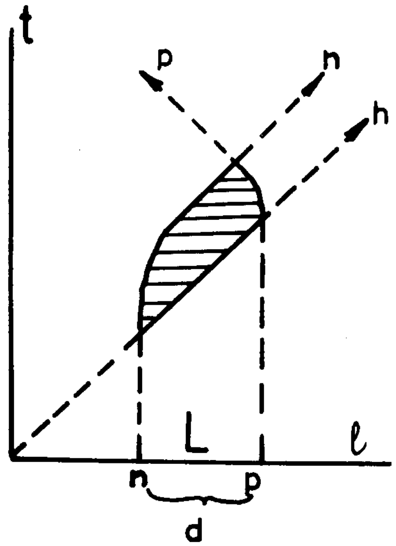


Fig.1. Colour exchange diagram for backward proton production off deuteron.

Fig.2. Space-time evolution of the $hd \to hp_B n$ reaction. Dashed lines are colour singlets, solid lines represent colour octets.

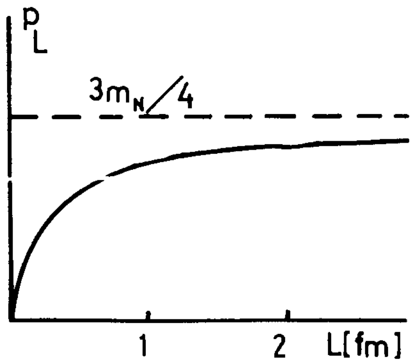


Fig.3. The longitudinal backward momentum of the proton as a function of the initial distance L between the nucleons in the deuteron.

The contribution to backward production coming from the mechanism under consideration can be estimated as follows. The cross section of the first colour exchange is equal to σ_{in}. The probability of the second colour exchange provides the factor $|\Psi_d(L)|^2 \sigma_{in}^{hN} dL$, where $\Psi_d(R)$ is the deuteron wave function. This factor corresponds to the Glauber correction for the double scattering. (The finite size of nucleons can be taken into account by replacement $L \to L' = L + R_0$ in the argument of the wave function, where $R_0 \approx 0.5$ is the radius of nucleon repulsive core). The probability of the third colour exchange is of order of α_s^2, since we have fixed already the configuration with the nucleons at the same impact parameter.

In the above pionless reaction the tube should not break. The corresponding probability is

$$D(L) = \exp(-W \int d\ell\, dt) \approx \exp(-WLm_N/\kappa). \qquad (2)$$

Hence the contribution of the present mechanism could be written as:

$$\frac{d^3\sigma}{d^3p} = C \cdot B \exp(-Bp_T^2)(\sigma_{in}^{hN})^2 |\Psi_d(L')|^2 D(L) \left(\frac{dp_L}{dL}\right)^{-1} \qquad (3)$$

Here C includes α_s^2 and other dimensionless constants, p_T and p_L are the transversal and longitudinal momenta of the backward proton.

The constant C and the slope parameter B could be estimated by calculating the Feynman diagram with three gluon exchanges shown in Fig.1. Similar calculations of two gluon diagrams provide quite a good description of data for diffraction processes on nucleons [2,6,7] and nuclei [8,9]. The Feynman graph in Fig.1 does not take into account the confinement phenomenon, thus it has sense only for small L values. Long transversal distances are cut off by hadronic form factors.

The differential cross section shown by the diagram in Fig.1 is equal to

$$\frac{d\sigma}{d^2p_T d^2k} = (2\pi\alpha_s)^6 \left| \int \frac{d^2q}{(2\pi)^2} \frac{d^2Q}{(2\pi)^2} \frac{F(\vec{q}, -\vec{q}_2)F(-\vec{q}, \vec{q}_3)F(\vec{q}_2, -\vec{q}_3)}{\vec{q}^2 \vec{q}_2^2 \vec{q}_3^2} \times \right. \qquad (4)$$

$$\left. \times \Psi_d(\vec{Q}, L) \right|^2,$$

where $\vec{q}_2 = \vec{q} + \vec{k}$, $\vec{q}_3 = \vec{q} + \vec{k} + \vec{p}_T - \vec{Q}$. $F(q,k)$ is the vertex of emission of two gluons by the nucleon with transversal momenta q and k:

$$F(q,k) = \int |\Psi_N(\vec{b}_i)|^2 \prod_{i=1}^{3} d^2b_i\, \delta(\sum_i \vec{b}_i) \{\exp[i\vec{b}_1(\vec{k}+\vec{q})] - \exp[i(\vec{b}_1\vec{k} - \vec{b}_2\vec{q})]\} \qquad (5)$$

$$= \exp[-(\vec{k}+\vec{q})^2/4\lambda^2] - \exp[-(\vec{k}-\vec{q})^2/4\lambda^2].$$

The one-particle quark density of the nucleon is taken here in the Gaussian form, λ is related to the proton charge radius: $\lambda^2 = 3/(2R_N^2) \approx 3.2\,fm^{-2}$. $\Psi_d(Q,L)$ is defined as

$$\Psi_d(Q,L) = \int \Psi_d(R) e^{i\vec{Q}\vec{b}} d^2b,$$

where $R = (\vec{b}, L)$.

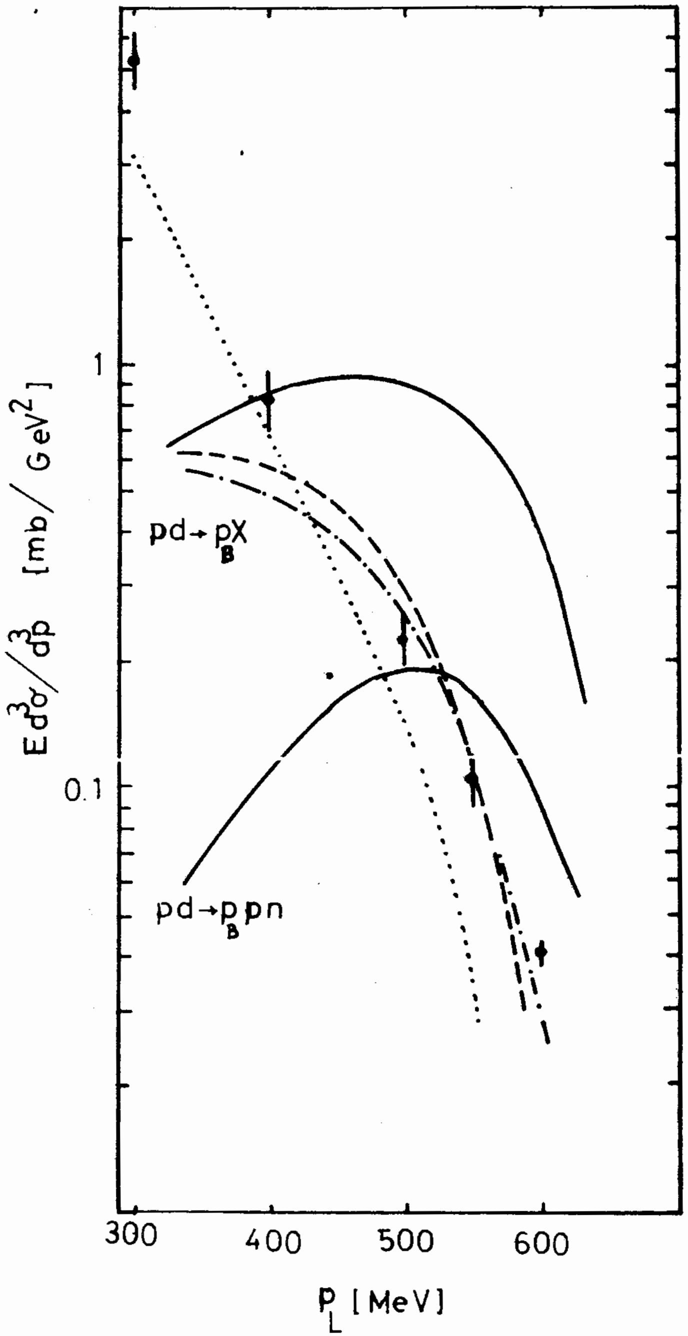


Fig.4. Invariant cross section for backward protons for $pd \to pnp_B$ and $pd \to p_BX$ reactions. Solid lines represent contribution from the colour exchange mechanism for $\kappa = 1.5$ GeV/fm, $W = 2\sqrt{3}$ fm$^{-2} \approx 3.5$ fm^{-2}; dashed line for $\kappa = 1.1$ GeV/fm, $W = 3.5$ fm^{-2}; dash-dotted line for $\kappa = 1.5$ GeV/fm; $W = 7$ fm^{-2}. The dotted line shows the contribution of the spectator mechanism, ref./5/. The data are from ref./10/.

Expression (4) includes colour factor $(1/27)^2$ (we use a conventional definition of the coupling constant with colour matrices $t^a = \frac{1}{2}\lambda^a$), and a quark counting factor $(27)^2$ if the bombarding particle is a proton. (For incident pion (4) should be multiplied by 4/9).

The function $\Psi_d(Q,L)$ has a sharp dependence on Q, so everywhere in (4) one can set Q=0. Integral over d^2Q gives the factor

$$\int \frac{d^2Q}{(2\pi)^2} \Psi_d(Q,L) = \Psi_d(b=0,L). \qquad (6)$$

Expression (4) can be estimated now, assuming Gaussian dependence on k and p_T:

$$\frac{d\sigma}{dp_T^2} = 4\pi^2 \frac{\alpha_s^6}{\lambda^6} \frac{N^2}{I} |\Psi_d(L)|^2 \exp(-Bp_T^2). \qquad (7)$$

Here $N = \frac{3}{2}(3\ln 3 - 4\ln 2)$. The expression for the slope B is logarithmically divergent because the amplitude does not decrease sufficiently fast at large impact parameters. Introducing an effective gluon mass Λ one obtaines

$$B = I(\epsilon)/\lambda^2; \quad \epsilon = (\Lambda/\lambda)^2.$$

Similar calculations for the diffraction slope in elastic scattering agree with the data for $\epsilon = 0.1$. For this value of ϵ we have found $I \approx 2.6$ and $B \approx 20$ GeV^{-2}.

The two-gluon approximation yields for the inelastic cross section $\sigma_{in}^{NN} = 16\pi \ln 2\,\alpha_s^2/\lambda^2$. Thus expressions (3) and (7) coincide for small values of L if

$$C = \left(\frac{\alpha_s N}{8 \ln 2 \cdot I}\right)^2 \approx 8.1 \cdot 10^{-4}. \qquad (8)$$

The spectrum of backward protons in the reaction $pd \to p_Bpn$ at 180° calculated by means of (3) is shown in Fig.4.

The backward spectrum for the inclusive reaction $pd \to p_BX$ can be obtained from (3) by minor modifications. First, the incident hadron can be excited, which results approximately a factor $(1+\sigma^{NN}_{diff}/\sigma^{NN}_{el}) \approx 1.4$. Moreover, the nucleon can obtain the backward momentum even if the tube breaks. The value of this momentum is also given by eq. (2) with L being the distance between the location of the last and the second nucleon. One gets the corresponding modification in (3) by replacement

$$|\Psi_d(L')|^2 \to |\Psi_d(L')|^2 + \frac{W m_N}{\kappa}\int_{L'}^{\infty} |\Psi_d(\ell)|^2 d\ell . \qquad (9)$$

The cross section of the reaction $pd \to p_B X$, corresponding to modified expression (3) is shown in Fig.4. This contribution should be added to that of the spectator mechanism, also shown in Fig.4.

The comparison with the experimental data shows that the contribution of the colour exchange mechanism has the correct order of magnitude. The calculations above contain no free parameters. However, the values of parameters κ and W used here, are theoretical estimates only and they strongly influence the backward spectrum (especially the string tension κ). This is demonstrated in Fig.4 where curves corresponding to the values $\kappa = 1.1$ GeV/fm, $W = 3.5$ fm^{-2} and $\kappa = 1.5$ GeV/fm, $W = 7$ fm^{-2} are also shown.

In conclusion we make some remarks.

1. Besides the form of spectra of backward nucleons, there are several other possibilities to single out the contribution from the colour exchange mechanism. It is a sensitive method to study polarization effects. The third act of colour exchange between the nucleons of the deuteron takes place at energies of the order of κL, i.e., at few GeV. Thus polarization depends only on the momentum of the backward proton, but not on the energy of the incident hadron. The spin non-flip colour exchange amplitude is given by one-gluon exchange and is real as opposed to the case of elastic scattering. The spin flip amplitude is described here by exchange of "colour reggeons". The intercept of leading colour Regge trajectory, calculated in the leading logarithmic approximation is $\sqrt{8}$ times smaller than the intercept of the corresponding "white" Regge trajectory*. As a consequence, the polarization in our case is expected to be about 3 times less than for elastic scattering. The backward proton asymmetry for the polarized deuteron target will be about 10%.

The spectator mechanism predicts a small polarization which decreases with increasing energy. Thus polarization effects should be present only in the hard part of the backward spectrum. We would like to mention that if the mechanism of multiple rescatterings[11] makes appreciable contribution, then high polarization is expected for large atomic number A.

* We thank M.Ryskin for calling our attention to this point.

2. Multiplicity of produced hadrons in the spectator mechanism is considerably higher than in the colour exchange mechanism and grows with the incident energy. Indeed, in the latter case only diffractive pions are produced since the incident hadron remains white after leaving the deuteron.

3. In nuclei with $A > 2$ there are possible multiple colour exchange with n nucleons resulting in backward nucleon momenta up to the value $m_N(n^2-1)/2n$, i.e., the kinematical boundary for n-nucleon target. The cross section of backward nucleon production predicted by this picture is proportional to $A^{4/3}$, while for pionless events it grows only as A.

4. Needless to say, the existence of confining colour forces is far from being established. The hadron-hadron interactions may provide only very scarce information on this phenomenon[12]. Hopefully, the study of the mechanism suggested here for hadron-nucleus collisions may shed more light on space-time development of colour confinement.

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Работа выполнена в Лаборатории ядерных проблем ОИЯИ.

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