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B.Z.Kopeliovich, N.A.Russakovich

COLOUR SCREENING EFFECTS IN HADRON PRODUCTION ON NUCLEI IN THE TRIPLE REGGE REGION

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1. Colour Screening in Quasielastic Scattering on Nuclei

As hadrons are colourless, their interaction with a colour field is only possible owing to the internal colour distribution. Consequently, when a hadron transversal dimension $\rho \to 0$, its interaction cross section $\sigma(\rho) \sim \rho^2$. Indeed, calculations based on a two-gluon exchange Feynman diagram (Fig. 1) yields /1-3/ $\sigma(\rho) \sim \rho^2 \ln \rho$.

Let us consider quasielastic scattering of a π -meson on a nucleus at a sufficiently high energy $E \gg R_A \cdot m_\pi^2$. In this case the transversal distance ρ between the pion quarks will not be changed at distances of the order of R_A. The relevant cross section can be written in the form:

$$\frac{d\sigma_{qel}^{\pi A}}{dq^2} = A_{eff}^{qel}(q) \frac{d\sigma_{qel}^{\pi N}}{dq^2} .$$

The expression for $A_{eff}(q)$ at q=0 in the optical approximation is /4/

$$A_{eff}^{qel}(0) = \frac{1}{(\sigma_{tot}^{\pi N})^2} \int d^2 b\, T(\vec{b}) \left| \int d^2\rho\, \Psi_\pi(\rho) \right|^2 \sigma_{tot}(\rho) \exp\left[-\frac{1}{2}\sigma_{tot}(\rho) T(\vec{b})\right] \Bigg|^2 . \quad (1)$$

Here $\Psi_\pi(\rho)$ is the pion wave function; $\vec{b}$ is the impact parameter; $T(\vec{b}) = \int_{-\infty}^{\infty} dz\, \rho_A(\vec{b}, z)$ is the nuclear profile function; $\rho_A(\vec{b}, z)$ is the nuclear density, further used in the Woods-Saxon form. If we put down

$$\sigma_{tot}(\rho) = \frac{\rho^2}{\langle \rho^2 \rangle_\pi} \sigma_{tot}^{\pi N}$$

$$|\Psi_\pi(\rho)|^2 = \frac{1}{\pi \langle \rho^2 \rangle_\pi} \exp(-\rho^2/\langle \rho^2 \rangle_\pi) \quad (2)$$

then (1) takes the form

$$A_{eff}^{qel}(0)=\int d^2b\,\frac{T(\vec{b})}{\left[1+\frac{1}{2}\sigma_{tot}^{\pi N}T(\vec{b})\right]^4}\,, \qquad (3)$$

$A_{eff}(0)$ calculations by formula (3) are compared in the Table with the results of Glauber's approximation:

$$A_{eff}^{Gl}=\int d^2b\,T(\vec{b})\exp\left[-\sigma_{tot}^{\pi N}T(\vec{b})\right]. \qquad (4)$$

Table

Target nucleus	A_{eff}^{Gl} (expressions (4))	A_{eff}^{qel} (express.(3))	A_{eff}^{cex} (express.(5))
Be	4.9	3.5	5.4
Al	9.1	5.8	11.4
Cu	15.0	9.0	21.1
Pb	23.4	14.2	44.0

As is seen allowance for colour screening in (3) leads to lower A_{eff} values as compared with (4). Difference between (3) and (4) is due to contribution of inelastic corrections. Calculation of (1) in the two-gluon approximation (see Ref. /4/) also yields an underestimated value of A_{eff}, as compared with (4).

Note that $A_{eff}(q^2)$ slowly grows with q^2 in quasielastic scattering /4/ and exceeds A_{eff}^{Gl}. At $q^2 \gg 1\ (GeV/c)^2$ the gluon component in the hadron wave function /5/ leads to a large $A_{eff}(q^2) \simeq A$.

2. Quasifree Charge Exchange on Nuclei

As is shown in Fig. 2, when Regge Poles exchange (e.g. in reactions of charge exchange) only one valence quark interacts. Therefore, the quark colour is not screened, and the charge exchange amplitude at q=0 does not depend upon ρ - distance between quarks /4/. Hence, the value of $A_{eff}(0)$ for pion quasifree charge exchange on a nuclei can be calculated in approximation (2) by the formula

$$A_{eff}^{CEX}=\int d^2b\,T(\vec{b})\left|\int d^2\rho\,|\Psi_\pi(\rho)|^2\exp\left[-\frac{1}{2}\sigma_{tot}(\rho)T(\vec{b})\right]\right|^2=$$

$$=\int d^2b\,\frac{T(\vec{b})}{\left[1+\frac{1}{2}\sigma_{tot}^{\pi N}T(\vec{b})\right]^2} \qquad (5)$$

Results of the calculations are given in Table 1. One can see that in this case $A_{eff} > A_{eff}^{Gl}$, i.e., inelastic corrections make the nucleus more transparent.

B.G.Zakharov and one of the authors (B.Z.K.) showed /4/ that $A_{eff}^{cex}(q^2)$ grows with q^2 faster than $A_{eff}^{qel}(q^2)$ does and already at $q^2 \simeq m_\rho^2$ it becomes $A_{eff}^{cex}(q^2) \simeq A$. The data on quasifree charge exchange $\pi^- \to \pi^0$ and $\pi^- \to \eta^0$ at 40 GeV /6/ prove this prediction.

3. Triple Regge Diagrams

Let us consider inclusive charge exchange $a+b \to c+X$ in the triple Regge region of kinematic variables: $s/M_X^2 \gg 1$, $M_X^2 \gg 1\ GeV^2$. One can single out contributions of triple Regge diagrams of two types - RRR and RRP - in the cross section of this process (see Fig. 3a and 4a). The dashed line denotes the absorption part of the amplitude. X - dependence of contributions of these diagrams is described by the following expressions (see, for example, Ref. /7/):

$$\left(\frac{d\sigma}{dx\,dq^2}\right)_{RRR}=\frac{1}{\sqrt{s/s_0}}\,\frac{G_{RRR}(0)}{\sqrt{1-x}}\exp\left\{-q^2\left[R_{RRR}^2-2\alpha_R'\ln(1-x)\right]\right\}, \qquad (6)$$

$$\left(\frac{d\sigma}{dx\,dq^2}\right)_{RRP}=G_{RRP}(0)\exp\left\{-q^2\left[R_{RRP}^2-2\alpha_R'\ln(1-x)\right]\right\}. \qquad (7)$$

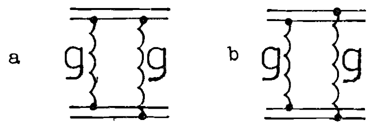


Fig. 1

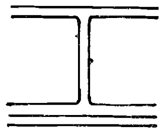
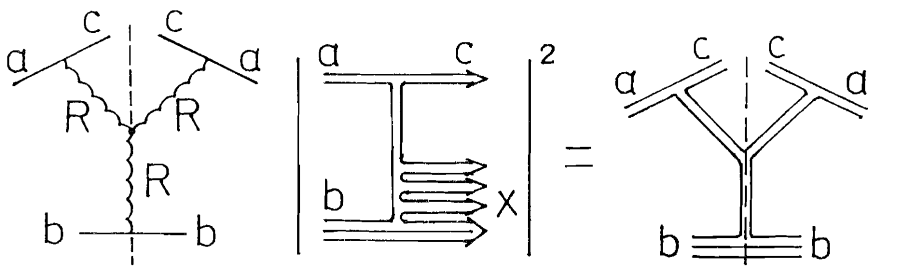
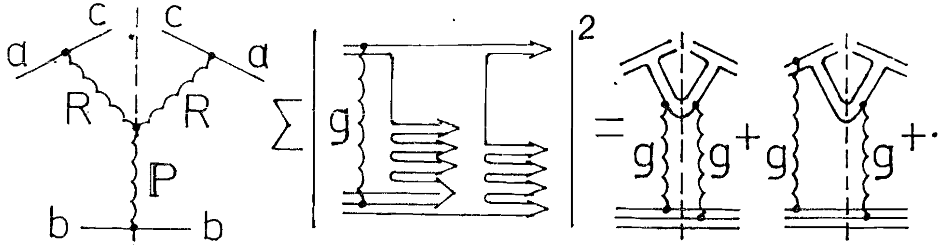


Fig. 2



a b c

Fig. 3



a b c d

Fig. 4

Figs 1-4. The basic Feynman's diagrams described in the text.

Here $G(q^2) = G(0)\exp(-q^2R^2)$ are the relevant effective triple Regge vertices; $\alpha'_R \simeq 1\ (\mathrm{GeV}/c)^{-2}$ is the Regge trajectories slope parameter; values of $\alpha_R(0) = 1/2$, $\alpha_P(0) = 1$ are accepted for intercepts. There are planar graphs (Fig. 3b and c) corresponding to the diagram in Fig. 3a. The space-time picture of the process is following. Quarks of the incident hadron are in a strongly momentum-asymmetric configuration: one of the quarks carries the total momentum. Probability of this configuration is suppressed by the factor $1/\sqrt{s}$. After the slow quark (antiquark) annihilated, fragmentation of the fast quark begins, e.g. through hadronization of the coloured triplet string between the fast quark and the target diquark (to make it determined, let target to be nucleon). Hadronization occurs up to momenta $p \simeq (1-x)S/2m_N$; after that the antiquark produced with this momentum is picked up by the leading quark. The picking-up probability is proportional to $1/\sqrt{1-x}$. All these factors are present in expression (6).

Interpretation of the graph RRP in Fig. 4a is less trivial. As is shown in Fig. 4a, the incident meson is in the configuration, where the fast quark carries part of the momentum x_1, while the slow quark part is $1-x_1$. After gluon exchange between one of the quarks and the target the slow quark completely fragmentates into a jet with the mass $M_1^2 = x_1 S$, and the fast quark fragmentates to the mass $M_2^2 = S \cdot x_2$ and then picks up the quark with the momentum $(1-x_2)S/2m_N$. The picking-up probability is proportional to $1/\sqrt{1-x_2}$. The product of the incident meson structure function and of the fragmentation function should be integrated over x_1, x_2; the result is as follows:

$$\int dx_1\, dx_2\, \delta(x_1 x_2 - x)\left(\sqrt{1-x_1}\,\sqrt{1-x_2}\right)^{-1} = \int_x^1 dx_1 \left[x_1(1-x_1)(x_1-x)\right]^{-\frac{1}{2}} \tag{8}$$

It is clearly seen that at $1-x \ll 1$ this integral is independent of x. This just corresponds to expression (7) and is the result of a non-planar (cylindrical) shape of the graph in Fig. 4b.

Thought quark diagrams in Fig. 4b,c lead to x-dependence of the relevant triple Regge phenomenology (7), there is a radical difference between the graphs in Fig. 4a and in Fig. 4c,d. A conventional interpretation of graph 4a is that the reggeon R elastically scatters on the target by means of pomeron exchange. It can be seen, however, that the graph in Fig. 4c does not have a similar one with colour screening inside the reggeon (compare, for instance, with Fig. 1a,b). Moreover, the graph in Fig. 4d admits no three-reggeon interpretation. This is caused by the fact that the idea of a triple Regge vertex, localized in the rapidity scale, is justified in QCD only for an RRR vertex, as in Fig. 3. Unlike the commonly used in past scalar theory $\lambda\varphi^3$, QCD allows gluon exchange interactions through a large rapidity gap. Therefore the graphs $RR\mathbb{P}$, $\mathbb{P}\mathbb{P}\mathbb{P}$, etc., can only be employed for phenomenological purposes, because they yield a correct x-dependence. However, interactions with a nucleus require a correct "decoding" of this graphs (see Fig. 4), as is shown below.

4. Leading Hadron Fragmentation Length

In the inclusive process, unlike to elastic scattering or binary charge exchange, the leading hadron is not produced immediately, but at some distance l_f after interaction with the target. One should not think, however, that interaction is impossible in this interval l_f. Before hadronization is over, the colour string with the transversal dimension of the order of 1 fm and the string length less than 1 fm (in lab frame) can interact with a cross section of the order

of the hadron one. But the string interaction does not practically affect the leading hadron momentum /8,9/, since the fast quark is already slowing down by the string with a force $\varkappa$ - effective coefficient of the string tension (with allowance for the gluon bremsstrahlung). The slowing ceases only after hadronisation finished, i.e. after the fast quark picks up the antiquark and a colourless object is produced. In opposite, inelastic interactions should be prohibited during the passing of colourless hadrons through a nucleus as a significant part of the momentum is lost in the process $hN \to hX$.

Thus in an inclusive process A_{eff} has the form that differs from (5):

$$A_{eff}(q^2=0,x)=\int d^2b\int_{-\infty}^{\infty} dz\,\rho(\vec{b},z)\left|\int d^2\rho\,|\Psi_\pi(\rho)|^2\times\right.$$
$$\left.\times\exp\left\{-\frac{1}{2}\sigma_{tot}(\rho)\left[T(\vec{b})-\int_z^{z+l_f} dz'\rho(\vec{b},z')\right]\right\}\right|^2. \qquad (9)$$

Expression (1) is modified in a similar way.

The quantity A_{eff} in (9) depends on x, because l_f depends on x /8,9/

$$l_f = \frac{E}{\varkappa}(1-x)\,. \qquad (10)$$

Here E is the incident meson energy in the laboratory. The sense of (10) is clear: before hadronisation is over, the quark with the energy E loses the energy $\varkappa$ per unit of length. Therefore, the time of fragmentation into a hadron with the energy xE is given by expression (10). At $x \to 1$ the $l_f \to 0$*). In this case expression (9) turns into (5).

*) The behaviour (10) is opposite to an energy dependence of the formation length in the standard parton model /10/ where $l_f \simeq xE/\mu^2$, - this dependence is valid in the region $x \lesssim 0.5$ only.

The value of $\varkappa$, obtained from the data on hadron pairs production with large P_T on nuclei [11] or from the data on J/ψ hadroproduction on nuclei [12], appears to be quite large: $\varkappa \simeq 3$ GeV/fm. It is noticeably larger than the value for a static string $\varkappa = (2\pi\alpha'_R)^{-1} \simeq 1$ GeV/fm. This is explained by the effective contribution of the gluon bremsstrahlung. Such large value of $\varkappa$ implied that at energy about 10 GeV (see next section) and $x > 0.6$ $l_f < 1.4$ fm, i.e. less than the mean internucleon distance in a nuclei. Thus fragmentation length effects can be neglected.

5. Reaction $\pi^+ A \to \eta X$

In Ref. [13] the relative yields of η mesons, produced on various nuclei at the momentum 10.5 GeV/c, were measured. Fig. 5 shows ratios $R_A(x) = \frac{d\sigma^A}{dx} \Big/ \frac{d\sigma^D}{dx}$ for various nuclei A. Noteworthy is the increase of $R_A(x)$ with x in a disagreement with results for other processes (e.g., see Ref. [14]).

Let us consider some non-asymptotic corrections to formula (7), where a relative phase volume of two jets should be taken into account (see Fig. 4b). At $x \to 1$ each jet turns to be a resonance and a suppressing factor Ω due to a two-body phase volume appears near the production threshold of two hadrons $M_0 = m_1 + m_2$:

$$\Omega = \frac{\sqrt{M^2 - (m_1 + m_2)^2}}{M} . \tag{11}$$

This factor is only effective at $1-x \simeq (m_1+m_2)^2/S$, i.e., at high energies it can be neglected.

The minimal masses which can be substituted to (11) are $m_1 = m_\pi$, $m_2 = m_N$. However, the probability of quark recombination into a pion is statistically suppressed by a factor 1/3, as compared with a ρ-meson. Comparison of the

data [15] on cross sections for reactions $\pi^- p \to \eta n$ and $\pi^+ p \to \eta \Delta^{++}(1236)$ shows that isotopic amplitudes of these processes with I = 3/2 and I = 1/2 are approximately equal. This means that in hadron-deuteron (and heavy nuclei) interaction the target diquark fragmentates into $\Delta(1236)$ with the probability twice as large as that of fragmentation into a nucleon. So, we estimate (11) with $m_1 = m_\rho$, $m_2 = m_\Delta$.

Let us denote the effective numbers for the graphs in Fig. 3 and 4 by A^R_{eff} and A^P_{eff} , respectively. Ignoring the Glauber corrections in the deuteron, we can put down for $R_A(x)$:

$$R_A(x) = \frac{1}{2}\left(\frac{A^R_{eff}/\sqrt{s/s_0} + \lambda A^P_{eff}\sqrt{x_0 - x}}{1/\sqrt{s/s_0} + \lambda\sqrt{x_0 - x}}\right) . \tag{12}$$

Here expressions (6) and (7) are used with $R^2_{RRR} = R^2_{RRP}$; expression (7) is multiplied by the factor (11); $x_0 = 1 - (m_\rho + m_\Delta)^2/S$; the contribution of the RRP graph equals zero at $x > x_0$; the q^2-dependence of a cross section is considered to be the same for all nuclei [13]; $\lambda = G_{RRP}(0)/G_{RRR}(0)$ by definition.

Let us consider three possible variants:

(i) $A^R_{eff} = A^P_{eff} = A^{Gl}_{eff}$ in the Glauber approximation. In this case $R_A = 1/2\, A^{Gl}_{eff}$ is independent of x. The corresponding values are shown by dashed lines in Fig. 5, 6.

(ii) If the three-reggeon graph RRP is considered as a result of the reggeon scattering on the target, then $A^P_{eff} = A^R_{eff}$ is given by formula (5). $R_A = 1/2 A^R_{eff}$ is independent of x. The corresponding value from the Table is shown by dash-and-dot line in Fig.6 with the data on $R_{Cu}(x)$ [13].

(iii) If the colour screening effect is taken into account, A^P_{eff} is calculated by formula (3). Substituting values from the Table to (12), we obtain the function $R_A(x)$ which increases with x. It is shown by solid lines in Fig. 6.

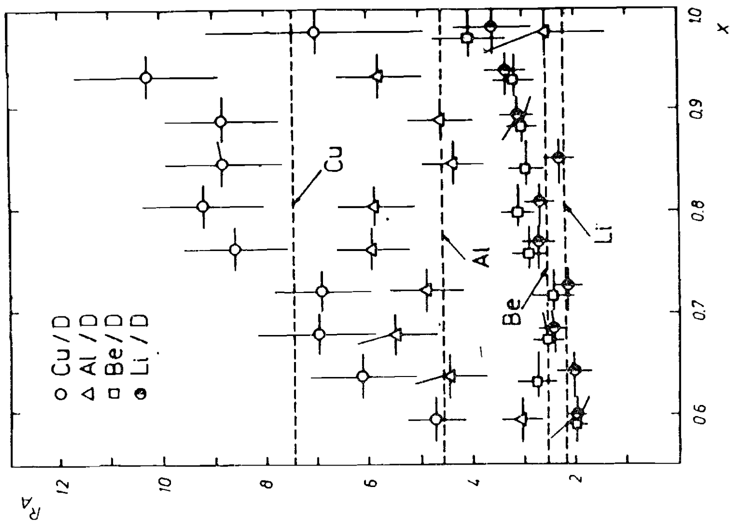


Fig. 5. The experimental data /13/ on $R_A(x)$ = $\frac{d\sigma}{dx}(\pi^+A \to \eta X)/\frac{d\sigma}{dx}(\pi^+D \to \eta X)$; A ≡ Li, Be, Al, Cu.

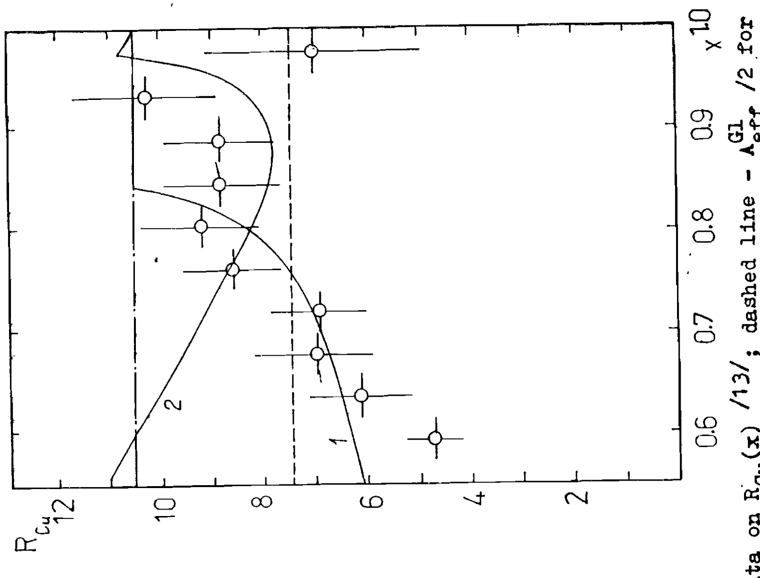


Fig. 6. The data on $R_{Cu}(x)$ /13/; dashed line - $A_{eff}^{Gl}/2$ for the copper target; dash-and-dot line - $A_{eff}^{cex}/2$; curve 1 - A_{eff} calculation by formula (12) with λ = 0.96 (the best agreement); curve 2 - prediction for 40 GeV incident energy with allowance for $l_f(x)$ dependence (10).

6. Conclusions

Comparison of the results, obtained from calculations and measurements /13/ of η-meson relative yields in the reactions $\pi^+A \to \eta X$, showed the Glauber approximation (without inelastic screening) cannot explain increase of the spectrum ratio $R_A(x)$ with x, but gives the correct mean value of A_{eff}.

To include inelastic corrections, we used the eigenstate method /16/ which takes into account the colour screening inside the hadrons.

It is shown here that quark diagrams for the charge exchange process do not correspond literally to the RR$\mathbb{P}$ graph. This fact and the effect of colour screening inside hadrons result in "abnormal" increase of the ratio R_A (x). At higher energies the contribution of the RRR graph decreases, as is seen from (12), and R_A (x) must increase at larger x.

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Копелиович Б.З., Русакович Н.А. E2-86-298

Эффекты экранирования цвета при образовании адронов на ядрах в трехреджеонной области

Экранирование цвета при "мягком" взаимодействии адронов приводит к тому, что в квазиупругом рассеянии на ядрах неупругие поправки "затемняют" ядро. Наоборот, в реакции квазисвободной перезарядки неупругие поправки делают ядро более прозрачным. По этой же причине вклады трехреджеонных графиков RRR и RRP экранируются ядром в разной степени. Учет эффектов экранирования позволяет объяснить рост $A_{eff}(x)$ при $x \to 1$ в реакции $\pi^+A \to \eta X$ при энергии 10,5 ГэВ.

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Kopeliovich B.Z., Russakovich N.A. E2-86-298

Colour Screening Effects in Hadron Production on Nuclei in the Triple Regge Region

Colour screening in soft hadron interactions manifests in a less transparent nucleus due to inelastic corrections in quasielastic scattering on nuclei. On the contrary, inelastic corrections make the nucleus more transparent in the reaction of quasi-free charge exchange. This is also the reason of different screening of three-reggeon graph contributions RRR and RRP. Taking this into account allows one to understand "anomalous" growth of $A_{eff}(x)$ when $x \to 1$ in the reaction $\pi^+A \to \eta X$ at 10.5 GeV/c.

The investigation has been performed at the Laboratory of Nuclear Problems, JINR.

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