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ON COLOR TRANSPARENCY

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1 Introduction

In strong interactions physics, hadron-nucleon cross section is about 30–40 mb. In nuclear medium with a density of about 0.17 nucleon/fm^3, the mean free path of incoming hadron before having an interaction should be about 2 fm. Nuclear or color transparency (CT) means that at large transverse momentum initial- and final-state interactions cross sections will vanish as the energy scale increases [1, 2]. Perturbative Quantum Chromodynamics (QCD) predicts [3] color transparency effect which is based on the idea that if small distances dominate in the hard scattering process then the participating quark configurations are not absorbed in the nuclei. This results in A^1-dependence of the cross section of the processes. Nonperturbative QCD is characterized by large distances between quarks that leads to color transparency breaking. Hard scattering processes on nuclei are considered as proper objects for an observation of the color transparency phenomenon. It was the reason of the experiment performed in BNL on $p-p$ quasielastic scattering from several nuclei compared to $p-p$ elastic scattering in hydrogen at 6, 10, and 12 GeV/c [4, 5, 9]. Data were presented in the form of the ratio

$$T = \sigma^A/(A\sigma^N), \tag{1}$$

where σ^A, σ^N are cross sections of a reaction on nucleus and free proton, respectively, near 90^0 c.m. CT–hypothesis predicts that at high energy the transparency of nuclei should approach unity. The experimental data [4, 5, 9] showed that QCD expectation did not occur. Primarily the ratio rises up to beam momentum 10 GeV/c, in agreement with QCD, and then the drop was observed. The decrease of the ratio, apparently violating CT, is the subject of active discussion (see review [3] and references therein).

The aim of the paper is to study the influence of standard nuclear mechanisms, such as Fermi motion and rescattering of incident proton inside target nucleus, on the behaviour of T. The analysis is performed in the framework of modified cascade model of hadron-nucleus collisions [11]. The paper is organized as follows. The modified cascade model is described in Section 2. The results of our calculations, their interpretation and comparison with available experimental data are given in Section 3. The conclusions are summarized in Section 4.

2 The model of hadron-nucleus collisions

Our calculations of CT are based on the assumption that the first interaction of beam proton is hard and then both nucleons (beam and target ones) undergo soft rescattering inside nuclear medium. This means that small configuration in the projectile proton is prepared before the collision with the nucleus. Hence, putting aside the discussion concerning oscillating character of denominator in ratio (1), we investigate the influence of Fermi motion and soft rescattering on the behavior of T. Target nucleus is considered as a fermi-gas of nucleons bounded in definite volume with diffuse boundary. Nucleon coordinates are generated according to standard nuclear density distributions:

$$\rho(r) = \rho_0 \exp(-r^2/R_0^2), \quad A < 10, \tag{2}$$

$$\rho(r) = \rho_0/(1 + \exp((r-a)/b)), \quad A \geq 10, \tag{3}$$

where parameters $b = 0.545$ fm and $a = r_0 A^{1/3}$, where $r_0 = 1.07$ fm. Nucleon momenta inside the nucleus, $\mathbf{p}$, are generated uniformly in the space $0 \leq |\mathbf{p}| \leq p_F$. The bound Fermi momentum p_F relates to the local nucleon density as

$$p_F = (3\pi^2)^{1/3} \cdot \hbar \cdot \rho^{1/3}(r). \tag{4}$$

In general, proton-nucleus collision is a superposition of baryon-baryon, meson-baryon and meson-meson elastic and inelastic interactions ordered in time. The probability of interaction of particle i and j is defined by black disk approximation:

$$P(b^2) = \Theta(b^2 - \sigma/\pi), \tag{5}$$

where b is the impact parameter between hadrons i and j; σ is the cross section of the process which equals σ_{tot} in the case of soft rescattering. The scattering cross section of the first (hard) proton–nucleon collision is approximated by

$$\sigma_{hard} \approx \sigma_{tot} \cdot b^2 / \left\langle b^2 \right\rangle, \tag{6}$$

where σ_{tot} is the total cross section, b^2 and $\langle b^2 \rangle$ characterize transverse separation (impact parameter) of colliding nucleons in hard and soft interactions, respectively. These transverse distances are defined by corresponding momentum transverse characterizing the process according to $b^2 \leq 1/Q^2$. The parametrizations of angular distributions of cross sections in hard pp and pn elastic scattering were taken from [10]

$$\frac{d\sigma}{dt}(pp \to pp) = s^{-10}\left\{\left[(1+z)^2\left(B_1\left|\frac{s}{t}\right|^{n_1} + B_2\left|\frac{s}{u}\right|^{n_2}\right)^2 + (z \to -z)\right]\right.$$
$$\left. + 4 \cdot \left[B_1\left|\frac{s}{t}\right|^{n_1} - B_2\left|\frac{s}{u}\right|^{n_2} + (z \to -z)\right]^2\right\}; \tag{7}$$

$$\frac{d\sigma}{dt}(pn \to pn) = s^{-10}\left[(1+z)^2\left(B_1\left|\frac{s}{t}\right|^{n_1} + B_2\left|\frac{s}{u}\right|^{n_2}\right)^2\right.$$
$$\left. + 4 \cdot \left(B_1\left|\frac{s}{t}\right|^{n_1} - B_2\left|\frac{s}{u}\right|^{n_2}\right)^2\right]. \tag{8}$$

For soft elastic and inelastic nucleon-nucleon and pion-nucleon rescatterings experimental values of cross sections are used. Cross sections for interactions of resonances are taken to be the same as for stable meson (in the case of ρ and ω) and nucleon (in the case of Δ-isobar) interactions. All interactions and decays are checked on Pauli blocking principle.

At high energies hadron considerations as interacting particles are not sufficient: the model overstimulates multiparticle production in hadron-nucleus and nucleus-nucleus collisions. In this range one used to apply parton or string models, in frame of which space-time evolution of particle production is treated as two step process: first, during interaction parton or string is created, and then this parton (string) fragments into second rank parton (string) or final hadrons. The idea of our approach is that remaining in the frame of hadron consideration, we take into account space-time evolution of ejectiles involving formation-time concept. The formation time is connected with interaction cross sections of secondaries during their propagation inside nucleus. As soon as two hadrons collision occurs, we apply at the instant of their overlap the following sum rule for geometrical cross sections of particles produced in forward (backward) hemisphere in c.m. frame

$$x_F^l \sigma_{in}^I + \sum x_F^m \sigma_{in}^I = \sigma_{in}^I, \tag{9}$$

where x_F^l is Feynmam variable for the remnant of the incident particle, x_F^m is the same one for produced particles and σ_{in}^I is the inelastic cross section of the interacting hadrons. The first term in the equation is the cross section of the incident particle remnant and the second term is the sum of the cross sections of produced particles at the instant after interaction. At that moment all secondaries possess reduced cross section and could be considered as semibare and bare particles. In the case of hard elastic interaction colliding nucleons already possess reduced cross section (6), hence the geometrical cross sections of beam and recoil nucleons for succeeding rescattering inside nucleus are defined by (6).

During propagation of secondaries inside the nucleus their cross sections evolve. We use the exponential form for the evolution of cross sections until the subsequent collision occurs

$$\sigma_2^{m(I)} = \sigma_1^{m(I)} - (\sigma_1^{m(I)} - x_F^{m(I)} \sigma_1^I) e^{-\tau_1/(\gamma\tau_0)}, \tag{10}$$

where σ_1^l is normal cross section of the incident particle in the first collision, σ_2^l is cross section of the remnant of the projectile in the second collision, σ_2^m is cross section of the m-th produced particle, σ_1^m is cross section for this type of particles in the normal state, γ is the Lorentz-factor and τ_0 is the adjustable parameter corresponding to the mean value of the formation time in the rest frame of the particle. For $(r+1)-th$ inelastic rescattering of the incident particle the cross section is defined as

$$\sigma_{r+1}^l = \sigma_1^l \prod_{i=1}^{r} (1 - (1 - x_{F_i}^l) e^{-\tau_i/(\gamma_i \tau_0)}). \qquad (11)$$

Characteristics of soft elastic rescattering are calculated according to parametrizations of experimental distributions. Inelastic hadron-nucleon interactions are simulated using the modified cylindrical phase space model, described in paper[11].

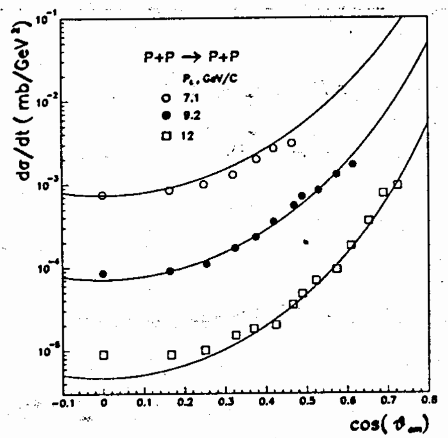
3 Results and discussion

In BNL experiment [4, 5, 9] the ratio of cross sections of the quasielastic process $p+A \to pp+X$ and $p-p$ elastic scattering on hydrogen target near 90^0 c.m. was investigated. Nuclear targets Li, C, Al and Cu have been used to study the ratio. Data were collected at incident proton momenta 6, 10 and 12 GeV/c, corresponding to the transverse momenta 4.8, 8.5, 10.4 $(\mathrm{GeV/c})^2$, respectively. It was found that the ratio T increases with p_L and than it reveals the drop at $p_L = 12$ GeV/c. The result was interpreted as an indication of color transparency violation [4, 5, 9]. Up to now there is not unambiguous explanations of the results and therefore the different interpretations of the experimental data [4, 5, 9] are widely discussed [3].

In the paper, the ratio T is analyzed in the framework of the modified cascade model of proton-nucleus collisions [11]. Simulation of cross section of the quasielastic processes $p+A \to pp+X$ for nuclei carbon and aluminum was performed. Total number of events for every processes used in calculation of T are 10^5. In our analysis the parametrizations of the angular distributions of elastic proton-nucleon cross section were taken from [10].

Figure 1 shows the calculated results of differential cross section of elastic pp (a) and pn (b) scattering as a function of $cos(\theta_{cm})$ for different incident proton momenta, $p_L = 7, 9, 12$ GeV/c. Experimental data are taken from [6, 7, 8]. One can see that the calculated results are in reasonable agreement with experimental data.

To study the influence of Fermi motion and multiscattering on the behaviour of the ratio T simulation of $p-Al$ collisions including only single hard



a)

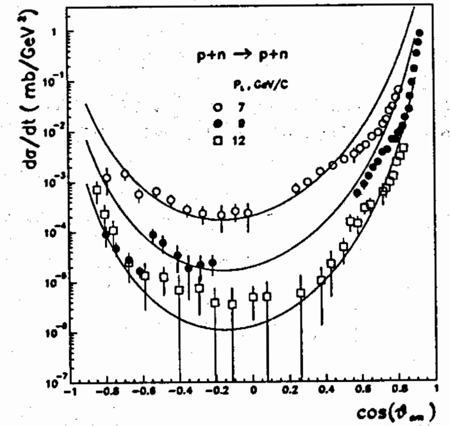


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Figure 1. Differential cross section of elastic pp (a) and pn (b) scattering as a function of $cos(\theta_{cm})$. Experimental data are taken from [6, 7, 8].

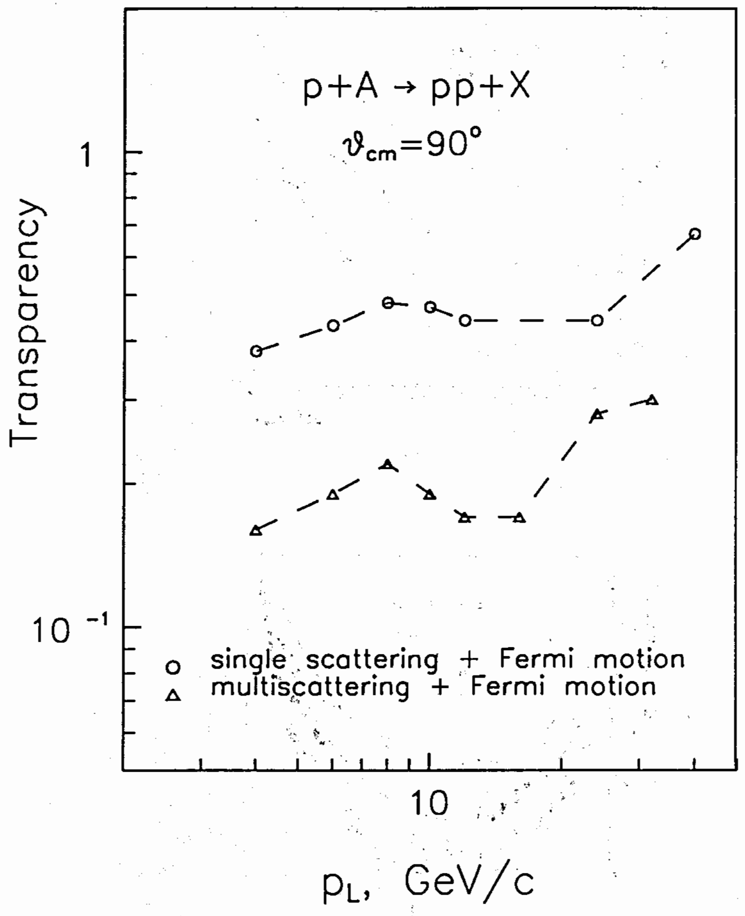

Figure 2. Ratio of quasielastic and elastic cross sections of the $p+Al \to pp+X$ and $p+p \to p+p$ processes as a function of proton momentum p_L at $\theta_{cm} \simeq 90^0 \pm 3^0$. Points, $\circ$ and $\triangle$, are results obtained for single and multiscattering mechanisms with taking into account the contribution of nucleon Fermi motion.

elastic collision of the projectile with one of protons of a target nucleus were performed. The same number of events (10^5) for $p-p$ elastic scattering is used. All initial and final rescatterings were excluded.

Figure 2 shows results for the ratio as a function of p_L calculated for two cases. In the first one, single scattering and Fermi motion are taken into account. Second one includes multiscattering mechanism. The growth of the ratio T with p_L up to 8 GeV/c for both cases was found. Effect of Fermi motion of target nucleon leads to the decrease of the ratio in the whole p_L-region. In the region $8 < p_L < 24$ GeV/c value of the ratio T strongly decreases with taking into account multiscatterings. It is due to the fact that effect of Fermi motion enhances as incident proton momentum decreases. At larger p_L the ratio slowly grows.

In the calculation, we assumed that the first interaction of projectile is hard scattering. Elastic cross section is defined by (6). Subsequent rescatterings of the projectile and recoil nucleon with cross sections defined by (9-11) can be both elastic and inelastic with production of pions and mesonic and baryonic resonances. However, the probability of these rescatterings according to (10) decreases at higher energies that leads to $T \to 1$.

Figure 3 shows the dependence the ratio T on proton momentum p_L for carbon and aluminum targets. The results were obtained at $\theta_{cm} = 90^0 \pm 3^0$. The small acceptance $\delta\theta = 3^0$ was used in order to choose the quasielastic scattering and to decrease the contribution of rescattering mechanism. The good agreement with experimental data for carbon target was found. Calculated results for the ratio T for aluminum target are in qualitative agreement with experimental data. Drastic drop of T at the momentum $p_L = 12$ GeV was found.

We would like to emphasize that in the experiment [4, 5, 9] the different number of events (1701, 650, 220) corresponding to the quasielastic scattering in the $p + Al \to pp + X$ reaction at proton momentum p_L (6, 10, 12 GeV/c) were analyzed. In our analysis 10^5 events of quasielastic proton-nucleus and the same number of events of elastic proton-proton scattering were used. We found that the contribution of the rescattering mechanism depends on the momentum p_L and the different acceptance for extraction of quasielastic process should be used. Therefore we study the dependence of the ratio T on the angular acceptance $\delta\theta$.

Figure 4 shows the ratio T as a function of p_L for different $\delta\theta = 3^0$, 10^0, 20^0. The strong dependence of the ratio on angular acceptance $\delta\theta$ is observed. The ratio T decreases with increasing $\delta\theta$ in the whole p_L-range. It corresponds to the growth of multiscattering mechanism contribution. The contribution is large enough at $\delta\theta = 20^0$ and therefore the ratio T becomes small.

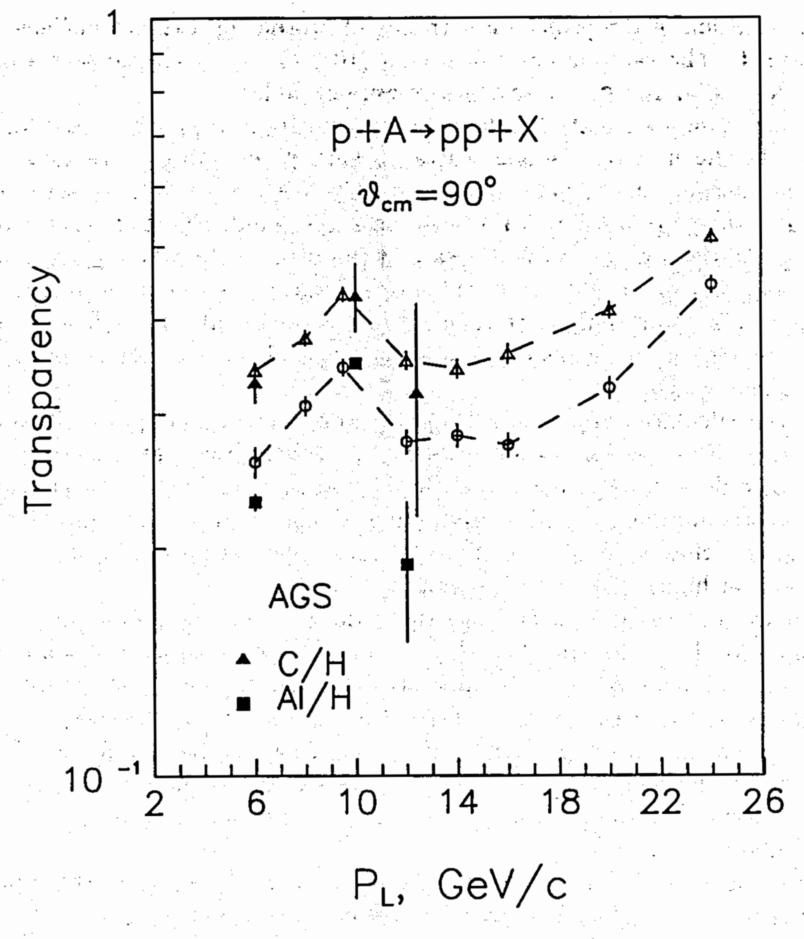

Figure 3. Ratio of quasielastic and elastic cross sections of the $p + A \to pp + X$ and $p + p \to p + p$ processes as a function of proton momentum p_L at $\theta_{cm} \simeq 90^0 \pm 3^0$. Points Δ and $\circ$ are calculation results for nuclei C and Al, respectively. Experimental data are taken from [4, 5, 9].

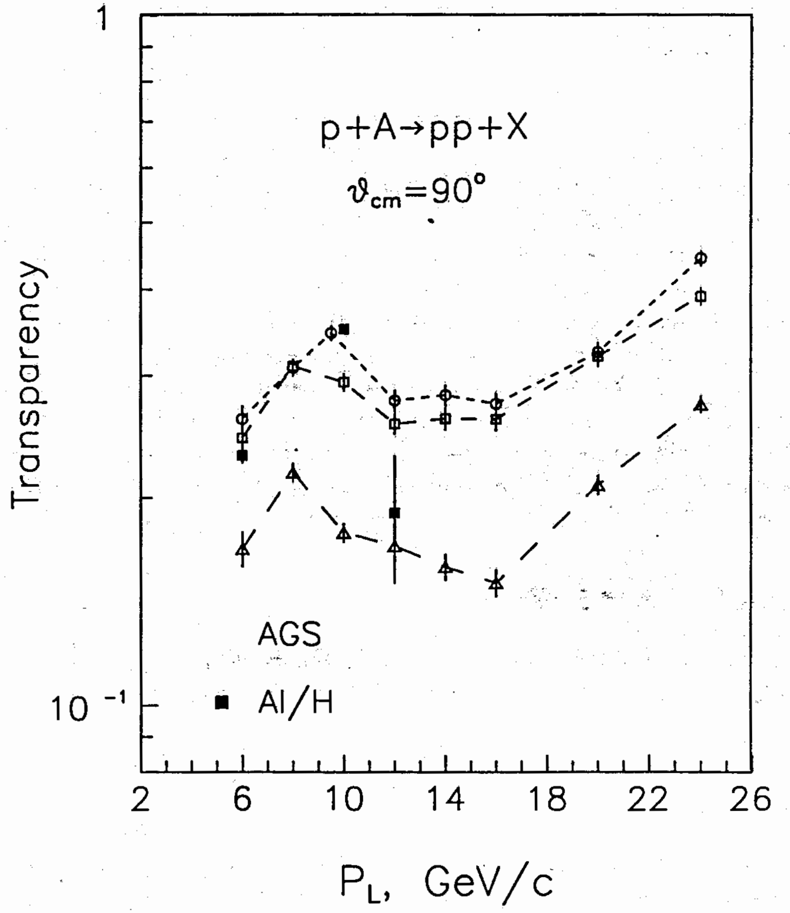

Figure 4. Dependence of the ratio of quasielastic and elastic cross sections of the $p + A \to pp + X$ and $p + p \to p + p$ processes at $\theta_{cm} \simeq 90^0$ and angular acceptance $\delta\theta$ ($\circ - 3^0, \bar{\square} - 10^0, \Delta - 20^0$) as a function of incident proton momentum p_L. Experimental data are taken from [4, 5, 9].

4 Conclusions

The influence of the nuclear mechanisms, such as Fermi motion and multi-scattering, on nuclear transparency of the quasielastic process $p + A \to pp + X$ is studied. Monte Carlo simulation of the ratio of the quasielastic and elastic cross sections of the processes $p + A \to pp + X$ and $p + p \to p + p$ in the framework of cascade model was performed. The dependence of the ratio T on momentum of incident proton p_L was investigated. The strong dependence of the ratio on the angular acceptance $\delta\theta$ was found. The value of the ratio T decreases with increasing $\delta\theta$. The comparison with available experimental data was performed and reasonable agreement with calculated results was found. In conclusion we would like to emphasize based on obtained results that to understand the color transparency phenomena of the process $p + A \to pp + X$ more higher accuracy of the experimental data for T is required in order to reduce the contribution of rescattering mechanism.

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