ROLE OF SOFT AND HARD QUARK PROCESSES IN DILEPTON PRODUCTION IN HADRON-NUCLEUS COLLISIONS

By G. I. Lykasov and B. Kh. Sherkhonov

Laboratory of Computing Technique and Automation, Joint Institute for Nuclear Research, Dubna*

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The contribution of multiple soft quark collisions to the spectra of lepton pairs produced in high energy interactions is investigated as a function of their effective mass m. It is found that if this contribution is presented in the form A^{α}, where A is the atomic number of the nucleus, then α increases slowly to $\alpha \approx 1$, as m increases. Comparison of theoretical and experimental data is presented.

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The processes involving the production of high transverse momentum (P_t) single particles in hadron-nucleus reactions have recently been investigated theoretically [1-3]. It has been shown that multiple soft quark collisions occurring inside the nucleus mainly explain the behaviour of the P_t spectra of mesons as a function of the atomic number of the target nucleus A, as A^{α}, $\alpha < 1$, at certain values of P_t. The A dependence of these spectra at some P_t has also been observed in other spectra both of single particles and of particle jets [4, 5] produced in h–A interactions.

The present study is aimed to analyse the contribution of multiple soft quark collisions to the spectra of lepton pairs produced in hadron-nucleus reactions at high energies. By soft quark collisions we here mean collisions occurring at such small t values for which quarks do not leave the hadron boundaries, within which they have been produced, according to a version of the dual topological unitarisation model (DTU) [6, 7].

In such collisions the hadron consisting of quarks can be assumed to interact with another hadron as a whole. We can estimate approximately the maximum momentum transfer t at which quarks do not yet leave the hadron boundaries in h–h interactions. For example, let us consider the collision of two nucleons. For simplicity, we shall take it to be an elastic quark-quark (q–q) collision. In the c.m. system we have $t = -4k^2 \sin^2 \frac{\theta^*}{2}$,

* Address: Joint Institute for Nuclear Research, Head Post Office, P. O. Box 79, 101000 Moscow, USSR.

where k is the initial quark momentum and θ^* is its scattering angle. At large k and small t we can write approximately: $\theta_L \approx \frac{\theta^*}{2} = \frac{\sqrt{|t|}}{2k}$ where θ_L is the laboratory scattering angle. After scattering on the angle θ_L and passing the average distance between nucleons inside the nucleus, r_0, the quark deviates from the initial direction by the distance $r_\perp \approx r_0 \sin \frac{\sqrt{|t|}}{2k}$. Hence one can deduce that at the initial nucleon energy, for example, $E_0 = 300$ (GeV), $r_\perp \gtrsim 0.3$–0.4 (fm), at $|t| \gtrsim 3$–4 (GeV/c)^2. Another scattered quark of the nucleon can fly in the opposite direction, so that after the collision the two nucleon quarks considered will be separated by the distance $r_\perp \approx 0.6$–0.8 (fm) at $|t| \approx 3$–4 (GeV/c)^2. However we note that the constituent quarks can scatter inelastically, the probability of this process increasing with increasing initial energy. But in this case, at the same momentum transfer t the emission angle of the quark scattered should be larger than in the elastic case. Therefore the estimates presented are approximate, rather setting the upper limit of transfer in q–q collisions, at which quarks do not yet leave the boundaries of theconfinement radius, if it is the nucleon radius. Thus at momentum transfers $|t| < 3$–4 (GeV/c)^2 it is legitimate to assume that the projectile nucleon as a whole interacts with the nuclear nucleon [6, 7].

We shall now consider dilepton production in high-energy hadron-nucleus interactions. As is known [8–10], massive lepton-pair production in h–h interactions at large effective m, in particular, $\mu^+\mu^-$ production at $m > 4$ (GeV/c^2), is described by the Drell-Yan [6] mechanism rather well. In principle, the process of $\mu^+\mu^-$ production at $m < 4$ (GeV/c^2) can evolve via the production of a vector meson in the intermediate state, followed by the decay of this meson, $V \to \mu^+\mu^-$. Naturally the mechanism itself should be independent of the atomic number A of the target nucleus if this process occurs on the nucleus.

In the present paper we shall analyse the ratios of the spectra of lepton pairs produced in h–A reactions on different nuclei, rather than their absolute values. Therefore the mechanism of $\mu^+\mu^-$ production is of no importance in our case.

The inclusion of multiple soft q–q collisions or multiple rescattering of the initial hadron is made within the framework of the approach developed in Refs [1–3]. The process of $\mu^+\mu^-$ production in the hadron-nucleus interaction is shown schematically in Fig. 1.

According to Refs. [1–3, 8–10], the contribution of multiple soft collisions to the lepton spectrum in the effective mass m, $d\sigma_A/dm^2 \equiv F_A^{(S)}(m^2)$ can be written in the following

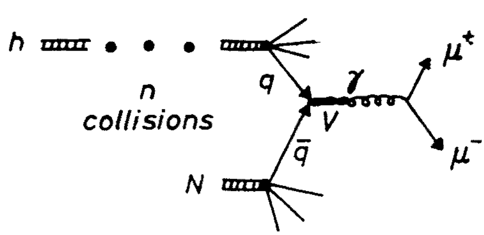

Fig. 1. Schematic view of the hA → $\mu^+\mu^-$X process taking into account the multiple rescattering of the initial hadron inside the nucleus

form:

$$F_A^{(S)}(m^2) = \sum_{\substack{n=0\\ q}} N_n \int_0^1 dx_1 \int_0^1 dx_2 \int d^2P_{1t}d^2P_{2t}\{G_q^{(n)}(x_1, P_{1t})G_{\bar{q}}(x_2, P_{2t})$$

$$+G_{\bar{q}}^{(n)}(x_1, P_{1t})G_q(x_2, P_{2t})\}\delta(m^2-\hat{S}_{q\bar{q}})\sigma_{q\bar{q}\to\mu^+\mu^-}(m). \quad (1)$$

Expression (1) is written for the reaction $hA \to \mu^+\mu^-X$.

In what follows, for the sake of simplicity we shall consider $\mu^+\mu^-$ production in proton-nucleus interactions. The following notations are introduced here: N_n is the so-called "effective" number characterising n collisions of the incident proton inside the nucleus, which is calculated as in Ref. [11]:

$$N_n = \frac{1}{n!}\int_{-\infty}^{\infty} dz \int d^2b(\sigma T_-(b, z))^n \exp(-\sigma T_-(b, z))\varrho(b, z);$$

$$T_-(b, z) = \int_{-\infty}^{z} \varrho(b, z')dz'. \quad (2)$$

where $\varrho(b, z)$ is the nuclear density, normalised in the following way:

$$\int_{-\infty}^{\infty} dz \int d^2b\varrho(b, z) = A;$$

$G_q^{(n)}(x, P_t)$ is the distribution of the quark with fraction x of the longitudinal momentum and the transverse momentum P_t after n collisions of the initial nucleon inside the nucleus. The method used to calculate it is discussed in detail in Refs. [1, 2], therefore we present only its final form:

$$G_q^{(n)}(x, P_t) = \int_0^1 dx_1 \int_0^1 dx_2 \int d^2P_{1t}d^2P_{2t}\cdot f_p^{(n)}(x_2, P_{2t})$$

$$\times G_q(x_1, P_{1t})\cdot\delta(x-x_1x_2)\delta^{(2)}(P_t-P_{1t}-P_{2t}). \quad (3)$$

Here, in contrast to Refs. [1, 2] $f_p^{(n)}(x, P_t)$ is the probability for the initial proton to have the fraction x of the longitudinal momentum and the transverse momentum P_t after n collisions inside the nucleus. It can be calculated as in Refs. [1, 2].

$$f_p^{(n)}(x, P_t) = \int_0^1 \prod_{i=1}^{n} dx_i \int \prod_{i=1}^{n} d^2P_{it}f_p(x_i, P_{it})$$

$$\times\delta(x-\prod_{i=1}^{n} x_i)\delta^{(2)}(P_t-\sum_{i=1}^{n} P_{it}),$$

where $f_p(x, P_t)$ is the proton spectrum, normalised to unity, observed in the p–N interaction as a function of x and P_t; it is taken, as in Refs. [1–3] in the following formw [12]:

$$\frac{1}{\sigma}\frac{d\sigma}{dxd^2P_t} = (\beta+1)x^\beta\frac{B^2}{2\pi}\exp(-BP_t);$$

$$\beta \approx 0.5; \quad B \approx 4.6(\text{GeV}/c)^{-1}.$$

Here

$$\hat{S}_{q\bar{q}} = x_1 x_2 S + \frac{x_2}{x_1} P_{1t}^2 + \frac{x_1}{x_2} P_{2t}^2 + 2P_{1t}P_{2t}$$

is the square of the total energy of the q–q collision in the c.m. system; P_{1t}, P_{2t} are the transverse momenta of the quark $\bar{q}$ and the antiquark q, respectively; x_1, x_2 are their momenta fractions; S is the square of the total c.m. energy of the p–N collision; and σ is the cross section of the inelastic p–N collision.

Now we shall analyse qualitatively the behaviour of expression (1) for $F_A^{(S)}(m)$ as a function of A. Calculating $G_q^{(n)}(x, P_t)$ according to (3) and using the factorised form of $G_q(x, P_t)$ [1, 2] and $f_p(x, P_t)$, we can present (1) for small m values in the following form:

$$F_A^{(S)}(m) \approx C \sum_{n=0}^{A} N_n \Phi^{(n)}(m), \tag{4}$$

where C is some constant obtained after the approximate integration of (1) over dx_i, namely:

$$\Phi^{(n)}(m) = \frac{B^2}{2\pi} \frac{1}{\Gamma(\frac{3}{2}n+3)} \left(\frac{Bm}{2}\right)^{\frac{3}{2}n+2} K_{\frac{3}{2}n+2}(Bm); \qquad n = 1, 2, 3, \ldots$$

$$\Phi^{(0)}(m) = \frac{B^2}{2\pi} \frac{1}{\Gamma(\frac{3}{2})} \left(\frac{Bm}{2}\right)^{\frac{1}{2}} K_{\frac{1}{2}}(Bm).$$

Expression (4) is analogous to the one for the contribution of multiple soft q–q collisions to the inclusive P_t-spectrum of hadrons produced in p–A reactions, which behaves like A^α at $\alpha < 1$ [1–3]. Therefore the spectrum $F_A^{(S)}(m)$ should also be characterised by a similar behaviour of A.

Detailed calculations using Eq. (1) have shown that $\alpha(m)$ increases from its minimum value to $\alpha \approx 1$, as m increases. The A dependence of the effective mass spectrum of the lepton pair $\mu^+\mu^-$ produced in the p–A reaction at $E_0 = 400$ (GeV) is presented in Fig. 2, where one can see satisfactory agreement between the calculated curve and experimental data [13].

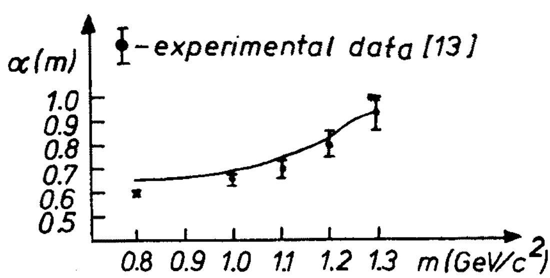

Fig. 2. Dependence of $\alpha = \ln \frac{F_{A_1}^{(S)}(m)}{F_{A_2}^{(S)}(m)} \Big/ \ln \frac{A_1}{A_2}$ where $A_1 = {}^{64}Cu$, $A_2 = {}^{207}Pb$, on the effective mass m for the $\mu^+\mu^-$ pair produced in the process $pA \to \mu^+\mu^- X$ at $E_0 = 400$ (GeV); the curve is calculation results

As is shown above, soft quark collisions can be considered at small momentum transfers t only. At large t values it is necessary to take into account hard q–q collisions. One can easily demonstrate that the latter give a contribution to the spectra of high-P_t particles produced in hadron-nucleus reactions and this contribution depends on A linearly. A similar dependence has been clearly shown in terms of QCD [14]. In particular, if the quark undergoes n soft collisions at small transfers followed by hard scattering at large t and fragmentation to a hadron with high P_t, then the P_t spectrum of the quarks befoie their fragmentation can be presented in the followiñg form:

$$\frac{d\sigma_A}{d^2P_t} = \sum_{n=0}^{A} \frac{1}{n!} \int_{-\infty}^{\infty} dz \int d^2b(T_-(b, z))^n$$

$$\times \exp(-\sigma T_-(b, z))\varrho(b, z) \prod_{i=1}^{n} \frac{d\sigma}{d^2P_{it}} \delta^{(2)}\left(P_t - \sum_{i=1}^{n} P_{it} - P_t'\right)$$

$$\times \prod_{i=1}^{n} d^2P_{it} d^2P_t' \frac{d\sigma_{qq}}{d^2P_t'} . \tag{5}$$

If $\sum_{i=1}^{n} P_{it} \ll P_t'$, it is easy to transform expression (5), after integration over d^2P_{it}, to the following form:

$$\frac{d\sigma_A}{d^2P_t} \approx \frac{d\sigma_{qq}}{d^2P_t} \int_{-\infty}^{\infty} dz \int d^2b\varrho(b, z) = A \frac{d\sigma_{qq}}{d^2P_t} .$$

The same behaviour of the spectrum at large m follows for the considered process of $\mu^+\mu^-$ production in p–A interactions because in this case one can regard the annihilation process $q\bar{q} \to \mu^+\mu^-$ as a hard one. Taking hard quark rescattering into account gives a small value of the contribution to the spectrum investigated, as shown in Ref. [15].

Thus the above analysis of the processes of dilepton production in h–A reactions at high energies has shown the following. If the m spectrum of these pairs is presented in the form A^α, then multiple soft quark collisions are just responsible for the increase in α from its minimum value ($\alpha < 1$) to $\alpha \approx 1$, as the effective mass increases to $m \approx 3$–4 (GeV/c^2). At large m values the linear A dependence of the spectrum in question has been conditioned by hard quark processes occurring inside the nucleus.

In conclusion we note that the processes $hA \to \mu^+\mu^-X$ have been considered within the framework of the multiple scattering theory in Ref. [16]. There the value of $\alpha(m)$ was calculated at m equal to the mass of vector mesons ϱ_0, $\omega_0(m_{\varrho,\omega})$ and turned out to agree with the experimental value, but the dependence of $\alpha(m)$, $m > m_{\varrho,\omega}$ was not calculated. In that case the multiple rescattering of both the initial hadrons and intermediate vector resonances or π mesons were not taken into account. However a large uncertainty arises in the analysis of the contribution of vector meson rescattering processes occurring inside the nucleus, because there is no adequate knowledge of the cross sections of the interaction of ϱ, ω, φ-mesons with nucleons at the energies considered. Furthermore, according to modern theoretical concepts [17] and, in particular, the DTU model [6, 7, 18], secondary fast mesons and the excited states of quark-antiquark pairs $(q+\bar{q})$, vector mesons, are produced outside the nucleus, and the fast incident hadron instantly.

Therefore in the present paper we restrict ourselves to taking into account the multiple soft collisions of the incident hadron.

In recent experiments [4, 5, 19] an interesting fact has been observed. In hadron--nucleus processes involving the production of hadron jets, $\alpha(\boldsymbol{P}_t) > 1$ even at high $\boldsymbol{P}_t$ if their $\boldsymbol{P}_t$ spectra are presented in the form A^{α}. Therefore, in our view, a systematic theoretical study of such processes is of considerable interest.

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