MEAN MULTIPLICITY OF g-PARTICLES IN INTERACTION OF HIGH-ENERGY LEPTONS WITH NUCLEI

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Expressions for mean multiplicity of g-particles in deep inelastic lepton-nuclei interactions are obtained in the framework of multiple scattering theory. These expressions allow one to get information on space-time picture of quark-parton hadronization. A-dependence of mean multiplicity of g-particles for (anti-)neutrino-nuclei interactions is obtained using these expressions.

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Comprehensive investigation of the hadroproduction processes on atomic nuclei at high energies is very important for the strong interaction physics, in particulaı for clarifying the space-time struc'ure of the hadroproduction process. One of the basic physical quantities characterizing the space-time picture of hadroproduction on atomic nuclei is multiplicity of g-particles (representing mostly the recoil protons with velocities $0.3 \lesssim \beta \lesssim 0.7$). Ref. [1] describes within the multiple scattering theory all the available experimental data on mean multiplicity of protons with energies $T_p = 30 \div 300$ MeV produced in high-energy interactions of various hadrons with atomic nuclei. It has been shown in [1] that besides multiple re-scattering of the leading hadron, a certain contribution to g-particle multiplicity is made by secondary interactions of relatively low-energetic pions ($p_\pi < 3$ GeV/c) from the target fıagmentation region.

The situation will be somewhat different in the case of deep-inelastic leptoproduction processes. In this case, the incident particle (lepton) in the nucleus does not undergo multiple collisions (except for the case of electroproduction at a small value of Bjorken variable $x_B \lesssim 0.1$, when a transition of virtual photon into quark-antiquark pair is possible [2]; in this work we do not deal with the quoted kinematic region). As a result of the deep-inelastic interaction of lepton with one of the nucleus nucleons an energetic current quark-parton is produced, while a "residual" nucleon fragments into nucleon and relatively low-energetic (in laboratory system) pions the secondary interactions of which make a certain contribution to multiplicity of g-particles. Mean multiplicity $\langle n_g \rangle$ is determined

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both by this contribution and the one of secondary interactions of knocked-out quark or the products of its hadronization with nucleus nucleons, which depend on such parameters as mean times of transition of quark-parton into constituent quark [3] and of the latter into hadron, mean length of their interaction in nuclear matter, etc. Thus, experimental data on $\langle n_g \rangle$ can give, in principle, information on parameters characterizing the hadronization process in the current quark fragmentation region.

As such a parameter, which can be estimated from a comparison with experiment, we have chosen in this work time-averaged cross section σ of interaction of energetic quark or its hadronization products with nucleon. Though this parameter is a rather rough characteristic of the current quark hadronization process, nevertheless its experimental estimation would allow one to make important qualitative conclusions. Thus, to the value $\sigma \ll 10$ mb there corresponds a pattern in which the space-time interval of evolution of the current quark-parton into the constituent one exceeds considerably the nucleus size, $\tau \gg R$; at the values of σ being of the order of cross section of interaction of constituent quark with nucleon ($\sigma \sim 10$ mb) $\tau < R$; to larger values of σ, e.g. $\sigma \gtrsim 15$–20 mb, there corresponds a pattern in which quark-parton hadronization takes place during space--time intervals of the order of internucleon distances in nucleus, so that the formed hadron or a jet of hadrons suffers secondary interactions in nucleus.

In Ref. [1] we have obtained an expression for mean multiplicity of g-particles in hadron-nucleus interactions in the energy range of 100 GeV and above, with account of the pion secondary interactions from the fragmentation region of the target. Analogously, one can easily obtain the expression for $\langle n_g \rangle$ in the case of lepton-nucleus interaction at high energies (the energy ν transferred to quark-parton exceeds a few tens GeV):

$$\langle n_g \rangle_{lA} = w_l + w\frac{\sigma}{2A}\int T^2 d^2b + m_1 w_1\left[1-\frac{N(0,\sigma_1)}{A}\right] + \frac{\sigma}{\sigma_1} m w_1\left[\frac{\sigma_1}{2A}\int T^2 d^2 b - 1 + \frac{N(0,\sigma_1)}{A}\right]. \tag{1}$$

The first term in the right-hand-side of (1) represents the mean number of g-particles (in the following, the recoil protons with energies $T_p = 30 \div 300$ MeV are implied) in elementary lepton-nucleon interaction; the second term describes the mean number of g-particles produced as a result of multiple collisions of energetic quark or products of its hadronization with the nucleons; the third and fourth terms describe a constribution to g-particles mean multiplicity from interactions in nucleus of secondary low-energetic pions, produced in the target fragmentation region in lepton-nucleon scattering (the third term) and in subsequent collisions of energetic quark or products of its hadronization with nucleus nucleons (the fourth term). The meaning of averaged cross section σ appearing in (1) as a free parameter is explained above. $T(b) = \int \varrho(b, z)dz$ is a projection of nuclear density $\varrho(\vec{r})$ ($\int \varrho(\vec{r})d\vec{r} = A$) on the plane of the impact parameter; $N(0, \sigma)$ is the so-called effective nucleon number

$$N(0,\sigma) = \int \frac{1-e^{-\sigma T(b)}}{\sigma} d^2 b.$$

The other quantities in (1) are determined from the data on elementary lepton-nucleon and pion-nucleon interactions. Consider the (anti-) neutrino-nucleus interaction process. The choice of this process is motivated by the fact that at present there are enough experimental data on (anti-) neutrino-nucleon interactions, which enable one to determine the characteristics of the elementary act in (1). Thus, ω_1 is the mean number of g-particles in elementary lepton-nucleon interaction (averaged over protons and neutrons of nucleus). In case of (anti-) neutrino-nucleon interactions, using the result of [4], we have

$$w_1(\nu p) = 0.11, \quad w_1(\bar{\nu} p) \approx w_1(\nu n) \approx 0.09, \quad w_1(\bar{\nu} n) \approx 0.03.$$

m_1 is the mean multiplicity of pions (of all signs) in the target fragmentation region in lepton-nucleon interaction; in case of (anti-) neutrino-nucleon interactions, making use of the results of Refs. [4, 5], one can parametrize the dependence of π-meson mean multiplicities on the effective mass of hadron system W as follows:

$$\langle m_{\pi^+}\rangle_{\nu p} \approx \langle m_{\pi^-}\rangle_{\bar{\nu} n} \approx 0.26+0.28 \ln W^2,$$

$$\langle m_{\pi^-}\rangle_{\nu p} \approx \langle m_{\pi^+}\rangle_{\bar{\nu} n} \approx -0.38+0.28 \ln W^2,$$

$$\langle m_{\pi^+}\rangle_{\bar{\nu} p} \approx \langle m_{\pi^-}\rangle_{\bar{\nu} p} \approx \langle m_{\pi^+}\rangle_{\nu n} \approx \langle m_{\pi^-}\rangle_{\nu n} \approx 0.12+0.18 \ln W^2,$$

$$\langle m_{\pi^0}\rangle_{\nu(\bar{\nu})N} \approx \tfrac{1}{2}\left[\langle m_{\pi^+}\rangle_{\nu(\bar{\nu})N}+\langle m_{\pi^-}\rangle_{\nu(\bar{\nu})N}\right];$$

$$m_1 = \langle m_{\pi^+}\rangle+\langle m_{\pi^-}\rangle+\langle m_{\pi^0}\rangle.$$

σ_1 is averaged cross section of interaction of secondary pions from the target fragmentation region with nucleon, w_1 is the mean number of g-particles in these interactions; to estimate σ_1 and w_1 (averaged over pion energy spectrum) we have used the data of [6] on partial and differential cross sections of exclusive channels of pion-nucleon interactions in the region $p_\pi < 3$ GeV/c:

$$\sigma_1 \approx 27 \text{ mb}, \quad w_1(\pi p) \approx 0.55, \quad w_1(\pi n) \approx 0.30$$

Quantities w and m are the inclusive characteristics of interaction of energetic quark with nucleus nucleons: w is the mean number of g-particles, and m is the mean number of pions from the target fragmentation region in interactions of quark or products of its hadronization with nucleon. We assume (see also [1]) that these characteristics at sufficiently high energies do not depend on the type of incident particle and we use estimations given in [1], $w \approx 0.15$, $m \approx 3$.

Parameters in (1) are practically independent of the value of quark energy ν in the region of sufficiently high values of the latter (ν is above several tens GeV), this leading to independence of quantity $\langle n_g\rangle_{1A}$ on ν. Hereafter we shall consider the required modifications in (1) at not too high ν ($\nu \lesssim 20$ GeV).

The result of calculations by expression (1) were approximated by the dependence

$$\langle n_g \rangle_{\nu A} = B(\sigma, W^2) A^{\alpha(\sigma, W^2)}. \tag{2}$$

Note, that such parametrization does not hold for a large range of variation of atomic number A ($12 \lesssim A \lesssim 208$) (e.g. index α in the light nuclei region is always larger than in the heavy nuclei one). For this reason, parametrization (2) was used separately for the region of light ($A \lesssim 40$) and the region of medium-weight and heavy ($A \gtrsim 40$) nuclei. The dependences of α and B on σ and W^2 for νA interactions are presented in Figs. 1a and 1b separately for the two mentioned regions of A (solid lines). As one can see from Fig. 1, the A-dependence of g-particles yield is defined practically by the cross section σ (index α depends weakly on the invariant energy W). At $\sigma \approx 0$ the A-dependence of $\langle n_g \rangle$ is weak ($\alpha \sim 0.1$ for medium-weight and heavy nuclei, $\alpha \sim 0.2$ for light nuclei) and enhances noticeably at $\sigma \approx (10 \div 20)$ mb, reaching the value $\alpha \sim 0.3$ for nuclei with $A \gtrsim 40$, and $\alpha \gtrsim 0.3 \div 0.35$ for light nuclei. Thus, experimental measurement of the A-dependence of g-particles yield enables one to estimate parameter σ and thus obtain information on the space-time picture of the hadronization process of quark-parton "knocked-out" from nucleon.

Quantities $B(\sigma, W^2)$ are increasing functions of lg W^2 with a slope practically independent of σ. As it was expected, $B(\sigma, W^2)$ for light nuclei depend on σ very weakly (at $A \to 1$ the σ dependence must vanish).

Consider now the region of not too high values of ν (ν is less than a few tens GeV). In this case one cannot make use of approximation made in deriving expression (1). First, one should take into account that at multiple inelastic collisions with nucleons the quark loses energy, owing to which the mean multiplicity of pions m in the target-nucleon fragmentation region begins to decrease if the quark energy ν is less than a few tens GeV (as was mentioned above, at higher energies $m \approx 3$ being practically energy-independent). To estimate the energy dependence of quantity m (the fourth term of (1)) we have used the pion-nucleon data [6] and found that the mean multiplicity m versus momentum p of incident hadron (quark) in the region $2 < p < 20$ GeV/c can be parametrized as $m = Cp^\gamma$, where $C \approx 1.1$, $\gamma = \frac{1}{3}$, p in GeV; while in the region $p > 20$ GeV/c, $m \approx \text{const} \approx 3$.

Moreover, in hadron-nucleon interactions in the region of energies below a few tens GeV the mean multiplicity w of recoil protons (g-particles) depends on incident particle energy (w grows with decreasing energy). The same dependence should be expected in case of quark-nucleon collisions. Using the data given in [6] one can parametrize the energy dependence w in the range from a few GeV/c to a few tens GeV/c in the form of $w = w_0 - bp^\delta$, where $w_0 \approx 0.5$, $b \approx 0.2$, $\delta \approx 0.16$, p — in GeV; in the region $p > 30$ GeV/c $w \approx \text{const} \approx 0.16$. The account of the energy dependence results in modification of the second term in (1).

To obtain the expression for $\langle n_g \rangle_{lA}$ with respect to the energy losses of the quark propagating in the nucleus, we assume that quark, just like hadrons, in collision with nucleon loses on the average about $\bar{\kappa} = 0.5$ of its energy; approximately the same estimation follows from the suggested in [7] expression for the energy loss distribution in quark-nucleon collision. To simplify the calculations we shall use the approximation that the inelasticity coefficient in each elementary act of quark-nucleon interaction is equal to its mean value $\kappa = 0.5$. In the quoted approximations the calculations in the multiple scattering theory lead to the following expressions for the second and fourth terms of formula (1), respectively

$$\langle n_g \rangle_2 = w_0 \frac{\sigma}{2A} \int T^2 d^2 b - v \left[1 - \frac{N(0, \eta\sigma)}{A} \right] \tag{3}$$

$$\langle n_g \rangle_4 = m w_1 \left[\frac{1}{\beta} - \frac{\sigma_1 N(0, \beta\sigma)}{\beta(\sigma_1 - \beta\sigma)A} + \frac{\sigma N(0, \sigma_1)}{(\sigma_1 - \beta\sigma)A} \right] \tag{4}$$

where

$$\eta = 1 - \kappa^\delta \approx 0.1, \quad \beta \approx 1 - \kappa^\gamma \approx 0.21, \quad v = bp^\delta/\eta, \quad m = Cp^\gamma, \quad p \approx \nu$$

is the quark initial energy in GeV.

The results of calculations of $\langle n_g \rangle_{\nu A}$ at $\nu = 20$ GeV by means of expressions (3) and (4) are given in Figs. 1a, 1b (dotted lines). As one can see from Fig. 1, the qualitative picture of dependences $\alpha(\sigma, W^2)$ and $B(\sigma, W^2)$ on σ and W^2 is the same as the one at higher energies. Note also, that the results of calculations of g-particle mean multiplicity in antineutrino-nuclei interactions, $\langle n_g \rangle_{\bar{\nu}A}$ differ only by a few percent from the results of Fig. 1.

The only data published [8] on g-particle mean multiplicity in deep-inelastic $\nu(\bar{\nu})$A interactions concern $\nu(\bar{\nu})$Ne interactions (at mean values of $\nu \sim 20$ GeV and $W^2 \sim 25$ GeV^2 for neutrino and $\nu \sim 10$ GeV and $W^2 \sim 15$ GeV^2 for antineutrino). The value $\langle n_g \rangle_{\nu(\bar{\nu})\mathrm{Ne}} = 0.71 \pm 0.12$ presented in Ref. [8] is obtained by averaging the neutrino and antineutrino data based approximately on the same statistics. This experimental value is compared in Fig. 2 with the theoretical predictions at various σ. The calculations are performed using expression (1), where the second and fourth terms are replaced by expressions (3) and (4), at the values $\nu = 20$ GeV and $W^2 = 25$ GeV^2 for νNe interactions and $\nu = 10$ GeV and $W^2 = 15$ GeV^2 for $\bar{\nu}$Ne ones. As it is seen from Fig. 2, the large experimental errors allow one to estimate the averaged quark-nucleon cross section only qualitatively: $\sigma \approx (11.5 \pm 6.5)$ mb. Nearly the same estimation, $\sigma \approx 10$ mb, is obtained from the analysis [9, 10] of inclusive spectra of fast hadrons in deep-inelastic eA scattering [11]. The result obtained in this work points out that in the energy region up to a few tens GeV transferred to quark in deep-inelastic lepton-nucleon scattering one must not neglect the secondary interactions of quark (or the products of its hadronization) with the nucleons, i.e. a transition of the current quark-parton into the constituent quark (or into a jet of hadrons) occurs during the space-time intervals τ not exceeding the nuclei sizes. This conclusion is in agreement with the recent estimation $\tau \approx 0.1$ fm $\cdot\, \nu$ (GeV) obtained in Ref. [12], where the process of fast hadrons production in deep-inelastic μCu and μC interactions at 200 GeV initial energy has been studied. New, more detailed experimental investigations of inclusive and multiple characteristics of hadrons produced both in the region of current quark fragmentation and in the region of the target fragmentation in the deep-inelastic lepton-nucleus interactions will allow one to obtain a more trustworthy information on the space-time picture of quark hadronization.

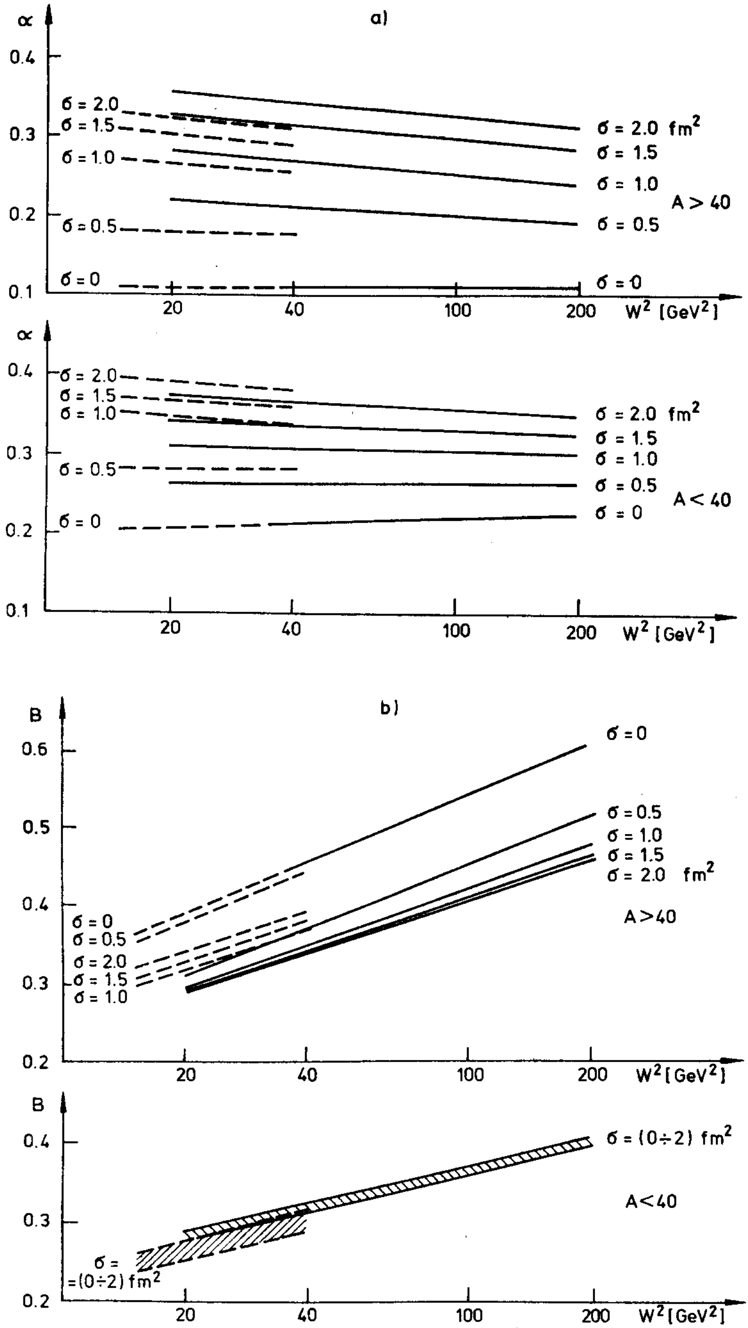

Fig. 1. The values of the exponent α (Fig. 1a) and coefficient B (Fig. 1b) determining the mean multiplicity of g-particles in νA interactions ($\langle n_g \rangle_{\nu A} = B(\sigma, W^2)A^{\alpha(\sigma, W^2)}$) versus the effective mass of hadronic system W and averaged quark-nucleon cross section σ (see the text). Solid lines denote the case when the energy ν transferred to quark exceeds a few tens GeV; dotted lines — the case when ν is less than a few tens GeV

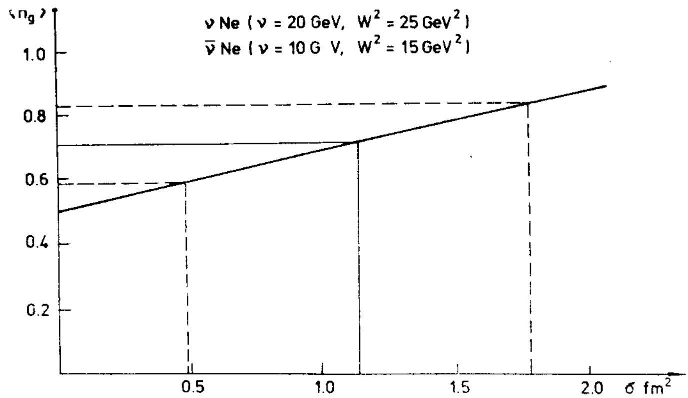

Fig. 2. A comparison of experimentally measured mean multiplicity of g-particles in $\nu(\bar{\nu})$Ne interactions with the theoretical predictions versus σ (see the text)

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