Role of hard and soft quark-nucleon collisions in the A dependence of the production of high-p_t hadrons in interactions with nuclei

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A single hard collision and several soft collisions of a quark of the incident hadron with the nucleons of the nucleus play the major role in shaping the A dependence of the production of hadrons with large values of p_t.

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1. The measured inclusive differential cross sections for the production of hadrons with large transverse momenta in hadron-nucleus interactions are ordinarily written in the form[1,2]

$$\frac{Ed^3\sigma_A}{d^3p} = A^{\alpha(p_t)}\frac{Ed^3\sigma_N}{d^3p}, \tag{1}$$

where the parameter $\alpha(p_t)$ increases from $\alpha(0)\cong 2/3$ to $\alpha(p_t)\cong 1.1$–1.4 in the range $p_t = 3$–5 GeV and then decreases. Possible explanations of this behavior have been taken up repeatedly in theoretical papers (see Refs. 3 and 4, for example). Most of the papers attribute the observed behavior to hard rescatterings of a quark of the primary hadron (or of the incident hadron itself) by nucleons of the nucleus, followed by a fragmentation into an observable hadron with a large p_t. The differential cross section for the interaction of the quark with the nucleon, $d^2\sigma_N/d^2p_t$, is assumed known from data on hadron–nucleon interactions.

In this letter we make a case for the following assertion: A major role in shaping the observed behavior $\alpha(p_t)$ is played by processes in which the resultant scattering of a quark through a large angle occurs in a single hard collision with a nucleon of the nucleus in several relatively soft collisions. Our basis for this assertion consists of the following observations: With a power-law decrease in the differential cross section, $d^2\sigma_N/d^2p_t \sim 1/(p_t^2)^n$, the quark acquires a large transverse momentum as a result of two interactions, primarily after undergoing one hard collision and one soft one, not hard collisions (with a momentum transfer $\mathbf{q}_t \approx \mathbf{p}_t/2$ in each), since the probability for the latter event is proportional to[1)] $(p_t^2)^{-2n}$.

2. We write the differential cross section $d^2\sigma_A/d^2p_t$ as an incoherent sum of terms corresponding to different multiplicities of the collisions of the incident quark with the intranuclear nucleons (coherent interactions are important at very small values of p_t and will not be considered here[4]):

$$\frac{d^2\sigma_A}{d^2p_t} = \sum_{n=1}^{\infty} \sigma^{(n)} \frac{d^2w^{(n)}}{d^2p_t}, \tag{2}$$

where $d^2w^{(n)}/d^2p_t$ is the transverse-momentum distribution of a quark which has undergone n collisions $[\int(d^2w^{(n)}/d^2p_t)d^2p_t = 1]$, $\sigma^{(n)}$ is the cross section for the n-fold interaction of an incident quark with intranuclear nucleons, given in the optical model by

$$\sigma^{(n)} = \int d^2b\, [T\sigma]^n/n!\, \exp[-T\sigma],$$

$T = \int \rho(b,z)dz$, $\rho(b,z)$ is the density of nucleons in the nucleus, and σ is the total cross section for the quark-nucleon interaction. Series (2) can easily be summed.[4] We introduce the notation $w^{(n)}(\mathbf{c}) = \int \exp(-i\mathbf{p}_t\mathbf{c})(d^2w^{(n)}/d^2p_t)d^2p_t$; then we have $w^{(n)}(c) = [w^{(1)}(c)]^n \equiv [w(c)]^n$ and Eq. (2) can be written

$$\frac{d^2\sigma_A}{d^2p_t} = \frac{1}{(2\pi)^2} \int d^2c\, e^{-i\mathbf{p}_t\mathbf{c}} \int d^2b\, e^{-T\sigma}[e^{T\sigma w(c)} - 1]. \tag{3}$$

Below we will need the ratio

$$R(p_t) = A^{\alpha(p_t)-1} = (d^2\sigma_A/d^2p_t) : (A d^2\sigma_N/d^2p_t). \tag{4}$$

3. Let us consider various types of behavior of $d^2\sigma_N/d^2p_t$.

a) We assume that $d^2\sigma_N/d^2p_t$ is Gaussian. Then $d^2w^{(n)}/d^2p_t$

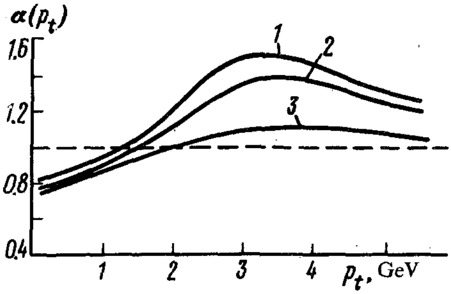

FIG. 1. Behavior of the parameter $\alpha(p_t)$ for the nuclei $A = 64$ (curve 1) and $A = 216$ (curve 2). Here $d^2\sigma_N/d^2p_t$ is calculated from Eq. (5). Curve 3—Calculations of $\alpha(p_t)$ for $A = 64$ and for a purely power-law behavior of $d^2\sigma_N/d^2p_t$.

$= (\pi n p_0^2)^{-1}\exp(-p_t^2/p_0^2)$. We see from Eqs. (1) and (4) that in this case $R(p_t)$ increases exponentially with increasing p_t^2; correspondingly, we have $\alpha(p_t) \sim p_t^2$ at $p_t^2 \gg p_0^2$. b) We now consider a power-law dependence, $(d^2w^{(1)}/d^2p_t) = (a^2)^{k-1}\pi^{-1}(k-1)^{-1}(p_t^2+a^2)^{-k}$. With $k=2$, this dependence corresponds to the predictions of quantum chromodynamics.[4] We have used (3) to calculate $\alpha(p_t)$ (Fig. 1). The results show that the function $\alpha(p_t)$ initially increases with increasing p_t, reaches a maximum at $p_t \cong 4$ GeV, and then asymptotically approaches unity. With $\sigma = 10$ mb and $a^2 = 0.25$ GeV^2, the maximum value is $\alpha(p_t) \cong 1.07$, which is lower than the value observed experimentally. We might note that Levin and Ryskin[4] have concluded that for a power-law behavior of the function $d^2\sigma_N/d^2p_t$ (specifically, with $k=2$) the parameter $\alpha(p_t)$ cannot exceed unity. This conclusion is not refuted by the results of our calculations. The numerical calculations are also supported by analytic calculations of $dw^{(2)}/d^2p_t$. Zmushko[3] has carried out detailed calculations of the cross section for double rescattering under the assumption of a power-law behavior of $d^2\sigma_N/d^2p_t$; Zmushko asserted that a dominant role is played by two hard rescatterings. In light of the results of Ref. 4 and the present paper, Zmushko's interpretation of the results of Ref. 3 is not justified. c) We finally consider the most realistic case of the behavior of $d^2w^{(1)}/d^2p_t$:

$$\frac{dw^{(1)}}{d^2p_t} = \frac{\beta}{\pi p_0^2}\exp\left(-\frac{p_t^2}{p_0^2}\right) + (1-\beta)\frac{a^2}{\pi(p_t^2+a^2)^2} \tag{5}$$

Equation (5) presupposes that at small values of p_t the spectrum is Gaussian (a Regge spectrum), while at large p_t the distribution falls off in a power-law manner (in accordance with quantum chromodynamics). Figure 1 shows the results of numerical calculations of $\alpha(p_t)$ from (3) for case (5). These calculations were carried out with the parameter values $\sigma = 10$ mb, $p_0^2 = 1$ GeV^2 (in accordance with estimates of the radius of a constituent quark reached from data on the elastic and diffraction pp interactions[5,6]), $a^2 = 0.25$ GeV^2, and $\beta = 0.9$. For these parameter values the first and second terms in (5) are comparable at $p_t \cong 2$ GeV. It can be seen from Fig. 1 that the mechanism for the rescattering of a quark by a nucleon of a nucleus under the assumption that (5) is correct completely explains the experimentally observed behavior of $\alpha(p_t)$, both qualitatively and quantitatively. A detailed analysis shows that under the conditions corresponding to mechanism (5), at $p_t \gtrsim p_0$, the events are dominated by processes in which the incident quark undergoes a single hard collision and several soft collisions, each with a momentum transfer $q_t \sim p_0$, in the nucleus.

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[1)]The picture is completely different if $d^2\sigma_N/d^2p_t \sim \exp(-p_t^2/p_0^2)$. In this case the most probable process is that in which a transverse momentum $q_t \cong p_t/2$ is acquired in each of two interactions.

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