Multiple Production of Quark Jets off Nuclei

Fujio Takagi
Department of Physics, Tohoku University, Sendai 980, Japan
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The target dependence of jet production at large transverse momentum observed in π-Al collisions can be explained in terms of contamination of double-quark jets. Qualitative explanations are given for the difference between pion- and proton-induced jet production.

Interesting experimental results on jet production at large transverse momentum in hadron-proton and hadron-nucleus (aluminum) collisions at 200 GeV have recently been reported.[1] The main features of the data are as follows. (i) The exponent α which describes the A (mass number) dependence of the jet-production cross section increases rapidly with increasing p_T (transverse momentum) of jets. (ii) This abnormal nuclear enhancement is more prominent in proton-induced collisions than in pion-induced collisions. (iii) The exponent $\alpha_h(p_T)$ for single charged particles is considerably smaller than $\alpha_{\text{jet}}(p_T)$ and is almost independent of the beam type, i.e., $\alpha_h^{\pi}(p_T) \simeq \alpha_h^{p}(p_T)$. (iv) The multiplicity density functions $D(z)$ of jets show a strong dependence on the target type; in fact, the relative multiplicity density function $D_{h\,\text{Al}}(z)/D_{hp}(z)$ decreases monotonically as z increases, where $z = p_T(\text{particle})/p_T(\text{jet})$. (v) The mean charged multiplicity $N_{\text{jet}}(p_T)$ of jets shows a strong A dependence, $\bar{N}_{\text{jet}}^{h\text{Al}}(p_T) > \bar{N}_{\text{jet}}^{hp}(p_T)$ for both $h=\pi$ and p. (vi) However, it is almost independent of the beam type, i.e., $\bar{N}_{\text{jet}}^{\pi p}(p_T) \simeq \bar{N}_{\text{jet}}^{pp}(p_T)$, $\bar{N}_{\text{jet}}^{\pi\,\text{Al}}(p_T) \simeq \bar{N}_{\text{jet}}^{p\,\text{Al}}(p_T)$. (vii) The larger are the event charged multiplicities, the stronger is the A dependence of the jet production.

These experimental facts, in particular, (i), (iii), (iv), and (v), imply a serious difficulty of conventional quark-parton models[2] for hadron and jet production at large p_T if the observed hadron jets are induced by single-quark jets. In such models, it is assumed that the production of high-p_T quarks via hard collisions between constituent partons of incident particles and their decay into hadrons (quark fragmentation) factorizes. The experimental facts (iv) and (v) apparently contradict this factorization hypothesis. The experimental facts (i) and (iii) also mean essentially the same difficulty.

In this Letter, we would like to show that this apparent difficulty can be avoided if there is contamination of double-quark jets in hadron-nucleus collisions. The idea is illustrated in Fig. 1. A similar picture has been utilized to explain a strong A dependence of large-p_T proton production in proton-nucleus collisions.[3]

Since production of double- (or triple-) quark jets will be mainly due to simultaneous double (or triple) hard collisions of the constituent quarks of the incident particles (see Fig. 1), the A dependence might be $A^{4/3}$ (or $A^{5/3}$), which is, however, insufficient to explain the observed values of $\alpha_{\text{jet}}(p_T)$. Hence, we are forced to take into account the rescattering effect as well.[4]

Consider the following reaction:

$$\pi + A \to \text{jet} + \text{anything}. \tag{1}$$

The normalized cross section (the p_T distribution at pion-nucleon c.m. angle 90°) is written as follows:

$$\frac{d^2\sigma_{\pi A}^{\text{jet}}}{dp_T\,d\Omega}\left(\frac{d\sigma_{\pi A}^{\text{jet}}}{d\Omega}\right)^{-1} = (1-\epsilon_A)Q_A(p_T) + \epsilon_A\int_{\mu}^{p_T-\mu} dk\, Q_A(k)Q_A(p_T-k), \tag{2}$$

where the first and the second terms on the right-hand side correspond to the contribution from the single-quark jets and that from the double-quark jets, respectively; ϵ_A is the rate of contamination of double-quark jets; μ is the cutoff momentum; and $Q_A(p_T)$ is the normalized p_T distribution of hadron jets induced by single quarks produced on the nucleus A, satisfying

$$\int_{\mu}^{\max p_T} dp_T\, Q_A(p_T) = 1. \tag{3}$$

Throughout this paper, the c.m. angle is always fixed at 90° so that the momentum is denoted as p_T. In Eq. (2), the contribution from the double-quark jets is simply given by a convolution of two independent single-quark jets. This is certainly a rough approximation to be improved in more detailed calculations. We assume that the cross section for jet production in π-p collisions is dominated by the single-

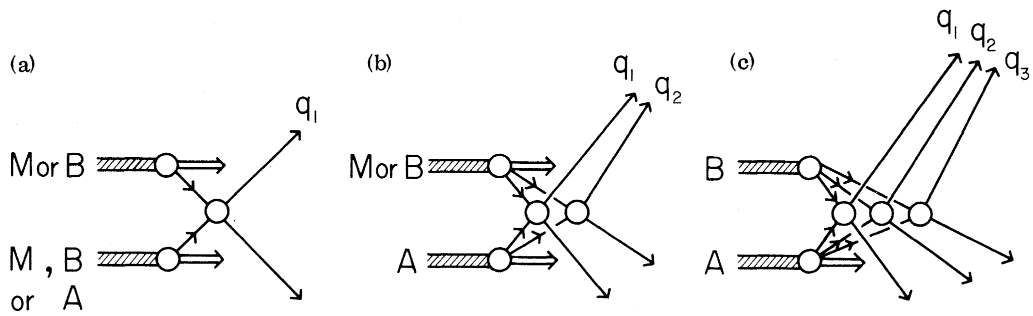

FIG. 1. Production of (a) single, (b) double, and (c) triple pairs of quark jets. The single quark q_1 in (a), two quarks (q_1,q_2) in (b), and three quarks (q_1,q_2,q_3) in (c) are detected as single-hadron jets. M, B, and A are, respectively, a meson, a baryon, and a nucleus.

quark term and that the single-quark term in π-A collisions is A times that in π-p collisions times a rescattering correction factor. For simplicity, we do not introduce a soft-collision term of which the A dependence is weaker than A^1. Therefore, we do not claim quantitative reliability of our analysis for small p_T, say $p_T \lesssim 1.5$ GeV/c. The distribution $Q_A(p_T)$ is then expressed as

$$Q_A(p_T) = AF_A(p_T)(1-\epsilon_A)^{-1}\left(\frac{d^2\sigma_{\pi p}{}^{\text{jet}}}{dp_T\,d\Omega}\right)\left(\frac{d\sigma_{\pi A}{}^{\text{jet}}}{d\Omega}\right)^{-1}, \tag{4}$$

where $F_A(p_T)$ is the rescattering correction factor normalized as $F_1(p_T)=1$, i.e., no rescattering correction in π-p collisions. We use the following parametrization for $F_A(p_T)$:

$$F_A(p_T) = \frac{1+A^{1/3}C\exp(Dp_T)}{1+C\exp(Dp_T)}, \tag{5}$$

where C and D are positive constants. The jet cross section for π-p collisions is parametrized as

$$\frac{E\,d^2\sigma_{\pi p}{}^{\text{jet}}}{p_T{}^2\,dp_T\,d\Omega} = \text{const}\times\exp(-B_\pi p_T), \tag{6}$$

where the slope parameter B_π is assumed to be the same as that for p-p collisions[5]; $B_\pi = B_p = 3.33$ $(\text{GeV}/c)^{-1}$. Precisely speaking, B_π seems slightly smaller than B_p,[5] but the difference is only 0.21–0.28 $(\text{GeV}/c)^{-1}$. For simplicity, we use the following relation[6] for the c.m. energy E and the transverse momentum p_T of the quark jet produced at c.m. angle = 90°:

$$E = p_T + M_0, \quad M_0 = 1.2\ \text{GeV}/c^2. \tag{7}$$

The ratio of the jet-production cross section for π-A collisions to that for π-p collisions is given as

$$\frac{d^2\sigma_{\pi A}{}^{\text{jet}}}{dp_T\,d\Omega}\left(\frac{d^2\sigma_{\pi p}{}^{\text{jet}}}{dp_T\,d\Omega}\right)^{-1} = AF_A(p_T)\left(1+\frac{\epsilon_A}{(1-\epsilon_A)Q_A(p_T)}\int_\mu^{p_T-\mu} dk\,Q_A(k)Q_A(p_T-k)\right). \tag{8}$$

The charged multiplicity density function for π-A collisions is expressed as

$$D_{\pi A}(z,p_T) = \frac{(1-\epsilon_A)Q_A(p_T)D(z,p_T) + 2\epsilon_A p_T\int_{zp_T}^{p_T-\mu} dk\,Q_A(k)Q_A(p_T-k)k^{-1}D(zp_T/k;k)}{(1-\epsilon_A)Q_A(p_T)+\epsilon_A\int_\mu^{p_T-\mu} dk\,Q_A(k)Q_A(p_T-k)}, \tag{9}$$

where $D(z,p_T)$ is the fragmentation function of single quarks with momentum p_T. The multiplicity density function of hadron jets in π-p collisions is equal to $D(z,p_T)$ by assumption:

$$D_{\pi p}(z,p_T) = D(z,p_T). \tag{10}$$

For simplicity, we use the standard parametrization[6,7] for $D(z,p_T)$:

$$D(z,p_T) = 2p_T{}^2(p_T-\mu)^{-2}(1-z)z^{-1}, \tag{11}$$

where the coefficient of $(1-z)z^{-1}$ is determined by the normalization condition

$$\int_{\mu/p_T}^{1} dz\, z D(z,p_T)=1\,.$$

The momentum cutoff μ is determined to be 0.25 GeV/c by fitting the mean charged-hadron multiplicity of jets given by

$$\bar{N}_{\pi p}{}^{\rm jet}(p_T)_{\rm charged}=\tfrac{2}{3}\int_{\mu/p_T}^{1} dz\, D(z,p_T) \tag{12}$$

to the observed values.[1] Here, we have assumed that $\frac{2}{3}$ of the hadrons in jets are charged. The mean charged multiplicity of hadron jets produced in π-A collisions is then given by

$$\bar{N}_{\pi A}{}^{\rm jet}(p_T)_{\rm charged}=\tfrac{2}{3}\int_{\mu/p_T}^{1} dz\, D_{\pi A}(z,p_T)$$

$$=\frac{(1-\epsilon_A)Q_A(p_T)\bar{N}_{\pi p}{}^{\rm jet}(p_T)_{\rm charged}+2\epsilon_A\int_\mu^{p_T-\mu}dk\,\bar{N}_{\pi p}{}^{\rm jet}(k)_{\rm charged}Q_A(k)Q_A(p_T-k)}{(1-\epsilon_A)Q_A(p_T)+\epsilon_A\int_\mu^{p_T-\mu}dk\,Q_A(k)Q_A(p_T-k)}\,, \tag{13}$$

where (9) and (12) were used. Finally, the inclusive single-hadron production cross section for π-p and π-A collisions is written in terms of the corresponding jet cross sections and the fragmentation functions as

$$\frac{d^2\sigma_{\pi a}{}^{h}}{dp_T d\Omega}=\int_{p_T}^{\max p_T} dk\, D_{\pi a}(p_T/k;k)\frac{d^2\sigma_{\pi a}{}^{\rm jet}}{k\,dk\,d\Omega}\quad \text{for } a=p \text{ and } A\,, \tag{14}$$

where $\max p_T$ is the maximum possible value of p_T in π-nucleon collisions.

There are three adjustable parameters ϵ_A, C, and D. Instead of attempting the least-χ^2 fit, we simply demonstrate that a reasonable choice of these parameters gives satisfactory fits to all the relevant data. Numerical results for the following choice of the parameters are shown and compared with the experimental data[1] in Figs. 2–4:

$$C=0.15,\quad D=0.4\ ({\rm GeV}/c)^{-1},\quad \epsilon_{\rm Al}=0.0151\,. \tag{15}$$

Here the exponent α for jet production and that for single-hadron production are calculated by using the formulas

$$\alpha_\pi{}^{I}(p_T)=\ln\left[\left(\frac{d^2\sigma_{\pi\,{\rm Al}}{}^{I}}{dp_T d\Omega}\right)\left(\frac{d^2\sigma_{\pi p}{}^{I}}{dp_T d\Omega}\right)\right]^{-1}(\ln 27)^{-1} \tag{16}$$

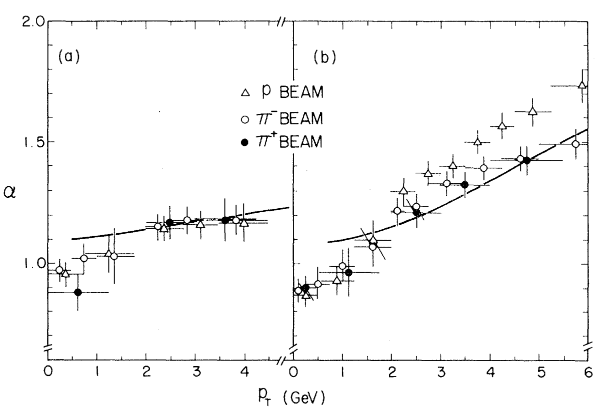

FIG. 2. (a) $\alpha_h{}^{\pi}(p_T)$ and (b) $\alpha_{\rm jet}{}^{\pi}(p_T)$. The curves show the theoretical fit. Data for proton-induced collisions are also shown.

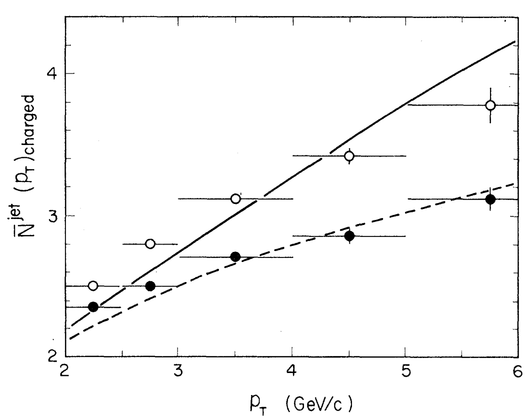

FIG. 3. Mean charged multiplicity of hadron jets. The solid circles (experiment) and the dashed curve (theory) are for π-p collisions; the open circles (experiment) and the solid curve (theory) are for π-Al collisions.

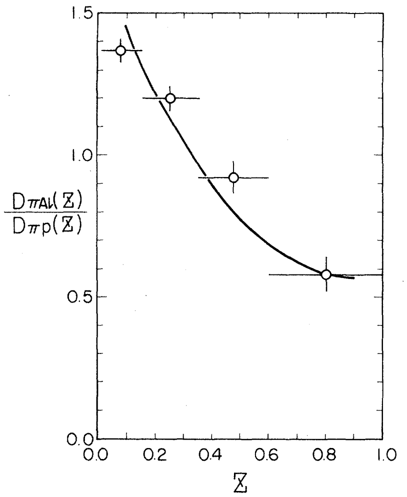

FIG. 4. Relative multiplicity density function. The experimental values are for 4.0 GeV/$c < p_T <$ 6.5 GeV/c. The theoretical curve is calculated for $p_T =$ 4.33 GeV/c.

with Eqs. (8) and (14), where $I =$ jet and h. The value of ϵ_{Al} is determined almost uniquely by fitting to the observed values of $D_{\pi\,Al}(z;p_T)/D_{\pi p}(z;p_T)$ for 4.0 GeV/$c < p_T <$ 6.5 GeV/c, while the range of values of C and D which gives reasonable fits to data is fairly wide though C and D are strongly correlated with each other. For example, an equally good fit is obtained for $C = 0.10$, $D = 0.5$ (GeV/c)$^{-1}$, and $\epsilon_{Al} = 0.0146$. Anyway, only 1.5% contamination of double-quark jets (in the cross section integrated over p_T at a fixed c.m. angle) is enough to explain every aspect of the A dependence of the hadron jets. However, we do not discuss here experimental fact (vii) because its explanation requires information on both hard and soft processes. It should be noted here that $\alpha_h(p_T)$ for $h =$ meson is essentially determined by the rescattering effect alone. Therefore, it is expected that $\alpha_h(p_T)$ for $h =$ meson is almost independent of the beam type in agreement with experimental fact (iii).

As for the πA-pA difference (ii), there are at least two alternative explanations. One is the contamination of triple-quark jets in p-Al collisions as is shown in Fig. 1(c). Another is the larger contamination of double-quark jets in p-Al collisions than in π-Al collisions. In the former, a simple convolution of three-quark jets should result in a considerable increase of $\bar{N}_{pA}{}^{\rm jet}(p_T)$ in comparison with $\bar{N}_{\pi A}{}^{\rm jet}(p_T)$. Experimentally, $\bar{N}_{pA}{}^{\rm jet}(p_T) \simeq \bar{N}_{\pi A}{}^{\rm jet}(p_T)$. This difficulty may be eliminated if baryons are formed frequently in triple-quark jets. If the latter is the case, the A dependence at large A should be essentially independent of the beam type.

An immediate prediction from our picture for jet production off nuclei is that the semi-inclusive cross section for production of simultaneous two-hadron jets with small relative angle will show a dramatically strong A dependence. Further theoretical justification of our picture requires a detailed calculation of multiple production of quark jets in simultaneous hard collisions.

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