Jets Produced in π^-, π^+, and Proton Interactions at 200 GeV on Hydrogen and Aluminum Targets

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This paper presents results from an experiment on the production of jets (groups of particles) with high $p_\perp$ produced in 200-GeV/c interactions. Results are presented on the comparison of jet cross sections on aluminum and hydrogen targets. The jet fragmentation distributions are also examined. Both the cross section and the jet structure are found to depend strongly on the beam and target types.

During the past three years, several groups have studied the production of single, high-transverse-momentum ($p_\perp$), charged hadrons in proton-nucleus collisions.[1-5] It is found in all these experiments that the A dependence of the cross section with all the other parameters fixed is well described by a power law: σ (target of mass number A) is proportional to A^α. At low $p_\perp$, α becomes ~ 0.7 as expected from Glauber theory[6] and found from total cross-section measurements. As $p_\perp$ increases, α increases rapidly until at the highest $p_\perp$ measured so far it is significantly larger than 1.0. This phenomenon has been called[7] the anomalous nuclear enhancement.

In this Letter we will present the first experimental data on $\alpha(p_\perp)$ for the reaction

$$b + A \to \text{jet} + X, \qquad (1)$$

where we observe a jet (group) of particles at high $p_\perp$. Here the beam $b = p$, π^-, or π^+ has a momentum of 200 GeV/c, and the target A = hydrogen or aluminum. We also collected data on the corresponding single, charged, high-$p_\perp$ hadron (h) reaction:

$$b + A \to h + X. \qquad (2)$$

The results in this Letter are from a study of hadron jets produced in hadron-hadron collisions using a calorimeter-triggered multiparticle spectrometer. A complete discussion of our results will be presented elsewhere.[8] Detailed description of the apparatus and previous publications are included in papers by Bromberg *et al.*[9-11] and Fox.[12] The experiment has three major triggers:

(1) Single-particle trigger, with $p_\perp$ in any one of the four modules in either calorimeter (there are two calorimeters, centered at 90° in the c.m. system and placed symmetrically about the beam axis) greater than the trigger bias of 2 or 3 GeV/c.

(2) Jet trigger, with the summed $p_\perp$ of the four modules (in either calorimeter) greater than the trigger bias (set at 3 or 4 GeV/c).

(3) Minimum-bias or interacting-beam trigger. This is a sample of low-$p_\perp$ events defined by the absence of a charged particle in a 5-cm square scintillation counter placed on the beam line 11 m downstream from the target. This gives an essentially unbiased sample of high-multiplicity events but is inefficient for elastic and diffractive scattering.

A jet is defined here by the vector sum of all charged and neutral particles going into a cone defined in the c.m. system and pointing to the center of the calorimeter. This vector sum is required to lie within the fiducial window: |c.m. rapidity| < 0.2 and azimuthal angle $|\varphi| < 20°$ or $|180 - \varphi| < 20°$. We have modified the definitions described in detail earlier[10]; however, the basic idea remains the same. In particular, we use the spectrometer itself to measure the charged particles in the jet and the $p_\perp$ of our jets is measured with much better resolution than is possible with a calorimeter alone. We used the data and Monte Carlo studies to evaluate the reliability of our jet definition. The cuts necessary to define the jets whose $p_\perp$ are well measured lead to small losses of good events. We have checked that such losses do not alter the results presented here.

In Fig. 1, we display the nuclear dependence of the cross sections by defining $\alpha = \ln(\sigma_{\mathrm{Al}}/\sigma_{\mathrm{H}})/\ln A_{\mathrm{Al}}$ where σ are cross sections per nucleus (after correction for beam attenuation in the target) and A_{Al} is the mass number of aluminum. With only two targets, we cannot investigate the validity of the parametrization $\sigma \propto A^\alpha$ which is found to be approximately true for single particles in Ref. 5. Our hydrogen target is 28 cm long after a fiducial cut while our aluminum target, which is placed 4 cm after the hydrogen target, is measured to be 0.08 ± 0.01 cm thick. There is a slight acceptance difference between the aluminum and hydrogen data but this was shown to be negligible both by using a Monte Carlo simulation of the data and by studying the variation of the hydrogen jet cross section on the vertex position within the long target. The error in the aluminum thickness and the acceptance difference leads to an estimated 0.05 systematic error in the value of α which is included in our plots of α vs $p_\perp$ in Fig. 1. Such plots were also made separately for different trigger biases (not shown here); they agree very well. We also show the α's interpolated from cross sections published by Antreasyan *et al.*[5] They agree with our data within the estimated errors. A relative shift of 0.04 between the experiments leads to a better agreement. This is a small shift compared to the large effects shown in the α plots in Fig. 1 and is consistent with normalization uncertainties between the experiments. Not only is α much larger for the jet than for the single-particle trigger in Fig. 1, but the α for jet production also depends on the beam particle. The value of α for a proton beam is significantly larger than that for $\pi^\pm$ beams, especially when $p_\perp > 3.5$. This could be related to the sharper slope of the proton-beam high-$p_\perp$ spectrum; it has been observed[11-13] that the ratio of jet production on hydrogen by proton beams compared to π^- beams decreases from 1.5 to 0.5 (a factor of 3) between $p_\perp = 2$ and 6 GeV/c. The difference $\Delta\alpha = 0.2$ between proton and pion beam in Fig. 1 corresponds to the p/π ratio changing not by a factor of 3 but rather by a factor of 1.5 off an aluminum target. If one imagines that the nuclear jet cross section is gotten by smearing (of

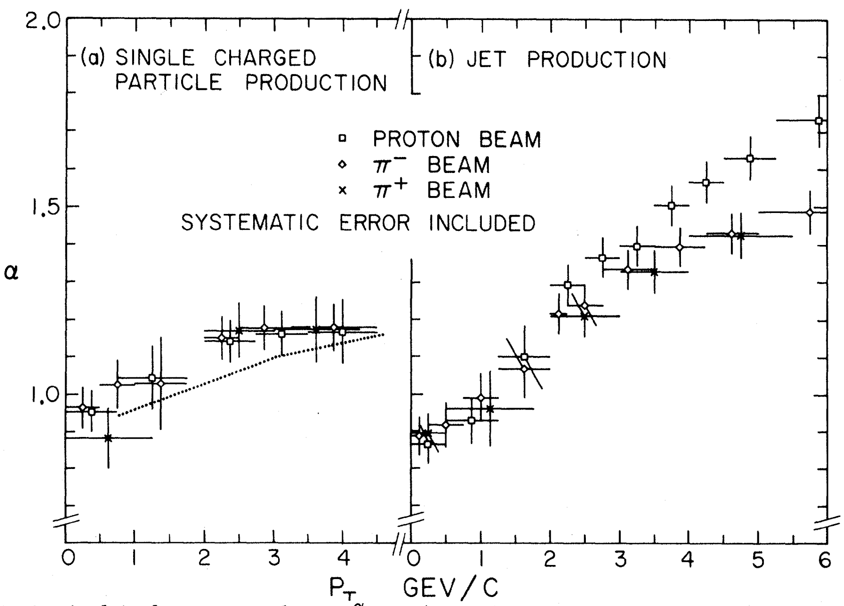

FIG. 1. A plot of α vs $p_\perp$, where $A^\alpha = \sigma_{\mathrm{Al}}/\sigma_{\mathrm{H}}$. The dotted curve comes from Ref. 5.

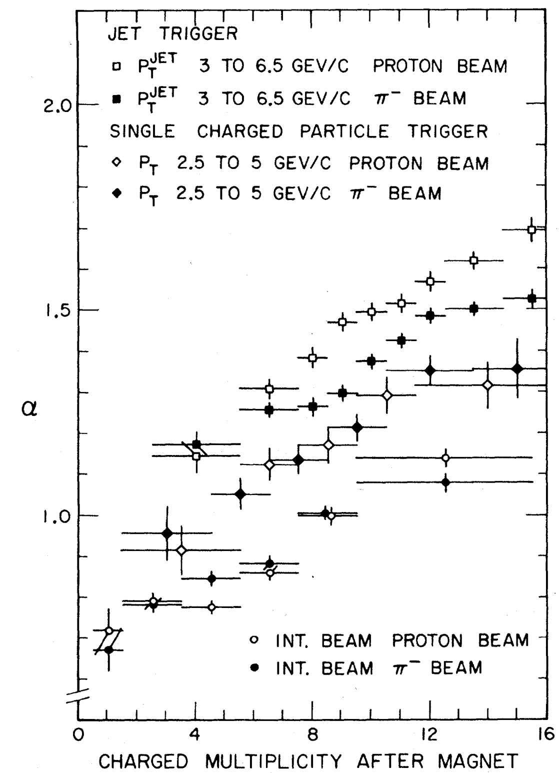

FIG. 2. α vs the charged multiplicity seen after the magnet. These plots clearly indicate that α increases with event multiplicity for all three triggers.

whatever kind) of the hydrogen data, one will always smear the sharper cross section more and so find a larger value of α for it.

One smearing effect in any jet experiment is due to additional low-$p_\perp$ particles that happen to be the cone defining the jet although, in fact, they come, for instance, from the beam or target fragmentation. This smearing is more pronounced for aluminum compared to the hydrogen target as the former has a substantially higher multiplicity at zero rapidity (see Figs. 2 and 3, and Ref. 14). We investigated this effect by generating random particles in the c.m. rapidity range -0.5 to 0.5, with equal probability to be plus, minus, or zero charges. The $p_\perp$ distribution used for the random particles was a Gaussian with a mean $p_\perp$ equal to 330 MeV. We added these extra particles to the events in our hydrogen data and analyzed these modified data just like our original hydrogen data. We repeated this "particle adding" process until the mean charged multiplicity in the jets from our modified hydrogen data agreed with the aluminum target data. The addition of two to three particles gave the best fit. We found that this smearing contributes about 0.15 to the anomalous α value reported in Fig. 1, but it did not appear that it can explain the difference of about 0.4 between the jet and single-particle value of α.

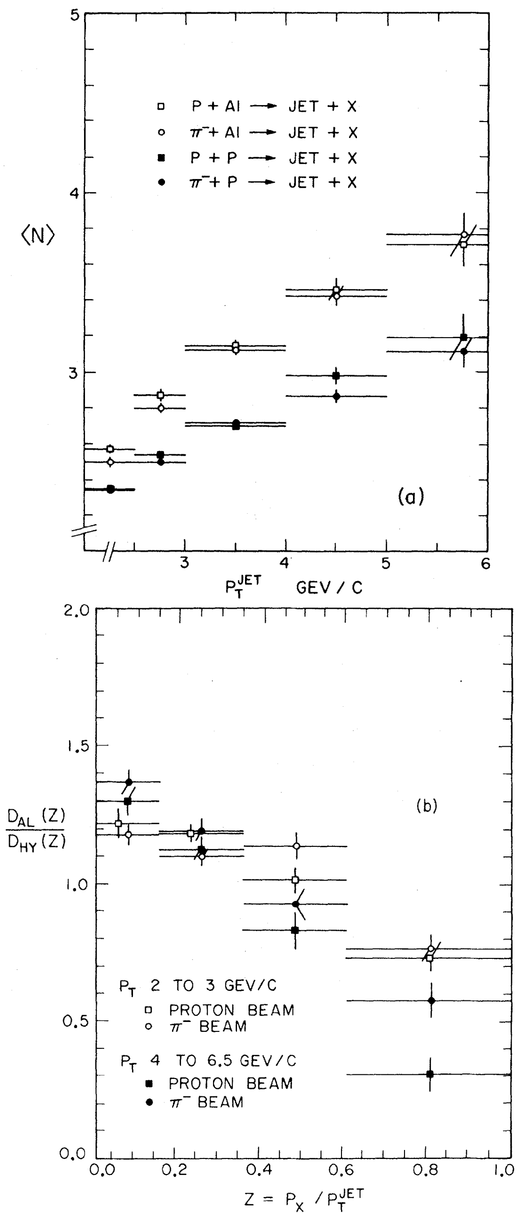

FIG. 3. (a) Charged multiplicity in the jet vs $p_\perp$ for aluminum and hydrogen targets; p and π^- beams. (b) The ratio of fragmentation functions $D(z)$ defined in the text for the aluminum divided by the hydrogen-target data.

At low $p_\perp$, the value of α for our interacting-beam data does not approach 0.7 as $p_\perp$ approaches 0. This could be due to the way we define our minimum-bias sample. The antibeam counter defining this sample has removed most of the low-multiplicity diffractive type of interactions. Further, when we analyze our data, we require at least two charged particles detected before the magnet to form a good vertex. All these conditions mean that we have a very poor efficiency for low-multiplicity events. This will not affect our high-$p_\perp$ data at all since the mean charged multiplicity seen in our experiment for such events is around 10, but it does affect our very low-$p_\perp$ interacting-beam events. Note that the large kinematic acceptance of our apparatus allows us to momentum analyze charged particles with c.m. rapidity $\gtrsim -0.5$. Our track-finding efficiency is 95%. We plot the mean charged multiplicity ($\langle N \rangle$) seen after the magnet versus α in Fig. 2. It shows clearly that α increases monotonically with $\langle N \rangle$ and so the high value of α in Fig. 1 for the interacting-beam data is due to our loss of low-multiplicity events.

In Fig. 3(a), we plot $p_\perp$ versus the charge multiplicity in the jet, and in Fig. 3(b), we plot the relative multiplicity density function $D(z)$ for jets from the two targets, where z =(component of particle $p_\perp$ along jet $p_\perp$)/(jet $p_\perp$), and $D(z) = (dN/dz)/N_{\text{jet}}$, which is usually interpreted as the parton fragmentation function in models where the jets are produced by constituent scattering.[15]

Figures 2 and 3(a) show that aluminum target interactions are associated with a higher multiplicity (in the region of c.m. rapidity $\gtrsim -0.5$) both inside and outside the jet. Figure 3(b) clearly indicates that the high-$p_\perp$ jets from the aluminum target contain more low-momentum particles than the jets produced off protons, and that this effect increases with jet $p_\perp$.

There are strong indications that high-$p_\perp$ scattering is due to interactions among the hadron constituents (quarks and gluons).[15] It seems likely, therefore, that our nuclear target data shed light on the behavior of partons in nuclear matter.[16,17] Our data show that both the production and fragmentation of the produced partons are affected by the presence of nuclear matter in which the partons presumably have secondary interactions. Although this seems the most likely mechanism for the anomalous nuclear enhancement, we are, unfortunately, not aware of any quantitative theories with which we can compare our results. The data presented in this Letter are the first to study the nuclear anomalies with detailed measurement of the event structure. The strong dependence of α on multiplicity and sensitivity to inclusion of diffractive events shown by our data implies that one should be wary of interpretation of α's from previous experiments that have not distinguished diffractive from central collisions. This sensitivity of α to cuts on the data does not seem to agree with many theoretical pictures.[16,17]

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Analysis of the $R_1(J)$- and $P_1(J)$-Branch Absorption Spectrum of HD-Rare-Gas Mixtures: An Example of Positive Intercollisional Interference

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A theory for the intensities and shapes of fundamental band $R_1(J)$ and $P_1(J)$ lines of HD under pressures of rare gases is presented, with specific application to the $R_1(1)$ line of HD-Kr. The absorption contours principally consist of a broad (~100 cm^{-1}) feature representing the ordinary intracollisional dipole intensity, and narrow components arising from the small HD permanent dipole moment function; permanent-dipole–collisionally-induced-dipole interference; and positive intercollisional interference between dipoles induced in successive collisions.

For many years now, pressure-induced vibration-rotation absorption spectra of molecular hydrogen and its isotopes have been of considerable interest both experimentally and theoretically. One of the outstanding features of these spectra as induced by foreign gases is the existence of a pronounced dip[1] in the intensity contour at the position of the Q branch in the fundamental band $(v=0,\ J)\to(v=1,\ J)$. This dip has been interpreted[2] with success in terms of a destructive interference effect associated with the relative orientations of the transition dipoles induced during different (primarily successive) collisions. In addition to these destructive intercollisional effects Lewis and Van Kranendonk[3] have predicted positive intercollisional interference effects (represented by the appearance of peaks rather than dips) in the depolarized components of collision-induced Rayleigh scattering by gases. Such effects have not yet been observed, however.

Superposed on the broad features characteristic of the H_2-induced dipole spectrum, sharp peaks have been observed at the positions of the pure rotation lines[4] $(0,J)\to(0,J+1)$, the fundamental band[5,6] $R_1(J)$ branch $(0,J)\to(1,J+1)$ and $P_1(J)$ branch $(0,J)\to(1,J-1)$ lines, and in at least three overtone bands[5] $(v=0\to 2, 3, 4)$ in pure HD at various pressures. These lines have been attributed,[4-7] at least partially, to the existence of the very small permanent dipole which gives rise to weak transitions. Even more recently, a similarly sharp feature has been observed[8,9] at the $R_1(1)$ line position in HD-Kr and HD-Xe mixtures which is too intense to be explained solely in terms of the permanent dipole moment function. Poll, Tipping, Prasad, and Reddy[9] (henceforth referred to as I) have ascribed its intensity to an interference between the permanent and collisionally induced dipole moments. However, they did not calculate the frequency distribution of this contribution, which is necessary for comparison with spectroscopic observations, nor have they obtained all of the contributions to the sharp feature.

The purpose of this paper is to identify in detail the mechanisms responsible for producing $R_1(J)$ and $P_1(J)$ features in HD-Kr (and, in principle, HD mixtures with lighter rare gases) and to calculate their shape and intensity. According to our findings, these lines each consist of five distinct contributions, as listed later in this paper. In particular, there are three distinct contributions to the sharp feature yielding identical line shapes in the impact limit, including an intercollisional interference contribution, proportional to $\rho_{HD}\rho_{Kr}^2$, as well as the collisional-dipole–permanent-dipole interference term mentioned above, which is proportional to $\rho_{HD}\rho_{Kr}$. While the experiments of Prasad and Reddy indicate only that an enhancement in line strength due to collisions exists, our numerical calculations reveal that the intercollisional term is competitive with the permanent-dipole–collisional-dipole interference term over the pressure range studied. Further experimental work is necessary to isolate the effects of these contributions.

