Production of High-Transverse-Energy Events in p-Nucleus Collisions at 400 GeV/c

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High-transverse-energy events produced in proton-nucleus collisions at 400 GeV/c were studied with use of the Fermilab multiparticle spectrometer. The cross sections for such interactions increase more rapidly than the atomic mass number for both small- and large-acceptance data. The nuclear events are less planar than the corresponding high-transverse-energy pp events.

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It is now widely accepted that the interactions of high-energy particles with nuclear targets provide a unique opportunity to study the space-time development of the hadron production process.[1] The hadronic matter formed as a consequence of a primary interaction may interact again with another nucleon long before it has time to convert into hadrons. In this approach the nucleus is treated as a kind of detector which helps to observe phenomena not accessible to ordinary detectors used in high-energy physics. It has also been argued that high-energy nuclear experiments provide information on the structure of the incident hadrons.[1]

Cross sections for inclusive particle production in hadron-nucleus reactions have been found[1-3] to grow as a power of A, the number of nucleons in the nucleus: $d^3\sigma/d^3p \propto A^\alpha$. The exponent α depends on the flavor and momentum of the produced particle, in particular on the particle transverse momentum, p_t. For particles emitted around 90° in the hadron-nucleon center-of-mass frame, the values of α increase from 0.8 observed in the low-p_t region[2] to values larger than 1 for $p_t \geq 2$ GeV/c.[3] The latter effect, called[4] the "anomalous nuclear enhancement," is also observed when cross sections for production of a group of particles (a "jet") are studied.[5] Values of $\alpha \geq 1$ are often considered as an indication that hard scattering of hadronic constituents plays a dominant role in the production process.[4,6,7]

In this paper we investigate the A dependence of cross sections for the emission of a certain amount of transverse energy, E_t ($E_t \simeq \sum |p_t|$ for relativistic secondaries) into a given solid angle, $\Delta\Omega^*$, in the proton-nucleon c.m. system. The studied range of transverse energy extends up to 80% of the available proton-nucleon c.m. energy and results are presented for both small and large values of $\Delta\Omega^*$. This is the first time that such data have been available and they should provide new types of sensitive tests for models of hadron-nucleus interactions.

These data came from an experiment performed in the Fermilab multiparticle spectrometer with 400-GeV protons. The beam was incident on a 45-cm H_2 target followed downstream by two interchangeable metal foils, of Al, Cu, or Pb. The results from the hydrogen data as well as details of the apparatus have already been published.[8,9] In this report we analyze nuclear-target data taken with three different triggers. The low-E_t "interacting beam" trigger required only the detection of an inelastic collision. The high-E_t triggers made use of the highly segmented calorimeter[10] placed downstream of the magnetic spectrometer, 9.1 m from the nuclear targets; the triggers consisted of the interacting-beam trigger with an additional requirement that the E_t detected in the entire calorimeter ("2π" trigger) or in a smaller region of the calorimeter ("$\pi/3$" trigger), exceeded a threshold.

The geometrical acceptance of the apparatus for the 2π trigger was estimated to be 2π in azimuth for the polar angle range $47° < \theta^* < 127°$ as measured in the proton-nucleon center-of-mass frame. This corresponds to c.m. rapidity range $-0.70 < y^* < 0.84$ and to $\Delta\Omega^* \approx 8.0$ sr. The c.m. solid angle covered by the $\pi/3$ trigger was $\Delta\Omega^* \approx 1.35$ sr. The acceptances for p-A collisions given above were larger by 2% than those for pp interactions.[8,9] The difference in the acceptances for the two nuclear foils was negligible. Table I lists types and thicknesses of the nuclear targets as well as the number of events from each used in the analysis.

The magnetic spectrometer was used only to locate the position of the interaction vertex. The distributions of the vertex coordinate along the incident beam direction, z_{vertex}, are shown in Figs. 1(a) and 1(b) for the interacting-beam–trigger data and for the high-E_t 2π-trigger data, respectively. It is clear from these figures that the relative cross sections for different nuclei depend strongly on the observed E_t. To determine cross sections for the different targets a fit was performed to the z_{vertex} distributions for various regions of E_t. The fitted curve was a sum of two vertex resolution functions and a constant background. The background term accounted for $\approx 10\%$ of all events found in the nuclear-target region. An example of such a fit is presented in Fig. 1(c).

Cross sections per nucleus, $d\sigma/dE_t$, are shown in Fig. 2 for the large-acceptance data (including interacting-beam–trigger data). The data are consistent with the parametrization $d\sigma/dE_t \propto A^{\alpha(E_t)}$ when the hydrogen data are not included. The pp data lie below extrapolated straight lines drawn through the nuclear points. A similar deviation of the pp data has been also seen for single-particle production.[3]

The values of the exponent $\alpha(E_t)$ were determined separately for pairs of nuclear foils for which data were collected simultaneously. This way systematic errors due to threshold effects, calibration of the E_t scale, and absolute normalization have been minimized. The errors in the target thicknesses, estimates of the background, and the acceptance differences (for H_2 and Al) lead to an estimated 0.03–0.05 systematic error in the values of α. There is very good agreement between values of α obtained for the Al-Cu and Al-Pb pairs. However, the Al-Cu data are not available for the entire E_t range.

The variation of α as a function of E_t for the

TABLE I. Targets used in this experiment, and the number of events (N_{event}) taken with different triggers ("IB" denotes interacting-beam trigger).

Target	A	Thickness ($g\ cm^{-2}$)	$10^{-3} \times N_{\text{event}}$ "IB"	"2π"	"$\pi/3$"
H_2	1.0	2.832	32	21.5	5.0
Al	27.0	0.214	0.8	7.5	1.3
Cu	63.5	0.356	0.25	6.5	2.2
Pb	207.2	0.174	0.4	8.7	0.2

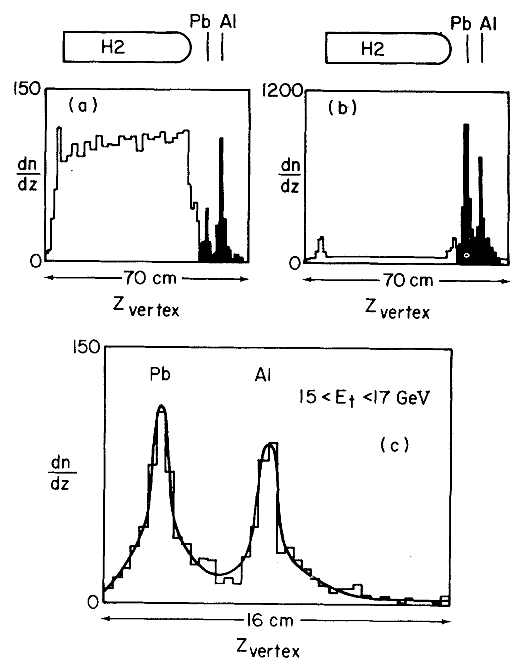

FIG. 1. Distributions of the interaction vertex coordinate along the incident beam direction, z_{vertex}. The nuclear-target region is marked in black in (a) and (b). (a) Interacting-beam–trigger data. (b) 2π-acceptance data with $E_t > 15$ GeV. (c) Enlargement of nuclear-target region for the 2π-trigger data. The curve superimposed on the data represents a fit described in the text.

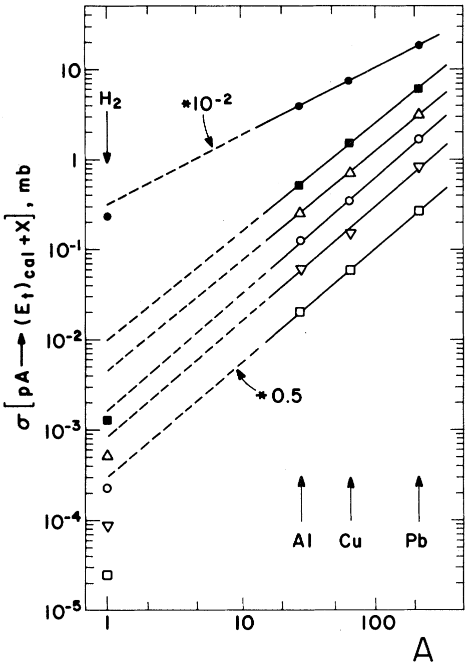

FIG. 2. Cross sections, $d\sigma/dE_t$, for the 2π-acceptance data as a function of atomic mass number, A. Different symbols represent various E_t regions: $1 < E_t < 11$ GeV (full circles); $15 < E_t < 16$ GeV (full squares); $16 < E_t < 17$ GeV (upward triangles); $17 < E_t < 18$ GeV (open circles); $18 < E_t < 19$ GeV (downward triangles); $19 < E_t < 21$ GeV (open squares). The lines represent A^{α} fits to the complex-nuclei data.

2π-azimuthal-acceptance trigger is shown in Fig. 3(a). The exponent α agrees with the expected value of ≈ 0.7 at low E_t,[1] becomes 1 at $E_t \approx 10$ GeV, and, after rising to ~1.20 for $E_t \geq 15$ GeV, flattens off. An increase of α from 0.8 to at least unity is also observed for the smaller-

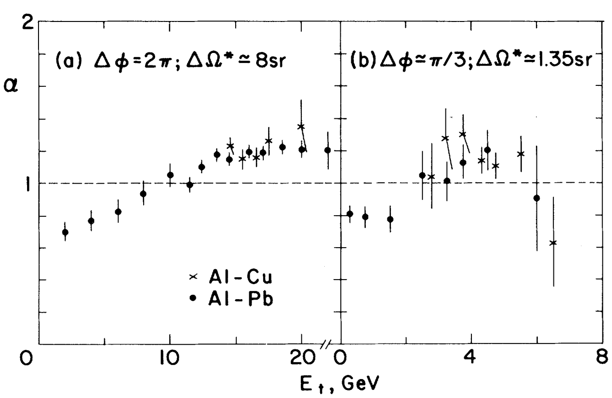

FIG. 3. Exponent α as a function of E_t for (a) the 2π-trigger data, and (b) the $\pi/3$-trigger data. The 0.05 systematic error in the value of α is not included.

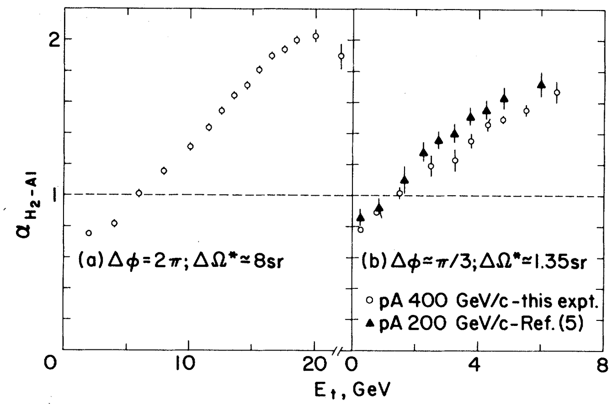

FIG. 4. Exponent $\alpha_{H_2-Al} = \ln(\sigma_{pAl}/\sigma_{pp})/\ln 27$ as a function of E_t. (a) 2π-trigger data. (b) $\pi/3$-trigger data (open circles). Data of Ref. 5 (triangles) are shown for comparison. They correspond to $\Delta\Omega^* \simeq 1$ sr and are plotted as a function of p_t of a jet. The 0.03 systematic error in the value of α_{H_2-Al} is not included.

acceptance trigger ("$\pi/3$") [see Fig. 3(b)]. This behavior of α, as seen in Figs. 3(a) and 3(b), resembles the dependence of α on p_t found for single-particle production.[3]

The trend of α to exceed unity has also been reported for the production of jets from an experiment[5] using a small-acceptance calorimeter. However, α in Ref. 5 was determined only by comparison of p-Al and pp data. The values of α for the $\pi/3$ trigger obtained the same way (shown in Fig. 4) are in good agreement with those of Ref. 5.

The 2π-trigger p-nucleus data exhibit event structure that is slightly less planar in azimuth than that observed for the corresponding pp data.[8,9] One also observes an excess of transverse energy emitted backwards in the proton-nucleon center-of-mass system as compared with the hydrogen data. These two observations are quantified in Table II by using the variable planarity

TABLE II. Mean planarity, $\langle P \rangle$, and average ratio of transverse to total energy observed in the calorimeter, $\langle E_t/E_{tot} \rangle$, for the 2π-trigger data ($E_t > 15$ GeV). The value of $\langle E_t/E_{tot} \rangle$ for H_2 target has been increased by 0.0008 to account for the difference in the acceptance.

Target	$\langle P \rangle$	$\langle E_t/E_{tot} \rangle$
H_2	0.406 ± 0.005	0.0628 ± 0.0005
Al	0.385 ± 0.004	0.0668 ± 0.0003
Cu	0.374 ± 0.005	0.0669 ± 0.0003
Pb	0.376 ± 0.004	0.0681 ± 0.0003

as defined in Refs. 8, 9, and 11 and the average ratio of transverse to total energy observed in the calorimeter, respectively.

Many authors propose to explain the "anomalous nuclear enhancement" for both single-particle and small-azimuthal-acceptance data as due to multiple scattering of the incoming hadron constituents[6] and/or "multijet" production.[7] These explanations exploit the standard four-jet QCD model for pp scattering and therefore cannot be directly applied to the 2π-trigger data, for which the model was found inappropriate.[8,9,11] At this point we cannot determine whether values of α greater than 1 imply hard scattering or can be explained by an extrapolation of low-p_t phenomena to the domain of large transverse energies. In particular, we have checked that we can reproduce some qualitative features of the 2π-trigger data by extrapolating available multiplicity distributions for p-A collisions. However, quantitative results are extremely sensitive to many of the *ad hoc* assumptions we had to make. There are two recent approaches to description of the 2π-trigger pp data: QCD model of parton showers[12] and a low-p_t type multiple Pomeron exchange model.[13] The latter is an extension of a dual parton model[14] which has already been generalized successfully to describe soft hadron-nucleus collisions.[15] The new p-A data present a new challenge for these two models.

We conclude that cross sections for the production of high-transverse-energy events in proton-nucleus collisions increase more rapidly than the atomic mass number. This effect is observed for both small- and large-azimuthal-acceptance data despite the substantial differences in the event structure of the two cases. The nuclear events are less planar than the corresponding pp events and exhibit more energy emitted backward in the proton-nucleon center-of-mass system.

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