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Inclusive Charged-Particle Production in Neutron-Nucleus Collisions

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We have measured inclusive particle production in neutron-nucleus collisions at high energies. Data on positive and negative particles produced in nuclei, ranging in size from Be to Pb, are presented for essentially the full forward hemisphere in the center-of-mass system. Fits of the form A^α to the invariant production cross section indicate that α changes from ~ 0.85 to ~ 0.55 for laboratory rapidities ranging from 3 to 8. Multiperipheral models which invoke cut contributions to particle production in nuclei predict such behavior.

There has recently been renewed interest in the study of hadronic production using nuclear targets.[1] This has largely been fostered by the hope that through an examination of particle production in nuclear matter we can obtain information about the space-time development of hadronic collisions during their nascent stages. The fact that the produced-particle multiplicity at high energies is only a weak function of atomic number has already dispelled any naive notions regarding the presence of intranuclear cascading. Previously available data appeared to favor formulations such as those provided by the energy-flux cascade model and the simple multiperipheral model,[1] both of which predict a moderate increase of multiplicity with increasing atomic number for pion production at central rapidities, and essentially no dependence of multiplicity on nuclear size for larger rapidities (regime of projectile fragmentation). The data we present, although in general agreement with earlier measurements at high energy, clearly demonstrate that multiplicity at large rapidities is a decreasing function of atomic number. Our observations are consequently not consistent with the simplest ideas favored previously for describing production on nuclear targets, but are in accord with expectations from models which admit contributions from exchanges involving several multiperipheral chains.

We have performed an experiment to measure charged-particle production in neutron collisions with the following nuclear targets: Be, Al, Cu, Sn, and Pb. The beam was the broad-band, 1-mrad, $M3$ neutral beam at Fermilab, consisting of neutrons, with minor $K_L{}^0$, $\bar{n}$, and γ components (at $\lesssim 1\%$ level). The neutron momentum spectrum was peaked at about 300 GeV/c, with a full width at half-maximum of ~200 GeV/c.[2] The primaryproton energy was 400 GeV.

Our experimental apparatus, shown schematically in Fig. 1, consisted of a single-arm spectrometer with an aperture of ±80 mrad in the horizontal (bending) plane, and ±2.4 mrad in the vertical plane. The trigger requirement was that no charged particle registered in the veto counter A, and that a charged particle traversed counters S and L. A was a 10 cm×10 cm counter located about 1 m upstream of the target, S was located immediately downstream of the target, and L was a liquid scintillation counter situated downstream of the analyzing magnet about 10 m from the target. Except for a 0.75-in.-thick lead radiator, positioned in front of the L counter (to aid in electron-hadron discrimination), there was no provision made for particle identification in the spectrometer.

The BM109 analysis magnet, having an aperture of 8 in. in the vertical and 24 in. in the bending plane, provided a 0.5-GeV/c transverse impulse to charged tracks. Trajectories were assumed to originate from the target and were measured using magnetostrictive wire spark chambers downstream of the magnet. The small vertical dimensions of the chambers (~1 in.) provided excellent rejection for tracks originating from secondary scatterings off the faces of the magnet. In addition, the simple chamber geometry made pattern recognition relatively straightforward.

The neutron flux was monitored using a total-absorption calorimeter.[3] We estimate that our absolute normalization is known to ±15%, but the relative normalization between elements is reliable to better than ±5%. The target thicknesses used were typically 2% to 5% absorption lengths of material. We ran with a beam intensity of ~50 000 neutrons during a 2-sec spill and a beam-spot size of about 1 mm in diameter.

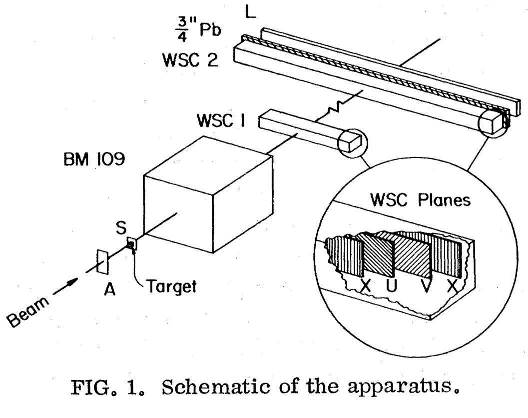

FIG. 1. Schematic of the apparatus.

Target-empty background subtractions were made, and these ranged from 7% to 15% for the different targets. No corrections were made for secondary interactions within the targets because the effect is estimated to be at the 5% level. Electron contamination of the data, resulting from γ conversions of π^0 decays, was greatly reduced with the help of pulse-height information obtained from both ends of the L counter. Specifically, events with large signals in the L counter (caused by electron showers formed in the Pb converter) were eliminated from the sample, and appropriate corrections were made for the loss of hadrons that interacted either in the Pb converter or in the liquid scintillator. An internal check on this procedure was made using two thicknesses of Pb targets. The corrections for $p_T < 0.05$ GeV/c, particularly for $y_{\rm lab} \lesssim 5$, were quite substantial, and consequently these regions of phase space are poorly determined. (We point out, however, that only ~2% of the cross section occurs for $p_T < 0.05$ GeV/c.)

In Fig. 2 we display, for the five elements, the measured multiplicity (i.e., the differential cross section for each element divided by the respective total inelastic neutron-nucleus cross section[4]) integrated over transverse momentum, as a function of the rapidity in the laboratory frame ($y_{\rm lab}$). For the average value of the beam momentum, the rapidity for a particle at rest in the center of mass is about 3.2; consequently, our data span essentailly the full forward hemisphere in the center-of-mass system. The multiplicity shows the expected falloff at large $y_{\rm lab}$ values, with the positively charged particles showing an excess over negative particles at the very largest values of $y_{\rm lab}$. This excess could be due to the presence of protons from neutron dissociation. (Using a pion mass for a possible proton track typically causes an upward shift of about 1.5 units in the value of the rapidity.)

The measured invariant cross sections were fitted to a function of the form A^α, where the parameter α is used to characterize the dependence of the data on the atomic weight A. Although the χ^2 values for such fits are generally acceptable, indicating that, on the average, this form is a good approximation to the data, the value of α appears to decrease somewhat with increasing A. Nevertheless, we have chosen this simple parametrization to allow comparison of our results with other available data.[1]

The dependence of the multiplicity on A in Figs. 2(a) and 2(b) is displayed in terms of the α pa-

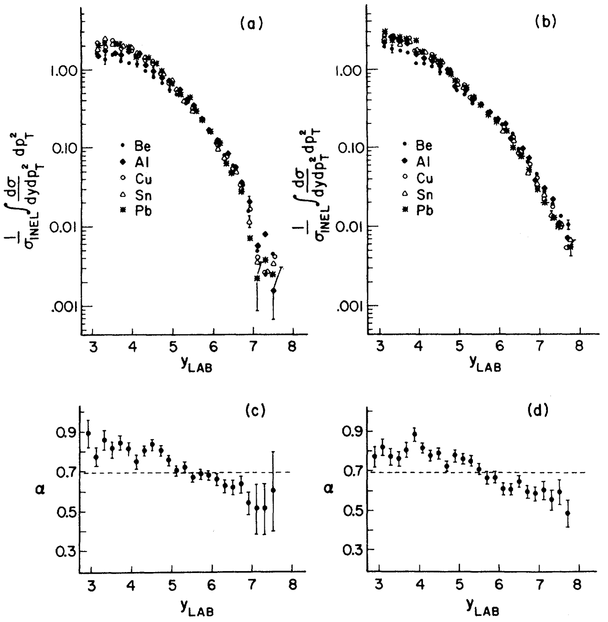

FIG. 2. Charged-particle multiplicity as a function of rapidity for different nuclei. (a) For $n + A \rightarrow q^- + \cdots$; (b) for $n + A \rightarrow q^+ + \cdots$. The symbols q^+ and q^- refer to positive and negative particles, respectively. The parameter α shown in (c) for q^- and (d) for q^+ reactions is from a fit of the cross section with the form A^α; α would be 0.69 if the multiplicity did not depend on nuclear size.

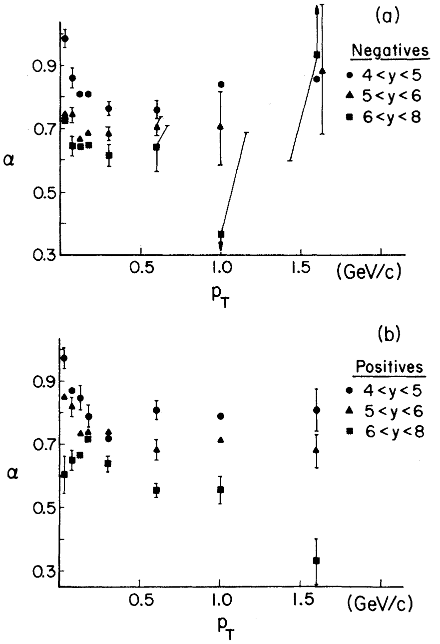

FIG. 3. Variation of α with transverse momentum for three regions of y_{lab}.

rameter in Figs. 2(c) and 2(d) for negative- and positive-particle production, respectively. It is observed that α changes uniformly over the entire region of y_{lab}, indicating that the produced multiplicity is a continuously falling function of A as y_{lab} increases. For most forward rapidities ($y_{\text{lab}} > 6$), the produced multiplicity on small nuclei. This result is not consistent with predictions from simple Regge-pole models or with the energy-flux model, but is expected from models which involve cut contributions to hadronic production in nuclear targets.[5]

The dependence of the cross section on A is examined in more detail in Fig. 3. There we display the values of α as a function of the transverse momentum (p_T) for three regions of y_{lab}: $4 < y_{\text{lab}} < 5$, $5 < y_{\text{lab}} < 6$, and $6 < y_{\text{lab}} < 8$; for negative particles in 3(a), and positive particles in 3(b). The variation of α with p_T appears to depend on y_{lab}. In particular, the value of α for the smallest band of y_{lab} drops with increasing p_T (for $p_T \lesssim 0.5$ GeV/c); however, at larger p_T, α appears to be constant (or possibly increasing).[6] At larger y_{lab}, the variation of α with p_T is less pronounced, α being essentially independent of p_T for negative particles and falling with increasing p_T for positive particles. (The difference could be attributed to the proton component in the positive-particle spectra.)

In conclusion, we have measured the A dependence of inclusive particle production in n-A collisions at high energies. Using the parametrization of A^α for the invariant cross section we have established that the dependence of the multiplicity on A varies with the rapidity in the forward hemisphere in the center-of-mass system and is, in addition, a systematic, albeit complex, function of p_T.

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[1] An excellent summary and an extensive list of references is available in W. Busza, in *Proceedings of the*

Seventh International Colloquium on Multiparticle Production, Tutzing, Germany, 1976, edited by J. Benecke *et al.* (Max-Planck-Institut für Physik und Astrophysik, München, Germany, 1976).

[2] R. Gustafson *et al.*, private communication.

[3] We thank R. Gustafson *et al.* (the University of Michigan group) for the use of their calorimeter monitor.

[4] To obtain the differential charged-particle multiplicity we assumed that the inelastic cross section for n-A collisions is the same as for p-A collisions, namely, $46A^{0.69}$ mb. See Ref. 1 for details.

[5] See, for example, J. Koplik and A. H. Mueller, Phys. Rev. D 12, 3638 (1975); A. Capella and A. Krzywicki, Orsay Report No. LPTPE 77/16, 1976 (unpublished). In addition, see the review of N. N. Nikolaev, to be published.

[6] Similar effects have been reported previously in measurements at different values of y_{lab}. See, for example, J. W. Cronin *et al.*, Phys. Rev. D 11, 3105 (1975); D. Garbutt *et al.*, Phys. Lett. 67B, 355 (1977).

Observation of D^0-Meson Decay into $K^-\pi^+\pi^0$

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In a sample of multihadron events with a π^0 from e^+e^- annihilation data at 3.77-GeV center-of-mass energy, we observe the decay $D^0 \rightarrow K^-\pi^+\pi^0$ with direct observation of the π^0. The observed branching fraction is $(12 \pm 6)\%$.

In e^+e^- annihilation data taken at the $\psi(3772)$,[1] we have observed the $K^\mp\pi^\pm\pi^0$ decay mode of the D^0 ($\overline{D^0}$). This is the first reported observation of a D decay mode containing a π^0.

The data were collected with Stanford Linear Accelerator Center—Lawrence Berkeley Laboratory magnetic detector at SPEAR,[2] augmented by a system of lead-glass counters which replaced one octant of the magnet return yoke[3] for improved γ and electron detection. This system (referred to as the LGW) consists of a 2×26 array of lead-glass blocks (used as active converters) 3.3 radiation lengths (X_0) thick, a 14×19 array of lead-glass blocks $10.5X_0$ thick, and three planes of magnetostrictive spark chambers. The fiducial volume of the LGW covers a solid angle of $0.053\times 4\pi$ sr. This slightly smaller than the solid angle covered by the actual dimensions of the lead-glass counters in order to insure containment of the entire shower resulting from a γ entering the system.

γ's are identified by energy deposited in active converters which are cleanly separated spatially from the calculated intersection points of charged tracks (identified in the inner detector) with the surface of the active converter plane. Correlated deposits in the $10.5X_0$ back blocks and spark chambers are used to give complete information on the γ energy and angles. γ's which convert in the $1X_0$ aluminum magnet coil are tagged by the spark chambers between the coil and active converters, and the appropriate energy-loss correction is made (approximately 55 MeV). If only γ's with energy greater than 100 MeV are considered, there is essentially no background. Thus, in the remainder of the analysis, this energy cutoff is used. The energy resolution for γ's of energy less than 1 GeV is approximately described by $\sigma/E = 0.09/E^{1/2}$ (E in GeV) and the angular resolution is $\Delta\theta \approx 0.3°$.

π^0's are identified by pairs of γ's in the LGW which reconstruct to have a mass consistent with the π^0 mass. Figure 1(a) shows the $\gamma\gamma$ invariant mass ($M_{\gamma\gamma}$) for a sample of multihadronic events containing two or more γ's in the LGW. Clear evidence for π^0 production is observed. A cleaner signal which more clearly shows the magnitude and width of the π^0 signal is obtained if the γ-energy cutoff is increased, as can be seen by the shaded region in the histogram in which an ener-

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