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Abstract The inclusive production of neutrons by 400 GeV protons incident on targets of H, Be, Cu, and Pb has been measured at Fermilab. Neutron spectra from 15 to 400 GeV ($0 < x_F < 1$) have been obtained at laboratory production angles from 0 to 10 mr using an ionization calorimeter detector. The double differential cross sections differ significantly from those for protons and lambdas. Although the total inclusive neutron production is proportional to the inelastic cross section, there is an excess neutron production in heavy elements for $x > 0.6$ and $\theta < 1$ mr. This is probably due to diffraction dissociation and Coulomb dissociation of the incident proton. The result of a triple Regge analysis of the data is in agreement with one-pion exchange.

Introduction In proton-nucleus collisions at very high energies, baryon number conservation and the general properties of collisions lead us to expect a forward-going baryon in the final state, either a proton or a neutron. Hyperon and antinucleon production represent only small corrections. A large body of systematic data on proton and meson inclusive production exists, but there are few experiments on inclusive neutron production.[1,2,3,4,5]

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In the present experiment 400 GeV protons incident on targets of H, Be, Cu, and Pb produced neutrons which were detected in an ionization calorimeter with the production angle stepped between 0.7 and 10 milliradians. The consequent three-dimensional data set (energy-angle-target element) permits a critical study of neutron production systematics. This paper is a report on the final data and some conclusions. It represents the first publication of these data, but the integration and interpretation are still in progress.

Method The system used to make these measurements is indicated schematically in Figure 1. Magnet M2 swept protons and other charged particles from the secondary beam. Magnet M3 was

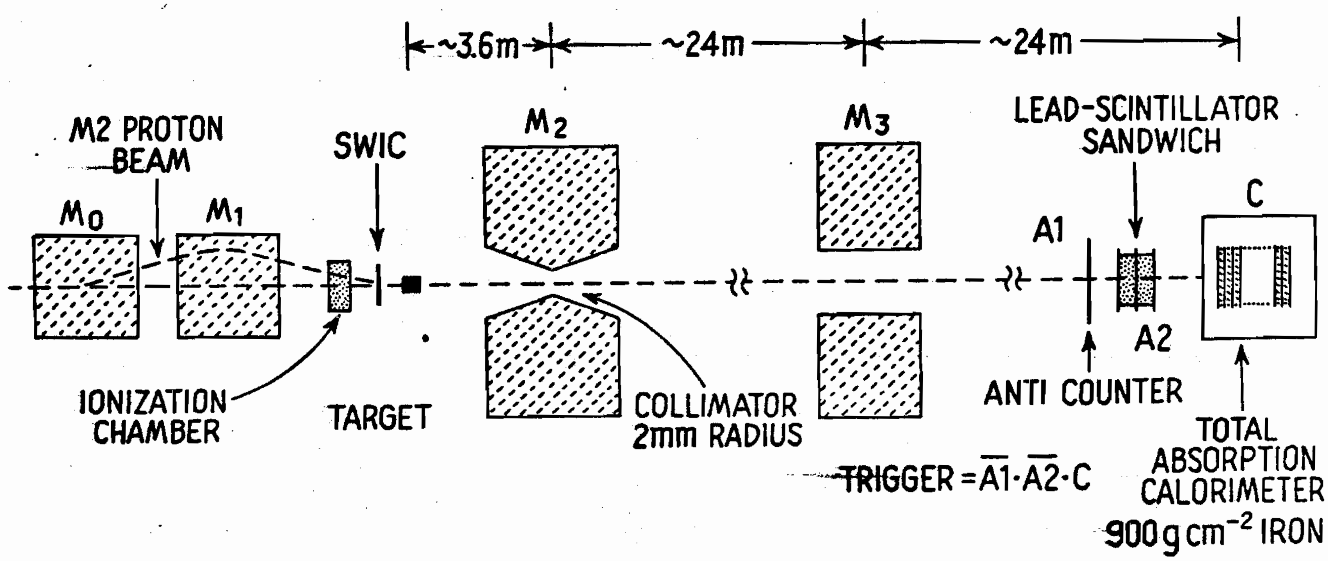

Figure 1: Schematic elevation of the experiment

a part of a spectrometer to study Λ° production and polarization simultaneously.[6] The first magnets, M_o and M_1, permitted the incident 400 GeV proton beam to be steered onto the target over vertical angles ± 10 milliradians with respect to the secondary beam line defined by the 2 mm (radius) collimator and the target. The targets used were typically 1/4 interaction length λ, (although some data was taken with $1/2\lambda$ and λ targets). The hydrogen target was $1/10\lambda$. Charged particles incident on the calorimeter were vetoed by scintillation counter A1; γ rays were converted in 3.8 cm Pb (99.9%) and the showers vetoed in counters A2. The neutrons were detected in a calorimeter described previously[7]; the pulse height from each event was digitized and recorded. The calorimeter events thus vetoed were assumed to be neutrons or $\bar{K}^\circ$; data from the hyperon experiment were used to make a correction for the K° (important at low energies). The calorimeter was calibrated with 200, 300 and 400 GeV protons and determined to have a resolution corresponding to a FWHM = $2.2/\sqrt{E(GeV)}$. Data were corrected for target self absorption, neutron interactions in the lead, and K° contamination. Data were taken at nominal angles of 0, 1.5, 3, 5, 6, 8, and 10 mr for nuclear targets and 0, 1.0, 1.5, 4, 5, 6, and 10 mr for hydrogen. The collimator subtended an angle of ± 0.6 mr, and there was a 0.5 mr horizontal offset to the proton beam direction, so that the true, average angles are those quoted added in quadrature to 0.5 mr. The "0 mr" nominal angle, including the finite aperture and horizontal offset was determined to be effectively 0.7 mr.

Results The corrected neutron production data per unit energy (momentum) and solid angle were converted to the more useful invariant cross section using the relation:

$$E\, d^3\sigma/dp^3 = (E/p^2)\, d^2\sigma/dpd\Omega. \qquad (1)$$

The data are plotted in Figure 2 as $E\, d^3\sigma/dp^3$ vs. x_{cm}, where x_{cm} is defined as $(p_z/p_o)_{cm}$, and p_o is the incident proton cm momentum.

Discussion The total neutron inelastic cross section from Be through U varies as A^α where $\alpha \simeq 0.71$ in this energy range.[8] The same exponent may be used to parameterize the A dependence of the differential production cross section as a function of x and p_t, or x_{cm} and θ. This is done in Figure 3 for a comparison between Pb and Be, where $\alpha(x,\theta)$ is evaluated from the ratio $\alpha = \ell n(\sigma_1/\sigma_2)/\ell n(A_1/A_2)$ where σ_1 is the invariant cross section at that x,θ for the element of atomic weight A_1, etc.

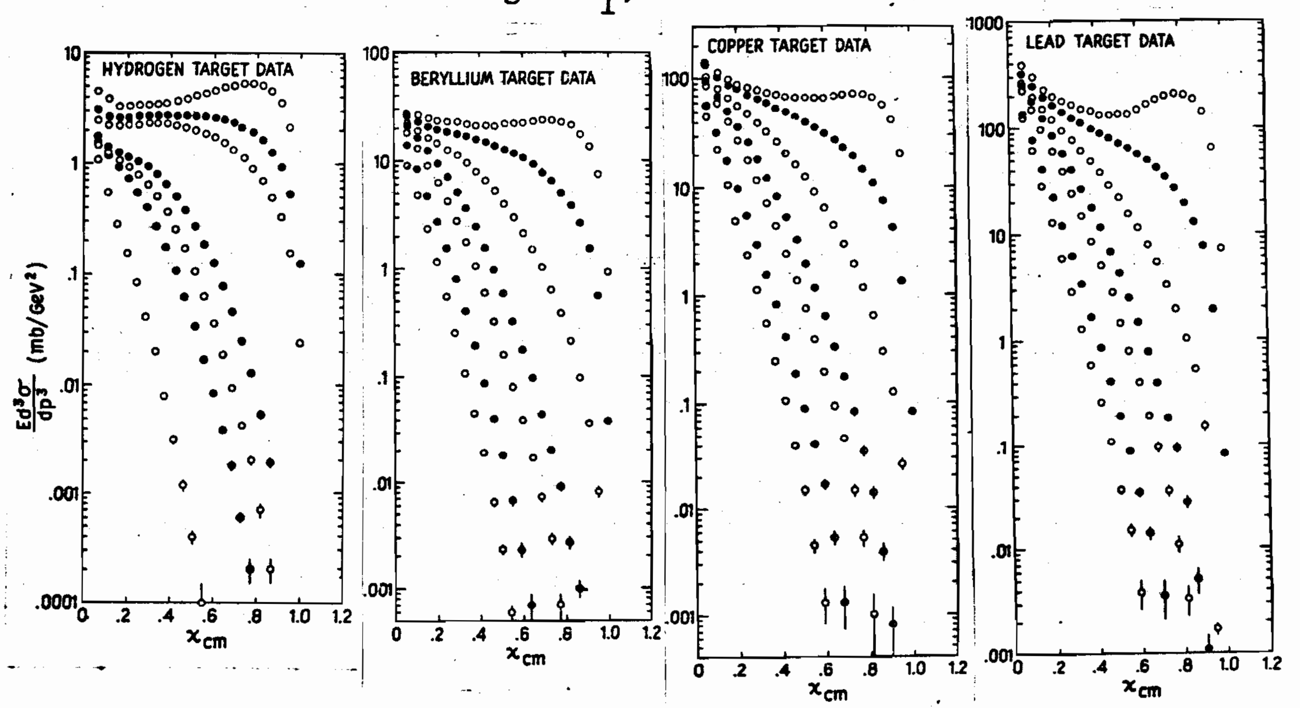

Figure 2: Invariant differential cross sections. Hydrogen data are from 0.7, 1.1, 1.6, 4.0, 5.0, 6.0, and 10.0 mr. The Be, Cu, and Pb data are from 0.7, 1.6, 3.0, 5.0, 6.0, 8.0, and 10.0 mr.

Three features of the data are observed: First, there is a tendency for α to decrease with increasing x for small p_t. Second, α increases at large p_t. This trend is also apparent in the inclusive production of pions and protons where $\alpha \gtrsim 1$ for large p_t. Third, for $x > 0.6$ and $\theta < 1$ mr, α increases sharply. This is understandable as the result of the diffraction dissociation of the incident proton in processes such as $p+A \rightarrow (n+\pi^+)+A$. Coulomb dissociation becomes significant for $Z \gtrsim 9$ and contributes a component proportional to Z^2. The first two effects are also seen in inclusive production of pions and $\Lambda°$.

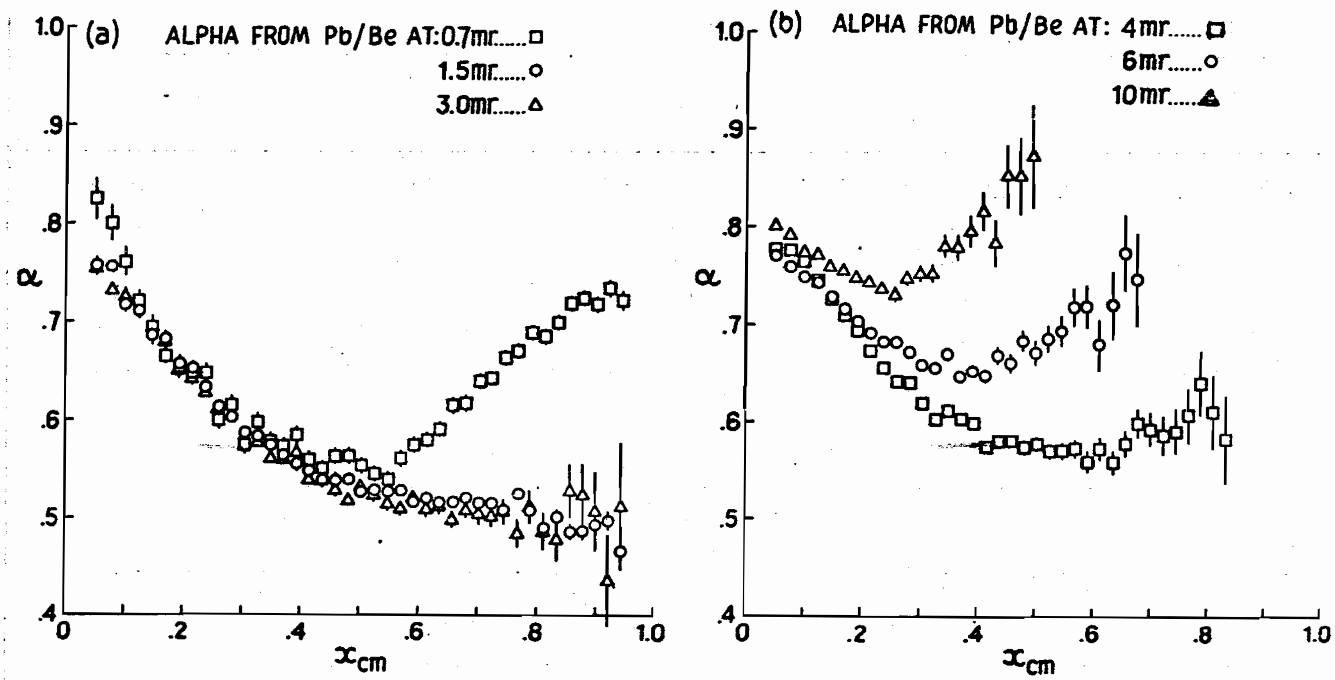

Figure 3: Values of α in the relationship $E\, d^3\sigma/dp^3 \propto A^\alpha$ from the ratio of Pb to Be differential cross sections for different angles and values of x. (α = 0.71 for the total inelastic cross section.)

The average transverse momentum is $\sim$ 550 MeV/c at small x, and decreases to $\sim$ 400 MeV/c as x approaches unity.

The differential cross section for neutron production vs. energy in the laboratory frame may be expressed in either of three forms, differing approximately by powers of E or p (laboratory). The observed neutron spectrum through a fixed solid angle near 0 mr, $d^2\sigma/dpd\Omega$, rises more or less linearly with energy to a maximum at about $(3/4)E_o$ (the incident proton energy). The invariant cross section $Ed^3\sigma/dp^3$ differs from $d^2\sigma/dpd\Omega$ by a factor $\sim 1/E$ (for $E \simeq p >> m_o c^2$), and is hence almost flat, as seen in Figure 2 for θ = 0.7 mr. Examination of these data shows that the cross sections may be factored approximately to a form such as $f(x)\, g(p_t)$. It is then straightforward to evaluate

$$\frac{d\sigma}{dx} = \frac{\pi\sqrt{s}}{2} \int_0^\infty \left(E \frac{d^3\sigma}{dp^3}\right) \frac{dp_t^2}{E_{cm}}$$

where s is the square of the cm energy in the nucleon-nucleon system. At these energies, $x \simeq E/E_o$ (laboratory); i.e. $d\sigma/dx$ may be approximately interpreted as the "inelasticity", in cosmic ray parlance. From $Ed^3\sigma/dp^3$ and $d\sigma/dx$, where

$$\frac{d\sigma}{dx} \propto \frac{E_o}{E} \left(E \frac{d^3\sigma}{dp^3}\right) ,$$

the data of Figure 2 show that $d\sigma/dx$ falls approximately as 1/E. This is in contrast to the conventional wisdom of inelastic proton spectra, where the inelasticity is often taken as nearly flat. In fact, ISR data and hydrogen bubble chamber data demonstrate that the inelastic proton spectra are characterized by an inelastic peak at $E \lesssim E_o$, and a more or less flat region at lower x. At this time a comprehensive set of graphs of dσ/dx integrated over p_t is not complete. We hope to be able to use our data to express such differential cross sections as well as the total cross section for inclusive, forward ($x_{cm} > 0$) neutron production for each of our four target elements.

The transverse momentum dependence of the cross sections is typified by distributions such as plotted in Figure 4 for the hydrogen data at x = 0.35. It is seen to compare reasonably well with other experiments in overall shape.

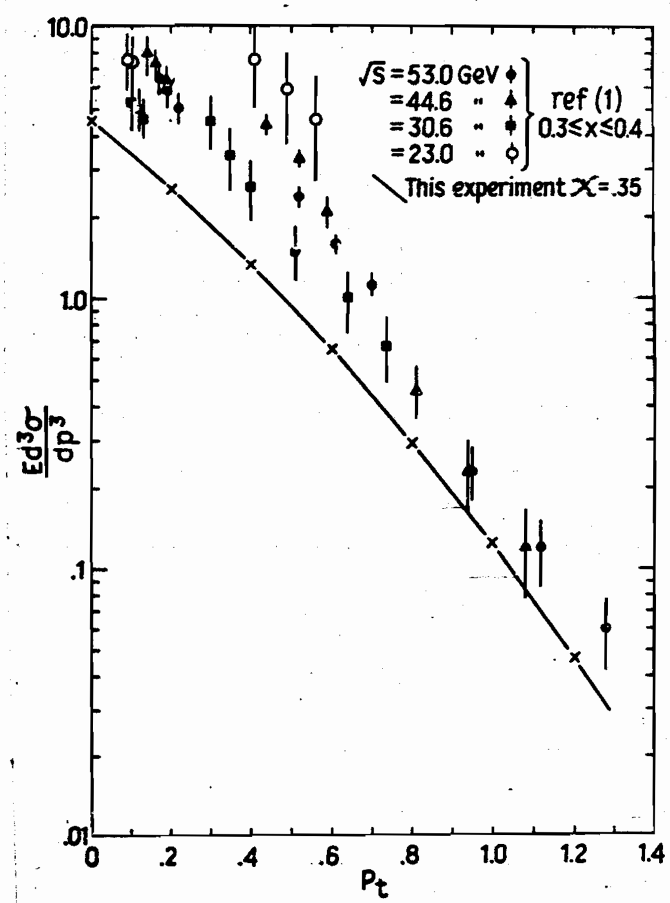

Figure 4: Transverse momentum distribution for 0.3<x<0.4 from this experiment compared with the ISR results.

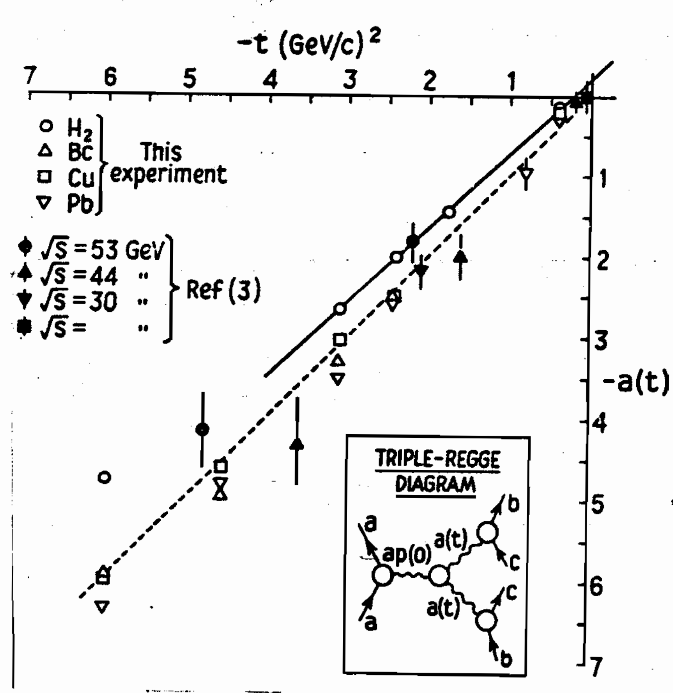

Figure 5: Triple Regge analysis from these data (open symbols) and the ISR data (closed symbols), where a(t) is defined from
$E\, d^3\sigma/dp^3 = C(t)(1-x_{cm})^{(1-2a(t))}$.
The dashed line corresponds to the expected pion trajectory.

A triple Regge analysis was done using these data and provides good agreement with single pion exchange as the dominant process at high x and low p_t (as reported also by other groups). This analysis is summarized in Figure 5.

Conclusions A comprehensive data set on inclusive neutron production by protons on various targets provides useful orientation for calculations of hadron charge and energy flow in cosmic ray proton-initiated cascades. While final integrated cross sections are not yet in hand, the inelasticity (x) distributions already reflect departures from the conventional wisdom of the cosmic ray community.

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