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Calculated Inclusive Neutron Production from 400 GeV Proton-Nucleus Collisions

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Engineering Physics and Mathematics

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ABSTRACT

Calculated inclusive neutron production from 400 GeV proton-nucleus collisions is presented and compared with experimental data. Target nuclei H, Be, Cu, and Pb are considered and the comparisons cover the laboratory energy range of 20 to 400 GeV, and angular range 0.7 to 10 mr. Moderately good agreement between the calculated and experimental data is found, but the agreement in the case of Be, Cu and Pb is significantly better than in the case of H.

1. INTRODUCTION

Particle production spectra from high-energy (hundreds and thousands of GeV) hadron-nucleus collisions are of interest in shielding calculations for accelerators such as the proposed Superconducting Super Collider (SSC)[1,2] and also in design calculations for high-energy calorimeters.[3] In studies such as those contained in Refs. 1 and 2, the high-energy very forward neutrons are of particular interest since these neutrons are not affected by the magnetic field.

In this paper, calculated results for these neutrons are presented and compared with available experimental data.[4]

A multi-chain fragmentation model that may be used to generate exclusive events has been implemented into a cross section code, EVENTQ, embedded in the transport code FLUKA87[5] by J. Ranft et al. (see also Ref. 6 and the references given therein). A slightly modified version of this cross section code (see Ref. 7), has been incorporated into the high-energy transport code HETC88.[8] The calculations reported here were done using the version of the code described in Ref. 7, but at the neutron energies and angles considered here there should be no substantial difference between the results given by the code of Ref. 7 and the differential cross section code in FLUKA87.[5]

2. DETAILS OF THE CALCULATIONS

In Ref. 4, the experimental data are presented in the form of the invariant cross section for neutron production as a function of center-of-mass Feynman-x and laboratory angle so this is the form in which the comparisons will be made. The invariant cross section is defined to be

$$E \frac{d^3\sigma}{dp^3}$$

where

σ = total nonelastic cross section,
E = total energy,
p = momenta.

The invariant cross section is related to the usual double differential cross section by the relation

$$E \frac{d^3\sigma}{dp^3} = \frac{E}{p^2} \frac{d^2\sigma}{dpd\Omega} \tag{1}$$

The calculations were performed by calculating the double differential cross section for a given momentum and angular range and then converting to the invariant cross section by means of Eq. (1). The calculational model does not provide an estimate of the total cross section, so total cross sections based on experimental data are used. These cross section values were obtained from the cross section module in FLUKA87 and for the nuclei considered here are given in Table 1.

Table 1

Total Nonelastic Cross Sections for 400 GeV Proton-Nucleus Collisions

Nucleus	Cross Section (mb)
H	32.9
Be	199
Cu	801
Pb	1879

The laboratory z-momentum, p_z, used in calculating the invariant cross sections can be transformed into the center-of-mass by Lorentz transformation and the center-of-mass Feynman-x defined by

$$x_{cm} = \left(\frac{p_z}{p_o}\right)_{cm} \tag{2}$$

where

p_o = the incident proton momentum,

may be calculated. Then, the invariant cross section may be compared with the experimental data as a function of x_{cm} for specific average values of the laboratory polar angle.

3. RESULTS AND DISCUSSION

The experimental and calculated invariant cross sections are compared for the elements H, Be, Cu, and Pb in Figs. 1, 2, 3, and 4, respectively. In the case of H, the laboratory polar angles 0.7, 1.6, 4.0, 5.0, 6.0, and 10.0 mr are considered and the angular intervals over which the calculations are averaged are 0.0-1.4, 0.9-2.3, 3.0-5.0, 4.0-6.0, 5.0-7.0, and 9.0-11.0 mr, respectively. In the cases of Be, Cu and Pb, the polar angles 0.7, 1.6, 3.0, 5.0, 6.0, 8.0, and 10.0 mr are considered and the angular intervals over which the calculations are averaged are 0.0-1.4, 0.9-2.3, 2.3-3.7, 4.0-6.0, 5.0-7.0, 7.0-9.0, 9.0-11.0 mr, respectively. It should be noted that in order to obtain adequate statistical accuracy in the calculations, some of the angular intervals overlap. This means that not all of the comparisons in a given figure are independent in the sense that some calculated particles contribute to more than one calculated histograms. The calculated error bars where shown are statistical only and represent one standard deviation in the calculations. The error bars on the other histograms are of the same order as those shown.

At the higher momenta when calculated results are not shown, it is to be understood that the value is zero within the statistical accuracy of the calculations.

In all of the figures, the calculations underestimate the invariant cross sections at the higher momenta for 0.7 mr. The experimental data at 0.7 mr exhibits a broad shallow peak in the vicinity of $x_{cm} = 0.7$ to 0.8 and the calculated results give no such peak but rather, in all cases, exhibits a broad shallow peak in the vicinity of $x_{cm} = 0.2$ to 0.3. In the case of H, Fig. 1, for the other angles, the calculations overestimate, by factors of two to three, the invariant cross section at the smaller values of x_{cm} but tends to agree better at intermediate values of x_{cm}. Comparing Fig. 1 to Fig. 4, it can be seen that the calculated results are substantially poorer in the case of H than in the cases of Be, Cu, and Pb. In the cases of Be, Cu, and Pb the calculated and experimental results agree to within approximately a factor of two over the angular and momenta ranges considered, in which the experimental data varies over three to four orders of magnitude.

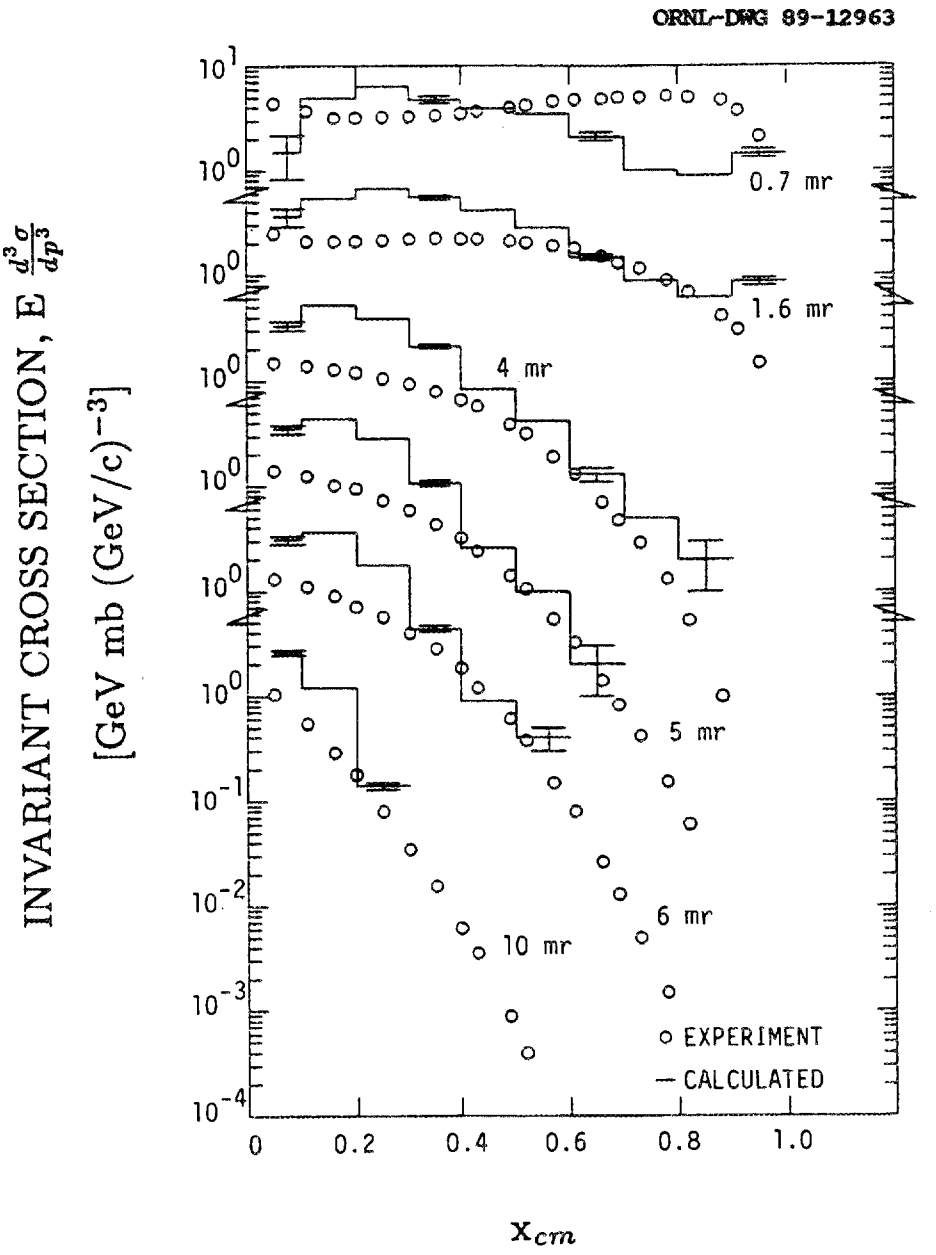

Fig. 1. Invariant cross sections for neutron production vs. $x_{cm}\left[=\left(\frac{p_z}{p_o}\right)_{cm}\right]$ for 400 GeV proton-hydrogen collisions.

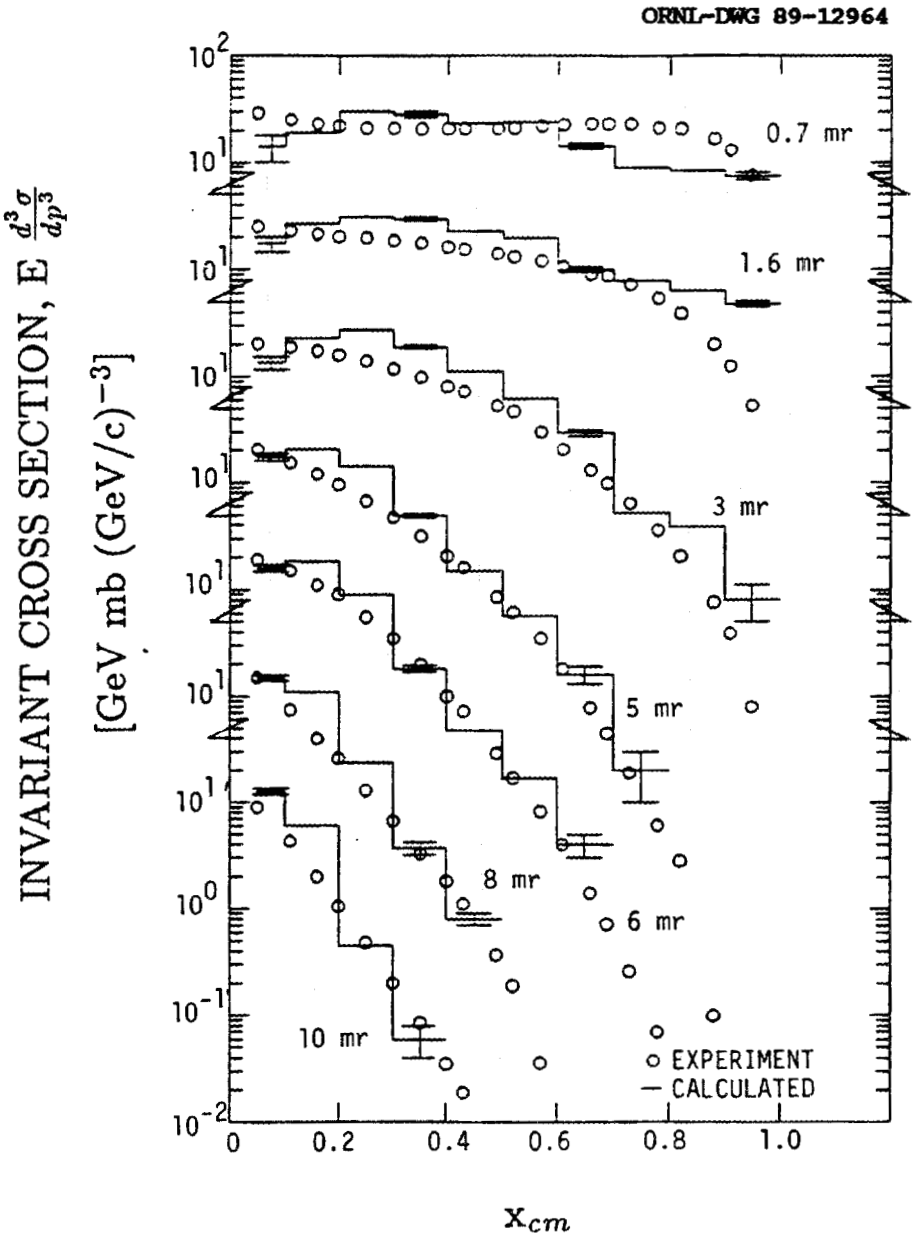

Fig. 2. Invariant cross sections for neutron production vs. $x_{cm}\left[=\left(\frac{p_z}{p_o}\right)_{cm}\right]$ for 400 GeV proton-beryllium collisions.

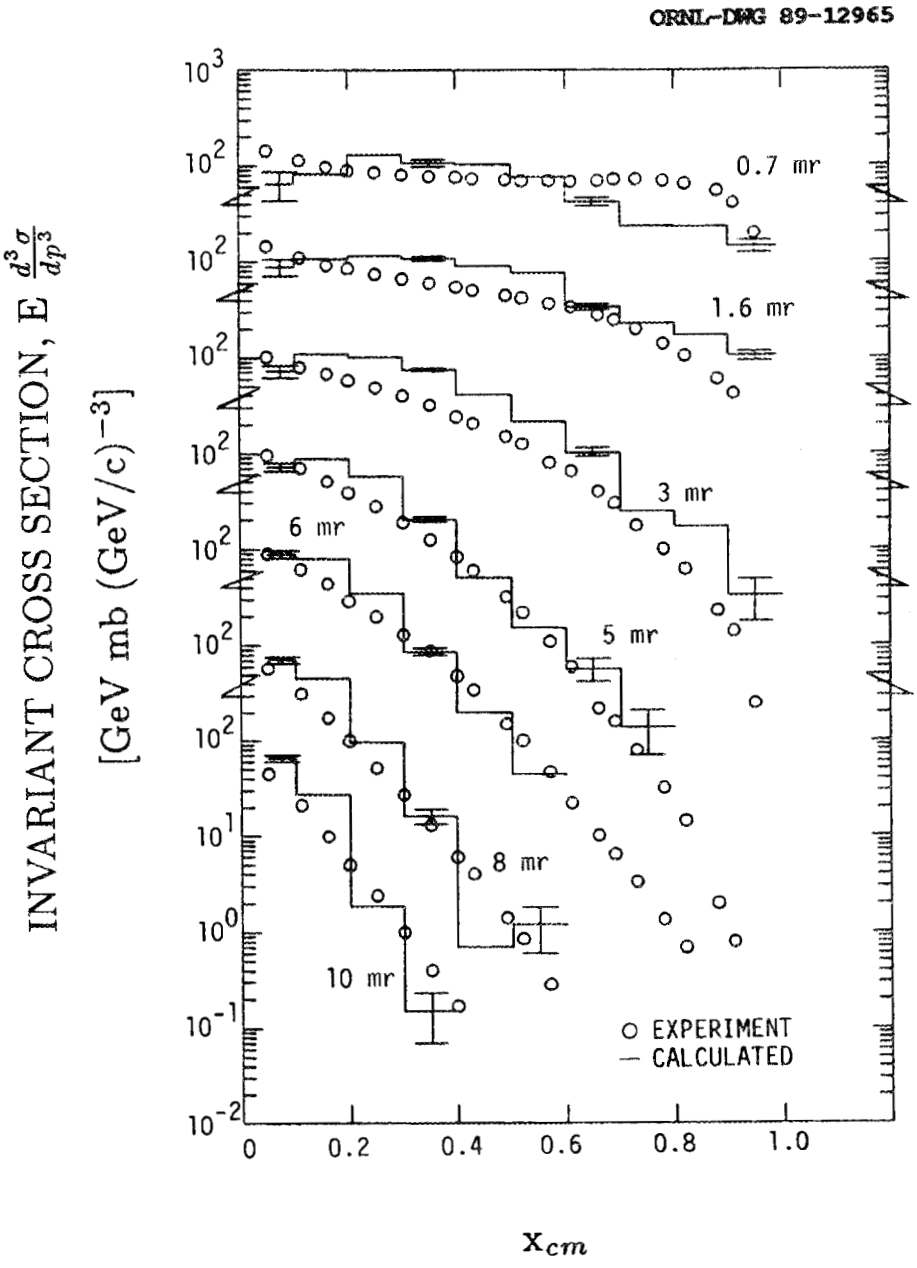

Fig. 3. Invariant cross sections for neutron production vs. $x_{cm}\left[=\left(\frac{p_z}{p_o}\right)_{cm}\right]$ for 400 GeV proton-copper collisions.

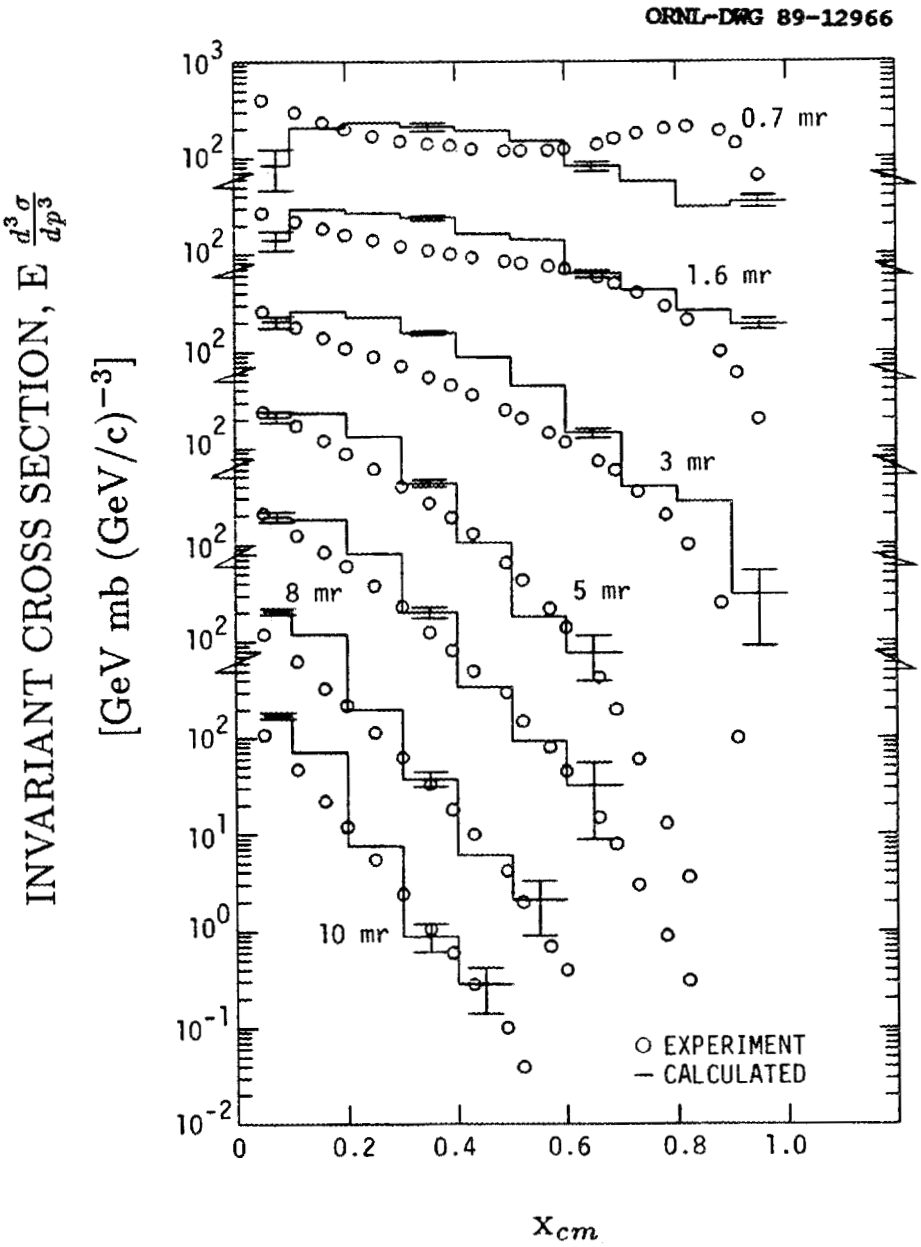

Fig. 4. Invariant cross sections for neutron production vs. $x_{cm}\left[=\left(\frac{p_z}{p_o}\right)_{cm}\right]$ for 400 GeV proton-lead collisions.

REFERENCES

1. T. A. Gabriel, F. S. Alsmiller, R. G. Alsmiller, Jr., B. L. Bishop, O. W. Hermann, and D. E. Groom, "Preliminary Simulations of the Neutron Flux Levels in the Fermilab Tunnel and Proposed SSC Tunnel," SSC Central Design Group Report, SSC-110, Lawrence Livermore National Laboratory (1987).

2. D. E. Groom, "Measurements and Simulations of the Neutron Flux in the Tevatron Tunnel," included in SSC Central Design Group Task Force Report, SSC-SR-1033, 163, Lawrence Livermore National Laboratory (1988).

3. T. A. Gabriel, "Detectors for the Superconducting Super Collider, Design Concepts and Simulation," presented at the Workshop on Calorimetry for the Superconducting Super Collider, University of Alabama, Tuscaloosa, Alabama, March 13-17, 1989, and to be published in the Proceedings.

4. L. N. Jones et al., "Inclusive Neutron Production by 400 GeV Protons," presented at the X International Symposium on Multiparticle Dynamics Group, India, September 1979. (Preprint UMHE79-33 supplied by L. N. Jones, University of Michigan)

5. P. A. Aarnio, J. Lindgren, J. Ranft, A. Fasso, and G. R. Stevenson, "Enhancements to the FLUKA86 Program (FLUKA87)," CERN Division Report TIS-RP/190 (1987).

6. J. Ranft and S. Ritter, "Rapidity Ratios, Feynman-X Distributions and Forward-Backward Correlations in Hadron-Nucleus Collisions in a Dual Monte Carlo Multi-Chain Fragmentation Model," *Z. Phys. C. – Particles and Fields* **10**, 249 (1981).

7. F. S. Alsmiller and R. G. Alsmiller, Jr., "Inclusions of Correlations in the Empirical Selection of Intranuclear Cascade Nucleons from High-Energy Hadron-Nucleus Collisions," to be published in *Nuclear Instruments & Methods in Physics Research.*

8. R. G. Alsmiller, Jr. et al., "The High-Energy Transport Code HETC88," presented at the Workshop on Calorimetry for the Superconducting Super Collider, University of Alabama, Tuscaloosa, Alabama, March 13-17, 1989, and to be published in the Proceedings.

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