how F_n and F_p approach the scaling limit, it is almost impossible to make any meaningful comparsions between these functions with data presently available.

[11]L. S. Rochester, private communication.

[12]Such a picture has been discussed by M. Ida and R. Kobayashi, Prog. Theor. Phys. 36, 846 (1966), and by D. B. Lichtenberg, Phys. Rev. 178, 2197 (1969).

[13]H. J. Melosh, Phys. Rev. D 9, 1095 (1974).

Neutron-Nuclear Total Cross Sections between 30 and 300 GeV/*c**

J. Biel, E. Bleser, C. Bromberg, T. Ferbel, D. Freytag, B. Gobbi, L. Kenah,† J. Keren, J. Rosen, R. Ruchti, P. Slattery, D. Spelbring, and D. Underwood

Fermilab, Batavia, Illinois 60510, and Northwestern University, Evanston, Illinois 60201, and University of Rochester, Rochester, New York, 14627, and Stanford Linear Accelerator Center, Stanford, California 94305

(Received 4 December 1975)

We report new measurements of neutron-nuclear total cross sections obtained at Fermilab. The data are for neutron momenta between 30 and 300 GeV/c and for nuclear targets of carbon, aluminum, copper, and lead.

Precision determinations of neutron total cross sections on nuclear targets in the 30- to 300-GeV/c range have recently been reported.[1] We have performed a similar set of measurements in the M-3 neutral beam at Fermilab using the standard good-geometry transmission technique. A novel feature of the experiment was the method employed for neutron detection. A 0.25-in.-thick Pb neutron "converter" was placed in front of a high-resolution forward-V spectrometer. The spectrometer was triggered on the coherent dissociation of the neutron into a $p\pi^-$ system (V), produced in the reaction $n + \mathrm{Pb} \to (p\pi^-) + \mathrm{Pb}$, and provided us with excellent positional and energy-measuring capability for transmitted neutrons.[2] Figure 1 illustrates schematically the basic principle of our good-geometry transmission measurement. We measure the rate of V production with (I_A) and without (I_0) a nuclear transmission target located ~200 m upstream of the spectrometer; the ratio of these yields, normalized by an independent beam monitor, is used to determine total cross section for neutrons on specific targets.[3]

The reason for normalizing by an independent monitor is to correct for time variations in the intensity of the incident neutron beam. For this purpose we employed a Fermilab-designed counter telescope which directly monitored the primary Meson Lab target from which the neutrons originated. To minimize the dependence of our measurements on time variations in the efficiency of this monitor, we continuously alternated, under computer control, the target-in and target-out conditions. We have examined the ratio I_0/I_A as a function of time for each transmission target, and have detected no statistically significant temporal variations in this quantity.

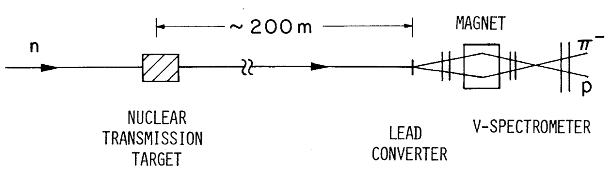

FIG. 1. Schematic illustration of transmission method for measuring total cross section.

For the sake of brevity, we will comment here on only three major points in the analysis[4]:

(1) *Correction for small-angle scattering.*—The primary advantage of employing a detector with excellent spatial resolution is that it provides a means for making this important correction with justifiable confidence. The need for such a correction arises because neutrons which scatter in the transmission target through a small angle can still strike the Pb converter and yield detectable V's. Because for large nuclei the elastic differential cross section peaks sharply at very small scattering angles, the magnitude of the required correction is not in general negligible. Figure 2 presents data which we use to correct our measured total cross sections for such small-angle scattering. The figure displays distributions in the square of the radial position (R) of the reconstructed vertexes of V's for each transmission element employed. For comparison purposes, the data for each target have been normalized to the distribution for the target-out situation (dashed histograms). The amount by which the solid histograms exceed the dashed histograms as this transverse coordinate increases is a direct measure of the fractional importance

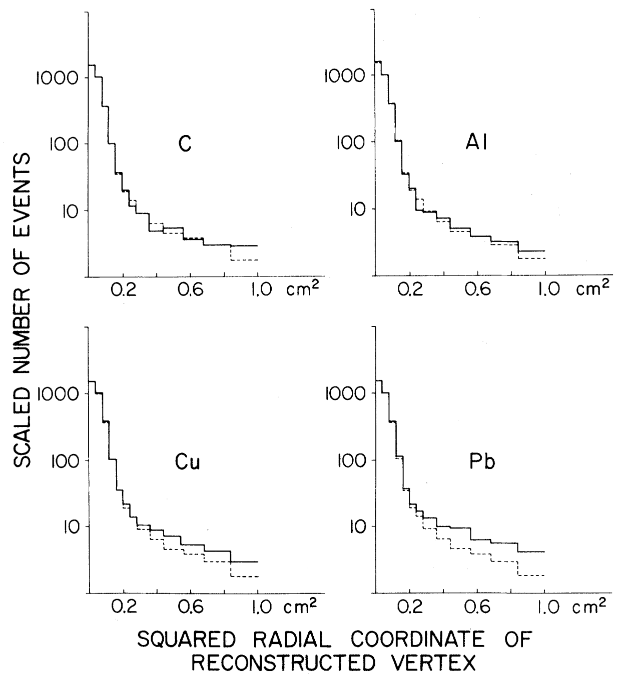

FIG. 2. Distributions in the square of the radial coordinate of the reconstructed V vertexes relative to the beam axis. The data for each element have been normalized to the target-out distribution (dashed histograms).

of the small-angle-scattering correction for each element. As expected, the effect is more significant for the heavier elements (Cu and Pb).

The differential cross section for the scattering of neutrons at small four-momentum transfers ($t=|t|\approx p_T^2$) is well represented by the function Ae^{-bt}, with A and b being constants; and because t can be approximated by the expression $(pR/L)^2$, where p is the incident neutron momentum and L is the distance between the transmission target and the Pb converter, a quantitative estimate of the number of detected V's, which are in reality small-angle scatters, may be made for each element and for each momentum band through the use of the data in Fig. 2.[5] By restricting the sample of V's to those with radial coordinate less than 4 mm, the absolute magnitude of the small-angle-scattering correction was kept less than $\frac{1}{2}$ of the statistical error in even the worst case (the highest-momentum Pb point), and the absolute uncertainty in the magnitude of the correction applied was in all cases truly negligible.

(2) *Determination of momentum dependence.*—Because our spectrometer enables us to precisely measure the momentum of each detected V, we obtain directly the momentum dependence of the total cross section for each element. The only significant limitation on the accuracy of this determination arises if there is significant contamination in the final sample of V's from the competing three-body dissociation reactions $n+\text{Pb}\rightarrow(p\pi^-\pi^0)+\text{Pb}$ and $n+\text{Pb}\rightarrow(n\pi^+\pi^-)+\text{Pb}$. Equating the neutron momentum with the momentum of the charged V would in these reactions yield a systematic underestimation of the momentum value for the event in question. (This effect would be most significant in the case of dissociation into $n\pi^+\pi^-$, where the outgoing neutron tends to carry off most of the incident momentum.) We have examined the dependence of our measurements on the dynamic properties of the detected V's (e.g., the mass of the $p\pi^-$ system, the momentum transfer to the V, etc.) and found no significant effect. The insensitivity of the measured total cross sections to the presence of the residual three-body dissociation events may be attributed to the near energy independence of the neutron-nuclear total cross sections.

(3) *Effect of target thickness.*—To ascertain that our measurements of total cross sections do not depend on geometric dimensions of the transmission targets or on interaction rates in these targets, we compared data for two different thicknesses of carbon material. Using 15-cm and 50-cm graphite targets we detected no statistically significant difference in the extracted total cross sections for the full range of incident neutron momenta. (The typical transmission target we employed in our experiment was equivalent in thickness to approximately one interaction mean free path of material along the beam direction.)

To summarize, our spectrometer enabled us to measure the momentum of each detected V to $\pm 1\%$ accuracy; we therefore obtained directly the momentum dependence of the total cross section for each target element. Furthermore, the excellent spatial resolution ($\sim\pm 0.03$ cm) of our neutron detector was a valuable asset in making corrections for those neutrons which undergo small-angle scattering in the transmission target but still strike the Pb converter and yield detectable V's. We found that corrections for such small-angle scatters even for a Pb transmission target never exceeded 1% of the measured cross sections. We have investigated other possible sources of systematic error and believe that our total cross section determinations constitute measurements which are effectively model independent,

TABLE I. Neutron-nuclear cross section.

Momentum range (GeV/c)	Cross section Carbon	Aluminum	Copper	Lead
30–80	336 ± 9	645 ± 23	1268 ± 36	3087 ± 88
80–130	319 ± 6	603 ± 14	1167 ± 22	2830 ± 53
130–170	323 ± 5	623 ± 12	1206 ± 19	3037 ± 47
170–200	309 ± 5	588 ± 12	1181 ± 19	2963 ± 48
200–220	323 ± 6	607 ± 14	1204 ± 23	2953 ± 56
220–240	312 ± 6	611 ± 15	1238 ± 23	2944 ± 57
240–260	326 ± 7	620 ± 16	1272 ± 25	3063 ± 62
260–300	320 ± 7	631 ± 17	1200 ± 27	2982 ± 67

and limited only by statistical uncertainty.

The results of our measurements are presented in Fig. 3 and tabulated in Table I. The data points on the figure are our measured values; the cross-hatched region represents previously published results in this energy regime.[1] (The limits of the cross-hatched region correspond to ± 1 standard deviation variations from the measured values.) The solid curve summarizes results at lower energies. The two high-energy measurements appear to be in good agreement for Pb, but display systematic disagreement as the atomic number decreases. (We can provide no obvious explanation for this small but significant discrepancy; if the method of correcting for small-angle scattering were at fault, the disagreement would be expected to be most pronounced for large A.) One effect of the disagreement between the two experiments is that if one chooses to parametrize the A dependence of the neutron-nuclear total cross section $\sigma_T(A)$ in the form $\sigma_0 A^\nu$, then our ν values are systematically larger than those reported in Ref. 1.[6] Another, perhaps more interesting, consequence is that while the qualitative agreement between the data and Glauber theory (including inelastic screening) remains,[1] the quantitative level of this agreement is worsened.

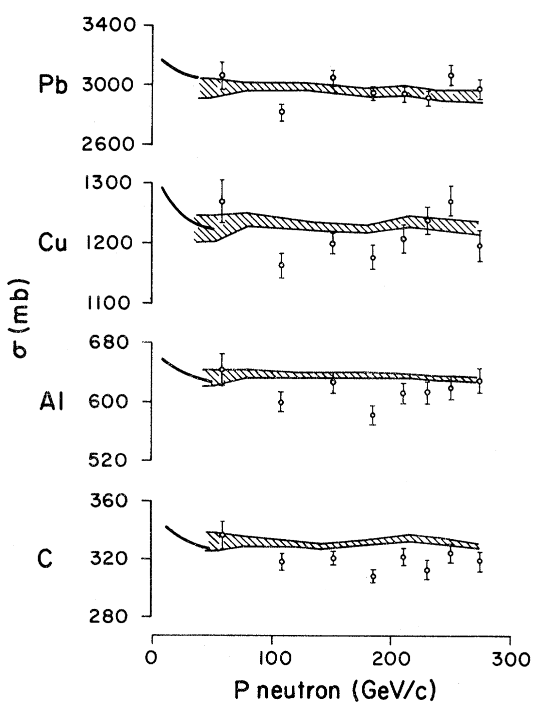

FIG. 3. Neutron-nuclear total cross sections measured in this experiment. The cross-hatched region represents the previously available data in this energy regime (Ref. 1); the curves summarize lower energy results.

We thank J. P. DeBrion, D. Chaney, R. Lipton, P. Mühlemann, and H. Scott for assistance in the running of the experiment. We also acknowledge the excellent support of P. Koehler and the staff at the Meson Detector Laboratory during the execution of the experiment.

*Research supported by the U. S. Energy Research and Development Administration.

†Present address: Digital Equipment Corp., Maynard, Mass. 01754.

[1]L. W. Jones *et al.*, Phys. Rev. Lett. 33, 1440 (1974); P. V. R. Murthy *et al.*, Nucl. Phys. B92, 269 (1975). These papers also provide an excellent summary of work performed at lower energies.

[2]Detailed descriptions of our spectrometer, and of the explicit triggering scheme employed, have been presented elsewhere. See, for example, J. Biel *et al.*, Phys. Rev. Lett. 36, 504 (1976); T. Ferbel, in Proceedings of the International School of Subnuclear Physics, "Ettore Majorana," Erice, 1975, edited by A. Zichichi (Academic, New York, to be published).

[3]The neutral beam contained minor components of γ, $K_L{}^0$, and $\bar{n}$. The γ's were effectively removed using a 2-in.-thick Pb filter. Corrections due to $K_L{}^0$ and $\bar{n}$

contaminants were negligible because of the nature of the detection scheme. This point will be discussed more fully in a forthcoming publication.

[4]A more complete discussion of the experimental details is being prepared for publication. For a preliminary presentation of these measuremnts, see P. Slattery, in *Particles and Fields, 1975,* edited by H. Lubatti and P. M. Mockett (Univ. of Washington, Seattle, Wash., 1975).

[5]This correction requires a knowledge of the momentum spectrum of the incident neutrons. This momentum spectrum has been independently determined in our experiment (see Ferbel, Ref. 2), and by M. Longo *et al.*, University of Michigan Report No. UM-HE-74-18 (unpublished), and the two measurements are in very close agreement.

[6]The average value of ν is ~ 0.78 near 30 GeV/c; in excess of 30 GeV/c, ν falls below 0.77 for the data of Ref. 1, and rises to 0.79 for our data. Although small, these differences are statistically significant.

Evidence of Pair Origin of Prompt Muons

H. Kasha, R. G. Kellogg, M. J. Lauterbach, and R. K. Adair
Yale University, New Haven, Connecticut 06520

and

L. B. Leipuner and R. C. Larsen
Brookhaven National Laboratory, Upton, New York 11973

and

R. J. Stefanski
Fermi National Accelerator Laboratory, Batavia, Illinois 60510
(Received 9 February 1976)

A comparison of measurements of prompt single muons, produced in the forward direction by 400-GeV proton interactions, with the results of measurements of muon pairs produced under the same conditions shows that the pair intensity accounts for the inclusive single-muon flux in a manner which is insensitive to the details of the production and decay of the muon pairs. The mean invariant mass of the pairs is about 900 MeV/c^2.

It has been known for some time that the inclusive production of single leptons in high-energy interactions is anomalously large[1] inasmuch as elementary estimates of the production of leptons from conventional sources, such as the electromagnetic decays of the known short-lived vector mesons, fail to account for the observed intensity by about one order of magnitude. Most conjectures concerning the origins of these leptons consider that the leptons are produced either electromagnetically or through the weak decays[2] of heretofore unknown particles produced in the strong interactions. If the leptons are produced electromagnetically, they will always be produced in pairs; if they are produced through the weak-interaction decay of an intermediate particle, the proportion produced in pairs will be equal to or smaller than the branching ratio for the particle's decay to the lepton and that branching ratio will probably be smaller than one-fourth. In view of the importance of the question of pair production, we have conducted measurements designed to determine the proportion of prompt muons produced in pairs by the nuclear interactions of 400-GeV protons.

Since we had not invented an ideal 4π detector able to identify muons of all energies, we proceeded to design a measurement such that the ratio of measured dimuon intensities to single-muon inclusive intensities in a more limited kinematic region would depend on the proportion of dimuon parentage of the prompt muons in a manner which was insensitive to the largely unknown production and decay characteristics of the dimuons. In general, the production of dimuons will depend upon M, the invariant mass of the pair, and p_T and p_L, the transverse and longitudinal momenta of the center-of-mass of the pair. The decay of the pair will depend upon M and α and φ, where α is the angle of decay with respect to the direction of production of the pair and φ is the azimuthal decay angle. Our experimental design is such that the ratio is nearly independent of the distribution in M and p_T, quite insensitive to the