RECENT EXPERIMENTAL RESULTS ON n-p SCATTERING FROM 6 TO 30 GeV/c

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I would like to present new results from several experiments at the Bevatron and the AGS. The distinguishing feature of all these experiments is that they were all done with neutron beams using counter and spark chamber techniques. This work was done by a Michigan-SLAC-Princeton collaboration. The participants were B. Gibbard, L. Jones, S. Powell, J. O'Fallon, and myself from the University of Michigan; J. Cox, W. Toner, and M. Perl from SLAC; and M. Kreisler from Princeton. I shall not elaborate on the experimental details, but mainly point out any unusual techniques.

n-p Total Cross Sections, 14 to 27 GeV/c

The first experiment I shall discuss is a measurement of n-p total cross sections in the 14 to 27 GeV/c region. These measurements were made with an incident neutron beam rather than with the more common (pd-pp) subtraction technique with the Glauber shadowing correction. This allows an interesting check on the Glauber correction and also can provide more accurate cross sections since previous measurements have been limited in accuracy by uncertainties in the Glauber correction.

The experimental arrangement is shown in Fig. 1. The technique used is essentially the standard transmission technique.[1] A well-collimated neutron beam is incident on a liquid hydrogen target. The flux of neutrons transmitted with target empty and full was measured with a "total absorption spectrometer" or "calorimeter" of the sort frequently used in cosmic ray research. This consisted essentially of an array of steel slabs interspersed with scintillation counters. The summed output of the counters was thus roughly proportional to the neutron energy. The neutrons were required to interact first in a 5 cm steel slab just in front of the calorimeter. Counters S_2 and S_3, 7.0 cm and 12.1 cm in diameter respectively, defined the solid angle subtended by the neutron detector. Coincidences between each of these and the rest of the array were scaled separately to allow the usual extrapolation of the cross sections to "zero solid angle."

The discriminator on the summed output pulse was set so that only neutrons which gave unusually large pulses were accepted. This strongly favored neutrons near the upper end of the incident neutron spectrum. The rather sharp cutoff on the high end of the incident neutron spectrum just below the AGS energy determined the upper limit of the effective neutron spectrum. The effective momentum spectrum is shown schematically in Fig. 2 for a typical point. The width of the response curve was estimated by studying how the rate fell off when the AGS energy was lowered. The momentum resolution achieved is comparable to that resulting from the internal motion of the neutron in the deuteron when a (pd-pp) subtraction technique is employed. It was necessary to change the AGS energy for each neutron energy studied. This seriously limited the amount of running time available at the lower energies. The neutron beam intensity was monitored by a pair of counter telescopes placed in the neutron beam upstream of the last sweeping magnet.

Between six and forty-five separate measurements of the cross section were made at each momentum, and the results averaged. Sources of systematic errors in the results seem to be small. Contamination of the beam by gammas, kaons, and antineutrons was negligible since the neutron detector only responded to particles with energy approximately equal to the AGS energy. A linear extrapolation of the data taken at the two different solid angles to zero solid angle was made. The resulting corrections were very small (≈ 0.2 mb for hydrogen), and a more elaborate extrapolation procedure was therefore not required. We also measured nd total cross sections at two momenta (14.6 and 27.0 GeV/c). These agree very well with results of Galbraith et al.[2] for $\sigma_T(pd)$. This serves as a very important check on our technique.

Our results are given in Table 1 and Fig. 2. The crosshatched curve in Fig. 2 shows the trend of the data for $\sigma_T(pp)$.[2,3,4] Also shown are the results of Galbraith et al.[2] for σ_T(np) based on a (pd-pp) subtraction with the Glauber correction. Our results tend to be slightly lower than those of Galbraith et al. This discrepancy is within the uncertainty in the Glauber corrections they used (see below).

TABLE 1: Neutron Total Cross Sections

Momentum (GeV/c)	σ_T(np) (mb)	σ_T(nd) (mb)
14.6	37.1 ± 1.2	72.2 ± 1.5
17.8	37.5 ± 1.1	
21.6	37.7 ± 0.8	
27.0	38.9 ± 0.6	69.7 ± 0.7

Our results appear to confirm that σ_T(np) becomes less than σ_T(pp) around 14 GeV/c as previously suggested by the data of Galbraith et al. There is also an indication that the two cross again near 28 GeV/c. It is of considerable interest to verify this behavior of the pp and np cross sections. Theorists would like to see σ_T(np) approach σ_T(pp) asymptotically from above while the data are more consistent with σ_T(np) varying about σ_T(pp) below 30 GeV/c.

Another interesting question we can study is the high energy behavior of the Glauber shadowing correction. Abers et al.[5] have suggested on the basis of Regge theory that the shadowing correction may decrease rapidly with increasing energy. We define the experimentally measured shadowing term as

$$\delta\sigma_{\mathrm{exp}} = \sigma_T(pp) + \sigma_T(np) - \begin{cases}\sigma_T(pd)\\ \text{or}\\ \sigma_T(nd)\end{cases},$$

where $\sigma_T(np)$ is measured directly with a neutron beam. The available data are tabulated in Table 2.

TABLE 2: Experimentally Observed Screening Correction

Momentum	$\delta\sigma_{\mathrm{exp}}$	References
3.0 GeV/c	1.3±1.4	Palevsky *et al.*; Bugg *et al.*
6.5	3.0±1.7	Khachaturyan *et al.*; Bugg *et al.*
14.6^*	4.3±1.9	This exp't; Foley *et al.*
17.8	3.9±1.7	This exp't; Foley *et al.*; Galbraith *et al.*
21.6	5.0±1.5	This exp't; Foley *et al.*; Galbraith *et al.*
27.0^*	8.1±0.9	This exp't; Foley *et al.*

$^*\sigma_T(nd)$ used in calculation; otherwise $\sigma_T(pd)$ is used.

It must be emphasized that the errors quoted for $\delta\sigma_{\mathrm{exp}}$ are purely statistical, and systematic errors could greatly affect the results for $\delta\sigma_{\mathrm{exp}}$. It can be seen from Table 2 that the data are highly suggestive of a *rising* Glauber correction rather than one decreasing with increasing energy. How seriously one should take this is unfortunately a matter of personal taste because of possible systematic errors, but a decreasing correction seems to be excluded by the data.

It is amusing to note that the two experiments which studied the Glauber correction in pion-nucleon scattering also give results suggesting that the correction is rising with increasing energies,[2,6] but again the systematic errors are too large to allow strong conclusions. Glauber[7] gives the correction in terms of a parameter $\langle r^{-2} \rangle$ representing the mean inverse square of the separation of the nucleons in the deuteron. By comparing cross section measurements of pions on hydrogen and deuterium, Baker *et al.*[6] found $\langle r^{-2} \rangle = .0239$ mb in the momentum range 2.5 to 6 GeV/c while Galbraith *et al.*[2] found $\langle r^{-2} \rangle = .0423$ mb in the range of 6 to 20 GeV/c. (The quoted systematic errors are ±.009 mb for the first measurement and ±.005 mb for the second.) If Galbraith *et al.* had used $\langle r^{-2} \rangle = .0239$ mb instead of .0423 mb their values for $\sigma_T(np)$ would be reduced about 2 mb near 20 GeV/c, which would make their points generally lower than ours. This illustrates how important the Glauber corrections are in determining $\sigma_T(np)$ relative to $\sigma_T(pp)$. Since most of the existing data on $\sigma_T(np)$ at high energies was obtained from experiments employing a (pd-pp) subtraction technique, the questions of the behavior of the screening correction at high energies and that of the difference between $\sigma_T(np)$ and $\sigma_T(pp)$ are closely related. Further theoretical and experimental work along these lines is clearly of great interest.

Total Cross Sections for Neutrons on Nuclei at 27 GeV/c

In the same experiment we also measured total cross sections for 27 GeV/c neutrons on various nuclei. For heavy nuclei the use of a neutron beam presents a considerable advantage over charged beams due to the absence of coulomb scattering. This allows measurements to be made at very small angles. Our experimental arrangement was optimized for the measurements with hydrogen, and this advantage was not utilized fully. For the heavy elements we had to make significant corrections for that part of the elastic scattering which was contained within the smallest counter.

Preliminary results for the total cross sections are given in Table 3 and Fig. 3. The results of Bellettini *et al.*[11] for 20 GeV/c protons are also given. A substantial discrepancy, most noticeable for large A, exists between the two experiments despite the fact that the total nucleon-nucleon cross sections are quite flat in this energy region and $\sigma_T(np) \cong \sigma_T(pp)$. In extracting the total cross sections from their measurements, Bellettini *et al.* had to assume that the real part of the scattering amplitude was zero. Data now available show that $\alpha_{pp} \approx \alpha_{np} \approx -0.26$. We would expect a similar value for nuclei at small four-momentum transfers. It appears to be possible to account for the discrepancy if $\alpha \approx -0.26$ is assumed.

TABLE 3: Total Cross Sections for Nuclei

Nucleus	A	σ_T (mb) 27 GeV/c Neutrons (This Experiment)	σ_T (mb) 20 GeV/c Protons (Bellettini et al.)
H	1	38.9 ± 0.6	-
D	2	69.7 ± 0.7	-
Li	6	-	232. ± 5.
Li	7	-	250. ± 5.
Be	9	255. ± 5.0	278. ± 4.
C	12	308. ± 6.0	335. ± 5.
Al	26.9	585. ± 10.	687. ± 10.
Fe	55.8	1060. ± 20.	-
Cu	63.5	1135. ± 22.	1360. ± 20.
W	183.9	2500. ± 200.	-
Pb	207.2	2800. ± 100.	3290. ± 100.
U	238.0	3040. ± 100.	-

n-p Elastic Scattering in the Diffraction Peak

The next experiment I shall discuss is a measurement of cross sections for np diffraction scattering from 8 to 30 GeV/c done at the AGS. The results are quite preliminary, and based on only about 5% of the total sample of data available. The technique is the same as that used in a previous experiment at the Bevatron.[12] The apparatus is shown schematically in Fig. 4. A neutron beam containing neutrons of all energies is incident on a hydrogen target. Scattered neutrons are detected by allowing them to interact in steel-plate spark chambers. The position of the vertex gives the scattering angle of the neutron. The recoil proton is detected in a spark chamber spectrometer and its angle and momentum are thus determined. The kinematics are overdetermined (a 2C fit), and the momentum of the incident neutron can be determined for each event. The events are then binned according to the momentum of the incident neutron.

In Fig. 5 we compare our results at 3 different mean neutron energies, 5.9, 10.5, and 22.5 GeV. The data at 5.9 GeV are from a previous experiment done at the Bevatron with the same technique. Some results from the Bevatron experiment have been previously published,[12] but the data in Fig. 5 include a sample of data several times larger than that in Ref. 12. We have also cleaned up a problem in matching up cross sections measured with different settings of the apparatus which had caused some spurious structure in the cross sections. As can be seen, the new Bevatron data fall off very smoothly with no evidence of any structure. This is true at all energies from 1 to 28.5 GeV, though at present the Bevatron data have much better statistics. The Bevatron data extend well beyond 90°. The large t data have been discussed by M. Perl, and his paper can be consulted for details.

Returning to Fig. 5, we see there is evidence for shrinkage of the diffraction peak between 6 and 10.5 GeV, but none is apparent between 10.5 and 22.5 GeV with the present statistical accuracy.

In Fig. 6 we compare our results at 10.5 GeV with pp results[13] at a similar energy. It can be seen that the two agree quite well. Our data extend up to 30 GeV/c, and I can summarize it very well by saying that at the present level of statistics there are no surprises. There is no evidence of any structure in the diffraction peak. The cross sections fall off about as $e^{-9|t|}$, and in all cases the np differential cross sections closely resemble the pp.

References

1. A somewhat more detailed account of the experimental technique is given in an article by Michael N. Kreisler, Lawrence W. Jones, Michael J. Longo, and John R. O'Fallon (submitted to Phys. Rev. Letters).
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Figure Captions

Figure 1. Experimental arrangement for σ_T measurement (schematic).

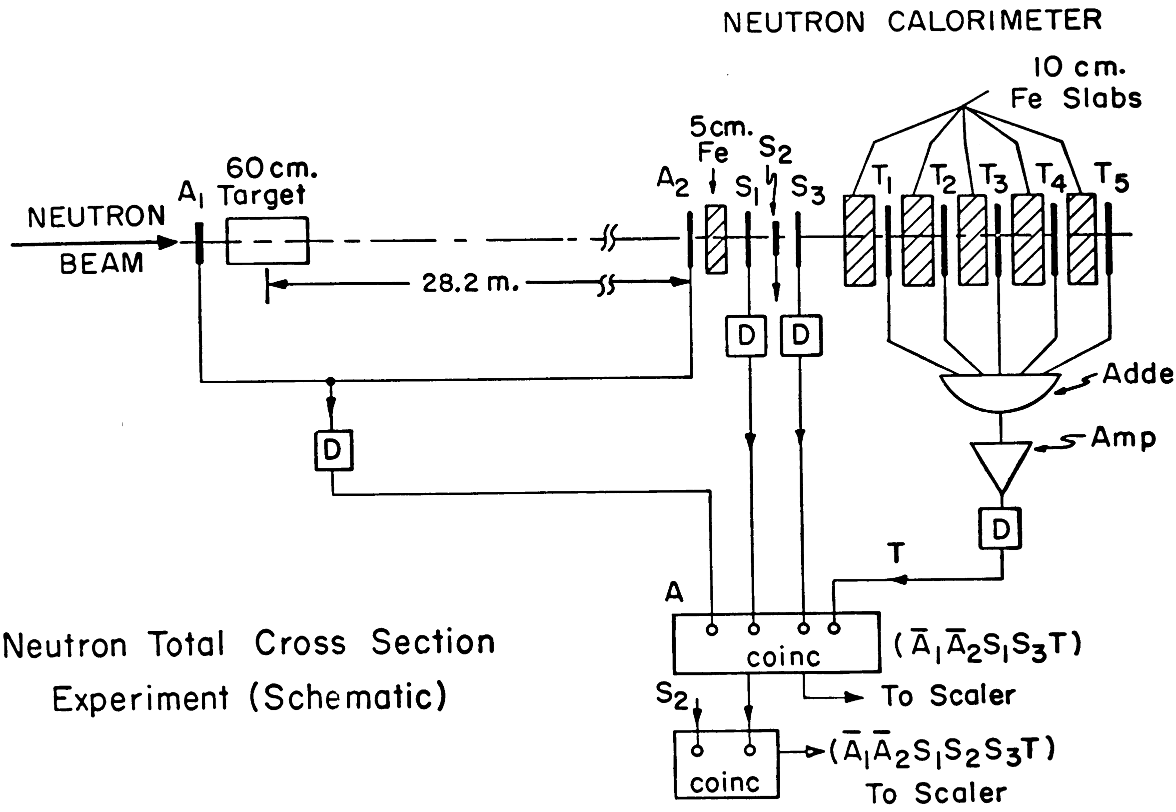
Figure 2. Results for $\sigma_T(np)$. The data of Ref. 2 have been lowered by 0.34 mb to take into account data now available on the real part of the forward scattering amplitude which enters into the Glauber correction. The inset shows our estimated effective momentum resolution for a typical point.

Figure 3. Preliminary results for total cross sections of 27 GeV/c neutrons on nuclei.

Figure 4. Apparatus for measurement of n-p elastic scattering.

Figure 5. Preliminary results for $d\sigma/dt$ for n-p scattering at three energies.

Figure 6. Comparison of $d\sigma/dt$ for np forward scattering with $d\sigma/dt$ for pp scattering near 11 GeV.



Neutron Total Cross Section Experiment (Schematic)

FIG. 1

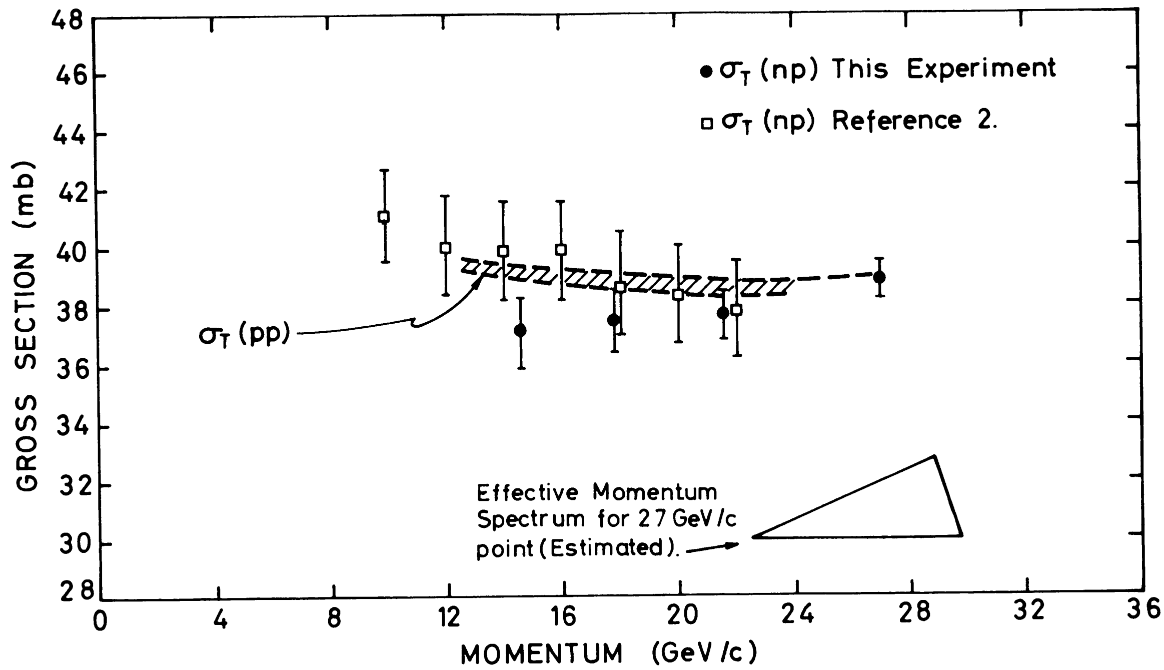
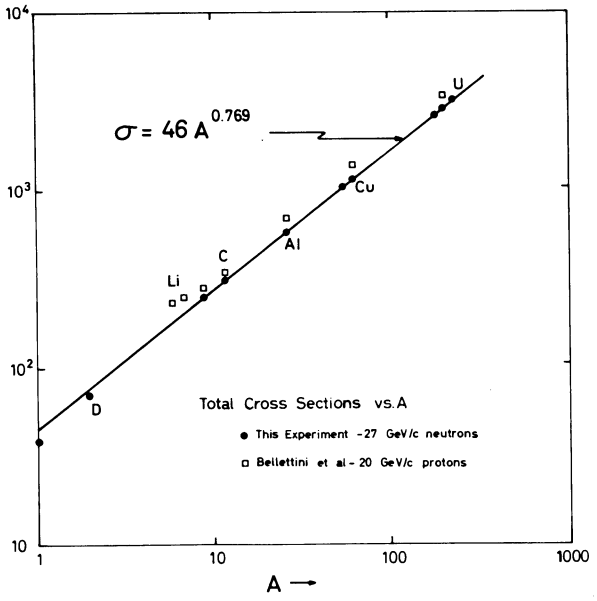


FIG. 2



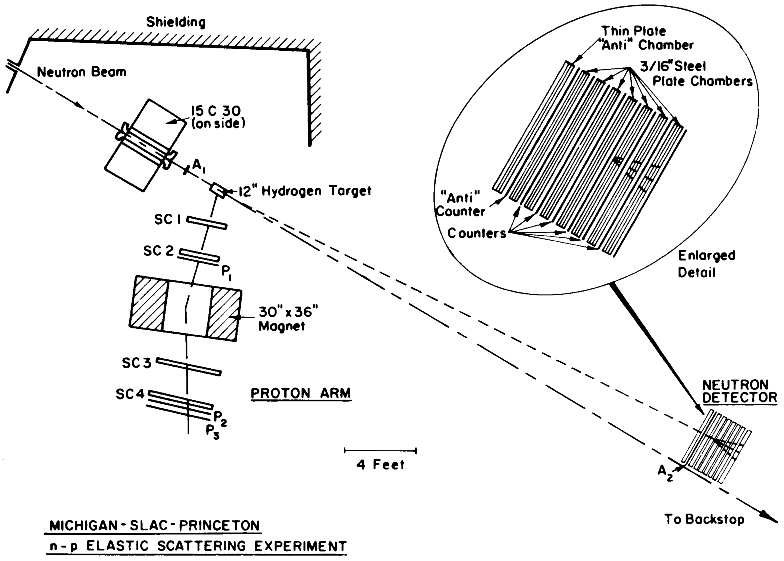


FIG. 4

FIG. 3

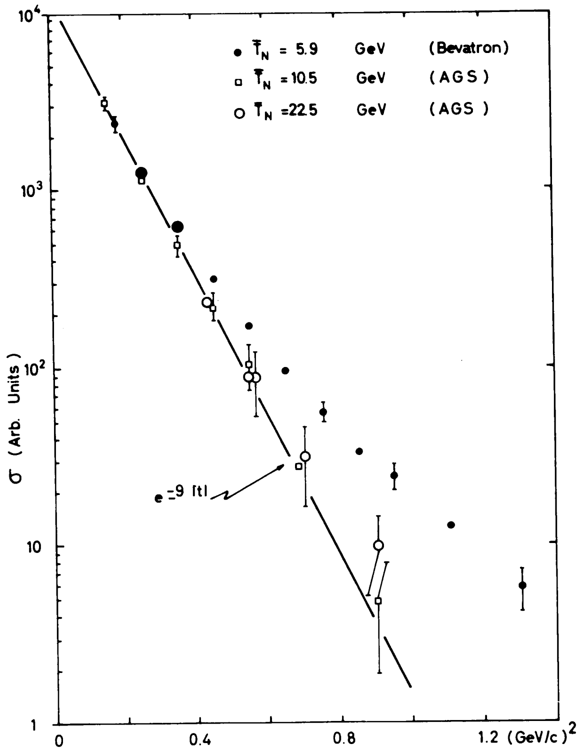


FIG. 5

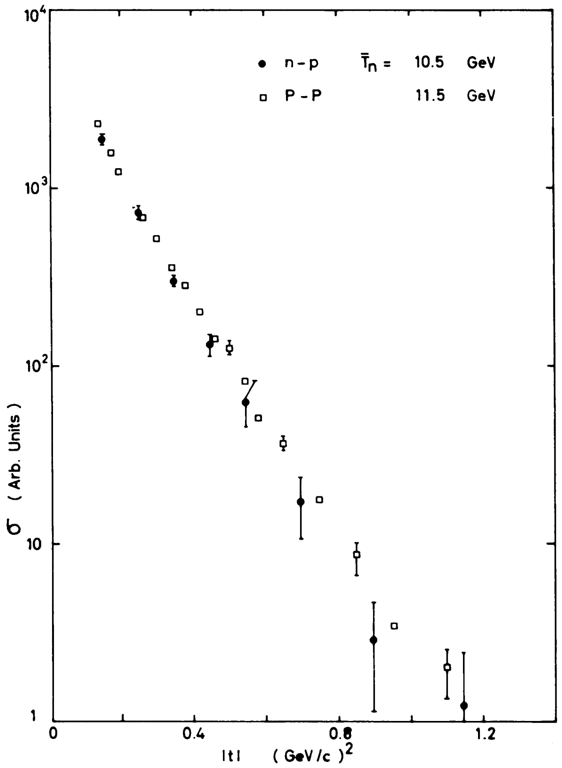


FIG. 6