NEUTRON TOTAL CROSS SECTIONS ON PROTONS AND NUCLEI IN THE 10 TO 30 GeV/c MOMENTUM RANGE *

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We present the results of a recent AGS measurement of the total cross section for neutrons on protons, deuterons and other nuclei in the momentum range 10 to 30 GeV/c. The standard good-geometry transmission technique was used with a total absorption spectrometer to detect the transmitted neutrons. Biasing the spectrometer towards high neutron momenta together with the strongly-peaked momentum spectrum of the beam gave relatively good momentum resolution. Measurements were made at mean momenta of 12, 13, 18 and 26.5 GeV/c. Results are presented and the cross sections for nuclei are compared with theoretical predictions.

The total cross sections for neutrons on various nuclei at mean momenta of 12, 13, 18 and 26.5 GeV/c were measured directly with a neutron beam at the Brookhaven AGS [1]. The experiment used a good-geometry transmission technique in combination with a total absorption spectrometer (TAS) for neutron energy determination [2]. The experimental technique was similar to that used by our group in previous total cross section measurements [3-5] with improvements in the TAS and reductions in systematic effects.

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The experiment arrangement is shown in fig. 1 The extranal proton beam was incident on an 18 cm long Be target and a neutral beam was taken off at 0°. Several magnets in the beam line swept out charged particles. Gamma contamination was removed by two lead filters in the beam with a total thickness of 10 radiation lengths. The collimators produced a sharply defined beam spot 1.1 cm in diam. at the target with negligible halo.

The flask for the liquid targets was 122.0 ± 0.16 cm long when empty at room tempera-

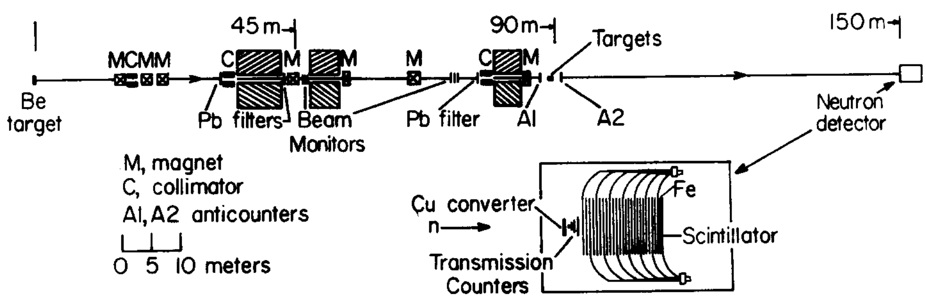

Fig. 1. Schematic drawing of the experimental arrangement. The insert shows a detailed sketch of the transmission counter - TAS system.

ture. The targets produced attenuations from 20% to 40%. Anticounters A1 and A2 were placed upstream and downstream of the targets to veto charged particles. Counter A2 was preceeded by a 2.2 radiation-length converter to convert γ's from inelastic events accompanied by π^0 production. Target cycling times were kept short to minimize systematic effects caused by drifts in the electronics.

Transmitted neutrons were detected in the transmission counter-TAS system approx. 60 m downstream of the target. (See inset in fig. 1.) A 1.6 cm-thick copper plate, which converted about 13% of the incident neutrons, preceeded four circular transmission counters. The charged particles produced in the copper plate tend to go along the neutron direction, so that the transmission counters effectively measured the angular distribution of the transmitted neutrons. These counters subtended solid angles of approximately 0.31, 0.85, 2.7 and 8.2 μsr as seen from the target position. The total absorption spectrometer followed the transmission counters; it consisted of 13 iron plates $56 \times 82 \times 3.8\,\mathrm{cm}^3$, interleaved with 14 plastic scintillators. The scintillators were grouped into two interleaved sets of seven. The light from the scintillators in each set was summed optically and viewed by a 56AVP photomultiplier tube. The output of the two tubes was then passively added to give a pulse whose amplitude was roughly proportional to the neutron energy Accepting only large pulses from the TAS biased the measurements toward high neutron momenta. When combined with the fact that the incident neutron spectrum is strongly peaked at the high momentum end [e.g. 6], this produces fairly good momentum resolution. As an example the effective spectrum for the 26.5 GeV/c point is shown in the inset in fig. 2.

The relative intensity of the beam was monitored by two independent counter telescopes upstream of the targets (fig. 1). These telescopes tracked well during the experiment. Cross sections measured by each of the transmission counters were calculated in the standard manner using the ratio of the target empty to target full counting rates and the length and density of the targets.

Several small corrections had to be made to the attenuation cross sections measured by the transmission counters. The first was a correction for a "rate effect", that is, a change in the gain of the TAS photomultipler tubes with instantaneous neutron intensity. The quantity (TAS$\cdot$TAS$_{\mathrm{delayed}}$/TAS) served as a measure of

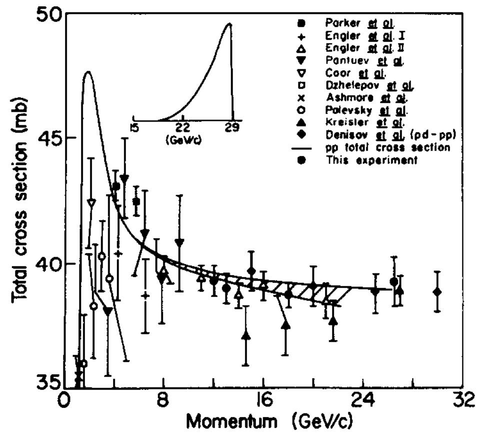

Fig. 2. Neutron-proton total cross sections versus momentum. The proton-proton cross sections are also shown. The inset shows the effective spectrum for the 26.5 GeV/c point.

this instantaneous rate. Running with different neutron intensities incident on the TAS showed that the measured attenuation cross sections decreased linearly with rate. Typically a correction of about 1% had to be made to the measured cross sections for this effect. The uncertainty in this correction was included in the errors for the cross sections. A correction (< 1%) was made for the liquid targets to account for the residual gas in the empty target.

Three methods were used to extrapolate the measured attenuation cross sections to zero solid angle to obtain the total cross section. The spread in the extrapolated cross sections was taken as the measure of the uncertainty in the extrapolation procedure and was combined quadratically with the other errors. In the worst case - that of lead - the full spread was 0.5% of the total cross section. Because of the exceedingly small angle subtended by the smallest transmission counter at the target, the attenuation cross section measured by this counter differed from the total cross section by less than 1% for all the elements studied.

Table 1 lists the measured total cross sections at the four mean neutron momenta. The uncertainties listed are the quadratic combination of all the errors discussed above plus an additional error of 0.4 mb for hydrogen and 0.3 mb for deuterium due to uncertainties in the densities of these targets because of pressure fluctuations. The quantities FWHM and P_{B} listed with each of the mean momenta are the full width at half maximum of the effective neutron spectrum and the AGS proton momentum respectively. Fig.

Table 1.
Total cross sections (in mb) for neutrons on various nuclei. $\bar{P}$ is the mean effective neutron momentum. P_B is the AGS proton momentum. FWHM is the full width at half maximum of the effective neutron spectrum.

Nucleus	A	$\bar{P}$ = 12 GeV/c P_B = 15.5 GeV/c FWHM = 3 GeV/c	$\bar{P}$ = 13 GeV/c P_B = 15.5 GeV/c FWHM = 4 GeV/c	$\bar{P}$ = 18 GeV/c P_B = 21.3 GeV/c FWHM = 6 GeV/c	$\bar{P}$ = 26.5 GeV/c P_B = 29.1 GeV/c FWHM = 3.5 GeV/c
H	1	39.3 ± 0.6	39.0 ± 0.6	38.7 ± 0.5	39.3 ± 1.0
D	2			75.8 ± 0.8	
Be	9				266 ± 6
C	12	342 ± 3	340 ± 3	342 ± 3	330 ± 7
Al	26.9				656 ± 11
Cu	63.5	1305 ± 9	1295 ± 8	1265 ± 8	1251 ± 19
Cd	112.4				1907 ± 32
W	183.9				2720 ± 41
Pb	207.2	3167 ± 21	3150 ± 19	3100 ± 19	3044 ± 45

2 shows our n-p data together with previous n-p and p-p measurements. Our data are in excellent agreement with those of Engler et al [7, 8]. The 27 GeV/c data previously reported by our group for the heavier elements 4 are inconsistent with our current results. We now believe our previous results were in error because of an incomplete understanding of the rate dependence of the TAS, which was considerably more complicated than we realized, and because of an oversimplified procedure for extrapolating to zero solid angle which gave low cross sections for the larger nuclei. As can be seen in fig. 2, there now seems to be very good agreement between n-p and p-p total cross sections in this momentum range. There is no evidence for any unusual behavior of the cross sections. Our values for n-d and n-p cross sections agree within errors with recent Serpukhov results [16] for p-d and n-p (from a p-d minus p-p subtraction technique). On the basis of our results and those of previous experiments [4, 5, 7-12] it is found that the neutron-nucleus total cross sections fall smoothly and monotonically with increasing energy.

Table 2 compares our 26.5 GeV/c data (column 1) with several models. Columns 2 and 3 give total cross sections calculated from the multiple scattering theory of Glauber [20] using Gaussian [18] and Fermi [17] nuclear density distributions respectively. For these calculations the nuclear density parameters deived from electron scattering have been used [21]. Column 4 gives results of a model of Bochmann and Margolis [19] in which one allows diffractive production of heavy mass isospin $\frac{1}{2}$ isobars in the nucleus followed by the regeneration of the neutron. Such a process causes a "shadow" through the elastic channel and produces a decrease in the total cross section. In column 5 we show this last model with regenerative contributions omitted. In this case this model is easily shown to reduce to the Glauber theory with an "optical" approximation - i.e., the approximation in which one ignores the q^2 dependence of the nucleon-nucleon elastic scattering amplitude when compared to that of the nuclear form factor Nuclear radii deduced from ρ photoproduction [22] have been used in this last model. The electromagnetic radii would yield cross sections

Table 2
A comparison of our measured total cross sections at 26.5 GeV/c (column 1) with those calculated from several theories (columns 2-5). See the text for an explanation of this table.

Nucleus	A	Measured total cross sections (mb) 1	Calculated total cross sections (mb) 2	 3	 4	 5
Be	9	266 ± 6	263 ± 4.5	261 ± 4.5	269 ± 11	275 ± 7.5
C	12	330 ± 7	333 ± 5	335 ± 5	340 ± 12	348 ± 9
Al	26.9	656 ± 11	680 ± 12.5	681 ± 12.5	654 ± 24	674 ± 18
Cu	63.5	1251 ± 19	1283 ± 26	1286 ± 26	1268 ± 40	1309 ± 30
Cd	112.4	1907 ± 32	1930 ± 44	1910 ± 44	1883 ± 60	1938 ± 50
W	183.5	2720 ± 41	2868 ± 63	2794 ± 63	2640 ± 80	2704 ± 70
Pb	207.2	3044 ± 45	3085 ± 66	2970 ± 66	3001 ± 110	3081 ± 100

smaller by several percent for the lighter nuclei. Given the large uncertainties - due principally to uncertainties in the nuclear radii - in the calculated cross sections, it is not clear that one is seeing regenerative effects at these energies. The question should be resolved at NAL energies where these effects are expected to be larger.

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