NEUTRON-NUCLEI TOTAL CROSS SECTIONS AT 27 GeV/*c* *

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The total cross sections for 27 GeV/*c* neutrons on eight heavy elements, Be through U, has been measured and found to obey the empirical relationship $\sigma_T = 48A^{0.75}$ mb.

The total cross sections for 27 GeV/*c* neutrons on various nuclei were measured in an experiment performed in a 1° neutron beam at the Brookhaven Alternating Gradient Synchrotron. This experiment was a part of an experimental program which included the measurement of np and nd total cross sections [1] and np diffraction elastic scattering [2]. Previous data on nucleon-nucleus cross sections at high energies include proton-nucleus cross sections at 19.3 GeV/*c* [3] and neutron-nucleus cross sections at 5.4 GeV/*c* [4], as well as measurements below 3 GeV [5,6].

The technique used in this experiment was identical with that used in the np and nd cross section measurements [1]. Briefly, a good-geometry attenuation measurement was made of the neutrons passing through targets of Be, C, Al, Fe, Cu, W, Pb and U between 10 and 30 g/cm^2 thick. The neutron detector was a simple ionization calorimeter 26.5 m from the target. At the front of the calorimeter a 5 cm thick iron slab converted a fraction of the neutrons. The charged particles formed were detected in circular counters 7.0 and 12.1 cm in diameter and coaxial with the beam. These counters were separately placed in coincidence with the calorimeter output. Anticoincidence counters just ahead of the target and the calorimeter insured that the incoming particles were neutral. Lead filters and sweeping magnets in the incident neutron beam removed the photons and electrons from the beam. The neutron beam was 3.4 cm diameter at the target position and 5.3 cm diameter at the calorimeter. The effective average momentum of the neutrons was 27 GeV/*c* with a roughly triangular momen-

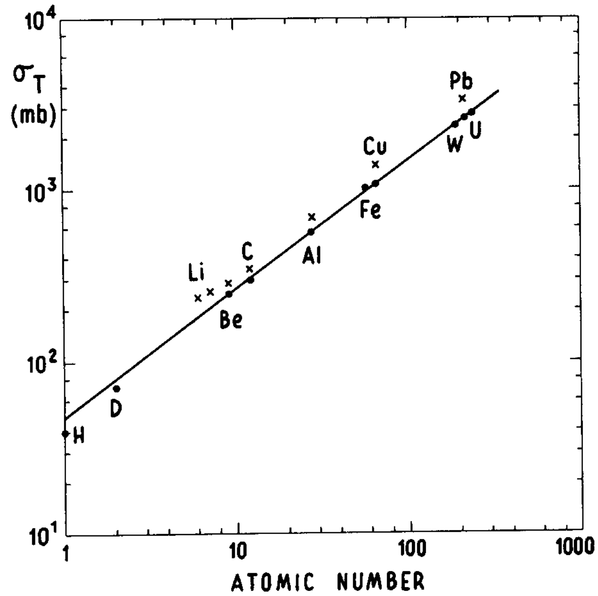

Fig. 1. The total cross section σ_T for neutrons on various nuclei at 27 GeV/*c* (solid circles). Also indicated are total cross sections for protons on various nuclei from Bellettini et al. [3] (crosses). The solid line corresponds to $\sigma_T = 46A^{0.75}$ mb.

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tum spectrum extending from 22 to 29.4 GeV/c (the momentum of the beam protons in the A. G. S.). This momentum band was in effect the folding of the resolution function of the calorimeter with the spectrum of the small-angle neutron beam. Further details of the experimental arrangement are given in ref. 1.

Target-in and target-out counting rates N/M (normalized to three independent neutron beam monitors upstream of the target) were taken and the measured cross section σ_m were found for each element from the usual formula

$$\sigma_m^j = \frac{1}{nx} \ln \frac{(N_j/M)\ \text{target out}}{(N_j/M)\ \text{target in}} \tag{1}$$

for each of the two defining counters, $j = 1, 2$ at the front of the calorimeter. The measured cross sections were smaller than the total cross sections because some of the neutrons are scattered at angles within those angles subtended by the defining counters. The measured cross sections can be written as

$$\sigma_m^j = \sigma_T - \int \left(\frac{d\sigma}{d\Omega}\right)_{el} K_j(\theta)\, d\Omega - \epsilon \bar{\theta}_j^2 \tag{2}$$

where σ_T is the total cross section and $K_j(\theta)$ is the calculated geometrical acceptance of the 7.0 and 12.1 cm circular counters over the beam. The values of K_j vary from unity at $\theta = 0$ to zero for θ of a few mr. For the smaller counter, $K_1 = 0.50$ for $\theta = 1.17$ mr, and for the larger counter, $K_2 = 0.50$ for $\theta = 2.22$ mr. The last term is a correction for inelastically scattered neutrons falling within the angular ranges of the two counters. This contribution is approximately proportional to the solid angle subtended by the counter with ϵ a small number. It is necessary to use this form in finding the total cross section from the measured values as the elastic diffraction scattering cross section varies significantly over the angles subtended by the counters. This is in contrast to the np case where a simple linear extrapolation of 0^o is adequate. The elastic differential cross section was taken to be

$$\left(\frac{d\sigma}{d\Omega}\right)_{el} = (1 + \alpha^2)\left(\frac{k\sigma_T}{4\pi}\right)^2 \left(\frac{2J_1(kR\theta)}{kR\theta}\right)^2 \tag{3}$$

where α is the ratio of the real to the imaginary amplitudes for elastic scattering. The data were analyzed using various values of R consistent with existing data, values of α from 0 to -0.30, and small values of ϵ. The results for σ_T are relatively insensitive to the choice of R and ϵ. Best fits to the data were obtained for $\epsilon \approx 0$ (consistent with the proton-nucleus data of ref. 3), and $R = 1.3\, A^{0.375}$fm. The values of σ_T are also insensitive to α over the range given, and the value $\alpha = -0.26$ from pp scattering [7] was used in the tabulated values of σ_T. The quoted errors include the uncertainty in σ_T resulting from reasonable variations in R, α and ϵ as well as the statistical errors.

The resulting values of σ_T are tabulated together with measured values σ_1 and σ_2 in table 1. Also tabulated are values for proton-nucleus total cross sections from ref. 3 at 19.3 GeV/c. It should be recalled that the cross section measured in proton-nucleus scattering contains a significant correction for Coulomb scattering. In extracting the nuclear scattering cross sections from their data, Bellettini et al. [3] set $\alpha = 0$ so that

$$\left(\frac{d\sigma}{d\Omega}\right)_{el} = C^2 + I^2 , \tag{4}$$

where C is the Coulomb scattering amplitude and I is the imaginary part of the nuclear scattering amplitude. This procedure is justified in their analysis by consistency between the calculated optical theorem point using their deduced σ_T and the extrapolation of their $d\sigma/d\Omega$ (nuclear) to $\theta = 0^o$. However more recent data on nucleon-nucleon scattering at small angles show a significant real amplitude in this energy region, and this should give a corresponding real part in the nuclear scattering amplitude. We have recalculated their data using

$$\begin{aligned}\left(\frac{d\sigma}{d\Omega}\right)_{el} &= C^2 + 2CR + R^2 + I^2 \\ &= C^2 + 2\alpha CI + (1 + \alpha^2)I^2\end{aligned} \tag{5}$$

with $\alpha = -0.26$ (assumed to be independent of θ). Since α and C are both negative, the interference term is positive. Thus including the effect of a real term will give a nuclear cross section value lower than obtained by setting $\alpha = 0$. From the elastic scattering data points of ref. 3 and the known Coulomb interaction, the values of I were found using eq. (5). A Bessel function appropriate for each nucleus was computed and the resulting $I(\theta)$ were extrapolated to $\theta = 0^o$. The total cross sections were then deduced with the aid of the optical theorem. These values of the total cross section, labeled σ_T^*, are also given in table 1. The σ_T^* agree well with our results, but our attempt to correct the proton data for the interference term should be regarded with caution as it does not make use of the independent inelastic cross section data of ref. 3. It is important to keep in mind, however, that the Coulomb amplitude C and

Table 1
Total nucleon-nucleus cross sections.

	Neutron cross sections (mb) at 27 GeV/c [a] (this experiment)			Proton cross sections (mb) at 19.3 GeV/c [b]	
Element	$\sigma_m^{(1)}$	$\sigma_m^{(2)}$	σ_T	σ_T	σ_T^{*}[c]
Be	245.6 ± 4.4	237.0 ± 4.2	250 ± 6	278 ± 4	250
C	294.7 ± 5.3	281.4 ± 5.2	300 ± 7	335 ± 5[d]	312
Al	551 ± 13	516 ± 12	573 ± 17	687 ± 10	570
Fe	965 ± 18	886 ± 17	1023 ± 25		
Cu	1024 ± 22	932 ± 20	1090 ± 30	1360 ± 20	1100
W	2088 ± 111	1864 ± 104	2330 ± 200		
Pb	2313 ± 50	2051 ± 44	2630 ± 120	3290 ± 100	2850
U	2448 ± 55	2178 ± 51	2770 ± 150		

a. $\sigma_m^{(1)}$ and $\sigma_m^{(2)}$ are measured beam attenuation cross sections for particular counters and σ_T is the total cross section deduced from these values (see text).
b. From ref. 3.
c. The values σ_T^* were computed from the elastic scattering data or ref. 3 using the optical theorem and setting $\alpha = -0.26$.
d. The carbon data of ref. 3 are for 21.5 GeV/c.

thus the interference term diverges at $\theta = 0^{\circ}$. Therefore the interference term *must* be subtracted out to extrapolate the measurement to $\theta = 0^{\circ}$ in a sensible way. In making this subtraction we have assumed that $\alpha_{np} = \alpha_{pp}$ and that this same α applies to the entire nucleus. These assumptions are somewhat arbitrary, so that the proton-nucleus cross sections remain uncertain to this extent. It can be seen from table 1 that our results differ from the proton cross sections reported [3] using $\alpha = 0$ by up to 25% while the np and pp cross sections are equal to within 2% in the same interval [1]. The disagreement is largest for the heavy elements, which suggests that a Coulomb effect is involved. It is interesting to note that our results for the total cross section of neutrons on deuterium [1] agree with those of Bellettini et al. [8] for protons to within 4% and with those of Galbraith et al. [9] to about 2%. It is difficult to think of a Z-dependent source of systematic error in our measurements large enough to account for the discrepancy.

Our results fit well the simple expression $\sigma_T = 48A^{0.75}$ for $A > 7$ (fig. 1). A similar fit to the data of Coor et al. [6] for 1.4 GeV neutrons gives $\sigma_T = 59A^{0.753}$. The smaller coefficient at the higher energy is consistent with the decreasing nucleon-nucleon cross section.

The significant discrepancy between our results for neutrons and those of Bellettini et al.[3] for protons emphasizes the need for caution in interpreting such cross section data for charged particles on nuclei. The possibility of a large interference term between the Coulomb amplitude and the real part of the nuclear amplitude can lead to large uncertainties in the total cross sections. For this reason neutron beams offer a considerable advantage for such measurements due to the absence of Coulomb effects.

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References

1. M.N.Kreisler, L.W.Jones, M.J.Longo and J.R. O'Fallon, Phys.Rev.Letters 20 (1968) 468.
2. M.J.Longo, Topical Conf.on High energy collisions of hadrons, CERN Report 68-7 (February, 1968).

3. G.Bellettini, G.Cocconi, A.N.Diddens, E.Lillethun, G.Matthiae, J.P.Scanlon and A.M.Wetherell, Nucl. Phys. 79 (1966) 609.
4. J.H.Atkinson, W.N.Hess, V.Perez-Mendez and R.W.Wallace, Phys.Rev.Letters 2 (1959) 168; J.H.Atkinson, W.N.Hess, V.Perez-Mendez and R.W.Wallace, Phys.Rev.123 (1961) 1850.
5. For a summary of other relevant data at energies of about 1 GeV see, for example, G.J.Igo, J.L.Friedes, H.Palevsky, R.Sutter, G.Bennett, W.D.Simpson, D.M.Corley and R.L.Stearns, Nucl.Phys.B3 (1967) 181.
6. T.Coor, D.A.Hill, W.F.Hornyak, L.W.Smith and G.Snow, Phys.Rev.98 (1955) 1369.
7. L.Van Hove, Proc.Thirteenth Intern.Conf.on High energy physics (University of California Press, 1967) p.253; K.J.Foley, R.S.Jones, S.J.Lindenbaum, W.A. Love, S.Ozaki, E.D.Platner, C.A.Quarles and E.H.Willen, Phys.Rev.Letters 19 (1967) 857.
8. G.Bellettini, G.Cocconi, A.N.Diddens, E.Lillethun, G.Matthiae, J.P.Scanlon and A.M.Wetherell, Phys. Letters 19 (1965) 341.
9. W.Galbraith, E.W.Jenkins, T.F.Kycia, B.A.Leontic, R.H.Phillips, A.L.Read and R.Rubinstein, Phys.Rev.138 (1965) B913.

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