Nuclear Cross Sections for 270-Mev Neutrons*

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The total cross sections of eleven different elements were measured for the neutrons resulting from the bombardment of a 2-in. Be target by the 350-Mev protons of the 184-in. cyclotron. Bismuth fission ionization chambers served as the neutron detectors and had an estimated mean neutron detection energy of 270 Mev for the measurements. The attenuating materials were placed inside the concrete shielding and the monitor was placed to one side of the attenuators. The detector was placed about 30 ft. from the attenuators in line with the target and the attenuators. Collimators in the concrete shielding and a concrete block immediately behind the attenuating materials limited the detection of neutrons scattered through small angles to 20 min. "Poor" geometry cross sections of carbon, copper, and lead were measured by placing a shallow fission chamber behind attenuators of large cross-sectional area over which the neutron flux was uniform. The inelastic cross section is at least half the total for all three elements.

I. INTRODUCTION

NUCLEAR collision cross sections for 95-Mev neutrons[1] have been measured using bismuth fission ionization chambers for neutron detection. Since the chambers have excellent operating characteristics for high energy neutron detection, they were employed again in attenuation measurements of nuclear cross sections for the neutrons produced by the bombardment of a 2-in. beryllium target with the 350-Mev protons of the 184-in. cyclotron.

Measurements of the ratio of the cross section for bismuth fission relative to the $(n,2n)$ cross section for carbon show an increase by a factor of 3.5 in the energy interval between the two sets of measurements. The $C(n,2n)$ cross section is expected to be fairly flat in this interval, decreasingly by less than a factor of two; hence the fission chambers are more efficient neutron detectors for the 270-Mev neutrons than for the 90-Mev neutrons of the previous experiments.

These new measurements were undertaken to shed further light on the transparency of nuclei to neutrons of high energy. The model of the transparent nucleus,[2] developed by Fernbach, Serber, and Taylor, for nuclear cross-section measurements in the vicinity of 90 Mev gave consistent interpretations for the total cross sections[3] using $C(n,2n)$ and bismuth fission[1] for detection, which have estimated mean detection energies of 84 and 95 Mev, respectively, for the neutrons produced by "stripping" 190-Mev deuterons with a 0.5-in. Be target. Both sets of data, when interpreted by this model, gave as the relation of best fit for the radii: $R=1.38A^{\frac{1}{3}}\times 10^{-13}$ cm.

Inelastic cross sections for four nuclei were measured in the earlier experiments employing bismuth fission detection at 95 Mev, and the ratios of inelastic to total cross sections obtained were in approximate agreement with the values predicted by the transparent model. The nuclear cross sections measured using "poor" geometry for the 270-Mev neutrons will represent lower limits to the true inelastic values, since inelastically scattered neutrons can lose large amounts of energy and still be above the bismuth fission threshold.

II. AVERAGE ENERGY OF DETECTION

The energy distribution of the neutrons knocked out of the 2-in. Be target by the 350-Mev protons has been measured by Hadley and by Fox *et al.*[4] The distribution of neutrons is peaked around 270 Mev with a width at half-maximum of 60 Mev. The ratio of the bismuth fission cross section to the $(n,2n)$ cross section of carbon for the 270-Mev neutrons relative to the ratio for the 90-Mev neutrons was measured by placing an $\frac{1}{8}$-in. thick, $1\frac{11}{16}$-in. diameter polystyrene disk in front of a fission chamber mounted in the collimated neutron flux outside the shielding. The number of fission pulses in the chamber was recorded for steady, 10-min. bombardments and the beta-activity resulting from the $(n,2n)$ reaction of carbon was counted on a standard Geiger-Müller counter. Bombardments were also made with brass plugs in the collimator to eliminate background effects at both energies. The ratio of the bismuth fission cross section to the $(n,2n)$ cross section of carbon increased by 3.56 ± 0.11 when the mean neutron energy was changed from 90 to 270 Mev.

Measurements were made inside the shielding of the ratio of the two cross sections by varying the radius of the 0.5-in. Be target and therefore the energy of the incident protons. A fission chamber and polystyrene disk were placed near the cyclotron tank wall behind 4 in. of lead which absorbed stray protons but allowed the neutrons to reach the two detectors. The results indicated that the ratio of the bismuth fission to the $C(n,2n)$ cross section increased almost linearly with proton energy and presumably, therefore, linearly with the average energy of the ejected neutrons. Since the carbon $(n,2n)$ cross section is theoretically fairly flat in

* This work was carried out under the auspices of the AEC.
[1] J. DeJuren and N. Knable, Phys. Rev. 77, 606 (1950).
[2] Fernbach, Serber, and Taylor, Phys. Rev. 75, 1352 (1949).
[3] Cook, McMillan, Peterson, and Sewell, Phys. Rev. 75, 7 (1949).
[4] Fox, Leith, Wouters, and MacKenzie, Phys. Rev. 80, 23 (1950), preceding paper.

the interval between 90 and 270 Mev, decreasing by less than a factor of two,[5] the bismuth fission cross section increases slowly over the energy spectrum of the neutrons obtained by bombarding the 2-in. Be target with 350-Mev protons. The energy distribution of neutrons detected by bismuth fission should correspond very closely to the measured distribution which peaks at 270 Mev and the contribution from any low energy tail that may exist in the distribution will be further depressed by the decrease of the fission cross section with lowered neutron energy.

III. COUNTER CHARACTERISTICS

The bismuth fission chambers employed in these measurements were used previously and described in the report containing the 95-Mev results[1] and by Wiegand.[6] The counting rates were, in general, between 10 and 20 c/sec. using the 270-Mev neutrons, roughly half the rate at 95 Mev. Operation was essentially equivalent at both energies as regards pile-ups, distribution of fission pulse heights, and stability of counters.

The effect of background on the chambers at 270 Mev was checked by placing brass plugs in the collimator through the concrete shielding. Without the plugs 24,000 fission counts were obtained on the detector, and none with the plugs inserted for steady 10-min. runs. Repeated measurements of cross sections gave differences that appear to be statistical and the errors assigned to the cross-section values are expressed in standard deviations.

IV. EXPERIMENTAL ARRANGEMENT

The diffraction scattering of 270-Mev neutrons by nuclei is peaked so strongly in the forward direction that considerable distance must be placed between absorber and detector in order to obtain good geometry with negligible corrections for the total cross sections measured. Accordingly the monitor and absorber were placed inside the concrete shielding of the 184-in. cyclotron and the detector was placed outside the 10-ft. thick shielding in line with the target (Fig. 1). The distance between the absorber and the detector was 30 ft. An 8-ft. thick concrete block, in front of which the attenuating materials were placed, collimated the neutron beam to a 2-in. diameter (equal to the diameter of the bismuth-coated plates inside the fission chamber detector). Neutrons scattered through an angle greater than 20 min. could not activate the detector. The corrections for detection of neutrons diffracted into small angles, even for the heavy nuclei, are less than one-half of one percent of the measured cross sections.

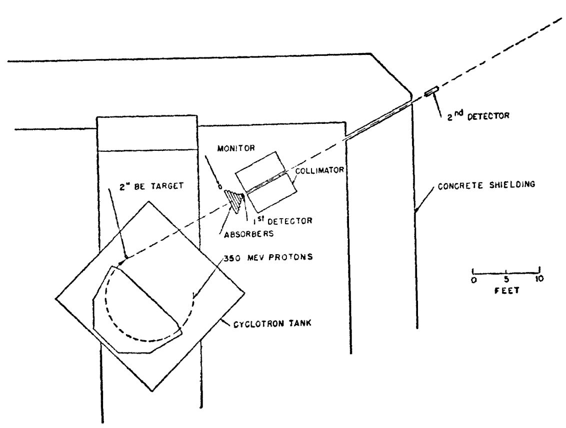

Fig. 1. Plan view of experimental arrangement.

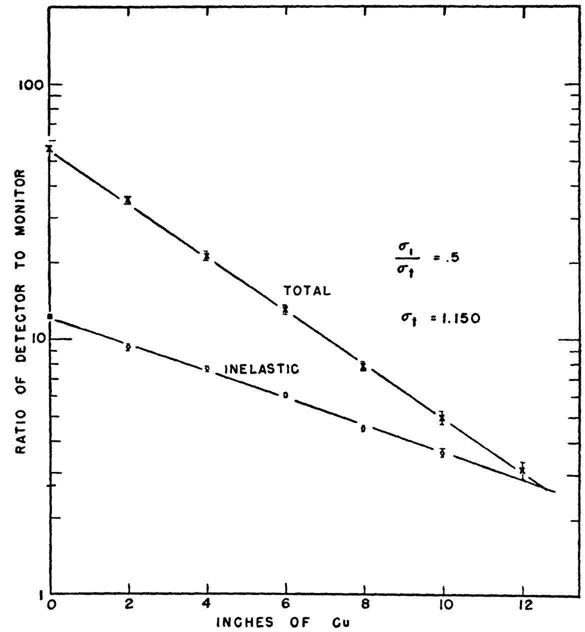

Fig. 2. Attenuation of 270-Mev neutrons in copper for "good" and "poor" geometries.

The ratios of inelastic to total cross sections were measured with the "poor" geometry arrangement[1] used at 95 Mev. Slabs of attenuating material were placed in tront of a detector which was centered at the peak of the angular distribution of neutrons emerging through the cyclotron tank wall, in line with the collimator in fhe concrete block mentioned above. The detector placed ouside the concrete shielding simultaneously measured total cross sections as described above.

The neutron angular distribution from proton bombardment of the 2-in. Be target is much broader than the distribution resulting from "stripping" 190-Mev deuterons; the total angular width at half-maximum is about 50° for the 270-Mev neutrons (measured with bismuth fission detection). Thus it was possible to employ absorbers of greater cross-sectional area than in the former experiment and still have uniformity of neutron flux over the faces of the absorbers.

[5] L. Baumhoff (private communication).
[6] C. Wiegand, Rev. Sci. Inst. 19, 790 (1948).

V. TEST MATERIALS

Practically the same attenuating materials used at 95 Mev were employed for the present measurements, except that longer lengths of absorber were used (because of the smaller cross sections) at 270 Mev. The hydrogen cross section was measured using pentane-carbon difference and the difference between the deuterium and hydrogen cross sections was measured directly by D_2O-H_2O difference. For most of the materials the ratios of detector to monitor were taken for several thicknesses of absorber. For both "good" and "poor" geometry the logarithm of the ratio decreased linearly as a function of absorber thickness, with no transition effects, over several mean free paths of length. Figure 2 contains the experimental data for copper.

VI. RESULTS

Table I contains the experimentally measured total cross sections. Comparison with the 95-Mev values[1] reveals a surprising constancy in the ratio of

$$\sigma_t(270\ \text{Mev})/\sigma_t(95\ \text{Mev})$$

for the elements from deuterium to tin.

Although the "poor" geometry cross sections measured at 270 Mev may not represent true inelastic cross sections, since neutrons may lose energy inelastic collisions and still be above the bismuth fission threshold, the ratios of inelastic to total cross section for the nuclei studied were higher than the ratios obtained at 95 Mev (Table II).

The values of σ_i/σ_t at 270 Mev indicate that the inelastic cross sections are at least half of the total cross sections.

Secondary or inelastic neutrons resulting from the interaction of an incident neutron with a nucleus would have lower energies and presumably a greater attenuation in matter than the primary neutrons. Consequently the logarithm of the attenuation should not be linear as a function of absorber thickness if neutrons degraded in energy comprise a large fraction of the detected neutrons. For lead the logarithm of the attenuation was linear through 3.5 mean free paths of absorber, but since the measured inelastic cross section is a slowly varying function of neutron energy this evidence is not a conclusive argument for calling the "poor" geometry measurement the inelastic collision cross section. But it is possible to state for lead that at 270 Mev the inelastic cross section is at least 80 percent of its value at 95 Mev. This is a smaller reduction than that observed for the total cross section.

VII. CONCLUSIONS

The total neutron collision cross sections measured by scintillation counters and bismuth fission chambers in

TABLE I. Total cross sections for 270-Mev neutrons measured with bismuth fission chambers.

Element	Atomic number Z	Mass number A	$A^{1/3}$	270 Mev total cross section $\sigma_t \times 10^{24}$ cm²	$\sigma_t(270\ \text{Mev})/\sigma_t(95\ \text{Mev})$	Density g/cm³
Hydrogen	1	1	1.00	0.037±0.002	0.52 ±0.03	
				0.039±0.002		
				0.038±0.0015(av.)		
Deuterium	1	2	1.26	0.057±0.003	0.55 ±0.03	
Beryllium	4	9	2.08	0.229±0.003	0.58 ±0.01	1.847
Carbon	6	12	2.29	0.287±0.007		1.580
				0.293±0.005		
				0.277±0.005		
				0.290±0.009		
				0.288±0.003(av.)	0.58 ±0.01	
Oxygen	8	16	2.52	0.372±0.007	0.56 ±0.01	
Aluminum	13	27	3.00	0.555±0.010		2.714
				0.552±0.019		
				0.561±0.024		
				0.555±0.008(av.)	0.56 ±0.01	
Copper	29	63.57	3.99	1.14 ±0.02		8.90
				1.15 ±0.02		
				1.145±0.0015(av.)	0.57 ±0.01	
Tin	50	118.7	4.92	1.87 ±0.003	0.59 ±0.01	7.28
Tungsten	74	183.9	5.69	2.56 ±0.07		19.3
				2.66 ±0.07		
				2.61 ±0.05(av.)		
Lead	82	207.2	5.92	2.83 ±0.04		11.34
				2.81 ±0.06		
				2.91 ±0.06		
				2.84 ±0.03(av.)	0.635±0.01	
Uranium	92	238.1	6.20	3.32 ±0.07		18.88
				3.30 ±0.07		
				3.35 ±0.08		
				3.31 ±0.07		
				3.28 ±0.12		
				3.12 ±0.09		
				3.29 ±0.03(av.)	0.67 ±0.01	
Deuterium-hydrogen	0	1	1.00	0.019±0.002	0.61 ±0.10	

TABLE II. Ratios of "poor" geometry to total cross section measured with bismuth fission chambers.

Element	σ_i/σ_t (270 Mev)	σ_i/σ_t (95 Mev)
Carbon	0.505±0.02	0.46±0.015
Copper	0.50 ±0.02	0.39±0.005
Lead	0.51 ±0.01 0.49 ±0.02	0.40±0.01

the neighborhood of 270 Mev agree well with each other from beryllium to lead. To obtain a reasonable fit with the data in terms of the transparent model of the nucleus,[2] the potential change experienced by the bombarding neutron when entering a nucleus must be dropped to zero. New measurements, to be published later, indicate the total cross sections for these elements are flat in the vicinity of 270 Mev.

The experimentally measured value of the total $n-p$ cross section for the 270-Mev neutrons is $38\pm1.5\times10^{-27}$ cm^2. The value predicted[7] by the model proposed by Christian and Hart, in which tensor forces are combined with a Yukawa potential, is 37×10^{-27} cm^2 at 280 Mev.[8]

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[7] R. S. Christian, private communication.
[8] The value published by R. S. Christian and E. W. Hart, Phys. Rev. 77, 441 (1950), is erroneous.

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Measurement of Absolute Electron Capture Rates with an Application to the Decay of Ni^{57}*

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Observation of radiations from 36-hour Ni^{57} with a proportional counter and pulse-height analyzer shows that cobalt x-rays are emitted. Decay is divided equally between K-capture and emission of 845-kev positrons. The positron spectrum has the allowed shape. Coincidence measurements involving the comparison of Ni^{57} and Na^{22} give the result that both K-capture and positron emission in Ni^{57} are followed by emission of a 1.9-Mev gamma-quantum. In the K branch there are some 120-kev gamma-rays and possibly others of energy less than 0.5 Mev in cascade with the hard gammas.

I. INTRODUCTION

PULSE analyzers and proportional counters suitable for the detection and identification of x-rays[1,2] have recently been developed. With the aid of such an instrument, the quantitative investigation of electron capture processes is being undertaken. The first case studied is that of 36-hour Ni^{57}, which, it has been reported, emits 0.67- to 0.72-Mev positrons, 1.97-Mev gamma-rays, and some softer gamma-rays.[3,4] The observation[5] that the apparent yield of the reaction Ni$^{58}(\gamma, n)$Ni^{57} as measured by β-counting was lower than expected from (γ, n) yields in neighboring elements led to the suspicion that Ni^{57} might decay by electron capture.

The Ni^{57} was produced by bombardment of iron with 30-Mev alpha-particles in the cyclotron of the Department of Terrestrial Magnetism of the Carnegie Institution. With the aid of carriers the nickel activity was chemically separated from the target and purified from other activities, especially those of cobalt, manganese, and copper, which may have been produced by alpha-particles, deuterons, or neutrons either in the iron or in its supporting materials. The treatment involved dissolution of the iron target in 12N HCl; oxidation of the iron to the ferric state and its removal from the solution by ether extractions; and precipitation then of nickel dimethylglyoxime in the presence of tartrate ion to keep ferric ion in solution and of carriers to "hold back" cobalt, manganese, and copper. The nickel precipitate was dissolved and reprecipitated under the above conditions twice more. The Ni^{57} with its 0.1 to 4 milligrams of nickel carrier was finally converted to NiS and mounted on thin aluminum foil.

* Work carried out under the auspices of the AEC.
[1] Curran, Cockroft, and Angus, Phil. Mag. 40, 53, 522, 631, 929 (1949).
[2] Bernstein, Brewer, and Rubinson, Nucleonics 6, No. 2, 39 (1950).
[3] G. T. Seaborg, and I. Perlman, Rev. Mod. Phys. 20, 585 (1948).
[4] F. Maienschein and J. L. Meem, Jr., Phys. Rev. 76, 899 (1949).
[5] M. L. Perlman, Phys. Rev. 75, 988 (1949).

II. X-RAY MEASUREMENTS

It was found that cobalt K x-rays are emitted in the decay of Ni^{57}. The counter for measurements of the energy and intensity of the x-rays was made from a four-inch diameter brass tube, 12 inches long, in which