Inelastic Collision Cross Sections for 14-Mev Neutrons*

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(Received July 21, 1952)

The inelastic collision cross sections of a number of elements for 14-Mev neutrons have been measured, using threshold detectors inside spherical shells of the scattering material. Reactions in copper, aluminum, and phosphorus with thresholds at approximately 11.5 Mev, 2.6 Mev, and 1.4 Mev were used as threshold detectors.

I. INTRODUCTION

THE purpose of the present experiment is to measure the neutron cross section of various elements for processes other than elastic scattering. This type of cross section will be referred to as inelastic collision cross section. The method used was essentially the same as that described by Gittings, Barschall, and Everhart for their measurement of the inelastic collision cross section of lead for 14.5-Mev neutrons.[1] In this method the neutron transmission through spherical shells of the material under investigation is observed. The neutrons are detected by means of threshold detectors. It is assumed that the threshold detector has the same sensitivity for elastically scattered neutrons as for the primary neutrons and does not detect neutrons which have been inelastically scattered to energies below the threshold of the detector. For a thin shell the effect of elastic scattering on the transmission should be small since the neutrons scattered into the detector should compensate those neutrons which are scattered out of the direct path between the source and the detector. A detailed analysis of this assumption has been made and estimates of its rigor derived.[2] The analysis justifies the use of the assumption.

In the past several investigators have used threshold detectors for measurements of inelastic collision cross sections for fast neutrons. Grahame and Seaborg[3] used reactions in iron and aluminum for a study of the inelastic scattering of neutrons from a RaBe source. Amaldi *et al.*[4] studied the inelastic scattering of Li+d neutrons by Al, Fe, Hg, and Pb by means of the Cu^{63} $(n,2n)$ Cu^{62} reaction.

In the present experiment the following three threshold reactions were used: $P^{31}(n,p)Si^{31}$, $Al^{27}(n,p)Mg^{27}$, $Cu^{63}(n,2n)Cu^{62}$, with thresholds at 1.4 Mev, 2.6 Mev, and 11.5 Mev, respectively. Since the reaction cross sections for the various threshold detectors rise slowly above the threshold, the effective thresholds are somewhat higher, i.e., approximately 2 Mev, 3 Mev, and 12.5 Mev. The use of different threshold detectors enables one to get a rough idea of the energy distribution of the inelastically scattered neutrons.

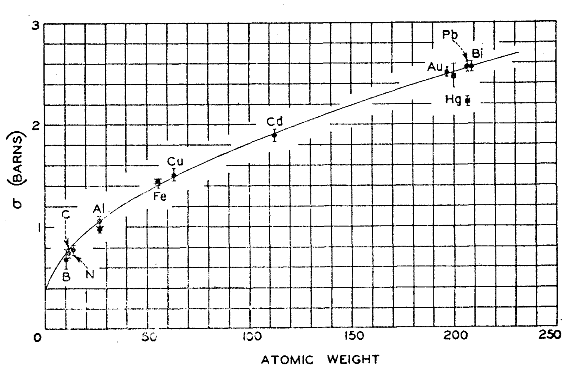

FIG. 1. Inelastic collision cross sections for 14-Mev neutrons measured with copper threshold detectors plotted against atomic weights. The smooth curve was calculated from the empirical relation $\sigma=\pi R^2$, where $R=(2.5+1.1\ A^{\frac{1}{3}})\times10^{-13}$ cm. The squares are values of Amaldi *et al.* taken from reference 4.

II. EXPERIMENTAL

Neutron Source

Neutrons were obtained from the T(d,n)He reaction by bombarding a thick tritium target with 220-kev deuterons. The target consisted of a tungsten disk to which was fused a zirconium foil in which tritium had been absorbed.[5] The intensity of the neutron source was monitored by counting α-particles from the d-T reaction. Neutrons emitted at 90° with respect to the incident deuteron beam were used in the present experiment. These neutrons have an average energy of 14.15 Mev and an energy spread of approximately ±0.05 Mev.

Threshold Detectors

Cu^{62} formed in the $Cu^{63}(n,2n)$ reaction was found to have a half-life of 9.9±0.1 min. The yield of this reaction as a function of energy has been measured by Fowler and Slye,[6] and Forbes has measured the isotopic cross section at 14 Mev to be 0.506±0.035 barn.[7] Other activities which are induced in normal copper by neutrons are the 12.8-hr activity of Cu^{64} and the 5-min activity of Cu^{66}. The Cu^{64} activity may arise from an $(n,2n)$ reaction in Cu^{65} or an (n,γ) reaction in Cu^{63}. In

* Work performed under the auspices of the AEC.
[1] Gittings, Barschall, and Everhart, Phys. Rev. 75, 1610 (1949).
[2] D. D. Phillips, AEC Report AECU-404 (1949) (unpublished).
[3] D. C. Grahame and G. T. Seaborg, Phys. Rev. 53, 795 (1938).
[4] Amaldi, Bocciarelli, Cacciapuoti, and Trabacchi, Nuovo cimento 3, 203 (1946).
[5] Graves, Rodrigues, Goldblatt, and Meyer, Rev. Sci. Instr. 20, 579 (1949).
[6] J. L. Fowler and J. M. Slye, Jr., Phys. Rev. 77, 787 (1950).
[7] S. G. Forbes, Phys Rev. (to be published).

TABLE I. Effects of source distance and shell thickness on measured cross sections.

Sphere	Detector	Distance source to detector cm	Sphere Outer radius cm	Sphere Thickness cm	Transmission T	σ barns	Av σ barns
Bi	Cu	16.6	5.5	4.22	0.740±0.006	2.53±0.07	2.56±0.05
Bi	Cu	16.6	7.0	5.72	0.660±0.006	2.58±0.06	
Bi	Al	16.6	5.5	4.22	0.765±0.012	2.25±0.13	2.28±0.08
Bi	Al	16.6	7.0	5.72	0.689±0.012	2.31±0.11	
Bi	Al	27.4	5.5	4.22	0.761±0.015	2.30±0.15	
Fe	Cu	16.6	7.62	6.82	0.4315±0.005	1.45±0.02	1.45±0.02
Fe	Cu	16.6	7.62	6.24	0.463±0.029	1.46±0.12	
Fe	Cu	15.0	7.62	5.02	0.535±0.006	1.47±0.03	
Fe	Cu	35.5	7.62	5.02	0.541±0.008	1.44±0.04	
Fe	Al	15.0	7.62	5.02	0.595±0.007	1.22±0.03	1.21±0.03
Fe	Al	16.6	7.62	6.24	0.539±0.013	1.17±0.05	

spite of several attempts to observe the 5-min activity, no evidence for its presence was found in the present experiment. Since irradiations were carried out for only 10 or 15 minutes, the effect of the 12.8-hr activity was negligibly small compared to the 9.9-min activity.

The copper was used in the form of strips about 12 in. long and $\frac{3}{8}$ in. wide, which could be wound in the form of a helix and fitted into a cylindrical brass holder about 1.5 in. long and 1 in. in diameter. This holder could then be placed on a Geiger counter in a reproducible geometry. Foils of different thicknesses were tried. The best results were obtained with foils 0.003 in. thick. The foils were rolled up in tight spirals for irradiation.

The $Al^{27}(n,p)$ reaction leads to Mg^{27}, which has a half-life of 9.6±0.1 min.[8] The yield of this reaction has been measured by Bretscher and Wilkinson.[9] In addition to the (n,p) reaction, (n,γ) and (n,α) reactions may be produced in aluminum. Of these, only the effect of the (n,α) reaction was observed which leads to Na^{24} with a half-life of 14.8 hr. Since no irradiations longer than 20 minutes were used, the effect of the 14.8-hr activity was negligible. Al foils of the same size as the Cu foils were used except that a thickness of 0.008 in. was employed.

The (n,p) reaction of P^{31} leads to Si^{31}, the half-life of which has been variously quoted from 146 min to 3 hr. The present experiment indicated a half-life of 160±10 min. The yield of this reaction as a function of energy has been measured by Taschek.[10] In addition to the 160-min activity, an activity with a half-life of 2 or 3 min was observed which could have been produced by an $(n,2n)$ reaction or an (n,α) reaction. The irradiation times used varied from 80 minutes to 2 hours. By waiting about 20 minutes after an irradiation before counting was started, it was possible to eliminate the effect of the short-lived activity.

Phosphorus foils were prepared by impregnating polythene with red phosphorus.[11] Such foils contained 49.5 percent P by weight. They were cut in strips $\frac{1}{2}$ in. wide and about 0.005 in. thick.

Some difficulties were encountered in the use of the P foils. The initial activity of the foils after 2 hours of bombardment was only 4 to 6 times the background counting rate of these foils. Each foil had a small amount of long-life activity which may have been caused by some impurity. A particular foil had a constant background but different foils had different backgrounds which varied appreciably.

Another difficulty was caused by non-uniformity of the foils which was due partly to non-uniform distribution of the P through the foil and partly to variation of thickness of the polythene. Consistent results could be obtained only by using the same foil both for the measurement with the sphere and for the measurement of the direct intensity.

III. PROCEDURE

If I denotes the activity of the detector in the presence of the sphere and I_0 the activity without the sphere, the inelastic collision cross section is given by

$$\sigma = -(1/nx)\ln(I/I_0),$$

where n is the number of nuclei per unit volume and x

TABLE II. Inelastic collision cross sections for 14-Mev neutrons.

Element	Atomic weight	Density g/cc	Cross section in barns Cu detector	Al detector	P detector
B[a]	10.20	1.08±0.06	0.69±0.10	0.24±0.04	
C shell 1	12.01	1.58±0.04	0.76±0.04	0.28±0.04	
C shell 2		1.50±0.04			
N	14.01	0.812±0.004	0.79±0.05	0.46±0.05	
Al	26.97	2.61±0.02	1.06±0.05	0.62±0.07	
Fe	55.85	7.88±0.04	1.45±0.02	1.21±0.03	0.78±0.03
Cu	63.57	8.92±0.02	1.51±0.06	1.32±0.05	0.87±0.06
Cd	112.41	8.61±0.05	1.89±0.06	1.66±0.07	1.14±0.04
Au	197.2	19.1 ±0.2	2.51±0.04	2.06±0.09	1.47±0.10
Pb	207.2	11.3 ±0.1	2.56±0.05	2.29±0.04	0.91±0.06
Bi	209.0	9.74 ±0.08	2.56±0.05	2.28±0.08	1.03±0.11

[a] 82 percent B^{10}, 18 percent B^{11}.

[8] S. Eklund and N. Hole, Arkiv Mat. Astr. fys. **A29**, No. 26, 4, (1943).

[9] E. Bretscher and D. H. Wilkinson, Proc. Cambridge Phil. Soc. **45**, 141 (1949).

[10] R. F. Taschek, Atomic Energy Commission unclassified report MDDC-360 (1946) (unpublished).

[11] These foils were prepared by Mr. James S. Church of the Chemistry and Metallurgy Division of the Los Alamos Laboratory.

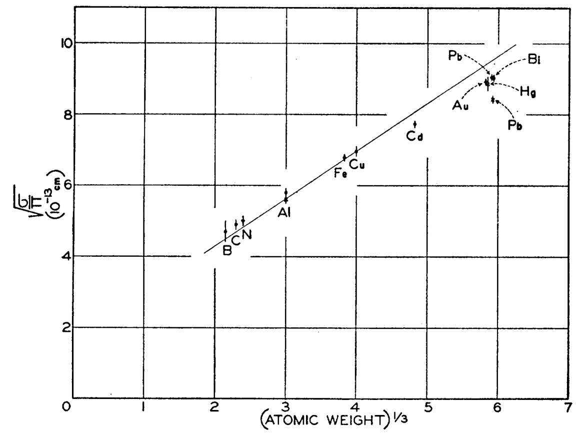

FIG. 2. Experimental values of $(\sigma/\pi)^{\frac{1}{2}}$ as a function of the one-third power of the atomic weights. Solid circles represent data presented here. Crosses represent the data of Amaldi *et al.* taken from reference 4. The curve is calculated from the theory of Feshbach and Weisskopf.

is the thickness of the shell. In order to eliminate the effect of fluctuation of the intensity of the neutron source, two identical foils were irradiated at different positions with respect to the source. If these two foils are irradiated through the same time interval and then counted simultaneously on two counters, the ratio of the observed counts will give the ratio of neutron intensity except for differences in counter efficiency. When the sphere is placed in position, the ratio of observed counts on the detector and monitor foils is reduced by the transmission of the sphere. This transmission is given by

$$T = I/I_0 = C_s/C_0,$$

where C_s is the ratio of observed counts from the detector foil to those from the monitor foil after the detector foil has been irradiated within a sphere, and C_0 is the ratio when no sphere has been used. If the same two counters are used for determining C_0 and C_s, effects due to differences in counter efficiencies are eliminated.

Transmission was measured for certain materials and detectors as a function of distance from source to detector and as a function of shell thickness. Results of these measurements are given in Table I. Although the variation in shell thickness is limited to 36 percent, the fact that this produced no significant variation in the calculated cross section either in the range of transmission of 43 to 53 percent (for Fe) or 66 to 76 percent (for Bi) is taken as assurance that multiple scattering is not appreciably influencing the results. In addition, the fact that elastic scattering[4] is almost entirely within 30° leads to the conclusion that certainly the Cu detector results are not appreciably affected by multiple scattering.

IV. RESULTS

The results obtained by using the three threshold detectors in spheres of various elements are shown in Table II. All spherical shells had transmissions of greater than 0.43, as measured by Cu detectors. Inelastic collision cross sections obtained by using copper foils are plotted against atomic weight A in Fig. 1. The data are best fitted empirically by the relation $\sigma = \pi R^2$, where $R = (2.5 + 1.1A^{\frac{1}{3}}) \times 10^{-13}$ cm. This equation is shown as the solid curve and may be useful for interpolation. Values of Amaldi *et al.* are also shown.

V. DISCUSSION

Feshbach and Weisskopf[12] have published a schematic theory of nuclear cross sections. Their "reaction cross section," σ_r, may be identified with the inelastic collision cross section reported here, measured with copper detectors. They have calculated σ_r using values of the nuclear raidus, R obtained from analysis of measurements of σ_{tot}. Since recent measurements[13] of σ_{tot} for 14-Mev neutrons are in disagreement with the values used by Feshbach and Weisskopf, the values of σ_r have been recalculated according to their theory upon the assumption that $R = 1.5 \times 10^{-13} \times A^{\frac{1}{3}}$ cm.

Figure 2 shows the measured values of $(\sigma/\pi)^{\frac{1}{2}}$ plotted against $A^{\frac{1}{3}}$. The values of Amaldi *et al.* are also shown. The curve represents the theoretical values derived as stated. The slope of the theoretical curve is steeper than desirable for the best fit to the data. This depends on the choice of r_0, the nuclear radius for $A = 1$. However, the absolute values of the σ's change faster with r_0 than does the slope so that the best fit seems to be as chosen.

The results with the lower threshold detectors indicate that the neutrons emerging from inelastic events for all the elements observed have an energy spectrum which is quite low compared to the primary energy. Uncertainties in the knowledge of the response of the detectors prevent detailed analysis of these results.

[12] H. Feshbach and V. F. Weisskopf, Phys. Rev. **76**, 1550 (1949).
[13] Coon, Graves, and Barschall, Phys. Rev. **87**, 562 (1952).