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Total Cross Section of Aluminum for Fast Neutrons

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The total neutron cross section of aluminum was measured as a function of neutron energy in the range from 10 to 1000 kev. Neutrons of known mean energy and small energy spread were produced by the Li(p,n) reaction. The cross section was found to be a rapidly varying function of energy indicating the presence of at least ten resonances in the range of energies investigated. The extreme values of the cross section were found to be 0.9×10^{-24} cm^2 and 11.5×10^{-24} cm^2.

INTRODUCTION

ALTHOUGH the total cross section of most elements for fast neutrons is known for some neutron energies, information about the variation of the cross section over a wide, continuous range of energy is still limited. The neutron energy region between 2 and 3 Mev has been explored by MacPhail and by Aoki.[1] Both authors found an anomalous behavior of the cross sections for several elements in this region. More recently, studies of the total neutron cross sections of some of the light elements have been carried out over a wider range of neutron energies.[2] Resonances were found in these investigations in helium, beryllium, carbon, oxygen, and aluminum.

In the energy region below 1 Mev, photo-neutron sources have been used by Good and Scharff-Goldhaber,[3] Leipunsky,[4] and Fields *et al.*[5] The work of the last authors shows that the total neutron cross sections of several elements do not vary monotonically with neutron energy, even for the heavier elements. In many cases the variation of the cross section does not follow the trend predicted by Feshbach, Peaslee, and Weisskopf.[6] The present measurements were undertaken to obtain more information about the variation of cross section with energy. Aluminum was selected for the first measurements because the results of Fields *et al.* showed a particularly anomalous behavior for this element. In addition, it has the advantage of having only one isotope.

APPARATUS

Neutrons were obtained from the Li(p,n) reaction. The protons were accelerated by an

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[1] M. R. MacPhail, Phys. Rev. **57**, 669 (1940); H. Aoki, Proc. Phys. Math. Soc. Jap. **21**, 232 (1939).

[2] Bailey, Bennett, Bergstrahl, Nuckolls, Richards, and Williams, Phys. Rev. **70**, 583 (1946); D. H. Frisch, Phys. Rev. **70**, 589 (1946); Nuckolls, Bailey, Bennett, Bergstrahl, Richards, and Williams, Phys. Rev. **70**, 805 (1946); H. Staub and H. Tatel, Phys. Rev. **58**, 820 (1940); P. G. Koontz and T. A. Hall, Los Alamos Report LADC No. 16; Allen, Burcham, and Wilkinson, Nature **159**, 473 (1947).

[3] W. E. Good and G. Scharff-Goldhaber, Phys. Rev. **59** 917 (1941).

[4] A. I. Leipunsky, J. Phys. USSR **3**, 231 (1940).

[5] Fields, Russell, Sachs, and Wattenberg, Phys. Rev. **71**, 508 (1947).

[6] Feshbach, Peaslee, and Weisskopf, Phys. Rev. **71**, 145 (1947).

electrostatic generator[7] which gives a proton beam of 3 to 5μa with an energy definition of about ± 3 kev. It is possible to get much higher energy resolution by electrostatic analysis of the proton beam,[8] but the resultant analyzed proton current would be too small for the present experiments. The protons impinged upon a lithium film evaporated onto a 0.010-in. thick tantalum disk. In order to prevent deterioration of this target, the proton beam was focused near the periphery of the tantalum disk which was rotated at slow speed, and a jet of compressed air cooled the outer surface of the disk.

The neutrons were detected by a proportional counter (see Fig. 1) which was filled with normal boron trifluoride to a pressure of 35 cm of Hg. To increase the sensitivity of the counter for fast neutrons, it was surrounded by a cylindrical shell of paraffin, $\frac{1}{2}$-in. thick. In order to reduce the sensitivity of the counter to slow neutrons, the paraffin shell was surrounded by a cylindrical layer, $\frac{1}{4}$-in. thick, containing a mixture of paraffin and boron carbide, and then the whole assembly was covered with cadmium. The center wire of the counter was held at 2100 volts positive with respect to the grounded outer cylinder. To avoid spurious pulses which often originate in condensers placed at such voltage,[9] the counter was coupled to the preamplifier by two condensers in series, with the point between the two condensers maintained at 1000 volts. Pulses from the counter were passed through a preamplifier, a linear amplifier[10] and a pulse height discriminator to a scale-of-64 counter,[11] and a mechanical recorder. The proportional counter did not have a plateau, but tests using a Ra-Be source showed that for a given discriminator setting, the counting rate remained constant from day to day. At the discriminator setting used for the present experiments, the counter was not sensitive to gamma-rays.

Two cylindrical disks of aluminum were used as scatterers. The purity of the aluminum was higher than 99 percent. Both disks were $1\frac{1}{2}$ in. in diameter and one was $\frac{1}{2}$-in. thick, containing 0.0766×10^{24} atoms/cm^2, while the other was 1-in. thick and contained 0.153×10^{24} atoms/cm^2.

The center of the active volume of the counter was placed 10 in. from the lithium target. The scatterers were located midway between the front of the counter and the target. Reproducibility of the location of the scatterer was obtained by placing it on a V-shaped support which was held rigidly in place by a $\frac{1}{8}$-in. iron rod and guy wires. In the geometry used, the maximum angle through which a neutron could be scattered and reach the center of the front surface of the counter was 20°.

The primary neutron intensity was monitored by measuring the number of protons incident upon the lithium target by a current integrator.

PROCEDURE

Since the distribution in angle of the neutron yield from the Li(p,n) reaction has a maximum in the forward direction, this direction was chosen for most of the experiment in order to obtain highest intensity. Also, the spread of energy of the neutrons for a given angle subtended by the counter is smallest in the forward direction. For neutrons of energy below 120 kev, however, a

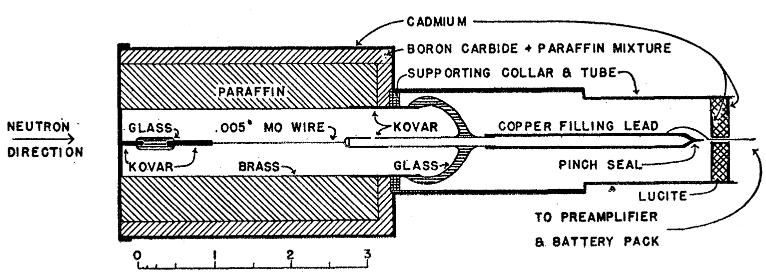

FIG. 1. BF_3-filled proportional counter for neutron detection.

[7] Herb, Turner, Hudson, and Warren, Phys. Rev. **58**, 579 (1940).
[8] Warren, Powell, and Herb, Rev. Sci. Inst. (to be published).
[9] J. H. Coon and R. A. Nobles, Rev. Sci. Inst. **18**, 44 (1947).
[10] Model 100 amplifier designed by M. Sands.
[11] Designed by W. A. Higginbotham.

second group of neutrons of lower energy is present in the forward direction, and these would be detected with a counter sensitive to slow neutrons. To avoid this double energy region, the energy range below 120 kev was covered by using neutrons emitted at an angle of 115° with respect to the proton beam.

The measurements consisted of counting alternately the number of neutrons incident on the counter with and without the scatterer in place. Cross sections were calculated under the assumption that the neutron intensity decreases exponentially in the scatterer.

Since both the lithium target and the neutron detector were only 4 ft. from the concrete floor of the laboratory, an appreciable number of the counts were due to neutrons which did not come directly from the target, in spite of the shielding surrounding the counter. This background was measured by placing a shadow cone of paraffin and boron carbide between the target and the detector. Such measurements were carried out for two different positions of the counter; first with the counter at the position at which the scattering data were taken, and then using a longer shadow cone, with the counter 22 in. from the target. The background count per current integrator count was approximately the same at both positions, indicating that the shadow cones absorbed practically all the direct neutrons. Measurements of background as a function of neutron energy were made both at 0° and at 115° with respect to the proton beam. The background varied from 3 to 10 percent of the direct neutron count for the distance at which the scattering measurements were performed.

In the geometry used, the cross section measured is approximately that for scattering through angles greater than 20°. The total cross section was obtained under the assumption that the average differential scattering cross section in the angular interval between 0° and 20° is the same as the average for angles greater than 20°. Since the solid angle between 0° and 20° is 3 percent of 4π steradians, 3 percent of the difference in count with and without the scatterer was subtracted from the count observed in the presence of the scatterer. No correction was made for multiple scattering.

Lithium targets of 5-kev and 10-kev stopping power were used. The stopping power was determined by observing the neutron counting rate as a function of proton energy near the threshold of the $\mathrm{Li}(p,n)$ reaction. The counting rate rises rapidly above threshold to a maximum. The difference in proton energy between threshold and the energy corresponding to this maximum yield was taken as the target thickness. The determination of target thickness has an accuracy of ± 3 kev.

The proton energies were measured by an electrostatic analyzer,[12] using the threshold energy of the $\mathrm{Li}(p,n)$ reaction (1.86 Mev[13]) as a reference point. To obtain the effective average proton energy, one-half of the target thickness was subtracted from the proton energy so obtained. When the neutron detector is placed at an angle of 115° with respect to the proton beam, the average energy of the neutrons incident on the face of the detector is very nearly the same as the energy of neutrons emitted at 115°. When the detector is placed in the forward position, however, the neutrons of highest energy are those emitted at 0°, and the average neutron energy is somewhat lower. Therefore, the average neutron energy for this position of the detector was taken as that of neutrons emitted at 5°.

RESULTS

The results of the measurements are shown in Fig. 2, where the total neutron cross section is plotted as a function of neutron energy for a target of 10-kev thickness and for the 1-in. thick scatterer. Each point is the average of two successive runs. The upper and lower part of the figure shows measurements taken several days apart. Some energy intervals were covered more than twice, but only two representative runs are shown in Fig. 2. Change of symbol representing experimental points indicates a lapse of more than a day between runs. All measurements were taken in the forward direction except the points marked as circles, which were taken at an angle of 115° with respect to the proton beam.

The statistical standard error in the cross section for all points plotted in Fig. 2 is less than 0.25×10^{-24} cm^2. In drawing a curve through the

[12] A. O. Hanson, Rev. Sci. Inst. **15**, 57 (1944).
[13] Haxby, Shoupp, Stephens, and Wells, Phys. Rev. **58**, 1035 (1940).

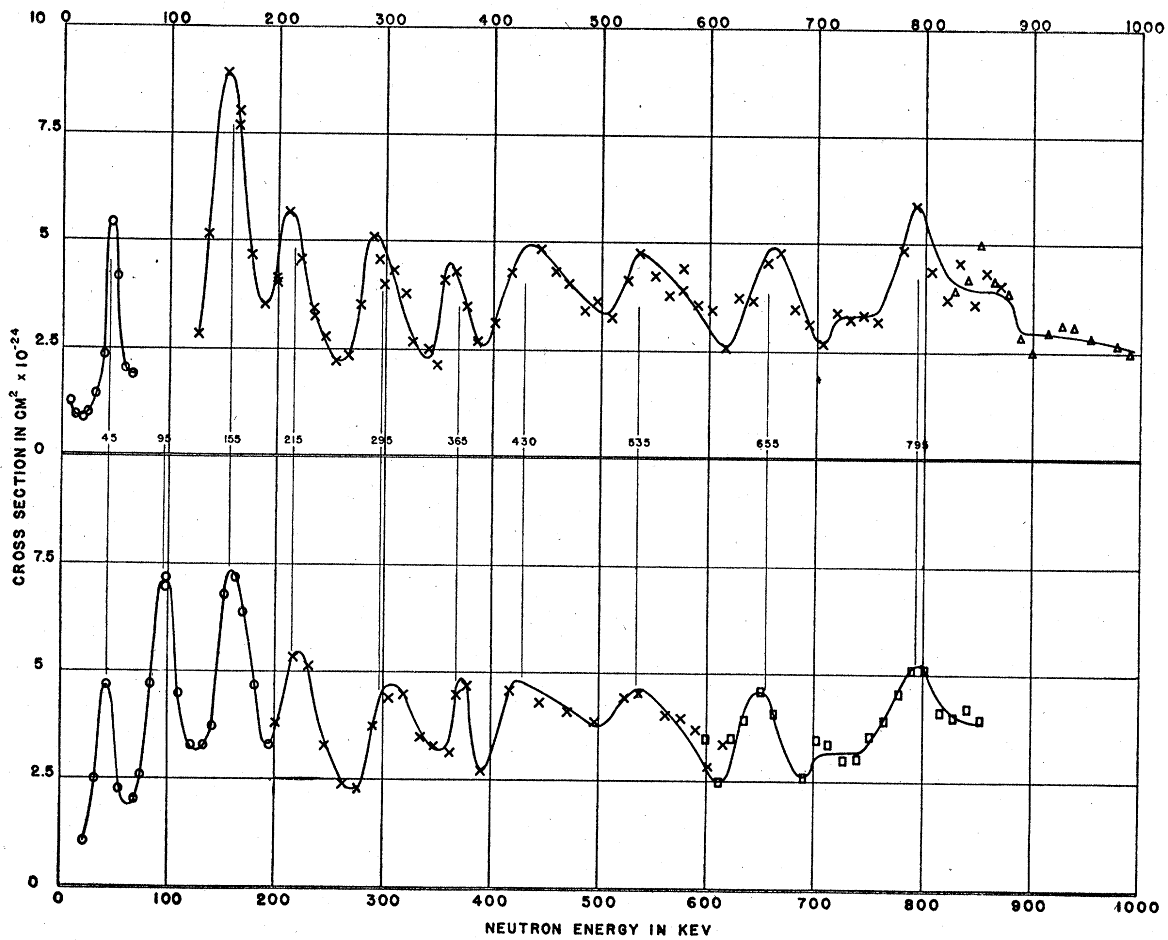

FIG. 2. The total neutron cross section of aluminum as a function of neutron energy. The neutrons were obtained by proton bombardment of a lithium film of 10-kev stopping power. The upper and lower curves represent measurements taken several days apart. Circles indicate measurements taken at 115° with respect to the proton beam, while all other symbols give results for neutrons emitted in the forward direction.

experimental points, peaks were indicated only when at least two successive points were clearly outside the statistical error from a smooth curve in at least two separate runs. Using this criterion, there appeared to be ten peaks in the energy interval covered, i.e., at 45, 95, 155, 215, 295, 365, 430, 535, 655, and 795 kev. In addition, there are indications of unresolved peaks, especially at higher energies. The neutron energies corresponding to the peaks are given to the nearest 5 kev because the separation of the experimental points by approximately 10 kev, combined with their statistical uncertainty, make the drawing of the curve through such points somewhat arbitrary and result in an uncertainty of the energy of the peaks of about 10 kev. In addition, there is an uncertainty in neutron energy of approximately 5 kev, which is primarily caused by the limit of reproducibility of the proton energy determined by the electrostatic analyzer.

The value of the cross section is strongly dependent on the spread in neutron energy as determined by target thickness, proton-energy spread, and geometry. For example, the peak appearing in Fig. 2, at a neutron energy of 155 kev, was measured with the detector in the forward direction for the upper curve and with the detector at 115° for the lower curve. Since the spread in energy of the neutrons emitted at 115° with a mean energy of 155 kev, is greater than the spread in energy of neutrons emitted in the forward direction with the same mean energy, the peak value of the cross section in the lower curve appears to be smaller. This effect is still more evident in Fig. 3 which shows the results of an investigation of this same peak using a lithium target of 5-kev stopping power and a scatterer, 1-in. thick. Figure 3 is plotted on the same scale as Fig. 2. The peak appears to be higher and narrower than the corresponding peaks in Fig. 2.

In measurements using a 10-kev target, the most important cause of spread in neutron energy is the target thickness. The magnitude of this spread varies with proton energy for a given target. For 150-kev neutrons in the forward direction, a 10-kev target causes a spread in neutron energy of 14 kev. Another limitation of resolving power is the spread of neutron energy over the face of the detector, since the energy depends upon the direction of neutron emission. In the geometry used, this spread amounts to 4 kev at a neutron energy of 150 kev in the forward direction. In addition, the spread in energy of the protons incident upon the lithium target of approximately ± 3 kev results in a neutron energy spread of approximately ± 4 kev. In view of the other limitations of the resolving power, it was felt that a target of less than 5-kev thickness would not give a sufficient improvement to warrant measurements at the resultant low neutron intensity.

In the upper part of Fig. 2, the peak shown at 155 kev has a width at half-maximum of about 35 kev, while according to Fig. 3, it has a width of about 16 kev. A width of 35 kev is somewhat more than one would expect from the above causes of neutron energy spread, although the relatively few experimental points through which the curve is drawn make the determination of the width uncertain. The considerable reduction in width, observed when a thinner target and a thinner scatterer were used, precludes any conclusion regarding the natural width of the resonance peak other than that the width of this peak is less than 16 kev.

The widths of the other peaks shown in Fig. 2 vary from 10 kev to 55 kev, the narrowest peak being at 45 kev where the resolving power is relatively high. Wider maxima appear at higher neutron energies and may well represent two or more unresolved peaks.

In Table I a summary of the results of other authors is given for measurements of the total cross section of aluminum in the range covered by the present measurements, and a comparison is made with cross sections obtained in the present experiment as read from the curves in Fig. 2. While the agreement appears rather poor, an inspection of Fig. 2 shows that small shifts in neutron energy would bring the values into good agreement. It is possible that the energy of the photo-neutron sources is slightly in error or that the different distribution in energy of the photo-neutrons from that of the Li+p neutrons might yield a different value of cross section.

The absorption cross section of aluminum at thermal energies[14] is only 0.2×10^{-24} cm^2, and it would be expected to be smaller at higher energies. One might assume, therefore, that the measured cross sections represent scattering cross sections.

The resonance curves for scattering should show a small decrease in cross section at energies just below the energy of each peak.[6] The complicated resonance structure, which is observed in the present experiment, makes it difficult to

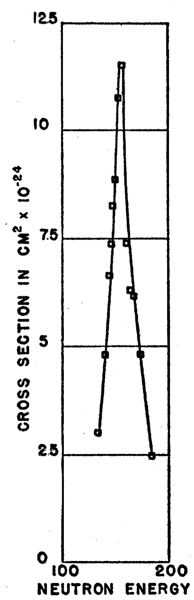

FIG. 3. The 155-kev peak of Fig. 2 measured using neutrons from a lithium target of 5-kev stopping power.

[14] R. D. O'Neal and M. Goldhaber, Phys. Rev. 59, 102 (1941).

TABLE I. Comparison of total neutron cross section of aluminum obtained in present measurements with the results of other authors.

Neutron energy (Mev)	Reference	Cross section (10^{-24} cm^2)	Cross section at same energy according to present data
0.024	a	0.80	1.0
0.13	b	4.0	3.7
0.13	a	5.3	3.7
0.20	c	5.8	4.0
0.22	a	3.2	5.2
0.22	b	3.8	5.2
0.60	c	3.6	3.0
0.62	a	4.1	2.7
0.83	a	3.5	4.1
0.88	b	3.1	3.9
0.88	d	3.4	3.9

a See reference 5.
b See reference 4.
c Barschall, Battat, Bright, Graves, Jorgensen, and Manley, Phys. Rev. (to be published).
d See reference 3.

recognize the expected minima. There may be an indication of such a decrease at 20 kev, however, provided that there are no further resonances below that energy. The total neutron cross section of aluminum at thermal energy[15] and at 1.4 ev[16] is 1.5×10^{-24} cm^2. The lack of variation in this energy range may indicate that there is no resonance in aluminum for slow neutrons. On the other hand, Lichtenberger[17] *et al.* report a resonance for capture in aluminum at 9.1 kev. In the present measurements, no resonance for the total cross section appears in this region.

The theoretical predictions[6] regarding the variations of total cross section with neutron energy are based on the assumption that the measurements represent averages over many resonances. The present measurements indicate that in aluminum the most prominent resonances are spaced at energy intervals of 50 to 100 kev. Thus, neither the present measurements nor measurements on aluminum using photo-neutron sources will give averages over several resonances. It is planned to extend the present measurements to heavier elements in which one would expect the energy-level density to be sufficiently great for the theory to be applicable.

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[15] Dunning, Pegram, Fink, and Mitchell, Phys. Rev. **48**, 265 (1935).
[16] H. B. Hanstein, Phys. Rev. **59**, 489 (1941).
[17] Lichtenberger, Nobles, Monk, Kubitschek, and Dancoff, Bull. Am. Phys. Soc. **22**, 18 (1947).