Capture Cross Sections for Fast Neutrons*

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The fast neutron capture cross section of Al^{27} was measured by observing the 2.3-minute activity of Al^{28} for neutron energies between 10 and 550 kev. Resonances were observed which showed some correlation with scattering resonances so that radiation widths of some of the levels could be estimated. Measurements of activation cross sections were also carried out for F, V, Cu^{65}, Ag, I, In^{115}, and Au.

I. INTRODUCTION

MEASUREMENTS of neutron cross sections have yielded a considerable amount of information about nuclear energy levels, in particular about their energies, their neutron widths, and the angular momenta of the incident particles and of the compound states. The present work is concerned with an attempt to obtain, in addition, information concerning the radiation widths of individual levels for light nuclei. In view of the small amount of data available on fast neutron capture cross sections and the inconsistencies in various determinations, further measurements of these cross sections appeared to be also of interest.

A summary of previous measurements of fast neutron capture cross sections is contained in a paper by Hughes *et al.*,[1] which describes the most recent determinations of the capture cross sections for fission neutrons. In almost all of the previous work, either neutrons with a large energy spread were used, or the determinations were carried out for heavy nuclei so that individual absorption resonances were not observed. It has been pointed out by Wigner[2] and Weisskopf[3] that radiation widths of levels can be deduced from measurements taken with poor neutron energy resolution, since the absorption cross section averaged over many levels can be calculated in terms of the radiation width. Nevertheless, it seemed desirable to obtain in a few cases direct measurements of the radiation widths which could be compared with the calculated values.

II. METHOD

Cross sections for the radiative capture of neutrons were determined through observations of induced radioactivities according to the method developed by Segrè[4] and Hughes.[1] In order to avoid the necessity for an absolute determination of neutron and of beta-particle counting efficiencies, the measurement consisted of a comparison of the activations induced by thermal and by fast neutrons in the same sample. A boron proportional counter served as a monitor to measure the relative neutron flux for the two types of activations. Since the variation of the boron disintegration cross section with energy[5] and the thermal activation cross sections of most elements are known, the fast neutron activation cross sections could be obtained.

III. APPARATUS

The samples to be activated consisted of hollow cylinders about 6 cm long and 2 cm in diameter which could be slipped over a Geiger counter. The cylinders were made of metal except in the cases of fluorine, where Teflon, $(C_2F_4)^n$, was used, and vanadium and iodine for which plastic cylinders were prepared from mixtures of NaI or V_2O_5 and polyethylene.

A BF_3 proportional counter served to monitor the neutron flux. The gas was contained between two thin concentric stainless steel cylinders. Four wires placed longitudinally between the cylinders formed the high voltage electrode. The cylindrical sample was inserted into this counter during the activations.

A thin-walled cylindrical Geiger counter was used for determining the induced beta-activity. In order to reduce the cosmic-ray background of the counter, it was surrounded by eight other identical counters mounted parallel to each other and the array was shielded with lead. By means of an anti-coincidence circuit,[6] pulses which were due to particles traversing an outer counter and the center counter were rejected. With this arrangement, the Geiger counter had a background of about six counts per minute.

IV. PROCEDURE

Fast neutrons were produced from the Li(p, n) reaction, using the electrostatic generator. These neutrons are monoenergetic in the forward direction with respect to the incident protons for energies of the main group between 120 and 650 kev. Monoenergetic neutrons below 120 kev could be obtained by carrying out measurements in a backward direction. Because of the low intensity of the neutrons under these conditions, small activation cross sections were difficult to measure below 120 kev, since the boron monitor count produced

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** Now at the Los Alamos Scientific Laboratory, Los Alamos, New Mexico.
[1] Hughes, Spatz, and Goldstein, Phys. Rev. **75**, 1781 (1949).
[2] E. P. Wigner, Am. J. Phys. **17**, 99 (1949).
[3] Feshbach, Peaslee, and Weisskopf, Phys. Rev. **71**, 145 (1947).
[4] MDDC-228, unpublished.
[5] R. K. Adair, Rev. Mod. Phys. **22**, 249 (1950).
[6] R. Tangen, Det Kgl. Norske Videnskabers Selskabs Skrifter 1946 NR1.

by neutrons scattered from the floor became comparable to or larger than that caused by the neutrons coming directly from the target. The magnitude of this background could not be determined accurately. When the energy of the main neutron group is greater than 650 kev in the forward direction, Be^7 may be left in its 430-kev state[7] and furnish a group of low energy neutrons. Since most absorption cross sections increase with decreasing neutron energy, the small number of low energy neutrons from the $Li^7(p, n)Be^{7*}$ reaction will make the measurements above 650 kev somewhat unreliable. Nevertheless, measurements were made in this range as a check for comparison of the present work with previous results, some of which were obtained also by the use of $Li(p, n)$ neutrons.

For measurements above 120 kev, the boron proportional counter containing the sample was placed in front of the lithium target so as to have its axis coincide with that of the incident proton beam as shown in Fig. 1. Care was taken in positioning the sample so that the sample and the active counting volume of the monitor subtended the same angle at the target.

The effective energy spread of the neutrons depends on the thickness of the lithium target, on the energy spread of the protons (5 kev), and on the variation of neutron energy over the length of the counter and sample due to the angle of emission from the target. This latter effect amounted to about 6 kev in the geometry shown.

In spite of the fact that the counter was surrounded by cadmium, an appreciable fraction of the monitor counts was caused by neutrons which did not come directly from the target. The corresponding background in the induced activity amounted to less than 5 percent. In order to measure these backgrounds, the counter was moved sufficiently far away from the target so that a neutron absorber consisting of paraffin and boron could be inserted between the target and the counter. Both activation and monitor backgrounds were measured at various distances from the target and then extrapolated to the position actually used in the cross-section measurements.

Thermal neutrons were produced by slowing down neutrons from a 100-millicurie radium-beryllium source in a block of paraffin, as shown in Fig. 1. It was found that the thermal neutron flux was most constant over the counter and the sample when the source was placed at the center of the sample and the counter hole was extended throughout the paraffin. Activations and neutron monitor counts caused by epithermal and fast neutrons were corrected for by subtracting the values obtained when the counter and sample were surrounded by cadmium.

Usually the length of activations and beta-counting periods were two half-lives each. A 15-second delay was sufficient to transfer the sample to the Geiger counter. The same schedule was followed for both fast and slow neutron activations. All operations requiring accurate timing were performed by mechanical timers and relay control circuits.

V. RESULTS

In Table I the substances on which measurements were carried out are listed together with the half-life of

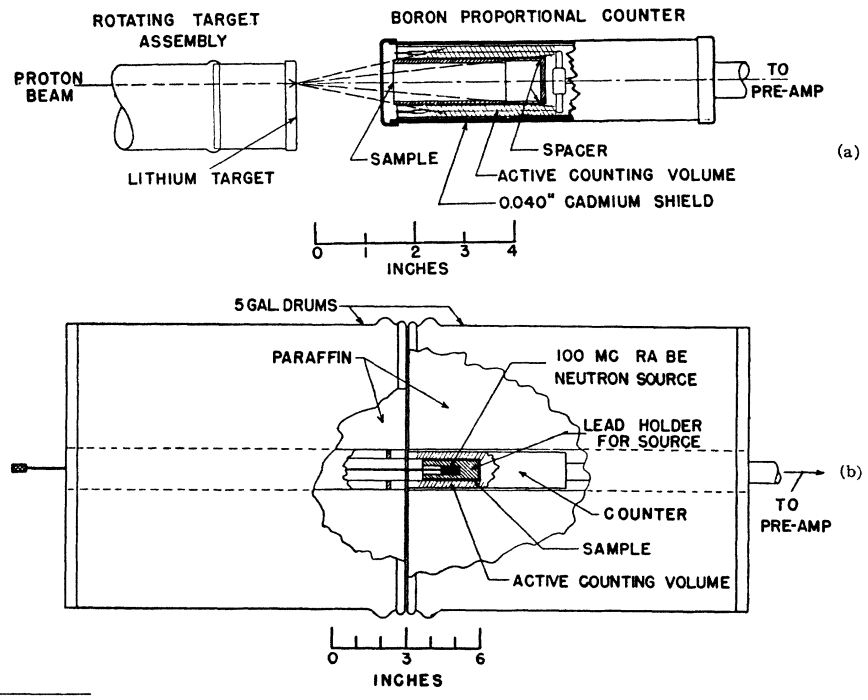

FIG. 1. Apparatus and geometry used for measurements of fast neutron activation cross sections. (a) Fast neutron activation. (b) Thermal neutron activation.

[7] Johnson, Laubenstein, and Richards, Phys. Rev. 77, 413 (1950).

the induced activity and the thermal activation cross section on which the present measurements are based. These substances were chosen because of the convenient half-lives of the induced activities, and because they absorb neutrons of energies below 1 Mev presumably only by radiative capture.

Comparison With Previous Results

Most of the previous measurements of capture cross sections were carried out for heavy elements which have high cross sections for fast neutrons; in particular, Ag^{107}, Ag^{109}, In^{115}, I^{127}, and Au^{197} were investigated carefully at Los Alamos.[4] As a check on the method used in the present work, data on these substances were compared with previous work. The most extensive measurements are available on gold, some of which are shown in the comparison of Fig. 2. Within the rather large uncertainty of both previous and present determinations, the agreement is good.

Similarly, good agreement with the data published in reference 4 was obtained for Ag^{107} and I^{127}. For Ag^{109} on the other hand, the present data give for neutron energies between 120 and 600 kev, cross sections about twice as high as those found by Segrè *et al.* In view of the fact that the measurement of such a short activity (24 sec.) offers some experimental difficulties, particularly because of the presence of the 2.3-min. activity of Ag^{107}, this discrepancy may not be too surprising. The 13-sec. activity of In^{115} gave a rather constant cross section varying from 140 millibarns at 15 kev to 90 millibarns at 1000 kev. The 1-Mev value agrees reasonably well with Hughes' data.

Aluminum

Aluminum appeared to be an element in which capture resonances might be relatively easy to observe. This element has a single isotope and the induced activity has a convenient half-life of 2.3 minutes. Previous measurements of the total cross section of aluminum indicated a sufficiently wide separation of energy levels that it could be expected that levels might be resolved with the energy spreads available in activation experiments.

In the lower part of Fig. 3, the absorption cross section of aluminum in millibarns is plotted against neutron energy in kev. The energy spread of the neutrons was about 10 kev below 100 kev and about 8 kev above this energy. Between 75 and 120 kev, measurements were difficult because of the relatively high background of neutrons scattered by the floor and the low value of the absorption cross section. In this energy range, evidence for at least one maximum was obtained, but because of the large uncertainty in the cross section the data are not shown in Fig. 3.

For comparison, the total cross section of aluminum in barns is shown in the upper portion of Fig. 3. In the total cross-section measurements, the energy resolution was about 10 kev below 50 kev, 25 kev between 50 and 130 kev, 2 kev between 130 and 200 kev, and 8 kev above this energy.

TABLE I. Thermal neutron activation cross sections.

Isotope	Percentage abundance	Induced half-life	Thermal activation cross section (barns)
F^{19}	100	10.7 sec.	0.01
Al^{27}	100	2.3 min.	0.22
V^{51}	100	3.7 min.	4.8
Cu^{65}	31	4.3 min.	2.05
Ag^{107}	51	2.3 min.	34
Ag^{109}	49	24 sec.	85
In^{115}	96	13 sec.	145
I^{127}	100	25 min.	6.1
Au^{197}	100	2.7 days	95

Fluorine

Measurements of the capture cross section for fluorine are complicated by the fact that its cross section is small and the half-life of the induced activity is so short (10.7 sec.). In the lower part of Fig. 4 the results of the investigations of two energy regions with an energy resolution of 20 kev are shown. The upper part of the figure gives the total cross section of fluorine, also measured with 20 kev energy spread.[8]

The mass values published in some of the literature[9,10] would lead to an exothermic $F^{19}(n, \alpha)N^{16}$ reaction which might be difficult to distinguish from the radiative capture process since the induced half-lives are 7.4 sec. for N^{16} and 10.7 sec. for F^{20}. However, recent work[11,12] has shown that the (n, α) reaction does not occur for fluorine in the energy range covered by this

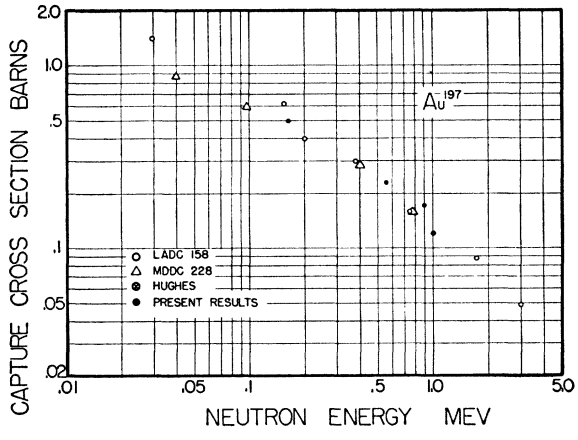

FIG. 2. Comparison of present results with previous values of neutron capture cross section for gold as a function of neutron energy.

[8] C. K. Bockelman (to be published).
[9] H. A. Bethe, *Elementary Nuclear Theory* (John Wiley & Sons, Inc., New York 1947), p. 124.
[10] J. Mattauch, *Nuclear Physics Tables* (Interscience Publishers, Inc., New York 1946), p. 126.
[11] H. S. Sommers and R. Sherr, Phys. Rev. **69**, 21 (1946).
[12] J. V. Jelley and E. B. Paul, Proc. Phys. Soc. London **63**, 112 (1950).

experiment, since the reaction energy is about -1.2 Mev.

Vanadium

According to measurements by Blair and Wallace,[13] energy resolutions of 5 to 10 kev are sufficient to find the effect of fast neutron resonances in vanadium but not to resolve the resonances fully. Determination of the capture cross section of vanadium carried out with 8-kev energy resolution indicated, in qualitative agreement with the total cross-section measurements, the presence of ten not fully resolved maxima between 120 and 650 kev. In view of the close spacing of the levels, it is difficult to judge whether the position of the resonances observed in total and capture cross sections agree, since the apparent spacing of the peaks is probably largely determined by the experimental resolution. The measured cross section of vanadium fluctuates by not more than 3 millibarns around a smooth curve which decreases from 16 millibarns at 120 kev, to 6 millibarns at 400 kev and to 3 millibarns at 650 kev.

Copper

With 8-kev resolution, the effect of individual levels on the capture cross section of copper could be noticed. Repetition of the measurements with 20-kev neutron resolution yielded a smooth curve. Observed values of the absorption cross section were 30 millibarns at 150 kev, 20 millibarns at 300 kev, and 13 millibarns at 500 kev. This cross section is for the Cu^{65} isotope only.

VI. SOURCES OF ERROR

The present determinations of fast neutron capture cross sections depend directly upon the boron disintegration cross section and the thermal activation cross sections, and are uncertain by at least the errors of these previous measurements. The probable error in the fast neutron boron cross section is about ± 15 percent, while the probable error of most thermal activation cross sections is ± 20 percent. An attempt was made to keep additional errors in the present comparison appreciably below 20 percent. In addition, the comparison used in the present determinations involves the assumption that both the boron cross section and the activation cross sections follow the $1/v$ law in the region of thermal energies. If the activation cross section deviated from this law, a small error is introduced for which no correction was made. It is estimated that the present data have a probable error of 30 percent.

VII. DISCUSSION

According to the Breit-Wigner theory of nuclear resonances, the resonance contribution to the cross sections for elastic scattering and radiative capture should be in the ratio of the neutron width to the

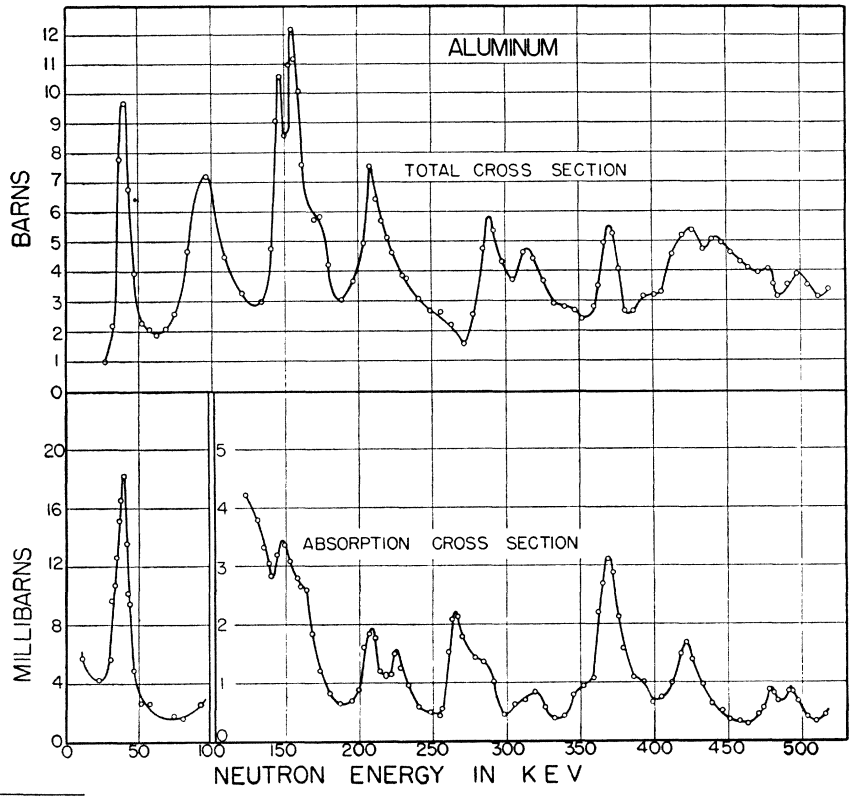

FIG. 3. Comparison of total cross section and capture cross section for aluminum as a function of neutron energy.

[13] J. M. Blair and J. R. Wallace, Phys. Rev. **79**, 28 (1950).

radiation width of a level. For the nuclei for which the effect of individual levels were observed in the present investigation, the neutron widths are of the order of a thousand times larger than the radiation widths. As a consequence, the total widths of both scattering and radiative capture resonances should be practically equal to the neutron width. From the observed width of the resonance and the ratio of the scattering and absorption cross sections, it should then be possible to obtain values for the radiation widths. Factors which have to be taken into account in the evaluation are the following: For the energy region covered, if the observed resonance is due to *s*-neutrons, resonance and potential scattering will interfere in such a way as to shift the peak in the scattering cross section to a higher energy with respect to the absorption maximum by about half the width of the level. This energy shift will cause some uncertainty in correlating maxima in the two cross-section curves, if the peaks are closely spaced. On the other hand, this effect might be helpful in some cases in determining the angular momentum of the neutrons responsible for the resonance.

Another consideration which complicates the determination of radiation widths is the difference in the effect of finite energy resolution on the shape of the observed resonances in scattering and absorption. For both scattering and absorption measurements, the resonance peaks will be spread out if the energy spread of the neutrons is greater than the width of the resonance. Since the scattering cross sections were determined from transmission experiments, there is an additional hardening effect which will reduce the peak heights. While the area under a peak in the capture cross section is independent of the resolution used, the area under a peak in the scattering cross section increases as the resolution is improved. Therefore, estimates of radiation widths obtained from comparing peak heights will be reliable only if the maxima are fairly well resolved. By comparison of the observed height of a maximum in the total cross section with the theoretical maximum predicted by the Breit-Wigner theory it is possible to determine how well this condition is fulfilled.

It would be expected that every resonance should be observable in both the scattering and in the absorption cross sections. Neither in fluorine nor in aluminum is this correlation found for all the resonances.

For fluorine, the positions of the 280- and 590-kev maxima agree well on the curves shown in Fig. 4. Both resonances probably have natural widths not

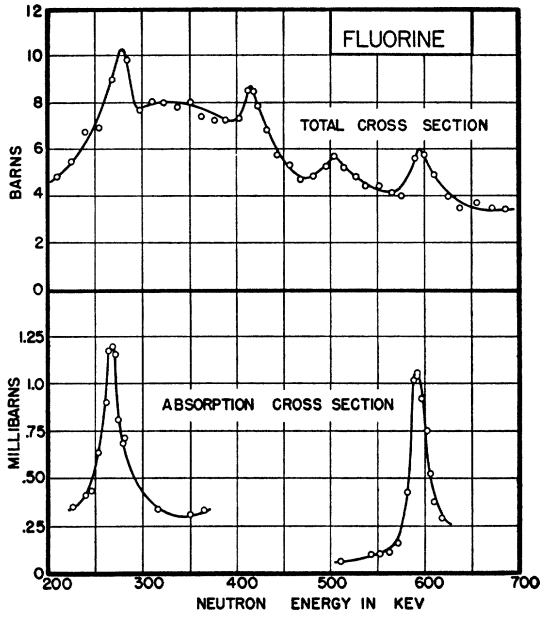

FIG. 4. Comparison of total neutron cross section and neutron capture cross section for fluorine.

appreciably smaller than the measured widths. A comparison of the peak heights for the two curves gives radiation widths of about 15 ev. No indications of peaks in the capture cross section were found, however, corresponding to the maxima shown at 340 and 510 kev in the total cross section. These latter two maxima are very broad so that the neutron widths may be too large compared to the radiation widths to give measurable peaks in the absorption cross section.

The aluminum curves show good agreement between some of the maxima, in particular those of the 40-kev, 215-kev, and 370-kev resonances. A reliable correlation of most of the other peaks is difficult since the structure is too complicated to be resolved in this experiment. For the three prominent absorption peaks a comparison of total and absorption cross section yields radiation widths of 5 to 15 ev for aluminum. These widths are larger by about a factor of 10 than the value of 1.25 ev calculated by Wigner from Hughes' measurement of the average capture cross section and a level spacing of 50 kev. It should be pointed out, however, that the present widths are determined for the levels which have the largest radiation widths. The average width, taking into account the narrower levels, appears to the of be same order of magnitude as the calculated value.