Total Cross Section of Be, O, Na, and Ca for Fast Neutrons

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The total cross sections of Be, O, Na, and Ca were investigated as a function of neutron energy in ranges between 30 and 1000 kev with a resolving power of approximately 20 kev. In Be a resonance was observed at 625 kev, presumably caused by *p*-neutrons. The resonance in O at 440 kev is probably due to *p*-neutrons forming a compound nucleus of spin $\frac{3}{2}$. In Na and Ca numerous peaks were found. The cross section of Ca has values below 1.5 barns over a considerable range of energies.

INTRODUCTION

IN previous experiments[1,2] carried out at this laboratory, an attempt was made to obtain information regarding the spacing of nuclear energy levels by measuring total neutron cross sections as a function of energy. It was found that in nuclei as heavy as nickel, the effect of individual levels could be observed with a resolving power of 20 kev. In the present measurements other nuclei were studied with the aim of filling in the gaps between elements previously investigated. In addition, it appeared desirable to try to obtain more detailed information on the character of the resonances in light nuclei.

EXPERIMENTAL

The procedure for measuring total cross sections as a function of neutron energy was the same as that described in reference 1. Neutrons were obtained by bombarding a lithium target of about 13-kev stopping power by protons. The energy of the neutrons was calculated using the value of 1.882 Mev obtained by Herb, Snowdon, and Sala[3] for the threshold of the Li(p,n) reaction. The geometry used in the experiments is shown in Fig. 1. Cross sections were obtained by measuring the transmission of the neutrons through a circular disk, assuming an exponential decrease of neutron intensity in the sample.

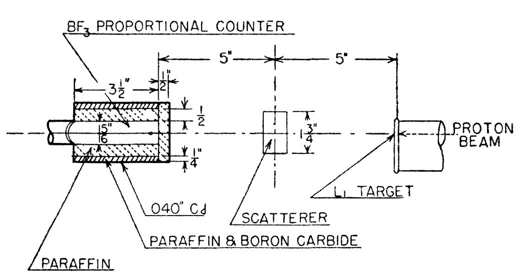

FIG. 1. Geometry used in scattering experiments.

For each element investigated, one curve showing the cross section as a function of neutron energy will be presented. In all cases, however, more than one measurement was carried out in each energy range, and the manner in which the solid curves are drawn through the experimental points was influenced by the reproducibility of the observed fluctuations in cross section. The vertical height of the symbols used to represent experimental results shows the standard statistical error of the measurement. Changes in symbols used indicate a lapse of time between measurements.

BERYLLIUM

The total cross section of beryllium has been measured at several energies between 20 kev and 900 kev.[4–8] Allen *et al.*[8] find that the cross section between 350 and 550 kev is higher than that found by earlier investigators[4–6] at both lower and higher energies, and they conclude that there is evidence for a resonance around 500 kev. This conclusion is, however, not convincing, if their measurements are compared with the more recent results of Fields *et al.*,[7] since both of these measurements taken together give a smooth variation of cross section with energy between 20 and 900 kev.[9] In view of the importance of beryllium as a moderator it seemed desirable to clear up the question of the existence of resonances in this energy range. The sample of beryllium used was a disk of metallic beryllium, $\frac{1}{4}''$ thick, containing 0.0859×10^{24} atoms/cm^2. The disk was manufactured by the Brush Beryllium Corporation.

The results of the measurements are shown in Fig. 2. The total cross section of beryllium appears to be a smooth function of the energy in the energy range between 25 and 750 kev except for a resonance

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which occurs at 625 kev. At this energy the cross section reaches 7 barns; the measured width of the peak at half maximum is 35 kev, which is almost twice the experimental resolving power.

According to the Breit-Wigner theory of nuclear resonances, the maximum value which the cross section can reach at the peak of an isolated scattering resonance is given by

$$\sigma_m = 2\pi k^{-2}(2J+1)/(2I+1),$$

where k is the wave number of the incident neutron, J the spin of the compound nucleus, and I the spin of the bombarded nucleus. This value of σ_m will be attained only if the width for absorption and inelastic scattering is small compared to the total width. This condition probably obtains for beryllium. According to the measurements of Hughes *et al.*,[10] the absorption cross sections for fast neutrons are very small compared to the total cross sections for light elements. The results of Aoki[11] combined with those of Nonaka[12] show that the cross section of beryllium for inelastic scattering is less than 0.1 barns even for 2.5-Mev neutrons. Taking the spin of Be^9 as $\frac{3}{2}$,[13] the theoretical maximum of the total cross section is given by $\frac{1}{2}\pi k^{-2}(2J+1)$ or for beryllium at 625 kev, $\sigma_m = 0.64 \times (2J+1)$ barns. If one assumes that the observed resonance is due to neutrons of zero orbital angular momentum, the maximum contribution to the total cross section by neutrons forming a compound nucleus of one unit of angular momentum is 1.9 barns, while for $J=2$ it is 3.2 barns. Even if one makes the very unlikely assumption that resonances for the two possible values of the spin of the compound nucleus occur at the same energy, the theoretical maximum is still considerably below the observed peak cross section, indicating that the resonance cannot be caused by s-neutrons. This conclusion is corroborated by the shape of the resonance. One would expect that the peak should be preceded by a region of decreased cross section if there is appreciable interference between potential and resonance scattering. At energies in the neighborhood of this resonance the potential scattering is almost entirely s-scattering.[14] Consequently, the fact that no decrease in cross section was observed in any of the runs, supports the belief that the resonance is caused by neutrons of at least one unit of angular momentum. In this case, interference between resonance and potential scattering should not be observable, and the contribution of the resonance scattering is only that above the potential scattering, i.e., approximately 3.7 barns. Assuming a Gaussian resolution function with a width at half maximum of 20 kev, the natural height of the resonance is 22 percent greater than that observed, giving a value of 4.5 barns. For a spin of the compound nucleus of 2 the theoretical maximum is 3.2 barns, while for $J=3$, $\sigma_m = 4.5$. Therefore, the value $J=3$ appears most likely to be applicable. While the experiment does not give any direct information about the orbital angular momentum of the incident neutrons, it does not seem likely that a resonance as wide as the observed one would be caused by neutrons of more than one unit of angular momentum, since the neutron width at this energy is expected to be thirty times smaller for $l=2$ than for $l=1$ (Eq. 45(a) of reference 14).

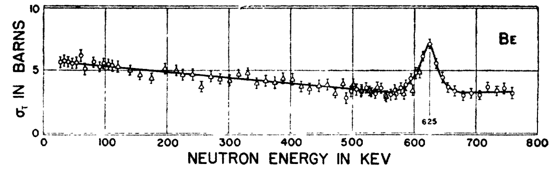

FIG. 2. The total cross section of beryllium as a function of neutron energy.

The measurements agree fairly well with the results of Allen *et al.*[8] and with those of Fields *et al.*[7] except for the value of Fields at 620 kev. This disagreement may be due to the uncertainty in the energy determination of the La-Be photo-neutron source, which is given by Wattenberg[15] as ± 70 kev. The theoretical work by Schlögl[16] predicts a variation of cross section with energy which is qualitatively in agreement with the present results, but this theory does not give information regarding the position of resonances.

OXYGEN

Extensive measurements of the total cross section of oxygen have been published.[7, 17–19] All the

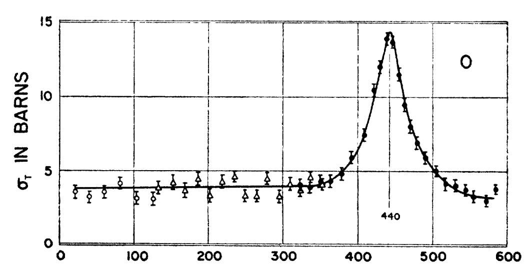

FIG. 3. The total cross section of oxygen as a function of neutron energy.

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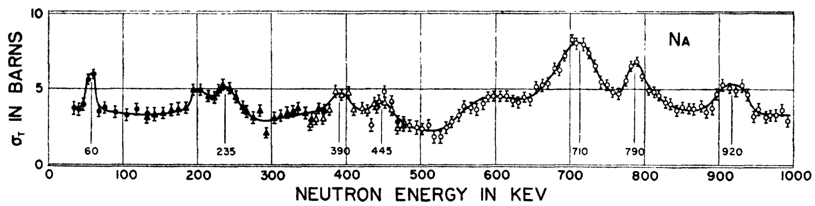

FIG. 4. The total cross section of sodium for fast neutrons.

results agree in showing a resonance around 450 kev, but below this energy the spacing in energy of the points is too great to preclude the existence of further resonances. In the present experiments it was hoped to obtain more definite information both about the low energy region and about the first resonance which was observed previously.

The oxygen cross section was measured by comparing the neutron intensity transmitted through a sample of beryllium oxide with that transmitted through metallic beryllium. The beryllium oxide sample contained as closely as possible the same number of beryllium atoms as the beryllium sample previously described. The beryllium oxide powder and the beryllium disk were placed in identical containers, and the two containers were placed alternately between the neutron source and the detector. The ratio of the neutron intensities observed in the two cases was taken as the attenuation produced by the oxygen. Measurements were carried out only in the energy region below the first beryllium resonance.

The cross section of oxygen as a function of neutron energy is shown in Fig. 3. No resonances were observed below the peak at 440 kev. At 440 kev the cross section reaches 14 barns. The width of the peak at half maximum is about 45 kev which is more than twice the experimental resolving power. Using the fact that the spin of O^{16} is zero, the theoretical maximum cross section at 440 kev is given by $\sigma_m = 3.35(2J+1)$ barns. The total cross section should actually reach this maximum value, as the absorption and inelastic scattering cross sections are small for oxygen.[10, 11]

As in the case of beryllium, the height of the maximum cannot be accounted for if the resonance is due to s-neutrons, since for s-neutrons $J=\frac{1}{2}$ and $\sigma_m = 6.7$ barns. Further, the absence of a region of reduced cross section preceding the peak also indicates that neutrons of more than zero angular momentum are responsible for the resonance. For $J=\frac{3}{2}$ one obtains $\sigma_m = 13.4$ barns, which is sufficient to account for the experimental amplitude of the resonance. $J=5/2$ would give $\sigma_m = 20.1$ barns, which is considerably more than the observed value. The assignment of the peak to neutrons of more than one unit of angular momentum is rendered unlikely by its width. One is thus led to the conclusion that the resonance is due to p-neutrons forming a compound nucleus of total angular momentum $\frac{3}{2}$.

A comparison of the present measurements with previous results[7, 17–19] shows fairly good agreement except for the height of the resonance at 440 kev. This difference is undoubtedly due to the somewhat better resolving power and closer spacing in energy used in the present experiment.

SODIUM

While O^{16} shows only one resonance up to 600 kev, previous investigations[1] of the total cross section of Al^{27} indicate the presence of at least eight resonances in this energy range. It was felt to be desirable, therefore, to study the level density for a nucleus of intermediate weight. Sodium was chosen since it has only one stable isotope, Na^{23}.

A circular disk of sodium, 1.5 in. thick, was cut out of a sodium brick and sealed in an air-tight container. The sample contained 0.0935×10^{24} atoms/cm^2. The effect of the sodium was measured by comparing the transmission through the container enclosing the sodium with that through an identical empty container.

The results of the measurements on sodium are shown in Fig. 4. Peaks appear at 60, 200, 235, 390, 445, 710, 790, and 920 kev. In addition, there is an indication of a maximum at 340 kev. The observed widths of the peaks show strong fluctuations and several of the maxima are considerably wider than the experimental resolving power. A decision as to

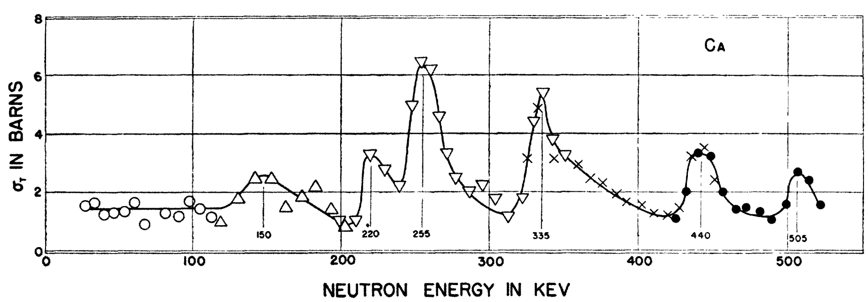

FIG. 5. The total cross section of calcium for fast neutrons.

whether this variation of width is due to different natural widths of the resonances or to the fact that not all the resonances were resolved will have to await a repetition of the measurements using better resolving power.

The total cross section of sodium has previously been measured at some energies by Fields *et al.*,[7] using photo-neutron sources. A comparison of these measurements with the present data is somewhat difficult because of the uncertainty in the energy of the photo-neutrons. If this uncertainty is taken into account, the agreement between the results is very good.

CALCIUM

Evidence for the existence of closed shells in nuclei was recently summarized by M. G. Mayer.[20] According to this theory, twenty neutrons or protons form a closed shell, and Ca^{40} is the best example of a closed shell nucleus. A nucleus of this type might be expected to behave in many respects like a light nucleus; in particular, the levels should be wide and show considerably greater separation than those of other nuclei of comparable weight. Since Ca^{40} has an isotopic abundance of 97 percent, measurements of the total cross section of calcium will give almost entirely the behavior of the Ca^{40} nucleus.

The calcium sample used in the experiments was machined out of Ca metal and painted with glyptal to retard oxidation. Because of the low density of Ca metal it was necessary to make the sample 3.5″ thick, since preliminary experiments indicated that the Ca cross section was unusually small. The sample contained 0.187×10^{24} atoms/cm². The use of a scatterer of thickness comparable to the separation of source and detector introduces an uncertainty in the determination of the absolute cross section, since the correction for scattering into the detector cannot be determined accurately.

The variation of the total cross section of calcium with energy is shown in Fig. 5. Maxima are indicated at energies of 150, 220, 255, 335, 440, and 505 kev. A less clearly pronounced maximum appears at 185 kev. The frequency of occurrence of these maxima and their sharpness do not appear to be in agreement with the idea that Ca^{40} should exhibit a behavior similar to light nuclei.

An interesting feature of the results is the small value of the calcium cross section over wide energy intervals. The cross section is 1.5 barns or less from 30 to 120 kev and drops again to a similarly low value between resonances at higher energies. The cross sections of other elements of comparable or smaller mass for similar energies are usually two or three times greater. According to the measurements of Fields *et al.*,[7] potassium also shows an abnormally small cross section. K^{39}, which has an isotopic abundance of 93 percent, contains the same number of neutrons as Ca^{40}. It is not clear, however, why a closed neutron shell would result in a particularly small neutron cross section.

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ACKNOWLEDGMENTS

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N^{17}, A Delayed Neutron Emitter

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The decay scheme of a 4.2-second neutron emitter has been investigated in detail. Chemical and physical evidence shows that it is N^{17}, which emits beta-rays to a broad excited state of O^{17}, which then breaks up into a neutron plus O^{16}. The energy spectrum of the neutrons is determined by measuring the energies of the O^{16} recoils in a proportional counter. The neutrons have a most probable energy of 0.9 Mev, a "half-width" of less than 0.5 Mev, and an upper limit of about 2 Mev. β-recoil coincidences are observed, as predicted by the Bohr-Wheeler theory, and the β-ray energy is measured by absorption. The beta-rays in coincidence with neutrons have an upper limit of 3.7 ± 0.2 Mev. Beta-rays directly to the ground state of O^{17} are not observed because of high background effects, but should have an energy of 8.7 Mev. Some evidence is presented to show that energy is conserved in the β-n transition through the broad excited state in O^{17}.

INTRODUCTION

SHORTLY after the discovery of fission, Roberts, Meyer, and Wang[1] reported that neutrons were emitted from neutron-bombarded uranium, with a period of approximately 12 seconds. Later work[2] showed that 6 separate half-lives could be identified

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