Total Cross Sections of Be, B, O, and F for Fast Neutrons*

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Previous studies of the cross sections of Be and O as functions of neutron energy have been extended to higher energies. Three resonances in oxygen were observed below 1.4 Mev, in agreement with those reported by the Minnesota group. In the range from 0.2 to 1.4 Mev, two resonances were found for Be. For energies below 1 Mev, one level was observed in B, while evidence for at least seven resonances was found for F in the energy interval from 0.01 to 0.7 Mev. The assignment of reduced widths and spin values to the compound states is possible in certain cases.

I. INTRODUCTION

MEASUREMENTS of the total cross sections of light elements are of interest because of the information they offer concerning the energy levels of these nuclei. In the lighter elements the levels are sufficiently broad and widely separated in energy that their true shapes may be obtained with neutron energy spreads which are conveniently attainable. The present paper is concerned with an extension to higher energies of previously[1] published measurements on beryllium and oxygen and also presents the results of measurements of the total cross sections of boron and fluorine.

Cross sections were measured by transmission experiments according to techniques previously described,[1] the neutrons being produced by the Li(p,n)Be reaction. The presence of a small number of neutrons of lower energy at energies above 650 kev for the main group[2] is believed to have a negligible effect in this experiment. If there were a significant number of low energy neutrons present, one would expect maxima observed with the main group to repeat as the energy of the second group passed through a resonance. No such effect was observed. Also, the close agreement of the oxygen data with those of Freier, *et al.*,[3] who used neutron detectors biased against this group, corroborates this argument.

For the interpretation of the observed resonances it will be assumed that elastic scattering is the only process of importance in the energy range and for the nuclei investigated in the present study. The cross section may then be considered to be composed of the contributions of potential scattering and of the resonant interaction of the incident neutrons with the target nuclei. Since at the neutron energies used here the potential scattering is almost entirely s-scattering, resonances produced by s-neutrons should be recognizable by a region of destructive interference between resonance and potential scattering preceding the resonance peak. If all interactions other than elastic scattering are neglected, the variation of the cross section at an isolated resonance is given according to the Breit-Wigner theory by $2\pi k^{-2}(2J+1)/(2I+1)$, 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. Thus, the spin of the compound state can be deduced from the measured variation of cross section at a resonance.

A convenient energy-independent parameter for the description of level widths is the reduced width γ^2, defined as

$$\gamma^2 = \Gamma/2kT_l,$$

where Γ is the natural width and T_l is the centrifugal barrier penetration factor. The sum of the reduced widths for transitions from a given level in the compound nucleus to all final states has been given by Wigner.[4] In certain cases this sum rule makes possible an assignment of the orbital angular momentum of the neutrons which produce a resonance.

II. BERYLLIUM

Determinations of the total cross section of Be from 0.03- to 0.75-Mev neutron energy were reported in reference 1. The measurements were extended to 1.40 Mev with an energy resolution of 20 kev, and those in the range from 0.20 to 0.85 Mev were repeated with a

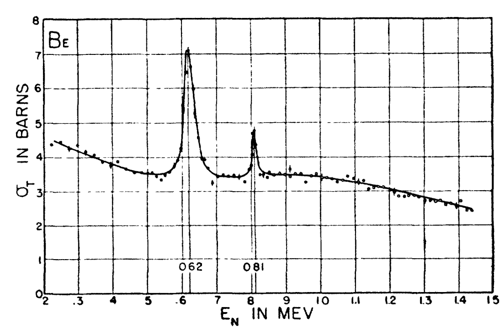

FIG. 1. The total cross section of beryllium. Points denoted by open circles represent data taken with a neutron energy spread of 20 kev; for the solid circles the energy spread was 12 kev. The length of the vertical bars through the points give the standard statistical error.

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[1] Adair, Barschall, Bockelman, and Sala, Phys. Rev. **75**, 1124 (1949).

[2] Johnson, Wilson Laubenstein, and Richards, Phys. Rev. **77**, 413 (1950).

[3] Freier, Fulk, Lampi, and Williams, Phys. Rev. **78**, 508 (1950).

[4] E. P. Wigner, Am. J. Phys. **17**, 99 (1949).

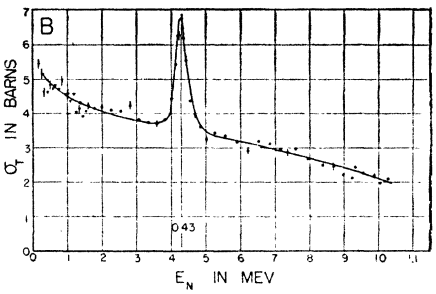

FIG. 2. The total cross section of boron. The neutron energy spread was 12 kev for energies above 0.13 Mev, and 25 kev for lower energies.

neutron energy spread of 12 kev. The results are shown in Fig. 1.

As might be expected, the shape of the 0.62 Mev resonance did not change appreciably from that described in reference 1, since its experimental width is considerable larger than the neutron energy spread used in either experiment. The peak at 0.81 Mev, however, has a measured width of 12 kev, equal to the experimental energy spread. Thus, it is not felt that the true shape of the resonance is sufficiently well known to specify the angular momenta involved. However, absence of any dips near the peak indicates that it must be caused by neutrons with orbital angular momentum $l>0$, and the height of the resonance is greater than that which would occur if the spin of the compound nucleus were zero.

III. BORON

The neutron flux transmitted through a sample of amorphous boron in a brass container was compared with that transmitted through an identical empty container. For measurements above 0.13 Mev a neutron energy spread of 12 kev was used; below this energy the resolution was about 25 kev. The total cross section is shown in Fig. 2. The results agree reasonably well with those of Wattenberg,[5] but are consistently higher than those of Barschall, *et al.*[6] While the geometry used in the latter work was such that the correction for scattering into the detector amounted to 7 percent on the assumption of isotropic scattering, this correction is 3 percent in the experiment reported here. Even after both sets of measurements are corrected, there remains a 0.7-barn difference between them. This discrepancy may be the result of anisotropic scattering of the neutrons.

At 0.43 Mev a maximum is observed at which the cross section reaches a value of 6.7 barns. Since the isotopic abundance of B^{11} is 81 percent, the resonance is ascribed to this isotope. The lack of any dip in the neighborhood of the peak indicates that it should not be attributed to s-neutrons. Since values of l greater than unity yield reduced widths which exceed the limit imposed by the sum rule,[4] the resonance is assigned to p-neutrons and has a reduced width of 1.0×10^{-13} Mev-cm, corresponding to the observed width of 45 kev. When it is assumed that inelastic scattering and absorption can be neglected at these energies, application of the single level dispersion formula yields maximum values of 2.2, 3.6, and 5.1 barns as resonance contributions for the spin of the compound nucleus $J=1$, 2, and 3, respectively. These values include a factor of 0.81 to account for the isotopic abundance of B^{11}. If the potential scattering is taken as equal to 3.7 barns in the neighborhood of the resonance, it seems most reasonable to attribute the resonance to interaction with p-neutrons forming a compound nucleus with $J=2$ although the value $J=3$ cannot be excluded.

Since an oxygen resonance occurs at very nearly the same energy, it was suspected that this maximum might actually be caused by an oxygen contamination of the sample. Therefore, the boron was tested for presence of the oxide by leaching it with hot water, in which boron oxide is soluble while boron is not. Less than 3 percent of the sample by weight dissolved, so it was concluded that the oxygen contamination was insufficient to affect the measurement significantly. Furthermore, if oxygen were responsible for the resonance, one would expect it to cause an increase in the cross section at the next oxygen resonance around 1 Mev. No such increase was found.

IV. OXYGEN

The oxygen cross section was obtained by comparison of the transmission through a brass container filled with BeO to that through an identical container enclosing a Be disk of such thickness as to match as closely as possible the number of Be atoms. The solid circles in Fig. 3 represent the present measurements, taken with an energy resolution of 20 kev. For the sake of completeness, the results cited in reference 1 are also shown, indicated by open circles. The data are in agreement with those of Freier, *et al.*[3] in the energy range they have in common.

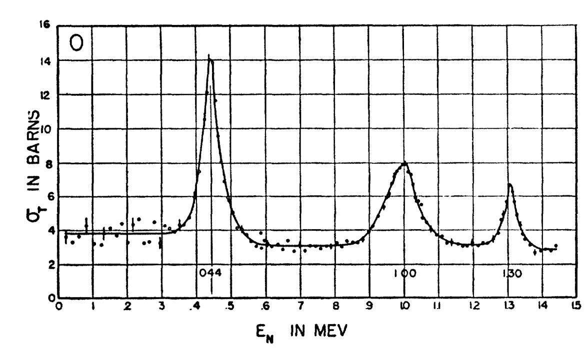

FIG. 3. The total cross section of oxygen. Solid circles represent the present measurements; open circles indicate the results described in reference 1. A neutron energy spread of 20 kev was used.

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

[6] Barschall, Battat, and Bright, Phys. Rev. **70**, 458 (1946).

The three resonances at 0.44, 1.00, and 1.30 Mev have experimental widths at half-maximum of 45, 100, and 40 kev respectively. The observed maxima are best fitted by taking $J=3/2$. This resonance contribution, added to the potential scattering, yields values of 16.8, 8.9, and 7.5 barns at 0.44, 1.00, and 1.30 Mev, respectively, as compared with the experimental values of 14.0, 7.9, and 6.7 barns. By assuming that the neutron energy spread is Gaussian in shape, one can estimate that the true maxima are about 10 percent larger than those observed, so that the agreement between experimental and predicted values is satisfactory. The lack of any dips near the peaks indicates that the resonances should not be assigned to *s*-neutrons. Since values of l greater than unity yield reduced widths which exceed the limit given by the sum rule[4] by more than 50 percent, the 0.44-Mev peak is attributed to an interaction with *p*-neutrons, and has a reduced width of 0.76×10^{-13} Mev-cm. Although the experiment does not give any further direct information about the orbital angular momentum of the incident neutrons, it does not seem likely that the maximum at 1.00 Mev would be caused by neutrons with $l>1$, since the reduced width for $l=2$ would amount to 50 percent of the sum. Thus, this resonance is assigned to *p*-neutrons, on which assumption the reduced width is 0.66×10^{-13} Mev-cm. For both of these levels, the reduced widths are about 4 percent of the sum-rule limit. If these resonances are caused by *p*-neutrons, the parities of these states are opposite to that of the ground state.

In the case of the resonance at 1.30 Mev it is not possible to choose between values of $l=1$ and $l=2$ for the interacting neutrons. If the compound state is formed by *p*-neutrons, the reduced width is 0.17×10^{-13} Mev cm; if by *d*-neutrons, the reduced width is 1.7×10^{-13} Mev cm.

Alvarez,[7] in his study of the neutrons emitted from O^{17} formed by β^- decay of N^{17}, reports the existence of a broad neutron group of 0.92-Mev energy. If neutrons were emitted from the excited states here reported, the energies of these neutrons would be 0.39, 0.89, and 1.16 Mev. The energy of the lowest group would not have been sufficient to have been observed in Alvarez' experiment. While neither the results of Alvarez nor those of Hayward[8] reveal the existence of more than one neutron group in this region, it would be difficult to explain why N^{17} would not decay to both levels since they both have the same spin, unless they differed in parity. However, it seems possible that the two groups were not separated.

If the binding energy of an additional neutron to O^{16} is taken[9] as 4.14 Mev, the resonances here reported arise from levels at 4.56-, 5.08-, and 5.36-Mev excitation. The 4.56-Mev level may correspond to that at 4.49 Mev reported by Burcham and Smith in their study of the $F(d,\alpha)O$ reaction.[10]

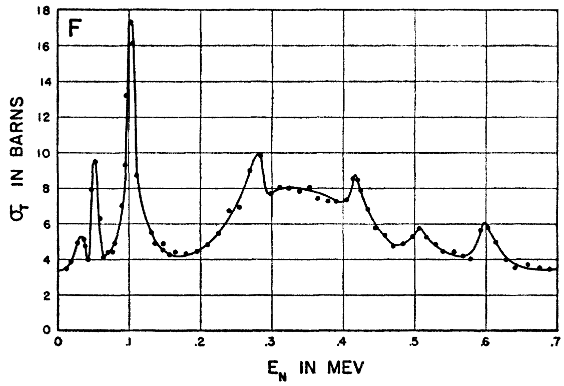

FIG. 4. The total cross section of fluorine. Neutron energy spreads of 20 kev were used for energies above 0.13 Mev and 9 kev for lower energies.

V. FLUORINE

The cross section of fluorine was determined by measuring the cross section of Teflon, $(CF_2)^n$, and subtracting the carbon cross section, which was measured under similar conditions.[11] For energies below 0.13 Mev, neutrons of an estimated energy spread of 9 kev were used, while above this energy the energy resolution was about 20 kev.

Figure 4 shows the results of the measurements. Fluorine has about the same level density as does sodium.[1] Only the 100-kev resonance is sufficiently resolved so that its width and spin can be surmised. If it is caused by the interaction of *s*-neutrons to form a compound state of spin one in F^{20}, the natural width is about 15 kev, leading to a reduced width of about 0.09×10^{-13} Mev-cm. This width is very much smaller than the reduced widths of the O^{17} levels, but it is of the same order of magnitude as the width of the levels which have been identified in sulfur.[12]

The cross section between 250 kev and 450 kev was further investigated with a neutron energy spread of about 5 kev in order to determine whether the behavior was the result of unresolved resonances. The results were the same as those shown in Fig. 4 which had been obtained with a resolution of 20 kev. It seems, then, most probable that this structure is the result of the superposition of three levels, each with a width of the order of 50 kev.

[7] L. Alvarez, Phys. Rev. **75**, 1127 (1949).
[8] E. Hayward, Phys. Rev. **75**, 917 (1949).
[9] Rosenfeld, *Nuclear Forces* (Interscience Publishers, Inc., New York, 1948).
[10] W. E. Burcham and Smith, Proc. Roy. Soc. **A168**, 176 (1938).
[11] D. W. Miller, Phys. Rev. **78**, 86 (1950).
[12] Peterson, Barschall, and Bockelman, Phys. Rev. **79**, 593 (1950).