This value is much larger than that obtained in recent electromagnetic measurements.[9] If it is assumed that all of the particles with l values up to six are completely absorbed, then the total nuclear absorption cross section for 21.7-Mev nitrogen on nitrogen is

$$\sigma_T=\pi\lambda\!\!\!^{-2}\sum_{l=0}^{6}(2l+1)=3.4\times10^{-25}\text{ cm}^2.$$

This value of the total cross section is close to that obtained by a calculation using the barrier penetrabilities of Feshbach *et al.*[10] and a sticking probability of unity.

[9] J. H. Fregeau and R. Hofstadter, Phys. Rev. **99**, 1503 (1955).
[10] Feshbach, Shapiro, and Weisskopf, U. S. Atomic Energy Commission Report NYO-3077 (unpublished).

It is concluded that Blair's strong absorption or opaque nucleus model adequately describes the elastic scattering of nitrogen by nitrogen near the energetic threshold for nuclear reactions. More accurate data will probably require a theory which will take into account barrier penetration and the diffuseness of the nuclear surface. This experiment indicates that a source of higher energy heavy ions would be useful to perform scattering measurements throughout the periodic table; this may lead to a better understanding of the nuclear radius and nuclear interactions in general.

ACKNOWLEDGMENTS

We are indebted to J. G. Harris who constructed the apparatus and Mrs. W. Bowelle who did the necessary scanning.

PHYSICAL REVIEW VOLUME 102, NUMBER 5 JUNE 1, 1956

Total Cross Sections of Light Elements for (α,n) Neutrons*

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(Received February 29, 1956)

The usefulness of the $Be^9(\alpha,n)$ and the $C^{13}(\alpha,n)$ reactions as sources of monoenergetic neutrons of variable energy was investigated. Measurements of the yield of the $C^{13}(\alpha,n)$ reaction are presented. Total cross sections for elements of atomic number from 3 to 9 were measured for neutron energies between 4.4 and 5.6 Mev and between 7.6 and 8.6 Mev. The results give some information about energy levels in C^{13} and O^{17}.

INTRODUCTION

THE purpose of the present study is to explore the usefulness of (α,n) reactions as sources of monoenergetic fast neutrons and to use the neutrons produced in such reactions for the measurement of total neutron cross sections of light elements. Usually (p,n) reactions are used to produce monoenergetic neutrons of energies up to 3 Mev, and (d,n) reactions for neutrons of higher energies.[1] Whenever deuterons are accelerated, neutrons are produced at places other than the target. Such spurious neutron sources frequently interfere with neutron experiments, particularly when a high-energy resolution is used in the experiments. Another difficulty is that with presently operating electrostatic accelerators neutron energies around 10 Mev cannot readily be reached with (d,n) reactions.

Two exothermic (α,n) reactions were employed:

$$Be^9+\alpha\rightarrow(C^{13})\rightarrow C^{12}+n+5.708\text{ Mev},$$

and

$$C^{13}+\alpha\rightarrow(O^{17})\rightarrow O^{16}+n+2.201\text{ Mev}.$$

On the basis of the known energy levels of O^{16}, the $C^{13}(\alpha,n)$ reaction[2] should give monoenergetic neutrons for α-particle energies up to about 5 Mev. Since the first excited state of C^{12} is at 4.4 Mev,[2] the $Be(\alpha,n)$ reaction will always yield at least two groups of neutrons. But it might be possible to eliminate the effect of all but the most energetic neutrons, as these neutrons have about 4.4 Mev more energy than any others.

$Be(\alpha,n)$ REACTION

Be targets were prepared by evaporation onto wolfram backings. Difficulties in the stability of these targets were encountered; under prolonged bombardment blisters developed in the Be deposit, and a layer of contamination formed on the surface. To retard these effects the He^+-ion beam was defocused, warm air was blown against the target backing, and a liquid air trap was placed near the target.

In order to check the target thickness and to detect the presence of foreign materials on the Be surface,

* Work supported by the U. S. Atomic Energy Commission, and by the Graduate School from funds supplied by the Wisconsin Alumni Research Foundation.
† National Science Foundation predoctoral fellow. Now at the University of Kentucky.
[1] Hanson, Taschek, and Williams, Revs. Modern Phys. **21**, 635 (1949).
[2] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 77 (1955).

the neutron yield of the $Be^9(p,n)B^9$ reaction[3] was measured near threshold. The apparent threshold energy and the width of the rise curve at threshold gave a measure of the thickness of a fresh target and of contamination buildup after bombardment. Because of the lower stopping power for protons than for alpha particles of the same energy this method was, however, not very sensitive.

The neutron detector should be able to discriminate against the neutrons of lower energies and against the 4.4-Mev γ rays from the decay of the excited state of C^{12}, and, at the same time, should have a high efficiency for the detection of the most energetic neutrons. A detector was constructed of alternate 3-mm thick layers of plastic phosphor and 8-mm thick layers of Lucite, so that electrons produced by the 4.4-Mev γ rays would lose most of their energy in the Lucite.[4] This detector when operated at sufficiently high bias gave a good efficiency for the most energetic $Be(\alpha,n)$ neutrons and was insensitive to γ rays from Ra. The sensitivity of the detector to γ rays was further checked with the aid of long shadow bars of paraffin and iron inserted between the source and detector. It was found that at some bombarding energies the counting rate in the presence of the paraffin shadow bar was higher than when the iron bar was used. At these energies the ratio of $Be(\alpha,n)$ reactions leaving C^{12} in the excited state to those leading to the ground state was apparently relatively high. While the detector was insensitive to γ rays from Ra, it detected some of the 4.4-Mev γ rays which produced pairs. A correction for the effect of these γ rays had to be applied.

The sensitivity of the detector to neutrons of lower energy was investigated with $C^{13}(\alpha,n)$ neutrons which had about the same energy as the $Be(\alpha,n)C^*$ neutrons. It was found that the pulses produced by these neutrons were not detected at the bias setting used for the detection of $Be(\alpha,n)C^{12}$ neutrons.

As a preliminary check of the usefulness of the $Be(\alpha,n)$ reaction for total cross-section measurements counting rates of the detector, placed at 0° with respect to the incident α particles, were determined at α-particle energies up to 3.7 Mev. Only in the energy range from 2 to 3 Mev was the counting rate high enough to make total cross-section measurements practical. Such α particles produce neutrons of energies between 7.6 and 8.6 Mev. It was possible to extend the useful energy range of the reaction downward by observing neutrons emitted at angles other than 0°. Total neutron cross sections could be measured at neutron energies between 7.0 and 7.6 Mev by the use of neutrons emitted at 60° with respect to the incident α particles.

$C^{13}(\alpha,n)$ REACTION

Targets of C^{13} were prepared by cracking methyl iodide enriched in C^{13} onto 0.25-mm thick wolfram disks.[5] The same precautions were taken to retard deterioration of the C^{13} targets as described in the case of the Be targets.

Since the neutrons from the $C^{13}(\alpha,n)O^{16}$ reaction should be monoenergetic at the α-particle energies used in the present experiment (below 4 Mev), and the number of γ rays from α-particle induced reactions should be small, a more efficient detector could be used for the $C^{13}(\alpha,n)$ neutrons than was empolyed for counting $Be(\alpha,n)$ neutrons. The detector was a scintillation counter consisting of a cylinder of plastic phosphor 2.5 cm in diameter and 2.9 cm long.

The yield of the $C^{13}(\alpha,n)$ reaction was measured for neutrons emitted at 0° and at 86° (90° c.m. system) with respect to the α-particle beam and is shown in Fig. 1. An estimate of the differential cross section of the reaction was obtained in the following manner. The sensitivity of the scintillation detector was determined with the aid of a long counter which in turn had been calibrated with a Ra—Be source of known strength. No accurate determination of the number of C^{13} atoms in the target was made, but the number was estimated in two ways. The wolfram disk was weighed before and after the carbon was deposited. Outgassing of the wolfram upon heating probably introduced some uncertainty into the weight determination. More serious was the fact that the carbon was deposited over an area much larger than that of the α-particle beam and that the deposit was probably not uniform.

A second and perhaps more reliable estimate was obtained by measuring the yield curve in the neighborhood of the peak at 2.7 Mev. This peak has a natural width of less than 15 kev. For targets in which the energy loss of the α particles was appreciably more than 15 kev, the number of carbon atoms could be deduced from the apparent width in energy of the peak. Both methods of determining the thickness of the carbon deposit agreed fairly well. The number of C^{13} atoms depends, in addition, on a knowledge of the isotopic composition of the carbon. According to the manufacturer[6] the carbon contained 60% C^{13}, and this number was used in the calculations.

The narrow peak in the yield curve at an α-particle energy of 2.7 Mev was also useful for detecting contamination on the target surface. The presence of contamination had the effect of shifting the peak in the yield to higher alpha-particle energies, and, because the contamination builds up nonuniformly, to broaden the peak.

In the range of α-particle energies investigated in the present experiment, the neutron yield is high enough to make total cross-section measurements practical for α-particle energies between 2.2 and 3.5 Mev. This

[3] Richards, Smith, and Browne, Phys. Rev. **80**, 524 (1950).
[4] McCrary, Taylor, and Bonner, Phys. Rev. **94**, 808 (1954).
[5] G. C. Phillips and J. E. Richardson, Rev. Sci. Instr. **21**, 885 (1950).
[6] Isotope separation by United Kingdom Atomic Energy Authority, Harwell, England. Chemical conversion by Distillation Products Industries, Rochester, New York.

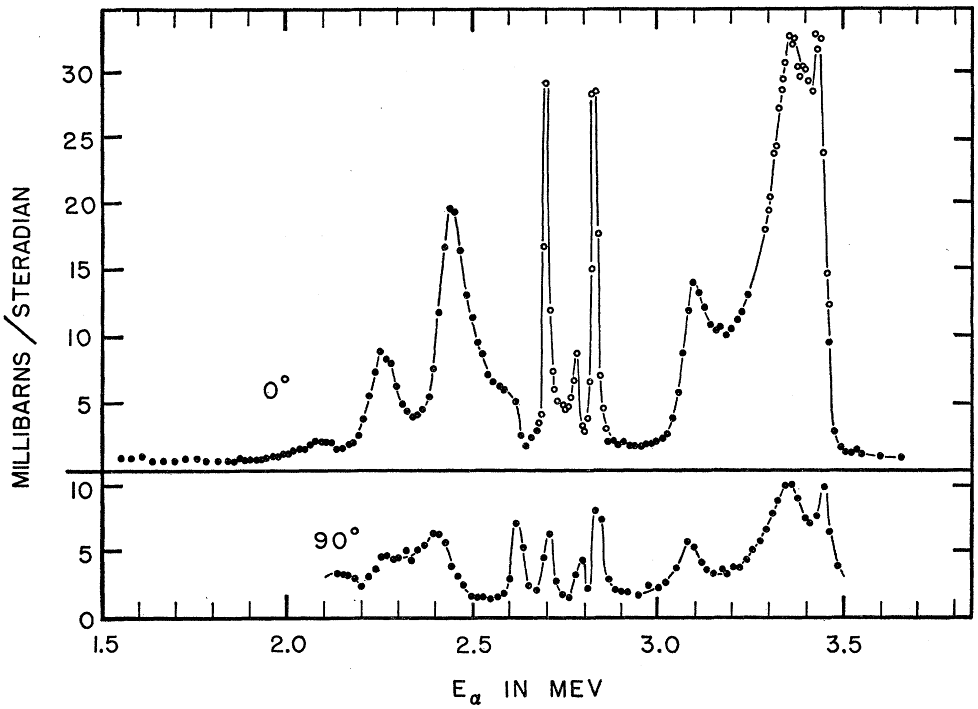

FIG. 1. Yield of the $C^{13}(\alpha,n)O^{16}$ reaction at 0° and at 90° in the c.m. system. Cross sections were estimated as explained in the text. The cross section and energy are given in the laboratory system of coordinates. Open circles represent points for which the neutron energy spread is 15 kev. For the solid circles, the energy spread is 30 kev.

corresponds to neutron energies between 4.4 and 5.6 Mev.

Yield measurements on the $C^{13}(\alpha,n)$ reaction have previously been performed in this energy range by Trumble[7] who reports resonances at α-particle energies of 2.44, 2.66, 2.76, and 3.30 Mev. The present experiments show these resonances and also some additional peaks.

TOTAL NEUTRON CROSS SECTIONS

Total cross sections were measured[8] for elements of atomic number from 3 to 9. In the case of boron two samples were used, one of normal boron, the other of boron enriched to 85% B^{10}. The samples were in elemental form except N, O, and F. The nitrogen cross section was obtained by comparing the transmission of a sample of aminotetrazole and carbon with that of a sample of paraffin as previously described.[9] Transmissions of a BeO sample were compared with those of a Be sample for determining oxygen cross sections, and a comparison of teflon with carbon gave the cross section of fluorine.

All samples were cylinders of such length as to give transmissions of around 50%, and their diameters were between 1.9 and 2.5 cm. The detector was placed 25 or 30 cm from the source.

A correction for scattering of neutrons by the sample into the detector was applied assuming only single scattering. The correction was calculated for an angular distribution corresponding to diffraction by an opaque sphere.[10] Such a distribution appears to be in reasonable agreement with experimental results for small-angle scattering of neutrons by light elements in the energy region studied in the present experiments.[11] The in-scattering correction amounted to about 5%.

Corrections were applied for background on the basis of measurements with a shadow bar. The fact that a small number of neutrons are transmitted through the shadow bar was taken into account.

In Figs. 2 and 3, the results of total cross-section measurements are presented for the elements investigated except carbon and oxygen. The data labeled "boron ten" refer to measurements on a sample enriched to 85% B^{10}, while the data marked "boron" were taken with a sample of normal boron.

The energy spread of the neutrons was approximately the same as the spacing of the points and amounted to 30 kev in most cases. The statistical accuracy of the measurements was about five percent. Some of the variations of cross section with energy shown in Fig. 2 are outside of the error of the measurements, particularly in nitrogen and fluorine these variations are large. It is not clear, however, that they are caused by isolated levels, and no attempt was made to analyze these data in terms of resonance theory.

The results presented in Fig. 3 show a rather smooth variation of cross section with energy and no clear effect of isolated resonances.

[7] R. E. Trumble, Jr., Phys. Rev. 94, 748 (1954).
[8] H. H. Barschall, Revs. Modern Phys. 24, 120 (1952).
[9] Johnson, Petree, and Adair, Phys. Rev. 84, 775 (1951).
[10] Feld, Feshbach, Goldberger, Goldstein, and Weisskopf, U. S. Atomic Energy Commission report NYO-636, 1951 (unpublished).
[11] M. Walt and J. R. Beyster, Phys. Rev. 98, 677 (1955).

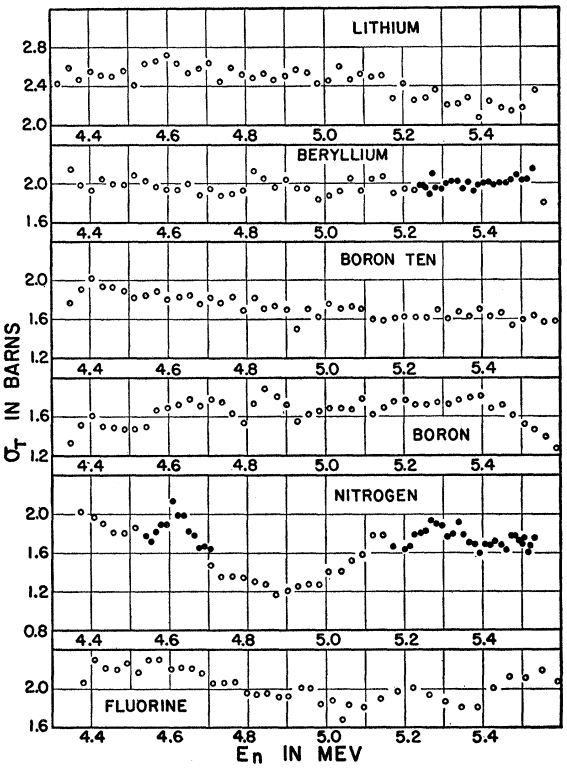

FIG. 2. Total cross sections of Li, Be, B^{10}, B, N, and F for neutrons from the $C^{13}(\alpha,n)O^{16}$ reaction. The solid points represent data for which the energy spread is about 15 kev, while for the open points the energy spread is about 40 kev.

Measurements of these cross sections have previously been carried out by Nereson and Darden[12] who used an energy spread of about 100 kev in this energy region. The results of the two experiments are in good agreement.

Total cross sections of carbon and oxygen are shown in Figs. 4 and 5. Most of the data were taken with a neutron energy spread of 30 kev. In those energy regions in which there was evidence for rapid variations of the cross section with energy the measurements were repeated with an energy spread of 15 to 20 kev. The latter results are shown by solid circles in the figures.

Previous measurements of these cross sections[12] with considerably larger energy spread gave about the same average cross section as the present data but did not show the resonances indicated in Figs. 4 and 5. In addition, the present measurements with $C^{13}(\alpha,n)$ neutrons may be compared with unpublished results obtained with *d-d* neutrons at Los Alamos by R. L. Henkel *et al.*[13] While the present data agree qualitatively with the Los Alamos data, the measurements presented in Figs.

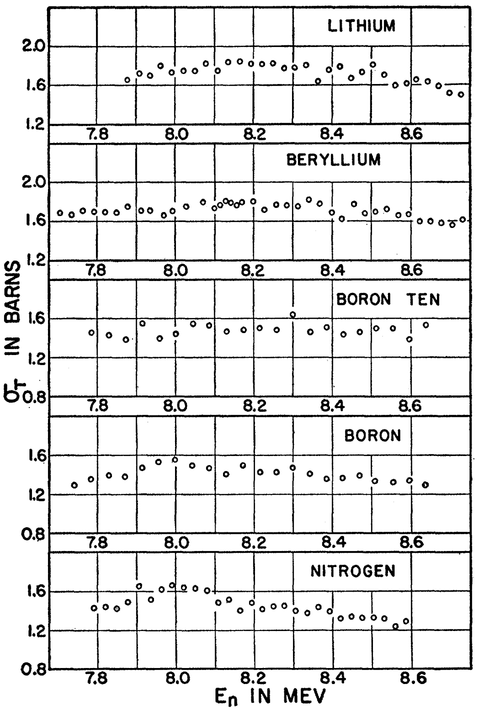

FIG. 3. Total cross sections of Li, Be, B^{10}, B, and N for neutrons from the $Be^9(\alpha,n)C^{12}$ reaction. The energy spread for these data is about 40 kev.

4 and 5 show more resonances, as might be expected, since a smaller energy spread was used. The present data overlap at the lowest energies measurements by Freier, Fulk, Lampi, and Williams[14] which were taken with (d,d) neutrons of 400-kev energy spread. Because of the difference in the resolution used in the two experiments a detailed comparison is difficult, but there does not appear any inconsistency.

Measurements of the total cross section of carbon were carried out also in the neutron energy range from 7.2 to 7.6 Mev by using neutrons from the $Be(\alpha,n)$ reaction emitted at 60° with respect to the incident α particles. The cross section rises from about 0.6 barn at 7.2 Mev to 1.6 barns at 7.4 Mev and then levels off. These results agree qualitatively with the Los Alamos measurements quoted in reference 13. The Los Alamos measurements are, however, plotted on an energy scale which is in error in this reference.

ENERGY LEVELS IN C^{13}

The structure in the total neutron cross section shown in Fig. 4 is caused by energy levels in the compound nucleus C^{13}. It is not possible, however, to draw definite conclusions about the character of these levels from the present measurements. At the neutron energies used other modes of decay of the compound nucleus compete with elastic scattering, i.e., inelastic scattering and, at

[12] N. Nereson and S. E. Darden, Phys. Rev. **89**, 775 (1953) and **94**, 1678 (1954).

[13] R. L. Henkel *et al.* (unpublished), quoted in U. S. Atomic Energy Commission Report BNL-325 (Superintendent of Documents, U. S. Government Printing Office, Washington, D. C., 1955).

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

the higher energies, emission of α particles. An additional difficulty in the interpretation is that the energy spread of the neutrons is probably not small compared to the width of the levels, and levels may actually overlap.

At an isolated resonance the variation in total cross section is given by

$$\Delta\sigma_T = 2\pi k^{-2}(2J+1)\Gamma_n/(2I+1)\Gamma, \quad (1)$$

where k is the wave number of the incident neutron in the c.m. system, J the spin of the compound state, I the spin of the bombarded nucleus, Γ_n and Γ the neutron width and total width of the compound state.

The height of the peak at 4.95-Mev neutron energy is less than the theoretical maximum for a level in C^{13} of total angular momentum $\frac{1}{2}$, while the height of the maximum at 5.40 Mev is about equal to the theoretical maximum for a state of total angular momentum $\frac{1}{2}$. Because of the effect of inelastic scattering and finite energy resolution it is probable that the state formed by 5.40-Mev neutrons has a spin of more than $\frac{1}{2}$. Some information might be gained about the orbital angular momentum of the neutrons forming the compound state from the interference between resonant and potential scattering. No interference is observed around 4.95 Mev, and the small minimum preceding the 5.40-Mev peak is within the experimental error. The absence of appreciable interference minima might be interpreted as indicating that the states are formed by neutrons of high angular momentum. Not enough is known, however, about nearby broad levels of low angular momentum to make any conclusions appear safe which are based on the assumption that potential scattering phase shifts may be estimated from hard-sphere scattering phase shifts.

The structure shown in the lower part of Fig. 4 appears to be caused by several levels in C^{13}. Additional information about these levels may be gained from a study of the $Be(\alpha,n)$ reaction, since the compound nucleus C^{13} is formed in this reaction also. At the α-particle energies used in the present experiments about the same range of excitation energies of C^{13} is covered as in the total cross-section measurements using the $Be(\alpha,n)$ neutrons. Although no attempt was made to study the yield of the $Be(\alpha,n)$ reaction in detail, an estimate of this yield as a function of energy may be based on the neutron counts without sample obtained in the course of the total cross-section measurements. The 0° yield of the high energy $Be(\alpha,n)$ neutrons shows four small maxima at excitation energies of the compound nucleus corresponding to neutron energies between 7.6 and 8.3 Mev. The presence of these maxima corroborates the conclusion that the structure in the total cross section shown in the lower part of Fig. 4 is caused by several levels in the compound nucleus. Maxima in the $Be(\alpha,n)$ yield in this energy range have previously been reported by Trumble,[7] and in the γ-ray yield for $Be^9(\alpha,n\gamma)C^{12}$ by Talbott and Heydenburg.[15]

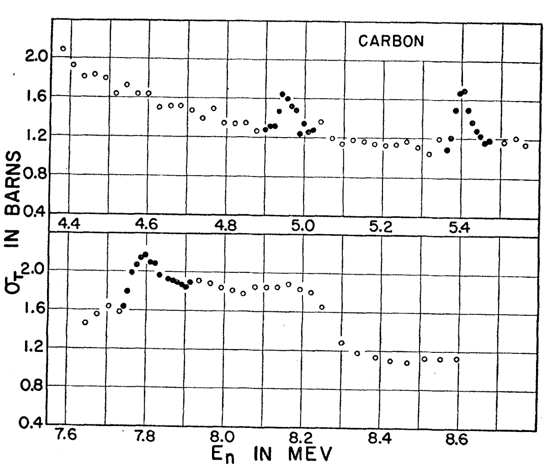

FIG. 4. The total neutron cross section of carbon. Data shown as solid circles were taken with an energy spread of about 15 kev, while for the open circles the energy spread is about 30 kev.

ENERGY LEVELS IN O^{17}

Information about energy levels in O^{17} may be derived both from the measurements of the O^{16} neutron cross section and from the results of the experiments on the $C^{13}(\alpha,n)$ reaction. When O^{16} is bombarded with $C^{13}(\alpha,n)$ neutrons O^{17} is formed at about the same excitation energy as in the reaction producing the neutrons. In Fig. 6, both the total neutron cross section of oxygen and the yield of the $C^{13}(\alpha,n)$ reaction are plotted against the excitation energy of O^{17}. At excitation energies of the compound nucleus for which both measurements have been performed, there is a correlation between the

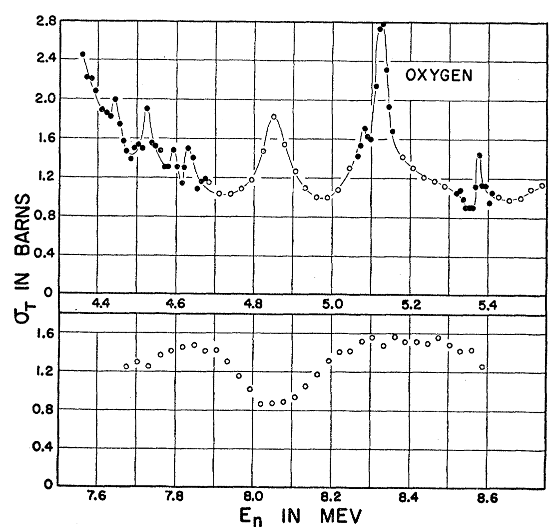

FIG. 5. The total neutron cross section of oxygen. Data shown as solid circles were taken with an energy spread of 15 kev, while for the open circles the energy spread is about 30 kev.

[15] F. L. Talbott and N. P. Heydenburg, Phys. Rev. 90, 186 (1953).

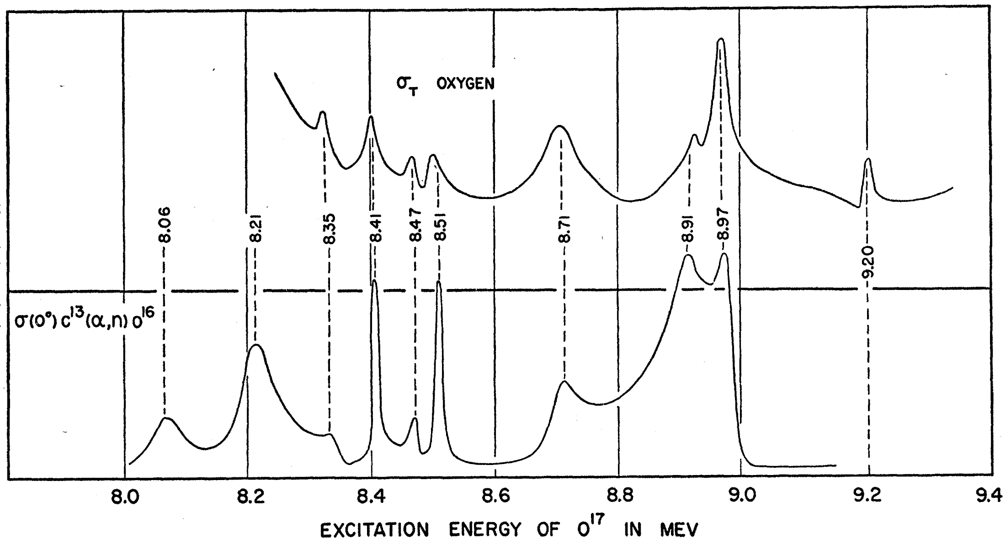

FIG. 6. The total neutron cross section of oxygen and the 0° yield from the $C^{13}(\alpha,n)O^{16}$ reaction, both plotted as a function of the excitation energy of the compound nucleus O^{17}.

position of the peaks shown in the upper and lower parts of Fig. 6.

For an (α,n) reaction in which the target and product nuclei have opposite parity, and the target nucleus has spin $\frac{1}{2}$ while the residual nucleus has spin 0, the peak height in the differential cross section at 0° is given at an isolated resonance by

$$\sigma(0°)=k^{-2}(2J+1)^2\Gamma_n\Gamma_\alpha/4\Gamma^2, \qquad (2)$$

where Γ_n and Γ_α are the widths for neutron and α-particle emission. Information about some levels in O^{17} may be obtained by the combined use of Eqs. (1) and (2). The levels at 8.41 and 8.51 Mev, for example, must have a total angular momentum of at least $\frac{3}{2}$ in order to account for the variation in the $C^{13}(\alpha,n)$ reaction cross section. The spin could be much larger, if the resonances are not well resolved, or if the widths for neutron and alpha-particle emission differ appreciably.

From an assignment of spin $\frac{3}{2}$ to the level at an excitation energy of 8.71 Mev either the height of the total neutron cross-section peak or the height of the $C^{13}(\alpha,n)$ reaction peak give for the ratio of neutron width to alpha-particle width about 20. For no other spin assignment can such an agreement be found; hence $\frac{3}{2}$ seems the most likely value of the spin, although the uncertainty in the absolute cross section of the $C^{13}(\alpha,n)$ reaction makes the argument not quite firm. No interference minimum is observed near the peak in the total neutron cross section, and since p-wave potential scattering is likely to be large at these neutron energies, the state is probably formed by d-wave neutrons.

A resonance in the total cross section at about 5.40 Mev neutron energy indicates a level at an excitation energy of 9.20 Mev. A minimum in the cross section near this level suggests interference between potential and resonance scattering. The height of the peak is the theoretical maximum for a state of spin $\frac{1}{2}$, but because of the possibility of processes competing with elastic scattering and because of the finite energy resolution of the neutrons, the spin may be brighter. The presence of the minimum makes likely a low value of the angular momentum of the neutrons forming this level.

Measurements of the energy of α particles from $F^{19}(d,\alpha)O^{17}$ have covered excitation energies of O^{17} to about 9.1 Mev.[16] In the energy region common to the present experiment and the $F(d,\alpha)$ measurements, the latter showed levels in O^{17} at 8.27, 8.59, and 9.06 Mev with an experimental uncertainty of ± 0.04 Mev. Whether these levels are the same as any of those found in the present study is not clear.

CONCLUSIONS

While the $Be(\alpha,n)$ and the $C^{13}(\alpha,n)$ reaction are usable sources of monoenergetic neutrons, they have some serious disadvantages. The discrimination against the 4.4-Mev γ rays from $Be(\alpha,n)$ offers some difficulty. For the $C^{13}(\alpha,n)$ reaction the rapid variation of yield with energy introduces complications. In both reactions, there are energy regions in which the neutron yield is so low that only experiments can be performed for which intensity is no serious problem.

[16] Burrows, Powell, and Rotblat, Proc. Roy. Soc. (London) **A209**, 478 (1951).