Interaction of Neutrons with Oxygen and a Study of the $C^{13}(\alpha,n)O^{16}$ Reaction*

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Measurements of the oxygen total neutron cross section from 3.5 to 4.4 Mev and the $O^{16}(n,\alpha)C^{13}$ reaction cross section from 4.0 to 5.2 Mev are presented. In a study of the $C^{13}(\alpha,n)O^{16}$ reaction the following quantities were measured: the 0° yield from 0.8 to 3.5 Mev, 29° and 146° yields between 2.0 and 3.5 Mev, and 47 angular distributions in the range from 1.0 to 3.5 Mev. Cross sections for the $O^{16}(n,\alpha)C^{13}$ and the $C^{13}(\alpha,n)O^{16}$ reactions are compared using the principle of detailed balancing. On the basis of the $C^{13}(\alpha,n)$ angular distributions spin assignments for 14 states of O^{17} between excitation energies 7 and 9 Mev are discussed, and in some cases relative parity assignments are made. Reduced widths of the states of O^{17} were derived from the results of the experiments on the $C^{13}(\alpha,n)$ reaction and the oxygen total neutron cross section.

INTRODUCTION

THE object of the present study is to investigate the nucleus O^{17} in the range of excitation energies between 7 and 9 Mev. At excitation energies between 6.34 and 9.43 Mev O^{17} can break up into either an α particle and ground-state C^{13} or a neutron and ground-state O^{16}.[1] Decay by γ-ray emission, although possible, is much less likely. Measurements of the following quantities were made: the total neutron cross section of oxygen, the $O^{16}(n,\alpha)C^{13}$ reaction cross section, the $C^{13}(\alpha,n)O^{16}$ cross section, and angular distributions of the neutrons from the $C^{13}(\alpha,n)$ reaction. The $O^{16}(n,\alpha)C^{13}$ and $C^{13}(\alpha,n)O^{16}$ reaction cross sections are also of interest because they may be compared using the principle of detailed balancing. The neutron cross sections of oxygen are of practical importance in problems involving the calculation of neutron flux in media containing oxygen.

Except for neutron energies between 3.5 and 4.4 Mev, the total cross section of oxygen has been measured previously with good energy resolution up to 5.5 Mev.[2,3] Six resonances corresponding to those observed in the $C^{13}(\alpha,n)$ reaction should appear in the oxygen total cross section in the gap between 3.5 and 4.4 Mev unless the neutron widths are much smaller than the α-particle widths. The present total cross-section measurements were undertaken in an attempt to resolve these resonances.

Measurements of the $O^{16}(n,\alpha)C^{13}$ cross section for neutron energies up to 4.2 Mev have been reported by Seitz and Huber[4] and at 14.1 Mev by Lillie.[5] Others[6,7] have observed resonances in this reaction using neutron sources with a continuous energy spectrum.

Yields from the $C^{13}(\alpha,n)O^{16}$ reaction have been studied previously for various ranges of α-particle energy extending up to 5.2 Mev.[3,8–10] In addition, angular distribution measurements similar to the present experiment have been published[10,11] since the completion of this investigation. Yield measurements up to 3.5 Mev were repeated in order to determine more accurately the positions and widths of narrow resonances and the absolute reaction cross section.

TOTAL NEUTRON CROSS SECTION OF OXYGEN

Neutrons for the oxygen total cross-section measurements were produced by bombarding a deuterium-gas target with deuterons from an electrostatic generator. The gas target used was similar to that described by Fowler and Brolley.[12] Cells containing the target gas were either 1 or 2 cm long. A $\frac{1}{2}$-micron nickel foil separated the gas at pressures up to 15 cm Hg from the vacuum system of the electrostatic generator. Deuteron energy losses in the foil were derived from the atomic stopping cross section of nickel as a function of proton energy together with a measurement of the shift in the Li(p,n) threshold when a Li target was placed behind the foil.

The total cross section was determined[13] from measurements of the transmissions of SnO_2 and Sn samples. The samples were packed in identical thin-wall brass cans of diameter 2.2 cm. A Hornyak scintillator, 1.8 cm long and 2.5 cm in diameter, served as

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[12] J. L. Fowler and J. E. Brolley, Jr., Revs. Modern Phys. 28, 103 (1956).
[13] H. H. Barschall, Revs. Modern Phys. 24, 120 (1952).

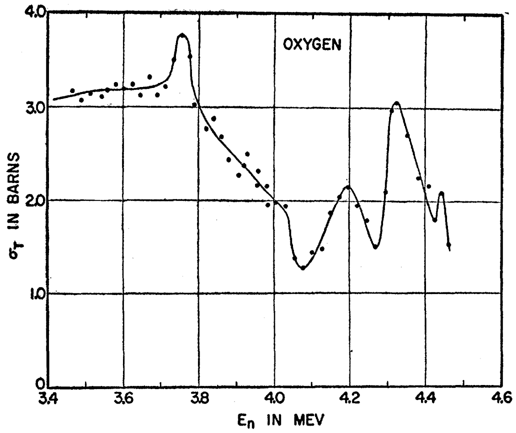

FIG. 1. Total neutron cross section of oxygen. Data below 3.9 Mev were taken with an energy spread of about 80 kev and those above 3.9 Mev with an energy spread of about 40 kev.

neutron detector. The distance from source to detector was 25 or 30 cm. Backgrounds from neutrons scattered by surrounding materials into the detector were measured by interposing a paraffin bar, 24 cm long, between the detector and target. Effects of neutrons produced at places other than in the deuterium target gas were determined by repeating all measurements at each energy with helium in the target.

Figure 1 presents the results of the total cross-section measurements. The cross sections were determined with a statistical accuracy of about 6%. Inscattering corrections amounting to about 3% were applied to the data. The neutron energy scale is uncertain by about 20 kev because of the uncertainty in the determination of the energy lost by deuterons in the target foil. Measurements for neutron energies above 3.9 Mev were made at an angle of 0° with respect to the deuteron beam direction. The energy spread of the neutron beam was about 40 kev, resulting primarily from energy losses of deuterons in the target gas. For neutron energies less than 3.9 Mev, measurements were made at an angle of 30° to the deuteron beam. For this geometry the variation of neutron energy with angle of emission caused the neutron energy spread to increase to about 80 kev.

The total cross section shown in Fig. 1 exhibits resonances with widths of 100 kev or less at neutron energies of 3.75, 4.19, 4.32, and 4.44 Mev. The resonance indicated by the high point at 4.44 Mev has been observed previously by Becker and Barschall.[3] From the $C^{13}(\alpha,n)$ data obtained in the present study, it is known that a resonance with a width of less than 100 kev should occur at 4.02 Mev. This resonance is probably responsible for the sharp decrease in the cross section near 4.03 Mev.

Previous measurements in this energy range by Freier *et al.*,[14] which were made with neutrons of 400-kev energy spread, show only a broad maximum centered about 3.6 Mev and another peak near 4.4 Mev. The present measurements appear to be consistent with these results when the difference in resolution used in the two experiments is considered. Zünti and Ricamo[15] have observed the resonance at 3.75 Mev, but their measurements do not extend above 3.8 Mev. The present measurements agree with those made by Bockelman *et al.*[2] near 3.5 Mev where the two sets of data overlap.

$O^{16}(n,\alpha)C^{13}$ CROSS SECTION

The procedure used for measuring the $O^{16}(n,\alpha)C^{13}$ reaction cross section is similar to that previously described for measurements of other disintegration cross sections.[16] Neutrons were produced by the *d-d* source which was used for the oxygen total cross-section measurements. The mean energy of the neutrons was uncertain by about 20 kev, and the neutron energy spread was about 35 kev. A cylindrical proportional counter similar to that designed by Koontz and Hall[17] was used to detect the oxygen disintegration pulses. The proportional counter, filled with CO_2, was placed with its axis coincident with the deuteron beam axis and its effective center 16 cm from the center of the gas target. Neutron flux measurements were made with a long counter at 0° and 1 meter from the target. The efficiency of the long counter was determined by placing a calibrated Ra-Be source at the target position. The proportional counter was swung out of the way of the long counter for flux determinations. A Hornyak detector, placed 8 cm from the target and at an angle of 60° to the deuteron beam direction, was used as a flux monitor while the oxygen disintegrations were counted.

CO_2 was selected because it permits detection by electron collection. For the neutron energies used in this experiment, the only neutron interaction which can occur in CO_2 with appreciable cross section besides elastic scattering is the $O^{16}(n,\alpha)$ disintegration. Pulses from the oxygen disintegrations should be larger than those from the carbon recoils for neutron energies greater than about 3.1 Mev.

As a preliminary check on the operation of the proportional counter, it was filled with N^{14} and irradiated with thermal neutrons. A resolution of 8% was obtained for the $N^{14}(n,p)C^{14}$ disintegration pulses.

When filled to a pressure of 1.4 atmospheres of CO_2, the proportional counter operated with a gas gain of about two, with a voltage of 2000 applied to the 125-micron center wire. Adequate separation of the (n,α) disintegration pulses from the carbon recoil pulses could not be obtained at higher pressures.

Distributions of the heights of disintegration pulses

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

[15] W. Zünti and R. Ricamo, Helv. Phys. Acta **24**, 419 (1951).

[16] C. H. Johnson and H. H. Barschall, Phys. Rev. **80**, 818 (1950).

[17] P. G. Koontz and T. A. Hall, Rev. Sci. Instr. **18**, 643 (1947).

were taken with a ten-channel analyzer. Two of the pulse height distributions are shown in Fig. 2. The steep rise at the lower pulse heights was caused by the carbon recoils, while the group appearing at higher pulse heights was due to the (n,α) disintegrations. The upper distribution was measured at a neutron energy of 4.14 Mev where the (n,α) cross section is relatively high. The lower distribution shows the worst case. It occurred at a neutron energy of 4.41 Mev where the (n,α) cross section is very small. No significance should be attached to the relative locations of the (n,α) group in the two distributions, since they were measured with different amplifier gains.

The energy spread of the (n,α) disintegration pulses was larger than what would have been expected from the spread in neutron energy and is attributed primarily to the presence of electronegative impurities in the CO_2 filling. However, the resolution was considered adequate since the uncertainty introduced by the lack of complete separation of the (n,α) pulses from the carbon recoil pulses was comparable to the uncertainty in the flux measurements.

The number of (n,α) pulses was determined by setting the discriminator bias at a voltage corresponding to the minimum in the pulse-height distribution between the carbon recoil pulses and the (n,α) group. The bias was changed at neutron-energy intervals of about 200 kev in accordance with the measured pulse-height distributions.

Backgrounds caused by neutrons produced at places other than in the deuterium gas were determined by repeating the measurements with helium in the target. Corrections for backgrounds from neutrons scattered by surrounding materials into the long counter were applied on the basis of measurements with a borated-paraffin shadow cone.

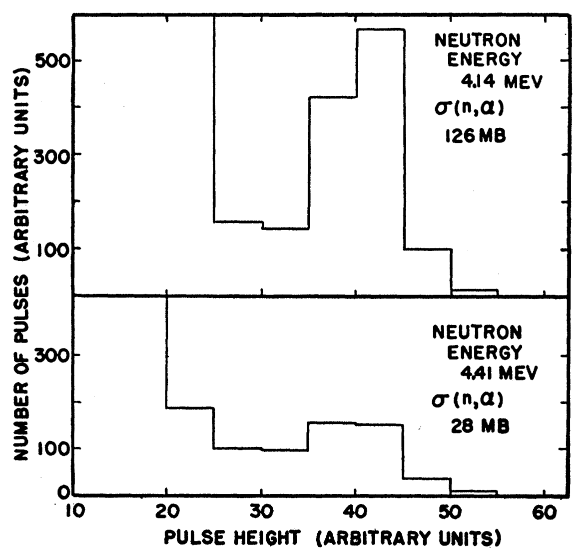

FIG. 2. Distributions in height of pulses from CO_2-filled proportional counter.

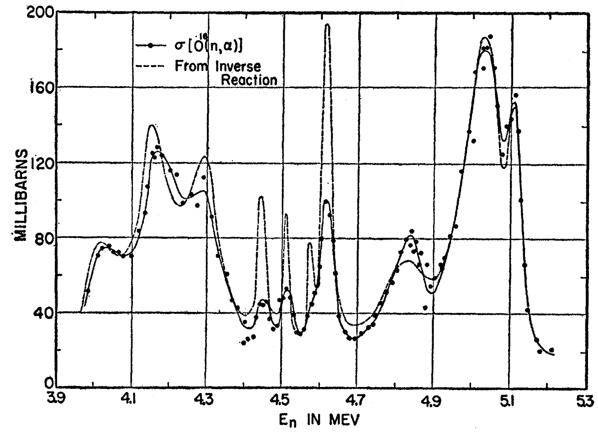

FIG. 3. Cross section for the $O^{16}(n,\alpha)C^{13}$ reaction. The neutron energy spread for these measurements was about 35 kev. The dashed curve represents the $O^{16}(n,\alpha)C^{13}$ cross section calculated using the principle of detailed balancing and the cross section for the $C^{13}(\alpha,n)O^{16}$ reaction. Both sets of data have not been corrected for the energy resolutions used in the measurements.

Figure 3 shows the observed $O^{16}(n,\alpha)C^{13}$ reaction cross section as a function of neutron energy in the laboratory system. The solid curve has been drawn through the experimental points. Corrections for the wall effect[18] which were applied to the data varied from 9% at a neutron energy of 4.0 Mev to 14% at 5.2 Mev.

The statistical accuracy of the measurements is about 5%, and the uncertainty in the flux determination is about 10%. Uncertainties in the estimate of the wall-effect correction and the determination of the number of target nuclei in the counter amount to about 5%. Based on estimates from the pulse-height distributions, the uncertainty caused by the imperfect resolution of the (n,α) pulses decreases from about 15% at the energies at which the cross section is smallest to 5% where it is largest. Relative cross sections should be accurate to about 15%.

Measurements of the $O^{16}(n,\alpha)$ cross section made by by Seitz and Huber[4] overlap the present measurements for neutron energies from 4.0 to 4.2 Mev. The results of the two experiments agree within the uncertainties.

$C^{13}(\alpha,n)O^{16}$ YIELDS

Targets of C^{13} were prepared by cracking methyl iodide enriched in C^{13} onto 0.25-mm thick wolfram disks. The enrichment of carbon content to 65% C^{13} quoted by the supplier was checked with a mass spectrometer and found to agree to 1%.

In Fig. 4 the 0° yield for α-particle energies from 0.8 to 2.3 Mev is shown. A target 40-kev thick for 1.34-Mev α particles was used except near the narrow resonances, where an 18-kev target was employed. The neutron yield was measured with a scintillation detector, which consisted of a cylinder of plastic phosphor 1.9 cm

[18] B. B. Rossi and H. H. Staub, *Ionization Chambers and Counters* (McGraw-Hill Book Company, Inc., New York, 1949), p. 236.

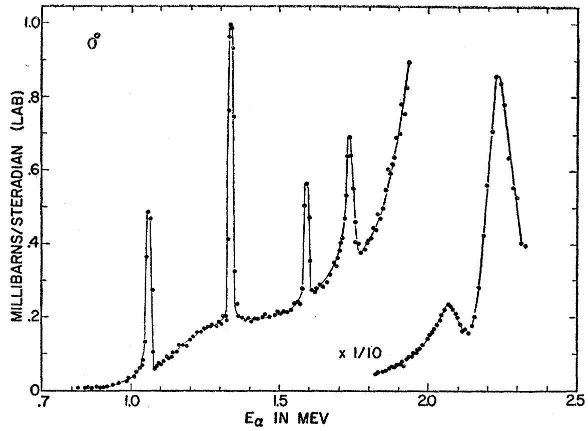

FIG. 4. Yield of the $C^{13}(\alpha,n)O^{16}$ reaction at 0°. A target 40-kev thick for 1.34-Mev α particles was used for the measurements except near the narrow resonances, where an 18-kev target was used.

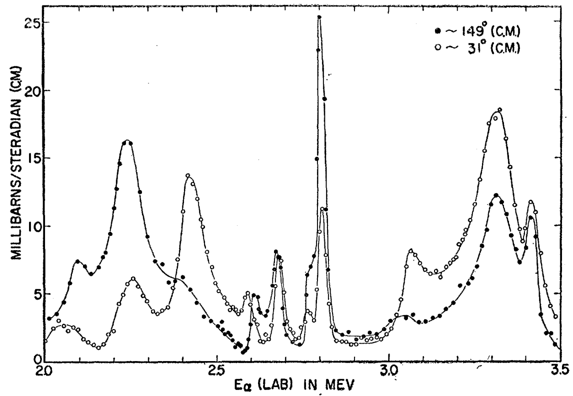

FIG. 5. Center-of-mass yields of the $C^{13}(\alpha,n)O^{16}$ reaction at laboratory angles 29° and 146° as a function of α-particle energy in the laboratory system. These angles correspond approximately to 31° and 149° in the center-of-mass system.

long and 2.5 cm in diameter. The face of the detector was placed 2.6 cm from the target and the discriminator bias was set so that the detector was energy insensitive for the range of neutron energies involved. Absolute cross sections shown in Fig. 4 are uncertain by 20% and are about 30% lower than those given in reference 10.

In order to verify that the narrow resonances observed in the excitation curve resulted primarily from the $C^{13}(\alpha,n)$ reaction and not the $C^{13}(\alpha,\gamma)$ reaction, measurements of the transmission of a lead sample were made at each of the narrow resonances. The observed transmissions were consistent with the cross section of lead for neutrons from the $C^{13}(\alpha,n)$ reaction. Measurements made with a blank target showed that γ rays produced by the interaction of α particles with the target backings were not detected in the neutron yield measurements.

To determine the importance of interference effects, measurements of the neutron yield in the neighborhood of the narrow resonances were made at several angles. At the resonances at 1.06 and 1.34 Mev the shapes of the yield curves as a function of energy were slightly dependent on the angle of observation, the peaks occurred at the same energy at all angles, and yields were not fore-aft symmetric in the center-of-mass system. The resonance at 1.59 Mev could not be discerned for angles between 40° and 140°. At 1.74 Mev the shape of the yield curve was strongly dependent on the angle of observation.

Measurements of the 0° differential cross section between 2.0 and 3.5 Mev were made using a long counter placed 1 meter from the target. Absolute cross sections agree with those reported by Becker and Barschall[3] and are about 50% higher than those by Bonner *et al.*[9]

The importance of interference effects between 2.0 and 3.5 Mev was investigated by measuring the yields with the long counter at angles of 29° and 146° with respect to the α-particle beam. For this energy range these angles correspond approximately to the center-of-mass angles 31° and 149°. Neutron yields at both angles are shown in Fig. 5, where center-of-mass cross sections are plotted as a function of α-particle energy in the laboratory system. If the resonances were isolated, or more unlikely, if the interference effects were due only to energy levels of the compound nucleus having the same parity, the two curves in Fig. 5 would be identical. The yields deviate markedly from fore-aft symmetry at almost every energy, and the peaks of some of the resonances appear at slightly different energies at the two angles.

Eight of the fourteen resonances occurring for α-particle energies of less than 3.5 Mev have widths less than 30 kev. The positions and widths of these peaks in the yield curves are: 1.060 Mev, 7 kev; 1.338, ≤ 5; 1.590, ≤ 5; 1.736, 28; 2.603, 23; 2.675, 14; 2.760, 12; 2.805, 14. A target of thickness ≤ 5 kev for 1.59-Mev α particles was used for the measurements, and the angle of observation was 0° except at 2.603 Mev, where it was 90°. The energies are accurate to about ± 5 kev.

Absolute cross sections are based on a measurement of the 0° differential cross section at 2.90 Mev, an energy at which the neutron yield varies slowly with energy and angle. The neutron flux was determined with the long counter which was calibrated with a Ra-Be source. The number of target nuclei per cm^2 was determined from the weight of the carbon deposit and independently by measuring the apparent width of the resonance at 2.68 Mev. These methods gave values which differed by 10%, and the average was used for the cross-section calculation. The observed 0° differential cross section is 1.95 ± 0.30 millibarns, where the error is the sum of uncertainties of 10% in the neutron flux determination and 5% in the number of target nuclei per cm^2.

$C^{13}(\alpha,n)O^{16}$ ANGULAR DISTRIBUTIONS

The plastic scintillation detector was used for the $C^{13}(\alpha,n)$ angular-distribution measurements because of its high detection efficiency. Since neutrons emitted at back angles have energies about 25% less than those in the forward direction, it was necessary to determine the energy sensitivity of the detector for this range of neutron energies. This was accomplished by measuring angular distributions at one α-particle energy using several discriminator biases to record the scintillator pulses. The biases were set relative to the "cutoff" pulse height obtained from the pulse-height distribution observed with the scintillator at 0°. These angular distributions were then compared to that observed with the long counter. For a bias of 33% of "cutoff" the energy sensitivity agreed with that of the long counter to within 4%, and the sensitivity varied slowly as a function of bias. For decreasing neutron energies the sensitivity with biases higher than 33% of "cutoff" decreased while the sensitivity with biases lower than 33% increased. These observations are consistent with calculations based on the *n-p* scattering cross section and the shape of the pulse-height spectrum.[19]

Forty-seven angular distributions were measured for α-particle energies between 1.0 and 3.5 Mev. Targets of 20 kev or less were used for measurements at narrow resonances. Above 2.0 Mev the face of the scintillation detector was placed 11.5 cm from the target. Because of the low yield of the reaction below 2.0 Mev, measurements were made with the face of the detector 6.4 cm from the target. Data were taken at angular intervals of 10° from 0° to 150° and at 85°, 95°, and 155° with enough counts at each angle so that statistical errors were usually much less than 5%. Each distribution was recorded by using three discriminators, the biases of which were set at approximately 0.15, 0.33, and 0.45 of the "cut-off" pulse height observed at 0°.

Center-of-mass angular distributions which were recorded with intermediate bias were analyzed into components of Legendre polynomials by the method of the least-squares fit with the aid of an IBM 650 computer. All the angular distributions observed in this study were fitted satisfactorily by expansions containing polynomials of order equal to or less than the sixth. By dividing each of the coefficients of the polynomials by A_0, the coefficient of the zero-order polynomial, the angular distributions were expressed in terms of $\sigma(\theta)/\langle\sigma(\theta)\rangle_{\text{Av}}$, the ratio of the differential cross section to the average differential cross section.

In the upper part of Fig. 6 the coefficients of the Legendre polynomials for the normalized angular distributions are plotted as a function of α-particle energy. Solid curves have been drawn through the experimental points except at the lower energies, where the number of angular distributions measured was insufficient to justify this procedure. The vertical dashed lines indicate the energies at which resonances occur.

Corrections for the angular resolution of the measurements have been applied to the coefficients.[20] The correction is largest for A_6/A_0, being 20% for measurements below 2.0 Mev and 5% for measurements above 2.0 Mev.

On the basis of angular-distribution data recorded with the high and low biases the uncertainty in the coefficients presented in Fig. 6 should be less than 0.1. Errors from sources other than the variation of energy sensitivity with bias are estimated to be much smaller.

The total $C^{13}(\alpha,n)O^{16}$ reaction cross section, which was derived from measurements of the angular distributions and the 0° differential cross section, is shown in the lower part of Fig. 6. The $O^{16}(n,\alpha)C^{13}$ cross section calculated using the principle of detailed balancing and the cross section for the $C^{13}(\alpha,n)O^{16}$ reaction is represented by the dashed curve in Fig. 3. Apparent discrepancies at the narrow resonances can be explained by the difference in energy resolution used in the two experiments.

ANALYSIS

1. Procedure

Data on the $C^{13}(\alpha,n)$ reaction and the total neutron cross section of oxygen may be used conjointly to derive information about the levels of O^{17}. The correlations between the resonances observed in the $C^{13}(\alpha,n)$ reaction and those occurring in the oxygen total neutron cross section are evident from Fig. 7, where the 0° yield from the $C^{13}(\alpha,n)$ reaction and the total neutron cross section of oxygen are plotted as a function of excitation energy of O^{17}. The narrow resonances corresponding to levels at 7.16, 7.37, and 7.56 Mev were not observed in the oxygen total neutron cross section because of the poorer energy resolution used in the total cross-section measurements.

Spins of levels in O^{17} may be derived from the $C^{13}(\alpha,n)$ angular distributions. Since the ground state spins and parities of C^{13} and O^{16} are $\frac{1}{2}^-$ and 0^+ respectively, both the incoming and outgoing channel spins are $\frac{1}{2}$ and the orbital angular momentum, l, of the α particle forming a state of O^{17} with spin J must differ from the orbital angular momentum, l', of the outgoing neutron by one unit. The differential cross section at an energy, E, near the energy E_R at which an isolated resonance occurs is given by[21]:

$$\sigma(\theta)=\tfrac{1}{2}k_\alpha^{-2}\textstyle\sum_L B_L P_L(\cos\theta),$$
$$B_L=(\Gamma_\alpha\Gamma_n/\Gamma^2)\sin^2\delta\, Z(lJlJ,\tfrac{1}{2}L)Z(l'Jl'J,\tfrac{1}{2}L),\quad (1)$$

[19] H. H. Barschall and H. A. Bethe, Rev. Sci. Instr. 18, 147 (1947).

[20] S. Frankel and A. M. Feingold, Phys. Rev. 97, 1029 (1955).

[21] J. M. Blatt and L. C. Biedenharn, Revs. Modern Phys. 24, 258 (1952).

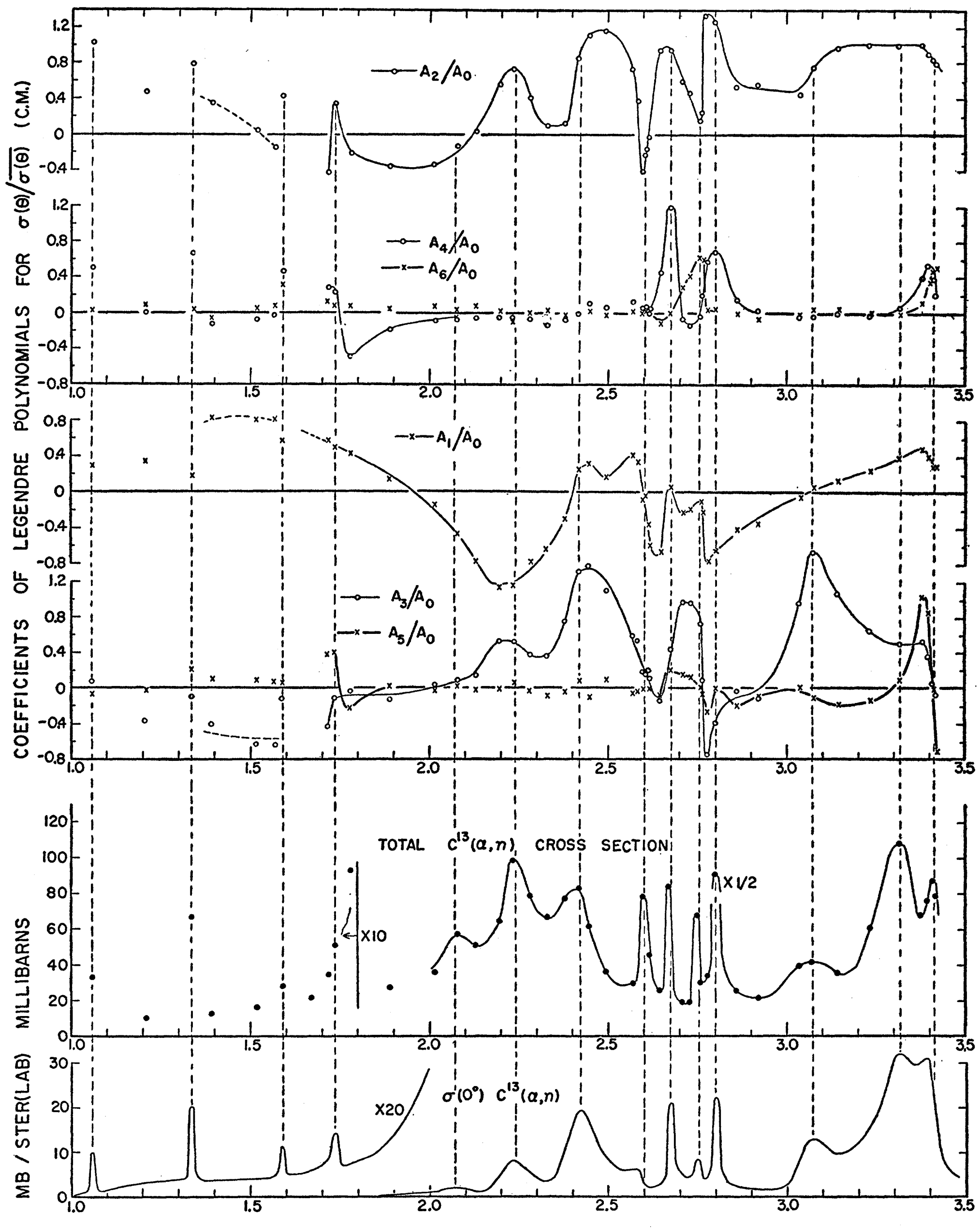

FIG. 6. Coefficients of Legendre polynomials for normalized $C^{13}(\alpha,n)O^{16}$ angular distributions as a function of α-particle energy. Also shown are the $C^{13}(\alpha,n)O^{16}$ 0°-yield and the total $C^{13}(\alpha,n)O^{16}$ reaction cross section, the latter having been corrected at the narrow resonances for the energy spread of the α particles.

where k_α is the center-of-mass wave number of the incident α particle; Γ_α, Γ_n, and Γ are the partial α-particle and neutron widths, and the total width of the compound state; and δ, the resonant phase shift, equals arc $\tan[\Gamma/2(E_R-E)]$. The parity of the compound state cannot be determined from angular-distribution measurements because the products of the Z-coefficients are unchanged when l and l' are interchanged. The upper part of Table I gives products of Z-coefficients for values of J through $\frac{7}{2}$.[22]

When levels which differ either by spin or parity, or both, interfere, the differential cross section may be approximated by adding single-level reaction amplitudes. Each coefficient B_L is the sum of the terms for

[22] L. C. Biedenharn, Oak Ridge National Laboratory Report ORNL-1501 (unpublished).

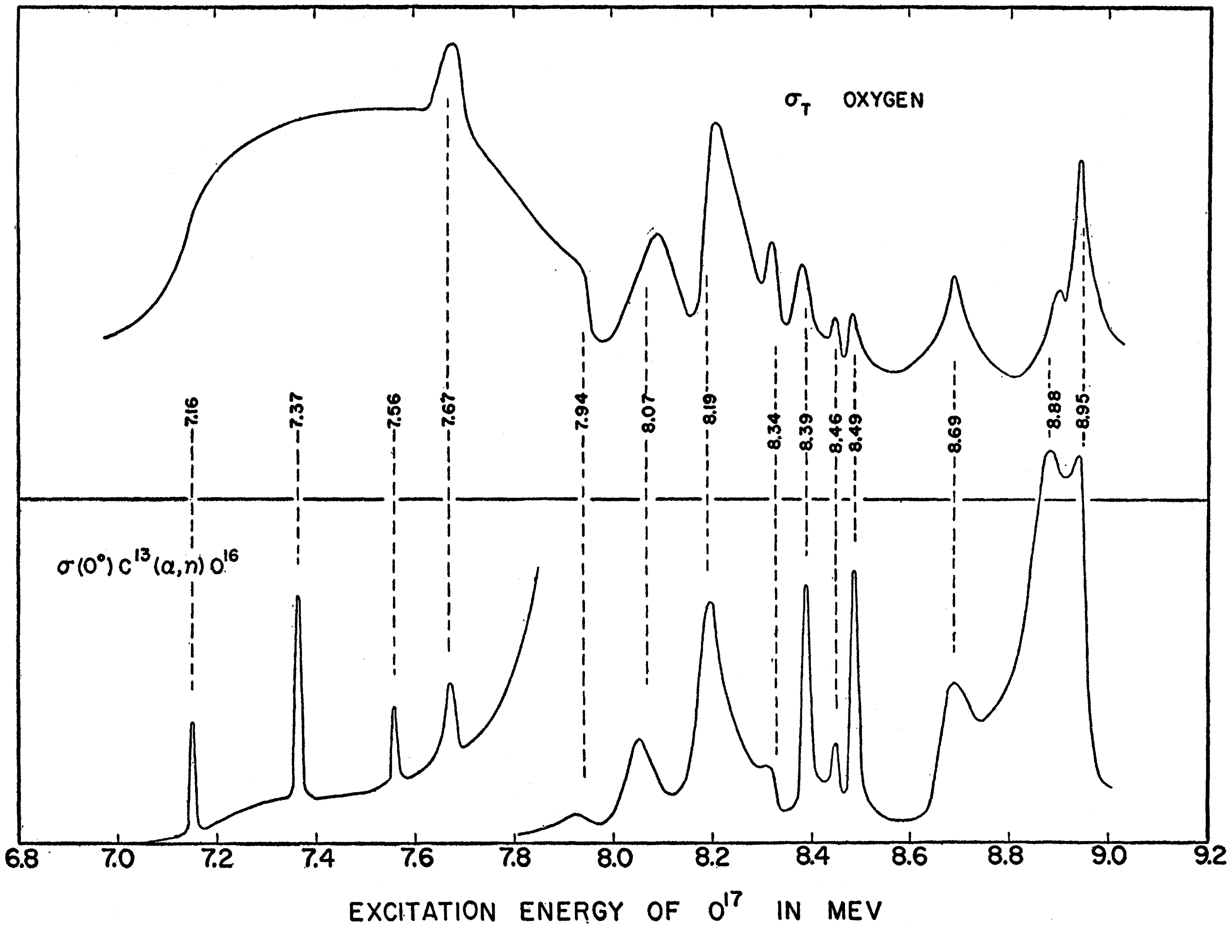

FIG. 7. The total neutron cross section of oxygen and the $C^{13}(\alpha,n)O^{16}$ 0°-yield plotted as a function of excitation energy of the compound nucleus O^{17}. The oxygen total cross section shown includes data taken from references 2 and 3. The energy scale of the data from reference 3 was corrected for target contamination.

individual levels [Eq. (1)] and terms resulting from interference between levels. Only two levels are involved in an interference term and in general each level will interfere with all the others. The term for interference between a pair of levels denoted by λ and μ is

$$\pm 2\frac{(\Gamma_{\lambda\alpha}\Gamma_{\lambda n}\Gamma_{\mu\alpha}\Gamma_{\mu n})^{\frac{1}{2}}}{\Gamma_\lambda\Gamma_\mu}\sin\delta_\lambda \sin\delta_\mu \cos\Phi_{\lambda\mu} \times Z(l_\lambda J_\lambda l_\mu J_\mu,\tfrac{1}{2}L)Z(l_\lambda' J_\lambda l_\mu' J_\mu,\tfrac{1}{2}L)$$

$$\Phi_{\lambda\mu}=\delta_\lambda-\delta_\mu+\varphi_{\lambda\alpha}+\varphi_{\lambda n}-\varphi_{\mu\alpha}-\varphi_{\mu n},$$

where the φ's are potential phase shifts. In the middle and lower parts of Table I are given the nonvanishing products of Z-coefficients for various combinations of spins and parities of interfering levels.[22]

If the spin of a state is known, the quantity $\Gamma_\alpha\Gamma_n/\Gamma^2$ may be calculated from the total reaction cross section which, for an isolated resonance, is 4π times the coefficient of P_0 in Eq. (1). Of the two sets of partial widths which are obtained, the correct one may be chosen using the variation in the oxygen total neutron cross section which, at an isolated resonance, is equal to $2\pi k_n^{-2}(2J+1)\Gamma_n/\Gamma$. For overlapping resonances corresponding to states which differ either by spin or parity, the total reaction cross section is the sum of the cross sections for the individual resonances.

2. Spin Assignments

The overlapping resonances at 3.06, 3.32, and 3.41 Mev are sufficiently well isolated from other resonances appearing in the excitation functions that they may be analyzed as a group. As is apparent from Fig. 6, Legendre polynomials through P_6 were required to fit the angular distributions in the vicinity of the resonance at 3.41 Mev. When the contributions to A_0 from the resonances at 3.06 and 3.32 Mev are taken into account, the value of A_6/A_0 at 3.41 Mev agrees with that for a level with spin $\frac{7}{2}$ listed in Table I. Spin assignments greater than $\frac{7}{2}$ for this level are excluded since polynomials of order higher than the sixth were not needed to fit the angular distributions in this region. The angular resolution used for the measurements and the

TABLE I. Nonvanishing products of Z-coefficients of Legendre polynomials for $C^{13}(\alpha,n)$ angular distributions.

Total angular momentum J	P_0	P_1	P_2	P_3	P_4	P_5	P_6
			Single level				
$\frac{1}{2}$	2						
$\frac{3}{2}$	4		4				
$\frac{5}{2}$	6		48/7		36/7		
$\frac{7}{2}$	8		200/21		648/77		200/33
			Interfering levels with same parity				
$\frac{1}{2}$ $\frac{3}{2}$			−4				
$\frac{1}{2}$ $\frac{5}{2}$			6				
$\frac{1}{2}$ $\frac{7}{2}$					−8		
$\frac{3}{2}$ $\frac{5}{2}$			−12/7		−72/7		
$\frac{3}{2}$ $\frac{7}{2}$			72/7		40/7		
$\frac{5}{2}$ $\frac{7}{2}$			−8/7		−360/77		−200/11
			Interfering levels with opposite parity				
$\frac{1}{2}$ $\frac{1}{2}$		−2					
$\frac{1}{2}$ $\frac{3}{2}$		4					
$\frac{1}{2}$ $\frac{5}{2}$				−6			
$\frac{1}{2}$ $\frac{7}{2}$				8			
$\frac{3}{2}$ $\frac{3}{2}$		−4/5		−36/5			
$\frac{3}{2}$ $\frac{5}{2}$		36/5		24/5			
$\frac{3}{2}$ $\frac{7}{2}$				−8/3		−40/3	
$\frac{5}{2}$ $\frac{5}{2}$		−18/35		−16/5		−100/7	
$\frac{5}{2}$ $\frac{7}{2}$		72/7		8		40/7	

statistical uncertainties were such that the effects of a level with spin 9/2 would have been observed. Spins greater than $\frac{3}{2}$ for the resonances at α-particle energies of 3.06 and 3.32 Mev are excluded because A_4/A_0 and A_6/A_0 are not significantly different from zero between 2.90 and 3.32 Mev. To account for the value of about one for A_2/A_0 in the region between the resonances at 3.06 and 3.32 Mev, a spin of $\frac{3}{2}$ is assigned to both levels. From Table I it is also evident that large coefficients of P_3 in this energy region can be attributed to interference between the spin $\frac{3}{2}$ levels if they have opposite parity. The shift of the maximum in A_4/A_0 from the resonant energy of 3.41 Mev to about 3.40 Mev may result from interference between the levels corresponding to resonances at 3.41 and 3.06 Mev since they have like parity. Similarly, interference between these two levels can cause A_2/A_0 to be smaller at the resonant energies than at energies between the resonances. The coefficients of P_1 between 2.9 and 3.4 Mev are inconsistent with the $\frac{3}{2}^{\pm}$ $\frac{3}{2}^{\mp}$ $\frac{7}{2}^{\pm}$ assignment for, according to this assignment, A_1/A_0 should not exceed 0.1. The observed values of A_1/A_0 may arise from interference between one of the spin $\frac{3}{2}$ levels and a broad spin $\frac{1}{2}$ level which is obscured in the excitation functions by the other resonances.

The values of A_2/A_0 and A_4/A_0 at 2.81 Mev indicate that the resonance at this energy corresponds to a state having either spin $\frac{5}{2}$ or $\frac{3}{2}$. In the latter case A_4/A_0 would be present only if this level interferes with a neighboring level having the same parity and a spin of $\frac{5}{2}$ or greater. The magnitude of A_6/A_0 near 2.76 Mev is evidence that the level at this energy has a spin of $\frac{7}{2}$. Since the resonances at 2.76 and 2.81 Mev are separated in energy by less than twice the sum of their widths, an assignment of $\frac{7}{2}^{\pm}$ $\frac{3}{2}^{\pm}$ can explain the interference effects exhibited by the variation of A_4/A_0 and A_2/A_0 in this energy region. A spin of $\frac{5}{2}$ for the level at 2.81 Mev with the same parity is excluded for two reasons: the interference terms would not be large enough to account for the low value of A_2/A_0 at 2.76 Mev, and a large interference term in A_6/A_0 would be present. Odd polynomials in the angular distributions in the vicinity of these resonances are attributed to interference with levels of opposite parity at higher and lower energies.

Although the resonance at 2.68 Mev interferes with surrounding resonances, it is sufficiently well isolated that a direct comparison can be made between the observed angular distribution and calculated single-level distributions. Figure 8 shows the observed angular distribution and the calculated angular distribution for spin $\frac{5}{2}$. Other single-level distributions fit the data poorly.

The spins of the broad overlapping levels at 2.08, 2.25, and 2.41 Mev are limited to $\frac{3}{2}$ or $\frac{1}{2}$ because the highest even-order polynomial required to fit the angular distributions in this energy region is P_2. Spin assignments of $\frac{3}{2}$ to the levels at 2.25 and 2.41 can account for the large values of A_2/A_0 near these resonances, and the P_3 terms can result from interference between the levels with spin $\frac{3}{2}$, providing they have opposite parity. The large values of A_1/A_0 near 2.20 Mev may be attributed to interference between the spin $\frac{3}{2}$ level at 2.25 Mev and a spin $\frac{1}{2}$ level with opposite parity at 2.08 Mev. Interference between the resonances at 2.08 and 2.41 Mev, which according to these assignments have the same parity, can account for the relatively small values of A_2/A_0 near 2.35 Mev and the change of sign of this coefficient near 2.10 Mev.

Since P_2 is the highest even-order polynomial involved in the distributions near 2.60 Mev, the spin of the level at this energy is either $\frac{1}{2}$ or $\frac{3}{2}$. If the spin were $\frac{3}{2}$, the negative coefficient of P_2 could be attributed to interference with the $\frac{5}{2}$ level at 2.68 Mev, providing the levels have the same parity; however, a large P_4 interference term would also occur. The behavior of A_2/A_0 can be explained if the spin of the level is $\frac{1}{2}$ and the parity is the same as that of either the spin-$\frac{3}{2}$ level at 2.41 Mev or the spin-$\frac{5}{2}$ level at 2.68 Mev. Although all three resonances may have the same parity, the energy variation of A_1/A_0 indicates that the spin-$\frac{1}{2}$ and spin-$\frac{3}{2}$ levels may have opposite parity.

The angular distributions at the four narrow resonances occurring at α-particle energies below 2.0 Mev are complicated by contributions from the tails of the relatively broad resonances between 2.0 and 2.5 Mev. In addition, it is apparent from the shape of the $C^{13}(\alpha,n)$ 0°-yield curve and the broad maximum in the O^{16} total neutron cross section as shown in Fig. 7, that there are one or more levels between O^{17} excitation energies 7.1 and 7.9 Mev which may contribute to the $C^{13}(\alpha,n)$ reaction between α-particle energies of 1.0 and 2.0 Mev. Since P_3 is the highest order polynomial contributing significantly to the $C^{13}(\alpha,n)$ angular distributions at energies between the narrow resonances, the spins of the levels which are responsible for the slowly varying cross section in this region are limited to $\frac{1}{2}$ and $\frac{3}{2}$. Baldinger *et al.*[23] have concluded from experiments on the elastic scattering of neutrons by O^{16} that two broad spin-$\frac{3}{2}$ levels with opposite parity are located at O^{17} excitation energies of 7.27 and 7.72 Mev. Although the resonance widths given by these workers are too large to be consistent with the oxygen total neutron cross section shown in Fig. 7, the spin and relative parity assignments are consistent with the $C^{13}(\alpha,n)$ angular distributions. Therefore, interference effects observed at the narrow resonances can be attributed to broad spin-$\frac{3}{2}$ and spin-$\frac{1}{2}$ levels.

Because of very strong interference effects, a spin assignment consistent with the angular distribution data cannot be made for the level at 1.74 Mev, but the presence of P_4 and P_5 terms indicates a spin of $\frac{5}{2}$ or greater. This level appears in the O^{16} total neutron cross section, and the variation in the cross section at resonance, when corrected for the spread in energy of the neutrons used in the experiment, exceeds the upper limit for a spin of $\frac{3}{2}$.

The spin of the level at 1.59 Mev is $\frac{7}{2}$ or greater since even polynomials through P_6 are present in the angular distribution. The coefficients of P_2, P_4, and P_6 are greatly reduced by the contribution to A_0 from the slowly varying cross section. In this energy range the angular resolution used for the measurements was not sufficient to establish the presence of spins greater than $\frac{7}{2}$.

[23] Baldinger, Huber, and Proctor, Helv. Phys. Acta **25**, 142 (1952).

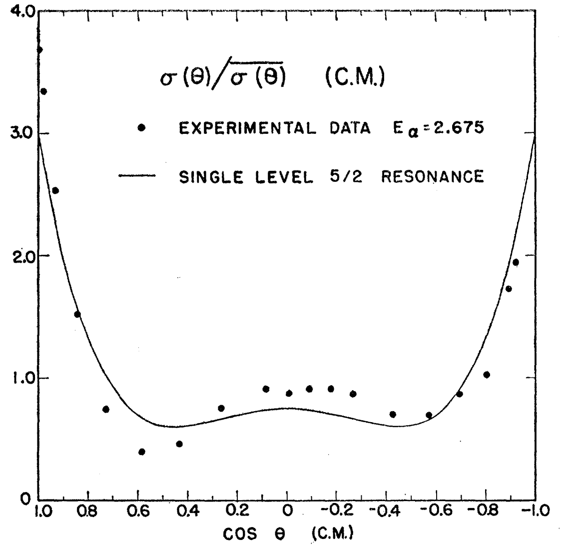

FIG. 8. $C^{13}(\alpha,n)O^{16}$ angular distribution at 2.675 Mev. The curve represents the calculated angular distribution for an isolated spin-$\frac{5}{2}$ level.

Spins of $\frac{5}{2}$ assigned to the levels at 1.06 and 1.34 Mev on the basis of angular-distribution measurements are unambiguous although these resonances interfere with the broad resonances.

3. Summary

Table II lists the information about the excited states of O^{17} obtained in this investigation and, for comparison, the results of references 10 and 11. Brackets in the column listing the parities indicate the group of levels within which relative parity assignments were determined, and l_α refers to the orbital angular momentum of the incoming channel for the $C^{13}(\alpha,n)$ reaction.

Except for the levels at O^{17} excitation energies 7.155, 7.367, and 7.559 Mev, the total neutron cross-section data showed that Γ_n is greater than Γ_α for the levels studied here. For the calculation of reduced widths of the levels at 7.155 and 7.367 Mev the set of partial widths for which $\Gamma_n > \Gamma_\alpha$ were assumed. Since absolute parities were not determined, the reduced widths of the states were computed assuming both even and odd parities. The reaction radii used were 5.7×10^{-13} cm for the α-particle channel and 4.7×10^{-13} cm for the neutron channel. α-particle penetrabilities were obtained from graphs by Sharp *et al.*,[24] and neutron penetrabilities were taken from the tabulation by Lax

[24] Sharp, Gove, and Paul, Atomic Energy of Canada, Ltd. Report No. 268, Chalk River, Ontario (unpublished).

TABLE II. Energy levels of O^{17}.

E_{ex} (Mev)	Center-of-mass Γ (kev)	J, π	Present measurements $C^{13}(\alpha,n)$ and $\sigma_T(O^{16})$: Γ_n/Γ_α	l_α	$\gamma_\alpha^2\times10^{12}$ (kev cm)	$\left(\frac{\gamma_\alpha^2}{3\hbar^2/2\mu_\alpha a_\alpha}\right)$	$\gamma_n^2\times10^{12}$ (kev cm)	$\left(\frac{\gamma_n^2}{3\hbar^2/2\mu_n a_n}\right)$	Schiffer et al.[a] $C^{13}(\alpha,n)$: E_{ex} (Mev)	J, π	Rusbridge[b] $C^{13}(\alpha,n)$: E_{ex} (Mev)	J, π	l_α	$\left(\frac{\gamma_\alpha^2}{3\hbar^2/2\mu_\alpha a_\alpha}\right)$	$\left(\frac{\gamma_n^2}{3\hbar^2/2\mu_n a_n}\right)$
7.155	5	$\frac{5}{2}+$	(1300)	3	(170)	(0.50)	(2.1)	(0.0015)			7.16	$\frac{5}{2}+$	3	1.6 ±0.3	(1.1±0.4)×10^{-3}
		−		2	(20)	(0.057)	(11)	(0.0081)				−	2	0.23±0.04	(1.1±0.4)×10^{-2}
7.367	≤4	$\frac{5}{2}+$	(450)	3	(≤26)	(≤0.08)	(≤1.4)	(≤0.001)			7.37	$\frac{5}{2}+$	3	0.35±0.08	≤5×10^{-4}
		−		2	(≤3.9)	(≤0.01)	(≤7.1)	(≤0.005)				−	2	0.05±0.01	≤5×10^{-3}
7.559	≤4	≥$\frac{7}{2}$									7.55				
7.67	22	≥$\frac{5}{2}$									7.67				
7.94	110	$\frac{1}{2}+$	10	1	32	0.090	12	0.0082	7.94	$\frac{1}{2}\pm$	7.91				
		−		0	19	0.055	15	0.010							
8.07	70	$\frac{3}{2}-$	10	2	39	0.11	6.6	0.0065	8.07	$\frac{3}{2}\mp$	8.04				
		+		1	14	0.038	18	0.013							
8.19	60	$\frac{3}{2}+$	13	1	6.6	0.019	16	0.011	8.20	$\frac{3}{2}\pm$	8.18	$\frac{3}{2}+$	1	0.04±0.01	(9±2)×10^{-3}
														or 0.14±0.03	or (2.5±0.6)×10^{-3}
		−		2	18	0.050	8.4	0.0060				$\frac{3}{2}-$	2	0.11±0.04	(3.3±0.8)×10^{-3}
														or 0.40±0.09	or 0.9±0.3 ×10^{-3}
8.335	18	$\frac{1}{2}+$	6.7	1	2.4	0.0068	1.8	0.0012	8.335						
		−		0	1.6	0.0044	2.2	0.0016							
8.390	11	$\frac{5}{2}+$	19	3	4.6	0.014	2.8	0.0020	8.40	$\frac{5}{2}\pm$					
		−		2	1.3	0.0036	10	0.0073							
8.46	9	$\frac{7}{2}+$	31	3	1.4	0.0039	69	0.049	8.465						
		−		4	14	0.039	8.3	0.0059							
8.489	11	$\frac{3}{2}+$	2.8	1	2.4	0.017	2.1	0.0015	8.50	$\frac{5}{2}\pm$					
		−		2	5.0	0.036	1.2	0.00084		($\frac{3}{2}\pm$)					
8.69	85	$\frac{3}{2}+$	17	1	2.3	0.0064	21	0.015	8.70	$\frac{3}{2}\pm$					
		−		2	4.9	0.014	12	0.0082							
8.88	110	$\frac{3}{2}-$	3.5	2	25	0.070	12	0.0088	8.89	$\frac{3}{2}\mp$					
		+		1	12	0.033	22	0.016							
8.95	35	$\frac{7}{2}+$	35	3	1.9	0.0053	200	0.14	8.95	$\frac{7}{2}\pm$					
		−		4	9.0	0.026	26	0.018							

[a] See reference 11.
[b] See reference 10.

and Feshbach.[25] The variations of the partial level shifts and partial widths are small for changes in energy comparable to total level widths and consequently have been neglected for the reduced-width calculations. The uncertainty in the reduced widths listed for levels above 7.91 Mev is estimated to be 50%. Reduced widths given for levels at 7.155 and 7.367 Mev are only order-of-magnitude estimates because the resonance widths were too narrow to be measured accurately.

For most of the levels studied in this investigation the reduced α-particle width, γ_α, differs from the reduced neutron width by less than an order of magnitude. Furthermore, all levels except possibly the spin-$\frac{7}{2}$ level at 8.95 Mev have reduced neutron widths which are less than 5% of the Wigner limit, $3\hbar^2/2\mu_n a_n$.

[25] M. Lax and H. Feshbach, J. Acoust. Soc. Amer. **20**, 108 (1948).

The results of this study are in good agreement with those of Schiffer *et al.*[11] and Rusbridge,[10] except for the reduced widths of the level at 8.19 Mev. Rusbridge[10] gives two sets of reduced widths for this level in accordance with the conclusion that Γ_α and Γ_n are almost equal. The disagreement may be due to the reaction radii used for the calculations and differences in the absolute cross sections and resonance widths obtained in the two experiments.

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Beta Decay and the Conservation of Parity

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An interpretation of recent experiments on the conservation of parity is proposed, which, utilizing a zero-rest-mass neutrino and Yukawa's model for the beta decay, conserves C and P separately for the nucleons as well as conserving CP for the over-all beta interaction.

THE conservation of parity in weak interactions has recently been questioned by Lee and Yang.[1] Experiments suggested by Lee and Yang have just been performed[2–4] which apparently show that parity is indeed not conserved.[5] There are, however, alternative interpretations which may not be superfluous to report here, despite their tentative nature.

To see in the simplest way the nature of these ideas let us consider an analogy to the situation of the oriented cobalt experiment. Assume the orientation to be complete so that all the Co atoms are in a *single* magnetic sublevel. If, instead of beta decay, a γ ray were to be emitted, and if the detector were sensitive only to right circular polarizations, then the angular distribution would clearly be asymmetric between the 0 and 180 degree directions. If our observer did not know that his detector incorporated a polarization selector, he would be faced with an apparent asymmetry in nature. Now let us apply this analogy to the beta decay experiments, and pose the question: what neglected feature of beta decay experiments may constitute an unconscious polarization selector? It is an attractive hypothesis that it is the determination of the *charge* of the emitted electron—an intrinsic element in every beta decay—that constitutes the "polarization selector." In formal terms, we assume that not parity but charge conjugation times parity is the operation that commutes with the beta decay interaction.[6]

It is an immediate consequence of this, by the Pauli-Lüders theorem,[7] that an equivalent statement—assuming invariance to the restricted Lorentz group—is that the Hamiltonian is invariant to time reversal.[8]

[1] T. D. Lee and C. N. Yang, Phys. Rev. **104**, 254 (1956).
[2] Wu, Ambler, Hayward, Hoppes, and Hudson, Phys. Rev. **105**, 1413 (1957).
[3] Garwin, Lederman, and Weinrich, Phys. Rev. **105**, 1415 (1957).
[4] J. I. Friedman and V. L. Telegdi, Phys. Rev. **105**, 1681 (1957).
[5] See also the suggestions for experiments made by Jackson, Treiman, and Wyld, Phys. Rev. **106**, 517 (1957).
[6] That CP is to be conserved has been stated by Professor Wigner in his address to the American Physical Society meeting, January, 1957 [Bull. Am. Phys. Soc. Ser. II, 2, 36 (1957)]. But very much earlier the fact that parity and charge conjugation may not separately be conserved was pointed out in reference 9 of the paper by Wick, Wightman, and Wigner, Phys. Rev. **88**, 101 (1952). The authors are indebted to Professor J. D. Jackson for these remarks. See also C. N. Yang, Revs. Modern Phys. **29**, 231 (1957).
[7] W. Pauli, *Niels Bohr and the Development of Physics* (McGra w-Hill Book Company, Inc., New York, 1955), pp. 30 ff. G. Lüd ers, Kgl. Danske Videnskab., Selskab, Mat.-fys. Medd. **28**, N o. 5 (1954).
[8] E. P. Wigner, Gött. Nachr. 546 (1932).