to Am^{241}, from five pulse analyses, was 0.0179 ± 0.0006 (Fig. 1).

RESULTS

The alpha half-life of Am^{243} was calculated from these data to be $(8.8\pm0.6)\times10^3$ years, using 470_{-10}^{+5} years as the half-life of Am^{241} [3] and assuming that there is no alpha fine structure of Am^{243} that might be obscured by Am^{241} alphas. The error reported is based upon standard deviation of the alpha counting data (3 percent), the mass spectrometer error (1 percent), the error in the half-life of Am^{241} (2 percent), and the estimated error due to the uncertain correction for the Am^{241} alphas in the Am^{243} peak.

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Spin-Orbit Coupling Energy in O^{17}†

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A proportional counter filled with carbon dioxide was irradiated with monoenergetic fast neutrons produced by bombarding thin lithium targets with protons from an electrostatic generator. Angular distributions of neutrons scattered by oxygen were deduced from the energy spectrum of recoil oxygen ions for neutron energies from 392 kev to 1412 kev, determining the parities of three spin-$\frac{3}{2}$ levels in O^{17}, 4.56, 5.08, and 5.39 Mev above the ground state. The 5.08-Mev state has even parity and appears to be the $D_{\frac{3}{2}}$ member of a $D_{\frac{5}{2}}-D_{\frac{3}{2}}$ doublet, where the $D_{\frac{3}{2}}$ level is then 5 Mev higher than the $D_{\frac{5}{2}}$ ground state of O^{17}. The other two states have odd parity and lie more than 1.5 Mev above the lowest spin-$\frac{1}{2}$ odd-parity level. This may indicate a spin-orbit splitting of the order of 2 Mev or greater in the P shell.

I. INTRODUCTION

It might be hoped that the examination of the states of nuclei made up of a closed shell plus one "outside" nucleon would result in information which could be interpreted to help determine the source and strength of spin-orbit forces in nuclei. Various results pertaining to the spin-orbit splitting of the P states of a single nucleon outside the closed 1 S shell, that is, states of He^5 and Li^5, appear to be inconsistent and therefore inconclusive.[1] The next heavier closed shell plus one nuclei are the isobaric $O^{17}-F^{17}$ pair. According to the ordering of levels in a potential well, the lowest state of these nuclei should be either a $2S$ or $1D$ state, the integer representing the number of nodes in the radial wave function. Alder and Yu[2] have shown that the spin of the ground state of O^{17} is $\frac{5}{2}$, and it can be concluded that this state is primarily $D_{\frac{5}{2}}$, a hypothesis in good agreement with the electric quadrupole[3] and magnetic dipole[2] moments. It might, then, be expected that a $D_{\frac{3}{2}}$ state of O^{17} should exist and lie at an excitation energy determined by the strength of the spin-orbit forces acting on the added neutron. Positions of the low-energy levels of O^{17} are known from a variety of experiments,[4] and the spins and parities of all states below 4 Mev can be deduced[5-7] either from experiments on O^{17} or from measurements pertaining to the mirror nucleus F^{17}. None of these states has spin $\frac{3}{2}$, and there is no reason to believe such a state would have been missed because of selection rules or experimental limitations. However, three spin-$\frac{3}{2}$ states are known[8] between 4.5 and 5.4 Mev, and it seemed probable that one of these was the $D_{\frac{3}{2}}$ member of the doublet including the ground state. It was the purpose of these measments to determine the parity of these levels in the hope of finding the $1D_{\frac{3}{2}}$ state in O^{17}, and thus to obtain a measure of the spin-orbit splitting in the $1D$ shell.

II. THEORY OF THE MEASUREMENTS

The variation of total neutron cross section with energy at an elastic scattering resonance associated with a state of spin J is $[(2J+1)/(2I+1)]2\pi\lambda\!\!\!^{-2}$, where I is the spin of the target nucleus, a result independent of the parity of either the target nucleus or the resonance level. Total cross-section measurements interpreted in this way were used to assign values of $\frac{3}{2}$ to the spin of levels in O^{17} at excitation energies of 4.56, 5.08, and 5.39 Mev.[8] If there is no interference between a resonant state and other states, the differential cross section for neutron scattering will also depend solely on J and I. However, an interpretation of the observa-

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1 E.g., see D. R. Inglis, Revs. Modern Phys. **25**, 390 (1953), p. 409.
2 F. Alder and F. C. Yu, Phys. Rev. **81**, 1067 (1951).
3 V. Low and C. H. Townes, Phys. Rev. **75**, 529 (1949).
4 F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **24**, 321 (1952).
5 Burrows, Powell, and Rotblat, Proc. Phys. Soc. (London) **209**, 478 (1951).
6 R. A. Laubenstein and M. J. V. Laubenstein, Phys. Rev. **84**, 18 (1951).
7 F. Eppling, thesis, University of Wisconsin, 1953 (unpublished).
8 Bockelman, Miller, Adair, and Barschall, Phys. Rev. **84**, 69 (1951).

tion of the interference which occurs between the resonant state and a state of known parity will usually serve to determine the parity of the resonance level. Such interference occurs between the resonance and the continuum or potential scattering in the case of the scattering of neutrons from oxygen. At the neutron energies involved in these measurements almost all of the background scattering is the result of the interaction of S-wave neutrons with the target nucleus O^{16}. Even-parity states with spin $\frac{3}{2}$ will be formed by the interaction of D-wave neutrons, and odd-$\frac{3}{2}$ states will result in the resonant scattering of P-wave neutrons. Considering only the resonance scattering from spin-$\frac{3}{2}$ resonances and the S-wave potential scattering, the differential neutron scattering cross section in the center-of-mass system will be proportional to $A+B\times\cos\vartheta+C\times\cos^2\vartheta$ for odd-parity states and $A'+C'\times\cos^2\vartheta$ for even-parity states, where the coefficients are functions of the scattering phase shifts[9] and hence, in turn, functions of the neutron energy, and ϑ is the scattering angle in the center-of-mass system. The distributions are obviously qualitatively different inasmuch as the odd-parity resonance angular distributions are asymmetric with respect to 90° and the asymmetry varies with energy, while the even-parity resonant angular distributions are fore-and-aft symmetric.

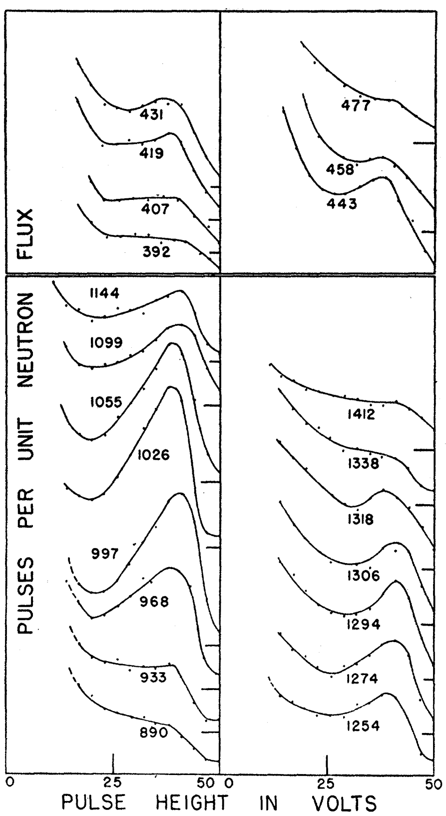

FIG. 1. Recoil-ion energy distributions resulting from the bombardment of carbon dioxide with monoenergetic neutrons of energies from 392 kev to 1412 kev. The amplifier gain was varied with neutron energy so that the maximum-energy oxygen recoil at each neutron energy produced a pulse of about 45 v. The ordinate scale is arbitrary for each distribution.

It seemed most convenient to determine the angular distributions by measuring the recoil energy spectrum of oxygen nuclei bombarded by monoenergetic neutrons Barschall and Kanner[10] have pointed out that the distribution in energy of recoil ions in the laboratory system is proportional to the differential cross section per unit solid angle as a function of $\cos\vartheta$.

II. EXPERIMENTAL PROCEDURE

The experimental procedure was similar to that previously reported.[11] A proportional counter filled with 10 cm of carbon dioxide was irradiated with neutrons produced by bombarding a lithium target with protons from an electrostatic generator. The lithium target had a stopping power of about 16 kev for 2-Mev protons. Since it was necessary to use electron collection and gas amplification to achieve a good signal-to-noise ratio, oxygen, which attaches electrons to form negative ions, could not be used as a counter gas; and carbon dioxide, which does not attach electrons appreciably, was used instead. Carbon has no scattering resonances in the energy region under investigation; therefore the pulse-height spectrum from carbon recoils should vary quite slowly with energy and not interfere with observation of the rapidly varying oxygen-recoil spectrum. Figure 1 shows pulse-height spectra at various neutron energies as measured with a single-channel pulse-height analyser.

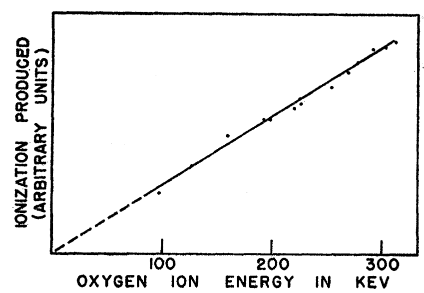

FIG. 2. Ionization produced by oxygen ions as a function of ion energy.

These pulse-height distributions are proportional to the distribution of ion recoil energies only if the number of ion pairs produced by the recoil ion is sensibly proportional to the recoil ion energy. A measurement was made which verified this proportionality within the limits required by this experiment. The maximum oxygen-recoil energy will be equal to 0.222 E_n, where E_n is the incident neutron energy, while the maximum

[9] J. A. Wheeler and H. H. Barschall, Phys. Rev. **58**, 682 (1940).

[10] H. H. Barschall and M. H. Kanner, Phys. Rev. **58**, 682 (1940).

[11] R. K. Adair, Phys. Rev. **86**, 155 (1952).

carbon-ion recoil energy will be equal to 0.28 E_n. Maximum pulse heights for carbon and for oxygen recoils could be determined for each neutron energy by inspection of the high-energy side of the pulse-height spectra, thus giving a measure of the ionization produced as a function of the recoil-ion energy. Points on Fig. 2 represent the variation in the ionization produced by oxygen ions as a function of the ion energy. Comparison of the points with the straight line drawn to pass through the origin shows that the ionization is nearly proportional to energy. This type of measurement actually pertains to the maximum ionization produced by the heavy ions, and the results do not eliminate the possibility that monoenergetic ions may produce an asymmetric pulse-height distribution with perhaps a large low-energy tail.

Aside from uncertainties concerning the effects of carbon recoils and the lack of knowledge of the ionization spectrum of the heavy ions, the measured angular distributions are affected by the rather poor energy or angular resolution of the counter and by end and wall effects. Since the evaluation of all these effects is uncertain and the corrections do not affect the qualitative features of the distributions, which are of primary physical importance, such corrections were not made.

IV. CONCLUSIONS AND DISCUSSION

From the total cross-section measurements[8] the resonant energies for the three resosnances are known to be 435, 1000, and 1311 kev. Widths of the resonances are, respectively, 42, 100, and 35 kev. It can be noted immediately upon inspection of the pulse-height distributions that the angular distributions at the 1000-kev resonance do not change in asymmetry as the neutron energy is increased through resonance. The minimum of the distribution, at about one-half of the maximum pulse height or at about 90° in the center-of-mass system, is clearly stationary with energy. This absence of a $\cos\vartheta$ term varying strongly with energy near resonance indicates that the resonance state has even parity. Distributions at the 435-kev resonance and the 1.311-Mev resonance show a strong asymmetry which varies with energy. At energies below resonance, backscattering predominates, while above the resonance, scattering is stronger in the forward direction. The minimum, therefore, moves from small angles and small pulse heights to larger angles and larger pulse heights as the neutron energy increases from below to above the resonance energy. The S-wave phase shift of neutrons scattered from oxygen must be negative from considerations of continuity, since the scattering length at zero energy is positive,[12] while the resonant P wave is expected to increase positively from near 0° below resonance to near 180° at energies above resonance. This will give a variation of angular distributions

[12] E. Fermi and L. Marshall, Phys. Rev. 71, 666 (1947).

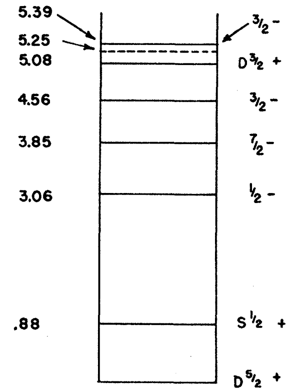

FIG. 3. Energy levels of O^{17} up to 5.5 Mev. The narrow state found in reaction experiments which may be involved in the N^{17} β decay is indicated by the dashed line. The delineation of this state by a dashed line is not meant to indicate that its presence is less certain than that of the other states.

similar to that observed near 435 kev and 1311 kev, that is, predominant backscattering below resonance and forward scattering at neutron energies above resonance. We conclude, therefore, that these resonances result from the formation of odd-parity states in the compound nucleus, O^{17}.

Though it is reasonably well established that the 5.08-Mev state is the lowest state of even parity and spin $\frac{3}{2}$, it is not obvious that it is the $D_{\frac{3}{2}}$ complement of the ground state. However, our knowledge of the width of the level gives some information concerning the wave function of the state. The reduced width of the state, defined[13] as $\Gamma/2kP$, measured in units of $\hbar^2/Ma$ (Γ is the measured width, k the neutron wave number, P the barrier penetration factor, M the reduced mass of the system, and a the nuclear radius) is likely to be approximately equal to the square of the overlap of the compound-state wave function with the initial-state wave function, which in this case consists of the O^{16} nucleus plus a $D_{\frac{3}{2}}$ neutron. The value of this quantity for the 5.08 Mev resonance is about $\frac{1}{2}$; so large a value indicates strongly that it is this level which is the $D_{\frac{3}{2}}$ single-particle state expected in this energy region.

Figure 3 shows an energy level diagram of O^{17} up to excitation energies of 5.4 Mev. Spins and parities of all states, except that shown by the dashed line,[14] are shown. States which can be represented by a single neutron outside a closed shell have the orbital angular momentum specified. The $D_{\frac{5}{2}}-D_{\frac{3}{2}}$ splitting is seen to be 5.08 Mev. It is attractive to regard the 3.07-Mev state as a $P_{\frac{1}{2}}$ hole in the P shell, with the two excess nucleons coupling to produce zero spin. we might then expect a $P_{\frac{3}{2}}$-hole state at higher energy. The energy difference would then be a measure of the strength of spin-orbit coupling in the P shell. Since the lowest $P_{\frac{3}{2}}$ states are 1.5 and 2 Mev higher, we can assume that the splitting is equal to or greater than 1.5 Mev.

[13] E. P. Wigner and L. Eisenbud, Phys. Rev. 72, 29 (1947).

[14] Inglis points out (reference 1) that this state probably has high angular momentum and is probably the state associated with the β decay of N^{17}.