$F^{19}(n,d)O^{18}$ Reactions and Energy Levels of O^{18}†

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The differential cross sections for the reactions $F^{19}(n,d)O^{18}$ leading to the ground- and first-excited states of O^{18} have been measured. Higher excited states were also observed but with insufficient accuracy for measurement of the corresponding cross sections. Comparison with results of pickup theory indicates a proton *s*-wave transition to the ground state of O^{18} and a probable *d*-wave transition of approximately equal reduced width to the first excited state. The estimated ratio of the two reduced widths is in agreement with recent theoretical results.

INTRODUCTION

THE use of pickup and stripping reactions to investigate single-particle nuclear transitions is well established.[1] For example, the angular distribution of the reaction

$$(A,Z)+n\rightarrow(A-1,\ Z-1)+d \qquad (1)$$

determines the angular-momentum and parity changes in the corresponding single-particle transition

$$(A,Z)\rightarrow(A-1,\ Z-1)+p, \qquad (2)$$

even though the latter transition is not generally energetically possible for the ground state of the initial nucleus (A,Z). In addition one may make use of the magnitude of the differential cross section of the reaction (1) in order to determine the reduced width γ_p^2 for the transition (2) and hence the overlap of the wave functions which represent the two sides of Eq. (2). Thomas and others[2] have shown that the essential normalizing factors of the Butler angular-distribution functions[1] which produce the magnitudes of the differential cross sections are just the single-particle reduced widths. One may thus expect to extract the purely kinematical effects of the pickup process, such as variation of peak cross section with the angular-momentum transfer and center-of-mass energy in reaction (1), and to obtain the absolute values of the reduced widths. Where comparisons have been made between the reduced widths so derived and those obtained directly by analysis of nuclear resonance reactions, it is found that there is a discrepancy in absolute magnitude of as much as a factor of four but that relative magnitudes are quite dependably represented.[3–5]

Another interesting application of stripping and pickup studies in the determination of reduced-width ratios is that in which these ratios are compared with those which can be deduced directly from the wave functions found theoretically for the initial and final states of transitions such as (2). Recently French *et al.*[6] have made such a comparison in the case of the transitions from the ground state of B^{10} to the ground and 2.43-Mev excited states of Be^9. The results of an experimental study[7] of the pickup reaction $B^{10}(n,d)Be^9$ were compared with those of their intermediate-coupling determination of the wave functions of B^{10} and Be^9, with good agreement.

There has been considerable interest recently in the nuclides of masses 18 and 19 due to their extensive theoretical investigation by means of intermediate-coupling calculations.[8,9] The present experiment on the pickup reactions $F^{19}(n,d)O^{18}$ was undertaken largely for the purpose of obtaining some experimental comparison with the theoretical predictions of the properties of the low-lying (even-parity) levels of O^{18}. We shall report measurements of the differential cross sections of the reactions leading to the ground and first excited state of O^{18} for a neutron bombarding energy of 14.1 Mev.

APPARATUS AND EXPERIMENTAL PROCEDURE

The apparatus for measuring the angular distributions of the deuterons consisted mainly of a counter-scintillator coincidence telescope mounted on a rotatable stand and has been described in detail in connection with a similar previous experiment.[7] Thin radiators of fluorine in the form of one- or two-mil sheets of Teflon were bombarded by monoenergetic 14.1-Mev neutrons produced by means of the $T(d,n)He^4$ reaction, using the 250-kev deuteron beam of a Cockcroft-Walton accelerator. The charged reaction products were detected by means of their triple coincidences in the two proportional counters and the NaI(Tl) scintillator which had the form of a one-inch circular disk of 2.5-mm thickness. The scintillator pulse-height spectrum corresponding to triple coincidences was presented on an 18-channel pulse-height analyzer. In addition a 10-channel analyzer displayed the ionization (dE/dx) pulses derived from the proportional counters through which the

† Work done under the auspices of the U. S. Atomic Energy Commission.
[1] S. T. Butler, Proc. Roy. Soc. (London) **A208**, 36 (1951).
[2] R. G. Thomas, Phys. Rev. **100**, 25 (1955). This paper gives a bibliography of earlier pertinent theoretical work.
[3] R. G. Thomas, Phys. Rev. **91**, 453(A) (1953).
[4] Fujimoto, Kikuchi, and Yoshida, Progr. Theoret. Phys. (Japan) **11**, 264 (1954).
[5] G. Abraham, Proc. Phys. Soc. (London) **A67**, 273 (1954).
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[7] F. L. Ribe and J. D. Seagrave, Phys. Rev. **94**, 934 (1954).
[8] J. P. Elliott and B. H. Flowers, Proc. Roy. Soc. (London) **A229**, 536 (1955), and private communication.
[9] M. G. Redlich, Phys. Rev. **99**, 1427 (1955), and **95**, 448 (1954).

charged particles passed on their way from the radiator to the scintillator. Following the design of Igo and Eisberg,[10] a special selector circuit was used in the proportional-counter channels which fed the smaller of the two dE/dx pulses to the 10-channel analyzer. With a 7.6-mm Hg counter filling of $Kr-CO_2$ mixture (3% CO_2) the resolution of the dE/dx pulse group corresponding to 8-Mev deuterons was about 30%, full width at half-maximum. With this resolution it was possible to set a bias window on the dE/dx channels of the coincidence circuit so that pulses from protons, tritons, and alpha particles could be excluded from reasonably wide ranges of the deuteron scintillator pulse-height spectrum without appreciably affecting the numbers of deuterons detected. Such discrimination was employed during most of the experiment, particularly when the very low yields of deuterons from the excited-state $F^{19}(n,d)O^{18}$ reactions were being measured.

The radiator mount was such that it could be rotated by means of a magnet external to the counter telescope in order to expose either the Teflon radiator, which was mounted on a platinum backing, or a clean platinum blank to the active counting volume, thus allowing background runs to be made in order to correct for triple-coincidence signals arising from counter-gas nuclear disintegrations and other causes.

DATA AND RESULTS

With the axis of the counter telescope set at zero degrees with respect to the incident neutron direction, a strong group of 8.3-Mev deuterons was observed in the scintillator pulse-height spectrum. The energy of the group was determined by means of the following procedure: a thin foil of deuterated polyethylene (CD_2) was mounted on that side of the radiator mount normally occupied by the platinum blank, and both this foil and a two-mil foil of Teflon were bombarded alternately with the counter-telescope angle set at zero degrees. In each case the scintillator pulse-height spectrum was recorded. After removing the effects of energy loss by the deuterons in the radiators and counter gas, slight nonlinearity of the electronics and of the NaI(Tl) luminescent energy response,[11] and a slight shift of the effective angle of observation away from the zero-degree axis setting of the spectrometer due to the effect of its finite window,[7] the energy spectrum of Fig. 1 was obtained. Here the energy scale has been normalized to the value 12.53-Mev for the zero-degree elastically

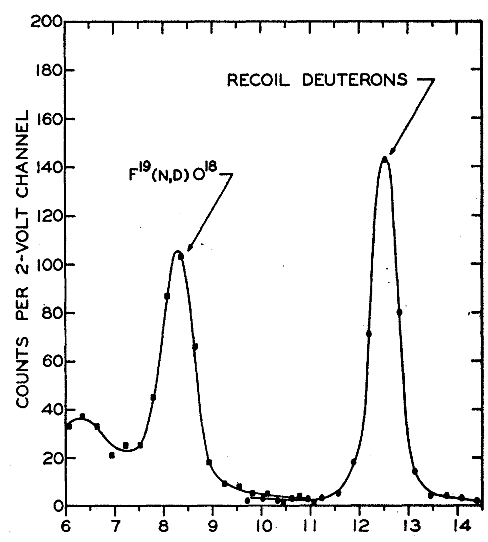

FIG. 1. Energy spectrum of forward D(n,n)D elastic-recoil deuterons and deuterons emitted in the forward direction from the $F^{19}(n,d)O^{18}$ ground-state reaction.

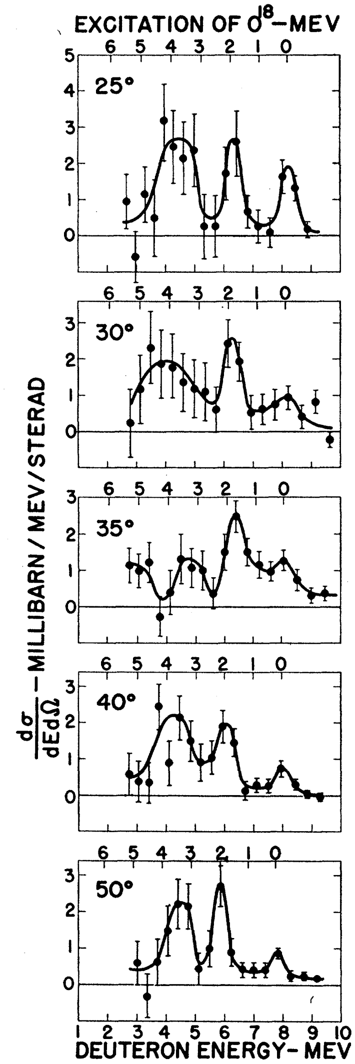

FIG. 2. Energy spectra of deuterons emitted in various directions from the $F^{19}(n,d)O^{18}$ reactions.

[10] G. Igo and R. M. Eisberg, Rev. Sci. Instr. 25, 450 (1954).

[11] J. E. Brolley, Jr., and F. L. Ribe, Phys. Rev. 98, 1112 (1955).

scattered deuterons represented by the peak of higher energy. The result for the Q value of the ground-state reaction $F^{19}(n,d)O^{18}$ is -5.79 ± 0.08 Mev.

For further runs the CD_2 foil was removed, exposing the platinum blank, and a one-mil Teflon foil was used as a radiator. At all telescope angles it was observed that deuteron yields corresponding to excited states of O^{18} were very low, and in order to obtain reasonably accurate data it was necessary to remove competing proton disintegrations from the scintillator pulse-height spectrum by biasing of the dE/dx coincidence channels. In particular, no excited-state group of deuterons of intensity comparable to that of the ground-state group appeared at zero degrees. Typical data giving the deuteron energy spectra at larger angles are shown in Fig. 2. Again the energy scale is corrected, and the ordinate scale is corrected for the fact that equal pulse-height channel widths correspond to unequal deuteron-energy differences due to slight nonlinearity of the electronics and to energy loss by the deuterons in the radiator and counter gas.

Analysis of the data of Fig. 2 gives the value 1.9 ± 0.1 Mev for the excitation energy of the first excited state of O^{18}. In addition there is a wide group of deuterons in the region of excitation from 3 to 4 Mev which appears at all angles.

The experimental values of the differential cross section for the ground-state reaction $F^{19}(n,d)O^{18}$ are plotted *versus* laboratory angle in Fig. 3. Also plotted are theoretical curves for the pickup angular distribution which will be discussed later. In Fig. 4 are plotted the experimental values of the differential cross section for the $F^{19}(n,d)O^{18}$ reaction leading to the 1.9-Mev excited state of O^{18}, along with theoretical angular distributions which will be discussed later. Note that the peak differential cross section for the excited state is lower than that for the ground state by a factor of 14.

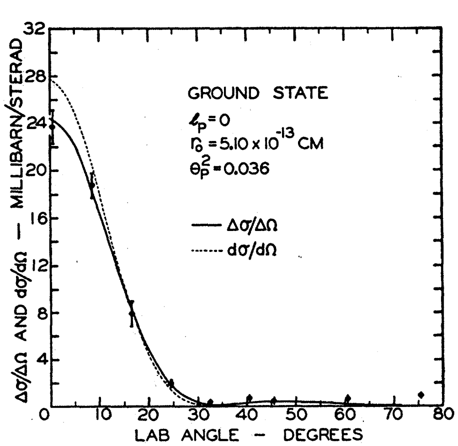

FIG. 3. Experimental and normalized theoretical differential cross sections for the ground-state $F^{19}(n,d)O^{18}$ reaction. The solid curve has been corrected for the effect of the finite aperture of the detector.

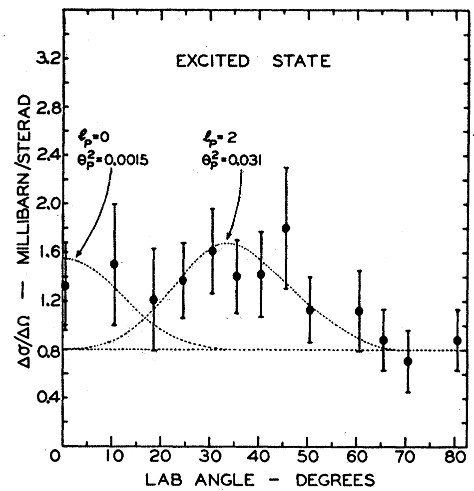

FIG. 4. Experimental and normalized theoretical differential cross sections for the $F^{19}(n,d)O^{18}$ reaction leading to the first excited state of O^{18}.

A careful search was made for ground-state protons from the competing reaction $F^{19}(n,p)O^{19}$ at a counter-telescope angle of zero degrees, and none were observed to within an upper limit of 0.2 millibarn/steradian; although some protons in a continuous spectrum of energies corresponding to excitations in O^{19} of greater than 1.5 Mev were found. At 50 degrees there was a trace of ground-state protons, amounting to about 0.7 mb/sterad.

DISCUSSION OF RESULTS

Although the determinations of the energies of the excited levels of O^{18} indicated in Fig. 2 are not sufficiently accurate to contribute greatly to their quantitative energy assignments, there is nevertheless confirmation of the accurate charged-particle-spectrometer measurements of Jarmie[12] who used the $F^{19}(t,\alpha)O^{18}$ reaction to observe levels with excitations as great as 6.33 Mev in O^{18}. The first level found in the present work corresponds to the well-known level placed by him at 1.99 Mev. The broader group in Fig. 2 between 3 and 4 Mev corresponds to the next two levels found by Jarmie at 3.50 and 3.93 Mev. These levels were unresolved in the present experiment, due largely to the effects of the radiator thickness which was necessary to give an observable yield. Observation of levels whose excitations are greater than that of this unresolved group was made impracticable both by lack of resolution and background. There is no indication of a level at 2.45 Mev as reported in preliminary observations[13] of the $O^{17}(d,p)O^{18}$ reaction.

In order to make spin, parity, and reduced-width assignments for the reactions $F^{19}(n,d)O^{18}$ it is necessary to compare the experimentally determined differential

[12] Nelson Jarmie, Phys. Rev. **104**, 1683 (1956).
[13] Holmgren, Hanscome, and Willett, Phys. Rev. **98**, 241(A) (1955).

TABLE I. Dimensionless reduced widths of the $F^{19}\rightarrow O^{18}+p$ transitions between the ground state of F^{19} and the ground- and first-excited states of O^{18}, assuming various orbital angular momenta l_p for the proton.

Proton orbital angular momentum l_p	State	Reduced width θ_p^2	Relative reduced width
0	Ground	0.036	1.00
0	Excited	$\leq$0.0015	$\leq$0.041
1	Excited	$\leq$0.0068	$\leq$0.19
2	Excited	$\leq$0.031	$\leq$0.87

cross sections with the theoretical expressions for the pickup differential cross section. We have used the expressions given by Thomas[2] on the basis of plane-wave Born-approximation calculations. In Fig. 3 the dotted curve $d\sigma/d\Omega$ is a graph of his expression for an angular-momentum $l_p=0$ of the picked-up proton and nuclear-radius parameter $r_0=5.10\times10^{-13}$ cm. The solid curve $\Delta\sigma/\Delta\Omega$ represents the "smeared" theoretical differential cross section in which account has been taken of the finite window of the counter telescope, according to a procedure discussed elsewhere.[7] It is seen that there is good agreement between the experimental and theoretical angular distributions, as would be expected in the present case where the low atomic number of the target nucleus and high bombarding energy make Coulomb effects almost negligible. Since the ground states of F^{19} and O^{18} are known to have spin $\frac{1}{2}^+$ and 0^+, only s-wave pickup is allowed.

In order to normalize the theoretical differential cross section of Fig. 3 to the experimental data, we have assigned the value 0.036 to the dimensionless reduced width θ_p^2, which is given in terms of the reduced width γ_p^2 by

$$\theta_p^2=(2Mr_0\epsilon/\hbar^2)\gamma_p^2, \qquad (3)$$

where M is the nucleon mass, and $\epsilon=(A_t-1)/A_t$ is the ratio of masses of the final and target nuclei. We shall use this value for the ground-state s-wave reduced width as a standard of comparison for those reduced widths which are found for the transitions to the 1.9-Mev excited state of O^{18}.

The differential cross section for the excited-state reaction shown in Fig. 4 is not as clear-cut as that for the ground-state reaction, owing largely to the low yield. In order to obtain an estimate of the d-wave reduced width and an upper limit for the s-wave reduced width, we have assumed an isotropic "compound nucleus" contribution to the differential cross section, on top of which we have plotted the theoretical expressions for the s- and d-wave differential cross sections with the dimensionless reduced widths 0.0015 and 0.031 respectively, which best represent the data. The assumption is made that interference between the compound-nucleus and single-particle (pickup) terms of the collision-matrix component representing the (n,d) reaction vanish. The justification[2] for this assumption in the case of the present experiment is that the levels of the highly-excited compound nucleus F^{20} are closely spaced compared to the energy spread of the incident neutron beam and that the signs of their reduced-width amplitudes are expected *a priori* to be uncorrelated.

A summary of the experimental results for the reduced widths is given in Table I. The third column gives the values of the reduced widths for s-wave pickup to the ground state of O^{18} as well as the upper limits of the reduced widths found for various assumed angular-momentum values of the picked-up proton in proceeding to the first excited state. As was pointed out in the introduction, these absolute values are not expected to be accurate to better than a factor of four. Therefore in the fourth column we have plotted the more dependable ratios of the experimental reduced widths to that for the s-wave ground-state reaction. From these ratios we see that s- and p- wave transitions to the first excited state are much weaker than the ground-state transition, while the upper limit for the d-wave transition has approximately the same strength. The fact that the corresponding d-wave differential cross section is actually much smaller than that for the ground-state s-wave reaction is accounted for by kinematical effects. This analysis is consistent with an assignment of any of the spins 1^+, 2^+, or 3^+ to the 1.9-Mev excited level of O^{18}.

This spin assignment is also consistent with the theoretical results of Elliott and Flowers[8] whose intermediate-coupling calculations of the even-parity levels of O^{18} result in a ground state with spin 0^+ and a first excited state with spin 2^+ with excitation energy lying between 1.5 and 2.0 Mev. In addition there is remarkable agreement between the theoretical ratio of reduced widths for the ground-state s-wave and excited-state d-wave $F^{19}\rightarrow O^{18}+p$ transitions and the experimental upper limit given in Table I. Elliott[14] has calculated this reduced-width ratio on the basis of the mass-18 and mass-19 wave functions of reference 8 for the value $V_c=40$ Mev of the coupling parameter which best fitted all other data and found the value 0.87, in agreement with the experimental upper limit.

In addition to the first excited level of O^{18}, Elliott and Flowers predict a group of three even-parity levels of spins 0, 2, and 4 in the region of excitation from 3 to 4 Mev. The $J=4$ level would be supressed by kinematical effects in a pickup reaction. This assignment is therefore not contradicted either by the present results or those of Jarmie[12] if it is assumed that the $F^{19}(t,\alpha)O^{18}$ reaction observed by him also proceeds predominantly by proton pickup. Unfortunately the present data on these higher excited states are not of sufficiently good quality to allow

[14] J. P. Elliott (private communication).

quantitative comparison with the reduced-width ratios of 0.36 and 0.12 calculated by Elliott for the $J=0$ and $J=2$ excited states. Qualitatively the second value is in agreement with the size of the differential cross section which was observed, but the first value would appear to be too high, since there was no clear indication of an excited state in this region of excitation at a laboratory deuteron angle of zero degrees.

ACKNOWLEDGMENTS

We are indebted to Dr. J. P. Elliott for communicating the results of his theoretical calculations of the reduced-width ratios referred to above and to the late Dr. R. G. Thomas for discussions of various theoretical aspects of the present experiment. In addition we thank Mr. R. W. Davis for indispensable aid in performing the experiment.

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Nuclear Spin-Orbit Energy for Oscillator Wave Functions*

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Matrix elements of the two-body spin-orbit interaction between two-nucleon states in LS coupling are expressed in a convenient form which is particularly suitable for oscillator wave functions. The interaction between an almost-closed shell and an external inequivalent nucleon is also considered.

1. INTRODUCTION

THE tensor operator methods of Racah[1] have been used to evaluate the matrix elements of two-body noncentral nuclear forces between antisymmetric LS-coupling states arising from two inequivalent nucleons[2–6] and for configurations involving almost-closed shells.[7] The results obtained expressed the elements of the energy matrix in terms of radial integrals and their coefficients, the radial dependent terms of the operator being first separated from the remainder.

In this paper we obtain expressions for the elements of the radial-orbit amplitude matrix of the spin-orbit operator in which the radial terms are not entirely separated from the orbital coefficients. It is shown that this approach leads to a gain in simplicity of form, and that the elements are not unduly difficult to evaluate. The true two-nucleon case is considered first, and some results for configurations involving almost-closed shells are derived later.

In the course of this work we evaluate single-nucleon amplitude elements for the tensor operators R^1 and P^1 with oscillator wave functions.

* Much of this work was carried out at the University of Southampton, Southampton, England, and forms part of the writer's Ph.D. thesis.

[1] G. Racah, Phys. Rev. **62**, 438 (1942).

[2] J. P. Elliott, Proc. Roy. Soc. (London) **A218**, 345 (1953).

[3] L. W. Longdon, Phys. Rev. **90**, 1125 (1953).

[4] J. Hope, Phys. Rev. **89**, 884 (1953).

[5] J. Hope and L. W. Longdon, Phys. Rev. **101**, 710 (1956), referred to as I.

[6] J. Hope and L. W. Longdon, Phys. Rev. **102**, 1124 (1956), referred to as II.

[7] The term "almost-closed shell" as used in this paper implies a shell closed except for a single vacancy.

2. SPIN-ORBIT OPERATOR

We begin by recalling some results in II.

Apart from the intrinsic spin[8] and isotopic spin[9] dependences, the two-nucleon spin-orbit operator is of the form $J(r_{12})L^1$, in which $J(r_{12})$ is a distance function and L^1 is a two-nucleon tensor operator.

It is convenient, following the methods used in nuclear central force calculations, to expand the distance function

$$J(r_{12})=\sum_{k=0}^{\infty} J_k(r_1,r_2)(C_{(1)}{}^k\cdot C_{(2)}{}^k) \tag{1}$$

in terms of the radius vectors of the individual nucleons and scalar products of the single-nucleon tensor operators C^k. In this the radial and orbital components of the function are separated.

The operator L_1 can be expressed

$$L^1=-i\sqrt{2}\sum_{s,t=1}^{2}(R_{(s)}{}^1\odot{}^1P_{(t)}{}^1), \tag{2}$$

in which the single-nucleon tensor operators R^1 and P^1 are constructed from the Cartesian components of the individual nucleon position and momentum vectors. Each of the operators R^1 and P^1 contain both radial and orbital components, so that the radial component of the operator L^1 is not separate. The tensor product $\odot^k$ is defined in I.

[8] An expression for the amplitude elements of the spin-orbit intrinsic spin operator is quoted in II.

[9] The elements of the isotopic spin operator for neutral, symmetric, and charged dependences are given in I.