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Differential Cross Sections for $O^{16}(d,n)F^{17}$†

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The absolute differential cross sections for neutrons from the $O^{16}(d,n)F^{17}$ reaction which leave F^{17} in its ground and first excited state (0.5-Mev) level have been obtained using a gas-recoil fast neutron spectrometer and CO_2 gas targets. The estimated target thickness was about 150 kev and the average bombarding energy at target center was 5.02 Mev. An $L_p=2$ distribution has been found for the ground state and an $L_p=0$ distribution for the 0.5-Mev level with the following c.m. differential cross sections in mb/sr at peak: 27 and 138 with estimated uncertainties of $\pm15\%$. The dimensionless reduced width θ^2 obtained from the differential cross section for neutrons which leave F^{17} in its ground state was approximately 0.025. Agreement of theoretical curves with the experimental points was poor at small angles. The value of θ^2 for the 0.5-Mev level was found to be 0.15 employing a curve fitting technique modification suggested by Macfarlane and French. Since C^{12} was present in the target, laboratory system differential cross sections at 0°, 20°, and 30° for the $C^{12}(d,n)N^{13}$ reaction (2.37-Mev) level are reported.

I. INTRODUCTION

In a recent review article Macfarlane and French[1] have directed attention to the extraction of reduced widths from stripping theory. Of the light nuclei, the system O^{16}+nucleon would represent a nucleus the levels of which would be expected to have reduced widths close to values based on an extreme single-particle model. Reduced widths for the $O^{16}(d,n)F^{17}$ reaction do not appear in reference 1 since absolute cross sections for this reaction are lacking. In addition to studying the similarity of F^{17} levels to a single particle picture, the suggestion has been made that for several nuclei immediately above O^{16} in atomic weight, information about reduced widths could be gained by measurements of absolute cross sections relative to $O^{16}+d$ cross sections.[2] In the present work $O^{16}(d,n)F^{17}$ differential cross sections have been measured for neutrons which leave F^{17} in its ground and first excited states.

Macfarlane and French have pointed out difficulties in assigning a reduced width from simple stripping theory to the F^{17} first excited state since this state is nearly unbound and the capture is $L_p=0$. The theoretical angular distributions are then very sensitive to the choice of interaction radius r_0 and point of normalization of experimental and theoretical angular distributions. This sensitivity leads to a considerable uncertainty in evaluating the dimensionless reduced width θ^2. A method is suggested in reference 1 of modifying the simple Butler-Born approximation theoretical angular distribution by inclusion of what is effectively a Coulomb correction. In addition to the study of the relative probability of binding an $s_{\frac{1}{2}}$ or $d_{\frac{5}{2}}$ nucleon to the O^{16} core, some interest possibly attaches to checking once again the validity of the modification of the simple Butler-Born approximation theory. A good fit to the experimental angular distribution using the modified procedure would lend credence to the reduced width extracted.

An incidental incentive to measuring the $O^{16}(d,n)F^{17}$ reaction cross sections is the provision of a very convenient secondary calibration standard for neutrons in an energy region not conveniently reached by the $D(d,n)He^3$ reaction and where the target problems encountered in calibration with the $T(p,n)He^3$ reaction are not justified.

II. EXPERIMENTAL PROCEDURE

The absolute differential cross section for neutrons from the $O^{16}(d,n)F^{17}$ reaction which leave F^{17} in its ground and first excited states (0.5-Mev level) have been obtained using a gas-recoil fast neutron spectrometer[3] and carbon dioxide gas targets. Carbon dioxide was chosen instead of oxygen to preserve the foil. The spectrometer was set up at laboratory angles of 0°, 20°, 30°, 45°, 60°, 90°, and 120° with the beam direction. CO_2 targets were bombarded by a deuteron beam whose energy at target center was estimated to be 5.02 Mev. The estimated target thickness was about 150 kev. Backgrounds were taken with hydrogen in the target chamber. The calibration was done with the $D(d,n)He^3$ reaction. $\bar{E}_d$ was obtained from nuclear magnetic resonance measurements of the analyzing magnetic field through which the deuterons passed and from estimated stopping losses in the nickel foil and CO_2 in the target cell.

The principal uncertainties introduced in the measurement were (1) sensitivity of spectrometer efficiency to angle at the large angle used in the $D(d,n)He^3$ calibration to obtain neutron energies similar to those encountered in the run, (2) approximations in formula (2) of reference 3 when calculating the dependence of spectrometer efficiency on neutron energy, (3) relatively crude pressure measurements in the target cell, (4) un-

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[1] M. H. Macfarlane and J. B. French, Revs. Modern Phys. 32, 567 (1960).
[2] B. J. Raz (private communication to L. J. Lidofsky).
[3] R. E. Benenson and M. B. Shurman, Rev. Sci. Instr. 29, 1 (1958).

certainty in $\bar{E}_d$ to which the spectrometer efficiency is particularly sensitive.

The spectrometer efficiency loss through accidental anticoincidences was measured at each point, and correction was made.

III. EXPERIMENTAL RESULTS

The neutron spectra observed at seven angles of observation by the fast neutron spectrometer are shown in Fig. 1.

The neutron spectra in Fig. 1 are uncorrected for

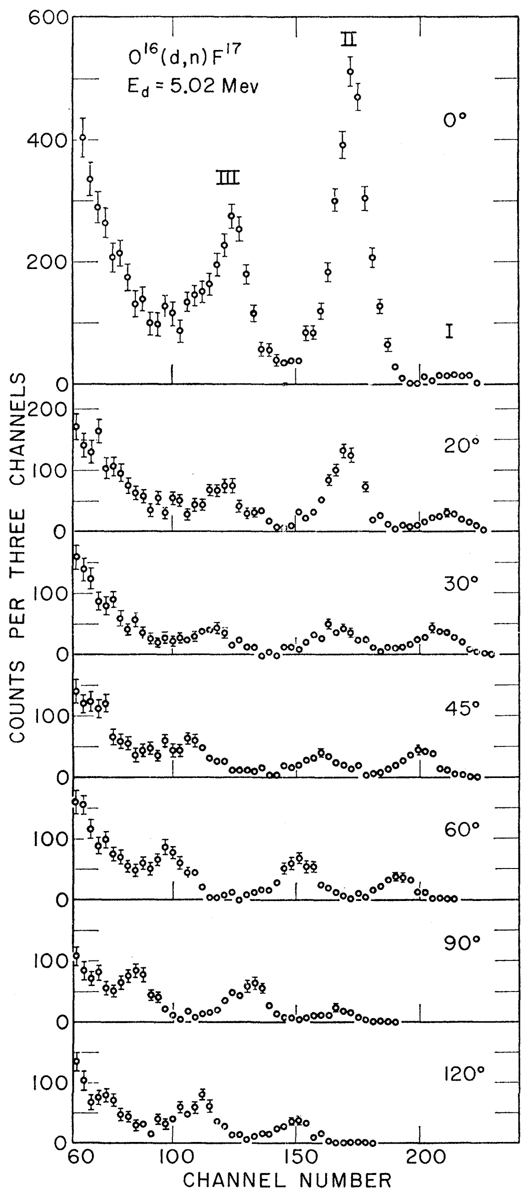

FIG. 1. Neutron spectra at seven angles of observation for reaction $O^{16}(d,n)F^{17}$. The neutron groups I, II, and III correspond to the ground state of F^{17}, 0.5-Mev level of F^{17}, and 2.37-Mev level of N^{13}, respectively.

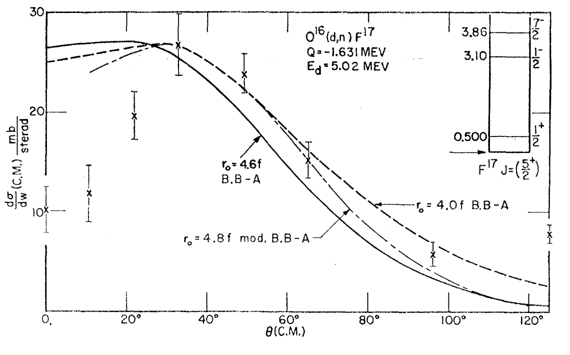

FIG. 2. Angular distributions in center-of-mass system for the ground state. The estimated uncertainties in the ordinate scale factors are $\pm 15\%$. Error bars shown are calculated only from counting statistics. The Butler-Born approximation (B.B-A) theoretical curves are plotted for two values fo r_0 (4.0 and 4.6 fermis) and the modified Butler-Born approximation curve (mod. B.B-A) for 4.8f.

the rapid variation of spectrometer efficiency with neutron energy. The graph represents one of the two complete angular distributions taken under very similar conditions. Groups I, II, and III correspond to the ground and 0.5-Mev levels of F^{17}, and to the 2.37-Mev level of N^{13} from the reaction $C^{12}(d,n)N^{13*}$. A brief second run at angles of observation 0° and 10° only was made at a later date to fill in the angular distributions.

Figure 2 shows the angular distribution obtained for neutrons which correspond to the ground state of F^{17} after correcting for the spectrometer efficiency variation with neutron energy-angle dependence. This angular distribution corresponds to $L_p=2$ capture as has been previously reported.[4] The 10° point was normalized to the zero-degree point, and the error bar at 10° includes a normalization error. The absolute differential cross section at peak in c.m. was found to be 26.7 ± 4 mb/sr. Errors in absolute cross section are estimated to be

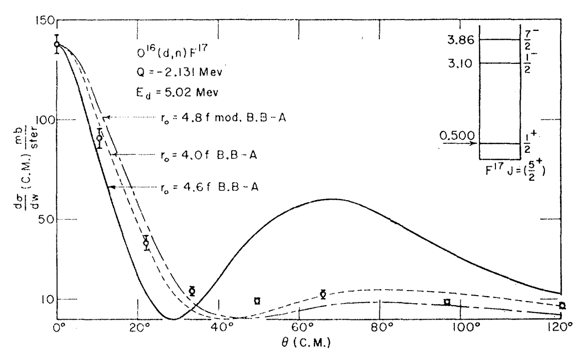

FIG. 3. Angular distribution in center-of-mass system for the 0.5-Mev level. The estimated uncertainties in the ordinate scale factors are of the order of 15%. Error bars shown are calculated only from counting statistics. The right side of the graph shows the low lying levels of F^{17}. The unmodified Butler-Born approximation (B.B-A) curves are drawn for $r_0=4.0$ and 4.6f. The modified (mod. B.B-A) theoretical curve is drawn for $r_0=4.8$f.

[4] F. Ajzenberg-Selove and T. Lauritsen, *Energy Levels of Light Nuclei* VI, *Z=1 to 10* (North-Holland Publishing Company, Amsterdam, 1959).

$\pm 15\%$, while errors in relative cross sections are estimated at less than 2% between adjacent points.

Figure 3 shows the angular distribution obtained for the first excited state (0.5-Mev level) of F^{17} with the same remarks as above applying about the corrections for spectrometer efficiency and inclusion of the 10° point. The absolute differential cross section at peak in c.m. was found to be 138 mb/sr with an estimated uncertainty of $\pm 15\%$.

The laboratory system differential cross sections for the $C^{12}(d,n)N^{13}$ reaction with N^{13} left in its 2.37-Mev level were obtained by fitting the group III peaks of Fig. 1 with a monoenergetic spectrum shape. The cross sections at 0°, 20°, and 30° with estimated uncertainties are, respectively: 70 ± 14 mb/sr, 18.0 ± 3.6 mb/sr, and 8.1 ± 1.6 mb/sr.

IV. DISCUSSION OF RESULTS

The first attempts to fit the experimental angular distributions prior to extracting reduced widths were made by direct application of the simple Butler-Born approximation theory with numerical values from Lubitz's tables.[5] For the ground state, as shown in Fig. 2, the shape of the $L_p=2$ angular distribution is relatively insensitive to the choice of r_0, and no reasonable choice within rather wide limits corresponds to a good fit at small angles. Two such theoretical angular distributions for $r_0=4.0$f and $r_0=4.6$f are shown on Fig. 2. Distributions for other $r_0=4.2$, 4.4, and 4.8f were no more encouraging. Reduced widths θ^2 were calculated from formula II.29 of reference 1 from the experimental differential cross section at peak. As r_0 was increased from 4.0f to 4.8f when evaluating $\sigma_{\mathrm{TAB}}{}^l r_0{}^3$ in the formula, θ^2 decreased from 0.034 to 0.024, a relatively small change. As a "best" value for θ^2 the value 0.025 is chosen as corresponding to an r_0 of around 4.7f associated with mass numbers near 16.

In the case of the 0.5-Mev level a quite good fit to the experimental angular distribution can be obtained for $r_0=4.0$f using simple theory as shown on Fig. 3, but the agreement between theory and experiment rapidly gets worse as r_0 is increased, particularly at the second maximum. A representative distribution for $r_0=4.6$f is shown on Fig. 3. Unless the O^{16} core corresponds to an extremely compact assemblage of nucleons and Coulomb effects are unimportant, such a small value of r_0 as 4.0f is inconsistent with values usually assumed for nuclei of mass numbers in the vicinity of $A=16$. Values of θ^2 calculated for the experimental differential cross section at 0° as r_0 was increased from 4.0f to 4.8f in 0.2f steps were 0.27, 0.35, 0.49, 0.78, and 1.07.

As Macfarlane and French point out, an $L_p=0$ nearly unbound state is unlikely to yield meaningful values of θ^2 because of the sensitivity of this quantity to $r_0{}^2$. They suggest a modification to the simple theory, summarized in formulas II.39 and II.40 of reference 1, which gave a good fit to earlier $O^{16}(d,n)F^{17}$ data using a more typical value of r_0. The modification amounts effectively to a Coulomb correction. Angular distributions based on this correction were calculated for nuclear radii of 4.6 and 4.8f. The theoretical curve for 4.8f provides a slightly better fit to experiment and is shown on Fig. 3. As can be seen from Fig. 3, the fit at the secondary maximum is much improved but is not as satisfactory as the 4.0f simple-theory curve at forward angles. The value of θ^2 from the modified theoretical angular distribution with $r_0=4.8$f is now 0.15. Assuming that the true value of θ^2 lies between 0.15 and 0.27, from the unmodified theoretical curve giving the best fit, the ratio $\theta^{*2}/\theta^2 \gtrsim 5$, larger than expected for a pure single-particle $d_{\frac{5}{2}}$ state.

For the F^{17} left in its ground state the shape of the modified theoretical angular distribution agrees slightly better with the experimental points than does the unmodified, as can be seen on Fig. 2, but the fit is not good. A more fundamental modification in stripping theory still seems necessary.

Since the $C^{12}(d,n)N^{13}$ reaction leads to N^{13} left in an unbound level, the likelihood of extracting reduced widths from present stripping theory seemed unlikely and was not attempted.

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[5] C. R. Lubitz, "Numerical table of Butler-Born approximation stripping cross sections," University of Michigan Report, Lansing, Michigan, 1957 (unpublished).