Reprinted from THE PHYSICAL REVIEW, Vol. 133, No. 2B, B350–B352, 27 January 1964
Printed in U. S. A.

Some (d,α) Reactions on Be^9, F^{19}, and Al^{27} at 27.5 MeV*

S. MAYO, J. TESTONI, AND O. M. BILANIUK†
Comisión National de Energía Atómica, Buenos Aires, Argentina

(Received 3 September 1963)

The angular distributions of absolute cross sections were measured for (d,α) reactions at 27.5 MeV leading to the following final states: 4.63 and 7.47 MeV in Li^7; ground and 0.872 MeV in O^{17}; ground, 1.61 and 3.399 plus 3.408 MeV in Mg^{25}. Measurements were carried out in the angular range from 15 to 120 lab deg, in 5-deg intervals for the forward, and 10-deg intervals for the backward hemisphere. A solid-state detecting system with a resolution in energy of about 1% was used. The angular distributions show pronounced forward peaking. Comparison is made with cross sections computed, in plane-wave Born approximation, for double pickup and knockout mechanisms.

1. INTRODUCTION

AMONG the deuteron induced reactions, the (d,α) reaction belongs to the category which still requires extensive experimental and theoretical work before definite conclusions as to its reaction mechanism can be drawn. Although considerable progress has been made in the interpretation of (d,α) data, many questions such as clustering of deuterons in the nuclear surface region, and the interplay of the different possible modes of reaction, remain unanswered. A detailed comprehension of the reaction mechanism and its dependence on energy is required to interpret fully the results of a number of experiments performed both at low and intermediate energies on light and heavy elements.[1]

The present report describes a partial extension to higher energies of earlier work[1] performed on light nuclei. The angular distributions are fitted with plane-wave Born approximation (PWBA) curves resulting from el Nadi's double stripping formalism which assumes the deuteron and the alpha as structureless particles.[2] A comparison with Butler-type curves[3] shows that fits similar to those mentioned above result both for pickup or a knockout process.

2. EXPERIMENTAL PROCEDURE

The 27.5±0.1-MeV magnetically collimated deuteron beam from the 180-cm Buenos Aires synchrocyclotron has been used to bombard thin foils of beryllium, Teflon, and aluminum. The beam was shaped by two pairs of magnetic quadrupoles to a spot 4 mm in diameter and about 0.02 μA in intensity on the target, located about 7 m away from the accelerator. The beam collecting Faraday cup, maintained at a vacuum better than 10^{-5} mm Hg, included a permanent magnet to avoid the leakage of secondary electrons from the beam stopper. The collected beam was electronically integrated to a prefixed amount, after which the counting was automatically stopped. The whole integrating system was checked by an array of tested leakage-free polystyrene capacitors charged to a calibrated voltage. The error in the charge collection was below 1.5%.[4]

The targets were mounted on a frame at 45±0.5 deg to the beam direction. Target thicknesses were determined by weight and area measurement, resulting in the following figures: beryllium target, 2.25±0.10 mg/cm²; Teflon target, 1.13±0.04 mg/cm²; aluminum target 0.28±0.03 mg/cm². Beryllium and aluminum targets were of commercial grade, 99.5% pure. The aluminum target was evaporated on a plastic film which was subsequently dissolved away. Measurements were done on several targets for each element, especially in the case of the Teflon target, which is known to melt under bombardment at lower energies. The 27-MeV deuteron beam loses less than 0.1 MeV in the target, and no change in yield was observed even after long exposures.

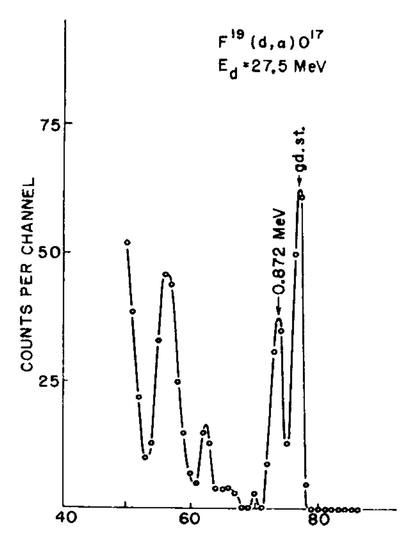

FIG. 1. Typical pulse-height spectrum of α particles from the reaction $F^{19}(d,\alpha)O^{17}$ at 50° in the laboratory system (56° center-of-mass). The alpha groups leading to the ground and first excited state of O^{17} are labeled. The corresponding angular distributions are shown in Fig. 3.

* Work performed under the auspices of Consejo Nacional de Investigaciones Científicas y Técnicas, Argentina.

† On leave from the Department of Physics and Astronomy, University of Rochester, Rochester, New York.

[1] K. Takamatsu, J. Phys. Soc. Japan **17**, 896 (1962), and references therein.

[2] M. el Nadi, Phys. Rev. **119**, 242 (1960).

[3] S. T. Butler, Phys. Rev. **106**, 272 (1957).

[4] S. Mayo and J. Testoni, Nucl. Phys. **36**, 615 (1962).

The detector used was of a gold-silicon surface barrier type properly biased to keep its sensitive region thick enough for the total stopping of the detected alpha group. Its maximum depletion depth was 0.5 mm. The detector and its collimator, mounted on an arm inside the evacuated scattering chamber, could be rotated from the outside to any scattering angle. The solid angle of detection was 1.2×10^{-3} sr; the angular aperture subtended by the detecting window was ±1 deg.

Pulses were fed into a charge sensitive preamplifier having a signal to noise ratio of about 600. The pulse spectra were analyzed on a Nuclear Data Model-120 analyzer. The over-all energy resolution was 1.0 to 1.2%.

Because of the poor duty cycle (about 5%) of this machine, the beam intensity during the irradiations had to be reduced to a low level in order to keep pileup pulses in the detector within reasonable limits. This is one of the most severe restrictions in the use of a synchrocyclotron when measuring very small cross sections. This circumstance accounts for the high statistical errors (10 to 25%) of the present experiment. A beam debunching device, contemplated for this machine, should improve the situation in future measurements. The zero angle of scattering was checked by letting the direct collimated beam stain a thick slab of glass placed on the movable detector arm. Scattering angles were known with an accuracy of ±1 deg. The energy of the deuteron beam, determined from its range in aluminum, was 27.5 ± 0.1 MeV. Its value remained constant, within the indicated error, throughout the experiment.

3. RESULTS

Figure 1 shows a typical alpha spectrum corresponding to the reaction $F^{19}(d,\alpha)O^{17}$ at 50 deg. The alpha groups corresponding to the ground state and the 0.87-MeV state of the residual nucleus are indicated. These groups were identified both by kinematics and by their energy shift when aluminum absorbers were placed in front of the detector. When appropriate detector bias was used, pulse heights corresponding to alpha groups became appreciably higher than those resulting from deuterons or protons, so that the latter could be suppressed at the analyzer input.

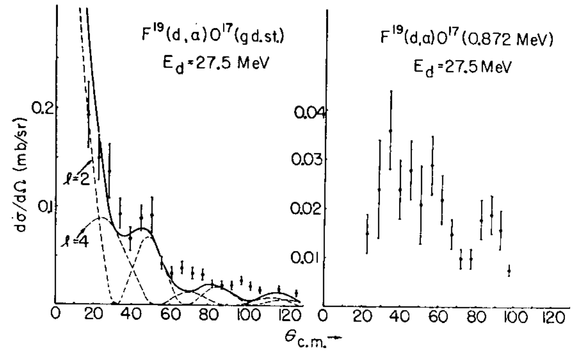

FIG. 3. Angular distributions corresponding to the ground state and the 0.87-MeV excited state in O^{17}.

Figures 2–4 show the angular distributions corresponding to (d,α) reactions on Be^9, F^{19}, and Al^{27} leading to the following final states: Li^7, 4.63 and 7.47 MeV; O^{17}, ground and 0.872 MeV; Mg^{25}, ground and 1.61 MeV. The angular distribution corresponding to the unresolved 3.399–3.408-MeV doublet in Mg^{25} was also measured. It is also forward peaked, with the combined cross section of the order of 0.1 mb/sr in the 30° region and 0.01 mb/sr in the 100° region. The vertical bars on experimental points indicate the absolute errors of differential cross sections due to statistics, background subtraction, target thickness, beam current integration, solid angle, and the instability of the system. Solid lines in each figure are PWBA curves computed by following el Nadi's approach to the double pickup process. Allowed l values used in each case are indicated. The PWBA curves are presented only for reference. Although the fits in most cases are satisfactory, the weight which can be attached to them is limited, since distortion effects have been neglected and the l values required are rather high (up to $l=6$).

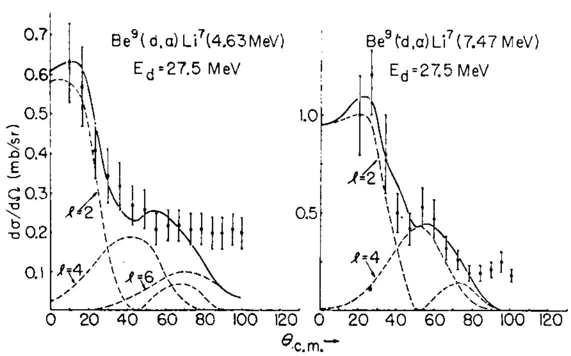

FIG. 2. Angular distribution corresponding to 4.63- and 7.47-MeV excited states in Li^7. The solid line is a fit to the data using el Nadi's formalism for the two-nucleon pickup process. The dashed lines are the contributions corresponding to the different l values.

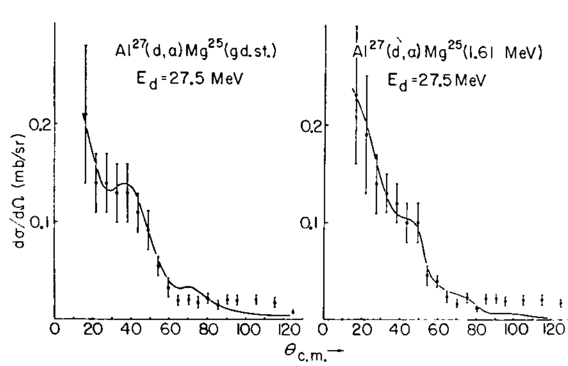

FIG. 4. Angular distributions corresponding to the ground state and the 1.61-MeV excited state in Mg^{25}.

4. DISCUSSION

Most of the present angular distributions show marked forward peaking indicative of a possible direct interaction mechanism. A plane-wave analysis of these data was performed in terms of a double pickup or a knockout process, assuming both the deuteron and the alpha particle to be structureless. Considering first a double pickup reaction mechanism, cross sections were computed from el Nadi's expression for double stripping reactions,[2]

$$d\sigma/d\Omega \propto F^2 \sum_l |A_l|^2[j_l(Qr)]_{r=r_0},$$

where $F^2=[3.07 \exp(-K^2/48\gamma^2) \exp(-K^2/16\gamma^2)]^2$ is a form factor to be determined; $K=k_d-k_\alpha/2$ is the internal momentum of a deuteron in an alpha projectile; A_l are overlap coefficients. $\mathbf{Q}=\mathbf{k}_d m_f/m_i-\mathbf{k}_\alpha$ is the momentum transferred to the residual nucleus; m_i and m_f are initial and final nuclear masses; k_d, k_α are deuteron and alpha wave numbers. l is the angular momentum of the transferred particle; only even l values are permitted here since no change of parity occurs in any of the studied transitions. To evaluate the form factor F^2 the parameter $1/\gamma$ must be adjusted for best fit to the data; at the same time $1/\gamma$ must remain consistent with the intrinsic wave function of the alpha particle and α binding energy. With γ defined by Gaussian $\psi_\alpha\sim\exp(-\gamma^2 \sum r_{ij}^2)$, or exponential $\psi_\alpha\sim\exp[-\gamma \sum_{i>j}(r_{ij}^2)^{1/2}]/(\sum_{i>j} r_{ij}^2)^n$ wave functions,[5] best fits were obtained in different experiments[1,6,7] with $1/\gamma$ ranging from 3 to 6 F. In the present analysis a somewhat smaller value of $1/\gamma=2.2$ F had to be used to obtain satisfactory fits. However, this value is in excellent agreement with the binding energy $\epsilon=28$ MeV of the alpha particle, as can be seen by evaluating $\gamma^2=2\epsilon m_\alpha/2\hbar^2$.

The fits by el Nadi's curves to the (d,α) angular distributions, at the present energy of 27.5 MeV, are surprisingly good. As has already been found for the $Be^9(d,\alpha)Li^7$ case by Ivanyts'kyĭ,[8] the direct reaction mechanism appears to become more important as the bombarding energy increases.

In computing the present curves, it was found that the fits are sensitive to changes as small as 0.1 F. Slightly different r_0 values had to be used for the different l components. The dependence of the fits on such small changes of r_0 may reflect the circumstance that the physical meaning of varying r_0 is that of sensitively changing the strength of the effective interaction potential of the reaction.

A plane-wave analysis of the data in terms of the Butler Wronskian was also performed. The differential cross section is expressed as

$$d\sigma/d\Omega \propto |(Q^2+\kappa^2)^{-1}W[j_l(Qr);h_l^{(1)}(i\kappa r)]_{r=r_0}|^2,$$

where $\kappa=\hbar^{-1}(2m_d{}^*\epsilon_{di})^{1/2}$, and ϵ_{di} is the binding energy of the deuteron in the initial nucleus. Fits were obtained with this expression using interaction radii similar to those needed for el Nadi's curves.

The alternate analysis in terms of a knockout reaction mechanism was also carried out, still using the above expression of the differential cross section. Here $\mathbf{Q}$ and κ are defined as follows:

$$\mathbf{Q}=\mathbf{k}_d(m_i-4)/m_i-\mathbf{k}_\alpha(m_f-2)/m_f,$$
$$\kappa=\hbar^{-1}[(2m_\alpha{}^*\epsilon_{\alpha i})^{1/2}+(2m_d{}^*\epsilon_{df})^{1/2}].$$

$\epsilon_{\alpha i}$ and ϵ_{df} are binding energies of the alpha particle in the initial nucleus, and of the deuteron in the final nucleus, respectively. The momentum transfer ratio for knockout to pickup processes is Q(knockout)/Q(pickup) $=(m_f-2)/m_f$. For Be^9, F^{19}, and Al^{27} this ratio has the values 0.71, 0.88, and 0.92, respectively. The corresponding ratios κ(knockout)/κ(pickup) are 1.20, 1.72, and 2.04. It was found that the difference in the momentum transfer could be compensated by admissible changes in r_0, so that the present data can be interpreted both in terms of the pickup and the knockout mechanisms. A similar inference was made, at the bombarding energy of 13 MeV, by Cindro, Cerineo, and Strzalkowski[9] for the ground-state transition in $F^{19}(d,\alpha)O^{17}$, but they found the pickup process to account more adequately for the (d,α) transition to the first excited state in O^{17}.

In conclusion, it should be pointed out that a distorted-wave Born approximation analysis of the data is required before further conclusions concerning the reaction mechanism in the present cases can be made.

ACKNOWLEDGMENTS

Continued support of this work by Consejo Nacional de Investigaciones Científicas y Técnicas, Argentina, is gratefully acknowledged. Thanks are due to Dr. W. P. Alford, Dr. J. B. French, and Dr. M. H. Macfarlane for useful discussions. The authors are indebted to H. O. Conde for his valuable help in the technical aspects of this work. The authors wish to commend the fine attention of the cyclotron crew throughout the experiment. One of the authors (O. M. B.) wishes to thank the Argentine A.E.C. for its generous hospitality.

---

[5] J. C. Gunn and J. Irving, Phil. Mag. **42**, 1353 (1951).
[6] M. el Nadi, Proc. Phys. Soc. (London) **A70**, 62 (1957).
[7] B. B. Marsh and O. M. Bilaniuk, Phys. Rev. **130**, 2372 (1963).
[8] P. G. Ivanyts'kyĭ, Ukr. Fiz. Zh. **7**, 1160 (1962).
[9] N. Cindro, M. Cerineo, and A. Strzalkowski, Nucl. Phys. **24**, 107 (1961).