Study of the Reactions $F^{19}(\alpha,t)Ne^{20}$ at 18.5 MeV and $F^{19}(He^3,d)Ne^{20}$ at 13.0 MeV*

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Angular distributions from the $F^{19}(\alpha,t)Ne^{20}$ and $F^{19}(He^3,d)Ne^{20}$ reactions have been measured for the particle groups leaving Ne^{20} in its ground state and in its first excited state at 1.63 MeV. A direct interaction mechanism was indicated by the forward peaking and the oscillatory structure of all angular distributions. Butler's stripping theory was applied to the (He^3,d) data and the reduced widths obtained were compared with corresponding $F^{19}(d,n)Ne^{20}$ data. From comparison of the (He^3,d) and the (α,t) cross sections it is suggested that the $F^{19}(\alpha,t)Ne^{20}$ reaction does not proceed by a stripping mechanism.

I. INTRODUCTION

THE (α,t) and (He^3,d) reactions on nuclei have become of increasing interest in recent years. From these reactions one might expect essentially the same information about nuclear level structure as would be obtained from the corresponding (d,n) stripping reaction. Consequently, difficult neutron spectroscopy could be replaced by charged particle spectroscopy.

At sufficiently high energies of the incident He^3 particle, evidence for a stripping mechanism[1–4] has been found for the (He^3,d) reactions. The (α,t) reactions on target nuclei of about $A=60$ and heavier seem also to proceed by a stripping process.[5,6] On the other hand, it is difficult to interpret the (α,t) reactions on *light nuclei* as stripping reactions. By comparing (α,t) reactions with (d,n) stripping reactions on the same nuclei, it has been found that the relative excitation of the levels in the residual nucleus may be quite different in the two reactions.[7,8] This has been interpreted in terms of elementary kinematics[7] as well as in terms of the dispersion theory.[9] The importance of a cluster structure, which would suggest a cluster exchange or knock-out mechanism, has been shown by comparing the $Li^6(\alpha,t)Be^7$ and $Li^7(\alpha,t)Be^8$ reactions[10] and the $C^{12}(t,\alpha)B^{11}$ and $C^{13}(He^3,\alpha)C^{12}$ reactions.[11]

In the experiment reported here the target nucleus F^{19} has been chosen because of its assumed cluster structure $O^{16}+t$. Both the final and the target nucleus are of considerable theoretical interest, because they can be treated in terms of three different nuclear models. In addition to fitting a cluster model[12] they are suitable for detailed shell-model calculations,[13,14] and their level structure can be explained in terms of collective rotational excitations.[15–17]

To obtain information on the $F^{19}(\alpha,t)Ne^{20}$ reaction mechanism, it is insufficient to measure the angular distribution only, since in a surface reaction[18] this depends predominantly on the kinematics and the optical potentials and yields little information on the mechanism involved, i.e., stripping, knock-out, etc. Comparison of the cross sections of $F^{19}(\alpha,t)Ne^{20}$ and $F^{19}(He^3,d)Ne^{20}$ reactions was expected to be useful in this respect. The binding energy of the last proton in the α particle is 19.8 MeV and substantially larger than the corresponding binding energy of 5.5 MeV in the He^3 particle. Considering the $F^{19}(He^3,d)$ reaction to be a stripping reaction, and tentatively assuming a stripping mechanism for the $F^{19}(\alpha,t)$ reaction, one would expect the cross section of the latter to be considerably smaller than that of the former.

II. EXPERIMENTAL METHODS

The external 18.5-MeV α particle and 13.0-MeV He^3 particle beams from the Purdue cyclotron were used for these measurements. The $E-\Delta E$-counter telescope[1] for the detection of the reaction products was attached to a 12-in.-diam target chamber. The geometry and mechanics of the chamber permitted observations of reaction particles at angles of 0° to 155°. Two monitor

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counters were attached to the target chamber at fixed angles of $\pm 30°$ with respect to the incident beam axis. A collimator with an aperture of $\frac{1}{16}$-in. diam was used to define the α beam, and one of $\frac{1}{8}$-in. diam for the He^3 beam. The acceptance angle defined by the aperture of the detector was 2.2° for all measurements.

Commercial targets of Teflon, $(CF_2)_n$, 2.1 mg/cm^2 and 1.4 mg/cm^2 thick, were used for the measurements with the α beam and He^3 beam, respectively. From the Q values it is known that the tritons and deuterons which arise from the (α,t) and (He^3,d) reactions on the carbon nuclei of the target have comparatively low energies and do not interfere with measurement of high-energy groups from the $F^{19}(\alpha,t)$ and $F^{19}(He^3,d)$ reactions.

The counter telescope and the electronic equipment for the particle detection and discrimination was essentially the same as described by Priest *et al.*,[1] except that two pulse stretchers were added to produce simi-

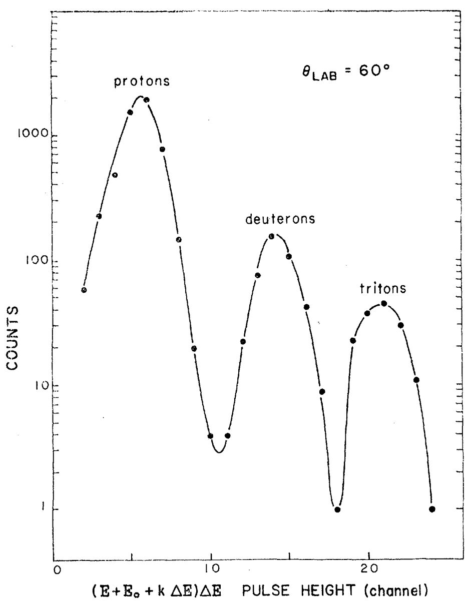

FIG. 1. Typical mass spectrum from Teflon target bombarded by α-particles.

larly square-shaped E (scintillation counter) and ΔE (proportional counter) pulses of 3 μsec at the input of the multiplying circuit. Figure 1 shows a particle spectrum illustrating the separation between protons, deuterons, and tritons.

A detection energy threshold of the counter telescope was given by the condition that a particle, after passing through the proportional counter, had to give a measurable pulse in the CsI counter. The response of CsI(Tl) to tritons, because of lack of direct measurements, has been calculated from the scintillation efficiency.[19] For higher triton energies there is little deviation from the

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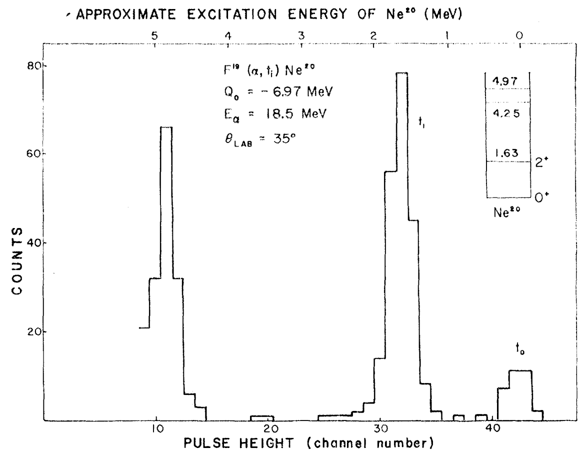

FIG. 2. Typical triton spectrum from $F^{19}(\alpha,t)Ne^{20}$.

linear proton response. The position of the peaks in the triton spectrum from $F^{19}(\alpha,t)$ Ne^{20} calculated in this way agreed well with the experiment. Figure 2 shows a triton spectrum from the reaction $F^{19}(\alpha,t)Ne^{20}$, and Fig. 3 a deuteron spectrum from the reaction $F^{19}(He^3,d)Ne^{20}$.

The performance of the equipment has been checked by gating a 20-channel analyzer with the α-particle group of the $(E+E_0+k\Delta E)\Delta E$ spectrum and measuring the elastic scattering of α particles on gold targets at several forward angles. This cross section was known to be a pure Rutherford cross section[20] at our energies and angles. There was a small deviation from this expected cross section due to multiple scattering losses in the argon-methane gas in the proportional counter, and all cross sections have been corrected for this. These corrections were never larger than 11% and, in most cases, much smaller.

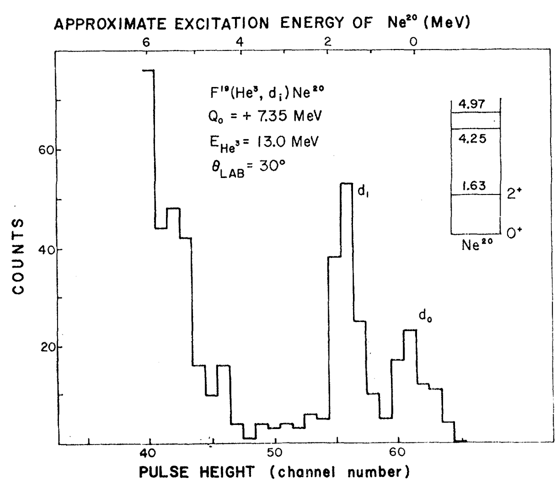

FIG. 3. Typical deuteron spectrum from $F^{19}(He^3,d)Ne^{20}$.

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III. RESULTS AND DISCUSSION

The observed angular distributions are shown in Figs. 4 and 5. The estimated standard errors indicated account for statistics, incomplete resolution, and other sources of random errors. The absolute values of the cross sections have an additional estimated standard error of $\pm 10\%$.

$F^{19}(He^3,d)Ne^{20}$

The angular distributions of the deuteron groups d_0 and d_1 corresponding to the 0^+ ground state and to the 1.63-MeV 2^+ state of Ne^{20}, respectively, are shown in Fig. 4. The forward peaking and the diffraction-type pattern of the angular distributions indicate a direct reaction mechanism. Butler's theory[21] of the (He^3,d) stripping reaction has been applied to the experimental data. The theoretical curves in Fig. 4 are based on Eq. (12.4) of reference 21. The absolute values of these cross sections have been normalized to the first maximum of the corresponding experimental angular distributions. The assignments $l_p=0$ for d_0 and $l_p=2$ for d_1 are unique with respect to the spins and parities[22] of the levels involved. Unusual large values of interaction radii, 7.8F for the d_0 group and 6.6F for the d_1 group, were required. Also the theory predicts values

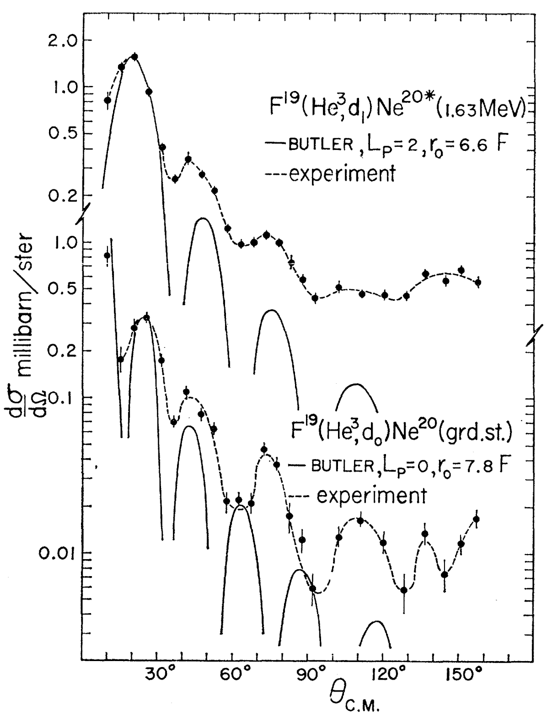

FIG. 4. Angular distributions of deuterons from $F^{19}(He^3,d)Ne^{20}$ at 13.0 MeV. The solid lines were calculated from Butler's stripping theory for (He^3,d) reactions.

[21] S. T. Butler and O. H. Hittmair, *Nuclear Stripping Reactions* (John Wiley & Sons, Inc., New York, 1957).

[22] Landolt-Börnstein, *Energy Levels of Nuclei: A=5 to A=257* (Springer-Verlag, Berlin, 1961), New Series, Group I, Vol. 1.

too low for the cross sections at large angles; this has also been found by Wegner and Hall[3] and by Priest *et al.*[1]

Using the method of Macfarlane and French,[23] the quantity $\Lambda\theta^2$ has been evaluated. For the d_0 group $\Lambda\theta^2=0.19$ F^{-1}, and for the d_1 group $\Lambda\theta^2=0.083$ F^{-1}. The ratio of these two is $\theta^2(d_1)/\theta^2(d_0)=0.44$. The corresponding values[24,25] obtained from the reaction $F^{19}(d,n)Ne^{20}$ are 0.65 and 1.1, respectively. Tentatively assuming the reduced widths θ^2 from our (He^3,d) and the (d,n) measurements[24,25] to be equal, the evaluation of the quantity Λ yields values between 1.3 F^{-1} and 15 F^{-1}, which are seriously smaller than the corresponding value $\Lambda=190$ F^{-1} for (d,t) reactions.[23]

Though the simple stripping theory used here fails to describe the experimental data quantitatively, a more refined analysis of the stripping reaction in terms of distorted waves may be expected to remedy some of these deficiencies.

$F^{19}(\alpha,t)Ne^{20}$

The angular distributions of the t_0 and t_1 triton groups, corresponding to the 0^+ ground state and to the 1.63-MeV 2^+ state of Ne^{20}, respectively, are shown in Fig. 5. Because of the detection energy threshold of the counter telescope mentioned above, the measurements have not been extended to larger angles or to triton groups of lower energy. The forward peaking and the structure of the angular distributions again suggest a direct interaction process. Omitting the form factor for simplicity, Butler's theory[26] of knock-out processes has been applied to the experimental data. The expression given in Fig. 5 is $|W\{j_l(Qr_0),h_l[i(\kappa+\kappa')r_0]\}|^2$ as defined in reference 26. To account for the finite mass of the target nucleus, the corresponding modified expressions for $\kappa+\kappa'$ and $\mathbf{Q}=[(M_i-m_t)/M_i][\mathbf{k}_\alpha-\mathbf{k}_tM_i/M_f]$ have been used. M_i, M_f, m_t are the masses of the initial and the final nucleus and of the triton, respectively; $\mathbf{k}_\alpha$ and $\mathbf{k}_t$ are the momentum vectors of the incoming α particle and of the outgoing triton, respectively. As in the $F^{19}(He^3,d)Ne^{20}$ reaction, the values $l=0$ for the t_0 group and $l=2$ for the t_1 group are fixed by the selection rules for spin and parity. The interaction radii required to fit the experimental data were $r_0=6.2$ F for the t_1 group and an unrealistically large $r_0=10$ F for the t_0 group. A similarly large interaction radius also has been reported for the reaction $Li^7(\alpha,t_0)Be^8$ (ground state).[27]

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TABLE I. Comparison of incident energies and integrated cross sections of the reactions $F^{19}(\alpha,t)Ne^{20}$ and $F^{19}(He^3,d)Ne^{20}$.

Reaction	Ne^{20} level	E_{inc} (MeV)	$\sigma(10°\cdots110°)/(2I_f+1)$ (mb)
$F^{19}(\alpha,t_0)Ne^{20}$	grd.st.(0^+)	18.5	0.64
$F^{19}(\alpha,t_1)Ne^{20*}$	1.63 (2^+)	18.5	0.66
$F^{19}(He^3,d_0)Ne^{20}$	grd.st.(0^+)	13.0	0.51
$F^{19}(He^3,d_1)Ne^{20*}$	1.63 (2^+)	13.0	0.37

Comparison of the $F^{19}(\alpha,t)Ne^{20}$ and $F^{19}(He^3,d)Ne^{20}$ Reactions

The cross sections $\sigma(10°\cdots110°)/(2I_f+1)$ are given in Table I. Here $\sigma(10°\cdots110°)=2\pi\int_{10°}^{110°}\sin\theta_{c.m.}\times(d\sigma/d\Omega)d\theta_{c.m.}$ and $(2I_f+1)$ is the statistical factor, I_f being the spin of the final state in the residual nucleus Ne^{20}. As pointed out in Sec. I, the (α,t) cross section is, in general, expected to be considerably smaller than the (He^3,d) cross section if the (α,t) reaction proceeds by a stripping mechanism. For the discussion of the data of Table I in this respect the energy dependence of the cross sections must be considered. For the (He^3,d) stripping reaction, one expects, from elementary plane wave theory, a smooth decrease of the integrated cross sections with increasing primary energy at energies well above the Coulomb barrier. Experimental data at these energies are available only for the reaction $C^{12}(He^3,d)N^{13}$, which has been measured at 14, 21, and 24 MeV.[1,3] The cross sections here show qualitatively the expected behavior. For (α,t) reactions, the energy dependence is known only for the reaction $Li^7(\alpha,t)Be^8$, which has been measured at several energies between[27] 8 and 15 MeV and at 40 MeV.[8] Again, the cross sections decrease very weakly with increasing energy. One may expect that this energy dependence holds also for the reactions considered here. Then the high cross sections of the reaction $F^{19}(\alpha,t)Ne^{20}$, as shown in Table I in comparison with the $F^{19}(He^3,d)Ne^{20}$ cross sections, might be an indication that the $F^{19}(\alpha,t)Ne^{20}$ reaction does not proceed by a stripping mechanism but rather by a cluster exchange process.

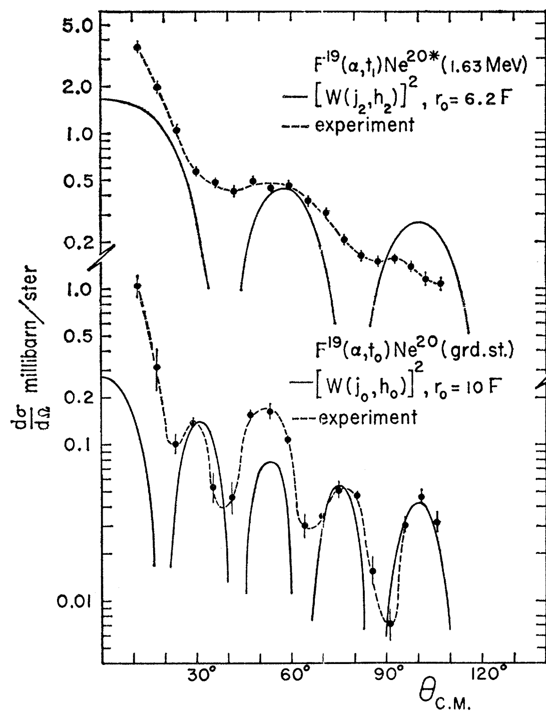

FIG. 5. Angular distributions of tritons from $F^{19}(\alpha,t)Ne^{20}$ at 18.5 MeV. The solid lines were calculated from Butler's theory of knockout processes, but the form factor has been omitted.

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