Allowing for S^{32} and P^{31} a contribution of about 20% of other configurations, we have to expect the same also for the closed shell nuclei O^{16} and Ca^{40}. The observed $l=2$ transition leading to the K^{39} 2.53-MeV state is an additional evidence that the Ca^{40} ground state is not a pure closed shell state.

(4) The first excited state of Si^{30} ($J=2^+$, $E=2.24$ MeV) as well as the second excited state of P^{31} ($J=\frac{5}{2}^+$, $E=2.23$ MeV) are $d_{\frac{5}{2}}$ hole states.

(5) It is somewhat surprising and not well understood that in the cases $F^{19}(d,He^3)O^{18}$ 4.8 MeV, $P^{31}(d,He^3)Si^{30}$ 2.24 MeV, and $S^{32}(d,He^3)P^{31}$ 2.23 MeV, where the proton is picked up from the lower, completely filled orbit, the spectroscopic factors S_{exp} are so low. In the first two cases they contribute only about one-tenth and in the last case about one-fifth to the total sum.

(6) The Mg^{26} ground state ($J=0$) and excited state at 1.83 MeV ($J=2$) are rotational levels of the $K=0$ band. The nature of the state at 2.97 MeV remains unclear.

(7) The probability of finding the deuteron ground state within the He^3 ground state was found to be ~ 0.7.

ACKNOWLEDGMENTS

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Angular Distributions for the $F^{19}(d,n)Ne^{20}$ Reaction*

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Angular distributions of neutrons corresponding to transitions to the ground and first (1.63 MeV) excited states in the reaction $F^{19}(d,n)Ne^{20}$ have been measured at incident deuteron energies of 1.0 and 1.3 MeV. Neutrons were detected using a single stilbene crystal spectrometer. Pulse shape discrimination in stilbene was employed to eliminate background radiation. The angular distributions of the ground-state neutrons were consistent with the predictions of nuclear stripping theory when exchange terms were incorporated in the analysis.

1. INTRODUCTION

THE reaction $F^{19}(d,n)Ne^{20}$ has been studied previously at deuteron bombarding energies of 9.06, 3.57 and 2.17 MeV.[1–3] Analyses of the angular distributions were in each case attempted in terms of nuclear stripping theory. Calvert *et al.*[1] obtained satisfactory fits to the angular distributions corresponding to transitions to the ground state of Ne^{20} in terms of the Butler[4] theory by choosing the value $1_p=0$ for the angular momentum with which the proton is captured. At lower energies[2,3] the data were represented better by choosing $1_p=2$.

Benenson *et al.*[2] have suggested that a study of the energy dependence of the ground-state neutron angular distribution would be desirable to find the crossover from the $1_p=0$ and $1_p=2$ distribution. The purpose of this paper is to report the preliminary results of this study.

In addition to the angular distributions of the ground state and first excited state neutrons, the neutron yields were taken for deuteron energies between 0.65 and 1.3 MeV.

2. EXPERIMENTAL ARRANGEMENT

Two types of targets were used in this experiment. CaF_2 targets were prepared by vacuum evaporation onto a thin nickel backing. The thickness of the evaporated film could be obtained by carefully weighing the target backing before and after evaporation. A typical result of this weighing might be (104 ± 5) μg. The area and density of the films were known so the thickness could be calculated. A crude check on this method was made by examining the width of the resonance peak of the $F^{19}(p,\alpha,\gamma)O^{16}$ reaction. Using the values of the stopping cross section of protons in CaF_2 tabulated by Bader *et al.*,[5] the results of the two thickness determinations were compared.

* Supported in part by the U. S. Atomic Energy Commission.
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[1] J. M. Calvert, A. A. Jaffe, and E. E. Maslin, Proc. Phys. Soc. (London) **A68**, 1017 (1955).
[2] R. E. Benenson, H. Y. Chen, and J. J. Lidofsky, Phys. Rev. **122**, 874 (1961).
[3] S. Morita and K. Takeshita, J. Phys. Soc. Japan, **13**, 1241 (1958).
[4] S. T. Butler, Phys. Rev. **80**, 1095 (1950); Proc. Roy. Soc. (London) **A208**, 559 (1951); Phys. Rev. **88**, 685 (1952).
[5] M. Bader, R. E. Pixley, F. S. Mozer, and W. Whaling, Phys. Rev. **103**, 32 (1956).

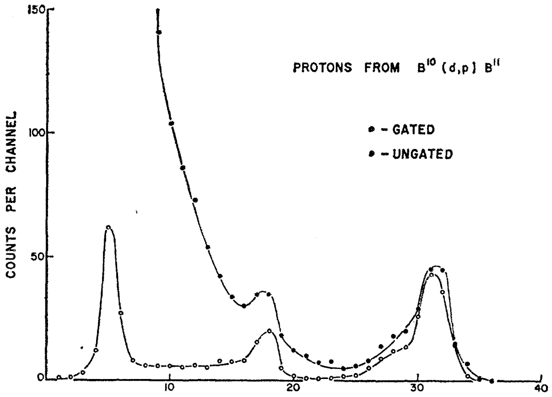

FIG. 1. The proton spectra from the $B^{10}(d,p)B^{11}$ reaction as measured by the stilbene crystal used in the $F^{19}(d,n)Ne^{20}$ problem. The effect of the pulse-shape discriminator is demonstrated by comparison of the gated and ungated outputs.

Some difficulty was experienced in preventing the deterioration of the CaF_2 targets when they were bombarded with the deuteron beam. This difficulty was eliminated by using TaF_5 targets[6] which have an excellent heat resistance. These targets could be made by exposing a clean piece of tantalum to the vapors of hydrofluoric acid. Fluorine was then deposited on the tantalum by chemical action. By careful selection of the geometry and the exposure time, a fairly uniform film of useful thickness could be prepared in a fewminutes. Thickness of the TaF_5 targets could only be obtained from the proton resonance method which was considerably less accurate than the microbalance method. Therefore all data taken with TaF_5 targets were normalized to similar data taken with CaF_2 targets.

Neutrons were detected in a stilbene crystal having a thickness of 1.2 cm mounted on an RCA 6810-A photomultiplier. In order to separate the neutrons from the gamma-ray background accompanying the reaction, a pulse-shape discriminator based on the design of Daehnick and Sherr[7] was constructed.

The effectiveness of the pulse-shape discriminator was tested by using the protons from the $B^{10}(d,p)B^{11}$ reaction. The linear output of the photomultiplier was displayed on a 40-channel pulse-height analyzer. The output of the pulse-shape discriminator was used to gate the analyzer. Figure 1 shows two proton spectra, one taken with the gate on and one with the gate off. It can be seen that the first and second excited state groups were removed from the background. Because the zero of energy in this plot is only slightly suppressed, it may be estimated that the peak in the low channels contained the third excited state group unresolved.

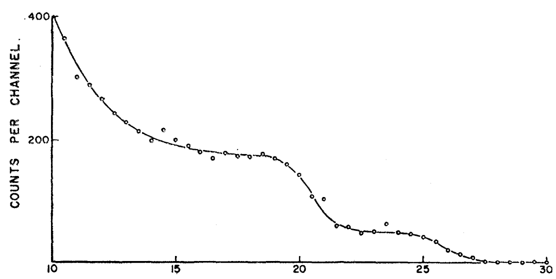

FIG. 2. A sample recoil proton pulse-height spectrum for the neutrons from $F^{19}(d,n)Ne^{20}$ corresponding to a deuteron bombarding energy of 1.3 MeV and a counter setting of zero degrees.

[6] K. N. Clarke (private communication).

[7] W. Daehnick and R. Sherr, Rev. Sci. Instr. 32, 666 (1961).

A more quantitative stimate of the gamma-ray rejection efficiency could be obtained as follows. During the actual experiment, recoil protons of energy less than 5 MeV were never measured; therefore, the discriminator could be set to reject all pulses up to a proton energy of about 4 MeV. An intense beam of 6 or 7 MeV gamma radiation from the 873-keV resonance of the $F^{19}(p,\alpha,\gamma)I^{16}$ reaction was allowed to fall on the crystal. Spectra in the pulse-height region of interest were taken with the analyzer gated and ungated. Gamma radiation rejection ratios of about 1.3×10^3 to 1 were recorded. The total counting rate was about 300 counts per second. This was a higher counting rate than was experienced during the course of the experiment. Daehnick[7] has pointed out that the efficiency of the pulse-shape discriminator will improve at lower counting rates because of the lower probability that two electron pulses will occur simultaneously and hence add

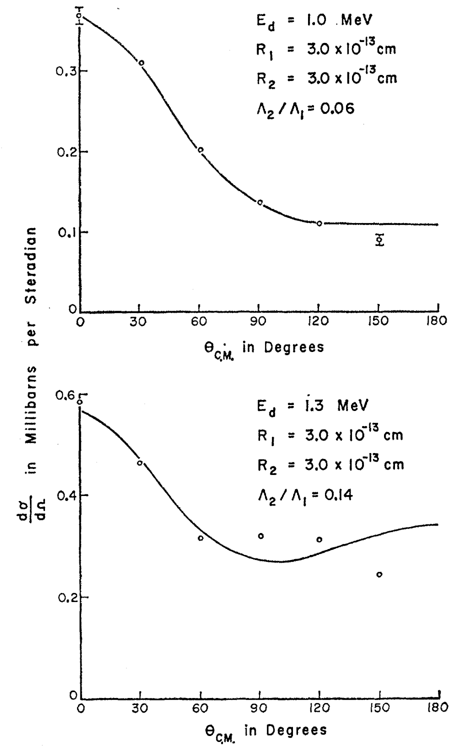

FIG. 3. Angular distributions of the neutrons from the $F^{19}(d,n)Ne^{20}$ ground-state transition at $E_D=1.0$ and $E_D=1.3$.

to appear as a proton. It must be remembered that in the above test the gamma-ray energy is 6 or 7 MeV, while in the $F^{19}(d,n)Ne^{20}$ reaction almost all of the background gamma radiation was below 3 MeV.

3. EXPERIMENTAL PROCEDURE

The deuterons used for the angular distributions and yield curves were obtained from the Johns Hopkins University 1.3-MeV Van de Graaff generator. Angular distributions were measured at bombarding energies of 1.0 and 1.3 MeV. Neutron spectra were obtained every 30 deg from 0° to 150° on both sides of the beam tube.

Beam currents were measured with a current integrator which was later calibrated with reference to an Eldorado Electronics Company C. I.-100 current integrator. The reaction was also monitored by counting the high energy electrons from the beta decay of the F^{20} nucleus which is produced in the $F^{19}(d,p)F^{20}$ channel of the reaction.

Changes in neutron intensity as a function of angle at fixed deuteron energy were normalized to the electron monitor count. However, changes in neutron intensity as a function of energy at the fixed angle (such as in the yield curves) had to be normalized to the current integrator, since the $F^{19}(d,n)F^{20}$ cross section as a function of energy is not known.

The yield curves were taken with the neutron detector located about 3.6 in. from the target. The solid angle subtended with this geometry was 0.118 sr.

Figure 2 shows a typical neutron spectrum taken at zero degrees with a 1.2-cm-thick stilbene crystal. The bombarding energy was 1.3 MeV. Absolute neutron intensities were calculated from spectra such as that in Fig. 2 by the method of Swartz and Owen.[8] Corrections were made for the nonlinear response of stilbene to protons and for the loss of recoil protons at the end of the crystal. Effects of multiple scattering were ignored.

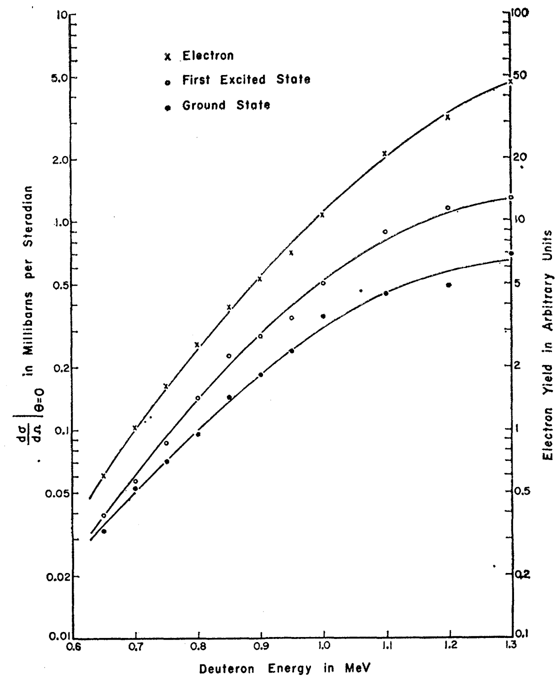

FIG. 5. Yield curve for the ground and first excited states at a counter setting of $\theta=0$ for $F^{19}(d,n)Ne^{20}$ from $E_D=0.65$ to 1.3 MeV.

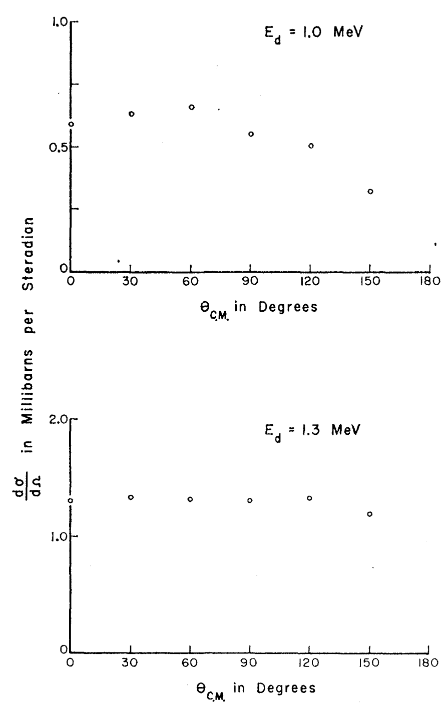

FIG. 4. Angular distributions of the neutrons from the $F^{19}(d,n)Ne^{20}$ first excited state transition at $E_D=1.0$ and $E_D=1.3$.

4. RESULTS AND DISCUSSION

Angular distributions for the ground-state neutron group at 1.0 and 1.3 MeV are shown in Fig. 3. Only statistical errors are shown.

The data were analyzed using the dual-mode stripping theory as given by Edwards.[9] For the heavy particle stripping mode the F^{19} target was described as a F^{18} core plus a single neutron which was then taken to be in an S state.

The forward peaks are consistent with an assignment of an orbital angular momentum capture of $1_p=0$. In the backward direction, the best fit is obtained using a core capture angular momentum of $1_c=0$.

The theoretical curves shown in Fig. 3 were calculated from the expression

$$\frac{d\sigma}{d\Omega}\propto |\Lambda_1C_1G_D(K_1)F_D(k_1R_1)|^2 +23.4|\Lambda_2C_2G_H(K_2)F_H(k_2R_2)|^2 -16.72\Lambda_1\Lambda_2C_1C_2G_D(K_1) \times G_H(K_2)F_D(k_1R_1)F_H(k_2R_2),$$

[8] C. D. Swartz and G. E. Owen, *Fast Neutron Physics* (Interscience Publishers, Inc., New York, 1960), Part I.

[9] S. Edwards, Phys. Rev. **113**, 1277 (1959).

where the notation is that of reference 9. The values of the interaction radii, R_1 and R_2, and the ratio Λ_2/Λ_1 were chosen to provide the best fit to the experimental data.

Figure 4 shows the experimental angular distributions of neutrons leaving the Ne^{20} nucleus in its first excited state. These distributions did not show sufficient character to warrant analysis. They are included for reference only.

Figure 5 shows the neutron yield in the forward direction as a function of deuteron energy from $E_d=0.65$ to 1.3 MeV.

The theoretical angular distributions of neutrons calculated on the basis of the plane wave Born approximation in which exchange effects are included are in good qualitative agreement with the experimental data. Of course, this interpretation of the experimental data is by no means unique. Any plane wave calculation of angular distributions in stripping reactions is subject to the qualification that various effects have been neglected. For a target nucleus as heavy as fluorine, Coulomb effects alone could be significant in explaining one of the principal characteristics of the distribution, i.e., the width of the forward lobe.

However, because of the conflicting results in the literature concerning the gross features of the reaction, it was felt that an effort to fit the smallest details of the angular distribution would be premature. Following the suggestion of Benenson *et al.*[2] an exhaustive but unsuccessful effort was made to fit the experimental data with an entirely different model. A separate plane wave Born approximation calculation was made in which exchange effects were neglected, but the effect of multiple values of proton capture angular momentum was incorporated. The capture angular momentum was given the values of $1_p=0$ and $1_p=2$. The same interaction radius was used in each case, but the magnitude of the interference then was chosen to fit the data. This procedure gave results in conflict with the experimental data. As a result, this approach was abandoned and exchange effects were incorporated in the calculation. The incorporation of the heavy particle stripping mode gave predictions consistent with the experimental observations.

Compound nucleus effects were also neglected in the calculation. The yield curves shown in Fig. 5 seem to indicate that this approximation was justified.

Further experimental work is being carried out at higher energies on both the angular distributions and the neutron gamma-ray correlations corresponding to the first excited state transition.

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Threshold Effect in Elastic Scattering According to the Optical Model*

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An expression is derived for change in the differential elastic scattering cross section caused by the presence of a reaction threshold, in a situation in which it is useful to average over many compound resonances. The derivation is based on the assumptions underlying the optical model and on the usual statistical assumptions made in the evaluation of energy-averaged cross sections. In essence the derivation gives the angular distribution of that part of the fluctuation cross section which is caused by the reaction, and relates this in a simple way to the reaction cross section.

It is shown, although not in a rigorous manner, that for closely-spaced resonances an energy average of the usual Wigner cusp expression, as given by Baz and Newton for example, yields the previously calculated threshold effect on the differential elastic scattering cross sections. Also an expression is given for the threshold effect on the differential elastic scattering cross section in a situation in which the phase shift of each partial wave consists of a part that varies slowly with energy and a part that fluctuates about zero as the energy of the bombarding particle is changed.

For simplicity all calculations are restricted to the case of spin-zero target nucleus and spin-zero and spin-one-half bombarding particle. Furthermore, the derivations assume that only one incident partial wave is dominant in the reaction cross section near threshold. The calculations are applied to recent measurements of Wells, Tucker, and Meyerhof of the differential elastic and inelastic neutron scattering cross sections of cerium in the neighborhood of the threshold for excitation of the 1.60-MeV, 2^+, first excited state of Ce^{140}. It is shown that the computed threshold effect appears to account completely for a marked decrease which had been found in the differential elastic scattering cross section of Ce above 1.60-MeV.

I. INTRODUCTION

RECENT investigation[1] of the elastic differential neutron cross section of cerium has shown a marked decrease in cross section above a neutron energy corresponding to the first excited state of Ce^{140}. Moldauer[2] has interpreted this effect in terms of the optical model and his theory[3] of average neutron reaction cross sections.

The present paper presents a simple calculation of the *change* in the differential elastic cross section caused by

* Supported in part by the U. S. Army Research Office (Durham) and the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.

[1] J. T. Wells, A. B. Tucker, and W. E. Meyerhof (to be published).

[2] P. A. Moldauer (to be published).

[3] P. A. Moldauer, Phys. Rev. 123, 968 (1961).