gible since the total transfer cross section for the O^{16} reaction is smaller than that for C^{12}.[4]

The expectation would certainly be that at higher bombarding energies transfers to excited states would be more probable than at lower incident energies. The data point to the reverse conclusion. We offer no explanation at the present time.

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ACKNOWLEDGMENT

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Measurement of Deuteron Polarization Produced by d-α Scattering at 1.07 Mev

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Elastic scattering from He^4 gas in the energy region of the 1.07-Mev resonance has been used to polarize deuterons. After scattering through 30° in the lab by the polarizer, the polarization of the deuteron beam has been analyzed by the reaction $He^3(d,p)He^4$ near 400 kev. This was accomplished by observing protons at 0° and 90°, and measuring the dependence of the counting rate ratio on the deuteron polarization. $He^3(d,p)He^4$ is well described in this energy region by a single-level Breit-Wigner formula, and therefore has a predictable sensitivity to deuteron polarization. The experimental results are consistent with the magnitude of the polarization component $\langle T_{20}\rangle$ calculated from the $d-\alpha$ phase-shift analysis.

INTRODUCTION

SEVERAL authors have suggested that deuterons elastically scattered from He^4 nuclei should be polarized, both at energies near the 1.07-Mev 3^+ resonance,[1,2] and at higher energies.[3,4] The phase shifts used to make the low-energy polarization predictions were obtained from experimental backward hemisphere differential cross-section measurements.[5] Figure 1, reproduced here for convenience, shows the results obtained in reference 1 for the expected differential cross section and deuteron polarization components at a deuteron scattering angle of 45° in the center-of-mass system, or 30° in the lab system. The "vector" polarization $i\langle T_{11}\rangle$ has been observed through the analyzing reaction $Li^6(d,\alpha)He^4$, and found to have an energy dependence consistent with Fig. 1.[6] The magnitude of $i\langle T_{11}\rangle$ has not been verified because no calibrated analyzer has been available. It was first pointed out by Galonsky *et al.*,[7] however, that the reaction $He^3(d,p)He^4$ should serve as a calibrated analyzer for the components $\langle T_{20}\rangle$, $\langle T_{21}\rangle$, and $\langle T_{22}\rangle$, because a broad single-level resonance dominates the cross section near 400 kev. In this experiment we use the He^3 reaction to check the magnitude and energy dependence of $\langle T_{20}\rangle$.

The quantum numbers for the $He^3(d,p)He^4$ resonance near 400 kev are ${}^4S_{3/2}\rightarrow{}^2D_{3/2}$, giving an isotropic unpolarized cross section.[8] The angular distribution of protons in the center-of-mass system for incident polarized deuterons then follows from the general formula of Simon,[9] and is

$$d\sigma/d\Omega=\tfrac{1}{6}\lambda\!\!\!^{-2}|S|^2\{1-\tfrac{1}{4}\sqrt{2}\langle T_{20}\rangle'(3\cos^2\theta-1)\\ -\sqrt{3}\langle T_{21}\rangle'\sin\theta\cos\theta\cos\phi\\ -\tfrac{1}{2}\sqrt{3}\langle T_{22}\rangle'\sin^2\theta\cos2\phi\}, \quad (1)$$

where S is a single-level resonance matrix element.[10] The primed polarization quantities are linear combinations of the first reaction components shown in Fig. 1, for they are quantized along the incident z axis of the *second* reaction; θ and ϕ are the usual polar and azimuthal angles for the second reaction, with xz plane lying in the plane of the first scattering. In this experiment the beam is scattered through 30° to the left in the laboratory by the "polarizer," and hence the new z axis is at an Euler angle $\beta=+30°$ in the original xz plane. If we ignore the small components $\langle T_{21}\rangle$ and

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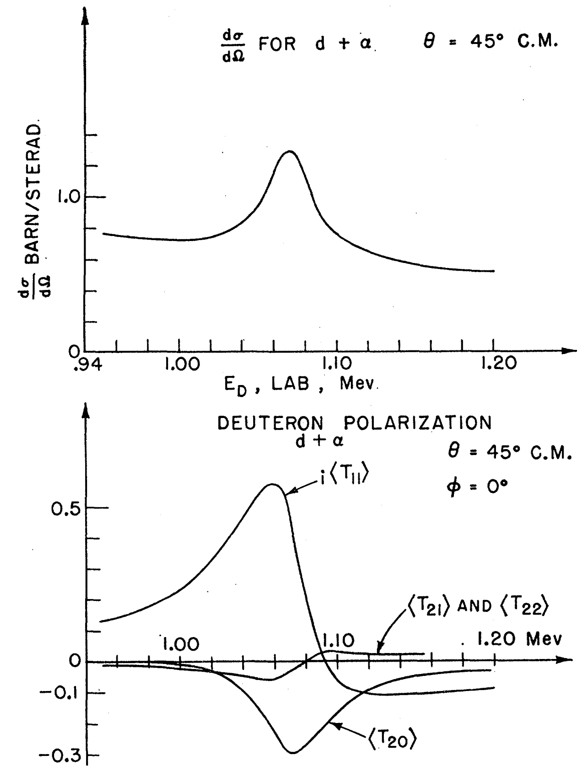

FIG. 1. Differential cross section and polarization for deuterons in $d-\alpha$ scattering, reproduced from reference 1. The polarization components are defined in terms of the spin components as follows: $\langle T_{11}\rangle = -\frac{1}{2}\sqrt{3}\langle N\rangle$, $\langle T_{20}\rangle = \frac{1}{2}\sqrt{2}\langle 3S_z^2-2\rangle$, $\langle T_{21}\rangle = -\frac{1}{2}\sqrt{3}\langle NS_z+S_zN\rangle$, and $\langle T_{22}\rangle = \frac{1}{2}\sqrt{3}\langle N^2\rangle$, where $N \equiv S_x+iS_y$. The quantization axis is the incident beam z direction.

$\langle T_{22}\rangle$ and apply the rotation matrix only to $\langle T_{20}\rangle$, we obtain

$$d\sigma/d\Omega = \tfrac{1}{6}\lambda\!\!\!^{-2}|S|^2\{1-[\tfrac{5}{32}\sqrt{2}(3\cos^2\theta-1) + \tfrac{3}{8}\sqrt{6}\sin\theta\cos\theta\cos\phi + \tfrac{3}{32}\sqrt{2}\sin^2\theta\cos 2\phi]\langle T_{20}\rangle\}. \quad (2)$$

This equation shows that the isotropic unpolarized cross section now has an angular dependence proportional to $\langle T_{20}\rangle$. If the deuteron energy is varied over the polarizing $d-\alpha$ resonance, the angular dependence of the analyzing reaction will resonate with $\langle T_{20}\rangle$. The energy dependence of the $He^3(d,p)He^4$ cross section itself is all contained in the factor $\lambda\!\!\!^{-2}|S|^2$. The narrow resonance in the polarizing reaction and the energy independence of the analyzing reaction suggest the experimental technique.

EXPERIMENTAL EQUIPMENT

Figure 2 shows the experimental configuration. The He^4 scattering chamber, or "polarizer," was identical to the one used in the vector polarization measurements described in detail in reference 6. The Ni windows for the incident beam were cooled with the target gas.[11]

[11] M. J. Scott and R. Lindgren, Rev. Sci. Instr. 28, 1090 (1957).

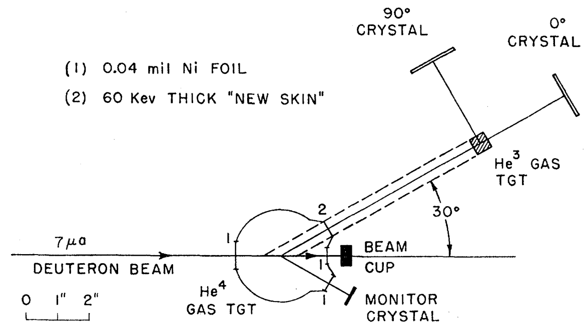

FIG. 2. Gas target setup for the double-scattering measurements. The He^4 "polarizer" is described in the text. The He^3 analyzer was designed to measure the 0° to 90° proton counting-rate ratio, which depends on the deuteron polarization.

The effective target was 40 kev thick, or approximately the full width of the $d-\alpha$ resonance. This sharp resonance in the differential cross section served as a sensitive indicator of the energy of the scattered beam. When the deuteron beam energy at the target center was on the resonance at 1.07 Mev, the ratio of the monitor rate to the incident beam current was twice as large as the off-resonance values obtained 50 kev on either side. The beam energy could easily be reset on the resonance to ± 5 kev. The polarized beam left the He^4 target through a collodion "New Skin" window, which was about 60 kev thick. The window was $\frac{1}{2}$ in. in diameter, and was supported by an 80% transmission set of parallel wires; it withstood a pressure of 15 cm Hg. The analyzer target was a cylinder of He^3 gas, $\frac{1}{2}$ in. in diameter and $\frac{1}{2}$ in. long, with its axis along the polarized beam direction. It intercepted a solid angle of 5×10^{-3} steradian of the polarized beam, which corresponded to a flux of $\sim 10^7$ deuterons/sec. A 0.075-mil Ni entrance foil degraded the deuterons from 900 to

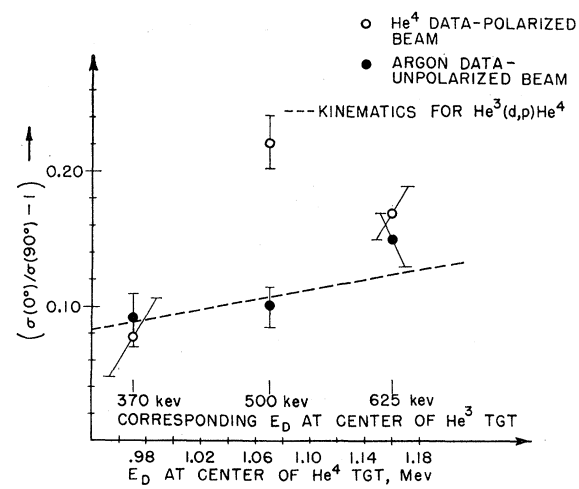

FIG. 3. Experimental results for $[\sigma(0°)/\sigma(90°)]-1$ as a function of deuteron energy, varied over the polarizing resonance (He^4 data), and the corresponding unpolarized energies (argon data). The dashed curve is the kinematic prediction for $He^3(d,p)He^4$ in the region of 500 kev.

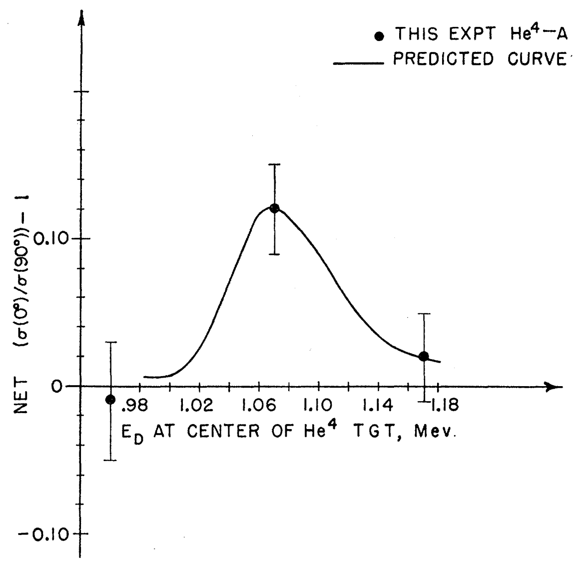

FIG. 4. Experimental results for the difference (He^4 minus argon) as a function of deuteron energy. The predicted curve is not normalized; it is obtained directly from Eq. (2) and energy dependence of $\langle T_{20}\rangle$ given by Fig. 1, with the energy resolution of the He^4 target and the angular resolution of the proton counters folded in. The errors are statistical.

500 kev, and the He^3 target itself, at a pressure of $\frac{1}{2}$ atmosphere, was about 100 kev thick. The proton detectors were 1-mm thick CsI(Tl) crystals, $1\frac{1}{2}$ in. in diameter, and 3 in. from the center of the He^3 target volume. The proton counting rates were typically about 10 per minute. Pulses from the 16-Mev protons were well above any background in the crystals, and were simultaneously recorded in two 128-channel sets of a 256-channel analyzer. As is discussed in reference 6, the first scattering chamber was filled with argon gas to Coulomb scatter an unpolarized beam into the He^3 chamber for checking purposes. A typical He^4-He^3 run lasted about two hours, and was preceded and followed by argon$-He^3$ check runs of about 30 minutes each.

RESULTS AND DISCUSSION

The experimental data consist of ratios of the forward direction proton counting rate to the 90° proton counting rate as a function of energy, for both a polarized and an unpolarized deuteron beam. Figure 3 shows the quantity $[\sigma(0°)/\sigma(90°)]-1$ as a function of deuteron energy through the polarizing resonance (He^4 runs), and at the same energies with a Coulomb-scattered unpolarized beam (argon runs). Each He^4 datum represents the average of two or three two-hour runs; the various runs were statistically consistent. The deuteron energies at the He^3 target center shown in the figure were obtained by measuring the excitation function for $He^3(d,p)He^4$ and comparing the results with the known energy variation of the cross section. The dashed curve in Fig. 3 is the kinematic prediction for $[\sigma(0°)/\sigma(90°)]-1$ which arises from the center-of-mass to lab solid angle transformation. This ratio favors 0° with respect to 90° in the lab system, and increases slowly with increasing energy. Figure 4 shows the He^4 results with the argon results subtracted out. This subtraction essentially transforms the data into the center-of-mass system, because the difference between center-of-mass and lab polar angles at 90° is about 2.5°, and can be ignored. Thus the data in Fig. 4 can be directly compared with the ratio calculated from Eq. (2). The solid curve shown in Fig. 4 is

$$[\bar{\sigma}(0°)/\bar{\sigma}(90°)]-1=-0.50\langle T_{20}\rangle_{av}$$

obtained from Eq. (2), where the "av" indicates that the energy resolution of the polarizing target has been folded into the $\langle T_{20}\rangle$ graph of Fig. 1, and the -0.50 contains the angular resolution of the analyzing counters. The agreement between the predictions and experimental results is quite good.

This experiment confirms the $d-\alpha$ phase-shift analysis for the deuteron polarization component $\langle T_{20}\rangle$. The correctness of the magnitude of $i\langle T_{11}\rangle$ is therefore strongly implied, although an absolute measurement of this component would be very desirable.

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