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POLARIZATION OF ^{3}He SCATTERED FROM ^{12}C†

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The polarization of ^{3}He particles elastically scattered from ^{12}C has been measured over an angular range $25° \leq \theta_{c.m.} \leq 74°$ at 18 MeV and $31° \leq \theta_{c.m.} \leq 61°$ at 20 MeV. Double-scattering techniques were used to determine the polarizations. A spin-orbit well depth of greater than 3 MeV is required in order to obtain reasonable agreement between optical-model predictions and the polarization data.

Several experiments have been performed recently in order to determine the spin-orbit potential in the optical-model description of ^{3}He elastic scattering. The spin-orbit potential $U_{so}(r)$ is defined here by

$$U_{so}(r) = V_{so}\left(\frac{\hbar}{M_\pi c}\right)\frac{1}{r}\frac{d}{dr}\left\{\left[1+\exp\left(\frac{r-r_{so}A^{1/3}}{a_{so}}\right)\right]^{-1}\right\}\vec{\sigma}\cdot\vec{L}. \tag{1}$$

Calculations[1] employing very simplified assumptions have predicted the factor V_{so} to be $\frac{1}{3}$ of the spin-orbit potential for nucleons,[2] that is about 2 MeV. In the experiment of Hutson et al.,[3] a 42-MeV ^{3}He beam was scattered from primary and secondary targets of ^{12}C at equal c.m. angles of 30°. The average energy of scattering at the second target was 36 MeV. An asymmetry consistent with zero (-0.001 ± 0.003) was observed, from which the authors concluded that the spin-orbit potential is less than 1.75 MeV. In another experiment, England et al.[4] scattered a 32-MeV ^{3}He beam from ^{12}C at a c.m. angle of 31.1°. The scattering of ^{3}He by protons was used as the polarization analyzer. Their measurement of a small polarization was consistent with spin-orbit potentials below 5 MeV according to optical-model predictions. Patterson and Cramer[5] made spin-flip measurements of 22.5-MeV ^{3}He particles inelastically scattered from the 4.43-MeV state of ^{12}C. From the optical-model parameters used in a distorted-wave Born approximation analysis of the spin-flip probability, they deduced a value of 2.7 ± 0.7 MeV for the spin-orbit potential. Luetzelschwab and Hafele[6] analyzed ^{3}He elastic-scattering cross-section data at 30 and 35 MeV and indicated that a spin-orbit potential of 2 to 5 MeV enabled good optical-model fits to be achieved. The present paper describes the first extensive polarization measurements of ^{3}He scattered by a target other than ^{4}He or protons in order to determine the strength of the ^{3}He spin-orbit potential.

A schematic diagram of the experimental arrangement is shown in Fig. 1. The natural carbon target used for most of the measurements had a thickness of 6.6 mg/cm^2 and was oriented

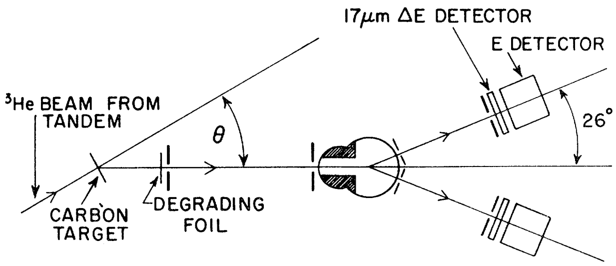

FIG. 1. A schematic representation of the double-scattering system.

at 45° to the incident beam. Typical beam currents were about 2 μA of $^3He^{++}$ ions. Collimators between the primary and secondary targets limited the angular acceptance to $\pm 1.1°$ and the solid angle to 0.003 sr. The second target was a gas cell containing ^4He at a pressure of 4.4 atm and a temperature of 150°K. This resulted in an effective target thickness of 10 atm cm (approximately 700 keV). The ΔE-E detector telescopes were set to the left and right at 26° (45° c.m.) and had a rms angular acceptance of $\pm 2.5°$. A detailed description of the polarimeter calibration will be presented elsewhere.[7] Calibration of the polarimeter was accomplished by using ^3He particles of a polarization known from polarization studies of ^3He-^4He scattering.[8] The average ^3He polarization analyzing power was determined to be +0.7 over a ^3He energy range of 11.5 to 13.0 MeV. Degrading foils were used to bring the energies of the scattered ^3He into that range at the center of the gas cell. Pulses from the ΔE and E detectors were mixed and sent to an on-line computer.[9] The pulses were mass identified and spectra corresponding to ^3He and ^4He particles were stored for each telescope. From the numbers of ^3He counts in the peaks due to ^3He scattered from ^4He, the quantity

$$r = [(N_L/N_R)_{\text{left}}(N_R/N_L)_{\text{right}}]^{1/2} \tag{2}$$

was calculated, where N_L, N_R are the number of counts in the left and right detectors, and "left", "right" refer to the setting of the polarimeter with respect to the incident beam. The quantity r is independent of the efficiencies of the detector telescopes. The quantity

$$P_1P_2 = \frac{r-1}{r+1}, \tag{3}$$

where P_1 is the polarization produced in scattering from the first target, and P_2 is the average analyzing power of the polarimeter.

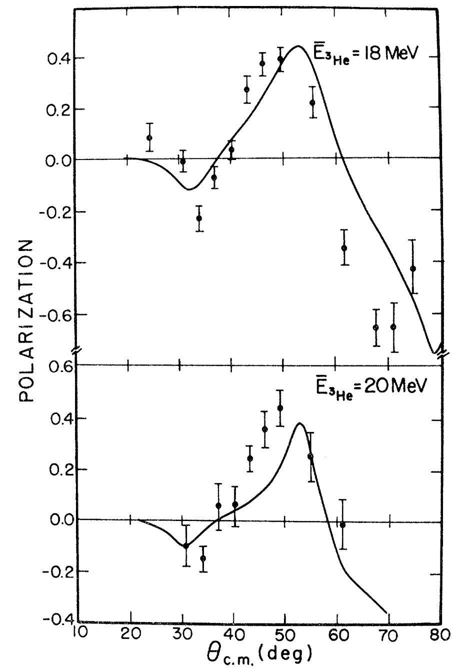

FIG. 2. The polarization angular distribution for ^3He particles scattered from ^{12}C at mean energies of 18 and 20 MeV. The solid curves are generated from optical-model parameters listed in Table I.

Figure 2 shows the polarization angular distributions measured at 18 and 20 MeV. Errors on the points are due to counting statistics only. Systematic errors are estimated to be less than ± 0.02. The scattering at 20° of 15-MeV ^3He particles from Au and Ta primary targets produced asymmetries which were less than 0.02, consistent with the small polarizations expected. Figure 3 shows the elastic-scattering cross-section angular distribution data of Fortune et al.[10] taken at 18 MeV, the 20-MeV data of Warshaw et al.,[11] and the 21-MeV data taken as part of the present work. The most striking feature of the differen-

Table I. Optical-model parameters.

$E_{^3He}$ (MeV)	V (MeV)	r_V (fm)	a_V (fm)	W (MeV)	r_W (fm)	a_W (fm)	V_{so} (MeV)	r_{so} (fm)	a_{so} (fm)	r_C (fm)
18	129.2	1.205	0.667	7.0	1.35	1.026	4.0	1.0	0.5	1.3
20 and 21	131.0	1.205	0.683	13.75	1.35	0.78	4.5	1.0	0.5	1.3

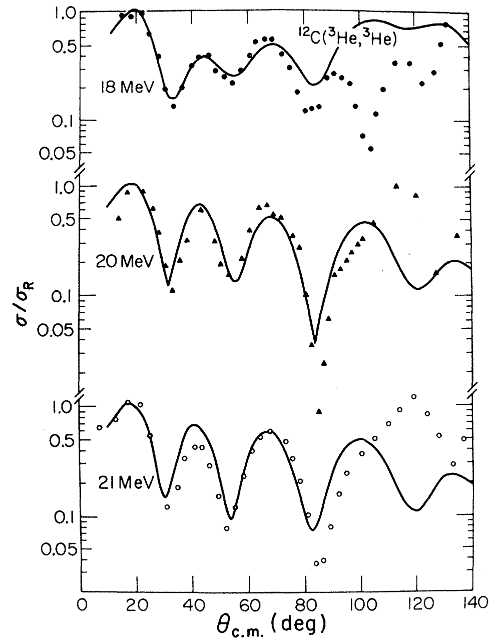

FIG. 3. The differential cross sections for ^{3}He particles scattered from ^{12}C, plotted as ratio to Rutherford, for energies of 18, 20, and 21 MeV. The solid curves for comparison with the 18- and 20-MeV data are optical-model fits to the respective data at angles forward of 80°. The 21-MeV curve was obtained from the parameters used for the fits at 20 MeV. Parameters are listed in Table I.

tial cross section is the strong diffraction pattern which exhibits little change with energy at forward angles. The rapid variation with angle seen in cross-section data also appears in the polarization angular distribution.

The optical-model code JIB3[12] was used to fit the forward-angle ($\leqslant 80°$) cross-section data taken at 20 MeV. The spin-orbit potential was held fixed at 4 MeV for these searches. The imaginary well had a surface form and the form of the spin-orbit potential is given in Eq. (1). The 20-MeV optical-model parameters were used to obtain predictions for comparison with the 21-MeV data and as starting parameters for searches on the 18-MeV cross-section data. The 20-MeV parameters and the final 18-MeV parameters listed in Table I differ mainly in the imaginary well depth.

The polarization predictions shown in Fig. 2 were made with parameters obtained from the cross-section searches. The spin-orbit potentials of 4 MeV for the 18-MeV data and 4.5 MeV for the 20-MeV data produce reasonable agreement with the magnitudes of the measured polarizations near 50° c.m. Other parameter sets have been found which give similar predictions of the forward-angle cross-section and polarization data. Each of these sets requires a spin-orbit potential larger than 3 MeV in order to predict polarizations of the measured magnitudes. Parameter sets which were employed to improve the fits to the backward-angle cross-section data produced poor comparisons with the forward-angle cross-section results and the polarization distribution. The optical-model curves shown in the figures predict the location of the forward-angle cross-section maxima and minima fairly accurately while the calculated polarization curves are shifted in angle with respect to the polarization data.

Other theoretical and experimental estimates for the spin-orbit potential can be compared with the present results. Our lower limit of 3 MeV exceeds the value of 1.7 MeV assigned by Hutson et al.[3] and slightly overlaps the upper limit of the value quoted from the spin-flip measurements. It is also larger than estimates of about 2 MeV based on the predicted fraction of the nucleon spin-orbit potential.[1]

In Ref. 10, an anomaly is reported in the excitation curves taken at very backward angles at a beam energy of approximately 17 MeV. Fits to these excitation curves were attempted here with a resonance term added to the optical-model scattering amplitude.[13] Acceptable best-fit resonance parameters produced little change in the prediction of the forward-angle polarization distribution and hence little change in the extracted spin-orbit potential. Another indication of negligible resonance effects on the polarization is the similarity of the polarization angular distributions measured at 18 and 20 MeV.

These data represent the first measurements of sizable polarizations for ^{3}He particles scattered from a nucleus other than ^{4}He. The extension of the present types of measurements to other energies and other target nuclei is necessary to determine the mass and energy dependence of the spin-orbit potential. Preliminary polarization data on ^{9}Be and ^{16}O have recently been obtained in our laboratory and further studies are planned.

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ELASTIC SCATTERING OF 580-MeV PROTONS FROM ^{3}He

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The elastic differential cross section for p-^{3}He scattering has been measured at 580 MeV. The data are compared with a Glauber model calculation.

In the past few years there has been much experimental and theoretical interest in the scattering of medium- and high-energy particles from light nuclei. The observation has been made regarding the scattering of protons[1,2] and pions[3] from deuterons that a diffraction minimum in the differential cross section was absent in contrast to the shape of the cross section for spin-zero nuclei (^{4}He, ^{12}C, ^{16}O). A number of explanations for this observation have been given: (1) the momentum dependence of the phases of the π-N or N-N scattering amplitudes, (2) the spin dependences in these amplitudes, and (3) effects due to the D state of the deuteron. Detailed theoretical studies[4] have then shown that a phase variation cannot explain the p-d and p-^{4}He data simultaneously. The spin dependence in the elementary amplitudes can partially account for the difference in shape of the p-d and p-^{4}He cross sections.[5] The main effect is due, however, to the D-state wave function in the deuteron.[6] In view of these results proton scattering from ^{3}He is interesting because of the ^{3}He spin and of the fact that the ^{3}He ground state contains components of angular momentum greater than that of the symmetric S state. In the present communication we are reporting our results on p-^{3}He scattering at 580 MeV.

The experimental arrangement was similar to the one used earlier.[7] A beam of 582-MeV protons was focused to a (1×4)-cm spot on a 15-cm-diam gaseous ^{3}He target (165 lb/in.^{2} for scattering angles greater than 21° and 30 lb/in.^{2} for smaller scattering angles). The walls of the cylindrical targets were 0.0075- and 0.0025-cm Havar, respectively, which was thin enough to permit the penetration of the recoiling ^{3}He for all angles studied. Since the energy spread in