for the lower yield from vanadium is that the reaction threshold is much higher for V^{51} than for the other cases. For example, the $V^{51}(\gamma,\alpha)Sc^{47}$ threshold is 10.3 Mev[21] while the $Cu^{65}(\gamma,\alpha)Co^{61}$ threshold is 6.3 Mev.[8] This means that for a given compound-nucleus excitation energy, the integral in the numerator of Eq. (1) will be evaluated over a smaller energy range (involving lower capture cross sections and level densities) for V^{51} than for the other cases, accounting for the observed yield differences.

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Measurement of Spin Polarization by Nuclear Scattering*†

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Accurate measurements of differential cross sections for elastic scattering of protons from He^4 and C^{12}, and of He^3 from He^4 in the energy range 2–6 Mev have been phase-shift analyzed and the expected spin polarization of scattered particles calculated. The results, plotted as contours of equal spin polarization *versus* energy and angle, should be useful in accurate measurements of spin polarization and in addition show a number of rather striking complexities due to interference effects.

INTRODUCTION

Because of the recognized importance of spin-orbit and spin-spin contributions to nuclear forces it is important to develop precise experimental techniques for measuring the spin polarization of particles emitted from nuclear reactions. This paper is concerned with a systematic study of possible techniques to measure spin polarization of charged spin-$\frac{1}{2}$ particles by nuclear scattering from spin-zero nuclei. It seems important to develop methods for making polarization measurements more precise and absolute; and it may be hoped that elastic scattering from different target materials may make a wider range of experiments possible both as regards intensity and the ease of target preparation.

We have studied the elastic scattering of spin-$\frac{1}{2}$ particles from spin-zero nuclei, especially for those cases where the only available channel is elastic scattering. This problem, fortunately, may be analyzed exactly, in the sense that the determination of precise differential cross sections at a number of angles and over a continuous range of energies (starting at low energies) usually allows a unique fit to all the data in terms of a few anomalous nuclear phase shifts corresponding to the nuclear scattering of low angular momentum partial waves. The wave function, f_c, for coherent scattering (no change of the projectile spin), and the incoherent (change of spin) wave function, f_i, are then determined for all distances outside the nucleus and the spin polarization effects are calculable.[1] The polarization along x, for scattering in the y-z plane, is

$$P_x(k,\theta)=\frac{2|f_i|\times|f_c|\sin[\arg f_c-\arg f_i]}{|f_c|^2+|f_i|^2},$$

and the notation is the same as in reference 1. Thus

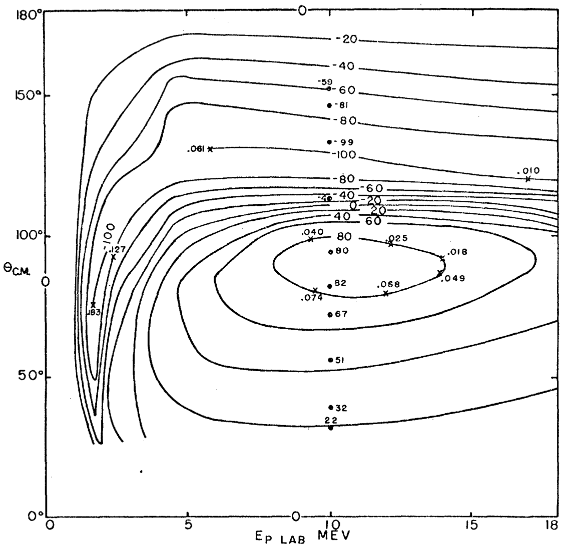

FIG. 1. H+He^4 scattering. Contour map of percent spin polarization along x for elastic scattering in the z-y plane. Contours of equal spin polarization are plotted *vs* the laboratory energy and the cm angle. The solid circles indicate experimental points of L. Rosen and J. E. Brolley [Phys. Rev. **107**, 1454 (1957)]. Each x and associated number gives cross section values in barns/steradian.

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[1] C. L. Critchfield and D. C. Dodder, Phys. Rev. **76**, 602 (1949).

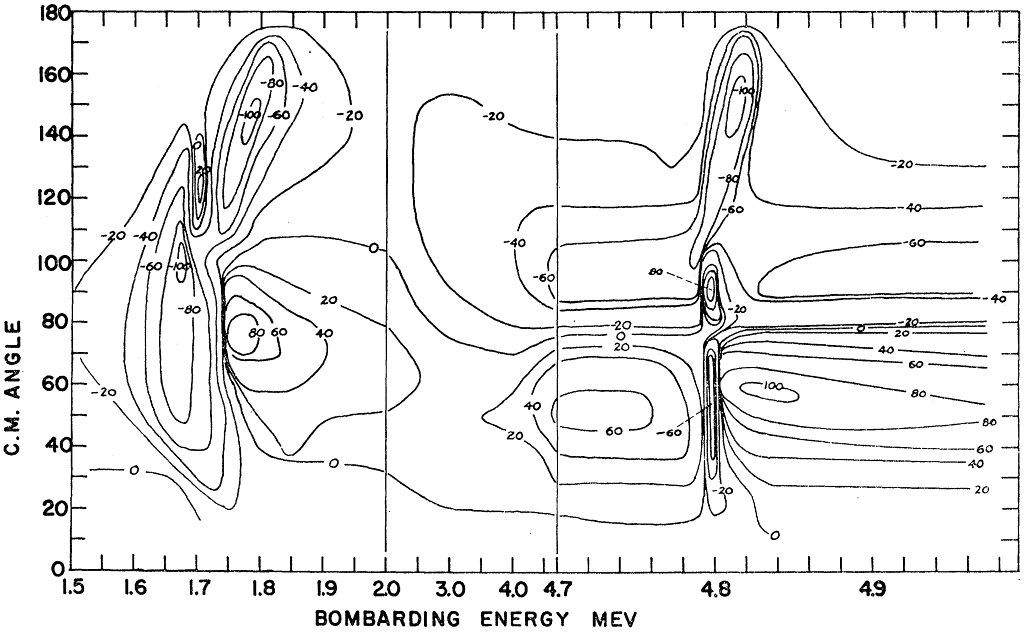

FIG. 2. H+C^{12} scattering. Contour map of percent polarization for elastic scattering (see Fig. 1).

accurate differential cross sections allow the determination of f_c, f_i, and permit the calculation of $P_x(k,\theta)$.

To use the known energy and angle properties of P_x to determine an *unknown partial polarization*, P, of the beam one measures the left-right ratio $R_{L,R}=PP_x=(N_L-N_R)/(N_L+N_R)$ so that $P=R_{L,R}/P_x$, where the N's are the counting rates.

MEASUREMENTS AND CALCULATIONS

Using the Rice Institute 6-Mev Van de Graaff accelerator and a large-volume, differentially pumped gas scattering chamber,[2] we have studied the scattering interactions (1) H+He^4,[3] (2) H+C^{12},[4] and (3) He^3+He^4.[5] Excitation curves were obtained for angles corresponding to the zeros of the first four Legendre functions at close energy intervals for energies between about 2 and 6 Mev. In addition several angular distributions were obtained for each of these reactions. The data have been phase-shift analyzed using an IBM-650 computer and the resulting phase shifts are estimated to be accurate to better than 5 degrees. The functions P_x have also been calculated and are plotted as contour maps of equal spin polarization *versus* cm angle and bombarding energy in Figs. 1, 2, and 3. Reference to the published excitation curves[3-5] affords a typical comparison between cross section and polarization behavior. The H+He^4 results include the measurements of others[6-10] and have been reanalyzed and included with the Rice data.[3]

DISCUSSION

Several interesting results appear from these measurements and should be noted. (1) In calculating the expected polarization effects it became apparent that the detailed behavior of the phase shifts with energy produces some remarkable and rather unexpected effects. For example, reference to Fig. 3 shows that there is a region of large polarization for He^3+He^4 scattering at an energy of about 4.5 Mev and at cm angles of about 160°. This anomaly is well separated in energy from the $f_{7/2}$ resonance at 5.17 Mev and apparently occurs because of interference effects due to the resonance f waves and the rather small p- and d-wave splittings that occur off resonance. Such an effect is extremely sensitive to small errors in the deduced phase shifts (it will essentially disappear by removing the few degrees of p- and d-wave splitting), and thus the exact details of Fig. 3 may be in error. *However, it is to be emphasized that large polarization effects may occur well away from resonances.* These facts certainly invalidate simple predictions of phase shifts, and of P_x, by employing the single-level dispersion theory and measured level parameters; the deviation of the phase shifts, and of P_x, from those predicted may be very large indeed.

(2) It may also be pointed out that the above pre-

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[2] Russell, Phillips, and Reich, Phys. Rev. **104**, 135 (1956).

[3] P. D. Miller and G. C. Phillips, Phys. Rev. **112**, 2043 (1958).

[4] Reich, Phillips, and Russell, Phys. Rev. **104**, 143 (1956).

[5] P. D. Miller and G. C. Phillips, Phys. Rev. **112**, 2048 (1958).

[6] K. W. Brockman, Phys. Rev. **108**, 1000 (1957).

[7] Kreger, Jentschke, and Kruger, Phys. Rev. **93**, 837 (1954).

[8] Putnam, Brolley, and Rosen, Phys. Rev. **104**, 1303 (1956).

[9] B. Cork and W. Hartsough, Phys. Rev. **96**, 1267 (1954).

[10] J. H. Williams and S. W. Rasmussen, Phys. Rev. **98**, 56 (1955).

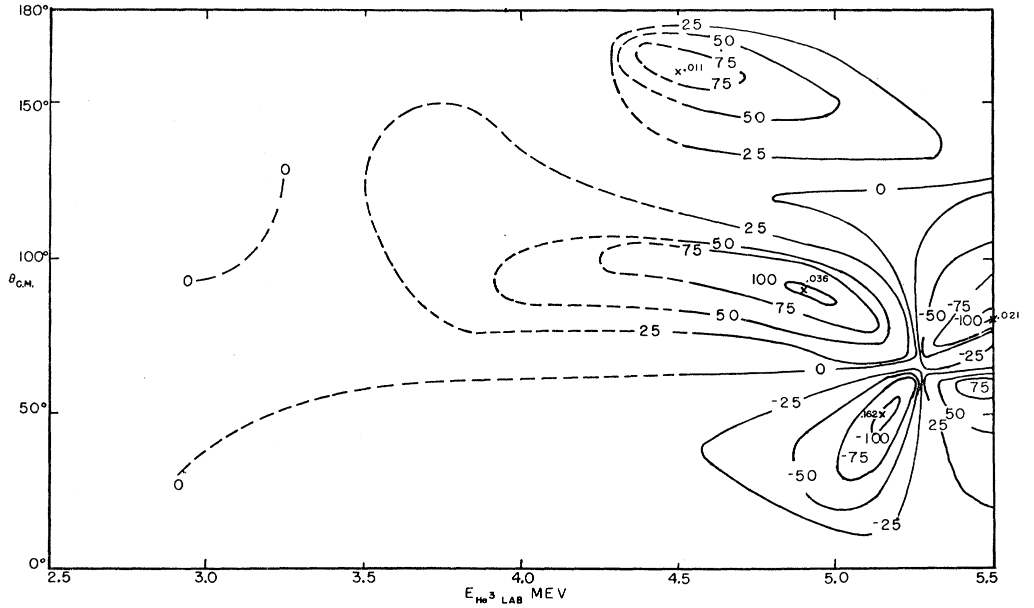

FIG. 3. He^3+He^4 scattering. Contour map of percent polarization for elastic scattering (see Fig. 1).

dictions of polarization may not be easily extended into energy regions where other disintegration channels open up; for example, it is *not* possible to predict accurately the phases of $H+C^{12}$ scattering by extrapolating the phase shifts much above 4.9 Mev (where inelastic scattering becomes possible), since the phase shift becomes complex there and, indeed, the R matrix is a more appropriate description.

(3) Figure 1 shows that P_x for $H+He^4$ scattering is very insensitive to energy and angle variations in the energy region 7–13 Mev and for cm angles near 130°. This region is probably the most favorable for high-energy proton spin polarization measurements. Brockman has published a very similar graph.[6] These results may be especially important where high-energy protons need to be slowed down in matter and a large resulting energy and angle straggling is introduced: a region of scattering that is relatively insensitive to these effects is desirable.

(4) The general complexity of the contour maps of P_x in regions where there is a discernible resonance behavior of the scattering cross section suggests that polarization measurements for such processes must experimentally take these effects into account either (a) by measuring very gross polarization properties by means of using inhomogeneous beams, averaging detectors, etc., or (b) by employing very exact energy and angular discrimination and attempting to define the details of the energy-angle variations of the polarization.

(5) Finally, all the processes studied and reported here have obvious applications to nuclear problems and allow the polarization of proton or He^3 beams to be measured with some absolute accuracy.