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Polarization of Elastically Scattered Tritons and ^{3}He

by

D. D. Armstrong
P. W. Keaton, Jr.

POLARIZATION OF ELASTICALLY SCATTERED TRITONS AND ^3He

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ABSTRACT

The measurement at the Los Alamos Scientific Laboratory of the polarization of tritons elastically scattered from ^4He has established this reaction as a good polarizer (or analyzer) for tritons. ~~We have recently extended~~ the polarization measurements were recently extended over a sufficient angular and energy range to allow a phase-shift analysis that more accurately describes both the cross-section and polarization data. Based on the assumption that the optical model potential for a triton is just the sum of the optical model potentials of its constituent nucleons suitably averaged over their internal motion in the triton, the polarization of tritons elastically scattered from nuclei is expected to be small. The measurements (at angles ∿ 60°) give small polarizations for tritons elastically scattered from nickel and ^{54}Fe. (auth)

I. INTRODUCTION

A few years ago an effort[1] to produce a beam of polarized tritons was undertaken at the Los Alamos Scientific Laboratory (LASL); the first triton polarization measurements were reported[2,3] in June 1968. This report is a review of that work as well as of our latest results. Similar reviews have appeared elsewhere.[4,5]

We present here some of the basic double-scattering techniques used to measure absolute polarization values. With these techniques, we have obtained over 1 pA of tritons elastically scattered from ^4He, with a polarization of 84%, and 1/2 pA of ^3He elastically scattered from ^4He, with a polarization of 64%.[6]

Several applications with polarized tritons and ^3He are presented, including few-nucleon problems and our latest attempt to measure the strength of the triton spin-orbit term in a triton optical potential for intermediate weight nuclei.

II. TECHNIQUES

A. Basic Concepts and Notations

Nucleon standards have existed for over a decade that could be used to "calibrate" an analyzer or polarizer. Before our work,* no such standards existed for polarized tritons or, in this energy region, for ^3He. Therefore, techniques that were common in the 1950's were used.

By choosing three appropriate energies and angles (Fig. 1), one can measure three dependent asymmetries,[8] P_1P_2, P_2P_3, and P_1P_3. An alternative is to measure P^2 but that was not practical for us. The sign cannot be determined by double-scattering experiments, but we have been able to determine this unambiguously by phase-shift analyses.

A typical pair of measurements would be: $^4He(t,\vec{t})^4He$ at the primary target to polarize the tritons, and $^4He(\vec{t},\hat{t})^4He$ at the secondary target to analyze the tritons. This introduces the notation that has been very helpful at LASL for several years. A vector (→) over a symbol to the left of

*An early attempt by Brolley et al.[7] at LASL was discontinued because of the low back-angle cross section and the use (for reasons of safety) of a low-pressure triton target, which gave a very low count rate. They did report a single asymmetry at the 1st Polarization Symposium, but because the primary and secondary center-of-mass energies were several MeV apart, one cannot extract the polarizations.

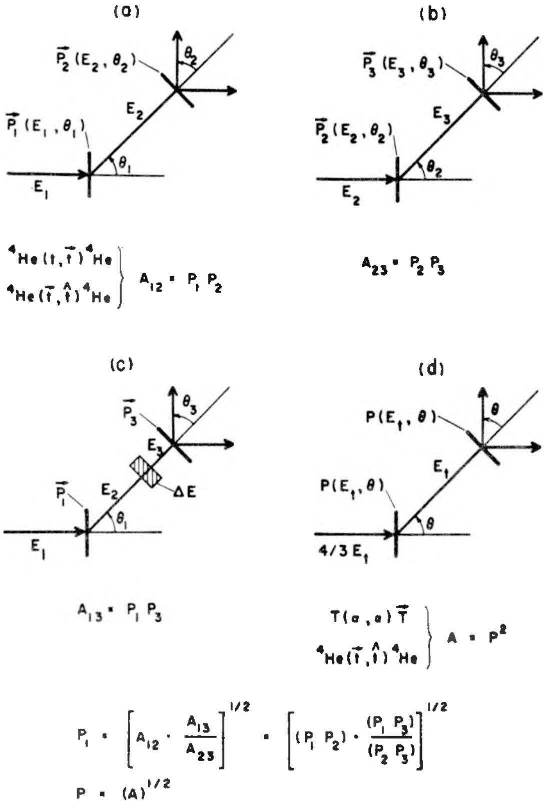

Fig. 1. Double-scattering methods for determining absolute polarization values.

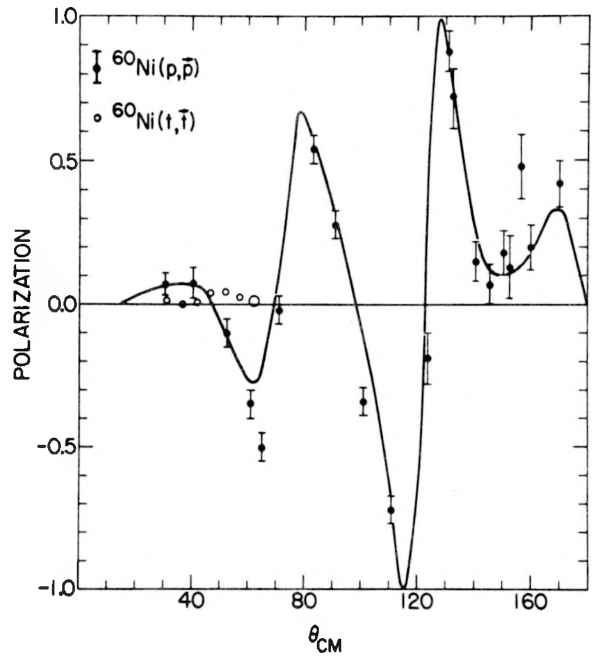

Fig. 2. Proton polarization measurements of Rosen et al. (Ref. 11) are compared with preliminary triton polarization measurements (this work).

the comma indicates a polarized beam (or target). A vector to the right of the comma indicates a polarization measurement of the designated particle. This part of our notation was adopted at the Third Polarization Symposium as part of a suggested convention for reporting polarization phenomena which is to be called the Madison Convention. We have also used a caret (^) over a symbol indicating that the left-right asymmetry of the specified particle was measured.

B. Brief History

In 1966, when we started to search for polarized tritons, we were impressed with the fact that large proton polarizations combined with large differential cross sections had been observed in scattering from intermediate weight nuclei. Indeed, Oak Ridge[9] successfully used the elastic scattering of protons from ^{40}Ca to produce 80 pA of 27% polarized protons. We began by double scattering tritons from nickel[10] at various angles and energies and also got very small asymmetries, consistent with zero. This was an indication, of course, that P_1 is small, that P_2 is small, or that both are small. Figure 2 shows the results of a recent measurement. The polarization of 14.5-MeV protons[11] on ^{60}Ni are compared with our preliminary polarization data involving 16-MeV tritons on a natural nickel target. There is now theoretical support[12] to indicate that the polarization is small for all intermediate weight nuclei--which means, of course, that we had spent a large effort in the wrong direction!

About the time we were modifying our double-scattering apparatus to utilize gas targets, Spiger and Tombrello[13] reported triton polarization predictions based on a phase-shift analysis. They derived phase shifts from extensive differential cross-section measurements of α particles elastically scattered from a tritium target.

Using the predictions of Ref. 13 as a guide, we obtained the data indicated in Fig. 3. At 40° c.m., notice that our choice of P_1 gives 92% polarization where the laboratory differential cross section is 640 mb/sr.

We have a very similar set of measurements for ^3He. In Fig. 4, a polarization of 64% is indicated at the place labeled P_2, where the laboratory cross

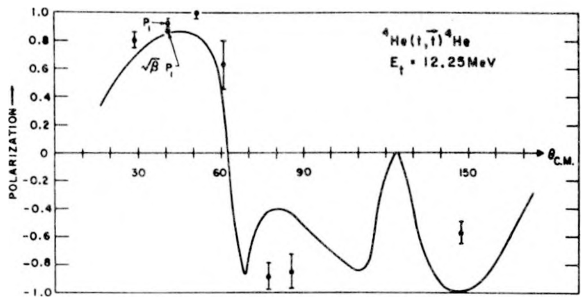

Fig. 3. Polarization distribution measurements (this work) for tritons elastically scattered from ^4He. The dot indicated as "$\sqrt{\beta}\ P_1$" is the actual measurement. The value of P_1 is obtained by correcting for a depolarizing effect on tritons in the magnetic quadrupole lens that focuses scattered beams from the primary target onto the secondary target (see also Fig. 6). The solid curve was calculated by using phase shifts from Spiger and Tombrello (Ref. 13).

section is 530 mb/sr.

C. Double-Scattering Apparatus

Triton beams are obtained at LASL by injecting T^- from the vertical 7-MeV Van de Graaff accelerator, or from a direct-extraction duoplasmatron, into the Model FN tandem accelerator. A schematic of the double-scattering apparatus is shown in Fig. 5 where the triton beam enters from the left. The primary target is a cylindrical cell with Havar windows containing ^4He gas. The scattered tritons are focused onto the secondary target with a magnetic quadrupole triplet lens system attached to a rotating gun mount. Small-angle detectors help in the alignment of the secondary chamber, and also monitor alignment while the data are being taken.

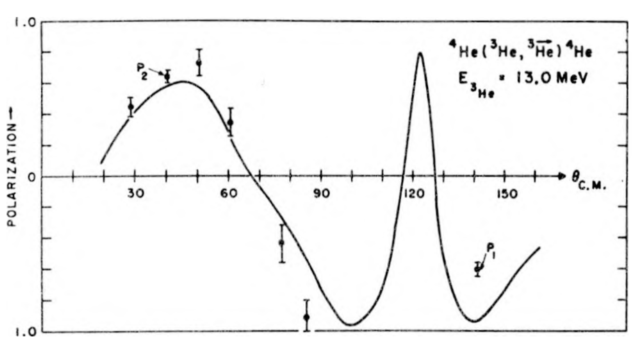

Fig. 4. Polarization distribution measurements (this work) for ^3He elastically scattered from ^4He. The solid curve was calculated by using phase shifts from Spiger and Tombrello (Ref. 13).

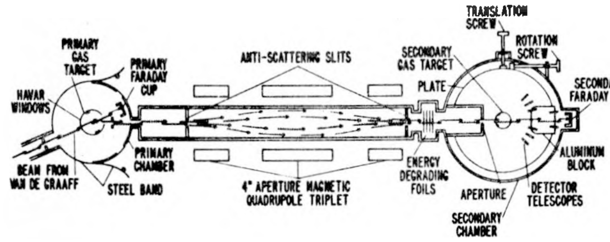

Fig. 5. A schematic of the double-scattering apparatus.

Eight ΔE-E telescopes can operate at one time. The signals are mixed and routed to the SDS-930 on-line computer for particle identification and energy sorting.[14]

There is a depolarization of about 10% for tritons passing through our magnetic quadrupole triplet because the Larmor precession frequency is almost ten times the cyclotron frequency for tritons. Therefore, if a triton is deflected 1° with a magnetic field in a direction perpendicular to its spin, the spin is processed by about 10°. The situation is shown for the present setup in Fig. 6.

The double-scattering apparatus is pictured in Fig. 7. There are, of course, energy limitations on these techniques. When ^4He is used as a polarizer, we are restricted to energy regions where the cross section and polarization are reasonably large. At present, this places an upper limit of 12.5 MeV for tritons and 13.5 MeV for ^3He.

III. APPLICATIONS

Some of these applications have been published and others appear here for the first time and will be published later. For greater detail, one is referred to the literature.

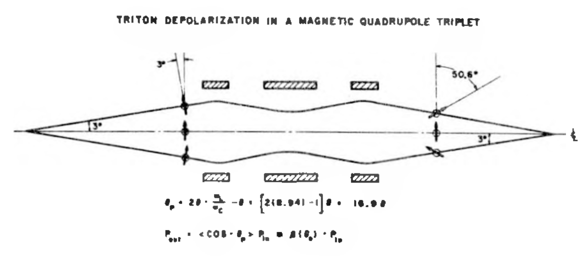

Fig. 6. Illustration of the depolarization effect on tritons passing through a quadrupole triplet magnet.

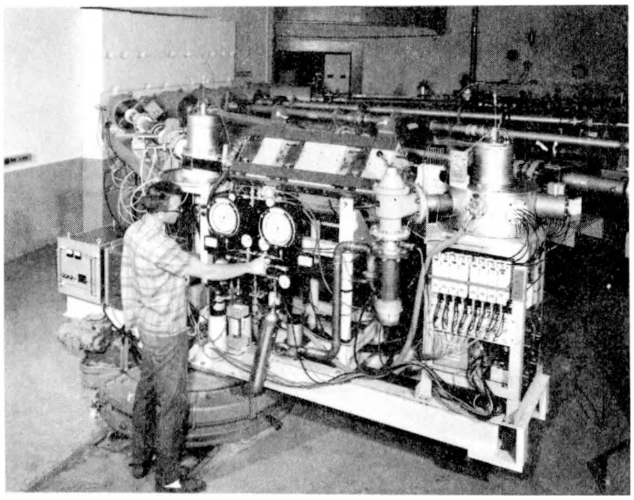

Fig. 7. The LASL double-scattering apparatus.

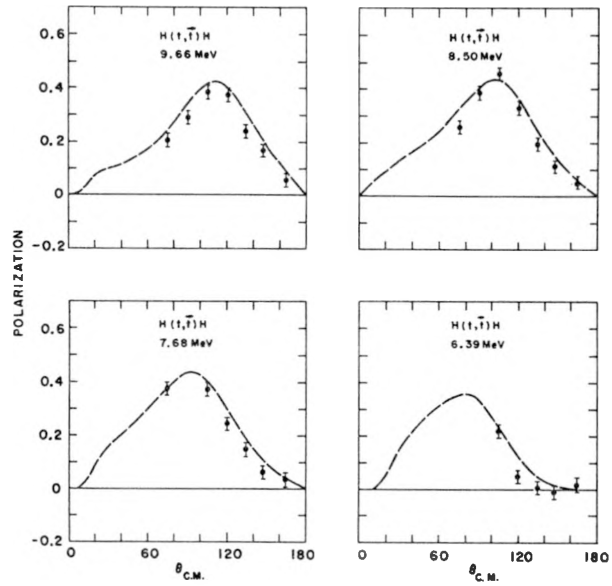

Fig. 8. Polarization distribution measurements (this work) for tritons elastically scattered from hydrogen. The dashed curves were calculated with Dodder's program (Refs. 17, 18) by using energy levels of Werntz and Meyerhof (Ref. 16).

A. <u>H($\vec{t}$,t)H</u>

We chose to elastically scatter polarized tritons from hydrogen[15] for two reasons: first, to study the excited states of ^{4}He, and second, to find an alternative to ^{4}He as an analyzer of polarized tritons. The bombarding energies range from 6.4 to 9.7 MeV where the only channels available are t+p and ^{3}He+n.

Werntz and Meyerhof[16] have assigned states in the mass-4 problem based on measurements of T(p,n)^{3}He and T(p,$\vec{n}$)^{3}He. Using these levels, we calculated the triton polarization appearing as dashed lines in Fig. 8. The agreement with our measured values is quite good. Notice that at 110° c.m., hydrogen can be used as an analyzer of about 40% over an energy range of 2 MeV, which allows use of either a thick gas target or more than 150 μ of polyethylene. One of our goals--a solid analyzer for tritons--has been thus achieved.

To make the calculations, we used a very general computer program by Dodder[17,18] of LASL that calculates the cross sections and polarizations from the reaction matrix using the formulas of Lane and Thomas.[19]

A search was undertaken at each of the four energies of the present measurements. In performing the searches, the computer program varied the reaction matrix elements to minimize the χ^2 function, where all available polarization and cross-section data were taken as input. The three reactions T(p,p)T, T(p,n)^{3}He, and ^{3}He(n,n)^{3}He were considered simultaneously. Only compound nuclear levels with total angular momentum and parity equal to that of one or more of the nine levels used in Ref. 11 were allowed. Angular momentum terms with $\ell \leq 2$ were used (ℓ = 2 terms were small).

One example of the results of this calculation is shown as solid lines in Fig. 9. In general, the agreement between the calculations and measurements is better than the uncertainties would indicate should be expected. Presumably, too many parameters are being varied in the search routine. Consequently, we have not yet found a significantly better set of energy levels than those of Werntz and Meyerhof.[16] A more realistic search would vary the level parameter and fit data at many energies simultaneously. Such a code is presently being written by Dodder[18] and we expect that it will permit a more meaningful search with the present data.

B. <u>Ni(t,$\vec{t}$)Ni and Fe(t,$\vec{t}$)Fe</u>

The problem we have worked on longest is still unfinished. The exciting question here is, "If one uses an optical potential to describe the elastic scattering of tritons from intermediate weight nuclei, what is the strength of the spin-orbit term?" Presumably, we would be able to answer this question

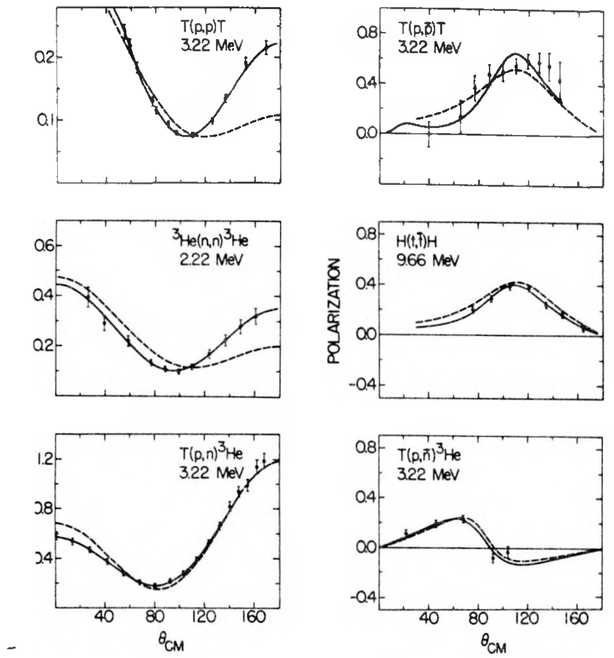

Fig. 9. The dashed curves were calculated with Dodder's program (Refs. 17, 18) by using energy levels of Werntz and Meyerhof (Ref. 16). The solid curves are the results of a two-channel search on reaction matrix elements. The input data are references by Veeser et al. (Ref. 15).

directly if we knew the triton polarization at several energies and many angles. This is a very difficult task because, for example, at 15 MeV the triton elastic differential cross section is about 50 times smaller than the proton elastic differential cross section at 90°. Forward of 90°, our measurements on ^{62}Ni and ^{54}Fe indicate that the polarization is less than a few percent (Fig. 2).

We review briefly a model for tritons first discussed by Abul-Magd and El-Nadi[11] that may give helpful insight to the problem. They fold the optical potential of each of the nucleons together with the internal motion of the tritons (Fig. 10). The resulting effective triton potential[20,21] is

$$V^t(R) = \int d\vec{r}\, d\vec{\rho}\, \phi^+(r,\rho)[V^p(r,\rho,R) + 2V^n(r,\rho,R)]\phi(r,\rho) ,$$

where R is the distance between the scattering nucleus and the center of mass of the triton, $\phi(r,\rho)$ is the internal triton wave function, and V^p and V^n are the optical potentials for the proton and neutron, respectively. We can extract the essence of

$$V^t(R) = \int d^3r\, d^3\rho\, \varphi^+(r,\rho)\, [V^p(r,\rho,R) + 2V^n(r,\rho,R)]\, \varphi(r,\rho)$$

$$\varphi(r,\rho) = (2\sqrt{3}\gamma/\pi)^{3/2} \exp[-\gamma(2\rho^2 + 3/2\, r^2)]$$

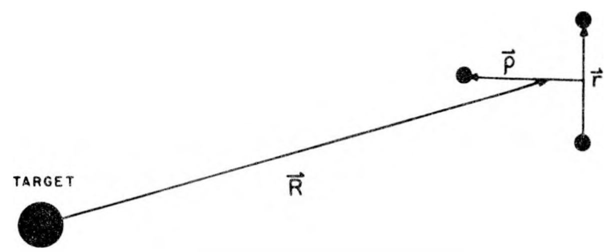

Fig. 10. Coordinates for the triton optical potential calculation.

the calculation if we make two simplifying assumptions: first, that $\phi(r,\rho) = \delta(r)\,\delta(\rho)$, and second, that $V^p = V^n$. The resulting triton optical potential then becomes

$$V^t(R) = -3V_o f(R) - i3W_o g(R) + \lambda_\pi^2 \frac{1}{R}\frac{df(R)}{dR} V_{So} \times \{\vec{\sigma}_1\cdot\vec{\ell}_1 + \vec{\sigma}_2\cdot\vec{\ell}_2 + \vec{\sigma}_3\cdot\vec{\ell}_3\} ,$$

where we have substituted a standard[10] optical potential form for the nucleons and where subscripts 1, 2, and 3 refer to each of the nucleons in the triton. Notice that the real and imaginary well depths are three times as deep for tritons as for nucleons. We also find

$$\vec{\ell}_1 \equiv \vec{\ell}_2 \equiv \vec{\ell}_3 \equiv \frac{\vec{\ell}_t}{3} ,$$

where $\vec{\ell}_t$ is the angular momentum of the triton, and $\vec{\sigma}_1 + \vec{\sigma}_2 + \vec{\sigma}_3 = \vec{\sigma}_t$, because the spin of the triton is one-half. Therefore, the spin-orbit term for tritons can be written

$$\lambda_\pi^2 \cdot \frac{1}{R}\frac{df(R)}{dR} \cdot \left(\frac{V_{So}}{3}\right) \cdot \vec{\sigma}_t \cdot \vec{\ell}_t ,$$

which indicates that the spin-orbit term of the triton (or ^{3}He) is one-third of the value for nucleons.

The consequences of this model for triton polarization can easily be demonstrated[21] using the first Born approximation. In that case, polarization scales as the ratio of V_{So}/V_o. Therefore,

$$P_t \propto \frac{\frac{1}{3}V_{So}}{3V_o} \propto \frac{1}{9} P_p ,$$

and P_t, the triton polarization, is predicted to be 1/9 of P_p, the proton polarization.

We used this model to calculate the effective optical potential for tritons. Triton breakup was not put into this model; therefore we searched on W_o, the depth of the imaginary well. The results of this "one free-parameter" model looked very promising. However, we found that if the triton Gaussian wave function, which we used first, is replaced by an Irving-Gunn wave function, the fits are not as good. Also, if we use nucleon parameters of Greenlees et al.[22] instead of Perey,[23] we also have difficulties. Of course, one could always get a fit by allowing several parameters to vary. In particular, there is no reason to believe that it is valid to treat the distortion term as negligible, and hence the imaginary geometry might be changed. However, such a study probably has little relevance until extensive triton polarization distributions are available. The expected availability of a polarized triton ion source at LASL would yield the measurements necessary to continue this study.

Such was the status of the problem until the University of North Carolina and Duke University--at their joint tandem facility, TUNL--reported large ^3He polarizations by elastic scattering from light elements.[24] These measurements were analyzed by a ^3He polarimeter calibrated with our absolute ^3He polarization measurements.[6,8] We felt that comparable measurements of tritons on carbon were sufficiently simple that it need not wait for a polarized triton ion source. Therefore, we recently used our double-scattering apparatus to make some forward-angle measurements. Our preliminary data are compared with the TUNL ^3He polarization measurements on carbon at 18 MeV as shown in Fig. 11. This was not an attempt to reproduce the TUNL data, but simply an experiment designed to answer the question, "After we obtained such small triton polarizations with iron out to 75°, will carbon yield large triton polarizations at 40° and 50°?"

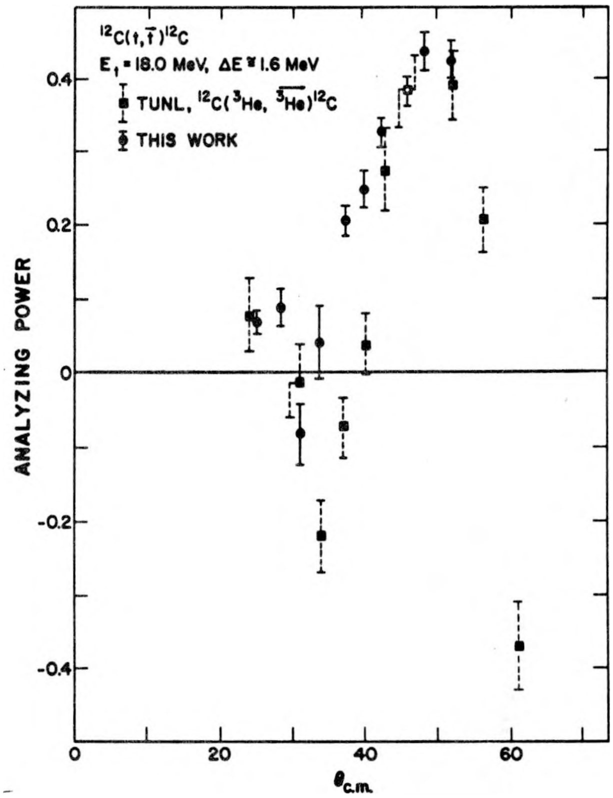

Fig. 11. Polarizations of tritons (this work) and ^3He (see Ref. 24) elastically scattered from a natural carbon target at 18 MeV.

The answer, of course, is yes. The implications of these data may be summarized as follows: First, the folding potential model may not be valid. Second, the polarizations may be due to a resonance. However, the TUNL data have shown that this pattern holds also at 20 MeV. It seems unlikely that $^{12}C+^3He$ has such a broad resonance. This possibility is not, of course, ruled out. Third, the folding potential model may predict this large polarization. It is true that the lighter the nuclei, the less valid is the simple scaling ratio approximation. This will be studied more carefully with Greenlees' nucleon parameters and an Irving-Gunn triton wave function. Fourth, it is difficult, as is normal for light elements, to find meaningful optical parameters that fit the data. Therefore, such measurements may not be a test of the folding potential model. Of these four possibilities, the last seems the most likely at this time.

C. $^4He(t,\vec{t})^4He$

Our first use of the $^4He(t,\vec{t})^4He$ reaction was

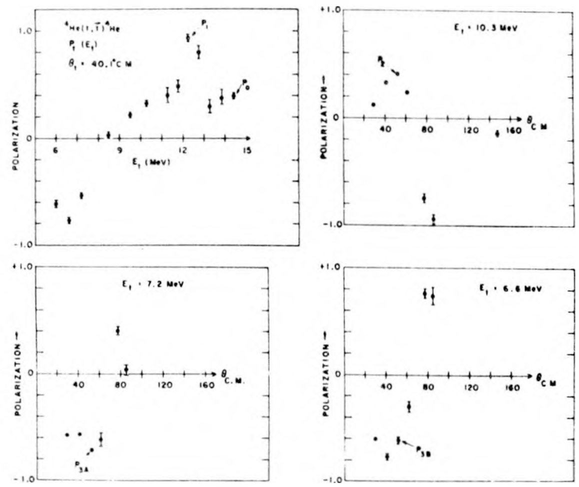

Fig. 12. Polarization distributions of measurements (this work) for tritons elastically scattered from ^{4}He. The labels "P_i" refer to points taken in dependent asymmetry measurements leading to absolute polarization determination.

as a tool--to polarize tritons. We have recently returned to this reaction to make extensive polarization distribution measurements. Some of the measurements are shown in Fig. 12.

Starting with the phase shifts of Ref. 12, we allowed all seven real phase shifts to vary in a search on cross-section and polarization data. From this preliminary search, several points of interest can be made. (1) The phase shifts change very little (usually less than 15°). (2) Fits are considerably better to the polarization data but the energy dependence of the phase shifts is not as smooth as those given in Ref. 12. (3) In the region where there is no $\ell = 1$ or 2 state nearby, the P and D waves exhibit very little splitting, even though they were not restricted. (4) Poor fits around E_t = 12.25 MeV indicate that the imaginary phase shifts are not correct in Ref. 12. Clearly, these data need more analyzing.

D. $D(\vec{t},\hat{\alpha})n$ and $D(^3\vec{He},\hat{\alpha})H$

In 1965, theoretical interest was aroused by a very interesting experiment at Rice[25] with a polarized ^{3}He target. Unpolarized deuterons were accelerated onto a polarized ^{3}He target and measured the left-right asymmetry of protons coming from the $^3\vec{He}(d,\hat{p})^4He$ reaction. Assuming time-reversal invariance (Ref. 26) and a 100% polarized target, this is equivalent to measuring ^{3}He polarization in the inverse reaction, namely, $^4He(p,d)^3\vec{He}$. Therefore, we define the left-right proton asymmetry divided by the magnitude of the target polarization as $\vec{P}_{^3He}$. The Rice University results imply that

$$\vec{P}_{^3He} \simeq -\vec{P}_p ,$$

where $\vec{P}_p$ is the proton polarization in the reaction $^3He(d,\vec{p})^4He$. However, early methods in determining ^{3}He target polarization gave a relative uncertainty range of 1.35 to 1.0. Using the Rice results, Tanifuji[27] showed that the reaction mechanism could not be pure stripping. He concluded that one must have a tensor term in the potential. His results strongly suggested that both ^{3}He and proton undergo spin flip. Duck[28] has shown in a partial wave analysis that only spin-flip amplitudes appear to be important (see also Ref. 29). Csonka et al.[30] have applied the formalism of nondynamical structure of particle reactions to $P_p \equiv -P_{^3He}$ and suggested a further set of experiments.

Very recently, in collaboration with R. M. Tapphorn of Kansas State University, we measured the asymmetries

$$D(\vec{t},\hat{\alpha})n \qquad \text{and} \qquad D(^3\vec{He},\hat{\alpha})H .$$

The second reaction here is equivalent to the polarized target reaction in Ref. 24. Some of the results of $\vec{P}_{^3He}$ vs $-\vec{P}_p$ and $\vec{P}_t$ vs $-\vec{P}_n$ are shown in Fig. 13, which includes proton (neutron) polarization data from the literature.[30-33] A detailed discussion of the theoretical deduction in this problem is beyond the scope of this report.[34,35] However, it is clear that a theory that assumes $P_{^3He} = -P_p$ (or $P_t = -P_n$) is in serious error.

IV. SUMMARY

We can summarize our work very simply. First, we have determined absolute polarization standards for tritons and ^{3}He. Second, we have found places where the polarization and the cross section for tritons and ^{3}He are large. We have demonstrated that it is feasible to use these beams for certain applications. Third, our observations indicate that triton spin-orbit effects are small except when near a resonance, and in the case of the one light element, carbon. And last, perhaps the nonresonant spin-orbit effect of mass-3 nuclei inter-

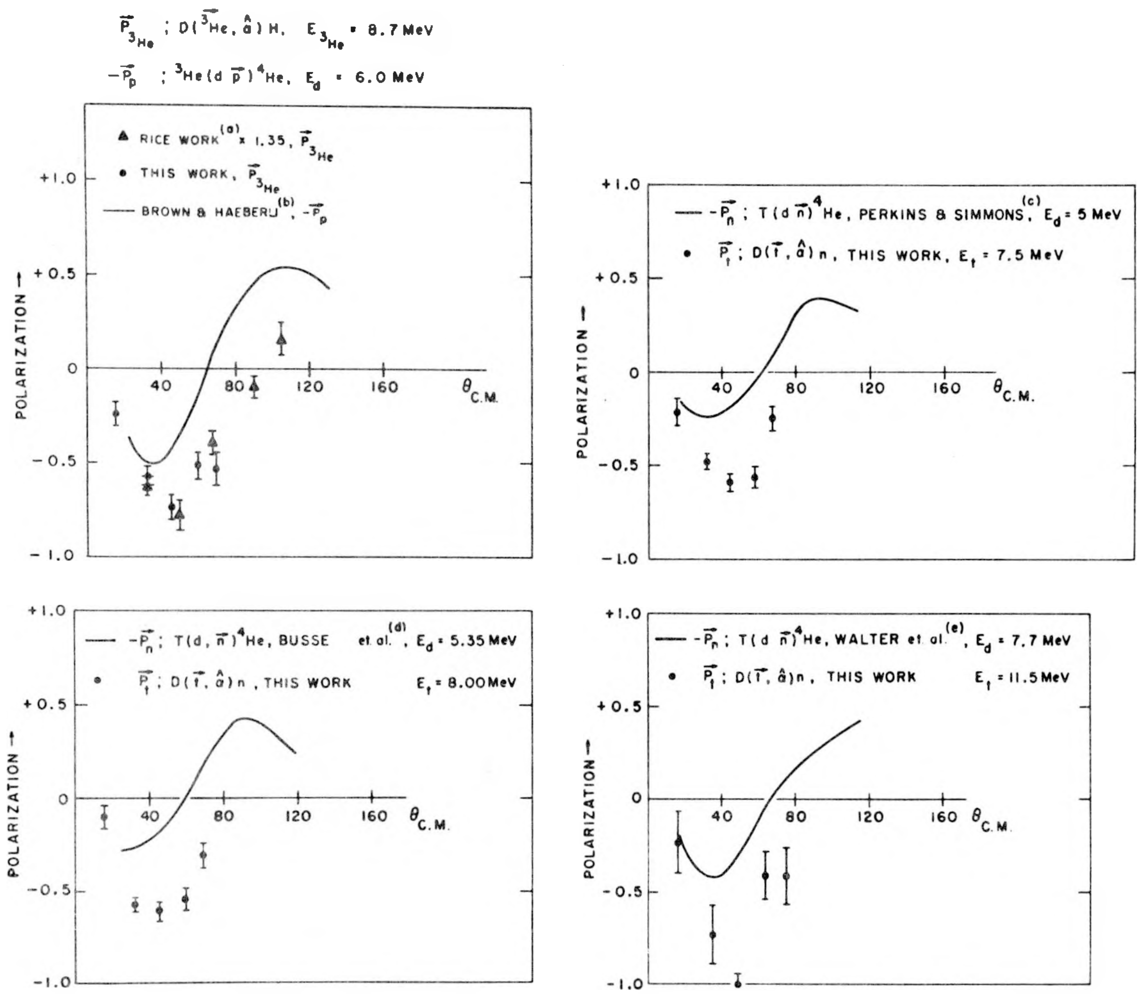

Fig. 13. Alpha left-right asymmetries resulting from polarized mass-3 projectiles incident on a deuterium target. The solid curves indicate proton or neutron polarization measurements: (a) see Ref. 25; (b) see Ref. 31; (c) see Ref. 32; (d) see Ref. 33; (e) see Ref. 34.

acting with intermediate weight elements should be considered as arising from the spin-orbit effect of the single unpaired nucleon which is then averaged over the three constituents.

ACKNOWLEDGMENTS

We wish to thank LASL Group P-9, the tandem accelerator facility, for supplying the triton and ^{3}He beams. We are also indebted to L. L. Catlin who has been a constant contributor to the development and improvement of the apparatus and technique that made this work possible.

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