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# Polarization and polarization transfer in the reaction $^3$H($p$, $n$)$^3$He at 5.97 and 9.9 MeV*

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Angular distributions of the polarization transfer coefficients $K_x^{x'}(\theta)$, $K_z^{x'}(\theta)$, $K_y^{y}(\theta)$, and the polarization $P(\theta)$ in the reaction $^3$H($p$, $n$)$^3$He have been measured for proton energies of 5.97 and 9.9 MeV. The measurements of polarization transfer were done with an incident polarized proton beam. The polarizations of the neutrons were measured with a liquid helium polarimeter. Comparisons are made with $R$-matrix calculations based on the levels of $^4$He from the analysis of Werntz and Meyerhof.

[NUCLEAR REACTIONS $^3$H($p$,$n$)$^3$He, $E$ = 5.97 and 9.9 MeV; measured polarization $P(\theta)$, and polarization transfer $K_x^{x'}(\theta)$, $K_z^{x'}(\theta)$, and $K_y^{y}(\theta)$.]

## I. INTRODUCTION

In this paper we report on further results of polarization and polarization transfer in the reaction $^3$H($p$,$n$)$^3$He. The motivation for the measurements was to provide additional information concerning polarization effects in this reaction at lower excitation energies in $^4$He than was previously reported.[1] The prior data at 13.55 MeV corresponded to an excitation energy in $^4$He near 30 MeV. The proton energies of 5.97 and 9.87 MeV correspond to excitation energies of about 24.3 and 27.2 MeV, where the comparisons with theory are more valid as indicated in Ref. 1.

Data of this type are interesting from a number of points of view. First, the data allow further comparisons to be made with $R$-matrix calculations based on the levels of $^4$He from the analysis of $^3$H($p$,$n$)$^3$He by Werntz and Meyerhof[2] (henceforth referred to as WM). The previous comparisons[1,3-6] of data for this reaction with $R$-matrix calculations based on the WM levels have indicated that some modification is necessary in their level structure of $^4$He. Secondly, by combining data for a number of different observables from the $^3$H($p$,$n$)$^3$He reaction with data from other reactions involving $^4$He, it is hoped that a multichannel $R$-matrix[7] analysis will yield a more reliable set of levels for $^4$He. Such an analysis has been started at this laboratory.[8] Thirdly, a calculation of observables of the four-nucleon system has been made by starting from a given nucleon-nucleon interaction and solving the Schrödinger equation using variational methods.[9] Data of the type we report here will serve to test the assumptions used in this type of calculation.

## II. EXPERIMENTAL METHOD AND DATA REDUCTION

In the measurement of polarization transfer a polarized proton beam was used which was produced by the Los Alamos Lamb-shift polarized ion source and accelerated by an FN tandem accelerator. The magnitude of the proton polarization was typically 0.90 and was measured by an atomic beam technique[10] to an accuracy of ±0.015. For measurement of the polarization [$P(\theta)$] of the outgoing neutrons the incident beam was unpolarized. The experimental details, nomenclature, and data reduction procedures are the same as in the previous paper.[1] We present here only a brief summary of essential points. A complete discussion of experimental details may be found elsewhere.[11]

The proton beam impinged upon a cylindrical, stainless steel target (3 cm in length by 0.9 cm diam) pressurized with gaseous tritium to 4.8 absolute atmospheres. The entrance foil to the target was a 9.8 mg/cm$^2$ molybdenum foil plated with 2.4 mg/cm$^2$ nickel. The beam was stopped in the end wall of the target cell which was 0.48 mm of gold.

The polarizations of the neutrons were measured by a liquid helium polarimeter which consisted of a 4.8 mole liquid helium scintillator operated in fast coincidence with two NE-102 plastic scintillators positioned at laboratory scattering angles of 115° above and below the helium scintillator. We define the scattering geometry by two frames of reference each forming an orthonormal basis. For both frames the vertical $y$ axes were parallel to each other and to $\vec{k}_i \times \vec{k}_f$ where $\vec{k}_i$ and $\vec{k}_f$ represent the initial (proton) and final (neutron) laboratory directions of motion. The laboratory-initial frame $(x, y, z)$ was then defined by $z$ pointing along the direction of the incident proton beam. The laboratory-final frame $(x', y', z')$ was defined by $z'$ pointing in the direction of the emitted neutron at the laboratory angle $\theta$. To measure the $y$ component of neutron polarization a spin precession solenoid was used. The solenoid provided a longitudinal field which precessed the neutron

TABLE I. Polarization-transfer functions for the reaction $^3$H($p$,$n$)$^3$He at $E_p = 5.97$ and 9.9 MeV. $E_p$ is the proton laboratory energy at the target center with an indicated uncertainty that is half the energy loss in the tritium gas.

| $\theta_{\text{lab}}$ (deg) | $K_x^{x'}$ | $K_z^{x'}$ | $K_y^y$ |
|---|---|---|---|
| | | $E_p = 5.97 \pm 0.09$ MeV | |
| 15.3 | $0.639 \pm 0.030$ | $-0.237 \pm 0.027$ | $0.652 \pm 0.032$ |
| 30.3 | $0.526 \pm 0.031$ | $-0.451 \pm 0.031$ | $0.598 \pm 0.036$ |
| 41.0 | $0.280 \pm 0.028$ | $-0.494 \pm 0.027$ | ⋯ |
| 45.3 | ⋯ | ⋯ | $0.372 \pm 0.042$ |
| 60.3 | $0.155 \pm 0.050$ | ⋯ | $-0.148 \pm 0.040$ |
| 80.3 | $0.589 \pm 0.067$ | $-0.281 \pm 0.062$ | $-0.141 \pm 0.066$ |
| | $E_p = 9.94 \pm 0.06$ MeV | | $E_p = 9.87 \pm 0.06$ MeV |
| 0.3 | $0.737 \pm 0.025$ | $-0.017 \pm 0.033$ | $0.642 \pm 0.037$ |
| 15.3 | $0.712 \pm 0.034$ | $-0.252 \pm 0.035$ | $0.734 \pm 0.046$ |
| 30.3 | $0.555 \pm 0.035$ | $-0.411 \pm 0.037$ | $0.608 \pm 0.060$ |
| 45.3 | $0.247 \pm 0.029$ | $-0.406 \pm 0.029$ | $0.310 \pm 0.054$ |
| 60.3 | $0.082 \pm 0.027$ | $-0.269 \pm 0.026$ | $0.025 \pm 0.056$ |
| 80.3 | $0.147 \pm 0.031$ | $-0.143 \pm 0.032$ | $-0.078 \pm 0.044$[a] |
| 100.3 | $0.301 \pm 0.052$ | $-0.500 \pm 0.054$ | $0.078 \pm 0.090$[a] |

[a] For these data $E_p = 9.94 \pm 0.06$ MeV.

spin ±90° about its direction of motion, thus rotating the $y$ component into the horizontal plane. When the solenoid was not energized, the polarimeter measured directly the $x'$ component of neutron polarization. In this case neutron spin polarization reversal was accomplished by reversal of beam polarization at the ion source. Further details describing the polarimeter are given in Ref. 12 with the modifications that $R_1 = 99$ cm and $R_2 = R_3 = 34.3$ cm. $R_1$ corresponds to the distance from the tritium target cell center to the helium cell center. $R_2$ and $R_3$ are the distances from the helium cell center to the centers of the NE-102 scintillators. At a distance of $R_1 = 99$ cm the helium cell subtends an angle of $\Delta\theta = 3.6°$ (full width).

For each of the observables an asymmetry $e_M = (N_+ - N_-)/(N_+ + N_-)$ was measured. The quantities $N_+$ and $N_-$ represent the combination of signal plus background corresponding to neutron spin parallel (+) or antiparallel (−) to the normal to the $n$-$\alpha$ scattering plane (which was parallel or antiparallel to the $x'$ direction in the final frame of reference). In general two cycles of + − − + were performed to reduce the effect of electronic drifts. The measured asymmetry was increased by multiplicative correction factors $f, g$, and $h$ corresponding to corrections for background, multiple scattering, and finite geometry. The resulting corrected asymmetry $e = fgh\, e_M$ was then divided by the $n$-$\alpha$ analyzing power at 115° lab to obtain the final neutron polarization. The $n$-$\alpha$ analyzing powers were obtained from the phase shifts of Satchler *et al.*[13] To obtain the polarization transfer observables, $K_x^{x'}$ and $K_z^{x'}$, the final neutron polarization was divided by the incident proton beam polarization. The parameter $K_y^y$ was calculated according to Eqs. (2) and (4) of Ref. 1 with the $^3$H($p$, $n$)$^3$He analyzing power values of Ref. 5. The errors in the observables were computed by adding in quadrature the statistical uncertainty in the measured asymmetry plus the uncertainty in the correction factors. An uncertainty of $\Delta f = \pm 2(f-1)/3$ was ascribed to the background cor-

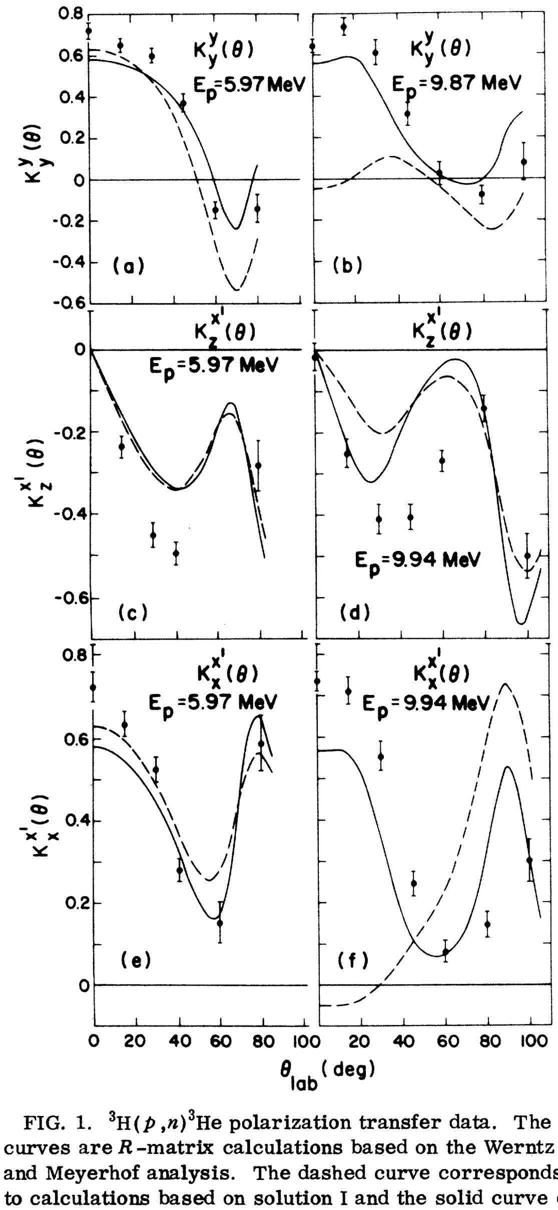

FIG. 1. $^3$H($p$,$n$)$^3$He polarization transfer data. The curves are $R$-matrix calculations based on the Werntz and Meyerhof analysis. The dashed curve corresponds to calculations based on solution I and the solid curve on solution II.

rection. The uncertainties in $g$ and $h$ were taken to be $\Delta g = \pm(g-1)/3$ and $\Delta h = \pm(h-1)/3$. For the angular distribution at 5.97 MeV the correction factors ranged in value (for increasing laboratory angle) as follows: $f(3 \rightarrow 11\%)$, $g(8 \rightarrow 22\%)$, $h \approx 4.5\%$. At 9.87 or 9.94 MeV the correction factors had the following range of values: $f(3 \rightarrow 10\%)$, $g(4 \rightarrow 8.3\%)$, $h \approx 4\%$.

## III. RESULTS AND DISCUSSION

The experimental values of the transfer observables are given in Table I. The errors in the data are standard deviations and include the statistical uncertainty and the stated uncertainty in the correction factors. Not included is the uncertainty in the beam polarization or the $n$-$\alpha$ analyzing power.

In Fig. 1 are shown the polarization transfer observables. Also plotted in the figure are $R$-matrix calculations[14] based on the levels of $^4$He from the analysis of $^3\mathrm{H}(p,n)^3\mathrm{He}$ by WM.[2] Their analysis included differential cross section and polarization data and resulted in two sets of levels for $^4$He which they designated as solutions I and II. In the figure the dashed line corresponds to the calculations based on solution I and the solid line on solution II. Figures 1(a) and 1(b) show the results for $K_y^y$ at 5.97 and 9.87 MeV. At 5.97 MeV both solution I and II reproduce the shape of the angular distribution reasonably well. At 9.87 MeV the calculations based on solution I deviate considerably from the data for angles less than 40°. Figures 1(c) and 1(d) show the results for $K_z^{x'}$ at 5.97 and 9.94 MeV. At both energies the calculations describe the qualitative shape of the angular distribution but quantitative agreement is lacking. Figures 1(e) and 1(f) show the results for $K_x^{x'}$ at 5.97 and 9.94 MeV. At 5.97 MeV both solutions describe the shape of the angular distribution; however, at 9.94 MeV solution I again deviates considerably from the data predicting the wrong sign for $K_x^{x'}$ for angles less than 30°.

At zero degrees $K_x^{x'}(0°) = K_y^y(0°)$ by rotational symmetry. At this angle these observables are measured to be about 70% of their maximum value, which represents a large transfer of polarization from the incoming proton to the outgoing neutron. For $K_x^{x'}$ these large effects exist also at large laboratory angles as can be seen in Fig. 1(e) where $K_x^{x'}(80°)$ is measured to be about 60% of its maximum value at $E_p = 5.97$ MeV.

Experimental values of the polarization data are given in Table II. The error analysis was the same as for the transfer observables. These polarization data were compared with theory and experiment in a separate paper.[5] We note here that the WM solution II gives a qualitative description of the polarization function at 5.97 and 9.87 MeV; however, it underestimates the magnitude of the large negative values near 40° (lab). The WM formulation does predict the near equality of the polarization and analyzing power as is found experimentally at these energies.[5] Neutron polarization data have been measured by others[15] at 6 and 10 MeV using similar experimental techniques. The magnitudes of those data tend to be somewhat smaller than those of the present data. This discrepancy is not understood.

TABLE II. Polarization function for the reaction $^3\mathrm{H}(p,n)^3\mathrm{He}$ at $E_p = 5.97$ and 9.87 MeV. $E_p$ and the uncertainty thereon are defined in Table I.

| $\theta_{\mathrm{lab}}$ (deg) | $P$ | $P$ |
|---|---|---|
| | $E_p = 5.97 \pm 0.09$ MeV | $E_p = 9.87 \pm 0.06$ MeV |
| 0.3 | ··· | $0.008 \pm 0.014$ |
| 15.3 | $-0.074 \pm 0.016$ | $-0.152 \pm 0.017$ |
| 30.3 | $-0.181 \pm 0.019$ | $-0.239 \pm 0.020$ |
| 33.9 | ··· | $-0.264 \pm 0.017$ |
| 45.3 | $-0.198 \pm 0.023$ | $-0.252 \pm 0.021$ |
| 60.3 | $-0.067 \pm 0.023$ | $-0.133 \pm 0.021$ |
| 80.3 | $0.191 \pm 0.032$ | $0.001 \pm 0.018$ [a] |
| 100.3 | ··· | $0.201 \pm 0.027$ [a] |

[a] For these data $E_p = 9.94 \pm 0.06$ MeV.

## IV. CONCLUSION

The present measurements have revealed large effects in the transfer of polarization from the incoming proton to the outgoing neutron. The comparison of these data with calculations based on the WM level structure of $^4$He has shown that both solution I and II describe the observables $K_x^{x'}$ and $K_y^y$ reasonably well at 5.97 MeV, but they are not described well by solution I at 9.94 MeV. The qualitative shape of $K_z^{x'}$ is described by both solutions at 5.97 and 9.94 MeV, but quantitative agreement is lacking. The conclusion of the present comparison is consistent with previous conclusions from comparisons of data from this reaction with $R$-matrix calculations based on the WM levels of $^4$He. With these data and experiments mentioned above a considerable body of new information on the $^4$He compound state has appeared. We would like to emphasize the need for further analysis of the four body system which would consolidate the present state of knowledge and indicate the direction for future experimental work.

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