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Reaction ^{3}H(d, n)^{4}He as a Calibrated Polarized Neutron Source and the Analyzing Power of ^{4}He(n, n)^{4}He from 20 to 30 MeV*

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Results are reported for the zero-degree analyzing power and longitudinal vector polarization transfer coefficient values of the reaction ^{3}H(d,n)^{4}He. These data allowed a calibration of the neutron polarization to an absolute accuracy of ± 2%. The analyzing power of ^{4}He was measured using the calibrated neutron beam for E_n in the range 20 to 30 MeV. The results of the ^{4}He analyzing power measurements are compared to phase-shift predictions as well as other data for ^{4}He(n,n)^{4}He and ^{4}He(p,p)^{4}He in the same energy region.

Neutron polarization experiments in the range between 20 and 30 MeV have been handicapped by the lack of a calibrated source of polarized neutrons and by uncertainties in the properties of neutron polarization analyzers. In this brief report we present two sets of results and two types of comparisons which have a significant impact on the solution to these problems. First, the development of the reaction ^{3}H(d, n)^{4}He as a new calibrated source of polarized neutrons is described. Second, the results of a calibration of the only practical neutron polarization analyzer [i.e., ^{4}He(n, n)^{4}He] are given for several angles at energies between 20 and 30 MeV. Next, the latter results for the analyzing power $A_y(\theta)$ are employed to test predictions using four available sets of phase shifts for ^{4}He(n, n)^{4}He. Finally, the values are compared to the $A_y(\theta)$ values for the charge-symmetric process ^{4}He(p, p)^{4}He. The work presented here as a whole should greatly benefit the interpretation of future neutron polarization measurements above 20 MeV.

The calibration of the beam of polarized neutrons was possible because the reaction ^{3}H(d, n)^{4}He possesses specific polarization transfer properties as a result of the $\frac{1}{2}+1 \rightarrow \frac{1}{2}+0$ spin structure. In 1971 Ohlsen, Keaton, and Gammel[1] pointed out that in such reactions the zero-degree longitudinal polarization transfer coefficient $K_z^{z'}(0°)$ is simply related to the zero-degree analyzing power $A_{zz}(0°)$. (In this paper the y axis is normal to the reaction plane and the z and z' axes are along $\vec{k}_{\text{in}}$ and $\vec{k}_{\text{out}}$, respectively.[2] Of course, at the reaction angle of 0° the z and z' axes are collinear.) The relation is given by the equation

$$K_z^{z'}(0°) = \tfrac{2}{3}[1 + \tfrac{1}{2}A_{zz}(0°)], \tag{1}$$

and the nuetrons emitted at 0° from the $d+{}^3$H reaction have polarization values $p_{z'}$ given by the expression[2]

$$p_{z'} = \frac{\frac{3}{2}K_z^{z'}(0°)p_Z}{1+\frac{1}{2}A_{zz}(0°)p_{ZZ}} = \frac{[1+\frac{1}{2}A_{zz}(0°)]p_Z}{1+\frac{1}{2}A_{zz}(0°)p_{ZZ}}. \tag{2}$$

Here p_Z and p_{ZZ} are the deuteron vector and tensor polarization components with respect to the polarization symmetry axis which is along $\vec{k}_{\text{in}}$.

Experimentally the determination of $A_{zz}(0°)$ is relatively simple, as it involves only a measurement of the ratio of neutron yields for different polarization states of the incident deuteron beam. Hence $A_{zz}(0°)$ may be measured very accurately and used to specify the polarization of the neutron beam emitted at 0°, an angle which provides other unique experimental advantages[3] in neutron polarization measurements as well. The $A_{zz}(0^\circ)$ measurements reported below allow a determination of $p_{z'}$ to an absolute accuracy of ± 2%.

Both experiments discussed here were performed at the Van de Graaff facility of the Los Alamos Scientific Laboratory (LASL) using a longitudinally polarized deuteron beam of about 60 nA intensity. The neutron-producing target consisted of a 5-cm-long gas cell filled with about 4 atm of tritium. The deuteron beam polarization was measured using the quench ratio method[4] which has been shown[5] to be accurate to better than 1%.

Values of $A_{zz}(0^\circ)$ for the reaction $^3\mathrm{H}(d,n)^4\mathrm{He}$ were determined for twelve energies from $E_d = 3.5$ to 12.8 MeV by measuring the relative neutron yield for incident deuteron beams with different values of tensor polarization. A liquid-^{4}He scintillator was used as the neutron detector. The half-angle subtended by the scintillator was about 2°, and in fact was the same as for the $^4\mathrm{He}(n,n)^4\mathrm{He}$ analyzing power measurements to be discussed later.

The results of the $^3\mathrm{H}(d,n)^4\mathrm{He}$ analyzing power measurements are presented in the top half of Fig. 1. Also shown are the earlier data of Broste *et al.*[6] The error bars shown for $A_{zz}(0^\circ)$ represent only the statistical uncertainties. The lower half of Fig. 1 shows values of the neutron polarization $p_{z'}$, calculated from the measured $A_{zz}(0^\circ)$. Note that the neutron polarizations are quite large which is an important requisite for a practical source of polarized neutrons. For these $p_{z'}$ calculations, we assumed the values $p_Z = p_{ZZ} = 0.8$ which are typical for the ion source at the LASL facility. The larger set of error bars in the lower half of Fig. 1 were calculated using an uncertainty of ± 1% in the deuteron polarization for the determination of both $\Delta A_{zz}(0^\circ)$ and $\Delta p_{z'}$, and thus reflect the absolute uncertainty with which the neutron polarizations were determined at LASL for the $^4\mathrm{He}(n,n)^4\mathrm{He}$ analyzing power measurements to be discussed below. In the future it should be possible to know deuteron beam polarizations to appreciably better than ± 1%. Anticipating this, we also show in the lower half of Fig. 1 smaller error bars which represent the uncertainties in $p_{z'}$ obtained using the present $A_{zz} \pm \Delta A_{zz}$ with a negligible error assigned to the polarization for the deuteron beam which would be used to generate the polarized neutrons. Therefore, these smaller error bars indicate the best accuracy to which the neutron polarization can be determined with the presently reported $A_{zz} \pm \Delta A_{zz}$ data. This way of presenting the uncertainties further illustrates that the error $p_{z'}$ is quite strongly dependent on the error in the magnitude of the deuteron beam polarization, but relatively insensitive to our reported error in $A_{zz}(0^\circ)$ which arises largely from our present ±1% deuteron-beam-polarization uncertainty.

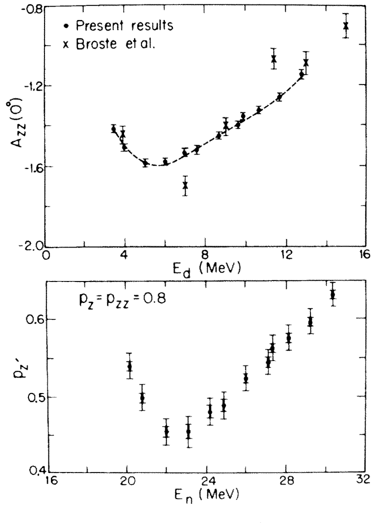

FIG. 1. Top: Results for $A_{zz}(0^\circ)$ for the reaction $^3\mathrm{H}(d,n)^4\mathrm{He}$. The dashed curve is from a least-squares fit to the data. Bottom: Values of neutron polarization $p_{z'}$ for the reaction $^3\mathrm{H}(d,n)^4\mathrm{He}$ calculated from the present $A_{zz}(0^\circ)$ data using deuteron beam polarization values $p_Z = p_{ZZ} = 0.8$. The significance of the two sets of error bars is discussed in the text.

After the neutron polarization from the reaction $^3\mathrm{H}(d,n)^4\mathrm{He}$ was calibrated, the polarized neutrons were employed to measure the analyzing power for the elastic scattering of neutrons from ^{4}He at five energies between 20 and 30 MeV. Although $^4\mathrm{He}(n,n)^4\mathrm{He}$ is the only practical polarization analyzer for neutron beams of energies above a few MeV, above about 18 MeV the uncertainties in existing data and in the n-^{4}He phase shifts have been too large to permit determination of the analyzing power with reliability. Previously, the best experimental results for the $^4\mathrm{He}(n,n)^4\mathrm{He}$ analyzing power above 20 MeV were obtained by Broste *et al.*[6] and Mutchler, Broste, and Simmons[7] who employed polarized neutrons emitted at forward angles in the reaction $^3\mathrm{H}(d,n)^4\mathrm{He}$. However their determination of the magnitude of the neutron polarization relied upon $^4\mathrm{He}(n,n)^4\mathrm{He}$ scattering measurements for neutrons produced at the same center-of-mass energies and angles in the similar reaction $^2\mathrm{H}(t,n)^4\mathrm{He}$. Although the reactions are identical in the center-of-mass system, in the latter case where the roles of the target and projectile are reversed, the neutron en-

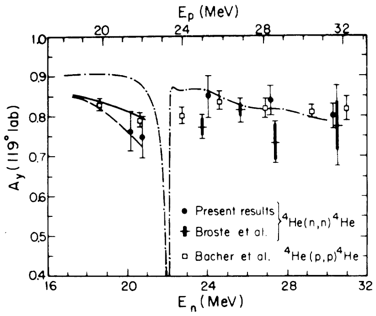

FIG. 2. Analyzing power for ^{4}He(n,n)^{4}He and ^{4}He(p,p)^{4}He near 119° (lab) from the present work and from Refs. 6 and 8. The p-^{4}He values are interpolated, and the error bars include the quoted "normalization uncertainties." The solid, dashed, and dash-dotted curves were calculated from the phase-shift solutions of Refs. 9, 10, and 11, respectively.

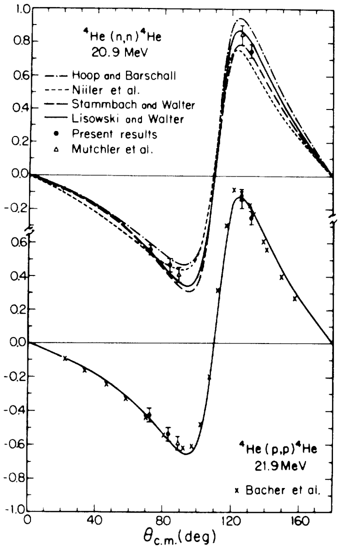

FIG. 3. Results for $A_y(\theta)$ for neutron and proton scattering from ^{4}He from the present work, that of Ref. 7 at 21.1 MeV, and that of Ref 8. The curves are phase-shift calculations for ^{4}He(n,n)^{4}He scattering at 20.9 MeV using various sets of phase shifts.

ergy at back angles is around 11 MeV. This is an energy region where the analyzing power of ^{4}He is fairly well known. Such measurements give identically the neutron polarization at corresponding forward angles in the reaction ^{3}H(d,n)^{4}He where the neutrons are emitted with 24 to 30 MeV of energy. The final results of Ref. 6 for the analyzing power for ^{4}He(n,n)^{4}He are illustrated in Fig. 2. Two sets of error bars are indicated. The thick bars indicate the uncertainties quoted in Ref. 6 but these neglect the uncertainty in their original ^{2}H(t,n)^{4}He neutron polarization determination. The larger error bars shown for the data of Broste *et al.* were obtained by incorporating these latter uncertainties.

For the present ^{4}He(n,n)^{4}He measurement the longitudinally polarized neutron beam from the reaction ^{3}H(d,n)^{4}He was employed. The neutrons emitted at 0° were collimated using 45 cm of brass inserted between the pole tips of a dipole magnet. The magnet was used to rotate the neutron polarization vector into a transverse orientation as well as to shield the helium cell and side detectors. Two arrangements for ^{4}He scatterers and neutron side detectors were utilized to measure $A_y(\theta)$ for ^{4}He. Initially a high-pressure ^{4}He gas scintillator was employed but with this equipment the counting rate was quite low and after two forward angle measurements the gas scintillator was replaced with a liquid-^{4}He scintillator. Five data points were acquired with the liquid-^{4}He polarimeter at 119° lab (132° c.m. system), an angle near the maximum analyzing power, and two points were obtained at 60° and 70° (lab) for $E_n = 20.8$ MeV to compare with the gas-scintillator measurements. The results for the analyzing power $A_y(\theta)$ are plotted in Figs. 2 and 3 where they are compared to earlier data[6,7] and to calculations of $A_y(\theta)$ for various phase-shift sets.[9-12] For the present data the error bars include the statistical error as well as the inaccuracy due to the uncertainty to which $p_{z'}$ is known at the present time.

The comparisons in Fig. 2 show that above the 22-MeV resonance the phase-shift set of Hoop and Barschall[11] predicts the analyzing power at 119° (lab) fairly well, but below the resonance predictions based on the extrapolated phase shifts of Stammbach and Walter[10] are in best agreement with the new 119° data. The data shown in the upper half of Fig. 3 further illustrate the disagreement with the $A_y(\theta)$ values calculated from the phase shifts of Hoop and Barschall below 22 MeV. Actually the data in Fig. 3 of Mutchler, Broste, and Simmons[7] obtained at 21.1 MeV are fairly consistent with the present data and both experiments slightly favor the recent phase shifts of Lisowski and Walter[9] over an extrapolation of those reported four years ago by Stammbach and Walter.[10]

In Fig. 2 and the lower half of Fig. 3 the data are compared to the more easily obtainable $A_y(\theta)$ results[8] for the charge-symmetric scattering process ^{4}He(p,p)^{4}He. The error bars for the proton data shown in Fig. 2 reflect the "normalization uncertainties" quoted by Bacher *et al.*[8] to cover the uncertainty in the calibration of the proton beam polarization. Their data shown for 119° (lab) were obtained by interpolation of measurements at 117.5° and 120°. In Figs. 2 and 3 the comparison is made for the same "compound-nuclear" energies by using two energy scales for E_n and E_p that are connected by the relation $E_n = E_p - 1.1$ MeV. Clearly the measured values of $A_y(\theta)$ for these two charge-symmetric reactions are identical within the accuracy of the experimental values. This is the first time $n+{}^4\mathrm{He}$ data have been compared to the data of Bacher *et al.* for $p+{}^4\mathrm{He}$ and the first illustration of the equality of $A_y(\theta)$ for $n+{}^4\mathrm{He}$ and $p+{}^4\mathrm{He}$ when they are compared in this way.

In summary, the reaction ${}^3\mathrm{H}(d,n){}^4\mathrm{He}$ can now be used to provide neutron beams from 20 to 30 MeV with a polarization known to about ± 2%. Such neutron beams were used to determine the ${}^4\mathrm{He}(n,n){}^4\mathrm{He}$ analyzing power $A_y(\theta)$ at 119° (lab) which is near the back-angle maximum. The data show that the phase shifts of Hoop and Barschall predict $A_y(119°)$ fairly well above 22 MeV, but not in the immediate region below the 22-MeV resonance. The angular distribution data at 20.9 MeV favor the phase-shift sets of Lisowski and Walter[9] and of Stammbach and Walter[10] over earlier sets. Comparison to ${}^4\mathrm{He}(p,p){}^4\mathrm{He}$ experimental data at the same "compound-nuclear" energies shows that the results for the two charge-symmetric reactions are identical within the accuracy of the measurements.

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$(\alpha, {}^2\mathrm{He})$ Reaction as a Spectroscopic Tool for Investigating High-Spin States*

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A ${}^2\mathrm{He}$ detection system has been developed and used to investigate the $(\alpha, {}^2\mathrm{He})$ reaction at 65 MeV on ${}^{12}\mathrm{C}$, ${}^{13}\mathrm{C}$, and ${}^{16}\mathrm{O}$ targets. Extreme spectroscopic selectivity with preferential population of final states with $(d_{5/2})^2_{4^+}$ character was observed. Applications of this experimental technique to the detection of other unbound reaction products are proposed.

Experimental systems capable of detecting nuclear reaction products in resonant final states with good efficiency and energy resolution can open up a wide range of unexplored nuclear reactions. Although at present such studies are largely confined to the detection of ${}^8\mathrm{Be}$ nuclei,[1,2] Robson[3] has pointed out many other interesting resonant systems which can be detected as reaction products. Additionally, the well known final-state interaction in the two-nucleon ${}^1S_0$, $T=1$ system can be utilized; in particular, this interaction in the ${}^2\mathrm{He}$ system localizes the two breakup protons into a narrow cone. Thus ${}^2\mathrm{He}$ can readily be detected with two proton detectors arranged in an appropriate geometry, and a few results on single neutron transfer via the $({}^3\mathrm{He}, {}^2\mathrm{He})$ reaction have been reported.[4,5]

A very interesting reaction which can be studied at reasonably high bombarding energies with such a detection system is $(\alpha, {}^2\mathrm{He})$, potentially a direct $2n$ transfer reaction very similar to the direct np-transfer reaction (α, d). The demonstrat-