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Polarization effects in two-nucleon transfer reactions and time-reversal invariance

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Polarized ^{3}He particles have been used to initiate ($^3\vec{\text{He}}$, p) reactions on light nuclei. The results obtained have been compared with the available data for (^{3}He, $\vec{\text{p}}$) and the inverse ($\vec{\text{p}}$, ^{3}He) reactions. It is suggested that the reactions proceed predominantly by a direct transfer mechanism and follow a simple reaction model which relates the polarization of the (^{3}He, $\vec{\text{p}}$) to the analyzing power of the ($^3\vec{\text{He}}$, p) reaction according to the S transfer. If time-reversal invariance is applied, the present ($^3\vec{\text{He}}$, p) results for ^{7}Li and ^{9}Be are in agreement with the ($\vec{\text{p}}$, ^{3}He) measurements on ^{9}Be and ^{11}B targets.

[NUCLEAR REACTIONS ^{7}Li($^3\vec{\text{He}}$,p)^{9}Be, ^{9}Be($^3\vec{\text{He}}$,p)^{11}B; $E=14$ MeV; ^{12}C($^3\vec{\text{He}}$,p)^{14}N, $E=33$ MeV; measured $A_y(\theta)$.]

Following the recent report by Slobodrian *et al.*[1] on the breakdown of time-reversal invariance (TRI) observed in (^{3}He, $\vec{\text{p}}$) reactions on ^{7}Li and ^{9}Be and the inverse ($\vec{\text{p}}$, ^{3}He) reactions, similar experiments have been carried out specifically to test TRI. In these tests the polarization (P) of the outgoing particles is compared with the analyzing power (A) of the inverse reaction, where P must be equal to A as a direct consequence of TRI. The polarization in the ^{9}Be(^{3}He, $\vec{\text{p}}$)^{11}B reaction has been measured at Los Alamos[2] showing results consistent with $P=A$ and in disagreement with the data of Ref. 1. The latter experiment has now been described in detail[3] including results of supplementary measurements. Similar measurements on the one-nucleon transfer reactions ($\vec{\text{p}}$,d) and ($\vec{\text{n}}$,d) have been reported recently[4,5] showing no evidence of a TRI breakdown.

Analyzing power measurements are experimentally much more convenient and reliable than polarization measurements of the reaction particles by double scattering techniques. As shown in the simple model for two-nucleon transfer reactions discussed below, the analyzing power of a reaction ($\vec{a}$,b) is equal to the polarization of the same reaction (a, $\vec{b}$), except for the sign which depends on the spin transfer. Thus it is possible to arrange a TRI test without a need to measure the polarization by double scattering, provided polarized beams of both a and b particles can be produced. Using the polarized ^{3}He beam available at Birmingham, we have measured the analyzing power of the ^{7}Li($^3\vec{\text{He}}$,p)^{9}Be and ^{9}Be($^3\vec{\text{He}}$,p)^{11}B ground-state reactions at a c.m. energy equal to that of Ref. 1. The ^{12}C($^3\vec{\text{He}}$,p)^{14}N reaction was also studied in comparison with the available data for the ($\vec{\text{p}}$, ^{3}He) reaction, to verify the validity of the simple model.

In a two-nucleon transfer reaction proceeding directly to a definite state of the final nucleus the quantum numbers (J,L,S,T) describing the transfer are not always uniquely specified. Conservation laws restrict the transfer of angular momentum J from the target state J_i to the final nucleus J_f to

$$|J_i-J_f| \leq J \leq |J_i+J_f| \quad , \tag{1}$$

where the quantum numbers (J,L,S,T) depend on the individual angular momenta of the transferred nucleons j_i,j_2; l_1,l_2; s_1 and s_2,

$$J=j_1+j_2=L+S;\ L=l_1+l_2 \ ,$$
$$S=s_1+s_2\ (=0 \text{ or } 1) \text{ and } T=t_1+t_2\ (=1 \text{ or } 0) \ . \tag{2}$$
$$(S+T \text{ odd}) \ .$$

Even in the simple case of a zero-spin target nucleus the value of the transferred orbital angular momentum need not be unique. For a nonzero spin target the position is even more complicated due to the larger number of the (J,L,S,T) combinations allowed within the restrictions (1). The multiplicity of the allowed angular momentum transfer in two-nucleon transfer reactions suggests no simple spin dependence of the analyzing power; consequently these reactions have not been widely used in spectroscopic studies.

The analyzing power measurements reported in the present work for ($^3\vec{\text{He}}$,p) reactions on both zero-spin (^{12}C) and nonzero spin (^{7}Li, ^{9}Be) targets suggest that the dominant mechanism of the reactions is less complex than anticipated. Considering first the ^{12}C($^3\vec{\text{He}}$,p)^{14}N reaction leading to the ground state (1^+;0) and the first two excited states of ^{14}N at 2.31 MeV (0^+;0) and 3.95 MeV (1^+;0), it can be seen that the differential cross-section data have patterns characteristic of a definite orbital angular momentum transfer. In Fig. 1 the differential cross sections plotted against the linear momentum transfer q (for ease of comparison) show a similar pattern for the 2.31 and 3.95 MeV transitions, while that for the ground state (g.s.) transition is quite different and out of phase with the other two. For direct transfers, the possible (J,L,S,T) quantum numbers for the g.s. and 3.95 MeV transitions are (1,0,1,0) and (1,2,1,0), whereas for the 2.31 MeV state the only possible direct transfer is (0,0,0,1). The similarity of the cross sections of the 2.31 and 3.95 MeV transitions implies that, for both, the dominant orbital angular momentum transfer is $L=0$ and for the ground state $L=2$.

The observed L-transfer values are consistent with the known[6] configurations of the states in ^{14}N in terms of a simple picture assuming a direct reaction mechanism. For the ground state of ^{14}N the configuration of the two transferred nucleons is dominantly $(^1p_{1/2})^2$, the transferred total angular momentum $J=1$, and the individual j's of the

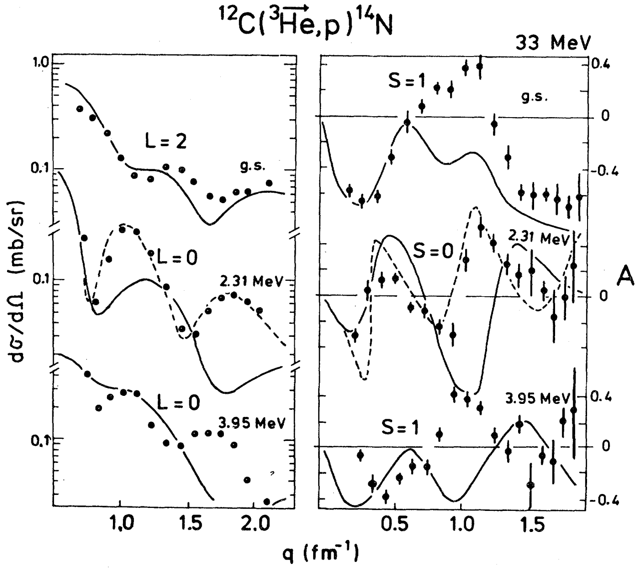

FIG. 1. Differential cross section and analyzing power of the $^{12}C(^3\vec{He},p)+^{14}N$ reaction at $E_0=33$ MeV leading to the ground state and the first two excited states of ^{14}N, plotted against the momentum transfer q. The lines represent DWBA predictions using the Bayman-Kallio (Ref. 7) form factor and spectroscopic amplitudes from Cohen and Kurath (Ref. 6).

two particles must be parallel; since $S=1$ the individual spins s must also be parallel. The simple picture for the $(^1p_{1/2})^2$ configuration can be represented as

$$\left.\begin{aligned}&\text{particle 1: } (l_1=1)\updownarrow(s_1=\tfrac{1}{2})\downarrow=(j_1=\tfrac{1}{2})\uparrow\\&\text{particle 2: } (l_2=1)\updownarrow(s_2=\tfrac{1}{2})\downarrow=(j_2=\tfrac{1}{2})\uparrow\end{aligned}\right\},\quad S=1,L=2\ . \tag{3}$$

For the second excited state the dominant transferred configuration is $(^1p_{1/2},{}^1p_{3/2})$. Again s_1 and s_2 must be parallel since $S=1$, but to be consistent with $J=1$, j_1 and j_2 as well as l_1 and l_2 must now be antiparallel:

$$\left.\begin{aligned}&\text{particle 1: } (l_1=1)\updownarrow(s_1=\tfrac{1}{2})\downarrow=(j_1=\tfrac{1}{2})\uparrow\\&\text{particle 2: } (l_2=1)\updownarrow(s_2=\tfrac{1}{2})\downarrow=(j_2=\tfrac{3}{2})\updownarrow\end{aligned}\right\},\quad S=1,L=0\ . \tag{4}$$

Similar elementary arguments lead to an $S=0$, $L=0$ transfer of two antiparallel $(^1p_{1/2})^2$ nucleons to the first excited state of ^{14}N.

Thus it has been shown that the observed L dependence of the differential cross sections of the $^{12}C(^3He,p)^{14}C$ reaction is consistent with the simple model assuming a direct transfer mechanism.

The analyzing powers of the $^{12}C(^3\vec{He},p)$ reaction leading to the three states of ^{14}N are presented in Fig. 1. Comparison of the empirical curves in the small-angle region (low momentum transfer) shows a similarity in sign and phase of the oscillation between the g.s. and the 3.95 MeV transitions, while the analyzing power for the 2.31 MeV state has an opposite phase. This implies, assuming a direct transfer mechanism and noting that the dominant L transfers for the two 1^+ states are different, that the pattern of the analyzing power depends more on the value of the transferred spin S than on the L value: For $S=1$ transfer the phase of the analyzing power is opposite to that for $S=0$. An example of a distorted-wave Born approximation (DWBA) calculation assuming a direct transfer with shell-model wave functions of Cohen and Kurath[6] and the Bayman and Kallio[7] form factor is shown in Fig. 1 (solid lines). A detailed theoretical analysis of the data is given elsewhere.[8]

The analyzing power of the $(^3\vec{He},p)$ reaction reported here can be compared with the existing data for the $(\vec{p},{}^3He)$ reaction.[9] In particular, the $^{12}C(^3\vec{He},p)^{14}N$ and $^{16}O(\vec{p},{}^3He)^{14}N$ reactions populate the same final states and, within the $1p$ shell, involve a transfer of the same pair of nucleons. The two sets of data are plotted together in Fig. 2 with an inverted sign of the $(\vec{p},{}^3He)$ analyzing power for the ground state, $S=1$ transition, and with the same sign for the 2.31 MeV, $S=0$ transition. In the forward angular region there is a striking similarity between the analyzing powers of the two reactions.

This interesting feature can be easily understood if we assume that the S-transfer value characterizes the behavior of the analyzing power. The following simple model, demonstrated schematically in Fig. 3, can explain the connection between the analyzing powers of the $(^3\vec{He},p)$ and $(\vec{p},{}^3He)$ reactions.

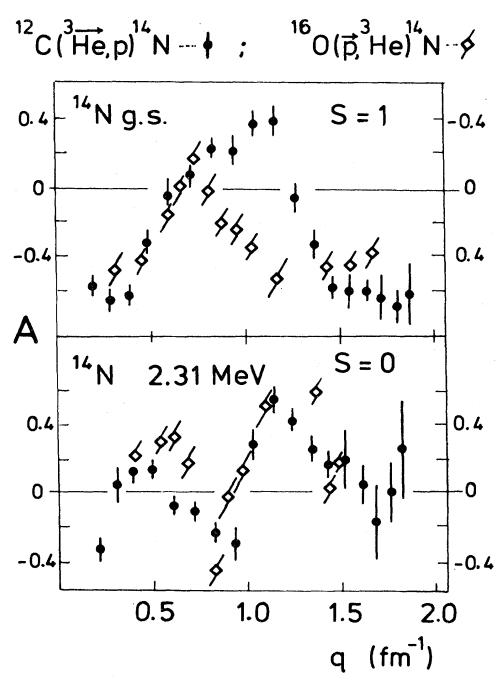

FIG. 2. A comparison of the analyzing power of the $^{12}C(^3\vec{He},p)^{14}N$ reaction at $E_0=33$ MeV with the $^{16}O(\vec{p},{}^3He)^{14}N$ data of Nelson, Chant, and Fisher (Ref. 9) at 49.5 MeV leading to the ground state and the 2.31 MeV state of ^{14}N, plotted against the momentum transfer q. Note that for ease of comparison the $(\vec{p},{}^3He)$ data for the ground state transition are shown with an *inverted* sign while those for the 2.31 MeV $S=0$ transition are *without* sign inversion.

For scattering to the left, at a certain angle θ, the analyzing power A is defined in terms of the differential cross section σ,

$$A(^3\vec{\text{He}},\text{p}) = (\sigma\uparrow - \sigma\downarrow)/(\sigma\uparrow + \sigma\downarrow) \ , \quad (5)$$

where arrows indicate spin orientation of the incident (100% polarized) beam. The polarization P of the outgoing protons in a reaction induced by an unpolarized ^{3}He beam is correspondingly determined as a difference between numbers of protons with spin "up" and "down" normalized to the total yield. Assuming that (i) the two protons in the incident ^{3}He are paired to spin = 0 and that (ii) the spin states of the three nucleons do not change during the interaction (spectator model), then from Fig. 3 it follows that

$$\begin{aligned} P(^3\text{He},\vec{\text{p}}) &= (\sigma\downarrow - \sigma\uparrow)/(\sigma\uparrow + \sigma\downarrow), \ \text{for } S=1 \ , \\ P(^3\text{He},\vec{\text{p}}) &= (\sigma\uparrow - \sigma\downarrow)/(\sigma\uparrow + \sigma\downarrow), \ \text{for } S=0 \ . \end{aligned} \quad (6)$$

Assuming (iii) the validity of time reversal invariance, i.e., $A(\vec{a},b) = P(b,\vec{a})$, it is evident that

$$\begin{array}{ccccccl} & & \text{Reaction model} & & \text{TRI} & & \\ A(^3\vec{\text{He}},\text{p}) & = & -\text{p}(^3\text{He},\vec{\text{p}}) & = & -A'(\text{p},^3\vec{\text{He}}), & \text{for } S=1, & \\ A(^3\vec{\text{He}},\text{p}) & = & \text{p}(^3\text{He},\vec{\text{p}}) & = & A'(\text{p},^3\vec{\text{He}}), & \text{for } S=0, & \end{array} \quad (7)$$

where A' indicates analyzing power of the inverse reaction, in agreement with the observed behavior of experimental data.

This result is not surprising since assumption (i) follows from the Pauli principle and assumption (ii) implies the absence of spin-orbit forces. DWBA calculations without spin-orbit distortions automatically give the result (7) but it is interesting that even with spin-orbit distortions included, Eqs. (7) are approximately satisfied by the DWBA theory for reactions within the $1p$ shell, where only $L=0$ and 2 are allowed.

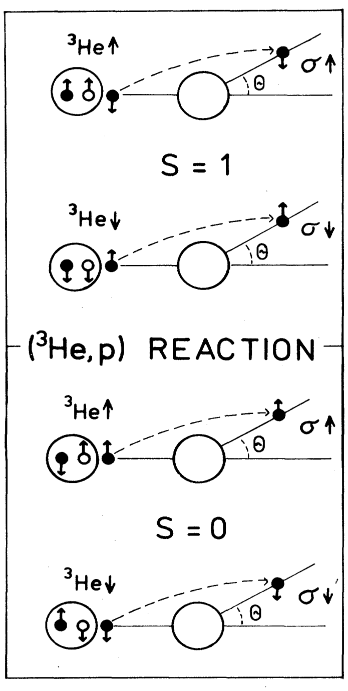

FIG. 3. A simple picture of the (^{3}He,p) reaction assuming that no change of the spin states of the three nucleon takes place during the interaction (spectator model). The analyzing power A and polarization P are defined in the text [Eqs. (5) and (6)] in terms of the differential cross sections $\sigma\uparrow$ and $\sigma\downarrow$ of the reaction initiated by ^{3}He particles with spin direction up (^{3}He$\uparrow$) and down (^{3}He$\downarrow$), respectively. By considering also the spin direction of the outgoing protons the model explains the connection between the analyzing power A and polarization P of the (^{3}He,p) reactions and the observed S dependence.

Assumption (iii), the time reversal invariance, is questioned by the recent results for the (^{3}He,$\vec{\text{p}}$) and ($\vec{\text{p}}$,^{3}He) reactions on ^{7}Li, ^{9}Be, and ^{11}B targets reported by Slobodrian *et al.*[1] Having in mind the above simple reaction model, a comparison of the results[1] with suitable ($^3\vec{\text{He}}$,p) reaction analyzing power data is meaningful. In the present work the analyzing powers of the ^{7}Li($^3\vec{\text{He}}$,p)^{9}Be and ^{9}Be($^3\vec{\text{He}}$,p)^{11}B reactions have been measured with the polarized ^{3}He beam at an energy of 14 MeV, to match the experimental conditions of Ref. 1. The outgoing particles were detected in $\Delta E \times E$ telescopes consisting of 3 and 5 mm Si(Li) detectors, ensuring a good charge and mass separation of reaction products needed to obtain clean proton spectra. This was essential since the (^{3}He,d) yields are

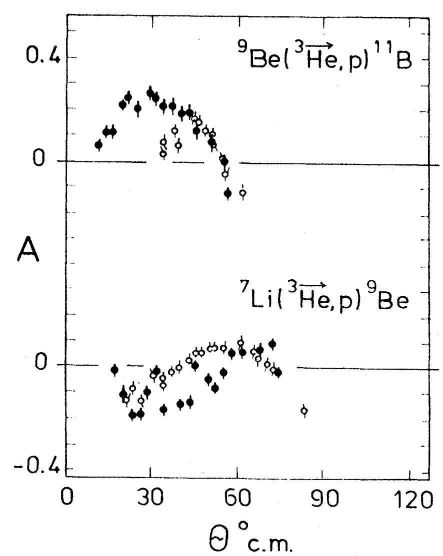

FIG. 4. A comparison of the analyzing power of the ^{9}Be($^3\vec{\text{He}}$,p)^{11}B and ^{7}Li($^3\vec{\text{He}}$,p)^{9}Be reactions at $E_0 = 14$ MeV (solid points) with their inverse ($\vec{\text{p}}$,^{3}He) measurements at Berkeley (Ref. 1) at the same c.m. energy represented by open circles. Note that the ($^3\vec{\text{He}}$,p) data have been plotted with an inverse sign.

much higher than those of the (^{3}He,p) reactions and the deuteron energy is very close to the energy of the g.s. proton group, especially for ^{7}Li. Furthermore, the ($^3\vec{\text{He}}$,d) analyzing powers are large and of the same magnitude as the (^{3}He,$\vec{\text{p}}$) polarization of Ref. 1. The ground state transition data for both ^{7}Li($^3\vec{\text{He}}$,p)^{9}Be and ^{9}Be($^3\vec{\text{He}}$,p)^{11}B reactions are shown in Fig. 4, together with the Berkeley analyzing power results reported by Slobodrian *et al.*

It is evident that the magnitude of the ^{7}Li($^3\vec{\text{He}}$,p)^{9}Be reaction analyzing power matches that of the ^{9}Be($\vec{\text{p}}$,^{3}He)^{7}Li reaction, which is consistent with time reversal invariance although the two analyzing powers do differ. The same conclusion can be drawn from comparison of the ^{9}Be($^3\vec{\text{He}}$,p) and ^{11}B($\vec{\text{p}}$,^{3}He) data in the common angular interval. While the present results clearly disagree with the polarization measurements of Slobodrian *et al.*,[1] they agree in magnitude with the recent ^{9}Be($^3\vec{\text{He}}$,p)^{11}B polarization measurements of Hardekopf *et al.*,[2] whose polarization data follow very closely the Berkeley ^{11}B($\vec{\text{p}}$,^{3}He)^{9}Be analyzing powers shown as open circles in Fig. 4.

In summary, the first measurements of analyzing powers of ($^3\vec{\text{He}}$,p) reactions indicate that the value of the transferred spin S dominates over the effect of the L transfer. Using a simple model it is possible to relate the analyzing powers of the inverse ($\vec{\text{p}}$,^{3}He) reaction to the ($^3\vec{\text{He}}$,p) reaction according to the S transfer, assuming time reversal invariance. There is no indication of the latter being violated when the present ($^3\vec{\text{He}}$,p) measurements are compared with those for the inverse ($\vec{\text{p}}$,^{3}He) reaction rather than with the (^{3}He,$\vec{\text{p}}$) results.[1]

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