Polarization Differences in the Reactions D(d,p)T and D(d,n)^{3}He and Charge Symmetry*

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(Received 17 December 1971)

Accurate measurements have been made of the analyzing power for the reaction T(p, d)D which are equivalent to proton polarizations from D(d, p)T. If allowance is made for the reaction Q-value difference between D(d,p)T and D(d, n)^{3}He, thus comparing the data at the same outgoing neutron and proton energies, the polarizations are identical. This agreement eliminates much of the concern about charge-symmetry violation in the $d+d$ reactions.

In light nuclei, Coulomb effects are expected to be small, and on the basis of charge independence of nuclear forces the measured cross sections and polarizations for mirror reactions should be similar. All previous comparisons[1-3] of the polarizations in the reactions D(d,p)T and D(d, n)^{3}He have shown, however, that the proton polarizations are consistently larger than the neutron polarizations, in fact by as much as a factor of 2 for an incident deuteron energy of 6.0 MeV. Such differences in the polarization are not unique to the $d+d$ reactions, but appear in many mirror reactions in very light nuclei, as has often been noted.[1,4] We have recently made new measurements of the proton polarization in the reaction D(d, p)T by using an incident polarized proton beam and measuring the analyzing power in the inverse reaction T(p, d)D. These two quantities are equivalent as a result of the reciprocity of nuclear reactions.[5] Our data generally agree with the earlier double-scattering results[2] but have improved experimental accuracy. The differences which were observed previously between the neutron and proton polarizations still persist, and are now much greater than the experimental uncertainties. However, these comparisons were made at the same incident deuteron energies as has always been done before. We report here that when this comparison is made at the same energy in the neutron and proton channels, our proton data agree very closely with the neutron data. This suggests that the polarization differences which have been noted in previous comparisons can be eliminated even down to 2 MeV by accounting for the Coulomb displacement energy and should not be taken as evidence that charge symmetry of nuclear forces is violated.

For the present measurements polarized proton beams were obtained from the Triangle Universities Nuclear Laboratory Lamb-shift polarized ion source[6] and were accelerated to energies between 6.7 and 14.7 MeV. The target was a tritiated titanium foil approximately 70 keV thick at 12 MeV. Beam currents on target averaged about 2 nA. Beam polarizations were typically 0.60 and were monitored continuously during the experiment by scattering from ^{4}He in a gas cell behind the main scattering chamber. Our values for the proton polarization in the reaction D(d, p)T are shown plotted in Fig. 1 together with the neutron polarization results.[3,7,8] Here the data are compared at the same energies in the $d+d$ channel and therefore at the same energies in the ^{4}He compound nucleus. The neutron data compared at 2.0 and 4.0 MeV were actually obtained at 1.9 and 3.7 MeV, respectively.[7] The differences in the neutron and proton polarizations mentioned above are seen to be largest at the lower energies and to be small at 14.0 MeV.

Differential cross-section angular distributions for D(d, p)T between 1.4 and 14 MeV were reported by Brolley, Putnam, and Rosen.[9] Porter and Haeberli[2] fitted these data with a series of Legendre polynomials and provide a convenient energy-dependent formula for obtaining the series coefficients. Using cross-section values calculated from their coefficients and our new polarization data, we determined the coefficients of the power series of associated Legendre functions which best fit angular distributions of the cross-section polarization product $\sigma(\theta)P(\theta)$. The curves shown in Fig. 1 were obtained by dividing the calculated values for $\sigma(\theta)P(\theta)$ at each energy by the $\sigma(\theta)$ val-

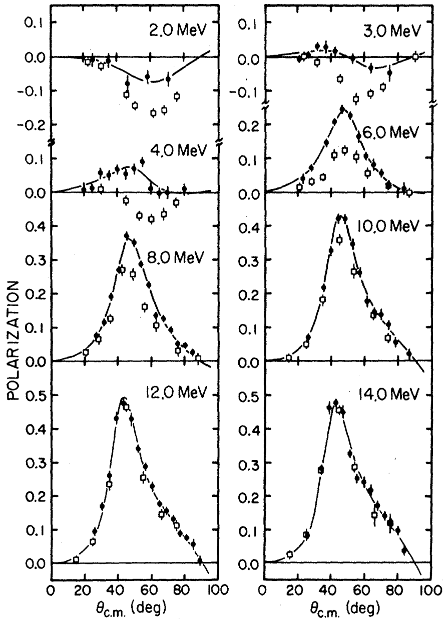

FIG. 1. The polarization of protons from the reaction D(d,p)T (circles, present work) is compared with that of neutrons from the reaction D(d,n)^{3}He (squares, from Refs. 3, 7, and 8) at incident deuteron energies from 2 to 14 MeV. The curves are calculated from Legendre polynomial fits to the proton data as outlined in the text.

ues used. Only two terms of the associated Legendre series were found necessary to fit $\sigma(\theta)P(\theta)$ in this energy range. In Fig. 2 these two coefficients are shown plotted as solid circles versus the incident deuteron bombarding energy. Odd-order terms are not needed because the identical particles in the $d+d$ channel require the polarization to be antisymmetric about 90°. The solid lines in Fig. 2 serve only to facilitate interpolation between the proton points.

The D(d,p)T coefficients shown in Fig. 2 were recognized to be quite similar to those found for the reaction D(d,n)^{3}He,[8] except for a shift in the energy scale. Because of Coulomb energy effects, the Q values of these reactions are different, +3.269 MeV for D(d,n)^{3}He and +4.033 MeV for D(d,p)T. Thus, deuteron laboratory bombarding energies 1.53 MeV higher in the reaction D(d,n)^{3}He lead to the same neutron and proton energies in the $n+{}^3$He and the $p+$T channels. When the coefficients for the reaction[8] D(d,n)^{3}He are plotted in Fig. 2 with this shift in energy scale, there is excellent agreement between the D(d,p)T and D(d,n)^{3}He coefficients. To emphasize this similarity of the reactions when compared at the same *exit*-channel energies, the neutron polarization data from Fig. 1 have been replotted in Fig. 3. They are compared here with curves calculated from coefficients taken from the lines through the D(d,p)T points in Fig. 2 at the same exit-channel energies. The excellent agreement between these curves and the neutron data demonstrates that the two mirror reactions do have identical polarizations when compared in this manner.

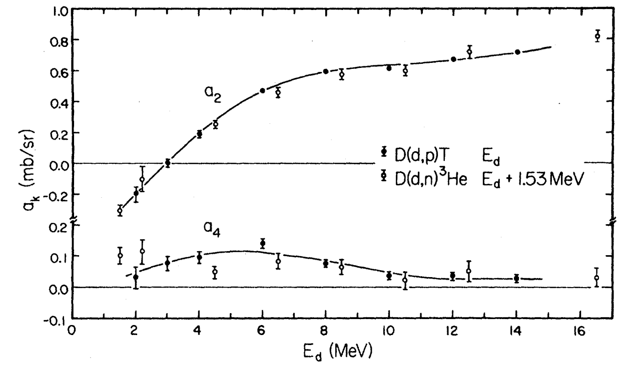

FIG. 2. The coefficients of the series of associated Legendre functions from fits to $\sigma(\theta)P(\theta)$ for D(d,p)T and D(d,n)^{3}He. For the D(d,p)T coefficients, the horizontal scale is the incident deuteron energy in the laboratory. The D(d,n)^{3}He coefficients at energies 1.53 MeV higher are plotted to allow comparison for the same outgoing proton and neutron energies. The curves are drawn through the D(d,p)T coefficients to facilitate interpolation.

One can speculate about the observed agreement between the neutron and proton polariza-

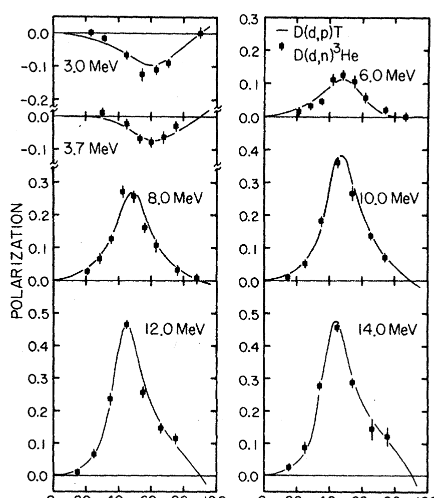

FIG. 3. The D(d,n)^{3}He neutron polarization data from Fig. 1 are compared with calculated curves of the D(d,p)T proton polarization for the same outgoing neutron and proton energies.

tions. It has been suggested that these reactions proceed predominatedly by $l=0$ stripping.[10] If so, conventional direct-reaction theory requires that polarization effects arise only from spin-dependent distortions in the entrance and exit channels.[11] Possibly when the polarizations are compared at the same entrance-channel energy, they differ because the $n+{}^3$He and $p+$T nuclear interactions are different for different energies, and when these exit-channel energies are made the same, the observed polarization agreement means the $n+{}^3$He and $p+$T nuclear interactions are alike. This interpretation is then consistent with charge symmetry. It assumes several things, however: (1) that the experimental observation of small polarizations over a wide energy range in $d+d$ elastic scattering[12,13] means that spin-dependent effects in the entrance channel are small and not sensitive to changes of energy; (2) that the Coulomb influence on the wave function in the $p+$T channel has a negligible effect on the polarization; and (3) that the differences which appear when the few ^{3}He$(n,n){}^3$He polarization measurements[14] are compared with the T(p,p)T results[15] at the same energy arise from experimental errors in the neutron results.[16]

Comparisons of the vector and tensor analyzing powers for D$(d,n){}^3$He and D(d,p)T between 10.0 and 12.3 MeV have been recently reported.[12,17-19] For the same energies in the deuteron channel, Grüebler *et al.*[18] observed differences only in T_{20}. Very accurate measurements at 10 MeV by Hilscher and Liers,[17] however, show small but significant differences in iT_{11} for the two reactions at back angles. The data of Ref. 18 were taken at 10.0 and 11.5 MeV which conveniently allows the comparison of the 11.5-MeV D$(d,n){}^3$He data with the 10.0-MeV D(d,p)T data at the same neutron and proton energy in the exit channels. When this is done, the large differences in T_{20} disappear, but then the data for iT_{11} disagree. However, in the case of incident polarized deuterons, spin-dependent effects in the deuteron channel become more noticeable, and therefore a comparison at the same exit-channel energies may not be appropriate.

In summary, the sizable differences previously reported in the neutron and proton polarizations for D$(d,n){}^3$He and D(d,p)T can be removed by shifting the D$(d,n){}^3$He energy scale to compare at the same *exit*-channel energies. This simple method does not explain differences in the vector analyzing powers for these reactions, and more of these data over a large energy range are necessary to draw further conclusions. Until the Coulomb effects are explored in more detail, our new comparison shows that it is premature to suggest that the differences in the mirror reactions D(d,p)T and D$(d,n){}^3$He indicate charge symmetry of nuclear forces is violated.

The authors would like to thank Mr. P. W. Lisowski, Mr. T. C. Rhea, and Mr. T. A. Trainor for their help in obtaining the proton polarization data, and Dr. W. J. Thompson for valuable discussion and criticism.

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*Work supported in part by the U. S. Atomic Energy Commission.

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Hyperfine Interactions of the First Excited 2^+ State of ^{18}O in 7^+ and 6^+ Ions

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(Received 11 October 1971)

Perturbed angular correlations were measured between 1.98-MeV γ rays de-exciting the 3.3-psec 2^+ state of ^{18}O and the ^{18}O* particles following the reaction ^{12}C(^{18}O, ^{18}O*)^{12}C at 33 MeV. A magnetic spectrometer was used to resolve the ^{18}O* ions into the component 8^+, 7^+, and 6^+ charge states, and the correlations were determined separately for each. The measurements yield information on hyperfine interactions in the 7^+ and 6^+ charge states. Limits are obtained on the ionic ground-state occupancies and on the value of the nuclear g factor.

The particle-γ angular correlation of the 1.98-MeV transition from the first excited state of ^{18}O following the reaction ^{12}C(^{18}O, ^{18}O*)^{12}C has been described recently.[1] These data are consistent with (i) pure $I_z=0$ population of the 2^+ state with the symmetry axis z close to the momentum-transfer direction, and (ii) strong hyperfine interaction (HFI) in the 7^+ ionization state. These measurements have now been repeated, with the difference that the predominant charge states 6^+, 7^+, and 8^+ of the scattered ^{18}O have been separated in a magnetic spectrometer and the correlations measured for each. For the 8^+ ions the correlation confirmed an essentially pure $I_z=0$ population. The 7^+ correlation exhibited a strong perturbation, and the 6^+ was almost unperturbed.

The experimental arrangement [Fig. 1(a)] was very similar to that of Ref. 1. A 100-μg/cm^2 carbon target was bombarded by 500 nA of 33-MeV ^{18}O 5^+ ions. The 8^+, 7^+, and 6^+ charge states of the ^{18}O ions in the 1.98-MeV state were resolved with a double-focusing, 188° magnetic spectrometer described by Start *et al.*[2] We placed the spectrometer at 21° to the beam, following Ref. 1. Both the magnetic rigidity and the energy of the particles were recorded by a position-sensitive counter at the spectrometer image. The only resolution problem encountered was overlap of the 6^+ ions with ^{12}C 5^+ ions emitted in the *same* reaction [but at a different c.m. angle, see Fig. 1(b)]. These groups were adequately separated by differential slowing down in a 1-mg/cm^2 nickel foil in front of the counter. The spectrometer entrance slit was 1° wide (in the reaction plane), 10° high, and curved to minimize kinematic broadening. Charge-exchange effects in the residual vacuum at any point around the whole of the magnet are estimated as being less than 0.3%.[3] The arrangement of the 3-in.×3-in. NaI scintillators is shown in Fig. 1(a). Coincidence spectra were recorded using the multiparameter system described in Ref. 2. Singles counting rates did not exceed 3×10^4/sec. The