Anomalous Quenching of $S = 1$ Two-Nucleon Transfer*

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Examination of the ground-state transitions of the (p,t) and $(p,{}^3\mathrm{He})$ reactions on all $T_z=\frac{1}{2}$ nuclei from ^{21}Ne through ^{39}K reveals a systematic suppression of the $S=1, T=0$ component of the $(p,{}^3\mathrm{He})$ transfer cross sections which is not explained in terms of current structure and reaction theories.

In this Letter we wish to call attention to a strikingly persistent feature of the ground-state transitions of (p,t) and $(p,{}^3\mathrm{He})$ reactions on the $T=\frac{1}{2}$ nuclei of the *sd* shell. These transitions populate mirror states with $T=\frac{1}{2}$ and $T_z=\pm\frac{1}{2}$; hence both members of each isospin doublet should have essentially identical nuclear wave functions. The (p,t) reaction can populate these states only via pickup of a $S=0$, $T=1$ nucleon pair, while the $(p,{}^3\mathrm{He})$ reaction can proceed via pickup of both $S=0, T=1$ and $S=1, T=0$, pairs. We have observed[1] that for every $T=\frac{1}{2}$ target in the *sd* shell from ^{21}Ne through ^{39}K, the ground-state $(p,{}^3\mathrm{He})$ transition appears to proceed by pure $S=0$, $T=1$ transfer. The presence of any incoherent $S=1$, $T=0$ contribution would result in cross sections for $(p,{}^3\mathrm{He})$ relative to (p,t) larger than those observed.

At present we are unable to explain this anomaly. Significant $S=1, T=0$ strength is predicted by the best available shell-model wave functions for these ground-state transitions. Also, such strength is both predicted and observed for various excited states. Thus, some aspect of either nuclear structure or direct-reaction mechanism serves to quench systematically the ground-state $S=1, T=0$ transfer strengths. The source of the quenching appears to lie outside the conventional realm of such theories. If this anomaly is confirmed by further experimental work, it will present a significant challenge to either current shell-model theory or distorted-wave Born-approximation (DWBA) theory, or both.

The experimental measurements employed 40-MeV protons from the Michigan State University cyclotron. The reaction products were momentum analyzed in a split-pole magnetic spectrograph and detected with position-sensitive proportional counters. This apparatus yielded excellent particle identification and energy resolutions in the range 15–30 keV. Angular distributions were usually measured in the region of 6° to 50°. In the context of the present note, the key experimental measurements were of the $(p,{}^3\mathrm{He})$-to-(p,t) cross-section ratios. These measurements were typically made by measuring both (p,t) and $(p,{}^3\mathrm{He})$ differential cross sections during the same experimental run, with the same configuration of target, beam, and counter. Only the magnetic field of the spectrograph was changed in order to bring both ^{3}He's and tritons to the same position on the focal plane. The errors in these relative cross-section measurements are estimated to be less than 10%. Absolute cross-section scales are estimated to be accurate to 20%. These were assigned by measuring elastic proton-scattering counting rates relative to the (p,t) and $(p,{}^3\mathrm{He})$ rates and assuming standard[2] optical-model estimates for the elastic cross sections.

The ground-state angular distributions are shown in Fig. 1, with the (p,t) values elevated by one order of magnitude. The curves through the (p,t) distributions are DWBA calculations with a single set of optical-model parameters, the proton values being adapted from Greenlees and Pyle[3] and the mass-3 values from Urone *et al.*[4] (The parameters used for the outgoing tritons and ^{3}He's are identical and have the characteristic that they fit ^{3}He and triton elastic scattering simultaneously.) The DWBA curves have been generated with current[5-7] mixed-configuration shell-model wave functions. However, the (p,t) shapes are independent of any variation of wave function within the *sd* shell and the absolute normalization of theory to experiment does not directly concern us in the present context. For the $(p,{}^3\mathrm{He})$ reaction, the contributions to the complete calculated differential cross sections (solid curves) from $S=0, T=1$ transfer (dotted curves) and $S=1, T=0$ transfer (dot-dashed curves) are added incoherently. A spin-isospin exchange term in the interaction potential[8] with values of $[D(0,1)]^2=0.71$ for the $S=0, T=1$ transfer strength and of $[D(1,0)]^2=0.30$ for the $S=1, T=0$ transfer strength[9] was employed in the DWBA calculations. The

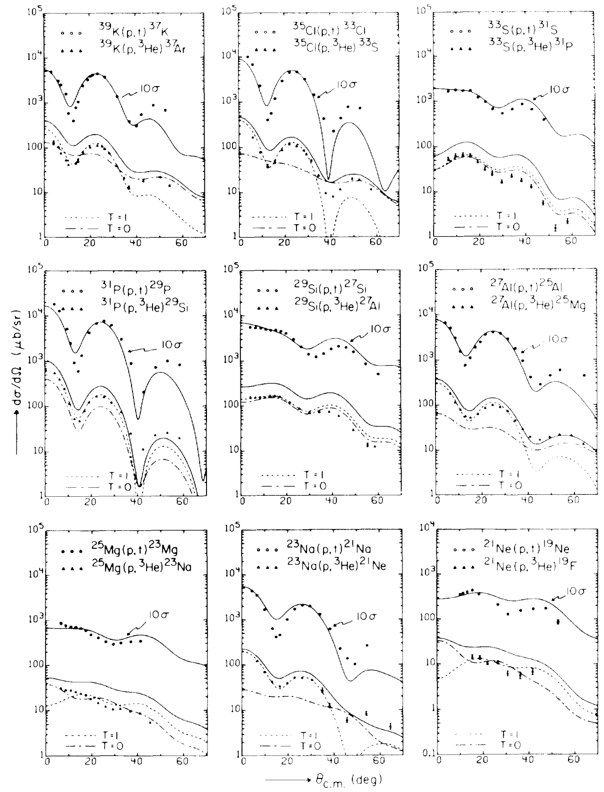

FIG. 1. Angular distributions of mirror (p,t) and $(p,{}^3\mathrm{He})$ ground-state transitions on $T_z=\frac{1}{2}$ nuclei in the *sd* shell. The curves represent DWBA calculations. The same optical parameters are used for all nuclei. Proton parameters: $V=45.5$ MeV, $r_0=1.20$ fm, $a=0.70$ fm, $W_D=14.0$ MeV, $r_0'=1.25$ fm, $a'=0.70$ fm, $r_c=1.25$ fm. Mass-3 parameters: $V=173.9$ MeV, $r_0=1.15$ fm, $a=0.72$ fm, $W=20.6$ MeV, $r_0'=1.50$ fm, $a'=0.82$ fm, $r_c=1.40$ fm.

$(p,{}^3\mathrm{He})$ DWBA calculations for these transitions have been multiplied by the same normalization factors which served to match the $S=0, T=1$ (p,t) DWBA calculations to the corresponding experimental (p,t) data. The shell-model wave functions, together with the above ratio $R=[D(1,0)/D(0,1)]^2=0.42$ and the theory-experiment normalization factors obtained from the (p,t) comparison, predict the additional amount of $S=1, T=0$ transfer strength for the $(p,{}^3\mathrm{He})$ transitions shown by the dot-dashed curves.

The uniform results for each of the nine pairs of mirror transitions shown in Fig. 1 is that the $S=0, T=1$ pickup strength, as predicted from the measured mirror (p,t) differential cross sections, reproduces all by itself the total observed $(p,{}^3\mathrm{He})$ intensity. The incoherent addition of *any* significant amount of $S=1, T=0$ strength serves to make the predicted $(p,{}^3\mathrm{He})$ differential cross sections too large, and often makes the agreement in shape worse, too. This result is essentially independent of nuclear-structure assumptions beyond the basic assumption that the mirror states have the same nuclear wave functions. It is anomalous in that no conventional theory, from the simplest one-component model through to full *sd*-shell space wave functions of many hundreds of terms, systematically predicts vanishing $S=1, T=0$ amplitudes for these transitions. In addition to typically predicting significant amounts of $S=1, T=0$ strength for ground-state transitions, such theories also predict significant, sometimes dominant, $S=1, T=0$ strength for various excited-state transitions. Another aspect of the present anomaly, then, is that the $S=1, T=0$ quenching phenomenon appears to be confined to the ground states. Extensive evidence for $S=1, T=0$ transfer is seen[10] in the data on excited-state transitions.

Our results depend, of course, on the correct treatment of the reaction theory of relative (p,t) and $(p,{}^3\mathrm{He})$ cross sections. We have tested our ability to relate (p,t) and $(p,{}^3\mathrm{He})$ cross sections correctly via DWBA by analyzing differential cross sections to isobaric-analog $(T=\frac{3}{2})$ and to excited mirror $(T=\frac{1}{2})$ final states. We correctly predict the $(p,{}^3\mathrm{He})$ to (p,t) cross section ratios for transitions to $T=\frac{3}{2}$ isobaric-analog states, which the selection rules allow to proceed only by $S=0, T=1$ transfer. This serves to validate that such aspects as relative Q values and optical-model parameters have been dealt with properly. On an opposite tack, we also correctly predict relative experimental cross sections for many of the transitions to excited mirror states in which the calculated $(p,{}^3\mathrm{He})$ cross sections are dominated by the $S=1, T=0$ transfer component. Here of course, the amount of $S=1, T=0$ transfer which is predicted for $(p,{}^3\mathrm{He})$ depends directly on the strength $[D(1,0)]^2$ of the effective interaction for the transfer. The value of $R=0.42$ which we have used is consistent with many theoretical and empirical estimates.[8,9] In particular, it serves to give a good average match between (p,t) and $(p,{}^3\mathrm{He})$ cross section for mirror excited states[10] in the same nuclei discussed here. The anomaly is that the ground-state data suggest a triplet-to-singlet transfer-strength ratio of $R\cong 0$.

A quenching of the $S=1, T=0$ transfer component in ground-state transitions was observed by Bass *et al.*,[11] who compared $({}^3\mathrm{He},n)$ and $({}^3\mathrm{He},p)$ reactions on $^{35}\mathrm{Cl}$, and by Hardy, Brunnader, and

Cerny,[12] who measured the (p,t) and $(p,{}^3\mathrm{He})$ reactions on $0^+, T=1$ target nuclei in the *sd* shell. The generality of the phenomenon has not been recognized previously, however. Hardy, Brunnader, and Cerny,[12] for example, attributed the $S=1, T=0$ quenching to the pickup of paired nucleons from the same orbit. This explanation is not adequate to explain our observations, however, since in the case of ${}^{33}\mathrm{S}$ and ${}^{29}\mathrm{Si}$, for example, the pair of picked-up nucleons come predominantly from two different orbits. Also, of course, the best available quantitative estimates of such effects come from the wave functions we are using in the analysis.

In a previous study of mirror (p,t) and $(p,{}^3\mathrm{He})$ transitions on $T_z=\frac{1}{2}$ nuclei in the p shell,[13] several transitions with cross-section ratios of (p,t) to $(p,{}^3\mathrm{He})$ were found in which the $(p,{}^3\mathrm{He})$ values were smaller even than the limits set by the corresponding (p,t) values. Interference terms arising through spin-orbit coupling in the optical potentials which mix the $S=0$ and $S=1$ contributions in the $(p,{}^3\mathrm{He})$ cross sections were suggested, though not tested, as a source of that anomaly. In none of our examples do the $(p,{}^3\mathrm{He})$ cross sections fall below the $S=0, T=1$ limit set by the mirror (p,t) cross sections. This, together with significant $S=1$ strengths observed for excited states,[10] leads us to think that spin-orbit effects in the DWBA and the consequent loss of incoherence do not explain our present results. This is consistent with the conclusion of the quantitative analysis of Nelson and Falk,[14] which finds that inclusion of spin-orbit coupling into the DWBA calculations alters cross sections by amounts which fluctuate from case to case within a range of about 10%.

If a solution to the present anomaly is sought in the area of nuclear structure, the goal can be either to find a mechanism particular to ground states which largely eliminates the $S=1$ two-nucleon overlap or to develop a theory with much enhanced $S=0$ overlap for ground states, so that in comparison the $S=1$ strength becomes negligible. The difficulties with these approaches are that the first requires a differentiation between ground and excited states more extreme than seems otherwise justified and that the second, if achieved, would disturb the relatively consistent reproduction of ground and various excited-state strengths already achieved for $S=0$ transfer with present wave functions. If a solution is sought in terms of reaction theory, one reasonable area to investigate would seem to be whether two-step processes, either sequential one-nucleon transfer or coupling of inelastic scattering and transfer, can cause a selective interference such that the $S=1$ strengths to the ground states alone are quenched. Other avenues to pursue include the possibilities of coherent charge-exchange processes or knockout contributions selectively affecting the ground-state transitions.

The $S=1, T=0$ transfer component can be studied directly by means of the (d,α) and (α,d) reactions, since these should transfer only $T=0$ to first order. Our present results hence suggest that the (d,α) strengths of the corresponding ground-state transitions should be very weak. Further experimental work comparing $({}^3\mathrm{He},p)$ and $({}^3\mathrm{He},n)$ cross sections is also needed to test the persistence of the effect.

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