Evidence for Higher-Order Processes in Single-Nucleon Transfer Reactions*

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(Received 31 August 1972)

Anomalies in the shapes of angular distributions with respect to predictions of the distorted-wave Born approximation for several weak transitions in the reactions ^{172}Yb(p,d) and ^{186}W(p,d) are interpreted as resulting from inelastic excitations in the entrance and exit channels. These anomalies are shown to be reproduced when the reactions are treated within the coupled-channel Born approximation.

The single-nucleon transfer reaction is perhaps the most widely used of all nuclear reactions for spectroscopic studies. The traditional model for extracting nuclear-structure information from such reactions is the distorted-wave Born approximation (DWBA). Since the DWBA is a first-order approximation, it can be invalidated by strong higher-order processes, the most important of which are usually those involving collective inelastic excitations in the target and residual nuclei.

In the past there have been many searches, both theoretical and experimental, for evidence of the presence of inelastic processes in single-nucleon transfer reactions,[1] but the results have been largely inconclusive. This has been due partly to the inadequacies of the theoretical methods employed, but in addition, the searches were generally for transitions which are anomalously large compared to DWBA predictions. However, it cannot be ruled out that such magnitude discrepancies may be due to inadequate descriptions of the structure of the states involved. On the other hand, the shapes of angular distributions are relatively insensitive to the nuclear structure. Thus, it seems that significant deviations in angular distribution shapes from DWBA predictions would be much stronger evidence for intermediate inelastic excitations than magnitude changes. Indeed, such has been the case for two-nucleon transfer reactions on rare-earth nuclei, where large shape anomalies have been observed.[2] It is not surprising that such anomalies have not previously been observed in single-nucleon transfer reactions, since most experiments in this mass region have been performed at only a few angles.[3]

In this Letter we present what we believe to be very strong evidence of inelastic effects in single-nucleon transfer reactions; and we base this evidence primarily on the shapes of the angular distributions. The specific reactions considered are ^{172}Yb(p,d) and ^{186}W(p,d). Both the $\frac{1}{2}^-$[521] band in ^{171}Yb and the $\frac{1}{2}^-$[510] of ^{185}W contain at least one direct transition with a small Nilsson coefficient ($\frac{3}{2}^-$ of ^{171}Yb and $\frac{1}{2}^-$ of ^{185}W), thus emphasizing any inelastic effects in these transitions.

The experiments were performed with proton beams from the Yale MP tandem accelerator, with the outgoing deuterons detected in a multigap magnetic spectrograph. In the ^{172}Yb(p,d) experiment two separate runs were performed at different sets of angles using a 97% isotopically enriched target of approximately 300 μg/cm^2 thickness, 17-MeV protons, and a total charge collection of 4000 μC and 2200 μC, respectively. The resultant average energy resolution was approximately 10 keV full width at half-maximum (FWHM). In the ^{186}W(p,d) experiment a single run of 10 000 μC was performed using 18-MeV protons and a 97% isotopically enriched target of approximately 200 μg/cm^2 in thickness. The energy resolution was approximately 14 keV FWHM.

The effects of the inelastic processes were calculated in the coupled-channel Born approximation using the source-term method, the details of which have been described elsewhere.[4] The inelastic scattering was calculated to all orders, and all possible transitions were considered between the states of the target nucleus up to the 4^+ member of the ground-state rotational band and those of the final nucleus band up to the $\frac{9}{2}^-$ state. In the ^{172}Yb(p,d) case it was found to be essential to include all of these states in the calculation in order to reproduce the experimental angular distribution. The structure of the nuclei was assumed to follow the Bohr-Mottelson adiabatic model. The intrinsic states of the odd nuclei were described as single-quasiparticle states determined by a BCS calculation with the single-particle orbitals obtained from a diagonalization of the Hamiltonian assuming a Woods-Saxon well with quadrupole (β_2) and hexadecapole (β_4) deformations.[5] In order to reproduce the angular distributions over the entire angular range, it was

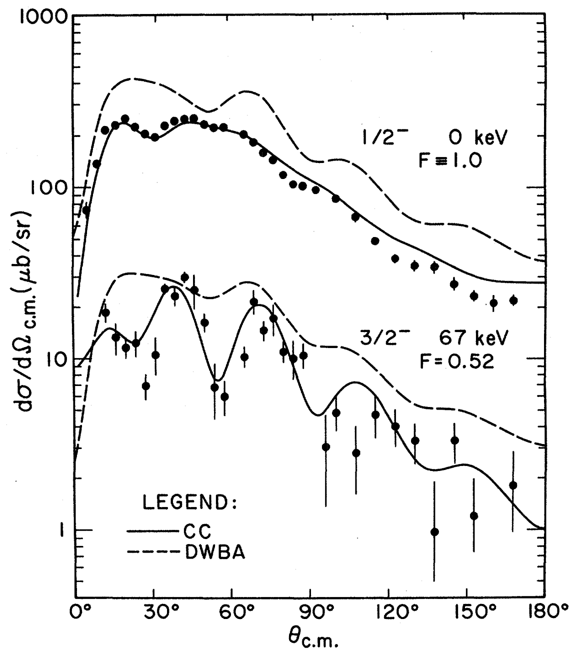

FIG. 1. The reaction ^{172}Yb(p,d) at 17 MeV to the $\frac{1}{2}^-$ and $\frac{3}{2}^-$ members of the ground-state rotational band of ^{171}Yb. The quantities F are the numbers by which both the coupled-channel (CC) and DWBA calculations were normalized in order for the coupled-channel results to reproduce the experimental relative magnitudes.

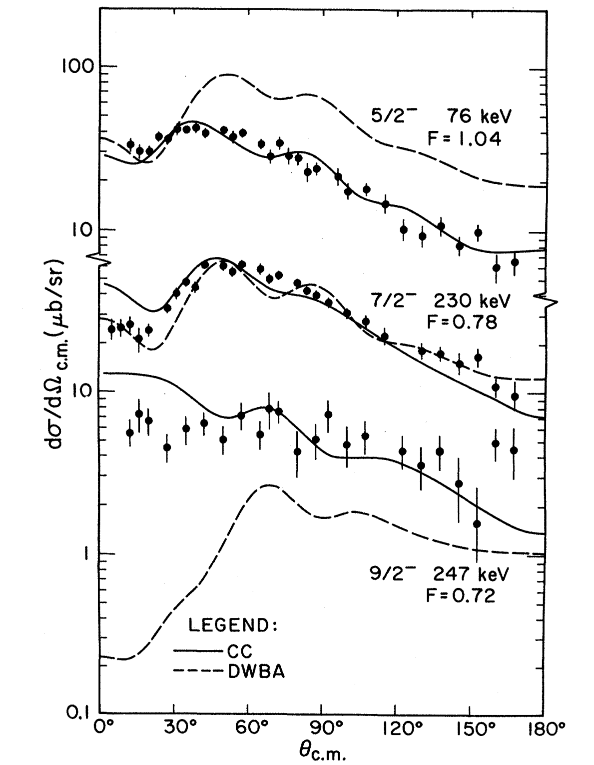

FIG. 2. The reaction ^{172}Yb(p,d) at 17 MeV to the $\frac{5}{2}^-$, $\frac{7}{2}^-$, and $\frac{9}{2}^-$ members of the ground-state rotational band of ^{171}Yb. The quantities F have the same meaning as in Fig. 1.

found to be essential to match the form factors outside the nuclear surface to Hankel functions corresponding to the proper neutron separation energy. The calculations tended to be insensitive to the proton optical-model parameters, and consequently average sets of parameters were chosen.[6] On the other hand, the calculations were extremely sensitive to the choice of deuteron optical-model parameters. Therefore, the parameters were determined by fitting the 12-MeV deuteron elastic-scattering data of Christensen *et al.*[7] in a coupled-channel calculation, using the optical parameters of these authors as a starting point and then adjusting the imaginary geometry.

The data and calculations for the ^{172}Yb(p,d) reaction to the $\frac{1}{2}^-$[521] band of ^{171}Yb are shown in Figs. 1 and 2. It should be noted that the angular distribution for the $\frac{3}{2}^-$ transition shows strong oscillations in contrast to the moderate oscillations for the $\frac{1}{2}^-$ transition, although the DWBA predicts these two angular distributions to be similar and only moderately oscillatory. As can be seen, the weak $\frac{9}{2}^-$ transition also exhibits strong deviations from the DWBA predictions at forward angles. On the other hand, the coupled-channel calculations shown as the solid lines in the figures reproduce the shapes of the angular distributions quite well, indicating that the shape anomalies can be explained by the presence of inelastic processes. The relative strengths of the states are not exactly reproduced, but the results of coupled-channel calculations using altered form factors and deuteron optical-model parameters, which will be presented in future publications,[8,9] suggest that reasonable variations in these quantities could improve the relative magnitudes.

The data and calculations for the ^{186}W(p,d) reaction to the $\frac{3}{2}^-$ and $\frac{1}{2}^-$ states of the $\frac{1}{2}^-$[510] band of ^{185}W are shown in Fig. 3. This band is well known to mix with the nearby $\frac{3}{2}^-$[512] band. However, since preliminary calculations indicated that for these two states only the magnitudes and not the shapes of the angular distributions are affected significantly by the interband coupling, this coupling has been ignored in the calculations shown in the figure. The full calculation including the Coriolis mixing will be presented in a future publication.[9] As can be seen, the angular

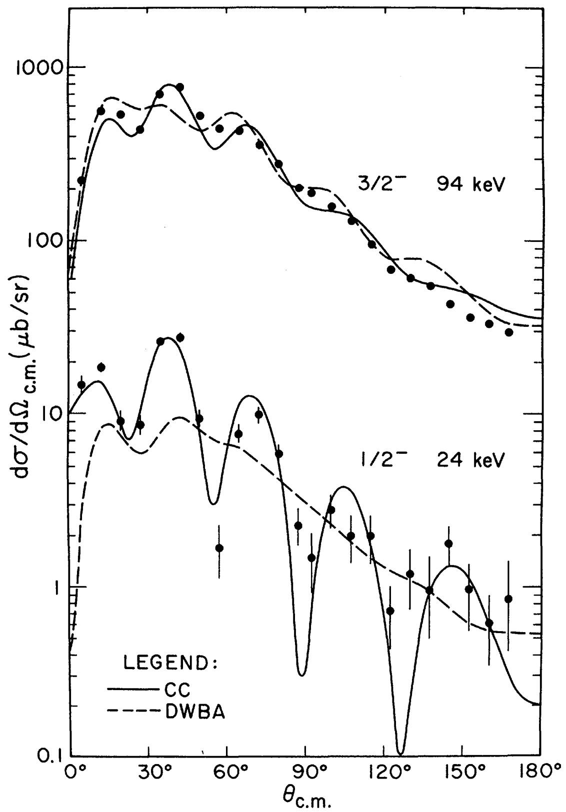

FIG. 3. The reaction $^{186}W(p,d)$ at 18 MeV to two states of the $\frac{1}{2}^-$[510] band of ^{185}W. The relative normalization of the calculations from one state to the other is arbitrary.

distribution for the $\frac{1}{2}^-$ state shows strong oscillations not seen in the $\frac{3}{2}^-$ state nor predicted by the DWBA. The coupled-channel calculation, on the other hand, accounts for the shapes of both experimental angular distributions.

The DWBA calculations shown in the figures were performed using the same optical-model parameters as in the coupled-channel calculations. Some improvement in the DWBA fits to the strong transitions can be achieved when the deuteron optical-model parameters are adjusted to yield the same elastic scattering as the coupled-channel calculation. This is not surprising since such parameters include implicitly some of the inelastic coupling. These considerations will be discussed in future publications.[8,9]

In summary, then, based on anomalies in the shapes of the angular distributions rather than the magnitudes, we believe we have found definite evidence for the presence of inelastic processes accompanying single-nucleon transfer reactions. In addition, these angular distributions are well reproduced by coupled-channel calculations using the source term method, which explicitly accounts for the inelastic effects. Non-negligible magnitude deviations from DWBA predictions are observed; however, because of their sensitivity to the specific description of the nuclei, such magnitude changes can be attributed with much less certainty to the effect of inelastic processes. These results call into question the spectroscopic information extracted on the basis of the DWBA from existing single-nucleon transfer experiments on deformed nuclei, especially for weak transitions.

The authors would like to acknowledge the interest and generous help of Dr. Bent Sørensen in the theoretical calculations and the assistance of Dr. Nelson Stein, Dr. W. D. Callender, Mr. C. F. Maguire and Mr. T. P. Cleary in the experimental aspects of this work.

*Work supported by the U. S. Atomic Energy Commission under Contract No. AT(11-1)-3074.

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