STRIPPING REACTIONS ON ODD-A NUCLEI INITIATED BY VECTOR-POLARIZED DEUTERONS*

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Stripping reactions on odd-A nuclei to states of nonzero spin may involve two or more values of the total angular-momentum transfer j_n for the captured nucleon. Results for the reaction $^{53}\mathrm{Cr}(d,p)^{54}\mathrm{Cr}^*$ ($Q=6.71$ MeV), initiated by vector-polarized deuterons, show that measurements of the vector analyzing power can be used to determine the separate cross-section contributions for the possible j_n values.

Measurements of the angular distribution in (d, p) stripping reactions have long been useful in determining the orbital angular momentum l_n of the neutron captured by the target nucleus. It has recently been shown[1] that measurements with polarized deuterons allow an unambiguous determination of the total angular momentum $j_n = l_n + \frac{1}{2}$ or $j_n = l_n - \frac{1}{2}$ transferred by the captured neutron when the target nucleus has zero spin. The quantity measured in these experiments is the vector analyzing power, which is proportional to the left-right asymmetry of the outgoing protons when the reaction is induced by vector-polarized deuterons.

For stripping reactions on target nuclei with spin (odd-A nuclei), two or more values of j_n are in general consistent with conservation of total angular momentum and parity. To understand the structure of the final states, it is important to determine the transition amplitudes for the different j_n values. Since the cross section is sensitive to l_n it can be used to determine the cross-section contributions for two different l_n values,[2] but such measurements do not distinguish between $j_n = l_n + \frac{1}{2}$ and $j_n = l_n - \frac{1}{2}$ transfers. The present Letter shows that measurements of the vector analyzing power determine the relative cross-section contributions for the different j_n values for the captured neutron.[3] The transition amplitudes can then be obtained by comparing these cross-section contributions with distorted-wave Born-approximation (DWBA) calculations.

We have studied the reaction $^{53}\mathrm{Cr}(d,p)^{54}\mathrm{Cr}^*$ ($Q = 6.71$ MeV) leading to the first excited state in $^{54}\mathrm{Cr}$ at a bombarding energy of 10 MeV. The target and final-state spins are $\frac{3}{2}^-$ and 2^+, respectively, so the allowed values of l_n are 1 and 3. However, previous cross-section measurements[2] have shown that contributions from $l_n = 3$ reactions are negligible. Therefore, we are concerned only with $j^\pi = \frac{1}{2}^-$ and $\frac{3}{2}^-$ reactions. The vector analyzing power for this reaction should be sensitive to the mixing of the j_n values, since $l_n = 1$ reactions show a pronounced j dependence of the vector analyzing power.[1]

Absolute cross sections and vector analyzing powers for this reaction were measured using the purely vector-polarized deuteron beam from the University of Wisconsin Lamb-shift polarized ion source.[4,5] At each reaction angle θ measurements were made with a spin-up deuteron beam (polarization axis parallel to $\vec{k}_d \times \vec{k}_p$) and with a spin-down beam using detectors placed on one side of the incident-beam direction only. The cross section for an unpolarized beam and the vector analyzing power, $iT_{11}(\theta)$, were calculated from Eq. (6) of Schwandt and Haeberli.[6] The experimental results are shown in panels (a) and (b) of Fig. 1.

To understand qualitatively if the vector-analyzing-power results can be explained in terms of a mixture of the allowed $\frac{1}{2}^-$ and $\frac{3}{2}^-$ reactions, the data were compared with the expected angular distributions if this reaction were either pure $\frac{1}{2}^-$ or pure $\frac{3}{2}^-$. The angular distributions of the cross section and of the vector analyzing power for pure $\frac{1}{2}^-$ and $\frac{3}{2}^-$ reactions were obtained from measurements on even-A nuclei at the same bombarding energy. Two sets of data for each j^π reaction were obtained, namely for $^{52}\mathrm{Cr}(d,p)^{53}\mathrm{Cr}$ ($Q = 5.73$ MeV for the $\frac{3}{2}^-$ and $Q = 5.17$ MeV for the $\frac{1}{2}^-$ reaction) and for $^{54}\mathrm{Fe}(d,p)^{55}\mathrm{Fe}$ ($Q = 7.01$ MeV for the $\frac{3}{2}^-$ and $Q = 6.60$ MeV for the $\frac{1}{2}^-$ reaction). The results are shown in panels (c)-(f) of Fig. 1. The similarities of the measurements on the two nuclei are quite striking. The small differences observed are perhaps due to the difference in Q value of about 1.5 MeV. The solid curves drawn through the data for the even-A nuclei are intended to serve as "calibration curves" for the cross section and the vector analyzing power for each j_n. In drawing the curves more weight was given to the $^{54}\mathrm{Fe}$ data for which the Q values are close to the Q value for the reaction on $^{53}\mathrm{Cr}$.

The calibration curves for the vector analyzing power are also shown with the data for the reaction on $^{53}\mathrm{Cr}$ in panel (b) of Fig. 1. It is immediately clear that these data cannot be explained by assuming a pure $\frac{1}{2}^-$ or pure $\frac{3}{2}^-$ neutron transfer. In general, the measured points lie between the two calibration curves. Thus one can ask whether it is possible to describe the data in terms of a mixture of pure $\frac{1}{2}^-$ and $\frac{3}{2}^-$ neutron transfers.

To give a quantitative description of the mixing of the two j_n values we use the results of Satchler[7] that the different j_n values contribute incoherently to the reaction cross section and vector analyzing power. From Eqs. (18) and (86) of Ref. 7 the cross section and vector analyzing power for the mixed reaction can be written, respectively, as

$$\sigma = \sigma(\tfrac{1}{2}^-) + \sigma(\tfrac{3}{2}^-), \tag{1}$$

$$\begin{aligned} iT_{11} &= \frac{\sigma(\frac{1}{2}^-)iT_{11}(\frac{1}{2}^-) + \sigma(\frac{3}{2}^-)iT_{11}(\frac{3}{2}^-)}{\sigma(\frac{1}{2}^-) + \sigma(\frac{3}{2}^-)} \\ &= \frac{iT_{11}(\frac{1}{2}^-) + [\sigma(\frac{3}{2}^-)/\sigma(\frac{1}{2}^-)]iT_{11}(\frac{3}{2}^-)}{1 + [\sigma(\frac{3}{2}^-)/\sigma(\frac{1}{2}^-)]}. \end{aligned} \tag{2}$$

In these equations, $\sigma(j^\pi)$ and $iT_{11}(j^\pi)$ are the cross section and vector analyzing power for the contributing j^π reactions. Equations (1) and (2) predict that the measured cross section at any angle for the mixed reaction on ^{53}Cr is just the sum of the cross-section contributions for the two j_n values at that angle, and that the measured vector analyzing power is the weighted average of the vector analyzing powers for each j_n, the latter being weighted by their respective cross-section contributions.

Equations (1) and (2) can be compared with the measured cross sections and vector analyzing powers to obtain the absolute-cross-section contributions $\sigma(\frac{1}{2}^-)$ and $\sigma(\frac{3}{2}^-)$ since the cross section gives the sum, and the vector analyzing power the ratio, of the two cross sections. In the calculation it was assumed that the vector analyzing power and the angular dependence of the cross section for the pure $\frac{1}{2}^-$ and $\frac{3}{2}^-$ transitions are given by the calibration curves of panels (c)-(f) of Fig. 1. The average value of the cross-section ratio for the three points near the stripping peak (10°, 15°, and 20°) was found to be $\sigma(\frac{3}{2}^-)/\sigma(\frac{1}{2}^-) = 1.6$. This value together with the calibration curves was then used to predict the cross section and vector analyzing power at all other angles. These predictions are shown by the solid curves in panels (a) and (b) of Fig. 1. An excellent fit is obtained to the cross section and vector analyzing power at forward angles, and even at back angles the fit is quite satisfactory.

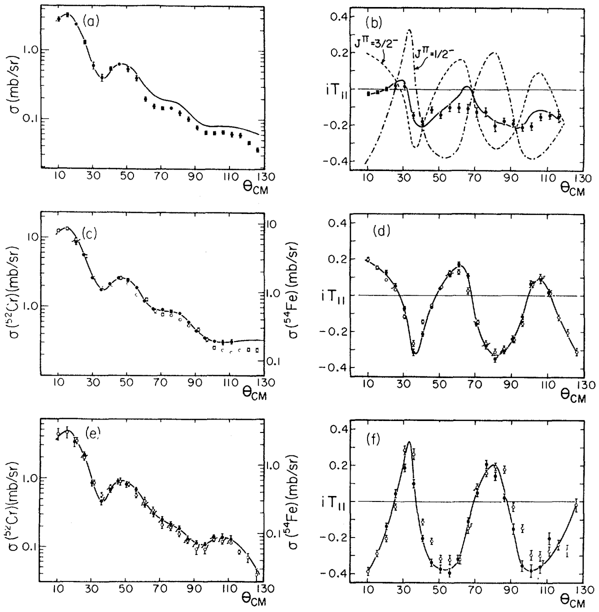

FIG. 1. (a), (b) Measured cross sections and vector analyzing powers for the reaction ^{53}Cr$(d,p)^{54}$Cr* ($Q = 6.71$ MeV) at 10-MeV bombarding energy. The solid curves are fits to the data assuming a mixture of $j^\pi = \frac{3}{2}^-$ and $\frac{1}{2}^-$ reactions (see text). The dashed and dashed-dotted curves in (b) are the results for the pure $j^\pi = \frac{3}{2}^-$ and $\frac{1}{2}^-$ reactions given by the solid curves in (d) and (f), respectively. (c), (d) Measured cross sections and vector analyzing powers for the $j^\pi = \frac{3}{2}^-$ reactions ^{52}Cr$(d,p)^{53}$Cr ($Q = 5.73$ MeV), open circles, and ^{54}Fe$(d,p)^{55}$Fe ($Q = 7.01$ MeV), closed circles, at 10-MeV bombarding energy. The solid curves show the trend of the data for ^{54}Fe. (e), (f) Measured cross sections and vector analyzing powers for the $j^\pi = \frac{1}{2}^-$ reactions ^{52}Cr$(d,p)^{53}$Cr* ($Q = 5.17$ MeV), open circles, and ^{54}Fe$(d,p)^{55}$Fe* ($Q = 6.60$ MeV), closed circles, at 10-MeV bombarding energy. The solid curves show the trend of the data for ^{54}Fe.

The absolute cross sections $\sigma(\frac{1}{2}^-)$ and $\sigma(\frac{3}{2}^-)$ obtained at the stripping peak may be compared with DWBA calculations to obtain the spectroscopic factors for the two j_n values. The deuteron optical-model parameters used in these calculations were obtained from an analysis of our measured cross sections and vector analyzing powers for elastic scattering from ^{53}Cr at 10 MeV. The DWBA calculations were performed with the University of Colorado code DWUCK.[8] From the ratio $\sigma(\frac{3}{2}^-)/\sigma(\frac{1}{2}^-) = 1.6$ at the stripping peak, the relative spectroscopic factor $S(\frac{3}{2}^-)/S(\frac{1}{2}^-) = 1.48$ was obtained. From the cross section contributions $\sigma(\frac{3}{2}^-)$ and $\sigma(\frac{1}{2}^-)$, which were determined from fitting the cross section at the stripping peak, the spectroscopic factors $S(\frac{3}{2}^-) = 0.31$ and $S(\frac{1}{2}^-) = 0.21$ were obtained.

The question may be raised whether the empirical calibration curves cannot be replaced by predictions based on DWBA theory. Calculations were made for the reactions on ^{52}Cr and ^{54}Fe. They are in good qualitative agreement with vector-analyzing-power measurements. However, the measured and calculated curves show significant quantitative differences, especially where the vector analyzing power is changing rapidly with angle. In addition, the calculations did not reproduce the shape of the observed cross-section angular distributions at back angles. These deviations cause a considerably poorer fit to the ^{53}Cr data than the fit shown in Fig. 1. The use of empirical calibration curves has the advantage that it allows a determination of $\sigma(\frac{1}{2}^-)$ and $\sigma(\frac{3}{2}^-)$ which is independent of any theory.

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EVIDENCE FOR Y_4 DEFORMATION IN ^{20}Ne AND OTHER *s-d* SHELL NUCLEI*

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The sign and magnitude of the haxadecapole deformation in ^{20}Ne is determined from measurements of the inelastic scattering of 24.5-MeV protons. A coupled-channels analysis yields a value for β_4 of +0.28. A similar analysis of other available data in the *s-d* shell suggests a large hexadecapole deformation in ^{28}Si (+0.25) and ^{32}S (+0.25); ^{24}Mg is found to have a Y_4 moment close to zero.

Accurate measurements of the large intrinsic quadrupole deformation of the first excited 2^+ states in ^{20}Ne, ^{24}Mg, and ^{28}Si have recently been performed.[1] Such data are a critical test of the detailed microscopic calculations of nuclear properties which are now being carried out by methods such as deformed Hartree-Fock.[2] Some of these calculations suggest that nuclei of the $2s$-$1d$ shell should also have a ground-state hexadecapole deformation which changes both in size and sign through the shell.[3-5] The size and sign of Y_4 moments of rare-earth nuclei have previously been determined by a coupled-channels analysis of the cross sections for excitation of the ground state rotational band by 50-MeV alpha particles.[6] The advantage of this method was that all multiple-excitation paths between these states were treated consistently. A similar analysis of scattering data in the $2s$-$1d$ shell has been performed only for ^{24}Mg, but no Y_4 deformation was observed in the ground-state band.[7] On the other hand, previous inelastic-scattering results analyzed with the distorted-wave Born approximation, Austern-Blair, and other less sophisticated models indicate that large direct transition strengths are needed in order to explain the magnitude of the cross sections for the first 4^+ states in ^{20}Ne and ^{28}Si.[8-10]

We have measured the inelastic scattering of 24.5-MeV protons from ^{20}Ne. The cross sections for the lowest 0^+, 2^+, 4^+, and 6^+ states are analyzed with the same coupled-channels method used for the rare-earth nuclei. The same model is then used to analyze the data of Crawley and Garvey[11] for inelastic scattering of 17.5-MeV protons from ^{24}Mg, ^{28}Si, and ^{32}S. Evidence is found for large positive hexadecapole deformation in ^{20}Ne, ^{28}Si, and ^{32}S, while ^{24}Mg is determined to have a small, possibly negative, hexadecapole moment. These results are relatively independent of the size and sign of β_2.

The ^{20}Ne experiment was performed at the Berkely 88-in. cyclotron. A 24.5-MeV proton beam was scattered from a gas target filled to 10- or 20-cm Hg pressure with enriched ^{20}Ne. A set of four Si(Li) detectors were used to count the scattered particles; the detectors were 4 mm thick and cooled to −25°C. The total energy res-