Unnatural parity transitions in $^{22}Ne(p, t)^{20}Ne$†

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New measurements have been made with the $^{22}Ne(p,t)$ reaction to excite the $K^\pi = 2^-$ rotational band in ^{20}Ne. Coupled-channel Born approximation calculations fail to account for the angular distribution of the transition to the 4^- member of this band, although they describe well that for the transition to the 2^- member. Particularly significant is the failure of the cross section for the 4^- transition to decrease at forward angles. This behavior is in disagreement with that expected for unnatural parity transitions in (p,t) reactions which proceed through multistep processes involving inelastic excitations. The implications of these results for the reaction mechanism are discussed.

[NUCLEAR REACTIONS $^{22}Ne(p, t)$, $E = 40$ MeV; measured $\sigma(\theta)$ for $E_{exc} = 4.97$ (2^-), 5.63 (3^-), and 7.01 (4^-) MeV. Compared to CCBA calculations.]

In view of the current interest in understanding the effects of higher-order (multistep) processes in nuclear transfer reactions, a class of transitions which are particularly important to study are those for which the first-order processes are forbidden or strongly unfavored. For these transitions comparisons between different higher-order reaction theories can be more easily made, since interference from the first-order processes is eliminated. One example of such "forbidden" reactions is a (p, t) transition from a 0^+ initial to an unnatural-parity final state. This transition is allowed in the first-order distorted-wave Born approximation (DWBA) if the full finite-range theory is used or if the usual restriction is removed that the nucleons in the triton be in zero relative-angular-momentum states. However, such effects have been shown to yield negligible contributions.[1] Thus, if compound-nuclear contributions are neglected, the reaction must proceed almost entirely via multistep processes. There are two main types of multistep processes normally considered: those that involve inelastic scattering intermediate steps[2] and those involving successive particle transfer.[3,4]

A particularly interesting case is that of ^{22}Ne-(p, t) to the $K^\pi = 2^-$ band in ^{20}Ne, for which the unnatural-parity transition to the 2^- bandhead at 4.97 MeV has been observed previously.[2,5,6] Because of the highly collective nature of the nuclei involved, the multistep processes involving inelastic intermediate steps are particularly strong. Olsen *et al.*[2] have shown, using the coupled-channel Born approximation (CCBA), that these effects account very well for the magnitude and shape of their experimental angular distribution for the 2^- transition. In addition, however, Udagawa and Olsen[3] have calculated the $(p$-d-$t)$ successive single-nucleon pickup contribution using the coupled-reaction-channel (CRC) formalism, and have found it to be of similar strength to that of the CCBA contribution. The principal difference between the two calculations is that the CCBA contribution drops rapidly at forward angles, whereas the CRC contribution rises. Udagawa and Olsen[3] showed that this result is a fundamental characteristic of the two processes (as long as contributions from the spin-orbit term of the optical-model potentials are negligible) and follows from the fact that the former proceeds mainly via a spin transfer $S = 0$, whereas the latter proceeds mainly via $S = 1$. There is some question as to the absolute normalization of the CRC calculations because the nonorthogonality of the basis functions used in the various channels is ignored.[3,7] Thus, it was suggested[3] that a measurement of the forward-angle cross section of the 2^- transition would distinguish which process is dominant and thus give some insight into the nonorthogonality correction required in the CRC formalism. Vourvopoulos *et al.*[5] have recently observed the 2^- transition at three angles more forward than the Olsen *et al.*[2] measurements. These data showed a significant decrease in the forward-angle cross section, an effect which was interpreted as unequivocally establishing the dominance of inelastic multistep processes for this transition.

In this note, we would like to report new measurements which show that the mechanism of the $^{22}Ne(p, t)$ reaction to the $K^\pi = 2^-$ band may be more complicated than suggested by Vourvopoulos *et al.*[5] An important test for the multistep calculations is that they be able to reproduce more than one unnatural-parity transition for the same reaction. Olsen *et al.*[2] have predicted that the inelastic multistep contribution for the $^{22}Ne(p, t)$ transition to the 4^- member of the $K^\pi = 2^-$ band in ^{20}Ne at 7.01 MeV is of strength similar to that for the 2^- transition. Therefore, the transition to this 4^- state has been investigated in the present work. At the same time, we have remeasured the 2^- transition with special attention to the forward-angle behavior. Whereas we have confirmed the observation of Vourvopoulos *et al.*[5] that the cross section for the 2^- transition is reasonably well reproduced by the CCBA calculations, our measurement of the cross section for the 4^- transition indicates a significant discrepancy at all angles with respect to the CCBA calculation.

To obtain these data we used a 40 MeV proton beam from the Michigan State University cyclotron. The target consisted of a gas cell containing 99.9% purity ^{22}Ne, and the reaction products were measured in an Enge split-pole spectrograph with a double-slit arrangement at the entrance aperture to eliminate particles coming from the gas-cell window. The particles were detected in the spectrograph by placing a single-wire proportional counter backed by a plastic scintillator in the focal plane. With this apparatus it is possible to obtain very clean spectra, as has been described elsewhere,[8] using coincidence requirements based on the energy-loss signal from the proportional counter and time-of-flight information from the plastic scintillator signal. Using this arrangement we were able to measure the cross sections forward to a laboratory angle of 8° with an average energy resolution of 60 keV full width at half-maximum (FWHM). By removing the double-slit entrance aperture to the spectrograph and replacing it by a standard single-slit aperture, we were able to continue the measurement down to 4°, but at the cost of receiving particles from the gas-cell window. Since peaks from the window obscured the 4^- peak, we were unable to measure the cross section for this transition below a laboratory angle of 8°. For the runs with the single-slit aperture we used a gas cell with an areal density of about 300 $\mu g/cm^2$. Thus, for the 2^- transition this technique was an improvement over that of Vourvopoulos *et al.*,[5] whose ion-implanted target was only 6.5 $\mu g/cm^2$ of ^{22}Ne. The data for the 2^- and 4^- transitions are shown in Fig. 1. Also shown are the data for the transition to the 3^- member of the $K^\pi = 2^-$ band at 5.63 MeV which, unlike Olsen *et al.*,[2] we resolve clearly from the 1^- state at 5.79 MeV. The strength of the 1^- transition was found to be about 10% of that of the 3^- transition. The cross sections agree very well with the data of Olsen *et al.*[2]

In the figure are displayed the predictions of Olsen *et al.*[2] for the inelastic multistep processes in all three transitions using the CCBA and those of Udagawa and Olsen[3] for the $(p\text{-}d\text{-}t)$ processes in the 2^- and 3^- transitions using the CRC formalism. A calculation of the successive-transfer contribution to the 4^- transition has not yet been made. The CCBA calculations have neglected the spin-orbit part of the optical-model potentials, but Olsen *et al.*[2] have shown that the effect of these terms is small, at least for the 2^- and 3^-

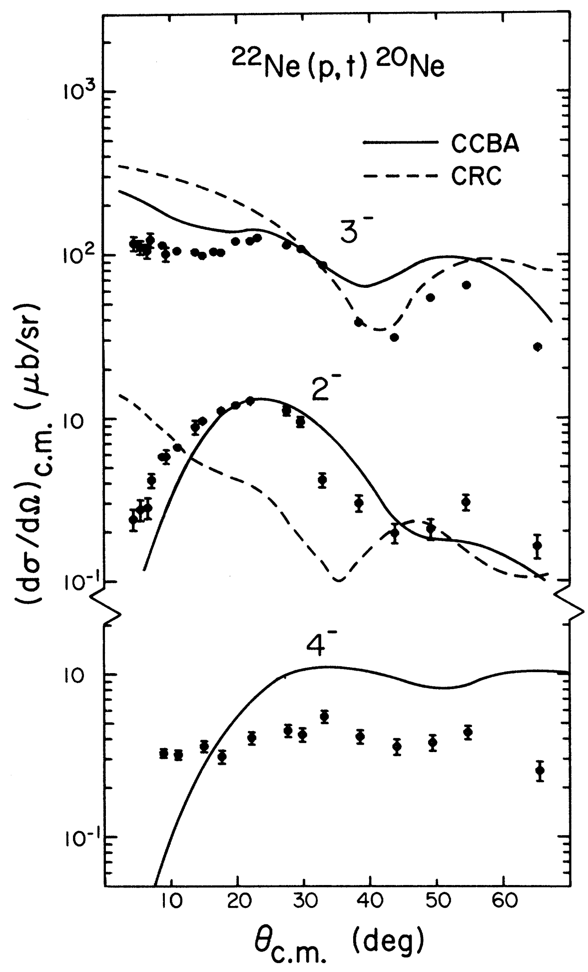

FIG. 1. Experimental differential cross sections for $^{22}Ne(p, t)^{20}Ne$ at 40 MeV incident energy to the 2^- (4.97 MeV), 3^- (5.63 MeV), and 4^- (7.01 MeV) members of the $K^\pi = 2^-$ rotational band in ^{20}Ne. The solid lines represent CCBA calculations of Olsen *et al.* (Ref. 2) for the inelastic multistep contributions, with overall normalization chosen so as to reproduce the magnitude of the 3^- transition. The dashed lines represent the CRC calculations of Udagawa and Olsen (Ref. 3) for the successive single-neutron pickup contributions.

transitions. The good agreement between the CCBA predictions for the 2^- transition and the data seems to favor the dominance of the inelastic multistep processes. In particular, the sharp decrease in the forward-angle 2^- cross section is in agreement with the characteristic behavior for inelastic multistep processes in an unnatural-parity transition.

On the other hand, it is evident that the CCBA calculation for the 4^- transition fails to account for either the magnitude or the shape of the angular distribution. Particularly significant is the lack of a forward-angle decrease in the cross section such as was seen for the 2^- transition. Although the discrepancy between the magnitude of the calculation and that of the data could possibly result from the inadequacy of the simple pairing model used by Olsen *et al.*[2] for the transfer form factors or of the macroscopic model used by them to describe the inelastic scattering, the forward angle decrease is expected to be independent of the nuclear structure model used. Thus, unless the effect of the spin-orbit component of the optical-model potential is anomalously large for this transition, it appears that the cross section for the 4^- transition cannot be explained entirely in terms of multistep inelastic processes. It can be seen from the figure that if the contribution from the $(p\text{-}d\text{-}t)$ process is approximately twice as large as that for the 2^- transition, it would be possible to account for the flatness of the 4^- cross section at forward angles without significantly affecting the CCBA prediction for the 2^- cross section. Of course, there may also be interference between the two types of multistep processes. This, for instance, might account for the fact that the 4^- cross section is below the CCBA prediction at angles beyond 20°. In addition, contributions could come from compound-nuclear processes; such as have been suggested to account for an unnatural-parity transition observed in ^{26}Mg(p, t) at lower energies.[9]

It is important now to have calculations of the $(p\text{-}d\text{-}t)$ contribution to the 4^- transition in ^{22}Ne-(p, t), and if possible a calculation which would include both the inelastic and the successive transfer contributions in order to see the effect of their interference. If compound-nuclear contributions can be ruled out, a comparison between such calculations and our data can be used as an important check on the approximations used in models of multistep processes.

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