Direct Experimental Evidence for Strong, Sequential, Two-Step, Transfer Processes in Allowed (p,t) Reactions

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A marked difference of (p,t) analyzing powers for the two isotones in $N=52 \rightarrow N=50$ ground-state transitions was observed between two reactions, $^{92}Zr(p,t)$ and $^{94}Mo(p,t)$. The difference is not explained by direct one-step processes but is interpreted by including strong two-step $(p,d)(d,t)$ processes. Interference between the two processes of comparable intensities is essential. Drastic incident-energy dependence of the analyzing powers is also interpreted only by including the two-step processes.

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Two-nucleon transfer reactions such as (p,t), (t,p), and (α,d) reactions are powerful probes for the investigation of two-nucleon correlations in nuclei. Thus many studies of the reaction mechanisms of the two-nucleon transfer reactions have been made, particularly on the effect of sequential two-step transfer processes. The conclusion whether or not large contributions from the sequential two-step processes exist in *allowed* two-nucleon transfer reactions is still indefinite, however. Existence of the strong two-step contributions has been explained in allowed (p,t) reactions[1] and (α,d) reactions,[2] while a serious doubt on such contributions has been cast on the basis of the exact finite-range distorted-wave Born-approximation (DWBA) analyses.[3] Many theoretical papers on the sequential two-step transfer mechanism have been published.[4] What is needed now, however, is direct experimental evidence for *strong* sequential two-step transfer processes, which is almost independent of the nuclear-structure models.

In this Letter, we report such evidence on the basis of a striking interference effect between one- and two-step processes, which is observed in vector analyzing powers for strong (p,t) ground-state transitions. Contrary to cross sections for reactions with unpolarized beams, analyzing powers for reactions with polarized beams are quantities which are very sensitive to interferences between various competing reaction processes. It will be shown in this Letter that analyzing powers are indeed a powerful probe for investigation of nuclear-reaction mechanisms.

At first, measurements of analyzing powers $A(\theta)$ for (p,t) reactions on a pair of $N=52$ isotones were made with use of a 22-MeV polarized proton beam: $^{92}Zr(p,t)^{90}Zr(0_g^{\,+})$ $(Q=-7.36$ MeV) and $^{94}Mo(p,t)^{92}Mo(0_g^{\,+})$ $(Q=-9.26$ MeV). The polarized beam was accelerated with the University of Tsukuba 12UD Pelletron. Emitted charged particles were analyzed with a magnetic spectrograph and detected with a position-sensitive single-wire proportional counter.[1]

Experimental results of the analyzing powers $A(\theta)$ and the differential cross sections $\sigma(\theta)$ are shown in Fig. 1. Although the nuclear-structure wave functions involved are quite similar in these two reactions, the observed angular distributions of the $A(\theta)$ around $\theta \approx 20°$ are completely different from each other; we can see a negative dip in $^{92}Zr(p,t)$ but a positive peak in $^{94}Mo(p,t)$. It should be noted that the difference in $A(\theta)$ is drastic around $\theta \approx 20°$, while the angular distribu-

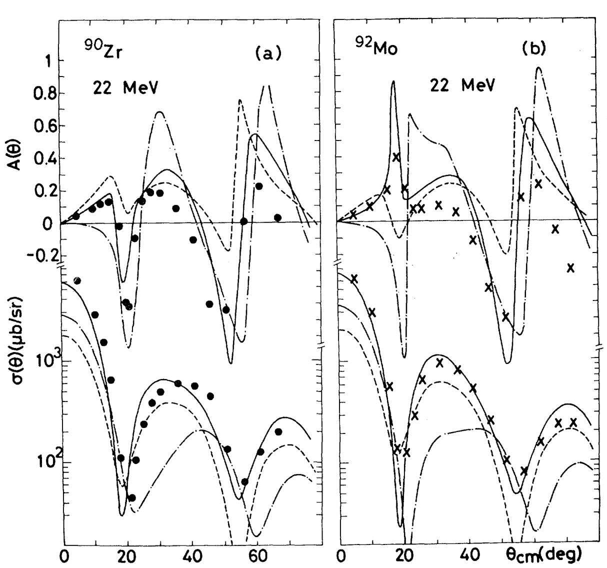

FIG. 1. Experimental and calculated analyzing powers $A(\theta)$ and cross sections $\sigma(\theta)$ for (a) $^{92}Zr(p,t)^{90}Zr(0_g^{\,+})$ and (b) $^{94}Mo(p,t)^{92}Mo(0_g^{\,+})$ at $E_p = 22$ MeV. Dash-dotted (dashed) curves are the first-order [$(p,d)(d,t)$ second-order] DWBA calculations and solid curves are the coherent sum of the two processes.

tions over the range of $35° \lesssim \theta \lesssim 65°$ are quite similar in shapes and magnitudes. In addition, the angular distributions of the $\sigma(\theta)$ also exhibit a small difference between the two isotones in the shape of the second maximum around 35°.

One- and two-step $(p,d)(d,t)$ DWBA calculations[5] in the zero-range approximation[6] were carried out for the reactions ^{92}Zr(p,t) and ^{94}Mo(p,t). The normalization constants of the zero-range calculation were taken[1] as $D_0^2(p,t) = 22$, $D_0^2(p,d) = 1.53$, and $D_0^2(d,t) = 3.37$ in units of 10^4 MeV^2 fm^3. The nuclear-structure wave functions were reasonably assumed to be pure two-neutron configurations of $(d_{5/2})^2$ for the $N = 52$ targets and a pure single-neutron $(d_{5/2})^1$ state for the intermediate $N = 51$ nuclei. Also, it was assumed that the $N = 51$ nuclei and deuterons are in their ground states. The calculated results are compared with the data in Fig. 1. It should be first noticed that the observed $A(\theta)$ for ^{90}Zr and ^{92}Mo cannot be reproduced at all by the one-step DWBA calculation (dash-dotted curves), which fails to predict the marked differences of the sign of the $A(\theta)$ near 20°. On the contrary, the calculation including two-step $(p,d)(d,t)$ processes can reproduce the experimental results beautifully, as shown by the solid curves in Fig. 1. A delicate interference effect between the one- and two-step processes produces a sharp negative dip in $A(\theta)$ in the case of ^{92}Zr(p,t) on one hand, and a sharp positive peak in the case of ^{94}Mo(p,t) on the other hand. In addition to $A(\theta)$, the shape and magnitude of the $\sigma(\theta)$ data are well reproduced by including only the two-step processes: We can get a rather flat top of the second maximum in the ^{90}Zr case, while a sharp peak is obtained in the ^{92}Mo case. The $(p,d)(d,t)$ processes are as strong as the one-step process. Throughout the above calculations we used the same optical-potential parameters for Zr and Mo, taken from the work of Becchetti and Greenlees[7] for protons, that of Hjorth, Lin, and Johnson[8] for deuterons, and that of Flynn *et al.*[9] for tritons. One- and two-step calculations were also made by employing a deuteron- (triton-) optical potential with a spin-orbit term obtained by Lohr and Haeberli[10] (Hardekopf *et al.*[11]). The resultant $A(\theta)$ and $\sigma(\theta)$ are found to be very similar to those given in Fig. 1.

In order to find a cause for the drastic change in the $A(\theta)$ for the two transitions, the original one- and two-step calculation of the ^{92}Zr$(p,t)^{90}$Zr is artificially modified only by replacing the Q value of the ^{92}Zr$(p,d)^{91}$Zr(g.s.) process [$Q(p,d) = -6.41$ MeV] by that of the ^{94}Mo$(p,d)^{93}$Mo(g.s.) process [$Q(p,d) = -7.45$ MeV]. As shown by a dashed curve in Fig. 2(a), one can obtain an abrupt change in $A(\theta)$ from the negative dip to a positive peak. This fact suggests that the kinetic energy of deuterons (E_d) in the intermediate channel is strongly related to the interference properties between the one-step and two-step $(p,d)(d,t)$ processes, and also that the striking difference in the $A(\theta)$ for the two isotones is caused by the difference in the propagation of the deuteron wave in the intermediate channel of the two-step processes. The motion of the deuterons is described by a Green's function in the two-step DWBA formulation.[5]

To confirm the deuteron energy dependence of $A(\theta)$, measurements of the reaction ^{92}Zr$(p,t)^{90}$Zr(0_g^+) were made by varying the incident energy from $E_p = 20.1$ to 22.5 MeV. As shown in Fig. 2(b), a marked change in the angular distribution of the $A(\theta)$ occurred between $E_p = 21.5$ and 21.0 MeV; a deep negative dip at $\theta \approx 20°$ which was continuously observed at $E_p = 22.5$, 22.0, and 21.5 MeV disappeared suddenly at $E_p = 21.0$ MeV and a positive peak became sharper at 21.0 MeV. The $A(\theta)$ obtained at 21.0 MeV has a characteristic angular shape which has just been observed in the ^{94}Mo$(p,t)^{92}$Mo at $E_p = 22.0$ MeV [Fig. 1(b)]. The deuteron energy ($E_d = 14.3$ MeV) of the ^{92}Zr$(p,d)^{91}$Zr(g.s.) at $E_p = 21.0$ MeV is just equal to that

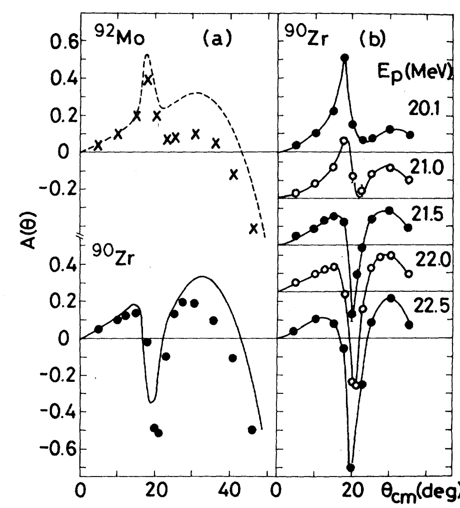

FIG. 2. (a) Experimental analyzing powers for ^{92}Zr(p,t) (circles) and ^{94}Mo(p,t) (crosses) at $E_p = 22$ MeV. The dashed curve is obtained from the original calculation (solid curve) by replacing the Q value of the ^{92}Zr(p,d) by that of ^{94}Mo(p,d). (b) Incident-energy dependence of $A(\theta)$ for ^{92}Zr(p,t). Solid curves are only to guide the eyes.

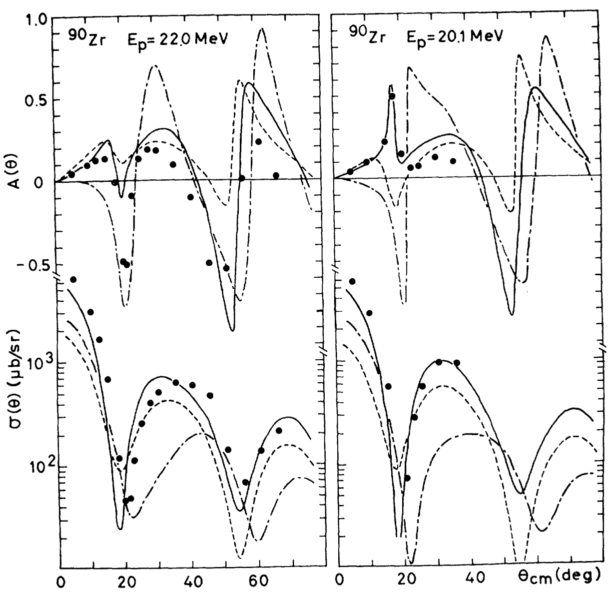

FIG. 3. Experimental and calculated analyzing powers and cross sections for $^{92}Zr(p,t)^{90}Zr(0_g^+)$ at two different incident energies. The definition of calculated curves is the same as that given in Fig. 1.

of the $^{94}Mo(p,d)^{93}Mo$(g.s.) at $E_p = 22.0$ MeV. Therefore we can conclude that the marked difference of $A(\theta)$ between the reactions $^{92}Zr(p,t)$ and $^{94}Mo(p,t)$ at $E_p = 22.0$ MeV (Fig. 1) is due to the difference of the deuteron energies in the intermediate channels of the $(p,d)(d,t)$ processes. It should be noted that the characteristic shape of $A(\theta)$ for the $^{92}Zr(p,t)$ obtained at $E_p = 21.0$ MeV remains at the lower proton energy of $E_p = 20.1$ MeV.

Next, the incident-energy dependence of $A(\theta)$ and $\sigma(\theta)$ for the reaction $^{92}Zr(p,t)$ thus obtained [Fig. 2(b)] was analyzed in terms of one- and two-step DWBA calculations. The calculations[12] were made in the two opposite cases of $E_p = 20.1$ and 22.0 MeV. As seen in Fig. 3, the calculations succeed in reproducing $A(\theta)$ and $\sigma(\theta)$. Here, again, inclusion of the two-step $(p,d)(d,t)$ processes is essential for reproducing the data through the interference effect.

One might think that routes via inelastic scattering to low-lying collective states could be an important difference between the ^{90}Zr and ^{92}Mo cases. The fact that the ^{92}Mo result can be obtained on the ^{90}Zr case by choosing the right bombarding energy (Figs. 2 and 3), however, clearly demonstrates that inelastic-scattering channels are not important in the present cases.

The deuteron wave propagation in the intermediate channel of $(p,d)(d,t)$ processes plays an essential role in reproducing the observed differences. The reason that the deuteron energy is so critical in the $(p,d)(d,t)$ processes is still an open problem. More work should be done on the distorting potential in the intermediate channel.

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