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Anomalous Analyzing Powers for Strong $(p_{\rm pol},t)$ Ground-State Transitions and Interference between Direct and $(p,d)(d,t)$ Sequential Process

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Strong ground-state (p,t) transitions in nuclei of neutron number ≈50–82 are found to show anomalous analyzing powers which cannot be reproduced by direct one-step distorted-wave Born-approximation calculations at all. The anomalies are explained as an interference between $(p,d)(d,t)$ sequential processes and the one-step process. The cross section of the sequential processes is as large as that of the one-step process in the $L = 0$ (p,t) reactions. The neutron-number dependence of the anomalies is interpreted.

Angular distributions of cross sections $\sigma(\theta)$ for (p,t) and/or (t,p) transitions between 0^+ ground states $(0_g{}^+)$ of medium- and heavy-mass nuclei are known to have diffractive patterns[1] which can be explained by a direct transfer of two neutrons in a $^1S_0$ state on the basis of the first-order distorted-wave Born-approximation (DWBA) theory.[2] In addition to the cross sections $\sigma(\theta, 0_g{}^+)$, vector analyzing powers $A(\theta, 0_g{}^+)$ for the same transitions have been analyzed so far by the method of the first-order DWBA[3] because anomalous analyzing powers $A(\theta, 0_g{}^+)$ which are far beyond the predictions by this method have not been reported in two-neutron transfer experiments. In the present Letter, however, we report anomalous angular distributions of $A(\theta, 0_g{}^+)$ for (p,t) which cannot be reproduced by the first-order DWBA calculations at all.

The experiment was performed by using a 22.0-MeV polarized proton beam accelerated with the University of Tsukuba 12-UD Pelletron. The experimental procedures were the same as those used in the recent studies of the $(p_{\rm pol},t)$ reactions[4,5] except for the following two points. The angular acceptance of the magnetic spectrograph was reduced from $\Delta\theta = 3.0°$ to $\Delta\theta = 1.5°$ and angular distributions of $A(\theta, 0_g{}^+)$ and $\sigma(\theta, 0_g{}^+)$ were measured in 2° or 1.5° steps around $\theta \approx 20°$. The ground-state transitions to nuclei of ^{98}Ru, ^{102}Pd, ^{108}Pd, ^{114}Cd, ^{116}Sn, ^{120}Te, ^{126}Te, ^{128}Te, and ^{142}Nd were measured.

As reported in previous papers,[4-6] the $A(\theta, 0_g{}^+)$ for the nine nuclei of $N \approx 50$–82 show quite similar angular distributions over an angular range of 25°

$\lesssim \theta \lesssim 65°$. However, the $A(\theta, 0_g{}^+)$ display distinguishable change in going from one nucleus to the other in the angular distributions around $\theta \approx 20°$ where the $\sigma(\theta, 0_g{}^+)$ have a deep minimum; see Fig. 1. The most striking change is observed between the two isotopes of Pd. A sharp positive peak of $A(\theta, 0_g{}^+)$ at $\theta \approx 20°$ changes to a sharp negative dip in going from ^{102}Pd to ^{108}Pd. On the other hand, the $\sigma(\theta, 0_g{}^+)$ do not show such a drastic change at $\theta \approx 20°$.

The $A(\theta, 0_g{}^+)$ observed cannot be interpreted by only direct one-step (p,t) process because it always predicts a sharp negative minimum at $\theta \approx 20°$ as shown by dot-dashed curves in Fig. 1. The analyzing powers $A(\theta, 0_g{}^+)$ which cannot be explained by the direct one-step (p,t) process are called *anomalous* in this Letter. The nine nuclei investigated all show the anomalous analyzing powers among which five cases are exhibited in Fig. 1.

It can be proved quite generally that a sharp oscillation with a negative dip and a positive peak in amplitude of the $A(\theta, 0_g{}^+)$ always appears around the first-dip in the cross-section angular distribution as far as the first-order DWBA theory is employed for an analysis of the $(A+2)(p,t)(A, 0_g{}^+)$ reactions. (i) A simple relation between two transition amplitudes $\beta_{m=0}(\theta)$ and $\beta_{m=1}(\theta)$ (for notation, see Satchler, Ref. 2) can be obtained by the perturbation treatment of spin-orbit distortion effects; an angular derivative of $\beta_{m=0}(\theta)$ is proportional to $-i\beta_{m=1}(\theta)$. (ii) The amplitude $\beta_{m=1}(\theta)$ is anyway small compared with $\beta_{m=1}(\theta)$, since the former arises from the spin-orbit corrections. From these two facts can a derivative relation $A(\theta, 0_g{}^+) \propto d[\ln\sigma(\theta, 0_g{}^+)]/d\theta$ be obtained also for the (p,t) reactions, which is well known in the elastic scatterings.

In consequence it can be concluded that other transition processes than the direct one-step process are essential to interpret the experimental $A(\theta, 0_g{}^+)$ around $\theta \approx 20°$. Then (p,d) (d,t) sequential transfer processes[7] are taken into account in terms of second-order DWBA theory.[8] The nuclear-structure wave functions involved are constructed under the BCS model[5,6] except for the case of the Nd isotopes where the nucleus ^{144}Nd (^{143}Nd) can be assumed to have a pure configuration $f_{7/2}$ ($f_{7/2}$) outside the core nucleus ^{142}Nd of $N = 82$. We consider five neutron orbits $1d_{5/2}$, $0g_{7/2}$, $2s_{1/2}$, $1d_{3/2}$, and $0h_{11/2}$ for the BCS calculations, of which binding energies are taken from the table of Kisslinger and Sorensen.[9] The initial $|A+2, 0_g{}^+\rangle$ and final $|A, 0_g{}^+\rangle$ states are assumed to be the BCS states and the intermediate states $|A+1, j\rangle$ are to be five one-quasiparticle states with spin j. The pairing interaction strength G is taken as[9] $G = 23/A$ MeV. By use of this force strength together with the single-particle energies, we calculate the spectroscopic amplitudes[10] for the relevant transitions in the one-step $(A+2, 0_g{}^+)(p,t)(A, 0_g{}^+)$ and sequential $(A+2, 0_g{}^+)(p,d)(A+1, j)(d,t)(A, 0_g{}^+)$ processes.

The first- and second-order DWBA calculations

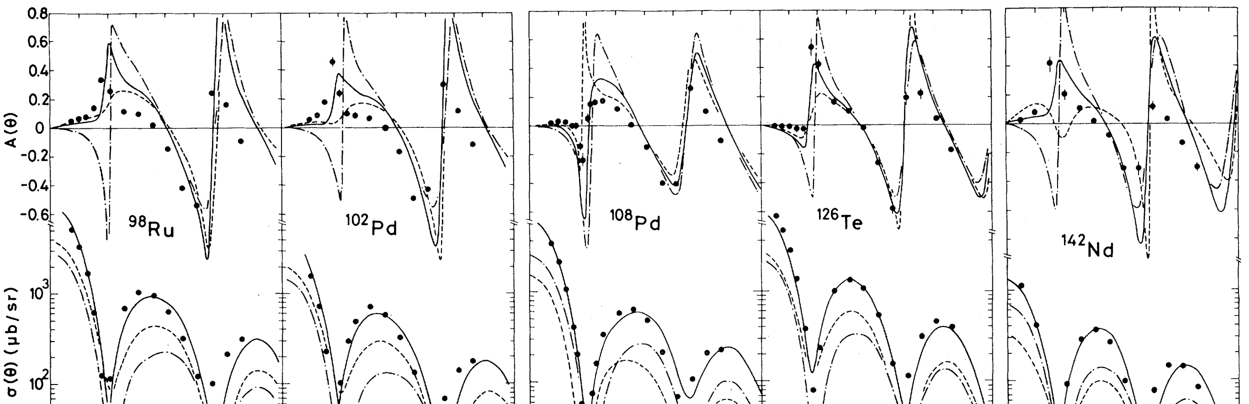

FIG. 1. Experimental and calculated analyzing powers $A(\theta)$ and cross sections $\sigma(\theta)$ for (p,t) ground-state transitions at $E_p = 22.0$ MeV. Each final nucleus is indicated. Dash-dotted (dashed) curves are the first-order [(p,d) (d,t) second-order] DWBA calculations and solid curves are the coherent sum of the two processes.

in the zero-range approximation are then carried out.[11] The normalization constants of the zero-range calculations are taken as[8] $D_0^2(p,t)=20.3$, $D_0^2(p,d)=1.53$, and $D_0^2(d,t)=3.37$, all in units of 10^4 MeV^2 fm^3. Optical-potential parameters are obtained from the work of Becchetti and Greenlees[12] for protons, that of Hjorth, Lin, and Johnson[13] for deuterons,[15] and that of Flynn *et al.*[14] for tritons.[15] The distorting potential for deuterons is modified to have a volume imaginary part[15] instead of a surface imaginary part.[13] Otherwise predicted analyzing powers for the $(p,d)(d,t)$ processes have always a sharp negative dip at $\theta \approx 20°$ as in the case of the analyzing powers for the one-step processes (dot-dashed curves in Fig. 1) and then the resultant total analyzing powers still have always a sharp negative dip at $\theta \approx 20°$. The effect of changing the imaginary part into a volume type is a reduction of the contribution to the scattering from the nuclear interior. This result is consistent[16] with that obtained by use of the Johnson-Soper approach,[17] and therefore suggests that deuteron breakup is responsible for the required change in deuteron potential. However, the differences between the Johnson-Soper effective parameters and those in the present analysis suggest further study of the problem.

As shown in Fig. 1, inclusion of both one-step and $(p,d)(d,t)$ processes results in a significant improvement of the analyzing powers. Furthermore, the interference between the one- and two-step processes is essential to reproduce the anomalies at $\theta \approx 20°$. Contributions of various neutron orbits to the two-step processes are explained in Fig. 2 for the cases of the Pd isotopes. A decrease of the contribution of the $d_{5/2}$ orbit and a relative increase of that of the $s_{1/2}$ orbit in going from ^{102}Pd to ^{108}Pd can explain an appearance of a sharp negative dip for ^{108}Pd and a disappearance of it for ^{102}Pd. A redisappearance of it for ^{126}Te is due to an increase of the contribution of the $h_{11/2}$ orbit. Large difference in analyzing powers for various orbits appears only in forward angles $\theta \lesssim 40°$, while the each analyzing power focuses almost on the same angular distributions in backward angles $\theta \gtrsim 40°$. It should be noticed that the j dependence of analyzing powers for one-nucleon transfer reaction[18] is similarly revealed in the $(p,d)(d,t)$ sequential processes: a $d_{5/2}$-$d_{3/2}$ pair in Fig. 2.

Appearance of a round positive peak in the $A(\theta, 0_g{}^+)$ at $\theta \approx 25°$ has been observed only in the case of ^{108}Pd. This can be reproduced quite well by adding a surface imaginary part[19] to the distorting potential for deuterons. This fact implies that deuterons in the intermediate channel break up and/or are absorbed more easily near the nuclear surface of ^{109}Pd than in the other nuclei. This seems to be correlated with[20] the fact that ^{110}Pd (^{108}Pd) has a very large deformation parameter of $\beta_2=0.25$ (0.24).

In addition to $A(\theta, 0_g{}^+)$, the observed $\sigma(\theta, 0_g{}^+)$

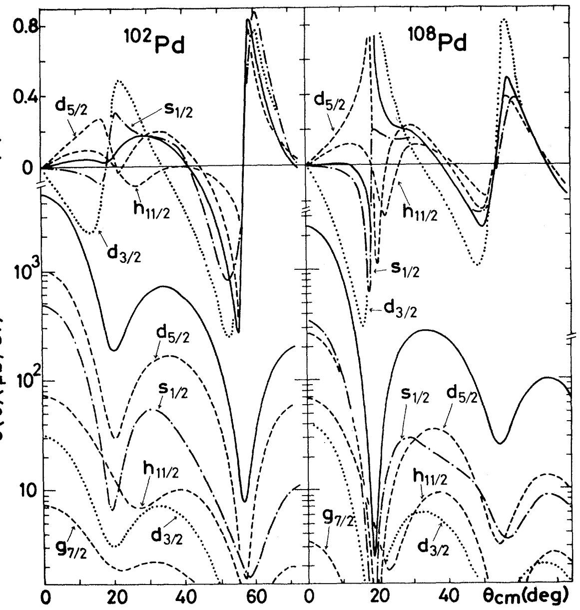

FIG. 2. Contributions of each orbit to the analyzing powers and cross sections in the two-step processes for the cases of Pd isotopes. Solid curves are the coherent sum of the each process.

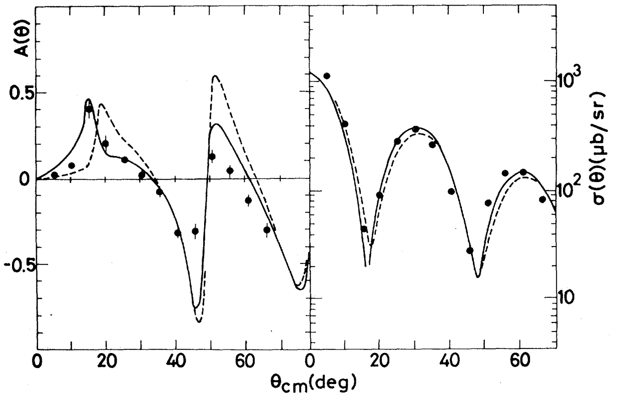

FIG. 3. Finite-range effect in analyzing power and cross sections for the ^{144}Nd$(p,t)^{142}$Nd$(0_g{}^+)$ transition. Solid (dashed) curves are the full finite-range (zero-range) calculations.

are also reproduced quite well in their shapes as well as in magnitudes by including the $(p,d)(d,t)$ processes as seen in Fig. 1. The contribution of the two-step $(p,d)(d,t)$ processes is as much as that of the one-step process in the strong (p,t) reactions.[8]

The finite-range effect in the one- and two-step processes is investigated in the case of ^{142}Nd. Figure 3 shows that this effect is small but a better fit is obtained by the finite-range calculation. Next the contribution of inelastic multistep processes via the first 2^+ states of the initial and final nuclei are estimated by use of quasiparticle random-phase-approximation wave functions[5,6] for the 2^+ states. The calculated cross sections are much smaller than the experimental $\sigma(\theta, 0_g{}^+)$ by a factor of less than 1/20. Therefore the inelastic multistep processes can be neglected.

In summary, (i) anomalous analyzing powers for (p,t) 0^+ ground-state transitions are observed around the angles where the contribution of the direct one-step process becomes minimum; (ii) the anomalies can be accounted for as an interference effect between the $(p,d)(d,t)$ sequential processes and the direct one-step process; (iii) the neutron-number dependence of the anomalous angular distributions is determined by the variation of the dominant one-quasiparticle neutron orbits in the intermediate states of the $(p,d)(d,t)$ processes; (iv) the ground-state (p,t) cross sections for superconducting nuclei are improved quite well by including the $(p,d)(d,t)$ processes which are as strong as the one-step process; (v) more works should be done for the distorting potential in the intermediate channel in the sequential two-step processes; (vi) the (p,t) analyzing powers are much more sensitive to both the nuclear structure and reaction mechanism involved than the cross sections.

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