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Analyzing power as a probe for clarifying nuclear reaction mechanisms: Study of the two-step unbound channel contribution

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The analyzing power at forward angles shows negative (positive) sign when the one-step (two-step) process is dominant. This distinguished feature has been confirmed for the unnatural-parity transition ^{208}Pb(p,t)^{206}Pb(3^+) at three proton energies 22, 35, and 50 MeV. The effect of a deuteron unbound state in the intermediate channels of the (p,d)(d,t) process is elucidated, which gives a contrary result to Pinkston and Satchler's conjecture. The natural-parity transition (p,t)(0^+) is also interpreted consistently on the same theoretical basis.

The (p,t) transfer reaction to the unnatural-parity states of even-even nuclei is completely forbidden in the framework of simple zero-range distorted-wave Born approximation (DWBA). However, the reaction can proceed via a (p,d)(d,t) two-step process since $\Delta S = 1$ transfer is realized owing to twice exchanges of spin $\frac{1}{2}$ nucleons. Actually the cross section $\sigma(\theta)$ data of the reaction ^{208}Pb(p,t)^{206}Pb(3^+, 1.34 MeV) at $E_p = 35$ MeV (Ref. 1) have been well reproduced by the second-order (p,d)(d,t) calculation by de Takacsy[2] and Charlton.[3] On the other hand, the same cross section data have been reanalyzed by Nagarajan *et al.*[4] as a one-step rather than the sequential (p,d)(d,t) process because the process is not forbidden in the finite-range (FR) DWBA if a realistic trition wave function containing a mixture of *S*, *S'*, and *D* states[5] is used. They reported that their calculation can predict the observed cross section[1] $\sigma(\theta, 3^+)$ in shape and absolute magnitude. Thus the cross section data[1,6] are not powerful enough to distinguish whether the dominant reaction mechanism for the ^{208}Pb(p,t)^{206}Pb(3^+) excitation is a one-step or two-step process.

In order to solve this problem, the first measurement of a vector analyzing power $A(\theta)$ for the ^{208}Pb(p,t)^{206}Pb(3^+) reaction has been carried out by the Tsukuba group[7] at $E_p = 22$ MeV. Then the result of $A(\theta, 3^+)$ and $\sigma(\theta, 3^+)$ has been analyzed by Igarashi and Kubo[8] by making the precise first- and second-order FR-DWBA calculations. A comparison of the calculation[8] with the experimental $A(\theta, 3^+)$ has clearly shown the predominance of the (p,d)(d,t) two-step mechanism. However, the following problems now come up. (i) How does this predominance go at higher incident energies such as $E_p = 35$ and/or 50 MeV? (ii) The effect of a deuteron unbound state in the intermediate channels of the (p,d)(d,t) process, which has not been taken into account in the previous calculation,[8] should be evaluated in order to clarify a doubt pointed out by Pinkston and Satchler.[9] They have pointed out, employing the closure approximation, that the analyzing power associated with a (p,d)(d,t) unnatural-parity state transition becomes very small when the deuteron unbound ($S = 0, T = 1$) state is included in the two-step calculation. (iii) Can one interpret consistently the natural-parity transitions, such as ^{208}Pb(p,t)^{206}Pb($0^+_{\rm g.s.}$), in addition to the unnatural-parity transition on the same theoretical basis? This Brief Report addresses these problems.

We measured analyzing powers and cross sections for ^{208}Pb(p,t)^{206}Pb(3^+) at $E_p = 35$ and 50 MeV with use of polarized proton beams from the Research Center for Nuclear Physics (RCNP) Osaka Cyclotron. Emitted tritons were momentum analyzed and detected with a magnetic spectrograph RAIDEN.[10] A 34.8- (50.2-) MeV polarized proton beam had an intensity of about 15(80) nA on target with the degree of polarization of 78(83)%. The ^{208}Pb target was a self-supporting metallic foil of 2.6(4.0) mg/cm^2 thickness with 99.1% isotopic enrichment for the 35- (50-) MeV experiment. The energy resolution in both cases was about 50 keV, which was mainly due to the target thicknesses. Measured $A(\theta, 3^+)$ and $\sigma(\theta, 3^+)$ are shown in Fig. 1, together with the data of $E_p = 22.0$ MeV (Ref. 7). The absolute values of the cross sections are estimated to have an error of 20%. Our cross section $\sigma(\theta, 3^+)$ data are quite consistent with the data obtained by use of unpolarized proton beams of $E_p = 35$ MeV (Ref. 1) and 50.5 MeV (Ref. 6).

The first- and second-order FR-DWBA calculations of the (p,t) transitions at $E_p = 22$, 35, and 50 MeV are carried out[11,12] with use of a triton wave function obtained by solving the three-body Faddeev equation.[13] In addition, we include the unbound deuteron states. For the intermediate channels in the sequential transfer (p,d)(d,t) process, the unbound $^1S_0$ and $^3S_1 + {}^3D_1$ states as well as the ground $^3S_1 + {}^3D_1$ deuteron state are taken into account. Those deu-

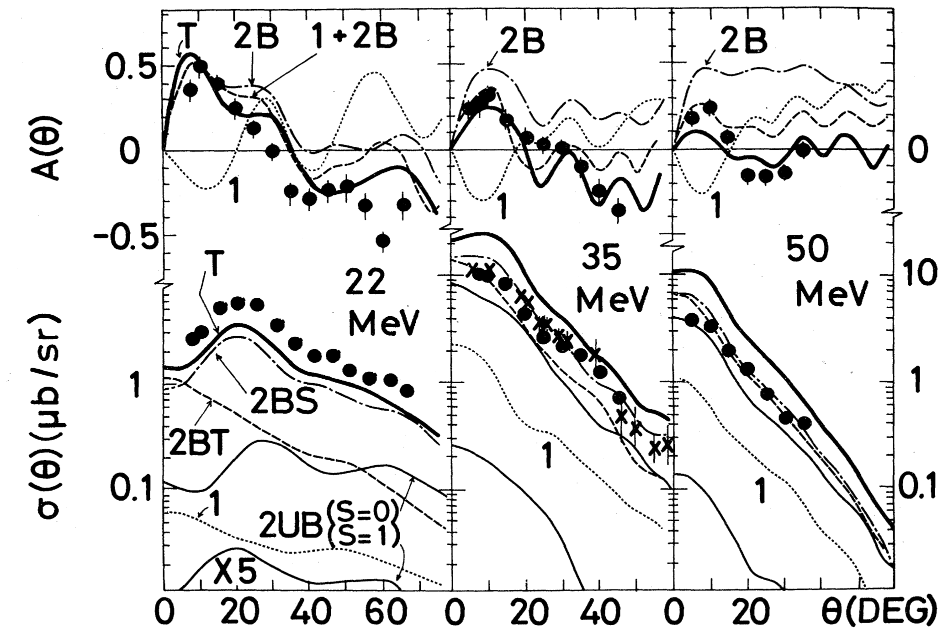

FIG. 1. Experimental and calculated analyzing power and cross section for ^{208}Pb(p,t)^{206}Pb(3^+) at three proton energies. 1: one step, 2: two step, B(UB): bound- (unbound-) deuteron channel, BS: scalar ($L=0$) component, BT: tensor ($L=2$) component, T: $1+2B+2UB$, i.e., coherent sum of the all processes. Crosses are data from Ref. 1.

teron g.s. and unbound state wave functions are solved by employing Reid soft-core interaction potential.[14] The same interaction is adopted for the transfer interaction. The deuteron bound state channels are evaluated by discretizing the momentum space.[15] The truncation of the relative momentum of the p-n continuum states is chosen to be $k_{\max}=1$ fm^{-1} for the $^1S_0$ state and $k_{\max}=1.5$ fm^{-1} for the $^3S_1+{}^3D_1$ state. The unbound channels are discretized into the finite number of momentum bins with the common width Δk, where the Δk is chosen to be $\Delta k = k_{\max}/8$. Optical potential parameters for protons, deuterons, and tritons in the case of $E_{\mathrm{p}}=22$ and 35 MeV (50 MeV) are obtained from Table I of Ref. 8 (Ref. 6). For simplicity, we use the same optical potential parameters for all the unbound deuteron state calculations as those at the energy corresponding to the g.s. deuteron channel.[12] The nuclear structure wave functions of the 3^+ and 0_g^+ states in ^{206}Pb are those obtained from shell model calculations:[16] the 3^+ state is a pure $(f_{5/2}p_{1/2})^{-1}$ configuration, while the 0_g^+ state is the mixed configurations of six neutron states. In the calculation of the (p,d)(d,t) transition to the $3^+(0_g^+)$ state, the intermediate single-hole states $h=p_{1/2}$ and $f_{5/2}(h=p_{1/2},f_{5/2},p_{3/2},i_{13/2},f_{7/2},$ and $h_{9/2})$ in ^{207}Pb are taken into account. The strengths of each one-neutron transfer reaction ^{208}Pb(p,d)^{207}Pb(h) and ^{207}Pb(d,t) ^{206}Pb(0_g^+, 3^+) are confirmed experimentally.[17,18]

The result thus obtained is quite important, namely, the analyzing power does not get very small even when both the g.s. and unbound-state deuteron channels are coherently summed over, in contrast to the prediction from the closure approximation.[9] The calculated results are shown in Fig. 1 and compared with the experimental ones. The analyzing power data are well reproduced by the predominance of the two-step process, whereas they are quite different from the one-step transfer calculation alone. A marked difference (opposite sign) between the one- and two-step processes appears at forward angles $\theta < 20°$ in the analyzing powers. The conclusion of Nagarajan *et al.*[4] is thus excluded. Fit of the analyzing-power calculation to the data is improved apparently by inclusion of the unbound deuteron channels. It is worthwhile to note that the contribution from the unbound deuteron channels ($2UB$) relative to that from the g.s. deuteron channel ($2B$) increases when the proton energy increases. The two-step process plays the main role in the unnatural-parity transition. The contribution from the one-step process is about one- (35 and 50 MeV) and two-orders (22 MeV) of magnitude smaller in the cross section than the two-step contribution due to the g.s. deuteron channel.

A discrepancy in the absolute magnitude of the cross sections $\sigma(\theta,3^+)$ between the calculation and the experiment is found to be a factor of 2.5. This can be, however, remedied by choosing other sets of optical potential parameters, as shown in Fig. 2 of Ref. 8. This result shows the necessity of carefully choosing the distorting potential parameters, although both the ratio of the two cross sections (one- and two-step) and the analyzing power $A(\theta,3^+)$ are not strongly affected by the choice.

In addition to the unnatural-parity transition a natural-parity transition ^{208}Pb(p,t)^{206}Pb(0_g^+) is analyzed on the same theoretical basis and is compared with the experiment (Fig. 2). The calculation reproduces both the experimental cross section $\sigma(\theta,0_g^+)$ and analyzing power $A(\theta,0_g^+)$ well. The cross section is increased by a factor of 8 by including the (p,d)(d,t) processes. This is quite consistent with our previous analysis[19] in which a simple zero-range approximation has been applied. The contribution from the unbound state is rather small.

The predominance of the sequential transfer mechanism over the one-step mechanism for both the unnatural-parity 3^+ and the natural-parity 0^+(p,t) reactions is thus confirmed by means of the measurements of their analyzing powers at three different energies. The accurate evaluation of the one- and two-step transfer processes provides large analyzing power and very important signature, thereby indicating a useful probe of analyzing power measurement for clarifying the reaction mechanisms.

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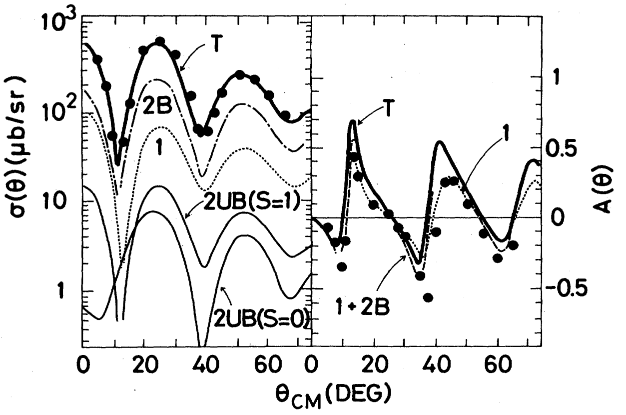

FIG. 2. Experimental and calculated analyzing power for ^{208}Pb(p,t)^{206}Pb(0_g^+) at $E_p=22$ MeV. Definition of calculated curves is the same as in Fig. 1.

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