Analyzing power for the ^{208}Pb($\vec{p}$,t)^{206}Pb(3^+) reaction and (p,d)(d,t) sequential transfer processes

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The analyzing power for the reaction ^{208}Pb($\vec{p}$,t)^{206}Pb leading to the unnatural parity 3^+ state at 1.34 MeV was measured at E_p = 22.0 MeV. The cross section of this reaction was fitted well by a two-step (p,d)(d,t) calculation, but the analyzing power was not at all. The reaction mechanism of this transition is not explained by only the sequential transfer processes.

[NUCLEAR REACTIONS ^{208}Pb($\vec{p}$,t), E=22.0 MeV; measured $\sigma(E_t, \theta)$, $A_y(E_t, \theta)$: First- and second-order DWBA analyses.]

In recent years, the reaction ^{208}Pb(p,t)^{206}Pb leading to the unnatural parity 3^+ state at 1.34 MeV in ^{206}Pb has been the object of intensive theoretical analyses. In the zero-range distorted wave Born approximation (DWBA), the transition is strictly forbidden, because the two neutrons in the triton have zero total spin and relative orbital angular momentum ($S_{12}=0$, $l=0$). However, the reaction has been interpreted as a two-step (p,d)(d,t) process.[1,2] The angular distribution of the cross section $\sigma(\theta, 3^+)$ measured at E_p=35 MeV (Ref. 3) has been well reproduced by the calculation based on this assumption.[2] On the other hand, the same cross section $\sigma(\theta, 3^+)$ has been recently reanalyzed[4] as a one-step rather than the sequential (p,d)(d,t) process, because the process is not forbidden in finite-range DWBA if a realistic triton wave function is used. The D state, for example, contributes components with $S_{12}=1$, l=odd to unnatural parity transitions in (p,t) reactions. Again the calculations predict the correct cross section $\sigma(\theta, 3^+)$ in shape and absolute magnitude.[4] Therefore the angular distribution of the cross section $\sigma(\theta, 3^+)$ is not powerful enough to distinguish whether the reaction mechanism for the ^{208}Pb(p,t)^{206}Pb(3^+) reaction is a one-step process or two-step process.

The purpose of the present work is to measure the angular distribution of the analyzing power $A(\theta, 3^+)$ for the ^{208}Pb($\vec{p},t$)^{206}Pb(3^+) reaction to clarify the reaction mechanism. The measurement of the analyzing power $A(\theta, 3^+)$ for this reaction has not previously been made mainly because of its small cross section.

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 used in the present work were the same as those used in the recent study of the (p,t) reactions.[5] The average beam polarization was 0.85 with a typical beam current of 80 na on target. The target was an evaporated 2.6 mg/cm^2 self-supporting ^{208}Pb metallic foil enriched to 99.1%. Angular distributions of the analyzing power and cross section were measured at θ_L = 7.5° and from θ_L = 10° to 65° in 5° steps with an angular acceptance of a magnetic spectrograph $\Delta\theta_L = \pm 1.5°$, which corresponds to a solid angle of 2.0 msr. Data for the ground-state (0_g^+) transition were also obtained at the same angles as for the 3^+ state with additional angles: 5°, 11.5°, 13.5°, 37.5°, and 42.5° using an angular acceptance of $\Delta\theta = \pm 0.75°$. A typical energy spectrum is shown in Fig. 1. The energy resolution was about 50 keV full width at half maximum (FWHM) which was mainly due to the target thickness.

Measured angular distributions of $\sigma(\theta,3^+)$, $A(\theta,3^+)$ and $\sigma(\theta,0_g^+)$, $A(\theta,0_g^+)$ are shown in Figs. 2 and 3, respectively. Error bars on the angular distributions include only statistical errors. The absolute cross sections are estimated to have an error of 20%.

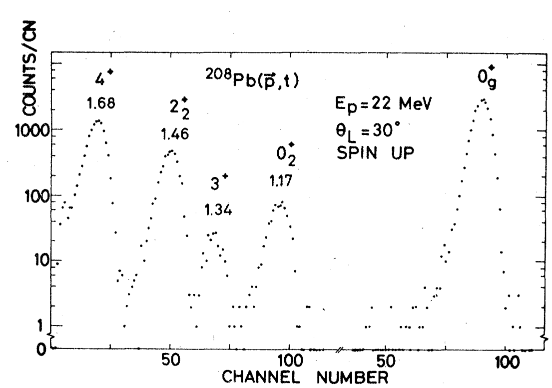

FIG. 1. Typical triton energy spectrum for the ^{208}Pb($\vec{p},t$)^{206}Pb. Excitation energies in MeV are indicated.

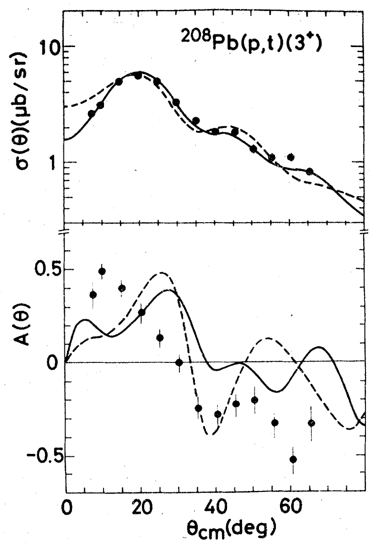

FIG. 2. Experimental and calculated cross section $\sigma(\theta)$ and analyzing power $A(\theta)$ for the $^{208}Pb(\vec{p},t)$ ^{206}Pb (3^+, 1.34 MeV) at E_p = 22.0 MeV. The solid and dashed curves correspond to the (p,d) (d,t) second-order DWBA calculations using potential set I and set II in Table I, respectively.

It should be noted that the analyzing powers for the 3^+ state $A(\theta, 3^+)$ have large values up to about ± 0.5 and the magnitude of the cross sections $\sigma(\theta, 3^+)$ is about half of that obtained at $E_p = 35$ MeV.[3] For the ground-state transition ($L = 0$), the angular distri-

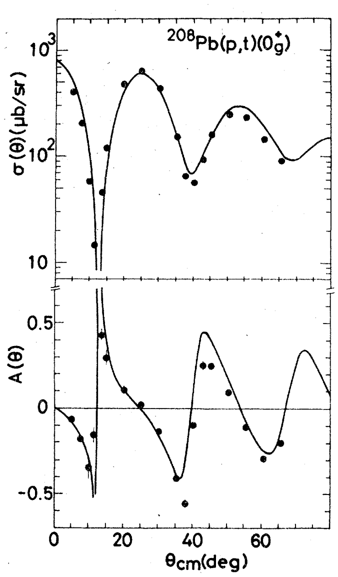

FIG. 3. Experimental and calculated cross section $\sigma(\theta)$ and analyzing power $A(\theta)$ for the $^{208}Pb(\vec{p},t)$ ^{206}Pb (0_g^+) at E_p = 22.0 MeV. The solid curves correspond to the first-order DWBA calculations using the proton and triton potentials of set II in Table I.

bution of the analyzing power $A(\theta, 0_g^+)$ shows large amplitude oscillations, which have been observed similarly at $E_p = 40$ MeV.[6] The oscillations are related approximately to the derivative of the differential cross section $d\sigma(\theta, 0_g^+)/d\theta$.

The calculations are done by the use of the program TWOSTP[7] assuming $(p,d)(d,t)$ sequential transfer processes for the 3^+ transition. The wave function of the 3^+ state can be assumed to have a pure configuration $(p_{1/2}{}^{-1}f_{5/2}{}^{-1})$ from the results of the shell model calculations by True and Ford.[8] Therefore the $\frac{1}{2}^-$ ground state and the $\frac{5}{2}^-$ state (0.57 MeV) in ^{207}Pb are taken into account as the intermediate channels. The parameters for the optical potentials used are listed in Table I. The proton and deuteron optical potentials of the set I are taken from the work of Satchler[9] in which $^{208}Pb(p,d)^{207}Pb$ cross-section data at $E_p = 22$ MeV are analyzed on the basis of the Johnson-Soper prescription. The triton potential of set I is taken from the work of Hardekopf *et al.*[10] The optical potentials of set II are global potentials obtained by Becchetti and Greenlees[11] for protons, Perey and Perey[12] for deuterons, and Becchetti and Greenlees[13] for tritons. The zero-range approximation is used for the (p,d) and (d,t) transitions. The values used for zero-range normalization constants are

$$D_0^2(p,d) = 1.53 \times 10^4$$

and

$$D_0^2(d,t) = 3.37 \times 10^4$$

in units of $MeV^2\,fm^3$. The one-nucleon transfer form factors are generated in terms of the conventional separation energy method with parameters of $r_0 = 1.25$ fm, $a = 0.65$ fm, and $V_{so} = 6.0$ MeV and by the use of the experimental neutron separation energies.

The results of the calculations are shown in Fig. 2. Solid curves correspond to the calculation with potential set I and dashed curves to the calculation with potential set II. It is noted that the calculated cross sections are multiplied by factors of 1.1 and 0.78 for potential set I and set II, respectively. It can be seen that the shape of the experimental angular distribution of $\sigma(\theta, 3^+)$ is well reproduced, especially with potential set I. On the other hand, the experimental angular distribution of $A(\theta, 3^+)$ cannot be reproduced using the same two potential sets. Finite-range calculations for the $(p,d)(d,t)$ transition were also tried using potential set I, and the resultant $A(\theta, 3^+)$ was found to be almost unchanged. Furthermore, calculations with several other reasonable potential sets were tried, and it was found that the calculated analyzing powers

TABLE I. Optical potential parameters (depths in MeV and lengths in fm).

	Set I			Set II		
	p	d	t	p	d	t
V	51.8	112	168.9	57.6	105	160.9
r_0	1.25	1.25	1.2	1.17	1.15	1.2
a_0	0.65	0.682	0.65	0.75	0.81	0.72
W	0	0	9.9	2.14	0	17.3
W_D	10	19.4	0	8.84	19.68	0
r_I	1.25	1.25	1.6	1.32	1.34	1.4
a_I	0.76	0.783	0.97	0.66	0.68	0.84
V_{SO}	6	6	6	6.2	0	2.5
r_{SO}	1.12	1.12	1.15	1.01	···	1.2
a_{SO}	0.47	0.47	0.92	0.75	···	0.72
r_C	1.25	1.25	1.3	1.25	1.15	1.3

have very similar structures to the curves shown in Fig. 2 and cannot predict the experimental analyzing power, especially at forward angles.

The contribution of an inelastic multistep process via the 3^- state (2.61 MeV) in ^{208}Pb to the ^{208}Pb(p, t)^{206}Pb(3^+) excitation is also estimated by using the Tamm-Dancoff wave function[14] for the 3^- state. The calculated cross sections are much smaller than the experimental $\sigma(\theta, 3^+)$ by a factor of more than 50. Therefore the inelastic multistep process can be neglected.

The potential sets used in the calculations for the 3^+ transition are proper to predict the experimental cross section and analyzing power for the ground-state transition. Solid curves in Fig. 3 are obtained from the zero-range (p, t) DWBA calculation with the proton and triton potentials of set II. The form factor for the one-step pickup process is calculated by the Bayman-Kallio method with the wave function of True and Ford.[8] The half-separation-energy method is employed to generate the single-particle-neutron wave functions. It can be seen that both the experimental cross sections $\sigma(\theta, 0_g^+)$ and analyzing power $A(\theta, 0_g^+)$ are reproduced quite well by the calculation.

In conclusion, the (p, d)(d, t) sequential transfer processes cannot explain the ^{208}Pb(p, t)^{206}Pb(3^+) transition at $E_p = 22$ MeV. It should be emphasized that the measurement of the analyzing power $A(\theta, 3^+)$ is essential to obtain the above-mentioned conclusion. In our recent study of (p, t) reactions, it has been found that the analyzing powers for the excitation of the quadrupole vibrational 2_1^+ states are important physical observables to study nuclear collective motion.[5,15,16] In the present work, measurements of the analyzing power for the unnatural parity transition in (p, t) reactions can provide a severe test for the reaction mechanism. To explain the experimental analyzing power for the ^{208}Pb(p, t)^{206}Pb(3^+), a reaction mechanism other than the (p, d)(d, t) sequential transfer processes and inelastic multistep processes is necessary. The calculation of analyzing power $A(\theta, 3^+)$ based on the exact finite-range DWBA using realistic triton wave functions should be done.

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