Difference in anomalous $0_g^+ \rightarrow 0_g^+$ (p,t) analyzing powers for the isotones and partial cross sections for spin up and down

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A drastic difference of anomalous $0_g^+ \rightarrow 0_g^+$ (p,t) analyzing powers on ^{92}Zr and ^{94}Mo is explained in terms of partial cross sections $\sigma_{m_p m_t}$ with $m_p = m_t = \pm\frac{1}{2}$. It results from $\sigma_{-1/2\,-1/2} \approx 0$ only for ^{94}Mo due to a completely destructive interference between the one-step and the two-step $(p,d)(d,t)$ sequential process.

[NUCLEAR REACTIONS Vector analyzing power $A_y(\theta)$ and partial cross sections $\sigma_{++}(\theta)$ and $\sigma_{--}(\theta)$ for g.s. (p,t) on ^{92}Zr and ^{94}Mo, $E_p = 22$ MeV. First- and second-order DWBA.]

Recently a marked difference in (p,t) analyzing powers for the two isotones of $N=52$ has been observed in reactions, ^{92}Zr$(p,t)^{90}$Zr (0_g^+) and ^{94}Mo(p,t)-^{92}Mo (0_g^+) with use of a 22-MeV polarized proton beam.[1,2] Although the nuclear-structure wave functions involved are quite similar in these reactions, the observed angular distributions of the vector analyzing powers $A(\theta)$ are completely different from each other around the angle $\theta \approx 20°$, where the cross sections $\sigma(\theta)$ have the first and deep minimum; see Fig. 1. The $A(\theta)$ shows a negative dip in ^{92}Zr(p,t) but a positive peak in ^{94}Mo(p,t). The difference has been accounted for as an interference effect between a direct one-step process and the $(p,d)(d,t)$ sequential transfer processes.[1,2] Thus the anomalous behavior of the $A(\theta)$ for the pair of isotones has provided direct experimental evidence for the strong sequential two-step transfer processes even in allowed ground-state (p,t) transitions. However, the following questions still remain which are related to the origin of the observed difference in the interference effect: (i) Which partial cross sections $\sigma_{m_p m_t}(\theta)$ with magnetic quantum numbers m_p and m_t produce the large difference in the observed analyzing powers? (ii) Why does the drastic difference in the $A(\theta)$ appear only around the first minimum ($\theta \approx 20°$) of the $\sigma(\theta)$ and not in other angles, say especially around the second minimum ($\theta \approx 55°$)? The present paper answers these questions.

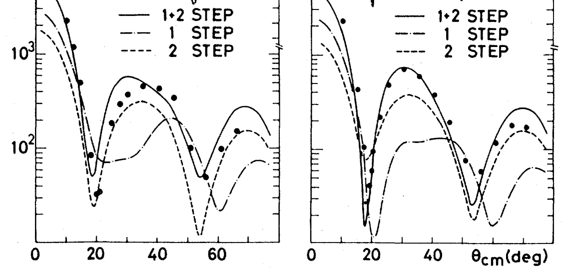

FIG. 1. Experimental and calculated analyzing powers $A(\theta)$ and cross sections $\sigma(\theta)$.

Before carrying out an analysis in terms of the partial cross sections, we have to confirm that the characteristic difference in the analyzing powers can be explained by the zero-range distorted wave Born approximation (DWBA) calculations including up to the second order even if a set of optical potential parameters for protons, deuterons, and tritons is changed. In the previous calculation[2] no spin-orbit terms were included in the optical potentials both for deuterons[3] and tritons.[4] In the present calculation, however, spin-orbit terms both for deuterons[5] and tritons[6] are included in the optical potentials with parameters determined so as to reproduce the elastic scattering data of cross sections and polarizations. Parameters for protons[7] are the same ones as used in the previous calculation.[2] The nuclear-structure wave functions for the $N=52$, 51, and 50 nuclei are assumed to be pure neutron configurations of $(d_{5/2})^2$, $(d_{5/2})^1$, and $(d_{5/2})^0$, respectively. The calculated[8,9] $A(\theta)$ and $\sigma(\theta)$ for the pair of isotones reproduce the experimental data quite well as shown in Fig. 1. A better fit in detail is obtained in the present calculation compared with the previous one.[2] What should be emphasized again is that the one- and two-step calculations can reproduce the characteristic difference in the $A(\theta)$ for the pair of isotones in spite of the different choice in a set of optical potential parameters.

According to the Bohr's theorem,[10] the spin-flip partial cross section $\sigma_{m_p m_t}$ for an $m_p = \pm\frac{1}{2} \rightarrow m_t = \mp\frac{1}{2}$ transition vanishes in a $0^+ \rightarrow 0^+$ (p,t) transition with the choice of a z axis *normal* to the reaction plane. We express this relation simply as follows:

$$\sigma_{+-}(\theta) = \sigma_{-+}(\theta) = 0 \ . \tag{1}$$

The suffix + and/or − refers to the sign of the spin projection of incoming protons and/or outgoing tritons; $\sigma_{+-}(\theta)$ $[\sigma_{-+}(\theta)]$ then is the partial cross section for outgoing spin-down (up) tritons produced by incoming spin-up (down) protons. It should be noted that the relation (1) is valid both for the direct one-step and the two-step $(p,d)(d,t)$ processes in $0^+ \rightarrow 0^+(p,t)$ transitions.

The analyzing power $A(\theta)$ with a polarized proton beam and the cross section $\sigma(\theta)$ with an unpolarized one for a $0^+ \rightarrow 0^+$ (p,t) reaction are thus expressed with use of the condition (1) as

$$A(\theta) = [\sigma_{++}(\theta) - \sigma_{--}(\theta)]/2\sigma(\theta) \ , \tag{2a}$$

$$\sigma(\theta) = [\sigma_{++}(\theta) + \sigma_{--}(\theta)]/2 \ . \tag{2b}$$

The measured cross section $\sigma_+(\theta)$ $[\sigma_-(\theta)]$ with a spin-up [spin-down] proton beam of the polarization p is expressed as

$$\sigma_\pm(\theta) = \sigma(\theta)[1 \pm pA(\theta)] \ . \tag{3}$$

Therefore the partial cross sections $\sigma_{++}(\theta)$ and $\sigma_{--}(\theta)$ are obtained from

$$\sigma_{\pm\pm}(\theta) = [\sigma_\pm(\theta)(1/p+1) - \sigma_\mp(\theta)(1/p-1)]/2 \ . \tag{4}$$

The typical value of the beam polarization[11] was $p = 0.85 \pm 0.01$.

The behavior of the $A(\theta)$ can be now understood in terms of the partial cross sections $\sigma_{++}(\theta)$ and $\sigma_{--}(\theta)$. The experimental $\sigma_{++}(\theta)$ and $\sigma_{--}(\theta)$ for the two reactions ^{92}Zr$(p,t)^{90}$Zr (0_g^+) and ^{94}Mo$(p,t)^{92}$Mo (0_g^+) are shown in Fig. 2 together with the corresponding theoretical cross sections. The curves are calculated partial cross sections by the first- and second-order DWBA.[9] The effect of an experimental finite angular spread ($\Delta\theta = 1.0°$) on the original theoretical partial cross sections, which are given in Fig. 3, has been taken into account for the curves in Fig. 2. The calculated partial cross sections reproduce the characteristic features of the experimental partial cross sections very well. The drastic difference in the analyzing powers for the isotones ^{90}Zr and ^{92}Mo around $\theta \approx 20°$ can be traced back to the fact that the partial cross section $\sigma_{--}(\theta)$ shows a very deep dip for ^{92}Mo at $\theta \approx 20°$ while it gives a shallow dip for ^{90}Zr at $\theta \approx 20°$. According to the definition of (2a), the analyzing power is a quite suitable quantity which can emphasize the difference between the $\sigma_{++}(\theta)$ and $\sigma_{--}(\theta)$ near the minimum of the cross section $\sigma(\theta)$.

Next, in order to understand why such an extremely deep minimum in the partial cross section $\sigma_{--}(\theta)$ appears only around $\theta \approx 20°$ for ^{94}Mo$(p,t)^{92}$Mo, and

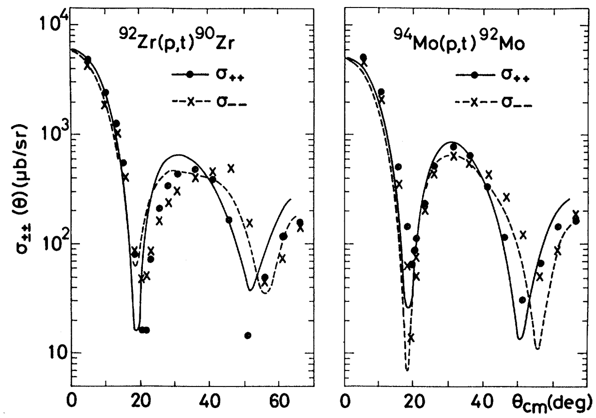

FIG. 2. Experimental and calculated (curves) partial cross sections.

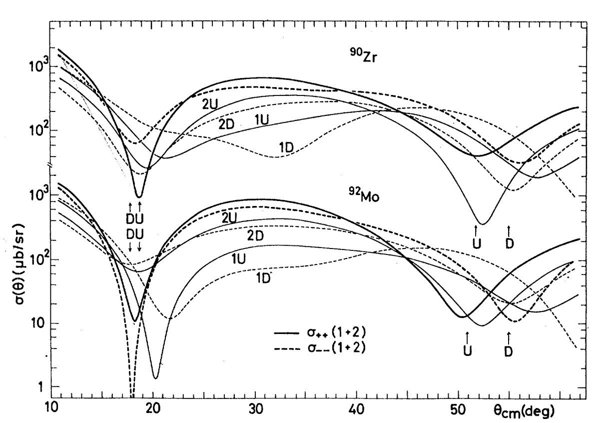

FIG. 3. Calculated partial cross sections for the (p,t) on ^{92}Zr and ^{94}Mo and decomposition into the one- and two-step cross sections: $1U = \sigma_{++}(\theta, 1)$, $1D = \sigma_{--}(\theta, 1)$, $2U = \sigma_{++}(\theta, 2)$, $2D = \sigma_{--}(\theta, 2)$. Arrows indicate "opposite-phase angles."

not for $^{92}Zr(p,t)^{90}Zr$, the theoretical partial cross section $\sigma_{--}(\theta)$ $[\sigma_{++}(\theta)]$ is decomposed into three parts, i.e., the one-step partial cross section $\sigma_{--}(\theta,1)$ $[\sigma_{++}(\theta,1)]$, the two-step $(p,d)(d,t)$ partial cross section $\sigma_{--}(\theta,2)$ $[\sigma_{++}(\theta,2)]$, and the interference term between the two processes:

$$\begin{aligned}\sigma_{--}(\theta) \equiv \sigma_{--}(\theta,1+2) &= \sigma_{--}(\theta,1)+\sigma_{--}(\theta,2) \\ &\quad + \text{interference term} \\ &= |B_{--}(\theta,1)|^2 + |B_{--}(\theta,2)|^2 \\ &\quad + 2\,\mathrm{Re}[B_{--}(\theta,1)B_{--}(\theta,2)^*] \ ,\end{aligned} \tag{5}$$

where $B_{--}(\theta,1)$ $[B_{--}(\theta,2)]$ is a transition amplitude for the one-step [two-step] $m_p=-\frac{1}{2}\rightarrow m_t=-\frac{1}{2}$ transition. Of course a similar equation as given by Eq. (5) can be written for the partial cross section $\sigma_{++}(\theta)$. Figure 3 gives all these partial cross sections for the $^{92}Zr(p,t)$ and $^{94}Mo(p,t)$ reactions.

A reaction angle where the phase of the one-step transition amplitude $B_{--}(\theta,1)$ $[B_{++}(\theta,1)]$ and that of the two-step transition amplitude $B_{--}(\theta,2)$ $[B_{++}(\theta,2)]$ differs exactly by π is indicated by an arrow with a letter D (U) in Fig. 3. We call this reaction angle as an "opposite-phase angle." In the $^{94}Mo(p,t)$ reaction, Fig. 3 shows that the $\sigma_{--}(\theta,1)$ equals to the $\sigma_{--}(\theta,2)$, i.e., $|B_{--}(\theta,1)| = |B_{--}(\theta,2)|$, at an angle $\theta=18°$ which coincides exactly with the opposite-phase angle of the $-\rightarrow-$ transition, i.e., the phase difference in these transition amplitudes equals to π at $\theta=18°$. Therefore a completely destructive interference between the one- and the two-step processes of the $-\rightarrow-$ transition occurs so that the partial cross section $\sigma_{--}(\theta,1+2)$ vanishes at this angle $\theta=18°$ leading to a sharply positive $A(\theta)$. On the other hand, in the case of the $^{92}Zr(p,t)$, the $\sigma_{--}(\theta,1)$ equals to the $\sigma_{--}(\theta,2)$ at $\theta=23°$ which is apart from the opposite-phase angle $(\theta=18°)$ by 5°. Thus the degree of cancellation in the partial cross section $\sigma_{--}(\theta,1+2)$ due to the destructive interference is not so large at $\theta=18°$ that we obtain only a shallow dip in the $\sigma_{--}(\theta,1+2)$ around $\theta\approx 20°$, contributing to a sharply negative $A(\theta)$ in the case of ^{90}Zr. The shift of the intersection of the two curves $\sigma_{--}(\theta,1)$ and $\sigma_{--}(\theta,2)$ away from the opposite-phase angle $\theta=18°$ in going from the $^{94}Mo(p,t)$ to the $^{92}Zr(p,t)$ arises from the dependence of the partial cross sections $\sigma_{--}(\theta,1)$ and $\sigma_{--}(\theta,2)$ on the reaction Q values.

As are indicated by arrows in Fig. 3, the opposite-phase angle of the $-\rightarrow-$ transition (18°) almost coincides with that of the $+\rightarrow+$ transition (19°) in the region of the first minimum of the cross section $\sigma(\theta)$ around $\theta\approx 20°$. On the contrary, however, the former (55°) is rather separate from the latter (51°) by 4° in the region of the second minimum of the $\sigma(\theta)$ around $\theta\approx 55°$. This fact provides the reason why the marked difference in the (p,t) analyzing powers appears only around the first minimum of the cross sections and not around the second minimum. In the first minimum region, the both partial cross sections $\sigma_{++}(\theta)$ and $\sigma_{--}(\theta)$ have very small values at about the same opposite-phase angle $\theta\approx 18.5°$ because of a large cancellation between the one- and the two-step transition amplitudes. In this situation the analyzing power, which is defined by Eq. (2a), results from the ratio of the difference between the *very small* partial cross sections $\sigma_{++}(\theta)$ and $\sigma_{--}(\theta)$ to the sum of the same partial cross sections. Therefore the analyzing power thus obtained at the first minimum is very sensitive to the various physical quantities involved such as the reaction Q value, the incident energy, etc.,[2] through the contribution of the two-step processes. In the second-minimum region, on the contrary, the analyzing power does not arise from the difference between such small partial cross sections since the two opposite-phase angles do not coincide. Thus the analyzing power at the second-minimum region is not so sensitive to the physical quantities as found in the case of the first minimum.

The zero-range approximation employed in the present calculations is expected to be valid enough to obtain the above-mentioned conclusion. This is due to the fact[1] that an exact-finite range one- and two-step DWBA calculation of the analyzing power and the cross section for $^{208}Pb(p,t)^{206}Pb$ (0_g^+) reaction at $E_p=22$ MeV has yielded essentially the same result as obtained by using the zero-range approximation.

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