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Systematic nuclear-structure dependence of analyzing powers for $(\vec{p}, t)$ reactions on medium-mass vibrational nuclei

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A neutron-number (N) dependence of analyzing powers $A(\theta)$ has been observed in $(\vec{p},t)$ reaction leading to the quadrupole vibrational states (2_1^+) in ^{98}Ru, ^{102,108}Pd, ^{114}Cd, ^{116}Sn, and ^{120,126}Te. Although analyzing powers for the ground-state transitions $A(\theta,0_g^+)$ are very similar to each other, $A(\theta,2_1^+)$ for the nuclei belonging to the beginning of the $N = 50$–82 shell are markedly different, having almost opposite signs, from those for nuclei belonging to the latter half of the shell.

[NUCLEAR REACTIONS ^{100}Ru, ^{104,110}Pd, ^{116}Cd, ^{118}Sn, ^{122,128}Te$(\vec{p}, t)$, $E = 22.0$ MeV; measured $\sigma(\theta)$, $A_y(\theta)$; enriched targets.]

In a previous paper[1] we reported on a striking feature of the analyzing power $A(\theta)$ revealed in the $(\vec{p}, t)$ reactions on ^{110}Pd and ^{128}Te targets. Although $A(\theta, 0_g^+)$, i.e., the analyzing powers for the process leaving nuclei in their ground (0_g^+) states, were very similar to each other, $A(\theta, 2_1^+)$ states, were markedly different, having almost opposite signs (at least at forward angles) in the two reactions. The corresponding cross sections $\sigma(\theta, 2_1^+)$ were also different. The difference was accounted for as a result of a phase change of the interference between a direct process and inelastic multistep processes in two-neutron pickup reactions. The origin of this phase change was elucidated[1] on the basis of the microscopic description of the collective quadrupole oscillation of nuclei.

A purpose of the present paper is to report on additional and systematic measurements of the $(\vec{p}, t)$ analyzing powers with better accuracies for target nuclei in the region of N (neutron number) $= 50$–82; ^{100}Ru, ^{104}Pd, ^{110}Pd, ^{116}Cd, ^{118}Sn, ^{122}Te, and ^{128}Te (Table I). In the present measurements the intensity of a polarized beam on target was graded up to ~100 nA from ~50 nA which had been obtained in the previous experiment.[1] In addition carefully produced targets were used (Table II); each target had a necessary and sufficient thickness so as to yield a sufficient counting rate but still with a reasonable energy resolution for the 0_g^+ and 2_1^+ states.

A polarized proton beam was accelerated with the University of Tsukuba 12 UD Pelletron at $E_p = 22.0$ MeV. The polarized beam was produced with a Lamb-shift-type ion source. The beam intensity on target was about 100 nA within a diameter of 2 mm. Emitted tritons were momentum analyzed with a magnetic spectrograph and detected with two silicon position-sensitive detectors mounted in the focal plane. The energy resolutions were indicated in Table II, which were mainly due to the target thicknesses and the uniformity. The upper limit of the instrumental and geometrical asymmetries of the whole detection system was estimated by measuring an asymmetry for $\text{H}(\vec{p},p)$ scattering at $\theta_L = 17.5°$ and found to be zero[2] within a statistical error of 1%. Measurements of angular distributions of the analyzing powers and cross sections were made from $\theta_L = 10°$ (or 7.5°) to 65° in 5° steps, with spin-up and spin-down runs taken at each angle. The degree of the proton-beam polarization was measured at the beginning and end of each run using the quench-ratio method and was found to be quite stable with an average value of $(86 \pm 1)\%$. This value agreed with the one obtained from a measurement of an asymmetry for $^4\text{He}(\vec{p},p)$ scattering[3] within an experimental error of 1%. The angular acceptance of the magnetic spectrograph was $\Delta\theta_L = \pm 1.5°$, which corresponded to a solid angle of 2.0 msr. A monitor detector was placed normal to the scattering plane and at $\theta_L = 155°$ and was used to measure the elastic proton scattering, monitoring the target thickness and charge collection of a Faraday cup. The monitor detector was insensitive to the polarization of protons with spin normal to the scattering plane.

Measured angular distributions of $A(\theta, 0_g^+)$, $A(\theta, 2_1^+)$, and $\sigma(\theta, 2_1^+)$ for the seven targets are shown in Figs. 1, 2, and 3, respectively. The present result of $A(\theta, 2_1^+)$ for $^{110}\text{Pd}(\vec{p},t)$ reaction has much better accuracies over a wider angular range compared with the previous measurement of $A(\theta, 2_1^+)$ for the same reaction,[1] besides the present $A(\theta, 2_1^+)$ is quite consistent with the previous $A(\theta, 2_1^+)$; see Fig. 1(b) in Ref. 1.

The angular distributions of $A(\theta, 0_g^+)$ are quite

TABLE I. Residual nuclei of (p,t) reactions. The neutron number, excitation energies of the first 2^+ states, reaction Q values for the 2_1^+ states are indicated.

Residual nucleus	^{98}Ru	^{102}Pd	^{108}Pd	^{114}Cd	^{116}Sn	^{120}Te	^{126}Te
N	54	56	62	66	66	68	74
$E(2_1^+)$ (MeV)	0.652	0.556	0.434	0.558	1.294	0.560	0.666
$-Q(2_1^+)$ (MeV)[a]	9.350	10.705	6.909	6.914	9.084	9.112	7.252

[a] Reference 8.

similar to each other both in shape and in magnitude as shown in Fig. 1. In addition the angular distributions of $\sigma(\theta, 0_g^+)$, which are not shown in this paper, are also very similar to each other. This result is consistent with the previous one[1]; the $A(\theta, 0_g^+)$ and $\sigma(\theta, 0_g^+)$ were well accounted for by distorted-wave Born approximation (DWBA) calculations using the BCS wave functions for both the target and residual 0_g^+ states [see Fig. 1(a) in Ref. 1].

On the other hand, $A(\theta, 2_1^+)$ show a systematic difference as shown in Fig. 2. The data have the following properties: (i) A pronounced difference exists between $A(\theta, 2_1^+)$ for the nuclei belonging to the beginning of $N = 50-82$ shell and that for the nuclei belonging to the end of $N = 50-82$ shell, i.e., the sign of $A(\theta, 2_1^+)$ for ^{98}Ru and ^{102}Pd is almost opposite to that for ^{126}Te over the whole angular range $10° \leq \theta \leq 65°$. (ii) Between these two opposites the sign and magnitude of $A(\theta, 2_1^+)$ change gradually and systematically as a function of N from $N \approx 50$ to $N \approx 82$. (iii) $A(\theta, 2_1^+)$ for ^{114}Cd and ^{116}Sn, however, have almost opposite signs in the forward angular region $15° \lesssim \theta \lesssim 40°$ although this pair of nuclei has the same neutron number $N = 66$.

The contrasting behavior of $A(\theta, 2_1^+)$ between the nuclei belonging to the beginning of the $N = 50-82$ shell and those to the latter half of the shell is now well established experimentally. As explained in Ref. 1, this difference is due to a phase change of the interference between a direct one-step process and inelastic multistep processes in (p,t) reactions; a destructive interference between the one-step and multistep reaction amplitude occurs for the nuclei belonging to the beginning of the shell while a constructive interference takes place for the nuclei to the latter half of the shell. The difference in the nature of interference mentioned above is found also in the behavior of the cross sections $\sigma(\theta, 2_1^+)$. Figure 3 shows that the magnitude of $\sigma(\theta, 2_1^+)$ for the nuclei belonging to the beginning of the shell is much smaller than that for the nuclei to the latter half of the shell because of the destructive and constructive nature of interference.

So far, the neutron-number dependence of the interference nature has been discussed. However, it is very interesting to note that a pair of nuclei ^{114}Cd and ^{116}Sn with $N = 66$ shows a different $A(\theta, 2_1^+)$ as described in (iii). This is considered to be ascribed to the fact that ^{114,116}Cd are much more collective than ^{116,118}Sn. This fact definitely suggests that there are nuclear structure effects on the

TABLE II. Experimental information on seven targets for (p,t) reactions.

Target	^{100}Ru	^{104}Pd	^{110}Pd	^{116}Cd	^{118}Sn	^{122}Te	^{128}Te
Thickness (mg/cm^2)	2.0	3.4	3.7	0.84	1.1	0.97	0.56
Form	RuO$_2$[a]	Pd[b]	Pd[b]	Cd[a]	SnO$_2$[a]	Te[a]	Te[a]
Method	CS[c]	rolling	rolling	Ar[d]	CS[c]	Ar[d]	Ar[d]
Enrichment (%)	97.5	99.4	97.7	96.9	95.8	94.7	99.2
Energy resolution (keV)	140	70	80	30	50	30	30

[a] On an aluminum backing of 0.4 μm thickness.
[b] Self-supporting metallic film.
[c] Centrifugal settling method (precipitation method).
[d] Argon sputtering method.

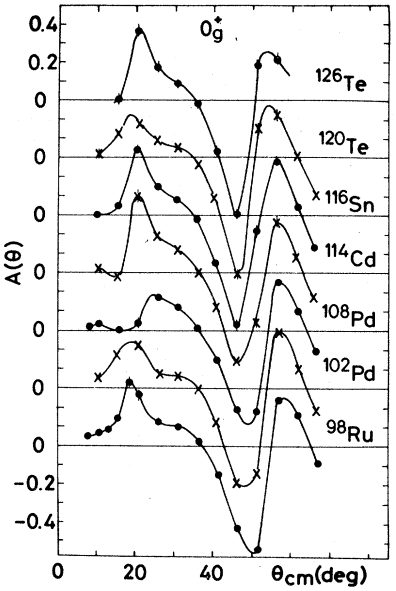

FIG. 1. Angular distributions of analyzing powers $A(\theta, 0_g^+)$ for $(\vec{p}, t)$ reactions at $E_p = 22.0$ MeV. Each residual nucleus is indicated. The lines are to guide the eye.

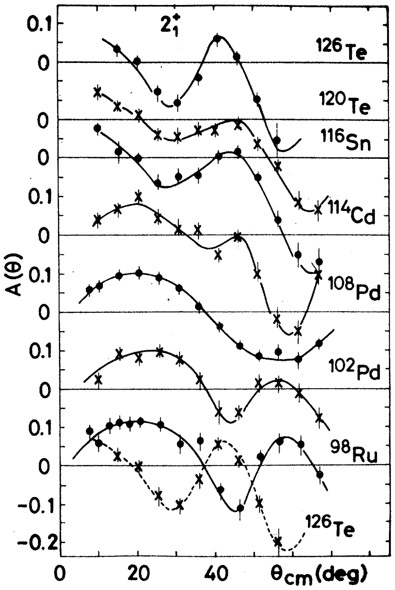

FIG. 2. Angular distributions of analyzing powers $A(\theta, 2_1^+)$ for $(\vec{p}, t)$ reactions at $E_p = 22.0$ MeV. Each residual nucleus is indicated. The lines are to guide the eye.

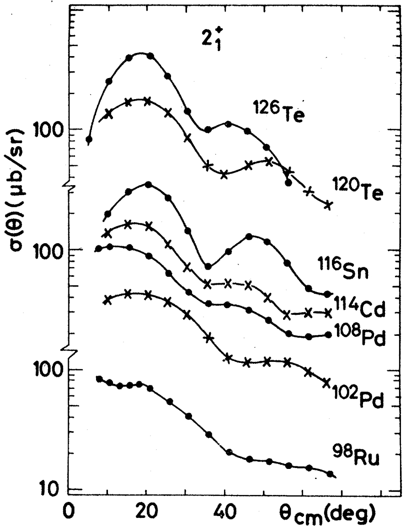

FIG. 3. Angular distributions of cross sections $\sigma(\theta, 2_1^+)$ for (p, t) reactions at $E_p = 22.0$ MeV. Each residual nucleus is indicated. The lines are to guide the eye.

analyzing power $A(\theta, 2_1^+)$.

The data of Ref. 1 with ^{110}Pd and ^{128}Te targets were analyzed by first obtaining the wave functions of the 0_g^+ and 2_1^+ states of both target and residual nuclei by using BCS and quasiparticle random phase approximation (RPA) theories, and the reaction dynamics were treated in terms of the coupled-channel Born approximation (CCBA); see Refs. 4 and 5 for detail. Although we succeeded in fitting $A(\theta, 2_1^+)$ for both reactions this way, a trouble encountered was that the form factor for the one-step transition $F_2(0_g^+(A+2) \rightarrow 2_1^+(A); r)$ had to be multiplied in the case of the ^{110}Pd target by an adjustment factor as large as 4. Such an adjustment factor just as large as 4 was necessary also to reproduce observed cross sections $\sigma(\theta, 2_1^+)$ of (p, t) reactions on Pd isotopes of $A = 104$, 108, and 110 at $E_p = 52$ MeV.[5] On the other hand, the form factor $F_2(0_g^+(A+2) \rightarrow 2_1^+(A); r)$ which was obtained just by using the quasiparticle-RPA theory was good enough for reproducing the experimental $A(\theta, 2_1^+)$ and $\sigma(\theta, 2_1^+)$ in the case of the ^{128}Te target.

In the present case a preliminary analysis in terms of CCBA indicates that the quasiparticle-RPA method is not good for reproducing the observed analyzing power $A(\theta, 2_1^+)$ for ^{98}Ru, ^{102}Pd, ^{110}Pd, and ^{116}Cd. These nuclei have quadrupole oscillation parameter β_2 as large as $\beta_2 \gtrsim 0.2$ (Ref. 6). Therefore it is quite possible that anharmonicity in the large-amplitude quadrupole oscillation of these nuclei affects the validity of the quasiparticle-RPA method. Indeed a simplified evaluation showed that the anharmonicity affected appreciably the nature of interference between a direct process and multistep processes.[7]

In conclusion, measurements of the analyzing powers $A(\theta, 2_1^+)$ in $(\vec{p}, t)$ reactions can provide a very severe test for microscopic models of collective quadrupole oscillation of nuclei. This ability which the analyzing powers $A(\theta, 2_1^+)$ have is due to the fact that analyzing powers $A(\theta, 2_1^+)$ are more sensitive than cross sections $\sigma(\theta, 2_1^+)$ to the nature of interference between a direct one-step process and multistep processes. In this sense measurements of the analyzing powers $A(\theta, 2_1^+)$ can provide a new field of application of nuclear polarization studies so as to investigate microscopic structure of nuclear collective motion. The distinctive feature of this method is to utilize the interference between a direct one-step process and strong inelastic multistep processes in two-nucleon transfer reactions.

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