Drastic changes of (p,t) analyzing powers for the isotopes ^{58,60,62,64}Ni and marked incident-energy dependence of the analyzing powers as evidence for strong, sequential, two-step processes

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Drastic changes of (p,t) analyzing powers for the four Ni isotopes in ground-state transitions were observed. The changes are not explained by direct one-step processes but are interpreted by including strong two-step (p,d) (d,t) processes. Interference between the two processes of comparable intensities is essential. Marked incident-energy dependence of the analyzing powers is interpreted similarly.

NUCLEAR REACTIONS Vector analyzing power $A_y(\theta)$ and cross sections $\sigma(\theta)$ for g.s. (p,t) on ^{58,60,62,64}Ni, E_p=22, 20, and 18 MeV, first- and second-order DWBA. Strong, sequential, two-step (p,d) (d,t) processes.

Analyzing power measurement by using a polarized beam is useful for solving problems which are not related directly to a spin-dependent interaction. For example, it can provide a powerful method for investigating nuclear reaction mechanism.[1] Two-nucleon transfer reactions such as (p,t), (t,p), and (α,d) are powerful probes for the investigation of two-nucleon correlations in nuclei.[2] Therefore, many studies of the reaction mechanisms of the two-nucleon transfer reactions have been made. What is most important is to investigate whether or not strong multistep transfer processes exist in *allowed* two-nucleon transfer reactions and how strong they are when they exist. Existence of the strong sequential two-step contributions has been explained in allowed (p,t) (Refs. 3 and 4) and (t,p) (Ref. 5) reactions and (α,d) reactions,[6,7] while a serious doubt has been cast on such contributions on the basis of the exact finite-range first-order distorted-wave Born-approximation (DWBA) analyses[8] with the use of realistic structure wave functions.[8,9] What is needed now, therefore, is direct experimental evidence for strong sequential two-step transfer processes, which is almost independent of the nuclear-structure models used. In this Brief Report, we present anomalous angular distributions of vector analyzing powers $A(\theta)$ for (p,t) reactions on the isotopes ^{58,60,62,64}Ni, which are not reproduced by the first-order DWBA calculations at all. In addition, we show that the inclusion of strong (p,d) (d,t) two-step processes results in reproduction of the qualitative features of the anomalous angular distributions.

The experiment was carried out with 22-, 20-, and 18-MeV polarized proton beams[10] from the University of Tsukuba 12 UD Tandem Pelletron. The average beam polarization was 80% with a typical beam current 80 nA on target. The Ni targets were isotopically enriched self-supporting metallic foils of around 1 mg/cm^2 thickness. Emitted tritons were momentum analyzed with a magnetic spectrograph and were detected with a single-wire-proportional-counter system.[11] Energy resolutions for the tritons were about 40 keV full width at half maximum. Measured analyzing powers $A(\theta)$ and cross sections $\sigma(\theta)$ for 0_g^+(g.s.) $\rightarrow$ 0_g^+(g.s.) (p,t) reactions on the Ni isotopes are shown in Figs. 1 and 2. The absolute values of the cross sections are estimated to have an error of 20%.

Figure 1 shows the isotope dependence of the analyzing powers and cross sections for the $0_g^+ \rightarrow 0_g^+(p,t)$ reactions on the four isotopes ^{58,60,62,64}Ni all obtained at an incident energy of E_p= 22.0 MeV. A marked change of the analyzing powers for the four isotopes is observed at forward angles around $\theta \approx 20°$. While quite a drastic change is observed in the analyzing powers for the four isotopes, changes found in the corresponding cross sections are much less pronounced.

In order to reproduce the data for the four $0_g^+ \rightarrow 0_g^+$ transitions, we first made a first-order DWBA calculation[12] in the zero-range approximation for the reactions $^{A+2}$Ni (p,t) ^{A}Ni (0_g^+) at E_p= 22 MeV. We simply assumed that the nuclear structure involved in the one-step (p,t) transitions is the $(p_{3/2})^2 \rightarrow (p_{3/2})^0$ configurations. The transfer configurations used are so much oversimplified ones that we justify the use of these configurations in our calculations later. We employed the optical potentials with parameters determined so as to reproduce the elastic scattering data for protons[13] and tritons;[14] see Table I. The one-step DWBA calculations thus obtained are shown by dash-dotted curves in Fig. 1. The experimental analzying powers are not reproduced at all by the one-step DWBA calculation especially for the cases of ^{56}Ni [Fig. 1(a)] and ^{58}Ni [Fig. 1(b)]; the one-step calculations always predict a sharp negative minimum around $\theta \approx 20°$ in the analyzing powers while the experimental analyzing powers for the reactions ^{58,60}Ni (p,t) ^{56,58}Ni have a sharp positive peak around $\theta \approx 20°$. In addition to the disagreement observed in the analyzing powers, the one-step DWBA calculations cannot reproduce well the shape of angular distributions of the experimental cross sections.

In the next step, we took into account $^{A+2}$Ni (p,d) $^{A+1}$Ni(d,t) ^{A}Ni (0_g^+) two-step processes in terms of the second-order DWBA (Refs. 12 and 15) and then summed the one- and two-step reaction amplitudes coherently.[12] Again we simplified the nuclear structures involved in the (p,d) (d,t) processes as $(p_{3/2})^2 \rightarrow (p_{3/2})^1 \rightarrow (p_{3/2})^0$. We used the deuteron optical potential parameters which were obtained from an analysis of the data of deuteron elastic

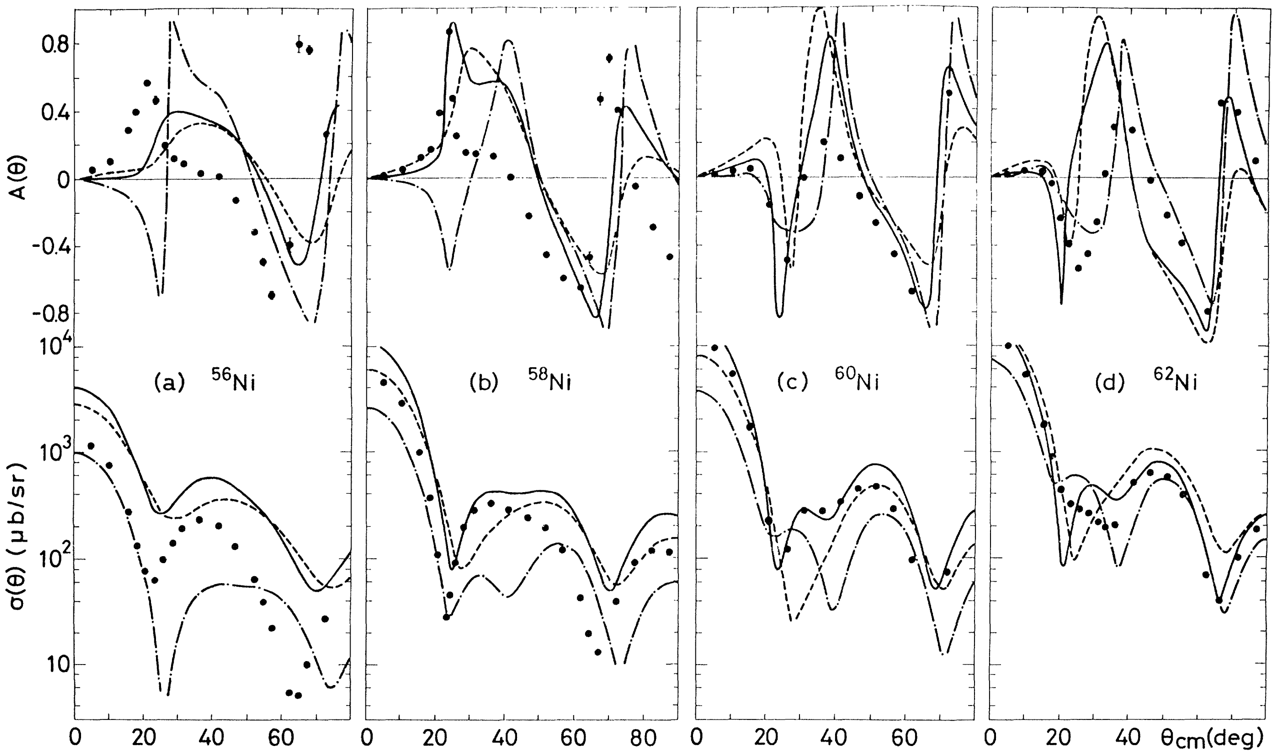

FIG. 1. Experimental and calculated analyzing powers $A(\theta)$ and cross sections $\sigma(\theta)$ for $^{A+2}$Ni (p,t) ^{A}Ni (0_g^+) at $E_p=22.0$ MeV. Each final nucleus is indicated. Dash-dotted (dashed) curves are the first-order [(p,d) (d,t) second-order] DWBA calculations and solid curves are the coherent sum of the two processes.

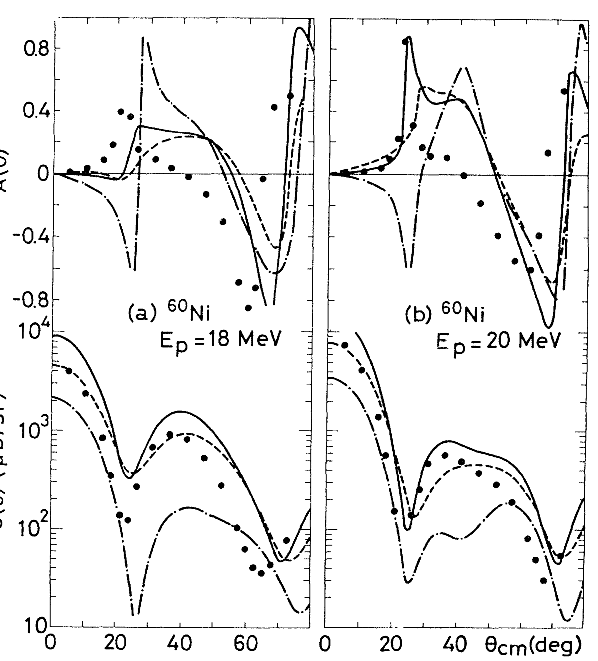

FIG. 2. Experimental and calculated analyzing powers and cross sections for ^{62}Ni (p,t) ^{60}Ni (0_g^+) at $E_p=18.0$ and 20.0 MeV. The definition of calculated curves is the same as that given in Fig. 1.

scattering;[16] see Table I. Throughout this paper, the following normalization constants[15] of the zero-range calculations of the first- and second-order DWBA were used so that no adjustable parameters for the relative amounts of the one- and two-step contributions existed in the calculations: $D_0^2(\text{p,t})=22$ (Refs. 3, 4, and 5), $D_0^2(\text{p,d}) = 1.53$ (Ref. 17), and $D_0^2(\text{d,t}) = 3.37$ (Ref. 18) all in units of 10^4 MeV^2fm^3. The above value of D_0^2(p,d) [D_0^2(d,t)] was actually obtained from the analyses of (p,d) [(d,t)] reactions on various target nuclei.[17,18] The D_0^2(p,t) value was also obtained systematically from the first- and second-order DWBA analyses of (p,t) reactions at $E_p \approx 22$ MeV (Refs. 1–4). The calculated results are compared with the data of Fig. 1. The calculation including the two-step (p,d) (d,t) processes reproduces a general trend of the experimental analyzing powers very well, as shown by solid curves in Fig. 1. An interference effect between the one-step process (dash-dotted curves) and two-step process (dashed curves) produces a sharp negative dip in $A(\theta)$ near $\theta \approx 20°$ in the cases of ^{62,64}Ni (p,t) ^{60,62}Ni on one hand, and a sharp positive peak in the cases of ^{58,60}Ni (p,t) ^{56,58}Ni on the other hand. In addition to the analyzing powers, the shape and magnitude of the cross section data are certainly improved by including the two-step processes. The contribution of the (p,d) (d,t) processes is as much as that of the one-step process in the strong (p,t) reactions.

Next, we investigated the incident-energy dependence of $A(\theta)$ and $\sigma(\theta)$ for the reactions Ni (p,t). Actually, mea-

TABLE I. Optical potential parameters used in the present calculations. Well depths in MeV and lengths in fm.

	Proton	Deuteron	Triton
V_R	52.1	92.2	146.0
r_R	1.17	1.15	1.20
a_R	0.75	0.81	0.66
W_V	2.14	17.7	18.3
W_{SF}	7.46	0	0
r_I	1.32	1.34	1.60
a_I	0.58	0.68	0.89
V_{SO}	6.2	0	7.5
r_{SO}	1.01		1.10
a_{SO}	0.75		0.77
r_C	1.25	1.15	1.30

TABLE II. Reaction Q values (Ref. 19) and the emitted triton energy E_t.

Reaction	Q (MeV)	E_t (MeV) E_p = 22.0 MeV	20.0 MeV	18.0 MeV
^{58}Ni(p,t) ^{56}Ni	−13.97	7.66		
^{60}Ni(p,t) ^{58}Ni	−11.90	9.73		
^{62}Ni(p,t) ^{60}Ni	−9.94	11.71	9.74	7.77
^{64}Ni(p,t) ^{62}Ni	−8.02	13.64		

surements of the reaction ^{62}Ni (p,t) ^{60}Ni (0_g^+) were made by varying the incident energy from $E_p = 22.0$ to 20.0 and 18.0 MeV (Fig. 2). It should be first noticed that the observed $A(\theta)$ and $\sigma(\theta)$ for ^{62}Ni (p,t) ^{60}Ni at $E_p = 18.0$ MeV (20.0 MeV) are quite similar to those for ^{58}Ni (p,t) ^{56}Ni [^{60}Ni (p,t) ^{58}Ni] at $E_p = 22.0$ MeV; compare Figs. 2(a) and 2(b) with Figs. 1(a) and 1(b), respectively. The incident-energy dependence of $A(\theta)$ and $\sigma(\theta)$ for ^{62}Ni (p,t) was analyzed in terms of the one- and two-step DWBA calculations by using the same assumptions employed in the previous calculations which resulted in Fig. 1. As seen in Figs. 2 and 1(c), the calculations succeeded in reproducing the characteristic features of $A(\theta)$ and $\sigma(\theta)$ observed at $E_p = 18.0$, 20.0, and 22.0 MeV. Here, again, inclusion of the (p,d) (d,t) process is essential for reproducing the data through the interference effect.

The similarity in $A(\theta)$ and $\sigma(\theta)$ between the theoretical curves in Fig. 2 and those in Figs. 1(a) and 1(b) is found not only in the final results obtained from the coherent sum of the two processes (solid curves) but also in both the one-step process (dash-dotted) itself and the two-step process (dashed) itself. In order to understand the similarity, we compare the energy of emitted tritons (E_t) of the reactions Ni (p,t) with each other. Because of the reaction Q values, the triton energy in the reaction ^{62}Ni (p,t) ^{60}Ni at $E_p = 18.0$ MeV (20.0 MeV) is almost equal to that in the reaction ^{58}Ni (p,t) ^{56}Ni [^{60}Ni (p,t) ^{58}Ni] at $E_p = 22.0$ MeV; see Table II. Therefore the similarity of $A(\theta)$ and $\sigma(\theta)$ for the (p,t) reactions arises from that of the energy of tritons produced by the (p,t) reactions. In consequence the isotope dependence of $A(\theta)$ and $\sigma(\theta)$ for the reactions Ni (p,t) (Fig. 1), which comes from the Q-value dependence of the reactions, and the incident-energy dependence of $A(\theta)$ and $\sigma(\theta)$ (Fig. 2) can be interpreted similarly in terms of the triton-energy dependence of the one- and two-step contributions of the (p,t) reactions. Because the drastic changes of the (p,t) analyzing powers for the Ni isotopes (Fig. 1) can be thus understood mainly in terms of the Q-value dependence of the one- and two-step contributions and not in terms of the detailed nuclear structures involved in the reactions, it might be justified to use the oversimplified transfer configurations such as $(p_{3/2})^2 \rightarrow (p_{3/2})^0$ and $(p_{3/2})^2 \rightarrow (p_{3/2})^1 \rightarrow (p_{3/2})^0$. More complex configurations, however, should be examined so as to make a definite conclusion.

One might think that routes via inelastic scattering to low-lying collective states such as (p,p′) (2_1^+) (p′,t) (0_g^+) and/or (p,t′) (2_1^+) (t′,t) (0_g^+) could be an important difference between the four isotopes (Fig. 1). The fact that the ^{58,60}Ni (p,t) results at $E_p = 22.0$ MeV can be obtained on the ^{62}Ni (p,t) case by choosing the right bombarding energy (Fig. 2), however, clearly demonstrates that inelastic-scattering channels are not important in the present cases.

There is room for improvement in fitting the (p,t) analyzing power data in Figs. 1 and 2. More refined nuclear structure wave functions including the configurations $f_{5/2}$ and $p_{1/2}$ and/or finite-range DWBA calculations can be expected to improve the fitting.

The importance of the (p,d) (d,t) processes in the reactions Ni (p,t) has been pointed out from an analysis of the cross section data for ^{60,62}Ni (p,t) reactions at $E_p = 27$ MeV.[20] The present work, however, demonstrates much more conspicuously the importance of the two-step (p,d) (d,t) contributions than the cross section data by using the analyzing powers for the Ni (p,t) reactions.

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[1]K. Yagi, in *Polarization Phenomena in Nuclear Physics 1980*, AIP Conf. Proc. No. 69 (AIP, New York, 1981), p. 254.

[2]R. A. Broglia, O. Hansen, and C. Riedel, Adv. Nucl. Phys. 6, 287 (1973).

[3]K. Yagi *et al.*, Phys. Rev. Lett. 43, 1087 (1979); S. Kunori *et al.*, *ibid.* 46, 810 (1981).

[4]Y. Aoki *et al.*, Phys. Rev. C 25, 1050 (1982); 25, 1696 (1982).

[5]W. P. Alford *et al.*, Phys. Rev. C 27, 1032 (1983).

[6]W. W. Daehnick, M. J. Spisak, and J. R. Comfort, Phys. Rev. C 23, 1906 (1981).

[7]J. R. Comfort and W. W. Daehnick, Phys. Rev. Lett. 50, 1627 (1983).

[8]Da Hsuan Feng *et al.*, Phys. Rev. Lett. 44, 1037 (1980).

[9]M. A. Nagarajan and G. R. Satchler, Phys. Rev. Lett. 49, 1899 (1982).

[10]Y. Tagishi and J. Sanada, Nucl. Instrum. Methods 164,

411 (1979).
[11]M. Matoba *et al.*, Nucl. Instrum. Methods 196, 257 (1982).
[12]M. Toyama and M. Igarashi, computer code FNR–TWOSTP (unpublished).
[13]F. D. Becchetti, Jr. and G. W. Greenlees, Phys. Rev. 182, 1120 (1969).
[14]R. A. Hardekopf *et al.*, Phys. Rev. C 21, 906 (1980).
[15]N. Hashimoto and M. Kawai, Prog. Theor. Phys. 59, 1245 (1978).
[16]C. M. Perey and F. G. Perey, Phys. Rev. 132, 755 (1963).
[17]Y. Toba *et al.*, Nucl. Phys. A359, 76 (1981); Y. Aoki *et al.*, *ibid.* A393, 52 (1983).
[18]H. Iida *et al.*, *Proceedings of the Research Center for Nuclear Physics International Symposium on Light Ion Reaction Mechanisms, Osaka, 1983,* edited by H. Ogata (Osaka University, Osaka, 1983).
[19]N. B. Gove and A. H. Wapstra, Nucl. Data Tables 11, 127 (1972).
[20]J. D. Burch, M. J. Schneider, and J. J. Kraushaar, Nucl. Phys. A299, 117 (1978).