PHYSICAL REVIEW C VOLUME 25, NUMBER 1 JANUARY 1982

Reaction mechanism for (p,t) and $(p,{}^3\mathrm{He})$ reactions on $^{13}\mathrm{C}$

S. Kato and K. Okada
Laboratory of Nuclear Studies, Faculty of Science, Osaka University, Toyonaka, Osaka 560, Japan

M. Kondo, K. Hosono, T. Saito, N. Matsuoka, T. Noro, and S. Nagamachi
Research Center for Nuclear Physics, Osaka University, Suita, Osaka 565, Japan

H. Shimizu
Department of Physics, Kyoto University, Kyoto 606, Japan

K. Ogino and Y. Kadota
Department of Nuclear Engineering, Kyoto University, Kyoto 606, Japan

M. Nomura
Institute of Physics, College of General Education, University of Tokyo, Komaba, Tokyo 153, Japan
(Received 9 July 1981)

Differential cross sections and analyzing powers of the $^{13}\mathrm{C}(p,t)^{11}\mathrm{C}$ and $^{13}\mathrm{C}(p,{}^3\mathrm{He})^{11}\mathrm{B}$ reactions to the ground and the first excited states were measured at $E_p=65$ MeV. They were analyzed by means of distorted-wave Born approximation calculations including both one- and two-step processes of p-d-t or -^{3}He. Attention was paid to an isospin symmetry of the reaction process consisting of both isospin 0 and 1 channels, which were important in a comparable order. As intermediate states of $^{12}\mathrm{C}$ in the sequential process, five states of either isospin 0 or 1, which were strongly excited by the $^{13}\mathrm{C}(p,d)^{12}\mathrm{C}$ reaction, were taken into account. A good fit between the data and the theoretical values was obtained, especially for the (p,t) reactions, concerning both differential cross sections and analyzing powers. The calculations including one-step and sequential processes induced, in some cases, remarkable differences from the one-step calculation for backward angles.

[NUCLEAR REACTIONS $^{13}\mathrm{C}(p,t)^{11}\mathrm{C}$, $^{13}\mathrm{C}(p,{}^3\mathrm{He})^{11}\mathrm{B}$, $E=65$ MeV; measured $\sigma(\theta)$ and analyzing powers for 4 transitions. One-step and sequential processes DWBA analysis.]

I. INTRODUCTION

Much attention has been given to simultaneous observations of (p,t) and $(p,{}^3\mathrm{He})$ reactions to analog final states having the same isospin as that of the target nucleus.[1-4] These specific reactions are closely related with each other through an isospin symmetry involved in both reaction processes as well as a nuclear structure. Hence, a measurement of the differential cross sections and the analyzing powers in these two reactions will provide an important clue to elucidate the reaction mechanism including two-step process.

In this work, we present results of simultaneous observation of the reactions $^{13}\mathrm{C}(p,t)^{11}\mathrm{C}$ and $^{13}\mathrm{C}(p,{}^3\mathrm{He})^{11}\mathrm{B}$ using a 65 MeV polarized proton beam. Both differential cross sections and analyzing powers have been measured. The same set of the reactions was reported at $E=49.6$ MeV,[1,2] and at several energies between 26.9 and 43.1 MeV.[3] The present measurement combined with the previous ones will provide further information on the energy dependence of the two-nucleon transfer reaction. We concentrate our attention on the transitions to the ground $\frac{3}{2}^-$ state and the first excited $\frac{1}{2}^-$ state of $A=11$ nuclei. These states have an isospin $\frac{1}{2}$ and then the analog final states here mean the mirror final states.

A breaking of isospin symmetry in the differential cross section due to a Coulomb interaction is small in light nuclei. It is at most a few percent in the target nuclei of ^{13}C.[1] Aside from this small correction, a distorted wave Born approximation (DWBA) calculation predicts[1] that an angular distribution of the (p,t) reaction would show the same shape as that of the $(p,^3\text{He})$, and that the cross section ratio of the two reactions R would amount to 4 unless there is transferred spin $S=1$ which is allowed in the $(p,^3\text{He})$ reaction, and unless there is a D state in the triton and ^{3}He wave functions. Hereafter we designate the angular momentum quantum numbers of the transferred pair as (S,L,J,T). In this case, both initial and final states are specified by the same spin and parity $\frac{1}{2}^-$, and the $S=0$ and 1 transfers are characterized by $(S,L,J)=(0,0,0)$ and (1,0,1), respectively. These two transfers are incoherent in the framework of DWBA and should be added in strength, irrespective of an $L\cdot S$ force in any optical potential. It implies that the cross section ratio should not exceed the value of 4 in this special case. A similar situation is expected in actual cases, since the interference of $S=0$ and 1 transfers due to $L\cdot S$ force will not be so strong. Harris pointed out that the ratio R could be modified by a Lane term in the optical potential in the DWBA calculation.[5] Its effect was, however, found to be very small. It is not seldom, however, that the ratio R deduced from observed cross sections integrated over the angular region of several tens of degrees exceeds the limit of 4.[1,4] A typical example of the puzzling cases is the set of reactions $^{13}\text{C}(p,t)^{11}\text{C}$ and $^{13}\text{C}(p,^3\text{He})^{11}\text{B}$ at 49.6 MeV.[1,2] Another example has recently been found in the reactions $^{29}\text{Si}(p,t)^{27}\text{Si}$ and $^{29}\text{Si}(p,^3\text{He})^{27}\text{Al}$ at 40 MeV.[4] The fact that the cross section ratio R exceeds the value of 4 claims reaction mechanism not included in the conventional DWBA calculation.

Importance of the sequential processes p-d-t for (p,t) and p-d-^{3}He for $(p,^3\text{He})$ reactions on medium or heavy weight nuclei has been studied by Yagi *et al.*[6] In Ref. 6, analyzing powers of the (p,t) reactions on Pd isotopes were interpreted as an interference between the one-step and the sequential processes. It is then natural to add sequential process for the two nucleon transfers on light nuclei to the one step process.

The experimental data of the present work were previously analyzed by means of finite-range DWBA including both one- and two-step processes.[7] The fit to the experimental data was not so good and the contribution of the sequential process to the cross section was larger by several times than that of the one step process in a wide angular region including forward angles. In the analysis of Ref. 7, only the ground and the first excited states of ^{12}C were taken into account as intermediate states in the sequential process. This prescription seemed at first to be natural, since the same approximation has been applied to the case in the (p,t) or $(p,^3\text{He})$ reactions on medium and heavy nuclei.[6,8] The contribution of isospin 1 channels in sequential process in which the $d+^{12}$C channel was contained was neglected in the calculation. It is crucial to include both isospin 0 and 1 states of ^{12}C as intermediate states because, in the case of light target nuclei, the strength of the isospin 1 channel is the same order as that of isospin 0 channels.

Paying attention to the above remark, one of the present authors attempted to fit the theoretical calculation to the experimental data of both ^{13}C (p,t) ^{11}C and $^{13}\text{C}(p,^3\text{He})^{11}\text{B}$ reactions at 49.6 MeV.[9] In the calculation, one step and sequential processes were taken into account with zero range interaction. In addition to the conventional analysis, specification of the reaction channel by a definite isospin was done in order to take fully into account the isospin symmetry involved in the reaction process and nuclear structure. The observed cross section ratio R exceeding the value of 4 at $E=49.6$ MeV was reproduced as a result of strong interference of isospin 0 and 1 channels. The interference is really associated with interference of one- and two-step processes. It will be better to say that the interference results from coexistence of $T=0$ and 1 channels. The interference arises mainly from the fact that the large energy difference of isospin upper $(=1)$ and lower $(=0)$ states of 2^+ in ^{12}C in the sequential process makes the deuteron coupled to the isospin lower state move faster than the deuteron coupled to the isospin upper state. The situation is analogous to that of a photon going through double slits: one slip is specified by a channel of isospin zero and the other by a channel of isospin one.

In the present measurement of $^{13}\text{C}(p,t)^{11}\text{C}$ and $^{13}\text{C}(p,^3\text{He})^{11}\text{B}$ reactions at $E=65$ MeV, suppression of the $(p,^3\text{He})$ cross section relative to (p,t) one was not so remarkable as at $E=49.6$ MeV. We analyzed both measured differential cross sections and analyzing powers using the same prescription as used in Ref. 9 and studied the contribution of the sequential process in the reactions.

II. EXPERIMENTAL PROCEDURE AND RESULTS

The experiments were performed using a 2.3 m cyclotron of the Research Center for Nuclear Physics, Osaka University. Polarized protons from an atomic beam type ion source were axially injected into the cyclotron. The direction of the beam polarization was altered at every 0.2 μC of beam charge by reversing the magnetic field of the ionizer in the polarized ion source.[10] The details of the experimental arrangement and procedures have been given elsewhere.[11] The beam spot on the target was about 2 mm $\times$ 2 mm. After passing through the target, the beam was focused again onto a carbon polarimeter.[11] The beam polarization was monitored continuously in whole measurements. A beam polarization of 60–70 % was routinely obtained with a beam current between 20 and 30 nA on the target.

A ^{13}C target whose isotopical enrichment was 99% was made by a thermal cracking method from enriched methane gas. The thickness was 1.5 mg/cm^2, which was measured by the energy loss of an α particle emitted from ^{241}Am. Emitted particles from the target were detected by two counter telescopes consisting of a ΔE (700 μm Si SSD) and an E (15 mm high purity Ge SSD) detectors placed at equal angle of both sides of the incident beam.[12] The high purity Ge detectors were cooled to liquid nitrogen temperature. A cross sectional side view of the scattering chamber and the detectors is illustrated in Fig. 1. The dectector slit was 6 mm in diameter and was located at 20 cm from the target. The p, d, t, and ^3He particle spectra were simultaneously obtained using a particle identification circuit. For deduction of the analyzing powers, asymmetries were determined by a geometrical mean method using four counts N_{LU}, N_{LD}, N_{RU}, and N_{RD}, where L or R refers to left or right side of the beam axis, and U or D refers to up or down of the spin direction of the incident beam, respectively.[13] Deuteron data were valuable to select strongly excited levels and examine the validity of intermediate (p,d) channels in the sequential process calculations.

Representatives of triton and ^3He energy spectra are shown in Fig. 2. A typical example of the

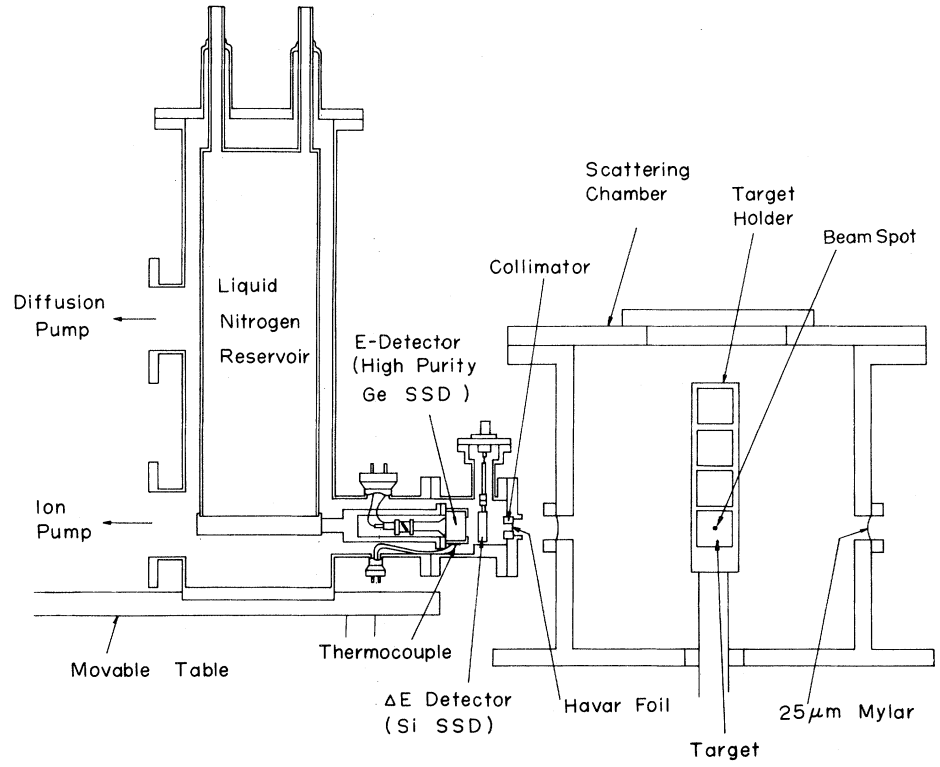

FIG. 1. Cross sectional side view of the scattering chamber and the ΔE-E counter telescope.

deuteron spectrum is illustrated in Fig. 3. Measured angular distributions of the cross sections and the analyzing powers are shown in Figs. 5 and 7–9 with theoretical curves. The errors cited in the figures are overall ones which mainly come from statistical uncertainty.

Angular distributions of the cross sections and analyzing powers leading to the mirror levels are different from each other in almost all cases. For ground state transitions, the cross sections of the (p,t) and $(p,{}^3\mathrm{He})$ reactions are similar in shape, while the analyzing powers are very different. The shape of the analyzing power of the (p,t) reaction has a peak at 60° and the signs are positive in all angular ranges measured, whereas the analyzing powers of the $(p,{}^3\mathrm{He})$ reaction turn to negative beyond 50°. For the excited states, an angular distribution of the cross section of the (p,t) reaction has sharp minima at 20° and 50°. However, that of the $(p,{}^3\mathrm{He})$ reaction varies smoothly. The same situation exists in analyzing powers for the transition to the excited states. The angular shape of the analyzing power of the (p,t) reaction leading to the ground and excited states are similar to each other and the resemblance is also observed in the $(p,{}^3\mathrm{He})$ reactions. The cross section ratio R of the (p,t) reaction to the $(p,{}^3\mathrm{He})$ reaction was obtained by integrating the data from 18° to 79°. The ratio S's for the ground and excited states are 3.8 and 3.5, respectively. The values of R at this energy are smaller than those at 49.6 MeV and also smaller than 4.

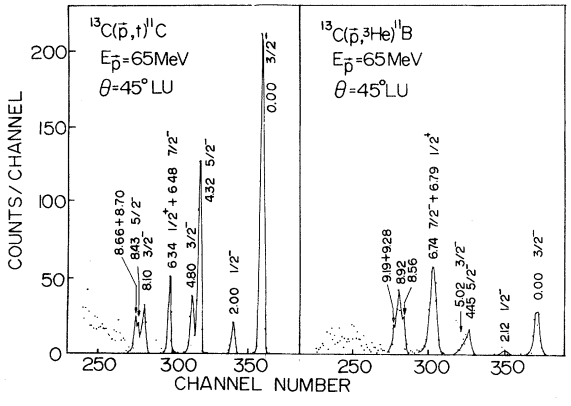

FIG. 2. Energy spectra for $^{13}\mathrm{C}(p,t)^{11}\mathrm{C}$ and $^{13}\mathrm{C}(p,{}^3\mathrm{He})^{11}\mathrm{B}$ reactions at 45°. The symbol LU means spectra taken at left side of the incident beam with up direction of incident beam polarization.

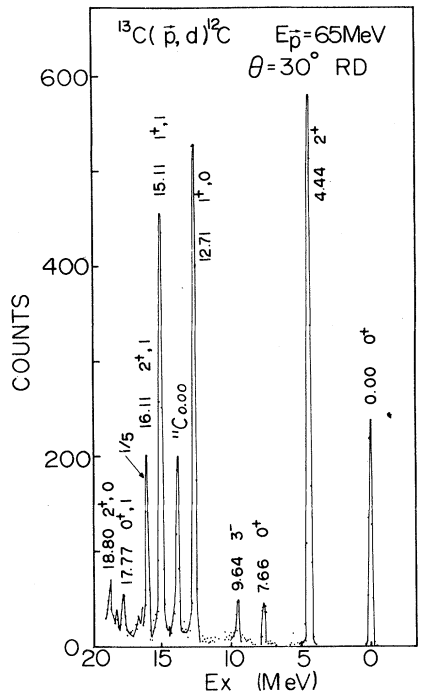

FIG. 3. Energy spectrum for $^{13}\mathrm{C}(p,d)^{12}\mathrm{C}$ reaction at 30°. The symbol RD means spectrum taken at right side of the incident beam with down direction of incident beam polarization.

III. OUTLINE OF THE CALCULATION

The prescription for analyzing the data is along the line of the work done by one of the present authors.[9] In the following, we briefly describe the parameters which were used in the present analysis. Five intermediate states of $^{12}\mathrm{C}$ shown in Fig. 4 were taken into account for the sequential process, as was the choice in Ref. 9. The number of channels interfering with each other amounts (for example, 9 and 14 for transferred angular momenta $J=0$ and 2, respectively), in the $(p,{}^3\mathrm{He})$ reaction, to the lowest $\frac{1}{2}^-$ state of $^{11}\mathrm{B}$. Adopted channels responsible to the sequential process are listed in Tables I and II for the state. Spectroscopic amplitudes necessary for (p,d) and $(d,t$ or $^3\mathrm{He})$ were deduced from Cohen-Kurath wave functions using the interaction "(8–16) POT" in Ref. 14 or 15. Some of them were really tabulated in Refs. 14 and 15, but the spectroscopic amplitudes between excited states were not shown in Refs. 14 and 15.

The Cohen-Kurath wave functions recalculated by Otsuka[16] were used to accomplish spectroscopic

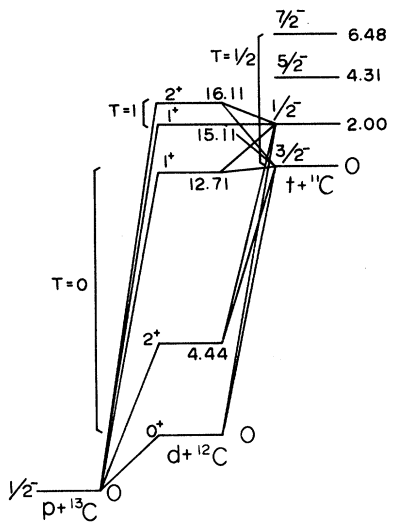

FIG. 4. Levels adopted in the calculation including the sequential process.

amplitudes. Attention was paid to consistence of the phase convention among one particle coefficient of fractional parentage (cfp) associated with (p,d) and $(p,t$ or $^3\mathrm{He})$ and two particle cfp for $(p,t$ or $^3\mathrm{He})$, because the phase convention of Ref. 14 seemed different from that of Ref. 15. A computer program TWOSTP, made by Toyama and Igarashi,[17] was fully used to calculate both one step and sequential processes. A correction due to nonorthogonal terms which were characteristic to the sequential process was neglected.

The separation energy method was adopted to calculate the radial shape of the form factor for a transferred nucleon. The values of $V_{LS}=6.0$ MeV, $r=1.25$ fm, and $a=0.65$ fm were used. In the case that the separation energy was negative, a weakly bound state was assumed. The two-nucleon transfer form factors were calculated by means of the method of Bayman and Kallio[18] and with the same parameters as above. The range parameter k for triton was taken to be 0.24 fm^{-1}, then the value of the rms radius of the triton was $\Delta=1/(\sqrt{6}k)=1.7$ fm. The zero-range approximation was used for both the one step and the sequential processes. The normalization constants of the zero-range approximation were taken to be the conventional values[19]

$$D_0{}^2(p,d)=1.53,\ D_0{}^2(d,t)=3.33,$$

$$D_0{}^2(d,{}^3\mathrm{He})=2.95\ ,$$

TABLE I. Adopted channels with transferred angular momentum $J=0$ associated with $^{13}\mathrm{C}(p,t)^{11}\mathrm{C}$ and $^{13}\mathrm{C}(p,{}^3\mathrm{He})^{11}\mathrm{B}$ reactions yielding spin $\frac{1}{2}$ and isospin $\frac{1}{2}$ states are shown. T' and J' are the isospin and spin of the intermediate nuclear levels, l_1j_1 and l_2j_2 represent the shell occupied by the transferred nucleons, respectively. S_1 or S_2S_3 is the spectroscopic amplitudes for one- or two-nucleon transfer.

Channels	Steps	T'	J'	$l_1j_1=l_2j_2$	S_1 (or S_2S_3)
1	1			$p\frac{3}{2}$	−0.8184
2	1			$p\frac{1}{2}$	0.2316
3	2	0	0	$p\frac{1}{2}$	−0.9605
4	2	0	1	$p\frac{3}{2}$	0.4794
5	2	0	1	$p\frac{1}{2}$	0.0014
6	2	0	2	$p\frac{3}{2}$	−0.8602
7	2	1	1	$p\frac{3}{2}$	0.7260
8	2	1	1	$p\frac{1}{2}$	0.0059
9	2	1	2	$p\frac{3}{2}$	−0.3390

TABLE II. Adopted channels with transferred angular momentum $J=2$ associated with the $^{13}C(p,^3He)^{11}B$ reaction yielding spin $\frac{1}{2}$ and isospin $\frac{1}{2}$ states. T' and J' are the isospin and spin of the intermediate nuclear levels, l_1j_1 and l_2j_2 represent the shell occupied by the transferred nucleons, respectively. S_1 or S_2S_3 is the spectroscopic amplitudes for one nucleon transfer.

Channels	Steps	T'	J'	$l_1j_1\,l_2j_2$	S_1 (or S_2S_3)
1	1			$(p\frac{3}{2})^2$	0.2681
2	1			$p\frac{3}{2}p\frac{1}{2}$	1.5690
3	1			$p\frac{3}{2}p\frac{1}{2}$	−0.7582
4	2	0	0	$p\frac{1}{2}p\frac{3}{2}$	1.8690
5	2	0	1	$(p\frac{3}{2})^2$	0.2212
6	2	0	1	$p\frac{3}{2}p\frac{1}{2}$	−0.6887
7	2	0	1	$p\frac{1}{2}p\frac{3}{2}$	0.0087
8	2	0	2	$(p\frac{3}{2})^2$	0.0605
9	2	0	2	$p\frac{3}{2}p\frac{1}{2}$	−1.1104
10	2	1	1	$(p\frac{3}{2})^2$	0.4605
11	2	1	1	$p\frac{3}{2}p\frac{1}{2}$	−1.1284
12	2	1	1	$p\frac{1}{2}p\frac{3}{2}$	−0.0284
13	2	2	1	$(p\frac{3}{2})^2$	−0.0631
14	2	2	1	$P\frac{3}{2}p\frac{1}{2}$	−1.3028

all in units of 10^4 MeV^{2}fm^3. We take the two nucleon transfer strength to have the value

$$\left[\frac{3\pi\Delta^2}{2}\right]^{3/2} D_0{}^2(p,\,t \text{ or } {}^3\text{He}) = 1200\,,$$

that is, $D_0{}^2=24$. The calculated cross sections including one- and two-step processes are multiplied by the enhancement factor ϵ which is dependent on each final state. However, the same ϵ has to be used for analog final states of the same spin and parity. For example, the enhancement factor for $^{13}C(p,^3He)^{11}B(\frac{1}{2}^-)$ is kept to be that for $^{13}C(p,t)^{11}C(\frac{1}{2}^-)$.

The computer program TWOSTP does not include the phase factor arising from antisymmetrization of transferred particles together with core nucleons before and after transition. Therefore, the sign of the transition amplitude for the process p-d-t or p-d-^{3}He had to be changed relative to the transition amplitude for the one step process. The relative phase of one step and sequential processes gives rise to confusion in the actual calculation process due to the factor mentioned above. So we recalculated some of the results obtained by Hashimoto and Kawai[20] to find an agreement of our result with theirs. For the case of the $(p,^3He)$ reaction, transferred two nucleons can be coupled into either isospin by the ratio $D(S=1,\ T=0)/D(0,1)$ of weight factor $D(S,T)$ in the spectroscopic overlap integral involving the light particles in the reaction[21] as an input parameter. We took its value as

TABLE III. Optical model parameters used in this calculation.

Particle	E (MeV)	V_R (MeV)	r_R (fm)	a_R (fm)	W_V (MeV)	W_D (MeV)	r_I (fm)	a_I (fm)	V_{LS} (MeV)	r_{LS} (fm)	a_{LS} (fm)	r_C (fm)
p	65	44.6	1.09	0.57	7.52	6.35	1.09	0.50	5.50	1.09	0.57	1.10
d	49.62	97.4	1.15	0.62	0.0	12.0	1.15	0.62	3.6	1.15	0.62	1.30
$t,{}^3\mathrm{He}$	60.0	165.54	1.17	0.73	32.73	0.0	1.39	0.84	1.47	1.29	0.161	1.30

0.33.

A choice of optical parameters was one of the difficult problems in this calculation, because it is somewhat hard to reproduce the elastic cross sections and polarizations with an optical model for such light nuclei of concern here. The set of optical potential parameters used in the present work are summarized in Table III. The proton optical potential was determined by the global analysis performed by Watson, Singh, and Segel[22] at the beginning and a slight change of the parameters V_R and W_D was tried. The deuteron optical potential was difficult to choose. The parameters for the deuteron potential were at first taken from Ref. 23 and then they were modified according to the prescription by Johnson and Soper.[24] Values of V_R, V_{LS}, and W_D for the deuteron potential were also modified slightly, as they reproduced both cross sections and analyzing powers on (p,d) as well as (p,t) and $(p,{}^3\mathrm{He})$ reactions discussed in the next section. The optical potentials for t and ${}^3\mathrm{He}$ were taken to be the same. The parameter set given in Ref. 25 was adopted without any changes. A calculation including Lane potential terms, which would be included in p and t, ${}^3\mathrm{He}$ optical potentials, was tried, but we did not find remarkable change in the results. The Lane potential was omitted in our calculation. Calculations of the present work were performed using a FACOM M-180 II computer at the Institute of Nuclear Study, Univeristy of Tokyo.

IV. DISCUSSION OF THE INDIVIDUAL TRANSITIONS

A. (p,t) reaction to the ground state of $^{11}\mathrm{C}(\frac{3}{2}^-)$

As shown in Fig. 5, fits to the experimental data are fine for the angular distribution of the cross section and satisfactory for the angular shape of the analyzing power, although the calculation of the analyzing power is shifted from the data by about 0.3 over the entire angular range. It is clearly indicated that the contribution from the sequential process is dominant in the region of $\theta \gtrsim 60°$, while it is very small at forward angles. The enhancement factor to be multiplied with the theoretical cross section is found to be $\epsilon = 1.2$. This factor may come from an incompleteness of the wave functions used. To check the adequacy of the parameters of the (p,t) reaction in the sequential process, the cross sections and analyzing powers of the (p,d) reactions to the five states of $^{12}\mathrm{C}$ were calculated as curves illustrated in Fig. 6, which shows a fair fit to the data for the cross section.

B. $(p,{}^3\mathrm{He})$ reaction to the ground state of $^{11}\mathrm{B}$ $(\frac{3}{2}^-)$

Figure 7 indicates a comparison between observed data and the calculated results. The same

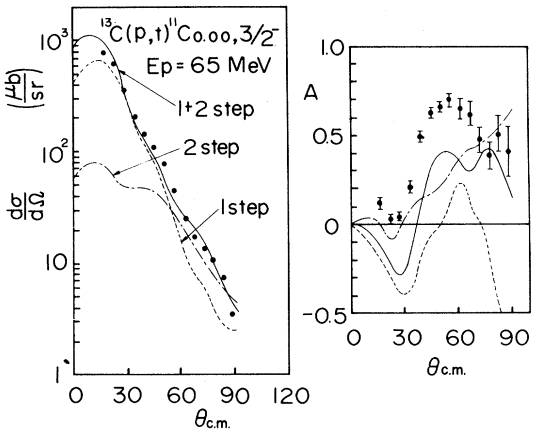

FIG. 5. Differential cross section and analyzing power of the $^{13}\mathrm{C}(p,t)^{11}\mathrm{C}$ reaction to the ground state of $\frac{3}{2}^-$. The solid curves are the calculated ones including both one step and sequential processes with enhancement factor $\epsilon = 1.2$, the dotted curves are the result of the calculations including only the one step process, and dotted-dashed curves are the results of the calculations including only sequential process.

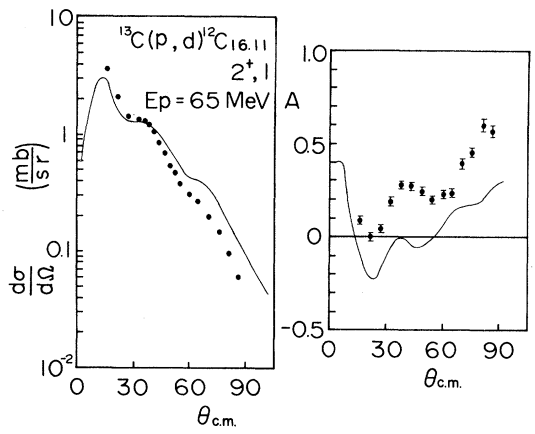

FIG. 6. Differential cross sections and analyzing powers for the $^{13}C(p,d)^{12}C$ reaction leading to the 16.11 MeV level. The curves are the result of the calculations. The (p,d) reaction is a first step of the sequential process. In the calculation Cohen-Kurath spectroscopic amplitudes and optical potential parameters shown in Table III are used.

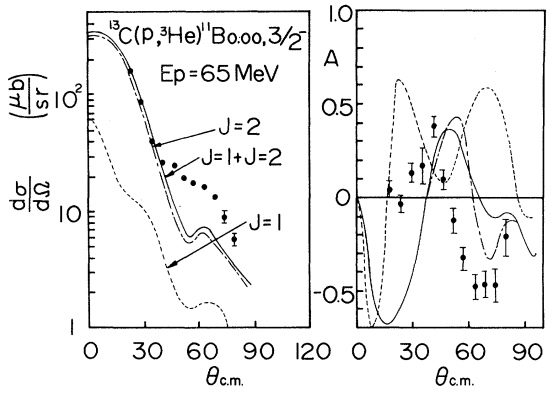

FIG. 8. Differential cross sections and analyzing powers of the $^{13}C(p,^3He)^{11}B$ reaction to the ground state of $\frac{3}{2}^-$. Dotted curves and dotted-dashed curves are the results of the calculations for $J=1$ and 2 transitions, respectively, including both one step and sequential processes. Solid curves are the incoherent sum of both transitions. The enhancement factor ϵ is 1.2.

enhancement factor as that of (p,t) to the ground state of ^{11}C as mentioned before was used. Fits to the data are not so good. The theoretical cross sections beyond 40° are smaller compared to the observed ones. The curve of the calculated analyzing power is rather poor. As in the case of the (p,t) reaction, the two-step process becomes predominant in backward angles. There are two possible transferred angular momenta $J=1$ and 2 in the $(p,^3He)$ reaction. In each case, transferred isospin of two nucleons can be either 0 or 1. In Fig. 8, the contributions from $J=1$ and 2 are represented separately. The contribution to the cross section of $J=2$ transfer is much larger in comparison with $J=1$ transfer.

C. (p,t) reaction to the first excited state of ^{11}C ($\frac{1}{2}^-$)

In this transition, the experimental cross section provides two very clear peaks around 30° and 60°. This is a characteristic pattern associated with $L=0$ transition. The cross section is well reproduced in the present analysis, as shown in Fig. 9.

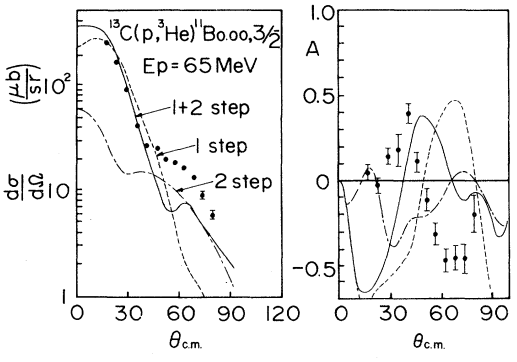

FIG. 7. Differential cross sections and analyzing powers of the $^{13}C(p,^3He)^{11}B$ reaction to the ground state of $\frac{3}{2}^-$. For the curves, see Fig. 5. The enhancement factor ϵ is 1.2.

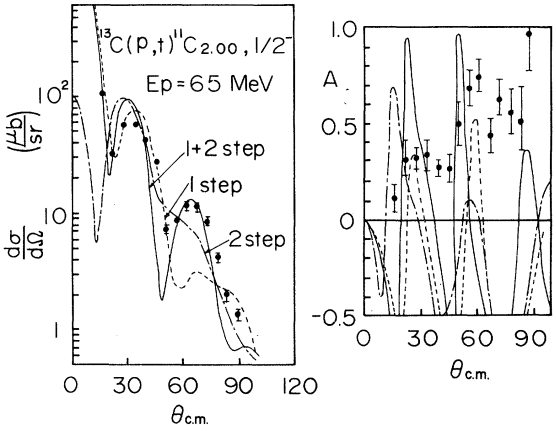

FIG. 9. Differential cross sections and analyzing powers of the $^{13}C(p,t)^{11}C$ reaction to the first excited state of $\frac{1}{2}^-$. For the curves, see Fig. 5. The enhancement factor ϵ is 2.2.

The first peak of the cross section is reproduced tolerably by either the one step or the sequential process; however, cooperation of the two processes together with interference between them reproduced the peak better. The second peak cannot be reproduced by either the one step or the sequential process. An interference between two processes seems essential. An enhancement factor of $\epsilon=2.2$ is necessary to reproduce the magnitude of the cross section. An interference of channels 1 and 2 specified in Table I results in cancellation which arises from different phases in the spectroscopic amplitude S_1 of these two channels. As the results of the cancellation, the contribution of the one step process is decreased even for forward angles and is comparable to that of the sequential process in whole angular range. A fairly large value of ϵ is associated with this fact and may depend sensitively on parameters used in the shell model calculation for p-shell nuclei. The analyzing power cannot be reproduced by present calculation.

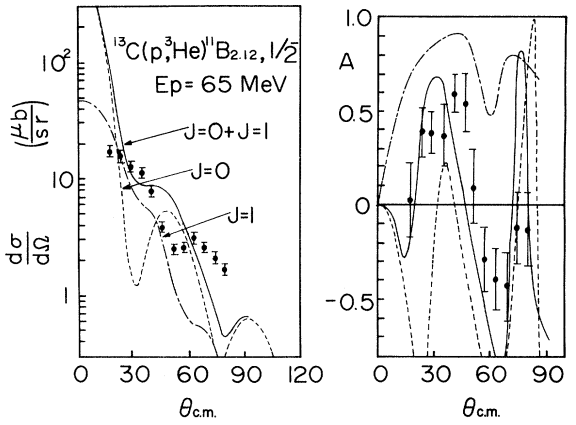

FIG. 11. Differential cross sections and analyzing powers of the $^{13}\mathrm{C}(p,{}^3\mathrm{He})^{11}\mathrm{B}$ reaction to the first excited state of $\frac{1}{2}^-$. Dotted curves and dotted-dashed curves are the results of the calculations for $J=0$ and $J=1$ transitions, respectively, including both one step and sequential processes. The enhancement factor ϵ is 2.2.

D. $(p,{}^3\mathrm{He})$ reaction to the excited state of $^{11}\mathrm{B}$ $(\frac{1}{2}^-)$

No peak is observed in the region of 30°—40° as shown in Fig. 10, which is contrary to the (p,t) cross sections. This feature is hardly reproduced when only the one step process is taken into account. The transition amplitudes from the one step process and the sequential process cancel each other in the region of 30°—40°. The observed peak around $\theta=60°$ could not be reproduced in the present calculation. Figure 11 shows the contribution from the $J=0$ and 1 transitions to the angular distributions. The analyzing power is fairly well fitted by the theoretical curve. If we make the potential depth of the real LS term very deep in the deuteron optical potential, the peak of the $J=0$ transition in the cross section moves toward a large angle, that is, toward the observed peak. However, use of a strong LS term in the deuteron optical potential makes the fit to the analyzing power of (p,d) reaction very poor, and the calculated analyzing powers have some amount of negative values over almost all angles $\theta \lesssim 90°$.

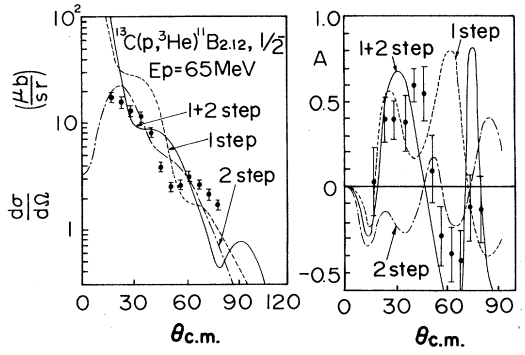

FIG. 10. Differential cross sections and analyzing powers of the $^{13}\mathrm{C}(p,{}^3\mathrm{He})^{11}\mathrm{B}$ reaction to the first excited state of $\frac{1}{2}^-$. For the curves, see Fig. 5. The enhancement factor ϵ is 2.2.

V. CONCLUSIONS

In this paper a comparative study of the (p,t) and $(p,{}^3\mathrm{He})$ reactions on the mirror levels in $^{11}\mathrm{C}$ and $^{11}\mathrm{B}$ was made for cross sections and analyzing powers in order to investigate the reaction mechanism of the two-nucleon transfer reactions in a microscopic way. Special attention was paid to make clear the importance of the sequential two step process on these two-nucleon transfer reactions. The treatment of the sequential process was carried out in a straightforward way using Cohen-Kurath spectroscopic amplitudes. It was crucial to take into account both $T=0$ and 1 levels as the intermediate states, because the spacing of the two levels was very large in the intermediate $^{12}\mathrm{C}$ nucleus.

Satisfactory fits to the experimental cross sec-

tions were obtained for $^{13}(p,t)^{11}$C reactions to both ground and first excited states but the fits to the analyzing power were poor. The importance of the sequential process was remarkable in large angles where the one step process alone could not reproduce the experimental angular distributions.

On the other hand, less satisfactory fits were obtained for the ^{13}C(p, ^{3}He)^{11}B reaction to both ground and first excited states. The calculated cross sections were smaller than the measured ones at large angles. The analyzing power for the ground state of ^{11}B was rather poorly fitted. The angular distribution of analyzing power to the first excited state of ^{11}B was fairly well reproduced up to large angles.

We conclude that a microscopic description of the (p,t) and (p, ^{3}He) reactions requires both one- and two-step processes, as well as taking into account both isospin 0 and 1 levels in the intermediate states in the sequential process. While the overall description of the data was less than satisfactory, the inclusion of two-step processes did improve the data representation from that obtained with the one-step description alone.

ACKNOWLEDGMENTS

The authors would like to thank the cyclotron crew for operation of the cyclotron and also Professor K. Nisimura, Dr. K. Imai, and Dr. K. Hatanaka for the operation of the polarized ion source. The authors are grateful to the late Professor S. Yamabe for his continuous advice and encouragement during this work. One of the authors (M.N.) would like to thank Dr. M. Igarashi for his kind guidance concerning the computer code TWOSTP. This experiment was performed at the Research Center for Nuclear Physics, Osaka University, under program No. 5A17.

[1]D. G. Fleming, J. Cerny, and N. K. Glendening, Phys. Rev. 165, 1153 (1968).
[2]J. A. Macdonald, J. Cerny, J. C. Hardy, H. L. Harney, A. D. Bacher, and G. R. Plattner, Phys. Rev. C 9, 1694 (1974).
[3]S. Micheletti, M. Pignanelli, and P. Guazzoni, Phys. Rev. C 11, 64 (1975).
[4]H. Nann and B. H. Wildenthal, Phys. Rev. C 19, 2146 (1979).
[5]S. M. Harris, Phys. Rev. C 1, 362 (1970).
[6]K. Yagi, S. Kunori, Y. Aoki, K. Nagano, Y. Tagishi, and Y. Toba, Phys. Rev. C 19, 285 (1979); S. Kunori, Y. Aoki, H. Iida, K. Nagano, Y. Toba, and K. Yagi, Phys. Rev. Lett. 46, 810 (1981).
[7]T. Kammuri, Proceedings of the INS International Symposium on Nuclear Direct Reaction Mechanism, Fukuoka, 1978, edited by M. Tanifuji and K. Yazaki (unpublished), p. 166.
[8]N. Hashimoto and M. Kawai, Prog. Theor. Phys. 59, 1245 (1978).
[9]M. Nomura, *Proceedings of the 1980 RCNP International Symposium on Highly Excited States in Nuclear Reactions, Osaka, 1980,* edited by H. Ikegami and M. Muraoka (RCNP, Osaka University, 1980), p. 618.
[10]K. Imai, N. Tamura, and K. Nishimura, Research Center for Nuclear Physics Annual Report, 1976, p. 23.
[11]S. Kato *et al.*, Nucl. Instrum. Methods 169, 589 (1980).
[12]N. Matsuoka, K. Hosono, T. Saito, A. Shimizu, and M. Kondo, Research Center for Nuclear Physics Annual Report, 1976, p. 97; M. Nakamura *et al.*, J. Phys. Soc. Jpn. 44, Suppl. 41 (1978).
[13]G. G. Ohlsen and P. W. Keaton, Jr. Nucl. Instrum. Methods 109, 41 (1973).
[14]S. Cohen and D. Kurath, Nucl. Phys. A101, 1 (1967).
[15]S. Cohen and D. Kurath, Nucl. Phys. A141, 145 (1970).
[16]N. Otsuka, private communication.
[17]M. Toyama and M. Igarashi (unpublished).
[18]B. F. Bayman and A. Kallio, Phys. Rev. 156, 1121 (1967).
[19]P. D. Kunz, instruction manual for DWUCK 4; R. H. Bassel, Phys. Rev. 149, 791 (1966).
[20]N. Hashimoto and M. Kawai, Prog. Theor. Phys. 59, 1245 (1978).
[21]N. K. Glendenning, Annu. Rev. Nucl. Sci. 13, 191 (1963); Phys. Rev. 137, B102 (1965).
[22]B. A. Watson, P. P. Singh, and R. E. Segel, Phys. Rev. 182, 977 (1969).
[23]G. M. McAllen, W. T. Pinkston, and G. R. Satchler, Part. Nucl. 1, 412 (1971); P. G. Roos, S. M. Smith, V. K. C. Cheng, G. Tibell, A. A. Cowley, and R. A. J. Riddle, Nucl. Phys. A255, 187 (1975).
[24]R. C. Johnson and P. J. R. Soper, Phys. Rev. C 1, 976 (1970).
[25]W. E. Burcham, J. B. A. England, R. G. Harris, O. Karben, and S. Roman, Nucl. Phys. A246, 269 (1974); the set *B* for ^{9}Be.