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A COMPARATIVE STUDY OF THE $^{13}C(p, p')^{13}C$ AND $^{13}C(p, n)^{13}N$ REACTIONS AT $E_p = 35$ MeV

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Abstract: Differential cross sections were measured at $E_p = 35$ MeV for the $^{13}C(p, n)$ and $^{13}C(p, p')$ reactions leading to the four low-lying states in the mirror nuclei ^{13}N and ^{13}C. In addition, the analyzing powers were measured for the $^{13}C(p, p')$ reaction. The data are generally well accounted for by DWBA calculations except for the $^{13}C(p, p')^{13}C(3.09\ \text{MeV}, \frac{1}{2}^+)$ reaction, for which the calculations cannot even reproduce the qualitative features of the data. A comparison of the (p, n) and the (p, p') results suggests that the isoscalar part of the $^{13}C(\text{g.s.}, \frac{1}{2}^-) \to {}^{13}C(3.09\ \text{MeV}, \frac{1}{2}^+)$ transition is not correctly described by currently available shell-model wave functions.

E | NUCLEAR REACTIONS $^{13}C(p, n)$, (p, p'), $E = 35$ MeV; measured $\sigma(\theta)$, $A(\theta)$. ^{13}C level deduced transition isoscalar component. Enriched target. DWBA analysis.

1. Introduction

The recent discovery [1]) of enhanced large-angle cross sections in the $^{16}O(p, n)^{16}F(\text{g.s.}, 0^-)$ reaction at $E_p = 35$ MeV has generated much interest [2-4]). The experimental angular distribution for this reaction shows a second maximum (about 20 μb/sr) around 110°, but distorted-wave Born approximation (DWBA) calculations predict a minimum (<1 μb/sr) near that angle. This large enhancement of the $0^+ \to 0^-$ cross section at large momentum-transfer has been suspected to be due to medium correction effects. Because of its purely longitudinal nature this transition is ideally suited for a study of dimesic polarization effects, and a recent calculation has explained this enhancement at least qualitatively [4]). However the validity of a

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number of approximations and assumptions in the models used for the reaction and nuclear structure calculations should be carefully checked before a positive statement is made on possible pionic effects. Thus data on similar transitions would be useful to test our understanding of the (p, n) reaction at 35 MeV.

The isovector $0^+ \to 0^-$ and $0^+ \to 1^-$ transitions in $^{16}O(p, n)^{16}F$ are almost pure $\nu p_{1/2} \to \pi s_{1/2}$ excitations. This is similar to the $\frac{1}{2}^- \to \frac{1}{2}^+$ transition in $^{13}C(p, n)^{13}N$ which is predicted [5,6]) to be predominantly a $\nu p_{1/2} \to \pi s_{1/2}$ excitation also. The $^{13}C(p, n)^{13}N(2.37\text{ MeV}, \frac{1}{2}^+)$ reaction proceeds by $(\Delta J, \Delta T) = (0, 1)$ [like $^{16}O(p, n)^{16}F(0^-)$] but also by $(\Delta J, \Delta T) = (1, 1)$ [like $^{16}O(p, n)^{16}F(1^-)$]. Here ΔJ and ΔT are the total angular momentum transfer and the isospin transfer, respectively. Additional information on the $p_{1/2} \to s_{1/2}$ transition can be obtained from inelastic scattering experiments on ^{13}C to the $\frac{1}{2}^+$ state at 3.09 MeV. This transition in ^{13}C involves four amplitudes with $(\Delta J, \Delta T) = (0, 0), (0, 1), (1, 0)$, and $(1, 1)$. The relative importance of these amplitudes predicted by the shell model can be tested using a variety of reactions.

However, serious problems have been encountered in describing inelastic electron [7]), pion [8]), and proton [9,10]) scattering data for the $\frac{1}{2}^+$ state in ^{13}C. In inelastic pion scattering (which can proceed only by $\Delta J = 1$ since the pion has no spin) the π^- angular distribution for the $\frac{1}{2}^+$ state was reproduced reasonably well by distorted wave impulse approximation (DWIA) calculations but in the case of π^+ the predicted cross section was a factor of 6 smaller than the data. DWIA calculations also failed to fit the (p, p′) angular distribution for the $\frac{1}{2}^+$ state taken at $E_p = 547$ MeV [9]). The calculated cross sections were out of phase with the data and much smaller. The predicted analyzing powers were out of phase with the data at the second maximum. Similarly, 135 MeV (p, p′) data [10]) could not be fitted well by DWBA calculations. Furthermore, it has been reported [7]) that the longitudinal form factor for the 3.09 MeV state in ^{13}C measured in an (e, e′) experiment is about a factor of 5 larger than predicted by theory, whereas the discrepancy between theory and experiment is much smaller for the transverse form factor.

Peterson *et al.* [11]) studied the $^{13}C(^3He, ^3He')$, $(^3He, t)$, and (α, α') reactions to determine the ratio of the $\Delta T = 1$ and $\Delta T = 0$ transition amplitudes. Their results for the $\frac{1}{2}^+$ states in ^{13}C and ^{13}N were consistent with the pion data. However the microscopic DWBA calculations for the $(^3He, ^3He')$ and $(^3He, t)$ reactions employed very simple transition densities which makes comparisons with the other studies difficult. The cross section magnitudes were fitted by adjusting the interaction strengths V_0 and V_τ using only the $\Delta J(\Delta L, \Delta S) = 1(1, 0)$ part of the transition density. (Here ΔL and ΔS are the transferred orbital angular momentum and the transferred spin, respectively.) It will be shown later that the 1(1, 0) component gives the largest contribution to the $\frac{1}{2}^- \to \frac{1}{2}^+$ transition. However the 1(1, 1) component is actually quite important and cannot be neglected. Further complications in the analysis are expected from contributions of two-step processes which have been shown [12]) to be quite important in $(^3He, t)$ reactions.

For (p, p′) and (p, n) the reaction mechanism is better known and the effective interaction has been well studied [13,14]) at incident energies near 35 MeV where the ^{16}O(p, n)^{16}F(0$^-$) reaction was done [1]). The ^{13}C(p, n)^{13}N(2.37 MeV, $\frac{1}{2}^+$) cross sections were measured previously by Clough *et al.* [15]) at $E_p = 30$ and 50 MeV, but only at a few angles. Greaves *et al.* [16]) measured the ^{13}C(p, p′)^{13}C(3.09 MeV, $\frac{1}{2}^+$) cross sections and analyzing powers at $E_p = 30.4$ MeV, but data were obtained only for $\theta_{c.m.} > 45°$.

In this paper we report a study of both the ^{13}C(p, p′) and (p, n) reactions at $E_p = 35$ MeV over a wide range of angles. We have found that DWBA calculations using shell model transition densities cannot account for the (p, p′) data for the 3.09 MeV state in ^{13}C. However, the data for (p, n) to the analog state in ^{13}N(2.37 MeV) as well as the data for several other states in ^{13}C and ^{13}N are reasonably well described by the calculations.

2. Experimental procedure

The (p, p′) experiment was performed using a 35 MeV polarized proton beam from the variable-energy, sector-focusing cyclotron at the Institute for Nuclear Study at the University of Tokyo. The beam polarization was checked periodically by inserting a carbon foil upstream from the target to measure the asymmetries of the elastically scattered protons with a pair of plastic scintillators. The target was a 0.5 mg/cm^2 thick, self-supporting carbon foil, enriched in ^{13}C(99%). Outgoing protons were momentum analyzed by a QDD magnetic spectrometer [17]), and detected by a focal plane detector system [18]). This system consists of a single-wire position-sensitive proportional counter, two ΔE proportional counters, and a plastic scintillator which measures the residual energy. Angular distributions were measured from 10° to 120°. The errors in the absolute normalization of the cross sections were estimated to be less than 15%.

The (p, n) data were taken using a 35 MeV proton beam from the AVF cyclotron and the time-of-flight facility [19]) at the Cyclotron and Radioisotope Center at Tohoku University in Sendai. We utilized a beam-swinger system and measured angular distributions of emitted neutrons between 0° and 140°. The target was a 0.7 mg/cm^2 thick, self-supporting carbon foil, enriched in ^{13}C(99%). Overall time resolution was about 1 ns. The detector efficiencies were calibrated at several neutron energies using the known (p, n) cross sections [20]) on ^{7}Li. An absolute calibration of the detector efficiencies has also been made recently by measuring the residual ^{7}Be activity in the ^{7}Li(p, n) reaction. Good agreement with a Monte-Carlo calculation was found. The errors in the absolute magnitude of the cross sections were estimated as <20%, and the relative errors as <7%.

Typical (p, p′) and (p, n) spectra are shown in fig. 1. The measured cross sections and analyzing powers are displayed in figs. 2–8 along with the calculated curves which will be discussed below. We could not separate the 3.51 MeV ($\frac{3}{2}^-$) and 3.55 MeV

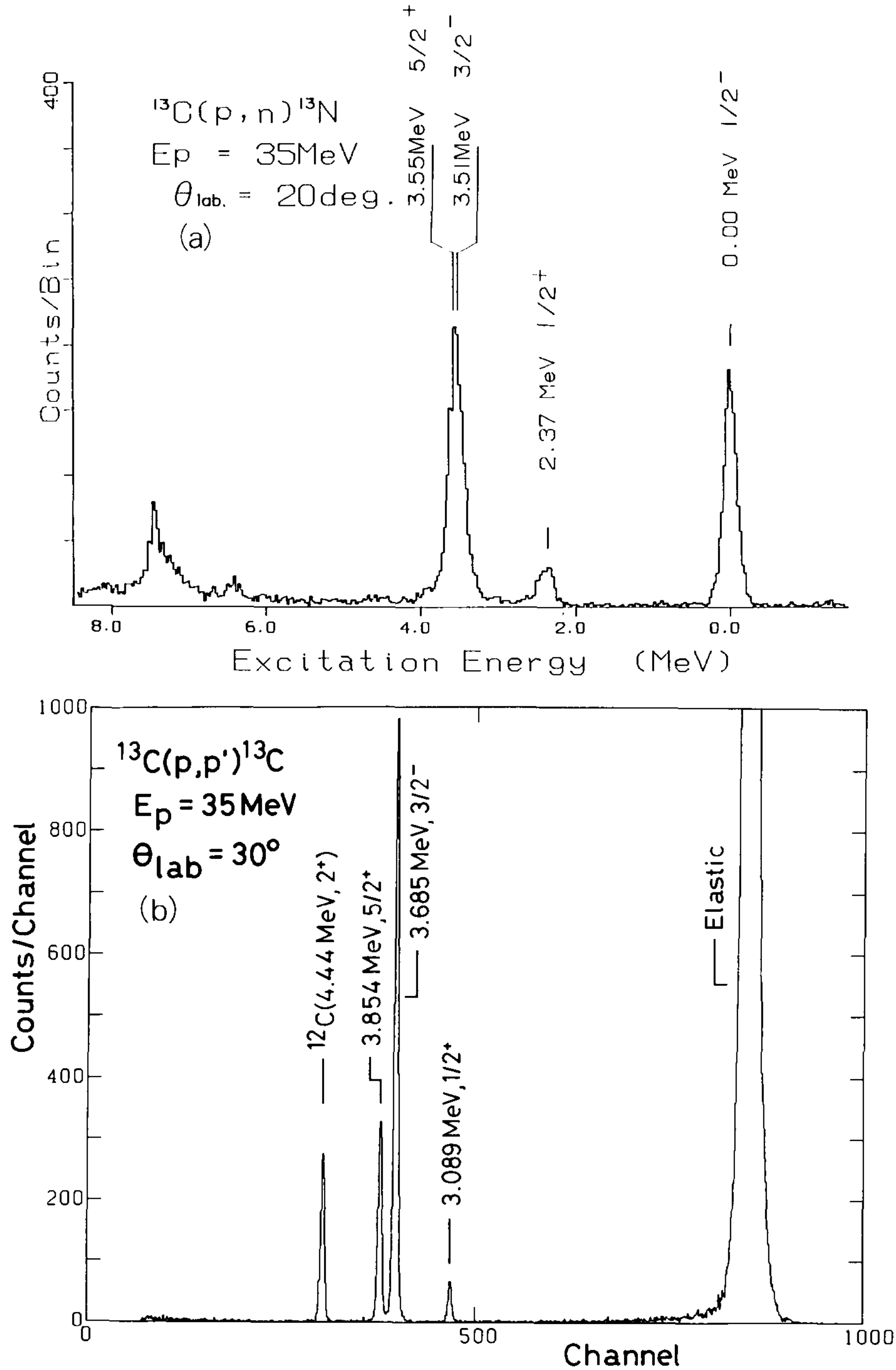

Fig. 1. (a) A neutron energy spectrum obtained for the $^{13}C(p, n)^{13}N$ reaction at $\theta_{lab} = 20°$. (b) A proton momentum spectrum obtained for the $^{13}C(p, p')^{13}C$ reaction at $\theta_{lab} = 30°$.

($\frac{5}{2}^+$) states in ^{13}N with the experimental resolution for the (p, n) reaction which was about 120 keV (FWHM) for states near this energy. Fig. 5 shows the angular distribution for the unresolved doublet. Error bars in the figures indicate relative errors only.

3. Optical model and DWBA analysis

In fig. 2 the elastic scattering cross sections and analyzing powers are shown and compared with an optical model calculation. The present data are very similar to the 35 MeV proton elastic data on ^{12}C obtained by the Kyoto group [21]) at the Research Center of Nuclear Physics in Osaka. The proton potential parameters obtained from ref. [22]) and listed in table 1 are used in the optical model and subsequent DWBA calculations. They give a reasonable account of the proton elastic data on ^{13}C, although they predict somewhat small analyzing powers around 60°. Recently a proton optical-potential parameter set has been given by Ieiri *et al.* [21]) for the p+^{12}C system at 35 MeV. We have found that this parameter set reproduces the present p+^{13}C elastic analyzing power data much better, but the use of this parameter set in DWBA calculations changes the cross sections only slightly. The neutron optical potential parameters, listed also in table 1 and used in the present DWBA analysis, are those obtained by Carlson *et al.* [23]) from the systematic analysis of quasielastic (p, n) data.

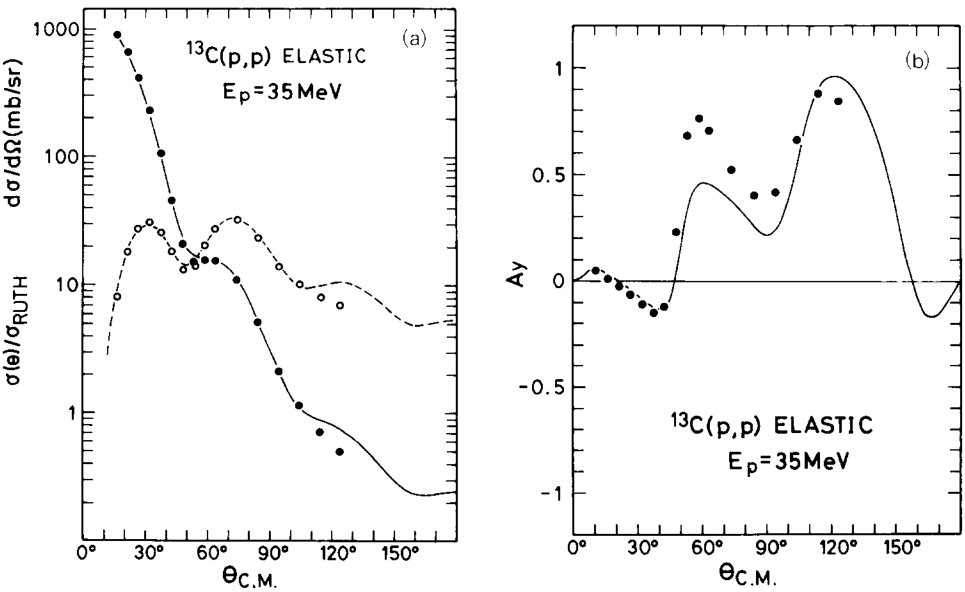

Fig. 2. The differential cross sections (a) and analyzing powers (b) for the ^{13}C+p elastic scattering at $E_p = 35$ MeV. Circles in (a) show the ratio to the Rutherford cross sections. The curves are optical model calculations with the parameters taken from ref. [22]).

TABLE 1

Distorting potential parameters used in the DWBA calculations

	V_0	r	a	W	W_D
$p+{}^{13}C$	53.4	1.064	0.623		6.045
$n+{}^{13}N$	45.68	1.17	0.75	4.34	4.72
	r_i	a_i	V_{LS}	r_{LS}	a_{LS}
$p+{}^{13}C$	1.20	0.6	6.4	1.0	0.575
$n+{}^{13}N$	1.32	0.456	6.2	1.0	0.75

Potential strengths are in MeV, and radius and diffuseness parameters are in fm.

The code DWBA 74 [ref. [24]] has been used in the DWBA calculations for (p, p′) and (p, n). The effective interaction (M3Y) of Bertsch *et al.* [25]) was employed. A few other effective interactions [13,26,27]) have also been tried but no significant differences in the final results were found. A major difference between the M3Y of ref. [25]) and other interactions is in the short-range odd force as pointed out in ref. [27]). This explains why the DWBA calculations are insensitive to the choice of the effective interaction, since the direct and exchange amplitudes have opposite signs and cancel for a short-range odd-force. Furthermore, because of this cancellation in the odd channel, one cannot assess the relative importance of the exchange contribution from DWBA calculations, and only the coherent sum of the direct and exchange contributions is meaningful.

Transition amplitudes were calculated using the Cohen-Kurath wave functions [28]) for the negative-parity states, and those obtained with the Millener-Kurath interaction [5,6]) for the positive-parity states. The radial dependence of the transition density was calculated from single-particle wave functions in a Woods-Saxon well with the parameters $r_0 = 1.25$ fm, $a = 0.65$ fm and $V_{LS} = 6$ MeV. The well depth was adjusted to reproduce the binding energies.

4. Results for the (p, n) reaction

The DWBA cross sections for the ${}^{13}C(p, n){}^{13}N$ reaction are compared with the data in figs. 3-5. The DWBA calculations are in overall good agreement with the (p, n) data.

For the isobaric analog transition (fig. 3) to the ground state of ${}^{13}N$, the calculated angular distribution is not steep enough at small angles and gives only one half of the measured cross section at 0°. This problem has been noted previously in microscopic analyses of many IAS transitions [29-31]). It is probably due to the strong collective (coherent) nature of IAS transition, i.e. many small components not contained in the shell-model space of ref. [28]) are expected to add constructively and generate the large cross sections at 0°.

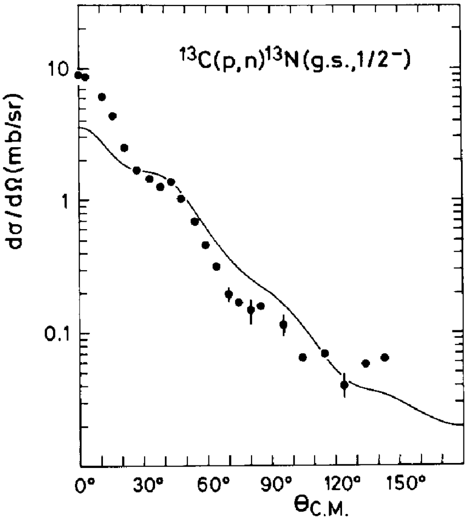

Fig. 3. Experimental and calculated differential cross sections for the $^{13}C(p, n)^{13}N$ reaction leading to the ground state of ^{13}N.

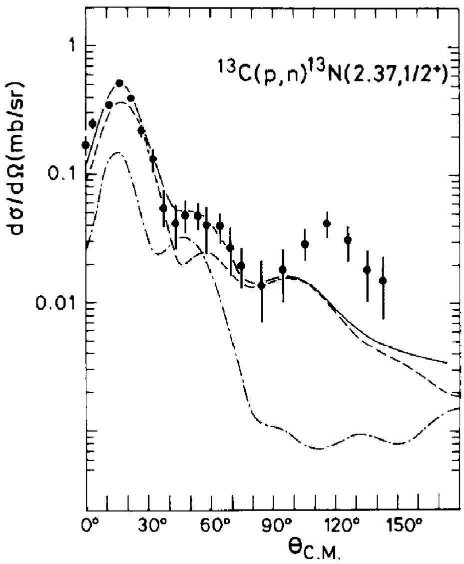

Fig. 4. Experimental and calculated differential cross sections for the $^{13}C(p, n)^{13}N$ reaction leading to the 2.37 MeV state ($\frac{1}{2}^+$) of ^{13}N. The dashed and dash-dotted curves show the calculated $\Delta J = 1$ and $\Delta J = 0$ components, respectively, and the solid curve the sum of the two.

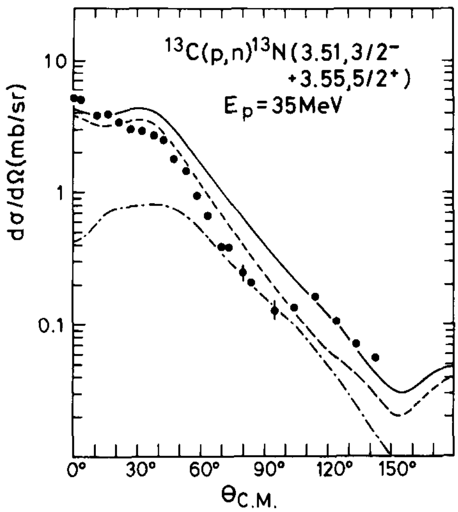

Fig. 5. Differential cross sections for the $^{13}C(p, n)^{13}N$ reaction leading to the unresolved doublet at 3.51 MeV ($\frac{3}{2}^-$) and 3.55 MeV ($\frac{5}{2}^+$). The dashed and dash-dotted curves show DWBA cross sections for the $\frac{3}{2}^-$ state and the $\frac{5}{2}^+$ state, respectively, and the solid curve the sum of the two.

The fit to the shape of the 2.37 MeV ($\frac{1}{2}^+$) angular distribution (fig. 4) is remarkably good for $\theta < 90°$. The shoulder in the angular distribution around 50° is very well accounted for by the tensor contribution in the $\Delta J = 0$ channel. The calculated cross section beyond 90° is almost entirely due to the $\Delta J = 1$ component. The $\Delta J = 0$ DWBA cross section near 120° is an order of magnitude smaller than the $\Delta J = 1$ cross section, which is a factor of 4 smaller than the data. It is clear that, as in the $^{16}O(p, n)^{16}F(0^-)$ reaction, a much better agreement with the (p, n) data for the $\frac{1}{2}^- \rightarrow \frac{1}{2}^+$ transition could be obtained if a process were found that would raise the calculated $\Delta J = 0$ cross section by an order of magnitude at large angles.

The DWBA prediction for the unresolved doublet at 3.5 MeV ($J^\pi = \frac{3}{2}^-, \frac{5}{2}^+$) are about 30% larger than the data (fig. 5). Probably this reflects the effects of universal quenching of Gamow-Teller and other isovector unnatural parity transitions.

5. Results for the (p, p′) reaction

The features of the (p. p′) data for the 3.68 MeV ($\frac{3}{2}^-$) and 3.85 MeV ($\frac{5}{2}^+$) states are also accounted for by the present DWBA calculation as shown in figs. 6 and 7. The use of the bare transition amplitudes of refs. [5,6,28]) in DWBA calculation gives the results shown by dashed lines. The predicted cross sections are too low in both cases. It has been found [32]) necessary to modify the transition densities by introducing effective charges, or enhancement factors, in order to obtain a consistent description of the experimental data for electromagnetic transition probabilities and the (π, π')

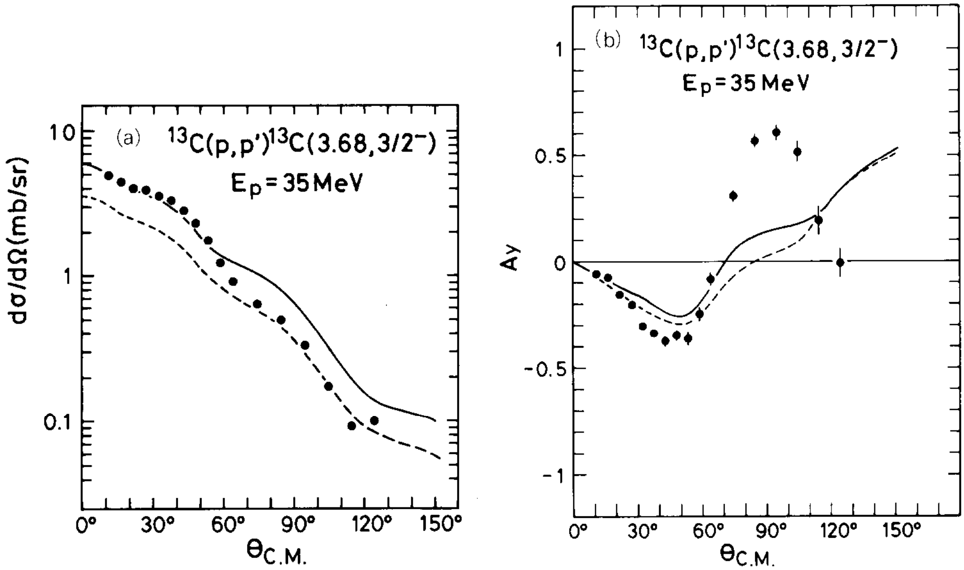

Fig. 6. Differential cross sections (a) and analyzing powers (b) for the $^{13}C(p, p')^{13}C$ reaction leading to the 3.68 MeV state ($\frac{3}{2}^-$) of ^{13}C. Solid and dashed curves are DWBA calculations with and without polarization charges, respectively, as described in the text.

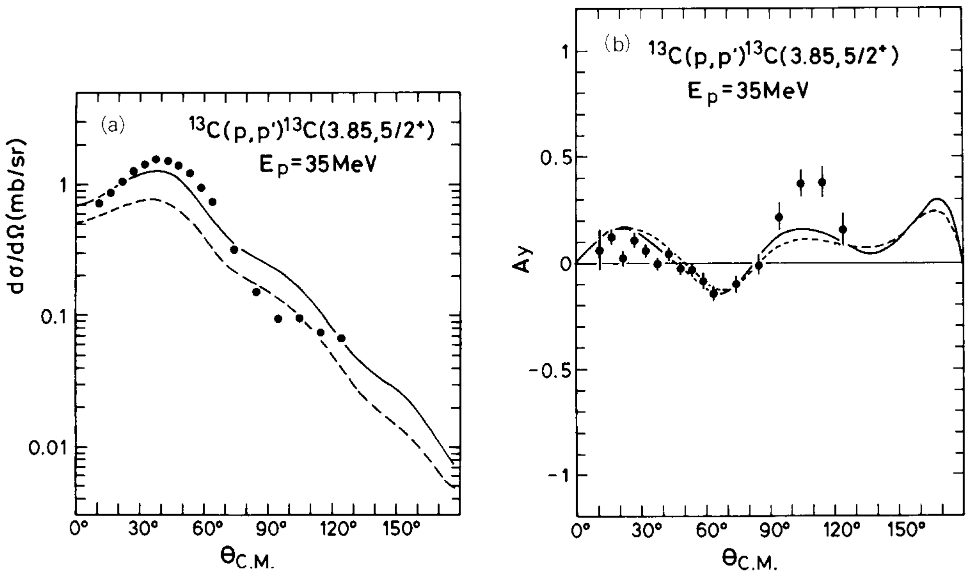

Fig. 7. Differential cross sections (a) and analyzing powers (b) for the $^{13}C(p, p')^{13}C$ reaction leading to the 3.85 MeV state ($\frac{5}{2}^+$) in ^{13}C. See caption for fig. 6.

and intermediate-energy (p, p′) reactions. The present cross section data are described very well with an isoscalar polarization charge $\delta_0 = 0.4$ for the $\Delta J(\Delta L, \Delta S) = 2(2, 0)$ component in the g.s. → 3.68 MeV ($\frac{3}{2}^-$) transition, and $\delta_0 = 0.5$ for the $\Delta J(\Delta L, \Delta S) = 3(3, 0)$ component in the g.s. → 3.85 MeV ($\frac{5}{2}^+$) transition. These isoscalar polarization charges are consistent with those used by Seestrom-Morris *et al.* [9]). They also introduced an isovector polarization charge $\delta_1 = -0.54$ for the $\Delta J(\Delta L, \Delta S) = 2(2, 0)$ component in the g.s. → 3.68 MeV ($\frac{3}{2}^-$) transition to account for the observed π^+/π^- cross section ratio. This isovector polarization charge is also included in the present DWBA calculation for the $\frac{3}{2}^-$ state, although the isovector part of this 2(2, 0) component is very small and its further reduction hardly affects the results. Solid lines in figs. 6 and 7 show DWBA calculations with polarization charges. The calculation fails to reproduce the analyzing powers beyond 70° for the 3.68 MeV state, but the overall agreement between the experiment and theory is quite reasonable. The analyzing powers for the 3.68 MeV ($\frac{3}{2}^-$) state resemble those for the 4.44 MeV (2^+) state in ^{12}C observed as an impurity peak in the present experiment. Greaves *et al.* found [16]) that microscopic-model calculations failed to reproduce large analyzing powers around 100° measured at $E_p = 30.4$ MeV for the 4.44 MeV (2^+) state in ^{12}C, and that DWBA calculations with collective form factors (including the spin–orbit deformation) gave substantially better description of the data. Their analysis, combined with the present results, suggests that core polarization effects cannot be fully taken into account by an overall renormalization with a polarization charge.

In contrast to the reasonable fits just shown, the fit to the 3.09 MeV ($\frac{1}{2}^+$) data (fig. 8) is very poor. The calculated angular distribution is not much different from that for the (p, n) reaction to the 2.37 MeV ($\frac{1}{2}^+$) state, i.e. it has a peak near 18° and then gradually falls off toward large angles. The observed angular distribution has a local minimum around 30° and a peak at 50°. Neither is seen in the calculated angular distribution. Furthermore, the measured and calculated analyzing powers have opposite signs beyond 60°. The large discrepancies between the data and calculations observed here is similar to those noted at higher incident energies [9,10]).

6. Discussion

Except for the ^{13}C(p, p′)^{13}C(3.09 MeV, $\frac{1}{2}^+$) transition reasonable fits to the 35 MeV (p, n) and (p, p′) data have been obtained by DWBA calculations. Fine tuning of the distorting potentials, the effective interactions, and effective charges would result in slightly better overall fits.

The calculations did not even reproduce the qualitative features of the (p, p′) data for the $\frac{1}{2}^+$ state, whereas good agreement was obtained for the (p, n) data for its analog. The calculated angular distributions for these two reactions are very similar but the experimental data are quite different from each other. This fact

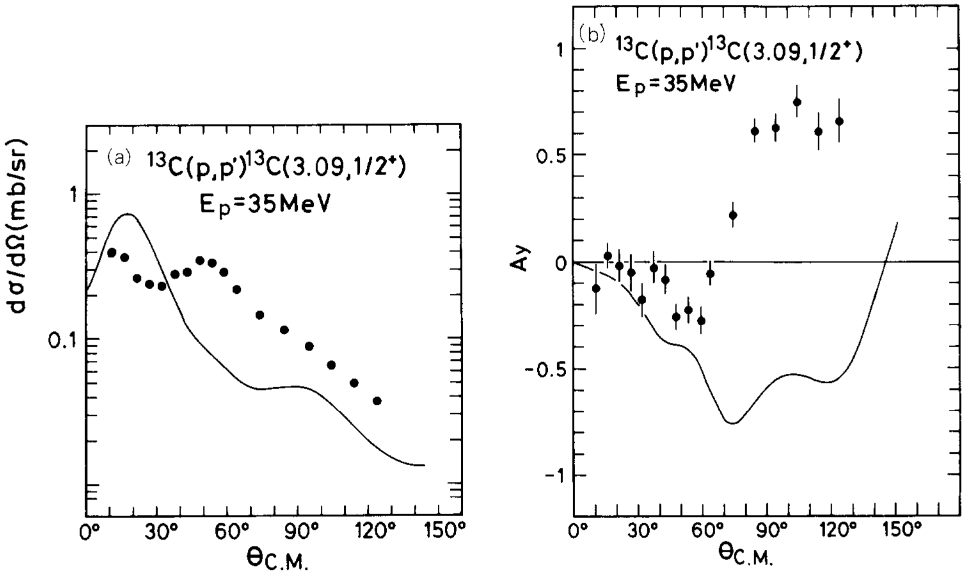

Fig. 8. Differential cross sections (a) and analyzing powers (b) for the $^{13}C(p, p')^{13}C$ reaction leading to the 3.09 MeV state ($\frac{1}{2}^+$) in ^{13}C. Solid curves show DWBA calculation.

readily eliminates several possible sources of the discrepancy between the data and the calculations for the $^{13}C(p, p')$ reaction to the $\frac{1}{2}^+$ state.

Firstly, it is highly unlikely that the distorting potentials and/or the effective interactions used in our calculations are responsible for the difficulty in fitting the (p, p') reaction. As mentioned earlier, the calculated curves are fairly stable against changes in these parameters. Thus the large modifications of the parameters needed to reproduce the (p, p') data would destroy the fit to the (p, n) data.

Secondly, higher-order processes, such as (p, d) followed by (d, p) are also unlikely to be the origin of the discrepancy. If the p-d-p process had a large influence on the (p, p') reaction, the p-d-n reaction would affect the (p, n) reaction in nearly the same way and the DWBA fit to (p, n) should be just as bad as for (p, p'). A similar argument excludes effects from the collective excitations of the ^{12}C core to the 2^+ state as a possible explanation. In addition, the discrepancy between theory and experiment for the (p, p') reaction to the $\frac{1}{2}^+$ state is nearly the same over a wide range of incident energies, 547 MeV, 135 MeV, and 35 MeV, but two-step effects are expected to be energy dependent.

Evidently the source of the problem in fitting the (p, p') data for the $\frac{1}{2}^+$ state lies in the shell-model calculations and not in the reaction model. Since the (p, n) data are well reproduced by the shell model transition densities, we conclude that the isoscalar part of the transition is not correctly described by the wave functions used here and in the previous work at higher energies and with different projectiles. The

(π, π') data require larger proton components than predicted by refs. [5,6]). This is corroborated by the (e, e') data [7]).

In an attempt to find out whether modifications to certain parts of the transition density would improve the fit, we calculated the cross sections for each possible combination of $\Delta J(\Delta L, \Delta S)\Delta T$. The results are shown in fig. 9. It is clear from these calculations that no particular component gives an angular distribution close to the (p, p') data. A subtle cancellation of the different amplitudes must therefore occur. Assuming that the isovector part was predicted correctly, since the (p, n) data were well described by the model, we modified the isoscalar parts with the expectation that the (p, p') data could be fitted with a certain combination of amplitudes. This effort has not been successful yet.

In conclusion, we have studied the (p, n) and (p, p') reactions on ^{13}C at 35 MeV. The good fit to the angular distribution at $\theta < 100°$ for the (p, n) reaction to the $\frac{1}{2}^+$ state in ^{13}N is in sharp contrast to the complete failure in fitting the (p, p') data for its analog. Apparently the isoscalar part of the transition amplitudes is not correctly described by the shell model. However, attempts to fit the (p, p') data for the $\frac{1}{2}^+$ state by adjusting the isoscalar transition amplitudes or, equivalently, the proton contribution, were thus far unsuccessful. The data for the other states both in ^{13}C and ^{13}N are reproduced quite well by introducing the renormalizations (effective charges or quenching factors) consistent with other work. The experimental cross

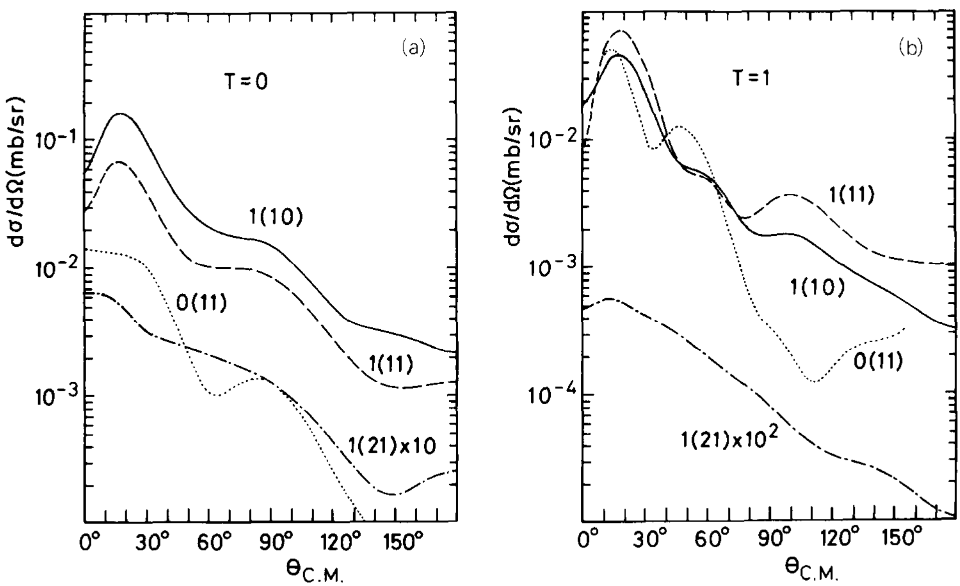

Fig. 9. Decomposition of the DWBA cross sections for the $^{13}C(p, p')^{13}C(3.09\ \text{MeV}, \frac{1}{2}^+)$ reaction. Each curve is labeled by the transferred $\Delta J(\Delta L, \Delta S)$. Panel (a) is for the isoscalar components, and panel (b) for the isovector components.

section for the $^{13}C(p, n)^{13}N(\frac{1}{2}^+, 2.39$ MeV) reaction shows an enhancement over the DWBA predictions at $\theta > 100°$ like the $^{16}O(p, n)^{16}F(0^-)$ reaction, which is worth of further theoretical investigations.

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