# Mechanism of $(p, t)$ and $(p, {}^3He)$ reactions by the analysis of the energy dependence of mirror transitions

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The reactions ${}^{13}C(p, t){}^{11}C$, ${}^{13}C(p, {}^3He){}^{11}B$, ${}^{16}O(p, t){}^{14}O$, and ${}^{16}O(p, {}^3He){}^{14}N$ have been studied at several incident energies between 24 and 44 MeV. Previous results on the ${}^{15}N(p, t){}^{13}N$ and ${}^{15}N(p, {}^3He){}^{13}C$ reactions are also considered in the analysis. The energy dependence of cross section ratios for mirror transitions evidences that these reactions cannot be described below 35–40 MeV simply as a direct two-nucleon pickup. The values for spin and isospin dependent terms in the effective interactions obtained from a distorted-wave Born-approximation analysis differ from those used in shell model calculations and in microscopic analyses of inelastic scattering.

[NUCLEAR REACTIONS ${}^{13}C(p, t)$, $(p, {}^3He)$, $E = 26.8–43.1$ MeV; measured $\sigma(E_t, \theta)$, $\sigma(E_{{}^3He}, \theta)$; $\theta_{lab} = 10–72.5°$. ${}^{16}O(p, t)$, $(p, {}^3He)$, $E = 32.2$, 36.6, 43.5 MeV; measured $\sigma(E_t, \theta)$, $\sigma(E_{{}^3He}, \theta)$, $\theta_{lab} = 10–82.5°$; resolution 200 keV. Reaction mechanism analysis.]

## I. INTRODUCTION

In the theoretical approach used for the two-nucleon pickup reactions, the interaction responsible for the process is a two-body force acting between the incident particle and each of the two transferred nucleons.[1,2]

Mathur and Rook, in their early papers,[3] and more recently other authors[4] have pointed out that, in order to have the absolute magnitude of the predicted cross sections, the form and the strength of the interaction potential must be taken into account. The problem of calculating the absolute cross sections for these reactions has, however, received little attention because the calculated values depend heavily on a number of other factors such as the bound state wave functions of the transferred nucleons or the chosen optical model parameters.

In the analysis of $(p, t)$ and $(p, {}^3He)$ reactions the triton and ${}^3He$ wave functions are assumed to be spatially symmetric and each nucleon pair has zero relative orbital angular momentum. As a consequence, selection rules apply to spin $S$ and isospin $T$ of the transferred pair; for $(p, t)$: $S = 0$, $T = 1$; for $(p, {}^3He)$: $S = 0$, $T = 1$ or $S = 1$, $T = 0$. Fleming, Cerny, and Glendenning[5] and Hardy and Towner[6] have shown that, by comparing the cross sections of analog transitions in the $(p, t)$ and $(p, {}^3He)$ reactions or of $(p, {}^3He)$ transitions with different $(S, T)$ transfers, it is possible to examine the relative strength of the isospin- (or spin-) dependent terms which appear in the interaction potential.

The analyses reported in the literature usually concern experimental data collected at only one incident energy.[5–13] Mangelson, Harvey, and Glendenning[14] take into account the ${}^{12}C({}^3He, p){}^{14}N$ reaction at four incident energies between 10.1 and 31.2 MeV and Fleming, Hardy, and Cerny[15] the ${}^{16}O(p, {}^3He){}^{14}N$ reaction at 43.7 and 54.1 MeV. Effects depending on the bombarding energy have been found in both analyses. Moreover, it has been recently found[16] that the energy dependence of a two-nucleon transfer reaction on a light nucleus is poorly described by a distorted-wave Born-approximation (DWBA) calculation.

An additional interest of the present study is to provide a further test of the accuracy of the reaction model.

In the present paper we consider the energy dependence of the reactions: ${}^{13}C(p, t){}^{11}C$, ${}^{13}C(p, {}^3He){}^{11}B$, ${}^{15}N(p, t){}^{13}N$, ${}^{15}N(p, {}^3He){}^{13}C$, and ${}^{16}O(p, {}^3He){}^{14}N$, for proton incident energies between 24 and 44 MeV. The experimental cross section ratios, for mirror transitions in the reactions on ${}^{13}C$ and ${}^{15}N$ and for transitions involving different $(S, T)$ transfers in the $(p, {}^3He)$ on ${}^{16}O$, are compared with the DWBA predictions as a test of the model outlined by Hardy and Towner.[6]

## II. EXPERIMENTAL METHOD AND RESULTS

The measurements were performed with 20 to 45 MeV proton beams of the Milan AVF cyclotron. A gas target consisting of a 70 mm diam cylindri-

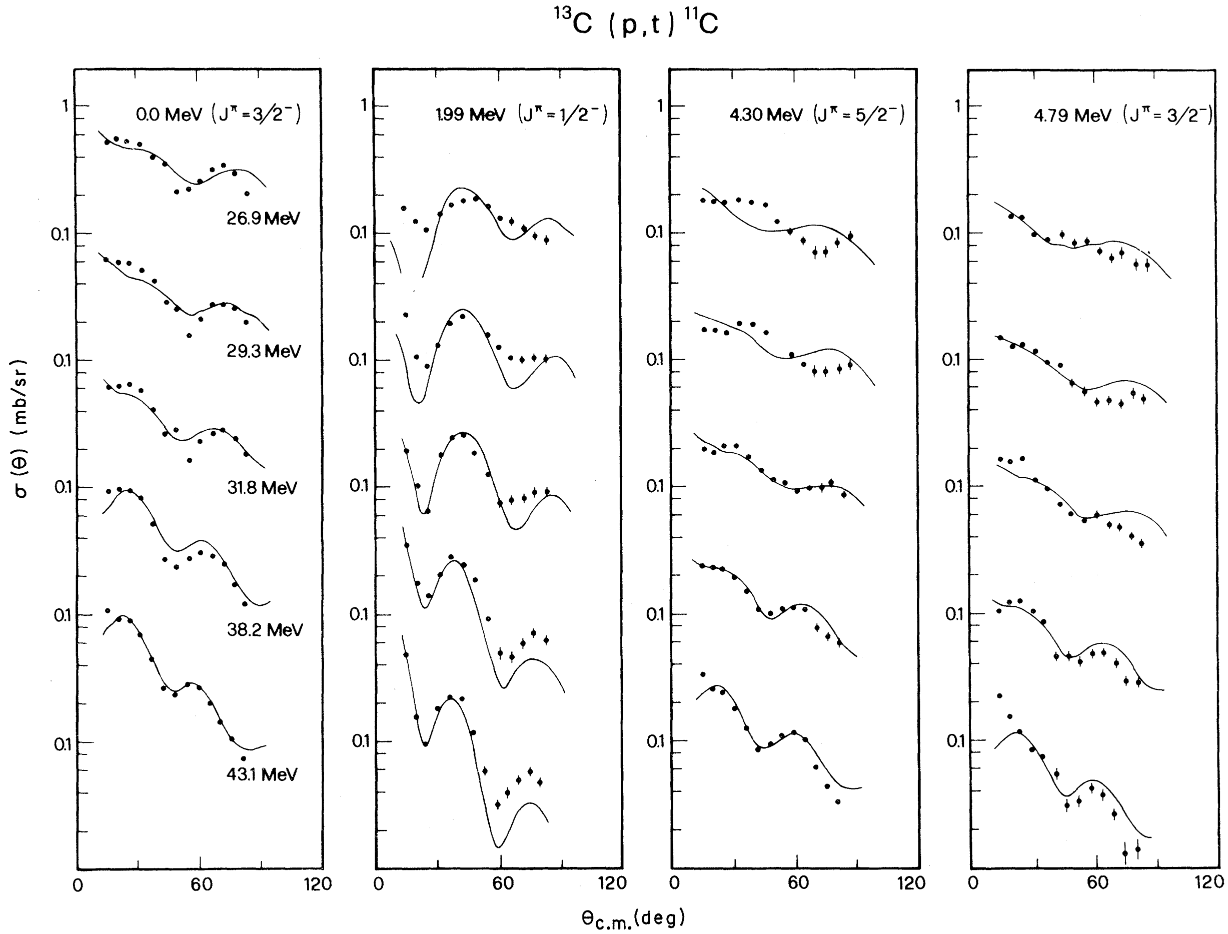


FIG. 1. Differential cross sections for the reaction ${}^{13}C(p, t){}^{11}C$ to the ground, 1.99, 4.30, and 4.79 MeV states. Where not indicated, statistical errors are smaller than point size. Proton energies for the excited states transitions are the same and in the same order as for the ground state. The full curves are the result of the DWBA calculations discussed in the text.

cal cell with entrance and exit windows of 2 mg/ $cm^2$ Havar foil was used. The cell was run at a pressure of about 0.5 atm, using ${}^{16}O$ (natural oxygen) and $CH_4$ (methane) enriched to 93% in ${}^{13}C$. The ${}^{15}N$ data used in the present analysis had been taken previously.[16] In this last reference the details of the detection system are also given. The over-all energy spread was of the order of 200 keV and the angular spread was about ±1°.

The differential cross sections are given in Figs. 1 to 4. Error bars, shown when significant, represent statistical errors only. The over-all

TABLE I. Integrated cross sections of transitions to ${}^{11}C$ levels observed in the ${}^{13}C(p,t){}^{11}C$ reaction.

| | | | Integrated cross section[a] (μb) | | | | |
|---|---|---|---|---|---|---|---|
| Transition | Energy (MeV) | $J^\pi$ | $E_p$ =26.8 MeV | $E_p$ =29.3 MeV | $E_p$ =31.8 MeV | $E_p$ =38.2 MeV | $E_p$ =43.1 MeV |
| $t_0$ | 0.00 | $\frac{3}{2}^-$ | 1798 | 1664 | 1690 | 1969 | 1703 |
| $t_1$ | 1.99 | $\frac{1}{2}^-$ | 763 | 778 | 723 | 684 | 568 |
| $t_2$ | 4.30 | $\frac{5}{2}^-$ | 673 | 679 | 678 | 623 | 565 |
| $t_3$ | 4.79 | $\frac{3}{2}^-$ | 472 | 391 | 381 | 300 | 283 |

[a] Cross section integrated from 10 to 72.5° in the laboratory system.

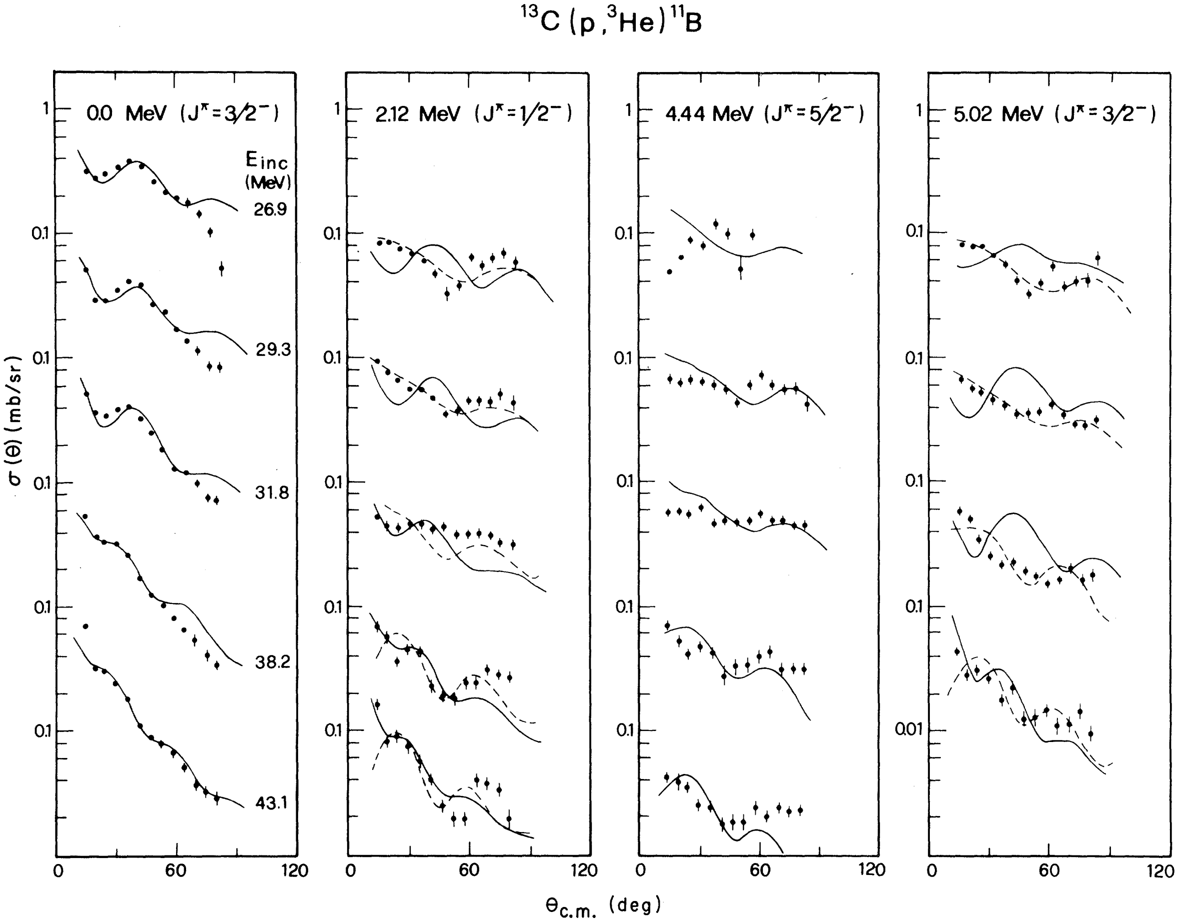


FIG. 2. Differential cross sections for the reaction $^{13}C(p, {}^3He)^{11}B$ to the ground, 2.12, 4.44, and 5.02 MeV states. The full curves are the result of DWBA calculations by using Cohen and Kurath wave functions, the dashed curves correspond to pure $L = 2$ transfer. See caption of Fig. 1 for other details.

normalization error is estimated to be within 10%. The transitions observed are listed in Tables I–III, together with the cross sections integrated over the indicated angular ranges.

## III. THEORY AND PREVIOUS RESULTS

The DWBA expression for the differential cross section of a two-nucleon pick-up reaction $A(a, b)B$ can be written, following Towner and Hardy,[2] as

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{pickup}} = \frac{\mu_a\mu_b}{(2\pi\hbar^2)^2}\,\frac{k_b}{k_a}\,\frac{2s_b+1}{2s_a+1}\sum_{M\sigma_a\sigma_b}^{J}\left|\sum^{[n_1l_1j_1][n_2l_2j_2]LSJ} b_{ST} S_{AB}^{1/2}([n_1l_1j_1][n_2l_2j_2];JT)(T_BN_BTN|\,T_AN_A)\times\begin{bmatrix} l_1 & l_2 & L\\ \frac{1}{2} & \frac{1}{2} & S\\ j_1 & j_2 & J\end{bmatrix}\mathcal{B}^{LSJT}_{M\sigma_a\sigma_b}\right|^2, \tag{1}$$

where $[n_1l_1j_1]$ and $[n_2l_2j_2]$ are the quantum numbers defining the single particle states of the two transferred nucleons and $L$, $S$, $J$, and $T$ are the quantum numbers of the transferred pair. The spins of particles $a$ and $b$ and their $z$ components are denoted by $s_a$, $s_b$ and $\sigma_a$, $\sigma_b$, respectively. The

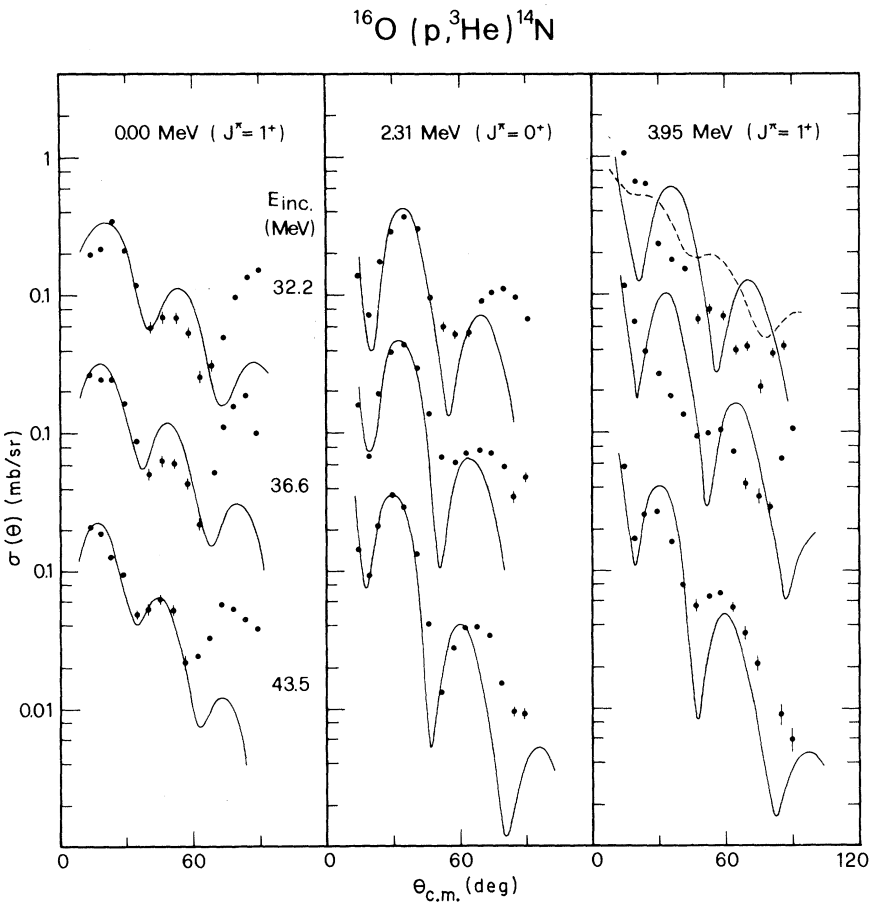


FIG. 3. Differential cross sections for the reaction $^{16}O(p, {}^3He)^{14}N$ to the ground, 2.31 and 3.95 MeV states. The full curves are the result of DWBA calculations using Cohen and Kurath wave functions, the dashed curve corresponds to a larger $L = 2$ contribution. See caption of Fig. 1 for other details.

reduced mass and relative momentum in the initial (final) channel are $\mu_a(\mu_b)$ and $\hbar k_a(\hbar k_b)$. The quantity $b_{ST}$ is essentially a spectroscopic factor for the light particles; all the nuclear structure information is contained in the spectroscopic amplitude $S_{AB}^{1/2}$. The term $\mathcal{B}$ contains the details of the integration of the radial wave function and depends on the kinematics, the optical distortions, the bound state wave functions and the character of the two-body force. The two-body potential, with an arbitrary exchange mixture, is often written as

$$V(r) = V_0 g(r)(W + MP_x + BP_\sigma - HP_\tau) \ ,$$

TABLE II. Integrated cross sections of transitions to $^{11}B$ levels observed in the $^{13}C(p, {}^3He)^{11}B$ reaction.

| | | | Integrated cross section[a] (μb) | | | | |
|---|---|---|---|---|---|---|---|
| Transition | Energy (MeV) | $J^\pi$ | $E_p = 26.8$ MeV | $E_p = 29.3$ MeV | $E_p = 31.8$ MeV | $E_p = 38.2$ MeV | $E_p = 43.1$ MeV |
| $h_0$ | 0.00 | $\frac{3}{2}^-$ | 1188 | 1195 | 1112 | 737 | 604 |
| $h_1$ | 2.12 | $\frac{1}{2}^-$ | 339 | 274 | 218 | 164 | 116 |
| $h_2$ | 4.44 | $\frac{5}{2}^-$ | 255 | 343 | 293 | 160 | 127 |
| $h_3$ | 5.02 | $\frac{3}{2}^-$ | ... | 310 | 227 | 126 | 94 |

[a] Cross section integrated from 10 to 72.5° in the laboratory system.

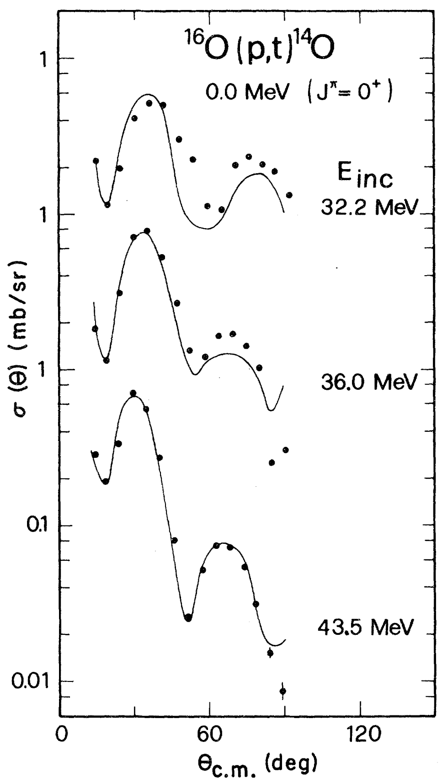


FIG. 4. Comparison of differential cross sections for the analogous reactions $^{16}O(p, {}^3He)^{14}N(2.31$ MeV) and $^{16}O(p, t)^{14}N(0.00$ MeV). The data points represent the $(p, t)$ cross section, the full curves are eye fits to the $(p, {}^3He)$ angular distributions multiplied by $2k_t/k_{^3He}$.

where $W+M+B+H=1$ and $P_x$, $P_\sigma$, and $P_\tau$ are space, spin, and isospin exchange operators. If, as in this formula, the same radial dependence is taken for the different terms, the two-body force can be factored out from $\mathcal{B}$ in a quantity $D(S, T)$, that can be simply expressed as[6]:

$$D(S,T) = 1 - (0.5 + \delta_{S,1})(B+H) \ . \qquad (2)$$

TABLE III. Integrated cross sections of transitions to $^{14}N$ and $^{14}O$ levels observed in the $^{16}O(p, {}^3He)^{14}N$ and $^{16}O(p,t)^{14}O$ reactions.

| Transition | Energy (MeV) | $J^\pi$ | Integrated cross section[a] ($\mu$b) $E_p = 32.2$ MeV | $E_p = 36.6$ MeV | $E_p = 43.5$ MeV |
|---|---|---|---|---|---|
| $h_0$ | 0.00 | $1^+$ | 368 | 314 | 222 |
| $h_1$ | 2.31 | $0^+$ | 810 | 787 | 445 |
| $h_2$ | 3.95 | $1^+$ | 803 | 862 | 502 |
| $t_0$ | 0.00 | $0^+$ | 1568 | 1455 | 886 |

[a] Cross section integrated from 10 to 82.5° in the laboratory system except for $h_0$ which is restricted to 57.5°.

By comparing the relative strengths of transitions with $S=0$ and $S=1$ it is therefore in principle possible to obtain the relative importance of spin-isospin exchange terms in the interaction. Actually the quantity determined experimentally is $R$, where

$$R = \left|\frac{D(1.0)}{D(0.1)}\right|^2 = \left|\frac{1-1.5(B+H)}{1-0.5(B+H)}\right|^2 \ . \qquad (3)$$

An interaction independent of spin and isospin would have $R$ equal to unity.

The ratio $R$ has been calculated for several effective interactions used in nuclear structure calculations: The values found range from 0.4 to 0.6 and are reported in Table IV. Obviously a determination of $R$ from nuclear reactions depends on the reliability of the DWBA method, on the parameters used and on the wave functions of the initial and final states. It is therefore desirable to compare cross sections of transitions which, apart from having different values of $D(S, T)$ are similar in most respects, as the transitions to mirror states. Several determinations of $R$ have been attempted up to now. The reactions used and the

TABLE IV. The factors $|D(S)|^2$ and the ratio $R$ evaluated for several effective interactions.

| Interaction | $W$ | $M$ | $B$ | $H$ | $\|D(0)\|^2$ | $\|D(1)\|^2$ | $R$ |
|---|---|---|---|---|---|---|---|
| Wigner | 1 | 0 | 0 | 0 | 1 | 1 | 1 |
| Serber | 0.5 | 0.5 | 0 | 0 | 1 | 1 | 1 |
| Rosenfeld[a] | −0.13 | 0.46 | −0.26 | 0.93 | 0.81 | 0.49 | 0.60 |
| Soper[b] | 0.40 | 0.17 | 0.10 | 0.33 | 0.75 | 0.35 | 0.47 |
| Gillet-$^{16}O$[c] | 0.35 | −0.10 | 0.40 | 0.35 | 0.72 | 0.30 | 0.42 |
| True-$^{14}N$[d] | 0.41 | 0.41 | 0.09 | 0.09 | 0.82 | 0.52 | 0.63 |
| Ferrel-Visscher $^{16}O$[e] | 0.32 | 0.5 | 0.0 | 0.18 | 0.82 | 0.51 | 0.62 |

[a] L. Rosenfeld, *Nuclear Forces* (North-Holland, Amsterdam, 1948).
[b] J. M. Soper, Phil. Mag. 2, 1219 (1957).
[c] V. Gillet and N. Vinh-Mau, Nucl. Phys. 54, 321 (1964).
[d] W. W. True, Phys. Rev. 130, 1530 (1963).
[e] W. M. Visscher and R. A. Ferrell, Phys. Rev. 107, 781 (1957).

values derived are reported in Table V; as can be seen the values obtained from different reactions differ considerably. Different $R$ values have also been obtained from the same reaction when using different final nucleus wave functions.[15] Sensitiveness to bombarding energy has been found in the two experiments[14,15] performed at more than one incident energy.

Another comparison, interesting from the point of view of the reaction mechanism concerns analogous reactions, i.e., $(p,t)$ and $(p,{}^3\text{He})$ reactions leading to $T=1$ analog states. These will have, ignoring charge-dependent effects, angular distributions with the same shape and with relative intensities governed by the factor $b_{ST}(T_N N_B T N T_A N_A)$ and by the momenta. In the case of the $(p,t)$ transition to the ground state of $^{14}$O and the $(p,{}^3\text{He})$ transition to the 2.31 MeV state of $^{14}$N, the ratio of the cross section is given by

$$\frac{\sigma(p,t)_{\text{g.s.}}}{\sigma(p,\text{He})_{2.31}}=\frac{2k_t}{k_{^3\text{He}}}\ .$$

This relationship has been verified by Fleming *et al.*[15] at 54.1 MeV, while violations have been found at 27 MeV[17]; our results, given in Fig. 4, show that the agreement which is good at the higher energy deteriorates at lower incident proton energies.

## IV. DWBA CALCULATIONS

The present calculations have been performed using the DWBA code of Nelson and Macefield.[18] Proton optical model parameters derived from elastic scattering data[16,19] (for $^{15}$N and $^{16}$O) and the average proton parameters of Watson, Singh, and Segel[20] have both been used. The choice of mass-3 optical potentials presents more difficulties[16]; the parameters used are those of Hiebert, Newman, and Bassel[21] with small modifications in order to improve the fits to the angular distributions. In one case (for mass-13) also the parameters derived in Ref. 16 from elastic scattering data have been used. Bound state calculations use for the two transferred nucleons Saxon-Woods wave functions expanded in terms of harmonic oscillator wave functions generated by an oscillator parameter $\nu=0.32\ \text{fm}^{-1}$ as appropriate to $1p$ shell nuclei. Bound state well depths have been determined binding each nucleon with half the total binding energy; as customary a radius of 1.25 fm and a diffuseness of 0.6 fm have been taken with a spin orbit term 25 times the Thomas value. Intermediate coupling wave functions of Cohen and Kurath[22] have been used for all the states concerned. The DWBA predictions of the angular distributions are compared with the data in Figs. 1 to 3. Satisfactory agreement is generally found. The transitions $h_1$ and $h_3$ leading to 2.12 and 5.02 MeV levels in $^{11}$B, respectively, and $h_2$ to the 3.95 MeV level in $^{14}$N, are however fitted only at the higher energy. Attempts to extend the agreement to all the energy range by varying the optical model potentials have been made but with no success. In these cases the wave functions of Cohen and Kurath[22] lead to a coherent sum of $L=0$ and $L=2$ contributions; their use results in the full curves given in the Figs. 2 and 3. Especially at the lower energies better fits are obtained, as shown by the dashed curves in the same figures, by changing the spectroscopic amplitudes, in particular by taking a pure $L=2$ transfer for the two transitions to $^{11}$B and a larger $L=2$ contribution for the transition to $^{11}$N. Also the strong peak at 70°–90° in the angular distribution for the ground

TABLE V. Previous determinations of the ratio $R$.

| Author and reference | Reaction | $E_{\text{inc}}$ (MeV) [a] | $R$ |
|---|---|---|---|
| Fleming *et al.* (Ref. 5) | $^{13}$C$(p,t)^{11}$C; $^{13}$C$(p,{}^3\text{He})^{11}$B | 49.6 | 0.33 |
| Scott *et al.* (Ref. 10) | $^{14}$N$(p,{}^3\text{He})^{12}$C | 50.0 | 0.46 |
| Mangelson *et al.* (Ref. 14) | $^{12}$C$(^3\text{He},p)^{14}$N | 10.1 (11) | 4.40 |
| | | 13.9 (14) | 1.40 |
| | | 20.1 (19) | 1.10 |
| | | 31.2 (27) | 0.70 |
| Fleming *et al.* (Ref. 5) | $^{15}$N$(p,t)^{13}$N; $^{15}$N$(p,{}^3\text{He})^{13}$C | 43.7 | 0.33 |
| Nelson *et al.* (Ref. 7) | $^{16}$O$(p,{}^3\text{He})^{14}$N | 49.5 | 0.30 |
| Fleming *et al.* (Ref. 15) | $^{16}$O$(p,{}^3\text{He})^{14}$N | 43.7 | 0.30 |
| | | 54.1 | 0.25 |
| Olsen *et al.* (Ref. 8) | $^{17}$O$(p,t)^{15}$O; $^{17}$O$(p,{}^3\text{He})^{15}$N | 39.8 | 0.33 |
| Nann *et al.* (Ref. 9) | $^{29}$Si$(p,t)^{27}$Si; $^{29}$Si$(p,{}^3\text{He})^{27}$Al | 40.1 | 0.42 |
| Barz *et al.* (Ref. 11) | $^{40}$Ca$(^3\text{He},p)^{42}$Sc | 18.0 (18) | 0.49 |
| Ohnuma *et al.* (Ref. 12) | $^{48}$Ca$(^3\text{He},p)^{50}$Sc | 12.0 (16) | 0.39 |
| Laget *et al.* (Ref. 13) | $^{54}$Fe$(^3\text{He},p)^{56}$Co | 18.0 (22) | 0.50 |

[a] The number given in parentheses is the average energy of proton channels.

state transition in the $^{16}O(p, {}^{3}He)$ reaction is not reproduced. These discrepancies might reflect the onset at lower energies of other reaction mechanisms.

The energy dependence of the integrated cross sections relative to single transitions are plotted in Fig. 5. The $^{13}C$ and $^{15}N$ data pertain to all the angular range measured; very similar results are, however, obtained also restricting the integration to forward angles. In the case of the transition to the ground state of $^{14}N$ the integration has been limited to 58° in order to exclude the strong peak in the angular distribution at 70°–90° cited above and to use the data of Brown[23] at 40 MeV. Also plotted, both for the ground state and the 2.31 MeV transitions, are the values of the integrated cross section given by Nelson *et al.*[7] at 49.5 MeV and by Fleming *et al.*[15] at 54.1 MeV. The full curves show the results of the DWBA calculations discussed above; the fits are generally very poor. For the two transitions to $^{11}B$ discussed above the energy dependence resulting for pure $L = 2$ transfer has also been plotted; as can be seen no significant improvement is obtained. In a previous analysis of the energy dependence of two-nucleon transfer reactions in light nuclei, performed recently by us,[16] it has been suggested that the inadequacy of one-step pick-up DWBA calculations in describing the excitation functions, may be attributed to angular momentum mismatch effects or to contributions from multistep processes.

## V. DISCUSSION AND CONCLUDING REMARKS

As remarked in the previous section, the fits to the energy dependence of the integrated cross sections given by DWBA calculations are not very

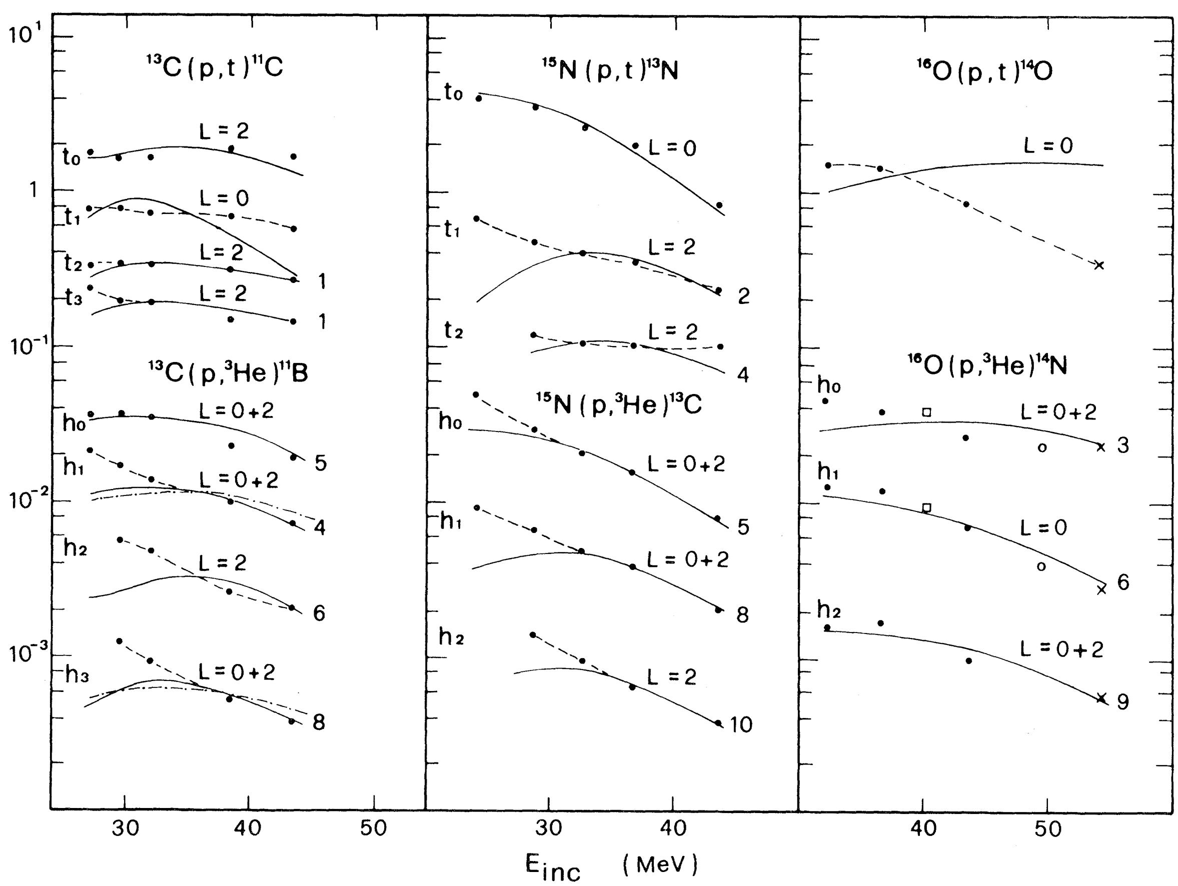


FIG. 5. Energy dependence of integrated cross sections. See Tables I-III for details of the transitions. The full curves are the result of the present DWBA calculations and are arbitrarily normalized to the data. Point and dash curves are the result of the same calculations with only $L = 2$ contributions. Dashed curves are only drawn to aide the eye. The absolute cross section values are obtained as the product of the plotted cross sections times $2^n$ where $n$ is the number given in the right side of the figure for each transition. The data of Ref. 23 are given by squares, those of Ref. 7 and Ref. 15 by open circles and crosses, respectively.

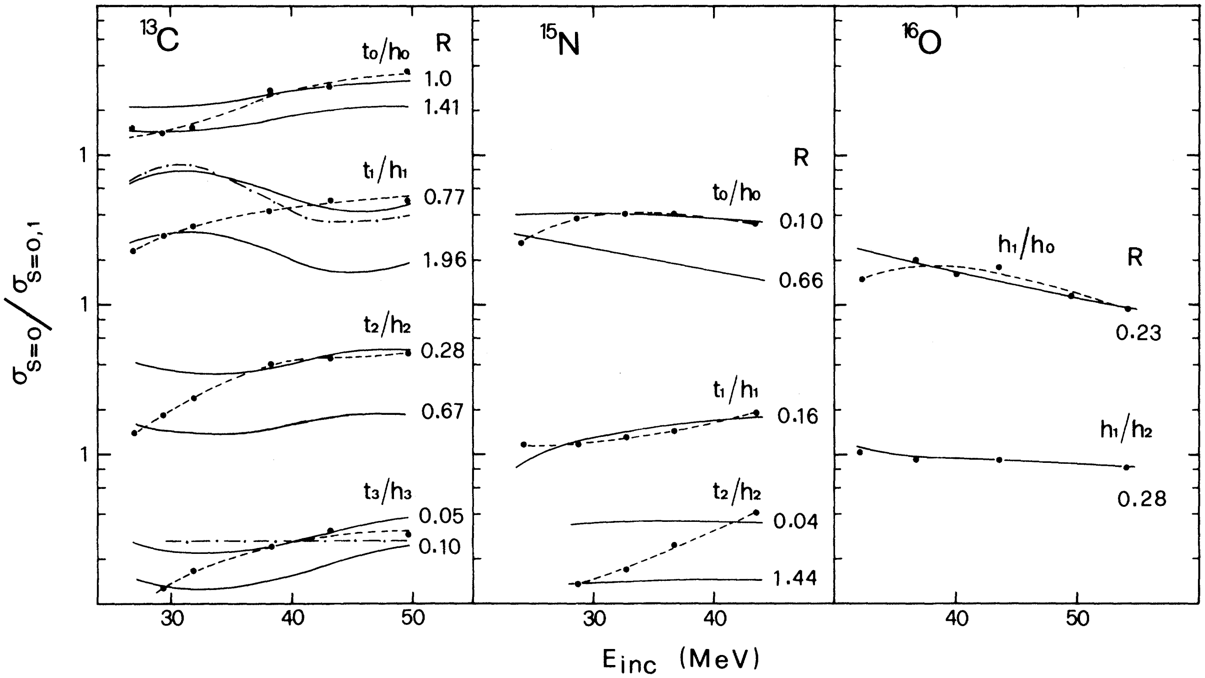


FIG. 6. Energy dependence of ratios of cross sections corresponding to $S=0$, $T=1$ transfer to the coherent sum of $S=0$ and $S=1$ transfer. Dashed curves only connect the experimental points. The full curves are the result of the present DWBA calculations using the $R$ values given on the right side of each part of the figure. Point and dash curves are the result of the same calculations with only $L=2$ contributions.

satisfactory. Since the effects of angular momentum mismatch are comparable in both $(p, t)$ and $(p, {}^3He)$ reactions, it is possible that they cancel in a comparison between ratios of cross sections. We have then compared, in the framework of the method of Hardy and Towner,[6] the theoretical predictions with the experimental ratios of the integrated cross sections for transitions to mirror levels in the case of the reactions on $^{13}C$ and $^{15}N$ and for the ratios of the 2.31 MeV $(T=1)$ to $T=0$ transitions in the case of the $^{16}O(p, {}^3He)^{14}N$ reaction. Since the $^{16}O$ ground state has $T=0$, the value of the transferred spin in the latter reaction is determined uniquely by the isospin of the final level.

Both the experimental ratios and the results of DWBA calculations are shown in Fig. 6. The $R$ values used in the calculations are given in the same figure for each transition. A satisfactory fit to the experimental energy dependence is obtained for the $^{16}O(p, {}^3He)$ reaction with $R$ values similar for the two transitions and in agreement with those found by Fleming *et al.*[15] Also the $t_1/h_1$ ratio in $^{15}N$ is well reproduced by a DWBA curve even if a lower $R$ value is required. No agreement has been found for the other transitions, for which the $R$ value needed varies with the incident energy, the higher value being systematically required at the lower energy.

The dependence of the theoretical ratios on the choice of the optical model parameters has been tested and found to be small. Also rather limited is the effect of a different choice of the spectroscopic factors. In Fig. 6 is also given the theoretical ratio for a pure $L=2$ transfer in the two cases in which this assumption gives better fits to the helion angular distributions, namely the $h_1$ and $h_3$ transitions to $^{11}B$. The energy dependence, shown by a point-dash curve, remains rather similar to that obtained by using the spectroscopic amplitudes deduced from Cohen and Kurath wave functions.[22]

In principle the exchange terms in the effective interaction, and then $R$, could be energy-dependent. However the energy dependence of the spin and isospin-dependent terms, as known from inelastic scattering and charge-exchange reactions,[24] leads to a nearly constant $R$-value. The strong energy dependence needed to reproduce part of the data here reported, as also the $^{12}C({}^3He, p)^{14}N$ reaction studied by Mangelson *et al.*,[14] may instead evidence the inadequacy of the reaction model. In this connection it is remarkable that the experimental ratios $\sigma(p, t)/\sigma(p, {}^3He)$ also show a strong energy dependence, changing from values between 3 and 4 in the 40–50 MeV energy region to values very near to unity at lower energies. This effect might indicate the growth, at low energies, of a reaction mechanism governed by selection rules different from those of a direct two-nucleon pickup. A precompound emission,[25] for instance, which is governed by statistical rules in the exit channels, would lead to a ratio near to unity.

The above effects, therefore, suggest that the dominant reaction mechanism changes with the incident energy and that the simple one-step two-nucleon pick-up model becomes inadequate below 35–40 MeV so that no $R$ value can be derived.

Approximate agreement between the energy dependence of the experimental and theoretical ratios is, on the other hand, obtained for most of the transitions at higher energies. A better agreement is also found in this region for the energy dependence of each single transition (Fig. 5) and for the shape of the differential cross sections (Figs. 1–3). This indicates that, at least above 40 MeV, the direct pick-up model can be used with some confidence. The $R$ values which are found are however often very small in comparison with the values quoted from the effective interactions used in the shell model calculations of light nuclei and even smaller in comparison with the $R$ values consistent with the effective interactions, of the Serber type, used in DWBA microscopic calculations of $(p, p')$ and $(p, n)$ reactions.

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