PHYSICAL REVIEW C VOLUME 17, NUMBER 4 APRIL 1978

Energy dependence of two-step (p,t) cross sections

Ken-ichi Kubo*
Cyclotron Institute, Texas A&M University, College Station, Texas 77843

Hirotaka Amakawa†
Department of Physics, Faculty of Science, University of Tokyo, Hongo, Tokyo, Japan
(Received 22 June 1977)

The energy dependence of two-step distorted-wave Born approximation calculations is studied for unnatural-parity state excitations by the (p,t) reaction involving (p,p',t), (p,t,t'), and (p,d,t) processes. The calculations which provide rapidly decreasing cross sections with an increase in the incident energy are found to be quite consistent with the observed results for the $^{18}O(p,t)^{16}O$ (8.88 MeV, 2^-) reaction at the energy range of $E_p = 20$–45 MeV. The remarkable difference of kinematical features between one-step and two-step processes is pointed out and the importance of higher-order effects for one-step allowed transitions is apparently indicated.

[NUCLEAR REACTIONS Energy dependence of second-order DWBA cross sections, $^{18}O(p,t)^{16}O$ (8.88 MeV, 2^-) and (9.85 MeV, 2^+) $E=20.0$–43.6 MeV.]

I. INTRODUCTION

The successful results of the second-order distorted-wave Born approximation (DWBA) (or two-step) treatment for the unnatural-parity state excitation of the $^{18}O(p,t)^{16}O$ (8.88 MeV, 2^-) reaction at 24.4 MeV have been reported.[1] The calculations involving processes via inelastic excitations (p,p',t) and (p,t,t') and successive transfer reactions (p,d,t) were found to reproduce the observed results[2] quite well. The importance of coupling of inelastic channels to transfer channels has been point out not only for such first-order forbidden transitions, but also even for some allowed transitions.[3] Most studies of successive particle transfer processes have been carried out for the charge-exchange reactions $(^3He,t)$ (Ref. 4) and $(^6Li, ^6He)$ (Ref. 5), and also for unnatural-parity state excitations by the (p,t) reactions.[1,6–9] The results of analysis for such unnatural-parity state transitions are as follows. The transitions to the ^{16}O (2^-) state[1] and Ni isotope (3^+) states[6] are well understood as cases where both successive and inelastic two-step processes are equally responsible for excitations. The ^{206}Pb (3^+) transition[7,8] can be reasonably reproduced by only the successive two-step process. In this case no calculation has been done including the inelastic two-step. However, the fits of the ^{20}Ne (2^-) transition[9] are drastically disturbed by adding the successive transfer process.

On the other hand, the energy dependence of such two-step calculations has not been well investigated. Experimental data exist for the ^{16}O (2^-) state excitation[10] which show a strong energy dependence; the integrated cross sections decrease by a factor of $\frac{1}{30}$ with changes of energy from 20 to 45 MeV. Therefore, it is worthwhile to test the energy dependence of two-step calculations for these data. It is the main purpose of the present paper to investigate this point.

Recently, the successive nucleon-transfer process (p,d,t) was found to be important[7,8,11] for several cases of the natural-parity state (or one-step allowed) excitations. However, the fact that an arbitrary reversal of phase between one-step and two-step (p,d,t) amplitudes is required has been pointed out[7] for several transitions, if they are evaluated employing the zero-range approximation. The finite-range calculations[8] do not need such prior adjustments of phase, but the absolute normalization problems are not resolved. The fits of angular distribution shape are drastically changed by adding the successive term and very dependent on the choice of distorting potential parameter set. The finite-range effects in the (p,d,t) process itself have been studied qualitatively[12] and also quantitatively,[8] and both conclude a large effect for natural-parity state transitions, but very small for unnatural-parity state transitions.

The energy dependence of the natural-parity state transition was also investigated in Ref. 10. Their conclusion was that one-step DWBA calculations provide only a very weak energy dependence, contrary to the observed results for transitions to natural-parity states, with the exception of the transition to the ground state 0^+. It is therefore very desirable to study two-step effects for the energy dependence too. However, several difficulties exist in such natural-parity state transitions as above mentioned; parametrization of

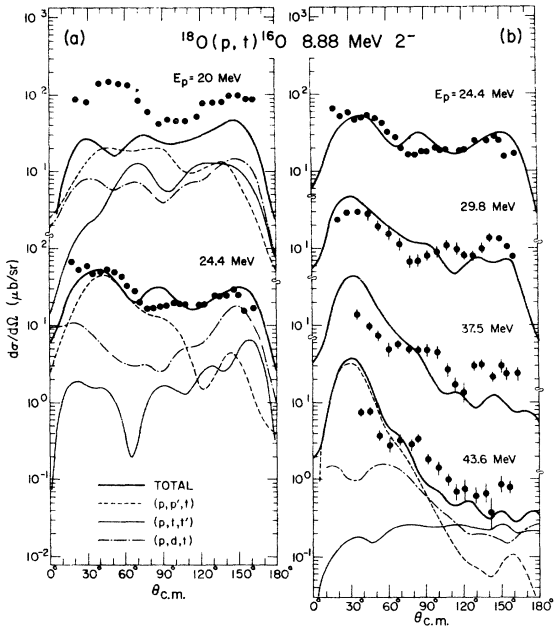

FIG. 1. Angular distributions of the $^{18}O(p,t)^{16}O$ (8.88 MeV, 2$^-$) reaction for five different incident energies. The calculated results for $E_p = 20$ and 24.4 MeV by use of the two-step excitation model are shown at the left hand side (a) and they are compared with the observed data (shown by the solid circles). The contributions of each three different process (p,p',t), (p,t,t'), and (p,d,t) considered here are illustrated by such different lines as designated in the figure. The coherent sum of them is shown by the thick solid line. The calculated results for the four higher incident energies are compared with the observed data at the right hand side (b). The contributions of each process are shown for the highest 43.6 MeV case. All calculated cross sections are normalized by a multiplicative factor of 0.7. The experimental data are taken from Ref. 10.

amplitudes, finite-range effects, and choice of potential set. In this paper then, a very restricted subject is studied for which the (p,p',t) process for the ^{16}O (9.85 MeV, 2$^+$) transition is an example. The Q-value dependence of this process is also studied and a difference from that of elementary (p,p') inelastic scattering cross sections is pointed out.

II. RESULTS OF CALCULATION AND DISCUSSION

The present calculations have been carried out using energy dependent distorting potential parameters which are given in Table I. The nuclear deformation parameter of $\beta_2 = 0.447$ is used for the ^{18}O (1.98 MeV, 2$^+$) state instead of 0.37 employed in Ref. 1. The value of 0.37 was found[13] to give an effective deformation strength $\beta_2 R_0 = 1.46$ for the imaginary radius parameter $r_{0i} = 1.52$ fm. The present potential set P11 gives a similar value of 1.53 for the deformation strength which turns out to be $\beta_2 = 0.447$ for the imaginary radius parameter $r_{0i} = 1.32$ fm used here. The brief summary of other assumptions used in the calculations is as follows: The intermediate states are restricted to $p + ^{18}$O (2$^+$) state for (p,p',t), $t + ^{16}$O (1$^-$ and 3$^-$) states for (p,t,t') and four $d + ^{17}$O ($\frac{5}{2}^+$, $\frac{1}{2}^-$, $\frac{3}{2}^-$, and $\frac{3}{2}^+$) states for (p,d,t) processes. For ^{18}O and ^{16}O, the shell model wave functions are taken from Refs. 14 and 15, respectively. The values used for zero-range constants are $D_0^2(p,d) = 1.58 \times 10^4$, $D_0^2(p,t) = 1.45 \times 10^6$, and $D_0^2(d,t) = 3.37 \times 10^4$ in units of MeV^2 fm^3, which were the same as used in Ref. 1. The value of D_0^2 for (p,t) process is about factor of 5 times larger than that normally used and the need for such normalization has been pointed out for the light nucleus ^{18}O→^{16}O transition.[16]

A. 2$^-$ transition

The results of the calculations are shown in Fig. 1. The observed angular distributions for different incident energies are well reproduced by the present calculations [shown in Fig. 1(b)] except for the lowest energy case [shown at the top of Fig. 1(a)]. For the 20-MeV reaction, attempts to use different distorting potential parameters for the proton channel[13] and the triton channel[17]

TABLE I. Distorting potential parameters used in the calculations.

		V	r_0	a	W	W_D	r_0'	a'	$V_{s.o.}$	$r_{s.o.}$	$a_{s.o.}$
^{18}O+p	P11 [a]	56.0	1.17	0.75	$0.22E-2.7$	$13.13-0.25E$	1.32	0.588	6.2	1.01	0.75
^{17}O+d	D5 [b]	$119.9-0.22E$	1.07	0.717	•••	$4.544+0.24E$	1.39	0.67	5.0	1.03	0.59
^{16}O+t	T2 [c]	146.8	1.4	0.44	$7.5+0.4E$	•••	1.4	0.551	•••	•••	•••

[a] From Ref. 10, based on Becchetti-Greenlees [Phys. Rev. 182, 1190 (1969)].
[b] From Ref. 2, based on Perey-Perey [Phys. Rev. 132, 755 (1963)].
[c] From Ref. 10, based on Glover-Jones [Phys. Lett. 16, 69 (1965)].

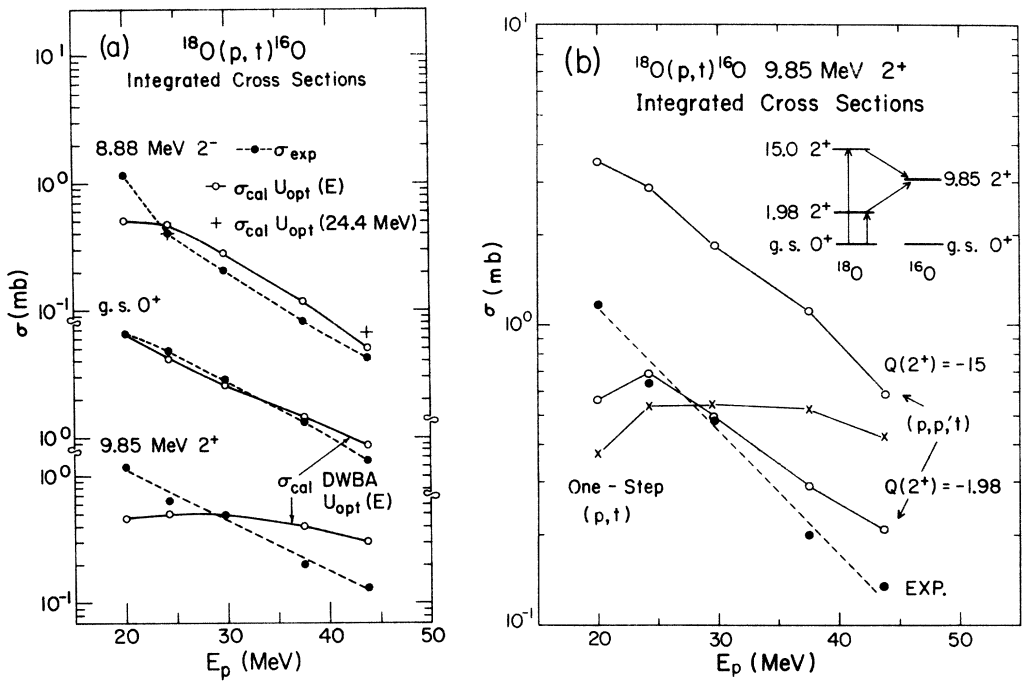

FIG. 2. Incident energy dependence of the integrated cross sections. The solid circles show the observed results from Ref. 10. (a) The open circles in the 2^- excitation show the results of present two-step calculations. The cross marks at 24.4 and 43.6 MeV show the calculated results with no account of the energy dependence of distorting potentials. The open circles for the ground 0^+ and 2^+ transitions show results of one-step DWBA calculations, after normalizing them to the observed 0^+ cross section at 20 MeV. (b) Two-step (p,p',t) cross sections leading to the 2^+ state are compared with one-step DWBA calculations (shown by × marks) and with the observed data. The angular range of integration is in (a) for the data existing and in (b) for whole angles.

were made; however, no appreciable improvement of the fit to the data was achieved. The most conspicuous feature that appeared at this energy is a plateau-type angular distribution of the (p,p',t) process, contrary to higher energy cases where this component provides a forward peak which reproduces the broad peak observed in the forward angular region. Such comparisons are illustrated in Fig. 1(a) for the incident energies of 20 and 24.4 MeV. More complex reaction processes may be necessary for this transition as will be mentioned later. In Fig. 1, the calculated cross sections are multiplied by a factor of 0.7 to provide an overall good fit to the observed angular distributions, instead of 1.8 needed in Ref. 1, owing to mainly the difference in proton channel potentials used. The absolute magnitude calculated must be finalized by more careful considerations with a realistic interaction as well as full account of coupling effects among channels.

The cross sections, integrated over the angular range where experimental data exist, are shown at the top of Fig. 2(a) by solid circles. The results of the present calculations (shown by the open circles) reproduce very well the energy dependence of the observed cross sections, except for the 20 MeV case for which a poor fit of the calculated angular distribution to the data was noted above. If the calculated cross sections are normalized by a multiplicative factor of 0.7 which was used in Fig. 1, the observed results are well reproduced by the present two-step calculations for the higher four incident energies. The details of distorting potentials are not essential for reproducing the energy dependence. The cross section at 43.6 MeV was calculated using the same distorting potential parameters as used at 24.4 MeV. The results are shown in Fig. 2(a) by the cross marks normalizing them to the observed data at 24.4 MeV.

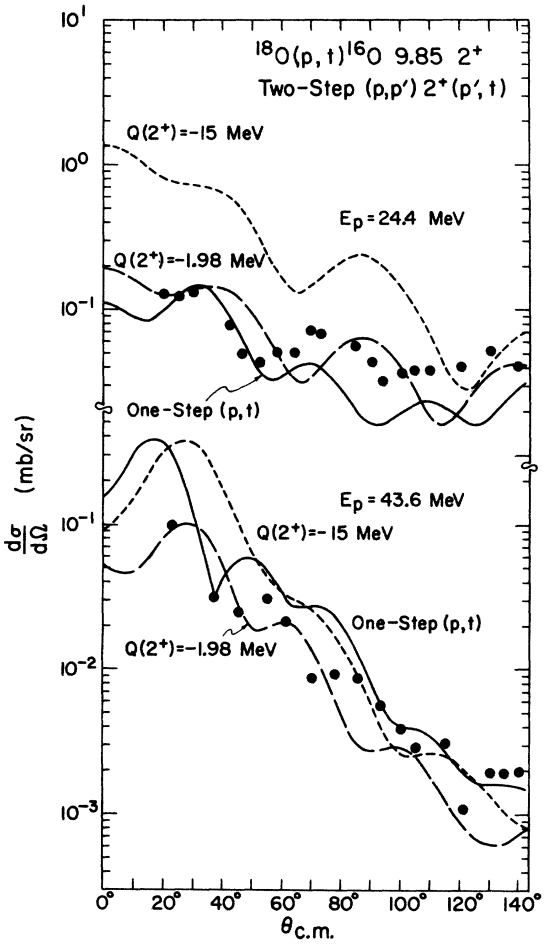

FIG. 3. Angular distributions of the $^{18}O(p,t)^{16}O$ (9.85 2^+) reaction at two different incident energies. The two-step (p,p',t) results with $l=0$ transfer in the second step are compared with the data and the one-step DWBA results.

B. 2^+ transition

The observed one-step allowed transitions in $^{18}O(p,t)^{16}O$ also show a steeply decaying energy dependence. All one-step DWBA calculations can give only a weak energy dependence except for the ground state transition, even though reasonable fits of angular distributions can be obtained by the calculations.[10] Such situations are shown in Fig. 2(a) for the ground state (0^+) and 9.85 MeV (2^+) state transitions. The Q value of the 2^+ transition differs by only 1 MeV from the 2^- transition. The momentum matching conditions are best fulfilled at 29.8 MeV in the 2^+ transition; therefore one-step DWBA calculations provide the maximum cross section at this energy. It is then noticed that two-step type calculations give very different kinematical features from one-step DWBA calculations. A steeply decaying cross section of the two-step calculation is found to be produced by the more frequent oscillation of the first-step overlap function, which contains the Green's function, form factor, and initial distorted wave, compared with the distorted wave in one-step DWBA calculations. The function shows a regularly oscillating behavior as usually found for one-step DWBA calculation under the best fulfilled momentum matching condition.

The second-order (p,p',t) cross section was estimated for the 2^+ transition assuming the first excited state as an intermediate state and the transferred angular momentum of $l=0$ for the second step. The result is shown in Fig. 2(b) by open circles designated as $Q(2^+)=-1.98$. The absolute magnitudes are close to the one-step DWBA calculations, but they show a strong energy dependence. The angular distributions are simply compared with the data and the one-step results in Fig. 3 by the long dashed lines for different two incident energies.

C. Q-value dependence

The intermediate channel dependence of the (p,p',t) cross sections was tested and one of the results is shown also in Figs. 2(b) and 3. The calculations were carried out assuming a higher excited state [$Q(2^+)=-15$ MeV] for the intermediate state,[18] the same β_2 value as for the case of $Q(2^+)=-1.98$ MeV and again $l=0$ for the second step. The cross sections are enhanced by a factor of about 5 and they show quite strong energy dependence as is observed. The present estimation for contributions from a higher excited state may be overestimated. However, these results apparently suggest the importance of inelastic channel contributions through such higher excited states for pickup reactions, although the strength of coupling to the target ground state needs to be strong. The enhancement of the cross section through higher excited states results from a decrease of the separation energy for the transferred particles. Reduction of the cross section due to an increase in Q value for the first step is negated by a change in separation energy. Such situations are illustrated in Fig. 4, where the first step Q value and separation energy were changed successively in the calculations.

The intermediate Q-value dependence of the (p,p',t) cross section is very different from the Q dependence of the elementary (p,p') inelastic cross section. The results are shown in Fig. 4. The (p,p') cross section leading to the ^{16}O 2^+

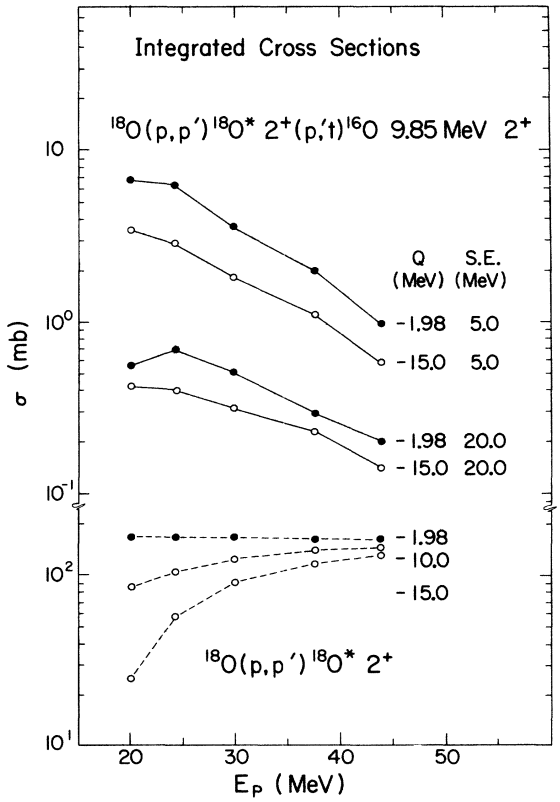

FIG. 4. The two-step (p,p',t) cross sections calculated by successive change of the first step Q value and the separation energy of the transferred two neutrons. The bottom portion shows the elementary (p,p') inelastic cross sections calculated for three different Q values.

state is easy to understand; it shows more reduction for lower incident energies due to the increase in Q value. The (p,p',t) cross section, however, shows almost a constant reduction for all energies when the Q value is increased from 1.98 to 15.0 MeV. One of the reasons may arise from the larger cross section of the (p,t) reaction with $l=0$ transfer for lower incident energy.

III. CONCLUSION

For the 2^- transition, the two-step calculation can reproduce very well the observed energy dependence of the cross section. For the 2^+ transition, the (p,p',t) cross section is estimated to be of comparable magnitude to that of one-step DWBA calculations and shows a strong energy dependence as is observed. However, the one-step DWBA calculations fail to reproduce such observed results. The higher excited intermediate states are expected to be more important for such processes. Therefore the calculated absolute magnitude of the cross section for the 2^- transition must be finalized by more careful calculations, although the present results give a good fit to the data within a factor of 2. Also, it was pointed out that the intermediate Q-value dependence of (p,p',t) cross sections is quite different from that of elementary (p,p') inelastic process.

One of the authors (K.-I.K.) wishes to express his thanks for the hospitality accorded him by Professor T. T. Sugihara and the Cyclotron Institute personnel at Texas A & M University.

*On leave from Department of Physics, Faculty of Science, University of Tokyo, Japan.
†Present address: The Institute of Physical and Chemical Research, Wako-Shi, Saitama 351, Japan.

[1]H. Segawa, K.-I. Kubo, and A. Arima, Phys. Rev. Lett. 35, 357 (1975).
[2]M. Pignanelli, J. Gosset, F. Resmini, B. Mayer, and J.L. Escudié, Phys. Rev. C 8, 2120 (1973).
[3]References for study of coupling effects from inelastic channels are given in Ref. 10.
[4]R. Schaeffer and C. F. Bertsch, Phys. Lett. 38B, 159 (1972); W. R. Coker, T. Udagawa, and H. H. Wolter, *ibid.* 41B, 237 (1972); N. B. de Takacsy, *ibid.* 42B, 1 (1972) and other references are given in Ref. 10.
[5]H. Duhm, H. Hafner, R. Renfordt, M. Goldschmidt, O. Dragun, and K.-I. Kubo, Phys. Lett. 48B, 1 (1974); K.-I. Kubo, Nucl. Phys. A246, 246 (1975); F. Osterfeld and H. H. Wolter, Phys. Lett. 60B, 253 (1976).
[6]M. J. Schneider, J. D. Burch, and P. D. Kunz, Phys. Lett. 63B, 129 (1976).
[7]N. B. de Takacsy, Phys. Rev. Lett. 31, 1007 (1973); Nucl. Phys. A231, 243 (1974).
[8]L. A. Charlton, Phys. Rev. C 14, 506 (1976). The finite calculations have also been reported by J. D. Burch *et al.*, including the (p,d,t) process for Ni isotope: J. D. Burch, J. J. Kraushaar, M. J. Schneider, and P. D. Kunz, Bull. Am. Phys. Soc. 14, 544 (1977).
[9]D. K. Olsen. T. Udagawa, and T. Tamura, Phys. Rev. C 8, 609 (1973); T. Udagawa and D. K. Olsen, Phys. Lett. 46B, 285 (1973); W. S. Chien, C. H. King, J. A. Nolen, Jr., and M. A. M. Shahabudding, Phys. Rev. C 12, 332 (1975).
[10]M. Pignanelli, S. Micheletti, I. Iori, P. Guazzoni, F. G. Resmini, and J. L. Escudié, Phys. Rev. C 10, 445 (1974).
[11]N. Hashimoto and M. Kawai, Phys. Lett. 59B, 223 (1975).
[12]P. D. Kunz and L. A. Charlton, Phys. Lett. 61B, 1 (1976).
[13]F. Resmini, R. M. Lombard, M. Pignanelli, J. L. Escudie, and A. Tarrats, Phys. Lett. 37B, 275 (1971).
[14]T. Inoue, T. Sebe, H. Hagiwara, and A. Arima, Nucl.

Phys. 59, 1 (1964).
[15]J. P. Elliot and B. H. Flowers, Proc. Roy. Soc. A 242, 57 (1957).
[16]R. A. Broglia, C. Riedel, and T. Udagawa, Nucl. Phys. A184, 23 (1972).
[17]D. J. Pullen, J.R. Rook, and R. Middleton, Nucl. Phys. 51, 88 (1964).
[18]G. J. Vanpraet, Phys. Lett. 17, 120 (1965).