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Energy Dependence of the Three-Nucleon Transfer Reactions on Light Nuclei

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Excitation functions and angular distributions for (p,α) reactions on ^{12}C, ^{15}N, and ^{16}O have been measured from 19- to 45-MeV incident energy. The mean slope of the integrated cross sections for all the above reactions and for (p, α) reactions on ^{9}Be, ^{11}B, and ^{19}F is the same, when plotted as a function of the intermediate-system excitation energy, and is of the type $[(E_p)_{c.m.} + B_p]^{-3.75}$. For the ^{12}C and ^{16}O targets, the differential and integrated cross sections, which have been measured in energy steps of the order of some hundred keV, show a marked resonant structure with modulations having widths and spacings of the order of 1 MeV. Angular distributions, although presenting a well-developed diffraction pattern especially at forward angles, vary very rapidly with energy, particularly below 30 MeV. The analysis of excitation functions performed with a distorted-wave Born-approximation point triton pickup calculation gives ambiguous results. A statistical Hauser-Feshbach calculation gives too steep a slope which agrees with experimental data only when direct transitions are hindered. The analysis of the excitation functions, performed in the framework of the pre-equilibrium decay model, gives satisfactory results. This could indicate that α emission from light nuclei cannot be treated as a simple direct effect.

I. INTRODUCTION

The mechanism of (p, α) reactions on light nuclei has been the subject of several recent publications.[1-6] Analyses with the aim of testing the applicability of triton pickup in the distorted-wave Born approximation (DWBA) have been performed.[1,2,7] Particularly in nuclei where clustering effects may be hypothesized, exchange processes should be taken into account. For this reason in a previous work[3] we analyzed angular distributions at two energies in the plane-wave Born approximation (PWBA) taking into account all possible direct mechanisms (pickup, heavy-particle pickup, knockout, and heavy-particle knockout) and their interference terms. A recent analysis, also in the PWBA, by Cavaignac, Longequeue, and Honda,[5] takes into account the last two mechanisms.

The results of these analyses, however, cannot be considered conclusive and, at least for some nuclei, the model or the formalism seems inadequate to describe the experimental situation. These analyses have also borne out[3] the necessity of obtaining further experimental data, especially on the energy dependence of the reaction cross sections.

Differential cross sections for the (p, α) reac-

tion on several light nuclei have been obtained previously in this laboratory[3,4] at a few proton energies between 24.5 and 44.5 MeV. Marked variations in the shape of the angular distributions with proton energy have been observed in the (p, α) reaction on ^{12}C and ^{16}O targets. In order to evidence this behavior better and to obtain detailed data on the cross-section energy dependence, further data on these last two nuclei and on ^{15}N have been collected as part of this investigation.

The present results, and those previously obtained in our and in other laboratories, are discussed on the basis of the available reaction models. Other reactions on the same nuclei are also considered. Some aspects of the behavior of the (p, α) reactions may be successfully described if these reactions are not analyzed as a conventional direct effect, but as a multistage process.

II. EXPERIMENTAL METHOD

The measurements were performed using the external proton beam of the Milan University AVF cyclotron. The beam energy spread was of the order of 200 keV; its mean energy was monitored by means of an apparatus described in the work of Micheletti and Giannini.[8] The precision of the method was of the order of 70 keV in relative energy value and of the order of 150 keV in absolute value.

The α particles were detected by one or more 700-μm-thick surface-barrier silicon detectors. The detector bias voltage was set to the value required to obtain the minimum depth of the sensitive region necessary to exhaust the range of the α particles. This procedure provided discrimination against protons and deuterons; contamination

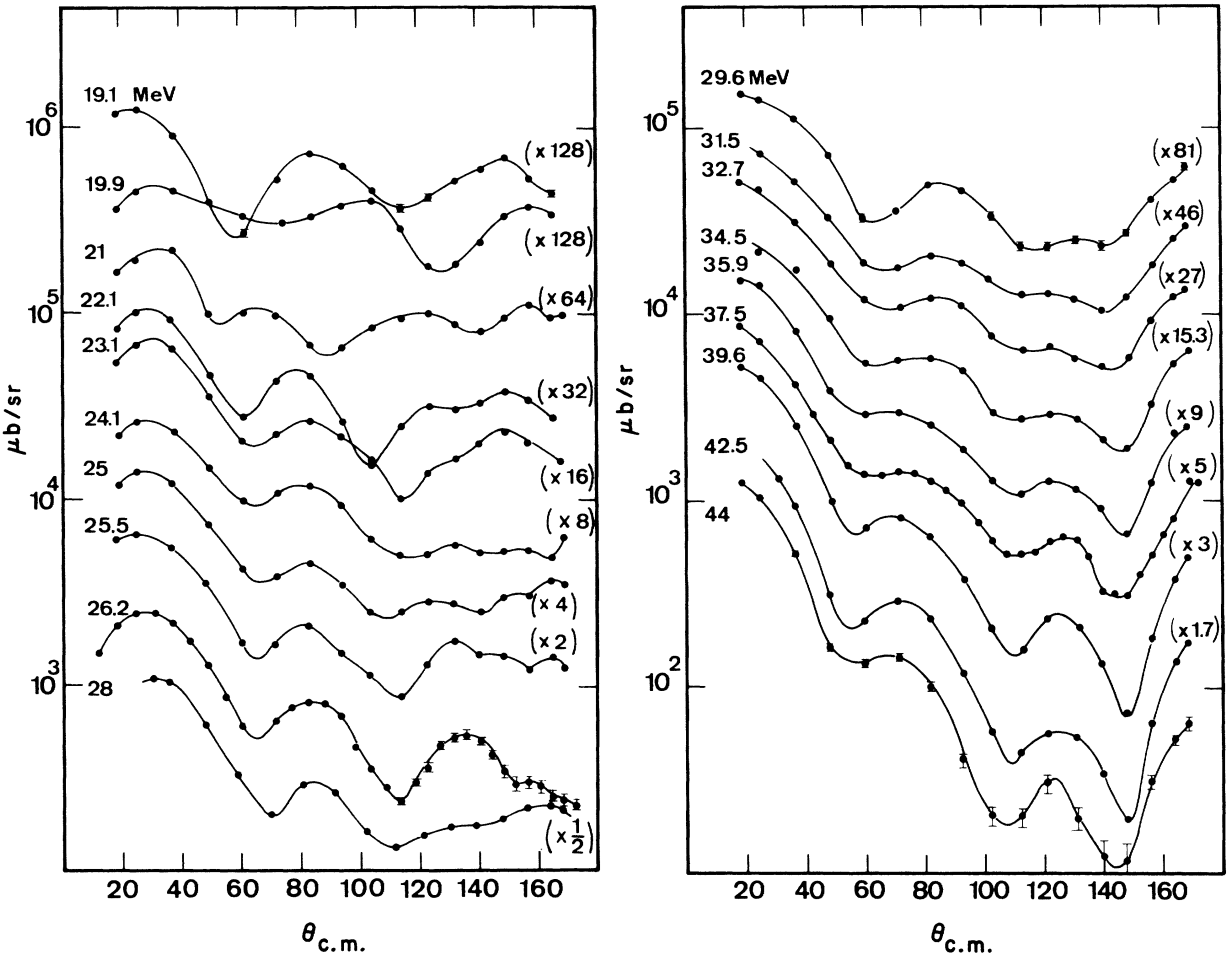

FIG. 1. Differential cross section for the reaction $^{12}C(p,\alpha)^{9}B_{g.s.}$. Where not indicated, statistical errors are smaller than point size. The full lines are the result of a visual fit to the experimental points. The numbers in parentheses are the factors by which the plotted cross sections must be divided in order to obtain the true cross sections.

by other particles was ruled out by the large negative Q value of other proton-induced reactions on the studied nuclei.

A Moplefan (trade name by Montedison) $(C_3H_4)_n$ foil 1.1 mg/cm^2 thick was used as the carbon target. Gas targets were used for the measurements on ^{15}N and ^{16}O. The nitrogen gas was enriched to 99.5% in the isotope ^{15}N; the oxygen gas was the natural isotopic mixture. The gas target consisted of a 70-mm-diam cylindrical cell, with two windows covered by 2-mg/cm^2-thick Havar (trade name by Hamilton Precision Metals) foils, each 15 mm high and extending over 150°, filled to gas pressures in the range 15–30 cm Hg.

The counting geometry was defined, for each detector, by pairs of tantalum collimators located at 45 and 181 mm from the center of the gas cell. The front collimator was a slit 4 mm wide, the rear one was circular with a diameter of 4 mm. An antiscattering baffle was placed halfway between the defining apertures.

III. EXPERIMENTAL RESULTS

Differential cross sections, shown in Figs. 1 to 5, have been measured at 19, 6, and 30 energies, respectively, for the $^{12}C(p, \alpha)^9Be$, $^{15}N(p, \alpha)^{12}C$, and $^{16}O(p, \alpha)^{13}N$ reactions. The most noticeable features are well-developed diffraction patterns, typical of a direct effect and a nonregular energy dependence, particularly marked in the $^{16}O(p, \alpha)$ reaction below 30 MeV.

Excitation functions have been measured in steps of the order of some hundred keV between 18.5 and 44.5 MeV for $^{12}C(p, \alpha)^9Be$ ground-state transition, and for the $^{16}O(p, \alpha)^{13}N$ reaction to the

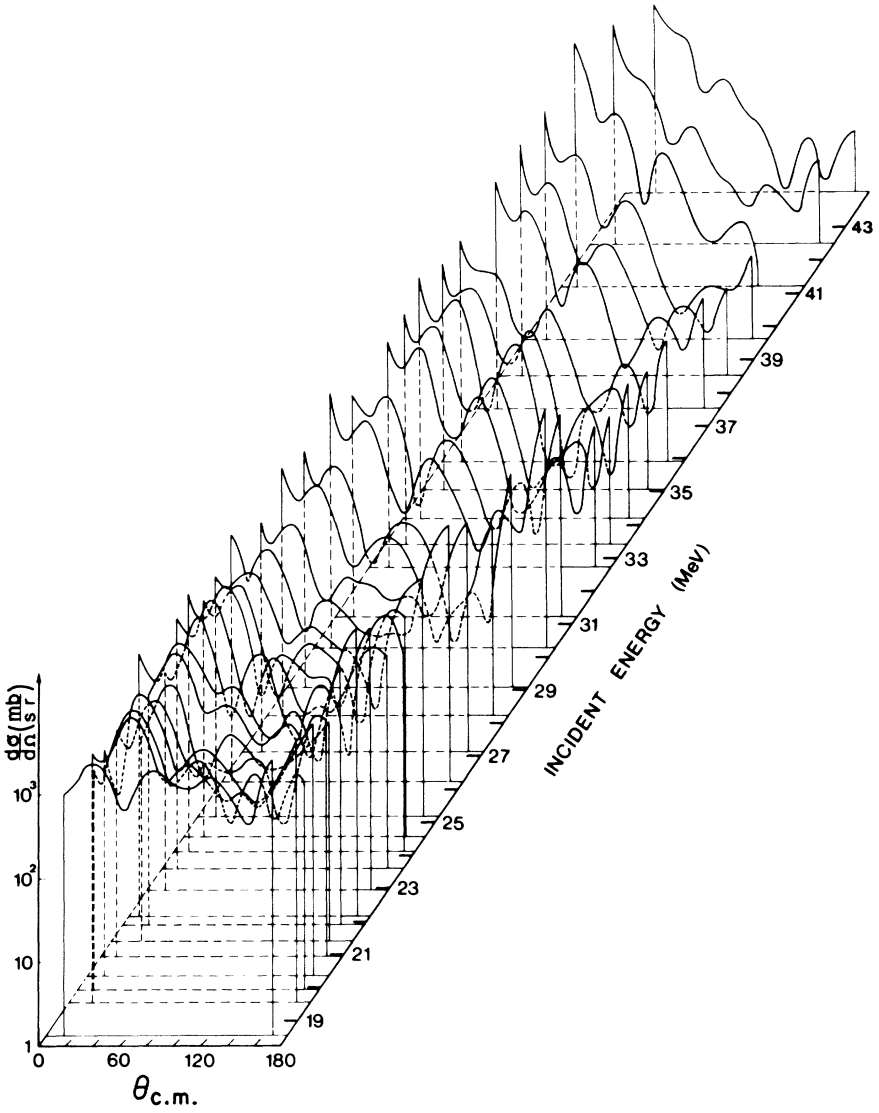

FIG. 2. Differential cross section for the reaction $^{16}O(p, \alpha)^{13}N_{g.s.}$. The full lines are the result of a visual fit to the experimental points.

following ^{13}N levels: α_0 (0 MeV, $J^\pi = \frac{1}{2}^-$); α_1 (2.37 MeV, $J^\pi = \frac{1}{2}^+$); α_{2+3} (3.51 MeV, $J^\pi = \frac{3}{2}^-$ and 3.56 MeV, $J^\pi = \frac{5}{2}^+$); and α_4 (6.38 MeV, $J^\pi = \frac{5}{2}^+$). Marked modulations, persisting over wide angular ranges are present, as shown in Figs. 6 and 7. These modulations are also found, over the whole measured energy range, in the integrated excitation functions plotted in Figs. 6 and 8. There is no systematic correspondence among the structures in the various excitation functions for different final states reached in the ^{16}O$(p, \alpha)^{13}$N reaction.

The mean slope, obtained averaging over the modulations, is about the same for the α_0 and α_{2+3} groups. The α_1 and α_4 groups have a smaller cross section and a steeper slope, especially at lower energies. In the ^{15}N$(p, \alpha)^{12}$C reaction, which has been measured in steps of 5 MeV, the transition to the final-nucleus ground state presents a smaller cross section and a steeper slope than that to the first excited state (4.43 MeV, $J^\pi = 2^+$).

With the exception of these three smaller-cross-section transitions, the integrated average cross

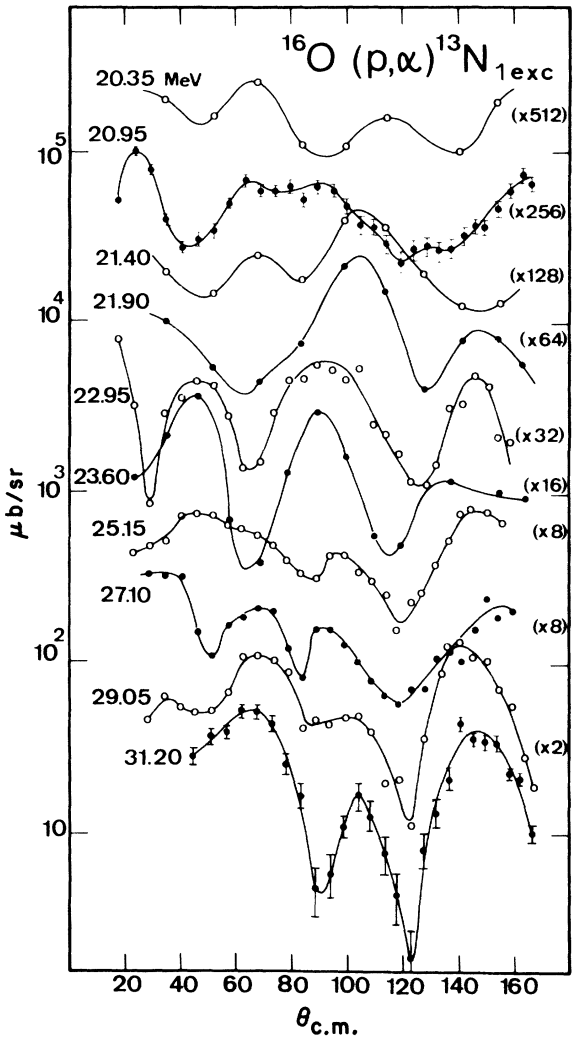

FIG. 3. Differential cross section for the reaction ^{16}O-$(p, \alpha)^{13}$N to the 2.37-MeV level of ^{13}N. See caption for Fig. 1.

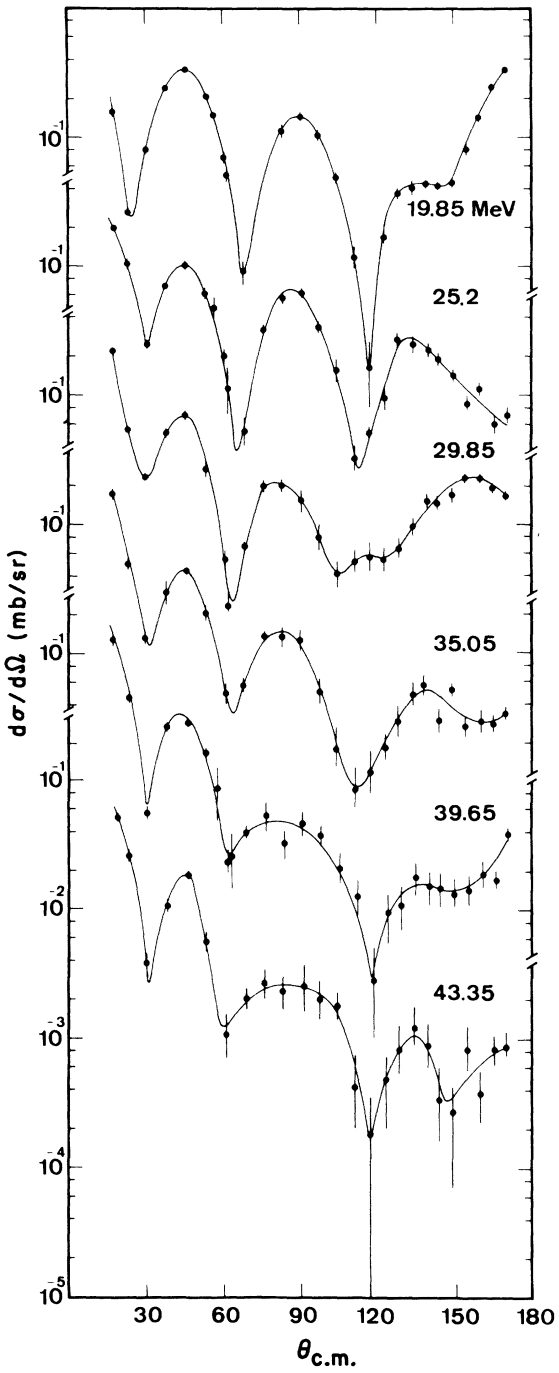

FIG. 4. Differential cross section for the reaction ^{15}N-$(p, \alpha)^{12}$C$_{g.s.}$. Where not indicated statistical errors are smaller than point size. The full lines are the results of a visual fit to the experimental points.

sections show an incident-energy dependence of the type $\sigma \propto E_p^{-n}$ with n between 2 and 3.5 as can be seen in Fig. 9 in which some data from other laboratories[1,2,5-7,9] are also given. The same excitation functions are plotted in Fig. 10 as a function of the excitation energy of the intermediate system $E_{exc} = (E_p)_{c.m.} + B_p$ (binding energy of incoming proton in the target nucleus). It is remarkable that in this case the slope is nearly exactly the same for all the nuclei studied and corresponds to $\sigma \propto E_{exc}^{-3.75}$.

On a first inspection of the data we can make the following remarks:

(a) The modulations exhibited by the ^{12}C and ^{16}O excitation functions are probably due to resonant effects and not to statistical fluctuations, as borne out by their persistence over wide angular ranges. Their width is of the order of 1 MeV or more and their spacing is of the same order, so that the presence of overlap cannot be excluded.

(b) The excitation functions have a steeper slope than that usually obtained for direct processes, moreover the presence of structure and the importance of intermediate-system excitation energy in determining the mean slope are hardly compatible with a simple direct effect.

(c) There is no systematic correspondence among resonances in excitation functions for the different outgoing channels.

(d) At a given energy the experimental cross sections for α_1 and α_4 in the $^{16}O(p,\alpha)^{13}N$ reaction are of the same order, and smaller than those for the α_0 and α_{2+3} transitions. The α_1 and α_4 transitions are strongly hindered in a direct process as indicated by the known configurations[10,11] of the initial and final states involved in the transitions. In the $^{15}N(p,\alpha)^{12}C$ reaction the experimental cross sec-

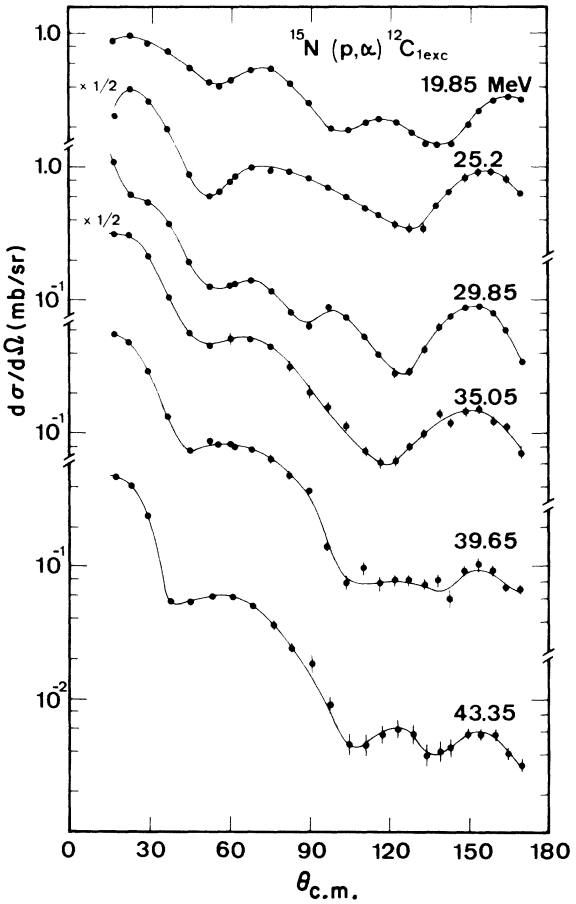

FIG. 5. Differential cross section for the reaction $^{15}N(p,\alpha)^{12}C$ to the 4.43-MeV level in ^{12}C. See caption for Fig. 4.

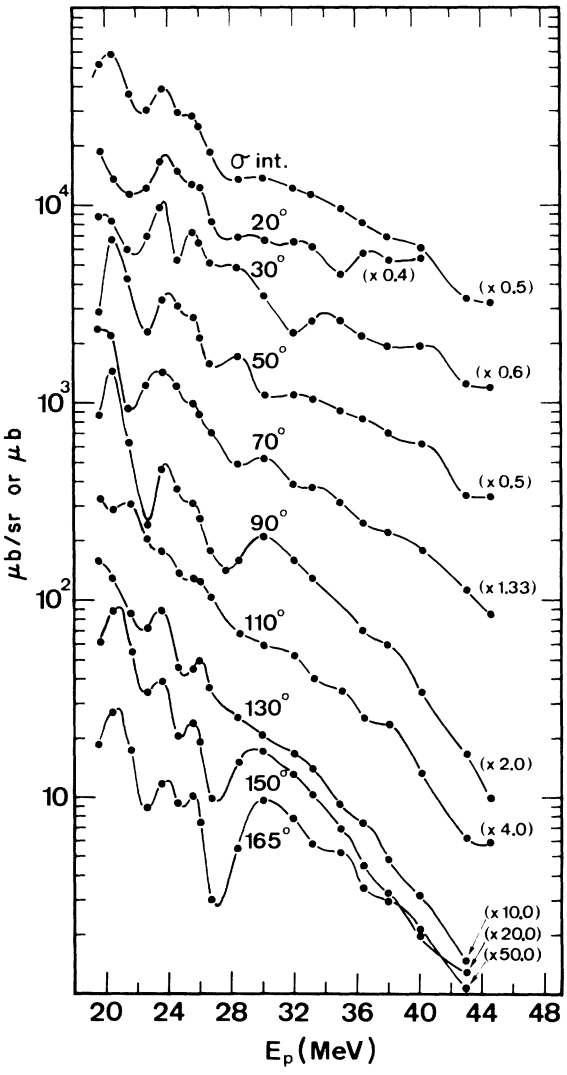

FIG. 6. Excitation functions for the reaction $^{12}C(p,\alpha)^9B_{g.s.}$ at different lab angles. The top curve is the integrated excitation function between 15 and 165° lab angles. See caption for Fig. 1.

tion for the α_0 transition is smaller than that for α_1 in agreement with the calculated spectroscopic factors.[12] These differences in α yields indicate that nuclear structure plays an important role as in a direct effect. However, because of the arguments given in (a) and in (b), it is difficult to attribute the α emission to a direct process in the usual sense.

IV. DATA ANALYSIS

The complexity of the experimental results discussed in the preceding section suggests that the analysis cannot be limited to a single mechanism but, rather, possible contributions from different mechanisms must be evaluated using the known methods of analysis. Direct effects and compound-nucleus contributions can be evaluated by means of DWBA and Hauser-Feshbach calculations. An explanation of some features of the experimental results (energy dependence of the cross section) may be attempted on the basis of a pre-compound reaction mechanism.

A. Direct Interaction

It is known that several difficulties arise in treating many-nucleon-transfer direct reactions, and no detailed approach has been developed for three-nucleon transfer. The importance of exchange processes, particularly in cases where nucleon clustering in the surface region of the target or residual nucleus may be possible, has also been pointed out.[3,4] Due to intrinsic and technical difficulties in treating knockout and heavy-particle processes, most of the calculations have been performed in the plane-wave approximation.[3,5] In this approximation, at least for the reaction on ^{12}C and ^{16}O, pickup and knockout give the same shape for the differential cross section and a similar energy dependence of the integrated cross section, which is flatter than the experimental one.

Exchange and transfer mechanisms with interference terms have been considered in the PWBA[3]; no conclusive results have been reached, because absolute values for the various amplitudes cannot be obtained. Similar calculations have been proposed also in the DWBA by Thompson[13]; up to now, however, the only DWBA calculations compared with (p, α) cross sections have been limited to the pickup process.[1,2,7] α-particle angular distributions from $^{19}F(p, \alpha)^{16}O$ have been analyzed in this last scheme at a few energies by Cole *et al.*,[1] by Holmgren and Fulmer,[7] and by Hird and Li.[2] A calculation for $^{12}C(p, \alpha)^{9}B$ has also been attempted

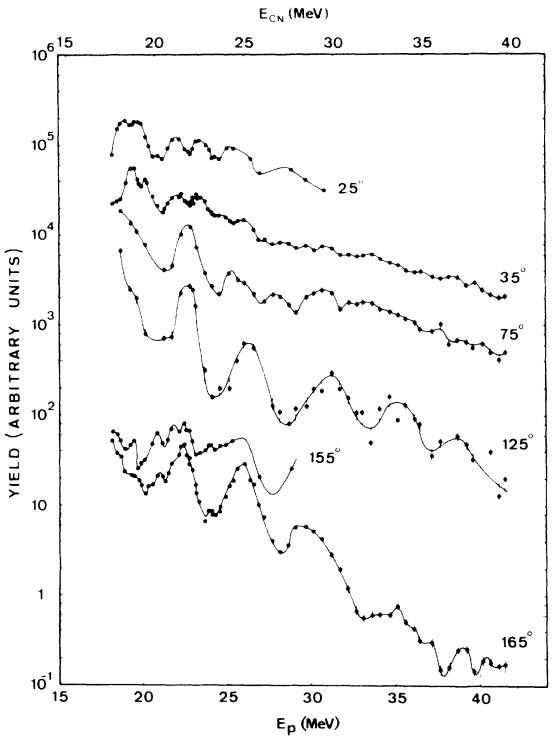

FIG. 7. Differential excitation functions for the $^{16}O(p,\alpha)^{13}N$ reaction. Angles are in the lab system.

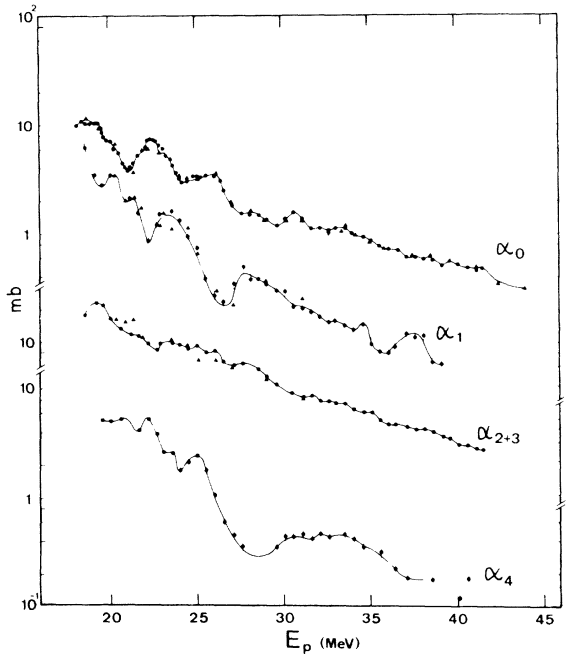

FIG. 8. Integrated excitation functions to nitrogen-13 excited levels in the reaction $^{16}O(p,\alpha)^{13}N$. Dots give the sum $\sum\sigma(\theta)\sin\theta$ of the differential cross sections at 35, 75, 125, and 165°. This was normalized to the integrated cross section deduced from the angular distributions obtained at a number of energies and indicated with triangles.

by the last two authors. Satisfactory agreement as regards absolute values and the general diffraction pattern is obtained although the actual shapes are poorly fitted.

In view of the partial success of the above analysis, we have performed a DWBA calculation using the code DWUCK on the basis of a point triton pick-up mechanism in the zero- and finite-range approximation, in order to see if the cross-section energy dependence could be reproduced. In this case additional difficulties are caused by the requirement of knowing the energy dependence of the optical-potential parameters. However, the choice of proton and α-particle optical potentials and the use of the DWBA presents more fundamental difficulties; it is immediately apparent that both in the case of $^{16}O(p, \alpha)^{13}N$ and $^{19}F(p, \alpha)^{16}O$ (the two extreme cases with respect to Q values, which are -5.2 and $+8.11$ MeV), a severe angular momentum mismatch is present. Proton and α-absorption coefficients $|\eta_L|$ are plotted for the two reactions in Fig. 11. These were calculated using the optical-model parameters given by Watson, Singh, and Segel[14] for protons and by Hird and Li[2] for α particles. The angular momentum mismatch may result in significant contributions from the nuclear interior.[15, 16]

The choice of the optical potentials, which in this case can no longer be derived from elastic scattering, becomes very questionable. This choice, on the other hand, strongly affects the calculated values of the cross sections and their energy dependence. Varying for each nucleus the op-

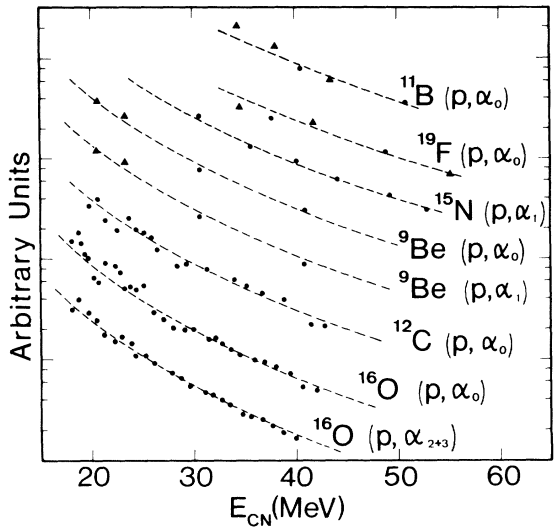

FIG. 10. Mean energy dependence of (p,α) cross sections as a function of compound-system excitation energy. All dashed curves correspond to $E_{CN}^{-3.75}$.

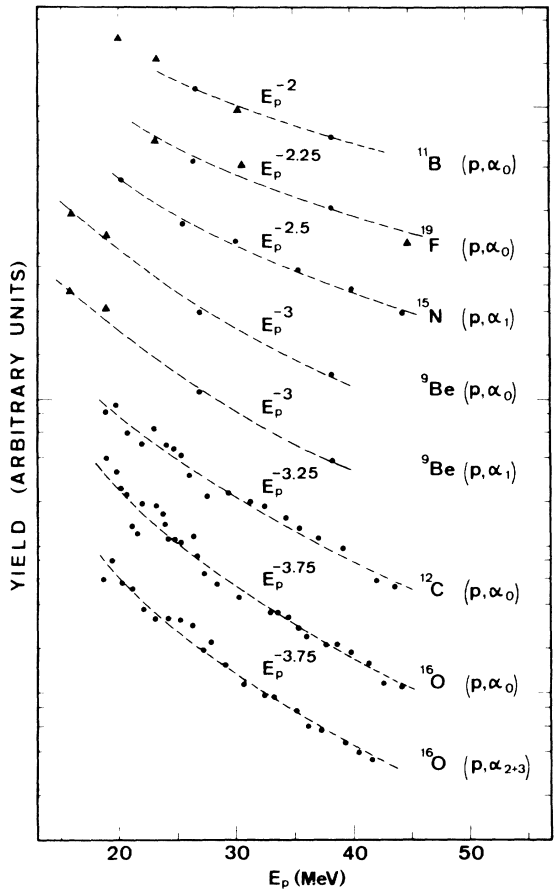

FIG. 9. Mean energy dependence of (p,α) cross sections against incident proton energy. Experimental data are fitted with exponential curves.

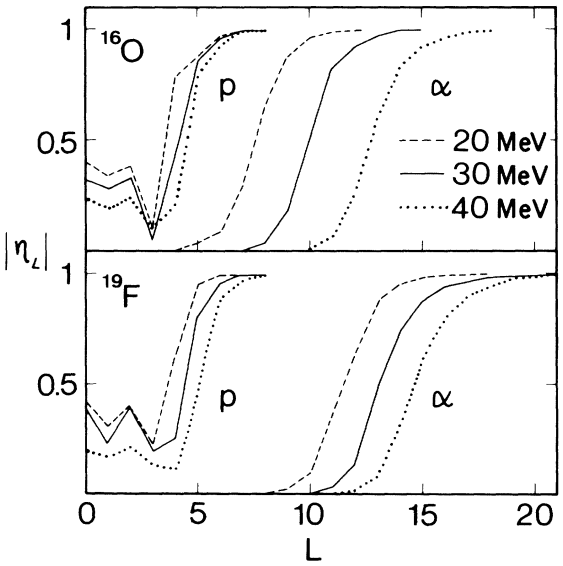

FIG. 11. Proton and α-absorbtion coefficients $|\eta_L|$ for the $^{16}O(p,\alpha)^{13}N_{g.s.}$ and the $^{19}F(p,\alpha)^{16}O_{g.s.}$ reactions at three incident proton energies.

tical parameters within acceptable limits, the energy dependence can be varied between E and E^{-3}. However, provided general rules are used, such as $V_\alpha = V_p + V_t$ for the α real well depth,[15] and mean proton optical potentials such as those given by Watson[14] and Perey[17] are used, independent of the particular choice of the parameters, the incident-energy dependence of the cross sections is practically the same for all the nuclei studied, in disagreement with the experimental data shown in Fig. 9.

Given the uncertainties in the above calculations, performed with the simplest form of the DWBA, it seems premature at this point to investigate the effect of varying the proton-triton residual interaction or to consider other less-simple direct mechanisms, such as a two-step process, which can give steeper energy dependences as shown by Dupont and Chabre[18] for a $(d, {}^3\mathrm{He})$ reaction.

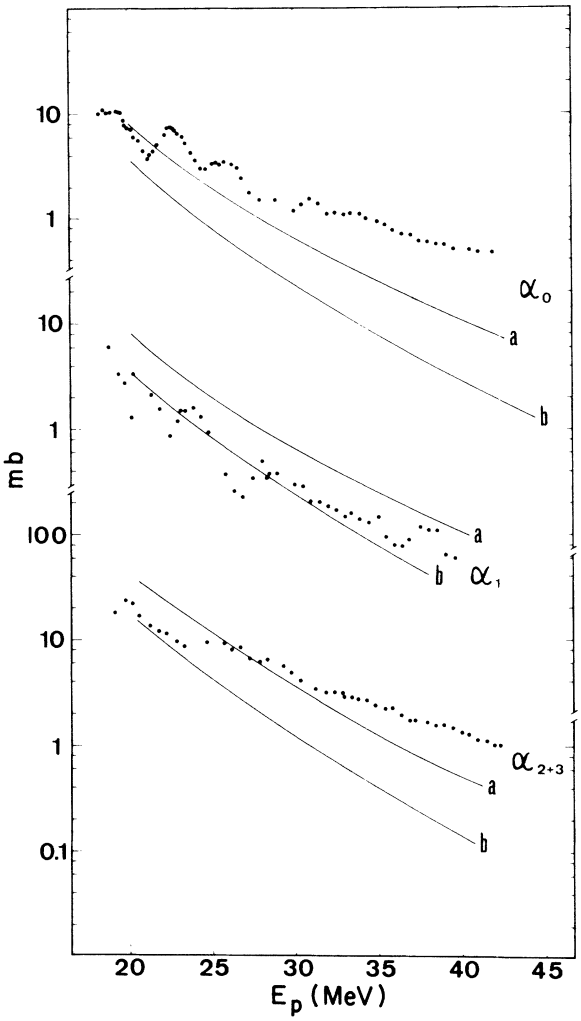

FIG. 12. Theoretical curves plotted as obtained (i.e., not normalized) from a Hartree-Fock calculation of the mean energy dependence of the integral excitation function for the reaction $^{16}\mathrm{O}(p,\alpha)^{13}\mathrm{N}$ corresponding to two choices of level-density parameters. The data are the same as in Fig. 8; in curve "b" the prescription of Ref. 21 with $a = 0.126A$ was used, and in curve "a" the level density as obtained directly from the residual-nuclei level scheme, corresponding to about $a = 1.6$, was used.

B. Compound-Nucleus Analysis

The apparent inadequacy of a simple direct-interaction analysis, as described by the DWBA, suggests an attempt to make an interpretation by other mechanisms. We discuss here the Hauser-Feshbach calculations performed for the (p, α) reaction on $^{16}\mathrm{O}$. Similar conclusions are also reached, with the reservation which one has to make for such light nuclei, for the other nuclei studied. We consider only proton, neutron, deuteron, and α outgoing channels; contributions from other channels are negligible. Penetrabilities have been calculated using the optical-model potentials of Refs. 2, 14, 19, and 20.

Level-density parameters, and in particular those for the dominating proton channel, are very critical. Few data, and only at low excitation energies, are available on light-nuclei level densities. Possible means of obtaining the level-density parameter a, leading to different cross-section values, are to use the prescription of Gadioli and Iori[21] with $a = 0.126A$ or to evaluate it directly from experimental level schemes. Pairing energy is another important parameter which can have a significant effect on the cross section at high proton energies and on which scarce data[22] are available for light nuclei; values extrapolated for $A \leq 20$ have been used in the present calculation.

Results for two choices of the parameter a are given in Fig. 12. Calculations for the α_0 and α_{2+3} groups give a steeper slope and a smaller cross section than the experiment. The lower curve calculated using the prescription of Ref. 21 is, in the low-energy region, slightly higher than the experimental α_1 excitation function and therefore overestimates the correct value also in the limit hypothesis that this transition is mainly due to a statistical mechanism. The statistical contribution to the other two transitions is therefore appreciable only at the lower energies. Statistical contributions seem then to be significant only in transitions for which direct mechanisms are forbidden or strongly hindered, as in the case of the α_1 group.

C. Pre-Compound Decay

The energy dependence of all the reactions considered is, as reported above, of the type $\sigma \propto [(E_p)_{\mathrm{c.m.}} + B_p]^{-3.75}$, and is steeper than that usually obtained for a direct-reaction mechanism such

as pickup or knockout, is less steep than that due to a statistical process, and may indicate the decay of a system with an intermediate number of degrees of freedom.

An intermediate mechanism is outlined in the pre-compound model of Griffin.[23] The applicability of Griffin's model to these problems is being explored also by Gadioli.[24] In this model it is assumed that the incident nucleon initially shares its energy between a small number of particles and holes (excitons), forming an intermediate system. The system then evolves, via two-body-type interactions with $\Delta n = 0, \pm 2$, towards a statistical equilibrium configuration centered about a most probable exciton number $n = \bar{n}$. Decays with nucleon emission can occur at each stage. This pre-compound decay probability is calculated in the model from phase-space considerations. The level density of n-exciton states at excitation energy E^* is given by[23]

$$\rho(E^*) = \frac{g(gE^*)^{n-I}}{n!\,(n-I)!},$$

where particles and holes are assumed indistinguishable and g is the average single-particle level density. Since $\rho_n(E^*)$ is a very rapidly increasing function of n, the assumption is made that for $n < \bar{n}$, transitions with $\Delta n = +2$ are more probable.

The pre-compound decay probability with emission of a nucleon with channel energy between ϵ and $\epsilon + d\epsilon$ from an n-exciton state is given by

$$P_n(\epsilon)d\epsilon = \frac{2s+1}{\pi^2\hbar^3}\mu\epsilon\sigma(\epsilon)\frac{\rho_{n-1}(U)}{\rho_n(E^*)}\tau_n d\epsilon\,, \qquad (1)$$

where s and μ are the spin and reduced mass of the emitted particle, $\sigma(\epsilon)$ is the inverse cross section, $\rho_{n-1}(U)$ is the density of states of the residual nucleus at excitation energy $U = E^* - B - \Delta - \epsilon$, B is the binding energy of the emitted particle, Δ is the pairing energy of the residual nucleus, $\rho_n(E^*)$ is the density of n-exciton states of the intermediate system at excitation energy E^*, and τ_n is the mean lifetime of an n-exciton state and is assumed constant.[25] The total pre-compound decay probability is

$$P(\epsilon)d\epsilon = \sum_{\substack{n \geq n_i \\ \Delta n = 2}}^{\bar{n}} P_n(\epsilon)d\epsilon\,,$$

where the sum is extended from an initial value n_i to $\bar{n}$.

With n increasing, the excitation energy is shared among a larger number of excitons, and the probability that a particle has enough energy to be emitted in the continuum decreases exponentially. The system then decays in the very first stages or progresses towards the equilibrium configuration.

Assuming that a part of the interacting proton flux causes the pre-compound decay, the (p, α) cross section to a given final state is proportional to the product probability of formation of the intermediate system through the entrance channel and of decay through the considered exit channel, and its energy dependence is given by the following expression:

$$\sigma_{p\alpha} \propto \frac{\sigma_p \sigma_\alpha^{\text{inv}}}{\sum_\nu \sum_{n \geq n_i} \int_0^{\epsilon_\nu^{\max}} \rho_{n-1}^\nu(U)\epsilon_\nu \sigma_\nu(\epsilon_\nu)d\epsilon_\nu}\,, \qquad (2)$$

where ν labels the different open decay channels for the n-exciton states with $n_i \leq n \leq \bar{n}$, and ϵ_ν is the energy of the emitted nucleon. For the nuclei considered, $\bar{n}$ is of the order of a few units (from 4 to 9 depending on mass and excitation energy); at high excitation, n_i is also introduced as a parameter.

When the system decays, in the very first stages the slope of the excitation function is less steep than that given by a statistical mechanism which is approximately obtained when the system decays predominantly from the n-exciton equilibrium state. The energy dependence of the (p, α) average cross sections was calculated using Eq. (2) and taking into account only neutron and proton decay channels. Contributions to pre-compound decay by composite-particle emission involve, if correlations are ignored, higher-n states which are not reached in the above hypothesis of emission from very early stages of the process.[25] We have assumed σ_p and $\sigma_\alpha^{\text{inv}}$ to be constant with the energy; an assumption that is justified in the energy range we have analyzed, which is well above the Coulomb barrier; for $\sigma_\nu(\epsilon)$, optical-model reaction cross sections have been taken.[26]

Experimental energy dependences were fitted considering n as a parameter; as shown in Fig. 13, good results are obtained with only the $n = 3$ term on even targets (^{12}C and ^{16}O) and with only $n = 2$ on odd targets (^{11}B, ^{15}N, and ^{19}F) except for ^{9}Be which requires $n = 3$. These results indicate that decay from a very early intermediate stage characterizes the slope of the excitation functions. The higher exciton number required by ^{9}Be can be explained by the failure of such a procedure in a very light nucleus. The theory should in fact only be applied in regions of mass and excitation energy for which $\bar{n} \gg 1$. The same pre-compound model could be also applied to other reactions on the same nuclei.

The most complete set of data concerns reactions on ^{16}O. In Fig. 14 some of the known excitation functions for proton inelastic scattering[27,28] and the (p, d) reaction[29] are reported. The energy

dependence of proton elastic and inelastic cross sections integrated over all the angular range is the same as that of the $^{16}O(p,d)^{15}O$ excitation function, as shown only for the p_2 transition to the 6.13-MeV ($J^\pi = 3^-$) level in ^{16}O. This one has a slope $\sigma \propto E_p^{-1}$, as usually expected for a direct effect. The energy dependence for the p_5 transition to the non-natural-parity state 2^- at 8.88 MeV, which is allowed only by spin flip, is steeper and is of the type $\sigma \propto E_p^{-3}$. The energy dependence for this transition may be explained, as was done by Austin *et al.*,[27] by considering some possible features of the spin-dependent part of the effective two-nucleon interaction. Otherwise one can call for a multistage process, such as pre-compound decay from the very first steps, which may be important also in inelastic scattering when selection rules hinder direct effects.

For elastic scattering, as shown by Karban *et al.*,[30] and for inelastic transitions, as shown by some of us,[31] resonating processes leading to marked modulations give a sizable yield at backward angles. These modulations are probably due to intermediate resonances as discussed in Sec. V and in the work of Guazzoni *et al.*[32] The mean slope of the backward-angle excitation functions is steeper than the slope of the integrated cross sections as shown in Fig. 14 for the p_2 transition. These facts might suggest the presence of a multistage process relatively important at backward angles.

It is, however, very difficult to discriminate between such effects and optical effects. In fact it is well known that by increasing the incident energy, the diffraction pattern of differential cross section changes, causing a decrease of the backward-angle cross sections. It has been shown by Karban *et al.*[30] that the mean energy dependence of the elastic cross section at backward angles (equal to that of the p_2 transition) can be fitted by optical-model elastic scattering calculations. The intermediate mechanism, which seems to be responsible for the resonances in $^{16}O(p,p')$, could be important in determining the mean energy dependence of forbidden transitions, but scarcely affects the integrated cross sections for allowed transitions.

The pre-compound yield in (p,p') reactions, if not quantitatively important for the reaction itself, may contribute, owing to the different order of

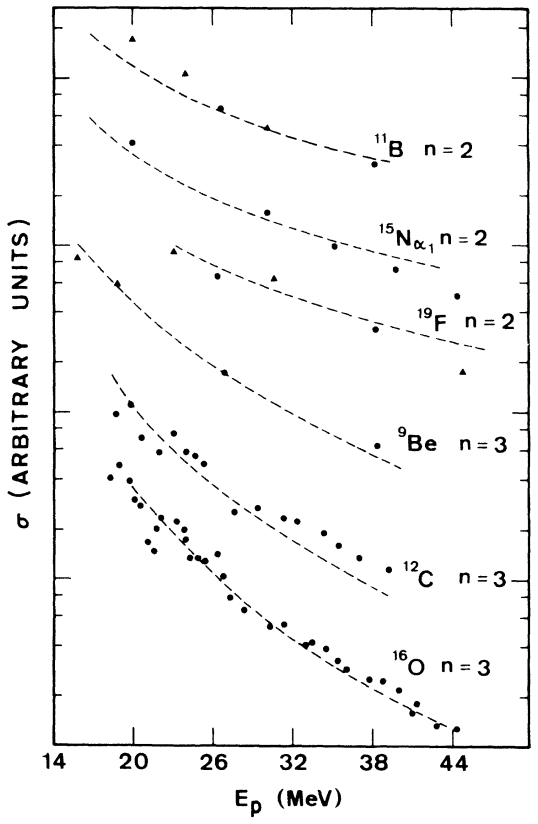

FIG. 13. Experimental energy dependence of (p,α) reactions compared with the results (dashed curves) of pre-compound calculations (see text for details). All data, except those for nitrogen 15, refer to ground-state transitions.

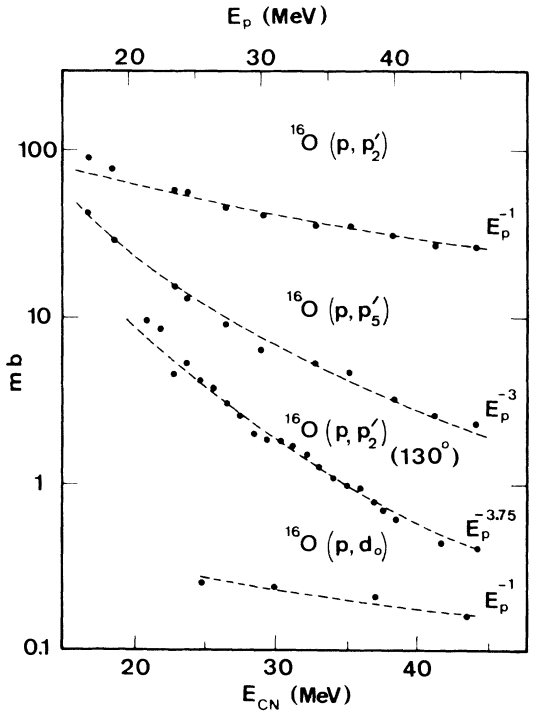

FIG. 14 Mean energy dependence of proton-induced reactions on oxygen 16. Proton inelastic data are from Refs. 27, 28 and (p,d) data from Ref. 29. The 130° excitation function is plotted out of scale.

magnitude of the (p,p') and (p,α) cross sections, to the depletion of the exciton states which seem to determine the mean energy dependence of (p,α) reactions. The good over-all agreement obtained for (p,α) reactions with the Griffin model is, in our opinion, more an indication that these reactions on light nuclei might require multistage processes than a favorable test of the model in the present form, because of its limits of applicability, which are the same as those of the statistical model, and for other reasons as given in Sec. VI. Moreover, before one-step mechanisms are discarded, less approximate direct-interaction calculations, not yet performed, would be required.

V. STRUCTURES IN THE EXCITATION FUNCTIONS

The resonances found in the excitation functions suggest the presence of a reaction mechanism slower than a direct pickup or knockout. While more data are needed to formulate a hypothesis on the nature of these resonances, a comparison with the available data[32] on other reactions having the same intermediate system as $^{16}O(p,\alpha)^{13}N$, such as $^{16}O(p,p')^{16}O$, $^{14}N(^3He,\alpha)^{13}N$, and $^{14}N(^3He,p)^{16}O$, permits us to exclude the presence of resonances in the compound system, since these should appear in all reactions.

Statistical fluctuations are excluded by the large experimental angular coherence and by the mean energy dependence of the cross sections which is less steep than for a statistical mechanism except for a few transitions as discussed in Sec. IV.

The hypothesis of the presence of intermediate structures can be formulated. As is well known, a virtual state of the incident nucleon in a single-particle well can progress, via a residual interaction, towards more complex 2p-1h, 3p-2h, etc., states which originate intermediate resonances. Effects due to this mechanism, which is characteristic of the incoming channel, should lead to similar behavior in reactions having the same entrance channel.

Within the precision of the experiment, there is a correspondence between different outgoing channels in the reaction $^{16}O(p,p')^{16}O$ [30]; this correspondence indicates that intermediate states could be involved in the elastic and inelastic scattering. No correspondence, however, is found between the reactions $^{16}O(p,p')^{16}O$ and $^{16}O(p,\alpha)^{14}N$, while the excitation function for the last reaction shows a remarkable correspondence to that for the reaction $^{14}N(^3He,\alpha)^{13}N$; this suggests, as discussed in Ref. 32, the presence of resonances in the outgoing α channel. These resonances seem intimately connected to the presence of an α particle, since no evident correspondence is found for other reactions having the same outgoing channel as $^{16}O(p,p')^{16}O$ and $^{14}N(^3He,p)^{16}O$.

VI. CONCLUSIONS

From the analysis of the experimental results and, in particular, of the mean energy dependence of the cross sections, even if more data were desirable, a hypothesis on the mechanism of the (p,α) reaction on light nuclei can be formulated.

As discussed in Sec. IV, the data cannot be explained in the framework of the direct-interaction formalism with the usual approximations, or in the framework of the statistical model. A possible way of explaining the mean slope of the (p,α) excitation functions and the fact that this becomes the same for different nuclei when plotted against intermediate-system excitation energy can be based on a multistage process such as the decay from few-exciton states. The same process also seems to determine the energy dependence of other reactions when selection rules hinder direct interaction, as discussed in Sec. IV for the transition to the non-natural-parity state 2^- in the $^{16}O(p,p')^{16}O$ reaction.

However, the proposed model cannot easily account for other features of the data, at least in the present form. The most noticeable of these features are: the resonances discussed in Sec. V, characteristic of the outgoing α channel; the diffraction pattern of the α angular distributions persisting also where resonances in the excitation functions are present; and the existence of selection rules acting, at least approximately, as in a direct process. This last effect has been discussed in Sec. IV in connection with the α_1 and α_4 transitions in the reaction on oxygen 16, which are hindered by the shell-model predictions. In these cases the mean energy dependence of the (p,α) cross section has a different slope, showing compound-nucleus contributions.

It should, on the other hand, be noted that precompound intermediate calculations take into account only phase-space considerations in the various decay channels and do not take into account correlation effects or nuclear-structure properties which may play an important role in α emission.

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Spin-Flip Probability for Inelastic Proton Scattering from Carbon and Sulfur*

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The spin-flip probability for scattering protons inelastically to produce the first excited 2^+ states in ^{12}C and ^{32}S has been measured at proton energies of 15.9 and 17.5 MeV using the de-excitation γ rays emitted perpendicular to the scattering plane. The carbon results agree with previous measurements in the same proton energy region. The measured inelastic spin-flip probability on sulfur is higher than that reported for any other nucleus, exceeding a peak value of 0.5. A collective distorted-wave Born-approximation analysis employing the full Thomas spin-orbit interaction was carried out. Poor fits are obtained for the spin-flip-probability data when the depth and range of the spin-orbit optical potential are determined from elastic polarization data.

I. INTRODUCTION

The spin-dependent contributions in the inelastic scattering of nucleons are not well understood. The angular distributions of scattered particles are not very sensitive to such terms, although they apparently play some part even in elastic scattering. On the other hand, polarizations, asymmetries, and spin-flip probabilities are all sensitive to spin-dependent forces in various ways.

In an attempt to learn new information about the spin-dependent terms of the optical model, we have performed a measurement of the spin-flip probability in the inelastic scattering of protons