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Some dynamical aspects of pickup reactions studied in $^{13}C(p,d)^{12}C$ at 200–500 MeV

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Differential cross sections at 22.5° are reported for $^{13}C(p,d)^{12}C$ to the ground state and first excited state which are characterized as $1p_{1/2}{}^{-1}$ and $1p_{3/2}{}^{-1}$ states. These results on the energy variation and previous ones on angular distributions show a prevailing momentum transfer (Q) dependence as has been observed earlier for $^4He(p,d)^3He$. We discuss this apparent scaling of the (p,d) cross section in the variable Q and its implication on the question of the reaction mechanism in comparison with analogous information from other nucleon removal reactions.

[NUCLEAR REACTIONS $^{13}C(p,d)^{12}C$, $T_p = 200-500$ MeV, $\theta_d = 22.5°$; measured $\sigma(T_p)$, discussed momentum transfer dependence and reaction mechanisms.]

I. INTRODUCTION

The pickup reaction $A(p,d)A-1$ is characterized by a large momentum transfer $Q = |\vec{p}_p - \vec{p}_d|$ which at high incident energies can reach high values even for colinear reactions; for instance, the momentum difference $\Delta p = |p_p - p_d|$ reaches values of ~0.5 GeV/c at $T_p = 800$ MeV. Momenta at the order of Δp must be provided by the dynamics of bound nuclear states, but it is not known precisely how these are utilized. Certain reaction mechanisms[1-3] have been proposed in order to formulate the questions pertinent to the dynamics of large Q and high incident energies and to provide interpretations to some particular reaction features observed. Other efforts have gone into using the DWBA approach[4] which has a proven record of success at lower energies. There are presently problems connected with quantitative evaluations of the various reaction mechanisms, and we are far from a comprehensive reaction theory, which is a problem pertinent to the (p,d) reaction as well as to other analogous reactions such as (π, N), (γ, p), etc. Common to these reactions is that a single nucleon is removed from the target nucleus at large momentum transfer. A comparison of these reactions is therefore motivated to learn about the basic reaction mechanisms involved and their dependence on the interaction and kinematics characteristics of the incident and exit reaction channels; the rest mass of the projectile/ejectile is one interesting parameter in such a comparison as is the difference between the electromagnetic and hadronic forces with consequences for the initial and final state interactions. Information on the energy dependence of these reactions is crucial for unraveling the reaction mechanism, but such data are very scarce for (p,d) at higher energies. One study[1] was recently done for a very light nucleus, ^4He, and here we present results for $^{13}C(p,d)^{12}C$. Besides the question of the reaction mechanism, we examine these results on the (p,d) reaction with respect to the much discussed topic of scaling variables for nuclear reactions at large momentum transfer such as for[5,6] inclusive proton back scattering $A(p,p')X$. A good scaling variable will provide a "universal" representation of the data, and the interesting question is to what extent this can be used as an inference criterion for the prevailing reaction mechanism.

II. EXPERIMENT AND RESULTS

This study of the reaction $^{13}C(p,d)^{12}C$ was done with the new 1.5-GeV/c magnetic spectrometer using the variable energy proton beam of the TRIUMF cyclotron. The energy of the incident protons was varied in steps of 50 MeV between 200 and 500 MeV, and the particles emitted from the target were detected in the spectrometer at the fixed angle of 22.5° (see Ref. 1 for more information and references). The relative beam intensity was measured with an ion chamber downstream from the target, which was calibrated at a few energies by measuring the $p+p$ scattering yield from a CH_2 target and normalizing to the known $p+p$ cross section.[7]

The ground state and the first excited state of

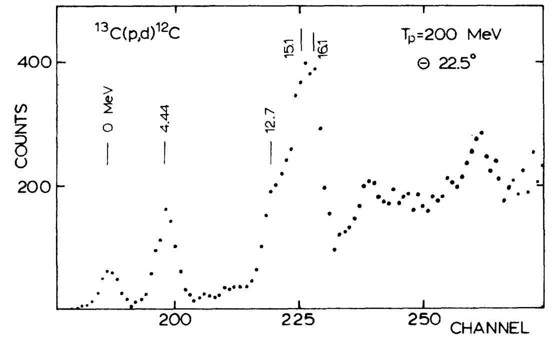

FIG. 1. Spectrum for the reaction $^{13}C(p,d)$ at $T_p = 200$ MeV and $\theta = 22.5°$; known states in ^{12}C contributing to the prominent peaks have been marked.

^{12}C were clearly separated in the recorded $^{13}C(p, d)$ spectra, an example of which is shown in Fig. 1. The excitation of known $1p_{1/2}^{-1}$ and $1p_{3/2}^{-1}$ states dominate the spectrum up to $E_x = 17$ MeV. Two broad peaks appear at $E_x \approx 20.3$ and 28.7 MeV. Since they seem to appear at larger angles only (they were not seen[8] at $E_p = 185$ MeV and $\theta = 2.5°$), we suspect that two-step processes[9] might be responsible for these excitations.

Results on the differential cross sections for the first two states in ^{12}C are shown in Fig. 2. In addition to the statistical uncertainties shown in this figure, there is an overall uncertainty of ±15% in the absolute cross section scale. Figure 3 shows the results for the 4.4-MeV state of ^{12}C plotted versus the momentum transfer $Q = |\vec{p}_p - \vec{p}_d|$ in the laboratory frame. For comparison we show angular distributions plotted versus Q using $^{12}C(p, d)^{11}C$ data available at $T_p = 100$, 185, and 700 MeV[10-12]; the ^{11}C and ^{12}C final states populated in these reactions are of the same single particle character, namely $1p_{3/2}^{-1}$.

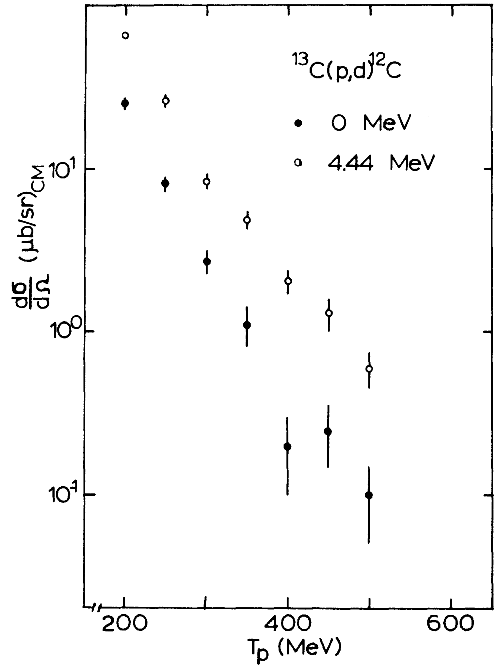

FIG. 2. The differential cross section at $\theta = 22.5°$ for $^{13}C(p,d)^{12}C$ to the ground state and first excited state in ^{12}C as a function of the laboratory bombarding energy.

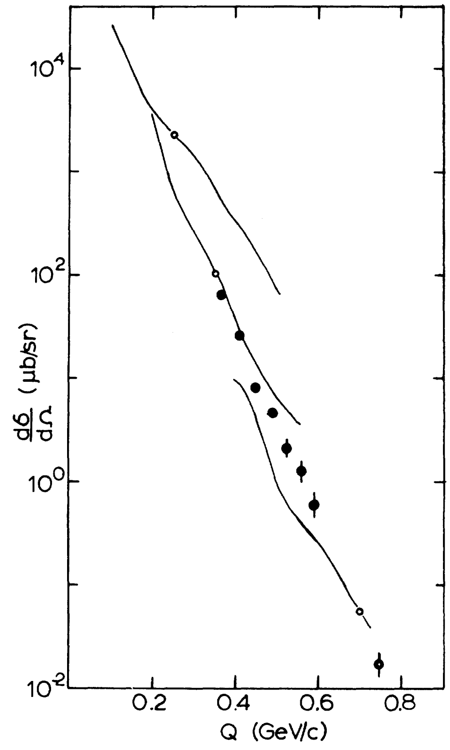

FIG. 3. The differential cross section at $\theta = 22.5°$ for $^{13}C(p,d)^{12}C$ to the 4.44-MeV state of ^{12}C (large black dots) plotted versus the momentum transfer Q. The point at $Q = 757$ MeV/c is taken from the data (Ref. 13) at 800 MeV. The solid lines represent the experimental angular distributions (Refs. 10–12) for $^{12}C(p,d)^{11}C$ at 100, 185, and 700 MeV with the open circles marking the point $\theta = 22.5°$.

III. DISCUSSION

Characteristic of the measured $^{13}C(p, d)^{12}C$ cross section is the rapid falloff with momentum transfer (Fig. 3) with an average slope of $Q_0 \approx 47$ MeV/c in the parametrization $d\sigma/d\Omega = C \exp(-Q/Q_0)$. There is little difference between the excitation of the two final states in this respect (Fig. 2) which is a nontrivial result since the ground state and first excited states of ^{12}C are different in character; i.e., $1p_{1/2}^{-1}$ and $1p_{3/2}^{-1}$ neutron hole states based on the ^{13}C ground state. There is a difference in cross section magnitude, but the ratio remains mainly constant with increasing energy or momentum transfer which persists up to an incident energy of 800 MeV.[13] This can be compared to the situation for the $1p_{1/2}{}^{-1}$ and $1p_{3/2}{}^{-1}$ states in ^{15}O at 0 and 6.2 MeV which have been seen in ^{16}O$(\pi^+, p)^{15}$O at 66 MeV[14] but with a surprisingly large ratio of about 1 : 10, i.e., five times larger than the expected ratio of about 1 : 2 which is seen in ^{16}O$(p, d)^{15}$O for $T_p < 200$ MeV.[14,15] In this experiment we checked this ratio at $T_p = 400$ MeV and $\theta = 22.5°$ and found it to be 1 : 2.2. The momentum transfer of this (p, d) reaction is 520 MeV/c as compared to $Q = 500$–700 MeV/c for the angular range $\theta = 20°$–$120°$ in (π^+, p). However, with respect to the parameter Δp the value for (p, d) is substantially smaller ($\Delta p = |p_p - p_d| \approx 310$ MeV/c) than for (π, p) ($\Delta p \approx 460$ MeV/c). The value of this parameter may be crucial for how the nuclear dynamics is utilized, while a directional change of momentum can always be obtained through on-shell multiple scattering. It is quite obvious that information on the energy dependence is needed for evaluating the spectroscopic implications of (p, d) data where any detailed conclusions must rest on a firm knowledge of the reaction mechanism.

To continue the discussion of the gross features of the (p, d) cross section, we note that the exponential falloff with Q is very much the same ($Q_0 \approx 47$ MeV/c) for the $1p_{1/2}{}^{-1}$ and $1p_{3/2}{}^{-1}$ states populated in ^{13}C$(p, d)^{12}$C as for the $1s_{1/2}{}^{-1}$ state of the previously studied[1] reaction ^{4}He$(p, d)^3$He. It seems to indicate that the slope function is not very sensitive to the kind of final state populated or the mass of the target nucleus, at least for light nuclei.

In the study of ^{4}He$(p, d)^3$He it was observed that the cross sections $d\sigma/d\Omega(T_p, \theta)$ (angular distributions at different incident energies) are very close to a function of the single variable Q. This is approximately true also for (p, d) in carbon, as demonstrated by the excitation function of ^{13}C$(p, d)^{12}$C to the 4.4-MeV state and the ^{12}C$(p, d)^{11}$C angular distributions at 100, 185, and 700 MeV (cf. Ref. 9). These (p, d) cross sections show largely a simple Q dependence with some excursions from the general trend for the larger angles at the lowest incident energy. The low energy angular distributions can be fairly well reproduced by DWBA calculations,[10,11] which show that the angular dependence, i.e., the dependence on the transverse component of momentum transfer $Q_\perp$, is in part determined by multiple scattering. These effects are quite weak for (p, d) in helium as compared to carbon as evidenced by only small excursions of the ^{4}He$(p, d)^3$He cross section from the average Q dependence.

The formal motivation for introducing the variable Q rests on the assumption of a simple pickup reaction mechanism for $A(p, d)A - 1$, where $Q = |\vec{p}_p - \vec{p}_d|$, the momentum with which the residual nucleus recoils in the laboratory frame. This is pictorially shown in the reaction diagram [Fig. 4(a)] with the $A(p, d)A - 1$ cross section given by (see Ref. 1)

$$\frac{d\sigma}{d\Omega} \propto \frac{E_p E_A E_d E_R}{s} \frac{|\vec{p}_d|}{|\vec{p}_p|} (u - m_p{}^2)^2 |\psi_1(q_1)|^2 |\psi(Q)|^2$$
$$= F\,|\psi(Q)|^2 \,.$$

The variables in the nuclear wave functions ψ_1 and ψ are the relative one-body momenta q_1 and Q, while s and u are the invariant Mandelstam variables for total energy and momentum transfer $u = (p - d)^2$. The scaling factor F is nearly constant for $Q \gtrsim 200$ MeV/c, i.e., $d\sigma/d\Omega$ is roughly a function of Q only.

The recent interest in the scaling behavior of nuclear reactions has arisen from the many new results[5,6] on inclusive proton back scattering, $A(p, p')X$. These cross sections show an impressive universality when expressed as a function of a scaling variable, the minimum momentum of the recoiling system, which relates to the momentum of the struck nucleon. The scattering is assumed to take place from a single nucleon. The cross section shows a general exponential falloff as a function of this variable with a slope parameter somewhat larger than we find for (p, d), namely $Q_0 \approx 70$ MeV/c. It is still possible that there is a basic connection between the utilization of the nuclear dynamics for achieving the large momentum transfer in the two reactions and that the slope parameter reflects final state differences. The reaction $A(p, d)A - 1$ leads to a discrete final state as compared to the nondiscrete final states of $A(p, p')X$, where the only constraint on X is the minimum mass of the recoiling system required by energy and momentum conservation. One could argue that the larger Q_0 values observed for the (p, p') reaction stems from few-body nuclear correlations where only the correlated nucleons need to take up recoil which might absorb the momentum transfer more efficiently than if a larger conglomerate of nucleons have to recoil coherently. At the elastic limit, however, the condition should

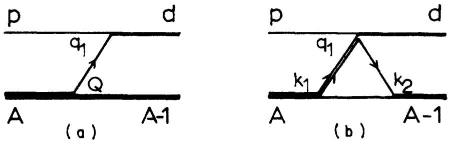

FIG. 4. Reaction mechanisms for the $A(p,d)A - 1$ reaction discussed in the text; (a) the neutron pickup and (b) the d-p triangle diagram.

be the same for (p,p) and (p,d), and some (p,p) data tend to indicate[7] that Q_0 decreases with the proximity to the elastic limit; for lower energies where the nucleon pickup mechanism dominates both reactions this is trivially true.[2]

From the observation that the (p,d) cross section appears as a nearly universal function of Q, one might be tempted to infer that a simple neutron pickup is the prevailing reaction mechanism and that the Q dependence represents the single particle momentum distribution in the nucleus. It is in the latter inference one runs into problems since the single particle wave functions, as we know them for ^{4}He at least, are difficult to reconcile with the cross section slope functions observed,[1] and the problems cannot be discarded as trivial multiple scattering distortion effects as they are taken into account by standard DWBA calculations.[4] The pickup mechanism may be a good motivation for introducing the Q parametrization of the (p,d) cross section, but it may not be the true reason for the "universal" Q dependence.

A two-nucleon reaction mechanism[1,2] such as the p-d triangle diagram [Fig. 4(b)] would also give a prevailing Q dependence since each vertex is a function of Q. There is, of course, an energy dependence inherent in the $pd \rightarrow dp$ vertex (mainly due to the onset of pion exchange for $T_p \gtrsim 300$ MeV),[1,2,16] but this is quite weak compared to the variation in Q for varying T_p. The energy dependence would thus be very much washed out in this two-nucleon interaction, and the same would be true for analogous multinucleon interactions. The (γ,p) reaction is similar to (p,d). Data on ^{16}O-$(\gamma,p)^{15}$N are very nicely presented as a function of Q when the cross section is factorized according to the one-nucleon interaction model, i.e., the equivalent of diagram 4(a).[17] There are reasons, however, to consider two-nucleon interactions of the type in Fig. 4(b), and such calculations[18] can reproduce the data but give another meaning to the Q dependence. A different situation is met for the (π,N) reaction where the forward angle cross sections indeed show a prevailing Q dependence but with an energy dependent scale factor which follows the resonance behavior of the $\pi+N$ scattering.[1,19] In this case it is clear that the basic reaction mechanism involves pion interaction with at least two nucleons and that the Q dependence does not represent the nuclear single particle momentum distribution.

IV. CONCLUSIONS

We have presented new results on the energy variation of the (p,d) reaction in ^{13}C. It was found that this cross section depends strongly on Q. There is little or no direct energy dependence, but comparison with previous ^{4}He$(p,d)^3$He indicates increasing multiple scattering (affecting $Q_\perp$) with increasing A. Our results show no basic difference in the Q dependence of the cross section for exciting $1p_{1/2}{}^{-1}$ and $1p_{3/2}{}^{-1}$ states, which appears to contradict the results of previous ^{16}O$(\pi,p)^{15}$O measurements at the same Q values. Before drawing conclusions on possible dynamical differences between nuclear states described as simple $1p_{1/2}$ and $1p_{3/2}$ wave functions, one must await corroborative results from analogous reactions such as (p,d), (π,p), (γ,p), etc. at the same Δp values. The meaning of Q in terms of nuclear momenta is still an open question, and we argue that the fact that Q is a good scaling variable for (p,d) and other reactions does not necessarily imply that the reaction mechanism used to define Q is the prevailing one.

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[1] J. Källne *et al.* Phys. Rev. Lett. 41, 1638 (1978).

[2] J. Källne and P. C. Gugelot, Phys. Rev. C 20, 1085 (1979).

[3] C. Wilkin, J. Phys. G (to be published).

[4] E. Rost, J. R. Shepard, and D. A. Sparrow, Phys. Rev. C 17, 1513 (1978).

[5] R. M. Woloshyn, in the *Proceedings of the International Conference on Clustering Aspects of Nuclear Structure and Nuclear Reactions*, edited by W. T. H. van Oers, J. P. Svenne, J. S. C. McKee, and W. R. Falk (American Institute of Physics, New York, 1978), p. 457.

[6] S. Frankel, W. Frati, R. M. Woloshyn, and D. Yang, Phys. Rev. C 18, 1379 (1978).

[7] R. A. Arndt, R. H. Hackman, and L. D. Roper, Phys. Rev. C 9, 555 (1978).

[8] L. J. Parish *et al.*, Phys. Rev. C 9, 876 (1974); and J. Källne (unpublished).

[9] J. Källne and A. W. Obst, Phys. Rev. C 15, 477 (1977).

[10] T. K. P. Lee, S. K. Mark, P. M. Portner, and R. B. Moore, Nucl. Phys. A106, 357 (1968).

[11] J. Källne and E. Hagberg, Phys. Scr. 4, 151 (1971).

[12] S. D. Baker *et al.*, Phys. Lett. 52B, 57 (1974).

[13] R. Boudrie *et al.*, in abstracts of contributed papers to the 8th International Conference on High Energy Physics and Nuclear Structure, Vancouver, Canada, 1979; and G. R. Smith (private communication).

[14] D. Bachelier *et al.*, Phys. Rev. C 15, 2139 (1977).

[15] J. Källne, The Gustaf Werner Institute Report No. GWI-PH 2/74 (unpublished).

[16] A. N. Anderson *et al.*, Phys. Rev. Lett. 40, 1553 (1978).

[17] D. J. S. Findlay *et al.*, Phys. Lett. 74B, 305 (1978).

[18] B. Schoch, Phys. Rev. Lett. 41, 80 (1978).

[19] J. Kallne *et al.*, Phys. Rev. Lett. 40, 378 (1978).