Nuclear Excitation Functions: Ar^{40}, $Zn^{68}(d,He^3)$†

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The (d,He^3) reaction has been studied by radiochemical techniques. Absolute excitation functions have been determined to 15 MeV for the reactions $Ar^{40}(d,He^3)Cl^{39}$ and $Zn^{68}(d,He^3)Cu^{67}$. The $Ar^{40}(d,He^3)Cl^{39}$ cross section is 0.37 ± 0.07 mb at 14.8 MeV and the $Zn^{68}(d,He^3)Cu^{67}$ cross section is 0.54 ± 0.08 mb at 15.4 MeV. These cross sections are shown to be more than an order of magnitude greater than predicted by the statistical model of nuclear reactions. The energy dependence of the cross section appears to be governed by the Coulomb barrier felt by the outgoing He^3 particle, at least when the He^3 energy is less than the classical barrier height. The shape of the observed excitation functions may be reproduced moderately accurately by a very simple proton pickup model.

THERE are very few data available on reactions involving emission of He^3 particles except for targets lighter than carbon[1] or for high-energy reactions.[2,3] The reaction $Ce^{142}(\alpha,He^3)Ce^{143}$ has been observed[4] and a number of (α,He^3) reactions on targets in the first transition series has been studied.[5] The results indicated that the (α,He^3) reaction takes place primarily by a direct process, probably stripping. The $Ga^{71}(p,He^3)Zn^{69}$ cross section has been measured at 22 MeV, and the results were in order-of-magnitude agreement with the statistical model of nuclear reactions.[6]

The (d,He^3) reaction has been observed at 21.6 MeV on several targets near $Z=28$.[7] The spectra and angular distributions of the He^3 particles emitted were interpreted in terms of the Butler theory. There are no other data on (d,He^3) reactions, other than for the very light nuclei.[1]

Qualitatively, the (d,He^3) reaction should be similar to the analogous (d,t) reaction, except for the much larger Coulomb effects. The (d,t) reaction has received considerable study, especially as a tool in nuclear spectroscopy,[8,9] and it has been shown to proceed primarily by direct mechanisms, probably neutron pickup.[10,11]

This paper describes a radiochemical determination of the excitation functions of the reactions $Ar^{40}(d,He^3)Cl^{39}$ and $Zn^{68}(d,He^3)Cu^{67}$. The results are compared with the predictions of the statistical model of nuclear reactions and also are discussed in terms of a pickup mechanism. During these experiments, information on several other reactions was obtained, and these results will be discussed in the following paper.[12]

EXPERIMENTAL

Argon Bombardments

The argon was bombarded in a cylindrical brass chamber which the beam entered on the axis through a thin aluminum window. The chamber was lined with 1.8 mg/cm² aluminum foil. Over 90% of the chlorine activity settled on this liner and could be recovered by removing the liner after bombardment and processing chemically.

The deuteron energy was varied by placing the appropriate thickness of iron degrading foils immediately in front of the aluminum window. The energy was calculated for each bombardment from a knowledge of the range-energy relationship[13] and the undegraded beam energy (15.5 ± 0.1 MeV).[11] The deuteron beam lost about 0.3 MeV traversing the argon target. No bombardments were carried out at energies less than 10 MeV, since the (d,He^3) reaction was undetectable at this energy.

The integrated deuteron beam was determined by placing a weighed 0.25-mil copper foil in front of the degrading foils and measuring the 12.8-h Cu^{64} induced by the reaction $Cu^{63}(d,p)Cu^{64}$. The geometry was such that all deuterons passing through the copper monitor entered the argon chamber. The monitor was standard-

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[1] N. Jarmie and J. D. Seagrave, Los Alamos Scientific Laboratory Report LA-2014, University of California, Los Alamos, New Mexico, 1957 (unpublished); D. B. Smith, Los Alamos Scientific Laboratory Report LA-2424, University of California, Los Alamos, New Mexico, 1960 (unpublished).

[2] L. E. Bailey, thesis, University of California Radiation Laboratory Report UCRL-3334, 1956 (unpublished).

[3] G. R. Martin, S. J. Thompson, G. Wardle, and K. I. Mayne, Phil. Mag. 45, 410 (1959).

[4] B. M. Foreman, Phys. Rev. 122, 1283 (1961).

[5] J. Saudinos, R. Beurtey, P. Catillon, R. Chaminade, M. Crut, H. Faraggi, A. Papineau, and J. Thirion, Compt. Rend. 252, 3776 (1961).

[6] G. H. McCormick, H. G. Blosser, B. L. Cohen, and E. Newman, J. Inorg. Nucl. Chem. 2, 269 (1956).

[7] J. L. Yntema, T. H. Braid, B. Zeidman, and H. W. Broek, *Proceedings of the Rutherford Jubilee International Conference, Manchester, 1961*, edited by J. B. Berrks (Heywood and Company Ltd., London, 1961), p. 521.

[8] B. L. Cohen and R. E. Price, Phys. Rev. 121, 1441 (1961).

[9] M. H. Macfarlane and J. B. French, Rev. Mod. Phys. 32, 567 (1960).

[10] J. Gonzalez-Vidal and W. H. Wade, Phys. Rev. 120, 1354 (1960).

[11] L. H. Bowen and J. W. Irvine, Jr., Phys. Rev. 127, 1698 (1962).

[12] D. C. Williams and J. W. Irvine, Jr., following paper [Phys. Rev. 130, 265 (1963)].

[13] R. M. Sternheimer, Phys. Rev. 115, 137 (1959).

ized by bombarding similar copper foils in a Faraday cup with a negatively charged guard ring placed at the cup entrance in order to eliminate secondary electron effects. Total charge collected was measured with a current integrator.[14] Duplicate runs, made at different guard ring potentials, agreed to about 1%.

After bombardment, the aluminum liner was dissolved in NaOH solution and the chlorine activity purified by means of a procedure based upon AgCl precipitations and $Fe(OH)_3$ scavengings. It was found that 80±8% of the chlorine activity produced by the deuteron bombardment was recovered in the final sample.

The chlorine activity consisted of small amounts of 55.5-min Cl^{39} from the $Ar^{40}(d,He^3)Cl^{39}$ reaction and much larger amounts of 37.3-min Cl^{38} from the $Ar^{40}(d,\alpha)Cl^{38}$ reaction. The decay of this mixture was followed on a gamma scintillation counter using a 2 in.×2 in. well-type NaI(Tl) crystal as detector. The associated electronics were such that integral and differential counts could be taken simultaneously. The latter were taken using a single-channel analyzer with the window centered on the 0.246-MeV gamma ray of Cl^{39}. Initial activities were of the order of 5×10^6 dis/sec, and counting was deferred until several hours after bombardment. The Cl^{39}/Cl^{38} ratio increased by a factor of about ten over this period. The Cl^{39} and Cl^{38} counting efficiencies were determined relative to an end-window beta-proportional counter which had been calibrated by counting an Y^{90} preparation standardized by 4π beta counting.

Zinc Bombardment

The stacked-foil technique[15] was used to investigate the reactions of 15.5-MeV deuterons on zinc. Enriched (96.8%) Zn^{68} was employed to study the $Zn^{68}(d,He^3)Cu^{67}$ reaction, and this meant that an economical method of target foil preparation was required. Zinc oxide was ground under CCl_4 in an agate mortar until a fine suspension was formed. This was transferred to a glass chimney clamped over a 1.8-mg/cm² aluminum foil coated with about 0.2 mg/cm² of shellac. The ZnO was permitted to settle on the shellacked surface of the foil. After the supernatant liquid was withdrawn, the foil was heated briefly in an oven, which softens the shellac and binds the ZnO tightly to the aluminum. About 0.025 mg/cm² of Dekadhese plastic cement served as additional binder. The shellac was essential. Without it, the oxide tended to crumble away from the aluminum backing.

The target foils, containing about 5–8 mg/cm² of ZnO, were interleaved with aluminum spacer foils and bombarded with 15.5-MeV deuterons. Deuteron exposure was monitored with copper foils and the monitor standardized as in the argon experiments. Four stacked-foil experiments were carried out, two using ZnO of natural isotopic composition and two using the enriched Zn^{68}. In the latter experiments, the ZnO was only thick enough to degrade the beam to 9–10 MeV, since the (d,He^3) reaction was not observable at lower energies.

The range-energy relationship of Sternheimer[13] was used to calculate the deuteron energy at the position of each foil. Straggling shifted the position of the excitation curves by less than 0.15 MeV except at deuteron energies under 5 MeV.

After bombardment, the foils were dissolved in dilute H_2SO_4 containing Cu^{++} carrier. The copper was precipitated twice as the metal by addition of $NH_4H_2PO_2$ solution and once as CuI by addition of KI solution. This procedure left no detectable contaminant. The procedure used in the first stacked foil experiment, run Cu-I, was inadequate (only $NH_4H_2PO_2$ precipitations were used) and many of the samples isolated were contaminated with long-lived activities. After counting was completed, the chemical yield was measured by iodometric determination[16] of the copper content of each sample.

The copper activity was counted on the scintillation equipment used in the argon experiments. The single-channel analyzer was set for the 0.184-MeV gamma ray of Cu^{67}. The scintillation counter efficiency for Cu^{67} was determined by scintillation-counting and 4π beta-counting equal aliquots of a solution of Cu^{67}. This measurement is subject to a small uncertainty arising from the 9.3-μsec metastable state[17] of Zn^{67}, but the results should be accurate to about 5%.

RESULTS

Argon Bombardments

The $Cl^{38}-Cl^{39}$ decay curves were analyzed by the least-squares method. When the Cl^{39}/Cl^{38} ratio is very small, the results are quite sensitive to the value of the Cl^{38} half-life assumed in the analysis. Bombardments at energies less than 10.5 MeV produced no Cl^{39}, and the Cl^{38} half-life obtained from these experiments, 37.0±0.1 min, was used in analyzing the data from the higher energy bombardments. This value is somewhat less than the literature value, 37.29±0.04 min,[18] probably due to the production of traces of 32.5-min Cl^{34m} by the reaction $Ar^{36}(d,\alpha)Cl^{34,34m}$. The literature value of the Cl^{39} half-life, 55.5±0.2 min,[19] was used in these analyses; a small error in this value is not serious. The effects of these factors were investigated rather carefully and were found to be less than other errors in the cross-

[14] B. W. Shore, N. S. Wall, and J. W. Irvine, Jr., Phys. Rev. 123, 276 (1961).
[15] E. T. Clarke and J. W. Irvine, Jr., Phys. Rev. 66, 231 (1944).
[16] E. H. Swift, *A System of Chemical Analysis* (Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1939).
[17] L. H. Th. Rietjens and H. J. Van den Bold, Physica 21, 701 (1955).
[18] J. W. Cobble and R. W. Atteberry, Phys. Rev. 80, 917 (1950).
[19] R. N. H. Haslam, L. Katz, H. J. Moody, and H. M. Skarsgard, Phys. Rev. 80, 318 (1950).

section measurements for deuteron energies above 12.5 MeV, but at energies under 12 MeV they make the uncertainties in the results quite large.

The Cl^{39} and Cl^{38} half-lives are too similar to permit resolution of the decay curve into components by the usual semilog plot, and thus, the Cl^{39} purity could not be checked by determination of the half-life. The presence of Cl^{39} could be established from the scintillation spectrum in those experiments which gave relatively large amounts of Cl^{39}. In all cases, both the integral-count and the differential-count decay data were analyzed, and comparing the results gave a valuable check as to the reality of a small Cl^{39} component.

The $Ar^{40}(d,He^3)Cl^{39}$ excitation function is plotted in Fig. 1. Two points at the high-energy end lie conspicuously below the others, probably because the aluminum liner came loose and obstructed the beam, cutting its energy. This is known to have happened in one of the two cases. The uncertainty in the absolute excitation function is of the order of 20%. The largest single source of error was the uncertainty in the efficiency of recovery of the chlorine activity. Errors are larger at energies below 12.5 MeV due to the very unfavorable Cl^{39}/Cl^{38} ratios.

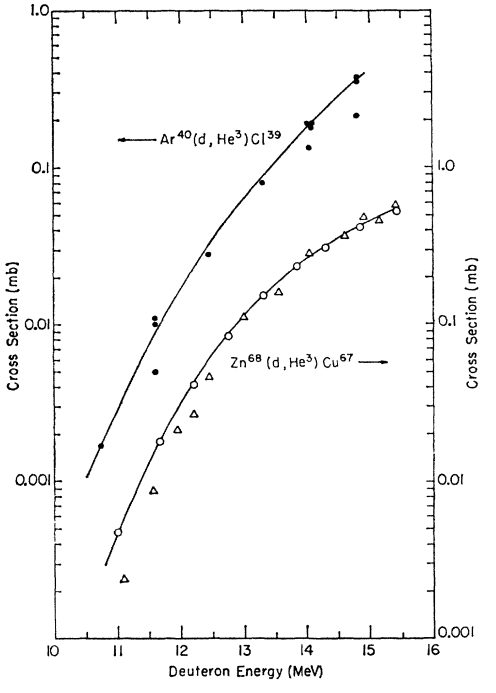

FIG. 1. Excitation functions of the reactions $Ar^{40}(d,He^3)Cl^{39}$ (closed symbols) and $Zn^{68}(d,He^3)Cu^{67}$ (open symbols).

Zinc Bombardments

The copper activity produced by the deuteron bombardment of zinc consisted of 3.32-h Cu^{61}, 12.8-h Cu^{64}, and 61.5-h Cu^{67}. Most of the decay curves were analyzed by computer, using a least-squares program written by Rogers.[20] Sample purity was established from the scintillation spectrum, the Cu^{67} half-life, and the differential-count/integral-count ratio. The long-lived impurities in most of the samples of run Cu-I made it impossible to obtain useful Cu^{67} data from this experiment except at the high-energy end of the excitation curve.

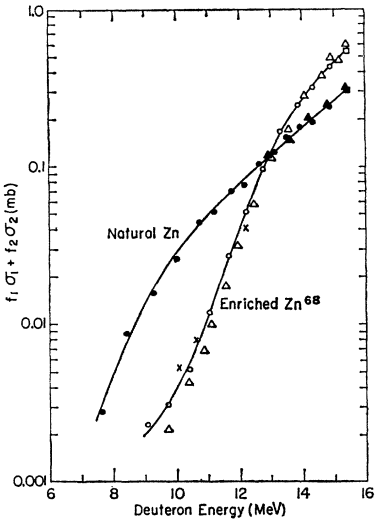

FIG. 2. $\Sigma f_i\sigma_i$ of reactions yielding Cu^{67} upon deuteron bombardment of zinc targets (see text). Closed symbols represent natural zinc data, open symbols represent enriched Zn^{68} data, and crosses represent data for an intermediate isotopic composition.

Cu^{67} may be produced by the reactions $Zn^{68}(d,He^3)Cu^{67}$ ($Q=-4.51$ MeV), $Zn^{67}(d,2p)Cu^{67}$ ($Q=-2.02$ MeV), and $Zn^{70}(d,\alpha n)Cu^{67}$ ($Q=0.18$ MeV).[21] The Cu^{67} yield is proportional to $\sum f_i\sigma_i$, the sum of the cross sections, σ_i, weighted by the corresponding isotopic abundances, f_i. These sums are plotted in Fig. 2 for both natural zinc and the enriched Zn^{68} targets. In run Cu-IV, three foils of an intermediate isotopic composition were also included in the stack. The isotopic compositions of all the zinc targets are given in Table I.

TABLE I. Isotopic composition of zinc targets.

	Enriched Zn^{68} [a]	Intermediate composition	Natural Zn
Zn^{70}	0.01%	0.07±0.01%	0.62%
Zn^{68}	96.8±0.1	89.3 ±0.1	18.56
Zn^{67}	0.6±0.05	0.93±0.05	4.11
Zn^{66}	0.9±0.05	3.46±0.05	27.81
Zn^{64}	1.7±0.05	6.21±0.05	48.89

[a] As given in the mass analysis supplied with the sample by Oak Ridge National Laboratory.

[20] P. C. Rogers, Massachusetts Institute of Technology Laboratory for Nuclear Science Technical Report No. 76, 1962 (unpublished).

[21] A. H. Wapstra, Physica 21, 385 (1955).

Let subscripts 1, 2, and 3 refer to Zn^{68}, Zn^{67}, and Zn^{70}, respectively. At energies below 10.8 MeV, the Cu^{67} yields at a given energy are approximately proportional to f_2 for all three isotopic compositions. This indicates that $\sum f_i\sigma_i$ receives its principal contribution from $f_2\sigma_2$ at these energies. In particular, if the $Zn^{70}(d,\alpha n)Cu^{67}$ reaction were an important source of Cu^{67} in the natural zinc bombardments, the Cu^{67} yield from the enriched Zn^{68} bombardments would be much lower than is observed, since f_3 is extremely small in the enriched Zn^{68}.

Energetically, the $Zn^{70}(d,\alpha n)Cu^{67}$ reaction is the most favored of the three reactions yielding Cu^{67}. Its cross section should, then, rise the least rapidly with increasing energy. Since $f_3\sigma_3$ is at most a minor component of $\sum f_i\sigma_i$ at 10.5 MeV, and since it is expected to rise less rapidly than $f_1\sigma_1$ and $f_2\sigma_2$, $f_3\sigma_3$ should be a minor component of $\sum f_i\sigma_i$ at all higher energies. We assume it to be negligible.

The two yield curves, then, provide two equations which may be solved for the two remaining cross sections. Since the Zn^{68}/Zn^{67} ratio is so large in the enriched Zn^{68}, the $Zn^{67}(d,2p)Cu^{67}$ reaction constitutes only a small correction to the Cu^{67} yield from the enriched Zn^{68}, and the $Zn^{68}(d,He^3)Cu^{67}$ excitation function is not sensitive to small errors in this correction. The $Zn^{67}(d,2p)Cu^{67}$ excitation function is discussed further in the following paper.[12]

The $Zn^{68}(d,He^3)Cu^{67}$ excitation function is plotted in Fig. 1. It may be seen that the two enriched Zn^{68} bombardments, runs Cu-III and Cu-IV, did not give very good agreement at energies below 12.5 MeV. Run Cu-III appeared to be more satisfactory, with less scatter of the data, and it has been weighted more heavily in drawing the indicated excitation curve. The uncertainty in the absolute excitation function is about 15%, except greater near threshold.

DISCUSSION

Since the radiochemical technique deals only with the residual nuclei, and not the emitted particles, it cannot, in itself, distinguish the reaction modes (d,He^3), $(d,d'p)$, and $(d,2pn)$ when these are energetically possible. In the present case, the reactions $Ar^{40}(d,d'p)Cl^{39}$ (threshold = 12.62 MeV) and $Zn^{68}(d,d'p)Cu^{67}$ (threshold = 10.30 MeV)[21] are energetically possible at the higher energies investigated. However, a rough calculation, based upon the statistical model of nuclear reactions, indicated that the cross sections are minute, 10^{-5} mb or less. This is due to the unfavorable ratios of available energies to barrier heights for the outgoing charged particles. These effects would inhibit the reaction $Zn^{68}(d,2pn)Cu^{67}$ (threshold = 12.60 MeV) even more severely, and the $Ar^{40}(d,2pn)Cl^{39}$ reaction (threshold = 14.97 MeV) is energetically impossible. The barriers would inhibit direct processes almost as severely. Furthermore, about the only way that the deuteron could transfer the necessary large amounts of energy to the target nucleus is to be captured and form the compound nucleus. In all probability, the observed results represent true (d,He^3) reactions.

A statistical model calculation of the (d,He^3) excitation functions was carried out in order to estimate the fraction of the observed cross section that could be accounted for by compound nucleus processes. The nuclear level-density parameter a was taken to be $A/10$ in the argon region and $A/8$ in the zinc region.[22] The radius parameter $r_0 = 1.7$ F was assumed. The nuclear level density was assumed to follow the degenerate Fermi gas formula,[22] with pairing effects taken into account by measuring the excitation energy from the "characteristic level"[23] rather than from the ground state. In calculating the He^3 emission widths, allowance was made for the effect of the discrete levels lying below the characteristic level. The inverse capture cross sections for He^3 particles were taken from Shapiro's tables,[24] and the necessary integration was performed graphically. Large amounts of energy are available for the competing emission of neutrons, protons, and alphas, so the corresponding emission widths could be calculated with sufficient accuracy from the approximate formulas given by Dostrovsky, Fraenkel, and Friedlander.[23]

The excitation energy available to the (d,He^3) product was always very low, and question might be raised as to the applicability of the statistical model formalism to such cases. Certain factors that might decrease the (d,He^3) cross section, such as possible angular momentum barriers, were not taken into account. On the other hand, the calculation did avoid the sharp cutoffs (e.g., opaque Coulomb barriers) that invalidate many approximate statistical model calculations near thresholds. The results should have an order-of-magnitude significance, especially if interpreted as upper limits.

The experimental $Ar^{40}(d,He^3)Cl^{39}$ cross section at 14.8 MeV exceeds the theoretical by a factor of 11, and the experimental $Zn^{68}(d,He^3)Cu^{67}$ cross section at 15.4 MeV exceeds the theoretical by a factor of 4100. Furthermore, theory predicts a much smaller cross section for the heavier target, while the actual cross sections are comparable. It appears that the (d,He^3) reaction proceeds primarily by a direct process, at least for $A \geq 40$.

The shapes of the experimental and theoretical excitation functions of the $Ar^{40}(d,He^3)Cl^{39}$ and $Zn^{68}(d,He^3)Cu^{67}$ reactions are compared in Figs. 3 and 4, respectively. In each case, curve (1) is the experimental excitation function and curve (2) is the theoretical excitation function from the statistical model normalized to the

[22] D. W. Lang, Nucl. Phys. 26, 434 (1961).
[23] I. Dostrovsky, Z. Fraenkel, and G. Friedlander, Phys. Rev. 116, 683 (1959).
[24] M. M. Shapiro, Phys. Rev. 90, 171 (1953).

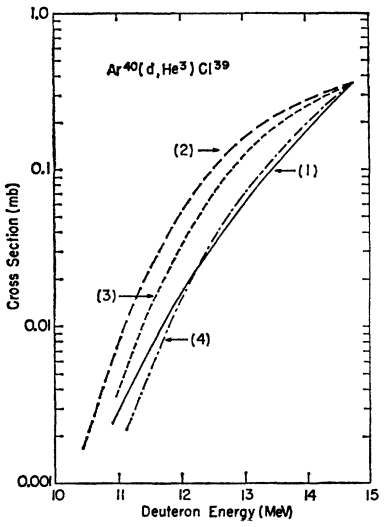

FIG. 3. Comparison of the $Ar^{40}(d,He^3)Cl^{39}$ excitation function with theoretical predictions: (1) experimental; (2) statistical model×11; (3) pickup mechanism with only the ground-state transition allowed; (4) single-particle pickup model. All curves are normalized to the experimental at 14.8 MeV.

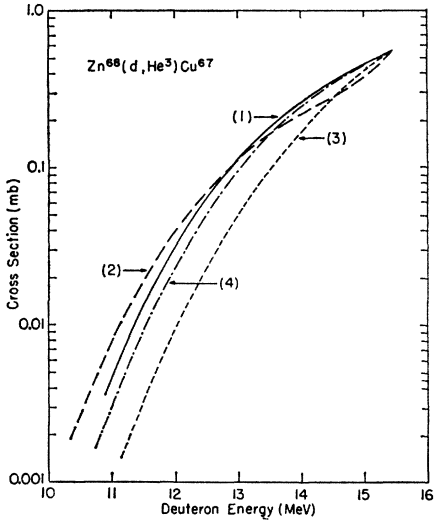

FIG. 4. Comparison of the $Zn^{68}(d,He^3)Cu^{67}$ excitation function with theoretical predictions: (1) experimental; (2) statistical model×4100; (3) pickup mechanism with transitions to all excited states up to 2 MeV allowed; (4) single-particle pickup model. All curves are normalized to the experimental at 15.4 MeV.

experimental at the high-energy end. The shapes of the two curves do not agree particularly well, but they are similar in one important respect: They both fall rapidly to very small values at energies several MeV above the thermodynamic thresholds of the two reactions (6.86 and 4.65 MeV, respectively). In the case of the theoretical curve, this represents the energy dependence of the penetrability of the Coulomb barrier faced by the emitted He^3 particle. At the high-energy end of both excitation functions, the maximum energy available for the He^3 particle is about equal to the classical barrier height, and the predicted cross section, therefore, falls rapidly with decreasing energy. The similar energy dependence of the experimental and theoretical curves suggests that, whatever the true mechanism, the Coulomb barrier is effective in inhibiting it at low energies. Similar inhibition near threshold has been observed for the (d,t) reaction.[11]

This behavior is not surprising if the (d,He^3) reaction takes place by a proton pickup mechanism. Such reactions are expected to take place in the diffuse nuclear surface zone.[25,26] While the nuclear potential is much weaker here than it is at the nuclear core, it is still far from zero, and this "reaction zone" should lie inside the maximum in the total (nuclear+Coulomb) potential curve. The outgoing He^3 wave must, then, traverse most, if not all, of the region of strongly positive potential. If this region is classically forbidden, the He^3 wave will be correspondingly attenuated.

If we assume that the Coulomb barrier does govern the energy dependence of the (d,He^3) cross section, the shape of the observed excitation functions may be reproduced surprisingly accurately by a very simple model, the single-particle pickup (SPP) model. We assume that the (d,He^3) reaction proceeds by plucking a proton from the target without altering the level assignments of the other nucleons. The product is, thus, left in a "single-hole" state. According to these assumptions, the probability of removing a proton from the ith subshell is proportional to N_i, the number of protons in the ith subshell, multiplied by $\sigma_c(\epsilon_i)$, the inverse capture cross section for He^3 particles of energy ϵ_i. The absolute magnitude of σ_c is of no significance here, but its energy dependence represents the effect of the barrier. The He^3 energy is given by energy conservation: $\epsilon_i = E_d + Q - E_i$, in center-of-mass coordinates, where E_d is the deuteron energy, Q is the (d,He^3) reaction Q value, and E_i is the excitation energy of the ith single-hole state (zero for the ground state). The energy dependence of the (d,He^3) cross section is then given by

$$\sigma \propto \sum_i N_i \sigma_c(\epsilon_i). \quad (1)$$

In the present case, E_d+Q is at most equal to the classical barrier height, and $\sigma_c(\epsilon_i)$ will be very small except for low-lying single-hole states. In particular, we may neglect breaking into closed major shells.

According to the shell model, the Ar^{40} proton configuration is $(d_{5/2})^6(s_{1/2})^2(d_{3/2})^2$. In agreement with this, the ground state of Cl^{39} is $\frac{3}{2}+$[27] and the first excited state, at 0.8 MeV, is $\frac{1}{2}+$.[28] No other Cl^{39} states are known, but Cl^{35} and Cl^{37} have excited states, of unknown

[25] S. T. Butler, in association with O. H. Hittmair, *Nuclear Stripping Reactions* (John Wiley & Sons, Inc., New York, 1957).
[26] S. T. Butler, Phys. Rev. **106**, 272 (1957).
[27] D. Strominger, J. M. Hollander, and G. T. Seaborg, Rev. Mod. Phys. **30**, 585 (1958).
[28] F. Gudden and J. Eichler, Z. Physik **150**, 436 (1958).

spin, at 1.76 and 1.73 MeV, respectively.[29] It is reasonable to suppose that removal of a $d_{5/2}$ proton from Ar^{40} gives a single-hole state of Cl^{39} at about this energy. Using these values of E_i, Eq. (1) was evaluated and σ plotted against E_d, after normalizing to the experimental cross section at 14.8 MeV [curve (4), Fig. 3]. For comparison, curve (3) gives the result if it is assumed that only the ground-state transition is significant. The curve predicted by the SPP model gives a much better fit than the other curves, at least for $E_d \geq 12$ MeV. For reasons described earlier, the experimental data are very unreliable at lower energies.

Zinc contains only two protons outside the $Z=28$ closed shell, and the model indicates that only the transition to the Cu^{67} ground state may take place. The low-lying excited states of Cu^{67} are not single-hole states. The predicted curve was calculated, normalized to the experimental cross section at 15.4 MeV, and plotted as curve (4) in Fig. 4. For comparison, curve (3) gives the result if it is assumed that transitions to the first several Cu^{67} levels (up to 2 MeV) contribute equally, except for barrier penetration. Again, the curve predicted by the SPP model gives a much better fit.

For the $Ar^{40}(d,He^3)Cl^{39}$ reaction, then, the experimental curve can be reproduced only by summing over transitions to certain low-lying levels of Cl^{39} (including the ground state), while the $Zn^{68}(d,He^3)Cu^{67}$ excitation function is reproduced if only the ground-state transition is included. This behavior is specifically predicted by the SPP model, but would be difficult to account for otherwise.

The single-particle interpretation of stripping and pickup reactions is actually greatly oversimplified.[30] The present examples are favorable cases for its application, since excitation energies were low and both targets are even-Z nuclides lying fairly near closed proton shells. Excitation function measurements are not suitable for elucidating the details of nuclear reaction mechanisms and there would be little point in seeking a more refined model to compare with the data obtained here.

The present results demonstrate that the (d,He^3) reaction does take place, and the cross sections, while low, are much larger than the statistical model predicts. The results strongly suggest a proton pickup mechanism, with the energy dependence of the cross section governed largely by the Coulomb barrier faced by the outgoing He^3 particle.

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[29] P. M. Endt, C. H. Paris, A. Sperduto, and W. W. Buechner, Phys. Rev. **103**, 961 (1956).

[30] A. M. Lane and D. H. Wilkinson, Phys. Rev. **97**, 1199 (1955).