(d,Li^6) Reactions in C^{12}, O^{16}, and F^{19} at 14.6 MeV*

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It was found that in the bombardment of light targets such as C^{12}, O^{16}, and F^{19} with 14.6-MeV deuterons, many-nucleon transfers often occur with relatively large cross sections. Differential cross sections are presented for the ground-state transitions $C^{12}(d,Li^6)Be^8$, $O^{16}(d,Li^6)C^{12}$, $F^{19}(d,Li^6)N^{15}$, and $F^{19}(d,Be^9)C^{12}$. All angular distributions show pronounced structure. The (d,Li^6) reactions leading to the ground states of N^{15}, C^{12}, and Be^8 show asymmetry with respect to $\theta=90°$, and have total cross sections on the order of 1–4 mb. The similarity of the angular distributions and a relatively minor sensitivity to energy variations suggest that a direct reaction mechanism predominates. Preliminary DWBA (distorted-wave Born approximation) calculations by Drisko, Satchler, and Bassel show qualitative agreement with the data, and support this view. Unique identification of the heavy reaction products was obtained by energy analysis in conjunction with simultaneous analysis of a second parameter, which was either the magnetic rigidity or the time of flight of the heavy ions. Both experimental procedures are described in detail.

I. INTRODUCTION

It has been known for some time[1,2] that for light nuclei, shell-model wave functions can be rewritten in a cluster form. These "clusters" are groups of nucleons with the correct symmetry properties (angular momentum, etc.); otherwise they do not necessarily resemble the corresponding free nuclei. The resemblance may improve when residual forces are introduced between the nucleons of the cluster. Attractive residual forces tend to enhance relative s states, and it has been calculated[3] that in heavy nuclei this can lead to a considerable increase in alpha-like clustering. Many arguments have also been advanced for the existence of alpha-like clusters in light elements,[4,2] and several recent experimental tests have been reported.[5]

Not all probable clusters are alpha-like. Li^6, for instance, seems to have large widths for alpha-plus-deuteron cluster states.[2] It has also been viewed as an alpha plus two nucleons.[6] Li^7 has a large probability to be found in the form (triton cluster + alpha cluster).[7] If clusters in various light nuclei are indeed similar to the corresponding free nuclei or at least to one another, the exchange of such clusters in nuclear reactions should be greatly enhanced over the transfer of the same number of uncorrelated nucleons. Information on cluster transfers would enhance our knowledge of the structure of parent or daughter nuclei, and permit interesting cross checks with theoretically predicted wave functions. Theoretically, the study of cluster transfers and the interpretation of experiments becomes practical if the interaction—to a good approximation—can be described as a direct reaction. We can then use the distorted-wave Born approximation (DWBA), and make calculations that treat the pickup of preformed clusters existing in a suitable potential well.[8] Once all optical-model parameters are known, such direct reaction calculations should yield spectroscopic factors which are simply related to the fractional parentage coefficients for the cluster in the target and "daughter" nuclei.

It is not always possible to know *a priori* that a certain reaction will be predominantly direct (in our operational definition). We shall have to investigate experimentally in each case whether this assumption is tenable. There are many examples for (p,t) and (p,α) reactions to low-lying final states that all show the characteristics of direct interactions, although the pickup of more than one particle is involved. Hence the transfer of two neutrons and two protons, especially in the form of an alpha-like cluster, might be well described as a direct α-pickup reaction. The simplest reaction of this type is the (d,Li^6) reaction (Li^5 and He^5 are extremely unstable). As mentioned above, the "daughter" Li^6 has a high probability to be found in an alpha + deuteron state, and pickup reaction cross sections should be reasonably large if the target nuclei have large widths for alpha clusters. This, indeed, seems to be the case for a number of light targets.[9] It might also be true for heavier elements,[10] but Coulomb barrier effects so far have limited our investigations to light nuclei.

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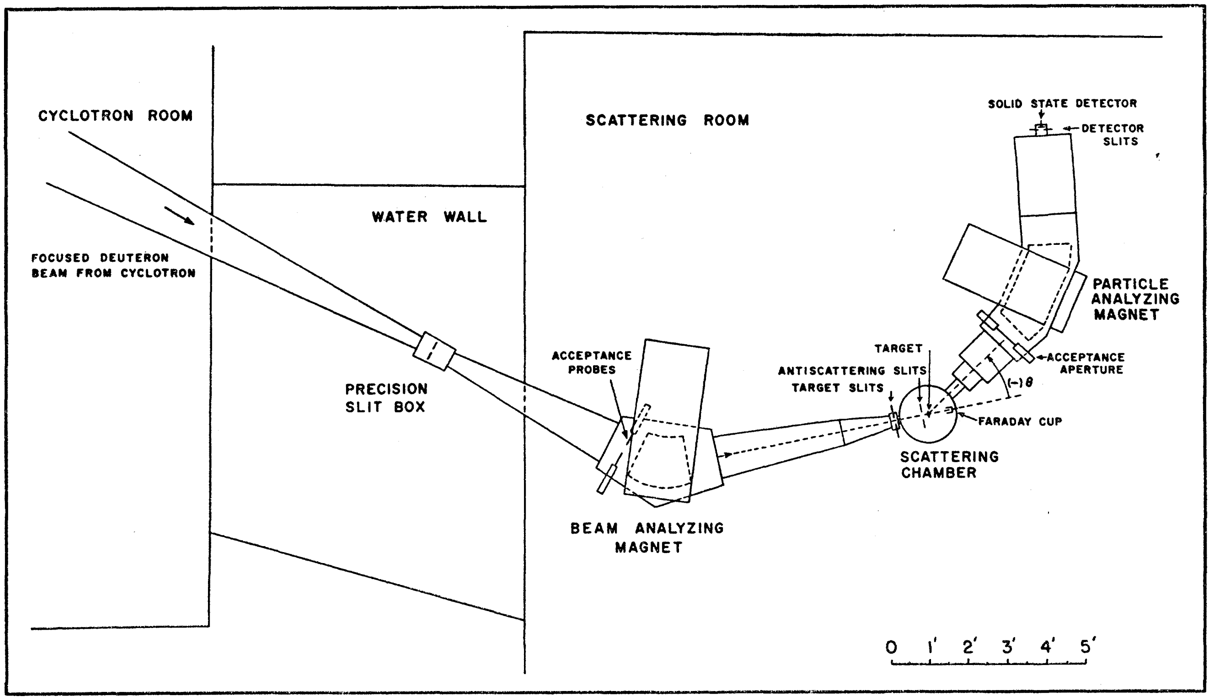

FIG. 1. Experimental arrangement for simultaneous momentum and energy analysis of charged reaction products. Slits in the analyzing magnet define particle momentum to 0.3%. Optimum energy resolution of the solid-state counter was about 30 keV.

II. EXPERIMENTAL PROCEDURE

The investigation of many-particle pickup reactions, such as (d,Li^6), presents several experimental problems: Cross sections are small, Q values are negative and the ranges of the reaction products are very short. In addition, one faces the problem of unique identification of the heavy reaction products of interest. This generally necessitates a complicated detection system and high beam energy. The Pittsburgh fixed-energy cyclotron provides an analyzed deuteron beam of typically 0.3 μA at about 15 MeV. This energy is comparable to some (d,Li^6) Q values, and our investigation has to be confined to favorable cases, e.g., nuclei with small negative Q values that also have reasonably low Coulomb barriers. Hence, the necessity to work with light target nuclei such as F^{19}, O^{16}, and C^{12}. Because of the short range of heavy fragments in matter, target thicknesses generally had to be kept to about 0.2 mg/cm^2. The preparation of thin targets was only moderately difficult; for it had been ascertained experimentally that high-Z backings, in particular Ni and Au, produced no appreciable heavy fragment background. C^{12} and CaF were deposited on 100-μg/cm^2 Ni foils, while oxygen targets were prepared by oxidation of thin Ni foils. The thickness of the targets was measured by weighing, as well as by comparison of elastic-scattering cross sections obtained from these thin targets with those from moderately thick commercial foils such as Mylar (for C^{12} and O^{16}) and Teflon (for C^{12} and F^{19}). Handling of the incident-deuteron beam and charge integration was accomplished in a conventional manner.[11] The energy spread in the residual deuteron beam was about 80 keV.

Various methods of identifying Li^6 particles were used. The first one, measuring the energy deposited by heavy particles in a limited-range counter (ion chamber with variable gas pressure), was discarded after it became apparent that other heavy particles (such as Be^9) of comparable energy were produced in appreciable quantity.[12] A more successful method of particle identification consisted of simultaneous momentum and energy analysis of the charged reaction products. For a given position (Fig. 1) in the focal plane of the magnet, the energies of the charged particle groups, reaching a solid-state counter are restricted to

$$E=\frac{Z^2e^2}{m}\frac{(B\rho)^2}{2}(\text{mks}),$$

[11] R. S. Bender, E. M. Reilly, A. J. Allen, R. Ely, J. S. Arthur, and H. J. Hausman, Rev. Sci. Instr. **23**, 542 (1952).

[12] Our preliminary results for $F^{19}(d,Li^6)N^{15}$ for $E_d=15$ MeV given in Refs. 8 and 9 were obtained with such a limited-range counter. Our more accurate 2-parameter analyses yield cross sections that agree qualitatively, but not in detail, e.g., the newer data (Fig. 8) yield cross sections that decrease less strongly with angle. We attribute this discrepancy mostly to the need for a large background subtraction in the limited-range data. Some of the difference may be due to the fact that the earlier data were taken near $E_d=15$ MeV, while our recent experiments were performed at $E_d=14.5$ MeV.

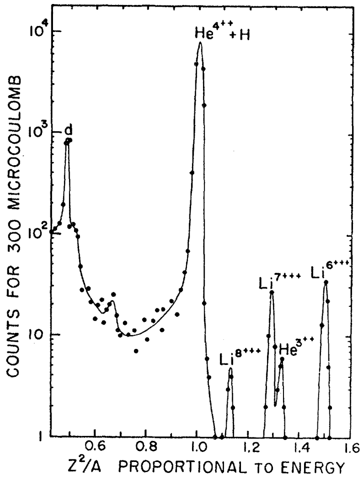

FIG. 2. Typical spectrum from a solid-state counter at the focal plane of an analyzing magnet, for fixed $B\rho$. The energy of the detected charged particles is proportional to Z^2/m. The continuous background is mostly due to neutron and γ-ray induced reactions in the detector. [For the magnitude and energy dependence of neutron induced reactions in Si counters see, for instance, G. Andersson-Lindström, Ph.D. thesis, University of Hamburg, 1964 (unpublished).] This spectrum was observed in an $O^{18}+d$ run (Ref. 9). It is shown because it simultaneously contains several interesting heavy groups.

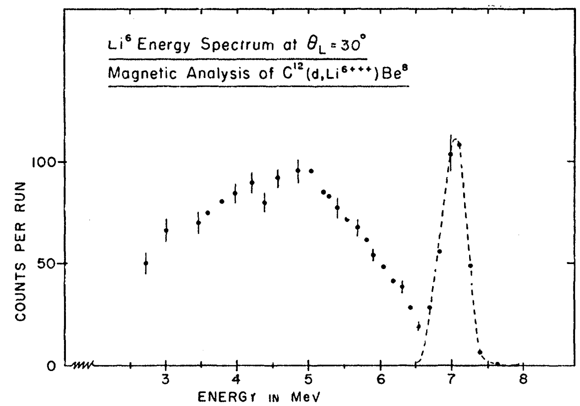

FIG. 3. Total energy spectrum of Li^{6+++} particles from the reaction C^{12}(d,Li^6)Be^8, obtained from 31 spectra of the type shown in Fig. 2. The width of the "sharp" peak reflects the target thickness rather than resolution of the detection system. The continuum is mostly due to Li^6 ions from the 3-body breakup of the ($C^{12}+d$) system. Errors shown are statistical. The dashed line marks the ground-state peak.

where $m\approx A\times$(proton mass). Thus, for $B\rho$=constant, transmitted particles have only discrete energy values, each value signifying a different mass or charge state. A typical spectrum seen by a small solid-state counter mounted in the focal plane of the analyzing magnet is shown in Fig. 2. As can be seen, all groups for values $Z^2/A>1$ are well resolved and easily identified by their Z^2/A number. For $Z^2/A\approx 1$ we might have either H^{1+}, He^{4++}, Be^{9+++}, etc.; hence this value would become useful only if the groups are dispersed by a thin absorber. For Li^{6+++} we have $Z^2/A=1.5$. The closest neighbors in magnetic rigidity are O$^{16++++++}$ with $Z^2/A\approx 1.56$ and O$^{17++++++}$ with $Z^2/A\approx 1.47$. These peaks could have been resolved from that at $Z^2/A=1.5$ since the counter had about 1% resolution at 6 MeV. In practice, oxygen ions do not present a problem, since their recoil energies remain smaller than that of ground-state Li^6 particles. Hence, Li^{6+++} particles would be uniquely identified. The Q values for various nuclear reactions are easily available[13]; thus it is easy to compute the values of $B\rho$ for which various particle types will be seen. It is then not hard to change B in small steps through the range for which the ions of interest are allowed, and obtain a complete energy spectrum. One such spectrum for C^{12}(d,Li^6)Be^8 at $\theta_{\rm lab}=30°$ is shown in Fig. 3. The Li^6 peak due to the ground-state transition is well resolved from those Li^6 ions which do not leave the daughter (Be^8) in its ground state. Preliminary cross sections obtained in this fashion were reported earlier.[9]

The difficulty that remains in the magnetic analysis approach is to estimate the percentage of Li^6 ions that enter the magnet with triple ionization. It is found empirically that the charge state of Li^6 ions changes somewhat with energy, but above 1 MeV per nucleon at least 70% of the Li^6 ions seem fully stripped. We assumed that typically 80% of the Li^6 ions were fully stripped. Allowing a $\pm 10\%$ error for our estimate, we

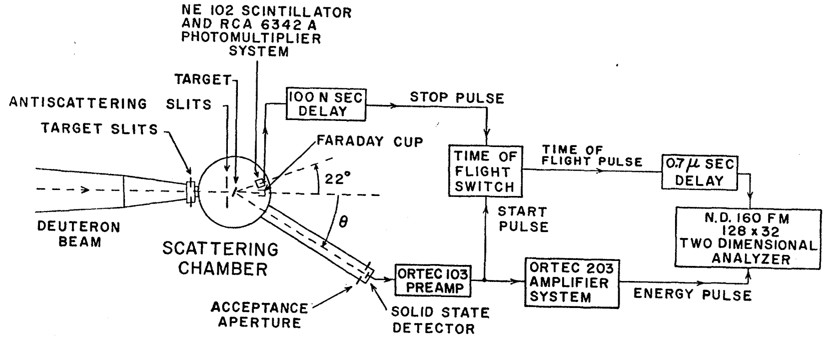

FIG. 4. Schematic for simultaneous time-of-flight and energy analysis. Energy resolution in all runs was limited by the target thickness and typically better than 400 keV. Experimental time-of-flight resolution was about 4 nsec.

[13] V. J. Ashby and H. C. Catron, University of California Radiation Laboratory Report, UCRL-5419 (unpublished); U. S. Atomic Energy Commission Report TID-4500 (14th ed.) UC-34, 1959 (unpublished).

found good agreement with time-of-flight data subsequently obtained.

For doubly ionized Li^6 ions the magnetic rigidity parameter Z^2/A equals 0.667. Here we face the obvious ambiguity between He^{6++} and Li^{6++}. Furthermore, this point is often affected by broad peaks from C^{12+++} and C^{13+++} recoils and by neutron background (for low Li^6 energies), so that acceptable measurements for Li^{6++} could be made only at a few angles. We therefore found it advantageous to employ a third experimental approach, that of simultaneous energy and time-of-flight analysis. This method does not depend on the ionic charge, but rather on the ion's mass; hence, for a given energy E and flight time T, all ions of like energy and mass are selected. If various reaction products of like mass are possible (He^6, Li^6, or Be^9, Li^9, etc.), Q value considerations usually can determine the origin of certain groups. If the ambiguity persists, a combination of both methods discussed or the insertion of absorber foils may be needed. In practice a two-dimensional analysis of counts versus energy and time of flight proved quite adequate for our (d,Li^6) experiments. (d,He^6) reactions were either energetically forbidden or unfavorable, and it seems safe to assume that Be^6 reaction products will be suppressed on account of higher Coulomb barriers, more negative Q values, and very short lifetimes.

The natural beam pulsation in a fixed-frequency cyclotron makes fast-time-of-flight work very simple: Energy-analyzed deuterons from the Pittsburgh cyclotron strike the target in intervals of 87 nsec for a duration of less than 4 nsec. An 8-MeV Li^8 ion traverses 1 m in about 72 nsec, a Li^7 ion in 67 nsec, a Li^6 ion in 62 nsec, and an alpha particle in 51 nsec. Hence, time-of-flight work which makes use of the natural beam pulsing is feasible under these conditions. We derive a fast cyclic (T_0 or "Stop") signal from a plastic scintillator (NE102) that detects deuterons elastically scattered through a small angle (see Fig. 4). A slightly damped ringing circuit of 87-nsec period averages over fluctuations in the number of elastically scattered deuterons, so that a (stop) pulse is available every 87-nsec (T_0). The event (start) pulse is obtained from a 50 mm², thin (200 μ) Au-barrier detector that also serves for energy analysis. Pulse shapers and a fast amplifier provide the time-of-flight start signal T_1 (see Fig. 5). The event (T_1) pulse turns on a tunnel diode which stays on until the next T_0 pulse turns it off (in less than 87 nsec). The total charge q in the output pulse is proportional to ($T_1 - T_0$+const) nsec. Typically, $q \sim (100-T)$, where T is the time of flight. The very short duration of the time-of-flight charge pulses permits their direct conversion into a pulse height spectrum P.H.$\sim(100-T)$ by amplification by a slow amplifier which has a rise time $\tau \gg 88$ nsec.

In the present experiment the energy spectrum was fed into the F side and the simultaneous time-of-flight

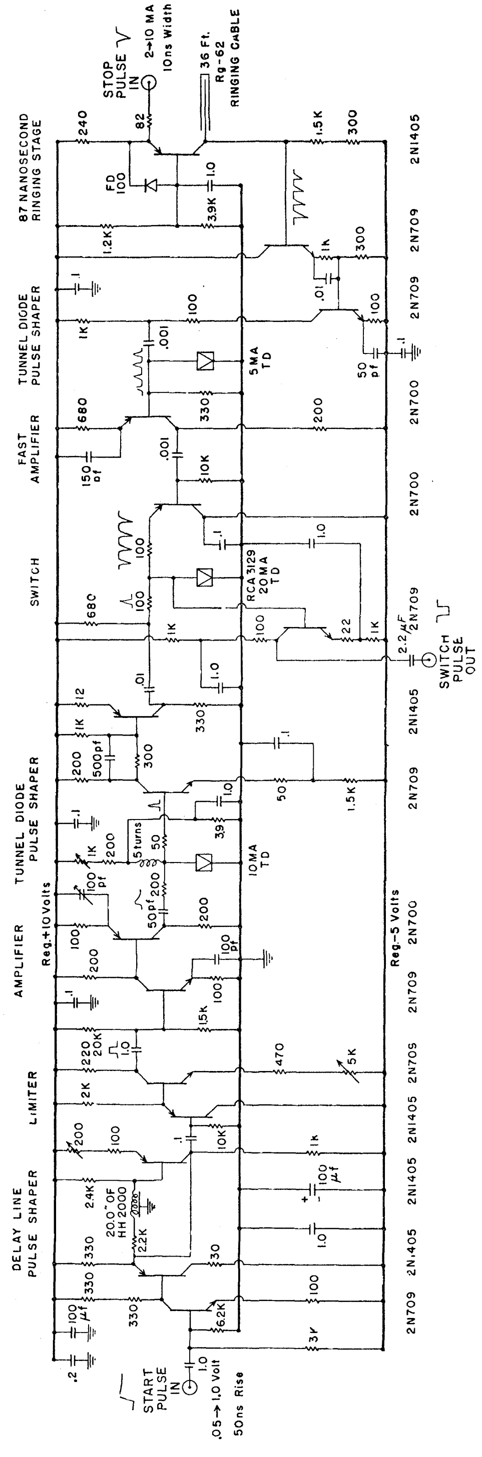

FIG. 5. Circuit diagram of the time-of-flight module. The circuit consists of fast amplifiers and pulse shapers for each input, both of which feed into a 20-mA RCA 3129 tunnel diode. This tunnel diode is switched on by the "start" pulse and stays on until turned off by the next T_0 (stop) pulse. (Since this circuit was put in operation, commercial fast signal pickups have become available, which would make some of the start pulse shaping circuits unnecessary.)

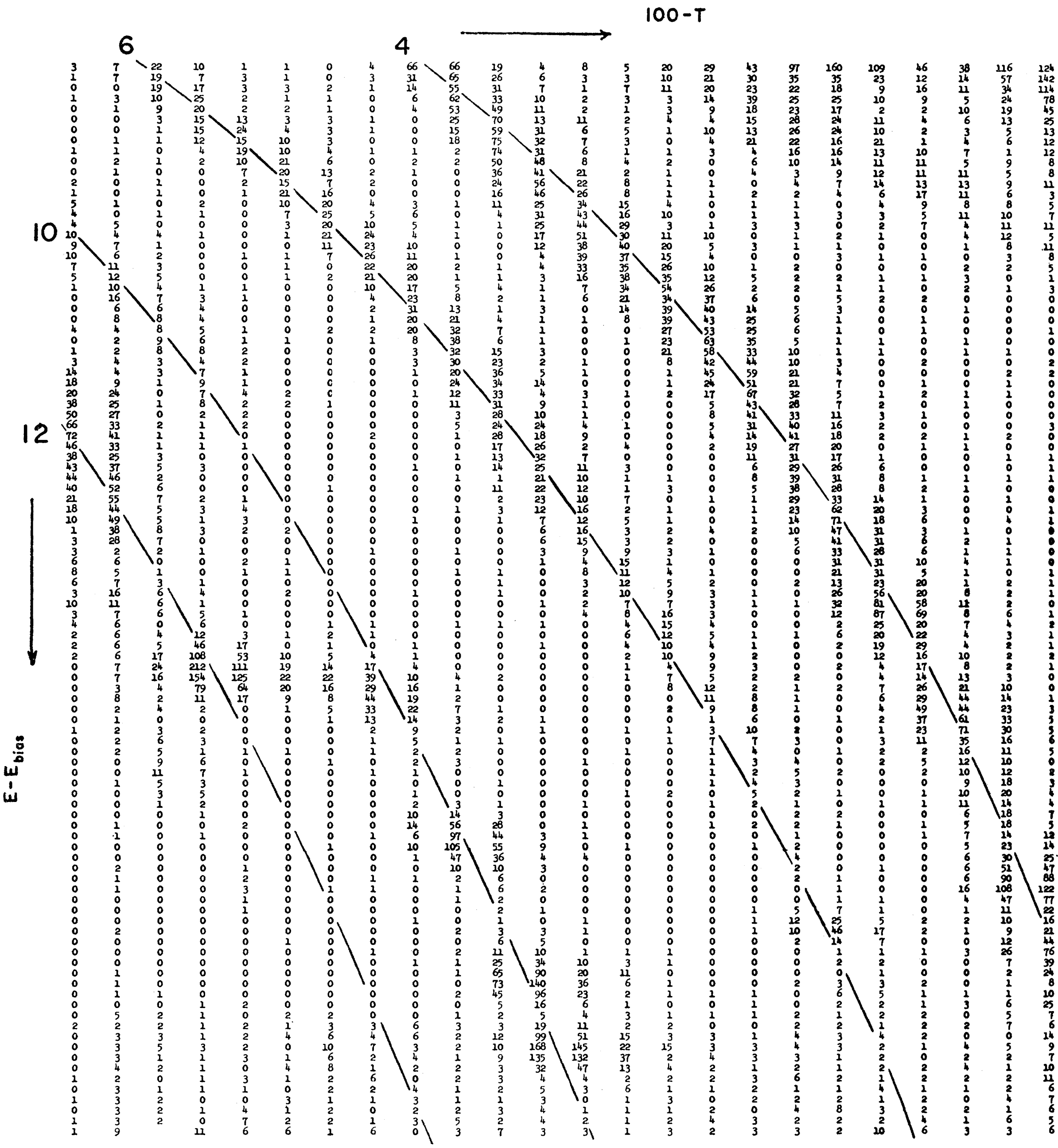

FIG. 6. Portion of the two-dimensional 128×32 channel analyzer printout, from a $C^{12}+d$ run at high counting rates (about 10^4 cps). The ordinate is proportional to (const$-E$) and the abscissa to $\tau \approx$ (100 nsec$-$time of flight). Loci for masses 4, 6, 10, and 12 are sketched in to aid the eye. Run was taken with a 1-m flight path at $\theta_L = 12°$.

spectrum into the M side of a 128×32 channel analyzer (Nuclear Data No. 160 FMR). Figure 6 shows part of a typical printout of such a two-dimensional spectrum for $C^{12}(d,Li^6)Be^8$. The abscissa is proportional to $(100-T)$ and the negative ordinate is proportional to the particle energy E. Four $A=$const. loci are sketched in. It can be seen that mass-4 and mass-6 particles are well resolved from all other groups.

III. EXPERIMENTAL RESULTS AND ERRORS

In our (d,Li[6]) energy spectra (Figs. 3 and 7) the most pronounced Li^6 peaks could easily be identified as resulting from transitions which leave both the daughter nucleus and the Li^6 particle in the ground state. In $O^{16}(d,Li^6)C^{12}$ [Fig. 7(b)] no other significant Li^6 groups were seen for $E_d \approx 14.6$ MeV. Groups corresponding to Li^6 in any of its excited states were not seen. Most Li^6

states are unstable against particle emission, and the excitation of the $T=1$ level at 3.56 MeV is inhibited by isospin selection rules and/or the Coulomb barrier effect. For the ground-state transitions $C^{12}(d,Li^6)Be^8$, $O^{16}(d,Li^6)C^{12}$, and $F^{19}(d,Li^6)N^{15}$, angular distributions were measured. Absolute differential cross sections are shown in Fig. 8. For $F^{19}+d$ we also observed the $F^{19}(d,Li^7)N^{14}$ and $F^{19}(d,Be^9)C^{12}$ reactions. The $F^{19}(d,Li^7)$ reaction is strong, about half as probable as the (d,Li^6) reaction. In addition an appreciable number of Li^7 ions emerge in their first excited state (at 0.478 MeV). Other many-particle transfers energetically possible for $F^{19}+d$ are $F^{19}(d,He^6)$, $F^{19}(d,Be^7)$, $F^{19}(d,B^{10})$. The unique identification of these reactions requires better resolution than was available in the present experiment. The 7-particle transfer $F^{19}(d,Be^9)C^{12}$ was energetically favorable ($Q=+0.28$ MeV) and easily observed.

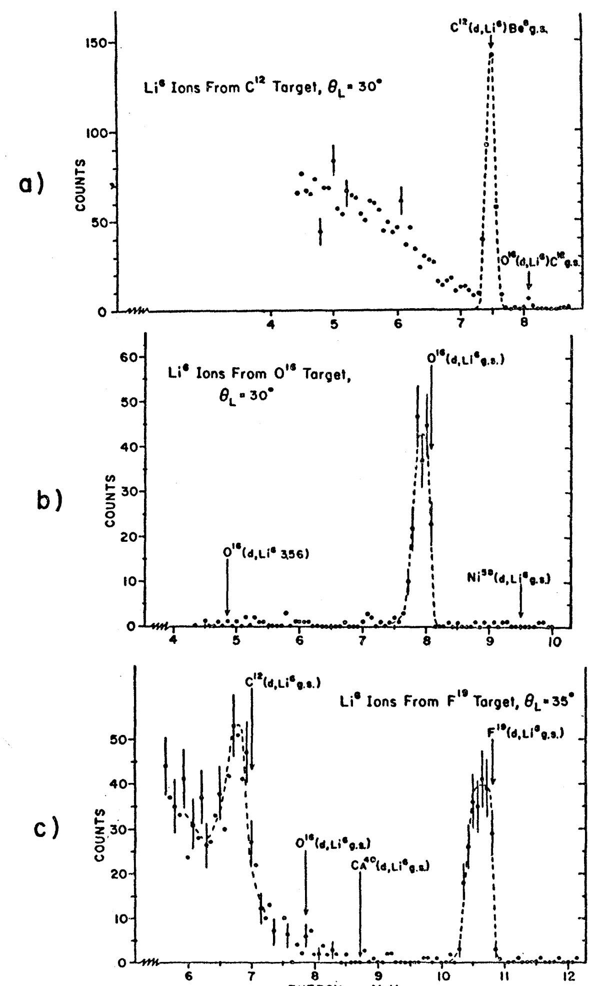

FIG. 7. Spectra of mass 6 particles (Li^6) as obtained from energy–time-of-flight analysis. Dashed lines mark the ground-state groups of interest. Peak widths are due to target thickness, not detector resolution. (a) $C^{12}+d$ run. The over-all energy resolution is better than that shown in Fig. 3, since more efficient particle analysis permitted the use of thinner targets. (b) Typical energy spectrum of mass 6 particles from $O^{16}+d$. Note the absence of groups that could be due to excited states of the Li^6 ions. (c) Typical energy spectrum from $F^{19}+d$. The $F^{19}(d,Li^6)$ ground-state group is well resolved. The large peak at lower energy is due to C^{12} contamination of the target.

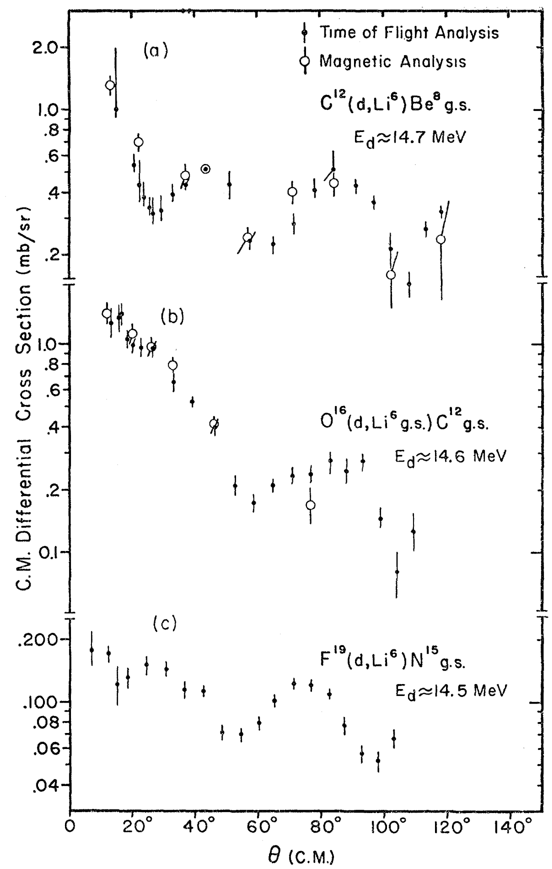

FIG. 8. Angular distributions, in the center-of-mass system, for three (d,Li^6) reactions. Time-of-flight data are indicated by solid dots, magnet data by open circles. Bars indicate relative experimental errors which are mostly, but not exclusively, due to statistics.

In Figs. 8, 9, and 10 all known random experimental errors are indicated by error flags. Where possible, an explicit comparison with data obtained from magnetic analysis[9] has been made. Systematic scale errors are not well known and are not shown. Very thin targets often were neither flat nor uniform so that their average thickness had to be found indirectly. We assign a probable error of ±30% to our thickness determinations. The measurement of integrated charge was reproducible to better than 5%, and the error in the absolute calibration is believed smaller than 10%. Geometrical errors were negligible, as were errors in the counting loss corrections for all but the smallest angles. We assign an over-all uncertainty of ±35% to our absolute cross-section scale.

The energy of incident deuterons could be measured accurately, but could not easily be reproduced from day to day. Hence, the given values of the bombarding

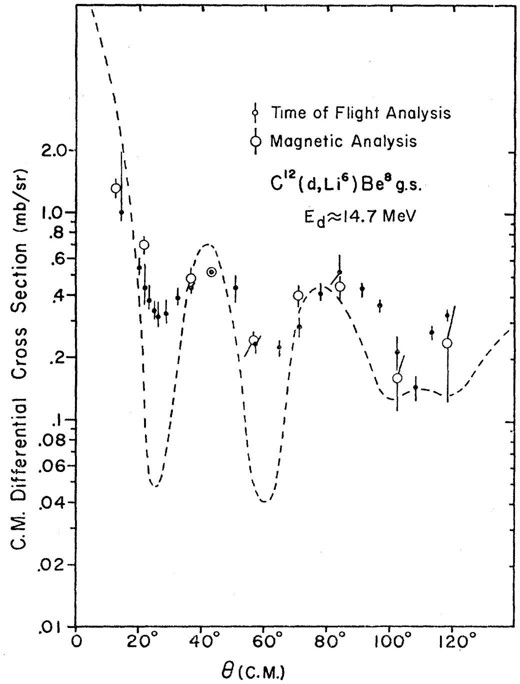

FIG. 9. $C^{12}(d,Li^6)Be^8$ data compared with a DWBA calculation (Ref. 8), which assumed direct pickup of a preformed α cluster (in zero range approximation). The theoretical curve is arbitrarily normalized.

energies E_d(lab system) represent averages over various runs for the same reaction. Some individual runs had energies that differed by as much as 100 keV from the typical values quoted. Preliminary excitation curves indicate that changes of ± 100 keV in bombarding energy do not cause significant changes in the (d,Li^6) cross sections.

Background subtraction presented no problem in the time-of-flight work. In the magnetic analysis experiment, low-energy Li^6 groups were sometimes affected by neutron background and proper allowance for the resulting uncertainty was made in the random errors given. Target impurities and contamination presented no problem for the data shown, but did inhibit the search for excited states of Li^6 and other heavy groups of lower energy. Target contamination usually occurred after prolonged use of the target, and was found to be mostly due to C^{12} [see Fig. 7(c)] and O^{16} [Fig. 7(a)].

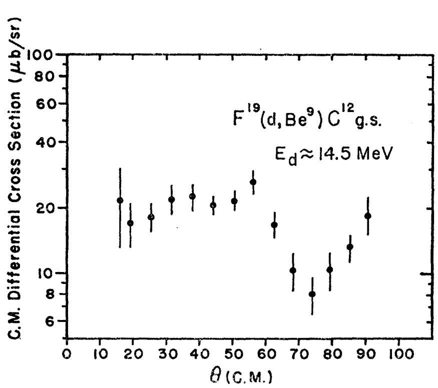

FIG. 10. Angular distribution for $F^{19}(d,Be^9)C^{12}$ obtained by energy and time-of-flight analysis. This reaction corresponds to a pickup of all F^{19} nucleons outside the C^{12} subshell. It is energetically favored and easily observed.

IV. DISCUSSION OF RESULTS

Inspection of the differential cross sections for the three (d,Li^6) reactions reported (Fig. 8) permits a few general observations: (a) Considering that these reactions involve the transfer of 4 nucleons, and are somewhat impeded by the Coulomb barriers, the experimental cross sections are larger than one might have expected. [Compare for instance, with (p,α) cross sections[14] which often are comparable or smaller.]

(b) All three reactions show similar angular distributions. They are forward peaked and have an oscillatory shape.

(c) All minima are fairly regularly spaced (40°–50° apart) and seem to move closer together and to smaller angles with increasing A.

While these systematic features, admittedly, may be accidental and do not prove the predominance of a direct interaction mechanism, they certainly encourage further analysis by such methods as the distorted-wave Born approximation.[15] Drisko, Satchler, and Bassel reported some rough predictions for (d,Li^6) reactions in light elements, using the DWBA approach and guessing at the optical parameters for deuteron and Li^6 scattering from the light elements involved.[8] One of these preliminary calculations for $C^{12}(d,Li^6)Be^8$ is reproduced in Fig. 9 together with our latest experimental data. We notice both a gratifying qualitative agreement and disagreements in detail. Maxima and minima occur about at the right places. But the minima predicted are much deeper than found experimentally. The experimental angular resolution was $\Delta\theta \approx 0.5°$ and the targets were very thin. Thus it is unlikely that limited experimental resolution led to a filling of the minima. It is possible that there are still noticeable compound nuclear contributions to the scattering cross section (as is the case in many other reactions involving such light nuclei).[14,16,17] Or else, some refinement of the DWBA calculations (more realistic deuteron and Li-scattering parameters, finite range interaction) may lead to predictions resembling the data more closely. Both possibilities are under further study.

In an earlier investigation of $C^{12}(Li^6,d)O^{16}$ for Li

[14] See, for example, R. L. Dangle, L. D. Oppliger, and G. Hardie, Phys. Rev. **133**, B647 (1964).

[15] R. H. Bassel, R. M. Drisko, and G. R. Satchler, Oak Ridge National Laboratory Report ORNL-3240, 1962 (unpublished).

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[17] E. B. Carter, G. E. Mitchell, and R. H. Davis, Phys. Rev. **133**, B1421 (1964).

energies near 3.5 MeV, strong variations of cross section with energy were found.[18] However, at such low energies a dominance of compound nuclear reactions is not surprising. Our center-of-mass energies are much higher and contributions from direct interactions should be greatly increased. Preliminary measurements of (d,Li^6) excitation functions at $\theta_{lab}=30°$ for $13<E_d<15$ MeV in this laboratory show no drastic sudden cross section changes with energy, and thus support this assumption. Other (d,Li^6) experiments have been reported for $B^{10}(d,Li^6)Li^6$ for deuteron energies up to 13.5 MeV.[19] The inverse reactions $Li^6(Li^6,d)B^{10}$, $Li^7(Li^6,d)B^{11}$, $B^{10}(Li^6,d)N^{14}$, $B^{11}(Li^6,d)N^{15}$ were investigated at lithium energies of about 2 and 4 MeV.[20,21] The authors of Refs. 19 to 21 do not draw definite conclusions with regard to the reaction mechanism, but suggest that direct interactions contribute noticeably to the reaction cross sections. Our results certainly agree with such an interpretation.

Once the reaction mechanism is well understood, (d,Li^6) reactions and other direct many-particle transfer reactions should be of great usefulness in the further investigation of the structure of nuclei. They should, in particular, help in the quantitative study of "clustering" in nuclei. We have evidence, some of it shown in Figs. 2 and 10, that large groups of nucleons (up to 7) can be transferred with relatively large cross sections in the deuteron bombardment of light nuclei. C^{12} and O^{16} do not have many open reaction channels, but F^{19} and O^{18} do (for the latter we have preliminary data). $F^{19}+d$ yielded He^4, Li^6, Li^7, and Be^9 in order of decreasing cross section. $O^{18}+d$ yielded He^4, Li^6, Li^7, and Li^8. (See Fig. 2.) On the other hand, we have not been able to uniquely identify He^6 ions for either target although they are energetically allowed. This may mean that there is very small probability for the formation of H^4 cluster in He^6 and possibly in O^{18} and F^{19} as well.

Summing up, it seems fair to say that many-particle transfer reactions such as (d,Li^6) promise to develop into useful spectroscopic tools. We plan to check the systematic features mentioned above by extending our preliminary excitation functions, and by investigating more target nuclei, preferably heavier ones. Preliminary measurements and calculations show, however, that there is little hope of carrying the investigation with 15-MeV deuterons beyond Al^{27}. The Coulomb barriers of higher Z targets inhibit the (d,Li^6) reaction drastically, so that accurate angular distributions cannot be measured. It would be necessary to continue experiments with deuteron beams of 20–40 MeV in order to investigate medium-weight nuclei, or to see transitions beyond those leading to the ground state with some probability.

ACKNOWLEDGMENTS

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