Systematics of the (d, ^{6}Li) Reaction and α Clustering in Heavy Nuclei*

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Data for the α-particle pickup reaction (d,^{6}Li) have been obtained at 35-MeV bombarding energy for even-even nuclei from ^{12}C to ^{238}U. The cross sections for the transitions to the ground states decrease approximately as $1/A_t^3$ where A_t is the target mass. α-particle transfer probabilities have been extracted from the data and are found to be substantially enhanced in heavy nuclei away from shell closures, particularly for deformed nuclei near $A \approx 150$. α-particle correlations appear to be related to two-nucleon pairing effects.

It is thought that clustering of nucleons, particularly α clustering, may be important in heavy nuclei. Hartree-Fock and other nuclear-matter calculations often predict significant clustering,[1] particularly in the surface region of heavy nuclei. Some evidence for such effects has been obtained from studies of α emission in (n, α) compound-nucleus reactions,[2] high-energy (p, $p\alpha$) and (α, 2α) knock-out reactions,[3-5] and, recently, (π, γ) reactions.[6] However, very little data from direct (d, ^{6}Li), (α, ^{8}Be), and (^{3}He, ^{7}Be) reactions exist for target nuclei $A > 70$.[7,8] Such data should be useful in the study of α clustering especially in the surface regions of heavy nuclei.[7,8]

We have studied the (d,^{6}Li) reaction on ^{12}C, ^{16,18}O, ^{20,22}Ne, ^{40}Ca, ^{58,60}Ni, ^{74}Ge, ^{88}Sr, ^{112,116,118,120,122,124}Sn, ^{140}Ce, ^{160}Dy, ^{166}Er, ^{208}Pb, and ^{238}U with a 35-MeV deuteron beam from The University of Michigan 83-in. variable-energy cyclotron. The targets (50–700 μg/cm^2) consisted of enriched isotopic material evaporated onto thin (≤ 40 μg/cm^2) carbon backings or enriched gas contained in a gas cell. The ^{6}Li reaction products were detected with a ΔE-E solid-state counter telescope located in a scattering chamber or with a position-sensitive detector placed in the focal plane of a magnetic spectrometer ($\Delta\Omega \approx 2$ msr). The latter permitted measurements for cross sections as small as ~5 nb/sr with an optimum resolution of about 30-keV full width at half-maximum.

Angular distributions for the ground-state → ground-state transitions have been measured[9,10] for the targets ^{12}C, ^{16,18}O, ^{20,22}Ne, ^{40}Ca, and ^{166}Er. In addition, angular distributions are available[11] at $E_d = 36$ MeV for several of the nickel and zinc isotopes as well as ^{114}Sn. Using the available angular distributions, we have performed distorted-wave Born-approximation (DWBA) calculations with parameters chosen to fit the existing data.[9-11] These calculations were the basis for choosing one (or more) observation angles for the heavier targets corresponding to maxima in the $L=0$ angular distributions ($\theta > 0°$). The measurements for nuclei $A > 40$ were made with a 6° (full-width) spectrometer aperture. Since this is a sizable fraction of the oscillation period of the predicted angular distributions (15° to 20°), errors of several degrees in the choice of the observation angles would not significantly affect our results. Although angular distributions are not available in the mass region $A \approx 200$, we have measured the elastic scattering of ^{6}Li on ^{208}Pb at $E_{^6\mathrm{Li}} = 51$ MeV and verified that our ^{6}Li optical model parameters are suitable. It should be noted that despite possible uncertainties in the choice of scattering angle particularly for $A \approx 200$, the measurements must represent lower limits to the cross sections and at most would *underestimate* the peak cross sections by about a factor of 5.

The laboratory cross sections observed at the measured or calculated first maximum beyond $\theta = 0°$ ($\theta \approx 10°$ to 25°) for the $L=0$ ground-state transitions are shown in Fig. 1. As determined from the data[9-11] with $A \lesssim 170$, the differential cross sections displayed also reflect the trend in the total (d, ^{6}Li) cross sections. The errors indicated are those due to statistics and estimated target thickness uncertainties. The general trend in the cross sections is a decrease with target mass A_t as $\sim 1/A_t^3$. The cross sections change less rapidly near $A \approx 100$ as noted previously.[7,8,11] Superimposed on the gross decrease with A_t are distinct and systematic variations of the cross sections, with local minima at $A \approx 58$, $A \approx 124$, and $A \approx 208$, and local maxima at $A \approx 116$ and $A \approx 160$.

The cross sections for the tin isotopes are shown in more detail in Fig. 2 where we display the results at $\theta_L \approx 17°$ for transitions to the ground

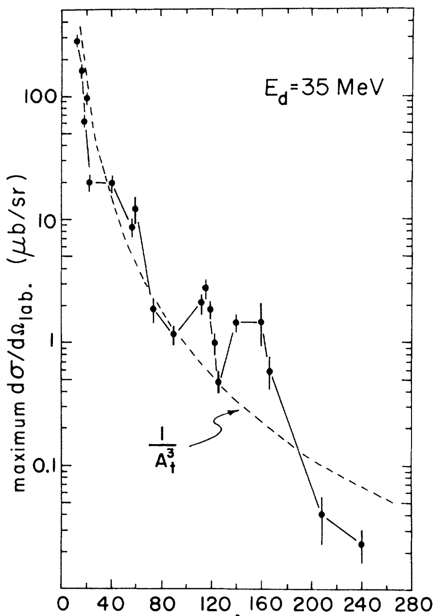

FIG. 1. Measured $(d,{}^6\mathrm{Li})$ ground-state cross sections at the calculated or measured first $L=0$ maximum beyond 0° versus the target mass number A_t (see text).

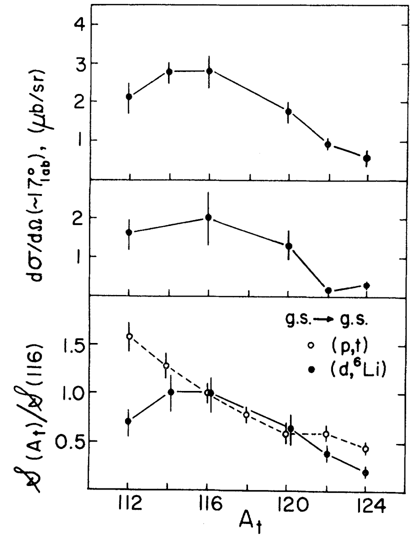

FIG. 2. Top and middle: Measured $\mathrm{Sn}(d,{}^6\mathrm{Li})\mathrm{Cd}$ ground state and 2^+ (first excited state) cross sections ($L=0$ maximum) versus target mass number. The ${}^{114}\mathrm{Sn}(d,{}^6\mathrm{Li})$ data ($E_d=36$ MeV) are taken from Ref. 11. Bottom: Comparison of the α and two-neutron spectroscopic factors deduced from $(d,{}^6\mathrm{Li})$ and (p,t) reactions (see text). The (p,t) data were taken from Ref. 17.

states and 2^+ first excited states. We include also data for ${}^{114}\mathrm{Sn}$ from Ref. 11 ($E_d=36$ MeV). Both the ground state and 2^+ cross sections exhibit the same type of behavior, namely a maximum for $A \approx 116$ and a substantial decrease as $A \to 124$. Data for the ground-state rotational bands in ${}^{162}\mathrm{Dy}$ and ${}^{234}\mathrm{Th}$ were also obtained. The measured cross sections for ${}^{162}\mathrm{Dy}$ at $\theta_L=12°$ are 0^+: 0.58 ± 0.18 μb/sr; 2^+: 0.29 ± 0.13 μb/sr; 4^+: 0.12 ± 0.08 μb/sr and for ${}^{234}\mathrm{Th}$ at $\theta_L=24°$, 0^+: 23 ± 7 nb/sr; 2^+: 14 ± 6 nb/sr; 4^+: 12 ± 5 nb/sr; 6^+: 14 ± 6 nb/sr.

The mass excess of ${}^{120}\mathrm{Cd}$ was measured by comparing the ground-state Q values for the targets ${}^{122}\mathrm{Sn}$ and ${}^{124}\mathrm{Sn}$. The result is $\Delta M({}^{120}\mathrm{Cd}) - \Delta M({}^{118}\mathrm{Cd}) = 2703\pm12$ keV which, when combined with the known[12] mass excess of ${}^{118}\mathrm{Cd}$, yields $\Delta M({}^{120}\mathrm{Cd}) = -84\,004\pm23$ keV. This result is close to the predicted values $-83\,920$ keV[13] and $-84\,176$ keV.[14]

As the $(d,{}^6\mathrm{Li})$ Q values are functions of A_t, we have attempted to separate kinematic (Q value) and spectroscopic effects by use of DWBA. We define a phenomenological quantity, S_α, the α spectroscopic factor, by

$$(d\sigma/d\Omega)^{\exp} = N S_\alpha (d\sigma/d\Omega)^{\mathrm{DWBA}}, \qquad (1)$$

where N is a normalization constant and $(d\sigma/d\Omega)^{\mathrm{DWBA}}$ is the no-recoil DWBA cross section.[15] Optical model parameters found suitable in other $(d,{}^6\mathrm{Li})$ studies[11] were used. The form factor was calculated by binding an α cluster in a Woods-Saxon well with $R=1.3A_t^{1/3}$ fm, $a=0.73$ fm, and adjusting V. The α-cluster quantum numbers were determined by forming a 1S cluster from protons and neutrons in valence orbitals. The nuclei $A_t \gtrsim 130$ are α-particle unbound by up to 5 MeV. Here, cross sections were calculated assuming α clusters bound at several energies and spectroscopic factors S_α were then obtained by extrapolation to binding energies greater than 0.

The S_α values deduced from our measurements for $A>40$ are shown in Fig. 3. The normalization factor N in (1) was arbitrarily adjusted to give $S_\alpha=1$ for ${}^{16}\mathrm{O}(d,{}^6\mathrm{Li})$. (The results for $A\le40$ including an investigation of finite-range effects, i.e., recoil and analysis of excited states, will be presented elsewhere.) The variations observed in the raw data (Figs. 1 and 2) are also reflected in the S_α values. In Fig. 3 we indicate the mass numbers[16] associated with the doubly magic nuclei ${}^{16}_{8}\mathrm{O}_8$, ${}^{56}_{28}\mathrm{Ni}_{28}$, ${}^{132}_{50}\mathrm{Sn}_{82}$, and ${}^{208}_{82}\mathrm{Pb}_{126}$. There appear to be minima in S_α associated with known shell closures. Furthermore, in the heavier nuclei we observe noticeable enhancements in S_α in the regions $N\approx66$ (open neutron shell) and $Z\approx66$, $N\approx94$ (open proton and neutron shells). The lat-

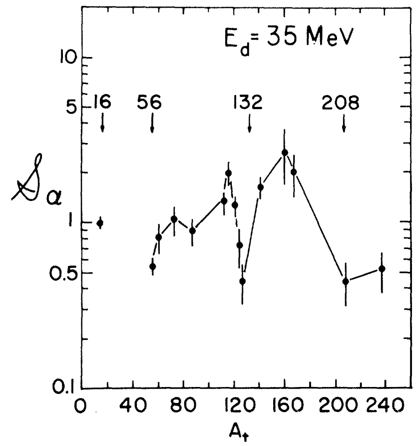

FIG. 3. The α-spectroscopic factors deduced from the $(d, {}^6Li)$ data using Eq. (1). Mass numbers associated with doubly magic nuclei are indicated at the top.

ter corresponds to permanently deformed nuclei, indicating that α clustering may be particularly important for these nuclei and may warrant further study. The variation of S_α with A_t near $A_t \approx 160$ appears to be remarkably similar (where data overlap) to the mass variation of the α preformation probability deduced from the study[2] of pre-equilibrium α emission in (n, α) reactions in the region $A_t = 140$ to 240.

In the lower part of Fig. 2 the relative variation of S_α extracted from our Sn$(d, {}^6Li)$ data is shown with the corresponding relative two-neutron "spectroscopic" factors which we have deduced from Sn(p, t) data.[17] Except for ^{112}Sn, there appears to be a close correspondence between the α and two-neutron correlations in these isotopes, supporting recent theoretical predictions.[18] In particular, the decrease in S for $A_t > 116$ appears to be associated with a neutron subshell closure, e.g., $2d_{5/2}$. Such an orbital is known[19] to be more favored in forming $1S$ nucleon pairs than the higher available neutron orbits such as $1h_{11/2}$.

The apparent relation between two-nucleon and α-particle correlations suggests that certain effects analogous to two-nucleon "superfluidity" may be present when α correlations are large. It has been suggested[20] that heavy-ion reactions involving transfer of two nucleons between "superconducting" nuclei, e.g., ^{118}Sn(^{120}Sn, ^{118}Sn)^{120}Sn, should exhibit enhancement phenomena similar to those observed in the Josephson effect in ordinary superconductors. Such an effect might also be observed in the α transfer between "α superconducting" nuclei, e.g., in ^{166}Er(^{162}Dy, ^{166}Er)^{162}Dy.

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