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α Transfer to ^{44}Ti by the (^{6}Li, d) Reaction

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The reaction ^{40}Ca(^{6}Li, d) has been studied at $E(^6\text{Li}) = 32$ MeV. Clearly structured angular distributions, with maximum cross sections of the same order of magnitude as those reported for the reaction ^{40}Ca(^{16}O, ^{12}C), are obtained. They are well described by α-transfer distorted-wave Born-approximation calculations.

The (^{6}Li, d) reaction, though rather extensively applied to the study of light nuclei,[1] has scarcely been used[2,3] for target nuclei with $A \geq 40$. Its cross section was believed to be very small in this mass region, and the (^{16}O, ^{12}C) reaction has been mainly used instead for α-transfer studies.[4,5] Increased interest in such studies has been prompted by the experimental results of the (^{16}O, ^{12}C) reaction on Ca and Ni isotopes and by the interpretation of these results in terms of quartet structures.[5]

In spite of its reported weakness, the (^{6}Li, d) reaction exhibits important advantages over the (^{16}O, ^{12}C) reaction which make it highly desirable to extend (^{6}Li, d) measurements to heavier nuclei. (i) Better energy resolution can be obtained because of the smaller energy loss of Li ions in the target. (ii) More clearly structured and hence more conclusive angular distributions are expected at energies easily obtained with tandem accelerators (Coulomb-barrier heights, $E_{\text{lab}} \approx 15$ MeV for Li+Ca and 40 MeV for O+Ca). (iii) The strongly developed α-d cluster structure[6] of ^{6}Li favors α transfer and justifies, at least as a first attempt, the utilization of an α-stripping distorted-wave Born approximation (DWBA) (which can be performed in zero-range approximation because of the s state of mutual α-d cluster motion). The parentage for $^{16}\text{O} \rightarrow \alpha + {}^{12}\text{C}$(g.s.) is weak,[7-9] and the comparably strong $^{16}\text{O} \rightarrow \alpha + {}^{12}\text{C}$(4.4 MeV) component impairs[10,11] the usefulness of the (^{16}O, ^{12}C) reaction for studies of α-particle transfer.

In the present study for the first time angular distributions for the reaction ^{40}Ca(^{6}Li, d)^{44}Ti are presented and discussed. This reaction is of special interest, ^{44}Ti with four nucleons outside a doubly closed shell being the fp-shell analog of ^{20}Ne, for which well-developed features of the α-like correlations are found.

The experiment was concurrently begun at Argonne[12] and at Rochester, and was finished at

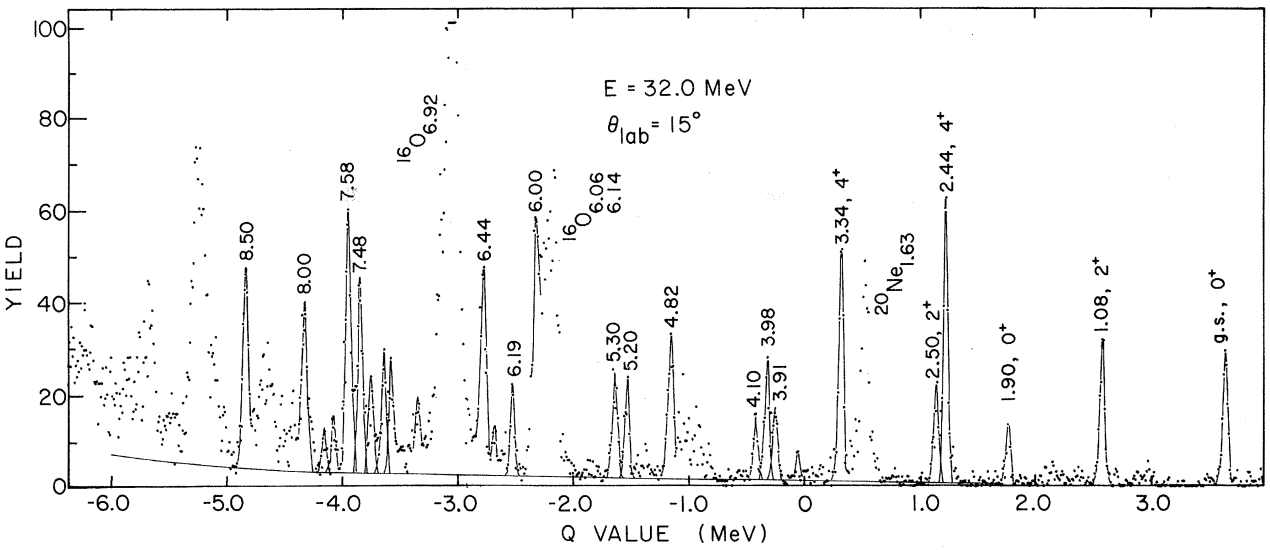

FIG. 1. ^{40}Ca(^{6}Li, d) spectrum.

Rochester using the MP tandem accelerator which provided a Li beam of up to 800 nA. The deuteron spectrum shown in Fig. 1 was obtained with a ~100-μg/cm^2 Ca target on a thin gold backing. The emitted particles were momentum analyzed with the Rochester split-pole spectrograph and detected by use of a spark counter[13] which allowed mass separation of the detected particles. The excitation energies given in Fig. 1 are those obtained in this experiment and may be compared with recent results from other reactions.[14-16] The question of the relative selectivity of the (^{6}Li, d) and the (^{16}O, ^{12}C) reactions cannot be answered because of the insufficient energy resolution obtained for the latter; the 2.44- and 2.50-MeV states and the states at ~4 MeV, for example, are not resolved in the (^{16}O, ^{12}C) spectra. The present energy resolution is 50 keV.

The spectra have been quantitatively analyzed by use of the code AUTOFIT.[17] Angular distributions have been obtained in the range from 5° to 42.5°, and some of them are displayed in Fig. 2. We stress the following important features of these results. (a) The angular distributions have maximum cross sections of the same order of magnitude as those reported for the (^{16}O, ^{12}C) reaction[4,5] at ~40 MeV; (b) they show structures typical of a direct mechanism, and, contrary to (^{16}O, ^{12}C) angular distributions, clearly discriminate between different final spins; (c) the angular distributions are surprisingly well described by zero-range DWBA results (solid curves).

In the DWBA calculations the transfer of a four-nucleon cluster with the same internal quantum numbers as those of a free α particle (in short, "α transfer") was assumed. In the framework of this simplified picture, as in single-nucleon transfer, the cross section can be factored into a kinematic factor and "spectroscopic factors" representing α strengths in ^{6}Li and ^{44}Ti so that

$$\frac{d\sigma}{d\Omega} = \frac{2I_f+1}{2I_i+1} S(^{6}\mathrm{Li}) S(^{44}\mathrm{Ti}) D^2 \frac{\sigma^{\mathrm{DW}}}{2J+1}. \quad (1)$$

The reduced cross section σ^{DW} was calculated by use of the zero-range DWBA code DWUCK.[18] The optical potentials used were those obtained at $E(d) = 34.4$ MeV by Newman *et al.*[19] and at $E(^{6}\mathrm{Li}) = 20$ MeV by Bethge, Fou, and Zurmuhle[20] except

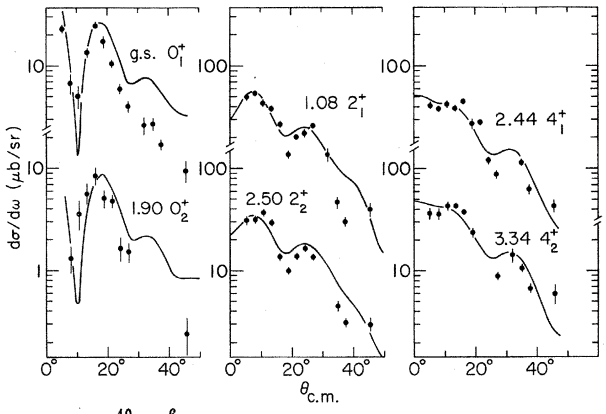

FIG. 2. ^{40}Ca(^{6}Li, d) angular distributions. The error bars indicate relative errors only. The absolute error is estimated at 25%. The curves represent α-transfer DWBA results as described in the text.

for an increase of the imaginary potential depth $W(^6\mathrm{Li})$ (to 8 MeV) due to the higher ^{6}Li energy in our experiment. The bound-state wave function of the transferred α cluster was generated with a real Woods-Saxon potential ($r = 1.8$ fm, $a = 0.65$ fm) whose depth was adjusted to reproduce the α separation energy. The number of nodes N in the bound-state wave function is determined by the requirement of energy conservation in the Talmi transformation from single-particle coordinates to internal and mutual cluster coordinates. The assumption that the α cluster and the Ca core are in their ground states restricts N to a unique value ($2N + L = 12$ for α transfer into the $0f1p$ shell, $L = l_f$). This is essential for the above-mentioned factorability of the cross section. A more realistic calculation would have to take account of coherent contributions from excited-cluster transfers with correspondingly different quantum numbers (N, L) for the mutual cluster motion. One may argue, however, that clusters in their lowest energy state correspond to wave functions of relative motion with maximum radial extension and thus make the maximum contribution to the cross section.

In view of the obvious success of the DWBA calculations in reproducing the characteristic features of the experimental angular distributions, it is reasonable to discuss spectroscopic factors on this basis. No absolute spectroscopic factors can be determined without knowledge of the constants D^2 and $S(^6\mathrm{Li})$. However, these factors cancel in deriving *relative* spectroscopic factors for different ^{44}Ti states. The relative spectroscopic factors for the "ground-state band" members 0_1^+(g.s.), 2_1^+(1.08 MeV), and 4_1^+(2.44 MeV) turn out to decrease strongly with increasing spin [$S/S(0_1^+) = 1$, 0.3, and 0.1, respectively] although they would be expected to remain constant if an extreme α-cluster model were valid.

Relatively strong transitions to the second 0^+ and 2^+ states at 1.90 and 2.50 MeV are observed [$S/S(0_1^+) = 0.3$ and 0.2]. These states are assumed to be based on core excitations[21] and to form the head of a rotational band.[14] The 4_2^+ state at 3.34 MeV populated with similar strength [$S/S(0_1^+) = 0.1$] is a possible candidate for the third member of this band.

A "quartet excited" state at an excitation energy[14] of ≈ 2 MeV has been predicted by Arima, Gillet, and Ginocchio.[22] It was suggested[14] that the 0_2^+ state might be of this 8p-4h (eight particle, four hole) configuration. In view of the small 4p-4h component[23] in the g.s. wave function of ^{40}Ca, however, the observed transition strength to this state is incompatible with such a configuration unless it has a strong 4p-0h admixture and/or a relatively strongly developed α-cluster configuration of the four transferred nucleons. More likely, the 0_2^+ state is of 6p-2h configuration[14,16] populated via the relatively large 2p-2h component in ^{40}Ca(g.s.).

The main results of this work can be summarized as follows. It has been shown that the (^{6}Li, d) reaction provides a suitable spectroscopic tool even in the region $A \sim 40$. The angular distributions are more conclusive than those of the (^{16}O, ^{12}C) reaction. Clearly the simple picture of α-particle stripping is open to skepticism. However, its surprising success in describing the angular distributions justifies its application as a first attempt to describe general features of the reaction.

This work is part of more comprehensive investigation of the (^{6}Li, d) reaction on Ca and Ti isotopes now in progress.

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Resolution of a Dilemma in ^{20}Ne†

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Spectroscopic strengths of 0^+ states observed in the reaction ^{19}F(^{3}He,d)^{20}Ne, together with calculations of α-particle widths, imply that the large α width of the 6.72-MeV state arises from mixing with a state of fp-shell character. A long-standing dilemma is thus resolved.

There are three excited 0^+ states in ^{20}Ne at E_x = 6.72, 7.20, and ~8.3 MeV.[1] From previous analyses of one- and two-nucleon transfer data,[2,3] it appears that the dominant configuration of the 6.72-MeV state consists of four nucleons in the $2s$-$1d$ shell outside an ^{16}O core. The 7.20-MeV state has been suggested[4] as an 8p-4h (eight-particle, four-hole) state, the dominant configuration being eight sd-shell nucleons outside a ^{12}C core. These two configurations are consistent with shell-model calculations.[5-7] The 8.3-MeV state has a very large α-particle reduced width,[1] much too large for this state to be of $(sd)^4$ configuration. Yet, the large α width requires good overlap with four nucleons outside an ^{16}O core. Thus, it is likely that the dominant configuration of this state is $(sd)^2(fp)^2$ or $(fp)^4$. The α-particle reduced widths for all three 0^+ states are displayed in Table I. The experimental α widths are from a recent compilation.[1] The single-particle α widths, Γ_α(s.p.), were calculated assuming that the α particle moves in a real Woods-Saxon potential well relative to an ^{16}O core. The well depth was adjusted to obtain the experimental separation energy.

The small α reduced width for the 7.20-MeV state is consistent with its supposed parentage, since its allowed α decay (to the 4p-4h state at 6.06 MeV in ^{16}O) is energetically forbidden. How-

TABLE I. α-particle widths for three excited 0^+ states in ^{20}Ne.

E_x (MeV ± keV)	Γ_α(expt)[a] (keV)	Γ_α(s.p.)[b] (keV)	$\frac{\Gamma_\alpha(\text{expt})}{\Gamma_\alpha(\text{s.p.})}$
6.722 ± 3[a]	15 ± 7	44	0.34 ± 0.16
7.196 ± 4[a]	4	234	0.017
~8.3[c]	~800[c]	1875	~0.43

[a]Ref. 1.
[b]Calculated in a Woods-Saxon well of radius R = 3.52 F, and diffuseness a = 0.60 F. The well depth was adjusted to reproduce the experimental separation energies.
[c]From present work.