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^{6}Li(d, d′): Direct Breakup Effects and Parameters of the First 2^+ Level of ^{6}Li

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Abstract

The reaction ^{6}Li(d, d′) has been used to populate the first $J^\pi = 2^+$ level of ^{6}Li. To obtain level parameters, use has been made of a reaction theory which allows for direct breakup effects. The width obtained is $1\cdot82 \pm 0\cdot11$ MeV, which is consistent with results of ^{4}He+d scattering experiments, though some detailed discrepancies remain unexplained. The position of the level is found to be $4\cdot32 \pm 0\cdot04$ MeV.

The levels at 4·57 and 5·36 MeV in ^{6}Li (Lauritsen and Ajzenberg-Selove 1966) are of some current interest (see e.g. Cocke and Adloff 1971; Debevec *et al.* 1971; DeVries *et al.* 1972; Kane *et al.* 1972; Artemov *et al.* 1973; Bray *et al.* 1973). They both have $J^\pi = 2^+$ and overlap, yet isospin mixing between them is very weak, because of their particular single-particle nature. During work aimed at determining their isospin mixing (Bray *et al.* 1973), it was pointed out by F. C. Barker (personal communication) that the width of the 4·57 MeV state, as populated by ^{4}He(d, d) scattering, was very much larger than that reported by Groce and Whaling (1963) from a study of the reaction ^{9}Be(p, α). The ^{4}He+d results are also in disagreement with other studies in which the levels of ^{6}Li were observed as final states (Hasselgren *et al.* 1965; Mani and Dix 1968; Eigenbrod 1969).

We report here on a study of the ^{6}Li(d, d′) reaction with beam energies of 20 and 25 MeV. Our purpose was twofold: (i) to detect the 4·57 MeV, $T = 0$ level populated strongly as a final state under conditions where the primary outgoing deuterons (d′) were unambiguously detected, and (ii) to investigate whether direct breakup effects, as recently proposed by Treacy (1975), would be evident in fitting the parameters of the final state. With reference to (i), we note that in the work of Groce and Whaling (1963), which used a beam of 10 MeV protons, the primary α-particles associated with the supposed state would lie just within the upper end of the energy range of 'secondary' α-particles from the α+d breakup of the 2·18 MeV level of ^{6}Li, which is strongly populated in the (p, α) reaction. This kinematic ambiguity is not present with higher energy beams, such as 20 MeV deuterons in (d, d′). The second aim (ii) relates to a rather obvious consequence of direct reactions to particle-unstable final states. In any model, the final state wavefunction has a non-decaying oscillatory amplitude outside the usually-assumed nuclear radius. For a direct reaction where there is overlap between the incident and final states, there are correspondingly significant contributions to the reaction amplitude external to the nucleus. Physically, this means that for a direct transition from ^{6}Li+d to

(^{4}He+d)+d the final state of three particles may be created well out in the 'tail' of the nuclear potential. Internal breakup, alone, has a simple resonant dependence on final state energy, while the total energy dependence is of a modified form, as defined in equation (1) below.

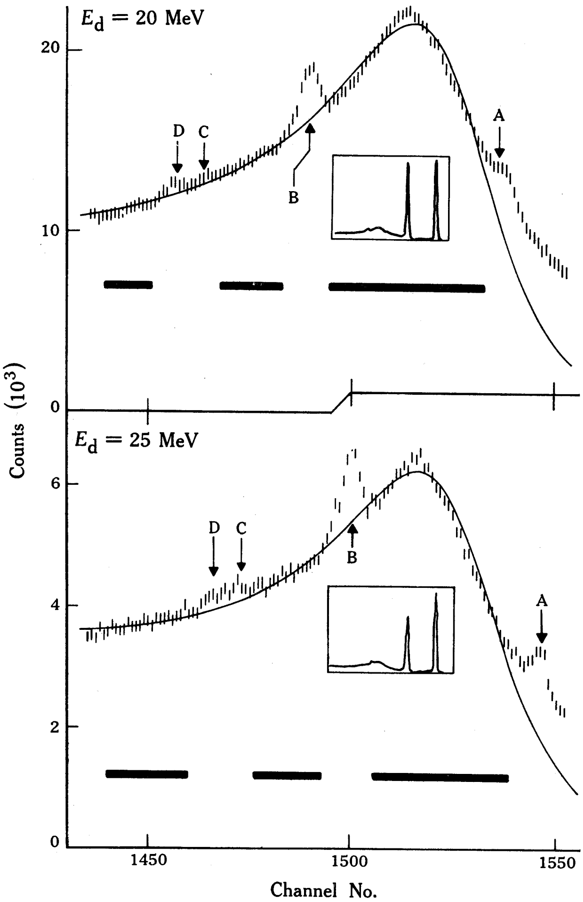

Fig. 1. Spectra for the ^{6}Li(d, d′) reaction at $\theta_{d'} = 30°$(lab.) with incident deuteron energies of 20 and 25 MeV. The data are shown by vertical lines (their lengths do not represent the uncertainties). The continuous curves are the fits to the data using equation (1). Peaks labelled A, B, C and D are inelastic deuteron groups due to the 4·4 MeV state of ^{12}C and the 6·1, 6·9 and 7·1 MeV states of ^{16}O respectively. The bold horizontal bars below each spectrum show the channels actually included in the fitting procedure. The insets show, on a smaller scale, the complete spectrum observed at each energy.

A deuteron beam from the A.N.U. Tandem Van de Graaff accelerator, using the sector-focused cyclotron as injector, was used to bombard a 5 mg cm^{-2} foil of ^{6}Li(99·3% isotopic purity) made by rolling lithium metal. Deuteron spectra were recorded using a ΔE–E particle identifier (England 1973). With this arrangement an energy resolution, determined mainly by the detector solid angle, of about 200 keV was obtained as well as, of course, exclusive deuteron detection. Scattered deuteron spectra were recorded over a range of energies and angles. Two of these, at 30°(lab.) and beam energies of 20 and 25 MeV, are plotted in Fig. 1. The insets in the figure show the complete spectra, including transitions to the ground and first excited states of ^{6}Li. Note that, as expected, the $T = 1$ states at 3·56 and 5·36 MeV are not evident. In each of the expanded spectra, the 4·57 MeV group is clearly seen, together with sharp peaks identified uniquely by their energies as being from ^{12}C(d, d′) and ^{16}O(d, d′), superimposed on a continuous background.

As mentioned under (ii) above, contributions from direct breakup are expected, and each spectrum was fitted with the form (Treacy 1975)

$$\sigma(E_{\mathrm{d}'}) = P(E_{\mathrm{d}'}) \sum_c | G_\lambda^{\frac{1}{2}}(\mathrm{d},\mathrm{d}') A_{\lambda\mu} \Gamma_{\lambda c}^{\frac{1}{2}} + B_c \Gamma_{\lambda c}^{\frac{1}{2}} |^2 , \tag{1}$$

where $P(E_{\mathrm{d}'})$ is a (kinematic) deuteron penetration factor, $G_\lambda(\mathrm{d},\mathrm{d}')$ a feeding amplitude for the (d, d′) process and B_c a complex constant breakup amplitude in the $\alpha+\mathrm{d}$ channel only. The other terms in equation (1) are standard R-matrix parameters for the single, fed level λ and channels c of ^{6}Li. Open channels include $\alpha+\mathrm{d}$, $\alpha+\mathrm{d}^*$, $\mathrm{p}+{}^5\mathrm{He}$ and $\mathrm{n}+{}^5\mathrm{Li}$, though isospin selection inhibits the decay $\alpha+\mathrm{d}^*$ to the singlet deuteron ($T = 1$) state. Fits were determined, as a function of the parameters $(E_\lambda, \gamma_{\lambda c}, B_c)$, for a range of channel radii from 3·8 to 4·6 fm, with allowance made for the finite widths of the 'final' levels in the $\mathrm{p}+{}^5\mathrm{He}$ and $\mathrm{n}+{}^5\mathrm{Li}$ channels. The best fits were obtained for 4·2 fm; these are plotted as continuous curves in Fig. 1, while the χ^2 measures of the fits are listed in Table 1, together with the constant

Table 1. Parameters for fits to data of Fig. 1 with equation (1)

Beam energy (MeV)	E_x (MeV)	$\gamma_{\lambda\alpha}$ (MeV$^{\frac{1}{2}}$)	$\gamma_{\lambda p}$ $(=\gamma_{\lambda n})$ (MeV$^{\frac{1}{2}}$)	E_r (MeV)	Γ^0 (MeV)	χ^2	Resonant to total ratio
20	4·36	2·20	0·35	4·52	1·71	6·66	0·60
25	4·29	2·31	0·03	4·58	1·93	3·60	0·43

E_r and $\gamma_{\lambda c}$ and 'useful' parameters (E_x is the peak excitation, E_r the resonance energy and Γ^0 the observed resonant (FWHM) width). Also listed in Table 1 is the resonant to total ratio of the calculated $\sigma(E_{\mathrm{d}'})$, averaged over $\pm\frac{1}{2}\Gamma^0$, for B_c zero and optimized respectively. This shows that the B_c term is of intensity about 50%. 'Natural' boundary conditions were applied for all channels at energy E_x. With an energy calibration based on the ground and 2·18 MeV states of ^{6}Li as well as the contaminant peaks, a mean excitation energy for the first 2^+ state of ^{6}Li of $4{\cdot}32 \pm 0{\cdot}04$ MeV was obtained, in agreement with Eigenbrod (1969). The fits to the spectra, using equation (1), are satisfactory and the mean observed width of $1{\cdot}82 \pm 0{\cdot}11$ MeV compares favourably with results from $^4\mathrm{He}+\mathrm{d}$ scattering (Galonsky and McEllistrem 1955; Senhouse and Tombrello 1964; Kraus *et al.* 1969; Schmelzbach *et al.* 1972). A more detailed analysis, including data obtained from several other reactions (to be published elsewhere), shows that individual reduced width amplitudes implied by scattering experiments and reactions differ in detail: in the former the α width is less and the nucleon widths apparently greater. Such discrepancies probably reflect our ignorance of the details of the mechanism of the direct reaction. However, it is clear that the type of coherent interference described by equation (1) does occur in this reaction. For example, the width Γ^0 of Table 1, which is compatible with scattering data, is considerably less than the peak width seen in Fig. 1. In the fit to the data, that peak evidently is considerably broadened by the nonresonant contribution.

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