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STRUCTURE OF ^{7}Be
(I). The ^{6}Li(p, p′)^{6}Li* reaction

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Abstract: The differential cross section for the ^{6}Li(p, p′)^{6}Li* (2.184 MeV) reaction was measured over a range of incident proton lab energies between 3.60 and 9.40 MeV. The analysis of a broad resonance indicates the presence of a 1.8 MeV broad state in ^{7}Be at about 10.0 MeV excitation energy with the properties $J^{\pi} = \frac{3}{2}^{-}$ or $\frac{5}{2}^{-}$, with $\frac{7}{2}^{-}$ or $\frac{9}{2}^{-}$ being possible but less probable, and $T = \frac{1}{2}$.

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NUCLEAR REACTIONS ^{6}Li(p, p′), E = 3.60 to 9.40 MeV; measured $\sigma(E, \theta)$. ^{7}Be deduced levels, J, π, l, T, Γ of levels. Enriched target.

1. Introduction

The ^{6}Li(p, p′)^{6}Li* reaction was studied to obtain further information about the structure of the compound nucleus ^{7}Be in the excitation energy region above the threshold for this reaction, 7.79 MeV. Previous study [1]) of the ^{6}Li(p, p)^{6}Li reaction indicated the existence of a broad state at about 10 MeV excitation in ^{7}Be; it was not possible, however, to obtain unambiguous assignments for the quantum numbers of this state due to the complexity of the problem. Subsequent studies of other reactions have indicated the existence of additional structure in this excitation region of ^{7}Be. Another broad state at about 9.2 MeV is observed in the ^{4}He(^{3}He, ^{3}He)^{4}He and ^{4}He(^{3}He, p′)^{6}Li* reactions [2]) and a narrower state at about 10.9 MeV, in the ^{6}Li(p, p″)^{6}Li**, ^{4}He(^{3}He, p″)^{6}Li** and ^{9}Be(p, t)^{7}Be reactions [refs. [3–5]) respectively].

Recent intermediate coupling shell model calculations [6]) predict four states in the region of ^{7}Be between 8 and 11 MeV. These are three $T = \frac{1}{2}$ states close to the L-S coupling limit with the configurations $^{4}D_{\frac{7}{2}}$, $^{4}P_{\frac{3}{2}}$ and $^{4}P_{\frac{1}{2}}$ dominant, and one $T = \frac{3}{2}$ state with the two configurations $^{2}P_{\frac{3}{2}}$ and $^{2}D_{\frac{3}{2}}$ mixed.

The experimental method and results are discussed in sect. 2 and the analysis is outlined in sect. 3. A summary is given in sect. 4.

2. Experimental method and results

Targets of ^{6}Li (isotopic abundance 99%) were bombarded with protons from the ONR-CIT tandem accelerator. The targets, ranging in thickness from 70 to 300

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$\mu g/cm^2$, were evaporated in situ on 500 Å thick nickel foils [1]). The beam spot size was 1.8 mm by 1.8 mm at the target position. Two silicon surface-barrier detectors were used, one at a fixed angle as a target monitor. The movable detector subtended a solid angle determined by an aperture 0.76 mm wide and 4.8 mm high, located 11 cm from the target. The overall resolution was about 70 keV, including a contribution from the natural width of the ^{6}Li* state, about 30 keV. A 10^4 Å nickel foil, used to

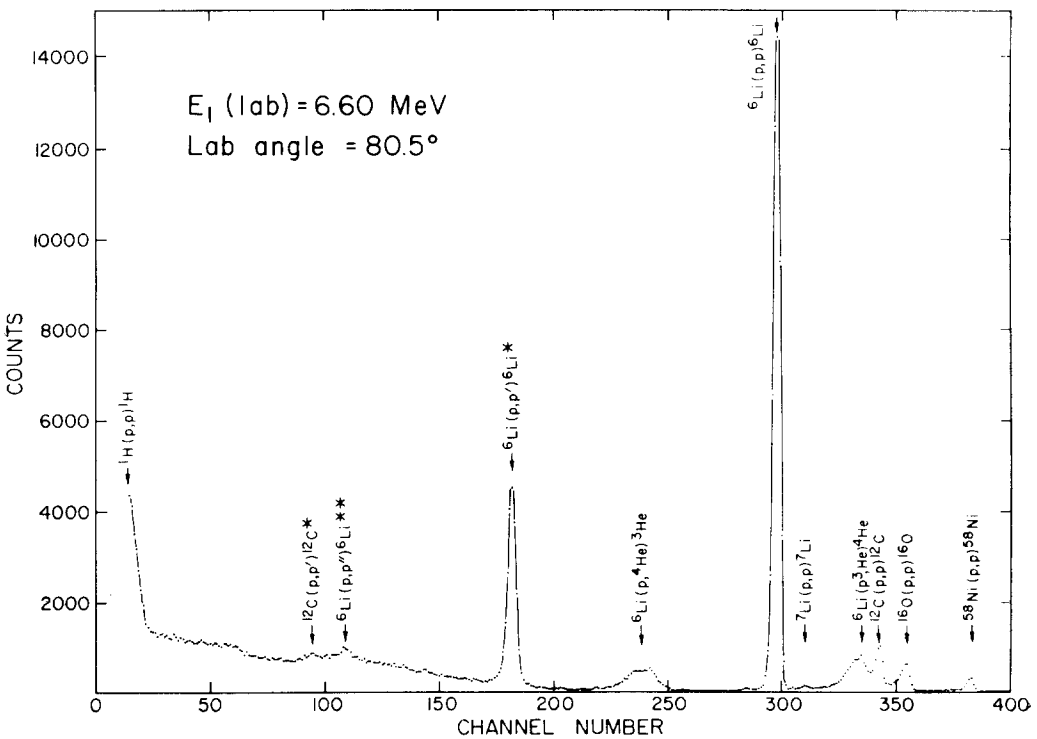

Fig. 1. Sample spectrum. One channel is approximately 16.7 keV.

separate proton and α-particle groups at some energies and angles, could be positioned in a slot between the detector face and the solid angle defining aperture. The arrangement was designed to eliminate changes in the effective solid angle induced by the foil.

At each energy and angle, the portion of the scattered particle spectrum containing the ^{6}Li(p, p')^{6}Li* proton group was recorded in a multi-channel analyser in order to estimate the many-body reaction background, typically about 20 %. At most energies, complete spectra were taken at two angles and used to obtain the normalization of the ^{6}Li(p, p')^{6}Li* data relative to ^{6}Li(p, p)^{6}Li data [1]) for which the absolute normalization was known. One of these spectra is shown in fig. 1. Twelve angular distribu-

tions were obtained for incident proton lab energies between 3.60 and 9.40 MeV. Two of these are plotted in fig. 2 and numerical values are given in ref. [7]).

The series of Legendre polynomials

$$c_1P_0+c_2P_1+ \ldots +c_MP_{M-1}$$

was fitted to each angular distribution. Using the CIT IBM-7090 computer, the coeffi-

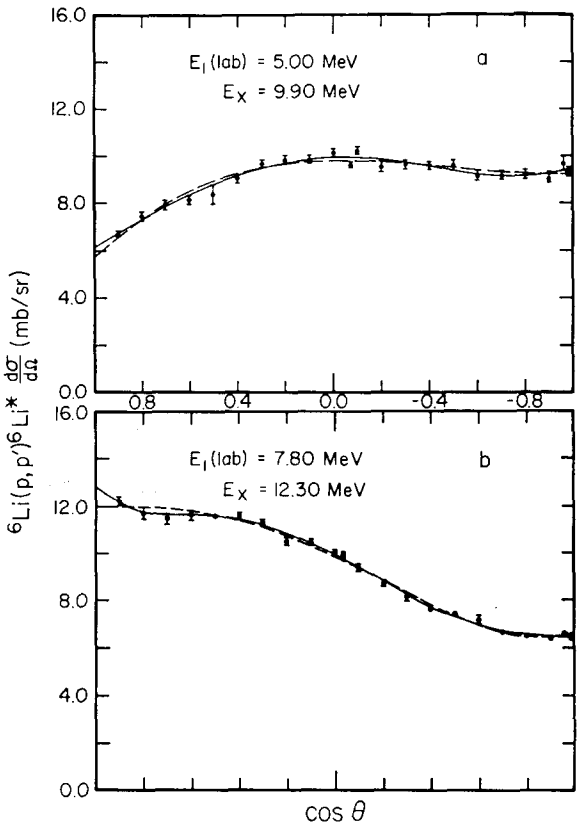

Fig. 2. Sample angular distributions and estimated standard errors. All quantities are expressed in the c.m. system. In fig. 2a, a Legendre polynomial series stopping at P_3 was used in fitting the broken curve; a series stopping at P_4, in fitting the solid curve. In fig. 2b, series stopping at P_4 and at P_5 were used in fitting the corresponding curves.

cients $c_1, \ldots c_M$ were evaluated by the method of least squares, with each data point weighted by the reciprocal of the square of its background error. Because the errors were poorly determined, the usual "goodness of fit" criteria were of little use in the determination of M, the number of polynomial terms required to fit each angular distribution. Fits obtained for different values of M are shown in fig. 2. In all cases, a value of M was chosen which corresponded to the simplest calculated angular

distribution judged to give an adequate fit to the experimental data. In fig. 3, the polynomial coefficients are plotted as a function of ^{7}Be excitation energy. The standard errors given were calculated from the background errors assumed for the data and from the errors, typically $\approx 2\,\%$, in the relative normalizations of the angular distributions.

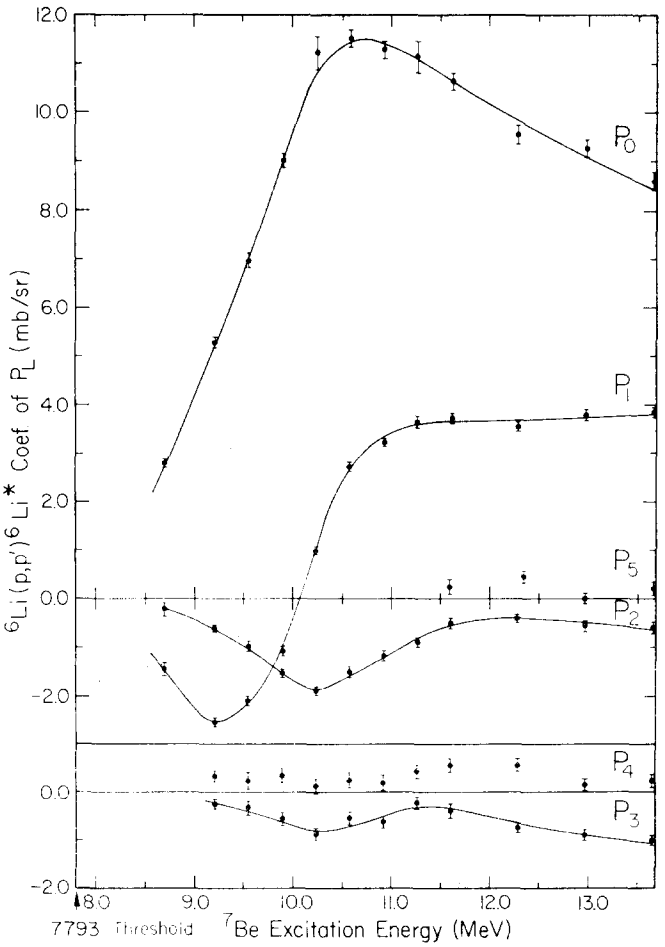

Fig. 3. The Legendre polynomial coefficients. Each coefficient is labelled by the polynomial, and smooth curves have been drawn through some of the points. The coefficient of P_0 is equal to the total c.m. cross section divided by 4π.

3. Analysis

An analysis of the Legendre polynomial coefficients was performed using some of the results of scattering and resonance theories. The scattering matrix $\boldsymbol{U}$ was used in the representation $U^J_{\alpha' s' l', \alpha s l} \equiv U_{c'c}$, where J is the total angular momentum, α labels

the particles in the incoming channel, s their channel spin, and l their relative orbital angular momentum. The primed quantities refer to the outgoing channel. Resonance formulae corresponding to the extreme single-level approximation of the complex-eigenvalue theory of Humblet and Rosenfeld [8]) were used:

$$|U_{c'c}|^2 = C_{c'c1}\,\frac{P_{c'}P_c}{(E-E_1)^2+\frac{1}{4}\Gamma_1^2}\,. \tag{1}$$

The resonant state has been given the label 1. The constants E_1 and Γ_1 are the resonant energy and the total width, and the constant $C_{c'c1}$ contains the partial widths. The energy-dependent quantities $P_{c'}$ and P_c are the penetration factors. Formula (1) is independent of the channel radii if the penetration factors of ref. [9]) are used. (An additional factor $k_c k_{c'}$ in the formulae of ref. [9]) has been absorbed in the definition of the penetration factors in formula (1).) Alternatively, the radius-dependent penetration factors of R-matrix theory [10]) can be used, and the resulting version of formula (1) is identical in energy-dependence to the corresponding formula of R-matrix theory, if linear functions of energy are assumed for the R-matrix level shift and total width. It was not possible to use the R-matrix formula without this assumption because of the large width of the resonant structure and the large number of open channels.

The Legendre polynomial coefficients can be written in terms of $\boldsymbol{U}$ using well-known formulae [10]). Formula (1) is not applicable to an odd order polynomial coefficient, but may be applicable to an even order coefficient dominated by a single resonant state. If, in such a case, the coefficient contains the form, $a|U_1|^2+b|U_2|^2$, where the terms are of the same J^π but refer to different channel spins, for example, the energy dependence of formula (1) is correct, although the meaning of the constant $C_{c'c1}$ is altered. If it is assumed that because of the Coulomb and centrifugal barriers only the contributions from the s, p and d incoming l-values, and from the s and p outgoing l-values are important, the P_2 coefficient contains only terms with $l = l' = 1$. The behaviour of the P_2 coefficient in the present case suggests that it may be dominated by a state having these properties. Because the reacting particles have the properties p($J^\pi = \frac{1}{2}^+$), ^{6}Li(1^+) and ^{6}Li*(3^+), the channel spins are $s = \frac{1}{2}$ or $\frac{3}{2}$ and $s' = \frac{5}{2}$ or $\frac{7}{2}$; the parity of an element $U_{c'c}$ is $(-)^l = (-)^{l'}$. The P_2 coefficient is then given by

$$\begin{aligned} k^2 \times (\text{coeff. of } P_2) = {} & \tfrac{1}{20}|U^{\frac{5}{2}}_{\frac{7}{2}1,\,\frac{3}{2}1}|^2 - \tfrac{4}{25}|U^{\frac{5}{2}}_{\frac{5}{2}1,\,\frac{3}{2}1}|^2 . \\ & - \sqrt{\tfrac{63}{1250}}\,\mathrm{Re}(U^{\frac{5}{2}*}_{\frac{5}{2}1,\,\frac{3}{2}1}\,U^{\frac{3}{2}}_{\frac{5}{2}1,\,\frac{3}{2}1}) \\ & - \tfrac{2}{75}|U^{\frac{3}{2}}_{\frac{5}{2}1,\,\frac{3}{2}1}|^2 + \tfrac{1}{30}|U^{\frac{3}{2}}_{\frac{5}{2}1,\,\frac{1}{2}1}|^2 . \end{aligned} \tag{2}$$

Fits of formula (1) to the P_2 coefficient were made in an attempt to determine the resonant l-values from the l-dependence of the penetration factors. Fits for $l' = 1$, $l = 1$ and 3 are shown in fig. 4. No fits were possible for other combinations of l-values allowed by the conservation of angular momentum and parity. The best fits were

obtained with radius-dependent penetration factors and the parameters $E_1 = 10.0$, $\Gamma_1 = 1.8$, where the units are MeV ^{7}Be excitation energy. Although even the incomplete expansion (2) contains contributions from several states, the quality of the fits suggests that a single state with $l' = 1$ does in fact dominate the P_2 coefficient. With the given l-values, channel spins, and intrinsic parities, the J^π assignment of the state is $\frac{3}{2}^-$ or $\frac{5}{2}^-$, with $\frac{7}{2}^-$ or $\frac{9}{2}^-$ being possible but less probable. The isospin assignment should be $T = \frac{1}{2}$, because the reacting particles have $T = 0$ and $T = \frac{1}{2}$, respectively.

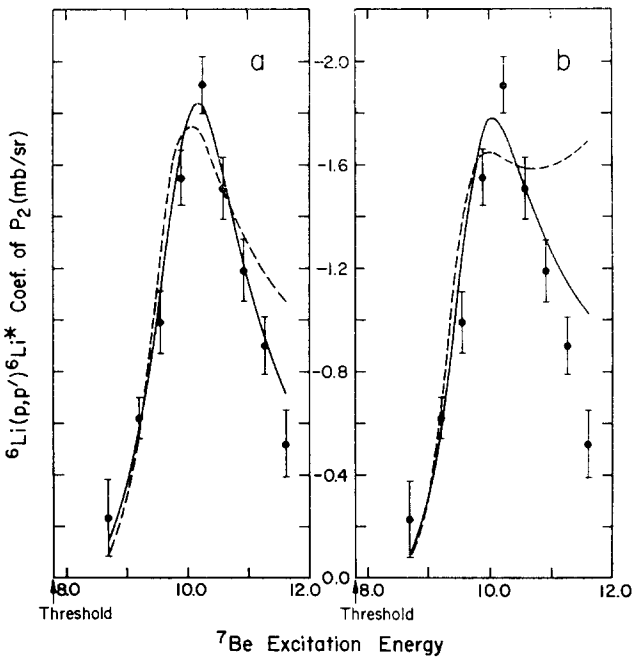

Fig. 4. Single-level fits to the P_2 coefficient. Radius-dependent penetration factors for both channel radii equal to 4.08 fm were used in fig. 4a; radius-independent penetration factors in fig. 4b. The solid curves are for $l = l' = 1$; the dashed curves for $l = 3$, $l' = 1$.

A single-level fit to the P_0 coefficient was not possible, implying that several states contribute significantly to its behaviour. Little can be inferred from the coefficients of the other polynomials, except that broad states of both parities, some with appreciable widths for higher l-values, contribute to the reaction, or direct interactions are playing an appreciable role. Little quantitative information about partial widths was obtained, although this problem is considered in more detail in ref. [7]).

4. Summary

A broad state at about 10.0 MeV ^{7}Be excitation energy with a width of about 1.8 MeV was identified, in agreement with the qualitative results of the ^{6}Li(p, p)^{6}Li

reaction. On the basis of an analysis using single-level formulae and scattering theory, the $l' = 1$ assignment for the decay of the state was made, permitting the limits $J^{\pi} = \frac{3}{2}^{-}$ or $\frac{5}{2}^{-}$, with $\frac{7}{2}^{-}$ or $\frac{9}{2}^{-}$ being possible but less probable, to be set. The isotopic spin $T = \frac{1}{2}$ was assigned. The state seems to have a large ^{6}Li + p width, an appreciable ^{6}Li* + p′ width, and a small ^{4}He + ^{3}He width. The state may possibly be identified with a predicted $^{4}P_{\frac{3}{2}}$ shell model state [6]), as discussed more fully in the following paper.

The best fits to the data were obtained with radius-dependent, rather than radius-independent, penetration factors, although the present reaction is too complicated to provide a good test of different versions of resonance theory.

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