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STRUCTURE OF ^{7}Be

(II). The ^{6}Li(p, p″)^{6}Li** and ^{4}He(^{3}He, p″)^{6}Li** reactions

WILLIAM D. HARRISON

California Institute of Technology, Pasadena, California

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Abstract: The total and the differential cross sections for the ^{6}Li(p, p″)^{6}Li** (3.562 MeV) reaction were measured over a range of incident proton lab energies between 4.26 and 9.40 MeV. The total cross section for the ^{4}He(^{3}He, p″)^{6}Li** reaction was measured over a range of incident ^{3}He lab energies between 13.81 and 18.45 MeV. The analysis indicates the presence of two interfering states, both with $J^{\pi} = \frac{3}{2}^{-}$, located at about 10.0 and 11.0 MeV excitation energy in ^{7}Be. The widths are 1.8 and 0.4 MeV, and isospins are $T = \frac{1}{2}$ and $T = \frac{3}{2}$, respectively. Values for the reduced widths of the isospin allowed channels of the $T = \frac{3}{2}$ state have been extracted, and the Thomas-Ehrman shift with respect to the corresponding ^{7}Li state estimated. The existence of an extremely broad $J^{\pi} = \frac{1}{2}^{-}$ state at roughly 10 MeV or greater ^{7}Be excitation energy is suggested. Measurements were made to determine the correct normalization of several sets of data on eight ^{7}Be-forming reactions.

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NUCLEAR REACTIONS ^{6}Li(p, p″), $E = 4.26$ to 9.40 MeV; measured $\sigma(E, \theta)$.
^{4}He(^{3}He, p″), $E = 13.81$ to 18.45 MeV; measured $\sigma(E)$.
^{7}Be deduced levels, J, π, l, T, Γ, γ^2. Enriched ^{6}Li target.

1. Introduction

These reactions were studied to obtain further information about the structure of the compound nucleus ^{7}Be in the excitation energy region above the threshold for the reactions, 9.17 MeV. A brief account of other work relating to this region is given in the introduction and summary of the preceding paper.

The experimental method and results of the studies of the ^{6}Li(p, p″)^{6}Li** and ^{4}He(^{3}He, p″)^{6}Li** reactions are given in subsects. 2.1 and 2.2 respectively. In subsect. 3.1 the analysis in terms of two interfering states of the same J^{π} is outlined. In subsect. 3.2 the extraction of reduced widths is considered, and a Thomas-Ehrman shift calculated. A summary is given in sect. 4. In appendix A the possible influence of the ^{6}Be+n threshold is considered, and in appendix B the results of a program to determine a consistent relative normalization for several ^{7}Be-forming experiments are given.

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2. Experimental method and results

2.1. THE ^{6}Li(p, p'')^{6}Li** REACTION

Several independent sets of measurements were made, and much of the apparatus was similar to that described in the preceding paper. In one set of measurements the total cross section was determined by measuring at one angle the yield of the 3.56

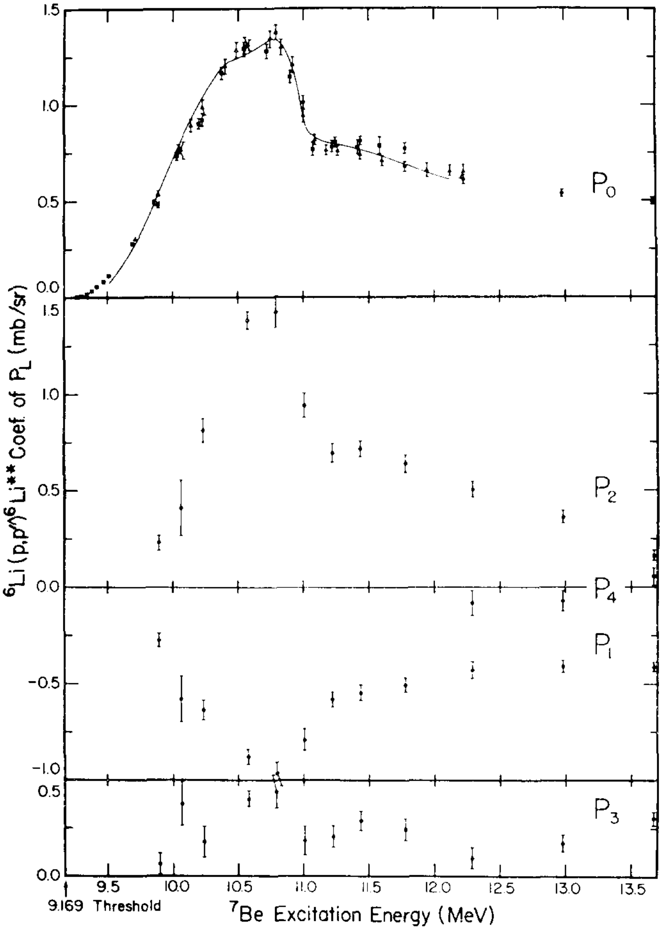

Fig. 1. The Legendre polynomial coefficients. The coefficient of P_0 is equal to the total c.m. cross section divided by 4π. The data represented by the squares and by the triangles were obtained from γ-ray measurements using 5.08 by 5.08 cm and 7.62 by 7.62 cm NaI(Tl) detectors respectively. The data represented by circles were obtained from the angular distributions. The curve represents a two-level fit with radius-dependent penetration factors and a radius of 4.08 fm.

MeV de-excitation γ-rays to the ^{6}Li ground state. This procedure is valid because the ^{6}Li** state has spin zero. The yield was measured at 90° where corrections due to the ^{6}Li** recoil velocity v are of order v^2/c^2 and completely negligible. Energy loss corrections were made for the target thickness (700 μg/cm^2) and the beam energy broadening in the target was about 40 to 55 keV. A γ-ray spectrum was taken at each energy and the 4.433 MeV γ-ray from ^{12}C contamination of the target was subtracted, using a 4.433 MeV γ-ray spectrum obtained from the proton bombardment of a ^{12}C foil. The results are plotted as a function of ^{7}Be excitation energy in the first part of fig. 1, and were obtained for incident proton lab energies between 4.26 and 7.80 MeV. The estimated standard errors are given. These data were normalized using a particle angular distribution at 5.80 MeV obtained in a second series of measurements.

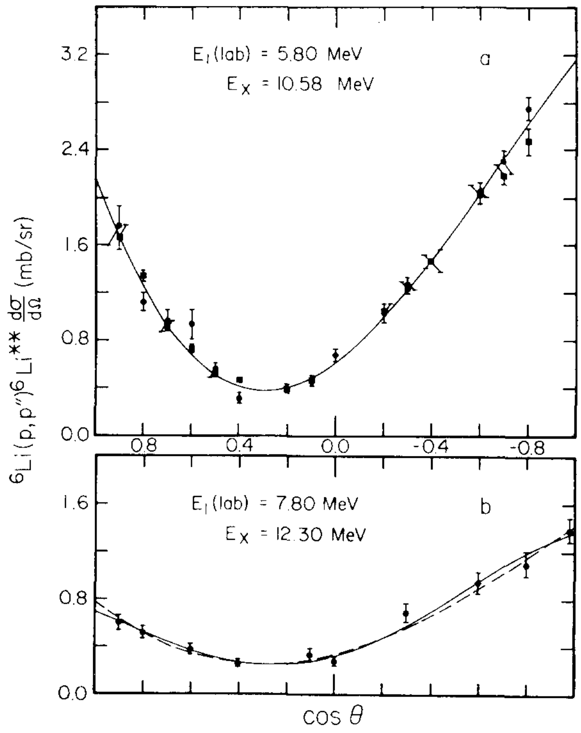

Fig. 2. Sample angular distributions and estimated standard errors. All quantities are expressed in the c.m. system. The data obtained by direct measurement are represented by circles; the data obtained by the p-γ coincidence technique, by squares. Polynomial series stopping at P_3 were used in fitting the curve in fig. 2a and the broken curve in fig. 2b; a series stopping at P_4, in fitting the solid curve in fig. 2b.

In the second series of measurements particle angular distributions were determined using the apparatus and technique described in the preceding paper. The ^{6}Li targets used ranged in thickness from about 30 to 130 $\mu g/cm^2$. The dominant error was the large many-body reaction background, which was typically from 2.5 to 10 times as large as the number of counts in the proton group. Typical angular distributions, normalized to the $^{6}Li(p, p)^{6}Li$ data of ref. [1]), are shown in fig. 2 and the results of the Legendre polynomial fits to the angular distributions are shown in fig. 1, with estimated standard errors.

At one energy an attempt was made to remove the many-body reaction background by requiring a coincidence between the proton and accompanying isotopic γ-ray. With the resulting low counting efficiency, however, the results (fig. 2) were little better than those obtained by direct background subtraction.

2.2. THE ^{4}He(^{3}He, p″)^{6}Li** REACTION

The total cross section was determined by measuring the yield of the 3.56 MeV de-excitation γ-rays. ^{3}He$^-$ ions were injected into the ONR-CIT tandem accelerator

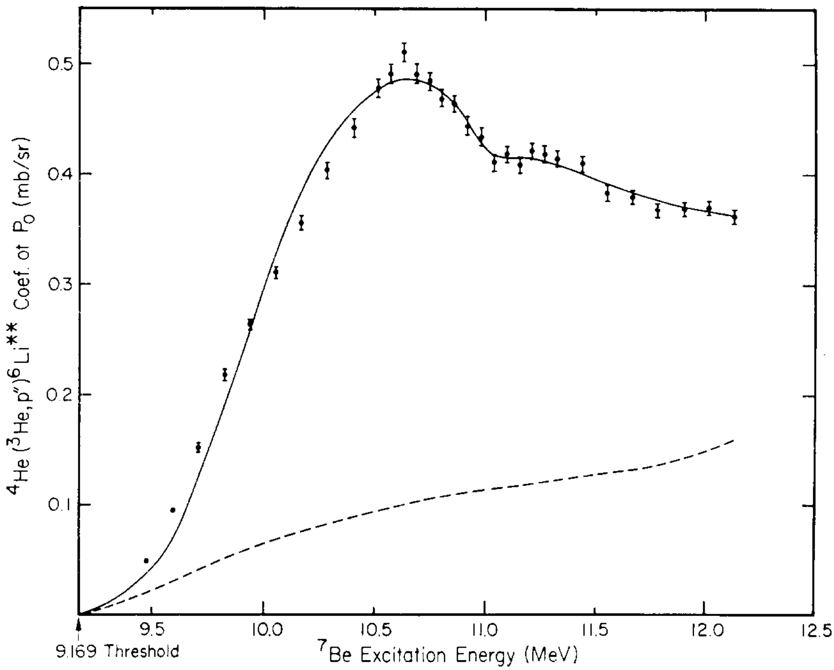

Fig. 3. The ^{4}He(^{3}He, p″)^{6}Li** data and estimated standard errors, expressed in the c.m. system. The solid curve represents a two-level fit over the entire range of data, using radius-dependent penetration factors with the incoming and outgoing channel radii of 4.39 and 4.08 fm, respectively. The arbitrary background represented by the broken curve has been subtracted.

and the ^{3}He^{++} component of the accelerated beam used to bombard ^{4}He gas at 80 mm Hg pressure. The gas was contained by a single 6250 Å nickel foil in a tube roughly 1 meter long, outside of which the 7.62 cm long by 7.62 cm diameter NaI(Tl) detector was placed, collimated to observe an effective target path length of about 10 cm, with the centre of the target length about 15 cm from the foil. With this arrangement effective shielding from the foil and the beam stopper could be provided. Corrections were made for beam energy loss. Straggling and loss effects gave a beam energy distribution with a standard deviation of typically 20 or 25 keV (lab). The background was smoothly varying, and over the upper $\frac{2}{3}$ of the energy range was typically about 15 % of the counts in the photo and first escape peaks of the γ-ray spectra. The absolute efficiency of the detector, and hence the absolute normalization of the data, were estimated from a combination of off-axis point source efficiency measurements and calculations, with an estimated standard error of roughly 20 %. The results and estimated standard errors are plotted in fig. 3 as a function of ^{7}Be excitation energy. They correspond to an incident ^{3}He lab energy range from 13.81 to 18.45 MeV.

Complete tables of data for both the ^{6}Li(p, p″)^{6}Li** and ^{4}He(^{3}He, p″)^{6}Li** reactions are given in ref. [2]).

3. Analysis

3.1. THE TWO-LEVEL ANALYSIS

The Legendre polynomial coefficients were analysed using the theory and notation outlined in the preceding paper, except that the Humblet-Rosenfeld two-level formulae, rather than the single-level formulae, were used [3]):

$$|U_{c'c}|^2 = P_{c'}P_c \left| \frac{C_{c'c1}}{E-E_1+\frac{1}{2}i\Gamma_1} + \frac{C_{c'c2}e^{i\zeta_{c'c}}}{E-E_2+\frac{1}{2}i\Gamma_2} \right|^2 \tag{1}$$

$$= P_{c'}P_c \frac{\alpha E^2+\beta E+\gamma}{[(E-E_1)^2+\frac{1}{4}\Gamma_1^2][(E-E_2)^2+\frac{1}{4}\Gamma_2^2]} . \tag{2}$$

The resonant states have been given the labels 1 and 2 and $\zeta_{c'c}$ is a relative phase. Formula (2) is suitable for fitting to experimental data and the constants (α, β, γ) and ($C_{c'cl}$, $C_{c'c2}$, $\zeta_{c'c}$) are related by

$$C_{c'c1} = \frac{(E_1^2+\frac{1}{4}\Gamma_1^2)\alpha+E_1\beta+\gamma\pm\frac{1}{2}\Gamma_1\sqrt{-\beta^2+4\alpha\gamma}}{(E_1-E_2)^2+\frac{1}{4}(\Gamma_1-\Gamma_2)^2}, \tag{3}$$

$$\mathrm{tg}\,\zeta_{c'c} = \frac{(E_1\Gamma_1-E_2\Gamma_2)\alpha-\frac{1}{2}(\Gamma_1-\Gamma_2)\beta\pm(E_1-E_2)\sqrt{-\beta^2+4\alpha\gamma}}{-2(E_1E_2+\frac{1}{4}\Gamma_1\Gamma_2)\alpha-(E_1+E_2)\beta-2\gamma\mp\frac{1}{2}(\Gamma_1+\Gamma_2)\sqrt{-\beta^2+4\alpha\gamma}}, \tag{4}$$

where sin $\zeta_{c'c}$ has the sign of the numerator of eq. (4) and $C_{c'c2}$ is found by interchanging the labels 1 and 2 in eq. (3).

Because the reacting particles have the properties p($J^\pi = \frac{1}{2}^+$), ^{6}Li(1^+), ^{3}He($\frac{1}{2}^+$), ^{4}He(0^+) and ^{6}Li**(0^+), the channel spins of the ^{6}Li(p, p″)^{6}Li** reaction are $s = \frac{1}{2}$ or $\frac{3}{2}$ and $s' = \frac{1}{2}$; those of the ^{4}He(^{3}He, p″)^{6}Li** reaction are $s = \frac{1}{2}$ and $s' = \frac{1}{2}$; the parity of an element $U_{c'c}$ is $(-)^l = (-)^{l'}$. 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 expansions of the Legendre polynomial coefficients in terms of the scattering matrix $U^J_{\alpha's'l',\alpha sl}$

have the following forms:

for the reaction ^{6}Li(p, p″)^{6}Li**,

$$k^2 \times (\text{coeff. of } P_0) = \tfrac{1}{12}|U^{\frac{1}{2}}_{\frac{1}{2}0,\frac{1}{2}0}|^2 + \tfrac{1}{12}|U^{\frac{1}{2}}_{\frac{1}{2}0,\frac{3}{2}2}|^2 + \tfrac{1}{12}|U^{\frac{1}{2}}_{\frac{1}{2}1,\frac{1}{2}1}|^2 + \tfrac{1}{12}|U^{\frac{1}{2}}_{\frac{1}{2}1,\frac{3}{2}1}|^2 + \tfrac{1}{6}|U^{\frac{3}{2}}_{\frac{1}{2}1,\frac{1}{2}1}|^2 + \tfrac{1}{6}|U^{\frac{3}{2}}_{\frac{1}{2}1,\frac{3}{2}1}|^2, \tag{5}$$

$$k^2 \times (\text{coeff. of } P_2) = \tfrac{1}{6}|U^{\frac{3}{2}}_{\frac{1}{2}1,\frac{1}{2}1}|^2 - \tfrac{2}{15}|U^{\frac{3}{2}}_{\frac{1}{2}1,\frac{3}{2}1}|^2 + \tfrac{1}{3}\,\mathrm{Re}\,(U^{\frac{1}{2}*}_{\frac{1}{2}1,\frac{1}{2}1}\,U^{\frac{3}{2}}_{\frac{1}{2}1,\frac{1}{2}1}) - \tfrac{1}{3}\sqrt{10}\,\mathrm{Re}\,(U^{\frac{1}{2}*}_{\frac{1}{2}1,\frac{3}{2}1}\,U^{\frac{3}{2}}_{\frac{1}{2}1,\frac{3}{2}1}), \tag{6}$$

for the reaction ^{4}He(^{3}He, p″)^{6}Li**,

$$k^2 \times (\text{coeff. of } P_0) = \tfrac{1}{4}|U^{\frac{1}{2}}_{\frac{1}{2}0,\frac{1}{2}0}|^2 + \tfrac{1}{4}|U^{\frac{1}{2}}_{\frac{1}{2}1,\frac{1}{2}1}|^2 + \tfrac{1}{2}|U^{\frac{3}{2}}_{\frac{1}{2}1,\frac{1}{2}1}|^2, \tag{7}$$

where the labels α and α' have been omitted.

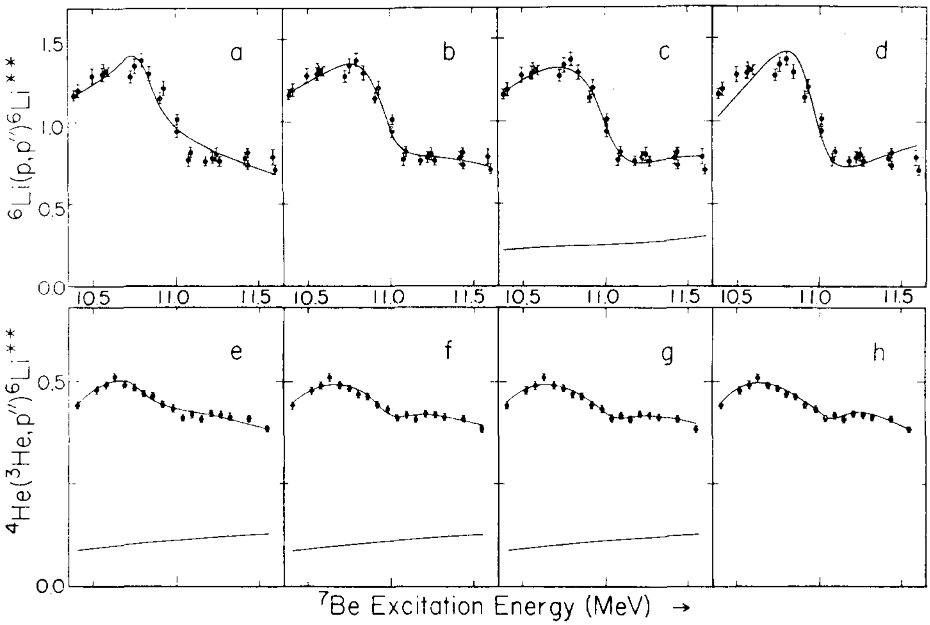

Fig. 4. Two-level fits to the P_0 coefficients. Radius-dependent penetration factors have been used in all fits except d and the arbitrary background shown has been subtracted in c, e, f and g. The radii are the same as in figs. 1 and 3. The parameters of the fits are

	E_1(MeV)	Γ_1	E_2	Γ_2
a	10.01	1.6	10.79	0.298
b	10.01	1.8	10.95	0.323
c	10.11	1.7	11.01	0.400
d	9.91	1.6	10.95	0.400
e	10.11	1.8	10.79	0.323
f	10.11	1.8	10.95	0.323
g	10.11	1.8	11.01	0.400
h	10.21	1.8	11.09	0.400

Fits of formula (2) to the coefficient of P_0 were made for both reactions in an attempt to determine if the energy behaviour could be understood in terms of two interfering states of the same J^π, and if so, to determine the resonant l-values. The good fits obtained for $l' = l = 1$ are shown in fig. 4. With other allowed values of l', no acceptable fits were possible for the ^{6}Li(p, p″)^{6}Li** reaction. The quality of the fits was insensitive to the inclusion of a smoothly varying non-interfering background from states of other J^π. (Only states of identical J^π can interfere in the P_0 coefficient.) The best fits were obtained for the radius-dependent penetration factors and the parameters $E_1 = 10.0$, $\Gamma_1 = 1.8$, $E_2 = 11.00 \pm 0.05$, $\Gamma_2 = 0.40 \pm 0.05$, where the units are MeV ^{7}Be excitation energy. Although even the incomplete expansions (5) and (7) contain contributions from many states, the quality of the fits suggests that two states with the same J^π and $l' = 1$ do, in fact, dominate the behaviour of the P_0 coefficient in both reactions.

The values obtained for E_1 and Γ_1 are the same as obtained from the ^{6}Li(p, p′)^{6}Li* analysis of the preceding paper, implying that this broad state contributes strongly to all three reactions. With the given values for l', channel spins and intrinsic parities, the J^π of both states is $\frac{1}{2}^-$ or $\frac{3}{2}^-$. This information can be combined with the limit $J^\pi \geqq \frac{3}{2}^-$ for the broad state obtained from the ^{6}Li(p, p′)^{6}Li* analysis, to yield the unique assignment $J^\pi = \frac{3}{2}^-$ for both states.

The fits to a very large range of P_0 data shown in figs. 1 and 3 are not particularly good, presumably because of the influence of other states. Although a fit to the ^{6}Li(p, p″)^{6}Li** P_2 coefficient was also achieved, it was not possible to use the values of E_1 and Γ_1 obtained from the ^{6}Li(p, p′)^{6}Li* analysis. At about 10.5 MeV the P_2 and P_0 coefficients are about the same size. The properties of the P_2 fit and the relative sizes of the P_2 and P_0 coefficients can be understood within the framework of eqs. (5) and (6) only if the terms of the form $\mathrm{Re}(U^{\frac{1}{2}*}U^{\frac{3}{2}})$ are significant, suggesting an appreciable contribution from a very broad $J^\pi = \frac{1}{2}^-$ state. Such a state would contribute to the non-interfering background of the P_0 coefficient. 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.

The initial channel spins of the ^{6}Li(p, p″)^{6}Li** reaction are not unique and although formula (2) remains correct, the meaning of the constants (α, β, γ) is more complicated than given by eqs. (3) and (4). As a result, the individual contributions from the two $J^\pi = \frac{3}{2}^-$ states cannot be separated. The initial and final channel spins of the ^{4}He(^{3}He, p″)^{6}Li** reaction are unique, and the decomposition of the fitted curve into two single-level parts plus an interference part using eqs. (3) and (4) is shown in fig. 5. There is another possible decomposition, which consists of an extremely large contribution from the narrower state almost exactly cancelled by an extremely large interference contribution; the first decomposition seems to be the more plausible, with the narrower state very weakly excited.

The isospin assignment $T = \frac{3}{2}$ is implied for the narrower state because it contributes only weakly to the ^{6}Li(p, p″)^{6}Li** and ^{4}He(^{3}He, p″)^{6}Li** reactions, where its formation is forbidden but its decay is not, and is not observed at all in the ^{6}Li(p, p)^{6}Li and ^{6}Li(p, p′)^{6}Li* reactions, where both its formation and decay are forbidden. This is because all the reacting particles have $T = 0$ or $T = \frac{1}{2}$ except the ^{6}Li** state, which has $T = 1$. The isospin assignment $T = \frac{1}{2}$ is implied for the broad state, which is observed in all of these reactions. Possibly the $T = \frac{3}{2}$ state is observed because of a small amount of mixing with the $T = \frac{1}{2}$ state.

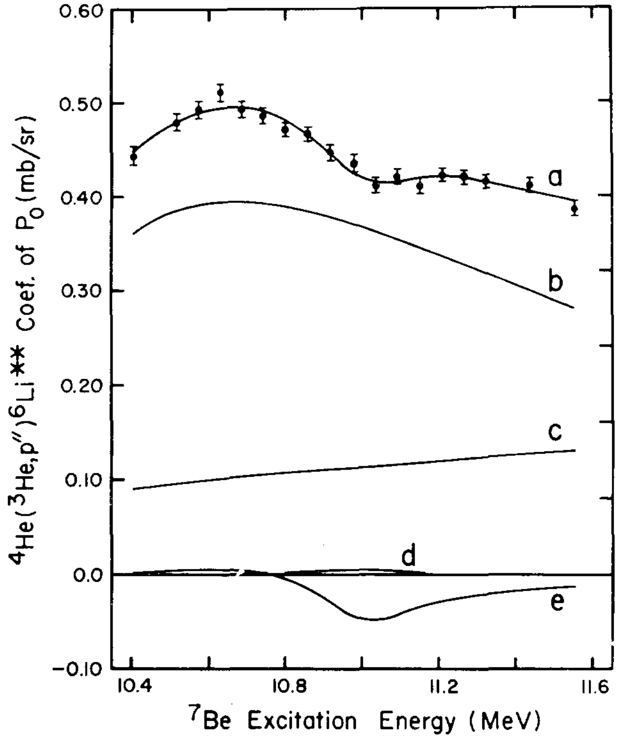

Fig. 5. Decomposition of the two-level fit of fig. 4f. Curve a is the sum of the other four curves. Curves b and d represent the single-level contributions of the two states; curve e represents their interference. Curve c represents an arbitrary background. A similar decomposition is obtained if no background is assumed.

3.2. REDUCED WIDTHS AND THE THOMAS-EHRMAN SHIFT

Because of the unknown background contribution from other states, little information about the partial widths of the $T = \frac{1}{2}$ state was obtained, as discussed more fully in ref. [2]).

Estimates of the partial widths of the $T = \frac{3}{2}$ state were made under the assumption that only the isospin-allowed two-body channels ^{6}Li**+p″ and ^{9}Be+n, with reduced widths $\gamma^2_{p''}$ and γ^2_n, are important. Because ^{6}Li** and ^{6}Be are members of the same isospin multiplet, these widths should be simply related [4]): $\gamma^2_{p''} = 2\gamma^2_n$. The standard methods of R-matrix theory were used together with the linear approximation [5]) for the energy dependence of the level shift Δ_λ and the total width Γ_λ. In this approximation Γ_λ is replaced by an "observed" width $\Gamma_\lambda^\dagger$ and the "observed" resonant energy E_R differs from the energy E_0 defined by $E_\lambda + \Delta_\lambda(E_0) - E_0 = 0$. The following formulae apply:

$$\gamma^2 = \left[\frac{P - S'\Gamma_\lambda^\dagger - \sqrt{P^2 - (P'\Gamma_\lambda^\dagger)^2}}{\Gamma_\lambda^\dagger(S'^2 + P'^2) - 2S'P}\right]_{E=E_0},$$

$$E_R = E_0 + \delta,$$

where

$$\delta = -\left[P\gamma^2 \frac{P'\gamma^2}{(1+S'\gamma^2)^2 + (P'\gamma^2)^2}\right]_{E=E_0}.$$

In the present case $\gamma^2 = \gamma^2_{p''}$, $P = P_{p''} + \frac{1}{2}P_n$, $P' = \mathrm{d}P/\mathrm{d}E$, and $S' = (\mathrm{d}/\mathrm{d}E)(S_{p''} + \frac{1}{2}S_n)$. The quantities $P_{p''}$ and P_n are the R-matrix penetration factors for the two channels; $S_{p''}$ and S_n, the shift functions. These relations were solved using the observed width Γ_2 for $\Gamma_\lambda^\dagger$, a radius of 4.08 fm, and values of P_n and S_n averaged over the 100 keV width [6]) of ^{6}Be. The calculation was repeated using the data of ref. [7]), both for ^{7}Be and for the mirror nucleus ^{7}Li. The data used and the corresponding results are summarized in table 1. The ^{7}Li channels ^{6}Li**+n$''$ and ^{6}He+p correspond to the ^{7}Be channels ^{6}Li**+p$''$ and ^{6}Be+n, respectively.

TABLE 1

Data and calculated parameters of the $T = \frac{3}{2}$ states in ^{7}Be and ^{7}Li

$E_R(^7\text{Be})$	$\Gamma_\lambda^\dagger(^7\text{Be})$	$E_R(^7\text{Li})$	$\Gamma_\lambda^\dagger(^7\text{Li})$	
11.00±0.05 MeV	0.40 ±0.05 MeV			present data
10.79±0.04	0.298±0.025	11.13±0.05	0.268±0.030	data of ref. [7])

$\gamma_{p''}{}^2(^7\text{Be})$	$\theta_{p''}{}^2(^7\text{Be})$	$\delta(^7\text{Be})$	$\gamma_{n''}{}^2(^7\text{Li})$	$\theta_{n''}{}^2(^7\text{Li})$	$\delta(^7\text{Li})$	
0.57±0.13 MeV	0.13±0.03	−0.045 MeV				present data
0.56±0.09	0.13±0.02	−0.027	1.0±0.4	0.24±0.09	−0.044	data of ref. [7])

The quantities γ^2 and θ^2 are related by $\gamma^2 = (3\hbar^2/2Ma^2)\theta^2$, where M is the reduced mass and a is the channel radius. The calculations using the data of ref. [7]) have also been done by Barker [8]), with the same results.

Although the proximity of the thresholds for the decay channels in ^{7}Be and ^{7}Li (fig. 6) might suggest an appreciable Thomas-Ehrman shift in the energies of the corresponding $T = \frac{3}{2}$ states, a calculation using the data of ref. [7]) implies that the shift is very small due to the accidental cancellation of the effects of the four channels involved. With the usual assumptions [5]), the shift is given by

$$[E_R(^7\text{Be})-E_R(^7\text{Li})]-[E_\lambda(^7\text{Be})-E_\lambda(^7\text{Li})]$$
$$= -[(S_{p''}+\tfrac{1}{2}S_n)-(S_{n''}+\tfrac{1}{2}S_p)]_{E_0}\gamma^2+[\delta(^7\text{Be})-\delta(^7\text{Li})]$$
$$= [(0.701+0.460)-(0.802+0.364)]\gamma^2+0.017 = 0.01\pm0.02 \text{ MeV}.$$

The radius 4.08 fm has been used. There is some discrepancy in the values of E_R for ^{7}Be given by the data of ref. [7]) and by the data of the present experiments. Nevertheless, the shift remains small. Using the present ^{7}Be data, the shift is -0.05 ± 0.02 MeV.

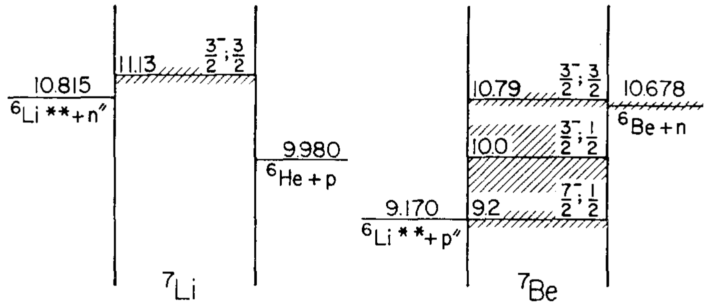

Fig. 6. Part of the energy level diagrams of ^{7}Be and ^{7}Li, with their ground states assumed to coincide. The energy given for the ^{7}Be $T = \frac{3}{2}$ state is that of ref. [7]) and disagrees somewhat with the value 11.00 MeV of the present measurement.

4. Summary

Two states with the same J^π ($\frac{1}{2}^-$ or $\frac{3}{2}^-$) were identified: a broad $T = \frac{1}{2}$ state at about 10.0 MeV ^{7}Be excitation energy, and a narrower $T = \frac{3}{2}$ state at 11.00 ± 0.05 MeV with a width of 0.40 ± 0.05 MeV. The properties of the first state are in agreement with the results of the ^{6}Li(p, p)^{6}Li and ^{6}Li(p, p′)^{6}Li* reactions; most of the properties of the second are in agreement with the results of the ^{9}Be(p, t)^{7}Be reaction. The unique assignment, $J^\pi = \frac{3}{2}^-$, was made using the limit, $J^\pi \geqq \frac{3}{2}^-$, obtained from the ^{6}Li(p, p′)^{6}Li* reaction.

The $T = \frac{1}{2}$ state seems to have a large width for ^{6}Li*+p′, and considerably smaller widths for ^{6}Li**+p″ and ^{4}He+^{3}He. It is probably to be identified with the predicted [8]) shell model state $^4P_{\frac{3}{2}}$. Evidently the two $J^\pi = \frac{3}{2}^-$ states dominate the structure observed in the ^{4}He(^{3}He, p″)^{6}Li** reaction, rather than the 9.2 MeV $J^\pi = \frac{7}{2}^-$ state, which is known to have an appreciable ^{4}He+^{3}He width [16]). The reason may be the attenuation of the influence of the 9.2 MeV state because of its location near threshold, and the f-wave decay required by its high spin. The 9.2 MeV state is probably to be identified with the predicted [8]) shell model state $^4D_{\frac{7}{2}}$.

The $T = \frac{3}{2}$ state seems to have very small widths for the isospin-forbidden channels ^{6}Li+p, ^{6}Li*+p′, and ^{4}He+^{3}He. Under reasonable assumptions, the dimensionless reduced widths for the isospin-allowed channels, $^6Li^{**}+p''$ and ^6Be+n, were found to be $\theta^2_{p''} = 2\theta^2_n = 0.13\pm0.03$. The properties of this state are in qualitative agreement with the properties of an expected $\frac{3}{2}^-$ shell model state [8]) containing a mixture of the configurations $^2P_{\frac{3}{2}}$ and $^2D_{\frac{3}{2}}$. Calculations from available data indicate that the Thomas-Ehrman shift of the energies of the $T = \frac{3}{2}$ states in ^7Be and ^7Li is very small.

Some evidence was found for extremely broad $J^\pi = \frac{1}{2}^-$ structure in ^7Be at an excitation energy of roughly 10 MeV or greater, which could be identified with the predicted [8]) shell model state $^4P_{\frac{1}{2}}$.

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

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Appendix A

The success of the two-level fits to the P_0 coefficients implies that the interpretation of their anomalous behaviour at about 11 MeV in terms of two interfering states of the same J^π is probably correct. However, the possible effect of the ^6Be+n threshold, located at 10.68 MeV and about 100 keV broad [6]), should be considered, even though it is fairly well separated in energy from the anomaly. The $^6Li(p,p')^6Li^*$, $^6Li(p,p'')^6Li^{**}$ and $^4He(^3He,p'')^6Li^{**}$ reactions [and probably also the $^6Li(p,p)^6Li$ reaction] all proceed through the broad 10 MeV state, as implied by the identical values for E_1 and Γ_1 obtained from their analysis. Therefore, if the anomaly were really a "cusp", associated with the neutron threshold, it should appear in all these reactions †. However, it is only observed in two of them. Moreover, because the anomaly seems to appear in the negative-parity scattering matrix elements, it would have to be associated with the p-wave part of the ^6Be+n threshold (since both these particles have positive parity). Large cusps, on the other hand, are usually associated with s-wave neutron thresholds, and should thus appear in the positive parity scattering matrix elements. Thus the experimental evidence strongly favours the two-level interpretation of the anomaly.

Appendix B

Several reactions forming ^7Be as the compound nucleus have been studied by different investigators, and in most cases different normalizations of the data have been

† This is exhibited explicitly in the R-matrix single-level formula, and is a possible advantage of the R-matrix formulation.

used. A program to determine the correct relative normalization was therefore carried out.

The relative normalization of reactions induced through the same entrance channel is straightforward if a thin target is used. The normalization of reactions induced through the ^{6}Li+p channel relative to those induced through the ^{4}He+^{3}He channel can be found from the study of the ^{6}Li(p, ^{3}He)^{4}He and ^{4}He(^{3}He, p)^{6}Li reactions and the use of the reciprocity theorem. From studies of these reactions, made in collaboration with Professor T. A. Tombrello, it was possible to find a consistent relative normalization for several sets of data. These results are summarized in columns 4 and 5 of table 2.

TABLE 2

Normalization [a])

Reaction	Reference [b])	Stated standard error of absolute measurement where applicable [c]) (%)	Relative normalization factor determined by present author [d])	Estimated standard error of relative normalization factor (%)
^{6}Li(p, p)^{6}Li	[9])*	8	1.000	
	[1])		1.000	1
	[10])		0.867	1
^{6}Li(p, p')^{6}Li*	preceding paper		1.000	1
^{6}Li(p, p'')^{6}Li**	present work		1.000	1
^{6}Li(p, ^{3}He)^{4}He	[11])		0.867	3
	[12])		0.867	3
	[13])*	15	0.675	3
	[14])		0.675	≈4
^{4}He(^{3}He, p)^{6}Li	[15])*	5	0.867	≈4
	present work*	6	0.850	2
	[16])*	5	0.795	2
^{4}He(^{3}He, p')^{6}Li*	[16])*		0.795	2
^{4}He(^{3}He, p'')^{6}Li**	present work*	20	1.0	20
^{4}He(^{3}He, ^{3}He)^{4}He	[15])*		0.867	≈4
	[16])*		0.795	2

a) The normalization of ref. [9]) has been arbitrarily taken as correct.

b) An asterisk implies that an absolute cross section has been measured.

c) The absolute measurements of the cross section for all of the reactions in ref. [15]) are subject to the same error and hence not independent. The same is true of ref. [16]).

d) The data from each experiment should be multiplied by this factor to obtain a consistent relative normalization.

A second and more difficult problem is the determination of the correct overall absolute normalization. The absolute cross sections given in ref. [9]), which were based on the thick target yield from the ^{6}Li(p, p)^{6}Li reaction, were arbitrarily taken as correct. The absolute cross section for the ^{4}He(^{3}He, p)^{6}Li reaction, refs. [15, 16]) and the present work, may, however, prove to be more reliable. Only further experimental work can resolve this question. The precision stated for an absolute measurement, when one has been made, is given in column 3 of table 2.

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