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Energy of the first $3/2^-$ excited state of ^{7}Li

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An S-matrix analysis of the integrated and differential cross sections of the reaction ^{6}Li$(n,t)\alpha$ over the energy range 0–3.9 MeV shows that the first $3/2^-$ excited state of ^{7}Li should be situated at about 8.87 MeV. This value is lower than the one obtained in previous parametrizations.

NUCLEAR REACTIONS S-matrix analysis, ^{6}Li (n,t) α, E_n up to 3.9 MeV, integrated and differential cross sections; first $^-3/2$ excited level of ^{7}Li located at $E_x = 8.87$ MeV.

Recently[1,2] experimental data pertaining to the ^{7}Li compound nucleus (see Fig. 1) have been reanalyzed in the framework of R-matrix theory.

In Ref. 1, the integrated cross section of the reaction ^{6}Li$(n,t)\alpha$, the integrated and differential elastic scattering cross sections ^{6}Li$(n,n)^6$Li, and polarization measurements were examined in an attempt to study the energy range above 8.1 MeV excitation energy of ^{7}Li. A good fit involving levels of Li at 6.56, 7.495, 9.7, and 11.13 MeV was reported. The energies of the 6.56, 9.7, and 11.13 levels were taken from Ref. 3 and held fixed. The energy of the 7.495 level was allowed to vary. One may, however, question the meaningfulness of the results obtained in Ref. 1 because of the following points:

(1) The 6.56 MeV level is ascribed a spin $J=\frac{1}{2}$ in Ref. 1 although it was tentatively assigned a spin $J=\frac{5}{2}$ in the compilation of Ref. 3 on which Ref. 1 is based. The spin $J=\frac{5}{2}$ was confirmed in the updated compilation of Ref. 4.

(2) The 9.7 MeV level has now been identified[4] with a $J=\frac{7}{2}$ level and not with a $\frac{3}{2}$ level as assumed in Ref. 1. This level should hence be of less importance for the energy range and the reactions considered in Ref. 1.

(3) The 11.13 MeV level has isospin $\frac{3}{2}$ level as already indicated in Ref. 3 and as confirmed in Ref. 4. It should hence play virtually no role in the reactions analyzed in Ref. 1 for which the initial and final channels have isospin $\frac{1}{2}$.

(4) In Ref. 1, the 6.56 and 9.7 levels are ascribed wrong parities.[4]

(5) One should notice, moreover, that the experimental data used by the authors of Ref. 1 are rather sparse in the energy region they intended to study. Indeed they used only 34 experimental points in that region namely 12 and 2 points respectively, for the integrated cross sections of the reactions ^{6}Li$(n,n)^6$Li and ^{6}Li$(n,t)\alpha$, 12 points (at $E_n=1$ and 1.5 MeV) for the differential cross sections of ^{6}Li$(n,n)^6$Li, and 8 points (at $E_n=3.2$ and 4.4 MeV) for the (crude) polarization measurements.

In Ref. 2, a more comprehensive study of the ^{7}Li system was undertaken (see Table I where the analyzed data are listed). The triton and neutron laboratory energies were less than 14 and 2 MeV, respectively. The corresponding excitation energy region contains the 4.633, 6.68, and 7.467 levels of ^{7}Li (we mention here the energy values quoted in Ref. 4 for the sake of definiteness). In the analysis of Ref. 2, it was also necessary to include the 9.61 ($J^\pi=\frac{7}{2}^-$) (only for the $\alpha+t$ reactions listed in Table I) and the 10.25 ($J^\pi=\frac{3}{2}^-$) levels. Moreover, a new $\frac{3}{2}^+$ level located at 11.279 MeV was introduced in order to account for the experimental data. The energies of all these mentioned levels were taken as free parameters. The agreement with the values given in Ref. 4 was good for the levels within the energy range of the data and for the 9.61 ($J^\pi=\frac{7}{2}^-$) level. However, the $\frac{3}{2}^-$ level located at 10.25 MeV in Ref. 4 was found to be situated at an energy of 9.853 MeV. In Ref. 2, this disagreement was ascribed to the fact that this level lies outside the energy range of the experimental data.

Since we had at our disposal very detailed experimental data[5,6] for the integrated cross section of the ^{6}Li$(n,t)\alpha$ reaction up to 3.9 MeV, we thought it worthwhile to reinvestigate part of the level structure of ^{7}Li by means of this reaction. More precisely we used the data of Refs. 5 and 6 for the integrated cross section (see Fig. 2) and the data of Ref. 7 for the differential cross sections at $E_n=0.080$, 0.150, 0.190, 0.200, 0.258, 0.270, 0.300, 0.350, 0.400, 0.565, 0.600, 1.100, 1.500, 2.000, 2.150, and 2.700 MeV.

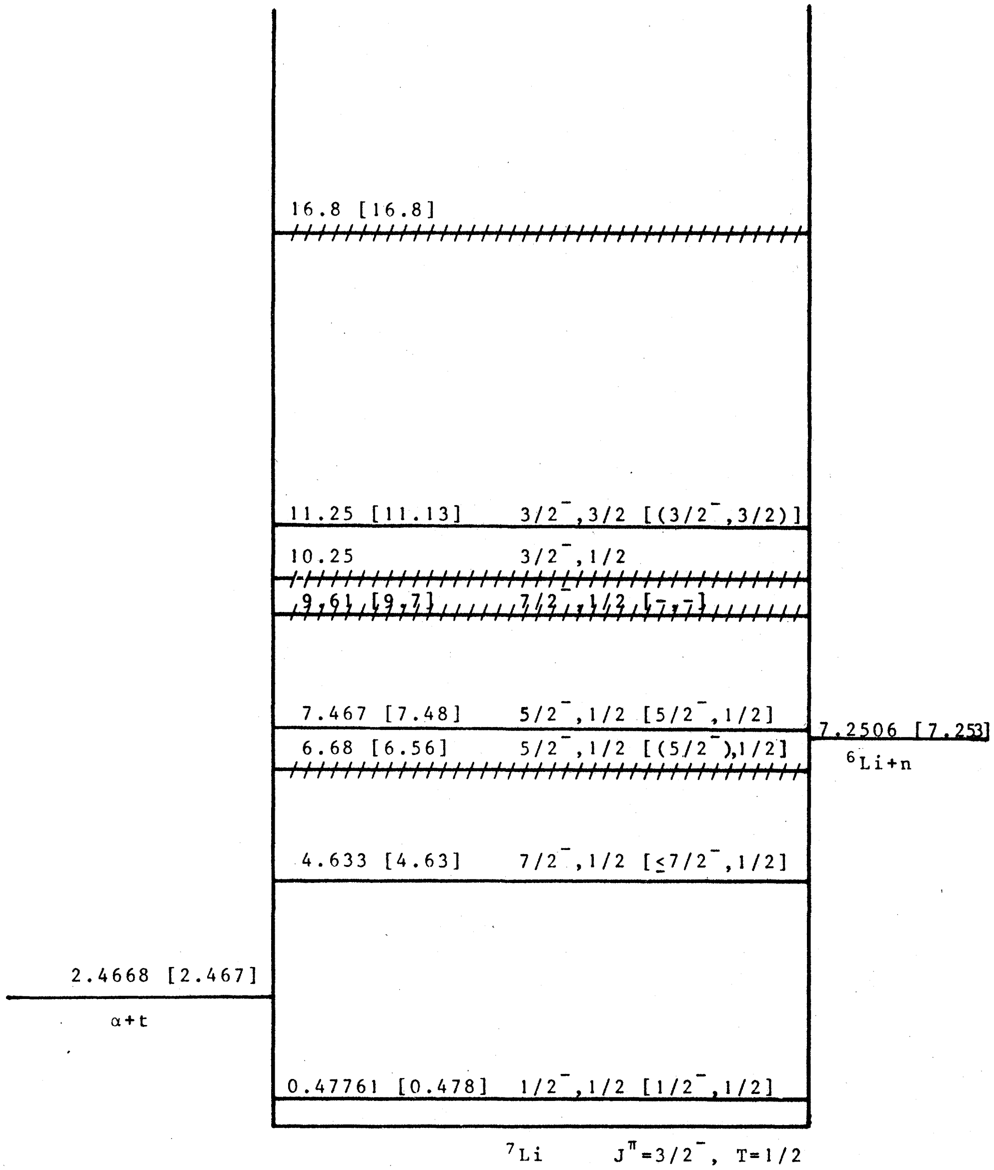

FIG. 1. Level diagram of ^{7}Li as taken from the updated compilation of Ref. 4. Numbers in square brackets were given in Ref. 3. Uncertain values quoted in Ref. 3 are enclosed in parentheses. The 10.25 level was not indicated in Ref. 3. A series of uncertain levels above the 11.25 (11.13) excited state which were mentioned in Ref. 3 but no longer in Ref. 4 are not represented.

TABLE I. Experimental data included in the analysis of Ref. 2.

Reaction	Total cross section	Reaction cross section	Integrated cross section	Differential cross section	Polarization
^{4}He$(t,t)^4$He				X	X
^{6}Li$(n,t)^4$He			X	X	
^{6}Li$(n,n)^6$Li			X	X	X
$\alpha+t$		X			
$n+^6$Li	X				

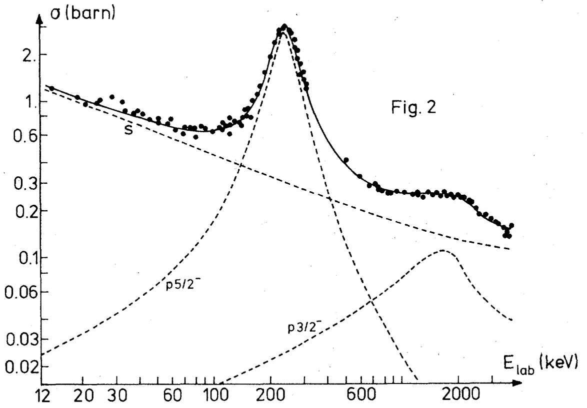

FIG. 2. Integrated cross section of the ^{6}Li(n,t) reaction. The experimental points are taken from Refs. 5 and 6. The continuous curve is the S-matrix parametrization of the data. The dashed curves marked s, $p_{5/2^-}$, $p_{3/2^-}$ give the contribution that arises from the s-wave capture and the p-wave capture on the $\frac{5}{2}^-$ and $\frac{3}{2}^-$ levels respectively.

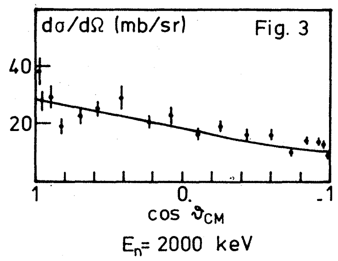

FIG. 3. Differential cross section of the ^{6}Li$(n,t)\alpha$ reaction at a typical energy. The experimental points are taken from Ref. 7. The continuous curve is the S-matrix parametrization of the data.

These data were analyzed within the frame of the S-matrix parametrization of nuclear reactions[8] which uses the following expansion of the transition operator:

$$T^{J\pi}_{c'c} = (k_c, k_c P_c, P_c)^{1/2}\left[Q_{c'c}(E) + i \sum_k \frac{g_{c'k}g_{ck}}{E-\mathcal{E}_k}\right]; \qquad (1)$$

the complex energies $\mathcal{E}_k = E_k - \frac{1}{2} i \Gamma_k$ give the position and width of the resonances, $Q_{c'c}(E)$ is a background term, P_c and $P_{c'}$ are penetration factors,[9] and g_{ck} is proportional to the square root of the partial width Γ_{ck}.

In a similar study[10] for E_n up to 600 keV, it was shown that the s-wave capture responsible for the increase of the cross section at low energies (see Fig. 2) could be rendered by a constant background-nonresonant approximation to $T^{1/2+}_{c'c}$ and $T^{3/2+}_{c'c}$. A one level approximation without background was used[10] for the $T^{5/2-}_{c'c}$ matrix element responsible for the resonance at $E_n \simeq 250$ keV.

TABLE II. Excitation energies and widths of the $\frac{5}{2}^-$ and $\frac{3}{2}^-$ levels of ^{7}Li as derived from the present study.

Level	Excitation energy (MeV)	Width (MeV)
$\frac{5}{2}^-$	7.457	0.080
$\frac{3}{2}^-$	8.870	1.420

To extend the S-matrix parametrization up to $E_n = 3.9$ MeV, we found it necessary to use a one level plus constant background approximation to the $T^{3/2-}_{c'c}$ matrix elements. As already pointed out in Ref. 2, it was not necessary to take the $\frac{7}{2}^-$ (9.61) level into account. We also do not need the far away $\frac{3}{2}^+$ level of Ref. 2: In practice, the influence of such levels is hidden in the constant background which appears in Eq. (1). For all the matrix elements $T^{J\pi}_{c'c}$ we used the penetration factors

$$P_c = \epsilon_c^{\,2} k_c^{2l}, \qquad (2)$$

$$P_{c'} = \epsilon_{c'}^{\,2}, \qquad (3)$$

which are independent of the channel radius.[9] One has in standard notation

$$\epsilon_c^{\,2} = \frac{1}{(l!)^2}\left[(l^2+\eta_c)\cdots(1+\eta_c^{\,2})\frac{2\pi\eta_c}{e^{2\pi\eta_c}-1}\right], \qquad (4)$$

$$\eta_c = \frac{Z_1 Z_2 e^2 M_c}{\hbar^2 k_c} \qquad (5)$$

($\eta_c \neq 0$ in the final channel only). The energies of all the levels involved in our analysis were considered as free parameters. The resulting energies and widths are given in Table II. The quality of the fit is illustrated in Fig. 2 for the integrated cross section and in Fig. 3 for the differential cross section at a typical neutron energy.

From Table II, one sees that the energy of the $\frac{3}{2}^-$ level is much lower than that found in Ref. 2. As far as level energies derived from shell model computations may be compared to the real part of the poles of the S matrix in the case of very broad states, let us mention that the value (9.17 MeV) predicted by Barker[11] is rather close to the one obtained in this work.

Notice that the value quoted in Ref. 4 for the energy of the ($J^\pi = \frac{3}{2}^-$, $T = \frac{1}{2}$) level was taken from

Ref. 12 where an S-matrix parametrization of the integrated cross sections of the ^{6}Li$(n,p)^6$He (0) and ^{6}Li$(n,n')^6$Li (3.56) reactions was performed. The result obtained in Ref. 2 and *a fortiori* ours suggest that these reactions should be reanalyzed.

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