Analysis of the 6Li(n, t) α reaction over the energy range 14 to 3 900 keV

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ANALYSIS OF THE ^{6}Li(n, t) α REACTION OVER THE ENERGY RANGE 14 TO 3 900 keV

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Résumé. — De nouvelles données expérimentales comprises entre 14 et 3 900 keV des sections efficaces intégrées et différentielles de la réaction ^{6}Li(n, t) α sont analysées dans le cadre de la théorie de la matrice S pour les réactions nucléaires. Nous construisons une expression paramétrique. Un niveau $3/2^-$ est situé à E_{exc} = 8,83 MeV avec une largeur de 1 780 keV.

Abstract. — New experimental data for the integrated and differential ^{6}Li(n, t) α cross sections, in the range 14 to 3 900 keV, are analysed within the framework of the S-matrix theory of nuclear reactions. A parametric expression is obtained. A $3/2^-$ level is located at E_{exc} = 8.83 MeV with a width equal to 1 780 keV.

1. **Introduction.** — The reaction ^{6}Li(n, t) α is of particular interest in reactor physics and in neutron spectroscopy and has been extensively investigated [1]. The compound nucleus ^{7}Li has also been studied in the theoretical frame of the shell model [2, 3] and of the rotational model [4] and also experimentally [5, 6]. Until a few years ago, most of the cross section measurements were concentrated between 30 keV and 600 keV. Recently however, extensive and precise measurements in the energy range 14 to 3 900 keV became available [7-10].

The purpose of the present paper is twofold. Firstly, we want to analyse both the integrated and the differential cross-sections, using the S-matrix theory [11] of nuclear reactions. Secondly, we determine the angular momentum, parity, excitation energy and width of a resonance as yet not well-established, at about 9 MeV excitation energy in ^{7}Li.

2. **The experimental data.** — Recently, Fort and Marquette [9] have done absolute measurements of the integrated ^{6}Li(n, t) α cross section from 14 to 1 700 keV. Thus, they cover all the preceding measurements [1] and provide, moreover, a coherent set of data. They generally agree with the preceding data. Another coherent set of σ_{int}, measured by Clements and Rickard [10], is available in the energy range 1 100 to 3 900 keV. We will use these two sets of data since the other measurements [7] are dispersed and imply a lot of renormalization corrections. The data of ref. [9] have been taken as reference. The two sets [9, 10] overlap in the energy range 1 100 to 1 700 keV. The two integrated cross-sections are similar in shape and slope. We multiply the Clements' results by a normalization factor equal to 1.79 to obtain a consistent set of σ_{int} from 14 to 3 900 keV.

The ^{6}Li(n, t) α differential cross sections, from 80 keV up to 2.70 MeV, are available from the BNL report [8]. The remaining problem is the normalization of the dσ/dΩ to the value of σ_{int}. At each energy, we fit the dσ/dΩ using the expression

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = A_0 + \sum_{i=1}^{5} A_i\, P_i(\cos\theta)\,. \qquad (1)$$

The normalization factor $\mathcal{N}_{E_i}$ is then given by the equation

$$\mathcal{N}_{E_i} = \left.\frac{\sigma_{\text{int}}}{4\,\pi A_0}\right|_{E=E_i}. \qquad (2)$$

We can now study from the theoretical point of view a full set of coherent data.

3. **The theoretical formulae.** — The values of σ_{int} in the energy range 14 to 600 keV had already been studied in ref. [1]. We keep the different channels introduced in that analysis, namely the p-wave $5/2^-$ resonance channel and the two s-wave $1/2^+$ and $3/2^+$ non resonant channels. The extended analysis of the new cross section will, of course, modify the values of the corresponding parameters. Figure 1 shows the integrated cross section versus energy, from 600 keV to 3 900 keV. A new resonance appears around $E_{n,\text{lab}} \approx 2.0$ MeV.

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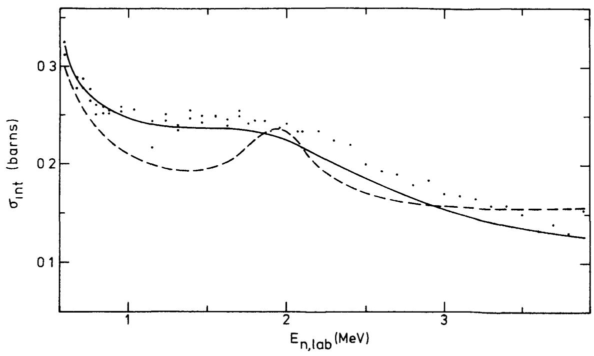

FIG. 1. — Plot of σ_{int} (C. M. system) versus energy $E_{n,lab}$. The dots represent the experimental results; errors are not indicated. The full and dashed theoretical curves refer respectively to the $3/2^-$ and $7/2^-$ resonances, the penetration factor in both cases being $\bar{\pi}$.

In a shell model calculation, Barker [2] found, in this excitation region, the levels ($P_{3/2^-}$, $E_x = 9.17$ MeV), ($D_{7/2^-}$, $E_x = 9.61$ MeV) and ($P_{1/2^-}$, $E_x = 9.80$ MeV). However, in their experiments, Spiger and Tombrello [5] observed only a ($D_{7/2^-}$, $E_x = 9.67$ MeV) level. This level has large (α, t) and (^{6}Li*, n') reduced widths but a negligible (^{6}Li, n) one. In addition, the centrifugal barrier favours the (^{6}Li*, n') channel rather than the (^{6}Li, n) one. We observe also that the ($F_{5/2^-}$, $E_x = 6.64$ MeV) has a large γ_α^2 and the ($P_{5/2^-}$, $E_x = 7.47$ MeV) has a small γ_α^2 and a large γ_n^2. A similar situation exists in the case of the miror nucleus ^{7}Be. This shows that the $F_{5/2^-}$ and $D_{7/2^-}$ levels have a large overlap with the (α, t) channel. On the contrary, the triplet $P_{5/2,3/2,1/2^-}$ will have a large overlap with the (^{6}Li, n) channel. These dynamical considerations lead us to believe that the new resonance is a $3/2^-$ one. Nevertheless, to test the above assumptions, we have also tried a $7/2^-$ spin assignment.

Three choices have been proposed for the penetration factors within the framework of the S-matrix theory of nuclear reactions [11]. We do not consider here the factor P_l [11] since it introduces an additional parameter, and we will only use the factors

$$\pi_c = k_c^{2l}\,\varepsilon_c^2 \tag{3}$$

and

$$\bar{\pi}_c = \varepsilon_c^2 \tag{4}$$

where

$$\varepsilon_l = \frac{1}{l\,!}\left[(l^2 + \eta_c^2)\dots(1 + \eta_c^2)\frac{2\,\pi\eta_c}{\exp(2\,\pi\eta_c) - 1}\right]^{1/2}, \tag{5}$$

and

$$\eta_c = \frac{2\,e^2\,M_c}{\hbar^2\,k_c}\,. \tag{6}$$

The tables I and II show the different channels needed for the analysis.

The approximations of the $\mathfrak{T}$ matrix which have to be used in the non-resonant channels are complex constant backgrounds, already described in details in ref. [1, 11, 13].

We use the one-level approximation without background of the $\mathfrak{T}$ matrix for the resonant channels.

TABLE I

	Entrance channel		J^π	Exit channel		
	s	ℓ		s'	ℓ'	
a	1/2	0	$1/2^+$	1/2	0	a'
b	3/2	0	$3/2^+$	1/2	2	b'
c	3/2	1	$5/2^-$	1/2	3	c'
d	1/2	1		1/2	1	d'
e	3/2	1	$3/2^-$	1/2	1	e'
f	3/2	3		1/2	1	f'

TABLE II

	Entrance channel		J^π	Exit channel		
	s	ℓ		s'	ℓ'	
a	1/2	0	$1/2^+$	1/2	0	a
b	3/2	0	$3/2^+$	1/2	2	b'
c	3/2	1	$5/2^-$	1/2	3	c'
g	1/2	3		1/2	3	g'
h	3/2	3	$7/2^-$	1/2	3	h'
i	3/2	5		1/2	3	i'

The expressions used in the analysis are the following. In the channels (a, a'), (b, b'), we take

$$\mathfrak{T}_{c'c}^{3\pi} = (k_{c'}\,k_c\,\pi_{c'}\,\pi_c)^{1/2}\,R_{c'c}\exp(2\,i\theta_{c'c})\,; \tag{7a}$$

or

$$\mathfrak{T}_{c'c}^{3\bar{\pi}} = (k_{c'}\,k_c\,\bar{\pi}_{c'}\,\bar{\pi}_c)^{1/2}\,R_{c'c}\exp(2\,i\theta_{c'c})\,. \tag{7b}$$

In the channels

$$(c\,,\,c')\,,\quad \left(\begin{Bmatrix} d\\ e\\ f\end{Bmatrix},\begin{Bmatrix} d'\\ e'\\ f'\end{Bmatrix}\right)\,,\quad \left(\begin{Bmatrix} g\\ h\\ i\end{Bmatrix},\begin{Bmatrix} g'\\ h'\\ i'\end{Bmatrix}\right)\,,$$

we use

$$\mathfrak{T}_{c'c}^{3\pi} = -\,iq_n\left(\frac{k_{c'}\,k_c\,\pi_{c'}\,\pi_c}{|\,\kappa_{c'n}\,\kappa_{cn}\,\pi_{c'n}\,\pi_{cn}\,|}\right)^{1/2}\times$$

$$\times\,\frac{e^{i\zeta_{c'n}}\,\Gamma_{c'n}^{1/2}\,\Gamma_{cn}^{1/2}\,e^{i\zeta_{cn}}}{E - \mathcal{E}_n}\,, \tag{8a}$$

or

$$\mathfrak{T}_{c'c}^{3} = -\,iq_n\left(\frac{k_{c'}\,k_c\,\bar{\pi}_{c'}\,\bar{\pi}_c}{|\,\kappa_{c'n}\,\kappa_{cn}\,\bar{\pi}_{c'n}\,\bar{\pi}_{cn}\,|}\right)^{1/2}\times$$

$$\times\,\frac{e^{i\bar{\zeta}_{c'n}}\,\Gamma_{c'n}^{1/2}\,\Gamma_{cn}^{1/2}\,e^{i\bar{\zeta}_{cn}}}{E - \mathcal{E}_n}\,, \tag{8b}$$

where

$$\bar{\zeta}_{cn} = \zeta_{cn} + \arg(k_{cn})\,, \tag{9}$$

and

$$\mathcal{E}_n = E_n - i\tfrac{1}{2}\Gamma_n\,. \tag{10}$$

The real and constant quantities q_n, Γ_{cn}, Γ_n, E_n, κ_{cn}, ζ_{cn} are defined in ref. [11].

We do not write the explicit expressions for the integrated and differential cross-sections because they are too long. They were derived from the general expression for the cross-section given in ref. [14]. There exist 16 parameters. The fit is obtained using the least χ_i squares method for both the integrated and differential cross-sections.

4. **The results.** — We tried the different possibilities i. e. the penetration factor π_c or $\overline{\pi}_c$ for all the channels and the spins $7/2^-$ or $3/2^-$ for the additional resonance. The comparison between the use of the two penetration factors favours the $\overline{\pi}_c$ one.

The two theoretical curves in figure 1 refer to the same penetration factor $\overline{\pi}_c$. The best agreement is obtained with the $3/2^-$ resonance shown by the full curve. We note, however, that this lies below the experimental points above 2 400 keV. The integrated cross-section below 600 keV [1] is very well reproduced using two ($5/2^-$, $3/2^-$) resonances and a little bit less by two ($5/2^-$, $7/2^-$). Figure 2 shows $d\sigma/d\Omega$, for $E_{n,\text{lab}} \geqslant 600$ keV, and the corresponding theoretical curves. Once more, the best general agreement is obtained with the ($5/2^-$, $3/2^-$) resonances. It gives also a good fit below 600 keV.

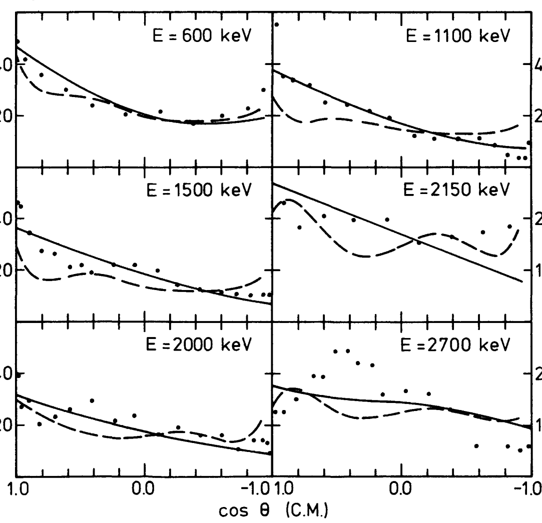

FIG. 2. — Plot of $d\sigma/d\Omega$(C. M. system) versus $\cos\theta$ (C. M.) for different energies $E_{n,\text{lab}}$. Same remarks as for figure 1.

The disagreement above 2 400 keV for σ_{int} and at 2 150 and 2 700 keV for $d\sigma/d\Omega$ may have various origins. One reason may be the existence of a third resonance in this energy range. We investigated that possibility by introducing the set of levels ($5/2^-$, $3/2^-$, $7/2^-$). The resulting fit was not significantly better because this $7/2^-$ level has, as already mentioned, a small partial width in the (^{6}Li + n) channel. We did not attempt other fits including new backgrounds because on the one hand, the number of parameters rises quickly, thus giving a non-significant result and, on the other hand, we lack information on the cross-section above 3.9 MeV. Another reason, might be the rising of direct processes which cannot be included in the present formalism.

Table III shows the main parameters values. The values of $E_{5/2^-}$ and $\Gamma_{5/2^-}$ are not very different from these of ref. [1].

TABLE III

$E_{5/2^-}$	=	207 keV
$\Gamma_{5/2^-}$	=	74.5 keV
$E_{3/2^-}$	=	1580 keV
$\Gamma_{3/2^-}$	=	1780 keV

5. **Conclusions.** — We locate the excitation energy of the proposed $3/2^-$ spin level at 8.83 MeV and determine its width $\Gamma_{3/2} = 1\,780$ keV. The value of $\Gamma_{3/2}$ is in agreement with the result of the mirror nucleus ^{7}Be [15] and the excitation energy E_x lies a little bit lower than the proposed result of Barker [2].

6. **Acknowledgments.** — The authors wish to express their thanks to Drs. Fort and Marquette for an early communication of their results. The calculations were performed on the IBM 370/158 computer of the University of Liège.

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