Spectroscopy of ^{6}Li Using the $^{3}He(^{7}Li,\alpha)^{6}Li$ Reaction

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The spectroscopic study of unbound states in the ^{6}Li nucleus was performed by measuring the energy spectrum of the α-particles emitted from the transfer reaction $^{3}He(^{7}Li,\alpha)^{6}Li$. The ^{7}Li beam at $E_{Lab} = 31.2MeV$ was produced at the São Paulo Pelletron accelerator. A ^{3}He gas cell was used as target. α-Particle spectra were measured from $\theta_{Lab} = 8^{\circ}$ up to $\theta_{Lab} = 20^{\circ}$ with steps of 1°. Due to its positive $Q = +13.3MeV$, the $^{3}He(^{7}Li,\alpha)^{6}Li$ reaction favours the population of states in ^{6}Li at high excitations energies up to about $20MeV$. We observed resonances at $17.29MeV$, $15.31MeV$, and a new state at $12.45MeV$, in addition to all previously known states of ^{6}Li. An $\Re$-Matrix analysis was performed and the positions and widths of these states were extracted.

1 Introduction

The ^{6}Li nucleus is one of lightest nuclei with a known sequence of excited levels. In general the theoretical predictions are in fair agreement with the experimental results only for the first six levels up to $\sim 6MeV$ excitation[1, 2]. The spectroscopy of ^{6}Li nucleus has been performed through the $^{3}He(^{7}Li,\alpha)^{6}Li$ reaction which has a binary exit channel. The mechanism of this reaction provide a transfer of a triton cluster to the target nuclei ^{3}He to lead to states in the ^{6}Li nucleus. Due to the binary character of the reaction mechanism, the ground-state and resonant states of ^{6}Li are observed in the α-particle spectrum. Moreover, the high positive $Q = +13.3MeV$ of the $^{3}He(^{7}Li,\alpha)^{6}Li$ reaction, favours the population of resonant states up to high excitation energies in ^{6}Li nucleus ($20MeV$). This reaction was performed in three previous works [3, 4, 5]. However, due to the poor statistics and insufficient experimental resolution, none resonances above $^{5}Li + n$ threshold ($5.4MeV$) were observed. Only structures in the α-particles spectra near the $^{3}He + t$ threshold ($15.8MeV$) were reported. In this work, we intend to populate resonant states in the ^{6}Li nucleus near the $^{3}He + t$ threshold, using the $^{3}He(^{7}Li,\alpha)^{6}Li$ reaction. The $\Re$-matrix formulas[6, 7] were used to fit the α-particle experimental spectra in order to extract the positions and reduced widths of the ^{6}Li resonances.

2 Experimental Procedure

A $31.2MeV$ beam of ^{7}Li was provided by the São Paulo Pelletron accelerator with a average current about $70nA$. We used a gas target cell with kapton windows of $3.5mg/cm^{2}$ thickness. The cell was filled with 99.95% isotopically enriched ^{3}He up to the pressure $255mbar$. The α-particles products of $^{3}He(^{7}Li,\alpha)^{6}Li$ reaction were detected by a $E-\Delta E$ telescope which consisted of two Si surface barrier detectors, conected to a system of multiparametrical analysis. The ΔE segment of the telescope had a thickness of $150\mu m$, while the E segment had a thickness of $700\mu m$. A rectangular double-slit system was used to prevent particles scattered in the windows of the gas cell from entering the detectors. This double-slit system defined a solid angle of the order of $0.5msr$, depending on the detection angle. The dimensions and the efficiency of the experimental setup (double-slit system and gas target cell) were calculated by a Monte Carlo code[8].

Energy spectra of α-particles have been obtained in the angle range $8^{\circ} - 24^{\circ}$ in the laboratory system. The typical energy spectra of α-particle from the $^{3}He(^{7}Li,\alpha)^{6}Li$ reaction is shown in Fig. 1. The α-particles are easily identified in the biparametrical spectrum and projected onto the total energy axis ($E + \Delta E$). As indicated in the α-particle spectrum, we observe all the low-lying states in ^{6}Li up to $6MeV$[2].

3 Analysis

As a first step in the analysis, the energy axis of the alpha particles spectra was converted into excitation energy of the recoil nucleus ^{6}Li, supposing a binary process. In order to improve the statistics of the ^{6}Li excitation energy spectrum, the spectra acquired in the angles of 12° and 14° in the laboratory system were summed. The result of this process is shown in Fig. 2.

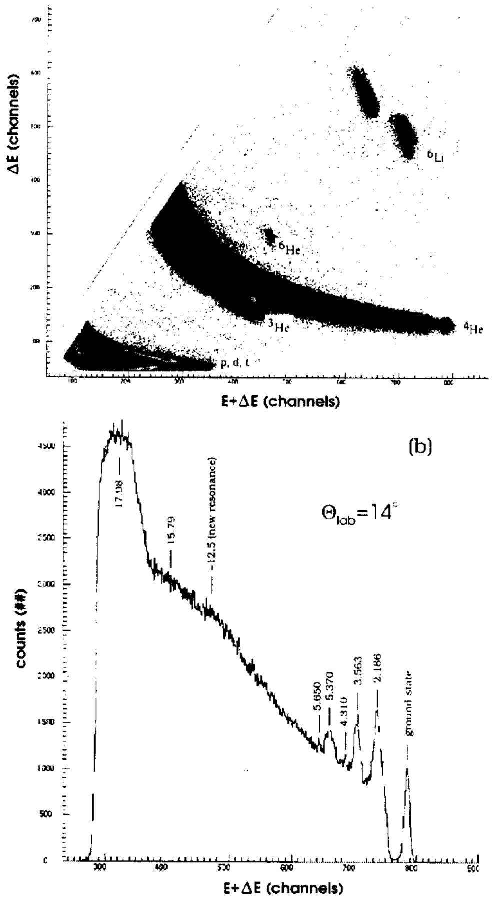

Figure 1. (a)Typical particle identification $E - \Delta E$ spectrum for the $^3He(^7Li, \alpha)^6Li$. (b)Projection of the α-particles events onto the total energy axis ($E + \Delta E$). The excitation energies of ^6Li are indicated in MeV.

Using the one-channel, one-level $\Re$-matrix[6, 7] , we attempt to fit the ^6Li excitation energy spectrum with a function of the form:

$$N(E, \theta) = \sum_i \mathcal{A}_i [g(E-\tau) * b(E)]_i + \mathcal{B} P_l(E) + \sum_j \mathcal{C}_j \left(\frac{d^2\sigma}{d\Omega_\alpha dE_\alpha} \right)_j \quad (1)$$

The $[g(E-\tau) * b(E)]_i$ term is the convolution of a Gaussian and a Breit-Wigner functions:

$$[g(E-\tau) * b(E)]_i = \int_{-\infty}^{+\infty} e^{-\frac{0.693}{\Gamma_G^i/4}(E-\tau)^2} \times \frac{\gamma_i^2 P_i}{[E_i - \gamma_i^2(S_i - B_i) - E]^2 + (\gamma_i^2 P_i)^2} d\tau \quad (2)$$

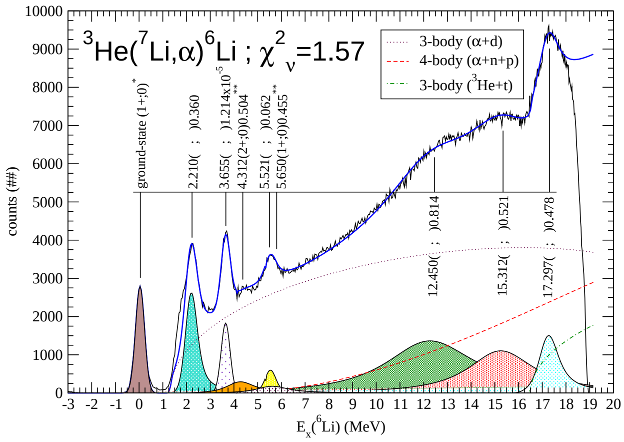

Figure 2. ^6Li excitation energy spectrum. The solid line is the best fit of the data obtained through the one-channel, one-level $\Re$-matrix calculations. Contributions from the ground-state and the known first five resonances in ^6Li were included. Above $6MeV$ three more resonant states were considered near the $^3He + t$ threshold ($15.8MeV$), namely: $E_x = 12.450MeV$, $E_x = 15.312MeV$ and $E_x = 17.297MeV$. The background was described through the 3-body ($^6Li \to \alpha + d$ and $^6Li \to ^3He + t$) and 4-body breakup ($^6Li \to \alpha + n + p$), which were calculated using the phase-space model.

where, i indicate the levels of the ^6Li nucleus, Γ_G^i is the gaussian FWHM, which corresponds to the experimental resolution, P_i and S_i are the penetration factor and shift factor, which are functions of E, B_i is the constant boundary condition parameter, and γ_i^2 is the reduced width. The second term in Eq. (1) is the $^6Li \to \alpha + d$ penetrability background[9, 10]. The third term is the phase-space background[11, 12], where j indicates the 3-body ($^6Li \to \alpha + d$, $^6Li \to ^5Li + n$ and $^6Li \to ^3He + t$) or 4-body breakup ($^6Li \to \alpha + n + p$), which depends on the threshold energy of ^6Li nucleus. $\mathcal{A}_i$, $\mathcal{B}$ and $\mathcal{C}_j$ are normalization constants.

The fit of the ^6Li excitation energy spectrum was performed by the χ^2 minimization, which was carried out by Simulated Annealing[13] combined with the Downhill Simplex Method[14] using the computer code AMEBA[8]. In this way, we included contributions from the ground-state and the known first five resonances in ^6Li. Above $6MeV$ three more resonant states were considered near the $^3He + t$ threshold ($15.8MeV$). The overall energy resolution of about $445keV$ was obtained via the ground-state fit. The background was described through the 3-body ($^6Li \to \alpha + d$ and $^6Li \to ^3He + t$) and 4-body breakup ($^6Li \to \alpha + n + p$), which were calculated using the phase-space model.

The best fit results are given in Tab. I. Our quality of fit is given by $\chi_\nu^2 = 1.57$. The values of E_i and $\Gamma_{c.m.}^i = 2P_i\gamma_i^2$ agree reasonably with the energies and widths given in Ref. [2]. The resonance at $17.29MeV$ was included recently in the ^6Li energy levels diagram[2]. The resonance at

$15.31 MeV$ have been also observed before[1], but it was not considered in the last compilation[2]. Thus, in this spectrum there is a confirmation of the resonances at $15.31 MeV$ and $17.29 MeV$. Furthermore, we identify a new resonant state in ^6Li at $12.45 MeV$ not observed yet.

TABLE 1. $\Re$-matrix parameter values from best fit to ^6Li spectrum of Fig. 2. (†), these parameters are obtained from the values in Ref.[2].

$E_i(MeV \pm MeV)$	$\gamma_i^2(MeV)$	$\Gamma^i_{c.m.}(MeV)$
2.21	0.359657	0.031
3.65	3.27119e-05	2.66×10^{-5}
$4.312\pm0.022^\dagger$		$1.3\pm0.10^\dagger$
5.52	0.0619265	0.43
$5.65\pm0.050^\dagger$		$1.5\pm0.2^\dagger$
12.45 ± 0.36	0.81369 ± 0.06	4.98 ± 0.37
15.31 ± 0.47	0.52072 ± 0.04	3.58 ± 0.29
17.29	0.478025	0.76

4 Conclusion

In summary, we performed measurements of the alpha particle spectra emmitted from the $^3He(^7Li,\alpha)^6Li$ reaction at $E_{Lab} = 31.2 MeV$. The first six known states of ^6Li have been observed. Above $E_x = 6 MeV$ three resonances have been observed at $12.45 MeV$, $15.31 MeV$ and $17.29 MeV$. The $^3He + t$ threshold is located at $E_x = 15.79 MeV$. An $\Re$-matrix analysis of the α-particles spectra plus background was performed and the position and widths of the resonances have been determined. The best fit results are given in Tab. 3. The main results of the present study are the confirmation of resonances at $15.31 MeV$ and $17.29 MeV$ and the identification of a new resonant state at $12.45 MeV$ in ^6Li.

Acknowledgments

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