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# Alpha Cluster Structure in $^{16}$O

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**Abstract.** The main purpose of the present work is the investigation of the α-cluster phenomenon in $^{16}$O. The $^{12}$C($^{6}$Li,d)$^{16}$O reaction was measured at a bombarding energy of 25.5 MeV employing the São Paulo Pelletron-Enge-Spectrograph facility and the nuclear emulsion detection technique. Resonant states around 4α threshold were measured and an energy resolution of 15 keV allows to define states previously unresolved. The angular distributions of the absolute cross sections were determined in a range of 4-40 degree in the center of mass system. The upper limit for the resonance widths was obtained, indicating that the α cluster structure information in this region should be revised.

## 1 Introduction

The α cluster phenomenon in the structure of light nuclei has been the subject of a longtime investigation since the proposal of the Ikeda diagrams [1], however the mechanism of the cluster formation is still not completely understood. In fact, if the cluster state has a fairly rigid crystal-like or a gas-like structure remains an open question [2-3]. The main purpose of the research program in progress is the investigation of this phenomenon in (xα) and (xα + n) nuclei through ($^{6}$*Li, d*) transfer reactions performed in São Paulo [4-5]. Particularly interesting are the regions around the xα thresholds recognized important in the production of the elements in the stars as primarily pointed out by Hoyle in $^{12}$C [1]. The interpretation of the Hoyle state as an condensate brought a renewed interest to this subject [3]. The resonant states around the 4α threshold (14.44 MeV) in the nucleus $^{16}$O are the focus of the present contribution. A rotational band with the α + $^{12}$C(Hoyle) cluster state structure was calculated by Ohkubo and Hirabayashi [2]. In order to explore this region the $^{12}C(^{6}Li,d)^{16}O$ reaction was measured at a bombarding energy of 25.5 MeV employing the São Paulo Pelletron-Enge-Spectrograph facility and the nuclear emulsion detection technique.

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## 2 Results

Several narrow resonances with a quasi-bound behavior embedded in the continuum are observed in the measured spectra and an energy resolution of 15 keV allows for the separation of doublets not resolved before. Figure 1 displays the region around the $4\alpha$ threshold in the position deuteron spectra at the scattering angle of $15^0$, $19^0$, $25^0$ and $32^0$, with an angular full width of $\Delta\theta_H = 1.75^0$. The transitions are identified by numbers. In this spectra region there are no influences of contaminants.

The averages of the energies and of the FWHM determined for each level are presented in Table 1. The $\alpha$ width $\Gamma_\alpha$ and line width $\Gamma_{c.m.}$ can be considered equivalent in the context of one level approximation [6]. In fact $\Gamma_\alpha = \Gamma_{c.m}$ has been considered often in the literature [7]. The present work assumes the $\Gamma_{c.m}$ as an upper limit for the resonance widths $\Gamma_\alpha$. The FWHM from Wheldon et al. [8] and the $\Gamma_{c.m}$ from Tilley et al. [9] are presented in Table 1 in comparison with the FWHM extracted in the present work. Note that Wheldon et al. measure the $^{12}C(^6Li,d)^{16}O$ reaction at an incident energy of 42 MeV using a Q3D spectrograph with an energy resolution of 60 keV, at $\theta_{Lab} = -21.5^0 \pm 3.0^0$. The deuteron spectrum was gated to select states decaying to the $^{12}C$ G.S. and $^{12}C$ $2_1^+$. In the present work, the upper limit for the resonance widths obtained is near the energy resolution. Note that the upper limit width for the states at 14.614 and 14.670 MeV is at least a factor of thirty smaller than the $\Gamma_{c.m}$ from the literature [9].

The experimental angular distributions, not previously reported, associated with four narrow resonances of natural parity, near the $4\alpha$ threshold at 14.614, 14.670, 14.825 and 14.931 MeV excitation energy are presented in Figure 2. The cross section uncertainties are relative and the DWBA predictions are also presented in comparison with the experimental data.

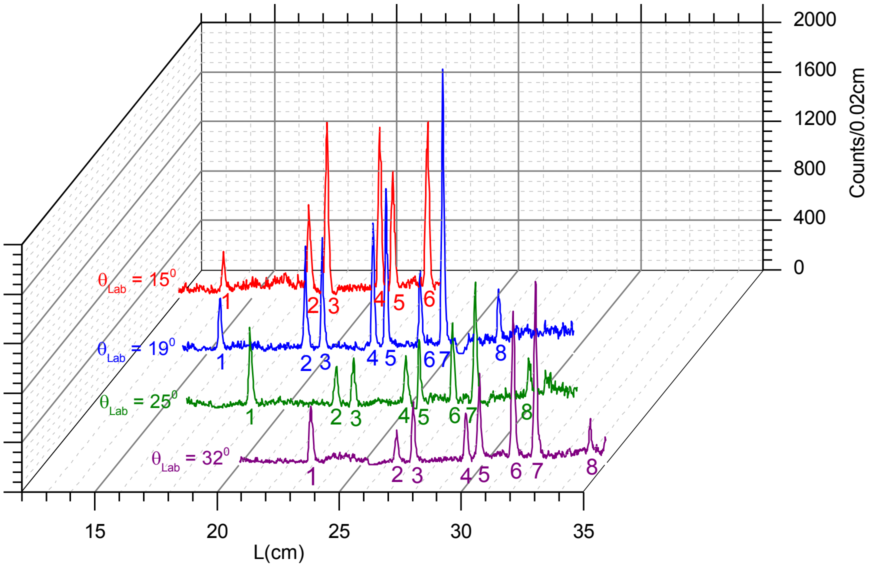

**Figure 1.** Examples of deuteron spectra measured.

**Table 1.** Energy levels and FWHM obtained in the present work in comparison with the results reported in the literature.

| Peak | Energy [(a)] (keV) | $J^{\pi}$ [(b)] | FWHM [(a)] (keV) | Energy [(c)] (keV) | FWHM [(c)] (keV) | Energy [(b)] (keV) | $\Gamma_{c.m.}$ [(b)] (keV) |
|---|---|---|---|---|---|---|---|
| 1 | 13988(2) | $2^-$ | 13(3) | 13983(2) | 70(6) | 13980(2) | 20(2) |
| 2 | 14316(6) | $4^{(-)}$ | 15(3) | 14297(3) | 66(7) | 14302(3) | 34(12) |
| 3 | 14392(6) | $5^+$ | 16(3) | 14396(2) | 64(5) | 14399(2) | 27(5) |
| 4 | 14614(2) | $4^{(+)}$ | 15(2) | | | 14620(20) | 490(15) |
| 5 | 14670(3) | $5^-$ | 15(3) | 14566(11) | 450(27) | 14660(20) | 670(15) |
| 6 | 14825(3) | $6^+$ | 18(3) | 14808(3) | 93(6) | 14815.3(16) | 70(8) |
| 7 | 14931(2) | $2^+$ | 18(2) | 14911(20) | 103(30) | 14926(2) | 54(5) |
| 8 | 15198(2) | $2^-$ | 18(3) | | | 15196(3) | 63(4) |

(a) Present work
(b) Tilley et. al. [9]
(c) Wheldon et. al. [8].

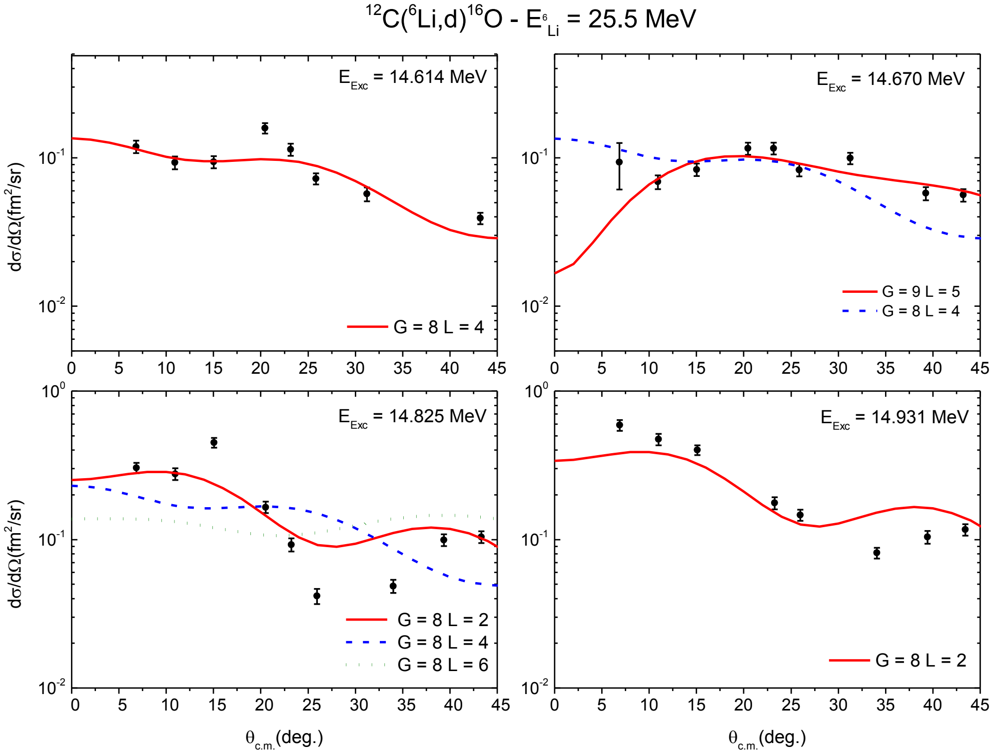

**Figure 2.** Experimental angular distributions in comparison with the DWBA predictions.

One-step alpha transfer finite-range DWBA calculations were performed employing the Cook [10] parameters with slightly modified geometrical parameters, $r_R$ = 1.25 fm and $a_R$ = 0.65 fm for the entrance channel and global optical model parameters from Daehnick et al.[11] for the exit channel. The binding potential of Kubo and Hirata [12] was taken for the $\alpha$+*d* description of $^6$Li. A Woods-Saxon binding potential bounded by 100 keV with reduced radius of 1.25 fm and diffusivity of 0.65 fm was assumed. Relative to the $^{12}C$ core, the global quantum number G [13] values 8 and 9 were considered, respectively, for positive and negative parity $\alpha$ states.

The state at 14.614 MeV, considered in the literature as a $J^{\pi} = 4^{(+)}$, is populated by an L = 4 transfer assuming a direct process, indicating the confirmation of the positive parity. The states at 14.670 and 14.931 MeV are reached by L=5 and L=2 respectively, in agreement with the $5^-$ and $2^+$ reported [9]. On the other hand, for the state at 14.81 MeV the shape of the experimental angular distribution is in principle in disagreement with the $6^+$ attribution [9], as can be appreciated in Figure 2. For a better illustration, besides the L = 6, the L = 2 and 4 DWBA predictions are also shown.

## 3 Conclusion

The $^{12}C(^6Li,d)^{16}O$ reaction, measured at a bombarding energy of 25.5 MeV, populated several narrow resonances in $^{16}$O around the 4$\alpha$ threshold. The energy resolution of 15 keV allowed the discrimination of at least three doublets and revealed a quasi-bound behavior of eight resonant states. The shape of the experimental angular distributions, not previously measured, associated with natural parity states could be reproduced by the DWBA calculations demonstrating the importance of the direct process in the transitions to these resonances. The upper limit for the resonance widths obtained is near the energy resolution. The upper limit width for the states at 14.614 and 14.670 MeV is at least a factor of thirty smaller than the $\Gamma_{c.m}$ from the literature [9], indicating that the $\alpha$-cluster structure information in this region should be revised. The present work is in progress and further analysis is undergoing.

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