Resonant states in ^{13}C and ^{16,17}O at high excitation energy

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Abstract. The ^{9}Be(^{6}Li,d)^{13}C and ^{12,13}C(^{6}Li,d)^{16,17}O reactions were measured at the São Paulo Pelletron-Enge-Spectrograph facility at 25.5 MeV incident energy. The nuclear emulsion detection technique was applied. Several narrow resonances were populated up to approximately 17 MeV of excitation energy. An excellent energy resolution was obtained: 40 keV for ^{13}C and 15-30 keV for ^{16}O. The upper limit for the resonance widths were determined. Recently, d-α angular correlations were measured at $\theta_d = 0°$ with incident energy of 25 MeV using the LNS Tandem-MAGNEX Spectrometer facility.

1. Introduction

The cluster phenomenon is important to understand the structure of light nuclei. This phenomenon is expected to be observed at excitation energies close to the cluster decay threshold, according to the Ikeda diagram [1]. The precise nature of cluster formation is still not completely understood. The main purpose of the present work is to study the structure of ^{13}C, ^{14}N and ^{16,17}O nuclei in order to investigate the cluster phenomenon at high excitation energy. In particular, the α cluster had a renewed interest with the interpretation of the Hoyle state as an α condensate state. By consequence, states analogous to the Hoyle state not only for (xα) nuclei but also (xα+n) ones become interesting objects of investigation. The question of whether the cluster has a fairly rigid crystal-like or a gas-like structure is still open to discussion [2-10]. In this context the study of the experimental evolution of the α-cluster phenomenon in (xα) and (xα+n) nuclei through (^{6}Li,d) transfer reactions has been pursued on ^{13}C and ^{16,17}O [11]. In addition, nuclear spectroscopy information of ^{14}N through (^{6}Li,α) reaction was obtained. The measurements performed at the São Paulo Pelletron-Enge-Spectrograph facility, used a ^{6}Li beam of 25.5 MeV employing the nuclear emulsion detection technique. The spectra reveal an unprecedented energy resolution of 15-40 keV, allowing the observation of unresolved states and measurement of resonant states. The absolute cross section and the respective angular distributions

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were determined up to 17 MeV excitation energy. Recently, in order to extract model independent the L transfer values, measurements at $\theta_d = 0°$ of d-α angular correlations [12] were obtained at an incident energy of 25 MeV using the LNS Tandem-MAGNEX Spectrometer facility.

2. Experimental Procedure

A 25.5 MeV ^{6}Li beam from the São Paulo Pelletron Accelerator bombarded uniform ^{9}Be (131 μg/cm^2) and natural C targets (110 and 30 μg/cm^2). The deuterons emerging from (^{6}Li,d) reactions ($\Delta\Omega$ = 0.268(3) msr, $\Delta\Theta_H$ = 0.38°) and ($\Delta\Omega$ = 1.237(4) msr, $\Delta\Theta_H$ = 1.75°) were momentum analyzed by the magnetic field of the Enge-Spectrograph and detected in emulsion plates (Fuji G6B, 50 μm thick). Spectra of ^{9}Be(^{6}Li,d)^{13}C and ^{12}C(^{6}Li,d)^{16}O associated respectively with seven scattering angles between 3° and 20° and eleven scattering angles between 5° and 32° in the laboratory frame, each one along 50 cm of the focal plane, were measured to investigate resonant states. The plates, after processing, were scanned in strips of 200 μm and a resolution of 40 keV was obtained for the first reaction. For the second reaction, excellent energy resolution of 30 keV and 15 keV was achieved for the thick and thin targets respectively. Due to the joint presence of tracks of deuterons and of elastically scattered ^{6}Li (charge state of two) above approximately 13 MeV of excitation in ^{13}C, the selective reading methodology was applied. The same energy of the beam and methodology were applied to investigate also the ^{13}C(^{6}Li,d)^{17}O reaction, however the data acquisition should be extended to reach the region the 4α + n threshold of interest. Figures 1, 2 and 3 displays portions of the measured position deuteron spectra for the ^{13}C, ^{16}O and ^{17}O respectively for illustration.
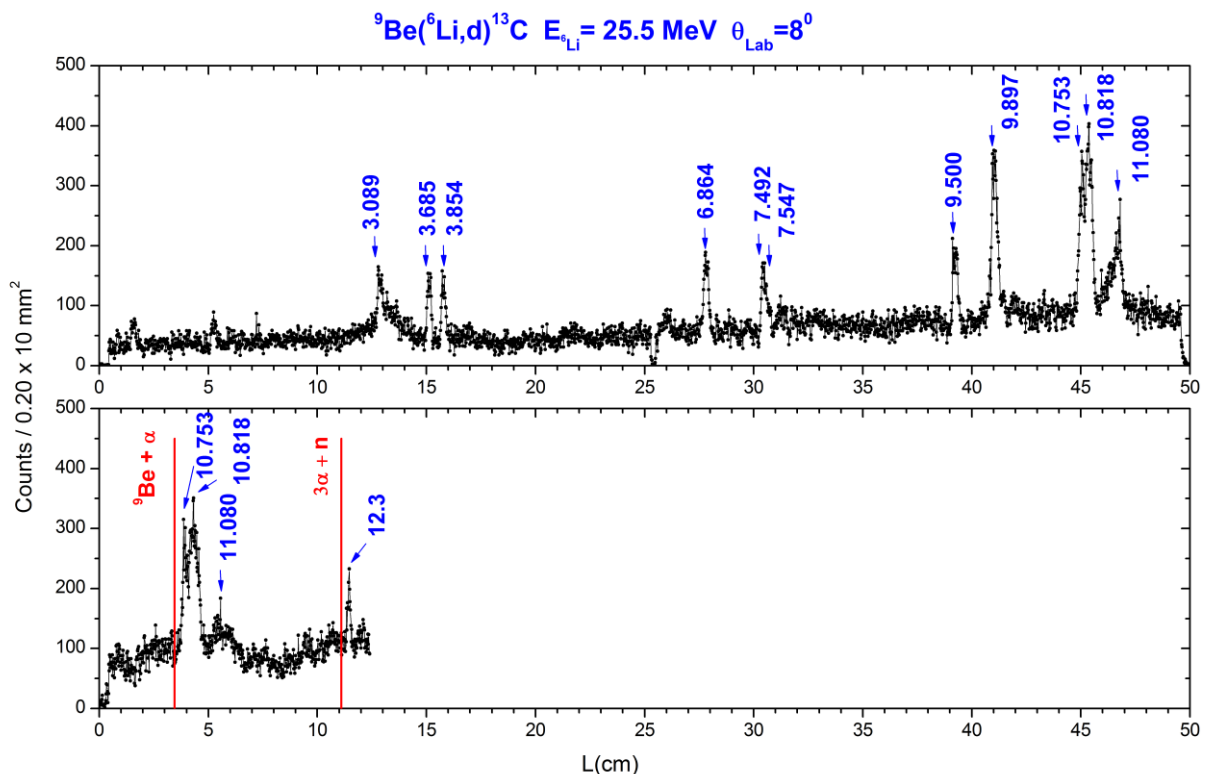

Figure 1. Portion of deuteron spectrum for ^{13}C at θ_{Lab} = 8°. The excitation energies are in MeV and the ^{9}Be+α and 3α+n thresholds are indicated.
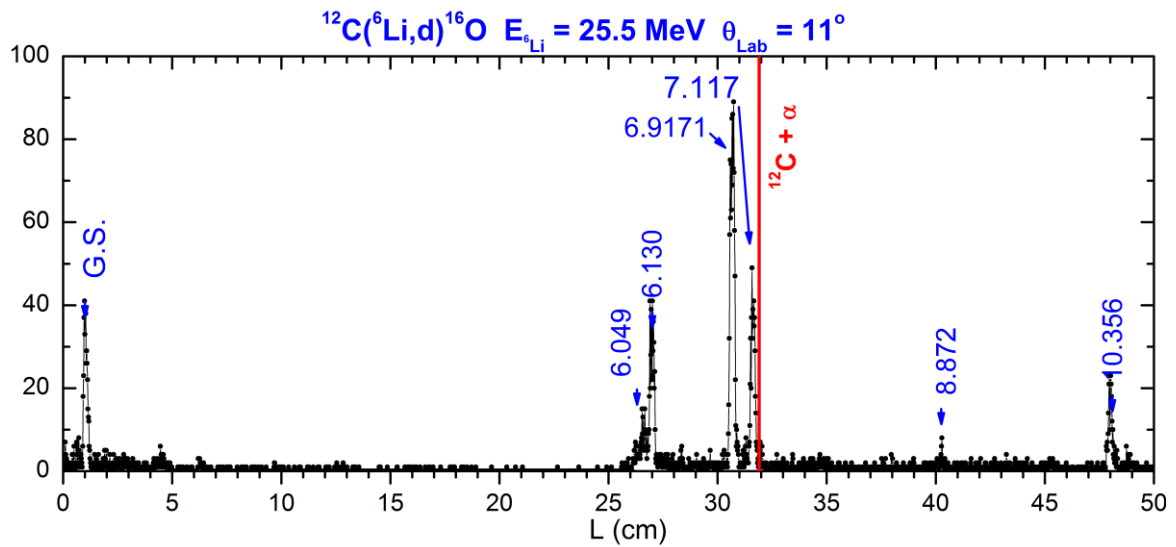
Figure 2. Portion of deuteron spectrum for ^{16}O at $\theta_{Lab} = 11°$. The excitation energies are in MeV and the ^{12}C+α threshold is indicated.

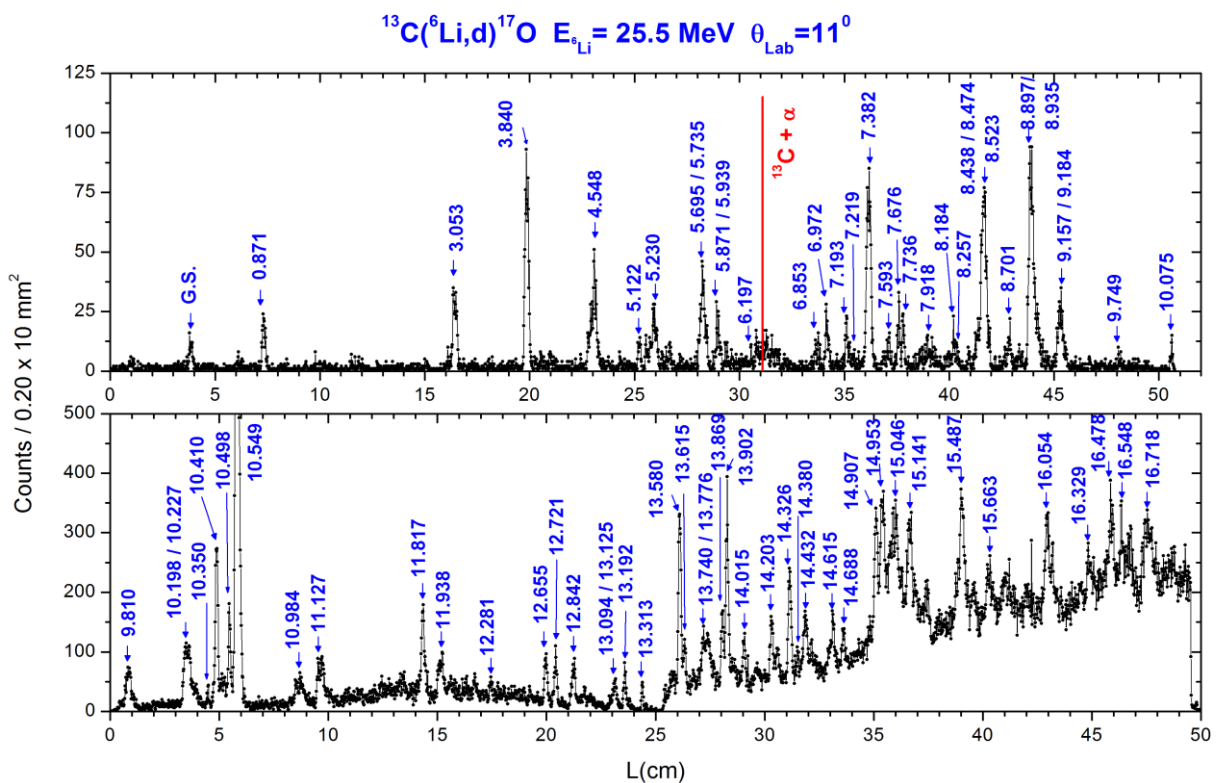**Figure 3.** Portion of deuteron spectrum for ^{17}O at $\theta_{Lab} = 11°$. The excitation energies are in MeV and the ^{13}C+α threshold is indicated.

The absolute scale of the cross sections was determined by the comparison of the optical model predictions for elastic scattering with measurements in the same target under similar conditions. The relative normalization of the spectra was referred to the beam total charge collected in each run.

In order to complement the data taken in São Paulo measurements of d-α angular correlation were obtained at similar conditions using the LNS Tandem- MAGNEX Spectrometer facility. The experiment was performed with an incident energy of 25.0 MeV, a natural C target with 17 $\mu g/cm^2$ thickness and a solid angle of $\Delta\Omega = 50$ msr (total angular width $\Delta\theta_H = 12^0$). The α particle were detected using the DINEX detector at the scattering chamber covering an angular range $\Delta\theta_H = 19^0$. Alpha angular distributions were measured from $\theta_{Lab} = 10^0$ to 60^0. The deuterons were detected at zero degree using the Focal Plane Detector (FPD). The trajectory reconstruction technique is applied in order to compensate the aberration due to the large solid angle of the spectrometer. The analysis is in progress.

3. Preliminary analysis and results
Several narrow resonances were populated in ^{13}C and ^{16,17}O. The alpha width Γ_α and line width $\Gamma_{c.m.}$ can be considered equivalent in the context of one level approximation [11]. In fact $\Gamma_\alpha = \Gamma_{c.m.}$ has been considered often in the literature [13]. In the present analysis the $\Gamma_{c.m.}$ was assumed as an upper limit for the resonance width Γ_α. The upper limit widths obtained are practically equal to the energy experimental resolution.
One step alpha transfer finite-range DWBA calculations using the code DWUCK5, in this preliminary analysis, were performed to describe mainly the shape of the experimental angular distributions associated with natural parity resonant states. The optical model used for the entrance and exit channels took the global parameter sets of Cook [14] and Daehnick et al. [15] respectively. The binding potential of Kubo and Hirata [16] was taken for the α + d description of ^{6}Li and, although α-resonant, the states under consideration were assumed to be bound by 100 keV in a Woods-Saxon binding potential ($r_0 = 1.25$ fm, a = 0.65 fm). Relative to the ^{9}Be core, G [10] values of 4 and 5 were applied respectively for negative and positive parity alpha states. Relative to the ^{12}C core, values 8 and 9 for positive and negative parity respectively were considered. For instance, the experimental angular distributions associated with the α resonances near the ^{9}Be + α and 3α+ n thresholds are presented in comparison with DWBA predictions in figure 4 [17]. For the resonance at 10.753 MeV, the DWBA angular distribution, calculated considering the wave function predicted by a simplified description of ^{9}Be + α system [18], is also shown.

4. Conclusions
Several narrow resonances were populated in ^{13}C and ^{16,17}O up to approximately 17 MeV of excitation energy. An unprecedented energy resolution was obtained: 40 keV for ^{13}C and 15-30 keV for ^{16}O. The upper limit for the resonance widths obtained is near the energy resolution. The present work is in progress and further analysis is undergoing.
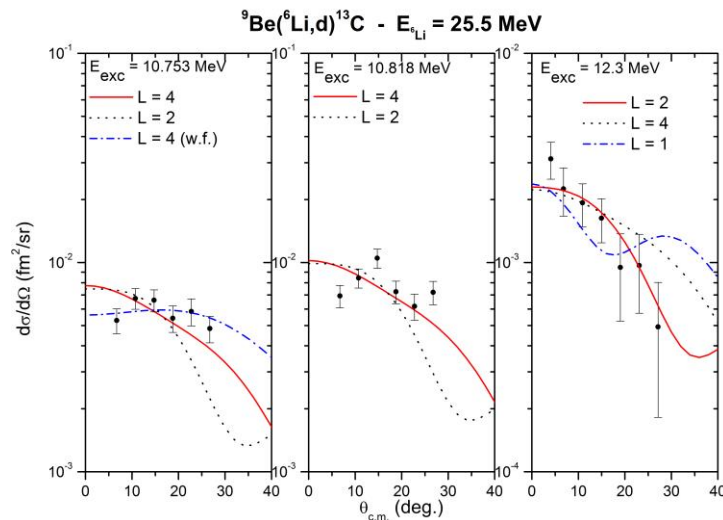
Figure 4. Experimental angular distributions associated with the α resonances near the ^{9}Be + α and 3α + n thresholds and DWBA predictions for different angular momentum transferred (L). The prediction labelled with w.f. considers the wave function obtained by a simplified description of ^{9}Be + α system [18].

Acknowledgments

References

[1]   Ikeda K, Takigawa N, and Horiuchi H 1968 *Prog. Theor. Phys. Suppl.* E **68**, 464
[2]   Funaki Y, Tohsaki A, Horiuchi H, Schuck P, and Röpke G 2005 *Eur. Phys. J.* A **24**, 321
[3]   Itoh M et al., *Phys. Rev.* C **84** 2011 054308
[4]   Ebran J P, Khan E, Niksic T, and Vretenar D 2012 *NATURE* **487**, 341
[5]   Kawabata T, Varenna 2009, *CERN Proc.* 2010-01, 95
[6]   Haigh P J, et al. 2010 J. Phys. G: *Nucl. Part. Phys.* **37** 035103
[7]   Yamada T and Funaki Y, 2008 *Int. J. Mod. Phys.* E **17** 2101
[8]   Yoshida T, Itagaki N, and Otsuka T, 2009 *Phys. Rev.* C **79**, 034308 1
[9]   Ohkubo S and Hirabayashi Y, 2010 *Phys. Lett*. B **684**, 127
[10]   Kanada-En'yo Y, 2014 *Phys. Rev.* C **89**, 024302
[11]   Rodrigues M R D et al., 2014 *Phys. Rev.* C **89** 024306
[12]   Cunsolo A et al. 1980 *Phys. Rev.* C **21,** 2345
[13]   Becchetti F., Flynn E, Hanson D and Sunier J 1978 *Nucl. Phys.* A **305**, 293
[14]   Cook J, *Nucl. Phys.* A 1982 **388**, 153
[15]   Daehnick W W, Childs J D, and Vrcelj Z 1980 *Phys. Rev.* C **21**, 2253
[16]   Kubo K I and Hirata M, 1972 *Nucl. Phys.* A **187**, 186
[17]   Borello-Lewin T et al., 2011 *Int. J. Mod. Phys.* E **20**, 1018
[18]   Souza M A and Miyake H, 2007 Proceedings of the XXX RTFNB, Brazil, 46