Alpha cluster states in light nuclei populated through the (^{6}Li,d) reaction

M. R. D. Rodrigues*, T. Borello-Lewin, L. B. Horodynski-Matsushigue, J. L. M. Duarte, C. L. Rodrigues, H. Miyake, G. M. Ukita
Instituto de Física, Universidade de São Paulo, São Paulo-SP, Brasil

F. Cappuzzello[1,2], C. Agodi[1], A. Foti[1,3], M. Cavallaro[1], D. Carbone[1]
[1] *INFN, Laboratori Nazionali del Sud, Italy*
[2] *Dipartimento di Fisica e Astronomia, Università di Catania, Italy*
[3] *INFN, Sezione di Catania, Italy*

B. T. Roeder
Cyclotron Institute, Texas A & M, College Station, Texas, USA

P. N. de Faria
Universidade Federal Fluminense, Niterói – RJ, Brasil

The alpha cluster correlation is an important concept in the nuclear physics of light nuclei [1]. The main purpose of this continuing research program is the investigation of the alpha clustering phenomenon in (xα) and (xα+n) nuclei through the (^{6}Li,d) alpha transfer reaction. In fact, there is scarce experimental information on the subject, in particular associated with odd-even nuclei and with resonant states predicted near (xα) and (xα+n) breakup thresholds [2].

Focusing on alpha resonant states in the nucleus ^{13}C, measurements of the ^{9}Be(^{6}Li,d) ^{13}C reaction, at an incident energy of 25.5 MeV, have been performed employing the São Paulo Pelletron-Enge Split-Pole facility and the nuclear emulsion detection technique. An excellent energy resolution of 50 keV was achieved, mainly due to the careful determination of the focal plane of the reaction, the use of nuclear emulsion plates, a uniform target (100 μg/cm^2), adequate spectrograph object and the good accelerator characteristics. The data allowed for the separation of the resonant contributions to the known 7/2$^-$ and (5/2$^-$) states near the ^{9}Be+ α threshold, both associated with an L = 4 transfer and revealed, up to 15 MeV of excitation, several narrow alpha resonant states, not previously reported [3]. In particular, the one at the 3α+n threshold, populated by an L=2 transfer at 12.3 MeV of excitation, indicates a ^{9}Be+α component for the ½$^-$ cluster candidate, associated with the ^{12}C Hoyle state. Above approximately 13 MeV of excitation in ^{13}C, due to the joint presence of tracks of deuterons and elastically and inelastically scattered ions of ^{6}Li (charge state of two), the selective reading methodology was applied,

*Spokesperson e-mail: marciadr@if.usp.br

thus removing the undesired background. A large E0 isoscalar transition, the signature of a spatially developed $1/2^-$ cluster-state [4], and reported by T. Kawabata [5] was detected near the (3α + n) threshold by alpha inelastic scattering. The L=2 transfer obtained in the excitation of the alpha resonant state at 12.3 MeV in the work under way is in agreement with the $1/2^-$ attribution [5] and reveals a ^{9}Be(g.s.) + α component not previously measured, supporting the predictions of the (3α + n) orthogonality condition model (OCM) calculations by Yamada and Funaki [6]. The OCM results [6] reveal that this state, although presenting a large component of the ^{12}C (Hoyle) + n channel, contains also components of the ^{12}C(2^+) + n and ^{9}Be(g.s.) + α channels. On the other hand, the $1/2^+$ state near the (3α + n) threshold, with a dilute alpha condensate character [6], was consistently not populated in the present investigation. It was shown that, the transfer of L = 1 does not reproduce the shape of the experimental angular distribution.

Alpha resonant states in the nucleus ^{16}O are also the focus of the present work. The known 0^+ state at 15.1 MeV of excitation , that has probably the gas-like configuration of the 4α condensate state with a very dilute density and a large component of α + ^{12}C(Hoyle) configuration [7,8], is of special concern. The existence of a rotational band with the α + ^{12}C (Hoyle) cluster state structure was recently demonstrated by Ohkubo and Hirabayashi [9]. Data measurements of the ^{12}C(^{6}Li,d)^{16}O reaction up to 18 MeV of excitation at an incident energy of 25.5 MeV, have been performed employing the São Paulo Pelletron-Enge Split-Pole facility and the nuclear emulsion detection technique. [10]

Within the international collaboration between the Nuclear Spectroscopy with Light Ions Group and the MAGNEX-Large-Acceptance Spectrometer Group - South Laboratory, INFN, Catania, Italy, measurements of α-d angular correlation applied to ^{12}C(^{6}Li,d)^{16}O → α + ^{12}C reaction at $\theta_d = 0^o$ were also taken in that laboratory. The MAGNEX is a Large-Acceptance Spectrometer with a solid angle of 50 msr (20 times bigger than the São Paulo Spectrograph) and a momentum resolution of ~1/2000, favored by the ion optics and the trajectory reconstruction programs. The data analysis is on progress.

Following the alpha resonant states investigation, ^{17}O is the next step of the present research program. The measurement of the states predicted above the 4α+n breakup

threshold, through the $^{13}C(^{6}Li,d)^{17}O$ reaction, not previously reported, is proposed. The following step would be measuring preliminary data for the $^{11}B(^{6}Li,d)^{15}N$ reaction.

The data will be taken using the Pelletron-Enge-Split-Pole facility, which is extremely adequate for this kind of experiment, as was already pointed out. The Pelletron accelerator provides a beam with an excellent profile and energy resolution, characteristics which are essential for the good quality of the data. The reaction products will be momentum analyzed by the Enge Spectrograph, which due to its focusing properties allows, for the same charge, the discrimination of different linear momenta of the particles, with an intrinsic resolution of $\Delta E/E \sim 3.6\ 10^{-4}$ .The detection with nuclear emulsion plates, which cover 50 cm along the focal plane, is especially relevant. This detector does not respond to the abundant background, mostly γ and X rays from (n,γ) reactions in the spectrograph iron core. Furthermore, the intrinsic resolution of this detector is negligible, maintaining the high resolution of the facility, an essential point in addition to its much reduced sensibility to the background, if low cross section results are to be detected in the presence of contaminant peaks. On the other hand, only three spectra can be measured with the same emulsion plate, i. e. without breaking the vacuum in the spectrograph.

Considering an ion beam of 100 nA on the target, the exposition time and the set ups proposed are shown on Table 1.

Reaction	**Terminal tension (MV)**	**E_{exc} (MeV)**	**Target thickness ($\mu g/cm^2$)**	**Solid angle (msr)**	**Counts in one peak**	**Average cross section (mb/sr)**	**Number of angles**	**Time per angle (h)**	**Total time (h)**
$^{13}C(^{6}Li,d)^{17}O$	8.0	15-25	100	0.825	500	0.05	11	4.0	69
$^{11}B(^{6}Li,d)^{15}N$	8.0	5-15	100	0.825	500	0.05	5	4.0	35
Experimental set-up for each period								24	48
Elastic angular distribution									24
							Total		176

Table 1: Time required per reaction considering a beam intensity of 100 nA. The total time also includes the time required for changing the emulsion plates.

For the $^{13}C(^{6}Li,d)^{17}O$ and $^{11}B(^{6}Li,d)^{15}N$ reactions a terminal tension of 8 MV is required in order to obtain well structured angular distribution. For the study of ^{17}O a complete data acquisition is planned while for ^{15}N only a preliminary data is requested. In both cases a detailed elastic angular distribution is necessary to obtain the absolute cross

sections. In the total time is also taken in account the break of 5 hours needed to change the emulsion plates. In conclusion for measurements of angular distributions, meant to allow L discrimination, 4+4 days of data acquisition will be necessary in the next year.

References:

[1] K. Ikeda, N. Takigawa and H. Horiuchi, Prog. Theor. Phys. Suppl. 464-475 (1968).
[2] M. R. D. Rodrigues et al., 12th International Conference on Nuclear Reaction Mechanism, Varenna, Italy 2009, edited by F. Cerutti and A. Ferrari, CERN Proc. 01, 331-335 (2010).
[3] T. Borello-Lewin et al., Proceedings of SOTANCP2, Brussels, Belgium 2010, edited by P. Descouvemont et al., Int. J. Mod. Phys E 20, 1018-1021(2011).
[4]Y. Sassamoto et al., Mod. Phys. Lett. A21, 2393 (2006).
[5]T. Kawabata, ”Alpha inelastic scattering and cluster structures in light nuclei” in 12th International Conference on Nuclear Reaction Mechanism, Varenna, Italy, edited by F. Cerutti and A. Ferrari , CERN Proceedings, 01, 95-98 (2010)
[6]T. Yamada and Y. Funaki, Int. J. Mod. Phys. E 17, 2101 (2008).
[7] Y. Funaki, T. Yamada, H. Horiuchi, G. Ropke, P. Schuck,A. Tohsaki Phys. Rev. Lett. 101, 082502 (2008)
[8] Y. Funaki, T. Yamada, A. Tohsaki, H. Horiuchi, G Ropke, and P. Schuck Phys. Rev. C 82, 024312 (2010).
[9] S. Okubo and Y. Hirabayashi Phys.Lett. B 681, 127-131 (2010)
[10] M. R. D. Rodrigues et al., Phys.Rev. C **89**, 024306 (2014).
[11] B. Buck, C. B. Dover and J. P. Vary, Phys. Rev. C **11** , 1803 (1975)

Previous Information on Project

Proposal approved	N **E98**
Period of beam time (date)	November 2014 – 6 days

Results or problems:

The last proposal approved considered the additional data acquisition of the $^{12}C(^{6}Li,d)^{16}O$ reaction, measurement of the $^{13}C(^{6}Li,d)^{17}O$ reaction and preliminary measurement data for the $^{11}B(^{6}Li,d)^{15}N$ reaction. The data for the $^{12}C(^{6}Li,d)^{16}O$ was completed. Due to a long strike in the university and problems with the ion source on 2014 and problems with the vacuum system of the spectrograph on 2015, the $^{13}C(^{6}Li,d)^{17}O$ and $^{11}B(^{6}Li,d)^{15}N$ measurements proposed were not performed.
A new turbo pump was installed on the system. There remains a vacuum leak in a dynamic bellows. Repair of this vacuum leak is in progress.

LABORATÓRIO ABERTO DE FÍSICA NUCLEAR

PAC 2016

Proposal	N° **E98**
Title: **Alpha cluster states in light nuclei populated through the (^{6}Li,d) reaction**	
Responsable: Márcia Regina Dias Rodrigues	e-mail: marciadr@if.usp.br
Participants Márcia Regina Dias Rodrigues, Thereza Borello-Lewin, Hideaki Miyake, Lighia Brigitta Horodynski-Matsushigue, José Luciano Miranda Duarte, Gilberto Mitsuo Ukita, Cleber Lima Rodrigues, Francesco Cappuzzello, Clementina Agodi, Antonino Foti, Manuela Cavallaro, Diana Carbone, Brian Thomas Roeder e Pedro Neto de Faria.	
Spokeperson: Márcia Regina Dias Rodrigues	e-mail: marciadr@if.usp.br
Telephone: +1-979-422-8877	Skype: marcia.rd.rodrigues
Number of days for experiment:	5 + 5
Period planned for the experiment (are the setup ready for beam time?): July 2016.	

Technical information

Ion source			Accelerator			Experimental Area	
Beam	Cathode	$I_{mínima}$	V_{min}	V_{max}	Bunched beam?	Beam line	Target
^{6}Li		100 nA	7,0 MV	8,0 MV	No	15° A	^{13}C, ^{11}B

Other relevant/needed information: