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
Instituto de Física, Universidade de São Paulo, São Paulo-SP, Brasil

A. Cunsolo, F. Cappuzzello, M. Cavallaro, A. Foti, C. Agodi, M. di Napoli
Universita di Catania and I.N.F.N., Laboratori Nazionali del Sud, Catania, Italy

G. M. Ukita
Faculdade de Psicologia, Universidade de Santo Amaro, São Paulo-SP, Brasil

The alpha cluster correlation is an important concept in the nuclear physics of light nuclei [1]. The main purpose of the research program in progress 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, an 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 reveal, 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, in the nuclear plates, of deuterons and elastically and inelastically scattered ions of ^{6}Li (charge state of two), the selective reading methodology was applied, 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

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

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]. In fact, 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. In fact, 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. On the other hand, 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. Several narrow resonances in ^{16}O from 12 to 18 MeV of excitation were observed. Around the 4α threshold, the discrimination of at least three doublets, allowed by the excellent energy resolution of the data [10], revealed a quasi bound behavior of eight resonant states. The associated experimental angular distributions, not previously measured, compared with DWBA predictions resolve parity doubt and give new information in this region of interest. Further analysis is undergoing. Additional data of ^{12}C(^{6}Li,d)^{16}O reaction are proposed for the next period. In the last period, five days of beam time allocated for this experiment were used, allowing measurements at nine scattering angles up to 18 MeV excitation energy. The other five days were not effectively used because of technical problems in the ion source. In order to extend the energy excitation range up to 20 MeV at least more twelve scattering angles measurements are required.

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 also proposed. The pursuing of the study by measuring preliminary data for the $^{11}B(^{6}Li,d)^{15}N$ reaction is included in this proposal.

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.

Cross sections between 0.5 and 10 mb/sr are expected for the even nuclei and at least one order of magnitude less for the odd ones. 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)**
$^{12}C(^{6}Li,d)^{16}O$	6.5	10-20	40	1.24	1000	1	12	3.5	62
$^{13}C(^{6}Li,d)^{17}O$	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								36	72
Elastic angular distribution									36
							Total		274

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.

The $^{12}C(^{6}Li,d)^{16}O$ set up was determined in order to give continuity on the previous measurements. 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+4 days of data acquisition will be necessary in the next year.

For the analysis of the experimental angular distributions associated with the quasi-bound resonances, DWBA predictions using, as form factors, wave functions to be calculated in the frame of the phenomenological alpha cluster model [11] will be employed, allowing the extraction of the experimental reduced alpha widths.

Within the international collaboration between the Nuclear Spectroscopy with Light Ions Group and the MAGNEX-Large-Acceptance Spectrometer Group - South Laboratory, INFN, Catania, Italy, further measurements will also be 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.

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