Investigation of α-cluster states in ^{13}C via the (^{6}Li,d) reaction

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Abstract

The $^{9}Be(^{6}Li,d)^{13}C$ reaction was used to investigate possible α-cluster states in ^{13}C. The reaction was measured at 25.5 MeV incident energy, employing the São Paulo Pelletron-Enge-Spectrograph facility and the nuclear emulsion detection technique. Ten out of sixteen known levels of ^{13}C, up to 11 MeV of excitation, were observed and, due to the much improved energy resolution of 50 keV, at least three doublets could be resolved. This work presents a preliminary analysis of five of the most intensely populated states, also in comparison with the results of former transfer studies.

1 Introduction

The systematic study of α-cluster spectroscopic strengths in odd-even light nuclei with (xα + ν) structure is the main purpose of the investigation in progress. Experimentally, the α-clustering phenomenon has been mainly studied through the (^{6}Li,d) reaction on even-even nuclei [1] and, only a few works focused on odd-A nuclei. Referring to the α-structure of ^{13}C, data for the $^{9}Be(^{6}Li,d)^{13}C$ reaction have been taken in São Paulo, using the Pelletron-Enge-Magnetic-Spectrograph facility, at an incident energy of 25.5 MeV. Calculations of the α-cluster model, which does not consider internal excitations of the constituents of the α + ^{9}Be system, are under way, aiming at generating alpha wave functions to be used in the DWBA description of the (^{6}Li,d) reaction.

The former $^{9}Be(^{6}Li,d)^{13}C$ works, by Gol'dberg *et al.* [2] and Aslanoglou *et al*. [3], presented energy resolutions of 400 keV and 110 keV, respectively. In the present work the resolution of 50 keV achieved contributes to a better understanding of the α + ^{9}Be structure in ^{13}C.

2 Experimental Procedure

The 25.5 MeV ^{6}Li beam of the São Paulo Pelletron accelerator was focused on a 131 μg / cm^2, clean and uniform target of ^{9}Be. The deuterons emerging from the (^{6}Li,d) reaction were momentum analysed by the field of the Enge Magnetic Spectrograph and detected in nuclear emulsion plates (Fuji G6B, 50 μm thick). The plates covered 50 cm along the focal surface and spectra were measured at seven scattering angles, between 3º and 20º in the laboratory frame, spanning up to approximately 11 MeV in ^{13}C excitation energies. After processing, the plates were scanned in strips of 200 μm and an energy resolution of 50 keV was achieved. Fig. 1 displays the deuteron spectrum corresponding to θ_{lab} = 8º, showing the number of tracks per strip versus the position along the focal plane. In the figure, the excitation energies of ^{13}C in MeV, taken from the systematics of Ajzenberg-Selove [4], associated with the deuteron peaks are indicated. A total of ten states, of the sixteen tabulated [4], was detected and the improvement of experimental conditions allowed for the separation of three doublets, corresponding respectively to the attributed ^{13}C excitation energies: 3.685 MeV and 3.854 MeV, 7.492 MeV and 7.547 MeV, and 10.753 MeV and 10.818 MeV.

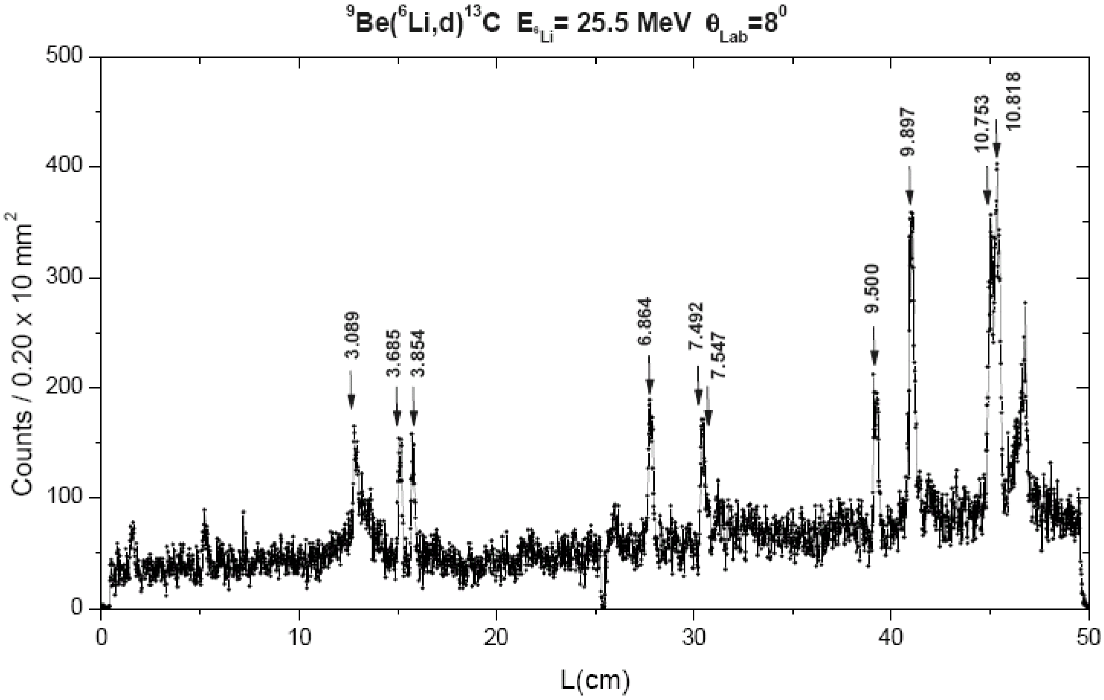

Fig. 1: Position deuteron spectrum. Indicated are the excitation energies from Ref. [4].

3 Preliminary analysis and Results

To describe the experimental angular distributions, particularly of the more intensely populated states, one step α transfer finite-range DWBA calculations using the code DWUCK 5 have been performed. In this preliminary analysis, the optical model description for the entrance channel (^{9}Be + ^{6}Li) took the global parameter set of Cook [5], with a slight decrease [6] in the geometrical parameters, as indicated by the fit of the elastic scattering angular distribution of ^{6}Li in ^{13}C, measured with the same incident energy. It is to be remembered that the optical potential for the entrance channel is quite important since it defines the door-way state of the transfer reaction. The exit channel (d + ^{13}C) optical potential applied was that of Daehnick *et al.* [7] and for the (α + d) description of ^{6}Li the Kubo and Hirata [8] binding potential was taken. A Woods-Saxon binding potential for the (α + ^{9}Be) system, with reduced radius of 1.25 fm and diffuseness of 0.65 fm was applied, the depth being adjusted to reproduce the binding energy of each ^{13}C state. The number of nodes N of the transferred α particle radial wave function and, the orbital angular momentum L, relative to the ^{9}Be core, were determined by the oscillatory energy conservation relation $G = 2(N - 1) + L = \sum_i [2(n_i - 1) + l_i]$, where (n_i, l_i) are the single nucleon shell quantum numbers. In the present work a $(1p)^4$ single particle configuration was assumed for the negative parity states (G=4) and for the positive parity states a $(1p)^3(1d)$ structure (G=5) was considered.

The known states [4] at 3.685 MeV ($3/2^-$) and at 3.854 MeV ($5/2^+$), seen as doublet in former α transfer studies [2,3], are well resolved in the present work. Fig. 2 shows the corresponding experimental angular distributions in comparison with DWBA predictions. The angular distribution associated with the $3/2^-$ state needs an L = 0 + 2 mixture to be reproduced, since, due to the experimentally observed filling of the predicted minimum, a pure L = 0 contribution as indicated by Aslanoglou *et al.* [3] is not sufficient. In the case of the $5/2^+$ state at 3.854 MeV, which could be reached through L = 1 and L = 3 transfers, the L = 1 dominates.

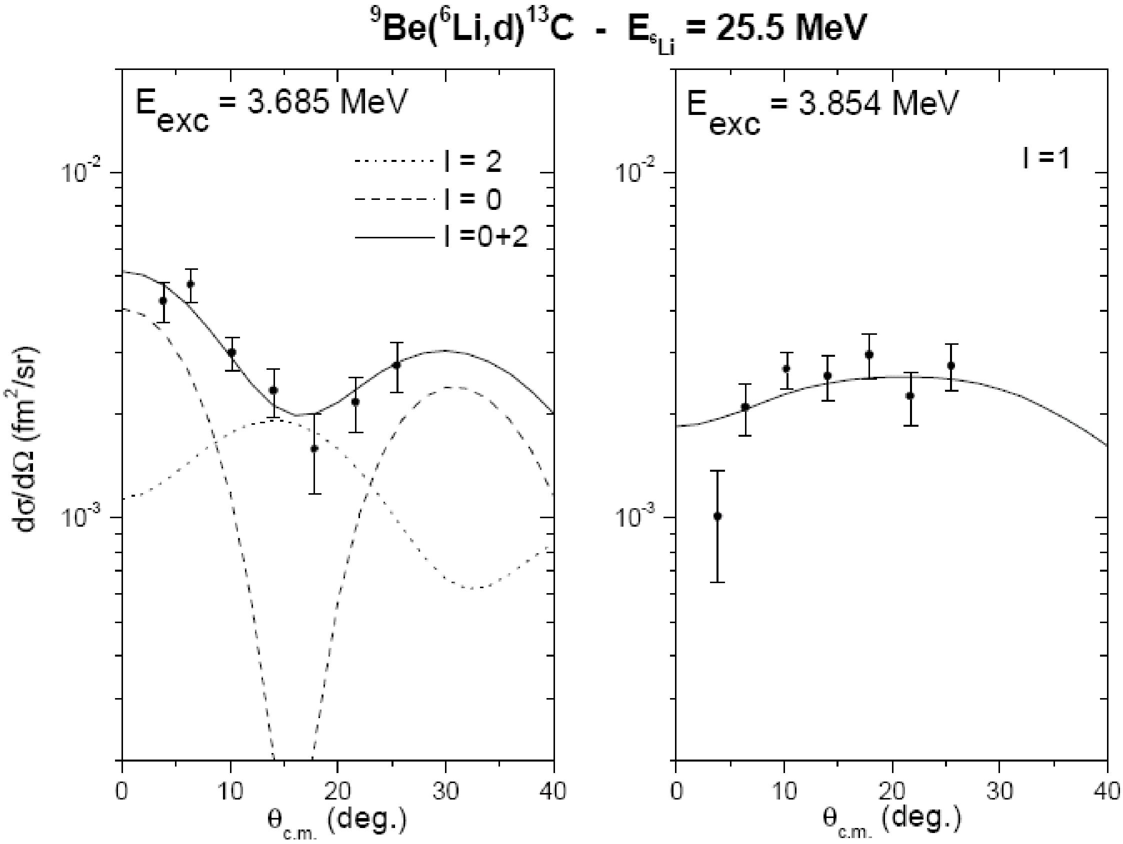

Fig. 2: Experimental angular distributions in comparison with DWBA predictions for the states at 3.685 MeV ($3/2^-$) and at 3.854 MeV ($5/2^+$).

The experimental angular distributions and DWBA predictions for the most intensely populated states, the doublet at 10.8 MeV, now resolved, and the state $3/2^-$ at 9.897 MeV, are presented in Fig. 3. The DWBA analysis for the states $7/2^-$ at 10.753 MeV and ($5/2^-$) at 10.818 MeV assumed both bound by 100 keV, although they are unbound. An almost pure $L = 2$ transfer can describe the experimental angular distribution of the $3/2^-$ state, even if an admixture of $L = 0$, as also tried by Aslanoglou *et al.* [3], could improve the fit somewhat. As was the case also for several other experimental angular distributions, the analysis of the previous work [3] was unable to reproduce their data, the structure of the data distribution being, at least, out of phase with the prediction. The integrated experimental angular distribution associated with the states $7/2^-$ and ($5/2^-$) in the former work [3] was fitted by a pure $L = 2$ transfer. In the present work, for both transitions, a pure $L = 4$ transfer is indicated instead.

According to Millener *et al.* [9], who performed a detailed investigation of electron inelastic scattering on ^{13}C, and in agreement with ^{13}C shell model calculations [10], the three states, $3/2^-$, $7/2^-$ and ($5/2^-$), under analysis present predominantly a $(1s)^4(1p)^7(2s1d)^2$ configuration, involving, therefore, components above the p shell. For the three states mentioned, the angular distributions and DWBA fits, considering the $(1p)^2(2s1d)^2$ single particle configuration and $G = 6$ for the transferred alpha, would only result in lower spectroscopic intensities, without any pronounced difference in shape of the predicted angular distributions.

The experimental angular distributions of the states $3/2^-$ (9.897 MeV) and $7/2^-$ (10.753 MeV) were also compared in Fig. 3 with the DWBA predictions using the form factor described by the radial wave functions taken from Souza and Miyake calculations [11]. The local cluster-core potential for the $\alpha + {}^9Be$ system uses the nuclear term based on the form proposed by Buck, Merchant and Perez [12], adding Coulomb and spin-orbit terms. A good agreement with the data was obtained specially for the $7/2^-$ state, which is associated in the calculation with an $L = 4$ angular momentum.

Intense resonances [4] in the neutron elastic scattering on ^{12}C can be associated with the states in ^{13}C which are excited in the α transfer, at 10.753 MeV and 10.818 MeV, slightly above the $^{9}Be + \alpha$ threshold, possibly with astrophysical implications.

The results here presented are still preliminary, in the short term the $\alpha + {}^{9}Be$ wave functions calculated [11] will be used in the DWBA descriptions to extract the α spectroscopic strengths of the most intensely excited states. Next, the influence on the DWBA predictions of the full complex remnant term [13] inclusion in the residual interaction will be investigated.

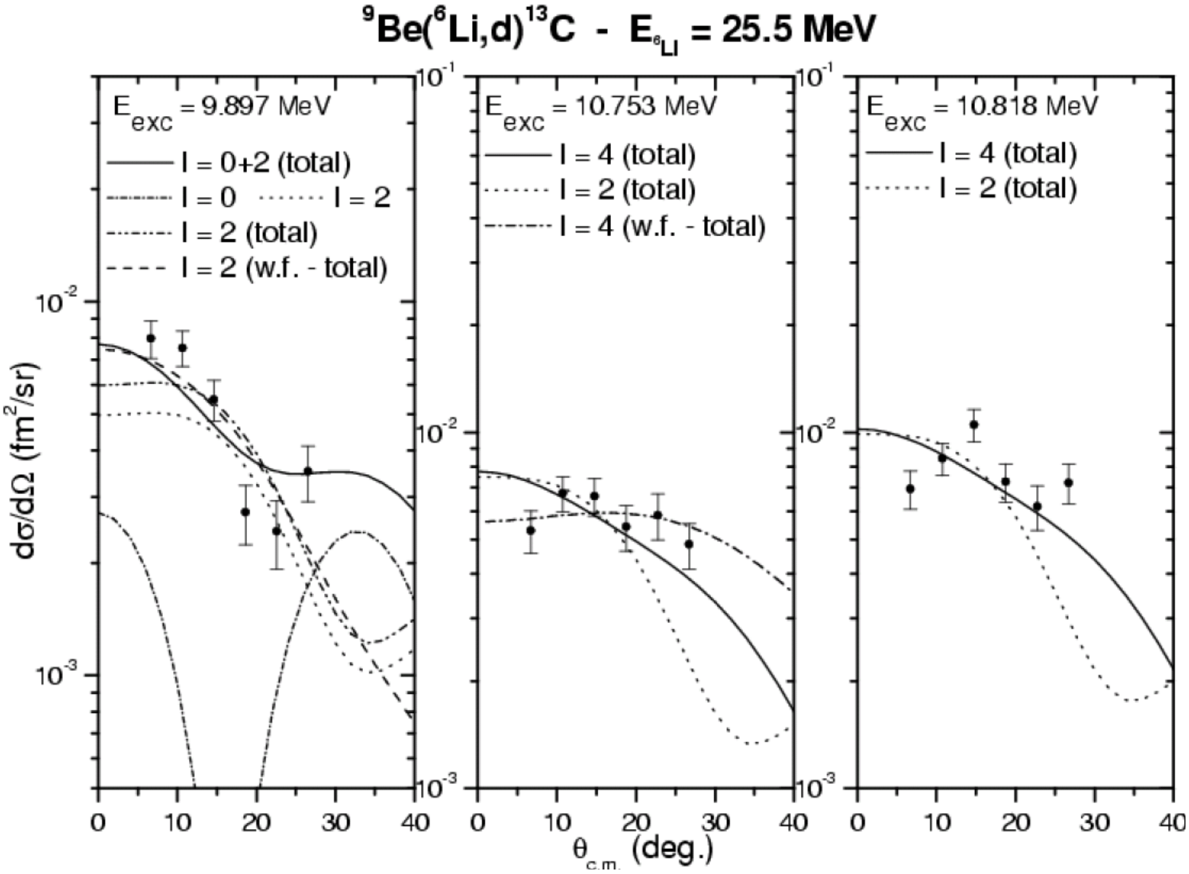

Fig. 3: Experimental angular distributions in comparison with DWBA predictions for the most intensely populated states. The results using the wave functions (w.f.) from Ref. [11] for the states 9.897 MeV and 10.753 MeV are also indicated.

Acknowledgments

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References

[1] H.W. Fulbright *et al*., Nucl. Phys. **A284**, 329 (1977).

[2] V.Z. Gol'dberg *et al*., Izv. Akad. Nauk SSSR, Ser. Fiz. **35**, 1663 (1971); Bull. Acad. Sci. USSR, Phys. Ser. 35, 1514 (1972).

[3] X. Aslanoglou *et al*., Phys. Rev. C **40**, 73 (1989).

[4] F. Ajzenberg-Selove, Nucl. Phys. **A523**, 1 (1991).

[5] J. Cook, Nucl. Phys. **A388**, 153 (1982).

[6] M.R.D. Rodrigues *et al*., Proceedings of the XXX Reunião de Trabalho sobre Física Nuclear no Brasil, 40 (2007).

[7] W.W. Daehnick, J.D. Childs and Z. Vrcelj, Phys. Rev. C **21**, 2253 (1980).

[8] K.I. Kubo and M. Hirata, Nucl. Phys. **A187**, 186 (1972).

[9] D. J. Millener *et al*., Phys. Rev. C **39**, 14 (1989).

[10] J. F. Dubach, Los Alamos Scientific Laboratory Report 2A 8303-C1980, p. 72.

[11] M.A. Souza and H. Miyake, Proceedings of the XXX Reunião de Trabalho sobre Física Nuclear no Brasil, 46 (2007).

[12] B. Buck, A.C. Merchant and S.M. Perez, Phys. Rev. C **51**, 559 (1995).

[13] N. Keeley, K.W. Kemper, Dao T. Khoa, Nucl. Phys. **A726**, 159 (2003).