STRUCTURE OF ^{13}C EXCITED STATES WITH LOW-ENERGY REACTIONS OF α PARTICLES ON ^{9}Be NUCLEI*

I. Lombardo, D. Dell'Aquila, L. Francalanza
G. Spadaccini, M. Vigilante

Dipartimento di Fisica "E. Pancini", Università degli Studi di Napoli Federico II
Via Cinthia 21, 80126 Napoli, Italy
and
INFN — Sezione di Napoli, Ed. 6, Via Cintia, 80126 Napoli, Italy

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We report results on the spectroscopy of ^{13}C obtained by analysing experimental data on ^{9}Be(α,α) and ^{9}Be(α, n) reactions at low energies ($E_\alpha \approx 2$–10 MeV). A comprehensive R-matrix fit of several excitation functions has allowed to improve the spectroscopy of ^{13}C states in the excitation energy region $E_x \approx 12$–18 MeV. Preliminary results on the structure of several excited states are discussed.

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1. Introduction

The study of low-energy nuclear reactions between light ions allows to carefully probe the structure of light nuclei. In particular, it is possible to derive evidences on the existence of α-cluster structures at high excitation energies [1, 2]. Although these effects are characteristic of self-conjugated ($N = Z$, even–even) nuclei, they can be also observed in neutron-rich isotopes of Be [3–6], C [3, 7] and O [8, 9]. In this case, the extra neutrons can play the role of covalent particle between the α-like centres [10], leading to the manifestation of shapes very far from the spherical symmetry (dimers, trimers, linear chains, triangles ...). In order to study this rich phenomenology, it is mandatory to have the broadest possible knowledge of the spectroscopy of light nuclei under investigations. In this way, it is possible to search on the existence of molecular rotational bands via E_x *vs.* $J(J+1)$ correlations and to investigate the α structure of excited states by analysing the α-decay partial widths.

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The study of resonant elastic scattering (in direct or inverse kinematic) of α particles on light target can be used to probe the cluster structure of light nuclei. In general, anyway, the analysis of nuclear reactions that form a compound nucleus subsequently de-exciting via α-particle emission is a powerful tool to study α clustering [11–13].

In this article, we will describe results on the ^{13}C spectroscopy probed by a R-matrix fit of data concerning several nuclear reactions induced by α-particle bombardment of ^{9}Be targets. Apart from the radiative capture channel, that are quite minor at excitation energies here investigated (well above the particle emission threshold), the open reaction channels are the elastic (referred to as α_0), inelastic (referred to as α_1, α_2 ... depending on the excitation energies of the residual nucleus, ^{9}Be) and neutron (referred to as n_0, n_1, n_2 depending on the excitation energies of the residual nucleus, ^{12}C) ones. In Section 2, we describe the main features of the experimental apparatus we used to measure the α+^{9}Be elastic and inelastic scattering excitation functions at various angles; we discuss briefly also the main features of the ^{9}Be(α, n) data set taken from the literature and used in the present analysis. In Section 3, we discuss the preliminary results of the comprehensive R-matrix fit of data with particular emphasis to the search for α cluster structure. Finally, in Section 4, we draw some conclusions and perspectives for future investigations starting from the preliminary results here described.

2. Details on the used data sets

The data sets used to perform the R-matrix fit analysis involved both ^{9}Be$(\alpha,\alpha)^{9}$Be and ^{9}Be$(\alpha,n)^{12}$C reaction channels in the bombarding energy range $E_\alpha \approx 1.6$–10 MeV. Low-energy data on the ^{9}Be$(\alpha,\alpha_0)^{9}$Be elastic scattering ($E_\alpha \approx 1.6$–3.6 MeV, $\theta_{\rm lab} \approx 160^\circ$) have been taken from Ref. [14], while in the energy domain $E_\alpha \approx 3.5$–10 MeV, we used data published in [15, 16] obtained by the TTT3 tandem accelerator in Napoli, Italy [17–20]. The absolute cross-section scale was benchmarked with a dedicated experiment with a thick Be target [15]. Starting form the energy analysis of the ejectile spectrum, in this experiment, we were also able to determine the excitation function for the ^{9}Be$(\alpha,\alpha_1)^{9}$Be$_{1.68}$ and ^{9}Be$(\alpha,\alpha_2)^{9}$Be$_{2.43}$ inelastic scattering channels at $\theta_{\rm lab} = 70^\circ$ [16] and in the energy window $E_\alpha \approx 7$–10 MeV.

Concerning the ^{9}Be$(\alpha,n)^{12}$C reaction, we used the angle integrated cross-section data reported in Ref. [21]. In this work, the authors succeeded in measuring separately cross sections for the ^{9}Be$(\alpha,n_0)^{12}$C, ^{9}Be$(\alpha,n_1)^{12}$C$_{4.44}$ and ^{9}Be$(\alpha,n_0)^{12}$C$_{7.65}$ reaction channels by means of a neutron spectrometer based on proton recoils. This data set covers the bombarding energy range $E_\alpha \approx 2$–7 MeV, in good overlap with the data obtained from the α+^{9}Be scattering.

3. Preliminary results of R-matrix fit of data

We performed a comprehensive R-matrix fit of the experimental data sets described in the previous section. In particular, we included in the fit α+^{9}Be elastic scattering data at $\theta_{\rm lab} = 160°, 150°, 135°, 110°$ [14, 15], inelastic scattering data at $\theta_{\rm lab} = 70°$ [22], and integrated cross section for the n_0, n_1 and n_2 reaction channels from [21]. We used the multi-channel, multi-level R-matrix code AZURE2 [23]. As a starting point, we used the spectroscopic information on ^{13}C levels reported in Ref. [24], coupled with the more recent determinations described in Ref. [25] from an R-matrix analysis of α+^{9}Be elastic scattering data obtained with the Thick Target Inverse Kinematic Method. When necessary, the J^π assignment tentatively reported in the literature have been changed to describe in the best possible way all the details of the excitations functions.

Preliminary results are shown in Fig. 1: the experimental excitation functions (open circles: elastic scattering data at 135° [15]; full circles in the inset: integrated cross section for the n_0 channel [21]) are reasonably well-reproduced by the R-matrix fit. We observed also a good description of all the other excitation functions mentioned in the previous section; they will be

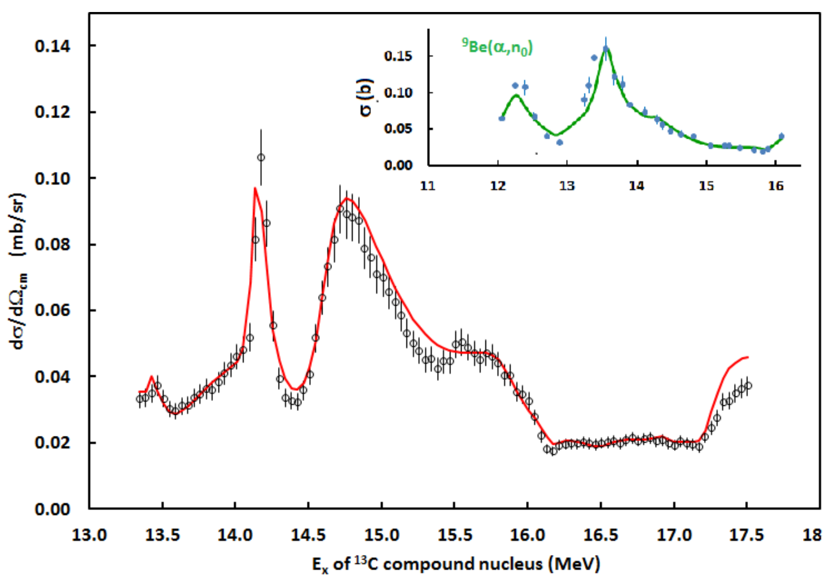

Fig. 1. (Main panel) Excitation function of the ^{9}Be(α,α_0)^{9}Be elastic scattering events at $\theta_{\rm lab} = 135°$. Open circles: experimental data taken from Ref. [15]. Solid line: preliminary results of the R-matrix fit of data. (Inset) Angle-integrated cross section of the ^{9}Be(α,n_0)^{12}C reaction. Full circles: experimental data taken from Ref. [21]. Solid line: preliminary result of the R-matrix fit of data.

the subject of a future, more extended, publication. Such a nice reproduction of the experimental data has been obtained by using states having J^π assignments consistent with the ones reported in the literature [14, 24–26] in the excitation energy region $E_x \approx 12$–14.5 MeV. At higher excitation energies, where the literature is much more patchy, we performed a high number of attempts by using various options for the J^π values of such states, until a good description of all the excitation functions was obtained.

Even if the results are still preliminary, some tentative conclusions on the structure of ^{13}C can be drawn. First of all, the 13.42 MeV state, that is responsible of the presence of a small peak in the elastic scattering excitation function, should have a $\frac{9}{2}^-$ assignment, otherwise it is impossible to reproduce the trend of the excitation functions in this energy region as a function of the angle. This assignment is in agreement with Refs. [14, 24, 25] and seems to rule out the $\frac{7}{2}^+$ suggestion done in Ref. [27] based on recurrences typical of the existence of rotational band.

Another preliminary finding concerns the narrow peak at about 14.11 MeV in the elastic scattering data. To correctly reproduce the angular evolution of the shape of this peak, it is necessary to use a couple of states with opposite parities (namely, a $\frac{5}{2}^-$ 14.13 MeV state and a $\frac{7}{2}^+$ 14.16 MeV state), in a good agreement with early suggestions reported by Goss *et al.* [14].

At higher excitation energies ($E_x \approx 15$–17 MeV), a larger number of excited states are needed to reproduce data (about 15 states in 2 MeV). Among them, a $\frac{1}{2}^-$ state at 16.12 MeV, leading to a marked dip in the elastic scattering excitation function, is of particular interest. Calculations done with the OCM model [28] suggest that the (presently unknown) fifth $\frac{1}{2}^-$ excited state in ^{13}C (predicted at about 16.6 MeV) could have a marked $|n \bigotimes {}^{12}\mathrm{C}_{7.65}\rangle$ structure, being therefore strongly related to the Hoyle state in ^{12}C.

The preliminary analysis of inelastic scattering channels, here performed for the first time at low energies, reserved interesting surprises. While the α_1 channel can nicely be described by only using resonant contributions, to reproduce correctly the shape and absolute value of the α_2 channel cross section, we need to include a non-resonant (direct) contribution. This point is in a qualitative agreement with the one of Ref. [29] where, at higher energies, a preferential excitation of the $\frac{5}{2}^-$ state in ^{9}Be (the second member of the ground state rotational band) by direct mechanisms is observed. Similar findings have been observed in α+^{25}Mg inelastic scattering events at 12.5 MeV [30].

Heaving in mind that the R-matrix results here reported are still preliminary and considering the very complex structure of the excitation functions here investigated, further studies are being currently carried out.

4. Conclusions and perspectives

In this article, we discussed preliminary results on the spectroscopy of ^{13}C studied by an R-matrix fit of experimental data on excitation functions related to $\alpha+^{9}$Be collisions at low energies ($E_\alpha \approx 2$–10 MeV), at several angles and for various reaction channels. This analysis allows to improve the spectroscopy of ^{13}C states in the excitation energy region $E_x \approx 12$–18 MeV. Preliminary results on the structure of several excited states have been discussed, in the light of the results previously reported in the literature. The state at 13.42 MeV should be assigned $\frac{9}{2}^-$, in disagreement with the $\frac{7}{2}^+$ assignment proposed in [27]. To describe the angular evolution of the pronounced peak at ≈ 14.15 MeV in the elastic scattering excitation functions, it is necessary to include the presence of two opposite-parity levels, in agreement with [14]. Further analyses are currently going on; they will allow to improve the complex scenario of excited states in ^{13}C above the α-emission threshold, with the aim of unveiling the presence of rotational bands due to pronounced α-cluster structure.

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