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Analysis of excited states in ^{13}C and their cluster structure

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Abstract. An accurate understanding of the spectroscopy of ^{13}C is key to understand clustering phenomena in light nuclear systems. In this nucleus, many theoretical models predict the existence of α-cluster configurations, stabilized by the presence of an extra neutron. Despite of its importance, the spectroscopy of ^{13}C is still affected by ambiguities, demanding for new data against which benchmarking the models. We improve the knowledge on the ^{13}C level scheme by means of a comprehensive R-matrix analysis of several experimental data sets. Our new spectroscopic information contributes to solve existing ambiguities in ^{13}C structure and will serve a valid benchmark for theoretical models attempting to describe clustering in neutron rich systems.

1 Introduction

Carbon isotopes represent a unique opportunity to investigate clustering phenomena in light nuclear systems as a function of the neutron excess. The clustered structure of carbon isotopes is a long standing problem. For a long time, the self-conjugate ^{12}C was associated to a linear chain configuration formed by 3α-particles [1]. Recently, high-precision experiments pointed out instead the occurrence of D_{3h} triangular symmetry in such nucleus [2, 3], triggering a renovated interest for three-centers cluster structures in nuclei. In this framework, it is fundamental to fully understand the spectroscopy of the carbon isotopes that are obtained by removing or adding a neutron to the self-conjugate ^{12}C, namely ^{11}C and ^{13}C. The first has been the subject of recent investigations [4–6] that pointed out excited states associated to cluster-like structures and discussed their relevance in astrophysics [7]. For the latter, the neutron rich ^{13}C, the situation is much more complicated. Recently, theoretical investigations predicted the possible manifestation of 3α cluster structures in this nucleus with the formation of highly-deformed shapes and rotational bands extending well above the α-emission threshold [8–10]. However, the presence of several ambiguities affecting the spectroscopy of such nucleus [11], in particular above the α-emission threshold (i.e. E_x = 10.648 MeV), prevent a fully unambiguous identification of the proposed bands, demanding for more firm experimental findings [12].

Because of the clustered structure of ^{9}Be, $\alpha+^9$Be reactions have been proposed to be very powerful tools to explore the spectroscopy of ^{13}C above the α-threshold [13]. When an α-particle strikes a ^{9}Be, dominant reactions are the elastic or inelastic resonant scatterings, respectively ^{9}Be(α,α) and ^{9}Be(α,α') [13–19], and the ^{9}Be(α,n) reactions [20, 21]. To help to clarify the spectroscopy of ^{13}C above the α-threshold, we performed, for the first time, a completely unified and comprehensive analysis of the above mentioned reactions in terms of the R-matrix theory.

In this paper, we report on the results of our R-matrix analysis that strongly contributes to better constrain the spectroscopy of ^{13}C. In Section 3, we describe the data sets used for the present analysis. Section 4 contains details on the R-matrix fit of the data sets. In conclusion, Section 4 contains interpretations of such results in terms of the clustered structure of ^{13}C. More details on this analysis and related interpretations can be found in Ref. [22].

2 Construction of data sets

Data regarding the elastic, ^{9}Be(α,α), and inelastic, ^{9}Be(α,α'), scatterings have been obtained from a dedicated experiment carried out at the TTT3 tandem accelerator [23, 24] of the University of Naples "Federico II", Italy. A ^{4}He beam with excellent qualities of collimation and energy resolution was delivered to a scattering chamber, where several detectors where installed, centered at 160°, 150°, 135°, 110° and 70° in the laboratory frame. Reactions were induced by a thin ($\approx$ $122\mu g/cm^2$) self-supporting ^{9}Be target. The beam energy was varied in 60 keV steps, covering the energy range E_α = 3.5-10 MeV. More details regarding the experimental setup and results of the experiment are discussed in a separate publication [25, 26]. Differential cross section (DCS) data of the elastic scattering have been measured at the backward angles 160°, 150°, 135°, 110°, while the inelastic scatterings ^{9}Be(α,α_1), ^{9}Be(α,α_2) and ^{9}Be(α,α_4), leaving the residual ^{9}Be in the E_x = 1.684 MeV, E_x = 2.429 MeV and E_x = 3.049 MeV states (respectively), have been obtained at 70° by using the procedure described in [22]. In the present data set, we include the measured excitation functions of the elastic scattering and the ^{9}Be(α,α_1) inelastic data. The ^{9}Be(α,α_2) and ^{9}Be(α,α_4) data have

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been excluded from our data set because of possible contaminations arising from the broad peak associated to the ^{9}Be(α,α_3) process as described in Ref. [22]. To better characterize the ^{13}C excitation energy region close to the α emission threshold, $E_\alpha < 2$ MeV, we added to our data sets also the differential cross section data of Ref. [15] in the bombarding energy region E_α = 1.0-1.7 MeV at θ_{lab} = 160°, 150°. We allowed for the presence of normalization factors for such data (within the range 0.85-1.15), to account for possible absolute normalization errors affecting the analysis done in Ref. [15].

We also included in our data set the ^{9}Be(α,n) reactions previously published in the literature. We used absolute integrated cross section data for the n_0 (i.e. leaving the ^{12}C in its ground state) and n_1 (when the ^{12}C residual nucleus is populated in its E_x = 4.44 MeV state) channels extracted from Refs. [27–29]. The n_1 data was normalized by a factor of 0.52 as discussed in Ref. [22].

3 R-matrix analysis of data

Data sets described in the previous section were interpreted in terms of the R-matrix theory to probe the spectroscopy of the ^{13}C nucleus formed as the intermediate state of the collision. We performed a simultaneous fit of the ^{9}Be(α,α) excitation functions at backward angles, the ^{9}Be(α,α_1) data at 70° and the ^{9}Be(α,n_0) and ^{9}Be(α,n_1) integrated cross section data. The latter, in particular, is a fundamental ingredient to adequately constrain the partial widths of ^{13}C states involved in the analysis. Additionally, the presence of several detection angles in the ^{9}Be(α,α) excitation functions enables to give firm J^π assignments to many states for which ambiguities were previously reported in the literature. As the starting parameters for the fit, we considered the spectroscopy of ^{13}C as reported in the compilation of Ref. [11], and we carefully took into account the findings of previous calculations published in Refs. [13, 15]. We used $\ell = 8$ as the maximum order for the partial waves contributing in the reaction or scattering events. We included in our calculation also the effects of the finite target thickness.

Results of the simultaneous R-matrix fit, performed with AZURE2 [30], are shown in Fig. 1 for the elastic scattering ^{9}Be(α,α) at three backward angles, θ_{lab} = 135°, 150°, 160°. With our refined spectroscopy, the overall agreement of the R-matrix calculation and the data is excellent at all energies, as clearly visible in figure. The reduced χ^2 values for our fit range between ≈ 0.6 to ≈ 2 depending on the reaction channel. We find a satisfactory agreement with the findings of Refs. [13, 15] at low value of excitation energy $E_x \leq 16$ MeV. In this energy region, some of the quoted J^π values of ^{13}C where ambiguous in the literature. When necessary, and taking advantage of the presence of a big body of data, J^π values previously quoted in the literature have been changed to reproduce our data. The resulting parameters are summarized in Ref. [22] and improve the overall spectroscopy of ^{13}C in this energy region.

At higher energies, 16MeV $< E_x <$ 19MeV, the situation is much more complicated as previous R-matrix analyses of the ^{9}Be(α,α) scattering don't extend to this high energies [13]. Furthermore, in the adopted ^{13}C level scheme of Ref. [11], one can observe a significant lack of information in such excitation energy region. Our ^{9}Be(α,α) extends to a higher energy region enabling us to improve the spectroscopy of ^{13}C in a wider energy domain.

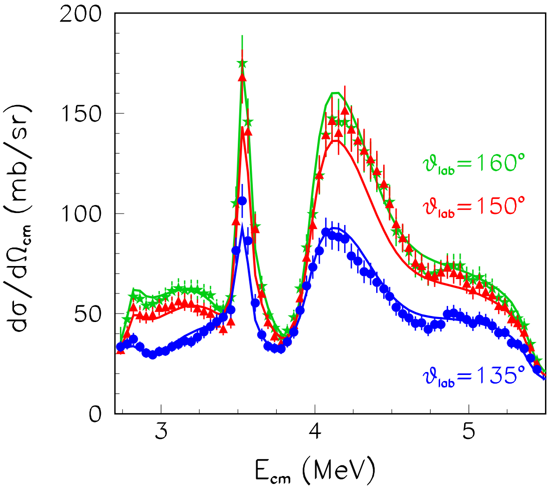

Figure 1. ^{9}Be(α,α) excitation functions for θ_{lab} = 135°, 150°, 160° backward angles. The solid lines represent the result of the simultaneous R-matrix fit of ^{9}Be(α,α), ^{9}Be(α,α_1) and ^{9}Be(α,$n_{0,1}$) as discussed in the text.

More details regarding this analysis can be found in Ref. [22], the complete spectroscopy of ^{13}C above the α-threshold is reported in Table 1 of such publication.

4 Conclusions and perspectives

The spectroscopy of ^{13}C is key to identify three-centers molecular states and their rotational bands in light nuclear systems. To contribute to solve ambiguities affecting the spectroscopy of this nucleus above the α disintegration threshold, we have performed a new comprehensive R-matrix fit of a large body of data. We have carefully reviewed previous experiments reported in the literature and involving $\alpha +^9$ Be reactions. The latter were chosen because of their high selectivity to cluster states in ^{13}C. Results of our R-matrix fit improve significantly the spectroscopy of ^{13}C, enabling to more firm J^π assignments thanks to the presence of several detection angles.

The improved spectroscopy of ^{13}C allows us to some speculations regarding the possible appearance of rotational bands characterized by cluster nature. Our results seem to support the theoretical suggestions proposed in the recent study of Ref. [31] and will be the subject of a successive more refined analysis in the effort to identify rotational bands in the neutron rich ^{13}C nucleus.

In the near future, we will exploit detection arrays with high granularity and/or large solid angle acceptance [32–36] to carry out a new experimental campaign to probe the spectroscopy of light nuclear systems with high precision. This, together with the opportunity to carry out new experiments by using large acceptance detectors as γ-ray arrays [37], will help to improve the understanding on clustering in neutron-rich nuclei.

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