Analysis of states in $^{13}\text{C}$ and their cluster structure

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Abstract. Accurate studies on $^{13}\text{C}$ spectroscopy have great impact in the present understanding of the role played by extra-neutrons in stabilizing $\alpha$-cluster structures formed in light nuclei. Carbon-13 is in fact the simplest systems that can be formed by adding a neutron to make a triple-$\alpha$ molecular-like structure. The accurate spectroscopy of excited states at energies above the $\alpha$ emission threshold is fundamental to benchmark the calculations of theoretical models aiming to describe clustering in light nuclei.

To improve our knowledge of $^{13}\text{C}$ structure, we performed a comprehensive $R$-matrix fit of $\alpha+9\text{Be}$ elastic and inelastic scattering data in the energy region $E_{\alpha} \approx 3.510$ MeV at several backward polar angles. To carefully determine the partial decay widths of states above the $\alpha$-decay threshold we included in the fit also $9\text{Be}(\alpha,n)12\text{C}$ cross section data taken from the literature. This analysis allows to improve the (poorly known) spectroscopy of excited states in $^{13}\text{C}$ in the $E_{x} \approx 12$-17 MeV region, and tentatively suggests the presence of a large-deformation negative-parity molecular band.

1. Introduction

The structure of light nuclear systems is very special and unusual. The dominance of surface effects can lead to a rearrangement between neutrons and protons to form $\alpha$-like clusters. They continuously (and dynamically) dissolve and clot in the nuclear medium, leading to important deviation from the spherical symmetry and introducing new types of symmetries in the nuclear domain [1, 2]. This behaviour is typical of the so called self-conjugate nuclei, that are even-even nuclei with an equal number of neutrons and protons. Beryllium-8, $^{12}\text{C}$, $^{16}\text{O}$, $^{20}\text{Ne}$ are the most representative cases; their $\alpha$-cluster nature emerges both in the structure of ground state (e.g. in the case of $^{8}\text{Be}$ [3]) or of excited states near and above the $\alpha$-decay threshold. An example of the latter case is the famous Hoyle state of $^{12}\text{C}$: from the ’50 to recent times, it was the subject of several theoretical and experimental studies [4, 5].

The cluster structure of nuclei plays a fundamental role also in collateral domains of nuclear physics. For example, in nuclear astrophysics, the cluster structure of self-conjugate nuclei such as $^{12}\text{C}$ and $^{20}\text{Ne}$, or of non-self-conjugate systems such as $^{11}\text{C}$, above particle-emission threshold, has an influence on reaction rates of stellar interest (see, for example, Refs. [6–10]). Furthermore, in collisions involving heavy ions at intermediate energies (e.g. Refs. [11–13]), the nuclear system can reach a dilute density condition in which alpha clusters can be copiously produced, and this process can have an influence on the dynamical evolution and the disassembly of the transient system consequently formed [14–16].

In the presence of extra-neutrons, new manifestations of $\alpha$-clustering can be observed [17]. In analogy with physical chemistry, extra-neutrons can give rise to a covalent bonding between alpha-centres. This behaviour has been experimentally ascertained for example, in $^{9}\text{Be}$, where
the two $\alpha$-centres are bound together by the valence neutron, leading to a super-deformation even in the ground state; on top of this, rotational states have been discovered [17]. Similar discussions apply to other neutron-rich beryllium isotopes (e.g. $^{10,11,12}\text{Be}$) at high excitation energies [18].

For nuclear states characterized by three centres, the phenomenology of clustering is still unclear. Several microscopic models pointed out the existence of a molecular-like structures of neutron rich carbon isotopes $^{13,14,16}\text{C}$ at high excitation energies [19, 20], but, unfortunately, experimental data on such aspects are incomplete or even missing [21–25]. Within this framework, the analysis of states of the simplest triple-$\alpha$ neutron-rich system, $^{13}\text{C}$, is a key ingredient. For such a nucleus, theoretical calculations suggest the appearance of two molecular bands with opposite parities, $K^\pi = 3/2^\pm$, in an excitation energy region close to the $3\alpha + n$ disintegration energy at 12.22 MeV [19, 26]. It is very interesting to underline that, in this conference, new, very interesting theoretical predictions on the structure of $^{13}\text{C}$ exploiting the algebraic symmetries of the Cluster Shell Model (CSM) were discussed.

Despite a large theoretical effort, the literature still shows too many ambiguities concerning the experimental $J^\pi$ values of states in $^{13}\text{C}$ in the excitation energy range relevant for clustering studies (i.e., $E_x \approx 13 – 16\text{MeV}$) [27]. Because of such ambiguities, a clear picture of the structure of $^{13}\text{C}$ is still missing and no well grounded conclusions on the existence of molecular bands in $^{13}\text{C}$ can be drawn. To clarify these aspects, we performed a new experiment on $\alpha + ^9\text{Be}$ resonant elastic scattering data with the aim of improving the spectroscopy of high energy states in $^{13}\text{C}$. According to the literature, this reaction channel seems to be highly selective for cluster states in $^{13}\text{C}$ because of the pronounced cluster structure of the $^9\text{Be}$ target nucleus.

The resonance parameters (partial widths, $J^\pi$, interference signs, resonance energies, etc) of excited states in the domain $E_x \approx 11.8 – 18\text{MeV}$ were estimated by a comprehensive $R$-matrix fit of cross section data by using the AZURE2 code [28, 29] of various reaction channels: the resonant scattering and the $^9\text{Be}(\alpha, n)^{12}\text{C}$ reactions. The detailed discussion on such results is given in the more extended Ref. [30]; in this proceedings, we will discuss some relevant results obtained from the data analysis.

2. $R$-matrix analysis on experimental data

The database used for the present analysis involves excitation functions of the $\alpha + ^9\text{Be}$ elastic scattering derived from an experiment performed at the TTT3 tandem accelerator in Naples, Italy [31–33]. To obtain the excitation functions, the beam energy was finely changed from 3.3 MeV up to 10 MeV, in steps of 60 keV. The target was a thin self-supporting $^9\text{Be}$ foil, having a thickness of 122 $\mu\text{g/cm}^2$ and some traces of C and O contaminants. The detection device constituted a system of silicon detectors placed at several angles in the backward hemisphere. More experimental details on such apparatus are discussed in Refs. [30, 34, 35]. From the available data, it was possible to measure excitation functions for both elastic and inelastic (to the first excited state in $^9\text{Be}$) scattering channels. The absolute cross section values derived with the thin target experiment was checked by means of a thick target experiment [35], giving good consistency to the data. Values of the absolute cross sections for the $^9\text{Be}(\alpha, n)^{12}\text{C}$ reactions were taken from the literature ([36, 37]); the need for a normalization factor between the data sets reported in the literature is detailed in Ref. [30].

The initial parameters of excited states in $^{13}\text{C}$ used in terms of the $R$-matrix to analyse the experimental data were derived from the table of states of Ref. [27]; we took into account also recent findings reported in Refs. [21, 38]. When contrasting assignments were reported in the literature, the $J^\pi$ values were chosen in order to reproduce, in the best possible way, the trend of excitations functions data. Finally, we had success in reproducing quite well all the experimental data with the $R$-matrix fit, as we show in the Figures of Ref. [30]. As an example, in Figure 1 of this proceedings we show a part of the differential cross section for the elastic scattering.
Figure 1. Excitation functions measured at $\theta_{\text{lab}} = 160^\circ, 135^\circ$ (green solid stars and brown circles, respectively) for the $\alpha + ^{9}\text{Be}$ elastic scattering in the $E_{\text{cm}} = 2.7-4$ MeV range. The solid green and brown lines represent the $R$-matrix fit of experimental data.

channel at $\theta_{\text{lab}} = 160^\circ, 135^\circ$, together with the $R$-matrix fit (solid lines); they nicely agree.

We can derive some interesting considerations from the $R$-matrix analysis performed. For example, the small structure seen at $E_{\text{cm}} \approx 2.8$ MeV has been associated with a high-spin ($J^\pi = \frac{9}{2}^-\text{--}$) state in $^{13}\text{C}$; this state has a sizeable reduced partial width if compared with the Wigner limit for the $\alpha + ^{9}\text{Be}$ channel [30]. As we will discuss later, this state is a candidate to be part to the $K^\pi = \frac{3}{2}^-\text{--}$ negative parity molecular band in $^{13}\text{C}$.

At higher energies, the pronounced maximum seen at $E_{\text{cm}} \approx 3.5$ MeV has been associated in the past with a resonance in the compound nucleus with contrasting $J^\pi$ assignments; furthermore, it was included (as $J^\pi = \frac{9}{2}^-\text{--}$) in the systematics of molecular cluster states reported in Ref. [19]. The presence of a benchmarked data set of elastic scattering excitation functions, and the availability of data at several angles allow us to firmly assign the $J^\pi = \frac{5}{2}^-\text{--}$ value to such resonance, due to the 14.13 MeV excited state. The alternative $J^\pi = \frac{9}{2}^-\text{--}$ assignment suggested in Ref. [19] does not reproduce the experimental data, both in term of the shape and the intensity of the peak seen in this energy region. As shown in Figure 1, a good reproduction of elastic scattering data at two different angles is obtained when we assume a $5/2^-\text{--}$ assignment for the 14.13 MeV excited state ($E_{\text{cm}} \approx 3.5$ MeV peak), a $9/2^-\text{--}$ assignment for the 13.41 MeV excited state ($E_{\text{cm}} \approx 2.8$ MeV peak), and the presence of two broad states (with $7/2^-\text{--}$ and $5/2^+\text{--}$ assignments) at 13.49 and 13.63 MeV; the last two states explain the trend of elastic scattering data in the $E_{\text{cm}} \approx 3 - 3.5$ MeV region.

In Ref. [30] we report the full discussion for all the states included in the level scheme of $^{13}\text{C}$ above the alpha emission threshold, and Table 1 lists the resonance parameters obtained from the present analysis. In particular, the coupling of a sub-alpha-threshold state at 9.897 MeV ($J^\pi = \frac{3}{2}^-\text{--}$), a state at 10.818 MeV ($J^\pi = \frac{5}{2}^-\text{--}$) very close to the threshold (at energies lower than the ones explored in the present analysis) and the two states at 12.45 MeV ($J^\pi = \frac{5}{2}^-\text{--}$)
Figure 2. The $K^\pi = 3/2^\pm$ rotational bands suggested from the spectroscopy of excited states reported in the literature, complemented with the data obtained from the present R-matrix analysis. The solid lines represent simple calculations of molecular rotational bands for a structure with $\hbar^2/2I \approx 0.17$ MeV moment of inertia parameter.

and 13.41 MeV ($J^\pi = 9/2^-$) seems to suggest the presence of a rotation band with negative parity, as visible in Figure 2 (solid circles). A simple calculation assuming a moment of inertia parameter of $\hbar^2/2I \approx 0.17$ MeV describes the experimental data well; the value of the $\hbar^2/2I$ parameter is quite similar to the one determined theoretically from microscopic models in which the carbon has a very pronounced molecular nature [39], and stimulates further analysis on this aspect. Two positive parity states at 11.97 ($J^\pi = 5/2^+$) and 14.36 MeV ($J^\pi = 9/2^+$) seem to belong to a positive parity band with features similar to the negative parity one, but the situation in this case is less clear and calls for new experiments.

3. Conclusions
In this proceeding, we discuss some findings obtained by investigating $^{13}$C spectroscopy in the excitation energy domain going from 11.8 up to about 18 MeV. This excitation energy region is very interesting because the existence of two opposite parity molecular bands with cluster nature has been suggested by various theoretical calculations. To improve our knowledge on this topic, we performed a comprehensive R-matrix analysis of various reaction data sets populating $^{13}$C excited states in the compound nucleus scenario. As a result, it was possible to improve several $J^\pi$ assignments for some excited states for which tentative values were reported in the literature. The possible existence of a negative parity molecular band with a moment of inertia compatible with a molecular-like structure in $^{13}$C has also been suggested from the analysis of excited states. As a perspective, we believe that in the future, the availability of new radioactive ion beam facilities able to identify the beam particles one by one [40], and the use of the high-granularity and/or large solid angles arrays for light particles [41–43] and/or gamma and neutron identification [44–46], would be very useful to unveil the cluster structure of neutron-rich carbon isotopes.
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