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New results on ^{13}C structure from α + ^{9}Be low energy reactions

I. Lombardo
INFN, Sezione di Catania - Catania, Italy

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Summary. — In the framework of clustering in light nuclei, ^{13}C plays a crucial role since it can show a pronounced 3α + n structure. Several theoretical models predicted the existence of molecular rotational bands characterized by large moment of inertia, typical of highly clusterized structures. In this paper, we investigated α + ^{9}Be reactions at low incident energies with the aim of improving our knowledge of ^{13}C spectroscopy by means of a comprehensive R-matrix fit of several reaction channels. Such procedure leads to a firmer determination of J^{π} assignments for several states and to a better determination of the branching ratio of each reaction channel.

1. – Introduction

In the light nuclei region of the nuclide chart, a special place is occupied by the so-called self-conjugate nuclei, i.e. N=Z even-even nuclei. Some of them, as ^{8}Be, ^{12}C, ^{16}O, ^{20}Ne, ^{24}Mg, manifest a pronounced α-cluster character that can appear in the structure of ground state (this is the case, for example, of ^{8}Be [1]) or of excited states of such nuclei. The so-called Hoyle state in ^{12}C is, probably, the most relevant example of the second case, and for this reason it has been the subject of several investigations in recent times (see [2,3] and references therein). Since the majority of self-conjugate nuclei are involved in fusion reactions taking place in stars, their structure plays a dramatic role also in the nuclear astrophysics domain (see, e.g., [4-8]). In recent times, clustering phenomena have been invoked to explain fine effects observed in nucleus-nucleus collisions. In this domain, they can help to better understand nuclear dynamics of heavy ion collisions at low and intermediate bombarding energies [9-12].

Furthermore, many theoretical calculations indicates also that extra neutrons added to self-conjugate system can give rise to a new form of α-clustering in nuclei [13]; they can in fact behave as *covalent* particles, being exchanged between the α-cluster centers. This hypothesis would represent the analog of covalent bonding in molecular physics. Some states of neutron-rich beryllium isotopes show such kind of molecular structure. In particular, for ^{9}Be, the two α particles are bound together by the exceeding neutron, and even the ground state has a super-deformed shape; on top of this, rotational states are seen [13]. For the other neutron-rich Beryllium isotopes (^{10,11,12}Be) molecular structures are seen in excited states near or above the alpha emission threshold [14].

For nuclear states characterized by three centers, the triple-α structure, the situation is less clear. Even if many microscopic models suggest the existence of molecular structures for neutron rich carbon isotopes (as ^{13,14,16}C) [15, 16], few experimental signatures have been reported in the literature [17-21]. We will focus our attention to the simplest triple-α neutron rich system, ^{13}C. For such nucleus, various models suggest the presence of two molecular bands with $K^\pi = 3/2^\pm$. The excitation energy at which the band-head is predicted is close to the 3α+n disintegration energy (i.e 12.22 MeV) [15, 22].

Despite the strong theoretical effort, many ambiguities in the experimental J^π assignments for states in ^{13}C in the range $E_x \approx 13 - 16$MeV [23] are currently persisting in the literature. This makes extremely difficult to draw a sufficient clear conclusion on the existence of molecular bands in ^{13}C as well as to determine the moment of inertia of the underlying structures. To overcome such difficulties, we investigated $\alpha+^9$Be resonant elastic scattering data; such reaction channel has been suggested in the literature to be highly selective in terms of cluster states in ^{13}C because of the marked cluster structure of the ^{9}Be target nucleus.

To estimate all the resonance parameters (partial decay widths, J^π assignments, interference signs, resonance energies, etc) of excited states in the domain $E_x \approx 11.8 - 18$ MeV, we performed a R-matrix fit of cross section data of several reaction channels, including the resonant scattering one and the ^{9}Be$(\alpha, n)^{12}$C neutron-emitting ones by using the AZURE2 code [24, 25]. A brief overview of such results is given in the following paragraphs.

2. – Experimental data sets

Differential cross section data of $\alpha+^9$Be elastic scattering were obtained by an experiment in direct kinematics performed at the TTT-3 tandem accelerator in Naples, Italy [26-28]. The beam energy was varied from 3.3 MeV up to 10 MeV in fine steps of 60 keV. The reaction target was made of a self-supporting ^{9}Be foil with a thickness of 122 $\mu g/cm^2$. The detection system was made of an array of high resolution silicon detectors put at various angles in the backward hemisphere. More details on the apparatus are reported in Refs. [29-31]. From the experimental spectra, it was possible to derive good quality excitation functions for both the elastic scattering channel and the inelastic one leading to the first excited state in ^{9}Be. It is important to underline that the absolute cross section scale derived with the thin target run was benchmarked with a dedicated thick target experiment, as discussed in details in Ref. [31]. Absolute cross section data of ^{9}Be$(\alpha, n)^{12}$C reactions were taken from Refs. [32, 33]; the need for a normalization factor to match the two data sets is discussed in details in Ref. [29].

3. – Analysis of excited states in ^{13}C from $\alpha+^9$Be reactions

To perform the R-matrix analysis of data, we used the values reported in the table of states of Ref. [23] as the starting parameters for excited states in ^{13}C, including also recent findings discussed in [34,17]. In some cases, J^π values that are tentatively reported in the literature were replaced by new ones in order to describe as best we can the peculiar shapes of excitations functions. The experimental data are well reproduced by the R-matrix fit, as it can be clearly seen in the Figures of the extended Ref. [29]. In Figure 1, we report a part of the excitation function for the elastic scattering channel at two

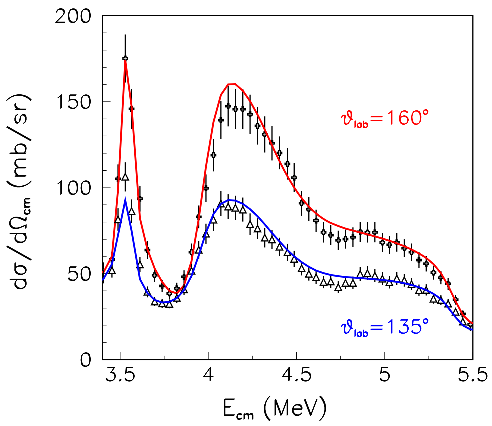

Fig. 1. – Differential cross sections measured at $\theta_{lab} = 160°, 135°$ (open crosses and triangles, respectively)) for the α+^{9}Be elastic scattering. The solid red and blue lines are the result of the R-matrix fit of experimental data.

backward angles, together with the R-matrix fit results (solid lines), and the agreement is quite satisfactory.

The R-matrix analysis points out some interesting results. The availability of data sets coming from different reaction channels and the presence of a broad angular range in the differential cross sections for the elastic scattering allow to firmly assign the $J^{\pi} = 5/2^{-}$ value to the 14.13 MeV excited state. This state was previously included (as $J^{\pi} = 9/2^{-}$) in the systematic of molecular states reported in [15]. We verified in our R-matrix analysis that the use of a $J^{\pi} = 9/2^{-}$ assignment for such state would result in a strong disagreement between data and calculations of the shape and the height of the peak seen at around E$_{cm}$ ≈ 3.5 MeV. Furthermore, as discussed in more details in [29], the broad structures seen at E$_{cm}$ ≈4.0-4.5 and 4.8-5.5 MeV are reproduced with relatively low-spin states. This finding does not support the evidence for 11/2 states in these energy regions as well as at higher energies, indicating a not complete agreement with high-spin molecular rotational states suggested in [15].

The table of excited states reported in Ref. [29] lists the resonance parameters of the excited states used in our comprehensive fit, and tentatively suggests the possible appearance of a negative parity rotational band that could have a molecular nature; such finding calls for further investigations especially in the low bombarding energy regime.

4. – Conclusions

In this proceeding we report an overview of results concerning ^{13}C spectroscopy in the excitation energies range from 11.8 up to 18 MeV. In this region, the existence of members of positive and negative parity molecular bands has been suggested by several theoretical works in the literature. To improve our knowledge on such aspects, we analyzed several reaction data sets related to α and neutron emission from ^{13}C excited states by a simultaneous R-matrix fit. As a result, we obtained well grounded J^{π} assignments for some excited states for which tentative values were previously reported in the literature. We tentatively point out the possible existence of a negative parity molecular band having a moment of inertia compatible with a molecular-like structure in ^{13}C. The currently ongoing development of new radioactive ion beam factories able to identify one by one the beam particles [35], coupled with the high-granularity and/or large solid angles arrays for light particles [36-40] and/or gamma and neutron identification [41,42], would be of help in understanding the cluster structure of neutron-rich carbon isotopes.

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