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Cluster states in ^{13}C investigated with nuclear reactions induced by α particles on ^{9}Be

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Summary. — ^{13}C is the simplest neutron-rich system that can be formed starting from three α-clusters. The study of its spectroscopy is therefore of large interest to unveil the presence of exotic structures, such as molecular rotational bands, where the α-cluster nature fully appears. Molecular bands should be characterized by very large moment of inertia, and they can be experimentally studied from the correlation between the excitation energy and the spin of ^{13}C states. In this work, we discuss the results of a spectroscopic investigation on ^{13}C states made by studying α+^{9}Be reactions at low energies. A comprehensive R-matrix fit of elastic, inelastic and reaction cross sections allows to shed light on contrasting J^{π} assignments and to determine the partial decay widths for each reaction channel.

1. – Introduction

Self-conjugated nuclei (as ^{8}Be, ^{12}C, ^{16}O, ^{20}Ne) show pronounced α-clustering effects, that can fully characterize the structure of the ground state (as for the case of ^{8}Be [1]) or of excited states of such nuclei (as, for example, the case of the Hoyle state in ^{12}C [2,3]). These beautiful manifestations of long-range correlations in a many-body system, as is the nucleus, can have a relevance also in the astrophysics domain [4-7] and can contribute to better understand the nuclear dynamics of heavy ion collisions at low and medium energies [8-12]. Several theoretical models suggest also that if neutrons are added to a self-conjugated system, peculiar aspects of clustering can arise [13]. In particular, it has been suggested that the extra neutrons can act as covalent particles, in analogy with the role played by electrons in molecular covalent bonding. Interesting examples of the existence of such nuclear cluster molecules are seen in states of neutron-rich beryllium isotopes. For example, for the ^{9}Be nuclide, the dimeric structure made of two α particles is bound by the extra neutron and assumes a very deformed shape; such molecular-like structure gives rise to rotational bands [13]. Similar findings characterize also other neutron-rich beryllium isotopes, as ^{10,11,12}Be.

The situation is more puzzling for trimeric structure. Several theoretical models predict the existence of trimeric structure for neutron rich carbon isotopes

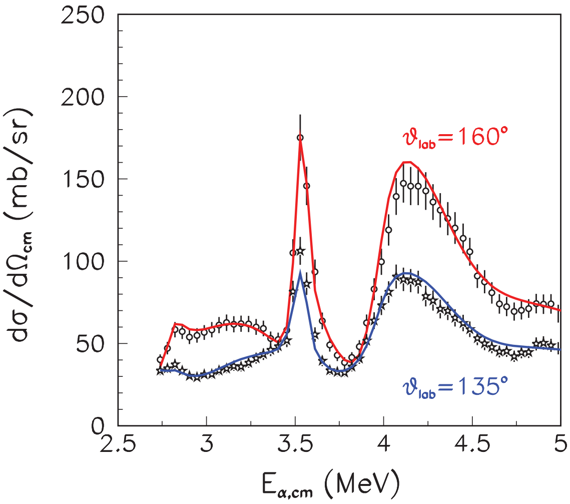

Fig. 1. – Excitation functions of the α+^{9}Be elastic scattering measured at $\theta_{lab} = 160°, 135°$. The solid red and blue lines represent the result of the comprehensive R-matrix fit of experimental data.

(as ^{13,14,16}C) [14, 15], that can give rise to molecular rotational bands, but experimental proofs of such hypothesis are still fragmentary [16-20]. In particular, for the simplest of such systems (^{13}C) different models predict the existence of two molecular bands having $K^\pi = 3/2^\pm$; the band-head is predicted to have an excitation energy not far from (and slightly lower than) the $3\alpha + n$ disintegration energy (*i.e.*, 12.22 MeV) [14, 21].

Unfortunately, from the experimental point of view, the J^π assignments in the excitation energy region $E_x \approx$ 13–16 MeV are not well established [22], thus preventing definitive conclusions on the existence of such bands and the determination of the moment of inertia from their analysis. To contribute to the solution of such uncertainties, we proposed to study the resonant elastic scattering of α particles on ^{9}Be, a collision that has been suggested to be a good tool to excite cluster states in ^{13}C because of the marked cluster structure present in the ^{9}Be target. The experimental measurements of resonant elastic scattering differential cross section were obtained by carrying out α+^{9}Be collisions at bombarding energies going from 3.3 MeV up to 10 MeV at the TTT-3 tandem accelerator in Naples, Italy [23-25]. The beam energy was finely changed in 60 keV steps, and an array of several silicon detectors placed at various angles in the backward hemisphere served as detection device. More details on the experimental apparatus can be found in refs. [26-28].

We performed a comprehensive R-matrix fit with the AZURE2 code [29,30] of the resonant scattering data, together with the cross section data for the ^{9}Be$(\alpha, n)^{12}$C reaction channels, to estimate the partial decay widths of excited states at $E_x \approx$ 11.8–18 MeV. A summary of results of such investigation is discussed in the following section.

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

As starting resonance parameters for the comprehensive R-matrix analysis, we adopted the ones reported in the table of states of ref. [22], taking into account also the more recent findings reported in ref. [31]. Some of the J^π values that were tentatively reported in the literature were changed to reproduce in the best possible way all the details of excitations functions. The reproduction of experimental data is very good, as reported in all the figures of the more extended ref. [26], and as evident, for example, from fig. 1. It reports data for the elastic scattering at two angles, together with the R-matrix fit results (solid lines).

From the R-matrix analysis of data we can derive some interesting results. The small resonant structure that is seen at $E_{cm} \simeq 2.76$ MeV is due to the 13.41 MeV state; for such a state conflicting J^π assignments have been proposed. If we use a $9/2^-$ assignment, as suggested in ref. [32], a good overall reproduction of the shape and of absolute value of the differential cross section data is seen, and an equally good description of the integrated cross section for the neutron channels is observed. Similarly, the availability of several reaction channel data and the presence of a wide angular range in the differential cross sections for the elastic scattering allow to establish the $J^\pi = 5/2^-$ value for the 14.13 MeV state, that was previously included (as $J^\pi = 9/2^-$) in the systematic of molecular states of ref. [14]. The table of excited states reported in the more extended ref. [26] collects all the spectroscopic information for the resonance parameters, and naively suggests that the possible grouping of excited states forms a negative parity rotational band with a large moment of inertia, posing the basis for further investigations on such aspect.

3. – Conclusions

In this contribution we report a summary of results deriving from the spectroscopic analysis of excited states in ^{13}C in the excitation energies window 11.8–18 MeV, a region where the existence of members of two alternate-parity molecular bands has been predicted in the literature. We performed a simultaneous R-matrix fit of data coming from various reaction channels and related to α and neutron emission. As a result, we succeeded to solve some ambiguities in J^π assignments of excited states, and we tentatively suggest the possible existence of a negative parity molecular band characterized by a moment of inertia compatible with a pronounced cluster structure. The availability of new radioactive ion beam facilities capable of identifying with excellent resolution the beam particles [33], coupled with the ongoing development of high-granularity and/or large solid angles arrays for particle [34-38], gamma and neutron identification [39-41], would allow to better understand the underlying cluster structure of neutron-rich carbon isotopes.

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