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Exotic clustering investigation in ^{13}B and ^{14}C using RIBs

A. DI PIETRO(1), J. P. FERNÁNDEZ-GARCÍA(1)(2), P. FIGUERA(1), M. FISICHELLA(1), S. HEINITZ(3), M. LATTUADA(1)(2), D. TORRESI(1)(2), M. ALCORTA(4), M. J. G. BORGE(5), T. DAVINSON(6), A. M. LAIRD(7), A. C. SHOTTER(4)(6), D. SHUMANN(3), N. SOIC(8), O. TENGBLAD(5) and M. ZADRO(8)

(1) *INFN, Laboratori Nazionali del Sud - Catania, Italy*
(2) *Dipartimento di Fisica, Università di Catania - Catania, Italy*
(3) *Paul Scherrer Institut - Villigen, Switzerland*
(4) *TRUMF - Vancouver, Canada*
(5) *Instituto de Estructura de la Materia, CSIC - Madrid, Spain*
(6) *School of Physics and Astronomy, University of Edinburgh - Edinburgh, UK*
(7) *Department of Physics, University of York - York, UK*
(8) *Ruder Boskovic Institute - Zagreb, Croatia*

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Summary. — This contribution reports on the investigation about the existence of molecular and/or exotic cluster configurations in boron and carbon n-rich isotopes. To this aim two experiments were performed: the first experimental study of exotic ^{9}Li + ^{4}He cluster states in ^{13}B using the resonance scattering method at TRIUMF, and, with the same technique, the measurement of ^{10}Be + ^{4}He scattering at LNS in Catania, where a ^{10}Be radioactive beam was produced for the first time. In the case of ^{13}B, the elastic excitation function shows the presence of various peaks in an excitation energy region never explored before. In the case of ^{14}C, our exclusive measurement of elastic scattering data with a high intensity beam, sheds some light on previously published results which seemed to be in contradiction.

1. – Introduction

In light nuclei some nuclear structure properties can be described assuming a nucleus made of two or more weakly interacting clusters. Generally, the clusters are strongly bound particles, in fact, αs are the typical cluster. In weakly bound or unstable nuclei, however, different types of clusters may be present. For example clusters can be made by unstable, deformed and easy to break-up particles. The presence of these types of clusters is expected to become more and more favored when nuclei approach the drip-line [1]. Structures made of such exotic clusters are predicted to exist in some of the excited states of beryllium and boron n-rich isotopes.

Antisymmetrized Molecular Dynamics (AMD) calculations [2], describe the structure of some states of n-rich B isotopes as made of Li-He clusters; these structures are predicted to exist in the excitation energy region above the decay threshold of the nucleus into the two components under consideration. In particular, some of the ^{13}B excited states are described by AMD calculations in terms of ^{4}He-^{9}Li clusters. In order to investigate the existence of these structures in ^{13}B, we studied the excitation function for the elastic scattering ^{4}He(^{9}Li,α) process from $E_{\mathrm{c.m.}} = 10\,\mathrm{MeV}$ down to $E_{\mathrm{c.m.}} = 3\,\mathrm{MeV}$ exploring the ^{13}B excitation energy range $14\,\mathrm{MeV} \leq E_x \leq 20\,\mathrm{MeV}$, were these structure are predicted to exist.

An additional phenomenon that may occur in light unstable nuclei, in particular in the n-rich ones, is a type of clustering where the α-α cluster structure as a core persists and the exchange of neutrons between the α-particle cores bounds the system, a similar phenomenon as for the electrons in a covalent bonding.

The existence of linear chain configurations of α-particles in excited states of nuclei, such as ^{12}C or ^{16}O, has been searched for a long time; however no evidence has been found so far. In the case of n-rich nuclei, theoretical predictions of a linear chain configuration in ^{14}C of α-particles bound together by neutrons, was made by Suhara and Enýo [3] with AMD. A rotational band associated to this configurations is predicted to exist at a few MeV above the $^{10}\mathrm{Be} + \alpha$ threshold. The experiments performed so far to look for this configuration in ^{14}C [4-6] have produced controversial results on the possible presence of the inelastic scattering contribution in the detected α-particle spectrum [4, 5]. The possible presence of inelastic scattering processes will affect the results, in particular about the rotational band associated to the linear chain configuration in ^{14}C reported in [4]. The present paper, along with the results of $^{9}\mathrm{Li} + {}^{4}\mathrm{He}$ scattering, will also report on the results of the $^{10}\mathrm{Be} + {}^{4}\mathrm{He}$ resonance scattering experiment performed to shed some light on the results reported in the literature [4, 5].

2. – The ^{9}Li + ^{4}He reaction

The experiment $^{9}\mathrm{Li} + {}^{4}\mathrm{He}$ was performed at TRIUMF (Canada) using a ^{9}Li beam at 32 MeV delivered by the ISACII facility. The gas target consisted of the TUDA chamber (1.5 m long) filled with ^{4}He gas at pressures of 650 and 680 Torr. The chamber was separated from the high vacuum beam line by a Kapton window 12 μm thick. ΔE-E and Time-of-Flight (ToF) techniques were used to discriminate elastically scattered α-particles from other reaction processes. Particles were detected in three telescopes made of a four-quadrants, $50\times50\,\mathrm{mm}^2$, 50 μm thick Si as ΔE and a $50\times50\,\mathrm{mm}^2$, 1000 μm thick single pad Si as residual energy detector. One of the telescopes (T1) was placed around 0° ($\theta_{\mathrm{c.m.}} = 180°$) and a second one (T2) next to it downstream the TUDA chamber. The gas pressure was chosen to be sufficient to stop the beam before it reached the 0° detector. A third telescope (T3) was placed at about half the distance from the entrance Kapton window with respect to the other two telescopes. The set-up is sketched in fig. 1.

The ToF was measured using a microchannel plate (MCP) as a stop detector, placed under vacuum upstream the entrance window, and the Si pad as start detector (inverse time logic). Along with the ToF information, the MCP gives a way to count the beam particles, necessary for the cross-section normalisation. The beam intensity during the runs with the MCP detector was kept at around 5×10^5 pps. In some of the runs of the experiment, the MCP detector was switched-off and the beam intensity was increased to 10^7 pps. In those runs the ToF was measured with respect to the accelerator HF signal. These runs were normalised to the low intensity ones where the MCP detector

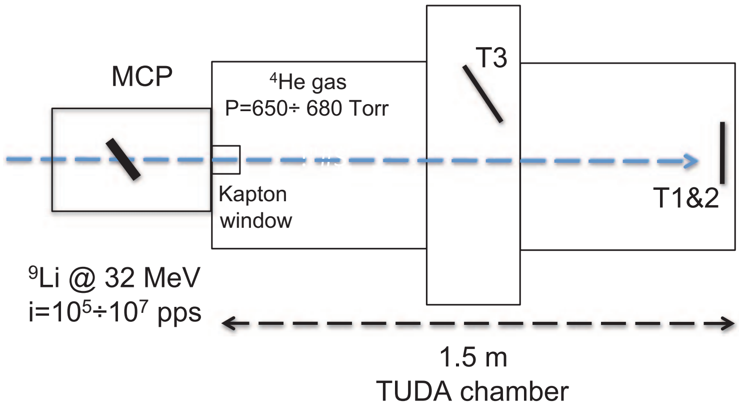

Fig. 1. – (Colour online) Sketch of the set-up used for the ^{9}Li + ^{4}He experiment.

was on. The detectors placed around 0° (T1 and T2) were detecting also the β's and the β-delayed α's coming from the radioactive decay of the ^{9}Li beam. These were producing a large background. Due to this background, only α-particles with energy ≥ 4 MeV were selected. The background above 4 MeV was less then 1% and in all cases subtracted.

The ^{13}B excitation energy spectra, at the various angles, were obtained from the α-particle energy spectra. In the thick target experiments, the elastic scattering process can occur at any point of the gas target, along the beam direction, at energies that go from 32 MeV down to practically 0 MeV. In the case of the elastic scattering process, energy and angles of the recoiling particles are uniquely related to the position in the target at which the process occurs. Therefore, via kinematics and energy loss calculations of the beam and recoiling particles, the excitation function for the elastic scattering process can be obtained. The data analysis was performed on an event-by-event base, reconstructing, for the events punching through the ΔE detectors, the total energy ($\Delta E + E_{\mathrm{res}}$). The total energy was corrected for the energy loss in the dead-layers of the detectors and in the gas in between the two detectors of the telescope. In fig. 2 it is shown the ^{13}B excitation energy spectra corresponding to the different measured angles. Due to the extension of the target, the angle of the recoiling α-particles depends on $E_{\mathrm{c.m.}}$ so it changes as the beam is slowed down in the ^{4}He gas.

In fig. 2 it is possible to observe at least two large peaks at excitation energies of 16.3 and 19.5 MeV. The peak at 19.5 MeV is very asymmetric, an indication that it could originate from the superposition of several states. This is confirmed by looking at the excitation function measured by the telescope T3 placed at the largest angles ($\theta_{\mathrm{c.m.}} \simeq 160°$). The theoretical analysis is on going to determine spin and parity of these states. According to the AMD predictions high spin states of ^{9}Li + ^{4}He type are to be populated. The rapid variation of the cross-section with the angle, seem to confirm these predictions.

3. – The ^{10}Be + ^{4}He reaction

The experiment was performed at Laboratori Nazionali del Sud using a radioactive ^{10}Be beam produced in batch-mode. The ^{10}Be radioactive material (0.1 mg of ^{10}BeO prepared at PSI Villigen, Switzerland) was inserted in the cathode of the TANDEM

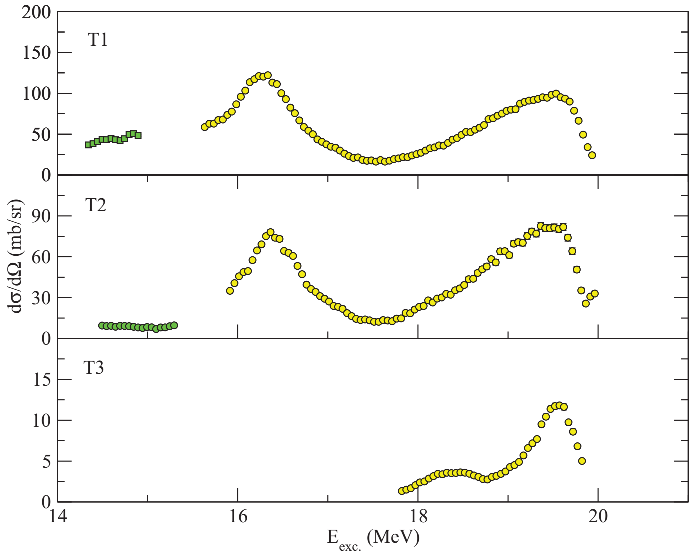

Fig. 2. – (Colour online) ^{13}B excitation energy spectra corresponding to the different telescopes *i.e.* different angles.

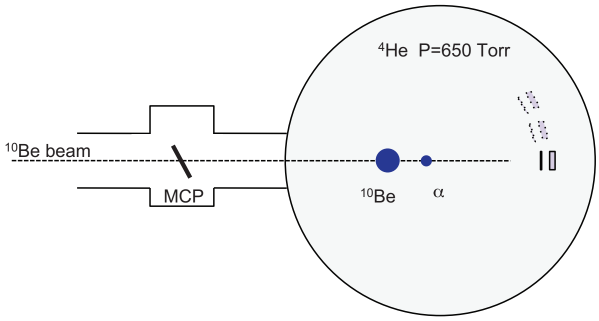

Fig. 3. – (Colour online) Sketch of the set-up used for the ^{10}Be + ^{4}He experiment.

sputtering source. The beam was then accelerated at 47 MeV by the TANDEM accelerator. For this experiment the Inverse Kinematic Thick Target method was used. The target consisted in the CT2000 scattering chamber (2 m diameter) filled with ^{4}He gas at a pressure of 650 Torr and separated from the beam line by a $\sim$12 μm thick Kapton window. As for the ^{9}Li + ^{4}He both ΔE-E and ToF techniques were used to discriminate elastically scattered α's. The detection system consisted of one telescope made of a 18 μm thick Si detector, as ΔE and a 500 μm thick Si as residual energy detector. The telescope was mounted on a rotating arm so that the detection angle could be changed during the measurement. The arm was rotating with respect to the center of the circular chamber, which is the target position in standard experiments. Three angular settings were used: $\theta_{\text{lab}} = 0°$ ($\theta_{\text{c.m.}} = 180°$), 5° and 10° measured with respect to the center of the chamber.

As for the ^{9}Li + ^{4}He experiment, a MCP detector was placed upstream the entrance window, in order to have a fast signal whenever a ^{10}Be beam particle entered into the

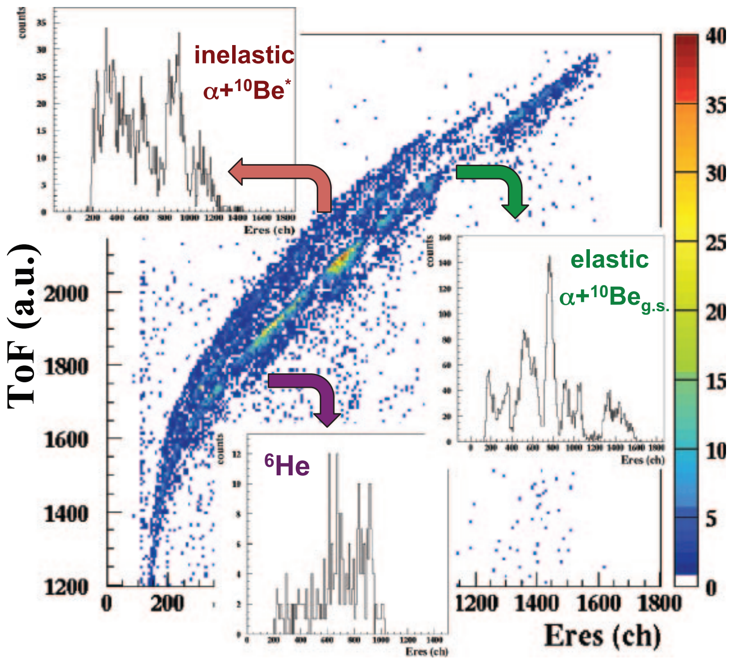

Fig. 4. – (Colour online) ToF *vs.* E_{res} spectrum. The insets show the energy spectra for elastic scattering, inelastic scattering and ^{6}He at $\theta_{\text{lab}} = 0°$. See text for details.

chamber. The beam intensity during the runs with the MCP detector was kept $<1 \times 10^7$ pps. In fig. 3 a sketch of the experimental set-up is shown.

In fig. 4 the ToF-E_{res} 2D-spectrum is shown. In the spectrum it is possible to identify ^{6}He, ^{4}He coming from elastic scattering, ^{4}He coming from inelastic scattering of the $^{10}\text{Be}_{2+}$ state at $E_x = 3.37$ MeV and of the group of states at $E_x \sim 6$ MeV. From the figure, one can confirm what was reported in [5] *i.e.* that the inelastic scattering contribution is not negligible as reported in [4].

Elastic scattering α-particle spectra were selected from the corresponding locus on the ToF-E_{res} plot. Similar plots were obtained for the inelastic scattering and ^{6}He data as shown in fig. 4 at $\theta_{\text{lab}} = 0°$. As one can see from the figure, the inelastic contribution is as large as the elastic one and shows some structures.

The results shown in this work contradict the conclusion of [4] about the possible presence of inelastic scattering, calling for a revision of the ^{14}C linear-chain claim of [4]. It could be that, since the data of [4] are measured at lower beam energy, the inelastic scattering is reduced. However, a comparison of the inclusive excitation function measured in the present experiment with the one of [4] shows a perfect overlap, thus confirming the inclusion of inelastic scattering in the case of the experiment reported in [4].

4. – Conclusions

In this paper results of the Resonant Elastic Scattering experiments ^{4}He(^{9}Li, α) performed at TRIUMF and ^{4}He(^{10}Be, α) performed at LNS have been shown.

Using the first reaction the excitation function of ^{13}B in the range $E_x = 14$–20 MeV was investigated. The excitation function shows two large structures whose cross-section changes strongly with angle. Those structure are likely to be due to several states in ^{13}B. The results of the R-matrix analysis, which is in progress, will allow to understand whether the observed structures can be associated to the predicted exotic cluster states of ^{13}B of ^{9}Li-^{4}He type.

With the ^{4}He(^{10}Be, α) reaction it was investigated the excitation energy spectrum of ^{14}C in the range $E_x = 16$–$24\,$MeV. In the present experiment, contrary to findings reported in [4] a large contribution of inelastic scattering events is observed. In the light of this result, the R-matrix analysis that led to the determination of the linear-chain rotational band reported in [4], has to be revised.

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