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Experimental investigation of exotic clustering in ^{13}B and ^{14}C using the resonance scattering method

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Abstract.
In order to investigate the existence of molecular and/or exotic cluster configurations in Boron and Carbon n-rich isotopes we undertook two experiments: the first experimental study of exotic ^{9}Li+α cluster states in ^{13}B using the resonance scattering method at TRIUMF (Canada), and, with the same technique, the measurement of ^{10}Be+α scattering at LNS in Catania, where a ^{10}Be radioactive beam was produced for the first time. In order to measure the excitation function in a wide energy range, the beams were stopped in a Helium-flooded chamber. 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 the contradictory previously published results [1, 2].

1. Introduction

Some of the properties of nuclei can be described by assuming a nuclear structure made of a few weakly interacting clusters. Generally the clusters are strongly bound particles and hence αs are the typical cluster particles. In light unstable nuclei different types of clusters may exist: clusters which are not ordinary stable particles (like the αs), but 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 [3]. Structures made of such exotic clusters are predicted to exist in some of the excited states of Beryllium and Boron n-rich isotopes.
Calculations, performed in the framework of the Antisymmetrized Molecular Dynamics (AMD) [4], describe some of the ^{13}B excited states in terms of ^{4}He-^{9}Li clusters, in the excitation energy region above the decay threshold of the nucleus into the two components under consideration. In

order to investigate the existence of these structures in ^{13}B, we studied the excitation function for the ^{4}He(^{9}Li,α) elastic scattering process. In this paper will be shown the results of the experimental investigation of the ^{9}Li+^{4}He at E_{lab}=32 MeV performed to explore upon the existence of exotic clustering in ^{13}B in the excitation region 14 MeV $\leq E_x \leq$ 20 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 $\alpha - \alpha$ cluster structure as a core persists; however, it is the exchange of neutrons between the α-particle cores that bounds the system, like electrons in the covalent bonding.
The existence of linear chain configurations of α-particles in excited states of 4N-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 [5] with AMD. Associated to this configuration, a band is predicted to exist (J_π=0^+, 2^+, 4^+) associated with a linear shape, at a few MeV above the ^{10}Be+α threshold. In order to look for this structure in ^{14}C, three experiments have been performed so far [1, 2, 6], where the ^{10}Be+^{4}He excitation function has been measured. Controversial results on the possible presence of the inelastic scattering contribution in the detected α-particle spectrum have been reported in [1, 2]. This could affect the observation reported in [1] of the rotational band associated to the linear chain configuration in ^{14}C. The present paper will also report on the results of the ^{10}Be+^{4}He resonance scattering experiment performed to shed some light on the controversial results reported in the literature [1, 2].

2. The ^{9}Li+^{4}He reaction

2.1. Experiment

The experiment ^{9}Li+^{4}He was done at TRIUMF (Canada) using a ^{9}Li beam at 32 MeV delivered by the ISACII facility. The target consisted of the TUDA chamber (1.5 m long) filled with an isotopically pure ^{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. Elastically scattered α-particles were detected and discriminated from other reaction processes using both ΔE-E and Time of Flight (ToF) techniques. The detection system consisted of three telescopes each made of one four-quadrants, 50×50 mm^2, 50 μm thick Si as ΔE detector and a 50×50 mm^2, 1000 μm thick Si detector as residual energy detector. One of the telescopes (T1) was placed around 0^0 ($\theta_{c.m.}$=180^0) 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 0^0 detector, but not the recoiling α-particles. A third telescope (T3) was placed closer to the entrance Kapton window, at about half the distance from the window of the other two telescopes, as sketched in figure 1. In this way some information on the angular distribution for the highest energy events (the ones occurring near the entrance window) could be gathered.

A microchannel plate (MCP) detector was placed under vacuum, just upstream the entrance window, in order to give a signal whenever a ^{9}Li beam particle entered into the chamber. The MCP gives a way to count the beam particles, necessary for the cross-section normalisation and, at the same time, provides a time signal for the ToF measurement. 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. These runs were normalised to the low intensity ones where the MCP detector was on. The detectors placed around 0^0 (T1 and T2) were detecting also the βs and the β-delayed αs 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 $\geq$4 MeV were selected. The background above 4 MeV was less then 1% and in all cases subtracted.

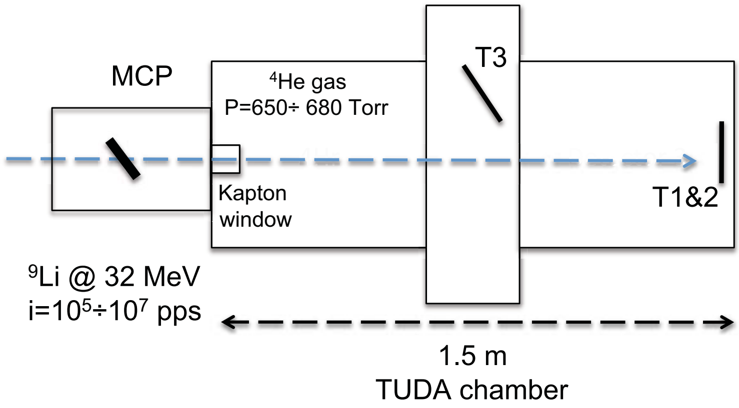

Figure 1. (Colour on line) Sketch of the set-up used for the ^{9}Li+^{4}He experiment

2.2. Results

From the detected-energy spectra of α-particles at the various angles, the ^{13}B excitation energy spectra were obtained. In the thick target experiments, the elastic scattering process can occur at any point of the 1.5 m long 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 from the recoiling α-particle spectra. The data analysis was performed on an event-by-event base, reconstructing, for the events punching through the ΔE detectors, the total energy ($\Delta E + E_{res}$). 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 figure 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 $E_{c.m.}$ so it changes as the beam is slowed down in the ^{4}He gas; $E_{c.m.}$ and $\theta_{c.m.}$ are reconstructed event-by-event from the energy and angle of the detected α-particles.

In figure 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 ($\theta_{c.m.} \simeq 160^0$). 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

3.1. Experiment

The experiment was performed at LNS 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 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 an isotopically pure ^{4}He gas at a pressure of 650 Torr and separated from the beam line

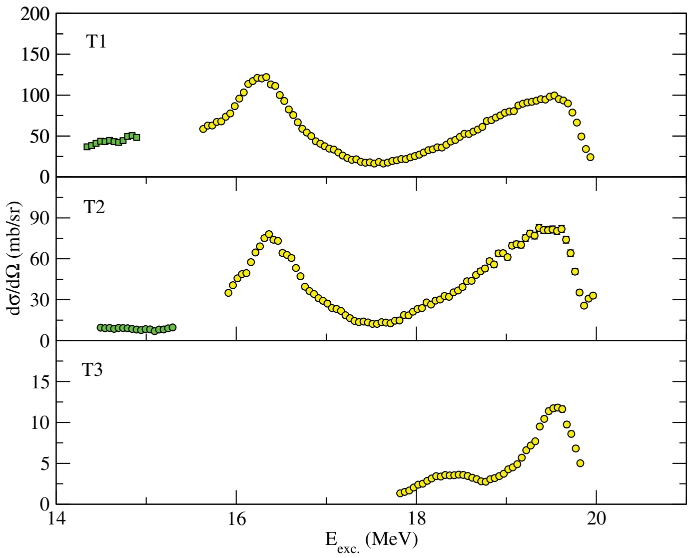

Figure 2. (Colour on line) ^{13}B excitation energy spectra corresponding to the different telescopes i.e. different angles.

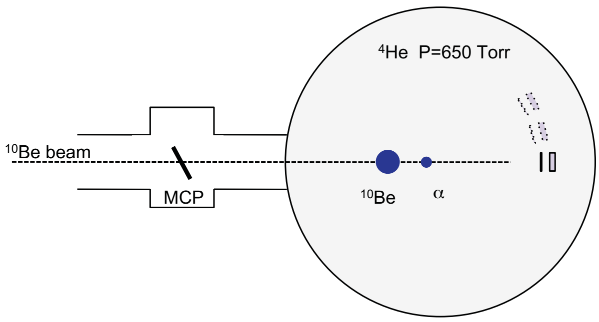

Figure 3. (Colour on line) Sketch of the set-up used for the ^{10}Be+^{4}He experiment

by a ~12 μm thick Kapton window. As for the ^{9}Li+^{4}He both ΔE-E and ToF techniques were used to discriminate elastically scattered αs. 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. In front of the telescope a collimator of ϕ= 6 mm was placed. 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: θ_{lab}=0^0 ($\theta_{c.m.}$=180^0), 5^0 and 10^0 measured with respect to the center of the chamber.

As for the ^{9}Li+^{4}He experiment, a microchannel plate detector was placed just upstream the entrance window, in order to have a fast signal whenever a ^{10}Be beam particle entered into the chamber, producing a reference signal for the ToF measurement and allowing to count the

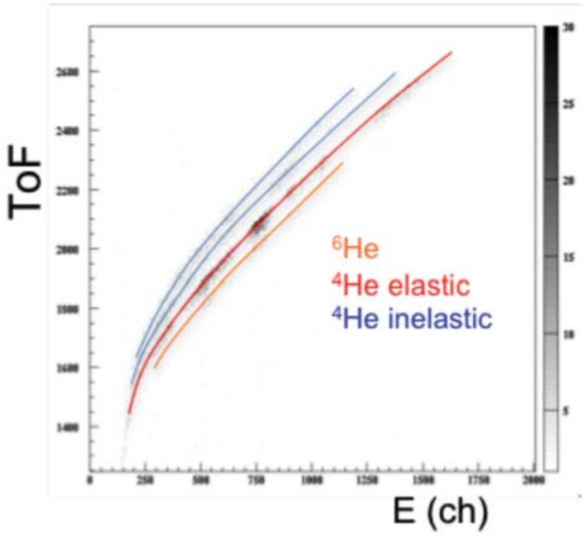

Figure 4. (Colour on line) ToF *vs* E_{res} spectrum. See text for details.

incoming beam particles. The beam intensity during the runs with the MCP detector was kept $<1\times10^7$ pps.
$E_{c.m.}$ and $\theta_{c.m.}$ are reconstructed on an event-by-event basis from the energy and angle of the detected α-particles as done for ^{9}Li+^{4}He analysis.
The gas pressure was chosen to be sufficient to stop the beam before it reached the detector when placed at $\theta_{lab}= 0^0$, but not the recoiling α-particles. In figure 3 a sketch of the experimental set-up is shown.
In figure 4 the ToF-E_{res} 2D-spectrum is shown. In the spectrum it is possible to identify ^{6}He (orange line), ^{4}He coming from elastic scattering (red line), ^{4}He coming from inelastic scattering of the $^{10}Be_{2+}$ state at E_x=3.37 MeV and of the group of states at $E_x\sim$ 6 MeV (blue lines). From the figure, one can confirm what was reported in [3] i.e. that the inelastic scattering contribution is not negligible as reported in [1] and it might affect the conclusions drawn in [1] about the existence of the linear chain configuration in ^{14}C.

3.2. Results
Elastic scattering α-particle spectra were obtained by putting a gate on the corresponding locus on the ToF-E_{res} plot. Similar plots were obtained for the inelastic scattering and ^{6}He data. The residual energy spectra of α-particles of elastic (top) and inelastic scattering (bottom) events selected at $\theta_{lab}=0^0$ are shown in figure 5. As one can see from the figure, the inelastic contribution is as large as the elastic one and shows some structures.
Although in [1] a similar technique as used in the experiment reported here was adopted, the authors claim that the contribution of inelastic scattering events is negligible. They also claim that the locus observed in [2] was not corresponding to true inelastic scattering events therefore, they suggest the data of [2] are not "a credible source for the discussion"[1]. Our results clearly contradict this conclusion, therefore the analysis performed in [1] has to be revised. It could be that, since the data of [1] 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 [1] shows a perfect overlap, thus confirming the inclusion of inelastic scattering in the case of the experiment reported in [1].

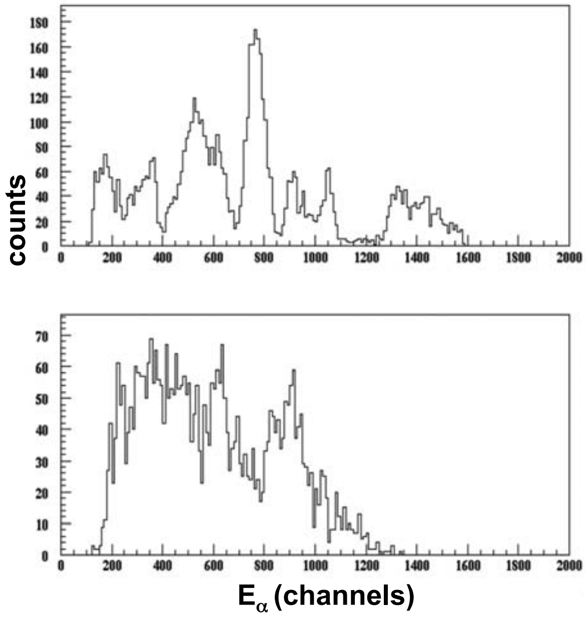

Figure 5. Detected α-particle energy spectra for elastic (top) and inelastic (bottom) scattering events selected at $\theta_{\rm lab}=0^0$.

4. Conclusions

In this paper details of the Resonant Elastic Scattering experiments ^{4}He(^{9}Li, α) performed at TRIUMF and ^{4}He(^{10}Be, α) performed at LNS, at $\theta_{\rm c.m.}\sim180^0$, have been discussed.
The first reaction allowed to investigate the excitation function of ^{13}B in the range E_x=14-20 MeV. The excitation function shows two large structures, which are likely to be due to more than two states in ^{13}B. The extraction of the excitation function at all angles, and, the following theoretical analysis, will allow to understand whether the observed structures can be associated to 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 where it shows the presence of many states. In the present experiment, contrary to findings reported in [1] a large contribution of inelastic scattering events is observed. These processes contribute to a large fraction of the measured alpha production cross-sections. In the light of this result, the R-matrix analysis that led to the determination of the linear-chain rotational band reported in [1], has to be revised.

5. References

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