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New experimental investigation of cluster structures in ^{10}Be and ^{16}C neutron-rich nuclei

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Summary. — The existence of cluster structures in ^{10}Be and ^{16}C neutron-rich isotopes is investigated via projectile break-up reactions induced on polyethylene (CH_2) target. We used a fragmentation beam constituted by 55 MeV/u ^{10}Be and 49 MeV/u ^{16}C beams provided by the FRIBs facility at INFN-LNS. Invariant mass spectra of ^{4}He+^{6}He and ^{6}He+^{10}Be breakup fragments are reconstructed by means of the CHIMERA 4π detector to investigate the presence of excited states of projectile nuclei characterized by cluster structure. In the first case, we suggest the presence of a new state in ^{10}Be at 13.5 MeV. A non-vanishing yield corresponding to 20.6 MeV excitation energy of ^{16}C was observed in the ^{6}He+^{10}Be cluster decay channel. To improve the results of the present analysis, a new experiment has been performed recently, taking advantage of the coupling of CHIMERA and FARCOS. In the paper we describe the data reduction process of the new experiment together with preliminary results.

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1. – Introduction

Clustering phenomena in light nuclei represent a topic of great interest in modern Nuclear Physics. Their investigation is in particular a powerful tool to explore the properties of nuclear forces in diluted nuclear systems [1]. The simplest example of clustering in nuclei is represented by self-conjugated nuclei. Thanks to the residual interaction between nucleons they can re-organize their structure into α particles [2]. A well used method to unveil on the possible existence of clustering phenomena in self-conjugated nuclei is to investigate the presence of states that exhibit large partial widths for the α emission [3]. For example, the disintegration of the ^{12}C nucleus in the Hoyle state proceeds essentially via α particles emission, indicating its strong α-cluster structure, well known for its importance in Nuclear Astrophysics [4-6]. Another interesting case is represented by the excited states of ^{20}Ne, which are involved in Nuclear Reactions of astrophysical interest [7-9] and for which a possible analogous of Hoyle state has been predicted close to the 5α threshold [2].

Clustering effects may play an important role also in non-self-conjugated nuclei. For example, in the presence of extra neutrons, highly deformed cluster structures can appear [10]. In this case, the extra neutrons can act as a sort of covalent particles between α-clusters, increasing the stability of the whole structure and generating the so called molecular nuclear structures. A very interesting example of nuclear molecules are the cases of beryllium and carbon isotopes. They represent the simplest cases of covalent binding in nuclei. The glue-like effect due to extra-neutrons appears evident by looking at the beryllium case. Indeed, while the ^{8}Be is unbound, ^{9}Be and ^{10}Be are bound. The formation of rotational bands of highly deformed molecular structures has been studied in several works. Anyway, for the ^{10}Be case the situation is still not fully understood [11]. The ground state of this neutron-rich nucleus is the band-head of a positive parity band (0^+_{gs}), having the at 3.37 MeV as 2^+ member. This state is predicted to be characterized by a π-type cluster structure with two valence neutrons extending perpendicularly to the axis identified by the two cores [12]. Contradictory results about the identification of the following (4^+) member have been published in the literature. In particular, while the 4^+ state at 11.76 MeV was considered a good candidate to be the 4^+ member of the 0^+_{gs} band [13, 14], these findings were recently questioned by [12], where no resonance were found at 11.8 MeV. A linear extrapolation of the ground band obtained in [12] suggests that the corresponding 4^+ member should be found at about 11 MeV excitation energy, but no evidences of these resonance were published in the literature. In proximity of the ^{4}He+^{6}He energy threshold, the evidence of a 0^+ state is reported (6.18 MeV). For this state, theoretical calculations suggest a highly deformed molecular structure [15]. A rotational excitation of this nuclear dimer is predicted at about 10.5 MeV. A resonance at 10.2 MeV excitation energy was reported in the ^{7}Li(^{7}Li,^{4}He+^{6}He) reaction by [16]. This state was firstly identified as 3^- state by [17], while more recent works suggest a 4^+ assignment [12, 18], indicating this state as 4^+ member of the 0^+_2 band.

Another interesting case is constituted by the carbon isotopes, where the possible formation of linear chains is expected [10]. For example, recent studies have been published on the proton-rich ^{11}C [19, 20] while several resonant elastic scattering experiments have been carried out on ^{13}C [21-24] and ^{14}C [25] nuclei. Anyway, a crucial isotope of the carbon isotopic chain is represented by the ^{16}C, being constituted by a possible symmetric chain-like structure. While theoretical calculations, based on the Antisymmetrized Molecular Dynamic model (AMD), have predicted the appearance of linear chains and triangular states [26], on the experimental point of view very few and low statistics information have been published to date [27, 28]. For these reasons, further investigation on this isotope are desirable, in order to shed light on these interesting clustering aspects, especially near and above the ^{6}He+^{10}Be (16.5 MeV) and ^{4}He+^{12}Be (16.5 MeV) disintegration thresholds.

To investigate the above discussed aspects, we have carried out two different experiments aimed to study ^{10}Be and ^{16}C excited states above the cluster emission threshold. In the first experiment we used the CHIMERA 4π multi-detector to reconstruct breakup fragments emitted in inverse kinematics reactions at intermediate energies. Studying ^{4}He+^{6}He and ^{6}He+^{10}Be invariant mass spectra we were able to, respectively, suggest the presence of a new 6^{+} state at 13.5 MeV in the ^{10}Be nucleus and to find a non-vanishing yield corresponding to 20.5 MeV excitation energy of ^{16}C. More recently, we performed another experiment with the aim of improving the previous results. In the new experiment the correlator FARCOS [29, 30] was coupled to CHIMERA to obtain a better granularity at forward angles. While sect. **2** is dedicated to the description of the first experiment, details and preliminary results of the second experiment are discussed in sect. **3**. Finally, conclusions and future perspectives will be discussed in sect. **4**.

2. – Experimental results

The experiment was carried out at the INFN-Laboratori Nazionali del Sud (LNS) of Catania (Italy) by using the In Flight Radioactive Ions Beams (FRIBs) facility. A 55 MeV/nucleon primary beam, accelerated by the LNS K-800 Superconductive Cyclotron, was used to produce a series of radioactive ion beams by impacting on a ^{9}Be (1500 μm) production target. A selection in magnetic rigidity ($B\rho \approx 2.8$ Tm) was obtained by means of a Fragment Recoil Separator (LNS-FRS) with a momentum acceptance of $\Delta p/p \approx 0.01$. Fragmentation products were delivered to the experimental hall along a beam line where a tagging system was installed. It is constituted by a large-area Micro Channel Plate (MCP), at about 15 m from the target and a Double Sided Silicon Strip Detector (DSSSD) [31]. A particle-by-particle identification is obtained by correlating the time of flight (ToF) in the beam line from the MCP to the DSSSD (≈ 13 m) and the corresponding energy loss inside the DSSSD. The fragmentation beam delivered to the experimental hall (mainly constituted by 10^{5} pps ^{16}C at 49.5 MeV/u and 4×10^{4} pps ^{10}Be at 56 MeV/u beams) is then used to induce nuclear reactions on a polyethylene $(CH_2)_n$ target. To identify and track each particle and fragment produced in nuclear collisions we used the CHIMERA 4π multi-detector [32-38]. This array is made of 1192 ΔE-E telescopes, covering the 94% of the whole solid angle and organized in two groups. A forward group is composed by 9 rings with different granularities (starting from 0.133 msr at the forward part) and covering the angular region from 1° to 30°, while the angular range from 30° up to 179° is covered by a sphere having the reaction target as center. Each ΔE-E telescope is a Si(300 μm)-CsI(Tl) two stage detector. The identification of particles was obtained by using the ΔE-E technique, which allowed us to unambiguously separate each Z value and to obtain a reasonable isotopic identification up to beryllium.

To investigate on the possible presence of excited states in the projectile nuclei, possibly characterized by clustering phenomena, we induced sequential breakup reactions. In particular, ^{10}Be and ^{16}C unstable nuclei are studied, respectively, by means of the reactions ^{1}H,^{12}C(^{10}Be,^{4}He+^{6}He) and ^{1}H,^{12}C(^{16}C,^{6}He+^{10}Be). The spectroscopy of the projectiles prior to decay is explored by means of the invariant mass spectroscopy technique on correlated breakup fragments, which allows to determine the energy position of

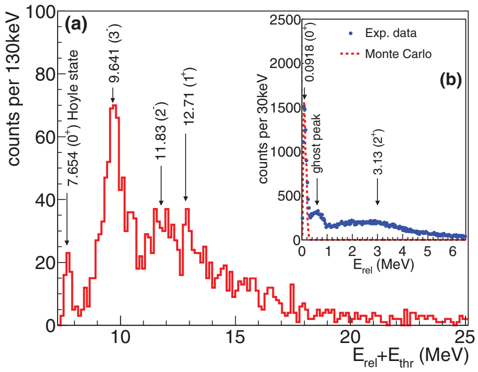

Fig. 1. – (b) α–α invariant-mass spectrum (blue points) compared with a complete Monte Carlo simulation (red line) including the emission process from the ^{8}Be ground state and the detection characteristics of the CHIMERA device. Arrows indicate the energies of the expected peaks. (a) 3α invariant mass spectrum. The expected populated states of the ^{12}C are indicated by arrows.

the decaying state by summing the energy in the center of mass of the decay (the so-called *relative energy*) E_{rel} to the corresponding emission threshold (E_{thr}) (more information about this technique can be found in the refs. [39, 40]).

As a preliminary check, correlations between α particles were studied. In particular, in fig. 1 we report the invariant mass spectra ($E_{rel} + E_{thr}$), respectively for (a) 3α and (b) α-α systems. In the first case we are able to identify, with reasonable resolution, excited states of the ^{12}C nucleus, indicated by arrows in figure. For example, the well separated peak at lower energy corresponds to the decays of 3α particles from the Hoyle state. Similar conclusions can be give for the α–α correlations, from which the spectroscopy of ^{8}Be can be obtained. In this case, the low energy peak at about 100 keV can be attributed to the ground state of ^{8}Be while the high energy broad peak at about 3 MeV is compatible with the first excited state of ^{8}Be. A dashed red line represents the result of a Monte Carlo calculation including both the generation of α particles from the ^{8}Be ground state and the detection with the CHIMERA device with the same prescription as described in our previous papers [41, 42]. A peak centered at $\approx$ 600 keV is the indication of the ghost peak due to the ^{9}Be decays, in agreement with findings of [43].

In fig. 2 the ^{4}He+^{6}He excitation energy ($E_{rel} + E_{thr}$) spectrum is shown. In this case the statistics is significantly lower the case of self-conjugated nuclei, but anyway we are still able to suggest the presence of peaks possibly corresponding to excited states of the ^{10}Be nucleus. In particular, arrows are used to indicate the position of known states in the literature. Clearly visible from the figure is the presence of low energy bumps, compatible with the position of states reported in the literature. Further, it is interesting the presence of a higher energy bump, centered at about 13.5 MeV. This peak could be the evidence of a new state in ^{10}Be. To support this hypothesis, a study of the detection efficiency and the background has been done. Having a composite target (hydrogen and carbon) we studied separately the detection efficiency, by means of Monte Carlo calculations, for the cases of projectile breakup induced by carbon (solid line) and hydrogen (dashed line). Both the curves are smooth, indicating that the corresponding peak cannot be attributed to the detection efficiency effects. Finally, the background has been evaluated via an event mixing procedure, to simulate coincidences between

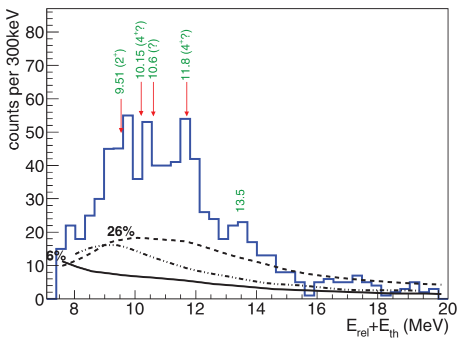

Fig. 2. – ^{10}Be invariant mass spectrum ($E_{rel} + E_{thr}$) for the ^{4}He+^{6}He break-up channel (blue line). The dashed and solid lines represent, respectively, the simulated detection efficiency for inelastic scattering on proton, peaking at 26%, or carbon, peaking at 6%. The positions of known states in the literature are indicated by arrows, while the green labels indicate the corresponding excitation energy. A dash-dotted line represent the trend of the event mixing background.

spurious couples of particles. In this case correlations between particles coming from different collision events have been constructed. The result is shown with the dash-dotted line, being clearly smooth in the region of the 13.5 MeV peak. We conclude that this peak could be attributed to the existence of a new unreported state of ^{10}Be. Further details about this analysis are reported in [41, 44, 45].

Finally, ^{6}He+^{10}Be correlations have been studied to unveil the spectroscopy of ^{16}C (fig. 3). In this case we report an extremely low statistics with a non-vanishing yield obtained at about 20.5 MeV excitation energy. By analogy with the previous case, a study of detection efficiency (dashed lines) suggests that this peak should not be attributed to the geometrical efficiency of the CHIMERA device. The result is compatible with suggestions of other low statistics experiments reported in literature [27, 28], but with statistics higher than the previous works. Anyway, since the statistics is extremely low, no firm conclusions can be drawn in this case, and further experiments are clearly required.

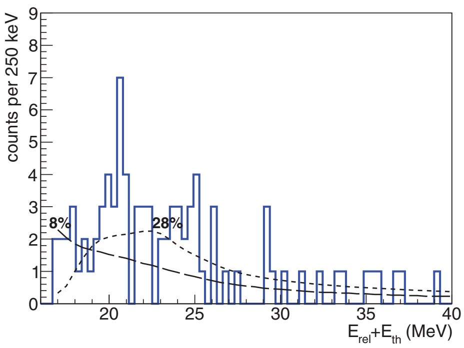

Fig. 3. – ^{16}C invariant-mass spectrum ($E_{rel} + E_{thr}$) for the ^{10}Be+^{6}He break-up channel. The dashed lines represent, respectively, the simulated detection efficiency for inelastic scattering on proton, peaking at 28%, or carbon, peaking at 8%.

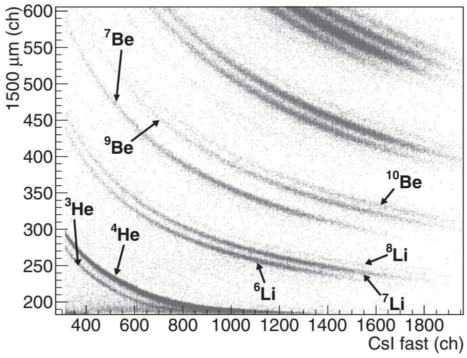

Fig. 4. – ΔE-E identification matrix obtained with the second and third detection stages of the FARCOS array. Arrows and labels indicate the first identified isotopes. The matrix has been truncated up to the beryllium lines for clarity reasons.

3. – The CLIR experiment: data reduction and preliminary analysis

The results of the previously discussed experiment have been used as a starting point to develop a new experiment at the FRIBs facility of INFN-LNS: the CLIR (Clustering in Light Ion Reactions) experiment. In this experiment we use the coupling of CHIMERA and FARCOS [29,30] at forward angles, where we expect to detect a large part of particles emitted in this type of reactions [41, 46]. FARCOS is a new array for correlation and spectroscopy, characterized by very high granularity and energy resolution and made of three detection stages (a 300 μm DSSSD, a 1500 μm DSSSD and a CsI scintillator crystal). While further details on this apparatus can be found in the ref. [30], we briefly report in this paragraph some details about the analysis of the CLIR experiment. The identification of particles is obtained, with excellent performances, by means of the ΔE-E identification technique. The lower energy particles, that stop into the second stage are identified by using the first and second DSSSDs as ΔE-E telescope, while the particles stopped by the CsI are identified using a DSSSD-CsI telescope, based on the second and third stages. In fig. 4 we report a typical identification matrix obtained in the latter

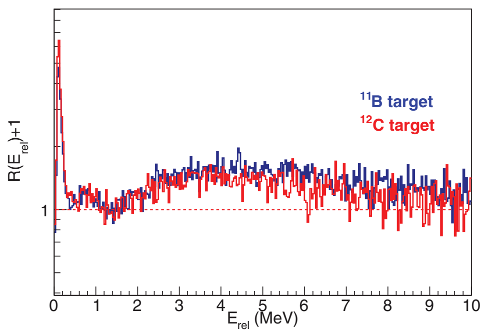

Fig. 5. – α-α correlation function $(R(E_{rel} + 1))$ in logarithmic scale for two different nuclear collisions ^{16}O+^{11}B (blue line) and ^{16}O+^{12}C (red line) at 55 MeV/u. The dashed line represents the line $R(E_{rel}) = 1$.

case. As clearly visible from the picture, every particle is correctly identified without significant ambiguities in the isotopic separation and a better quality in the analysis of correlations is therefore expected. An example similar to the one shown in fig. 1(b) but obtained with FARCOS is shown in fig. 5 in terms of correlation function for two different nuclear systems: ^{16}O+^{11}B (blue line) and ^{16}O+^{12}C (red line) at 55 MeV/u. In both cases we reconstruct correctly both the ground state of ^{8}Be and the first excited state with a significant improvement in resolution in comparison to the result obtained with CHIMERA. In particular, we obtain a FWHM of less than 70 keV for the ground-state peak. Finally, a further peak at $\approx$ 600 keV is also present in analogy with the findings of CHIMERA, indicating a possible contribution of the ghost peak due to ^{9}Be, weakly populated because of the n-poor projectiles.

4. – Conclusions and perspectives

In conclusion the spectroscopy of ^{10}Be and ^{16} is investigated with the CHIMERA 4π multi-detector. Results on the ^{10}Be spectroscopy suggest the possible existence of a new state at 13.5 MeV, while for the ^{16}C a peak-like structure is seen at about 20.5 MeV excitation energy. This peak cannot be attributed to the detector efficiency but, because of the very low statistics, it can be compatible with a non-resonant phase space component and we are not able to firmly suggest the existence of states in the continuum of ^{16}C. Finally, a new experiment have been performed at the FRIBs facility of INFN-LNS by coupling CHIMERA and FARCOS. Some details and preliminary results of this experiment have been discussed in the text. In the near future, we will explore again the spectroscopy of ^{10}Be and ^{16}C with a better resolution thanks to the use of the FARCOS array.

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