Neutron-rich clustering investigation at LNS with FARCOS detectors

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Abstract. The physics of clusters in heavy neutron-rich ions is a topic of constant interest in the worldwide scientific community. In recent times, many interesting phenomena have been investigated especially thanks to the development of new radioactive beam production facilities. One example is the clustering of α particles in neutron-rich isotopes of self-conjugated nuclei, such as ^{10}Be or ^{16}C, exhibiting even very large nuclear deformations. At Laboratori Nazionali del Sud of INFN, a study was carried out on the topic of α clustering, employing the CHIMERA and FARCOS detectors. Radioactive ions of interest, such as ^{10}Be, ^{13}B and ^{16}C, were produced in a cocktail beam through the In-Flight fragmentation technique by the FRIBs@LNS facility. Particularly important for this study was the employment of four FARCOS detectors, offering high angular and energetic resolutions. Several calibration and analysis techniques have been exploited and developed in this experiment for the analysis of the data collected by FARCOS. Finally, some preliminary results on the analysis of ^{10}Be and ^{16}C spectroscopy will be shown, in relation to some results already collected in the literature.

1 Introduction

Clustering in nuclei is an intriguing phenomenon, of growing interest in the worldwide scientific community [1–3]. Indeed, understanding this phenomenon in depth represents a powerful benchmark to explore the behavior of the nuclear force in complex systems of interacting nucleons. The most common and studied clustering phenomenon concerns the formation of α particles, even more likely thanks to their great internal stability. Several α cluster structures are known, especially in self-conjugated nuclei, such as in ^{8}Be, ^{12}C, ^{16}O, and ^{20}Ne [4]. Furthermore, depending on the excitation energy of the atomic nuclei, different types of structures can appear, such as dilute gaslike structures or linear chain structures, leading even to ring-like shapes [1, 5]. Clustering phenomena in neutron-rich non-selfconjugated nuclei are also of great interest, thanks to the variety of structures, especially as the excitation energy of the nucleus increases. The addition of these extra neutrons, in fact, modifies the stability of complex structures, introducing new degrees of freedom. In fact, exploiting their glue-like effect, neutrons can also increase the stability of more complex structures, theoretically allowing them to form even at lower excitation energies. In this context, the behavior of these extra nucleons, commonly called *valence* nucleons, is similar in fact to that of electrons in covalent molecular bonds, created in this case between clusters of α particles sharing the excess neutrons. Some examples are the isotopes of beryllium and carbon. Beryllium is an archetypal case: while its self-conjugated nucleus ^{8}Be is unbound at ground state, manifesting $2-\alpha$ clusters, with the addition of neutrons its stability increases, allowing its neutron-rich isotopes to remain bound. The presence of valence neutrons allows the formation of higher deformation structures, such as nuclear molecules of two α clusters held together by valence neutrons, with large moments of inertia. One such case is ^{10}Be presenting a molecular-like exotic configuration of α dimers configured with π-type or σ-type covalent bonds, in a linear fashion of type α:2n:α. Due to the presence of the two neutrons, the scheme of its energy levels is considerably intricate, compared to that of the near isotopes, allowing the formation of structures with different momenta of inertia. In this case, it is in fact possible to study through theoretical models of molecular dynamics [6] the presence of a rotational band associated with the config-

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uration α:2n:α at the energies of 6.179 (0^+), 7.542 (2^+), and 10.2 (4^+) MeV, as highlighted by [7] and references therein. The interest, especially for this structure, derives from the fact that the other states associated with this configuration theoretically predicted could be also present for spin 6^+ and 8^+. A possible candidate proposed by various studies for the first is at 13.5 MeV, previously studied also at the Laboratori Nazionali del Sud of INFN (INFN-LNS) [8], for which however further confirmation work is necessary. Theoretical studies similar to those conducted for the ^{10}Be structure have also been extended to the 3-α structure of carbon isotopes, in order to investigate also linear or triangular configurations [1]. Some studies for example have investigated the presence of linear structures in ^{13,14}C using molecular dynamics models, subsequently reported experimentally [9–11]. Other recent studies have predicted the existence of many linear chain states also in the case of ^{16}C, with decay towards ^{4}He+^{12}Be and ^{6}He+^{10}Be reaction channels. However, the observation of such states is rather complex, since the ^{10,12}Be of the final state can also end up in various excited states, requiring precise Q-value calculations. An experiment aimed at investigating such cluster states through their break-up decay channels, including those of ^{10}Be and ^{16}C mentioned above, has been carried out at INFN-LNS [12, 13]. In this work, the main preliminary results obtained so far will be presented, but further study and validation will be necessary.

2 Experimental apparatus

The experiment was performed at INFN-LNS, in Catania, using a radioactive ion beam produced by means of the FRIBs facility [14–16]. This was made by fragmenting a ^{18}O primary beam, accelerated by the Superconducting Cyclotron of LNS at about 55 MeV/u, on a thin ^{9}Be 1500 μm thick target placed on the beam line. By using a rigidity $B\rho \approx 2.8$ Tm and a momentum acceptance of $\Delta p/p \approx 0.01$, a cocktail beam was produced containing several ions of interest. To identify its components, a tagging system was employed [17], made of a MicroChannel Plate (MCP) detector and a Double Sided Silicon Strip Detector (DSSSD), installed on the beamline. The identification of ion components of the cocktail beam was based on the ΔE-ToF technique, by correlating the energy loss of incident ions of the cocktail beam on the DSSSD with their Time-of-Flight between the path from the MCP to the DSSSD. In this way a matrix was produced as in Fig. 1 thanks to which it was possible to recognize each ion component of the cocktail, ranging from ^{6}He to ^{17}C. To trigger the break-up reactions, a 50 μm thick polyethylene CH_2 target was used, while also in addition, a 75 μm thick carbon target was used for some runs. As for the experimental apparatus, reactions products were detected by four telescopes of the FARCOS array [18], coupled with CHIMERA 4π multidetector [19]. CHIMERA is made of 1192 Si-CsI(Tl) telescopic units, arranged in a 4π geometry, comprising of 9 rings in the forward part and a sphere, covering up to 98% of the whole solid angle. However, the real highlight of the measurement was the introduction of

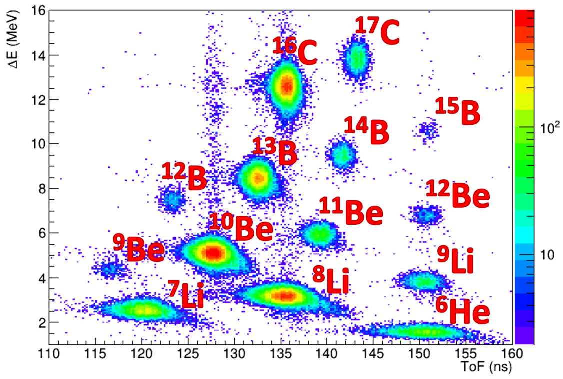

Figure 1. ΔE-ToF plot obtained from the tagging system. Labels indicate the several isotopic components of the cocktail beam employed, one for each distribution. Adapted from Ref. [12].

the FARCOS array, still in its early phase and used for the first time in studies on clustering physics with radioactive beams. Each FARCOS module is a three stage telescope: the first two stages are DSSSDs, while the third stage is made of 4 CsI(Tl) scintillators. DSSSDs of the first stages are 300 and 1500 μm thick respectively, consisting of 32 strips (2 mm pitch) on both front and back sides, for a total active area of 64×64 mm^2. The following four CsI(Tl) crystal, 6 cm thick, serve the purpose of detecting the final residual energy of the ion after passing through the first two stages. This allows the identification of the detected fragments through the ΔE-E method with the 1500 μm stage [12]. Unlike other detectors of this type, the main advantage of FARCOS is its high modularity, since thanks to its design and compactness, it can be positioned in strategic points. In this case, during the whole campaign, the four FARCOS telescopes were placed between the rings and the CHIMERA sphere, at a small angle around the beam axis, covering the angles $2.2^\circ \le \theta \le 8.8^\circ$. Concerning the calibrations of the FARCOS modules, the DSSSD strip fronts were calibrated by calculating the energy loss of the various components of the cocktail beam, elastically scattered on the reaction target. In order to obtain a good angular resolution, it was also necessary to calibrate the back side strips individually. This was performed through a fit of a 2D scatter plot linear distribution, obtained by comparing the signal on each of the back strips with the calibrated front signals. Moreover, the advantage of this method was also to being able to verify the conformity of the calibrations of all the strips of the DSSSD, exploiting the principle for which the energy loss obtained by the passage of an ion in a strip is equal to that obtained on the opposite face. An algorithm to approach the pixelation problem was also developed, in order to associate the correct front strip to the correct back strip. This is of extreme importance as it allows to correctly associate, for each ion hitting the detector, the correct couples of angles θ and ϕ as the centroids of each FARCOS pixels. More on the technique developed is described in Ref [20]. Moreover, much care was also given to the calibration of the CsI(Tl) scintillators, performed using the Recombination and Nuclear Quenching Model (RNQM) [21], parametrizing the non-

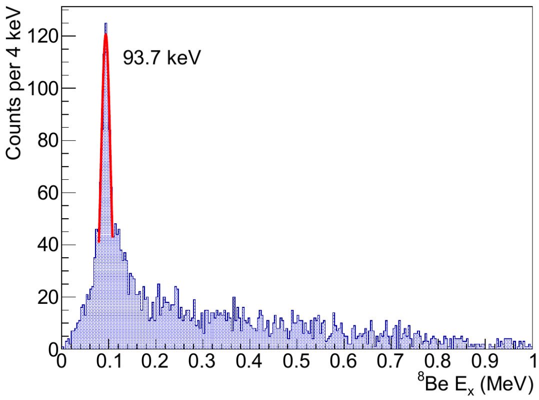

Figure 2. Energy spectrum obtained from $\alpha - \alpha$ correlations for ^{8}Be. The fit depicted by a red line identifies a peak centered at 93.7 keV, consistent with the ^{8}Be disintegration from the ground state.

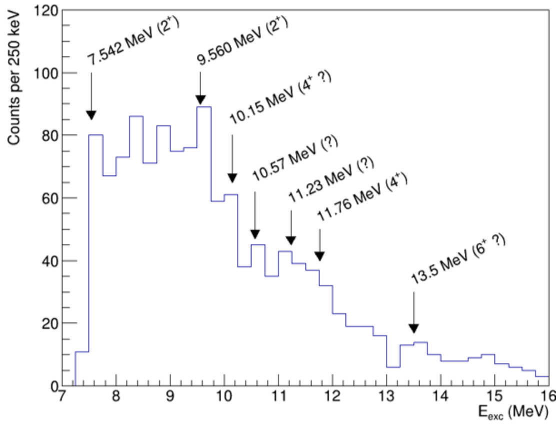

Figure 3. ^{10}Be excitation spectrum for the ^{6}He+^{4}He decay channel. The vertical arrows indicate energies known in literature for different states. Spin parity values J^{π} are shown in brackets.

linear response of the scintillators on the mass, charge and energy of the incident particles [12].

3 Analysis and experimental results

In order to study excited states of ions of interest, such as ^{10}Be and ^{16}C, the correlations between their break-up fragments are analyzed. By evaluating their energy and emission angle, it is possible to reconstruct the kinetic energy of the fragments in the center of mass frame of reference. In this way, using the invariant mass method, by adding the relative energy of the break-up channel products (E_{rel}) to the emission threshold energy for the reaction channel (E_{th}), the excitation energy of the parent nucleus is obtained, as extensively discussed in ref. [22]. As a first check, a validation of the calibrations and of the geometrical setup was done by studying the case of $\alpha - \alpha$ correlations. Since the cocktail beam is a set of different ionic species, the spectrum produced for this case was very convoluted without a proper selection of an entrance channel or a cocktail beam ion, with many possible contribution of different *ghost peaks* due to different reactions or neutron emissions. This was mainly solved by selecting the ^{16}C beam from the cocktail beam, by means of a simple tagging event selection. A ^{8}Be relative energy spectrum was reconstructed, as shown in Fig. 2. The spectrum presents a peak centered at 93.7 keV, clearly compatible with the emission of the $\alpha - \alpha$ pair from the ^{8}Be ground state. Furthermore, despite the selection on ^{16}C, some background is still present, possibly caused by the presence of residual *ghost* peaks, which could also explain the slight shift to the right of the shown ground state peak. The analysis was then performed on ^{10}Be, for which the ^{6}He+^{4}He cluster break-up reaction channel was investigated. After selecting the ^{10}Be beam on the tagging system, the events in which a pair of ^{6}He and ^{4}He detected by FARCOS telescopes in coincidence were collected, correctly identifying their tracks and total energy. Using the invariant mass method, by adding to the reaction threshold of $-Q_{val}$ = 7.408 MeV, the relative energy between the two fragments, it was possible to obtain the spectrum shown in Fig. 3 [13]. The spectrum, in which arrows indicate the energy of various cluster states already obtained from the literature [7, 23, 24], shows the presence of some peaks of interest, although there is a noticeable background contribution. For this reason a selection of the events was then performed, distinguishing two different classes: one in which both daughter fragments arrive on the same telescope, thus identifying a small relative angle between ^{4}He and ^{6}He ions, and events in which these end up on two different telescopes, at a large relative angle. The choice is also supported by a simulation of the decay of some excited states of ^{10}Be for the studied channel where the same selection shows a similar trend (Fig. 4) [25]. The result of this selection is shown in Fig. 5-6, which respectively show the ^{10}Be spectra obtained by filtering through these geometric selections. By selecting the ions arriving on the same telescope, a spectrum was obtained that presents a

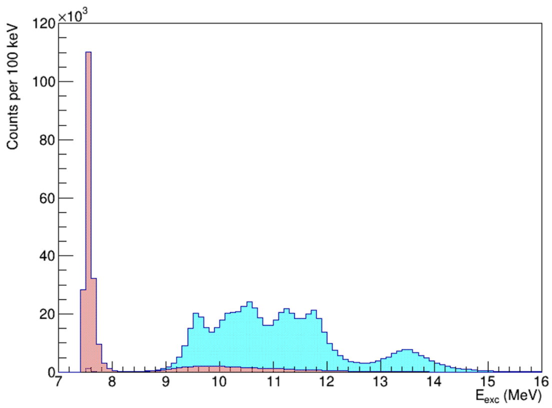

Figure 4. Simulated ^{10}Be excitation spectrum for the ^{6}He+^{4}He decay channel integrating also the FARCOS geometry. Red histogram represents simulated data in which daughter fragments arrive on the same FARCOS telescope, while blue histogram is obtained with fragments arriving on different telescopes. Adapted from [25]

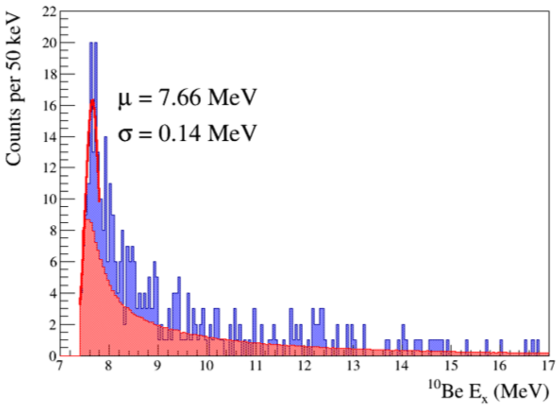

Figure 5. ^{10}Be excitation spectrum for the ^{6}He+^{4}He decay channel after selecting daughter fragments arriving in coincidence on the same telescope. Blue histogram represents experimental data, while red histogram is obtained through event mixing techniques (see text).

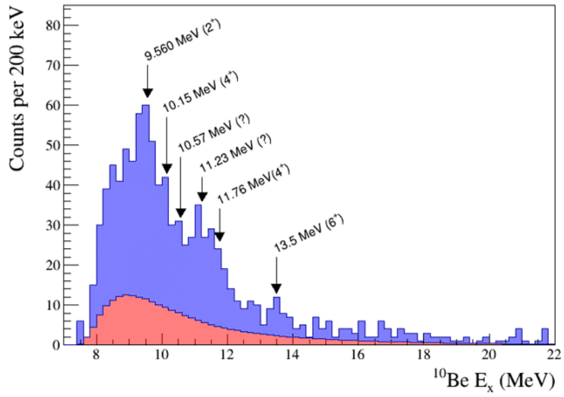

Figure 6. ^{10}Be excitation spectrum for the ^{6}He+^{4}He decay channel. The vertical arrows indicate energies known in literature for different states. Spin parity values J^π are shown in brackets.

single low energy bump, with a value around 7.66 MeV. A background spectrum was also obtained through an event mixing procedure, selecting daughter ions belonging to different events. Although the noise contribution evaluated with event mixing is high, the observed peak could be associated to the decay of the level at 7.542 MeV (2^+). This level is very near to threshold at 7.409 MeV and has a 2^+ spin so the question is if it can really be observed by particle decay due to the associated coulomb and rotational barriers. However, from Ref. [26], the α-particle decay probability of this level is not negligible, 0.35%. For comparison the level at 9.56 MeV, also 2^+, is reported to have an alpha-decay probability of $\Gamma_\alpha\ \Gamma \approx 0.16$, but with a larger error (0.04). This last level was observed in other breakup experiments [8, 27–29]. Therefore further studies are necessary to really establish the population of this level, for instance by investigating at angular distributions. The very good granularity of the FARCOS telescope, coupled to an efficient pixelation method, able to disentangle a very small kinematic decay cone is much helpful to observe such a level with very low decay probability. Fig. 6 instead shows the spectrum obtained for ^{10}Be, selecting pairs of ^{6}He+^{4}He events arriving in coincidence on different telescopes, therefore having a larger relative angle. The spectrum, although still preliminary, shows a better resolution than the one obtained previously, giving the possibility of observing some peaks of interest. Also for this case the background spectrum, obtained through event-mixing procedures, has been represented in red. Although the selection of the events has been effective, there is still a large part of background around the regions up to 9 MeV and between 12 and 13 MeV. The latter in particular makes it especially difficult to observe the peak at 13.5 MeV, already observed in the literature, also at LNS, through previous experiments [7, 8]. Finally, another result, still preliminary, was obtained from the observation of the ^{16}C cluster break-up, for the ^{12}Be+^{4}He decay channel. As before, even in this case study, through the invariant mass method, a excitation energy spectrum was obtained, shown in Fig. 7. The spectrum shows the presence of some structures, some of which could be associated with peaks of energy levels known in literature [22, 30, 31]. Some arrows also show some energy levels recently investigated and still under study, for which there could be a plausibility, although the resolution and yield is low. In future, it will be possible to obtain more details especially with the addition of the data collected by the CHIMERA multidetector, which has not been analyzed up to now. This will contribute to the overall study of the reaction, increasing the angular region of study and, above all, providing information on the recoil target ion. Analysing the recoil target of the break-up reaction will also give the possibility to study the reaction from a Q-value standpoint, so obtaining a much more precise evaluation of the relative energy of the daughter fragments. As a matter of fact indeed in the case studied in this work some excited state of ^{6}He and ^{12}Be daughter ions could be populated, affecting the evaluation of the excitation energy of the parent nucleus.

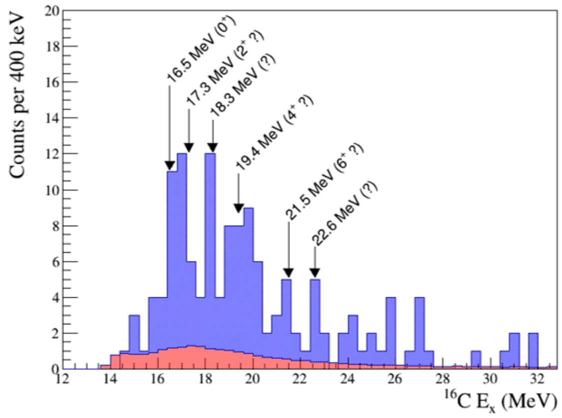

Figure 7. ^{16}C excitation energy spectrum for the ^{12}Be+^{4}He decay channel. The vertical arrows mark energies known in literature for different states. Red filled histogram is a background spectrum obtained through event mixing techniques.

4 Conclusions

In conclusion, some preliminary results of the analysis conducted on cluster states in some neutron-rich nuclei have been shown, highlighting how the performed study offers promising outcomes. Results on the spectroscopy of ^{10}Be have been shown, specifically for the ^{4}He+^{6}He cluster decay channel. Excitation energy spectra have been produced, in which the possible presence of cluster energy levels, also belonging to different rotational bands, is highlighted. In particular, the study on these structures will continue in the future, mainly investigating their confirmation, removing part of the background and increasing the yield thanks to the contribution also of the CHIMERA multidetector. Furthermore, some preliminary results on the spectroscopy of ^{16}C have been shown for the ^{12}Be+^{4}He reaction channel, for which, if validated, they would contribute to the study with a further confirmation of recent results, both theoretical and experimental, obtained in literature [22, 31]. As for the future, at LNS thanks to the construction of the new FRAISE fragment separator [14–16, 32, 33], currently being completed, it will be possible to broaden the field of study of cluster physics, essentially by producing much purer and intense radioactive beams. One of the approved future experiments will concern the study of cluster structures and measurements of branching ration in neutron-rich isotopes of boron [34], which will especially see the use of the new modern FARCOS array, with improved digital electronics. Furthermore, the construction of the recent neutron array NARCOS [35–37], will give the possibility to contribute to the study of such reactions, offering the possibility to acquire knowledge on the state of emitted neutrons and thus obtain greater precision in the calculation of branching ratios.

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