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Clustering and molecular states in neutron rich nuclei

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An investigation plan of different clustering and molecular states in neutron rich isotopes of Lithium, Beryllium, Boron and Carbon, in the context of an experimental campaign at INFN-Laboratori Nazionali del Sud, is presented. High statistics and new information on known states and study on new states will be possible thanks to the high intensities available for the exotic beams, delivered by the FRAISE facility and thanks to the opportunity of using very performing experimental apparatus, as well as the detectors CHIMERA, FARCOS, and NArCOS. Among these, the new hodoscope NArCOS, by detecting with high efficiency neutrons and providing high energy and angular resolutions, will allow also a precise study of reaction channels characterized by neutron emission.

KEYWORDS

clusters, molecular states, break-up reactions, light nuclei, neutron detection

Introduction

Recent advances in the production of nuclei far from the stability valley provide the opportunity of studying very fascinating exotic phenomena such as the presence of neutron halo and neutron skin, the vanishing of the magic numbers, Bose-Einstein condensation and cluster states in light nuclei. In particular, the study of clustering is one of the most important subject in nuclear physics because it constitutes a powerful tool to investigate the nuclear force and the resulting symmetries [1].

A relevant role is played by α correlations in nuclei with N (number of neutrons) = Z (number of protons) [2, 3], which have also remarkable involvements in astrophysics [4]. For example, the well-known Hoyle state [5], a 3 α structure which characterizes the second 0^+ excited state of the ^{12}C at 7.65 MeV, plays a fundamental role in the carbon synthesis, during the Helium burning phase in the evolution of the stars. Another peculiar case is ^8Be, which decays into two alpha particles. These alpha cluster structures are stabilized in the excited states of some nuclei by adding neutrons that play the glue-like role between the alpha structures; these states, by analogy with the covalent binding for the electrons, are called molecular states [6]. In fact, ^9Be is stable with respect to ^8Be, thanks to the presence of the extra neutron. Another isotope of beryllium, ^{10}Be exhibits a molecular structure, constituted by two alpha particles and two valence neutrons α + α + n + n. Molecular like states of 3α+xn type are observed in carbon isotopes as for example $^{13}C \rightarrow$ n+α+α+α and the $^{14}C \rightarrow$ α+α+α+n + n. In neutron rich nuclei, the appearance of molecular states is observed, with high probability, for energies close to the threshold for decaying into neutrons and cluster constituents. This is shown for carbon and beryllium, in the diagram in Figure 1, adapted from reference [6], in which an extension of famous Ikeda diagram [7] was proposed by Von Oertzen.

The existence of exotic clusters structures is predicted in the ground and excited states of neutron-rich isotopes of beryllium, boron and carbon. A very interesting case is the study of the $^{10}Be^* \rightarrow {}^{6}He + {}^{4}He$ break-up channel, conducted at Laboratori Nazionali del Sud by the CHIMERA collaboration, which highlighted the possible presence of a new state at 13.5 MeV [8]. Cluster configurations are suggested both theoretically and experimentally in the excited states of $^{10\text{-}12}Be$ and theoretically predicted in the ground states of $^{15\text{-}17}B$ [9].

In this context, the Antisymmetrized Molecular Dynamics (AMD) model [10] has been applied to study the ^{13}B isotope by predicting for the ground state a $3/2^-$ state with a p-shell closure configuration, while for the excited states of ^{13}B cluster like structures such as ^{12}Be + p, ^{9}Li + α [11, 12] and ^{10}Be + t, with large deformations leading to the appearance of rotational bands $k^\pi = 3/2^-$ and $k^\pi = 1/2^+$ [13]. Other configurations are possible, for example the CHIMERA group observed the $^{7}Li + {}^{6}He$ state in the data analysis of the UNSTABLE experiment, but with a very low statistic for these events because the experiment was focused on another topic.

Another very interesting case is the one of ^{16}C [14–18] which presents different cluster states, such as $^{10}Be+{}^{6}He$, α+^{12}Be, $^{7}Li+{}^{9}Li$, $^{8}Li+{}^{8}Li$, ^{13}B + t, ^{14}C+2n, ^{15}C + n, $^{6}He+{}^{6}He$+α and ^{10}Be+ α +2n. All of these are possible configurations with an excitation energy higher than 16.5 MeV and that can be studied *via* break-up reactions.

The experimental campaign

Several experimental and theoretical investigations have been conducted with the aim of studying cluster and molecular structures [8, 19–24] and reference therein]. Known and new cluster and molecular states in nuclei belonging to the isotopic chains of Li, Be, C and B can be studied in the context of an experimental campaign, in which break-up reactions of radioactive beams of intermediate energy will be realized by using mainly CH_2 but also CD_2 targets (proton and deuteron respectively). The use of a deuterated target will be important for instance to transfer a neutron to the projectile and eventually study more neutron rich systems.

The cross section of break-up reactions on a proton obviously is lower than the one of reactions on heavy targets, thus it become essential that the experimental set-up is designed to exploit the extremely forward-focused kinematics, which characterizes these reactions, in order to maximize the detection efficiency for this type of events.

The INFN-Laboratori Nazionali del Sud, in Catania are the perfect place to carry out these experiments, thanks to the construction of the new fragment separator, FRAISE (FRAgment In-flight SEparator) [25–29] to the implementation of devices for the identification of the different isotopes that compose the "cocktail beam", coming from the fragmentation of the primary beam on the target production and to the presence and construction of increasingly performing detectors.

Radioactive beams have long been produced at LNS with the In-Flight method (fragmentation in flight) by the FRIBs facility, but nuclei really far from the stability valley were produced with low statistics due to the low power released by the cyclotron. High intensity (up to 10^7 pps) and high quality exotic beams will be available thanks to the cyclotron upgrade project, currently in progress.

The use of a cocktail beam could be an advantage, because thanks to the new expected high intensities available, it offers the possibility of studying different physical cases with the use of a single primary beam. The intensity of the beam must be high enough to use a relatively thin reaction target, thus avoiding the loss of energy resolution which affects the excitation energy spectra and which could affect the observation of discrete levels which will be characteristic of the cluster structure. At the same time, the intensity should be such as not to make the tagging system work to the limit and to avoid radiation protection problems. For example, for the ^{10}Be isotope a good compromise is reached using a beam of 10^6 pps.

In this case, the experimental plan is to use a ^{18}O at 55 MeV/nucleon as primary beam, that impinges on a production target of ^{9}Be, 1.5 mm thick. The fragment separator should be set in order to optimize the transport of ^{16}C and then for the transport of ^{11}Be and thus to obtain cocktail beams with a good intensity of the beams of $^{16,17}C$, $^{13,14}B$, $^{10,11,12}Be$, ^{6}He and neutron rich isotopes of Lithium such as ^{9}Li.

When the cluster constituents are found in coincidence, by reconstructing their relative energy E_{rel}, it is possible to obtain the excitation energy of the father nucleus from $E^* = E_{rel} - Q$, where Q [30, 31] is the threshold for the selected break-up channel.

The search for correlations between the particles in the final state and the subsequent reconstruction of their relative energy require a high segmented apparatus with a geometric acceptance as large as possible.

The advantage of carrying out the experiment at the LNS is also in the possibility of using a detection apparatus that meets the needs previously expressed, consisting of the 4 π CHIMERA

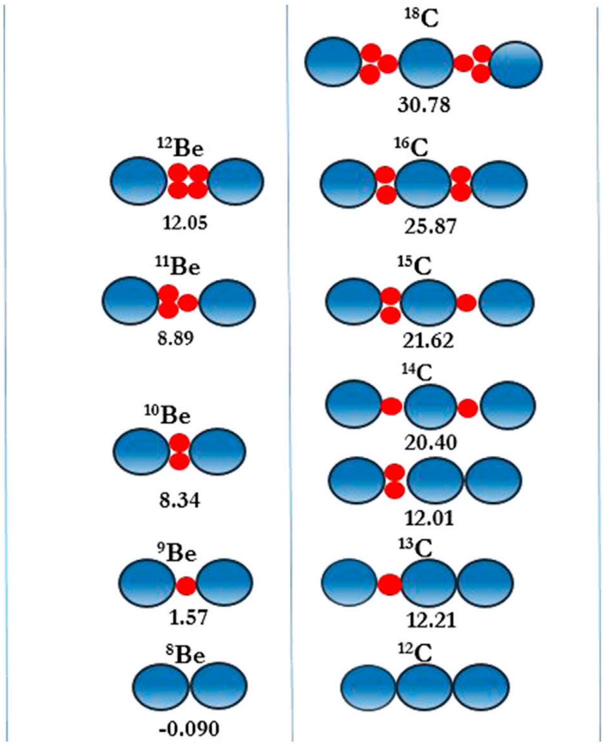

FIGURE 1
Extended Ikeda Diagram for covalently bound nuclear structures in carbon and beryllium,adapted from the one proposed in reference [6] by Von Oertzen. The threshold emission energies for neutrons and cluster constituents of molecular states are indicated.

multi-detector [32], coupled up to twenty FARCOS telescopes [33, 34], placed at selected angles, in order to obtain excellent angular resolutions.

CHIMERA is a device designed for the detection of charged particles emitted in heavy ion collisions, thanks to the implementation of different identification techniques it can be used in experiments realized in different energy regimes, from low energy [23, 24, 35–37] domain up to the fermi domain [8, 38, 39], allowing the investigation of different research topics.

The FARCOS (Femtoscope ARray for COrrelation and Spectroscopy) project consists of telescopes with high angular and energy resolution for the measurement of particle-particle correlations and the spectroscopy of emitting nuclei. Each of these telescopes is actually an independent module, that can be assembled to form an array of telescopes in various geometric configurations.

Thanks to the very small amplitude (2 mm) of the strips of the DSSSD (Double Sided Silicon Strip Detector), that compose the first two stages of the correlator, respectively 300 μm and 1500 μm of thickness followed by a CsI(Tl) scintillator, FARCOS apparatus provides very high energy resolutions, fundamental for the reconstruction of the states under study.

Because the reactions are realized in the intermediate energy domain, the reaction products have sufficient energy to punch through the first stage and thus they will be identified by ΔE-E technique, where the ΔE is the energy loss in the 1,500 μm thick silicon detector, and the E is the signal of the residual energy released in the scintillator.

An example of the good performance in the discrimination of the different clusters components of the level ^{10}Be → ^{6}He+α, is shown in Figure 2. After the selection of the isotope of interest (^{10}Be) in the cocktail beam one can observe the lines corresponding to the products emitted in decays into ^{6}He and α [40].

By coupling the CHIMERA detector with the FARCOS array at forward angles, we can extract the J^{π} of discrete levels with a nice statistic, by using the technique of the angular correlation [41–43].

The correlations between the angle θ (the recoil angle of the excited projectile with respect to the direction of the beam) and the angle ψ (angle of the vector velocity with respect to the beam axis), will show a periodic structure that can be interpreted, using the Legendre polynomials. The degree of the polynomials will give the angular momentum of the level.

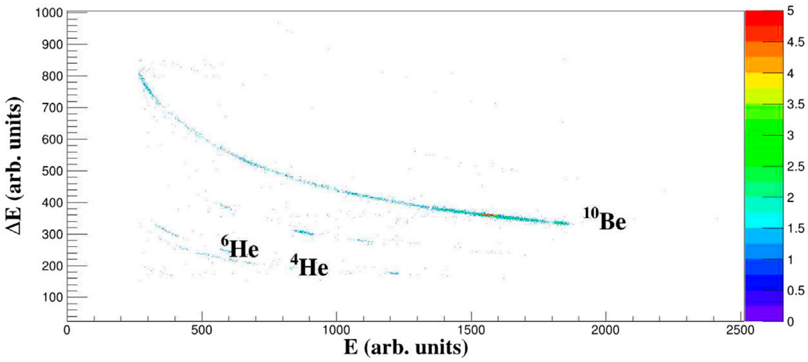

FIGURE 2
ΔE-E matrix relative to the signals released in the detectors of FARCOS, after the selection of the isotope of ^{10}Be in the cocktail beam [40].

Moreover, the use of CHIMERA allows a refinement of the data, not achievable with the use of only FARCOS. In fact, the coincidences among all the break up fragments, detected with 20 FARCOS telescopes placed around zero degree and the recoil proton detected with CHIMERA, allow to eliminate any background can be produced by the Carbon present in the target and the one constituted by other reaction mechanisms. Thus, the detection efficiency of the reaction products will be maximized and it will be very near to 100%.

In the context of the UNSTABLE experiment, as described in the previous section, it was possible to study some of the ^{16}C and ^{10}Be cluster states with proton and deuteron targets, with really high efficiency, thanks to the first CHIMERA rings, placed at small angles. In the experimental campaign proposed in this paper, thanks to the availability of higher beam intensities and the most performing apparatus, the efficiency is even higher for break-up events than the one obtained in UNSTABLE experiment [8].

With the aim of studying the molecular states with low neutron multiplicity, that is with the emission at most of 2 neutrons, in order to be sure to have the reconstruction of complete events, the experimental apparatus has to be completed with neutron detectors, which can be placed behind FARCOS, at the forward angles. For this purpose, the NARCOS device [4–46], at the moment in realization at LNS, will be used. The project provides the construction of a compact and segmented apparatus, consisting of plastic scintillators, with excellent neutron detection capabilities and that combine a great neutron efficiency (up to 30%) with high angular and energy resolution. The material of the detectors belongs to the EJ276 family.

Obviously, in order to recognize the different nuclei of the cocktail beam, it is necessary to use the so called "tagging detector". This device must have very specific characteristics: as for example to be resistant to high intensities, and allowing the identification of the different ions that compose the cocktail beam.

An implementation of the tagging system currently present on the CHIMERA beam line is at the moment in realization to satisfy the needs previously described.

Finally, to reconstruct the angular distribution of the events, it is necessary to know the angle of incidence of the beam on the target for this purpose a position-sensitive detector, a PPAC (Parallel Plate Avalanche Counter) can be used to complete the tracking measurements.

We can start the campaign with the CluB (Clustering in Boron isotopes) experiment, already approved by the PAC of LNS and postponed because of the pandemic emergency.

This experiment will be realized with the aim of the investigation of exotic clustering configuration and the calculation of the relative branching ratio in the isotopes of Boron.

Conclusion

A possible experimental campaign for the investigation of clustering and molecular states in nuclei belonging to the isotopic chains of Li, Be, C and B, has been presented.

The experiments have the aim of improving the information of known cluster states and to investigate the new states of the isotopes of interest.

The experiments will be performed at Laboratori Nazionali del Sud in Catania, by using the exotic beams delivered by the facility FRAISE.

The isotopes of interest compose a cocktail beam; thus different cases can be studied with the use of one primary beam. In order to obtain cocktail beams with a good intensity of the isotopes of ^{16,17}C, ^{13,14}B, ^{10,11,12}Be, ^{6}He and ^{9}Li, a primary beam of ^{18}O at 55 MeV/nucleon will be used and the transport should be optimized for the transport of ^{16}C and of ^{11}Be.

For the detection of the reaction products the FARCOS device coupled to the 4π CHIMERA multidetector will be used. In fact, thanks to the high angular and energy resolution, a good reconstruction of the states under study will be obtained.

Moreover, at forward angles, close to the beam direction the NArCOS detector will be placed.

Thanks to its very high neutron detection capabilities, it will be possible to investigate the molecular like structures with a low neutron multiplicity.

Author contributions

BG, SP, and GP have contributed to the conception and the design of the study. BG wrote the first draft of the manuscript. All the authors contributed to manuscript revision, read, and approved the submitted version.

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