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Study of ^{10}Be and ^{16}C cluster structure by means of breakup reactions

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Summary. — The study of cluster structures in nuclei far from stability represents a valid tool to explore the nuclear force in few-body systems. In this paper we discuss a new experimental investigation of the structure of ^{10}Be and ^{16}C nuclei by means of projectile sequential break-up reactions induced on CH_2 target at intermediate-energies. Their spectroscopy is obtained via a relative energy analysis of break-up fragments with the CHIMERA multi-detector. From ^{4}He+^{6}He correlations we suggest the presence of a new state at about 13.5 MeV in ^{10}Be. The inspection of ^{6}He+^{10}Be break-up channel reveals the existence of a possible high-lying excited state at 20.6 MeV in ^{16}C. Finally, new perspectives concerning the improvement of the present results are discussed.

1. – Introduction

It is known that the residual interaction between nucleons can lead to the formation of α-like structures in nuclei. These interesting configurations usually appear in light self-conjugated nuclei like ^{8}Be, ^{12}C, ^{16}O and ^{20}Ne [1]. The investigation of this type of phenomenon is important in fundamental Nuclear Physics. In fact it represents a powerful tool to understand the properties of nuclear forces in few-body systems [2]. Clustering phenomena play also an important role to understand the element abundances in the Universe; for example, the Hoyle state in ^{12}C (0^+, 7.654 MeV), which presents a well developed α-cluster structure [3], leads to the formation of ^{12}C by means of the 3α process in stars.

Cluster effects play an important role also in non self-conjugated nuclei [4]. This is the case of neutron-rich isotopes, in which possible α-cluster structures bound by

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extra-neutrons can be formed. In these particular molecular-like configurations, the extra-neutrons act as sort of covalent particles between clusters, and for this reasons they are often addressed as "valence neutrons", playing a glue-like effect and increasing the stability of the whole structure [2,5]. An interesting example is represented by beryllium isotopes, being the self-conjugated ^{8}Be unbound while the neutron-rich ^{9}Be and ^{10}Be are bound. In particular, the ^{9}Be has a largely deformed ground state, as pointed out in electron scattering experiments [6], and the presence of bands characteristic of rotating objects with large moment of inertia has also been observed. The case of ^{10}Be represents another example of rotational excitation of highly deformed structures, indicating the possible existence of molecular configurations. Unfortunately, for this nucleus many contradictory results on its spectroscopy have been published in the literature, and therefore the situation is still not fully understood. The 0^+ ground state of ^{10}Be is characterized by a largely deformed structure [7]. Theoretical studies predict a molecular configuration of the ground state with two valence neutrons extending perpendicular to the axis of the two α cores [8]. A rotational band is build on this state, with a 2^+ member at 3.37 MeV. For the 4^+ member, predicted at about 11 MeV and firstly indicated at 11.76 MeV in [9], no evidence has been recently reported in [10]. The existence of a 4^+ state at 10.2 MeV is reported [9, 11] and it is considered as the 4^+ member of the 0_2^+ molecular band, built on the second 0^+ excited state of ^{10}Be (6.179 MeV) and having the 7.54 MeV state as 2^+ member. Recently, a resonant elastic scattering experiment [12] has suggested the presence of a 6^+ state at about 13.5 MeV excitation energy, compatible with the linear extrapolation of the 0_2^+ band and, therefore, possibly representing the continuation of this band.

The case of carbon neutron-rich and neutron-poor [13, 14] isotopes is also very interesting. ^{13}C and ^{14}C have been recently investigated via resonant elastic scattering experiments in direct and inverse kinematics [15-18]. Moreover, theoretical calculation for the ^{16}C isotope [19], based on Antisymmetrized Molecular Dynamics (AMD) model, have been recently published, showing possible linear chains or triangular configurations with 4 valence neutrons correlated into $2n$ couples by pairing effects. These molecular states can give rise to rotational bands. Unfortunately, for the ^{16}C structure, very few experimental data are reported in literature above the helium disintegration threshold [20, 21], and therefore the experimental evidence of such configurations cannot be confirmed yet.

In this work we report a new experimental investigation of ^{10}Be and ^{16}C structures above the cluster disintegration thresholds. The spectroscopy of ^{10}Be is investigated via the projectile breakup in ^{4}He+^{6}He fragments, while the structure of the ^{16}C projectiles is studied selecting the ^{6}He+^{10}Be correlations. The CHIMERA 4π multi-detector is used to identify and track each fragments. We performed a relative energy analysis of these fragments. In particular, for the ^{10}Be we found the evidence of a new state corresponding to an excitation energy of about 13.5 MeV, in agreement with the preliminary findings of [12]. Finally, for the ^{16}C we suggest a possible indication of a new state at about 20.6 MeV, but, because of the very limited statistics, in this case no firm conclusions can be established.

2. – Experimental details

The experiment was carried out at the FRIBs facility of the INFN-Laboratori Nazionali del Sud (Catania, Italy). To induce projectile break-up reactions of radioactive nuclei we used a cocktail beam (mainly consisting of ^{16}C at 49 MeV/u, ^{10}Be at

56 MeV/u and ^{13}B) impinging on a $(CH_2)_n$ target. The radioactive ion beams are produced via the in-flight fragmentation of a primary beam (^{18}O at 56 MeV/u accelerated by the LNS-K800 superconductive cyclotron) on a production target (^{9}Be, 1500 mm thick). The fragmentation products are then selected in magnetic rigidity ($B\rho \approx 2.8$ T m) thanks to the LNS-Fragment Separator, having a momentum acceptance of about $\frac{\Delta p}{p} \approx 0.01$. In this way we produced and delivered to the experimental hall a cocktail of various radioactive isotopes. Each isotope present in the cocktail can be identified by a tagging system [22], installed along the beam line before the experimental hall, and consisting of a large area Micro Channel Plate (MCP) and a Double-Sided Silicon Strip Detector (DSSSD). The identification is obtained by means of the ΔE-ToF technique using the information on the energy loss in the DSSSD (ΔE) and the time of flight (ToF) of the beam particles from the MCP to the DSSSD ($\approx 13m$).

The reaction products, induced by the radioactive beams on the polyethylene $(CH_2)_n$ target, were identified and tracked by using the CHIMERA 4π multi-detector [23-29]. This device is constituted by 1192 ΔE-E (Si-CsI(Tl)) telescopes with an angular coverage of about the 94% of the whole solid angle. They are organized into 9 forward rings ($1^\circ \leq \theta \leq 30^\circ$) and 17 rings ($30^\circ \leq \theta \leq 179^\circ$) arranged to form a sphere around the target position. The first detection stage of each Si-CsI(Tl) telescope is a $\approx$300 μm silicon detector while the second one is a CsI(Tl) scintillator crystal, with thickness from 6 to 12 cm. Further details on the identification capabilities of the CHIMERA device can be found in [24].

The forward peaked cross section of breakup reactions, especially in inverse kinematics at intermediate energies (see [30] for further details), allowed us to reconstruct a large amount of breakup fragments from the p,^{12}C(^{10}Be,^{6}He+^{4}He) and p,^{12}C(^{16}C,^{10}Be+^{6}He) reactions by means of the 3 first forward rings of the CHIMERA array. Charges and masses of the detected fragments have been obtained by means of the ΔE-E identification technique.

Si and CsI calibration has been obtained by using elastic scattering peaks of various light ions impinging on polyethylene and gold targets. In particular, for the CsI crystal, the dependence of light response on the mass of the incident particle has been taken into account as discussed in [31].

3. – Data analysis and results

The possible presence of resonant states in the projectile nuclei can be inspected by analyzing the relative energy spectra of the corresponding sequential decay products. In particular, to study the spectroscopy of ^{10}Be and ^{16}C prior to decay, we investigated kinematical correlations of couples of breakup fragments from the above mentioned reactions. Thanks to the information on momentum and mass of the detected particles we reconstructed the kinetic energy of each couple of fragments in their center of mass frame ($E_{\rm rel}$). If each particle of the couple is emitted by the same source, the excitation energy of the emitting nucleus before decaying can be obtained with the relation

$$E_x = E_{\rm rel} + E_{\rm thr}, \tag{1}$$

where $E_{\rm thr}$ is the rest mass of the exit breakup channel respect to the ground state of the initial nucleus (*breakup threshold*).

As a starting check of the above described experimental technique we analyzed correlations between α particles, which allow the study of self-conjugated nuclei. The result

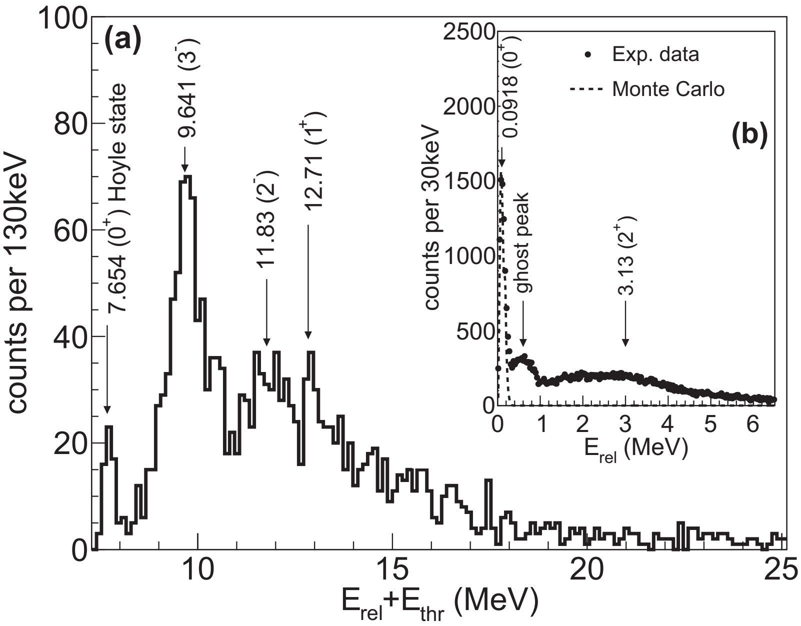

Fig. 1. – (a) ^{12}C excitation energy ($E_{\mathrm{rel}} + E_{\mathrm{thr}}$) spectrum obtained via the 3α breakup channel. Arrows and labels indicate the position of known states. (b) 2α relative energy spectrum (filled circles). The dashed line is the result of a Monte Carlo calculation considering the decays from the ^{8}Be ground state. The identified peaks are indicated with labels.

of our analysis is reported in fig. 1 respectively for the cases of 2α (b) and 3α (a) correlations. In the first case we have obtained the relative energy spectrum shown with filled circles in the top right pad (b). As indicated by arrows and labels we are able to identify a prominent peak centered at about 0.0918 MeV. This bump is compatible with the decays of couple of α particles from the ground state of ^{8}Be, and this finding is confirmed by the result of a Monte Carlo simulation of our device (dashed line in figure), whose details are explained in the following section for the ^{10}Be case. Other bumps, respectively at ≈ 0.6 MeV and ≈ 2.5 MeV, are also visible. The first is related to the so called *ghost peak* due to the decays from the ^{9}Be 2.43 MeV $5/2^{-}$ state into the low-energy tail of the ^{8}Be 3.13 MeV 2^{+} state, as seen for example in [32]. The second could be compatible with the excitation of the first excited state in ^{8}Be. The slight shift at lower energy seen in the spectrum reflects the geometrical efficiency of the detector and the presence of a non-vanishing background.

The fig. 1(a) shows the ^{12}C excitation energy spectrum obtained from the 3α decay channel. In this case we clearly identify the Hoyle state (narrow peak at lower energies) and other states of ^{12}C indicated by arrows in the figure. The Hoyle state is nicely separated from the 9.641 MeV state, confirming the good performances of our device in the relative energy determination.

3·1. ^{4}He + ^{6}He *correlations: the* ^{10}Be *structure*. – The spectroscopy of ^{10}Be can be investigated from the analysis of the ^{4}He+^{6}He correlations. In this case we identify, as is visible in fig. 2 even with low statistics, some peaks. They reasonably correspond to the excitation of states previously known in the literature and indicated by vertical arrows

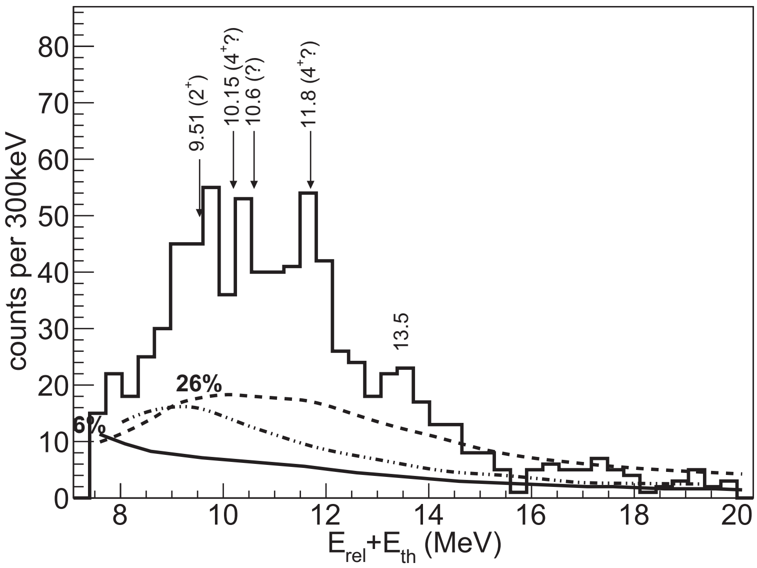

Fig. 2. – ^{10}Be excitation energy spectrum from ^{4}He+^{6}He correlations. Arrows indicate the position of known states in literature. The solid and dashed curves show respectively the detection efficiency for the cases of reactions on carbon or hydrogen target. The dash-dotted line represents the behaviour of the background estimated with an event mixing analysis.

in figure. Interestingly, we observe also the presence of a further peak centered at about 13.5 MeV which could be the evidence of a new state in ^{10}Be. To understand if this peak can be really attributed to the excitation of a state in ^{10}Be we evaluated both the detection efficiency of our device and the expected background due to possible spurious correlations.

The latter can be estimated via an event-mixing procedure. As a first approximation, a reasonable event mixing analysis could be done by coupling different particles taken from different collision events. In this case we ensure that the particles are really uncorrelated and we can extract the corresponding relative energy. The obtained spectrum is shown in fig. 2 with the dash-dotted line. This is obtained by considering collision events induced by the whole cocktail beam.

The geometrical efficiency of CHIMERA forward rings, used for the present analysis, was estimated by a Monte Carlo simulation of the experiment. To produce the physical data, we considered anelastic scatterings of ^{10}Be on the possible carbon or hydrogen targets of the CH_2. Following the suggestions of [30, 33], we considered a forward peaked distribution for the breakup products, in the center-of-mass frame, of the type $d\sigma/d\Omega(\theta_{cm}) \propto e^{-\theta_{cm}/\alpha}$, where θ_{cm} is the anelastic scattering angle in the center-of-mass frame and α is the fall-off factor, of the order of 12–16 degrees [30]. Because of the different kinematics, we decided to show the contributions from excitations on the two possible targets with two different curves in fig. 2. The solid line, peaking at 6%, is the detection efficiency simulated considering a carbon target, while the dashed line, peaking at 26%, is the hydrogen contribution. The two curves present different shapes reflecting the geometrical coverage of the detection device and the reaction kinematics.

Both the detection efficiency and the estimated background are very smooth, indicating that the peak at 13.5 MeV excitation energy could be ascribed to the presence of

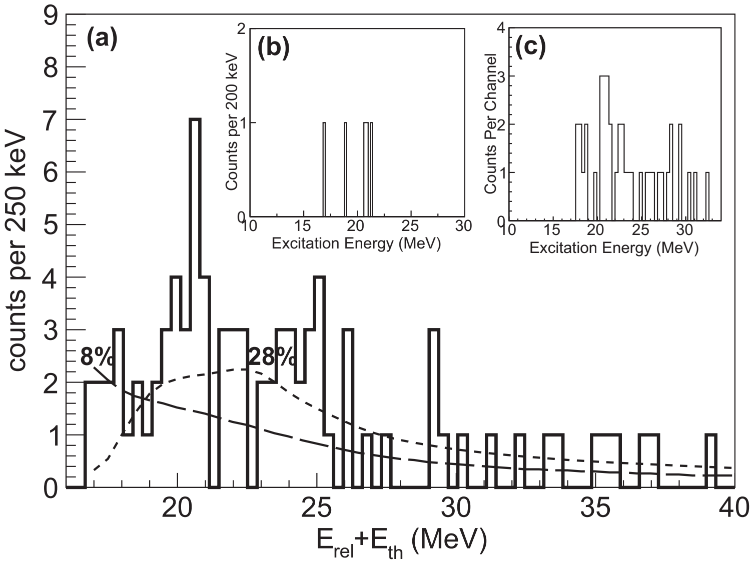

Fig. 3. – (a) ^{16}C excitation energy spectrum from ^{6}He+^{10}Be correlations. The dashed lines, peaking at 8% and 28%, represent respectively, the detection efficiency for anelastic scattering on carbon or hydrogen target, calculated via a Monte Carlo. In the insert panels are shown, for comparison, the ^{16}C excitation energy spectra from the ^{6}He+^{10}Be breakup channel previously reported in the literature by (b) Ashwood *et al.* [21] and (c) Leask *et al.* [20].

a new state of ^{10}Be. Recently, a resonant elastic scattering experiment [12] has tentatively pointed out the presence of a new state in ^{10}Be at 13.5 MeV, in agreement with the present findings, while no clear evidence of such state is reported in [34], where the ^{10}Be spectroscopy is studied by means of neutron transfer reactions. This could represent a confirmation of the cluster nature of this state, indicating a possible α+^{6}He configuration, with a much weaker component of single-particle structure.

3$\cdot$2. ^{6}He + ^{10}Be *correlations: the* ^{16}C *structure.* – By analogy with the ^{10}Be case, we explored the structure of ^{16}C analyzing its binary de-excitations in ^{6}He+^{10}Be fragments. In this case we are able to reconstruct the excitation energy spectrum reported in fig. 3(a). As is clearly visible from the figure, the accumulated statistics is very low. In spite of that, a non-vanishing yield can be identified at an excitation energy of approximately 21 MeV. This yield enhancement could not be attributed to efficiency effects, since the corresponding calculated curves are smooth in the whole energy domain (dashed lines in fig. 3(a)), and therefore, we could suggest to attribute this peak to the possible evidence of a new state in ^{16}C in the particle unbound region. Very interestingly, the same yield enhancement seems to be present also in the previously reported results [21] (fig. 3(b)) and [20] (fig. 3(c)), but with statistics lower than the present data. Moreover, the discussed energy region has also been the subject of theoretical predictions [19] about the possible formation of molecular states in ^{16}C. In particular, 6^+ states, belonging to linear chain or triangular bands, are predicted at about 20 MeV excitation energy. Unfortunately, because of the very low statistics, in this case we are not able to firmly suggest the presence of new states in ^{16}C, and our findings, together with the results reported in the literature, do not exclude a possible phase-space decay of ^{16}C in the

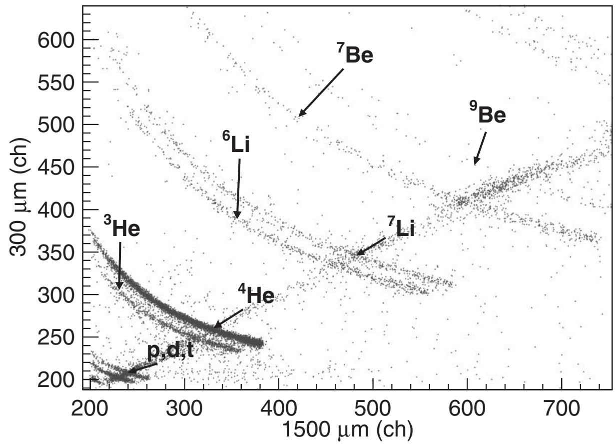

Fig. 4. – ΔE-E identification matrix obtained by using the first (DSSSD 300 μm) and the second (DSSSD 1500 μm) detection stages. The identified isotopes are indicated by labels.

continuum without assumption of any resonances in this nucleus. For these reasons, in order to test the theoretical predictions, further experimental investigations of the ^{16}C nucleus are clearly needed.

4. – Future perspectives: the CLIR experiment

To improve the present results we recently performed a new experiment at the FRIBs facility, CLIR (Clustering in Light Ion Reactions). In this experiment we coupled CHIMERA with a new generation hodoscope for spectroscopy, FARCOS [35]. FARCOS is an array of telescopes with three detection stages, each one constituted by a Double Sided Silicon Strip Detector (DSSSD) 300 μm thick as first stage, a 1500 μm DSSSD as

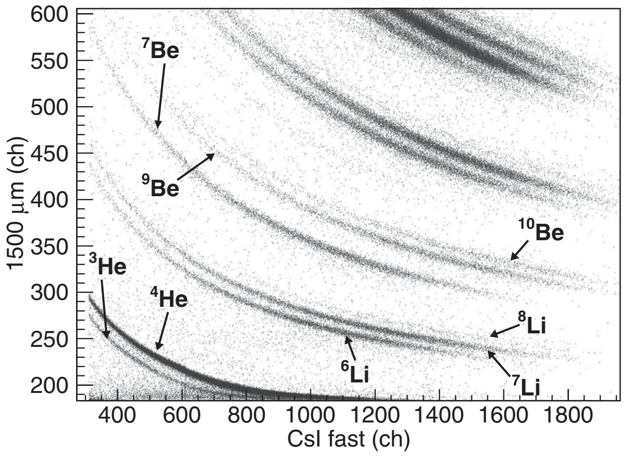

Fig. 5. – ΔE-E identification matrix obtained by using the second (DSSSD 1500 μm) and the third (CsI(Tl)) detection stages. The identified isotopes are indicated by labels.

second stage and 4 CsI(Tl) crystals as stopping detectors. For the CLIR experiment we used a cluster of 4 FARCOS telescopes covering a very forward part of the solid angle ($1^\circ \lesssim \theta_{lab} \lesssim 7^\circ$). In this angular region we expect the largest amount of breakup fragments, as above discussed. This configuration allows to identify particles in a wide energy range with very high granularity. For example, the low-energy particles that stop inside the second stage can be detected and unambiguously identified via the ΔE-E technique with the first two stages, as shown as an example in fig. 4. By increasing the energy, particles that punch through the $1500\,\mu$m DSSSD detector induce a signal within one of the CsI crystals. In this case we can obtain an excellent charge and mass identification by analysing the $\Delta E(1500\,\mu\mathrm{m})$-$E(\mathrm{CsI})$ correlations, as shown in fig. 5. The excellent identification capabilities of the FARCOS device, together with the high granularity, will allow to improve the resolution in the invariant mass analysis, leading to a more precise identification of the decaying nuclear levels and of their J^π. Furthermore, as a future perspective, we will also take advantage of an upgrade of the primary beam intensity of the FRIBs facility, giving us the possibility to obtain larger statistics and to give firmer conclusions on the structures of ^{10}Be and ^{16}C.

5. – Conclusions

In conclusion, we explored the spectroscopy of ^{10}Be and ^{16}C by means of intermediate energy breakup reactions at the FRIBs facility (LNS-Catania, Italy). The CHIMERA 4π multi-detector was used to identify and track the breakup fragments.

From the ^{4}He+^{6}He correlations we explored ^{10}Be spectroscopy. In the corresponding relative energy spectrum we are able to identify previously reported states in the literature and to point out the presence of a new possible state at about 13.5 MeV. This state could be compatible with the findings of [12], and, since there is not a marked evidence of such state in single-particle excitation experiments [34], we suggest a possible dominant contribution of a ^{4}He+^{6}He cluster configuration.

The spectroscopy of ^{16}C was studied via the ^{6}He+^{10}Be breakup channel. In this case a non-vanishing yield is found in correspondence of $\approx$21 MeV excitation energy. This peak is also visible, even with poor statistics, in the literature results [20, 21], but, because of the extremely low statistics, we are not able to firmly suggest the presence of a new state in ^{16}C.

We will improve the results of the present experiment with new investigations, taking advantage of the future upgrade of the FRIBs facility and using a new generation array for correlation and spectroscopy, FARCOS [35], coupled to CHIMERA. This configuration will improve both the statistics and the relative energy resolution, allowing a firmer discussion on the spectroscopy of light unstable nuclei.

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