EXPERIMENTAL STUDIES OF THE STRUCTURE OF ^{16}C WITH REACTIONS AT INTERMEDIATE ENERGY*

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The possible existence of cluster structures in ^{16}C has been investigated by inspecting their breakup (induced on CH_2 targets) in ^{10}Be+^{6}He events. The excitation energy of the projectile nucleus prior to decay is obtained via an invariant mass analysis of identified fragments. The experiment has been carried out at the FRIBs facility of INFN-LNS, by using a fragmentation cocktail beam at intermediate energies ($\approx$ 55 MeV/nucleon) and the CHIMERA 4π multi-detector. A non-vanishing yield in the ^{10}Be+^{6}He correlations is reported at an excitation energy of about 20.5 MeV in ^{16}C, in analogy with previous works. To improve these results, we recently performed a new experiment by coupling CHIMERA and FARCOS at forward angles. Preliminary details of the new experiment are reported in the text.

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1. Introduction

Clustering in light nuclei is a topic of fundamental importance in modern Nuclear Physics [1]. It consists in the spatial re-organization of nucleons into bounded sub-units, called clusters. The study of these phenomena is important in understanding the properties of nuclear forces in few-body systems [2]. Thanks to the great stability of α particles, self-conjugated nuclei are the principal candidates to clusterize. Typical examples are ^{8}Be and ^{12}C, which are involved in the 3α process in stars. The nucleus of ^{12}C is, in particular, a crucial example of clustering; indeed, the presence of a state close to the 3α threshold and strongly characterized by a cluster structure, called *Hoyle state*, has for long time attracted the interest of nuclear physicists for its consequences in Astrophysics [3–5]. Another important example is represented by the nucleus of ^{20}Ne, for which possible cluster states could have influence in the nucleo-synthesis of fluorine in stars [6–8].

Recently, the evidence that clustering phenomena could occur also in non-self-conjugated nuclei has attracted a renewed interest in the nuclear physics community [9]. As an example, in the presence of extra-neutrons, clustering can manifest features different than in the self-conjugated nuclei. A high deformation and peculiar nuclear structures can appear. These interesting structures are usually characterized by α-cluster centres bounded by neutrons, that, for these reasons, are called *valence neutrons* [9]. In this way, the stability of the structure is increased. Beryllium isotopes are a typical example, being the ^{8}Be unbound, while ^{9}Be is bound. Molecular-like structures have been observed in ^{10}Be [10–12]; these states have been described in therms of α:$2n$:α structures by microscopic calculations [13], while, on the experimental point of view, many ambiguities are still persisting in the determination of the possible rotating states of these dimeric structures [11].

Carbon isotopes represent an interesting case. Recent studies have been carried out for the proton-rich ^{11}C [14, 15] isotope via low-energy nuclear reactions, for the neutron-rich ^{13}C [16–18] via resonant elastic scattering experiments, and for ^{14}C [19] and ^{15}C [20, 21]. In this scenario, the isotope of ^{16}C is an interesting case. For this nucleus, a recent theoretical calculation via Antisymmetrized Molecular Dynamics model has predicted the existence of molecular states having linear chains and triangular shapes [22]. Unfortunately, the experimental knowledge of ^{16}C is extremely poor. Very few experiments have been done [23, 24] at excitation energies above the helium disintegration threshold, where different molecular states are predicted, reporting only very low statistics data. For this reason, we have performed a new investigation of the structure of ^{16}C at the FRIBs facility of INFN-LNS aimed, in particular to identify cluster states of this nucleus via the study of fragments emitted in breakup reactions. In this proceeding, we report results on the ^{10}Be+^{6}He breakup channel. The corresponding invariant mass spectrum, obtained with the 4π CHIMERA multi-detector, shows a non-vanishing yield corresponding to an excitation energy of 20.5 MeV, as observed in the previously published papers but with a larger statistics. Finally, more recently, starting from the results obtained with CHIMERA, we performed another experiment at the FRIBs facility by using the FARCOS array covering the most forward polar angles of CHIMERA. In the proceeding, we give preliminary details on this experiment.

2. ^{10}Be+^{6}He correlations

The experiment has been performed at the FRIBs facility of the INFN-Laboratori Nazionali del Sud (LNS) in Catania. A fragmentation cocktail beam was used in order to induce nuclear reactions with radioactive nuclei. To produce the beam, we used the in-flight fragmentation of $^{18}O^{7+}$ primary projectiles, accelerated by a superconductive cyclotron at 56 MeV$/u$, on a ^{9}Be 1500 μm production target. The fragmentation products, before to be delivered to the experimental hall, are selected in magnetic rigidity via a Fragment-Recoil Separator (LNS-FRS) with a magnetic rigidity of $B\rho \approx 2.9$ Tm. A tagging system [25] was then used to identify particle-by-particle the content of the cocktail beam. A very good identification, as seen in [26], is obtained by combining the time of flight of the particles measured between a large area MCP and a DSSSD (≈ 13 m) and the energy loss inside the DSSSD. The beam was constituted by a dominant contribution of ^{16}C ($\approx 10^5$ pps) at ≈ 49 MeV$/u$.

To study the structure of the ^{16}C nucleus, we used projectile breakup reactions induced by a CH_2 target. The excitation energy of the projectile nucleus prior to decay can be obtained by the invariant mass of the emitted fragments, as seen in [27–29]. This technique is well-suited for identifying states characterized by clustering phenomena, since these states usually present strong partial widths of disintegration in their constituent clusters. Fragments are detected and tracked by means of the CHIMERA 4π array [30–34]. The experimental technique used for identifying particles and fragments is the ΔE–E technique, by correlating signals of the first (Si, 300 μm) and second CsI(Tl) detection stages of CHIMERA; further details about the apparatus can be found in Refs. [35, 36].

A starting check of the experimental method has been done by selecting correlations between α particles. In particular, in Fig. 1, we report the ^{12}C excitation energy spectrum seen in the 3α coincidences with the described invariant mass method. As visible, a reasonable resolution is obtained and peaks, corresponding to known states of ^{12}C, are reasonably resolved. We used arrows and labels to indicate them. Interestingly, the Hoyle state appears, in the lower part of the spectrum, well-centered at 7.65 MeV. This preliminary check indicates that the CHIMERA device is well-suited for performing invariant mass studies of this type.

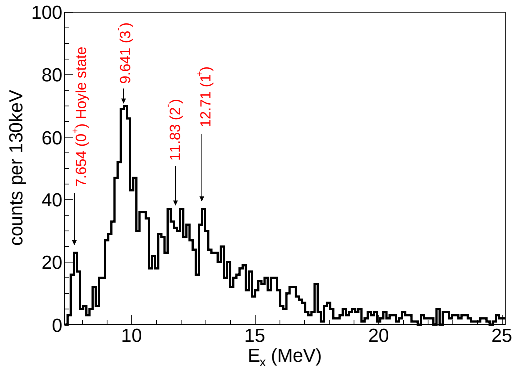

Fig. 1. ^{12}C excitation energy spectrum obtained from the 3α correlations. Arrows indicate the position of known states, while labels show their spectroscopic information. The low-energy peak corresponds to the Hoyle state.

The ^{16}C structure has been studied via the ^{6}He+^{10}Be correlations, Fig. 2. A selection of the reaction products induced by the ^{16}C in the fragmentation beams has been provided by imposing graphical cuts in the ΔE–ToF tagging matrix, as described in [26]. In this case, the reported statistics is extremely limited. A non-vanishing yield is observed at about 20.5 MeV excitation energy. Even with poor statistics, this enhancement is compatible with previously published data [23, 24] and, furthermore, a detection efficiency study, for both the two components of the target, indicates that it should not

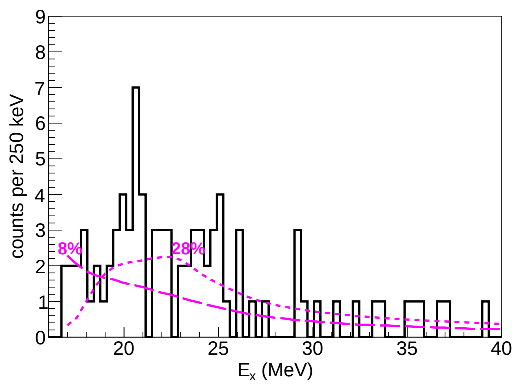

Fig. 2. (Color online) ^{16}C invariant mass spectrum of correlated ^{10}Be+^{6}He break-up fragments. The dashed/purple lines represent the simulated detection efficiency for inelastic scattering on proton, peaking at 28%, or carbon, peaking at 8%.

be attributed to efficiency effects (dashed lines in the figure, see [37] for more details). Anyway, due to the low statistics, we cannot firmly attribute this enhancement to a resonant phenomena in ^{16}C, and further experiments are clearly needed to confirm the possible existence of a state at these energies.

3. The CLIR experiment at INFN-LNS: future perspectives

Recently, starting from the previously discussed data, we performed another experiment at the FRIBs facility with a new generation device, FARCOS [38, 39]. This experiment, called CLIR (Clustering in Light Ions Reactions) has been devoted to the investigation of the structure of different unstable nuclei produced at LNS. The experimental apparatus was constituted by coupling the CHIMERA and FARCOS arrays [40], by using FARCOS for covering the most forward polar angles, where a large number of the projectile breakup fragments is expected [26]. FARCOS is a new generation array for correlations and spectroscopy developed by the CHIMERA Collaboration at LNS. It is constituted by three detection stages: two DSSSD highly segmentated detectors and 4 CsI(Tl) scintillators for each telescope. A configuration of four telescopes has been used for the CLIR experiment. The data analysis of the CLIR experiment is still in progress. We report here, in Fig. 3, a typical ΔE–E matrix constructed by correlating signals from the second (DSSSD) and third (CsI) detection stage of FARCOS. It clearly shows the good capabilities, in terms of particle identification, obtained with this device. The unambiguous isotopic identification provided by FARCOS would allow to reduce the possible background due to misidentified particles and the very high granularity will give a better invariant mass resolution, improving the signal/background ratio.

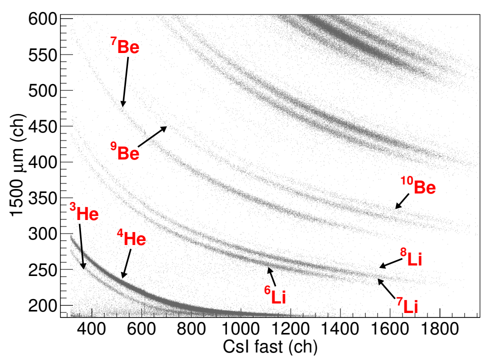

Fig. 3. A ΔE–E (DSSSD, 1500 μm-CsI) identification matrix obtained with FARCOS. Arrows and labels indicate lines corresponding to the firsts lightest isotopes identified.

In the Fig. 4, we show an invariant mass spectrum obtained with FARCOS from calibration runs with nuclear reactions where ^{16}O ions (at 55 MeV/u) impinged on ^{12}C and ^{11}B targets. Contributions coming from the two data sets are shown in different colors, and the spectra, given in terms of correlation functions, have been normalized for comparison. What we observe is a nice reproduction of the ^{8}Be ground state (the prominent peak centered at about 100 keV), while the first 2^+ state of ^{8}Be is visible around 3 MeV relative energy. A small peak in proximity of 600 keV can be the evidence of the so-called *ghost peak* [26, 41], confirming the good quality of our data.

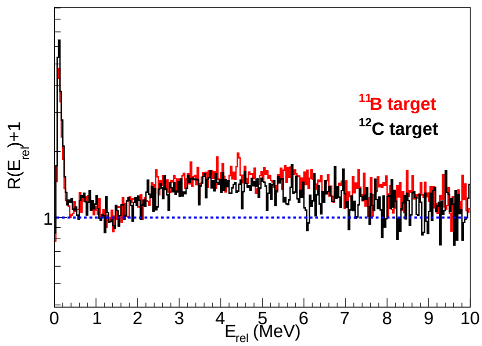

Fig. 4. α–α correlation function obtained with the FARCOS device from ^{16}O (55 MeV/u) on ^{12}C and ^{11}B targets data.

In the near future, we will extend our analysis to the data taken also with CHIMERA, obtaining a better detection efficiency; with such procedure, we will optimize statistics. Furthermore, by making precise constraints on the topology of the events, we can highly reduce the contribution of uncorrelated events. This will allow to improve our knowledge on the structure of ^{16}C.

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