Investigation of ^{10}Be and ^{16}C structure with break-up reactions at intermediate energies

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Abstract

The spectroscopy of ^{10}Be and ^{16}C isotopes is studied via projectile break-up reactions induced on polyethylene (CH_2) target, by using a 55 MeV/u ^{10}Be and a 49 MeV/u ^{16}C beams provided by the FRIBs facility at INFN-LNS. We reconstruct the ^{10}Be and ^{16}C relative energy spectra to evince the presence of excited states characterized by cluster structure. By inspecting the ^{4}He+^{6}He relative energy spectrum we find evidence of a new possible state of ^{10}Be at 13.5 MeV for which the corresponding angular correlation indicates a hypothetical 6^+ assignment. Finally, from binary (^{6}He+^{10}Be) cluster decomposition of ^{16}C we show the indication of a possible new state at about 20.6 MeV.

1. Introduction

The study of cluster structures in light nuclei is considered an important tool to understand the properties of nuclear forces in few body systems [1]. In fact, *clustering* in nuclei reflects the correlations between nucleons inside the nuclear volume, due to the quantum nature of nuclear systems. The simplest example is offered by the case of *self-conjugated* nuclei (such as ^{8}Be, ^{12}C, ^{16}O, ^{20}Ne), in which the nucleon-nucleon correlations, given the great stability of the α particle, could determine a spatial reorganization of nucleons into α-cluster structures [2]. These cluster structures could be characterized by very large deformations and peculiar shapes [3]. An important example is the Hoyle state in ^{12}C (0^+, 7.654 MeV), whose cluster structure is of fundamental importance also in Nuclear Astrophysics [4, 5, 6, 7].

An increasing interest on the study of clusters in nuclei has been triggered by the evidence (in the last decades) that clustering effects could also be observed in non-self conjugated nuclei. In this case clustering phenomena could show very different features. Important examples are the *neutron-rich* nuclei, where the extra-neutrons can provide sort of covalent bonds between α-like centers with the subsequent increasing of the nuclear stability (look for example at the ^{9}Be and ^{10}Be isotopes that are weakly bound while the ^{8}Be is unbound) eventually leading to the possible formation of the so called nuclear molecules [1, 8]. The neutron-rich beryllium isotopes, together with the carbon ones, represent a very important case also because of their possible, respectively, dymeric and linear chain configurations, discussed in several recent papers [3, 8].

In the study of the beryllium isotopic chain a special attention must be paid to the ^{10}Be isotope. This nucleus is characterized by a highly-deformed ground state [9] on which a positive parity rotational excitation is built. For this rotational band, the 2^{+} member is well known (3.37 MeV excitation energy), while its continuation has been object of recent publications because of the uncertainties of the 4^{+} member assignment [11, 10, 12, 13], predicted at about 11–12 MeV. A negative parity rotational band with a 1^{-} state at 5.96 MeV as band-head is also reported in [1]. The presence, close to the ^{4}He+^{6}He emission threshold, of a molecular 0^{+} state (≈ 6.18 MeV), predicted in the AMD calculation [9], has been experimentally confirmed. This state can be well described in terms of molecular dimeric $\alpha : 2n : \alpha$ structure. The existence of a 2^{+} state at 7.54 MeV, characterized by a strong molecular structure, is the indication of the rotational excitation of the 6.18 MeV state. The subsequent 4^{+} member of this molecular rotational band is predicted to be located at about 10.5 MeV excitation energy. A 10.2 MeV state was found via the ^{7}Li(^{7}Li,^{4}He+^{6}He)^{4}He reaction [14]. Curtis et al assigned J^{π}=3^{-} to this state via angular correlation measurements [15]. This assignment was subsequently contradicted in Ref. [16] and in recent ^{6}He+^{4}He inverse kinematic resonant elastic scattering experiments. This state could therefore be the 4^{+} member of the molecular rotational band. A very recent resonant elastic scattering ^{6}He+^{4}He experiment at the ANASEN facility [17] has also shown, as a preliminary result, the existence of a 6^{+} excited state in ^{10}Be at about 13.6 MeV. This state is compatible, on the energetic point of view, with the 6^{+} member of the cluster state band in ^{10}Be [18], of which could represent the continuation.

Another interesting isotopic chain is the carbon one. In particular, the neutron-rich carbon isotopes represent an important case for the Nuclear Physics of clusters, because of the various theoretical predictions of possible linear chain and triangular configurations of these nuclei. Interesting studies have been done recently on ^{13}C [19, 20, 21] and ^{14}C [22] structure via resonant elastic scattering in direct and inverse kinematics. The ^{16}C, for which the spectroscopy is absolutely not well known, especially above the helium disintegration threshold, has recently attracted a large interest [23, 24]. For this isotope, a recent theoretical calculation [25] indicated the possible existence of various molecular states, constituted by three α centers bounded by two couple of valence neutrons, with triangular and linear shapes. These states could give rise to molecular bands, but unfortunately an experimental confirmation of these predictions is still missing because of the poor statistics of the experiments reported in literature.

In the present paper we report new results on the spectroscopy of ^{10}Be and ^{16}C excited states above the cluster emission thresholds, investigated via sequential projectile break-up reactions. Break-up fragments have been detected by the Chimera array. A relative energy analysis of correlated break-up fragments has allowed us to point out the possible existence of new states of these nuclei. In particular, we found indications of a possible state at about 13.5 MeV in ^{10}Be, as seen from the ^{4}He+^{6}He coincidence data. The corresponding angular correlation analysis shows an high spin value (possibly 6^{+}) for this state, confirming the findings of [17]. For the ^{16}C nucleus, the ^{6}He+^{10}Be correlations suggest the presence of a new state at about 20.6 MeV, in agreement with calculations of [25].

2. Experimental details

Break-up reactions have been induced on a polyethylene CH_2 target. For the present experiment we have selected reaction products from the ^{1}H(^{10}Be,^{4}He^{6}He),^{2}H(^{10}Be,^{4}He^{6}He),^{12}C(^{10}Be,^{4}He^{6}He) and ^{1}H(^{16}C,^{6}He^{10}Be),^{2}H(^{16}C,^{6}He^{10}Be) reactions. To obtain spectroscopic information on ^{10}Be and ^{16}C nuclei we measured masses, energies and flight directions of the corresponding break-up fragments with the CHIMERA 4π multi-detector [27, 28, 29, 30]. It is constituted by 1192 Si-CsI(Tl) telescopes, covering $\simeq 94\%$ of the whole solid angle. The first stage of the telescope is constituted by a 300 μm thick silicon detector and it is followed by a CsI(Tl) crystal, having a thickness of 12 cm and read-out by a photodiode. In the present experiment we used the first three forward rings of the Chimera array, covering the polar angle range $2.2° \leq \theta \leq 6.4°$. Thanks, on one hand, to the forward peaked cross section of inelastic excitation on carbon [31], and, on the other hand, to the small limiting angle of inverse kinematics excitation on hydrogen, we expect to detect a large amount of fragments coming from projectile break-up in this present angular domain.

2.1 The ^{10}Be case

The ^{10}Be spectroscopy has been studied via the ^{4}He+^{6}He correlation with the above described technique. The corresponding relative energy ($E_{rel} + E_{thr}$) spectrum is reported in Fig. 2 with the green line. Despite the low statistics and the limited resolution some peaks are visible. They are in agreement with suggestions given in the literature, as pointed out by the arrows indicating the energy position of known states. It is very interesting to observe that the presence of another bump at $E_x \simeq 13.5$ MeV suggests the possible fingerprint of a new, unreported, state in ^{10}Be. To check if the observed peak can be really ascribed to the existence of an excited state in ^{10}Be we evaluated the detection efficiency. This contribution was calculated via a Monte Carlo simulation with the same prescriptions than for the ^{8}Be case. Because of the different kinematics between inelastic scattering on Hydrogen or Carbon, the two components of the composite target, we performed two different simulation taking into account the different possible target nuclei.

Spin and parity of the suggested 13.5 MeV state can be tentatively estimated via an angular correlation analysis. Fig. 1 shows the $|cos(\Psi')|$ distribution of the events falling into the 13.5 MeV peak, where we have indicated with Ψ' the angle formed by the relative velocity vector of the two fragments with the beam axis (Ψ) taking into account the phase shift term ($\Delta\Psi$), as suggested for example in [35, 36, 37]. This correction is useful to make direct comparisons with the corresponding Legendre polynomial squared, being $|cos(\Psi')| \propto |P_J(cos(\Psi'))|^2$, where P_J is the J-order Legendre polynomial and J is the spin of the resonance. As a first approximation, the phase shift term $\Delta\Psi$ can be calculated, following the suggestions of Refs. [35], by the relation $\Delta\Psi = \frac{\ell_i - J}{J}\theta_{cm}$, where ℓ_i is the angular momentum of the dominant partial wave in the entrance channel. Considering that, in a semi-classical picture, at intermediate energies inelastic scattering processes have essentially a direct and peripheral nature, only a narrow window of angular momenta centred around the grazing value ℓ_g would contribute to the scattering amplitude [37]. For this reason, we can assume $\ell_i \approx \ell_g$. The ℓ_g has been calculated with the Wilcke model [38]. For example, in the present case we have $\ell_g \approx 10\hbar$ for proton target. For clarity reasons we have presented in Fig.1 the behaviour of the experimental data (black points) corrected considering a $J = 6$ resonance and compared with the corresponding theoretical prediction (red line), for which we have obtained a better agreement. The last one has also been corrected for the estimated detection efficiency (represented by the dotted line). As clearly visible from the figure, the $J = 6$ theoretical prediction is in satisfactory agreement with the experimental data, possibly confirming the preliminary results reported in Ref. [17].

2.2 The ^{16}C case

Finally, we have studied the ^{10}Be+^{6}He correlations to investigate the spectroscopy of ^{16}C. The corresponding relative energy ($E_{rel} + E_{thr}$) is shown in Fig. 2. The red and black dashed lines are, re-

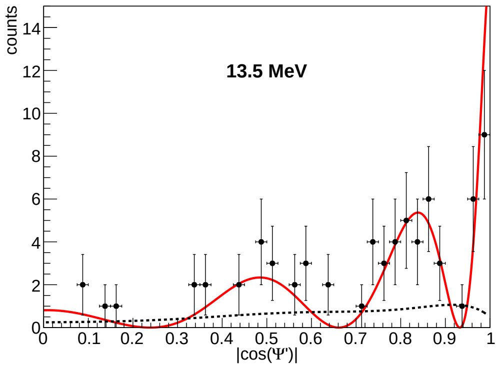

Fig. 1: (color online) ^{6}He-^{4}He angular correlations for the 13.5 MeV state of ^{10}Be corrected for the phase shift term considering a $J = 6$ resonance. The red line is the corresponding theoretical prediction $|P_6(cos(\Psi'))|^2$ corrected for the efficiency (dashed line).

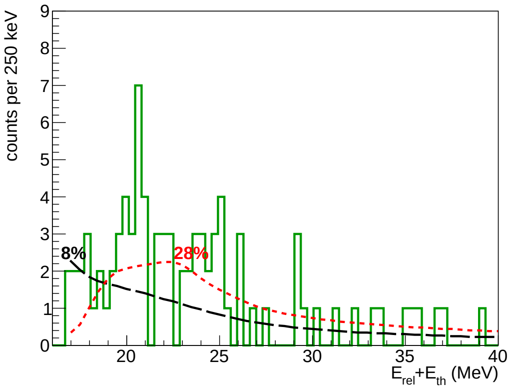

Fig. 2: (color online) ^{16}C relative energy spectrum $(E_{rel} + E_{thr})$ for the ^{10}Be+^{6}He break-up channel. The red and the black dashed lines represent, respectively, the simulated detection efficiency for inelastic scattering on proton, peaking at 28%, or carbon, peaking at 8%.

spectively, the efficiency for inelastic scattering on hydrogen or carbon, in analogy with the previous discussion. In this case the statistics is very low, but anyway an yield enhancement corresponding to an excitation energy of about 20.6 MeV is visible. As in the case of ^{10}Be, the efficiency curves exhibit a flat behaviour, indicating that the 20.6 MeV bump should not be attributed to efficiency effects. It is very interesting to note that also previous experiments [24, 23] show, with lower statistics, the same yield enhancement. For these reasons, we could attribute this bump to a new state; furthermore, in these energy region, some linear chain states and triangular states have been pointed out in the theoretical paper [25].

3. Conclusions and perspectives

In conclusion, we studied the structure of ^{10}Be and ^{16}C via break-up reactions induced on CH_2 target and using a radioactive cocktail beam produced at the FRIBs facility (LNS).

From the analysis of ^{6}He-^{4}He coincidences we investigate the spectroscopy of ^{10}Be, observing some excited state reported in literature and the evidence of a new state. For this new state, possibly observed also in the preliminary analysis [17], we studied the corresponding angular correlation, pointing out a tentative 6^+ spin and parity assignment in agreement with [17].

The structure of ^{16}C is investigated via the ^{10}Be+^{6}He break-up channel. In this case we find an yield enhancement at about 20.6 MeV excitation energy that could be the fingerprint of the possible existence of a new molecular state in ^{16}C, possibly seen also in the previous experiments [24, 23], but with lower statistics.

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