Interesting states in A = 10 mass region, populated in ^{10}B + ^{10}B nuclear reactions

Deša Jelavić Malenica[1,*], *Matko* Milin[2], *Alessia* Di Pietro[3], *Pierpaolo* Figuera[3], *Marcello* Lattuada[3], *Đuro* Miljanić[1], *Agatino* Musumarra[3], *Maria Grazia* Pellegriti[3], *Valentina* Scuderi[3], *Natko* Skukan[1], *Neven* Soić[1], *Suzana* Szilner[1], *Domenico* Torresi[3], and *Milivoj* Uroić[1]

[1]Ruđer Bošković Institute, Zagreb, Croatia
[2]Faculty of Science, University of Zagreb, Zagreb, Croatia
[3]INFN - Laboratori Nazionali del Sud and Sezione di Catania, Catania, Italy

Abstract. The ^{10}B+^{10}B reactions are measured at beam energies of 50 and 72.2 MeV. The large spin of ^{10}B nucleus (J^{π}= 3$^+$) makes this reaction particularly suitable to populate high spin states in the exit channels. Population and decay of different states in $A\approx$10 mass region is studied, and the results are discussed from the structure point of view. In particular, a new state in ^{12}C at E_x= 24.4 MeV is observed to be strongly populated in the triple α-particle coincidences.

1 Introduction

States of different structures occur in light nuclei around A=10, at similar excitation energies: from shell-model to very exotic ones. Experimental data in this region are incomplete and often controversial.

The most popular nucleus in this mass region is ^{12}C, because of its essential role in stellar nucleosynthesis. The so-called Hoyle state [1] - the second 0$^+$ state of ^{12}C, at excitation energy E_x= 7.65 MeV, is responsible for dramatic speed-up of helium burning [2] and crucial for production of all heavier elements. Modeling the Hoyle state is a non-trivial task because it seems to have a unique structure and can not be described within *e.g.* shell model calculations, even when $4\hbar\omega$ excitations are included [3]. Many recent experimental studies are focused on Hoyle state and its possible excitations. Recent work by Marin Lámbarri *et al.* [4] made an important step in completing and systematizing the ^{12}C spectroscopy in general, with a new state (5$^-$ at E_x= 22.4 MeV) reported, and most of the low-lying ^{12}C states explained as corresponding to the triangular oblate spinning top with a $\mathcal{D}_{3h}$ symmetry [5]. More details on theoretical progress made in explaining the ^{12}C structure are given in a very recent review of microscopic clustering in nuclei [6].

From the structure point of view, there are many other interesting states in $A\approx$10 mass region. One such example are molecular states, with the intense experimental research in the last decades (*e.g.* [7]). Molecular states were finally clearly established in ^{10}Be [8, 9], forming a rotational band starting with the 0_2^+ state at E_x= 6.18 MeV. Such states are predicted to exist in a number of other nuclei [10], but all of them have in common that the valence nucleons are in fact *neutrons*. *Protons* as valence particles are expected to make the molecules less stable, due to the Coulomb repulsion, especially while filling the σ-orbitals.

Possible molecular states with protons as valence particles are predicted to exist in ^{11}B and ^{11}C nuclei [11, 12], making their theoretical description in a framework of a single model rather demanding. While ground and low-lying states of these nuclei are well described as shell-model structures, in the highly excited states there are two types of cluster structures: three-body $2\alpha + t$ (or ^{3}He) cluster structures (corresponding to the 3α cluster structures in ^{12}C) and molecular structures with three valence nucleons (one or two of them being protons), moving in the mean field of 2α particles (which can be associated with molecular structures in ^{10}Be). These kind of coexistence of three-body cluster and molecular orbital structures inside similar energy region is one of the unique features of ^{11}B and ^{11}C nuclei [12].

The present paper reports on results of ^{10}B+^{10}B nuclear reactions, measured at beam energies of 50 and 72.2 MeV. ^{10}B nucleus is very special by itself - it is one of five stable nuclei with odd number of protons and neutrons and it is the one nucleus with the largest ground state spin J$^{\pi}$ = 3$^+$. Although ^{10}B ground state can be simply described as shell model stretched configuration with two nucleons in $p_{3/2}$ subshell coupled to maximum possible spin, fundamental no-core shell model calculations correctly reproduce its spin only if the three-nucleon force is taken into account [13]. This peculiar structure of ^{10}B, which can be described as a mixture of shell model and cluster configurations of the type ^{6}Li$_{gs}$+α or ^{6}Li(0_2^+,1)+α [11], together with a high spin of the ground state J^{π}= 3$^+$, is expected to enable the population of a range of different

*e-mail: djelavic@irb.hr

high-spin states in a variety of nuclei around $A \approx 10$, at high excitation energies.

Only few selected results will be presented in next sections, while the complete results for ^{12}C states can be found in Ref. [15].

2 Experiment

The ^{10}B+^{10}B experiment was performed at INFN-LNS Catania, using the SMP Tandem accelerator. The selectivity in populating different single particle and cluster states of neighbouring nuclei was studied, together with a sequential decay of states in question. This is the first time that such a reaction was employed for nuclear structure studies.

Two beam energies of 50.0 and 72.2 MeV were used, together with targets enriched in ^{10}B up to 99.8%. Highly segmented detector setup consisted of four ΔE-E silicon telescopes, each composed of a thin ΔE detector (57-67 μm), divided into 4 quadrants and a thick DSSSD detector (500 or 1000 μm), divided into 16 strips in both front and back sides. Three detector setups were used, with different azimuthal angles of the detector centers in a range from 20° to 53°.

Segmentation of DSSSD detectors makes the analysis of obtained experimental data rather demanding. Besides the calibration of a large number of apparently independent detector channels, there are complications associated with dead layers [16] and interstrip gaps [17, 18] that had to be taken in the account properly. Several novel procedure improvements [19] for easy and accurate calibration of DSSSD detectors were used in the analysis - details can be found in Ref. [20].

The detection efficiencies for a given setup was obtained from a Monte Carlo (MC) code that simulates two-body ^{10}B+^{10}B reaction, assuming an isotropic c.m. distribution of products, followed by sequential decay into fragments, again assuming an isotropic c.m. distribution.

At both beam energies the number of detected α particles was remarkably higher than the number of any other detected nuclei - even triple α-particle coincidences were detected with rather large statistics. Fig. 1 gives an example of ΔE-E spectrum for one quadrant of the telescope at 22.4°. Lines correspond to different isotopes of H, He, Li, Be, B and C, from bottom to top, respectively, being the most abundant ^{4}He and heaviest detected ^{13}C.

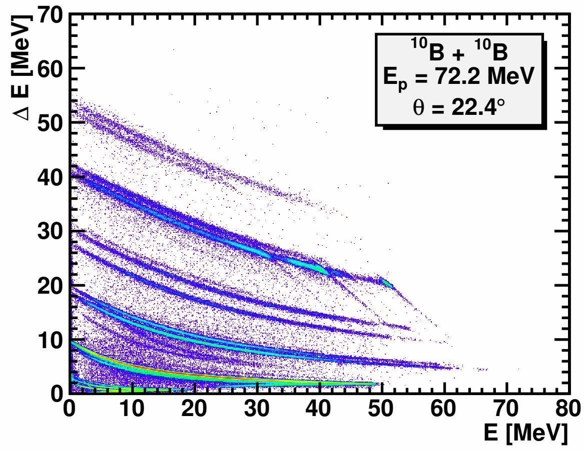


Figure 1: ΔE-E spectrum for the ^{10}B+^{10}B nuclear reaction measured at 72.2 MeV.

3 Results

3.1 Interesting states in ^{12}C

In the case where two α particles are detected in coincidence, by assuming the reaction to be a three body, one can reconstruct the excitation energy spectra of undetected ^{12}C, using the procedure suggested in [21]. An example of such spectra is shown in the inset of Fig. 2a. This spectra was obtained with the constrain that two detected α particles are coming from the ground state of the intermediate nucleus, ^{8}Be. After subtracting the background, one obtains the spectrum in the main panel of Fig. 2a.

Several strong peaks (states in ^{12}C) can be easily identified in Fig. 2a: 0^+ ground state, 2^+ state at 4.44 MeV, 3^- at 9.64 MeV and 5^- at 22.4 MeV (as proposed in Ref. [4]). The population of the g.s. is suppressed due to the large Q-value mismatch (Q= 19.25 MeV, $Q_{opt} \approx -12$ MeV). Furthermore, there is a small, but visible peak corresponding to the known ^{12}C state at 7.65 MeV (Hoyle state), and also peaks at E_x= 24.3 and 30.3 MeV, the last one being very pronounced in other reaction channel: ^{10}B(^{10}B, d^{10}B), reported in Ref. [15].

Even if rather restricted in angular range, angular distributions for the events given in Fig. 2a are very forward peaked, suggesting that the corresponding reaction mechanism is deuteron transfer - all the populated states have therefore non-negligible ^{10}B+d strength.

In a case where three α particles are detected in coincidence, the undetected part of the exit channel corresponds to the ^{8}Be nucleus, which is particle unstable, and decays exclusively (for E_x(^{8}Be) up to ≈17.3 MeV) through the α+α channel. So, by detecting three α particles in coincidence, one can reconstruct the details of ^{10}B+^{10}B→5α reaction and its different sequential paths, which is a rarely seen and measured reaction channel.

Fig. 2b gives the ^{12}C excitation energy spectrum, reconstructed from the triple α-particle coincidences, with two of them coming from the ^{8}Be g.s. decay (with an energy of only 92 keV this decay has a clear signature in the detectors and is easily recognized and extracted), and two undetected α particles coming from the ^{8}Be first excited state at the E_x(^{8}Be)= 3.03 MeV. The contribution from different two-body intermediate steps, which would proceed through the ^{16}O states, is dismissed throughout plotting Dalitz plots [21] and introducing additional cuts to the data. Spectrum in Fig. 2b shows only a fraction of the collected data - only events where 2α particles are detected in

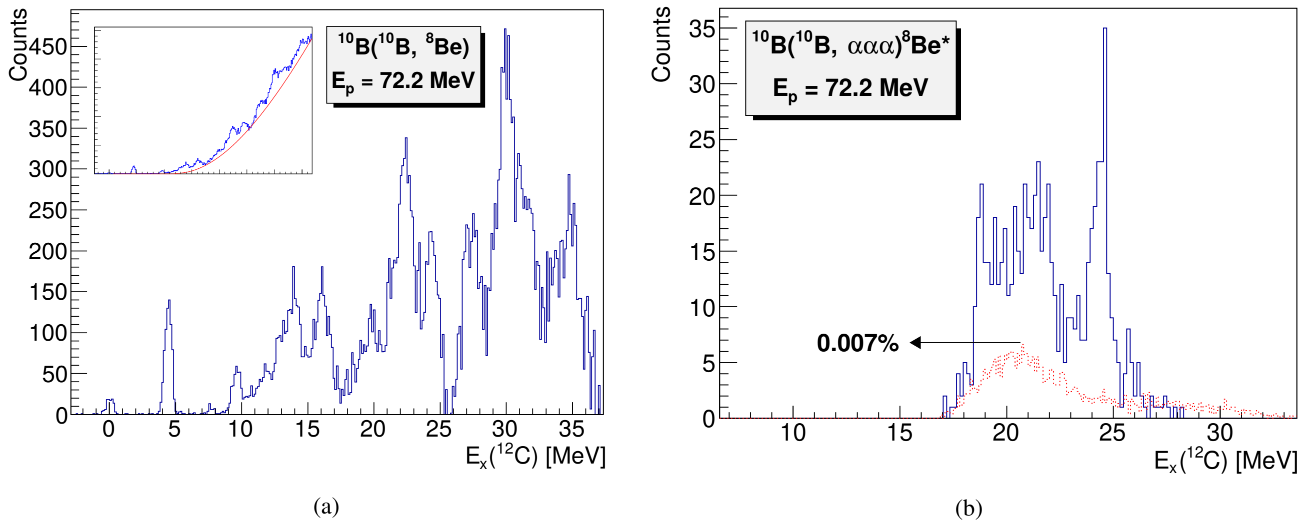


Figure 2: The results for ^{12}C measured in (a) double and (b) triple α coincidences (see text for details). The (red) dotted line in (b) shows the corresponding Monte Carlo efficiency curve.

telescope at 20°, and third α detected at 30° are included. Spectra for different detector combinations and setups can be seen in Ref. [15, 20]. All this spectra show same states in ^{12}C, but since the detection efficiency depend on excitation energy (being the consequence of geometry issues), not all states are seen in different detector combinations.

For many spectra obtained with different combinations of detectors and setups the dominant state at higher excitation energy (as clearly seen in Fig. 2b) is the state at E_x= 24.4 MeV. The peak is seen always at the same excitation energy (E_x= 24.4 MeV) and with the same width (Γ= 0.50 MeV); considering the smooth behavior of the efficiency in this energy region, we can be sure that this state at E_x= 24.4 MeV is a genuine state in ^{12}C.

Besides this state, for detector combination and setups with higher efficiency in low energy region, two additional states are measured in 3α particles coincidences: the states at E_x= 7.65 and 9.64 MeV. These states, together with the state at 24.4 MeV, were less populated in deuteron transfer channel shown in Fig. 2a. Considering that, and the reaction channel measured, we can suggest that the state at 24.4 MeV has a structure that is closer to the Hoyle state, than to the compact ^{12}C ground state. This is probably also a reason why this state is not seen in the recent precise measurements in which the ^{12}C states are populated with the inelastic scattering of ^{3}He or ^{4}He [4].

By comparing the state at E_x= 24.4 MeV (with $\Gamma\approx$ 500±40 keV), measured in this experiment, with energy and widths of states listed in last compilation for ^{12}C [22], we conclude that it is a new state, not listed before. The spin and parity assignments for this new state are essential to find its place in the spectroscopy systematics of ^{12}C.

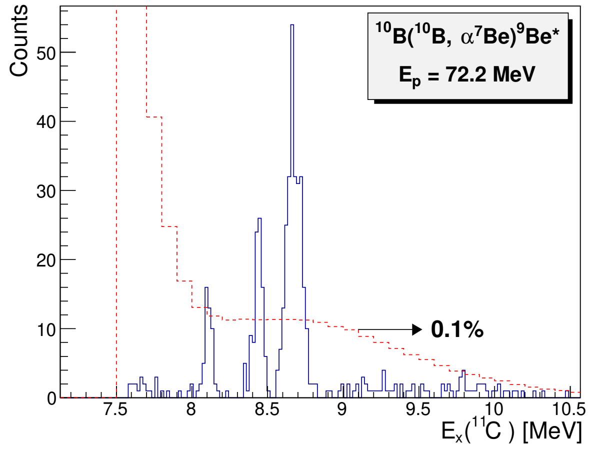
3.2 Interesting states in ^{11}C

Excitation spectra for ^{11}C, measured in reaction channel ^{10}B(^{10}B, α^7Be)^{9}Be*, in which undetected ^{9}Be is left in its second excited state at E_x= 2.43 MeV, shows four strong peaks, as seen in Figures 3a and 3b. Two of them, at 8.11 and 8.43 MeV (Fig. 3a), are well known states that predominantly decay by alpha emission [22]. The state at 8.11 MeV, populated only through this channel in present experiment, is a cluster state, with very dilute structure of the type α+α+^{3}He. Such a state is a famous Hoyle state analog, as discussed in Ref. [11], which can be considered also as a dilute Bose-Einstein condensate. On the other hand, neighbouring state at 8.43 MeV, is a shell model state, with very compact structure. That state is also populated trough one nucleon transfer reaction channel, unlike the state at 8.11 MeV. Third state in low energy region, at 8.67 MeV, is not listed as alpha-decaying state, but is seen to decay by alpha emission in Ref. [23].

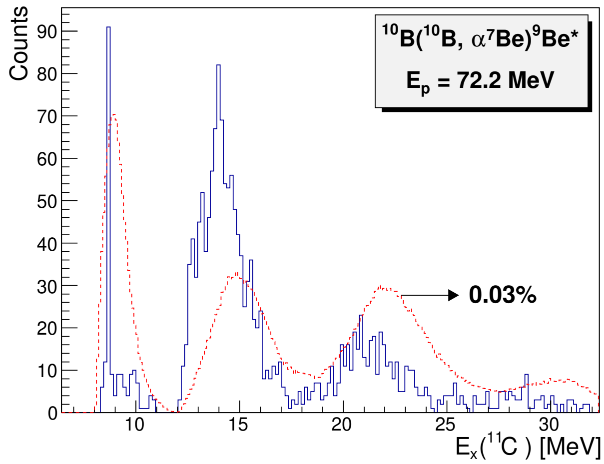
The fourth state seen in this channel lies in the higher excitation energy region, shown in Fig. 3b, at $E_x\approx$14MeV. Since the efficiency in this region is not smooth, and background is rather high, it is difficult to say weather this is a real state in ^{11}C. The fact that it is seen also in other detector combinations and for other excited states of undetected ^{9}Be, adds in favour that it is a real physical state. It is important to mention that a possible analog of this state is seen in the mirror reaction channel ^{10}B(^{10}B, α^7Li)^{9}B, where a broad state in ^{11}B is measured at $E_x\approx$15MeV.

3.3 Other interesting results

Besides shown results, there are many other channels measured in this experiment, which led to some interesting and rarely seen states.



(a)



(b)

Figure 3: The ^{11}C excitation energy spectra obtained from measured ^{7}Be and α-particle coincidences: (a) in detectors that lie on the same side of the beam (events in which both particles are detected in the same detector are included); (b) in all detector combinations, except the ones where both particles are detected in same detector. The (red) dotted lines show the corresponding Monte Carlo efficiency curves.

Excitation energy spectra of ^{13}C show a very strong α-decaying state at E_x = 18.9 MeV, just above the energy region reported in Ref. [24]. This state has a pronounced ^{9}Be+α structure, and is a good candidate for molecular state with one valence nucleon orbiting around 3α centers.

Two very important states in ^{14}N at E$_x$ = 13.2 and 15.39 MeV are populated in α-transfer reaction channel. Both of them fit nicely to a recent antisymmetrized molecular dynamics calculations as the head and the 5$^+$ state of the ^{10}B(3$^+$) + α rotational band (K$^\pi$ = 3$^+$) [25].

Acknowledgments

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