Exploring cluster structures in the high excitation energy region of Be, B, and C isotopes via ^{10}B + ^{10}B nuclear reactions

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Abstract. The unique opportunity presented by ^{10}B + ^{10}B reactions to study high-energy, high-spin states in the *A=10* mass region is explored. Results from the measurement at 72 MeV are presented, the most important being new and rarely seen states in the ^{12}C [1] and ^{13}C [2], which motivate targeted future experiments. In particular, a new state of ^{12}C at E_x = 24.4 MeV is strongly populated in the triple α-particle coincidences, while the rarely seen state at E_x = 30.3 MeV is found to be strong in the d+^{10}B decay channel, reinforcing the previous suggestions that it has the exotic 2α+2d molecular structure [3]. Regarding the ^{13}C nucleus, a potentially novel state at E_x = 19.0 MeV is prominently observed in α+ ^{9}Be coincidences and demonstrates a well-defined cluster structure. Lastly, high-spin states in mirror nuclei pairs ^{9}Be-^{9}B, ^{10}Be-^{10}C and ^{11}B-^{11}C populated in the presented measurement are explored.

1 Introduction

The high-energy region of isotopes in the A=10 mass range presents a dense concentration of overlapping states, making their study particularly challenging. Accurately identifying these states is crucial for unraveling the rotational bands of highly deformed cluster structures and recognizing their high-spin members. States selectively populated in specific experimental channels provide valuable insights into structural features. Although reaching high-spin states can be difficult, the unique experimental conditions of the ^{10}B + ^{10}B reaction study allow for the population of such states in the exit channels. Unlike the traditional method of resonant particle spectroscopy [4], where both the entrance and exit channels are selective, the entrance channel in this experiment offers the potential to excite a wide range of states, highlighting the significance of those that are selectively populated.

Among all light nuclei, ^{12}C has been extensively studied, largely due to its role in stellar nucleosynthesis and the importance of the Hoyle state at E_x = 7.65 MeV [5]. This state, just above the α-decay threshold, accelerates helium burning [6], making it crucial for the production of heavier elements. Understanding the Hoyle state and its related rotational excitations [7] is essential for completing ^{12}C spectroscopy. Recent work has uncovered new states, like the 5^- state at 22.4 MeV [8], contributing to this effort.

The ongoing interest in ^{12}C's structure has extended to neighboring nuclei like ^{13}C, which reveals the impact of an additional nucleon. The properties of ^{13}C up to ≈10 MeV excitation energy are well explained by the shell model (*e.g.* [9]), with negative parity states arising from various *p*-shell nucleon configurations, and positive parity states resulting from the weak coupling between a *sd*-shell nucleon and the ^{12}C core [10–12]. At higher excitation energies, cluster models become necessary, particularly the ^{9}Be + α configuration for ^{13}C.

It has also been proposed that a structure analogous to the Hoyle state may exist in ^{13}C, where a valence neutron couples with the Hoyle state core [13–15]. Recent studies using antisymmetrized molecular dynamics [16] suggest several possible candidates for such a state.

Mirror nuclei, pairs of isobars where the proton number in one equals the neutron number in the other ($Z_1 = N_2$ and $Z_2 = N_1$), provide further insight into nuclear structure and charge independence of nuclear forces. Studies on mirror pairs like ^{13}C and ^{13}N show how the Coulomb displacement energy is influenced by the spatial configuration of valence particles, with more compact orbitals experiencing a greater Coulomb shift [17, 18]. This research, which initially focused on bound states, has expanded to include resonant states and cluster structures, demonstrating the importance of different configurations in contributing to the Coulomb energy.

Despite the progress, experimental data on cluster states in mirror nuclei remain limited, especially for states populated simultaneously in the same experiment. The ^{10}B + ^{10}B reaction used in this study provides an ideal scenario for populating mirror pairs in the exit channels.

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2 Experiment

The $^{10}B+^{10}B$ experiment was conducted at the INFN-LNS facility in Catania, utilizing the SMP Tandem accelerator. The focus of the study was to explore the selectivity in populating different single-particle and cluster states of nearby nuclei, along with the sequential decay of the states involved. This experiment marks the first application of such a reaction for nuclear structure investigations.

Beam energies of 50.0 MeV and 72.2 MeV were employed, while the targets used were enriched with ^{10}B to a purity level of 99.8%.

A highly segmented detector system was implemented, consisting of four ΔE-E silicon telescopes. Each telescope was composed of a thin ΔE detector (ranging from 57-67 μm) divided into four quadrants, and a thick DSSSD detector (either 500μ m or 1000 μm), divided into 16 strips on both the front and back sides. Inside the DSSSD each signal is recorded twice, giving the precise information on the incoming angle, but also the possibility to promptly reduce the noise, requesting the difference in signal measured in the front and back to be within adjustable acceptance window (it was requested to be less than 3%). The experimental setup included three detector arrangements, with the azimuthal angles of the detector centers ranging from 20° to 53°.

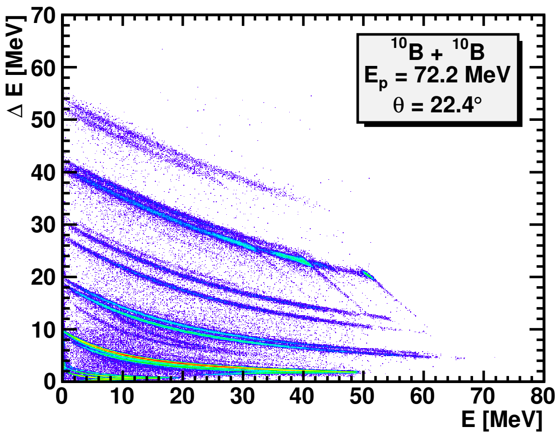

Figure 1. An example of the ΔE-E spectra for one quadrant of the thin detector and corresponding strips of the DSSSD thick detector in the telescope centered at 22.4°

At both beam energies, the detected number of α particles significantly exceeded that of any other nuclei (even triple α-particle coincidences were recorded with substantial statistics). Figure 1 illustrates a sample ΔE-E spectrum from one quadrant of the telescope positioned at 22.4°. The lines represent different isotopes of hydrogen, helium, lithium, beryllium, boron, and carbon, ordered from bottom to top, with ^4He being the most abundant and ^{13}C the heaviest detected isotope.

Originally, the experiment was designed as an exploratory study to search for molecular states in ^{10}C (which have been recently confirmed experimentally [19]). The aim was to detect four-particle coincidences (α-α-p-p), which could potentially reveal a rotational band analogous to the one observed in ^{10}Be, which at the time confirmed the molecular nature of the ^{10}Be states [20, 21]. Although four-particle coincidences were not observed due to threshold challenges and a longer than anticipated target-detector distance, the experiment yielded unexpected and exciting results. As we will discuss in the next chapter, new and previously unobserved states in ^{12}C and ^{13}C were discovered, marking a significant and unplanned success in the structure studies of these well-known nuclei.

3 Results and discussion

3.1 ^{12}C states

Thanks to the large solid angle and high segmentation of the detector setup, α particles were detected with high statistics in both double and triple coincidences. The $^{10}B+^{10}B$ reaction can lead to a unique exit channel containing five α particles (schematically shown in Fig. 2), rarely observed and measured. If three α particles are detected in coincidence, the remaining undetected part corresponds to the ^8Be nucleus, which is particle unstable and decays exclusively (for $E_x(^8Be)$ up to approximately 17.3 MeV) into two α particles. This allows for a systematic exploration of the $^{10}B+^{10}B\rightarrow 5\alpha$ reaction and its sequential decay pathways.

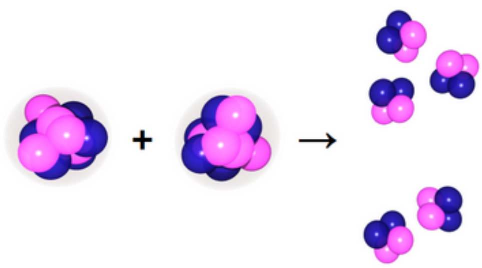

Figure 2. Schematic description of the rarely measured $^{10}B+^{10}B\rightarrow 5\alpha$ channel.

When two α particles are detected in coincidence, the excitation energy spectrum of the undetected ^{12}C nucleus can be reconstructed by assuming a three-body reaction, following the procedure outlined in Ref. [22]. An example of such a spectrum is provided in the inset of Fig. 3, where the analysis is constrained by the condition that the two detected α- particles originate from the ground state of the intermediate ^8Be nucleus. There are different contributions to the sharp rising background, but a simple polynomial fit (red line in the inset of Fig. 3) seems to fit it well. After background subtraction, the resulting spectrum is displayed in the main panel of Fig. 3.

Several prominent peaks, corresponding to states in ^{12}C, are clearly visible in Fig.3. These include the 0^+ ground state, the 2^+ state at 4.44 MeV, the 3^- state at 9.64 MeV, and the 5^- state at 22.4 MeV, as suggested in Ref. ˜[8]. The population of the ground state is suppressed due to the significant Q-value mismatch (Q = 19.25 MeV, $Q_{opt} \approxeq$ -12 MeV).

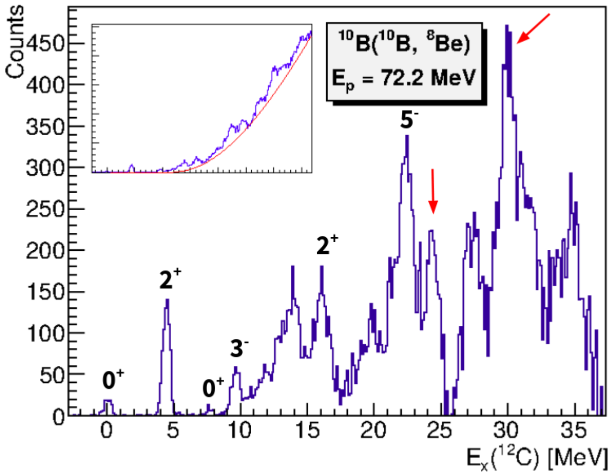

Figure 3. The excitation energy spectrum of ^{12}C for 2α coincidences, obtained with a constraint that the two detected α particles originate from the ^{8}Be ground state. The background-subtracted spectrum is shown in the main panel, while the inset displays the spectrum including the background.

Additionally, a small but noticeable peak is observed in Fig. 3 at 7.65 MeV, corresponding to the well-known Hoyle state in ^{12}C. Peaks at excitation energies of 24.4 MeV and 30.3 MeV are marked with red arrows.

The same procedure can be applied to other ^{8}Be intermediate states of two detected α- particles. Similar populations of the same states, with slight variations in relative intensities, are observed across all the spectra. The high-energy region is consistently dominated by the states at 22.4 MeV and 30.3 MeV.

As for the case where three α-particles are detected in coincidences, the first step is to determine if two of the α particles originate from the ground state decay of ^{8}Be. This decay, with an energy of just 92 keV, has a distinct signature that is easily identified and extracted by the detectors. Once these two α particles are identified, the energy and angle of the ^{8}Be ground state before decay can be reconstructed and combined with the third α particle to search for potential ^{12}C states involved in the sequential decay.

One such ^{12}C excitation energy spectrum is given in Fig. 4, reconstructed from triple α-particle coincidences. The two undetected α particles in this case, originate from the first excited state of ^{8}Be at 3.03 MeV. Contributions from other two-body processes, such as those proceeding through ^{16}O states, were excluded by analyzing Dalitz plots [22] and implementing additional data cuts. Spectra using other detector combinations, and other possible intermediate states of two undetected α-particles, can be found in Ref. [1, 23]. These spectra consistently reveal the same ^{12}C states, though detection efficiency varies with excitation energy due to geometric factors, causing some states to appear more prominently in certain setups.

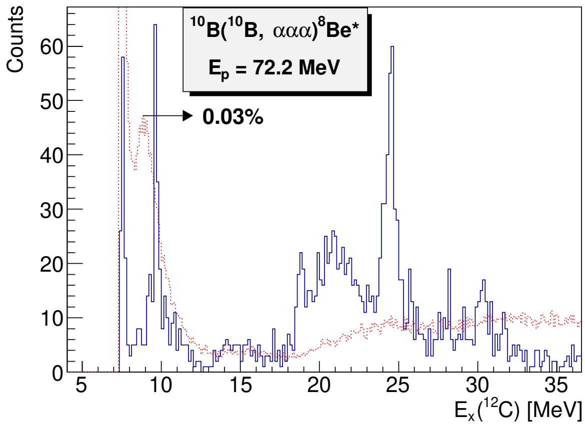

Figure 4. Excitation energy spectrum of ^{12}C from 3α coincidences (see text for details). The (red) dotted line shows the corresponding Monte Carlo efficiency curve.

Detection efficiencies for the experimental setups were determined using a Monte Carlo simulation that modeled the two-body ^{10}B+^{10}B reaction, assuming an isotropic center-of-mass distribution for the reaction products. The simulation also included the sequential decay into fragments, maintaining an isotropic distribution. The detection of these fragments was simulated with angular cuts to reflect the solid angles covered by the telescopes, as well as energy cuts to account for the detection thresholds. The resulting efficiency curve, showing efficiency as a function of excitation energy, is presented in Fig. 4 with a red dashed line.

In various spectra using different detector configurations, the state at 24.4 MeV consistently appears as the dominant feature at higher excitation energies (as shown in Fig. 4). The peak is observed at E_x = 24.4 MeV with a width of approximately 500 ± 40 keV, and the stable detection efficiency in this region confirms that this is a genuine state in ^{12}C.

In setups with better sensitivity to lower energies, two additional states at E_x = 7.65 MeV and 9.64 MeV were also observed in the 3α-particle coincidences. However, these states, like the 24.4 MeV state, were less populated in the deuteron transfer channel (Fig. 3). This suggests that the 24.4 MeV state may be more closely related to the Hoyle state than to the compact ^{12}C ground state, which may also explain why it was not detected in recent precise measurements of ^{12}C using inelastic scattering of ^{3}He or ^{4}He [8].

By comparing this 24.4 MeV state to the known states listed in the latest ^{12}C compilation [24], we conclude that it represents a previously unreported state. The cross-section ratio between this state and the well-known 3^- state at E_x = 9.64 MeV, which has a reduced α-width indicating a clear cluster structure [25], is 6.6:1 in Fig.3. After correcting for detection efficiencies, the ratio in Fig.4 remains similar at 6.3:1. While the detection efficiency was calculated assuming isotropic decay of ^{12}C states via Monte

Carlo simulation, this ratio is an approximation. Nevertheless, it is evident that the 24.4 MeV state, like the 9.64 MeV state, has significant overlap with the ^{10}B + d and ^{8}Be + α configurations. Both states are less prominent in the deuteron transfer channel (Fig. 3), compared to other states with $\mathcal{D}_{3h}$ symmetry, such as the 2^+ state at 4.44 MeV, 4^+ state at 14.08 MeV, and the recently proposed 5^- state at 22.4 MeV. Determining the spin and parity of the 24.4 MeV state will be key to understanding its role in the spectroscopy of ^{12}C.

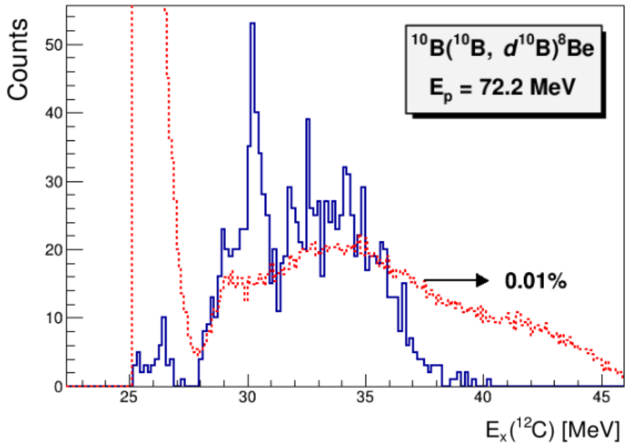

Figure 5. The ^{12}C excitation energy spectrum for the d+^{10}B coincidences. The (red) dotted line shows the corresponding Monte Carlo efficiency curve.

Furthermore, besides α-α pairs, several other particle combinations were detected in coincidence. One combination particularly relevant for studying the ^{12}C nucleus was ^{10}B+d.

Figure 5 shows the ^{12}C excitation energy spectrum reconstructed from d+^{10}B coincidences. Contributions from intermediate ^{10}B states were excluded from further analysis due to their narrow widths. No sequential decays via ^{18}F states were observed. The state at E_x = 30.3 MeV is the only clearly populated state, as the 22.4 MeV state is below the decay threshold. The detection efficiency curve shows a strong peak at low energies, corresponding to both particles being detected in the same telescope, but no distinct features in the region around the main peak. In addition to this channel, the state at E_x = 30.3(2) MeV (with $\Gamma \approx 540 \pm 40$ keV) is also populated in the previously discussed Fig. 3, where it dominates the high-energy region of the spectrum.

This state has been observed in previous experiments, such as ^{10}B(d,α_0)^{8}Be [26], ^{12}C(α,4α) [27], and ^{6}Li(^{6}Li,α_0)^{8}Be [3], but was not detected in more recent inelastic scattering experiments with α-particles [8] or ^{3}He [28] due to their insensitivity to such high excitation energies.

Although the 30.3 MeV state dominates in Figs.3 and 5, it is weak in the 3α-particle decay spectra (Fig.4), suggesting its structure involves configurations beyond the 3α system. The state's width varies between reactions, being larger ($\Gamma \approx 830$ keV) in the ^{10}B(^{10}B,d^{10}B) spectrum compared to the ^{10}B(^{10}B,^{8}Be) spectrum ($\Gamma \approx 540$ keV), likely due to background subtraction issues.

The relatively narrow width at such a high excitation energy suggests a unique structure that prevents it from mixing with the continuum. Analysis from the ^{12}C(α,4α) reaction [27] indicates $J^\pi = 2^+$. Its proximity to several thresholds, such as ^{6}Li+^{6}Li (28.2 MeV) and α+α+d+d (30.4 MeV), hints at an exotic 2α+2d molecular structure, distinct from lower-lying states.

3.2 ^{13}C states

In the present experiment, the ^{13}C nucleus was produced through direct reactions involving the pick-up or stripping of three nucleons:

$$\begin{aligned} {}^{10}\mathrm{B} + {}^{10}\mathrm{B} &\longrightarrow {}^{7}\mathrm{Be} + {}^{13}\mathrm{C}^{*} \\ &\longrightarrow {}^{9}\mathrm{Be} + \alpha + {}^{7}\mathrm{Be}, \quad Q = -5.441\mathrm{MeV}. \end{aligned} \tag{1}$$

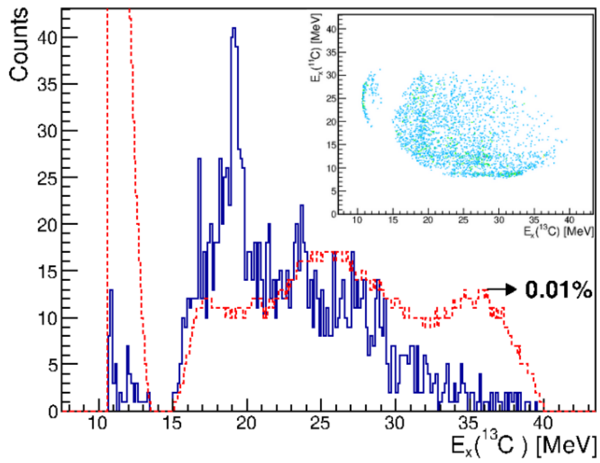

Figure 6. The excitation energy spectra of ^{13}C, obtained by detecting α and ^{9}Be in coincidence, in different detector combinations and setups. The undetected ^{7}Be is left in its ground state. The (red) dotted line shows the corresponding Monte Carlo efficiency curve. The inset shows the relative energy correlation plot (pseudo-Dalitz plot), used to distinguish intermediate ^{13}C states from ^{11}C states through a graphical cut [23].

Two distinct data sets were obtained and analyzed separately. The first data set was recorded in single mode, capturing events where only the recoil nucleus ^{7}Be was detected. Using the measured energy and momentum of ^{7}Be, the excitation energy of ^{13}C could be determined without any constraints on its decay mode. This approach allows all possible states of ^{13}C, starting from the ground state, to be populated within the limits imposed by conservation laws. All of the states populated in this way, listed in [2] correspond well to the previously reported states, (*e.g.* [29, 30]). Of particular interest are the states located above the α-emission threshold at E$_x$ = 10.648 MeV, where some experimental results appear to be in conflict [31–33].

The second data set was collected in the coincidence mode, requiring at least two particles to be detected in the exit channel, specifically ^{9}Be and α. In a case where undetected ^{7}Be is left in its ground state, the reaction proceeds through the ^{13}C, as well as the ^{11}C intermediate states (see inset of Fig. 6). With the appropriate grahical cuts, the ^{11}C states are excluded from the present analysis. The main pannel of Figure 6 shows the excitation energy spectra of ^{13}C from the channel ^{10}B(^{10}B, α^{9}Be)^{7}Be. Two well-separated efficiency peaks are present (below and above 14 MeV), corresponding to the detection of α and ^{9}Be on the same or opposite sides of the beam.

A pronounced state of ^{13}C at E_x = 19.0 MeV, with a width of $\Gamma \approx$ 660 keV, is clearly visible in Fig. 6, dominating the high-energy region. A partially cut-off state at E_x = 10.82 MeV is also visible near the edge of the efficiency range due to the α-emission threshold at E_x = 10.648 MeV. This state lies in a local minimum of the efficiency curve, suggesting a well-defined structure that allows it to be populated in this experiment while maintaining a relatively narrow width at high excitation energy. It appears to be the same state observed in the inclusive spectra [2] at 19.15 MeV, with a nearly identical width of 600 keV. This conclusion is further supported by the population of the 10.82 MeV state in both data sets. Notably, this state is absent from the TUNL database, where the closest recorded state is at 18.699 MeV with a width of approximately 100 keV [24]. A strong resonance at 18.7 MeV, with a width of 570 keV, was also reported by Soić *et al.* in the ^{9}Be + α reaction [31].

Given that the energy resolution in this channel is about 200 keV, the state observed at E_x = 19.0 MeV is distinct from the previously listed state at 18.699 MeV, leading us to identify it as a new resonance in ^{13}C.

Beyond the cases presented in Fig. 6, this 19.0 MeV state is consistently observed across various detector combinations, from opposite sides of the beam direction, using different setups and gates on the missing mass partner. It consistently appears at the same excitation energy with a similar width ($\Gamma \approx$ 660 keV), reinforcing our confidence that this is a genuine new state in ^{13}C.

In addition, there is a small contribution of a state (or states) at E_x ≈12.1 MeV and also some less pronounced states in the high excitation energy region around 22-24 MeV.

3.3 Mirror nuclei study

The ^{10}B + ^{10}B reaction offers a unique opportunity to explore high-energy, high-spin states in mirror nuclei pairs, such as ^{9}Be-^{9}B, ^{10}Be-^{10}C, and ^{11}B-^{11}C. By comparing these relatively simple nuclei, one can probe spatial and quantum symmetries within nuclei, which offer insights into fine details of strong nuclear interactions.

In the excitation energy spectra of ^{9}B and ^{9}Be, the first excited states, known for their highly clustered structures, are absent. However, states that fit well into the rotational bands of these nuclei's first excited states are clearly observed as their 9/2^{-} members.

The inclusive spectra from the ^{10}B(^{10}B,^{10}Be)^{10}C channel allow us to examine the ^{10}Be-^{10}C mirror pair. Several peaks correspond to known ^{10}C and ^{10}Be states, with a particularly interesting state observed in ^{10}C at an excitation energy of approximately 9.5 MeV. This state likely corresponds to a ^{10}C excitation at E_x = 9.45 MeV, which is the isospin analog of the 2^{+} state in ^{10}Be at E_x = 9.56 MeV. This state has not been previously reported in the TUNL compilation or other recent ^{10}C studies, such as [34].

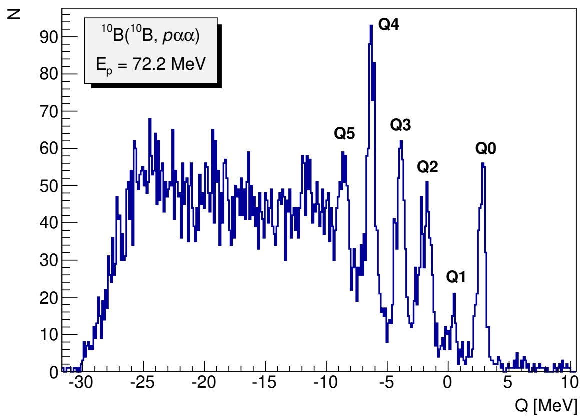

Figure 7. Q-value spectrum reconstructed from the triple coincidences α+α+p (see text for details).

The third mirror pair is obtained through a method demonstrating the utility of the detector setup, which features highly segmented strip detectors for multiple coincidence studies. The Q-value spectrum shown in Fig. 7 reconstructed from triple coincidences α+α+p (with specific cuts) shows ^{11}B states selectively populated in the ^{10}B(^{10}B,^{9}B$_{g.s.}$)^{11}B reaction. Due to the unbound nature of ^{9}B, this reaction has never been measured before. The excited ^{11}B states are mirror counterparts to ^{11}C states observed in the ^{10}B(^{10}B,^{9}Be)^{11}C reaction [23], with several higher excitation energy states not reported in previous nucleon transfer reactions on ^{10}B.

Further details on the mirror nuclei from this experiment will be presented in a forthcoming paper.

4 Conclusion

In this study, nucleon transfer reactions between ^{10}B nuclei were explored. High-spin states were effectively populated, emerging prominently above 10 MeV in excitation energy, due to the J^{π} = 3^{+} ground state of ^{10}B.

Various configurations near the well-studied ^{12}C nucleus, including Hoyle-equivalent states, molecular structures, and extremely deformed clusters, were investigated. Several new and rarely observed states were identified in the ^{10}B + ^{10}B reaction. A new state in ^{12}C at E_x = 24.4 MeV was found to exhibit strong α-cluster characteristics, while the rarely seen state at E_x = 30.3 MeV hinted an exotic $2\alpha+2d$ molecular structure. Additionally, a pronounced new state in ^{13}C is found at E_x = 19.0 MeV, decaying via the ^{9}Be + α channel, suggesting a well-defined cluster structure, potentially representing a high-spin state.

This work has enhanced the understanding of high-spin and cluster structures in the A = 10 region and highlighted the potential of the ^{10}B + ^{10}B reaction for further exploration of nuclear configurations.

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