CLUSTER STATES IN CARBON ISOTOPES $^{13-15}$C STUDIED WITH THE ^{10}Be + ^{9}Be REACTIONS*

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In this contribution, a set of results will be given of an experiment performed at LNS-INFN with a 54 MeV ^{10}Be beam and a ^{9}Be target. The experimental setup consists of four highly segmented telescopes covering polar angles from 20° to 90° which enable particle identification using traditional ΔE–E techniques. The ^{10}Be + ^{9}Be reactions are measured to get information on different types of structures of several light nuclei. Special attention is given to a search for cluster states in ^{14}C and ^{15}C. The experimental signature of these processes would be the first indication of the existence of cluster states inside the ^{15}C nucleus, while a positive result for the ^{14}C isotope would help to clear up the contradicting findings of other authors. The results for ^{14}C and ^{15}C are not yet fully interpreted, so here we show the ^{13}C excitation energies coming from the ^{6}He single detections and ^{6}He + ^{4}He coincidences.

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1. Introduction

Clustering of nucleons into two or more groups within an atomic nucleus is nowadays accepted as a common and essential feature of the structure of light nuclei [1]. The basic building block of cluster states is an alpha particle. Configurations based on two-alpha or three-alpha underlying structures have

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recently been in the focus of many experimental and theoretical studies of beryllium and carbon isotopes. The role of additional (valence) neutrons in such states is yet to be fully understood, making new experimental results for neutron-rich isotopes of these elements highly desirable.

Here, the ^{9}Be isotope has been chosen as the reaction target due to the existence of a cluster structure $^5\mathrm{He} + {}^4\mathrm{He}$ inside its ground state. Such target structure, alongside the choice of the ^{10}Be radioactive beam [2] with a suitable energy of 54.3 MeV, means that the transfer of one of the aforementioned clusters from the target to the beam should result in the creation of the sought ^{14}C or ^{15}C isotopes. This should be followed by sequential decay into several channels, some of which are $^4\mathrm{He} + {}^{10}\mathrm{Be}$ for ^{14}C and $^4\mathrm{He} + {}^{11}\mathrm{Be}$ or $^6\mathrm{He} + {}^9\mathrm{Be}$ for ^{15}C. The ^{14}C nucleus has been thoroughly studied in the last two decades, but the obtained experimental results are far from being consistent. On the other hand, the existing experimental data on ^{15}C is more or less limited to basic information on the low-lying states, below the alpha-decay threshold and the results on alpha-clustering have not been reported yet. Hence, the aim of this experiment was to obtain new data that would help create a consistent model of clustering in neutron-rich carbon isotopes. Since the results of the analysis for ^{14}C and ^{15}C are not yet fully interpreted, the results for ^{13}C are shown here.

The experimental setup consists of four telescopes covering polar angles from 15° to 65° which enable particle identification using traditional ΔE–E techniques. The E part of the telescope is a double-sided silicon strip detector, while the ΔE part is one-sided with each side segmented into 16 strips. The nominal width of ΔE part is 20 μm, while E is $\approx$ 1000 μm wide. The detector dimensions are 50×50 mm^2 and they are made by Micron Semiconductor Ltd.

2. Analysis

The raw ΔE–E data for one detector strip is shown in figure 1. The separation of isotopes is almost perfect in the helium and lithium regions, meaning no signs of wrongly identified nuclei were found for any of the cuts made, while the elastic peak of beryllium scattering complicates the separation in that region. Also, particles heavier than beryllium are outside of the optimal gain range which makes the separation of isotopes hard for boron and basically impossible for heavier nuclei. This discussion fully applies to the detectors at smaller polar angles, while the rest of the detectors have very few particles heavier than lithium.

In the process of calibration, information coming from ^{9}Be, ^{10}Be, and ^{16}O scattering on gold target as well as two different alpha sources is used. The extraction of real physical events was done by extracting all possible data combinations which could constitute a particle and then putting these

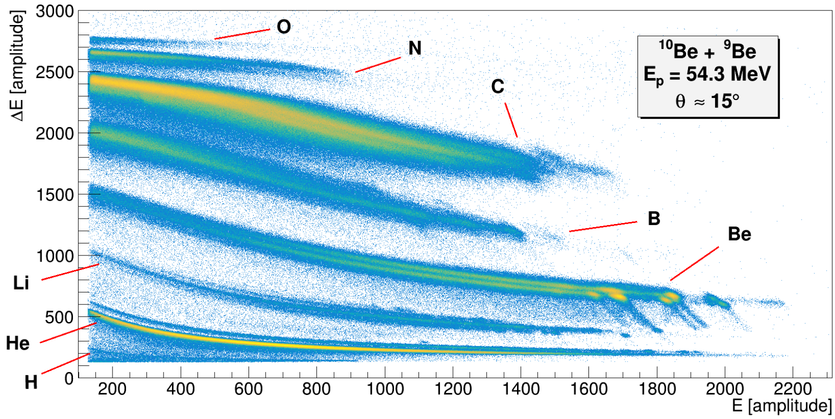

Fig. 1. ΔE–E particle identification plot. Nuclei from ^{1}H to ^{16}O are detected. Particles heavier than Be are outside of the optimal gain range which explains the different shapes of the slopes.

combinations through several filters at the end of which all noise and faulty data (*e.g.* inter-strip events) were eliminated. The filters use rules based on detector geometry and matching signal strengths and positions. Finally, with the particles and their energies being determined, the end results stem from standard methods of two- and three-body reaction analysis.

There were several systematic problems which have made the analysis more difficult and time-consuming. First and foremost is the known problem of inhomogeneity of thin large area detectors which makes the calibration of these detectors challenging. Second is the uncertainty in the thickness of the detector dead layer which was assumed at 0.5 microns according to standard specifications, but which can differ from it significantly. Finally, there was an uncertainty in the measured angles/distances of the detectors.

A more detailed description of the procedures and problems mentioned above is left for future publications.

3. Results

An intrinsic energy resolution of different telescopes was between 150 and 200 keV, but, as can be seen in the following figures, the resolution of excitation energy is somewhat worse, mainly due to the systematic error in determining the pixel angles. For example, it was not possible to fully separate the 3.68 and 3.85 MeV peaks in ^{13}C excitation energy spectra.

Figure 2 shows the ^{13}C excitation energy spectrum extracted from the ^{9}Be(^{10}Be,^{6}He)^{13}C reaction, with ^{6}He detected between $\theta_{\mathrm{lab}} = 15.5$ and 24.5 degrees. A number of states are strongly populated by this alpha-particle stripping reaction, rather similar to those seen in the ^{9}Be(^{6}Li,d)^{13}C measurement [3]. The population of the ground state is suppressed due to its low spin and Q-value matching conditions.

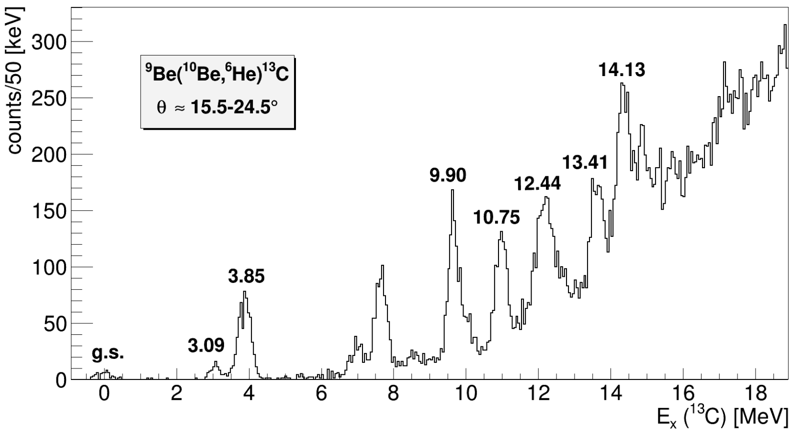

Fig. 2. ^{13}C excitation energies from ^{6}He single detections.

Figure 3 shows the ^{13}C excitation energy spectrum from ^{6}He + ^{4}He coincident detection with a third particle, ^{9}Be coming from ^{13}C decay, being undetected. A pronounced selectivity is seen in that spectrum and is only marginally caused by the detection efficiency, so it should be a signature of the alpha-cluster character of the state at E_x = 14.13 MeV. The state is suggested [4, 5] to have $J^{\pi} = 5/2^{-}$, so it is not clear how it fits into the

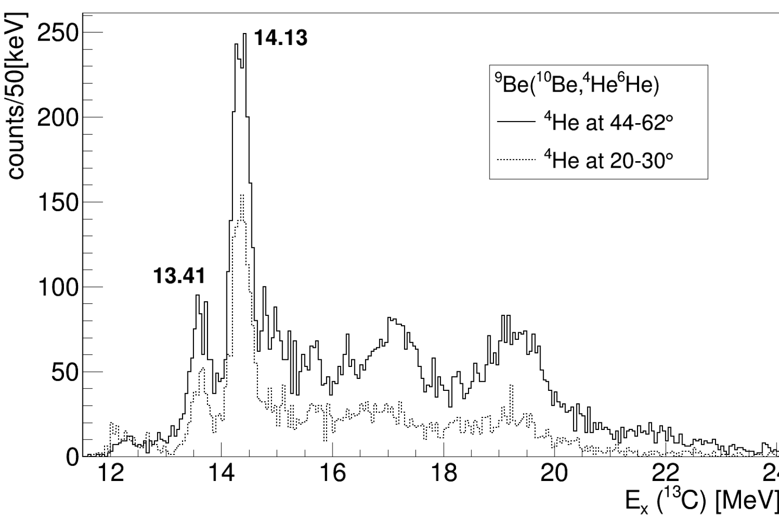

Fig. 3. ^{13}C excitation energies from ^{6}He + ^{4}He coincident detections.

systematics [5] of the ^{13}C cluster states, since at such high excitation energies, members of the rotational bands with cluster character are supposed to have higher spins; *e.g.* the 13.41 MeV state is suggested to have $7/2^+$ [4] or $9/2^-$ [5]. Further work is needed to clarify this point.

4. Conclusion

The ^{10}Be + ^{9}Be reactions were measured to get information on different types of structures of several light nuclei. The ^{13}C excitation energies coming from the ^{6}He single detections and ^{6}He + ^{4}He coincidences were shown. The results from single detections are similar to previous results coming from the ^{9}Be(^{6}Li,d)^{13}C reaction [3], while the results from coincident detections point to the alpha-cluster character of the $E_x = 14.13$ MeV state.

As at least one ^{13}C state is strongly populated by the transfer of alpha-particles to the (target) ^{9}Be nuclei, indicating its pronounced cluster structure, the aim of further analysis is to look for the analog state(s) in ^{14}C and ^{15}C. These would be populated by the ^{10}Be-induced pick-up of the alpha-particle or the ^{5}He-cluster, respectively, the latter not necessarily in one step. Such a simple comparison would be the direct proof of special structure for the populated states, offering a clear evolution of clustering effect with the addition of neutrons. The experimental signature of these processes would be the first indication of the existence of cluster states inside the ^{15}C nucleus, while a positive result for the ^{14}C isotope would help to clear up the contradicting findings of other authors.

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