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EXPERIMENTAL EVIDENCE FOR MOLECULAR STRUCTURES IN LIGHT NUCLEI

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Experimental studies of the cluster structures in ^{9,10}Be and ^{13,14}C have been performed. Evidence for the α+^{5}He decay of ^{9}Be excited states, α+^{6}He decays of ^{10}Be*, α+^{9}Be decay of ^{13}C* and for the decays of ^{14}C* into α+^{10}Be were found. These decay processes indicate the cluster structures of the excited states. The results are compared with recent suggestions for the presence of molecule-like structures based upon α-particles and valence neutrons in Be and C isotopes.

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1. *Introduction*

Studies of light nuclei are interesting in their own right as almost every nucleus possesses some unique properties which reflect its structure. The varied structures which appear in light nuclei, from spherical shapes to prominent clustering, are a considerable challenge to understand and model. It should be mentioned that limited and often contradictory information exists for many of them, restricting a full understanding of their structure. However, it is well known that cluster structures based on α-particle, the lightest doubly magic nucleus, appear in many light nuclei. Particularly even-even nuclei composed of integer number of α-particles can condense into their full α-particle structures [1]. The ^{8}Be nucleus, which is unbound to α-decay even in the ground state, exhibits a pronounced 2α cluster structure. Evidence for this structure are the large α-particle decay widths and the rotational characteristics of ^{8}Be. Similarly, ^{12}C can be explained as the 3α system with a compact ground state possessing triangular structure, 7.65 MeV 0_2^+ state which is just above the 3α decay threshold and which probably has a dilute 3-body structure [2, 3] and the third 0^+ state at 10.3 MeV which is a possible candidate for the 3α chain structure. It might be anticipated that the clustering present in such nuclei has a major role in the structural properties of heavier isotopes and that the neutrons introduced into these systems are affected by the many-centre nature of the underlying potential. Such nuclei would be then a nuclear analogues of covalent atomic molecules [4 − 6]. Valence neutrons around α-particle are in the p-type orbits and their linear combinations produce σ and π-type molecular orbits in neutron-rich Be isotopes. The π-type orbit is located around two centres providing a more compact structure, while the σ-type orbit, located between the centres, can make a very extended structure. There is reasonably good evidence for states with such characteristics in ^{9,10}Be [5] and also tentative evidence for such structures in ^{11,12}Be [5, 7 − 9]. A natural extension to more complex molecular systems would be the neutron-rich carbon isotopes. A recent analysis of available data [10] has provided tentative evidence for the existence of such a structure in ^{13}C.

Recent molecular orbit model (MOM) calculations [11 − 13] and calculations using the antisymmetrized molecular dynamics (AMD) framework [14 − 16] reproduce well the known properties of the beryllium and carbon isotopes and support this molecular picture. The microscopic cluster models also describe well these nuclei [17 − 19]. The MOM and AMD calculations show that the introduction of valence neutrons stabilize α-cluster structure and that clustering has a important role in the structural properties of heavier neutron-rich isotopes. AMD results even propose a new type of cluster structure in these nuclei with neutron-rich helium isotopes as a basic blocks [15]. It should be mentioned that the neutron-rich nuclei mainly can not be explained within the shell model.

Experimental signature for cluster structure is the observation of excited states with large decay and population probability for the channel corresponding to cluster structure and suppressed single-nucleon decay/population probability. These states should form rotational bands associated with large deformations. We report here some of our recent results on the exotic molecule-like structures in ^{9,10}Be and ^{13,14}C. The results on beryllium nuclei were obtained in the research carried by the Zagreb-Catania collaboration and the studies of carbon nuclei were done in collaboration with groups from UK universities.

2. *Experimental details*

We would like to note that the experimental techniques which we use in research are very similar to those utilized in experiments in high-energy nuclear physics. Our experimental tool for the detection and particle identification of charged products of nuclear reactions are detector telescopes consisting of large-area position-sensitive silicon detectors. Usual telescope setup for detection of light nuclei contains a thin silicon detector in front of the silicon strip detector divided into independent position-sensitive strips and thick CsI detector as the third element. The telescopes for heavier nuclei ($Z \geq 5$) consist of an ionization chamber for ΔE measurement and a position-sensitive silicon detector. Good energy and angular resolution as well as separation of different He, Li and Be isotopes can be achieved. A typical experimental setup includes $4-8$ such telescopes covering a significant angular range. Such setup permits a kinematically complete measurement, i.e. simultaneous measurement of the energies and angles of two or more charged particles in the many-body reaction exit channel which provide a complete determination of the reaction kinematics. We are able to identify and separate events for a particular reaction by reconstruction of the total energy (Q-value) in the reaction. Given the measurement of the momenta of the detected reaction products (in most cases two of three in total) it is possible to reconstruct the excitation energy of the parent nucleus. However, given that there are 3 particles in the final state, it is possible that they can be produced via the decay of either of 3 possible parent nuclei. All these possibilities should be reconstructed and contributions of different parent nuclei identified using modified Dalitz plots.

Here we present results from two measurements of the ^{7}Li+^{7}Li reactions done at the Ruđer Bošković Institute EN Tandem Van de Graaff accelerator ($E_{\rm beam}$ = 8 MeV) [20] and the SMP Tandem Van de Graaff accelerator at the Laboratori Nazionali del Sud, Catania ($E_{\rm beam}$ = 30 MeV) [21] and two measurements of the ^{7}Li+^{9}Be reactions performed at the Laboratori Nazionali del Sud ($E_{\rm beam}(^7{\rm Li})$ = 52 MeV) [21−23] and the 14UD Tandem Van de Graaff accelerator at the Australian National University, Canberra ($E_{\rm beam}(^9{\rm Be})$ = 70 MeV) [24, 25].

3. *Experimental results and discussion*

3.1. ^{9}Be *and* ^{10}Be

^{9}Be has one of the largest deformation among the stable nuclei. Its low excitation spectroscopy can be explained in terms of the sharing of the neutron between two α cores [5]. Its ground state corresponds to the π-type configuration, and the first excited $1/2^+$ state, which is not explained within the shell model, corresponds to the σ-type neutron orbit. Some of the states at higher excitations can be explained as rotational excitations of these two deformed structures. Our observation of the strong ^{7}Li+α quasi-free scattering in the ^{9}Be(^{7}Li,^{7}Liα)^{5}He reaction [23] shows that dominant structure of the ^{9}Be ground state is the ^{5}He+α configuration, in agreement with the result of the cluster model calculations [26] and other experimental results (see references in Refs. [23] and [27]). Figure 1a shows the ^{9}Be excitation energy spectrum for the ^{9}Be+^{7}Li scattering, obtained from the ^{7}Li data measured at $22.5^\circ - 31^\circ$. Four distinct groups are observed corresponding to ^{9}Be excitation energies of 0.0, 2.4, 6.7 and 11.3 MeV. The satellites seen for the first two groups correspond to the simultaneous excitation of ^{7}Li to its first excited state. The spectrum shows strong excitation of the states with energies approximately following the $J(J+1)$ rule, indicating that these states are members of a rotational band. Figure 1b presents the ^{9}Be excitation energy spectrum for the ^{9}Be(^{7}Li,^{7}Liα)^{5}He reaction. The spectrum was obtained from the ^{7}Li+α coincidence data where α was detected at 50.4° and ^{7}Li between 26° and 38°, with a cut imposed on the Q-value corresponding to the ^{5}He ground state. Three distinct peaks are visible at 3.0, 6.7 and 11.3 MeV. The first peak is interpreted as α+^{5}He decay of the 2.4 MeV state corresponding to the simultaneous excitation of ^{7}Li to its first excited state. From the spectrum, it is not possible to conclude whether the broad peaks centred at 6.7 and 11.3 MeV are due to a single broad state or two levels possible at each of these energies. Contributions of the events with ^{7}Li in the first excited state are expected for these two peaks. The experimental results unambiguously showed for the first time that states of ^{9}Be decay into α+^{5}He, which is also the dominant configuration of its ground state. This fact and their strong excitation in inelastic scattering suggest that states at 0.0, 2.4, 6.7 and 11.3 MeV form the rotational band [22].

The ^{10}Be spectroscopy has recently received a special attention in connection with the properties of the valence neutrons around the highly developed α-cluster

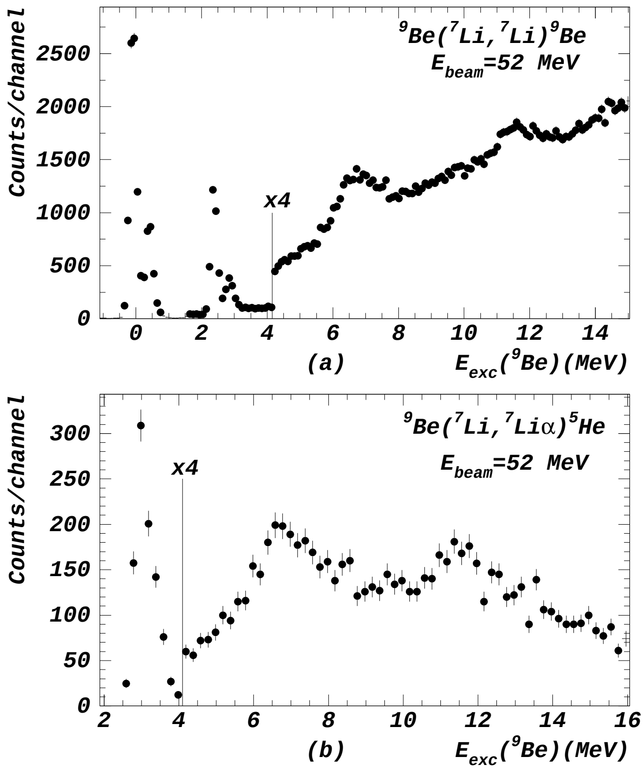

Fig. 1. (a) ^{9}Be *excitation energy spectrum for the* ^{9}Be+^{7}Li *scattering. (b)* ^{9}Be *excitation energy spectrum from the* ^{9}Be(^{7}Li,^{7}Liα)^{5}He *reaction. In both spectra, the data below 4.1* MeV *were divided by 4.*

system. The first evidence for the α-decay of ^{10}Be excited states was observed in our kinematically complete measurements of the ^{7}Li+^{7}Li $\rightarrow$ ^{4}He+^{4}He+^{6}He reaction at $E_{\rm beam} = 8$ MeV [20]. In these measurements, it was observed that the states at 9.6 and 10.2 MeV decay by ^{6}He emission. The ^{10}Be excitation energy spectrum for the ^{7}Li(^{7}Li,α^9Be)n reaction from the same data showed that the states at 9.3, 9.6 and 10.6 MeV decay into n+^{9}Be$_{gs}$ but the state at 10.2 MeV does not. These facts imply a special cluster structure of the 10.2 MeV state. It was speculated [20] that this state is a 4^+ member of the rotational band based on the 6.18 MeV 0^+ state with its 2^+ member at 7.54 MeV. The small energy separation between these states implies a large moment of inertia of that system. Evidence that the state at 7.54 MeV has a cluster structure and structural link with the 6.18 MeV state came from the measurements of the α-transfer reaction ^{6}Li(^{6}He,^{10}Be) [28] and from the α+^{6}He decay of the state observed in the measurements of the ^{7}Li(^{7}Li,α^6He) reaction [29]. α-decay of the 10.2 MeV state was confirmed in our recent measurements of the ^{6}Li+^{6}He $\rightarrow$ d+^{4}He+^{6}He reaction [28], ^{6,7}Li(^{7}Li,α^6He) reactions [30] and also in our measurements of the ^{7}Li+^{7}Li $\rightarrow$ ^{4}He+^{4}He+^{6}He reaction at $E_{\rm beam} = 30$ MeV and ^{9}Be+^{7}Li $\rightarrow$ ^{4}He+^{6}He+^{6}Li at 52 MeV [21]. The ^{10}Be excitation energy spectra obtained in our most recent measurements [21], presented in Fig. 2, show that the

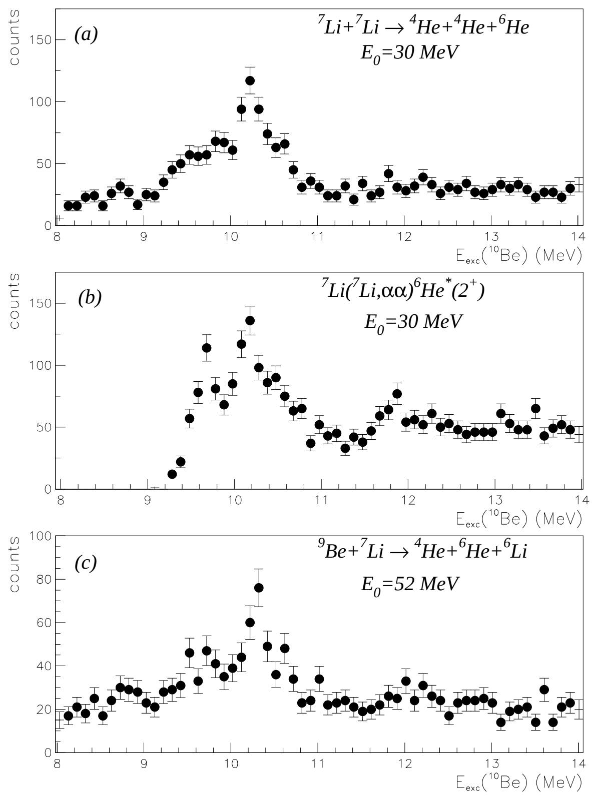

Fig. 2. ^{10}Be *excitation energy spectra from the coincidence measurements of the following reactions: (a)* ^{7}Li+^{7}Li $\longrightarrow$ *2*α+^{6}He *at* $E_{\rm beam}$ = 30 MeV, *(b)* $^7{\rm Li}(^7{\rm Li},\alpha\alpha)^6{\rm He}^*$(1.8 MeV), *(c)* $^9{\rm Be} + ^7{\rm Li} \longrightarrow \alpha + ^6{\rm He} + ^6{\rm Li}$ *at* $E_{\rm beam} =$ 52 MeV.

state at 11.8 MeV also decays by α-emission and that these three states also decay to the first excited state of ^{6}He. Indications that higher energy states decay into ^{6}He+α was found in [8, 30]. However, the analysis of the ^{6}He+α angular correlations in Ref. [30] indicates that the 10.2 MeV state has $J^\pi = 3^-$, which contradicts proposed rotational band and leaves open the question regarding the structure of the states in this nucleus. Certainly, this result requires further confirmation, and observation of the proposed 4^+ (and possible higher spin members of the band) remains an experimental challenge.

3.2. ^{13}C *and* ^{14}C

Indications for states with strong α-clustering and their relation to molecular states have been presented recently for the ^{13}C nucleus [10]. Via an examination of the previous experimental results, two rotational bands were proposed whose

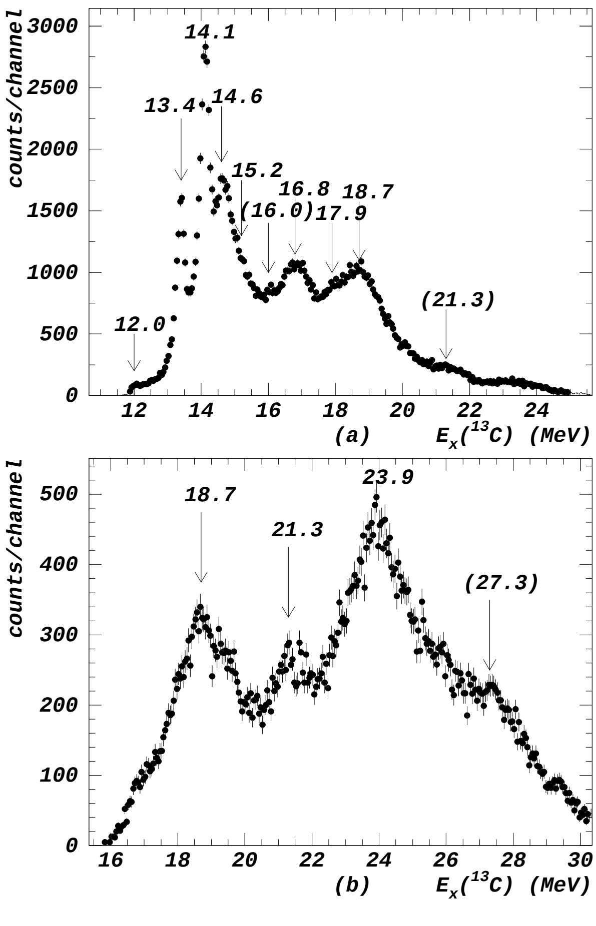

Fig. 3. ^{13}C *excitation energy spectra from the* ^{7}Li(^{9}Be, α^9Be)^{3}H *reaction at* $E_{\rm beam} = 70$ MeV *[25] for decays detected in detectors located with their centres at ∼ 17.5° (a), and for detectors at ∼ 29° (b). Observed peaks are labelled with excitation energies* (MeV).

deformations indicate a chain-like structure. However, the spin and parity of many of these states remain to be confirmed. The first evidence for the α+^{9}Be decay of low-lying ^{13}C excited states was found in the measurements of the ^{7}Li(^{9}Be,^{9}Beα) reaction [31]. The ^{13}C excitation energy spectra from our recent measurements using the ^{7}Li(^{9}Be,α^9Be) reaction at $E_{\rm beam}$ = 70 MeV [25] are presented in Fig. 3 for two detectors settings. The spectra show a number of strong peaks at 13.4, 14.1, 14.6, 16.8, 18.7, 21.3 and 23.9 MeV, and there is some evidence for additional states at 12.0, 15.2, 16.0, 17.9 and 27.3 MeV. Given that the threshold for α-decay is at much higher excitation (10.65 MeV) than that for neutron decay (4.95 MeV), prominent α-decay of the state indicates its cluster structure. It is probable that the peaks at 18.7, 21.3 and 23.9 MeV correspond to new resonances in this nucleus, which may possess a structural link with those at lower energies. Assuming the most likely reaction mechanism at these energies, α-transfer onto the α+n+α cluster nucleus ^{9}Be, it is very likely that some of the states observed here may be linked with the suggested 3α+n chain structure. An analysis of the angular distributions [25] suggests that the group of states at excitation energies 14.1, 14.6, 16.8, 18.7 and 21.3 corresponds to the α-transfer to a common orbital in ^{13}C. The results of our measurements suggest that there may be inconsistencies in the assignments made in identifying the chain structure in Ref. [10].

The ^{14}C nucleus possesses closed neutron shell and the structural properties of its low-lying states are well described within the shell model. However, one can expect that states at higher excitation feature molecular structure 3α+2n, in analogy with another neutron closed-shell nucleus ^{12}Be (2α+4n) [12, 14]. A study of the ^{7}Li(^{9}Be,α^{10}Be) reaction at $E_{\rm beam}$ = 70 MeV has been performed and provides the first evidence for α-decaying states in ^{14}C [24]. Figure 4a shows the reconstructed ^{14}C excitation energy spectrum for the decay to the ^{10}Be ground state, for coincidences between the detectors located with their centres at $\sim 17.5^\circ$. Figure 4b corresponds to α-decay to the ^{10}Be first excited state (2^+) as measured by the same detector pair. Finally, the α-decay spectrum for decays to the quartet of ^{10}Be states (2^+, 1^-, 0^+ and 2^-) around 6 MeV excitation is shown in Fig. 4c. These spectra show excited states at 14.7, 15.5, 16.4, 18.5, 19.8, 20.6, 21.4, 22.4 and 24.0 MeV. An interesting feature of the results is that the ^{14}C states which decay to the ^{10}Be ground and first 2^+ state appear to be the same, while decays to the 6 MeV states in ^{10}Be appear not to coincide with them. Thus, there appears to be a preference for the decay of the lower excitation energy states in ^{14}C to either the ^{10}Be ground or first excited state, while the higher lying states decay to the excited states at 6 MeV. This difference may perhaps be explained in terms of the structure of the various ^{10}Be states. In the MOM and AMD description, the ^{10}Be ground and first excited states correspond to the occupation of the π-orbit for the two valence neutrons, whereas the 6 MeV states require either two neutrons in the σ-orbit or a combination of σ- and π-like neutrons. It is possible that the lower-energy ^{14}C excited states are based upon neutrons in the π-type molecular configurations, whereas the higher-energy states contain some σ-orbit admixture. Whether these states correspond to molecular configurations is unclear and require measurements of the spins and parities of the states.

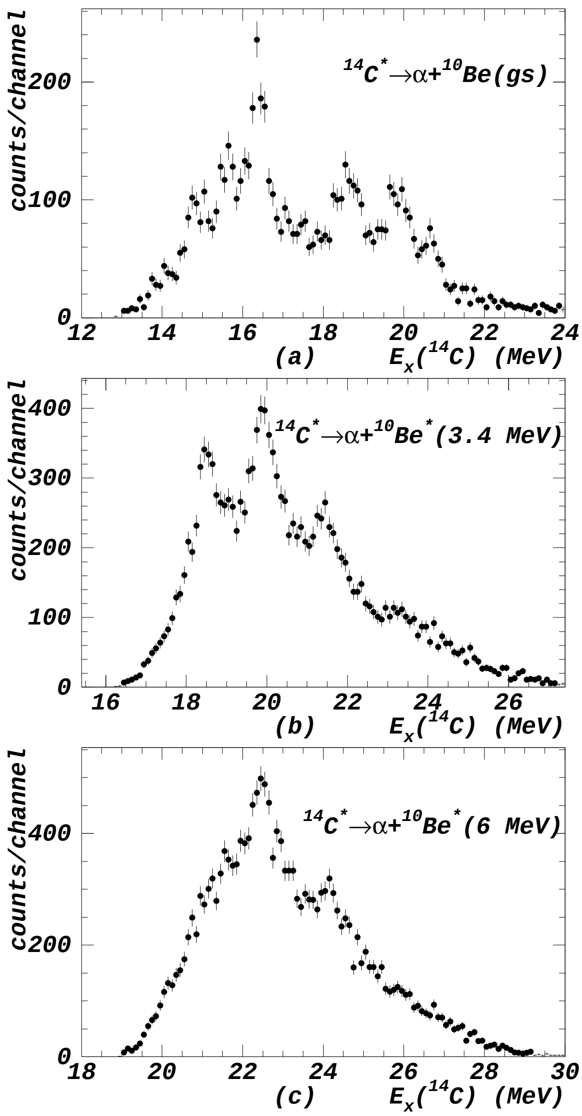

Fig. 4. ^{14}C *excitation energy spectra from the* ^{7}Li(^{9}Be, α^{10}Be)^{2}H *reaction at* $E_{\rm beam} = 70$ MeV *[24] for decays to (a)* ^{10}Be *ground state, (b)* ^{10}Be *first excited* 2^+ *state, and (c) quartet of* ^{10}Be *states around* 6 MeV *excitation.*

4. Conclusion

We have presented here a compilation of our results concerning molecular-like structures in ^{9,10}Be and ^{13,14}C. These results, as well as other relevant results mentioned in this paper, provide evidence for exotic structures composed of α-particles and valence neutrons around the cores. Clearly, more experimental data, especially spin and parity determinations, are imperative in order to fully understand the nature of observed α-decaying states in these nuclei. Such studies of the spectroscopy of nuclei above particle decay thresholds and the extraction of spin information are a considerable experimental challenge but are essential for understanding and modelling beryllium and carbon nuclei and reactions between them. This will then lead us to a greater insight into the structural properties of neutron-rich light nuclei and even heavier nuclei. It was recently proposed [32] that molecular-like structures based upon α+^{16}O (^{16}O is the second doubly magic nucleus) and ^{16}O+^{16}O cores could appear in neon, magnesium and heavier nuclei. We have performed and proposed measurements which will provide us with more detailed experimental data for nuclei considered here as well as for proposed more exotic structures in heavier nuclei.

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EKSPERIMENTALNI DOKAZI (POKAZATELJI) MOLEKULSKE STRUKTURE LAKIH JEZGRI

Eksperimentalno smo proučavali nakupinske strukture u ^{9,10}Be i ^{13,14}C. Našli smo α+^{5}He raspad uzbuđenog stanja ^{9}Be, α+^{6}He raspad ^{10}Be*, α+^{9}Be raspad ^{13}C* te raspad ^{14}C* u α+^{10}Be. Ovi procesi ukazuju na nakupinske strukture uzbuđenih stanja tih jezgri. Ishode mjerenja uspoređujemo s novim objašnjenjima o prisutnosti molekulama-sličnih struktura zasnovanim na α-česticama i valentnim neutronima u izotopima Be i C.