ISSN 1330–0016
CODEN FIZBE7

^{10}Be AND MOLECULAR STATES

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Dedicated to Professor Kseno Ilakovac on the occasion of his 70$^{\mathbf{th}}$ birthday

Received 15 August 2001; Accepted 21 January 2002
Online 6 April 2002

The ^{10}Be excitation energy spectra have been obtained from the inclusive and coincident measurements of the reactions: ^{7}Li + ^{7}Li at $E_0 = 8$ and 30 MeV and ^{9}Be + ^{7}Li at $E_0 = 52$ MeV. Contributions of the ^{10}Be states below 12 MeV in excitation have been observed. Decays of the states at 9.6, 10.2 and 11.8 into $\alpha + {}^6$He and, for the first time, into $\alpha + {}^6$He* have been found. The results are discussed in addition to the other experimental data and recent theoretical predictions. Proposals for future measurements to search for exotic structures in carbon nuclei are also made.

PACS numbers: 25.70.-z, 27.20.+n UDC 539.17

Keywords: nuclear reactions ^{7}Li + ^{7}Li, $E = 8$ and 30 MeV, ^{9}Be + ^{7}Li, $E = 52$ MeV, ^{10}Be levels deduced, $\alpha + {}^6$He and $\alpha + {}^6$He* decays

1. *Introduction*

^{10}Be nucleus has recently received special attention in connection with studies of neutron-rich nuclei. It is considered to be a good example of nuclei composed of α-particles and valence neutrons. Success of different cluster and molecular approaches [1–5] in explaining ^{10}Be level scheme, and some other experimental data, seems to support the idea that the structure of excited states below, at least, 12 MeV in excitation is the one of an $\alpha - \alpha$ core and two valent neutrons in orbits around the clusters. Because of these features, an analogy is sometimes drawn between the ^{10}Be nucleus and H_2 molecule (its isoelectronic analog, long-lived and poorly known ion, He_2^{++} [6], may be, in some aspects, a better example).

Experimentally, twelve levels have been well established below the $t+{}^7$Li decay threshold at 17.25 MeV (Fig. 1). A new level has been added recently from studies of the ^{7}Li(α,p) [7], ^{7}Li(^{7}Li, α^6He) [8,9] and ^{7}Li(^{6}He,dα^6He) reactions [10]. There are no firm assignments for all the states above the $2\alpha + 2$n threshold, although some convincing and other conflicting proposals for them have been made. Also, just recently, there have been claims of new states below the $t+{}^7$Li threshold [12,13]. Crucial role which ^{10}Be may have in understanding neutron rich nuclei makes any experimental information on its states very valuable. Because of that,

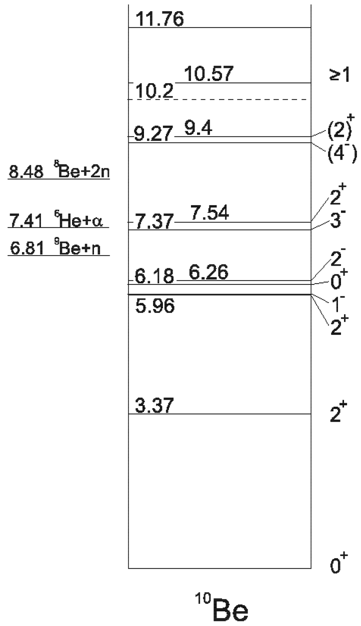

Fig. 1. Level scheme of ^{10}Be *below 12* MeV *in excitation, adopted from Ref. [11].*

we are presenting results from the ^{7}Li$+{}^7$Li and ^{9}Be$+{}^7$Li experiments and also are summarising available data on the states of ^{10}Be. At the end, several experimental proposals are given to search for possible molecule-like structures in carbon nuclei.

2. *Experiment*

Two measurements were performed at the Laboratori Nazionali del Sud using the ^{7}Li^{+++} beams from the SMP Tandem Van de Graaff accelerator. In the first experiment, isotopically enriched ^{7}LiF targets ($300 - 600$ μg cm^{-2}) on thin carbon backings were bombarded with the 30 MeV beam ($I = 20 - 50$ nA), while in the second experiment, a selfsupported beryllium target (400 μg cm^{-2}) with the 52 MeV beam ($I = 60 - 100$ nA) was used. Outgoing charged particles were detected and identified in the particle telescopes consisting either of standard surface barrier detectors (T_1) or of an ionization chamber and a silicon position-sensitive detector

(T_2). In the same scattering plane altogether three T_1 telescopes were positioned on one side and two T_2 on the other side of the beam. An angular range of 8° was covered by each T_2, while the openings of T_1 were 1°. Coincidence events of any T_1-T_2 pair were recorded. In a short experiment at the Ruđer Bošković Institute, an 8 MeV $^7Li^{++}$ beam ($I = 10-30$ nA) from the EN Van de Graaff accelerator was used to bombard an isotopically enriched ^{7}LiF target (100 μg cm^{-2}) on thin gold backing. For the detection of the outgoing charged particles, a particle telescope was used consisting of a 15 mm and a 300 mm silicon surface barrier detector.

3. Experimental results

Some results from the measurements concerning ^{9}Be nucleus were published earlier [14,15]. Here we concentrate only on the results relevant to ^{10}Be. Figure 2a shows a ^{10}Be excitation energy spectrum obtained from the measurement of the

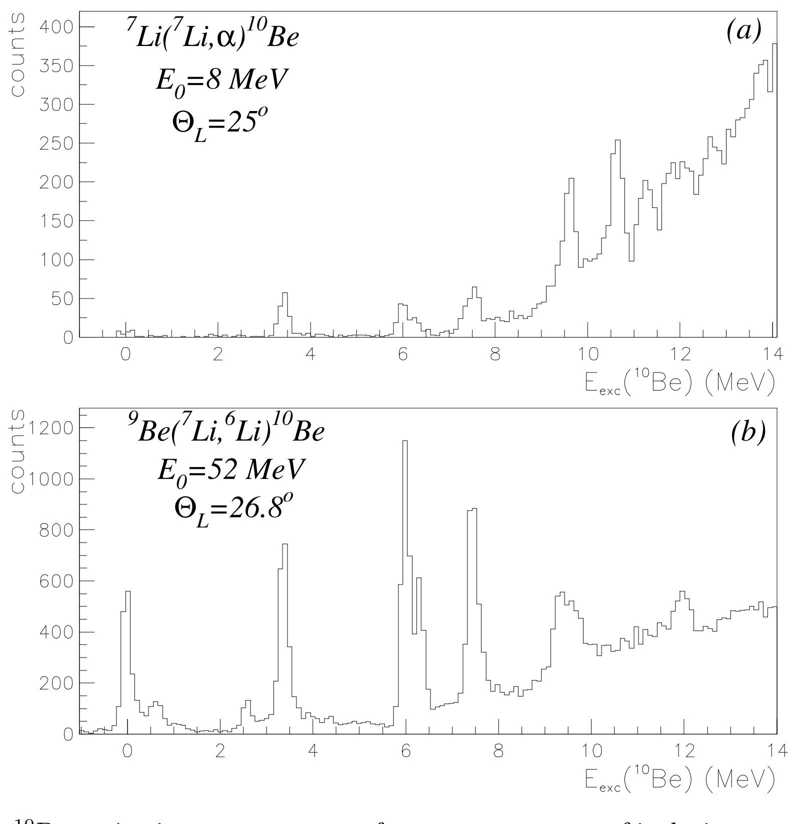

Fig. 2. ^{10}Be *excitation energy spectra from measurements of inclusive reactions: a)* ^{7}Li(^{7}Li, α) *at* $E_i = 8$ MeV *and* $\Theta_1 = 25°$, *b)* ^{9}Be(^{7}Li,^{6} Li) *at* $E_i = 52$ MeV *and* $\Theta_2 = 26.8°$.

^{7}Li(^{7}Li, α) reaction at E_0 = 8 MeV and Θ_L = 25°. Several similar spectra for other angles were measured, too. Their common features are: a weak population of the ground state, somewhat stronger contribution of the 3.37 MeV state and those around 6 and 7.5 MeV. The most intensive peaks correspond to excitation energies of 9.6 and 10.6 MeV. At higher excitations, together with many-body breakup contributions, a noticeable background is also present due to the (^{7}Li, α) reaction

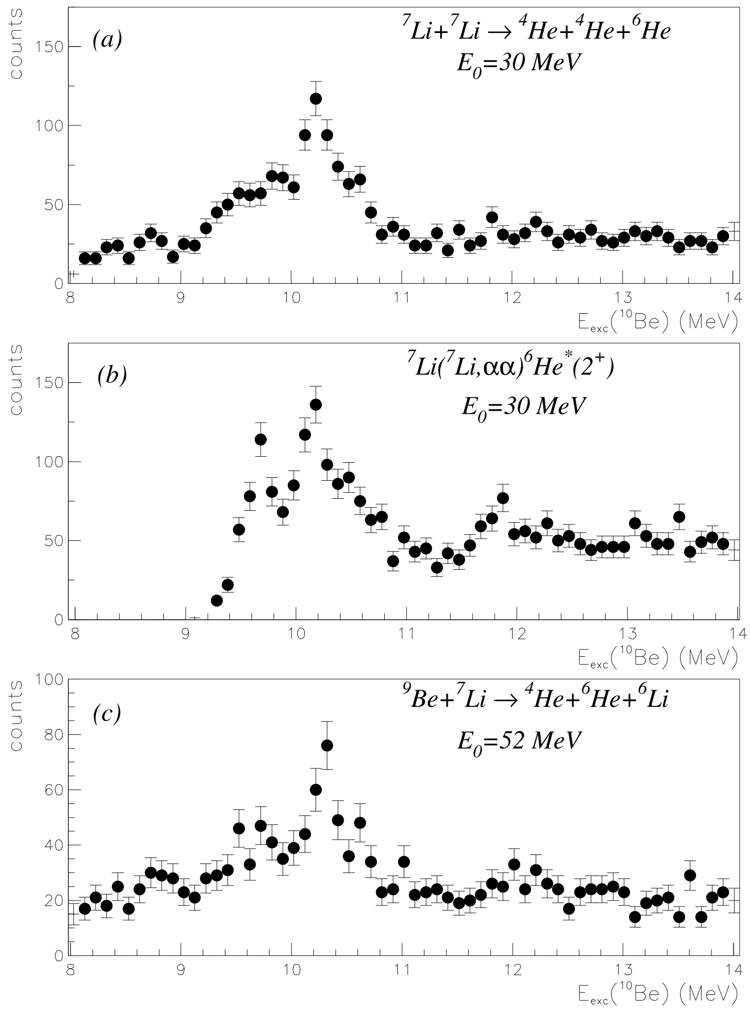

Fig. 3. ^{10}Be *excitation energy spectra from coincident measurements of the reactions: a)* ^{7}Li^7 + Li $\rightarrow \alpha +^6$He + α *at* E_i = 30 MeV *b)* ^{7}Li +^{7}Li $\rightarrow \alpha + \alpha +^6$He* ($E_x$ = 1.8 MeV) *at* E_i = 30 MeV *c)* ^{9}Be +^{7}Li $\rightarrow^6$ Li +^{6}He + α *at* E_i = 52 MeV. *Each spectrum is a sum of several spectra measured at different detector settings. Error bars represent statistical errors only.*

on carbon impurities. For example, a peak seen at 11.3 MeV is due to the most strongly populated ^{15}N states around excitation of 9.15 MeV. Background due to the ^{19}F(^{7}Li, α) reaction is very weak at this energy close to the Coulomb barrier [16]. It should be pointed out that in all spectra no significant contribution from the 10.2 MeV state is visible. It is seen only after coincidence requirement is imposed on its decay products, α and ^{6}He [8]. In some of these spectra, a contribution of the 11.8 MeV state could be seen, too.

Figure 2b shows a ^{10}Be excitation energy spectrum from the ^{9}Be(^{7}Li,^{6}Li) reaction measured at $E_0 = 52$ MeV by a T_2 telescope centered at $\Theta_L = 26.8°$. The background (e.g., small peaks at $E_{\rm exc} = 0.5$ and 2.5 MeV) is due to strong ^{7}Li scattering contributions and a not perfect separation between ^{6}Li and ^{7}Li ions. A similar spectrum was earlier observed at $E_0 = 34$ MeV [17]. Main difference between the spectra from Fig. 2 is in the population of the 9 MeV states and of the state at 10.6 MeV.

Figure 3 presents the ^{10}Be excitation energy spectra obtained from coincident measurements of the reactions ^{7}Li + ^{7}Li at $E_0 = 30$ MeV ((a) and (b)) and of the reaction ^{9}Be + ^{7}Li at $E_0 = 52$ MeV ((c)). Each spectrum represents a sum of coincident events recorded by all $T_1 - T_2$ telescope pairs. The following coincidences were included in the spectra: (a) $\alpha - \alpha$ and $\alpha - {}^{6}$He, (b) $\alpha - \alpha$, (c) ^{6}Li$-\alpha$ and ^{6}Li $-{}^{6}$He. The main results from the measurements are:

- α decay of the ^{10}Be states into the first excited state of ^{6}He is observed for the first time;
- the strongest contribution from the α decaying states belongs to the 10.2 MeV state;
- additionally, the only states below 14 MeV in excitation, which undoubtedly contribute to the decays, are those of 9.6 and 11.8 MeV. In the ^{9}Be + ^{7}Li reaction measurements it was noticed that only a minute part of many-body break-up data belonged to the $\alpha + {}^{6}$He + ^{6}Li channel.

4. *Discussion*

4.1. *States of* ^{10}Be *at* $0 \leq E_{\rm exc} < 8.5$ MeV

The assignments as well as many properties of all eight states are well established. Because of that, only brief comments are given here.

4.1.1. **0$^+$(0** MeV**) and 2$^+$ (3.37** MeV**)**

These states are strongly populated in different one-nucleon transfer reactions on neighbouring nuclei suggesting that their structure does not differ drastically from those of the ground states of ^{10}Be neighbours. A strong E2 transition between these states was an early indication of their large deformation. Several recent calculations [3,4] show that the $\alpha - \alpha$ core persists in these states. The α-clusters are closer than in ^{8}Be, which is indicated also by a larger energy difference between these first members of the ground state rotational band (3.37 MeV) with respect to the one in ^{8}Be (3.04 MeV).

4.1.2. $\mathbf{2^+, 1^-, 0^+, 2^-}$ (≈ 6 MeV)

These states were taken as one of the most important proofs of two-centre molecular structure in $A = 9, 10$ nuclei [2]. Much earlier, special attention was given to the 0^+ state which was considered to be an intruder (i.e., having the configurations with two neutrons in the sd shell). That was confirmed by the results from one-nucleon transfer reactions, where its contributions were either very weak, or unobservable. In recent molecular and cluster approaches, it was shown that this state should be a very extended object, with a very developed α–^{6}He cluster structure [2–5]. Concerning the 1^- state, the results in Ref. [3] contradict those in Ref. [5]. Namely, in Ref. [3], it was found that this state also has a very developed $\alpha - ^6$He cluster structure, contrary to a very small $\alpha - ^6$He spectroscopic factor (0.01) found in Ref. [5].

4.1.3. $\mathbf{3^-}$ (**7.37** MeV) **and** $\mathbf{2^+}$ (**7.54** MeV).

Both states were seen as resonances in neutron total cross section of ^{9}Be, the first being strong with a width $\Gamma = 15.7$ keV and the second weak with $\Gamma = 6.3$ keV [27–29]. Both of them are considered to be the members of corresponding rotational bands based on the 1_1^- and 0_2^+ states, respectively. From other neutron stripping reactions [21–23] and our (^{7}Li,^{6}Li) data it was observed that the cross sections for 3_1^- are at least an order of magnitude larger than those for 2_3^+, in accordance with the neutron data and different couplings of these states to the ^{9}Be ground state. In recent ^{6}Li +^{6}He reaction measurements, it was found that the unresolved doublet is strongly populated [10]. If it is true that the $\alpha - ^6$He spectroscopic factor is small for 3_1^-, as it was claimed to be for its band head 1_1^- [5], then this would be a direct proof of a pronounced α–^{6}He clustering of 2_3^+. Recently, the ^{6}Li$^*(T = 1) + \alpha$ decay either from one or from both of their analogs in ^{10}B ($E_{\mathrm{exc}} \approx 8.9$ MeV) was observed [30].

4.2. States of ^{10}Be *with* $8.5 < E_{\mathrm{exc}} < 14$ MeV

There are five well established states in this energy region, all of them above the four body break-up threshold and with no firm assignments. Although experimental data and theoretical predictions for them are scarce and less accurate than for the lower states, it is shown that there is enough evidence to claim the assignments for some, and to narrow them for others.

4.2.1. **9** MeV **states.**

In the last review of energy levels of light nuclei [11], two states are mentioned with energies $E_{\rm exc} = 9.27$ and 9.4 MeV, widths, $\Gamma = 150$ and 291 keV, and possible assignments, $J^\pi = 4^-$ and 2^+, respectively. The energies came from an old neutron total cross section measurement [27], in which a broad structure was seen in this region. A possible 4^- assignment to the lower level was deduced from the neutron polarization data. However, there are also claims for 2^- or even 3^- from the (d, p) reaction [22]. Common to all these assignments is $j^\pi = (\frac{5}{2})^+$ of the neutron involved, which coupled with $(\frac{3}{2})^-$ of ^{9}Be ground state could give all of them and 1^-, too. Forward parts of angular distributions from the (d,p) [22] and (α,^{3}He) reactions [23] for this doublet have the same ($l = 2$) shape as those for the 3_1^- state, indicating that contributions from the lower member predominates. All recent cluster and molecular approaches [2–4] predict existence of the $K^\pi = 1^-$ rotational band in which this state, if it is 4^-, together with the known $1^-, 2^-$ and 3^- naturally fits in. However, the molecular orbit model [4] predicts, close to the 4^- state, a 2_2^- state, the head of the $K^\pi = 2^-$ band, with a very strong coupling between two negative parity bands. From previous [8,9] and present coincident measurement data, there is no evidence that it decays into α+^{6}He, which may be an indication of its non-normal parity.

For the other state higher in energy, one can safely claim that it is a 2^+ state. Recent suggestion [31] that it is most likely a 3^+ state could be rejected by present and previous data [8,9] which show that it decays into $\alpha+^6$He. Its strong Gamow-Teller transition in the ^{10}B(t,^{3}He) reaction [31] leaves only 2^+ and 4^+ as possible assignments. Clear l=1 transition from the ^{11}B(d,^{3}He) reaction [20] narrows it to 2^+. Additionally, the results from the two-proton pickup [13,32], (d,^{2}He) [33] and (π^-, γ) reactions [34] all support this assignment. Recent and present coincident measurements support the same conclusion. Namely, an angular correlation analysis (not fully explained) of its $\alpha+^6$He decay gives 2^+, too [9]. Its $\alpha+^6$He* decay would not be so relatively strong (see Fig. 3b) if it were not a 2^+ state ($L = 0$ transition), because with its decay energy of only 0.4 MeV, any additional centrifugal barrier would strongly suppress it.

This state was well described even by old intermediate-coupling shell-model calculations [35] as was pointed out in Ref. [20]. The molecular orbit model [4] predicts a 2^+ state at these excitations as a member of the 1^+ band. However, there has not been any experimental evidence for the 1^+ state. From recent measurements, it was claimed that this state has $E_{\rm exc} = (9.56 \pm 0.02)$ MeV and $\Gamma = (153 \pm 10)$ keV [9].

4.2.2. **10.2** MeV **state.**

This state has been only recently discovered, simultaneously from the ^{7}Li(α, p) [7] and ^{7}Li(^{7}Li, α^6He)^{4}He reactions [8]. Its energy coincides with the ^{5}He$+^5$He decay threshold. Based on its energy, its $\alpha+^6$He, but no ^{9}Be$+$n decay, and also its absence in the spectra of different transfer reactions, it was speculated that it could be the 4^+ member of the rotational band based on 0_2^+. Its existence has been confirmed subsequently by the ^{6}Li$+^6$He reaction measurements [10], our present results, as well as by the most recent study of the ^{7}Li(^{7}Li, α^6He)^{4}He reaction at $E_0 = 34$ MeV [9]. From the analysis of the $\alpha+^6$He angular correlation, not fully explained in Ref. [9], it was concluded that it is a 3^- state. Also, its $E_{\rm exc}$ and Γ were found to be (10.15 ± 0.02) MeV and (310 ± 12) keV. One can mention that there are two conflicting predictions for the 3_2^- state. While Fujimura et al. [36] claim, that the 3^- molecular resonance in this energy region is totally different from the 3_1^- state, Itagaki and Okabe [4] predict that the first two 3^- states belong to different bands ($K^\pi = 1^-$ and 2^-), but with strong mixing between them. Obviously, more has to be learnt about this state.

4.2.3. **10.6** MeV **state.**

This state was observed for the first time as an anomaly in the neutron total cross section of ^{9}Be [29]. Its contributions have also been observed in the (d,p) [21], (α,p) [7], (^{7}Li, α) [37] and (^{15}N,^{17}F) [13] reactions. It was shown that it decays into n$+^9$Be [8]. Present and other recent results [8,9] do not show that it participates in the $\alpha+^6$He decay. Obviously, it cannot be the 4^+ member either of the 0_1^+ band [2] or 0_2^+ band [4], because the members of these bands would not have negligible spectroscopic factors for the $\alpha+^6$He channel [5]. Present results on the ^{7}Li(^{7}Li, α) reaction at $E_0 = 8$ MeV (Fig. 2a) show its strongest contributions (in comparison with all other states) observed in any reaction. Is this in any way connected with a possible resonance in ^{14}C at $E_{\rm exc} = 30.8$ MeV? Namely, an intensive narrow structure, $({\rm FWHM})_{\rm cm} < 1$ MeV, was observed in the excitation function for the ^{7}Li(^{7}Li, α_1)^{10}Be* reaction with a maximum at $E_0 = 8$ MeV [38].

4.2.4. **11.8** MeV **state.**

This state has been observed in almost all previously mentioned reactions. It decays into $\alpha+^6$He (Ref. [9] and present results) and $\alpha+^6$He* (Fig. 3b). Based on the (α,p) reaction results, it was claimed that it is the 4^+ member of the 0_1^+ rotational band [7], while von Oertzen [2] suggested that it may be the 5_1^- state of the $K^\pi = 1^-$ band. Its population by the (^{6}Li,^{8}B) [32] and probably even by the (t,^{3}He) reaction [31] is in favour of the 4^+ rather than 5^- assignment. Additionally, one would expect that the corresponding band in ^{8}Be (0, 3.04, 11.4 MeV) would be closely followed by this in ^{10}Be (0, 3.37, about 12 MeV). An easy experimental way to resolve the dilemma is to measure inelastic scattering of light ions, like α and ^{6}Li, on ^{10}Be, the members of the ground state band will clearly show up in the spectra, as it was the case, e.g., with ^{9}Be [14,39].

5. Conclusions and proposals

In summary, before turning to future experiments, only two experimental results on ^{10}Be states from those mentioned in discussion will be pointed out: the first observation of the $\alpha+^6$He* decay and unambiguous assignment of 2^+ to the state at 9.6 MeV. Obviously, more experimental data are necessary to find out how far one can go with the molecular approaches in describing the nucleus like ^{10}Be. The measurements with higher precision, better statistics and for different channels are needed, especially, for the unbound states. With the availability of radioactive ^{6}He beams, new possibilities are open to identify the states of the α+^{6}He cluster structure using, e.g., the ^{6}Li +^{6}He and ^{7}Li +^{6}He reactions. Another interesting prospect is an exit channel involving ^{10}Be nuclei only (e.g., ^{14}C +^{6}He→^{10}Be +^{10}Be, $Q = -4.6$ MeV). Simultaneous determination of different decay modes and their partial widths can give crucial information on the structure of ^{10}Be in unbound states. A special case is the 2_3^+ state at 7.54 MeV. Its decay energies into the n + ^{9}Be and α+^{6}He are 730 and 132 keV, respectively. Its small Γ_n (6.3 keV) probably reflects its cluster structure, which could be additionally tested by measurements of other two partial widths, Γ_α and Γ_γ. Due to the small energy of the decay, Γ_α should be very sensitive to the distance between the clusters. Our preliminary estimates from the data on the ^{7}Li +^{7}Li→ $\alpha + \alpha +$ ^{6}He and ^{6}Li +^{6}He→ d + α +^{6}He reactions show that Γ_α is lower than 50 eV. Itagaki and Okabe [4] predict a very strong E2 transition between the 2_3^+ and 0_2^+ states, reflecting their expected large deformation.

There are some other very selective tests for states higher in excitation, like the decay by neutron emission into the first excited, $(\frac{1}{2})^+$ state of ^{9}Be. This decay would not be so hard to measure like some others (e.g., ^{5}He +^{5}He, ^{8}Be + 2n).

As an extension of the idea of nuclear molecules, one can explore whether in carbon nuclei another type of clustering exists, built also on the two-centered ^{8}Be structure. In this case, two light clusters would take the role of two neutrons from ^{10}Be. There are different indications for possible existence of these four-cluster states.

Strong and narrow structures with $(\mathrm{FWHM})_{\mathrm{cm}} < 1$ MeV were observed in the excitation functions at 0° for the ^{7}Li(^{7}Li, α_1)^{10}Be* and ^{6}Li(^{7}Li,t_0)^{10}B reactions [38] close to respective $2\alpha + 2$t and $2\alpha +$ d + t decay thresholds. In order to clarify whether these structures are caused by the four-cluster states in ^{14}C and ^{13}C, it would be important to measure the excitation functions of the ^{7}Li +^{7}Li and ^{7}Li +^{6}Li reactions for different excited states in residual nuclei as well as to do coincident measurements exploring high excitations in ^{14}C and ^{13}C reached by, e.g., (^{7}Li, α) reaction on ^{11}B and ^{10}B, respectively.

It was hinted long time ago [40] that a 2α+2d molecular structure could exist in ^{12}C when a good candidate for that was discovered in the measurements of excitation function for the ^{10}Be(d,α_0)^{8}Be reaction. That was a narrow resonance with $\Gamma \approx 0.4$ MeV and $E_{\mathrm{exc}} = 30.3$ MeV, just 1 MeV below the $2\alpha + 2$d decay threshold, corresponding to a state observed in other reactions.

There are indications [12,41] that some states in ^{12}Be have the ^{6}He +^{6}He structure. One can then expect their $T = 2$ analogs in ^{12}C at $E_{\mathrm{exc}} > 30$ MeV. However, only for this nucleus there is also a possibility that the $T = 0$ states exist with the structure of ^{6}Li*($T = 1$)+^{6}Li*($T = 1$) and ^{6}Be +^{6}He (in other words $2\alpha +$ 2nucleon - nucleon ($T = 1$) pairs). Suitable processes to search for these states may be the

^{9}Be(^{7}Be, α^6Li*)^{6}Li* and ^{9}Be(^{7}Be, α^6He)^{6}Be reactions with Q-values of -10.6 MeV and -11.3 MeV, respectively.

Note added in proof. An extended version of Ref. [9] was published in the meantime (N. Curtis et al., Phys. Rev. C **64** (2001) 041604). Although the 3^- assignment for the 10.2 MeV state looks more convincing now, it awaits final confirmation from other, less complex processes.

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^{10}Be I MOLEKULSKA STANJA

Proučavamo ekscitacijske energijske spektre ^{10}Be iz inkluzivnih i koincidentnih mjerenja reakcija ^{7}Li$+^{7}$Li na $E_0 = 8$ i 30 MeV, te ^{9}Be$+^{7}$Li na $E_0 = 52$ MeV. Opaženi su doprinosi stanja ^{10}Be u energiji uzbude do 12 MeV. Nađeni su raspadi stanja na 9.6, 10.2 i 11.8 MeV na $\alpha+^{6}$He te, po prvi put, na $\alpha+^{6}$He*. Ovi se rezultati razmatraju zajedno s ostalim eksperimentalnim podacima i novijim teorijskim predviđanjima. Predlažu se buduća mjerenja u kojima bi se tražila stanja lakih jezgara egzotične građe.