ISSN 1330–0016
CODEN FIZBE7

α-PARTICLE DECAY OF ^{10}B AND ^{12}B OBSERVED IN ^{9}Be + ^{7}Li REACTIONS

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Paper devoted to honour the memory of Professor Nikola Cindro

Received 18 June 2003; revised manuscript received 21 August 2003
Accepted 1 December 2003 Online 3 March 2004

The ^{10}B and ^{12}B excitation energy spectra have been obtained from the inclusive and coincident measurements of the ^{9}Be + ^{7}Li reactions at E_{beam}=52 MeV. Contributions of the ^{10}B states below 10 MeV and of the ^{12}B states below 16 MeV excitation have been resolved. ^{10}B states at 4.77 and 6.56 MeV as well as groups of states around 5.1 and 6 MeV decaying into $\alpha + ^6$Li, and of the state at 7.0 MeV decaying into $\alpha + ^6$Li* have been found. These measurements give the first evidence for $\alpha + ^8$Li decay of the ^{12}B states. In our data, there is no evidence for the $\alpha + ^8$Li*(0.98 MeV) and $\alpha + ^8$Li*(2.26 MeV) decays of ^{12}B. The influence of α-decaying ^{12}B states on the cross section of the astrophysically important ^{8}Li(α,n)^{11}B reaction is discussed.

PACS numbers: 21.10.-k, 25.70.-z, 27.20.+n UDC 539.144, 539.172
Keywords: nuclear reactions, ^{9}Be + ^{7}Li, E_{beam}=52 MeV, ^{10}B and ^{12}B levels, $\alpha + ^6$Li, $\alpha + ^6$Li* and $\alpha + ^8$Li decays

1. Introduction

^{10}B is often considered to be the most complex of all stable nuclei in the 1p shell region. Although it has been studied extensively, both experimentally and theoretically, detailed information exist only for its low excited states. This is also true for ^{12}B. The following two examples may illustrate our inadequate knowledge of these nuclei. In theory, it was only recently shown that, in the ab initio shell model calculations, correct ordering of the first 3^+ and 1^+ states in ^{10}B (ground and the first excited state) can be achieved, and only in the case when the "true" three-nucleon potentials are included into realistic Hamiltonians [1, 2]. On the other side, no experimental evidence was known for the α-particle decay of ^{12}B states which could influence the thermonuclear rate of the ^{8}Li(α,n)^{11}B reaction. This reaction may have had a crucial role in primordial and supernovae nucleosynthesis [3, 4]. Although the reaction and the ^{12}B states at excitations above 10 MeV have attracted remarkable interest, available data are very limited and contradictory. With this in mind, any new information on these nuclei is valuable. This paper presents results of α-particle decay of the ^{10}B and ^{12}B excited states obtained from an experiment originally planned for the study of ^{9}Be and ^{10}Be nuclei by the ^{9}Be$+^{7}$Li reactions [5–8].

2. *Experiment*

The measurements were performed at the Laboratori Nazionali del Sud using the ^{7}Li^{+++} beam from the SMP Tandem Van de Graaff accelerator. A self-supporting beryllium target (400 μg cm^{-2}) was bombarded with a 52 MeV beam (50 – 100 nA). Outgoing charged particles were detected in particle telescopes consisting either of a very thin and a thick surface barrier detector (T1) or of an ionization chamber and a silicon position-sensitive detector (T2). The angular range covered by the T2 telescope was 8°, while the T1 angular opening was 1.5°. In the same scattering plane, three T1 telescopes were positioned on one side and two T2 on the other side of the beam. Coincidence events of any T1-T2 pair were recorded. For calibration purposes, inclusive energy spectra of different outgoing particles were also measured. The experimental details can be found elsewhere [7]. The experimental setup used in the measurements permits a complete determination of the reaction kinematics. Good energy and angular resolution as well as very good separation of different He and Li isotopes were achieved. In this way it was possible to identify and separate events for particular reaction exit channels. Given the measurement of the momenta of the two detected reaction products in the three-body final state, it is possible to reconstruct the excitation energy of corresponding parent nuclei (there are three such nuclei, one for each possible pair of particles in the exit channel).

In this paper, we concentrate on the coincidence events corresponding to the $\alpha+^{6}$He$+^{6}$Li and $\alpha+\alpha+^{8}$Li outgoing channels as well as on the α, ^{6}He and ^{6}Li inclusive spectra.

3. *Experimental results and discussion*

3.1. ^{10}B

Figure 1a shows the ^{10}B excitation energy spectrum obtained from inclusive ^{6}He data measured with a T2 telescope at $\Theta_{\rm L}$=26.8°. For a comparison, Fig. 1b presents the ^{10}Be excitation energy spectrum obtained from inclusive ^{6}Li data measured under the same conditions (and discussed earlier in Ref. [8]). In Fig. 1a, some ^{10}B decay thresholds are marked as well as the positions of the $T = 1$ states, the analogues of the first eight states in ^{10}Be. Large difference in the cross sections for the states in ^{10}Be and their analogues in ^{10}B can be in a large part accounted for by an

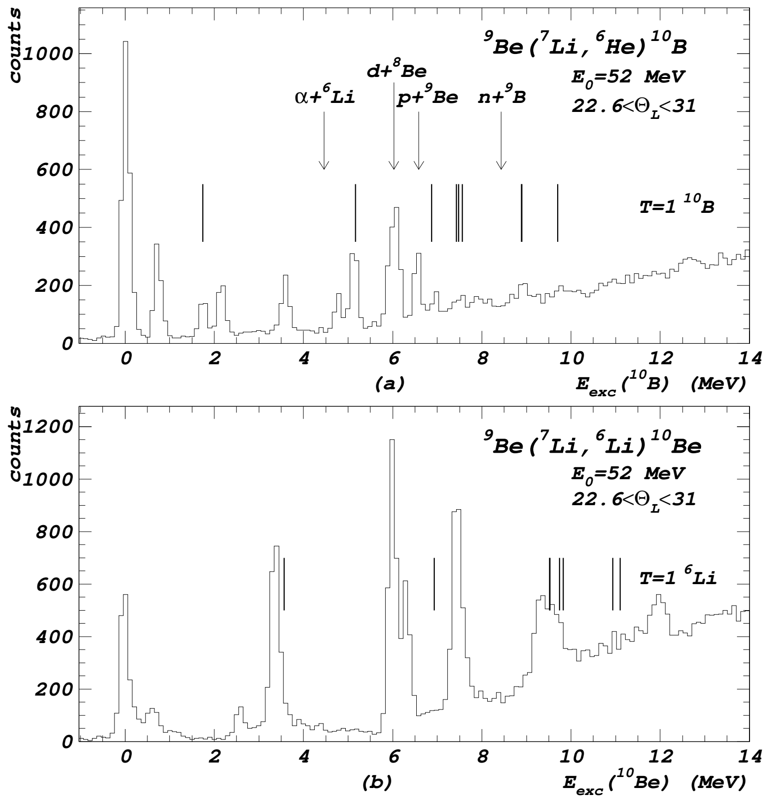

Fig. 1. a) ^{10}B *excitation energy spectrum from inclusive measurement of the* ^{9}Be(^{7}Li,^{6}He) *reaction at* E_{beam}=*52* MeV *and* Θ_L=*26.8°. Several decay thresholds as well as positions of the first eight* $T = 1$ *states are marked. b)* ^{10}Be *excitation energy spectrum from inclusive measurement of the* ^{9}Be(^{7}Li,^{6}Li) *reaction at* E_{beam}=*52* MeV *and 22.6°*$\leq \Theta_L \leq$*31.0° [8]. The lines mark positions where the contributions from the (*^{7}Li,^{6}Li**(3.56* MeV*)) reactions are expected.*

order of magnitude ratio in the corresponding spectroscopic strengths, $(2J_6+1)C^2S$, i.e. different spins of the ^{6}Li and ^{6}He ground states, different isotopic spin coupling coefficients and spectroscopic factors for ^{7}Li$\to$n$+^6$Li and ^{7}Li$\to$p$+^6$He [9]. This is also seen in Fig. 1b, where contributions of the (^{7}Li,^{6}Li*(T=1)) reaction may be only weakly present. There was a longstanding controversy about the discrepancy in relative spectroscopic factors obtained with standard DWBA calculations from the data on the (d,n), (^{3}He,d) and (α,t) reactions leading to the final states with different isospin in odd-odd light nuclei, especially in the case of ^{10}B [10–14]. Possible explanations include the isospin, charge exchange and coupled channels effects [13, 15]. Present ^{10}B excitation energy spectrum resembles very much the one obtained from the (α,t) reaction measured at E_{beam}=60 MeV and Θ_L=10° [13]. Their common characteristics are: strong contribution of the 3^+ ground state, other low lying states are less pronounced and a very weak feeding of the states above 9 MeV excitation. The last peak in the spectrum, which can still be discriminated against the many-body decay background, belongs to the $T = 1$ doublet of states at 8.9 MeV, which are analogues of ^{10}Be states at 7.37 and 7.54 MeV, with a very strong contribution in the (^{7}Li,^{6}Li) reaction.

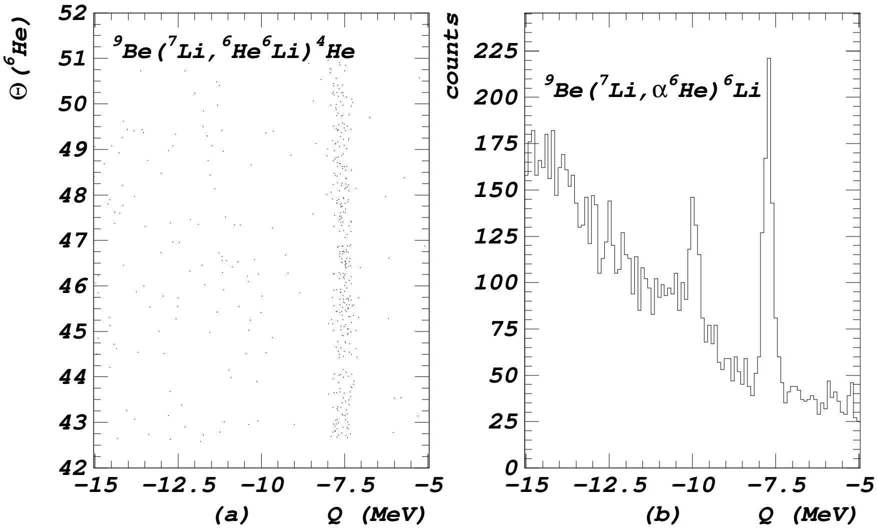

Fig. 2. a) Q-value vs $\Theta(^6\mathrm{He})$ *scatter plot of the* ^{6}He-^{6}Li *coincidencies. b) Q-value spectrum obtained from the* ^{6}He-α *coincidencies.*

Figure 2a presents a typical Q-value vs. $\Theta(^6\mathrm{He})$ scatter plot of ^{6}He$-^6$Li coincidencies from the ^{7}Li$+^9$Be reaction. The ^{6}Li ions were detected by a T1 telescope positioned at Θ_L=24.8°, and ^{6}He in a T2 telescope centred at Θ_L=46.8°. The only "strip" of events corresponds to the ^{4}He$+^6$He$+^6$Li exit channel with all nuclei being in their ground states. There is no clear evidence for possible contribution of the only other particle-stable ^{6}Li state (T=1 at 3.56 MeV). Figure 2b shows a projection on the Q-value axis of a similar plot for the ^{6}He–α coincidencies from the same reaction. The two peaks correspond to the ground and first excited states of the undetected ^{6}Li nucleus.

Figure 3a presents the ^{10}B excitation energy spectrum obtained as a sum of individual spectra of the $\alpha-^6$He and ^{6}Li$-^6$He coincidencies measured by all T1 – T2 combinations. Four distinct peaks are visible, all of them corresponding to known α-decaying states below the threshold for the p$+^9$Be decay at 6.59 MeV, and seen also in the spectrum in Fig. 1a. Although contributions from other states may also be present in some individual spectra, only those from the states around 7 and 7.9 MeV may be claimed with certainty. The isospin mixed 1^- state at 6.87 MeV has strong influence on the thermonuclear rates of the (p,γ), (p,d) and (p,α) reactions on ^{9}Be (see, e.g., Refs. [16, 17]). However, its contribution does not seem to be present in the spectra, which is similar to the results from other one-proton transfer reactions on ^{9}Be [10–14].

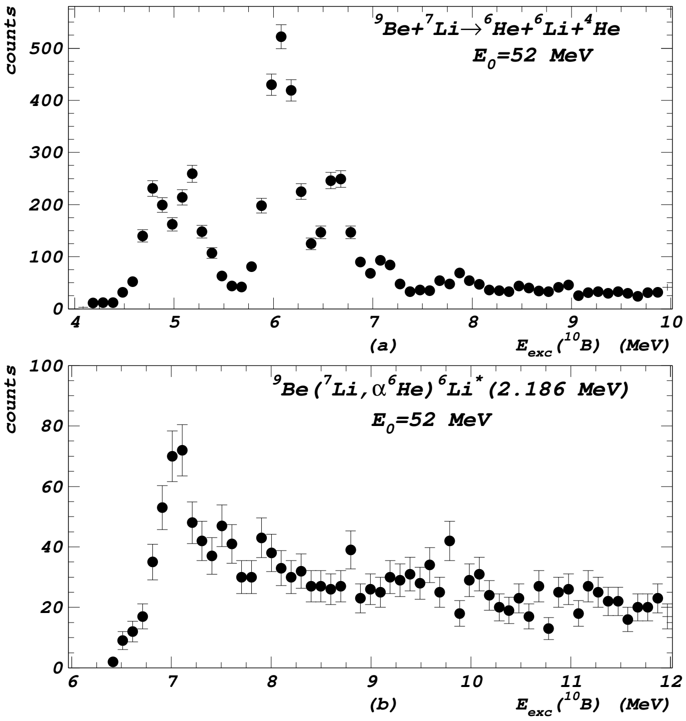

Fig. 3. a) ^{10}B *excitation energy spectrum obtained from all* α-^{6}He *and* ^{6}Li-^{6}He *coincident events from the* $^{9}\mathrm{Be}+^{7}\mathrm{Li} \longrightarrow \alpha+^{6}\mathrm{He}+^{6}\mathrm{Li}$ *reaction measured at* E_{beam}=52 MeV. *b)* ^{10}B *excitation energy spectrum obtained from all* α-^{6}He *coincident events from the* $^{9}\mathrm{Be}+^{7}\mathrm{Li} \longrightarrow \alpha+^{6}\mathrm{He}+^{6}\mathrm{Li}^{*}$*(2.18* MeV*) reaction measured at* E_{beam}=52 MeV.

Figure 3b presents the ^{10}B excitation energy spectrum obtained as a sum of individual spectra of $\alpha-^{6}$He coincidencies from all T1–T2 combinations fulfilling the requirement that the undetected nuclear system corresponds to the first excited state of ^{6}Li at 2.186 MeV. The most distinctive peak in the spectrum corresponds to the 7.0 MeV state. A verification that this peak corresponds to a state in ^{10}B has been done by selecting the events with more negative Q-value in Fig. 2b. No peak in ^{10}B excitation energy spectrum was found in that case. Its spin has not been determined previously; there are claims that it should be either a 1^{+} or a 2^{+} state [18]. However, from the ^{11}B(^{3}He,$\alpha\alpha$)^{6}Li reaction angular correlation measurements, it was concluded that the most probable assignment was 3^{+} [19], which was also suggested from the study of the ^{14}N(d,^{6}Li)^{10}B reaction [20]. The present result of the $\alpha+^{6}\mathrm{Li}^{*}(3^{+})$ decay of the state strongly supports the 3^{+} assignment. Namely, if it were not a 3^{+} state (i.e. $L=0$ transition), with its energy of only 0.35 MeV, the decay would be strongly suppressed by any additional centrifugal barrier. That decay of the state together with the $\alpha+^{6}\mathrm{Li}(1^{+})$, $\mathrm{d}+^{8}\mathrm{Be}(0^{+})$ and $\mathrm{p}+^{9}\mathrm{Be}(3/2^{-})$ decays were also observed in the ^{7}Li(^{12}C,^{10}B)^{9}Be reaction [21]. It is interesting that the old intermediate-coupling shell-model calculations predicted the third 3^+ state at 7.7 MeV [9, 22] and more recent calculations put it at 7.8 MeV (or 7.36 MeV above the first 3^+ state) [23].

The structure seen in the present data around 8 MeV may support the claims from previously mentioned measurements [21] about a new state at these excitations decaying into $\alpha + {}^6\mathrm{Li}^*(3^+)$. It was then suggested that its structure may be a close analogue of the molecular type of configurations proposed for ^{10}Be.

3.2. ^{12}B

Figure 4 presents the ^{12}B excitation energy spectrum obtained from inclusive α-particle data measured with a T2 telescope at Θ_L=46.8°. The peaks in the spectrum correspond to ^{12}B states observed also in the previous measurements of the ^{9}Be(^{7}Li,α)^{12}B reaction [24, 25]. It is seen that several states above the $\alpha + {}^8$Li decay threshold at 10.0 MeV have strong contributions, especially those in the astrophysically very interesting region between 10 and 11 MeV.

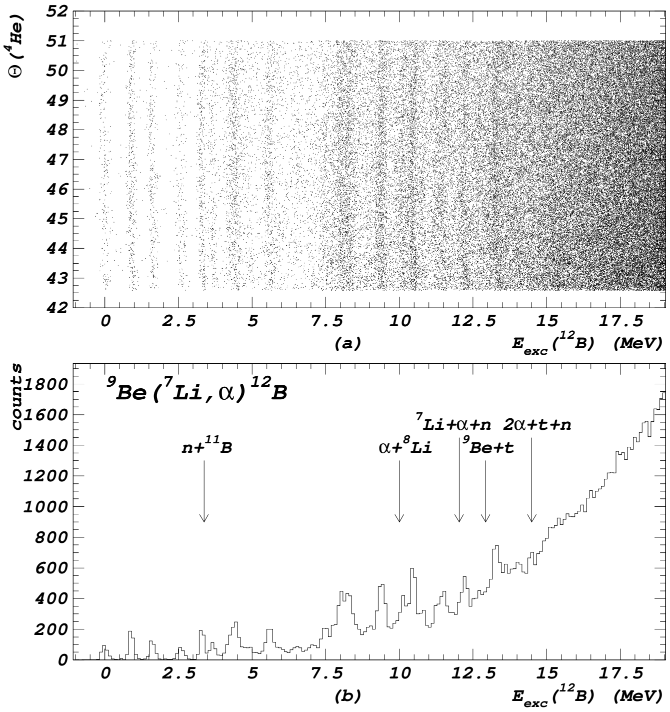

Fig. 4. a) $E_{\mathrm{exc}}(^{12}\mathrm{B})$ *vs* $\Theta(\alpha)$ *scatter plot of the data from inclusive measurement of the* ^{9}Be(^{7}Li,α) *reaction at* $E_{\mathrm{beam}} = 52$ MeV *and* $42.6° \leq \Theta_L \leq 51°$. *b)* ^{12}B *excitation energy spectrum obtained as a projection of (a). Arrows mark some decay thresholds.*

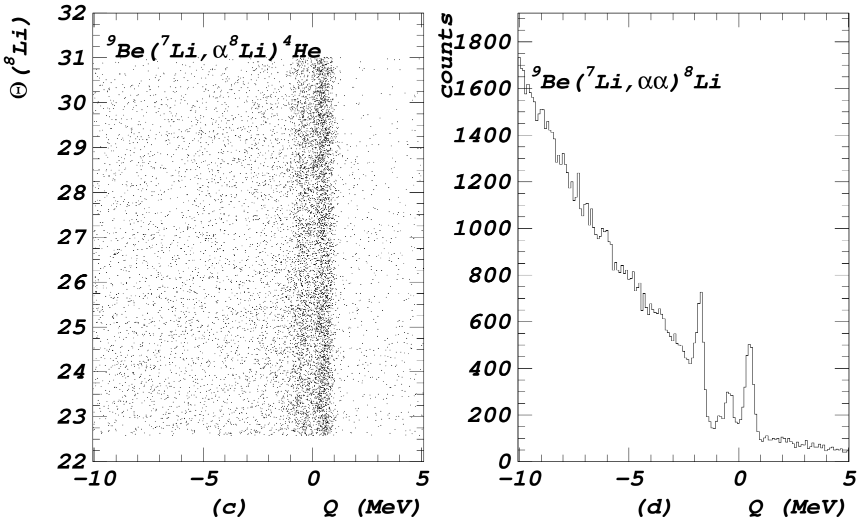

Fig. 5. a) Q-value vs $\Theta(^8\mathrm{Li})$ scatter plot of the α–^{8}Li coincidencies. b) Q-value spectrum obtained from the α-α coincidencies.

Figure 5a presents a Q-value vs $\Theta(^8\mathrm{Li})$ scatter plot for α–^{8}Li coincidencies when α-particles are detected at 40.3° and ^{8}Li in T2 at 26.8°. Contributions of both particle-stable states of ^{8}Li are resolved. Figure 5b shows a projection on the Q-value axis of a similar plot of the α–α coincidencies detected in T1 at 50.4° and T2 at 26.8°. In that case, in addition to two particle stable states, the contribution of the second excited state of ^{8}Li(3^+) at 2.26 MeV is also visible against the strong 4-body break-up background. In addition, a small bump around $Q = -6.1$ MeV is probably due to the narrow 4^+ state of ^{8}Li at $E_{exc} = 6.53$ MeV.

Figure 6 shows the ^{12}B excitation energy spectrum obtained as a sum of individual spectra of the α–α and α–^{8}Li coincidencies recorded by all T1-T2 pairs and corresponding to the exit channel of two α-particles and ^{8}Li ground state. These results and their implications for the structure of ^{12}B excited states as well as their astrophysical implications are discussed in more detail elsewhere [26] and only some points are presented here. The strongest contributions are due to the states of ^{12}B at 10.9, 11.6, 13.4 and 15.7 MeV. All these states, except the 15.7 MeV state, are also clearly seen in Fig. 4. In the present kinematical conditions (α-particle centre-of-mass angles larger than 35°), one can expect that both, the triton stripping off ^{7}Li and ^{5}He pick-up from ^{9}Be, are important and that the ^{12}B states with large α and t and/or ^{5}He spectroscopic factors are favoured in the process. Some of the observed α-particle decaying states may have strong influence on the cross section of the ^{8}Li(α,n)^{11}B reaction.

Unfortunatly, due to the kinematical conditions of the experiment, the most important energy region (10 – 11 MeV) for the analysis of the role of the ^{8}Li(α,n)^{11}B reaction in the big bang nucleosynthesis was only partially covered in the present measurements. Contribution of the state(s) around 10.5 MeV in excitation was ob-

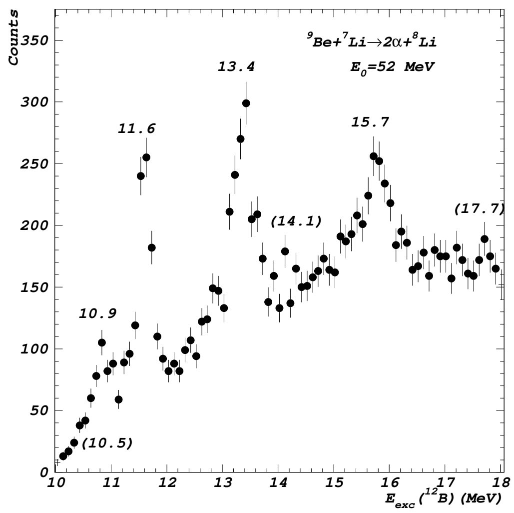

Fig. 6. ^{12}B *excitation energy spectrum obtained from all* α-α *and* α-^{8}Li *coincident events from the* ^{9}Be$+^7$Li $\longrightarrow$ $2\alpha+^8$Li *reaction measured at* $E_{\rm beam}$=52 MeV *[26]. Observed peaks are labelled with excitation energies (*MeV*).*

served only in the case when the recoiled α-particle was detected in T2 telescope centered at 46° and α-particle from ^{12}B decay in T1 telescope at 40° (Fig. 7a). In that spectrum, peaks at 10.5, 10.9, 11.6 and 13.4 MeV are clearly visible. Uncertainty in the excitation energy for these states is $\leq$100 keV and the resolution is $\approx$150 keV. Although the statistics for the states below 11 MeV are poor, it seems that both states have a very similar contribution in the spectrum. From Fig. 4, which shows inclusive α-particle spectrum for the same kinematical condition (recoil α-particle detected in T2 centered at 46°), it is obvious that 10.5 MeV state is more populated than that at 10.9 MeV. Figure 7b shows ^{12}B excitation spectrum corresponding to the same kinematical condition for recoil α-particle and ^{8}Li detected in T1 at 40°. In this case, the 10.9 MeV state is clearly seen, but there is no 10.5 MeV peak. Reason for that is very rapid decrease of the detection efficiency for the latter case due to the low ^{8}Li energy at these angles. It should be mentioned that for the spectrum shown in Fig. 7a, background contributions are weak and there are no contributions of ^{8}Be states which can mimic narrow states in ^{12}B (these events correspond to the excitations in ^{8}Be above 20 MeV where only very broad states exist), thus we can claim the observation of the 10.5 MeV peak with reasonable certainty. Our results indicate that main resonant contributions to the low energy reaction cross section may come from the states at 10.5 and 10.9 MeV. These results may serve as an additional quality check of data obtained from very complex direct measurements, like those of Refs. [27, 28] of that astrophysically very important reaction.

Similarly, the state(s) at 13.4 MeV, being only 450 keV above the t$+^9$Be threshold, may have a strong effect on thermonuclear ^{9}Be+t reaction rates. This seems to be confirmed by the only available excitation function data on the ^{9}Be(t,α)^{8}Li reactions measured for triton centre-of-mass energies between 0.4 and 1.3 MeV [29].

At the lowest energies, they show deviation from the expected nonresonant cross section behaviour below the Coulomb barrier. We have analysed the data for the ^{9}Be+t+α exit channel, searching for the decay of the ^{12}B states into ^{9}Be+t. Unfortunately, the experimental conditions in the present measurement were not suitable for its observation.

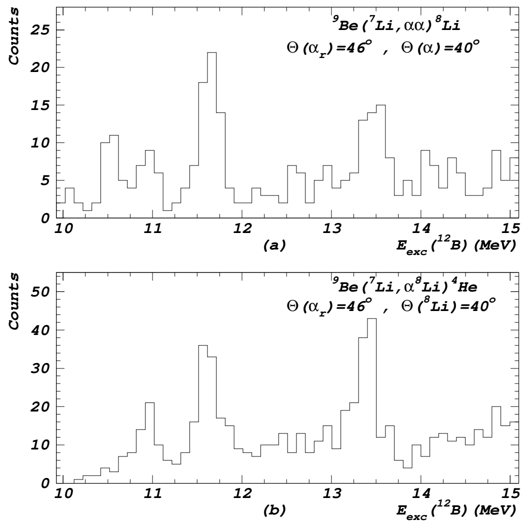

Fig. 7. ^{12}B *excitation energy spectra for 10*$\leq E_{\rm exc} \leq$*15* MeV *in the cases when recoil* α*-particle was detected in T2 telescope at 46*° *and particle from the* ^{12}B *decay in T1 at 40*° *for* α*-particle (a) and* ^{8}Li *(b).*

Figure 8 presents the ^{12}B and ^{8}Be excitation energy spectra corresponding to the exit channels of two α-particles and the first (a,b) or the second excited state (c,d) of ^{8}Li. The first ^{12}B (a) and ^{8}Be (b) spectra were obtained from recorded α–^{8}Li*(0.98 MeV) coincidence events and the second ^{12}B (c) and ^{8}Be (d) spectra from the α–α coincidencies. The main contributions to the α–^{8}Li* exit channel in the present kinematical conditions come from one-neutron transfer reactions forming simultaneously the state of ^{8}Li and α-decaying ^{8}Be states at low excitations J^π = 0^+, 2^+ and 4^+ (Fig. 8b). For the α–α coincidencies corresponding to ^{8}Li in its second excited state (Fig. 8d), the main contributions to the spectra are due to the four-body (2α+n+^{7}Li) continuum coming mainly from the inelastic excitation of ^{9}Be and its break-up and broad ^{8}Be states at higher excitations. These background contributions then mask possible contributions of the ^{12}B states and although there are some indications of the involvement of ^{12}B states in both spectra, their presence can not be confirmed.

Observation of strong α-decay of the ^{12}B excited states opens an interesting possibility for speculation on its exotic structure. In particular, states with prominent α-decay and small neutron partial width, as is the 11.6 MeV state [26], may possess exotic cluster structure. It has been proposed recently that neutron-rich isotopes of beryllium [30] and carbon [31] possess molecular structure in which valence

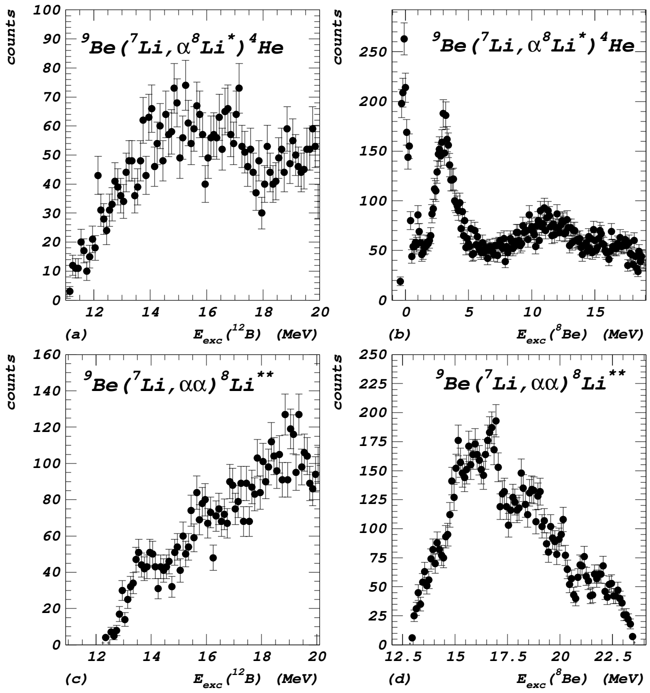

Fig. 8. ^{12}B *and* ^{8}Be *excitation energy spectra obtained from (a,b) all* α–^{8}Li**(0.98* MeV*) coincident events, and (c,d) from all* α-α *coincidencies from the* ^{9}Be$+^7$Li $\longrightarrow$ *2*$\alpha+^8$Li**(2.26* MeV*) reaction measured at* $E_{\rm beam}$*=52* MeV.

neutrons occupy molecular orbits around the α-cores. Such two- and three-centre nuclear systems would be the analogues of the atomic covalent molecules, where electrons move in multi-centre orbits around the nuclei. Indeed, experimental indications for such structures have been found recently for ^{10,12}Be [8, 32, 33] and ^{13,14}C [34, 35] nuclei. The ^{12}B nucleus could also fit into that picture, it could be described as a three-centre α+α+t system with one valence neutron. The threshold for ^{12}B decay into the 2α+t+n channel is at 14.5 MeV, thus states with such structure could appear above that excitation energy. Possible candidate for such a structure is the 15.7 MeV state. Observed α-decaying states below that energy could possess simpler ^{9}Be+t cluster structure, for which the threshold is at 12.9 MeV. Thus, its structure may be similar to the proposed ^{13}C molecular structure. Clearly, more experimental results (determination of the spin, parity and partial widths for observed states) are necessary for a better understanding of their structure.

4. Conclusion

At the end two main points will be stressed.

i) In the present measurements, it is observed that the state of ^{10}B at 7.0 MeV decays not only into $\alpha+^6$Li but also into the $\alpha+^6$Li*(2.18 MeV) channel, which strongly suggests its $J^\pi=3^+$ assignment. The third 3^+ state in that nucleus will be an strong challenge to different modern nuclear structure calculations. Its influence on the various thermonuclear $p+{}^9$Be reaction rates should be reevaluated.

ii) Strong α-particle decay of several ^{12}B states has been observed for the first time. States at 10.5 and 10.9 MeV may have a strong influence on the low energy cross section of the ^{8}Li(α,n)^{11}B reaction which is in agreement with existing results for this reaction. It would be highly desirable to determine both α-particle and neutron decay widths of these states. This information would serve for the estimates of the resonant parts of the cross section for the ^{8}Li(α,n)^{11}B at low energies. This will then be a good quality check of the data from performed and planned complex measurements of that astrophysically very important process. Also, information about these states would permit a better understanding of the ^{12}B structure.

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OPAŽANJE α-RASPADA ^{10}B I ^{12}B U ^{9}Be$+^{7}$Li REAKCIJAMA

Odredili smo uzbudne energijske spektre ^{10}B i ^{12}B uključivim i sudesnim mjerenjima reakcije ^{9}Be$+^{7}$Li na E_{snop}=52 MeV. Razdvojili smo doprinose stanja ^{10}B ispod 10 MeV i stanja ^{12}B ispod 16 MeV. Našli smo raspade stanja ^{10}B na 4.77 i 6.56 MeV i grupa stanja oko 5.1 i oko 6 MeV u $\alpha+^{6}$Li, i stanja na 7.0 MeV u $\alpha+^{6}$Li*. Ovo su prva mjerenja u kojima se nalazi $\alpha+^{8}$Li raspad viših stanja ^{12}B. Naši podaci ne ukazuju prisutnost $\alpha+^{8}$Li*(0.98 MeV) i $\alpha+^{8}$Li*(2.26 MeV) raspada ^{12}B. Raspravljamo utjecaj stanja ^{12}B koja podliježu α-raspadu na udarne presjeke astrofizički važne reakcije ^{8}Li(α,n)^{11}B.