$^8\text{Li}+\alpha$ decay of $^{12}\text{B}$ and its possible astrophysical implications

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Abstract. – The $^{12}\text{B}$ excitation energy spectrum has been obtained from coincidence measurements of the $^9\text{Be}+^7\text{Li} \rightarrow 2\alpha+^8\text{Li}$ reaction at $E_\alpha=52$ MeV. The decay of the states at excitations between 10 and 16 MeV into $\alpha+^8\text{Li}$ has been observed for the first time. Observed $\alpha$-decay indicates possible cluster structure of the $^{12}\text{B}$ excited states. The influence of these states on the cross section of the astrophysically important $^8\text{Li}(\alpha,n)^{11}\text{B}$ and $^9\text{Be}+t$ reactions is discussed and the results are compared with existing results.

Introduction. – Light nuclei are interesting in their own right as almost every nucleus possesses some unique properties which are fingerprints of its quantum structure. Their extremely varied structures, from spherical shell model shapes to prominent clustering, are a considerable challenge to understand and model. Although light nuclei have been studied intensively for many decades, very limited and often contradictory information exist for many of them. That is also the case for $^{12}\text{B}$ nucleus. It is interesting to draw a comparison with its structure and structures of the $^{11}\text{Be}$, $^{11}\text{B}$, $^{12}\text{Be}$ and $^{12}\text{C}$ nuclei which all show prominent $\alpha$-clustering. As an example, $^{11}\text{B}$ and $^{12}\text{C}$ nuclei are typical cluster nuclei and their $\alpha$-decays were experimentally observed in many particle coincidence measurements some 40 years ago (e.g. [1, 2], for full list of the references see [3]). The helium decays of $^{12}\text{Be}$ nucleus were reported only recently [4], but there is no experimental results on the $\alpha$-decays of $^{12}\text{B}$. Some experimental indications for cluster structure of $^{12}\text{B}$ states come from the measurements of the $^8\text{Li}(\alpha,n)^{11}\text{B}$ reaction. According to inhomogenous models of big bang nucleosynthesis this reaction would have had a crucial role in the production of $A \geq 12$ nuclides [5, and references therein]. Hence this reaction and the states of $^{12}\text{B}$ at excitations close to the $\alpha-^8\text{Li}$ separation energy ($E_s=10.001$ MeV) have attracted special interest. The 1996 status of the results obtained from both direct and indirect measurements was critically reviewed in [6]. Results from a recent direct measurement of the reaction [7] disagree with the conclusions from [6]. The reaction cross section obtained in that exclusive measurement at c.m. energies between 1.5 and 7 MeV is almost a factor of 2 lower than that obtained in previous inclusive measurements.
Similar large discrepancies exist between two different theoretical approaches [8,9]. With all the problems of direct measurements (radioactive $^8$Li beam, $^4$He gas target, detection of $^{11}$B ions and/or neutrons) one should not expect highly accurate data soon. In the meantime any new information about the states involved may help to narrow the uncertainties and may provide an additional quality check of the data obtained from direct measurements. Such an example, the $^8$Li+$\alpha$ decay of $^{12}$B states having excitation energy, $E_x$, between 10 and 18 MeV, is presented here.

**Results.** – The $^7$Li+$^9$Be reaction measurements were performed in order to study $^9$Be and $^{10}$Be nuclei [10–12]. The data also provide high quality results for the $2\alpha$+$^8$Li exit channel, which offer useful information on the $^{12}$B states. The measurements were performed at the Laboratori Nazionali del Sud using a $^7$Li$^{++}$ beam ($E$=52 MeV, $I$=60-100 nA) and a self-supported beryllium target (400 $\mu$g/cm$^2$). Outgoing charged particles were detected in detector telescopes consisting either of a very thin and a thick standard silicon 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 $8^\circ$, while the T1 angular opening was $1.5^\circ$. Three T1 telescopes were positioned on one side and two T2 on the other side of the beam, all in the same scattering plane. Coincident events of any T1-T2 pair were recorded. The experimental details were published elsewhere [10–12].

The measurement of the energies and angles of detected particles permitted the kinematics of the $^7$Li$^9$Be $\rightarrow 2\alpha^8$Li reaction ($Q=0.460$ MeV) to be fully reconstructed. Figure 1 shows the Q-value spectra for that reaction for particular T1-T2 pair in the case of $\alpha$-$\alpha$ (a) and $\alpha$-$^8$Li (b) coincidences. In both spectra the highest energy peak corresponds to the $^8$Li ground state ($J^\pi=2^+$) and the next one is the 0.981 MeV, $1^+$ state. For $\alpha$-$\alpha$ events there is also another peak which corresponds to the unbound $^8$Li second excited state ($3^+$) at 2.255 MeV. The obtained resolution, 500 keV for $\alpha$-$\alpha$ and 800 keV for $\alpha$-$^8$Li events, is sufficient to resolve these $^8$Li states. These resolutions are worse than the particle energy resolution (150-250 keV for $\alpha$ and 300-400 keV for $^8$Li) because all the uncertainties in the energies and angles of detected particles contribute to the error in determination of the total energy. Inferior resolution in the latter case is due to the light mass of the recoil particle, because a small uncertainty in the measured momenta gives a larger uncertainty in the energy of the unobserved particle. Part of the background events in both spectra is due to the $^7$Li+$\alpha$ coincidences leaking through the $^8$Li selection windows. Main background contributions for the $\alpha$-$\alpha$ events come from the reactions on carbon and oxygen impurities in the target, which are not present in the case of $\alpha$-$^8$Li events due to the very negative Q-values for the $(^7$Li,$\alpha^8$Li) reaction on these nuclei.

Fig. 2 presents two examples of collected data in 2-D $E(\alpha-\alpha)$ vs. $E(\alpha-^8$Li) plots of coincident $\alpha$-$^8$Li events. $E(x-y)$ are the c.m. energies in respective two-body systems obtained directly from the measured energies and angles of $^8$Li and $\alpha$. Excitation energy in the systems is given by $E_x=E(x-y)+E_\alpha$; in the $^{12}$B case that is $E_x^{(12B)}=E(\alpha-^8$Li)+10.001 MeV. These spectra were obtained by selecting only the events associated with the $2\alpha$+$^8$Li(gs) final state. In both cases $^8$Li were detected in a T1 telescope at $40^\circ$ together with $\alpha$-particles detected in a telescope T2 once set at an angle of $46.8^\circ$ and other time at $54^\circ$. One can notice horizontal and vertical groupings of the events corresponding to resonances in the systems i.e. to states in $^8$Be and $^{12}$B, respectively. The excitation energies of observed $^8$Be ground and first excited state are well reproduced and their contributions are well separated from the contributions of the $^{12}$B states below 20 MeV in excitation.

On Fig. 3 are displayed together: a $^{12}$B excitation energy spectrum from the present $^7$Li$^9$Be $\rightarrow 2\alpha^8$Li reaction measurements (top), $^{12}$B level scheme (center) and previously measured excitation functions of $^4$He($^8$Li,$^{11}$B)n and $^{11}$B(n,$^8$Li)$^4$He reactions (bottom).
Fig. 1 – Typical examples of the Q-value spectra reconstructed from measured $\alpha$-$\alpha$ (a) and $\alpha$-$^8$Li (b) coincident events. The highest energy peak corresponds to the $^8$Li ground state and lower are $^8$Li excitations.

Fig. 2 – Typical examples of the $\alpha$-$^8$Li coincident data for two detectors settings presented in 2D plots of relative energies $E(\alpha-^8\text{Li})$ vs $E(\alpha-\alpha)$. Strips of data points parallel to the axes correspond to resonances in respective two-body systems. The most prominent $^{12}\text{B}$ states are at the excitation energies of 10.9, 11.6, 13.3 and 15.7 MeV. The ground and first excited state of $^9\text{Be}$ are also populated, but don’t overlap with $^{12}\text{B}$ states below 20 MeV in excitation.

level scheme for excitations between 10 and 18 MeV is adopted from [3]. It was obtained mainly from the older measurements of the $^9\text{Be}(^7\text{Li},\alpha)$ and $^{10}\text{B}(t,p)$ reactions [13–15] and, for $10 < E_x < 13.5$ MeV, partially confirmed in more recent measurements of the $^9\text{Be}(\alpha,p)$ and $^{11}\text{B}(d,p)$ reactions [16–18]. Some of decay thresholds are also indicated. The most relevant one here is that for $\alpha$-$^8$Li decay at 10.001 MeV. The threshold for $n$-$^{11}\text{B}$ decay is at 3.37 MeV, which means that, for $E_x > 10$ MeV, channels for neutron decay into high excited states of $^{11}\text{B}$ are also opening. Similarly, some channels corresponding to excited states of other residual nuclei ($^6\text{Li}^*, ^7\text{Li}^*$ etc.) are also open at these energies. Having all this in mind, as well as the fact that there are 18 $^{12}\text{B}$ levels for $7 < E_x < 10$ MeV, the level scheme for $10 < E_x < 18$ MeV reflects more accurately our insufficient knowledge rather than reality.
Fig. 3 – The $^{12}\text{B}$ excitation energy spectrum from the present $^7\text{Li}+^9\text{Be} \rightarrow 2\alpha + ^8\text{Li}$ reaction measurements (top); adopted $^{12}\text{B}$ level scheme for excitations between 10 and 18 MeV [3] (center); and excitation functions from the measurement of $^{11}\text{B}(n,^8\text{Li})^4\text{He}$ reaction [21], and measurements of the $^4\text{He}(^6\text{Li},^{13}\text{B})n$ reaction [7, 19, 20](bottom). Observed peaks in the present spectrum are labelled with excitation energies (MeV). Known levels are marked with bold solid lines and the decay thresholds of the labelled channels with dashed lines.
Excitation function data for the \(^4\)He\(^{(8}\)Li,\(^{11}\)B)\(\alpha\) reaction [7, 19, 20], shown in Fig. 3 (bottom), represent the sums of transitions involving \(^8\)Li ground state and different \(^{11}\)B states. In all of the cases of direct measurements \(^{11}\)B ions were detected and only in one measurement [7] neutrons were also detected. As can be seen, the quality of the data, as well as the agreement between the inclusive [19, 20] and exclusive measurements [7] are not good. Also, only three data points fall into the upper part of the most interesting energy region (10-11 MeV) for big bang nucleosynthesis analyses. The data on the \(^{11}\)B(n,\(^8\)Li)\(^4\)He reaction [21] were obtained by the detection of 2\(\alpha\) following \(\beta^-\)-decay of \(^8\)Li. Up to \(E_x=11\) MeV the only contribution comes from the \(^{11}\)B(n,\(\alpha\))\(^8\)Li reaction, above this energy the reaction leading to the \(^8\)Li first excited state could also contribute. From similar measurements more refined data for \(10.3 < E_x < 11\) MeV were also obtained [22].

The \(^{12}\)B excitation energy spectrum (Fig. 3 top) was obtained from spectra shown on Fig. 2 by projecting it to the \(E(\alpha,\(^8\)Li)\) axis. It represents a sum of coincident events recorded by all the T1-T2 telescope pairs, corresponding to the exit channel of two \(\alpha\)-particles and the \(^8\)Li ground state. It should be mentioned that the data were collected at large \(\alpha\)-particle center-of-mass angles (> 35\(^\circ\)), where both direct reaction mechanisms, triton stripping off \(^7\)Li and \(^5\)He pick-up from \(^9\)Be, may contribute to the \(^9\)Be(\(^7\)Li,\(\alpha\))\(^{12}\)B reaction. A part of the smooth "background" in the \(^{12}\)B spectrum is due to the \(^8\)Be(\(^7\)Li,\(^8\)Li)\(^9\)Be reaction to different 2\(\alpha\) decaying states of \(^9\)Be. From the spectrum it is evident that the strongest contributions in these kinematical conditions come from the states at 10.9, 11.6, 13.4 and 15.7 MeV, with weaker or no contributions from other known states of \(^{12}\)B. Error in excitation energy for these states, determined from the excitation energies of the known \(\alpha\)-decaying states of the \(^{10}\)B and \(^{11}\)B nuclei, is \(\leq 100\) keV and resolution, estimated from the width of the 10.9 and 11.6 MeV states, is \(\sim 300\) keV. Another interesting result of the present measurement is that our data show no evidence for \(\alpha\)-decay of \(^{12}\)B states to the first two excited states of \(^8\)Li. That is probably consequence of the kinematical conditions of these measurements. The main contributions to these exit channels come from one neutron transfer reactions forming excited states of \(^8\)Li and \(^8\)Be, which mask contributions from the \(^{12}\)B states.

**Discussion.** – It should be mentioned that the excitation spectrum from the present measurements emphasizes \(^{12}\)B states with large \(\alpha\) and \(t\) or \(^5\)He spectroscopic factors, i.e. states with well developed cluster structure, whereas resonant contributions to the \((^8\mathrm{Li},\alpha)^{11}\mathrm{B})\) reaction come from \(^{12}\)B states with significant both \(\alpha\) and neutron partial widths. However, it is reasonable to expect neutron decay of all states at these high excitation energies, thus all observed \(\alpha\)-decaying states may influence the reaction rate. Weak neutron decay for some of these \(^{12}\)B states would indicate its exotic cluster structure.

The most important energy region (10-11 MeV) for the analysis of the \(^8\)Li(\(\alpha,\)n)\(^{11}\)B reaction role in big bang nucleosynthesis was only partially covered in present measurements due mainly to kinematical conditions of the experiment, thus detection efficiency for that energy region decreases rapidly (its estimated value for \(E_x=11.0\) MeV is a factor of 2.5 and for \(E_x=10.6\) MeV a factor of 7 lower than for \(E_x=11.5\) MeV). Very weak contributions of the state(s) between 10.4 and 10.6 MeV may be present in some individual spectra, but no definite conclusions can be made.

The presence of the 10.9 MeV state is evident in almost all of the individual spectra, the sum spectrum, as well as in the spectra from the \((^7\mathrm{Li},\alpha), (\alpha,\mathrm{p}), (\mathrm{t},\mathrm{p})\) and \((\mathrm{d},\mathrm{p})\) reactions [13, 15–18]. This state appears as a very weak peak in the \((\mathrm{n},^8\mathrm{Li})\) reaction excitation function or in the \((\alpha,\mathrm{n})\) S-factor [6, 21, 22] and noticeably stronger in the data of one of inclusive \((^8\mathrm{Li},^{11}\mathrm{B})\) reaction measurements [20]. From the neutron decay data [18] it was concluded that it is a \(3^+\) state and that its \(\Gamma_\alpha = 1/5 \Gamma_{\text{tot}}\). On the other hand, Descouvemont [9] puts
the $3^+$ state somewhat higher (12.0 MeV) and with a much larger $\Gamma_\alpha$ ($\Gamma_\alpha = 2/3 \Gamma_{\text{tot}}$) reflecting its $^8\text{Li}$-alpha “molecular” structure. The present result shows its conspicuous $\alpha$-decay indicating that the 10.9 MeV state could contribute significantly to the $(^6\text{Li},^{11}\text{B})$ reaction cross section.

The states at 11.3 and 11.6 MeV are both seen in the $(^7\text{Li},\alpha)$ and $(\alpha,p)$ reactions, in all the cases the higher state was more strongly populated. The present result shows almost exclusive population of the 11.6 MeV state, which probably reflects not only its preferential feeding by the primary reaction but also its larger $^8\text{Li}$-alpha decay probability. The data on the $(n,^8\text{Li})$ reaction indicate that the lower state is more strongly excited in the process. The prominent $\alpha$-decay of the 11.6 MeV state, its strong population in triton transfer reactions and its very weak contribution in neutron transfer reactions and also in the $^4\text{He}(^9\text{Li},n)$ reaction, suggest that this state has a small neutron partial width and may possess exotic $\alpha$-cluster structure.

Very strong population of the state(s) around 13.3 MeV is observed here. It was claimed that the state at 13.3 MeV has a width of 50 [13] or 55 keV [16]. A much broader structure around that energy was observed in the $(t,p)$ [15] and also in the $(\gamma,\pi^+)$ reaction [23]. The resolution and statistics of present results can not exclude the possibility that a broader state or several states are involved. The $^9\text{Be}(^7\text{Li},\alpha)$ reaction to the state has the largest cross section at forward angles (< 40°) of all transitions to $^{12}\text{B}$ states [14]. This was attributed to the so called “threshold” state having the $\alpha$+$^9\text{Be}$ cluster structure according to theoretical arguments by Baz [24] (later elaborated also by others [25] and experimentally confirmed for many nuclei). The structure in the $(n,^8\text{Li})$ excitation function [21] as well as the maximum cross section observed at these energies in the most recent $(^8\text{Li},^{11}\text{B})$ reaction measurement [7] may also be attributed to this state. Being only a few hundred keV above the $\alpha$+$^9\text{Be}$ reaction threshold (i.e. inside the Gamow peak), it would have a large influence on the thermonuclear $^9\text{Be}$+t reaction rates. Boyd et al [16] discussed the possible importance of the $^9\text{Be}(t,n)^{11}\text{B}$ reaction in the production of $^{11}\text{B}$ in primordial nucleosynthesis. They calculated its rate under the assumption that the sum of the neutron partial widths to all $^{11}\text{B}$ states is very nearly equal to the total width, which does not seem to be supported by the present result of a strong $\alpha$-decay. One can expect that the states with $^9\text{Be}$+t or $^7\text{Li}$+$^5\text{He}$ (or better $\alpha$+$^5\text{He}$+t) clustering below the Coulomb barrier for these channels, have relatively large $\alpha$+$^8\text{Li}$gs decay width. Also at these energies, in addition to $n+^{11}\text{B}$ and $\alpha+^8\text{Li}$gs, decays to the first two $^8\text{Li}$ excited states as well as to $^{10}\text{Be}$+d are possible and their widths may not be negligible. Obviously, the thermonuclear $^9\text{Be}(t,\alpha)^8\text{Li}$ reaction rate should be strongly affected by this state, claimed to be a $2^+$ state [13,16].

A broad peak at 15.7 MeV may correspond to a state claimed to be at 15.5 MeV in the $(^7\text{Li},\alpha)$ reaction spectrum measured at $E_\alpha=30$ MeV and $\Theta=0^\circ$ [14], which is the only measurement reporting state(s) at these excitations. It should be mentioned that close to these energies are the thresholds for the following decays: $^5\text{He}$+t+$\alpha$ (15.39 MeV) and $\alpha$+$^8\text{Li}$* (4th excited state) (15.4 MeV) and it may be one of those threshold cluster states. At higher energies there is no evidence for other peaks except maybe at 17.7 MeV.

Conclusion. – The $\alpha$+$^8\text{Li}$ decay of several $^{12}\text{B}$ states for $10 < E_\alpha < 16$ MeV has been observed for the first time. The most strongly populated states are at 10.9, 11.6, 13.3 and 15.7 MeV, which is the consequence of their cluster structure. The 11.6 MeV state is a good candidate for having an exotic cluster structure. Some of these states may have a strong influence on the cross section of the $(^8\text{Li},\alpha)^{11}\text{B}$ reaction which is, in part, supported by the $(n,^8\text{Li})$ reaction results and also by the crude data from the $(^8\text{Li},^{11}\text{B})$ reaction measurements. From the present results one can also expect that the thermonuclear $^9\text{Be}$+t reaction rates are strongly influenced by the 13.3 MeV $\alpha$-decaying state(s), for which the excitation energy is only 0.4 MeV above the $\alpha$+$^9\text{Be}$ threshold. The present results also show that the indirect method
of coincidence measurement of many-body nuclear reactions can give important information for key astrophysical reactions. Because one cannot soon expect more accurate data on the astrophysically important $^6\text{Li}(\alpha,n)^{11}\text{B}$ reaction, it would be much easier to more thoroughly explore the excitation energy region above 10 MeV in experiments similar to the present one, with reactions like $^7\text{Li}(^6\text{Li},p)$, $^7\text{Li}(^7\text{Li},d)$, $^9\text{Be}(\alpha,p)$, $^{11}\text{B}(d,p)$, $^{13}\text{C}(d,^3\text{He})$, $^{14}\text{C}(d,\alpha)$ etc. In these measurements one may simultaneously determine $E_x$, $\Gamma_{\text{tot}}$, $\Gamma_{\alpha}$, $\Gamma_{n}$, and in some cases even the spin, of all of the states in the region, which will make it possible to determine the resonant contributions, the dominant part of the reaction cross section at these low energies.

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