Abstract. – In a kinematically complete measurement of the $^7\text{Li}(^7\text{Li},\alpha^6\text{He})^4\text{He}$ reaction at $E_i = 8$ MeV it was observed that the $^{10}\text{Be}$ excited states at 9.6 and 10.2 MeV decay by $^6\text{He}$ emission. The state at 10.2 MeV may be a member of a rotational band based on the 6.18 MeV $0^+$ state.

Introduction. – In this paper we present the results of a search for the $\alpha + ^6\text{He}$ decay of $^{10}\text{Be}$. In the most recent compilation \cite{1} of the energy levels of light nuclei the only explicitly shown mode of decay of the $^{10}\text{Be}$ states between the thresholds for neutron (6.81 MeV) and triton (17.25 MeV) decay is neutron emission, although the channels $^6\text{He} + \alpha$, $2\alpha + 2n$, $^8\text{Be} + 2n$, and $^5\text{He} + ^5\text{He}$ are open from 7.41, 8.39, 8.48, and 10.17 MeV, respectively. However, in the studies of $^{11}\text{Li}$ decay \cite{2} the delayed emission of $^6\text{He}$ was observed and it was attributed to the decay of the excited states of $^{10}\text{Be}$. Namely, it was claimed that the coincident $^6\text{He}-\alpha$ spectra could be explained by the $\beta^-$ decay of $^{11}\text{Li}$ into the 10.6 and 18.5 MeV states of $^{11}\text{Be}$, which decay by neutron emission to the 9.4 and 11.6 MeV states in
Be and each of them then disintegrate into an $\alpha$-particle and a $^6\text{He}$. However, this is not the only way how the $^6\text{He}+\alpha+n$ final state can be reached. The $^{11}\text{Be}$ high excited states can also decay into the $^6\text{He}+^5\text{He}$ and $\alpha+^7\text{He}$ channels with subsequent disintegration of neutron unstable $^5\text{He}$ and $^7\text{He}$ nuclei. Taking into account experimental conditions in the $^{11}\text{Li}$ decay measurements, the involvement of the $^{10}\text{Be}$ states and their $\alpha+^6\text{He}$ decay cannot be unambiguously claimed. Another indication of possible $^6\text{He}+\alpha$ decay of the $^{10}\text{Be}$ states came from the studies of the $^7\text{Li}$ ($^7\text{Li},^6\text{He})^8\text{Be}$ reaction \[3\]. The $^6\text{He}$ spectra could not be explained exclusively by contributions from the sequential processes through different $^8\text{Be}$ states. A broad structure in the total $^9\text{Be}(n,\alpha)^6\text{He}$ reaction cross section \[4\], centered around 9.6 MeV in $^{10}\text{Be}$, may be another indication of the $\alpha+^6\text{He}$ clustering of the states in this region.

Nuclei in the middle of the 1p shell exhibit collective nature. Although the independent particle model can account for many features of the nuclei, there are many exceptions, like enhanced electromagnetic transitions, large quadrupole moments, "unexpected" low lying nonnormal parity states (like the $1/2^+$ ground state in $^{11}\text{Be}$), large rms radii and $\alpha$-decay widths etc. Some of these properties could be easily explained by the cluster structure of the nuclei. There have been several theoretical studies of the structure of the A = 10 nuclei. Gabr and Hackenbroich \[5\] chose the cluster functions of $^{10}\text{B}$ to belong to spatial symmetry [442], which correspond to $^8\text{Be}$ core [44] and an extra deuteron or a $^6\text{Li}$ core [42] and an extra $\alpha$-cluster. The intercluster relative motions were represented by a small number of Gaussian functions. Only positive parity states with low excitations were determined. In a two-$\alpha$-particle-plus-dinucleon cluster model by Nishioka \[6\], both $^{10}\text{Be}$ and $^{10}\text{B}$ states were calculated. The $(1^+_2,0)$, $(0^+_2,1)$, and $(2^+_2,1)$ $^{10}\text{B}$ level energies were reproduced, which had not been the case by any other model investigation. These states were found to have a well developed $^6\text{Li}_{g.s.}+\alpha$ or $^6\text{Li}(0^+,1)+\alpha$ cluster structure, respectively. In another investigation the 10-nucleon system was studied with the multiconfiguration and multichannel resonating group method \[7\]. The model space employed was spanned by the $\alpha+^6\text{Li}$, $d+^8\text{Be}$, $d+^8\text{Be}^*$, and $\alpha+^6\text{Li}^*$ cluster configurations with $^6\text{Li}^*$ and $^8\text{Be}^*$ being the rotational excited states of
$^6$Li and $^8$Be having $d+\alpha$ and $\alpha+\alpha$ cluster structure and $L = 2$. Bound and resonant levels obtained in such a way correspond fairly well to the known low lying states. However, in all these theoretical studies the states at higher excitations (> 9 MeV) were not investigated.

These states can be easily reached by the $^7$Li+$^7$Li reactions. The $^7$Li($^7$Li,$\alpha$)$^6$He reaction was chosen for the search of the $\alpha+^6$He cluster states in $^{10}$Be for the following reasons: i) it has high positive Q-value (7.37 MeV) allowing measurements at low energies; ii) only the well known $^8$Be states (0, 3.0, and 11.4 MeV) together with those from $^{10}$Be can contribute to the coincident spectra; iii) the complex nature of the reaction at low energies should be more suitable for the excitation of these special states than some "simple" reactions like (d,p), ($\alpha$,3He) etc.

Experiment – A 3 particle nA 8 MeV $^7$Li beam from the Ruđer Bošković Institute EN Tandem Van de Graaff accelerator was used to bombard isotopically enriched $^7$LiF targets (100 - 320 $\mu$g/cm$^2$) evaporated on a thin carbon backing. Reaction products were observed with two solid state detector telescopes, each consisting of a thin $\Delta E$ detector (9 $\mu$m) and a thick (280 $\mu$m) rectangular position sensitive detector (PSD). PSD covered an angle of 12° in horizontal and 1.5° in vertical axis. Their horizontal angular resolution was better than 0.3°. The telescopes were positioned on the opposite sides with respect to the beam. The measurements were performed for several setting angles between 40° and 65°. The particle energy, "position" and energy loss pulses were recorded by a data acquisition system [8]. From these measured values the energy-momentum (EP) plots as well as Q-value spectra were made [9]. Other details on the experiment and analysis can be found in [10].

Results and discussion – Fig. 1 shows measured Q-value spectra for the $^6$He-$\alpha$ and $\alpha-\alpha$ coincidences. In the case of $^6$He-$\alpha$ coincidences background is very small, but in the second case the contributions from the $^{19}$F($^7$Li,$\alpha\alpha$)$^{18}$O and $^{12}$C($^7$Li,$\alpha\alpha$)$^{11}$B reactions are also present. In this case, in addition to the $^6$He ground state peak, five-body ($3\alpha+2n$)
continuum starting at $Q = 6.4$ MeV together with a peak corresponding to the $^6$He first excited state ($E_x = 1.8$ MeV) are also visible. Other structures cannot be unambiguously attributed to the $^6$He states.

The $\alpha^6$He-$\alpha$ events have also been sorted into three relative energy plots. The $^6$He-$\alpha$ coincidences, measured at setting angles $\Theta_1=\Theta_2=45^\circ$ ($\Delta \Phi = 180^\circ$), are displayed in the first three plots of Fig. 2. Two prominent groupings are observed: one corresponding to the excitation energies in the $^6$He-$\alpha$ system ($E_{13}$) between 2.5 and 3 MeV and the other corresponding to the energies in the $\alpha$-$\alpha$ system ($E_{23}$) around 3 MeV i.e. to the first excited state of $^8$Be. Although a wider range of the $^{10}$Be excitation energies was covered in the experiment, we concentrate here only on the part of the spectra below 4 MeV in the $\alpha^6$He relative energy, which is not affected by the sequential processes in other two pairs.

From the recorded data the $\alpha$-X coincidences (X being heavy particles with $A \geq 7$) are also selected with the aim to obtain information on the $\alpha^9$Be-n contributions. These heavy particles, detected in the $\Delta E$-detectors, were not identified - only their energy was measured. With an additional requirement that the events fall into the allowed kinematical regions for the $^7$Li($^7$Li,$\alpha^9$Be)n reaction, they are sorted into the $E_{ij}$-$\Theta^L_{\alpha}$ plots. $E_{ij}$ are the relative energies in the $^9$Be-n pairs, calculated directly from the energy and detection angle of $\alpha$-particles, $\Theta^L_{\alpha}$. An example is shown on the fourth plot of Fig. 2. The vertical structures seen in the plot obviously correspond to the sequential processes through the neutron decaying states of $^{10}$Be. The “background” is due to the sequential processes through the $^5$He and $^{13}$C states from the same $^7$Li($^7$Li,$\alpha^9$Be)n reaction as well as to the reactions on $^{19}$F. (The low energy cut was made in order to avoid random coincidences caused by the $^7$Li elastic scattering).

Fig. 3 shows the results of the experiment: the $^{10}$Be excitation energy spectra from the $^7$Li($^7$Li,$\alpha^{4}$He)$^4$He and $^7$Li($^7$Li,$\alpha^9$Be)n reactions. The uncertainties of peak positions and the resolution in excitation energy were estimated by the peaks corresponding to the ($^7$Li,$\alpha$) reactions to bound states of $^{10}$Be. Their values were found to be $<100$ keV and 250 keV, respectively.
In the $\alpha$-$^{9}$Be spectrum two structures are visible. The first one corresponds to a doublet of $^{10}$Be states (9.27 and 9.64 MeV) and the second one to a state at 10.57 MeV, all of them previously observed in different processes. Until recently the value of 9.4 MeV was quoted for the energy of the second member of the doublet. The present measurements support recent findings from the study of the $^7$Li($\alpha,p$)$^{10}$Be reaction [11] that the energy is somewhat higher, i.e. 9.64 MeV. This state also decays into $\alpha+^6$He channel, which supports previous claims about the involvement of this state in one of the final stages of the $^{11}$Li decay.

The other spectrum, $^6$He-$\alpha$ and $\alpha$-$\alpha$ coincidences, has a distinctive peak centered at 10.2 MeV. The width of this state is less than 400 keV. There hasn’t been any mention of a state at this energy except for the $^7$Li($\alpha,p$)$^{10}$Be measurement [11]. A double peaked structure in this energy region can also be seen in an $\alpha$-particle spectrum from the $^7$Li($^7$Li,$\alpha$)$^{10}$Be reaction measured at 30.3 MeV [12]. This state does not decay into n+$^9$Be channel, which explains very well why it was not observed in any neutron transfer reaction on $^9$Be [13]. One can also mention that its energy coincides with the threshold for $^{10}$Be disintegration into two $^5$He$_{g.s.}$. It is interesting to note here that the proton angular distributions from the $^7$Li($\alpha,p$)$^{10}$Be reaction for the 10.2 and 11.8 MeV states are almost identical in shape [11]. If the 11.8 MeV state is the $4^+$ member of the ground state rotational band, as claimed, then from the similarity of the angular distributions it follows that the 10.2 MeV state should at least have the positive parity, and maybe even the spin of 4. One can then further speculate that this state may be the $4^+$ member of the rotational band based on the 6.18 MeV excited $0^+$ state with its $2^+$ state at 7.54 MeV. Its excitation (10.2 MeV) is close to the energy (10.7 MeV) expected from the J(J+1) rule and the energy difference (1.36 MeV) between the $0^+$ and $2^+$ states. These two states, both in $^{10}$Be and $^{10}$B, are known to have well developed $^6$He+$\alpha$ and $^6$Li($0^+,1)+\alpha$ cluster structure, respectively (see e.g. [11]). Following the sequence of these states in $^{10}$Be (6.18, 7.54, 10.2 MeV) and the first two in $^{10}$B (7.56, 8.89 MeV) one may expect that the $^{10}$B level at 11.5 MeV, the only well established state between 10.9 and 12.5 MeV, is the third member of this band. Small energy separation between these states would then imply a large moment of inertia, i.e. they would be very
extended nuclear systems. Because the state at 10.2 MeV decays by emission of $^6\text{He}$, the well established two-neutron halo nucleus (see e. g. [14]), and because other two states (6.18 and 7.54 MeV) have also the $\alpha+^6\text{He}$ structure, one may ask what is the relation between these states and the two-neutron halo states, which may be expected in $^{10}\text{Be}$ close to the 2n emission threshold (8.48 MeV).

To conclude: the existence of the poorly known $^{10}\text{Be}$ state at 10.2 MeV is confirmed. This state decays into the $\alpha+^6\text{He}$ channel, but not into n+$^9\text{Be}$. Together with other two states (0$^+$ at 6.18 MeV and 2$^+$ at 7.54 MeV) it may make a rotational band of a very extended nuclear system. Further studies of the states in all three A = 10 nuclei having T=1 states, $^{10}\text{Be}$, $^{10}\text{B}$, and $^{10}\text{C}$, would give clear answer about the possible existence of the peculiar nuclear systems.

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FIGURES

FIG. 1. – Q-value spectra for the \(^7\text{Li},\alpha^6\text{He}\) and \(^7\text{Li},\alpha\alpha\) reactions on a \(^7\text{LiF}\) target and its carbon backing.

FIG. 2. – The \(E_{ij}-E_{jk}\) plots of the \(^6\text{He}-\alpha\) coincidences and the \(E_{ij}-\Theta^L_\alpha\) plot of the X(heavy particle)-\(\alpha\) coincidences, all measured at \(E_i = 8\) MeV and \(\Theta_1 = \Theta_2 = 45^\circ\) (\(\Delta \Phi = 180^\circ\)).

FIG. 3. – \(^{10}\text{Be}\) excitation spectra obtained from the \(^7\text{Li}(^7\text{Li},\alpha^6\text{He})^4\text{He}\) and \(^7\text{Li}(^7\text{Li},\alpha^9\text{Be})n\) reactions at \(E_i = 8\) MeV (large difference in the number of events for these two processes is mainly due to the larger \(^9\text{Be}\) detector solid angle).
$^7\text{Li}(^7\text{Li}, \alpha^6\text{He})^4\text{He}$

$^7\text{Li}(^7\text{Li}, \alpha\alpha)^6\text{He}$

$E = 8 \text{ MeV}$

$^7\text{Li}(^7\text{Li}, \alpha^9\text{Be})n$

$E = 8 \text{ MeV}$

Counts / channel

$E_x (^{10}\text{Be})$ (MeV)