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Dissociation of Relativistic ^{10}B Nuclei in Nuclear Track Emulsion

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Abstract—The structural features of ^{10}B are studied by analyzing the dissociation of nuclei of this isotope at an energy of 1 A GeV in nuclear track emulsion. The fraction of the $^{10}\mathrm{B} \to 2\mathrm{He} + \mathrm{H}$ channel in the charge state distribution of fragments is 78%. It was determined based on the measurements of fragment emission angles that unstable $^{8}\mathrm{Be}_{\mathrm{g.s.}}$ nuclei appear with a probability of (26 ± 4)%, and (14 ± 3)% of them are produced in decays of an unstable $^{9}\mathrm{B}_{\mathrm{g.s.}}$ nucleus. The Be + H channel was suppressed to approximately 1%.

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Virtual nucleon associations (clusters) are the fundamental structural elements of atomic nuclei. Their simplest observable manifestations are the lightest ^{4,3}He and ^{3,2}H nuclei, which have no excited states. Superpositions of the lightest clusters and nucleons form subsequent nuclei (including unstable ^{8}Be and ^{9}B), which act as constituent clusters themselves. The balance of possible superpositions in states with suitable spin and parity values defines binding and the parameters of the ground state of the corresponding nucleus. Clusterization of the ground state of a light nucleus defines the structure of its excitations and the initial conditions of reactions it is involved in. Further attachment of nucleons and lightest nuclei leads to a shell-type structure. The entanglement of cluster and shell degrees of freedom turns the group of light nuclei into a "laboratory" of nuclear quantum mechanics. Clusterization forms the basis of processes that accompany the phenomena of physics of nuclear isobars, hypernuclei, and quark-parton degrees of freedom. The concept of clusterization of nuclei is essential to applications in nuclear astrophysics, cosmic-ray physics, nuclear medicine, and, possibly, nuclear geology.

The BECQUEREL project [1], which is focused on examining the cluster structure of light nuclei, involved irradiation of nuclear track emulsion (NTE) with relativistic Be, B, C, and N isotopes (including radioactive ones) at the JINR nuclotron [2]. Longitudinally irradiated NTE layers provide an opportunity to analyze the fragment ensembles fully. The events of coherent dissociation of nuclei with no tracks of slow fragments and charged mesons ("white" stars; see Fig. 1) are especially valuable in this respect. The irradiation of NTE with ^{10}B nuclei with an energy of 1 *A* GeV was performed in 2002 in the first run at the extracted nuclotron beam. The success of this experiment paved the way for subsequent irradiations with secondary beams enriched in ^{8}B and ^{9}Be nuclei that were formed based on acceleration and fragmentation of ^{10}B. The effect of dominance of 2He + H white stars (~70%) in the dissociation of ^{10}B nuclei was noted, but was not analyzed. In addition, the Be + H channel turned out to be suppressed (no more than 2%). This irradiation was "overshadowed" by irradiations with relativistic radioactive neutron-deficient nuclei. The discovery of a considerable contribution of an unstable ^{9}B nucleus to the structure of a radioactive ^{10}C nucleus [3] highlighted the importance of in-depth analysis of dissociation $^{10}\mathrm{B} \to 2\mathrm{He} + \mathrm{H}$. This analysis is aimed at determining the probabilities of coherent dissociation of a ^{10}B nucleus involving ^{8}Be and a ^{9}B nucleus. The continuation of studies into the ^{10}B nucleus structure was relevant to interpreting the data on ^{11}C, where ^{10}B may serve as a structural element [4].

Nuclei with a marked cluster structure should act as cores in ^{10}B. This is evidenced by the thresholds of separation of nucleons and the lightest nuclei $^{6}\mathrm{Li} + \alpha$ (4.5 MeV), $^{8}\mathrm{Be} + d$ (6.0 MeV), $^{9}\mathrm{Be} + p$ (6.6 MeV), and

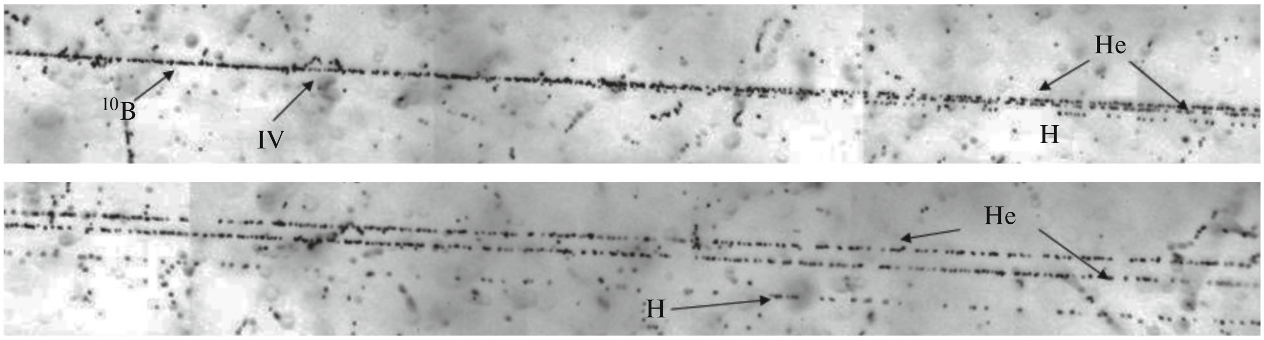

Fig. 1. Macrophotograph of the event of coherent dissociation of a ^{10}B nucleus into He and H fragments (IV is the approximate position of the interaction vertex). This event has the following parameters: $\Theta_{2\alpha}$ = 5.3 mrad, $Q_{2\alpha}$ = 87 keV, and $Q_{2\alpha p}$ = 352 keV.

^{9}B + n (8.4 MeV). As in the case of ^{10}C, decays of an unstable ^{9}B nucleus may serve as sources of ^{8}Be$_{g.s.}$ nuclei in the ground state 0^+ in the process of dissociation of ^{10}B. The ^{8}Be$_{2+}$ + d cluster configuration could serve as the source of ^{8}Be nuclei in the first excited state 2^+. Another ^{10}B component is based on a ^{9}Be nucleus with ^{8}Be$_{g.s.}$ and ^{8}Be$_{2+}$ featuring in almost equal measure in its structure. This component may manifest itself in the dissociation of ^{10}B both in the production of ^{9}Be nuclei and in the emergence of pairs of α-particles ^{8}Be$_{g.s.}$ and ^{8}Be$_{2+}$. The probability of coherent dissociation in the ^{9}B + n channel is expected to be the same as that for the ^{9}Be + p mirror channel. Likewise, a ^{6}Li nucleus can be present both as an integral formation and as virtual α + d bonding.

These considerations motivated us to resume the analysis of ^{10}B irradiation in 2015. The tracks of beam ^{10}B nuclei in NTE have already been examined over the length of 241 m. Altogether, 1664 inelastic interactions were found as a result. The charge topology distribution of 127 ^{10}B white stars (see Table 1) confirms the dominance of the 2He + H (78%) channel and the suppression of the Be + H (1%) channel, which should correspond to the ^{9}Be + p configuration.

In order to obtain a reliable reference ^{8}Be and ^{9}B signal based on angular measurements, the statistics of ^{10}B $\to$ 2He + H events was brought up to 296 (including 166 white stars). This increase was achieved by implementing a quick area search and adding "non-white" 2He + H stars to the measurements. The sampling is governed primarily by the geometric pattern of events in the emulsion volume relative to the fiducials and does not introduce any additional selection criteria.

The distribution of 2He pairs in this sample over spatial angle Θ_{2He} (Fig. 2, left panel) in the $0 < \Theta_{2He} < 10.5$ mrad interval indicates the existence of 56 ^{8}Be$_{g.s.}$ decays (with 40 of them from white stars). A total of 28 decays (including 22 decays in white stars; Fig. 2, right panel) assigned to ^{9}B$_{g.s.}$ (as in [5]) can be isolated from the distribution of all measured events over spatial angle Θ_{2HeH} between the ^{8}Be$_{g.s.}$ and H directions in the $0 < \Theta^8{}_{Be+H} < 25$ mrad interval. Thus, ^{8}Be$_{g.s.}$ nuclei form via ^{9}B$_{g.s.}$ decays in just a half of all events.

The decays of relativistic ^{8}Be and ^{9}B nuclei can be reconstructed based on excitation energy $Q = M^* - M$, which is the difference between invariant mass of fragments M^*, $M^{*2} = \sum(P_iP_k)$, and total fragment mass M. $P_{i,k}$ are 4-momenta determined in the approximation of conservation of the initial momentum of fragments per nucleon. In the region of small opening angles, it is reasonable to assume that the H isotope corresponds to protons and the He isotope corresponds to α-particles. The distribution over energy $Q_{2\alpha}$ (Fig. 3, left panel) at $0 < Q_{2\alpha} < 200$ keV has a mean value of 105 ± 7 keV with RMS = 46 keV and corresponds to the ^{8}Be$_{g.s.}$ ground state, while the distribution over energy $Q_{2\alpha p}$ of 2α + p triples (Fig. 3, right panel) at $0 < Q_{2\alpha p} <$ 400 keV has a mean value of 261 ± 23 keV with RMS = 91 keV and corresponds to the ^{9}B$_{g.s.}$ ground state. The distribution over transverse momentum $P_{T(9B)}$ of ^{9}B$_{g.s.}$ nuclei (Fig. 4) is a Rayleigh one with parameter $\sigma_{P_T}(^9B)$ = 121 ± 30 MeV/c, which does not contradict the statistical model (96 MeV/c). He and H isotopes are now being identified by the multiple scattering

Table 1. Distribution of 127 ^{10}B "white" stars over the charge configurations of fragments

Channel	Number of stars
Be + H	1 (1%)
2He + H, including ^{8}Be and ^{9}B	99, 24, 13 (78, 19, 10)%
He + 3H	16 (12%)
Li + He	5 (4%)
Li + 2H	5 (4%)
5H	1 (1%)

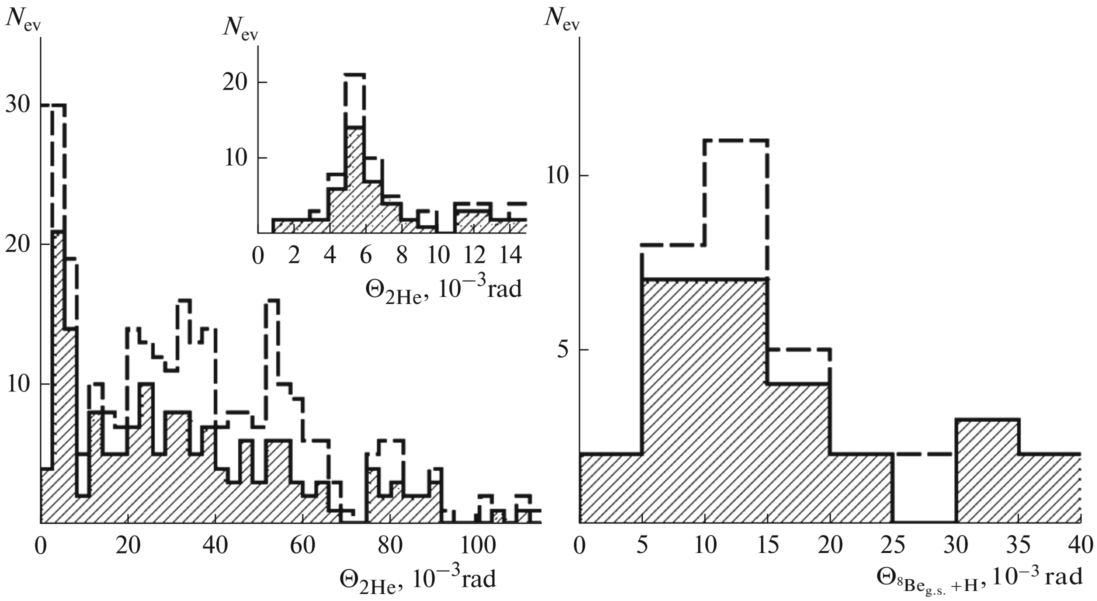

Fig. 2. Distribution of $^{10}B \rightarrow 2He + H$ events as a function of the opening angle Θ_{2He} in 2He pairs (left) and the opening angle $\Theta^8{}_{Be + H}$ in $^8Be_{g.s.}$ and H pairs (right) for all found events (dashed curve) and in "white" stars (hatched).

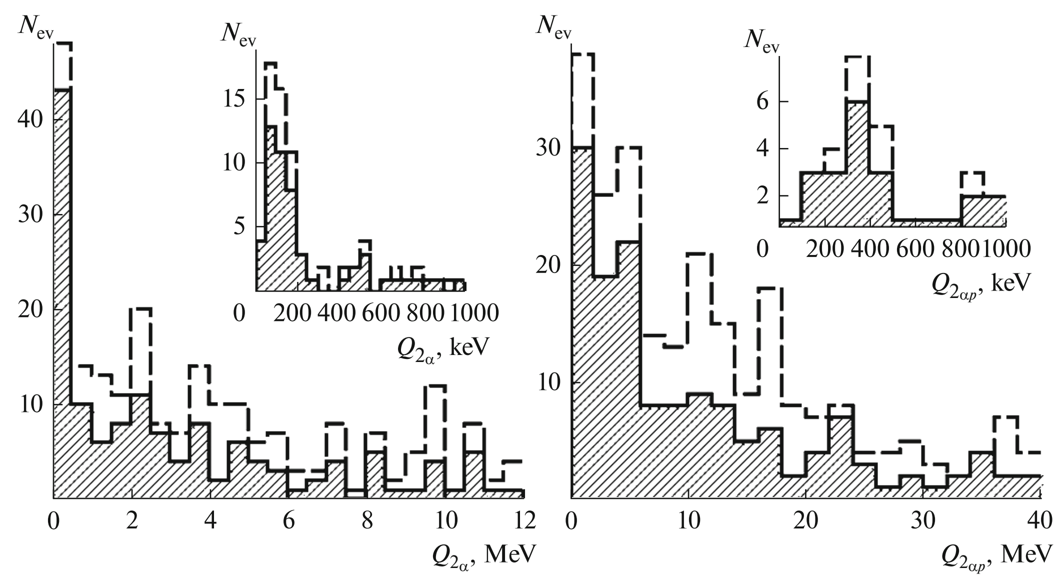

Fig. 3. Distribution of $^{10}B \rightarrow 2He + H$ events as a function of energy $Q_{2\alpha}$ of α-particle pairs (left) and energy $Q_{2\alpha p}$ of $2\alpha + p$ triples (right) for all found events (dashed curve) and in "white" stars (hatched). Magnified portions of distributions over $Q_{2\alpha}$ and $Q_{2\alpha p}$ are shown in the insets.

method, which should extend the region of the fragment opening angles under investigation.

Thus, unstable ^{8}Be and ^{9}B nuclei manifest themselves in coherent dissociation in the $^{10}B \rightarrow 2He + H$ channel with a probability of $(26 \pm 4)\%$ and $(14 \pm 3)\%$, respectively. Therefore, they are significant constituents of a ^{10}B nucleus. It is unexpected that the number of $^9B + n$ white stars is ten times higher than that of $^9Be + p$ (see Table 1). This observation may indicate that the spatial distribution of neutrons in a ^{10}B nucleus is wider than that of protons, which results in a larger cross section of the $^9B + n$ channel.

It appears that the physics behind this is as follows. A ^{9}B nucleus is a "loose" nuclear-molecular structure made of $2\alpha + p$ clusters. The Coulomb barrier can enhance the proton binding. The ^{9}Be core nucleus is

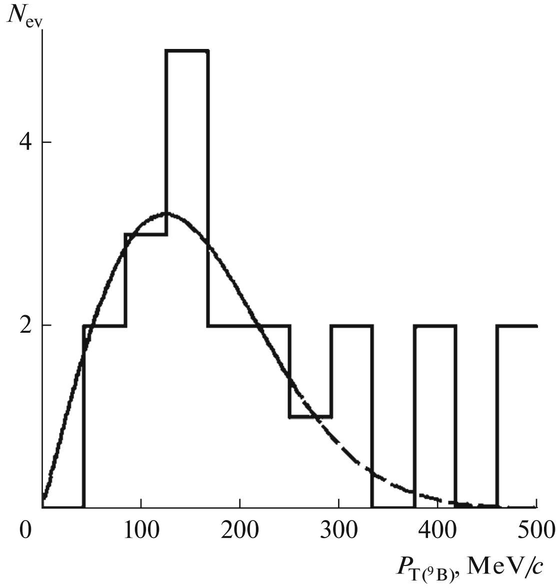

Fig. 4. Distribution of “white” stars as a function of the transverse momentum $P_{T(9B)}$ of 2He + H triples with the formation of a $^9B_{g.s.}$ nucleus.

also likely to be present in ^{10}B not as an integral formation, but in a “loose” form of $2\alpha + n$ (an approximately even superposition of $^8Be_{g.s.}$ and $^8Be_{2+}$ couplings with a neutron). The dominance of decays of $^8Be_{g.s.}$ over $^9B_{g.s.}$ in the dissociation may be attributed to the additional contribution of a “loose” ^{9}Be nucleus. Note that ^{9}Be may not be present in the structure of ^{10}C. Indeed, the decays of $^8Be_{g.s}$ in ^{10}C white stars are always associated with $^9B_{g.s.}$ decays. It is possible that a Li nucleus, which is manifested weakly in the dissociation of ^{10}B (see Table 1), is also present in ^{10}B primarily in its “dissolved” form and produces a nonresonance contribution to the Θ_{2He} distribution.

The study of ^{10}B allows one to trace the evolution from the cluster-type nuclear structure to the shell-type one and requires the data on relativistic dissociation of ^{6}Li and ^{9}Be nuclei and the identification of H fragments in the 2He + H channel. A detailed understanding of the coherent dissociation of ^{10}B serves, in turn, as the basis for interpreting the structure of the next isotope (^{11}C).

REFERENCES

1. http://becquerel.jinr.ru.
2. P. I. Zarubin, “Tomography” of the cluster structure of light nuclei via relativistic dissociation," in *Clusters in Nuclei*, Ed. by C. Beck (Springer, 2014), Vol. 3, p. 51.
3. K. Z. Mamatkulov, R. R. Kattabekov, S. S. Alikulov, D. A. Artemenkov, R. N. Bekmirzaev, V. Bradnova, P. I. Zarubin, I. G. Zarubina, N. V. Kondratieva, N. K. Kornegrutsa, D. O. Krivenkov, A. I. Malakhov, K. Olimov, N. G. Peresadko, N. G. Polukhina, et al., “Dissociation of ^{10}C nuclei in a track nuclear emulsion at an energy of 1.2 GeV per nucleon,” Phys. At. Nucl. **76**, 1224 (2013).
4. D. A. Artemenkov, V. Bradnova, A. A. Zaitsev, P. I. Zarubin, I. G. Zarubina, R. R. Kattabekov, N. K. Kornegrutsa, K. Z. Mamatkulov, P. A. Rukoyatkin, V. V. Rusakova, and R. Stanoeva, “Charge topology of the coherent dissociation of relativistic ^{11}C and ^{12}N nuclei,” Phys. At. Nucl. **78**, 794 (2015).
5. T. Toshito et al., “Measurements of projectile-like ^{8}Be and ^{9}B production in 200–400 MeV/nucleon ^{12}C on water,” Phys. Rev. C **78**, 067602 (2008).

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