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# Study of the Involvement of $^8$Be and $^9$B Nuclei in the Dissociation of Relativistic $^{10}$C, $^{10}$B, and $^{12}$C Nuclei

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**Abstract**—The results obtained by estimating the contribution of $^8$Be and $^9$B nuclei to the coherent dissociation of $^{10}$C, $^{10}$B, and $^{12}$C relativistic nuclei in nuclear track emulsions ("white" stars) are presented. The selection of white stars accompanied by $^9$B leads to a distinct peak appearing in the distribution of the excitation energy of $2\alpha 2p$ ensembles and having a maximum at $4.1 \pm 0.3$ MeV. A $^8$Be nucleus manifests itself in the coherent-dissociation reaction $^{10}\mathrm{B} \to 2\mathrm{He} + \mathrm{H}$ with a probability of $(25 \pm 5)\%$, $(14 \pm 3)\%$ of it being due to $^9$B decays. The ratio of the branching fractions of the $^9\mathrm{B} + n$ and $^9\mathrm{Be} + p$ mirror channels is estimated at $6 \pm 1$. An analysis of the relativistic dissociation of $^{12}$C nuclei in a nuclear track emulsion revealed nine $3\alpha$ events corresponding to the Hoyle state.

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## INTRODUCTION

A relativistic approach to studying nucleon clustering on light nuclei was developed within the BECQUEREL project [1] (for an overview, see [2, 3]). The project was aimed at an analysis of layers of nuclear track emulsion that were exposed to primary and secondary beams of nuclei accelerated to an energy of about 1 GeV per nucleon at the nuclotron of the Joint Institute for Nuclear Research (JINR, Dubna). The accelerator facility at the Institute for High Energy Physics (IHEP, Protvino), which may provide beams of $^{12}$C nuclei whose energy ranges from a few hundred MeV units (booster) to several tens of GeV units (main ring), opens new possibilities in this respect. In this context, we present below the results and prospects of studies of multiparticle states involving $^8$Be and $^9$B unstable nuclei originating from the dissociation of a $^{10}$C radioactive nucleus and $^{10}$B and $^{12}$C stable nuclei.

Observations of events of the multiparticle fragmentation of relativistic nuclei by means of nuclear track emulsions are unique in completeness and in angular resolution. In order to deduce conclusions on the structure of nuclei being studied, one analyzes the observed interactions, focusing on coherent-dissociation events, which do not involve slow fragments or charged mesons ("white" stars). This event selection gives grounds to assume that respective collisions have a tangential character and that colliding nuclei are minimally perturbed. White stars emerge upon nuclear diffractive dissociation without an overlap of the densities of colliding nuclei. The probability for final states of fragments in white stars provides an estimate of their contribution to the structure of nuclei being studied.

Unstable nuclei of $^8$Be and $^9$B may play a key role in a general picture of nuclear clustering. Although attempts at respective observations run into serious difficulties, the contribution of these nuclei deserves investigation over the whole available range of nuclei. On the basis of measuring emission angles for

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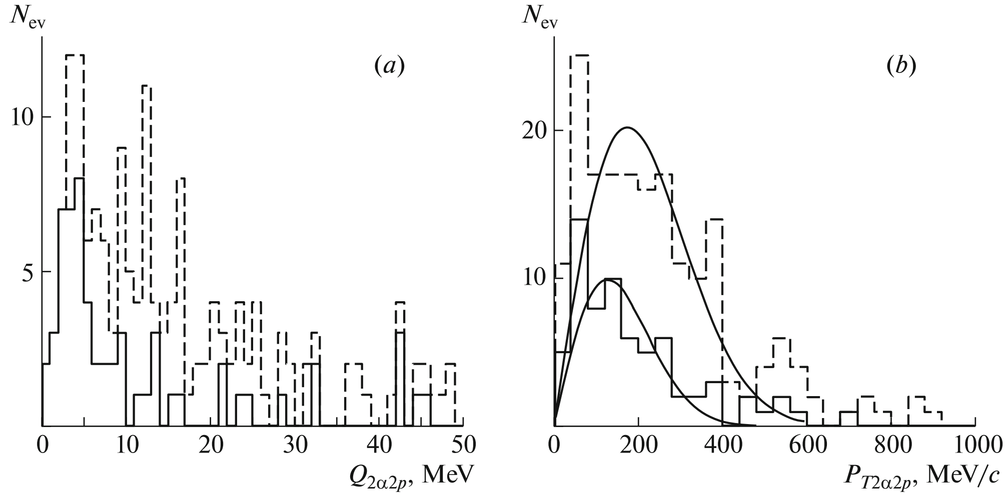


**Fig. 1.** (*a*) Energy ($Q_{2\alpha 2p}$) and (*b*) total-transverse-momentum ($P_{T2\alpha 2p}$) distributions of (dashed-line histogram) all $^{10}$C $\to$ 2He + 2H white stars and (solid-line histogram) stars that involve $^9$B.

helium and hydrogen isotopes, one reconstructs the decays of $^8$Be and $^9$B. The relativistic decays of $^8$Be and $^9$B nuclei can be identified in the distributions of the variable $Q = M^* - M$, where $M^{*2} = \sum(P_i \cdot P_k)$, $M^*$ is the invariant mass of the system of fragments, and $P_{i,k}$ stands for their 4-momenta determined in the approximation where the fragments conserve the primary momentum per nucleon.

## POSSIBLE $2\alpha 2p$ RESONANCE

The structure of the $^{10}$C radioactive nucleus was studied by the method of coherent dissociation at an energy of 1.2 GeV per nucleon [4]. It was found that events of the 2He + 2H channel saturate 82% of white stars. The assumption that helium nuclei correspond to $^4$He, while hydrogen isotopes correspond to proton is justified for $^{10}$C $\to$ 2He + 2H white stars. In analyzing the distributions of $2\alpha p$ three-particle combinations with respect to the energy $Q_{2\alpha}$, it was found that $^9$B manifests itself in $^{10}$C with a probability of $(30 \pm 4)$%, while $^8$Be$_{\text{g.s.}}$ originates from $^9$B decays exclusively.

A feature missed in [4] was found recently in the energy ($Q_{2\alpha 2p}$) distribution of $2\alpha 2p$ four-particle combinations (Fig. 1a). This is a distinct peak (RMS is 2.0 MeV) at $Q_{2\alpha 2p} = 4.1 \pm 0.3$ MeV for white stars featuring $^9$B decays. The number of events forming this peak is $(17 \pm 4)$% of the total number of $^{10}$C white stars and $(65 \pm 14)$% of events involving $^9$B decay. The distribution of all $2\alpha 2p$ ensembles with respect to the total transverse momentum $P_{T2\alpha 2p}$ (see Fig. 1*b*) is described by the Rayleigh function specified by the parameter value of $\sigma = 175 \pm 10$ MeV/$c$. In the presence of $^9$B, this distribution is substantially narrower—$\sigma = 127 \pm 16$ MeV/$c$.

An indication that such a resonance is present in the $^9$B + $p$ system was obtained in [5] by employing $^{10}$C nuclei at the energy of 35 MeV per nucleon, but this was not confirmed in a different experiment [6] where the energy of these nuclei was 10 MeV per nucleon. Later, the authors of [5] disavowed their original result, referring to insufficient resolution and supporting their statement by a simulation [7]. Nevertheless, a strong energy dependence of the inevitably peripheral excitation of this resonance may underlie the contradiction between [5] and [6].

In low-energy experiments involving the detection of all projectile fragments, the condition of its peripheral character cannot be strengthened by the requirement of the absence of target fragments. At the energy threshold for the dissociations reaction, such a resonance may either prove to be unobservable under conditions of an intricate reaction mechanism or not arise in principle. Our observation is based on a totally different implementation. It is maximally reliable and boasts the highest angular resolutions in measuring tracks of $2\alpha 2p$ four-particle combinations. In order to confirm the existence of such a resonance, which may prove to be a $2\alpha 2p$ nuclear-molecule system, it is highly desirable to obtain a vaster data sample on the basis of a new irradiation run and to apply a faster method of searches for jets of 2He + 2H fragments.

## ASYMMETRY IN MIRROR CHANNELS OF DISSOCIATION OF $^{10}$B

An irradiation of a nuclear track emulsion with $^{10}$B nuclei accelerated to an energy of 1 GeV per

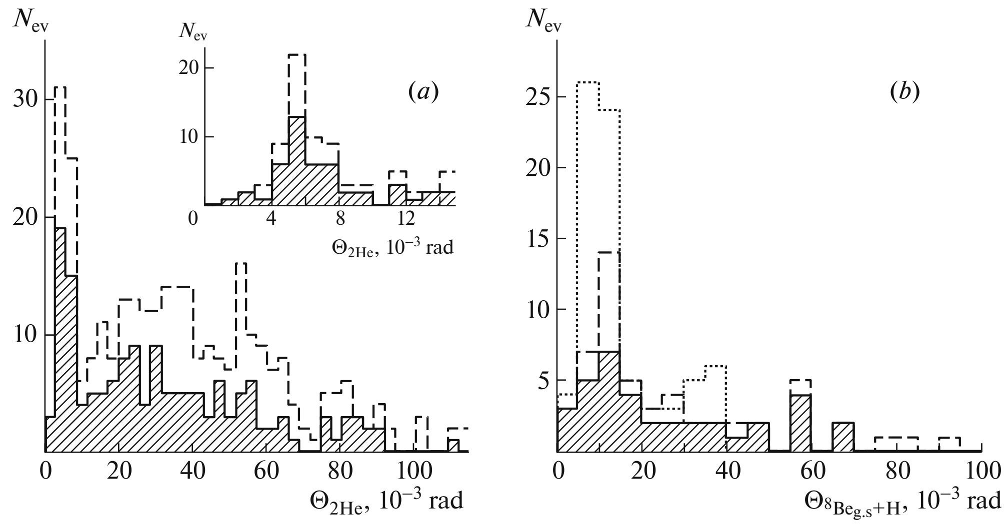


**Fig. 2.** Distribution of (*a*) the angle of divergence, $\Theta_{2He}$, of helium fragments in (dashed-line histogram) all stars and (shaded region) white stars involving $^{10}$B and (*b*) the angle of divergence, $\Theta(^8Be_{g.s.} + H)$, in (dotted-line histogram) white stars involving $^{10}$C, (dashed-line histogram) all stars, and (shaded region) white stars involving $^{10}$B.

nucleon was implemented in one of the first runs at the JINR nuclotron. An analysis of coherent-dissociation events revealed the dominance of white stars in the 2He + H channel and their suppression in the Be + H channel (its fraction was not more than 2%). That the contribution of the $^9$B unstable nucleus to the structure of the $^{10}$C radioactive nucleus was found to be significant [4] was indicative of the possible involvement of $^9$B in the dissociation of $^{10}$B. Moreover, an interpretation of the structure of the $^{10}$B nucleus with allowance for the possible presence in it of a superposition of $^8Be_{g.s.}$ and $^8Be_{2+}$ virtual states becomes possible upon resorting to appearing information about the dissociation of $^9$Be nuclei in a nuclear track emulsion. A determination of the contribution of unstable nuclei furnishes the basis for obtaining deeper insight into the structure of $^{11}$C [3] and $^{12}$N nuclei.

The repeated scanning in 2015 along the tracks of $^{10}$B beam nuclei over the length of 241 m resulted in finding 1664 nuclear stars [3]. The distribution of 127 $^{10}$B white stars found among them confirms the dominance of the 2He + H channel (78%) and the suppression of the Be + H channel (1%), which should correspond to the $^9Be + p$ configuration. The remaining events were distributed among the He + 3H (12%), Li + He (4%), and Li + He (4%) channels.

In the measurements of the divergence angle $\Theta_{2He}$, the sample of 2He pairs in the range of $0 < \Theta_{2He} < 10.5$ mrad, which corresponds to $^8Be_{g.s.}$ decay, includes $(25 \pm 5)\%$ of $^{10}B \to 2He + H$ white stars (see Fig. 2*a*). The divergence-angle interval of $\Theta(^8Be_{g.s.} + H) < 25$ mrad (see Fig. 2*b*), which corresponds to $^9$B decays, contains only $(14 \pm 3)\%$ of $^{10}B \to 2He + H$ white stars. Thus, $^9$B decays explain only $(5 \pm 16)\%$ of $^8Be_{g.s.}$ decays. It should be emphasized that this conclusion differs from that for the case of $^{10}$C, where there was a perfect correspondence. This lends support to the assumption that, in the $^{10}$B nucleus, there is a superposition of $^8Be_{g.s.}/^8Be_{2+}$ cores, along with $^9$B. This superposition manifests itself as an excess of events involving $^8Be_{g.s.}$.

The set of $^{10}$B white stars found without selections permits estimating the ratio of the branching fractions of the $^9B + n$ and $^9Be + p$ channels at $6 \pm 1$, which seems unexpected. An alternative explanation of the asymmetry of the branching fractions of these mirror channels could be based on a qualitatively broader distribution of neutrons in relation to protons. However, this version seems improbable, since the inelastic cross sections for the interaction of relativistic $^{10}$B nuclei do not exhibit exotic behavior.

Possibly, this fact is indicative of the presence of the $^9$Be core in $^{10}$B, predominantly in the form of a $^8Be_{2+}/^8Be_{g.s.} + n$ superposition (nuclear molecule), manifesting itself in the dissociation mode involving the direct formation of $^8Be_{g.s.}$ (without $^9$B decays) and $^8Be_{2+}$ states. As for the $^9$B core, it initially has this cluster form.

Relativistic hydrogen and helium fragments can be identified by the parameter $p\beta c$, which is determined on the basis of measurements of multiple scattering

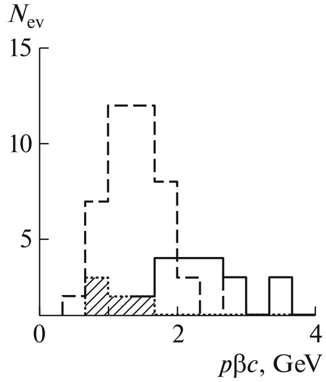


**Fig. 3.** $p\beta c$ distribution of tracks of (solid-line histogram) beam deuterons and (dashed-line histogram) hydrogen fragments in 52 $^{10}B \to 2He + H$ stars, including 36 white stars and nine $^9$B decays (shaded region).

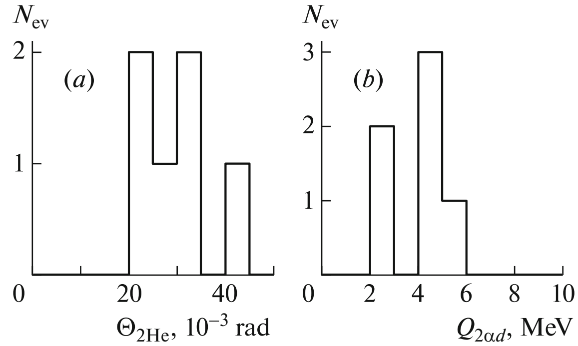


**Fig. 4.** Distribution of ($a$) the opening angle $\Theta_{2He}$ for helium fragments under the condition that $p\beta c$ is greater than 1.9 GeV (deuterons) in $^{10}B \to 2He + H$ white stars and ($b$) the energy $Q_{2\alpha d}$ for $^8Be_{2+} + d$ ensembles.

of tracks in a nuclear track emulsion, where $p$ is the total momentum and $\beta c$ is the speed. Measurement of the parameter $p\beta c$ for beam deuterons (calibration) makes it possible to test this cumbersome and not always implementable procedure (see Fig. 3). For their 20 tracks, the average value of $\langle p\beta c\rangle$ was $2.5 \pm 0.5$ GeV at RMS $= 0.6$ GeV; this complies with the expected value. In addition, a value of $\langle p\beta c\rangle = 1.1 \pm 0.3$ GeV at RMS $= 0.4$ GeV was obtained for hydrogen fragments from $^9$B decays in $^{10}B \to 2He + H$ white stars. This corresponds both to decay protons and to the primary momentum of $^{10}$B nuclei per nucleon.

In order to identify hydrogen isotopes in $^{10}B \to 2He + H$ white stars, we employed the procedure developed on the basis of constructing classifying functions. These functions were obtained from a statistical simulation of the average values of the second differences of track deviations $\langle|D|\rangle$ in cells of dimension 500, 600, 700, and 800 $\mu$m. The functions obtained in this way were used to associate the experimental values of $\langle|D|\rangle$ with groups of values characteristic of different isotopes.

According to this procedure, protons characterized by an average value of $\langle p\beta c\rangle = 1.2 \pm 0.1$ GeV at RMS $= 0.3$ GeV dominate the $p\beta c$ spectrum of hydrogen fragments in $^{10}B \to 2He + H$ white stars up to 1.8 GeV. The $p\beta c$ distribution above 1.8 GeV corresponds to deuterons for which $\langle p\beta c\rangle = 2.5 \pm 0.5$ GeV at RMS $= 0.7$ GeV. The ratio of the numbers of identified $p$ and $d$ tracks is $2 \pm 0.25$.

The identification of helium and hydrogen isotopes makes it possible to perform a more profound analysis of $^{10}B \to 2He + H$ white stars. In particular, the $^8Be_{2+} + d$ configuration may be a source of $^8Be_{2+}$ decays. In the present study, we observed six white stars of this type. Figure 4$a$ shows the distribution of the opening angle $\Theta_{2He}$ for helium fragments under the condition that $p\beta c$ is greater than 1.9 GeV. The distribution in question is characterized by a mean value of $\langle\Theta_{2He}\rangle = 30 \pm 3$ mrad at RMS $= 7$ mrad. This corresponds to $\langle Q_{2\alpha}\rangle = 2.8 \pm 0.5$ MeV at RMS $= 0.9$ MeV and, hence, to the $^8Be_{2+}$ state. Figure 4$b$ gives the distribution of the energy $Q_{2\alpha d}$ for these six $^8Be_{2+} + d$ ensembles; it has $\langle Q_{2\alpha d}\rangle = 4.1 \pm 0.3$ MeV at RMS $= 0.9$ MeV. Although this observation has a rather low statistical significance, it is indicative of the possible formation of states belonging to the nuclear-molecule type. Moreover, white stars in the channel $^{10}B \to {}^6Li + \alpha$ are observed with a probability of 8%. Therefore, one can expect a contribution of the cluster structure of $^6$Li to the $2\alpha + p(d)$ channel. However, investigation along these lines would require a vaster set of white-star data.

## SEARCH FOR THE HOYLE STATE

A search for combinations of three alpha particles in a Hoyle state (in the second excited state and in the first unbound state of spin–parity $0_2^+$) upon the coherent dissociation of $^{12}$C nuclei is promising task for the emulsion procedure. In nucleosynthesis, the merger of a $3\alpha$-particle ensemble into the $^{12}$C nucleus proceeds through this state. It is assumed that (along with $^8$Be) it corresponds to a Bose–Einstein condensate [8] of alpha particles that have zero relative angular momenta. The Hoyle state is expected to manifest itself experimentally in alpha-particle jets that have extremely small opening angles and in which all alpha-particle pairs correspond to

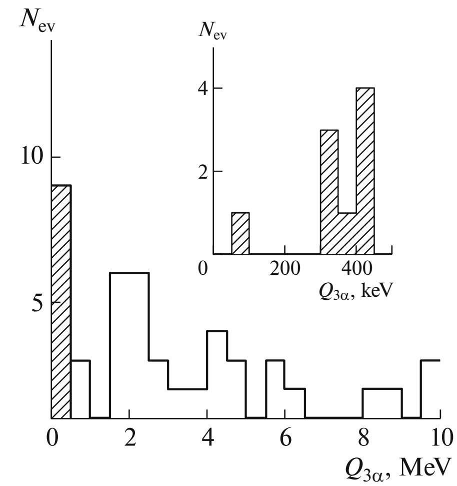


**Fig. 5.** Distribution of the energy $Q_{3\alpha}$ for combinations of three alpha particles in $^{12}C \to 3\alpha$ coherent-dissociation events at a momentum of 4.5 GeV/$c$ per nucleon. The region between 0 and 500 keV is shown in the inset on a magnified scale.

$^8Be_{g.s.}$. We will now expound on the experimental evidence in support of this statement.

In the early 1970s, a nuclear track emulsion was exposed to $^{12}C$ nuclei of energy 3.65 GeV per nucleon at the JINR synchrophasotron. Emulsion-layers stacks impregnated with lead salts were irradiated later. We performed a reanalysis of these irradiated emulsions and found nine events in which the total transverse energy of alpha particles in the reference frame comoving with the nucleus undergoing dissociation corresponds to the excitation of the $^{12}C^*$ to the level at 7.65 MeV (Hoyle state). Figure 5 gives the distribution of these events with respect to the variable $Q_{3\alpha}$. These observations of priority character motivate further searches for the Hoyle state at acceptable statistical-significance level.

For this purpose, emulsion stacks will be exposed longitudinally to $^{12}C$ nuclei at the JINR nuclotron and at the IHEP accelerator facility. The energy of $^{12}C$ nuclei will range from several hundred MeV units to a few tens of GeV units per nucleon, and this will permit tracing the behavior of the cross section for the emergence of $3\alpha$ combinations in the Hoyle state and establishing the universality of its formation. The nuclear track emulsion used will be enriched in lead nuclei in order to enhance the contribution of electromagnetic dissociation. We will measure opening angles in several hundreds of combinations of three alpha particles.

It is important to perform respective measurements over broader regions of energies of $^{12}C$ nuclei since theoretical calculations of cross sections for the electromagnetic dissociation of light nuclei predict a broad maximum in the region of several hundred MeV units per nucleon. At lower projectile energies, the implementation becomes more convenient in several aspects of practical importance. First, a visual contrast between $\alpha$-pair fragments and narrow pairs from $^8Be_{g.s.}$ decays becomes sharper. Second, the fraction of background events involving the production of charged mesons becomes lower. Third, it is easier to level out the beam profile at the entrance of the emulsion stack. The effect of deceleration of a primary nucleus in the emulsion medium can be compensated by the invariant representation of the $\alpha$-pair energy and by the narrowing the scanned region along the beam direction.

A medical beam of $^{12}C$ nuclei at IHEP is used at the initial and the mane stage of this project. It ensures the required uniformity of irradiation and has an energy that corresponds to the maximum of the cross section for electromagnetic dissociation. Its working intensity, which is not less than $10^8$ nuclei per cycle, should be reduced by a factor of not less than 1000 in order to avoid excessive irradiation and to accomplish beam monitoring. This presents a difficult challenge since a high beam intensity provides feedback for tuning the accelerator.

Work performed in December 2016 made it possible to irradiate controllably track-emulsion layers 500 $\mu$m in thickness. The production of such layers was renewed by the Slavich enterprise (Pereslavl-Zalessky). In order to ensure a particle density of 2000 to 4500 nuclei/cm$^2$ at the irradiation locus, we changed the slow-extraction mode, reduced the extraction efficiency, additionally shifted the point of emulsion exposure by 8 m along the beam direction, and reduced the extraction time from 600 to 400 ms.

The irradiation of track emulsions was monitored by means of three counters based on scintillators produced at IHEP (polystyrene plastic of the STs-301 type). The counters, equipped with photomultiplier tubes (PMT-85), were 1 cm thick and had cross-sectional dimensions of 10 × 10 mm. The irradiated emulsion stacks were placed in front of the counters. Figure 6 shows the content of the beam of carbon nuclei from the medical channel of the U-70 accelerator at the locus of emulsion exposure. The beam contained nuclei of charge number 6 (about 78%), 5 (2%), 4 (2%), 3 (2%), 2 (14%), and 1 (2%). This mixture is an expected consequence of the absence of a vacuum ion guide and separating magnets. This fact does not complicate the selection of white stars. On the contrary, there arises the possibility of additional calibrations in charge and in multiple scattering. At the present time, the irradiated samples are under analysis.

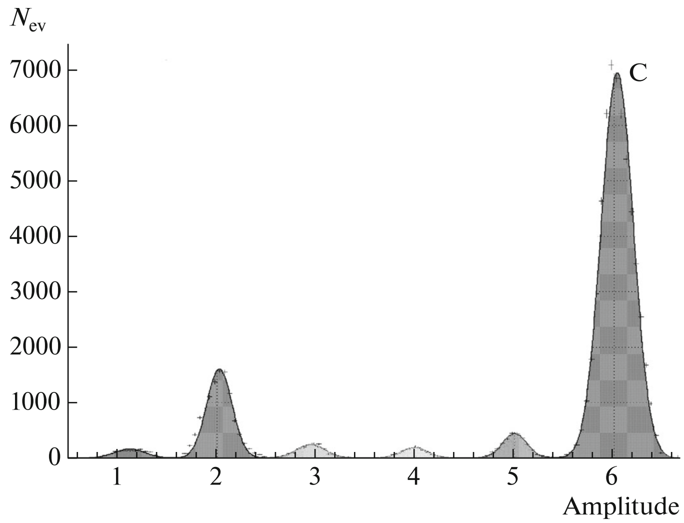


**Fig. 6.** Content of the beam of carbon nuclei from the medical channel of the U-70 accelerator at locus of emulsion exposure.

## CONCLUSIONS

By and large, the family of light nuclei, which form the beginning of the isotope table, remains a "laboratory" full of surprises, where one can trace the emergence of the shell structure. The relativistic dissociation of these nuclei, including radioactive ones, in nuclear track emulsions, makes it possible to study the whole variety of ensembles of extremely light clusters up to the binding threshold. The emerging physical picture can be summarized as follows.

In addition to nucleons, the structure of light nuclei involves clusters, such as alpha particles, tritons, $^3$He nuclei (helions), and deuterons, that do not have excited states. An alpha-particle pair may form an unstable nucleus of $^8$Be in the ground state and in the first excited state: ($^8\mathrm{Be}_{\mathrm{g.s.}}$ and $^8\mathrm{Be}_{2+}$). These configurations are present with nearly identical probabilities as cores in the $^9$Be nucleus, which is stable. The $^7$Be and $^7$Li stable nuclei play an important role in the structure of heavier neutron-deficient and neutron-rich nuclei. The $^9$B unstable molecule-like nucleus ($^8\mathrm{Be}_{\mathrm{g.s.}} + p$) and the $^9$Be stable nucleus may play nearly the same role as cores of the $^{10}$B nucleus. At the same time, the $^9$Be nucleus may be present in the $^{10}$B nucleus not only as a discrete unit but also as a $^8\mathrm{Be}_{\mathrm{g.s.}}/^8\mathrm{Be}_{2+} + n$ superposition similar to the $^9\mathrm{B}(^8\mathrm{Be}_{\mathrm{g.s.}} + n)$ unbound nucleus.

A balanced coexistence of possible superpositions of core nuclei, clusters, and nucleons determines ground-state parameters of the respective nucleus. Despite the relativistic scale of coherent interactions, searches for effects of few-body quantum mechanics and even for manifestations of nuclear-molecule systems can be performed in them. However, only the track-emulsion method possesses the required spatial resolution.

The absence of $^8$Be and $^9$B bound nuclei among existing isotopes has a crucial effect on the propagation of nucleosynthesis, making it circumvent these gaps in the isotope table. The absence of stable ground states of these nuclei does not prevent their involvement in the nuclear structure as cores. An analysis of the nucleosynthesis path to $^{10,11}$B through the chain $^7\mathrm{Be}(^3\mathrm{He}, \gamma)^{10}\mathrm{C}(e^+, \nu)^{10}\mathrm{B}$ (hot breakout) provides an estimate of their importance.

The synthesis of $^{10}$C is ensured by an energy "window" for the formation of the $^9\mathrm{B} + p$, $^8\mathrm{Be}_{2+} + 2p$, and $^6\mathrm{Be} + \alpha$ intermediate states. These configurations survive in the subsequent chain $^{10}\mathrm{C}(e^+, \nu)^{10}\mathrm{B}(p, \gamma)^{11}\mathrm{C}(e^+, \nu)^{11}\mathrm{B}$. The "window" for the reaction $^7\mathrm{Be}(^4\mathrm{He}, \gamma)^{11}\mathrm{C}$ permits only the fusion of $^7$Be and $^4$He, which also contributes to the structure of $^{11}$C and $^{11}$B.

Thus, the population of the hidden variety of virtual configurations in the $^{10,11}$C and $^{10,11}$B nuclei proceeds through electromagnetic transitions from real states involving unstable nuclei. In turn, these nuclei participate in the synthesis of subsequent nuclei via their involvement in proton-capture (or neutron-exchange) reactions or reactions of the addition of helium isotopes, and this leads to inheriting special features of preceding structures.

The identification of the Hoyle state in the dissociation of $^{12}$C would open prospects for searches by this method in the dissociations of heavier nuclei for condensate states featuring a large number of alpha particles. In turn, the discovery of alpha-particle condensates would enable one to consider new scenarios of nuclear astrophysics.

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