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Beryllium (Boron) Clustering Quest in Relativistic Multifragmentation (BECQUEREL Project)*

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Abstract—A physical program of irradiation of emulsions in beams of relativistic nuclei named the BECQUEREL Project is reviewed. It is destined to study in detail the processes of relativistic fragmentation of light radioactive and stable nuclei. The expected results would make it possible to answer some topical questions concerning the cluster structure of light nuclei. Owing to the best spatial resolution, the nuclear emulsions would enable one to obtain unique and evident results. The most important irradiations will be performed in the secondary beams of He, Be, B, C, and N radioactive nuclei formed on the basis of JINR Nuclotron beams of stable nuclei. We present results on the charged state topology of relativistic fragmentation of the ^{10}B nucleus at low energy–momentum transfers as the first step of the research.

INTRODUCTION

The investigations of light nuclei situated around the boundary of neutron stability have recently developed a new direction of quest—physics of exotic nuclei. New phenomena have been established in the structure of light nuclei and in the course of nuclear reactions (see Introduction in [1]). In this domain of anomalously large radii of nuclei, the production of nucleon clusters separated in space has been observed (see Introduction in [2]). The low binding energy of nuclear clusters makes it possible to determine the structure of such nuclei as a molecular-like one.

Great progress has been made towards studying the structure of nuclei with excess and maximum number of neutrons, while research into the structure of proton-rich (or neutron-deficient) nuclei is merely being planned. The major goal of the appropriate experiments is to define the structural features of nuclei near the boundary of proton stability. Such nuclei are stable in the absence of electron shells. The structure of such nuclei can turn out to be another key in understanding the processes of nucleosynthesis. For instance, the presence of the proton halo (a proton far removed from the nucleus core) may serve as a "stringboard" for the isotope generation when advancing along the boundary of proton stability with a subsequent decay into stable isotopes.

One of the candidates for the system of the proton halo type is the ^{8}B nucleus [3, 4]. We notice that the alternative transition to the solar CNO cycle can occur by the addition of a proton to the ^{7}Be nucleus and a consecutive addition of the ^{4}He nucleus. The produced ^{12}N nucleus decays into a stable ^{12}C isotope by electron capture. As compared with the well-known Hoyle version through ^{8}Be, the advantage of the above-mentioned case consists in that the lifetime of the ^{8}B nucleus even for a state with bound electrons is 16 orders of magnitude larger than that of the ^{8}Be nucleus. Another example is the fusion of one more proton to the ^{8}B nucleus resulting in the production of a ^{9}C nucleus, which is also stable in the absence of bound electrons. The fusion of a ^{4}He nucleus to a ^{9}C one does lead to the formation of an isotope

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^{13}N nucleus intermediating in the CNO cycle. An unstable ^{6}Be nucleus might play a mediator role like a ^{8}Be one. Such examples of cluster nuclear systems may still be cited, including some nuclei in excited states.

Clustering in the above-mentioned nuclei might reflect possible paths of their synthesis. The proposed series of investigations is mostly aimed at elucidating the applicability of the picture of clustering in neutron-deficient nuclei. A program of further research of the fragmentation of neutron-deficient Be, B, C, and N isotopes by means of an emulsion technique is considered below.

RESEARCH CONCEPT

The production of relativistic beams of radioactive light isotopes is currently under way at the JINR Nuclotron. The approaches based on the use of a charge exchange process or breakup of a lightest possible nuclide are most adequate for an emulsion technique. In this case, the mass number of an initial nucleus is conserved, beam losses in acceleration are lower, and a cluster nature of its intrinsic structure is partially set up. A certain advantage in the production of secondary beams toward increasing charge is a relative background reduction of other fragments with Z/A closer to the stability region.

In general, experiments with nuclear beams at an energy of a few GeV are recognized to be one of the most promising ways for understanding the basic properties and the intrinsic structure of radioactive and unbound nuclei. Such beams can be employed to produce short-lived nuclear beams by means of breakup, charge-exchange, or fission (splitting) reactions. In the framework of such an approach, there is almost no restriction due to the lifetime of relativistic nuclei in question. A technical benefit in the analysis of relativistic proton-rich nuclei with respect to lower energy studies is a decrease in ionization to a minimum and closest to complete observation of the charge fragmentation process.

The limiting fragmentation of nuclei serves as a basis of the study of the nuclear structure. The fragmentation picture, i.e., isotopic composition and energy spectra, for one of the colliding nuclei was found to undergo a weaker dependence upon the properties of fragmentation of the other. The study of the fragmentation of relativistic nuclei may effectively supplement classical experiments on breakup of nuclei used as a target. In such an approach, the detection threshold is close to zero. It makes it possible to study fragmentation processes at rather weak nuclear excitations. The experimental approach based on the registration of the fragments of a projectile nucleus imposes a crucial requirement on the measuring technique on provision of the maximum angular resolution and the identification of fragments in a narrow forward cone (typically, a few degrees). In addition, the fragmentation process leads to a noticeably smaller ionization, which is due to the reaction products, as compared with the primary nucleus signal. This fact imposes a special requirement on the width of the sensitivity range starting from the primary nucleus down to particles with minimal ionization.

The emulsion technique can be implemented in the above-listed circumstances. In relativistic fragmentation, the nucleons produce with a large probability charged clusters, which, when decaying, are detected in emulsion as in a perfect 3D track detector. It should be stressed that emulsions are utilized in this way to register multiparticle decays of nuclei or multifragmentation events. Known cases are observations of coherent dissociation of relativistic ^{12}C nuclei on three α particles and ^{16}O on four α particles. We intend to extend coherent dissociation studies toward heavier stable nuclei like F, Ne, and Mg isotopes. The emulsion serves as a universal detector of the full fragmentation keeping permanent track information mostly in a single layer. This gradually reduces analysis work. Using perfect angular measurements, it is possible to get information about the excitation energy of a fragmenting nucleus.

Our approach to the study of clustering in nuclei is justified by the experience obtained when studying the relativistic ^{6}Li in emulsion [5–7] and pilot results with a secondary beam of relativistic ^{6}He and ^{3}He nuclei ("beam cocktail") [8]. As development, we investigated the cluster structure of the stable isotope ^{10}B, comparing probabilities of dissociation channels $^{10}\mathrm{B} \to (^{8}\mathrm{Be}) + d$, $\alpha + \alpha + d$, $^{6}\mathrm{Li} + \alpha$, $^{9}\mathrm{Be} + p$, etc.

DISSOCIATION OF RELATIVISTIC ^{10}B NUCLEI

We used a beam of ^{10}B nuclei accelerated at the JINR Nuclotron to perform irradiation of an emulsion stack. The beam angular divergence was kept within an angle of 3 mrad. The beam profile for emulsion irradiations was formed in such a way that its horizontal size would correspond to irradiated emulsion width and the spatial beam density would be uniform enough. An emulsion irradiation dose was limited to 10^{5} beam tracks. The emulsion chamber was assembled as a stack of BR-2 type emulsion layers having sensitivity up to relativistic particles. Layers 550 μm thick had the dimensions 10×20 cm^{2}. During irradiation, the beam was directed in parallel to the emulsion plane. We present below pilot results of visual scanning that are important for the project major goal, i.e., determination of fragmentation probabilities.

Table 1. Charge-state distribution of the number of fragments in projectile fragmentation cone (<15°) in events of complete charge fragmentation (total number of events is 82)

Total charge (>4)	Fragment charge Z					Number of events
	5	4	3	2	1	
6		–	–	1	4	4
6		–	–	2	2	1
6		–	–	–	6	2
5		1	–	–	1	2
5		–	1	1	–	3
5		–	–	1	3	26
5		–	–	2	1	36
5	1	–	–	–	–	5
5		–	–	–	5	3

Table 2. Charge-state distribution of the number of fragments in projectile fragmentation cone (<15°) in events of white star formation [no accompanying tracks in wide cone (>15°); total number of events is 35]

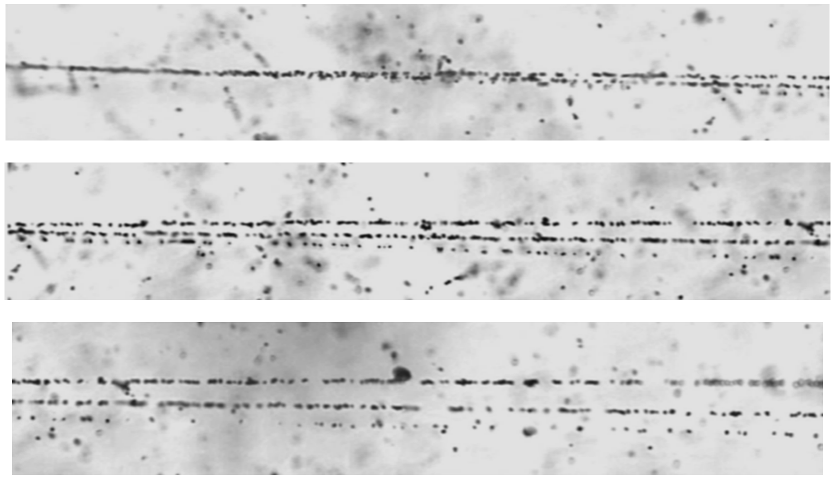
Total charge (>4)	Fragment charge Z				Number of events
	4	3	2	1	
6	–	–	1	4	3
5	1	–	–	1	2
5	–	1	1	–	1
5	–	–	1	3	9
5	–	–	2	1	18
5	–	–	–	5	2

All found charged tracks corresponding to relativistic boron ionization were followed to a nuclear interaction point or to an exit from the emulsion layer. In the first sample, 136 inelastic interactions were found over the scanned length of about 20 m of the initial particles. Within this sample, we defined a mean free path $\lambda = 14.7 \pm 1.2$ cm. This value is in good agreement with the mass number dependence established for uniform density nuclei like ^{4}He, ^{12}C, ^{16}O, and ^{24}Mg.

To clarify the general features, we concentrated current analysis on events of transfer of a total boron nucleus charge to relativistic fragments in a fragmentation cone of 15° ("complete charge fragmentation"). As correlation, such a selection gave dramatic suppression of mean target nucleus multiplicity. We have minimized the influence of interaction dynamic details in this way.

We describe a topological structure of 82 events having the total charge sum not less than five in a fragmentation cone. Table 1 presents the numbers of events with various fragment composition. The cases with total charge 6 correspond to the appearance of a relativistic meson in a fragmentation cone. As a further step, we selected 35 events (Table 2) containing neither target fragments nor produced mesons ("white stars," example shown in the figure). The obvious feature of both tables is a dominance of three-body charge states with respect to two-body ones. These data serve as a reference to explore features of ^{7}Be, ^{8}B, and ^{9}C fragmentation.

A complete restoration of the charged fragmentation component in the rest of the events allowed us to assign additional tracks with minimal ionization to charged meson production. It is found that about 22% of complete charge fragmentation events contain a single charged meson and just 2–3% a couple. We plan to perform relativistic fragment identification



Event of dissociation of 1 A GeV ^{10}B nucleus into two double charged and one single charged tracks in sequential evaluation (top to bottom) as an example of white star. A 3D image is reconstructed as a projection by means of the FIAN PAVICOM automatic microscope.

and analyze the described statistics in the spirit of paper [6].

FUTURE IRRADIATIONS IN SECONDARY BEAMS OF RELATIVISTIC NUCLEI

The cluster structure of ^{7}Be can manifest itself in the fragmentation channels like $^7\mathrm{Be} \to {}^3\mathrm{He} + {}^4\mathrm{He}$, $^3\mathrm{He} + {}^3\mathrm{He} + n$, $^6\mathrm{Li} + p$, $\alpha + d + p$, and others. The study of ^{7}Be nuclei is interesting from the point of view of its possible role of a core in ^{8}B one. Using charge exchange of 1.23 A GeV ^{7}Li nucleus, the ^{7}Be beam was produced at one of the Nuclotron beam lines. Emulsions irradiated by this beam are under analysis now

Table 1 contains an indication that a ^{8}B nucleus beam may be produced in ^{10}B nucleus fragmentation. Such an opportunity needs to be explored for this case and for ^{9}C and ^{10}C nuclei.

Being intended for investigations with the aid of the emulsion technique, the ^{8}B beam could make the problem of proton-halo existence clearer. The particular feature of the ^{8}B nucleus is the lowest binding energy of one of the protons (135 keV). Therefore, most probably, the ^{8}B nucleus has a core in the form of a ^{7}Be nucleus and a proton weakly coupled with the core. Their space distributions define the value of the ^{8}B radius, the transverse momentum distributions for relativistic protons and ^{7}Be, and the distribution with respect to the relative transverse momentum of the dissociation products. The probabilities of dissociation channels are suggested to be measured for $^8\mathrm{B} \to {}^7\mathrm{Be} + p$, $\alpha + {}^3\mathrm{He} + p$, $^3\mathrm{He} + {}^3\mathrm{He} + d$, $^6\mathrm{Li} + p + p$, $\alpha + d + p + p$, and others.

After that, the production of the ^{9}C nucleus beam becomes a next logical step. Of all the nuclei that we have considered, this one has the largest ratio of number of protons to that of neutrons. This nucleus has an additional proton as compared with the ^{8}B nucleus. The binding energy of this additional proton is far larger than that of the external proton in the ^{8}B nucleus. Therefore, it appears that the ^{9}C has no external two-proton shell. This nucleus is particularly interesting since the replacement of one of the protons by a neutron leads to the unstable ^{9}B isotope in spite of the reduction of the Coulomb energy. One of the possible explanations to be verified is a hidden ^{3}He clustering.

To do this, we suggest measuring the probabilities of dissociation channels like $^9\mathrm{C} \to {}^8\mathrm{B} + p$, $^3\mathrm{He} + {}^3\mathrm{He} + {}^3\mathrm{He}$, and others. An unavoidable feature of ^{9}C beam formation is the presence of accompanying ^{3}He nuclei having the same magnetic rigidity as in the case of our previous study with a triton and ^{6}He beam "cocktail." The feasibility of emulsion application needs to be justified by a dedicated study.

To conclude, in the performed and suggested investigations of the interactions of light radioactive nuclei in emulsion, one and the same method is reviewed for systematic studies of the structure of several proton-rich nuclei. Attention is paid to the search for the manifestation of a structure like the proton halo and structures with an unstable nucleus core. Thus, the combination of new beams and the classical technique may result in new intriguing and conclusive finds. The results can be employed in planning further studies on the Nuclotron's beams, in particular, for forming reaction triggers in the detection of particles by electronic methods.

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