The BECQUEREL Experiment: Status and Future Challenges

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We are glad to invite you to read the article "The BECQUEREL Experiment: Status and Future Challenges" by A. A. Zaitsev, P. I. Zarubin, and A. I. Malakhov. The article was published in the 3rd issue of the bulletin "JINR News" 2020.

The fragmentation of relativistic nuclei observed in nuclear track emulsion (NTE) serves as a source of ensembles of the lightest nuclei, topical for modern nuclear physics and nuclear astrophysics. NTE allows one to study production of such ensembles in full with record angular resolution and identification of He and H isotopes. The very first studies of interactions of relativistic nuclei took place in the late 1940s when analyzing NTE layers irradiated in the stratosphere. At the same time, break-up events of nuclei of cosmic origin containing groups of tracks of relativistic α particles concentrated in a narrow angular cone were discovered. Manifesting as a natural phenomenon, they reflect the α-particle clustering in the nuclear structure which is the research subject to date.

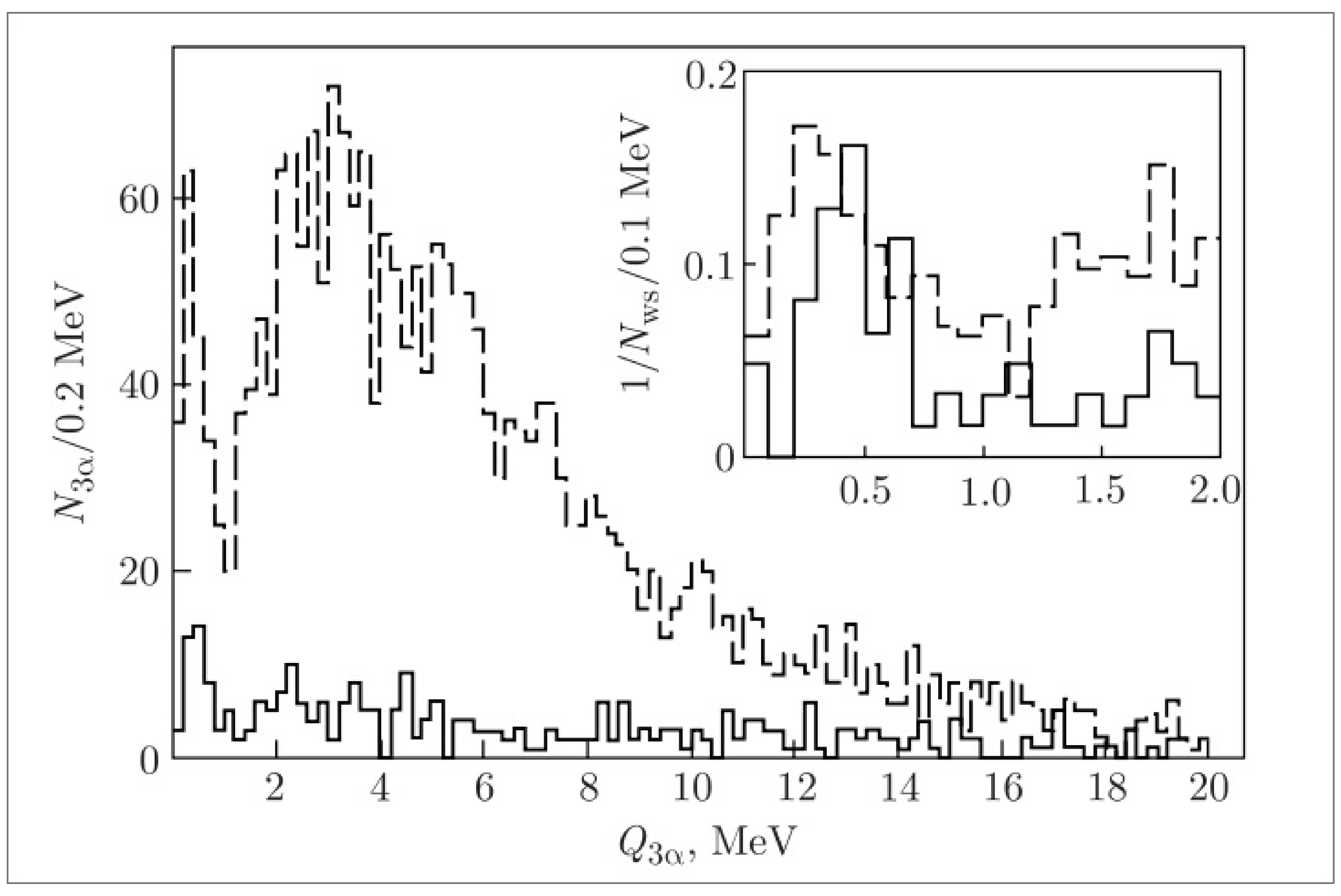
In the 1970s, exposures of NTE stacks to light nuclei at the Synchrophasotron (JINR) and Bevalac (LBL) began, and in the 1990s to medium and heavy ones at AGS (BNL) and SPS (CERN). The manifestation of the nuclear structure in the cone of limiting fragmentation was noted. However, electronic experiments in this direction run into fundamental difficulties due to the quadratic drop down of ionization on the charges of the nuclei, extremely small angular divergence of relativistic fragments, and often an approximate coincidence in magnetic rigidity with the beam nuclei. Therefore, the NTE method retains its uniqueness as the composition analysis tool in the relativistic fragmentation cone. In this aspect, the results obtained in the 1970s–1990s by NTE and the preserved data files have not lost their relevance, and the irradiated layers can be used for in-depth studies. One can hope that the progress of image analysis will intensify the use of the NTE method in the near future.

Since the early 2000s, the NTE method is used at the JINR Nuclotron in the BECQUEREL experiment to study the clustering in light stable and radioactive nuclei in the relativistic approach. Known and new structural features of the isotopes ^{7,9}Be, ^{8,10,11}B, ^{10,11}C, and ^{12,14}N are revealed in the dissociation channel probabilities. The identification of the relativistic decays of ^{8}Be and ^{9}B pointed out the possibility to search for triples of α particles in the Hoyle state (HS) in the relativistic dissociation.

^{8}Be and HS are considered as the simplest states of the α-particle Bose–Einstein condensate. The sixth excited state 0^+_6 of the ^{16}O nucleus at 660 keV over the 4α threshold is considered as a 4α-condensate. Its decay could go in the sequence $^{16}O(0^+_6) \to {}^{12}C(0^+_2) \to {}^{8}Be\,(0^+_2) \to 2\alpha$ or $^{16}O(0^+_6) \to {}^{28}Be(0^+) \to 4\alpha$. In addition, the ^{9}B and HS nuclei can serve as bases in the nuclear molecules ^{9}Bp, ^{9}BBα and $^{12}C(0^+_2)$ p. Like the α-condensing states the unstable states with an odd number of protons can meet excitations immediately above the corresponding thresholds having electromagnetic decay widths.

All these states can be studied uniformly in the peripheral interactions of relativistic nuclei. According to the widths, ^{8}Be, ^{9}B, and HS nuclei are real fragments in relativistic dissociation. The products of their decay appear along ranges from several thousands (^{8}Be and HS) to several tens (^{9}B) of atomic sizes, i. e., over the time many orders of magnitude longer than the time of the appearance of other fragments. Not being directly observable, they should manifest themselves as pairs and triples of He and H nuclei with the smallest opening angles due to the smallest decay energy.

Using the available angular measurements of the coherent dissociation events $^{12}C \to 3\alpha$ and $^{16}O \to 4\alpha$, the application of the invariant mass method can be easily extended to the identification of relativistic decays of the Hoyle state. In the latter case, HS decays can manifest themselves in the dissociation $^{16}O \to {}^{12}C^* (\to 3\alpha) + \alpha$. Both distributions over the invariant mass of 3α-triples Q3α show similarities (see figure). In both cases, distribution peaks are observed in the region $Q_{3\alpha} < 0.7$ MeV where the HS signal is expected. The contribution of HS decay to $^{12}C \to 3\alpha$ is (11 ± 3)%, and in the case of $^{16}O \to 4\alpha$ it is (22 ± 2)%.



Distribution of the number of 3α-triples $N_{3\alpha}$ over invariant mass $Q_{3\alpha}$ in 316 "white" stars $^{12}C \to 3\alpha$ (solid) and 641 "white" stars $^{16}O \to 4\alpha$ (dashed) at 3.65A GeV; in inset, enlarged part $Q_{3\alpha} < 2$ MeV normalized to the numbers of "white" stars N_{ws}

Being tested in the studies of the light nuclei, a similar selection is applicable to the dissociation of heavier nuclei to search for more complex states. In turn, the products of α-particle or proton decay of these states could be the Hoyle state or ^{9}B, and then ^{8}Be. A possible decay variant is the occurrence of more than one state from this triple. In any case, the initial stage of searches should be the selection of events containing relativistic ^{8}Be decays.

The available statistics on Si and Au nuclei have identified dozens of ^{8}Be and ^{9}B decays. At the same time, the small number of 3α triples is attributable to the decay of the Hoyle state, which requires increasing statistics to the current ^{8}Be equivalent. Then, the search for the excited state $^{16}O(0^+_6)$ will become feasible. There are no fundamental problems along this path since there are a sufficient number of earlier exposed NTE layers, with transverse scanning of which the required α-ensemble statistics is achievable.

The results obtained make it possible to assess the prospects of the presented approach in modern problems of nuclear physics. Among the most important of them is the verification of theoretical ideas about matter arising from the combination of nucleons in clusters that do not have excited states up to the coupling threshold. These are the lightest ^{4}He nuclei (α particles), as well as deuterons (d), tritons (t) and ^{3}He nuclei, or helions (h). The evolution of the composition of the lightest isotopes is predicted at a nuclear density less than normal and a temperature of several MeV. Passing through such a phase may be necessary on the way to the synthesis of heavy nuclei. Identification of ^{1,2,3}H and ^{3,4}He isotopes by multiple scattering allows expanding the analysis of cluster states in the direction of the properties of the rarefied matter.

It is hoped that the rapid progress in image analysis will give a whole new dimension to the use of the NTE method in the study of nuclear structure in the relativistic approach. The solution of the tasks set requires investment in modern automated microscopes and the reconstruction of NTE technology at a modern level. At the same time, such a development will be based on the classical NTE method, the foundations of which were laid seven decades ago in cosmic ray physics. This whole complex of problems united by questions of identification of unstable states was presented at the recent topical meeting on cluster physics [1, 2]. Suggestions for development of the BECQUEREL experiment in the framework of the JINR topic on the physics of relativistic heavy and light ions at the Nuclotron–NICA accelerator complex were reviewed at the January session of the PAC for Nuclear Physics.

References

1. Topical Workshop "Light Clusters in Nuclei and Nuclear Matter: Nuclear Structure and Decay, Heavy Ion Collisions, and Astrophysics", Trento, Italy, 2019. https://indico.ectstar.eu/event/52/.
2. Artemenkov D.A., Bradnova V., Chernyavsky M.M., Firu E., Haiduc M., Kornegrutsa N.K., Malakhov A.I., Mitsova E., Neagu A., Peresadko N.G., Rusakova V.V., Stanoeva R., Zaitsev A.A., Zarubina I.G., Zarubin P.I. Unstable States in Dissociation of Relativistic Nuclei. Recent Findings and Prospects of Researches. Preprint. https://arxiv.org/abs/2004.10277