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Nuclear track emulsion in search for the Hoyle's state in dissociation of relativistic ^{12}C nuclei

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Abstract

Study of production of ensembles of alpha-particle triples associated with the Hoyle state (the second excited state $0^+{}_2$of the ^{12}C nucleus) in peripheral dissociation of relativistic ^{12}C nuclei is started. Stacks of pellicles of nuclear track emulsion exposed to ^{12}C of energy from hundreds MeV to few GeV per nucleon serve as the material of the study. The Hoyle state decays are reconstructed via measurements of emission angles of α-particles with accuracy that allows one to identify the unstable ^{8}Be nucleus. A role in the Hoyle state of alpha-particle bonds corresponding to ^{8}Be is determined.

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1. Introduction

Potentially, the phenomenon of multiple peripheral dissociation established for relativistic nuclei long ago by the method of nuclear track emulsion (NTE) allows a holistic investigation of "cold" ensembles consisting of the lightest nuclei and nucleons. However, apparent simplicity of measurements in a fragmentation cone of an investigated nucleus, in which the information about "individual" features of it is concentrated, in practice turns out to be deceptive. The feasibility of such measurements in electronic experiments is not yet visible. Moreover, a complete study of the light isotopes Be, B, C and N in this approach is complicated by the requirement to reconstruct the relativistic decays of the unstable ^{8}Be and ^{9}B nuclei. This gap is filled only by NTE. With regard to the peripheral dissociation of relativistic nuclei, this technique remains the only means of observation, providing not only unique angular resolution and completeness of observation, but also a sufficient statistical provision of overview studies.

The cluster structure of light nuclei and the role of the unstable ^{8}Be and^{9}B nuclei in it is studied in the BECQUEREL project [1] on the basis of NTE layers longitudinally exposed at the JINR Nuclotron to relativistic Be, B, C and N nuclei, including their radioactive isotopes (reviews in [2, 3]). The actual objective of the project has now become a search and exploration of the Hoyle's state (HS) when excited in the dissociation of relativistic ^{12}C nuclei. It makes up a new challenge at the limit of the possibilities of the NTE technique. The material of the study is NTE layers exposed to ^{12}C nuclei from several hundred MeV to several GeV per nucleon at the IHEP accelerator complex and the JINR Nuclotron. The practical task is to search for sufficient statistics of 3α-events (several hundreds) and measure the angles of emission of α-particles in them with a resolution that allows reconstructing the decays of the unstable ^{8}Be nucleus and, then, of HS.

It should be recalled that the ^{12}C nucleus from the ground state 0^+ can pass into the second excited (and first unbound) 0^+ state above 0.29 MeV of the mass threshold α + ^{8}Be. The fundamental importance of HS, the history of discovery and the current state of its research are presented in the review [4]. The structure of HS is projected onto its decays in which the ^{8}Be nucleus, unbound with energy of 91 keV to decay into a pair of α particles is an indispensable participant. Therefore, the study of HS requires the identification of ^{8}Be.

The width of the HS is 8.5 eV which is close to the width of the ground state of ^{8}Be (5.6 eV). In order of magnitude, these values correspond to the lifetime of the π^0-meson experiencing electromagnetic decay. Analogously to the π^0-meson, the ^{8}Be nucleus and HS are full-fledged participants in reactions. Being produced in the fragmentation of relativistic nuclei, the ^{8}Be nuclei have ranges of about a thousand atomic sizes before decay into pairs of α particles with extremely small opening angles (*less angles just do not happen!*). For this reason, ^{8}Be tracks and decay vertices are not directly observed. Nevertheless, the identification of a relativistic ^{8}Be nucleus is possible by an invariant mass of the α-pair calculated from the opening angle in it. Such an approach requires a 3-dimensional image of tracks of relativistic α-particles taken with the best spatial resolution. So far, fulfillment of this condition is ensured only by using longitudinally irradiated NTE pellicles of a thickness of 200 to 500 microns.

In theoretical calculations, the ^{8}Be nucleus is represented as a molecular-like bond of a pair of α particles separated by a distance not less than their size [5]. HS arises due to the addition of a third α-particle with zero angular momentum to ^{8}Be. In this state, nucleon isolation in α-particles remains which leads to HS reduced density and increased radius. The role of ^{8}Be in HS can be enhanced in comparison with the 2-body configuration ^{8}Be + α as a consequence of interference of identical α-particles. The distribution of α particles in the ^{8}Be nucleus and, subsequently, HS are of fundamental importance for justification of the concept of the Bose-Einstein α-condensate (reviewed in [5]) for which both states are regarded as the simplest forms.

In dissociation via HS not only single but also pair-wise and even triple-wise combinations of α particles that are close to ^{8}Bc an be observed which is determined by the HS structure. Such observations, performed in contrast to relativistic energy of 3α-ensembles and minimum possible energy stored by them would clearly demonstrated HS as a full-fledged and sufficiently long-lived nuclear-molecular object. It can be expected that ^{8}Be and CX will become reference points for searches for more complex states of dilute nuclear matter upon dissociation of heavier nuclei into ultra narrow jets of the lightest nuclei.

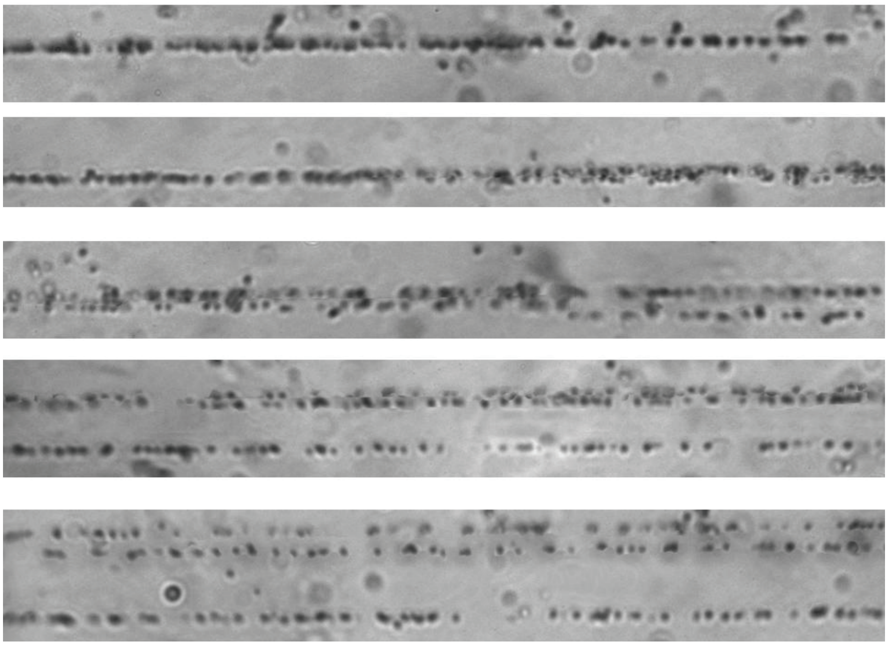

Figure 1: Sequential macro photographs of sections of the event of coherent dissociation in NTE ^{12}C → 3He at 1 *A* GeV/*c* (from top to bottom); when moving from the vertex along the jet of fragments, we three fragments of He can be distinguished.

Next, the preliminary results obtained on a small statistic will be presented which sets the outlines of the future analysis (*which does not exclude surprises!*). The research material will be stacks of NTE pellicles irradiated by ^{12}C nuclei at the IHEP accelerator complex and the JINR Nuclotron. In the future, the energy of ^{12}C nuclei can cover a range from hundreds of MeV to several tens of GeV per nucleon, which will allow to follow the cross section for the reaction of produced triplets of α-particles in HS and to establish universality of its formation. It will be necessary to measure the angles

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of emission of fragments in several hundred events of dissociation of ^{12}C nuclei into triplets of α particles. In order to reveal the HS effect, the analysis of the remaining measurements of the events of coherent dissociation ^{12}C → 3α at JINR was recently repeated [8, 9]. Its results will be further presented in comparison with the emerging data of irradiation at IHEP.

2. Early study

At the beginning of the 1970s, NTE was exposed to ^{12}C nuclei of energy of 3.65 *A* GeV (4.5 *A* GeV/*c* momentum) at the JINR Synchrophasotron. The statistics of 2,468 interactions included 28 "white" stars, the only channel of which was ^{12}C → 3α in the 3°cone. In the 80-ies, Lead-enriched NTE was used [9]. Search of events was performed in an accelerated manner over areas of NTE pellicles. As a result, the statistics included 72 "white" stars ^{12}C → 3α. Contribution of ^{8}Be decay was estimated to be about 20%. At that time, the problem of searching for HS has not been set. Recently, an analysis of these measurements was carried out by the FIAN group [10], the main conclusion of which is as follows Among the events of coherent dissociation of ^{12}C nuclei with momentum 4.5 *A* GeV/c, into three α-particles, a 2-body channel was extracted in which one of the fragments is the unbound ^{8}Be nucleus.. In 9 events, the total transverse energy of the fragments in the decaying carbon nucleus does not exceed 0.45 MeV which does not contradict the excitation of the ^{12}C nucleus to the level of 7.65 MeV.

It is worth mentioning the experimental problem of that time. Irradiation occurred by dropping a single cycle of ^{12}C nuclei focused to approximately 2 cm onto a NTE stack. Therefore, ^{12}C interaction analysis was possible only at the periphery of the beam, which limited an analyzed volume. The physics of peripheral dissociation of nuclei was further developed in the framework of the BECQUEREL project at the JINR Nuclotron. The uniformity of profiles of irradiation of NTE layers was achieved both for stable (*which is more complicated tack)* and radioactive nuclei which made it possible to radically increase NTE volume suitable for viewing. At the same time, the problem of HS observation has hitherto remained in the "shadow" of more popular studies of the nuclei lighter than ^{12}C.

3. Exposure at IHEP

To solve the problem of the possible formation of HS in relativistic dissociation, it was proposed to use a beam of 450 *A* MeV^{12}C nuclei (1 *A* GeV/*c* momentum) in IHEP used for radiobiological studies. With a decrease in the energy of the nuclei, a number of practical conveniences arise. First of all, it is useful to expand over the energy of ^{12}C nuclei since theoretical calculations of cross sections for electromagnetic dissociation of light nuclei indicate a wide maximum in the region of several hundred MeV per nucleon [9]. Second, the contrast between fragment α-pairs and narrow pairs of ^{8}Be decays increases. Third, the fraction of background events with charged mesons decreases. Finally, it is simplified to flatten the beam profile at the entrance to a NTE.

In practice, at an entrance to an NTE stack, the average energy of ^{12}C nuclei is about 420 *A* MeV, A somewhat smaller energy corresponds to braking in air, since there is as yet no ion pipeline on the channel path. This factor is not so significant and reparable in the future. Thanks to the use of rotating electrostatic diffusers (wobblers), this beam provides a high uniformity (about 2%) of irradiation of a region up to 10 cm in diameter along the entrance profile of a NTE stack. Recently stacks of NTE layers of a thickness of 200 microns on a glass substrate were irradiated in the IHEP beam channel with a controlled flux of ^{12}C nuclei.

To date, 54 events ^{12}C → 3α have been detected and measured in the NTE layers irradiated at IHEP. at 1 A GeV / c, including 23 ”white” stars. Figure 2 shows the dependence of the calculated invariant mass of α-pairs $Q_{2\alpha}$ on the measured opening angle $\Theta_{2\alpha}$in them for 72 events of coherent dissociation ^{12}C → 3α at 4.5 *A* GeV/*c*, 500 events ^{9}Be → 2α at 2 *A* GeV/*c* and 54 events ^{12}C → 3α at 1 *A* GeV/*c*. Figure 3 shows the projection of this dependence in the variable $Q_{2\alpha}$. The region $Q_{2\alpha}$ < 300 keV indicates the presence of ^{8}Be decays. The table in which the available mean values <$\Theta_{2\alpha}$ > and <$Q_{2\alpha}$ > for $Q_{2\alpha}$ <300 keV are collected according to the BECQUEREL project indicates that they correspond to the ^{8}Be nucleus. Mean square scattering values demonstrate that the resolution of the method is sufficient to identify relativistic ^{8}Be nuclei. in a wide region with respect to the initial momentum.

In the distribution over the invariant mass of α-triples $Q_{3\alpha}$ (Fig. 4) in the dissociation of ^{12}C → 3α. at 4.5 A GeV/c and ^{12}C → 3α. at 1 *A* GeV/*c* there is an indication of a peak in the $Q_{3\alpha}$ < 1 MeV region, where the HS decays should be reflected. In the case of irradiation at 4.5 *A* GeV / c, the average value for events in the peak <$Q_{3\alpha}$ >> is 443 ± 52 (at RMS 186) keV, and at 1 *A* GeV/*c*, respectively, 348 ± 32 (75) keV According to the ”soft” condition $Q_{3\alpha}$ < 1 MeV, in the irradiation of 4.5 *A* GeV/*c* 13 (out of 72) events can be attributed to HS, and at 1 *A* GeV/*c* - 8 (out of 54), including 4 ”white” stars (out of 23).. Thus, one can conclude that HS events are observed in both cases with a contribution of about 20%.

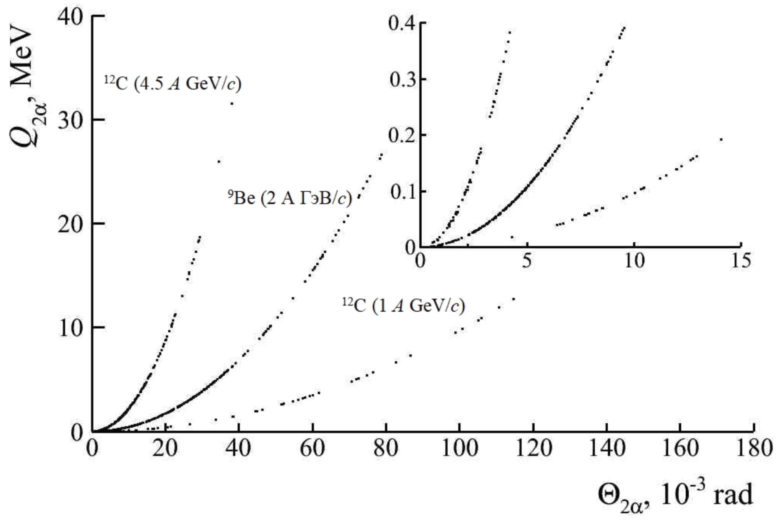

Figure 2: Dependence of calculated invariant mass of α-pairs $Q_{2\alpha}$ over opening angle $\Theta_{2\alpha}$ in dissociation of $^{12}C \rightarrow 3\alpha$ at 4.5 *A* GeV/*c*, $^{9}Be \rightarrow 2\alpha$ at 2 *A* GeV/c and $^{12}C \rightarrow 3\alpha$ at 1 *A* GeV/*c*; inset: region $Q_{2\alpha}$ < 400 keV.

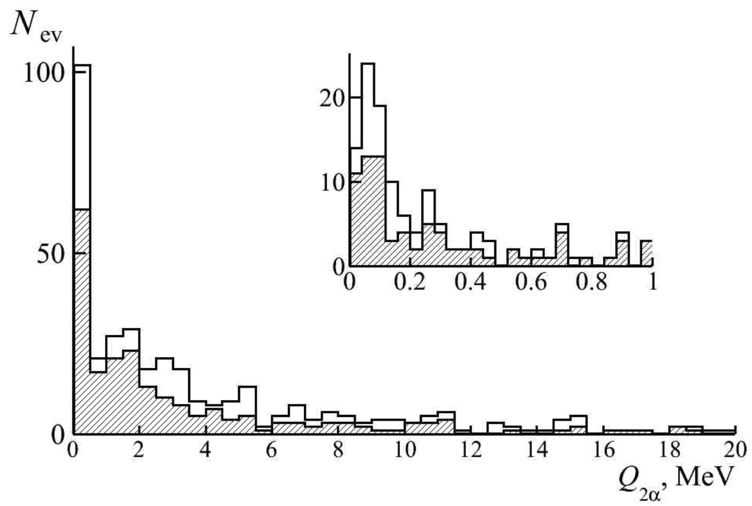

Figure 3: Distribution over invariant mass of α-pairs $Q_{2\alpha}$ in dissociation of $^{12}C \rightarrow 3\alpha$. at 4.5 *A* GeV/*c* (shaded) and at 1 *A* GeV/*c* (added); inset: the region of $Q_{2\alpha}$ to 1 MeV.

4. Summary

The first data for 2017 on the search for HS are very encouraging. Thus, there is a basis for a large-scale analysis of NTE layers irradiated longitudinally with high uniformity by ^{12}C nuclei with energy in the range from several hundred MeV and several GeV per nucleon in order to study HS on statistics corresponding of the order of 500 3α events. Undoubtedly, the statistics of events should and can be increased by a factor of at least 20, which already constitutes a practical problem. For its solution, there is already the necessary material and the possibility of its growth. With the experience gained and the gained pace, the problem can be solved in within two or three years.

Table 1: The average values of <$\Theta_{2\alpha}$ > and <$Q_{2\alpha}$ > ($Q_{2\alpha}$ <300 keV) in the angular regions of 8Be decays.

Nucleus (P_0, A GeV/c)	<$\Theta_{2\alpha}$ > (RMS), 10^{-3} rad. ($Q_{2\alpha}$ < 300 keV)	<$Q_{2\alpha}$ > (RMS), keV
^{12}C (4.5)	2.1 ± 0.1 (0.8)	109 ± 11 (83)
^{14}N (2.9)	2.9 ± 0.2 (1.9)	119.6 ± 9.5 (72)
^{9}Be (2.0)	4.4 ± 0.2 (2.1)	86 ± 4 (48)
^{10}C (2.0)	4.6 ± 0.2 (1.9)	63 ± 7 (83)
^{11}C (2.0)	4.7 ± 0.3 (1.9)	77 ± 7 (40)
^{10}B (1.6)	5.9 ± 0.2 (1.6)	101 ± 6 (46)
^{12}C (1.0)	10.5 ± 0.6 (3.6)	118 ± 13 (75)

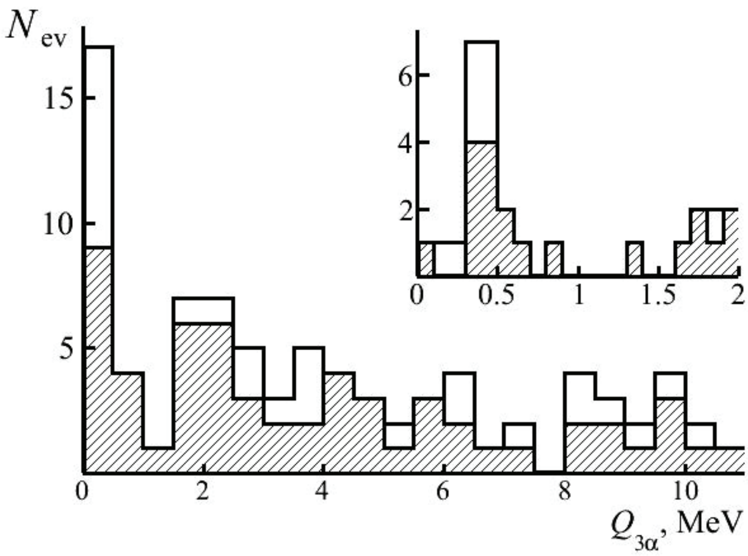

Figure 4: Distribution over invariant mass of α-triples $Q_{3\alpha}$ in dissociation of $^{12}C \to 3\alpha$ at 4.5 A GeV/c (shaded) and 1 A GeV/c (added); inset: the region $Q_{2\alpha}$ < 2 MeV.

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