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The search for unstable α-particle states in fragmentation of relativistic medium and heavy nuclei

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Since the discovery of the nuclear component of cosmic rays, the nuclear emulsion (NTE) method has been a powerful tool for studying the composition and fragmentation of relativistic nuclei at high-energy accelerators. The potential of this approach was first demonstrated in the 1970s using NTE layers exposed to beams of nuclei with energies of several GeV per nucleon, accelerated at the JINR Synchrophasotron and the Bevalac (USA). Since the 2000s, the NTE method has been further developed in the BECQUEREL experiment at the JINR Nuclotron, focusing on the cluster structure of nuclei, including radioactive isotopes, and the search for unstable nuclear-molecular states. Thanks to its exceptional sensitivity and spatial resolution, the NTE method provides a unified framework for analyzing a wide range of final states resulting from the dissociation of relativistic nuclei. This capability makes it particularly suitable for investigating exotic phenomena, such as the α-particle Bose-Einstein condensate (αBEC), an unstable S-wave state of α-particles. For example, the short-lived ^{8}Be nucleus is interpreted as a 2αBEC, while the ^{12}C(0_2^+) excitation, known as the Hoyle state (HS), is described as a 3αBEC. The study of such states is not only fundamental to nuclear physics but also highly relevant to nuclear astrophysics.

By analyzing layers of NTE exposed to longitudinal beams of relativistic nuclei, it is possible to determine the invariant mass of ensembles of produced α-particles using their emission angles under the assumption of initial momentum conservation per nucleon. This approach has been successfully applied to identify the decays of ^{8}Be and the Hoyle state in nuclear fragmentation processes, based on upper limits of the invariant mass [1]. Furthermore, it has been used to search for more complex αBEC states in the fragmentation of medium and heavy nuclei. In measurements of fragmentation involving nuclei ranging from oxygen to gold at energies spanning several to tens of GeV per nucleon, an increase in the probability of detecting ^{8}Be has been observed as the number of associated α-particles grows [2].The exotically large sizes and lifetimes of ^{8}Be and the Hoyle state suggest a possible mechanism for the synthesis of αBEC through the sequential coupling of α-particles: $2\alpha \to {}^{8}$Be, ^{8}Be + $\alpha \to {}^{12}$C(0_2^+), ^{12}C(0_2^+) + $\alpha \to {}^{16}$O(0_6^+), and $2{}^{8}$Be $\to {}^{16}$O(0_6^+). However, the probability of such processes decreases at each step due to the emission of γ-quanta or recoil particles. This report presents results on the contributions of ^{8}Be(0^+), ^{8}Be(2^+), ^{12}C(0_2^+), ^{12}C(3^-) [3], and the search for the ^{16}O(0_6^+) –4α-particle condensate state [4] in the fragmentation of relativistic medium and heavy nuclei.

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