^{8}He nuclei stopped in nuclear track emulsion

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Abstract

The fragment separator ACCULINNA in the G. N. Flerov Laboratory of Nuclear Reactions of JINR was used to expose a nuclear track emulsion to a beam of radioactive ^{8}He nuclei of energy of 60 MeV and enrichment of about 80%. Measurements of decays of ^{8}He nuclei stopped in the emulsion allow one to evaluate possibilities of α-spectrometry and to observe a thermal drift of ^{8}He atoms in matter. Knowledge of the energy and emission angles of α-particles allows one to derive the energy distribution of α-decays $Q_{2\alpha}$. The presence of a "tail" of large values $Q_{2\alpha}$ is established. The physical reason for the appearance of this "tail" in the distribution $Q_{2\alpha}$ is not clear. Its shape could allow one to verify calculations of spatial structure of nucleon ensembles emerging as α-pairs of decays via the state ^{8}Be$_{2+}$.

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I.

At the energy of a few MeV per nucleon, there is a possibility to study decays of radioactive nuclei by implanting them into a detector [1–4]. In particular, population of 2α- and 3α-particle states is possible in decays of light radioactive nuclei. In this respect, the unique, although somewhat forgotten, possibilities of nuclear track emulsion (NTE) for the detection of slow radioactive nuclei are worthy to be mentioned. The advantages of this method are the best spatial resolution (about 0.5 μm), the possibility of observing the tracks in a full solid angle and a record sensitivity starting with relativistic singly charged particles with a minimum ionization. In NTE, the directions and ranges of the beam nuclei, as well as slow products of their decays can be measured, which provides a basis for spectrometry. More than half a century ago, hammer-like tracks from the decay of ^{8}Be nuclei through the first excited state 2^{+} of about 2.0 MeV were observed in NTE. They occurred in the β-decays of stopped ^{8}Li and ^{8}Be fragments, which in turn were produced by high-energy particles [5]. Another example is the first observation of the ^{9}C nucleus from the decay 2α + p [6]. When used with sufficiently pure secondary beams, NTE appears to be an effective means for a systematic study of the decay of light nuclei with an excess of both neutrons and protons.

In March 2012 exposure of NTE to nuclei ^{8}He of energy of 60 MeV [7] is performed at the fragment separator ACCULINNA [8] in the G. N. Flerov Laboratory of Nuclear Reactions, JINR. Features of decays of the ^{8}He isotope are shown in Fig. 1, according to the compilation [9]. Fig. 2 shows a mosaic macrophotograph of a decay of a nucleus ^{8}He stopped in NTE. It is typical one among thousands observed in this study. Video recordings of such decays taken with the microscope and camera are collected [10].

When scanning the NTE pellicle with a 20× objectives on the microscopes MBI-9 a primary search for β-decays of ^{8}He nuclei was focused on hammer-like events (Fig. 2). The absence of tracks of the decay electrons in the event was interpreted as a consequence of an incomplete efficiency of observation. Often, in the events named “broken”ones gaps were observed between stopping points of primary tracks and subsequent hammer-like decays. In total 1413 ”whole” and 1123 ”broken” events were found. Decay vertices of 580 ”broken” events were found to be laying in a backward hemisphere with the respect to arrival directons of ions. Corresponding to a half of the statistics this number indicate that the forward-backward asymmetry is absent. The ”broken” events were attributed to a drift of thermalized

^{8}He atoms that arose as a result of neutralization of ^{8}He nuclei. This effect is determined by the nature of ^{8}He and such events are identified them particularly reliably.

The coordinates of stopping pointsof the ions ^{8}He (as well as arrival directions), the decay vertices and stops of decay particles were determined for "hammers"of 136 "whole"and 142 "broken"events. In "broken"events the decay points were determined by extrapolating the electron tracks. The emission angles and the ranges of α-particles were obtained on this basis. The distribution of the opening angles of α-particle pairs has a mean value $< \Theta_{2\alpha} >$ $= (164.9 \pm 0.7)^\circ$ at rms = $(11.6\pm 0.5)^\circ$. Some kink of "hammers"is defined by the momenta carried away by eν-pairs. The dependence of the α-particle ranges L_α and their energy values are determined by spline interpolation of calculations in the SRIM model [11]. The mean value of the α-particle ranges is (7.4 ± 0.2) μm at rms (3.8 ± 0.2) μm corresponding to a mean energy $<E(^4He)> = (1.70 \pm 0.03)$ MeV at rms 0.8 MeV. Correlation of ranges L_1 and L_2 of α-particles in pairs is clearly manifested. The distribution of the range differences L_1 - L_2 has rms 2.0 μm.

Knowledge of the energy and emission angles of α-particles allows one to derive the energy distribution of α-decays $Q_{2\alpha}$. The relativistic-invariant variable Q is defined as the difference between the invariant mass of a final system $M^\star$ and the mass of a primary nucleus M, that is, $Q = M^\star - M$, $M^\star$ is defined as the sum of all products of the 4-momenta $P_{i,k}$ of fragments, that is, $M^{*2} = \sum(P_i \cdot P_k)$. In general, the distribution of $Q_{2\alpha}$ (Fig. 3) corresponds to the ^{8}Be decay from the first excited state 2^+. However, the mean value $<Q_{2\alpha}>$ is slightly higher than expected. This fact is determined by the presence of a "tail" of large values $Q_{2\alpha}$, obviously not matched the description by a Gaussian function. Application of the selection criteria for ranges L_1 and L_2 less than 12.5 μm and opening angles $\Theta > 145^\circ$, provides a value $<Q_{2\alpha}> = (2.9 \pm 0.1)$ MeV at RMS (0.85 ± 0.07) MeV, which corresponds to 2^+ state. Ranges L_1 and L_2 stay to be well correlated above 12. 5 μm. Therefore, enhanced ranges L_1 and L_2 can not be attributed to fluctuations of ranges or recombination of ions He^{+2}.

The targeted measurements are continued to saturate statistics in the high energy "tail "$Q_{2\alpha}$ and to establish its shape. The insertion in Fig. 3 shows $Q_{2\alpha}$ with additional 98 α-pairs having L_1 and L_2 above 12.5 μm. It should be noted that the highly energetic α-pairs are among better measurable ones despite to relatively rare appearance. The physical reason for the appearance of the "tail" in the distribution $Q_{2\alpha}$ is not clear. Probably, its shape will allow one to verify calculations of spatial structure of 8-nucleon ensembles emerging as α-pairs of decays via the state ^{8}Be$_{2+}$ [12].

In the 142 “broken”events the distances L(^{8}He-^{8}Be) between the stopping points of the ^{8}He ions and the decay vertices as well as the angles Θ(^{8}He-^{8}Be) between directions of arrivals of the ions and directions from the stopping points of the ions towards the decay vertices are defined (Fig. 4). Uniformity of distributions of events over these parameters and absence of a clear correlation indicate on on a thermal drift of the atoms ^{8}He. The mean value $<$L(^{8}He-^{8}Be)$>$ amounting to (5.8 $\pm$ 0.3) μm at (3.1 $\pm$ 0.2) μm, can be associated with a mean range of atoms ^{8}He. The low value of a mean speed of the atoms ^{8}He defined as ratio of $<$L(^{8}He-^{8}Be)$>$ to the half-life of the nucleus ^{8}He supports a pattern of diffusion.

Observation of the diffusion points to the possibility of generating of radioactive atoms ^{8}He and pumping them out of sufficiently thin targets. Increasing of the mean speed and drift length is achievable due to heating of the target. There is a prospect of accumulating of a significant amount of ^{8}He atoms. In particular, a ^{8}He radioactive gas can be used to measure the half-life of the ^{8}He nucleus at a new level of precision and for laser spectroscopy of this isotope. Applied interest consists in studies of thin films by pumping atoms ^{8}He and their deposition on α-detectors. Such opportunities are developing intensively with respect of the ^{6}He isotope [13], [14].

To conclude, the result of this work is the demonstration of the opportunities of recently reproduced nuclear track emulsion in a way of exposure in a beam of ^{8}He nuclei. Nuclear track emulsion made it possible to identify decays of stopped ^{8}He nuclei, estimate possibilities of α-range spectrometry and observe the drift of ^{8}He atoms. The high quality of the beam of radioactive ^{8}He nuclei at the ACCULINNA fragment separator was confirmed. The presented analysis of the decay of nuclei ^{8}He can serve as a prototype for studying the decays of stopped nuclei ^{8,9}Li, ^{8,12}B, ^{9}C and ^{12}N. Statistics of hammer-like decays found in this study is a small part of the flux of ^{8}He nuclei, and the measured decays - about 10% of this share. This limitation is defined by “reasonable expenses”of human time and labor. However, nuclear track emulsion in which radioactive nuclei are implanted provides a basis for the application of automated microscopy and image recognition software, allowing one to rely on unprecedented statistics. Thus, a synergy of classical technique and modern technology can be achieved. This work was supported by the grants 12-02-00067, 11-02-00657 and 11-02-00657a of the Russian Foundation for Basic Research and grants of Plenipotentiary

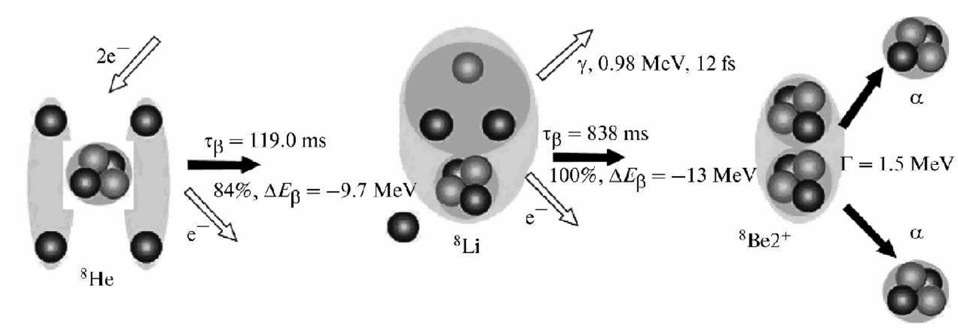

FIG. 1: Scheme of a major channel of the cascade decay of ^{8}He isotope; light circles correspond to protons, dark ones -neutrons.

representatives of Bulgaria, Egypt and Romania at JINR.

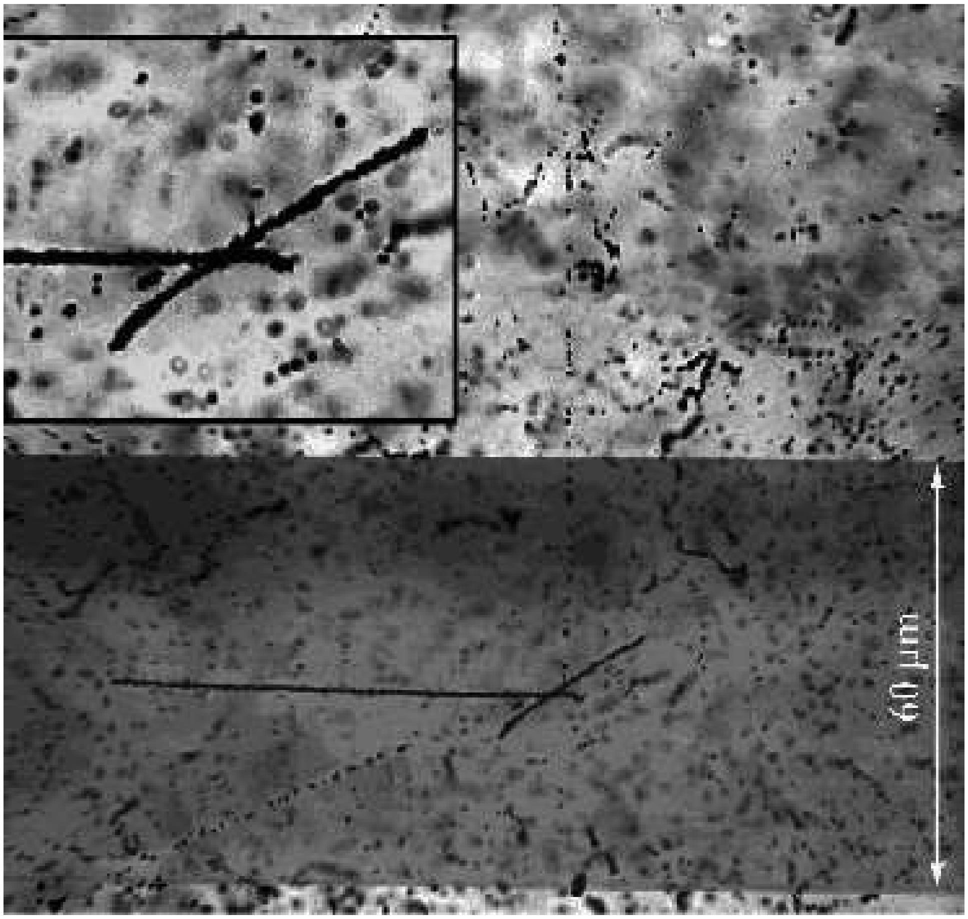

FIG. 2: Mosaic macrophotography of a hammer-like decay of ^{8}He nucleus (horizontal track) stopped in nuclear track emulsion. Pair of electrons (point-like tracks) and pair of α-particles (short opposite tracks). On insertion (top): enlarged decay vertex. To illustrate spatial resolution the image of the decay is superimposed to macrophotography of a human hair of thickness of 60 μm.

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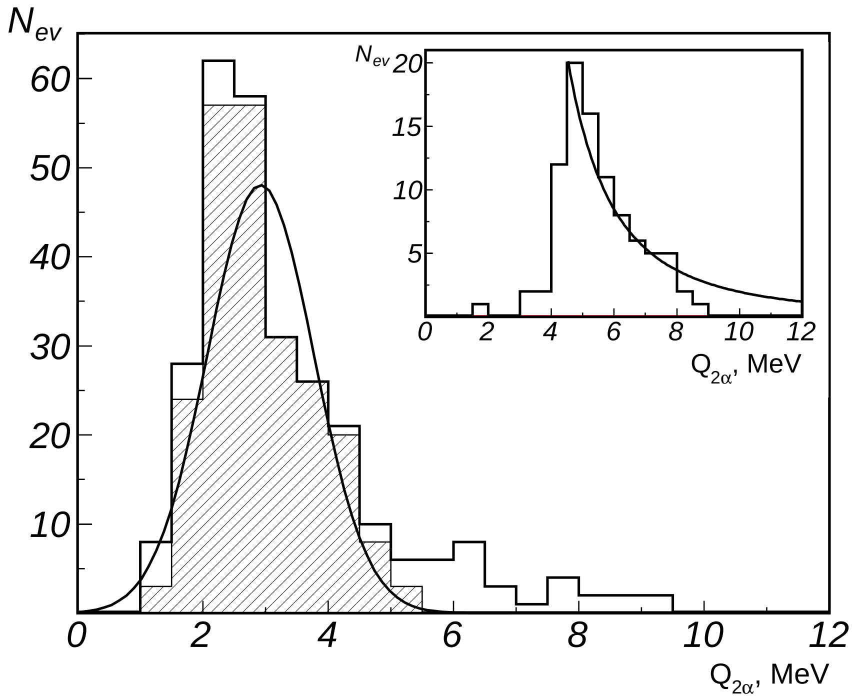

FIG. 3: Distribution on energy $Q_{2\alpha}$ of 278 pairs of α-particles; hatched histogram correspond to condition of selection of events L_1 and L_2 <12.5 μm, $\Theta > 145°$; line - Gaussian. On the insertion: $Q_{2\alpha}$ distribution of additional 98 α-pairs having L_1 and $L_2 > 12.5$ μm.

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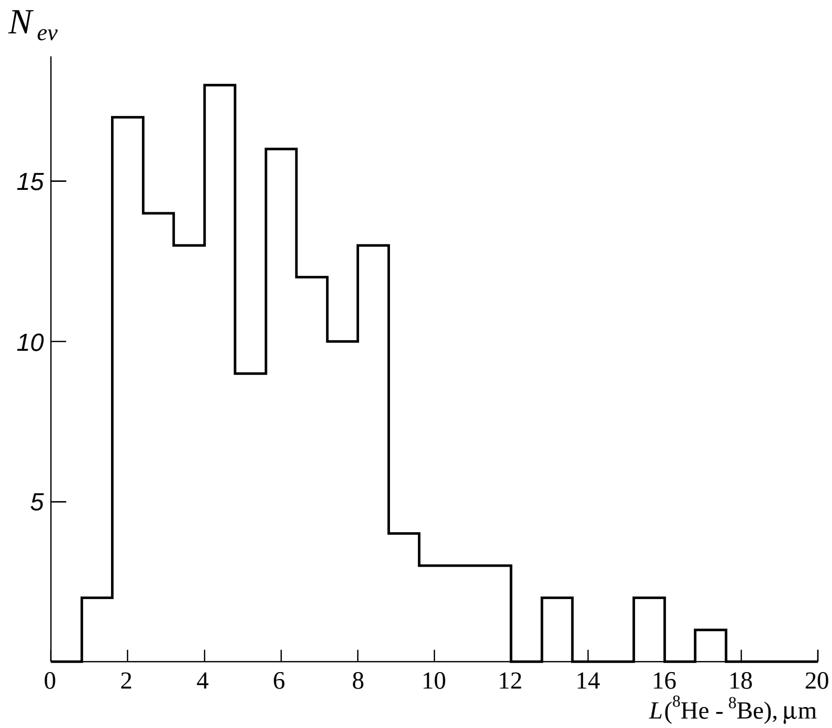

FIG. 4: Distribution of the distances L(^{8}He-^{8}Be) between the stopping points of the ^{8}He ions and the decay vertices in the broken events.