EPJ Web of Conferences **66**, 11044 (2014)
DOI: 10.1051/epjconf/20146611044

^{8}He nuclei stopped in nuclear track emulsion

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Abstract. The ACCULINNA fragment separator in the G. N. Flerov Laboratory of Nuclear Reactions was used to irradiate a nuclear track emulsion by a beam of radioactive ^{8}He nuclei of energy of 60 MeV and enrichment of about 80%. Measurements of 278 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.

At the energy of nuclei of a few MeV per nucleon, there is a possibility of implantation of radioactive nuclei into a detector material. In this approach the daughter nuclei arising in their decays can be investigated. In particular, population of 2α- and 3α-particle states is possible in decays of light radioactive nuclei. In this respect, the known, 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 α-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}B fragments, which in turn were produced by high-energy particles [1]. Another example is the first observation of the ^{9}C nucleus from the decay 2α + p [2]. 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.

As a first step in applying of such an approach NTE was exposed to ^{8}He nuclei of energy of about 60 MeV at the G. N. Flerov Laboratory of Nuclear Reactions of the Joint Institute for Nuclear Research in March 2012. Features of decays of the ^{8}He isotope are shown in Fig. 1, according to the compilation [3]. Fig. 2 shows a mosaic macro photograph of a decay of a nucleus ^{8}He stopped in

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NTE – one of thousands observed in this study. Video recordings of such decays taken with the microscope and camera are compiled the website of the BECQUEREL project [4].

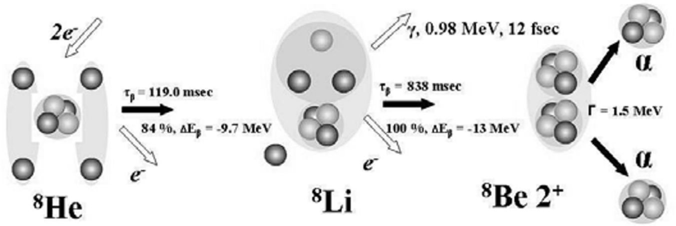

Figure 1. Scheme of a major channel of the cascade decay of ^{8}He isotope; light circles correspond to protons, dark ones – neutrons.

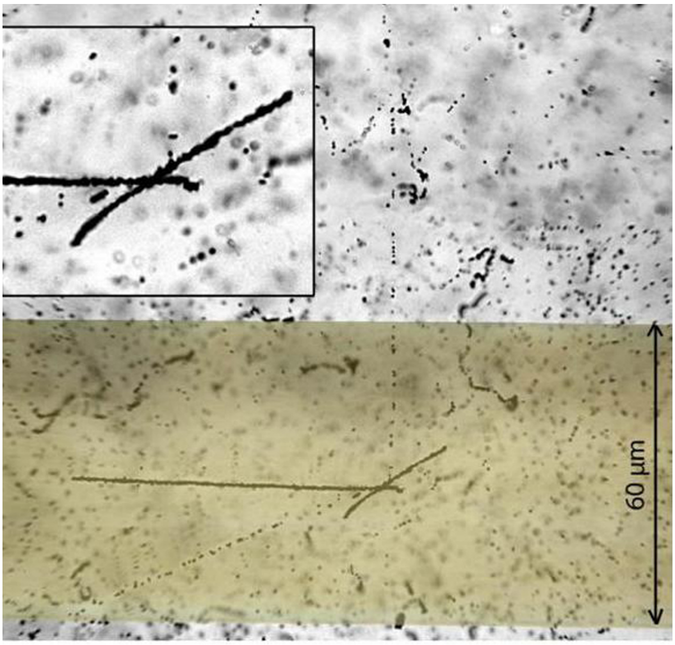

Figure 2. Mosaic macrophotography of a hammer-like decay of ^{8}He nucleus (horizontal track) stopped in nuclear track emulsion. Pair of electrons (point-like tracks) and pair of α-particles (short opposite tracks). On insertion (top): enlarged decay vertex. To illustrate special resolution the image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

Exposure of NTE to nuclei ^{8}He of energy of 60 MeV is performed at the fragment separator ACCULINNA in FLNR [5]. To obtain ^{8}He nuclei a beam of heavy ions ^{18}O is used derived from the cyclotron U-400M with an energy of 35 MeV/nucleon and an intensity of about 0.3 pμA. The following characteristics of the ^{8}He secondary beam are obtained in the final focus plane: energy – (59.2 ± 4.5) MeV, intensity – about 50 particles/s at intensity of the primary beam of about 0.3 pμA, enrichment of ^{8}He nuclei – about 80%.

When scanning the NTE pellicle with a 20x zoom lens 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 in the NTE pellicle. Often a gap was observed between the stopping point of a primary track and a subsequent hammer-like decay. Such "broken" events were attributed to a drift of thermalized ^{8}He atoms that arose as a result of neutralization of ^{8}He ions. This effect is determined by the nature of the He atom and such events are identified particularly reliably.

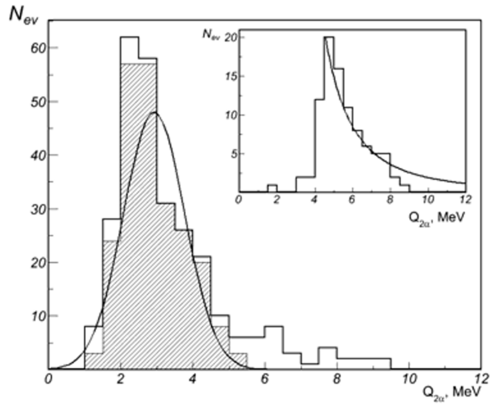

Figure 3. Distribution on energy $Q_{2\alpha}$ of 278 pairs of α-particles; hatched histogram correspond to condition of selection of events L_1 and L_2 < 12.5 μm, $\Theta > 145^0$; line – Gaussian. On the insertion: $Q_{2\alpha}$ distribution of additional 98 α-pairs having L_1 and L_2 >12.5 μm.

The simulation program SRIM [6] allows one to evaluate the kinetic energy of ^{8}He nuclei penetrated in the NTE pellicle on the basis of range measurements. Its mean value is $\langle E(^8He)\rangle = (29 \pm 1)$ MeV at rms 10 MeV. Significantly lower mean energy of ^{8}He and its greater spread at the entrance to the NTE pellicle as compared with the value set by the fragment separator is explained by a deceleration in the light protecting paper. The paper is an inhomogeneous structure that affects a significant spread of ranges L(^{8}He) not described by the calculation. Thus, the paper is a factor that can not be neglected and at the same time is difficult to be taken into account exactly.

The coordinates of the decay vertices and stops of decay α-particles were determined for "hammers" of 136 "whole" and 142 "broken" events. In "broken events the decay points were determined by extrapolating the electron track. 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 $\langle\Theta_{2\alpha}\rangle = (164.9 \pm 0.7)^o$ at rms $(11.6 \pm 0.5)^o$. 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 [6]. 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 $\langle E(^4He)\rangle = (1.70 \pm 0.03)$ 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^* and the mass of a primary nucleus M, that is, $Q = M^* - M$. M* is defined as the sum of all products of the 4-momenta $P_{i,k}$ of fragments, that is, $M^{*2} = (\Sigma P_j)^2 = \Sigma(P_i \cdot P_k)$. 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 $\langle Q_{2\alpha}\rangle$ 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 $\Theta > 145^o$, provides a value $\langle Q_{2\alpha}\rangle = (2.9 \pm 0.1)$ 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 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 despite to relatively rare appearance these highly energetic α-pairs are among better measurable ones. The targeted measurements are continued to saturate statistics in order to establish a shape of a high energy tail $Q_{2\alpha}$. The physical reason for the appearance of the high energy tail in the distribution $Q_{2\alpha}$ is not obvious. Probably, its shape will allow one to verify calculations of spatial structure of 8-nucleon ensembles emerging as α-pairs of decays $^{8}Be_{2+}$ [7].

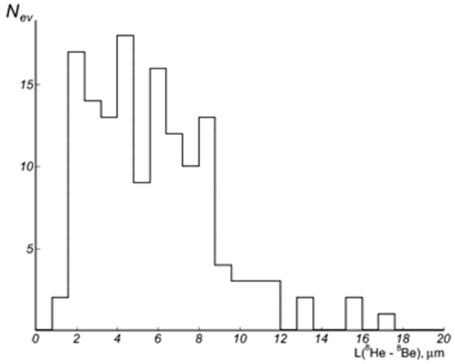

Figure 4. Distribution of distances L(^{8}He–^{8}Be) between points of stops of ^{8}He and vertices of decays ^{8}Be (2^{+}) in "broken" events.

The NTE resolution allows one to define the distance L(^{8}He-^{8}Be) between the stopping points of ^{8}He nuclei and the decay vertices $^{8}Be_{2+}$ in 142 "broken" events (Fig. 4). The mean value <L(^{8}He-^{8}Be)> amounting to (5.8 ± 0.3) µm at rms (3.1 ± 0.2) µm, can be associated with a mean range of drift of atoms ^{8}He.

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 thermalized ^{8}He atoms. The high quality of the beam of radioactive ^{8}He nuclei of energy of 10 - 30 MeV/nucleon 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 and 11-02-00657 of the Russian Foundation for Basic Research and grants of Plenipotentiary representatives of Bulgaria, Egypt and Romania at JINR.

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