JOINT INSTITUTE FOR NUCLEAR RESEARCH
Veksler and Baldin laboratory of High Energy Physics

FINAL REPORT ON THE INTEREST PROGRAMME

Irradiation of a nuclear emulsion with ^{8}He nuclei on an ACCULINNA fragment - separator

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At the ACCULINNA fragment - separator, the nuclear emulsion have been irradiated in a beam of radioactive ^8He nuclei with an energy of 60 MeV and an enrichment of about 80%. Measurements of 278 decays of ^8He nuclei stopped in the nuclear emulsion make it possible to evaluate the possibilities of α spectrometry, as well as to observe for the first time the drift of ^8He atoms thermalized in a substance.

1 Introduction

At energies of about several MeV per nucleon, it becomes possible to inject radioactive nuclei into the detector substance. In this method, it is not the embedded kernels themselves that are studied, but the child states that arise during their decay. With such introductory data, it is worth paying attention to the method of detecting slow nuclei in a nuclear track emulsion. The advantage of this method lies in the best spatial resolution (about 0.5 microns), the ability to observe particle tracks at full solid angle and a record sensitivity range starting with relativistic single-charge particles with minimal ionization. The nuclear emulsion makes it possible to measure the direction and path length of the beam nuclei and their decay products, which serves as the basis for spectrometry.

As a first step in applying this approach, the nuclear emulsion has been irradiated at the Flerov Nuclear Reaction Laboratory (JINR Nuclear Research Institute) with ^8He nuclei with energy of 60 MeV in March 2012. After stopping and neutralizing the ^8He nucleus in the substance, the produced ^8He atom remains unbound, due to the fact that it is a noble gas, and as a result of thermalization can experience drift in the medium up to β decay.

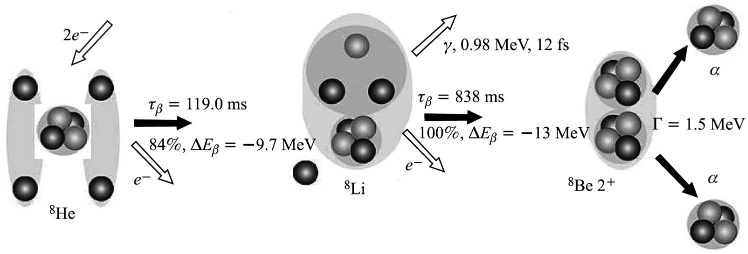

Figure 1: Diagram of the main channel of cascade decay of the ^8He nucleus; light circles correspond to protons, dark circles correspond to neutrons; clusters are highlighted with a dark background

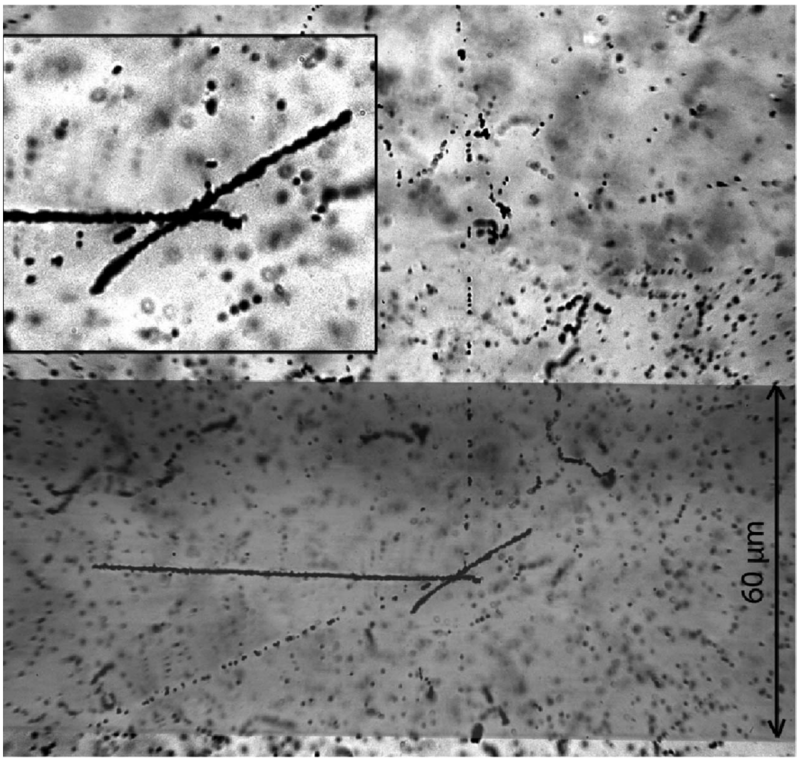

Figure 2: Mosaic macrophotography of the "hammer" decay of the ^8He nucleus stopped in a nuclear emulsion (horizontal track). A pair of relativistic electrons (dotted tracks) and a pair of alpha particles (short oppositely directed tracks) have been produced in the decay. The image shows the enlarged top of the decay, which is combined with a macrophotography of a human hair with a thickness of 60 microns to illustrate the spatial resolution.

The half-life of the ^8He nucleus is $\tau_\beta = (119.0 \pm 1.5) \cdot 10^{-3}$ s. With a probability of 84% and with $\Delta E_\beta = 9.7$ MeV, as a result of β decay, it will move to the level of 0.98 MeV of the ^8Li nucleus. Later, having a half-life of $\tau_\beta = (838 \pm 6) \cdot 10^{-3}$ s, the nuclei of ^8Li decays with 100% probability and energy of $\Delta E = 13$ MeV undergoes β decay to the level of ^8Be (2^+) nucleus with an energy of 3.03 MeV. And finally, having a width of 1.5 MeV, it decays into a pair of α particles.

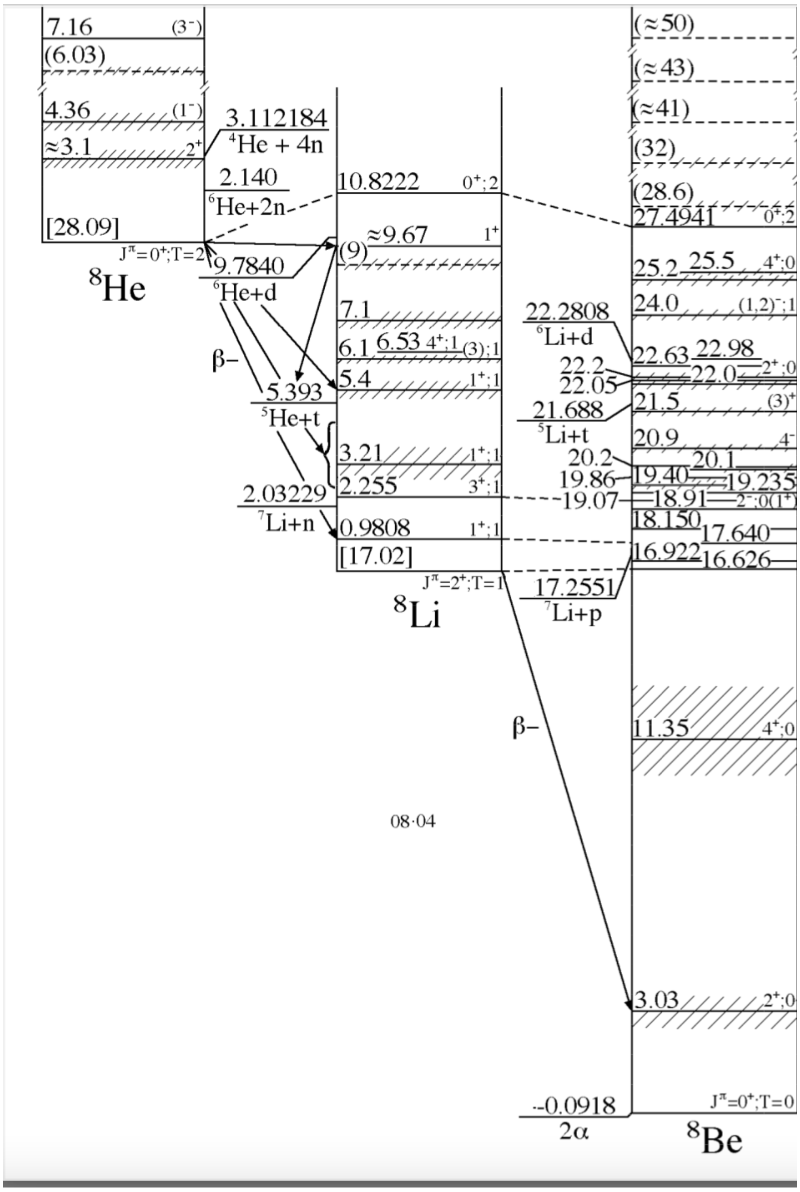

Figure 3: The decay diagram of the ^8He isotope

2 Some information about nuclear emulsion.

The photographic emulsion consists of a large number of small crystals of halide silver (mainly bromide with an admixture of iodide) distributed in gelatin. The main function of gelatin is that it forms a certain three-dimensional basis for distributed crystals and contributes to their displacement. This increases the accuracy of measurements.

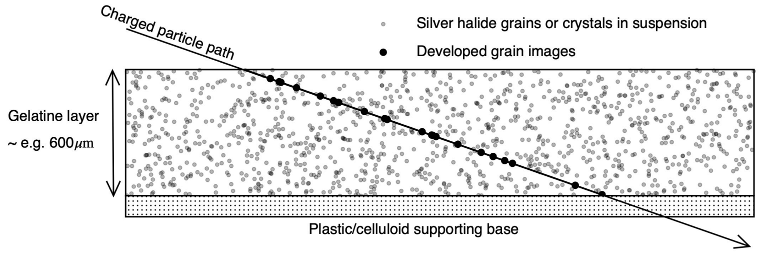

Figure 4: A schematic cross-sectional view of a nuclear emulsion.

Nuclear emulsion is a special type of substance that, after undergoing chemical processing and being viewed under a microscope, reveals the tracks of charged particles that have been formed as a result of ionization events. The presence of a charged particle field alters the chemical bonds within AgBr crystals, and after the development and fixation stages, these alterations become visible and form a track.

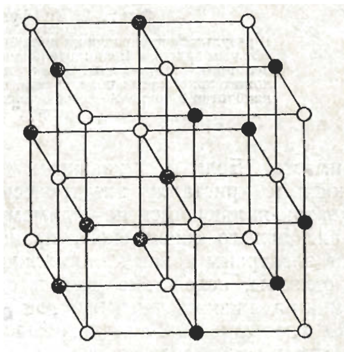

Figure 5: The lattice structure of a silver bromide crystal

3 Procedure for measuring tracks in an emulsion

The particle enters the emulsion layer at a slight angle to its surface, as shown in Figure 6, where L is the length of the run, L_{hor} is the horizontal projection of the track, h is the vertical.

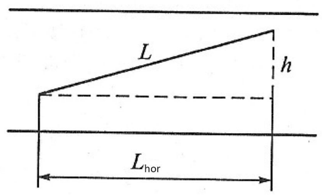

Figure 6

The height h is measured using a micrometer screw. To do this, focus the lens on the starting point of the track and fix its coordinates on the screw scale. Then the same should be done for the end point of the track. The difference in readings on the scale of a micrometer screw, multiplied by the price of division, will be the apparent height of h_c (due to the refraction of light, the apparent thickness is n times less than the true one, where n is the refractive index of the emulsion). In addition, it is necessary to take into account track distortions that occur during the processing of emulsions: dispersion, shrinkage, etc. Shrinkage has a particularly strong effect on the apparent height. The total true length of the projection on the vertical axis will be determined by the equation:

$$h = \chi n h_c$$

where χ is the shrinkage coefficient, n is the refractive index of the emulsion (n=1.52).

The shrinkage coefficient is determined from the ratio of the initial thickness of the emulsion d_0 to the thickness d after processing, which is determined by alternating focusing on the upper and lower surfaces of the emulsion:

$$c = \frac{d_0}{d}$$

$$d = nk(N_2 - N_1)$$

Here k is the division value of the micrometer screw, N_1 and N_2 are the corresponding values on the scale of the micrometer screw when focusing on the upper and lower surfaces of the emulsion.

In the end, we get a formula for calculating the length of the track range:

$$L = \sqrt{L_{hor}{}^2 + h^2} = \sqrt{L_{hor}{}^2 + (\chi n h_c)^2}$$

4 Experiment

As noted earlier, irradiation of the nuclear emulsion with ^8He nuclei with an energy of 60 MeV was carried out in the JINR Laboratory of Nuclear Reactions on an ACCULINNA fragment separator. A beam of ^8He nuclei was obtained by bombarding a target made of pyrolytic graphite with a thickness of 175 mg/cm^2 with heavy ions ^{18}O with an energy of 35 MeV/nucleon. The target, mounted in the plane F_1, consisted of a disk with a diameter of 20 mm and a thickness of 1 mm, fixed between two copper plates cooled with water. The initial beam was derived from the U-400M cyclotron.

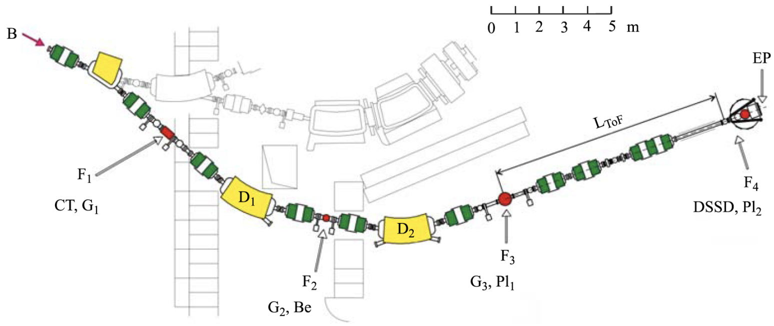

Figure 7: A scheme for obtaining a ^8He beam with an energy of 60 MeV on an ACCULINNA separator and the location of the nuclear emulsion layers in focus F_4 when irradiated with ^8He nuclei. B is the direction of the primary beam derived from the U-400M accelerator; CT is a carbon target; $F_{1,2,3,4}$ are focal planes; $G_{1,2,3}$ are collimator slits; Be is a beryllium wedge; $Pl_{1,2}$ are plastic scintillation detectors; DSSD is a strip silicon detector; L_{ToF} - the base for measuring flight time; EP - the place of irradiation of emulsion layers

The channel of the primary beam was adjusted through a collimator with a diameter of 8 mm, up to the maximum transmission of the beam ^{18}O, which reached 90 %.

Characteristics of the secondary beam ^8He in the plane F_4:

1. The energy is (23.8 ± 0.9) MeV per nucleon.

2. The intensity is approximately 50 particles per second at a primary beam intensity of about 0.3 p μA.

3. The enrichment of ^{8}He nuclei is approximately 80%.

The estimated energy of the ^8He nuclei before entering the emulsion assembly was about (59.2 ± 4.5) MeV. Several emulsion layers were irradiated with a beam with such characteristics. The irradiation time of each layer is 10 minutes. The integral flow is about $4 \cdot 10^4$ nucleus.

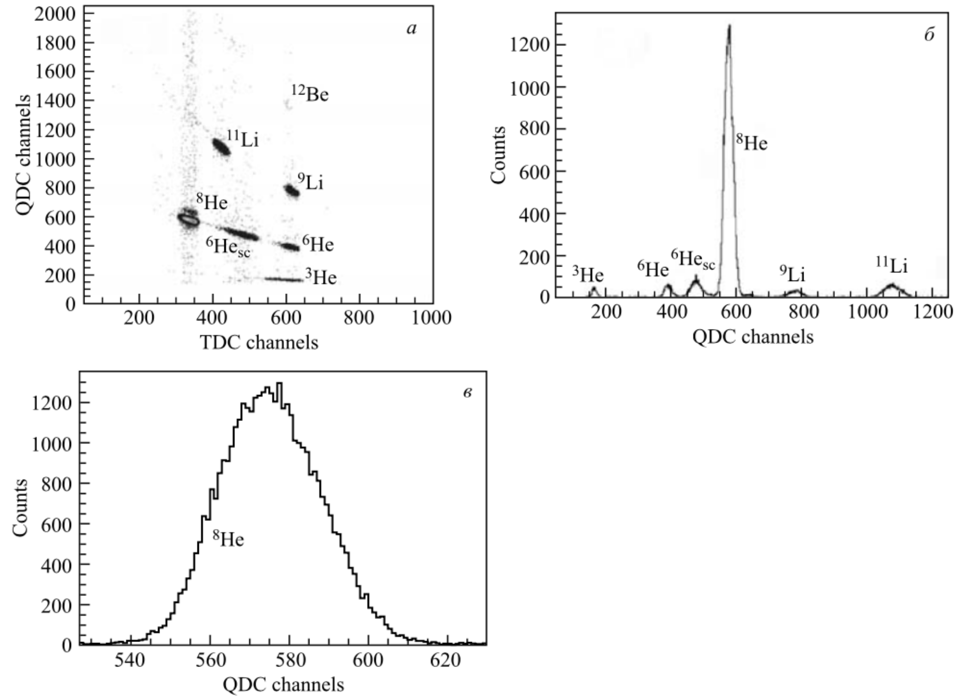

Figure 8: The composition of the beam formed on the ACCULINNA separator when tuned to the ^8He nucleus from the nuclear fragmentation reaction ^{18}O with an energy of 35 MeV/nucleon on the target ^{12}C: identification of particles using a silicon detector and flight time (a); spectrum energy losses of all beam particles in a 1 mm thick silicon detector (b); energy losses only for ^8He nuclei (c). With respect to the sum of the counts in Fig. b and c, the enrichment of the beam with ^8He nuclei was determined

Characteristics of emulsion layers:

1. Size: 9×12 cm^2.
2. Thickness: 107 μm

To select the optimal observation of the stops of the nuclei, ^8He were installed both perpendicular to the beam and at an angle that ranged from 10° to 20°. The layer that was located at an angle of 10° to the beam axis was considered the best for analysis. The tilt of the plate provided an increase in the braking layer. In addition, the irradiated layers were wrapped in two layers of black paper with a thickness of 100 microns, increasing the braking efficiency, especially sensitive at an angle of 10°.

5 Analysis of "hammer" decays

The primary search for β decays of ^8He when scanning the layer on an MBI-9 microscope with a 20x magnification of the lens was focused on "hammer" events (Fig.2). The absence of tracks in the found event of one of the decay electrons was interpreted as a consequence of the incomplete efficiency of observing all decay tracks in the emulsion layer. The most problematic background for selection according to this criterion could be the decay of ^{8}Li nuclei. However, according to Fig. 7, a, the presence of this isotope has not been noted. The same criterion could be met by β - the decay of stopped nuclei ^{9}Li with the formation of ^{8}Be and the emission of a delayed neutron (probability about 50 %). The admixture of these nuclei is small (Fig. 7, a). In addition, for the "hammer" decay from the state of ^{8}Be (2^{+}) nucleus , the settlement of the level ^{9}Be is required at least 4.7 MeV. Otherwise, the decay proceeds through the ground state 0^{+} of the ^{8}Be nucleus and, therefore, is unlikely to be observed even in an emulsion. Thus, it was possible to neglect the background from the decays of the nuclei ^{8}Li and ^{9}Li.

Many times there was a gap between the stopping point and the "hammer" decay. This effect can be explained by the drift of the thermalized ^{8}He atom, which occurs as a result of neutralization of the ^{8}He nucleus. Due to the dominance of ^{8}He nuclei in the beam (about 80%), the distribution of "hammer" decays over the emulsion area can be represented jointly for all the events found, including 1413 "whole" and 1123 "broken".

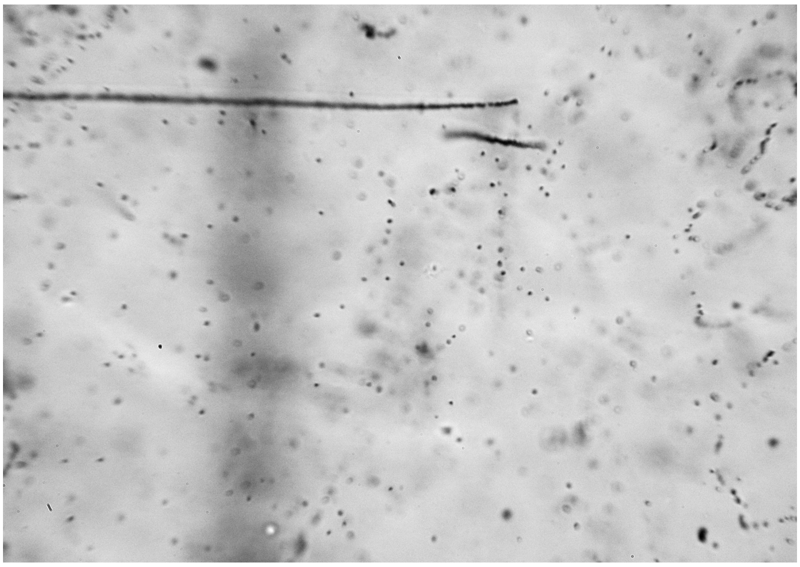

Figure 9: Macrophotography of the "hammer-torn" decay

Measurements of events in which at least one electron was present were performed on a KSM microscope with a 90-fold magnification. The average length of the ^{8}He tracks for 136 "whole" events was $\langle$L(^{8}He) $\rangle$ = (263 ±11) µm with RMS of 113 µm. In the case of "broken" events - (269 ± 10) µm at RMS 118 µm. Based on the measurement of track lengths, the SRIM modeling program allows us to estimate the kinetic energy of ^{8}He nuclei that have penetrated the emulsion layer. Their average value is $\langle$ E(^{8}He) $\rangle$ = (29 ± 1) MeV at RMS 10 MeV.

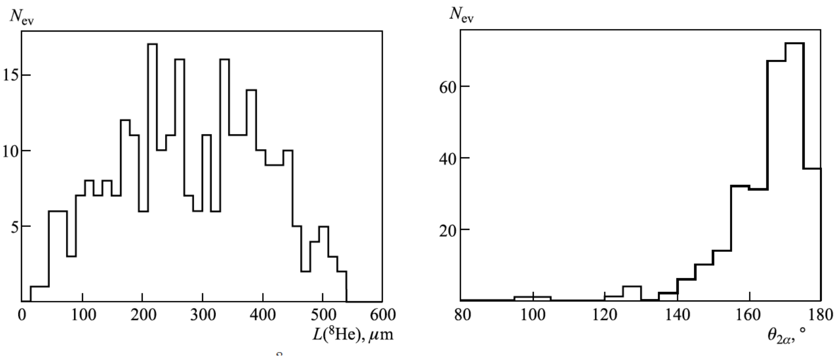

Figure 10: Distribution of tracks of ^8He along the path length in the emulsion (left); Distribution by angle of $\theta_{2\alpha}$ in pairs of α particles

The significantly lower value of the average energy ^8He and its large spread at the entrance to the emulsion compared to the value set by the fragment separator is explained by braking in the package.

The coordinates of the peaks of decays and stops of decaying α particles were determined for "hammer" decays of 136 "whole" and 142 "broken" events. In the case of "broken" events, the determination of the decay coordinate was made on the basis of extrapolation of the electron trace to the "hammer" trace. Thus, the emission angles and ranges of α particles were obtained.

Figure 9 (on the right) shows the distribution of the angles of separation of pairs of α particles: - $\langle\theta_{2\alpha}\rangle = (169.9 \pm 0.7)^{\circ}$ at RMS $(11.6 \pm 0.5)^{\circ}$ The small fracture is explained by the momentum carried away by electron-neutrino pairs

To determine the relationship between the ranges of α-particles L_{α} from "hammer" decays and the energy value of E_{α}, a model experiment was conducted in the SRIM program. The energy of ^4He is set from 0 to 20 MeV. The built-in emulsion emulsion - llford G5 with a density of 3.907 g/cm^3 has the following composition:

1. Ag - 48,53 %
2. Br - 35,63 %
3. C - 7,06 %
4. O - 7,06 %
5. H - 1,43 %
6. N - 0,07 %
7. S - 0,2 %

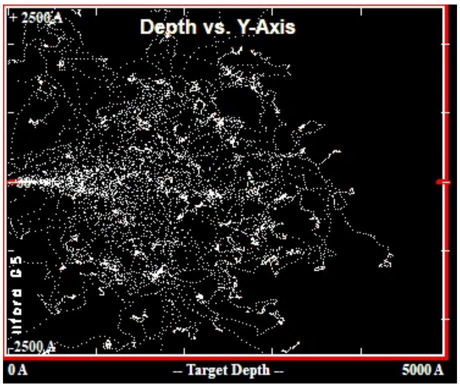

Figure 11: Tracks of simulated ^4He nuclei in the Ilford G5 emulsion

As a result, a table was obtained with the values of the ranges with the corresponding energy of the simulated α particles. With the subsequent approximation of the function of the form:

$$y = a * ln(x) + b * sqrt(x) + c * x + d$$

The corresponding coefficients a, b, c, d were obtained.

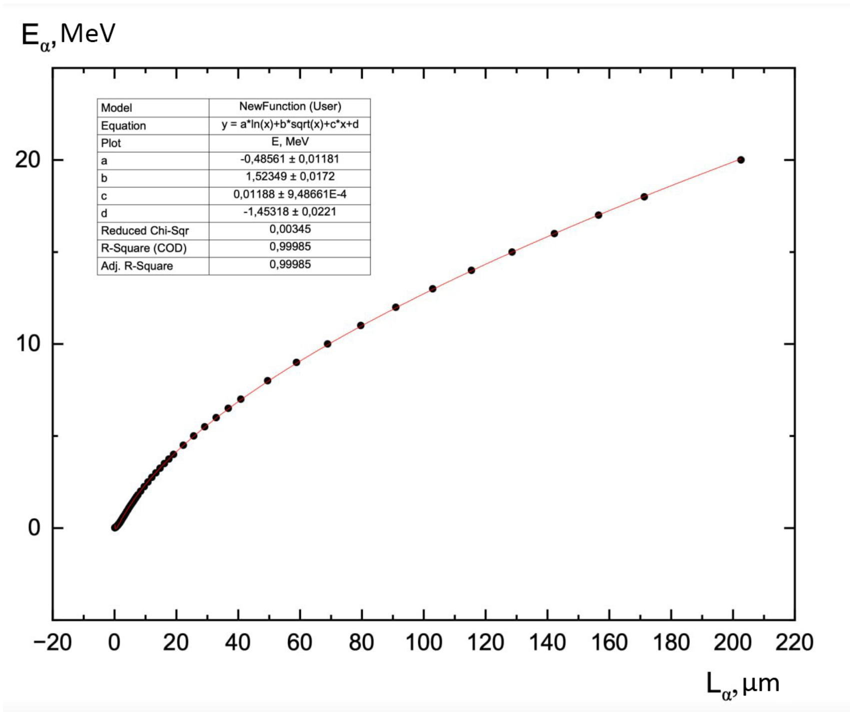

Figure 12: Determination of the dependence of the energy of α particles on the runs. The upper inset shows the values of the coefficients

The average value of the ranges of α particles has a value of (7.4 ± 0.2) µm at RMS (3.8 ± 0.2) µm, which corresponds to the average value of the kinetic energy of ⟨ E(^4He) ⟩ = (1.70 ± 0.03) MeV at RMS = 0.8 MeV. The correlation is clearly evident in the ranges of α particles L_1 and L_2 (Fig. 12).

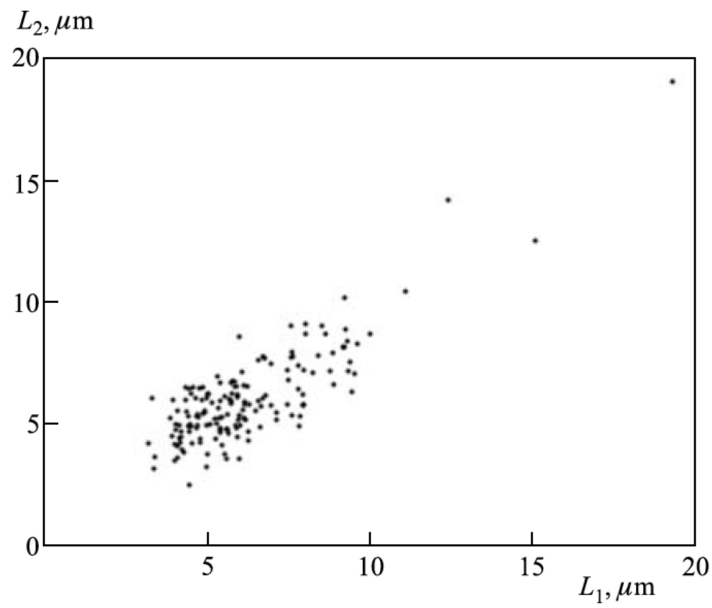

Figure 13: Distribution of runs of L_1 and L_2 in pairs of α particles

Knowing the energy and emission angles of α particles allows us to obtain the energy distribution of α decays of $Q_{2\alpha}$. Q is a relativistically invariant variable, which is defined as the difference between the invariant mass of the system M^* and the mass of the primary nucleus M. M^* is defined as:

$$M^{*2} = (\sum P_j)^2 = \sum(P_i P_k)$$

(The sum of all the products of 4-momentum $P_{i,k}$ fragments)

Basically, the distribution of the magnitude $Q_{2\alpha}$ corresponds to the decay of the ^8Be nucleus from the excited state 2^+. However, the average value turned out to be slightly higher than expected. This is due to the presence of a "tail" in the region of large values, which is not described by the Gaussian distribution. The application of selection conditions for runs L_1 and $L_2 < 12.5$ µm, as well as $\theta >145°$ allows us to obtain the value $\langle Q_{2\alpha} \rangle$ = (2.9 ± 0.1) MeV at RMS (0.85 ± 0.07) MeV, which corresponds to the state of 2^+ (Fig. 3).

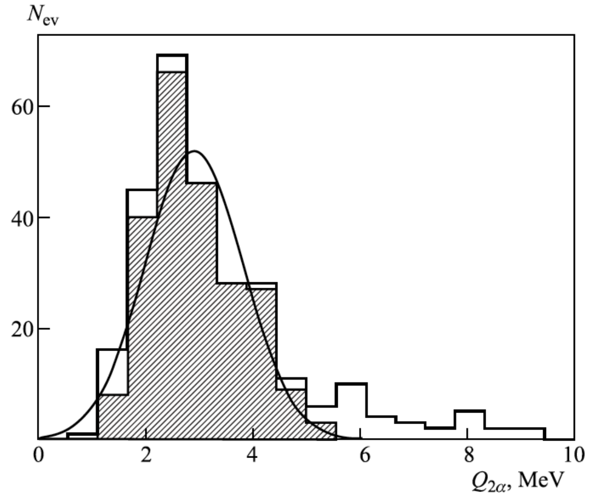

Figure 14: The energy distribution of $Q_{2\alpha}$ pairs of α particles; the shaded histogram meets the conditions for selecting events: L_1 and L_2 <12.5 microns , θ >145°

6 Conclusion

The result of this work is a demonstration of the capabilities of a recently reproduced nuclear emulsion under irradiation in a beam of ^8He nuclei. The test experiment made it possible to independently identify radioactive nuclei of ^8He by decays when stopped in an emulsion, evaluate the possibility of α spectrometry of these decays, and also observe for the first time the effect of drift of ^8He atoms thermalized in a substance.

In addition, a model experiment was conducted in the SRIM program, which allows you to repeat all the calculations performed in the original study.

It is shown that a nuclear emulsion can serve as a diagnostic tool for beams of radioactive isotopes.

7 List of literature

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