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

FINAL REPORT ON THE START PROGRAMME

Measurements of alpha-particle ranges in fragmentation of ^{12}C and ^{16}O nuclei with relativistic hadrons using nuclear track emulsions

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Abstract

The study of nuclear fragmentation is important for both fundamental science and applied problems. There are several ways to study this event, one of them is the nuclear photographic emulsion method. A significant role in the study of interactions at high energies is played by the nuclear track emulsion method, which has unique capabilities. Due to the best spatial resolution (0.5 μm) in a nuclear emulsion, it is possible to obtain an angular resolution along the tracks of relativistic fragments up to 10^{-5} rad, depending on the primary momentum of the nucleus. This ensures complete observability of all possible decays of relativistic nuclei into charged fragments. In addition, the emulsion method makes it possible to measure impulses and identify particles. Therefore, due to the high resolution of emulsions and the possibility of observing reactions in 4π-geometry, this method seems to be an effective way to study the processes of relativistic fragmentation, and so far no modern electronic detector has been able to replace this remarkable method, which can be used to study the structures and models of different nuclei in a large scale. Knowledge of the characteristics of fragmentation of relativistic nuclei is also necessary for solving a number of problems in nuclear astrophysics and cosmic ray physics.

The purpose of this work

Accumulation of statistics and analysis of the topology of nuclear fragmentation events from a nuclear emulsion induced by relativistic hadrons for analysis of correlations involving stopped alpha particles on nuclear track emulsion plates 4/7, 4/10 and 7-П. Measure and analyze the ranges of α-particles produced in fragmentation of ^{12}C and ^{16}O nuclei on a 4/10 plate. Experimental results are presented, including the multiplicities of shower particles and particles with high ionization, correlations between them from the reactions of the nuclear track emulsion nuclei with relativistic hadrons.

Introduction

The BECQUEREL (Beryllium Clustering Quest in Relativistic Multifragmentation) [5] experiment is aimed at solving topical problems in nuclear clustering physics. The used method of nuclear track emulsion (NTE) makes it possible, due to its unique sensitivity and spatial resolution, to study in a unified approach multiple final states arising in dissociation of relativistic nuclei. Progress in this direction relies on computerized microscopy. Currently, a research focus is on the theoretical concept of α-particle Bose-Einstein condensate (αBEC) - the ultra-cold state of several *S*-wave α-particles near coupling thresholds. The unstable ^8Be nucleus is described as 2αBEC, and the $^{12}C(0+ 2)$ excitation or Hoyle state (HS) as 3αBEC. Decays $^8Be \rightarrow 2\alpha$ and $^{12}C(0^+_2) \rightarrow {}^8Be\alpha$ can serve as signatures for more complex αBEC decays. Thus, the 0^+_6 state of the ^{16}O nucleus at 660 keV above the 4α threshold, considered as 4αBEC, can sequentially decay $^{16}O(0^+_6) \rightarrow \alpha^{12}C(0^+_2)$ or $^{16}O(0^+_6) \rightarrow 2^8Be(0^+)$. Its search is being carried out in several experiments on fragmentation of light nuclei at low energies. Confirmation of the existence of this and more complex forms of αBEC could provide a basis for expanding scenarios for the synthesis of medium and heavy nuclei in nuclear astrophysics. However, it is also essential to confirm similar phenomena in the more conventional low energy regime. Measuring the ranges and directions of stopped alpha particles in target nuclear fragmentation events induced by relativistic hadrons enables the reconstruction of 4-vectors and the search for decays of ^8Be and HS states based on this information.

Track classification

For each inelastic interactions found, produced charged particles were identified by the type of track they left. In a nuclear emulsion, the following classification of charged particles is accepted, depending on their relative ionization I/I0 and velocity β:

s-particles (shower) are single-charged relativistic particles with a velocity $\beta > 0.7$ and relative ionization $I/I_0 < 1.4$, where I_0 is the density of the particle trace at the minimum of the ionization curve; these are mainly born mesons, as well as non-elastically interacting protons with a departure angle greater than the fragmentation cone and unreacted fragments of the incident nucleus with a charge of Z = 1;

g-particles (gray) are these are mainly protons knocked out of the target nucleus with a relative ionization of $6.8 > I/I_0 \geq 1.4$ and $\beta < 0.7$, with a residual range > 3 mm. This type of particles also includes a small admixture of π mesons, which depends on the initial interaction energy;

b-particles (black) - represent traces of fragments of the target core with relative ionization $I/I0 \geq 7.0$ and $\beta < 0.23$, where I0 is the ionization on the tracks of relativistic particles 5 with charge $Z = 1$. However, in practical terms, it is often convenient to identify b-particles by their range in the volume nuclear photographic emulsion - $L \leq 3$ mm; Groups of b and g-particles are classified as particles with high ionization capacity h-particle.

f-particles (fragments) are ulti-charged fragments of the incident nucleus with a charge of $Z \geq 2$. They are not included in the b and g-particles category to which their ionization corresponds. Under a microscope, tracks of relativistic single-charged particles and fragments of the projectile nucleus with $Z = 2$ are easily distinguishable based on the number of grains developed per unit track length. At the same time, particles with a charge ≥ 3 are difficult to distinguish visually, but they can be identified by the number of δ-electrons formed near the track, which is proportional to the square of the charge. The method of NTE offer great opportunities for studying the nuclear interactions of high-energy hadrons. In terms of their atomic composition: hydrogen H (~ 4% of interactions), a group of light nuclei CNO (~ 26% of interactions), a group of heavy nuclei AgBr (~ 70% of interactions). The mean mass of emulsion nuclei is 60. The light nuclei have a mean mass equal to 14; and the heavy nuclei have a mean mass equal to 94. This composition allows for obtaining characteristics of nuclei that differ significantly in atomic mass number A. Table 1 presents the component composition of standard nuclear emulsion (BR-2) under normal conditions. It is assumed that during production, all technological requirements regarding the concentration of the emulsion's constituent components are met, and the atomic composition remains constant.

Element	Z	10^{22} atoms/cm^3
Argentum (Ag)	47	1.02
Bromine (Br)	35	1.01
Iodine (I)	53	0.006
Carbon (C)	6	1.39
Hydrogen (H)	1	3.19
Oxygen (O)	8	0.94
Sulfur (S)	16	0.014
Nitrogen (N)	14	0.32

Table 1 – Chemical composition of the nuclear emulsion (composition of BR-2 NTE sample; relative humidity 58%)

Depending on the type of the interacting nucleus with the incident relativistic particle, the nuclear emulsion method divides nuclear events into 3 groups:

1. Quasi-nucleon interactions. This group includes interactions on free hydrogen and on quasi-free nucleons in nuclei.

2. Interactions on the CNO group of light nuclei. This group includes events with the number of strongly ionizing h-particles $1 \leq n_h \leq 6$ and the number of b-particles $n_b \geq 1$, with a b-particle range $L_b \leq 80$ μm.

3. Interactions on the group of heavy nuclei ArBr. For such events, 2 groups are distinguished according to the number of formed h and b particles:

3.1. $1 \leq n_h \leq 6$, $n_b \geq 1$ and $L_b > 80$ μm

3.2. $n_h \geq 7$, such events are characterized by high excitation of the target nucleus.

Exposure

The exposure of NTE samples was conducted using the experimental facility Hyperon-M [1] located in channel №18 of the U-70 accelerator complex (NRC "Kurchatov Institute" - IHEP). This channel is used to create a secondary beam of positively charged hadrons (π – 60%, p – 35%, K – 5%) with momentum of 7 GeV/c. The target is placed in a vacuum chamber covered by dipole magnet №35 of the U-70 ring accelerator. The energy of the proton beam is 70 GeV. The magnet provides an initial deflection of particles produced on the target towards channel №18, which is positioned at an angle of approximately 30 degrees relative to the direction of the primary beam. Along the channel, there is a sequence of elements: a spectroscopic magnet (SM) SP032, a quadrupole lens (QL) 20K100, a horizontal collimator (HC) KG-75, QL 20K100, SM SP-129, a vertical collimator (VC) KG-75, collimator KG-75, a doublet QL 20K100, and SM SP-129. The collimators are adjustable absorbers made of bronze with a thickness of 75 cm along the beam.

The nuclear emulsion samples were exposed during the spring run in 2018. A total of 2 stacks, each consisting of 10 plates with an emulsion layer thickness of 100 μm, were used for exposure, along with 1 stack with an emulsion thickness of 200 μm. The total flux of hadrons passing through the nuclear emulsion stacks was 3×10^6 particles. During exposure, the stack of surface of NTE was oriented perpendicular to the beam direction. Such irradiation makes it possible to load NTE with a relatively large flow of particles. In the subsequent analysis, plates with an emulsion layer thickness of 100 μm were selected.

Search for hadron-nucleus interactions and results

Scanning of exposed layers of nuclear emulsion was carried out in the sector of developing thick-layer nuclear photographic emulsions of the Veksler and Baldin Laboratory of High Energy Physics of JINR. Scanning was carried out on the MBI-9 optical microscope (figure 1) using a 20x objective and 15x eyepieces (total magnification 300x). Scanning method selected - scanning by stripes with 1 mm wide side. This method makes it possible to conduct a full-fledged search for nuclear events over the entire area without loss of information.

Fig. 1. Laboratory for scanning emulsion layers with MBI-9 optical microscope.

The area of the photosensitive part of the NTE plates is 9x12cm^2, and the thickness is 100 μm (figure 2). The base of NTE is presented on a glass plate with 2 mm thickness. Therefore, some part of the background was generated in interactions of hadrons in the glass base. For the fixing of the vertex event position in NTE volume the coordinate marking grid was applied to the surface of the emulsion in a special way during chemical development.

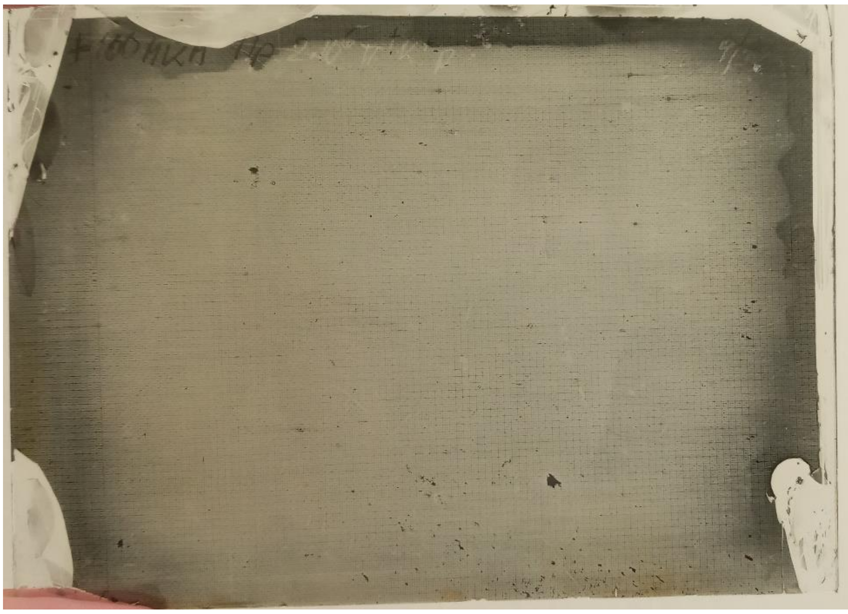

Fig. 2. Photo of NTE plate No. 4/10 exposed transversely by hadrons at Hyperon facility

The view of the coordinate grid under the microscope is presented in figure 3. In each square there are 2 numbers: from the left side you can see x coordinate, on the right side for y coordinate. The side width of one square is 1 mm. At the beginning of viewing, an extreme square is selected, which is at least 1 cm away from the edges of the plate. This condition is necessary to ensure comfortable viewing and the presence of edge defects on the plate.

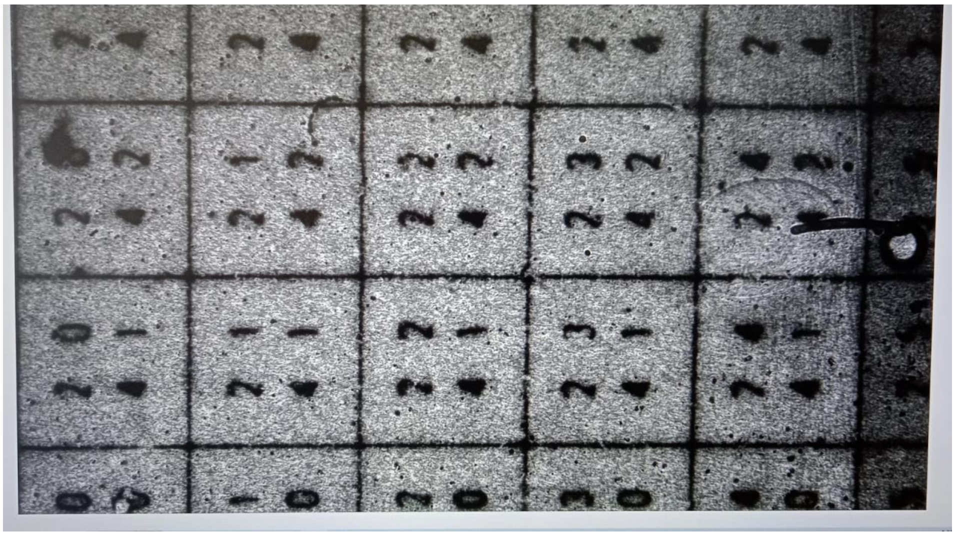

Fig. 3. Image of the coordinate grid on the surface of a nuclear photographic emulsion obtained with an Olympus BX63 optical microscope. The side of one square is 1 mm. The numbers indicate the coordinate of the position of this square in the XY plane.

During the START practice for the analysis of exposure in hadron beam at the Hyperon facility in 2018, 1 plate with a photosensitive layer area of 9x12 cm^2 and a thickness of 100 microns was selected (figure 2). The procedure for searching for hadronic interaction events is as follows: when viewed under microscope magnification 300x, the event that has solid tracks (at least two) with a single vertex are recorded. Next, a procedure is carried out to identify the type (described above) of particle by the type of track left. The table 2 and 3 shows results of the scanning. The total viewing area was 83 mm^2 with a depth of NTE layer of 70 μm. In the scanned NTE volume, 36 inelastic interactions of hadrons on nuclei from the composition of the NTE matter were found. The main criterion for selecting events during viewing was that the vertex of the event should be explicitly observed in the bulk of the emulsion. This criterion is associated with the presence of background events generated in the glass base (2 mm in thickness) of the NTE plate. The events found can be divided into 3 groups of events according to the number of observed particle tracks: interaction on hydrogen H, on the group of light nuclei - CNO, and on heavy nuclei - AgBr. The impact of events on light nuclei is 97.2%, on heavy ones - 2.8%. It should be noted that the contribution of the complete destruction of heavy nuclei is very small. For comparison, in the works [2] in the interactions of protons with energies of 4.5 6.2 and 22 GeV in NTE layers, the contributions of interactions with heavy nuclei were 0.5%, 2.2% and 3.2%, respectively. In sorted events, one can estimate the number of the produced ***g*** and ***s***-particles. The estimated average number of b, g and s-particles depending on the number of ***h***-particles are presented in Table 4.

№ Plate	Viewed squares (mm^2)	3b	4b	5b	<3b	>5b	Number of events
4/10	17	6	3	3	4	-	16

Table 2. Topology of events found as a result of scanning plates № 4/10

№ Plate	3b	4b	5b	<3b	6b	Big stars	All stars ∑
4/7	54	28	25	181	4	12	570
7-П	61	74	78	75	32	205	572
Total	115	102	103	240	36	217	1142

Table 3. Topology of events found as a result of scanning plates №. 4/7 and 7-П irradiated in a hadron beam at the Hyperon facility.

	$\langle n_b \rangle$	$\langle n_g \rangle$	$\langle n_s \rangle$	$\langle N_h \rangle$	№ events
$N_h \leq 6$	3.3±0.9	2±0.5	3	3.1±0.9	16

Table 4 – average particle multiplicities for events with different numbers of strongly ionizing particles $N_h = n_b + n_g$ for plate № 4/10

For the complete analysis with more statistics of events, the viewing logs (see Appendix) of plates № 4/7 and 7-П are available. The matrices 1 – 4 shows the multiplicities of produced charged particles in all found events. The figures 4 and 5 show the multiplicity correlations of produced particles $\langle n_i \rangle = f(n_i)$. It’s clear to see that the relatively constant number of produced mesons (*s*-particles) with multiplicity *h*-particles.

N_h n_s	0	1	2	3	4	5
0	-	-	2	5	3	4
1	-	-	-	-	-	-
2	-	-	-	-	-	-
3	-	-	-	-	-	2

Matrix 1 – Matrix distribution by multiplicity n_s – N_h for plate 4/10

n_b n_g	0	1	2	3	4	5
0	-	-	2	5	2	3
1	-	-	-	-	1	-
2	-	-	1	1	-	-
3	-	-	1	-	-	2

Matrix 2 – Matrix distribution by multiplicity $n_b – n_g$ *for plate 4/10*

It is worth highlighting the observation of events with the observation of completely stopped *b*-particles, the range of which does not exceed 100 μm. Such particles are interpreted as slow alpha particles. Examples of such events are shown in Figure 4.

Within the framework of the collaboration of the Becquerel experiment, statistics of data on the interactions of relativistic muons with momentum 7 GeV/c was accumulated. A detailed analysis of the events by the formed charged particles has been carried out. Figure 5 shows a comparative analysis of the observed *b*, *g* and *s*-particles in the events of inelastic interaction between muons and hadrons on nuclei from the composition of NTE matter.

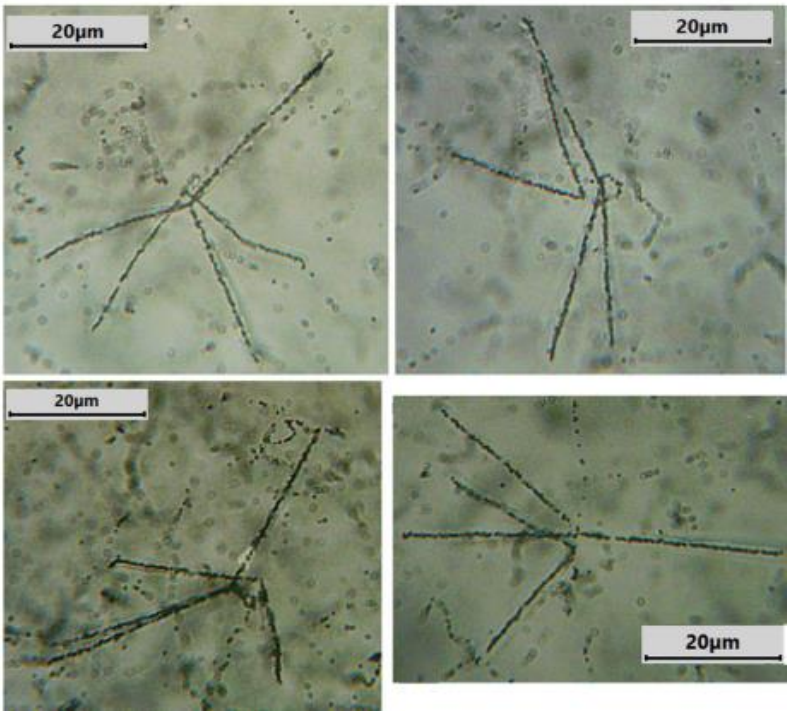

Fig. 4. Images of events with the b-particle tracks produced in the interaction of hadrons with nuclei from the composition of a nuclear emulsion. First two photos can be described as nα-fragmentation of ^{12}C *and* ^{16}O *nuclei, respectively.*

After studying the obtained results and drawing conclusions from them, a histogram was constructed based on the results for each particle, i.e., black, gray and shower particles The figure 7 shows the histogram results.

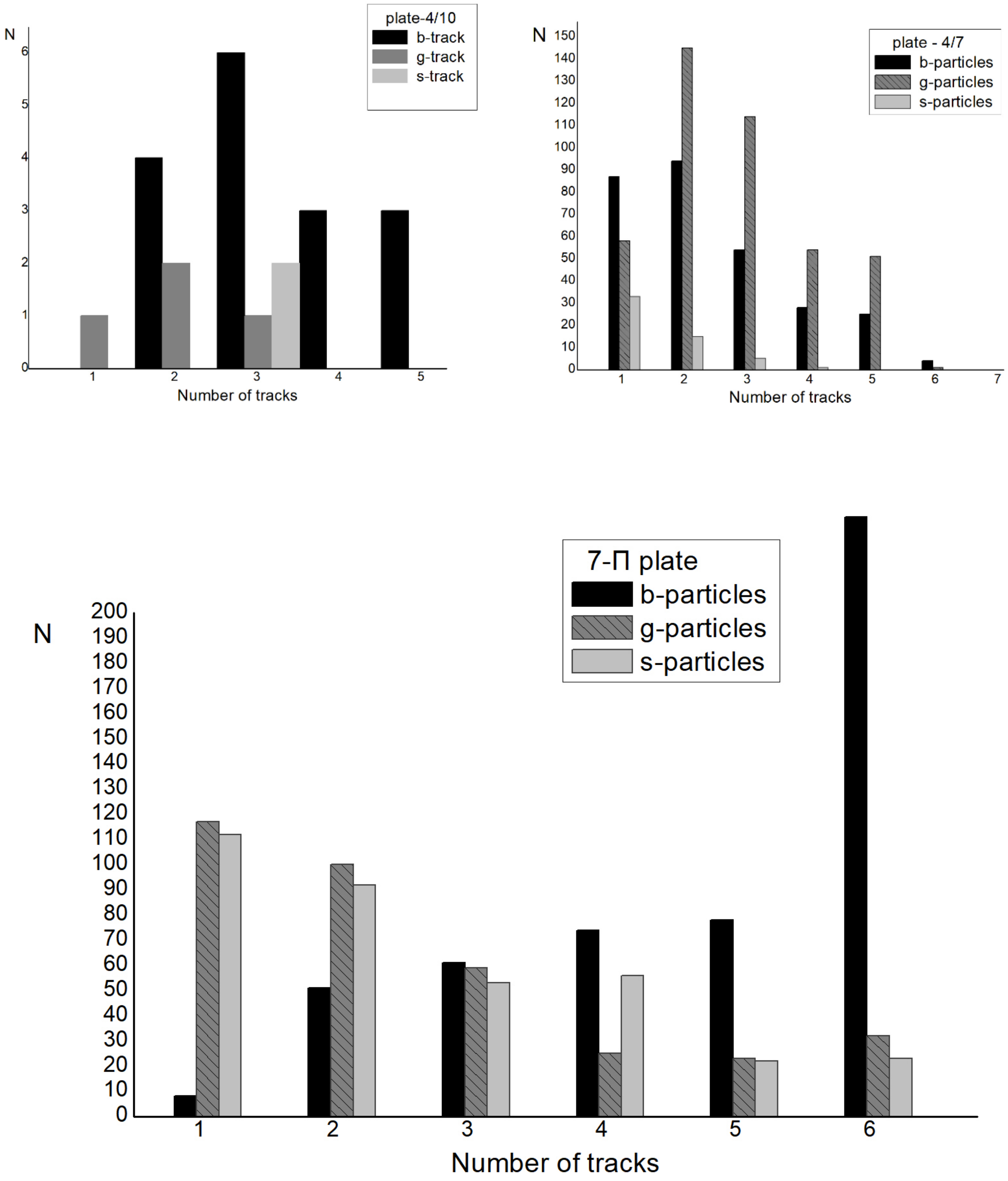

Fig. 7. Comparative distributions by multiplicities of produced particles in hadrons interaction on nuclei from NTE composition.

Measuring the ranges of short-range tracks of b-particles

The measurement was carried out on a KSM-1 microscope, which is much different from the BMI-9 microscope, but is considered to be much more accurate for measuring the true range of particles. This microscope had two types of objective

15x and 55x, 7 power handles and other details. With the help of this microscope, you can see the tracks on the Z-layers much more accurately and easily. This mainstream microscope is specialized for measuring the range, angles and inclination of particles. We mainly measured the range of 3b and 4b particles on a 4/10 plate, which is less than or equal to 80 µm. Here, the main fragmentation of the ^{16}O and ^{12}C nuclei into helium nuclei occurs. e difficult side of the measurements was to replace the two lenses, one had to be very careful the thickness of the emulsions was only 100µm and the glass was also very thin. Some of the events were located close to the glass and this complicated the work. After obtaining the coordinates for the beginning of events and the end of the tracks, it was possible to calculate the true range of the b-particle

The measurement procedure is as follows:

1) Prepare the microscope for operating mode;
2) Put the plate under study;
3) Install the 15-fold lens, which with the help of it we are looking for the desired event;
3) After finding the desired event, we change the lens to 55 multiples and begin to measure the true particle track;
4) Initially, we will measure the coordinates of the surface of the emulsions and the beginning of the glass, which will then find the typical coefficient;
5) After that, we measure the X, Y, Z coordinate of the beginning of the events and the end of the track;
6) Using the data obtained, we measure the true length of the track, below is the formula for calculating:

$$R = \sqrt{(x - x_0)^2 + (y - y_0)^2 + \left[\left(\frac{T_{ini}}{z_{se} - z_{bg}}\right)(z - z_0)\right]^2}$$

R-particle's true range;

x_0, y_0, z_0- coordinate of the event vertex;

x, y, z-coordinates of the end of the tracks;

z_{se} and z_{bg} - coordinates of the surface of the emulsions and the beginning of the glass;

T_{ini} - initial layer thickness.

It is worth noting that the effective viewing thickness differs from the original thickness due to shrinkage of the emulsion layer during chemical development. Ratio of NTE thickness before development to thickness after development is called the shrinkage factor. Typical factor equal to 1.3-1.6.

The value of the average range of alpha particles in a nuclear photographic emulsion in the events of fragmentation of C12 nuclei into 3a particles under the action of hadrons is 31,08273063±7,52604239 µm. In events O16->4a 27,65147998±6,895712814 µm.

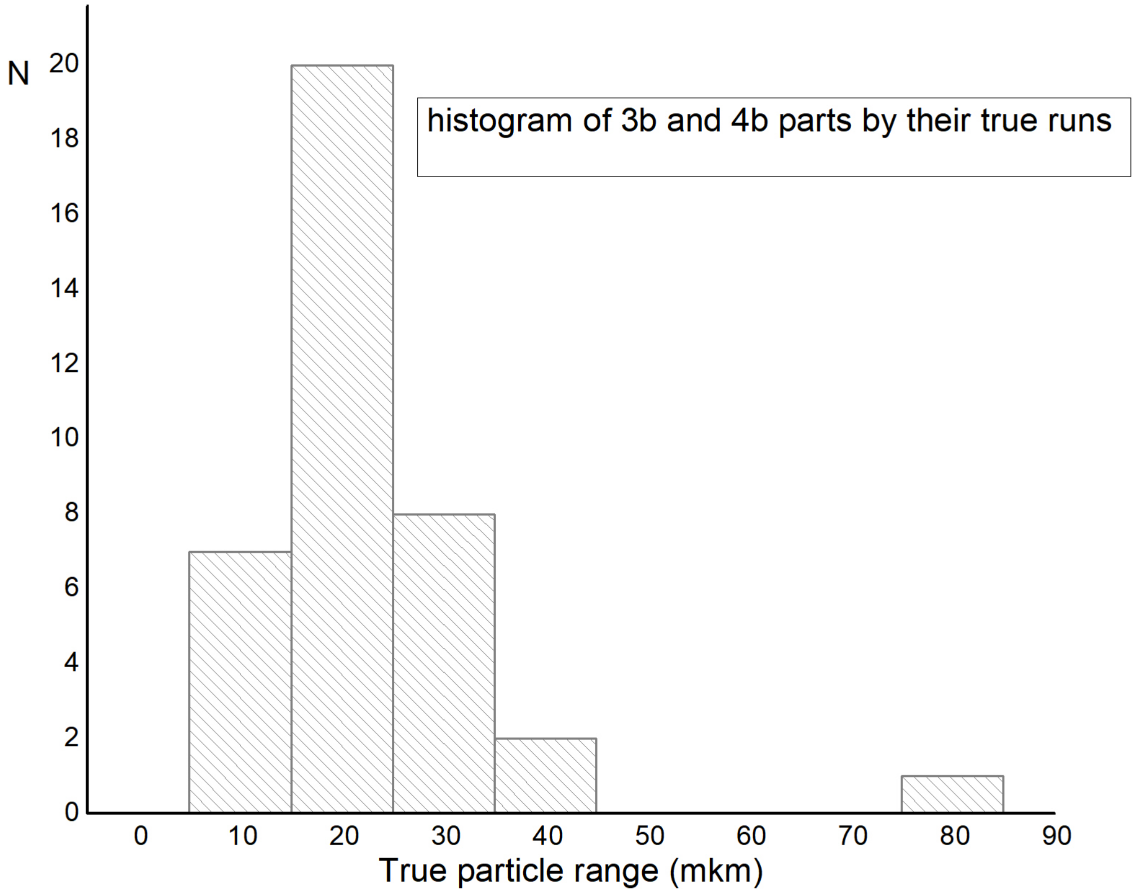

Fig. 8 Range distribution of alpha particles in ^{12}C *and* ^{16}O *nuclear fragmentation events.*

Fig. 9. Laboratory for measuring the ranges of short-range tracks of b-particles with KSM-1 optical microscope.

Conclusion

During this 2 month I have mastered the technique of nuclear photographic emulsions and mastered the technique of scanning emulsion layers on optical microscopes MBI-9 and KSM-1. Learned to analyze hadron-nucleus interactions. The task of practice included the search for nuclear events, the differentiation of the observed tracks of charged particles. The review material received was added to the existing one. The accumulated statistics of events is a continuation of studies of the Becquerel experiment on the study of hadron-nucleus interaction, in particular, α-partial fragmentation of ^{12}C and ^{16}O nuclei. By the end of this practice I have mastered how to measure the true range of a particle. The main one measured the true range of the α-particle, which is the fragmentation of the ^{12}C and ^{16}O nuclei. And I made a histogram based on these data. I concluded from these data that under these conditions the true range of α-particles will turn out to be large with a probability in the range from 10 microns to 40 microns. At the beginning, the thickness of the emulsions was 100 μm, after chemical treatment and after drying, the thickness of the emulsions decreased. When measuring, it turned out that the thickness of the emulsions became much smaller. Approximately 70-90 microns, and different points changed differently. But this deformation occurs only along the Z axis, and on the XY area the tracks did not change due to the gluing of emulsions onto thin glass. All these factors were taken into account when calculating the true particle ranges

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