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

FINAL REPORT ON THE START PROGRAMME

Application of film track detectors for registration of charged particles

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1. Introduction

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 projectile nucleus. This ensures complete observability of all possible decays of relativistic nuclei into charged fragments. In addition, the emulsion method makes it possible to identify the type of 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 nuclei is also necessary for solving a number of problems in nuclear astrophysics and cosmic ray physics, as well as medicine. One of the purpose of this work is to accumulate statistics of alpha fragmentation of NTE nuclei induced by relativistic hadrons in nuclear track emulsion and provide measurements of produced alpha-particle tracks in those reactions.

The method of using the solid-state nuclear track detectors (SSNTDs) is one of the methods of ion beam profilometry, which is based on application of solid-state materials able to detect tracks of nuclear fragments passing through them. When ions interact with solid-state material, tracks are formed whose location and shape depend on the energy, type of ions and angle of incidence. By measuring the parameters of the tracks on the surface of a solid-state detector, it is possible to obtain information about the distribution of ion charges in a monoenergetic beam [1[1],2[2]]. The SSNTD method has some advantages over

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[1] G. De Lellis et al., “Measurement of the fragmentation of Carbon nuclei used in hadron-therapy”, Nuclear Physics A Volume 853, Issue 1, 1 March 2011, Pages 124-134

[2] Web-page of BECQUEREL experiment: http://becquerel.jinr.ru

other profilometry methods, such as high spatial resolution, absence of the detector dead time, and low cost. This justifies an opportunity of using SSNTDs to monitor the density, position and total intensity of the heavy relativistic ion beam. This study was carried out in the framework of exposure in the beam of $_{124}Xe^{+(26\text{-}28)}$, accelerated for the first time at the JINR linear accelerator complex in December 2022. Thus, It was proposed to analyze exposed CR39 samples using a full scan method on an automated microscope Olympus BX63, followed by image analysis to count the formed Xe tracks (so called “hole”).

2. Experiment BECQUEREL

This work was carried out within the physical programme of the BECQUEREL experiment [2] at the Nuclotron/NICA accelerator complex located at Veksler and Baldin Laboratory of High Energy Physics. In the BECQUEREL experiment is studied cluster structure of light stable and radioactive isotopes that clearly appears in relativistic dissociation. The ability to form and extract beams of relativistic nuclei is provided by the accelerator complex of the Nuclotron/NICA laboratory. Known and new structural features of the isotopes $_{7,9}Be$, $_{8,10,11}B$, $_{10,11}C$, and $_{12,14}N$ are revealed in the dissociation channel probabilities. The identification of the relativistic decays of $_{8}Be$ and 9B pointed out the possibility to search for triples of α particles in the Hoyle state (HS) in the relativistic dissociation.

3. Analysis of alpha fragmentation of nuclei in NTE

Analysis of the alpha fragmentation of nuclei from NTE composition is provided by a set of experimental nuclear track emulsion (NTE) samples have been exposed at a beam of positively charged hadrons (beam composition: π – 60%, p – 35%, kaon – 5%) with momentum of 7 GeV/c. The exposure of the NTE was carried out in the area of the Hyperon-M experimental installation, located on channel 18 of the U-70 accelerator complex [3[3]]. The NTE samples were exposed during the spring session in 2018. The total flux of hadrons passing through the NTE stacks was $3 \cdot 10^{6}$ particles. After exposure the NTE plates were subjected to chemical development. The development procedure

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[3] Evdokimov S.V., Izucheev V.I., Kondratyuk E.S. and others. // 2021. T. 113. Rel. 5. C. 291.

mainly depends on the thickness of the NTE layer, so the development process included 2 stages: development of layers of 100 and 200 μm, respectively. During unpacking, most of the records were found to be defective, consisting in the peeling of the emulsion layer from the base - glass. The preliminary reason is non-compliance with the technological process of drying nuclear energy layers at the production stage. The sample of the developed NTE plate is shown in Fig. 1. For this work a plate was taken with more comfortable scanning under a microscope (without big damages of emulsion layer, more or less light due to overexposure).

Fig. 1. NTE plate after chemical development. The typical size of NTE plate is 9x12 cm2 with around 100 mkm thickness of sensitive emulsion layer.

The scanning of the NTE plate was carried out by means of the optical microscope of MBI-9 using a lens with 20x magnification and 15x eyepieces that gives the total optical magnification 300x (Fig. 2). The scanning method of the NTE plate was selected as scanning in strips 1 mm wide. This method allows for a full search for nuclear events over the entire area without loss of information. To fix the vertex position of nuclear events in NTE during the development process a coordinate marking grid is specially applied to the surface of the emulsion layer. The view of the coordinate grid is shown on Fig.

2.

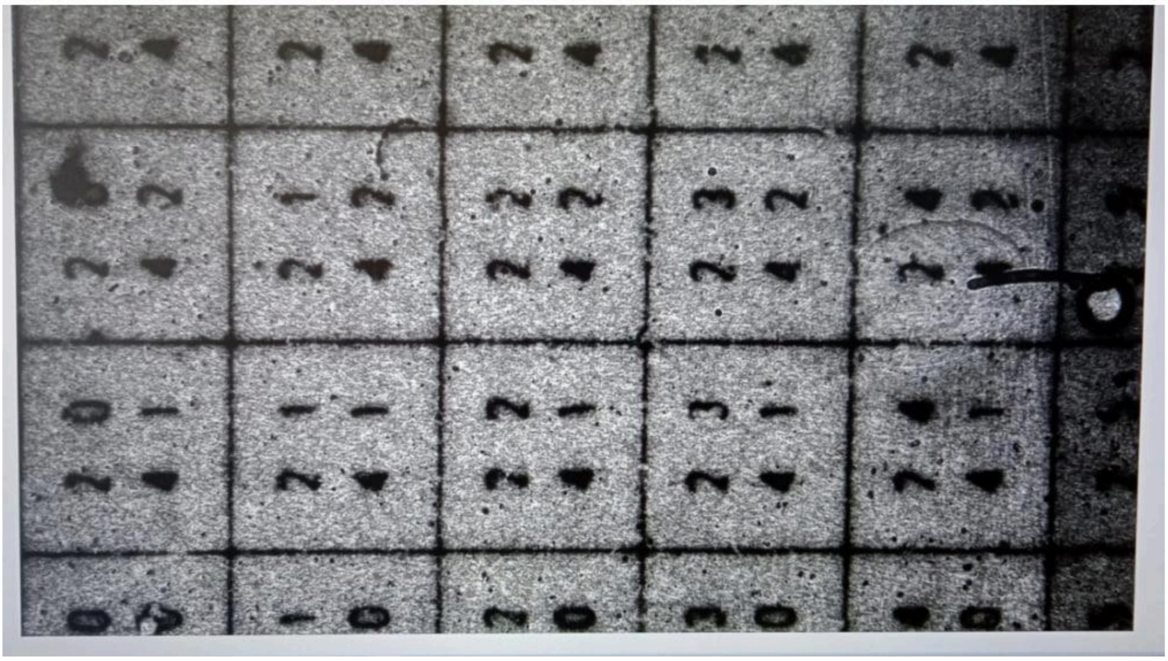

Fig. 2. Coordinate grid applied to the NTE surface. The size of one grid cell is 1x1 cm^2. Each cell has a pair of numbers corresponding to coordinates in the XY plane.

The side width of one square is 1 mm. At the beginning of viewing, the outermost square is selected, spaced from the edges of the plate at a distance of at least 1 cm. This condition is necessary to ensure comfortable viewing and the presence of edge defects on the plate. During my practice, I scanned ten strips of emulsion plate with a total area of 9 cm^2 with a layer thickness of 100 micrometers. In this area, 10 inelastic interactions of nuclei from the NTE composition with incident relativistic hadrons have been found. The precise identification of the interacting target nucleus in an emulsion experiment is not an easy task, since the medium has a multicomponent atomic composition (H, CNO and AgBr groups of nuclei). However, in the nuclear energy technique the following classification of charged particles is adopted, depending on their relative ionization I/I_0, range L and velocity β [4[4]]:

1. "black" (b-particles) - represent traces of fragments of the target nucleus with relative ionization I/I0 ≥ 7.0 and β < 0.23, where I0 is the ionization on the tracks of relativistic particles with charge Z = 1. However, in

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[4] M.I. Adamovich and others., «Multiple particle generation in the interaction of pions and protons with nucleons and nuclei in the energy domain 20-200 GeV» The works of FIAN vol.108 M., «Science» (1979), 65-149.

practical terms, b -particles are often conveniently identified by their path length in the nuclear energy volume - $L \leq 3$ mm;

2. “gray” (g - particles) - these are mainly protons knocked out from the target nucleus, with relative ionization $6.8 > I/I0 \geq 1.4$ and $\beta < 0.7$, with a residual path > 3 mm. This type of particle also includes a small admixture of π-mesons, depending on the initial interaction energy;

In this case, the combination of b and g particles is classified as a group of highly ionizing h particles.

3. “relativistic” (shower or s - particles) - this class of charged particles includes interacting protons of the incident nucleus and singly charged ($Z=1$) non-interacting fragments of the incident nucleus with relative ionization $I/I0 < 1.4$ and $\beta > 0.7$.

4. “fragments” (f - particles) - multiply charged fragments of an incident nucleus with a charge $Z \geq 2$. They are not included in the number of b- and g -particles, which they correspond to by the ionization they produce. Tracks of relativistic singly charged particles and fragments of a projectile nucleus with $Z=2$ are easily distinguishable under a microscope by the number of developed grains per unit track length.

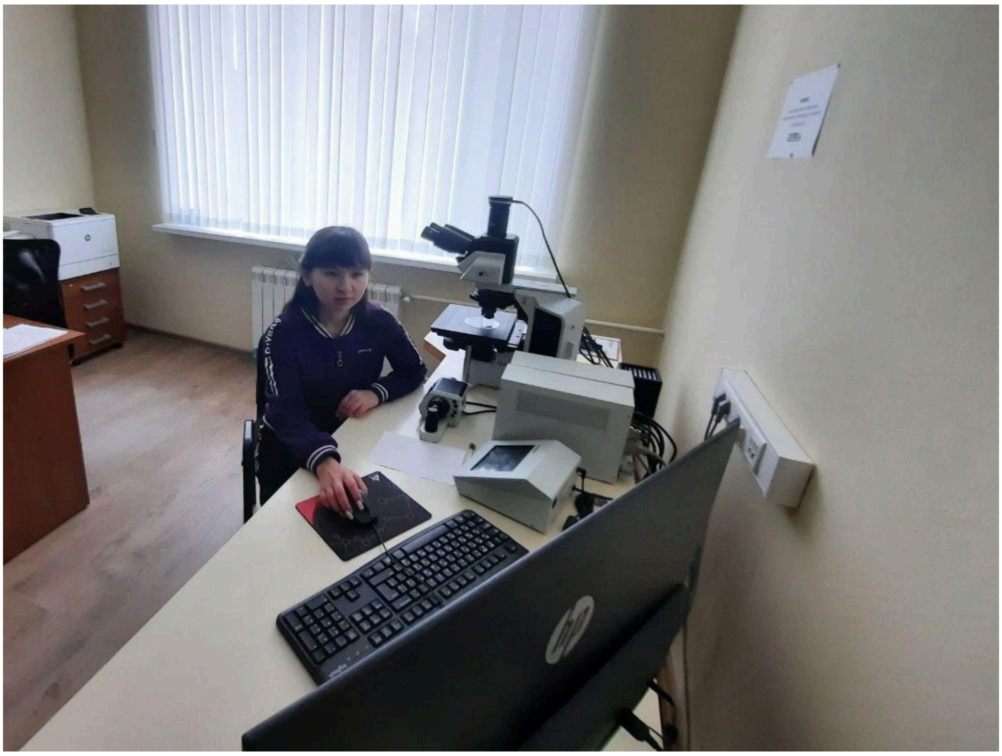

Fig. 3. Scanning emulsion layers and solid state detectors with Olympus BX63 optical microscope

According to its atomic composition, nuclear energy includes 3 groups: hydrogen H, a group of light nuclei CNO and a group of heavy nuclei AgBr (this group may also include other heavy components, depending on the type of nuclear element, but their relative weight contribution is not significant). Table 1 shows the component composition of standard nuclear energy under normal conditions.

Table 1. Elemental composition of nuclear energy [5[5]].

	G5 standart NE		
Relative humidity	0%	58%	84%
Density gram/cm^3	4.033	3.828	3.608
Ag (here and further 10^{22}atoms/cm^3)	1.092	1.013	0.929
Br	1.085	1.007	0.923
J	0.0062	0.0057	0.0052
H	2.83	3.20	3.57
C	1.498	1.390	1.274
N	0.343	0.318	0.291
O	0.705	0.938	1.190
S	0.0146	0.0135	0.0124

The focus of the search for inelastic interactions was only those events in which tracks of particles with path lengths of less than 100 μm are observed (b-particles). I have found 3 events that can be characterized as alpha

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[5] The study of elementary particles by the photographic method: пер. с англ. / Пауэл С., Фаулер П., Перкинс Д.Б - Москва: Издательство иностранной литературы, 1962. - 653 с.

fragmentation of the target nucleus (see Fig. 4) and this statistics has enriched the existing one.

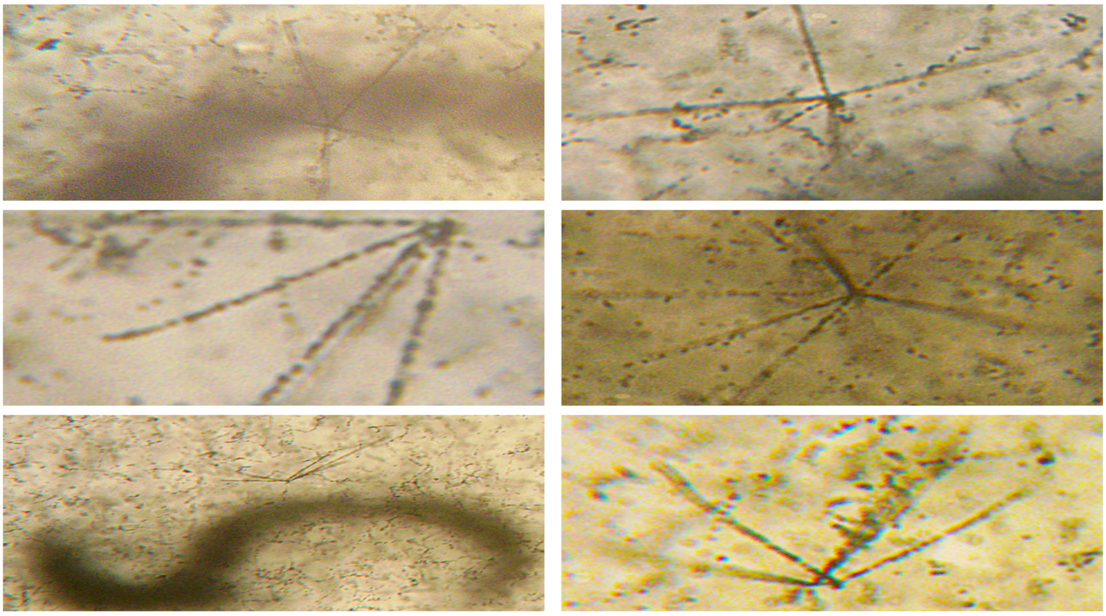


Fig. 4. Images of events with the formation of tracks of b-particles during the interaction of relativistic hadrons with nuclei from the composition of NTE.

After this, the track lengths of particles in the found events were measured using a KSM1 measuring microscope. The measurements were carried out using the standard coordinate method, in which the coordinates (x, y and z) of the vertex interaction and the three-dimensional coordinates of the stopping point of each b-particle track were measured. Then, real lengths of particles in NTE were calculated using the MathCad software package. It is worth noting that after chemical development, the NTE layer has a certain shrinkage coefficient, which must be taken into account when calculating the real particle length. In this way, the distribution of length in the events shown in Fig. 5 was obtained.

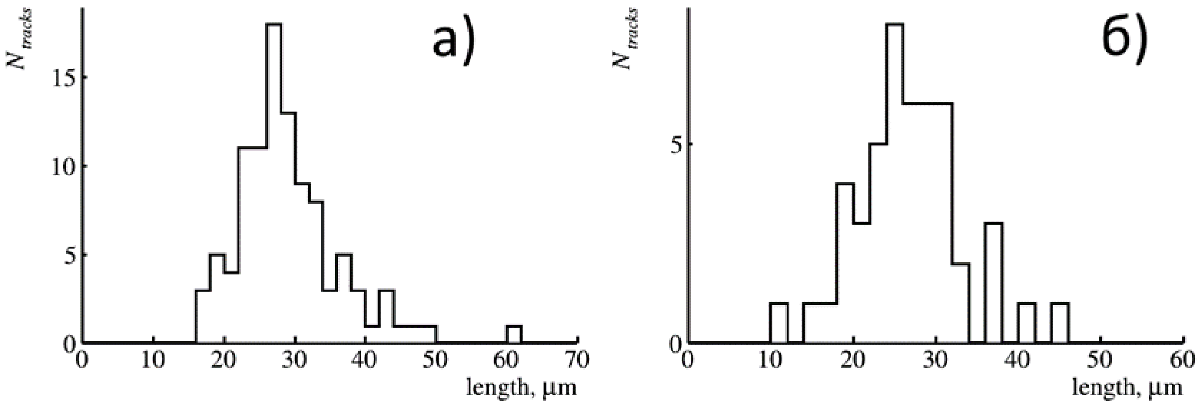


Fig. 5. Distribution over the measured real length in NTE of three (a) and four (b) b-particles in events of interaction of relativistic hadrons.

As you can see the average real length of the measured tracks in events with three b-particles is ⟨L⟩ = 25.9±1.5 μm and σ = 7.8±1.1 μm. And for events with 4b-particles, the average range is ⟨L⟩ = 28.1±3.4 μm at σ = 7.2±2.5.

4. Beam profilometry using SSSD CR39 method.

Irradiation of CR-39 detector was carried out on the experimental installation Baryonic Matter at Nucleotron (BM@N) in the 4th Commissioning Run at the NICA Complex. The energy of the $_{124}$Xe beam was 3.85 A GeV, and the expected loading of the detector was 5 spills of the order of 106 ions. The detector was located between the time-of-flight mRPC system and the zero degree calorimeter (Figure 3), while the surface normal of the CR-39 coincided with the beam direction.The investigated CR-39 detector was a 50x50 mm plate 1 mm thick initially. After irradiation, the CR-39 sample was etched in an aqueous solution of 6M NaOH. The system was in a thermostat maintaining the temperature equal to 85 °C with an accuracy of 0.1 °C. The etching time was 20 minutes. Scanning was carried out by means of a unique motorized microscope Olympus BX63 (Figure 5) using proprietary software Olympus cellSens which fulfills the acquisition of panoramic images while manual scanning or in automatic mode with focus maps

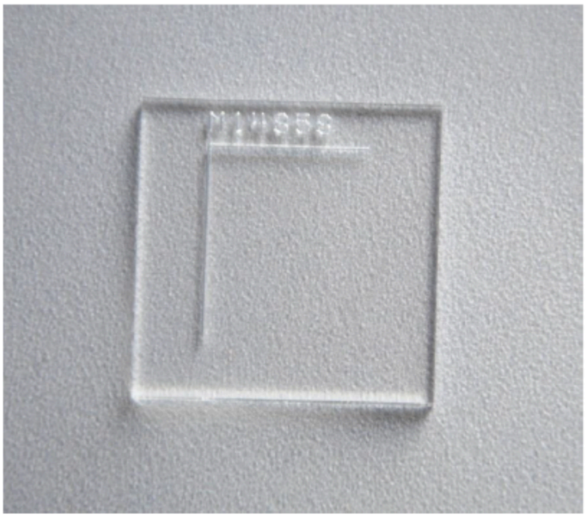


Fig. 6. Sample of solid state solid-state nuclear track detectors CR39 (Columbia Resin #39).

The tracks became visible by a chemical etching (acid or basic solution): during the etching, material is removed at Vt velocity along the track and isotropically at Vb velocity from the bulk material. Principle of the track detector: Vt (track etch rate) >Vb (bulk etch rate) The dimension and shape of the track depend on: • Energy of the impinging particle • Incidence angle • Etching procedure (etchant, temperature, duration). The use of nuclear photographic emulsions in the study of the interaction of high-energy particles with nuclei has played a significant role in the development of existing ideas about the mechanism of these interactions.Operation of the solid-state nuclear track detector is based on the fact that a heavy charged particle will cause extensive ionization of the material when it passes through a medium. For example, an alpha particle with energy of 6 MeV creates about 150,000 of ion pairs in cellulose nitrate. Since the range of a 6 MeV alpha particle in this material is only about 40 mm, that means on average 3700 ion pairs are created per micrometer, or 3–4 ion pairs per nanometer. An alpha particle ionizes almost all molecules close to its path. This primary ionizing process triggers a series of new chemical processes that result in the creation of free chemical radicals and other chemical species. Along the path of the alpha particle, a zone enriched with free chemical radicals and other chemical species is then created. This damaged zone is called a latent track. If a piece of material containing latent tracks is exposed to some chemically aggressive solution, chemical reactions would be more intensive along the latent tracks. Aqueous solutions of NaOH or KOH are the most frequently used chemical solutions in this regard. The overall effect is that the chemical solution etches the surface of the detector material, but with a faster rate in the damaged region. In this way, a “track” of the particle is formed, which may be seen under an optical microscope. This procedure is called “detector etching” or track visualization, and the effect itself is called the “track effect”. The track effect exists in many materials. It is particularly pronounced in materials with long molecules, e.g., cellulose nitrates or different polycarbonates, and such materials are the most convenient ones for application and detector manufacturing.The possibility of visual observation of single acts of nuclear interaction in the form of so-called "stars" in a nuclear emulsion allows us to obtain a large number of direct data on the characteristics of nuclear reactions: on the number and nature of charged particles formed during the splitting of the nucleus, on their angular and energy distributions, on the energy and momentum transmitted to the nucleus during a collision.The average density of the emulsion is about 3.5-4 g / cm^3, with a residual humidity of about 2.5%. Nuclear photographic emulsions are used to register and analyze traces of charged particles of almost any energy. By measuring the characteristics of these traces, it is possible to identify the particle and determine its kinematic characteristics.The effectiveness of the PolyAllyl Diglycol Carbonate (PADC) etched solid state nuclear track detector (SSNTD), commonly known as CR-39, as a muon detector is assessed. CR-39 is successfully used to detect higher rest mass particles such as neutrons and protons, and is, for example, widely used in neutron dosimetry applications. CR-39 is generally accepted as being less suitable to detect lower rest mass particles such as muons, and especially electrons, due mostly to their reduced momenta and consequently, reduced stopping power. However, there has been some evidence that CR-39 may have application in the detection of cosmic ray muons. Monte Carlo simulations indicate that CR-39 can detect muons with energies up to 2.8 MeV. Experimental data to demonstrate the ability of CR-39 to detect muons was acquired using the MuSR spectrometer station at the ISIS Neutron and Muon Source. Pits deposited in CR-39 generated by positive muons from the beamline have been characterized and compared with pits deposited by protons and neutrons from other sources. The extent to which a CR-39 SSNTD can discriminate muons from particles with different momenta and rest masses is discussed

During irradiation, the angle of incidence of Xe ions was close to perpendicular, which resulted in forming the tracks which approximately had a circular shape. The track images obtained using 4x objective are shown in Figures 7

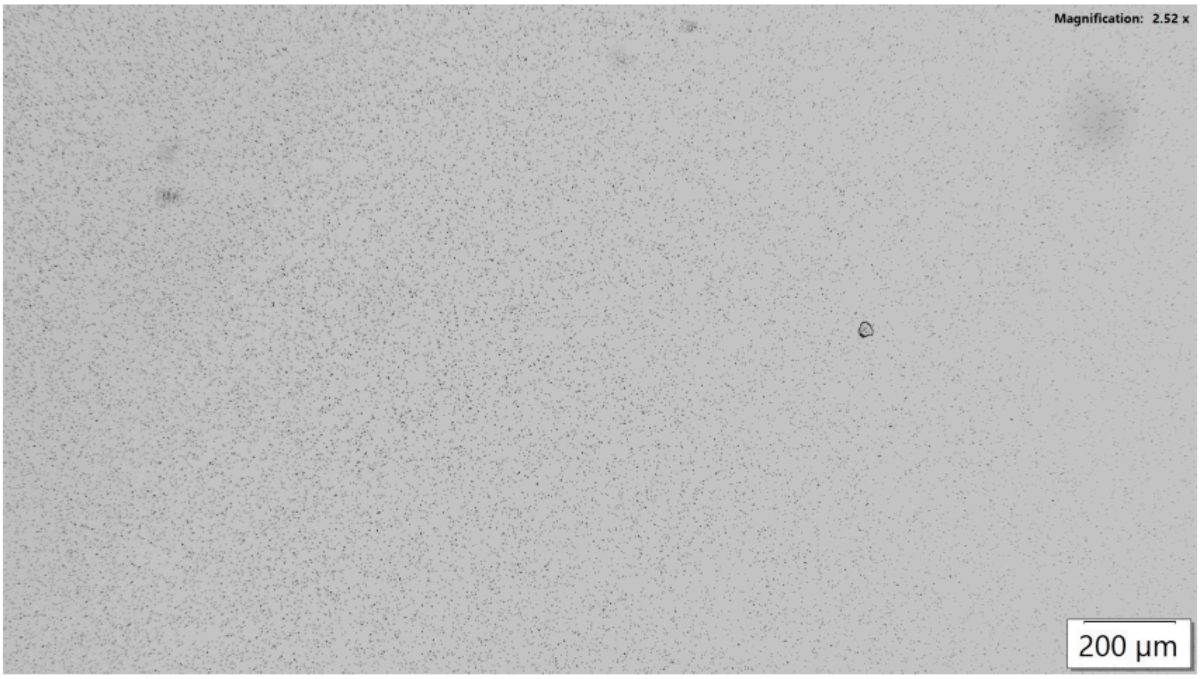
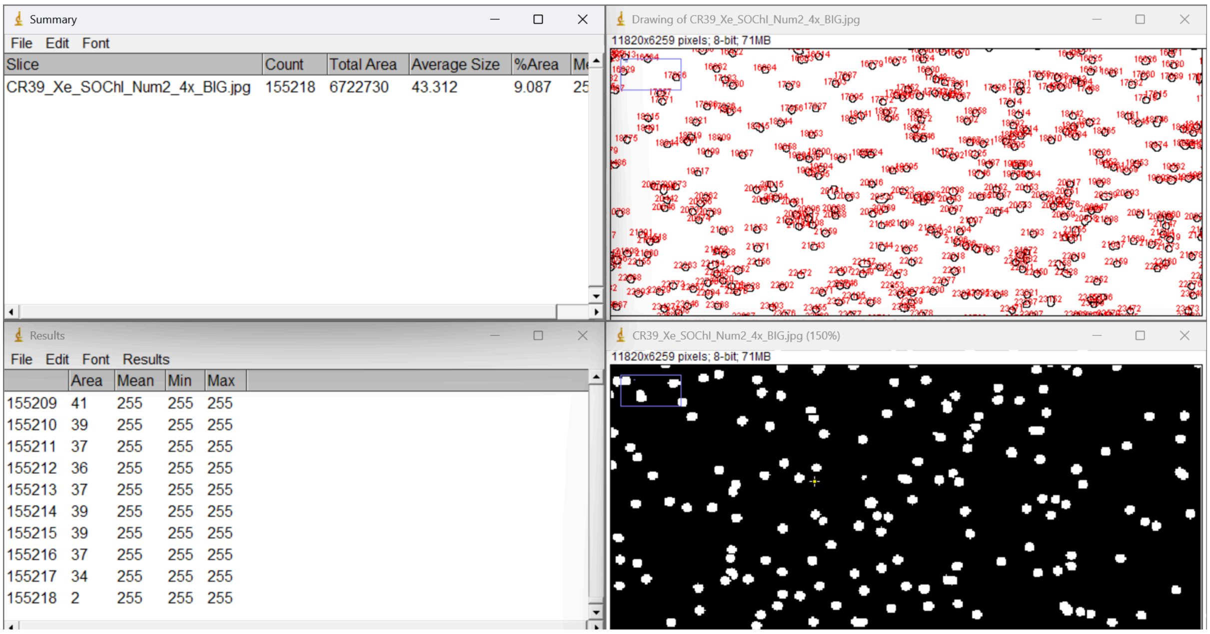


Figure 7: Photo of CR-39 SSNTD at the intermediate beam density, taken with the Olympus BX63 microscope using a 4x objective

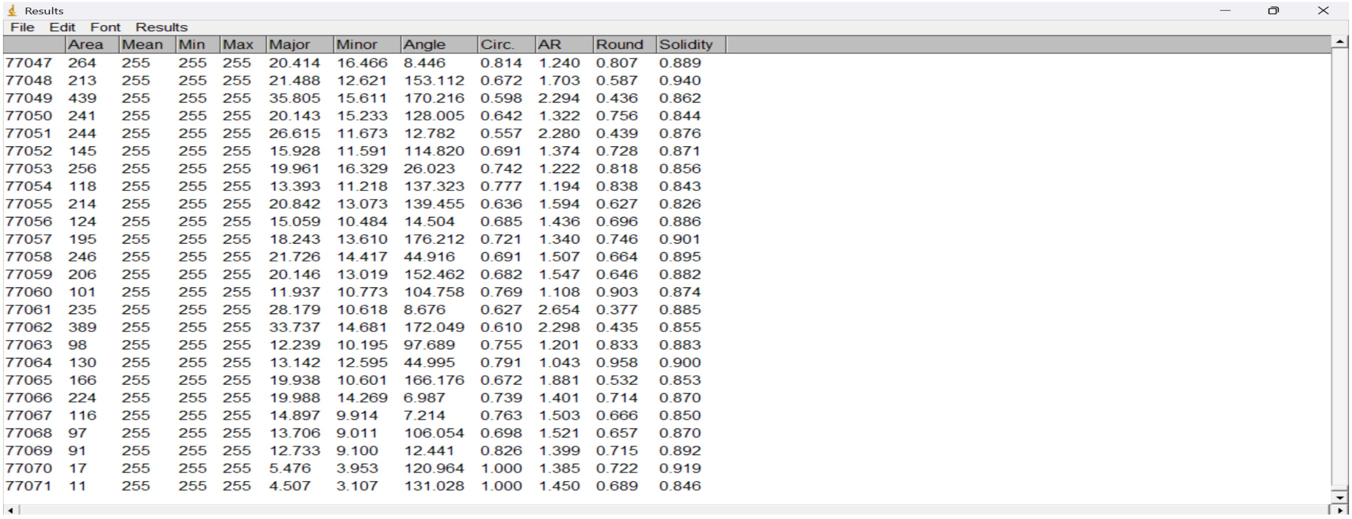
Method of tracks analysis .Procedure with the ImageJ



Slice	Count	Total Area	Average Size	%Area	Me
CR39_Xe_SOChl_Num2_4x_BIG.jpg	155218	6722730	43.312	9.087	25

	Area	Mean	Min	Max
155209	41	255	255	255
155210	39	255	255	255
155211	37	255	255	255
155212	36	255	255	255
155213	37	255	255	255
155214	39	255	255	255
155215	39	255	255	255
155216	37	255	255	255
155217	34	255	255	255
155218	2	255	255	255

Figure 8.Analysis of some characteristics of tracks using ImageJ software



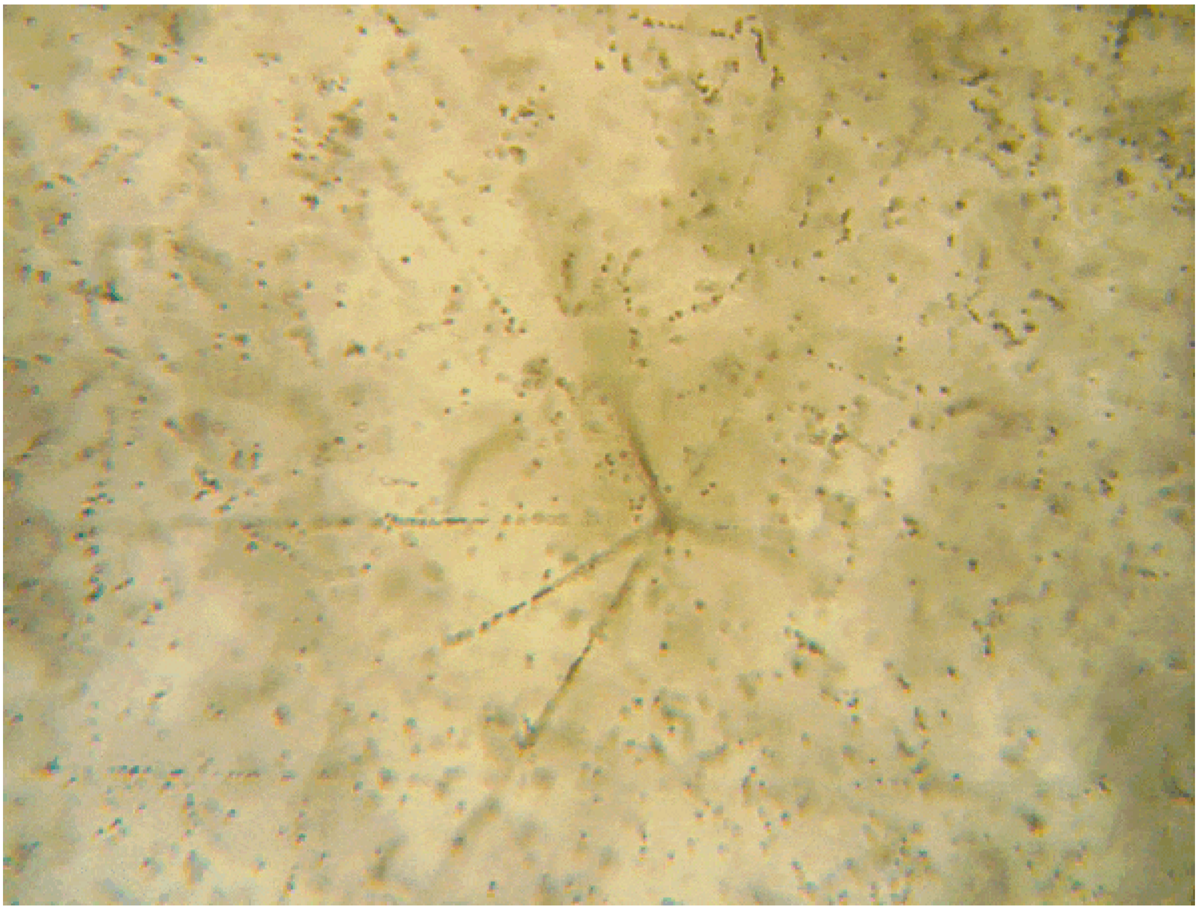
	Area	Mean	Min	Max	Major	Minor	Angle	Circ.	AR	Round	Solidity
77047	264	255	255	255	20.414	16.466	8.446	0.814	1.240	0.807	0.889
77048	213	255	255	255	21.488	12.621	153.112	0.672	1.703	0.587	0.940
77049	439	255	255	255	35.805	15.611	170.216	0.598	2.294	0.436	0.862
77050	241	255	255	255	20.143	15.233	128.005	0.642	1.322	0.756	0.844
77051	244	255	255	255	26.615	11.673	12.782	0.557	2.280	0.439	0.876
77052	145	255	255	255	15.928	11.591	114.820	0.691	1.374	0.728	0.871
77053	256	255	255	255	19.961	16.329	26.023	0.742	1.222	0.818	0.856
77054	118	255	255	255	13.393	11.218	137.323	0.777	1.194	0.838	0.843
77055	214	255	255	255	20.842	13.073	139.455	0.636	1.594	0.627	0.826
77056	124	255	255	255	15.059	10.484	14.504	0.685	1.436	0.696	0.886
77057	195	255	255	255	18.243	13.610	176.212	0.721	1.340	0.746	0.901
77058	246	255	255	255	21.726	14.417	44.916	0.691	1.507	0.664	0.895
77059	206	255	255	255	20.146	13.019	152.462	0.682	1.547	0.646	0.882
77060	101	255	255	255	11.937	10.773	104.758	0.769	1.108	0.903	0.874
77061	235	255	255	255	28.179	10.618	8.676	0.627	2.654	0.377	0.885
77062	389	255	255	255	33.737	14.681	172.049	0.610	2.298	0.435	0.855
77063	98	255	255	255	12.239	10.195	97.689	0.755	1.201	0.833	0.883
77064	130	255	255	255	13.142	12.595	44.995	0.791	1.043	0.958	0.900
77065	166	255	255	255	19.938	10.601	166.176	0.672	1.881	0.532	0.853
77066	224	255	255	255	19.988	14.269	6.987	0.739	1.401	0.714	0.870
77067	116	255	255	255	14.897	9.914	7.214	0.763	1.503	0.666	0.850
77068	97	255	255	255	13.706	9.011	106.054	0.698	1.521	0.657	0.870
77069	91	255	255	255	12.733	9.100	12.441	0.826	1.399	0.715	0.892
77070	17	255	255	255	5.476	3.953	120.964	1.000	1.385	0.722	0.919
77071	11	255	255	255	4.507	3.107	131.028	1.000	1.450	0.689	0.846

5. Experiments 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 MBI9 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. During the internship for the analysis of irradiation in a hadron beam at the Hyperon facility in 2018, 1 plate with a photosensitive layer area of 9x12 cm2 and a thickness of 100 microns was selected (figure 3). The table 2 shows the scan results. The total viewing area was 70 mm2 with a depth of field of 70 µm. It is worth noting that the effective viewing thickness differs from the original thickness due to shrinkage of the emulsion layer during chemical development. In the examined volume, 36 inelastic interactions of hadrons on nuclei from the composition of the nuclear emulsion were found

The area of the photosensitive part of the nuclear photographic emulsion plates is 9x12 cm2 , and the thickness is 100 µm (figure 2). For ease of viewing during development, a coordinate marking grid is applied to the surface of the emulsion in a special way. 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 (Figure 8)

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



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 . 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, αpartial fragmentation of NTE 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 ^{1}O nuclei. And I made a histogram based on this 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 micrometers to 40 micrometers. 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 range

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