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Final report on the student program

The method of nuclear photoemulsion for the study of multiple fragmentation of relativistic nuclei

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Introduction

Detailed study of the fragmentation phenomenon of relativistic projectile nuclei has important advantages over classical experiments on the splitting of target nuclei. In particular, the confident identification of fragmentation products makes it possible to study the nuclear structure under conditions of very small energy-momentum transfers. Knowledge of the fragmentation characteristics of relativistic nuclei is also necessary to solve a number of problems of nuclear astrophysics and cosmic ray physics.

The method of nuclear photoemulsions, which has unique capabilities, plays a significant role in the study of interactions at high energies. Due to the best spatial resolution (0.5 microns), angular resolution for tracks of relativistic fragments up to 10^{-5} rad can be obtained in the nuclear emulsion, depending on the primary momentum. This ensures complete observability of all possible decays of relativistic nuclei into charged fragments. In addition, the emulsion technique makes it possible to measure momenta 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 relativistic fragmentation processes.

I. Method of nuclear photoemulsion

I.1. General characteristics of nuclear photoemulsion

Nuclear emulsions are highly concentrated and highly dispersed silver bromide emulsions. The concentration of AgBr, which is in the form of almost spherical microcrystals, in most currently manufactured emulsions is about 83% by weight. Gelatin with a plasticizer is most widely used as the medium in which AgBr microcrystals are distributed. The average sizes of silver bromide microcrystals for most nuclear emulsions are in the range of 0.12-0.30 microns, the emulsions of NIKFI, Ilford, Kodak, Agfa, Eastman and others.

The specific density of all emulsions with a normal composition is in the range of 3.8-40 g/cm^3.

Nuclear emulsions are made either on a glass substrate with an emulsion layer thickness of 50 to 400 microns, or without a substrate with a layer thickness of 400-600 microns. The latter are mainly intended for assembling emulsion chambers.

The analysis of the elementary composition of nuclear emulsions shows that the emulsion mainly contains three groups of atoms far apart in atomic weight: light - H, medium - C, N, O and heavy - Ag, Br with a very small number of S, I, Au atoms. In terms of hydrogen concentration, nuclear track emission is similar to a liquid hydrogen target. Thus, the diversity of composition makes it possible to study a whole class of nuclear interactions in a unified approach.

The main components of the nuclear emulsion are:

- Halide silver is mainly bromide, having a density of 6.47 g/cm3;
- Gelatin and plasticizer (e.g. glycerin);
- Water.

Halide silver is in the emulsion in the form of microcrystals (or "grains") of cubic or almost spherical shape, depending on the method of preparation.

Gelatin and plasticizer contain the following elements: carbon, nitrogen, oxygen, hydrogen and sulfur. Gelatin is a complex substance, as a result of which there is inevitably a slight difference in the chemical composition of gelatin supplied by different manufacturers.

Glycerin is injected into the emulsion as a plasticizing agent. It reduces the fragility of the emulsion and promotes the appearance of plastic deformations when stresses occur in the layer. The latter is especially important in cases where the plates must be exposed in a vacuum, since in such conditions the emulsion without a plasticizer often breaks away from the glass. The adhesion between the emulsion and the glass is so great that the latter is often destroyed by the stresses that appear when the emulsion dries, and flakes of glass that firmly adhere to the emulsion break out of the plates.

According to their photographic (nuclear-sensitometric) characteristics, all nuclear emulsions are divided into three main types.

- Emulsions of low sensitivity designed for the registration of highly ionizing particles with energy losses ≥ 50 keV per 1 micron of mileage (fission fragments, multicharged ions, slow α-particles);
- Medium-sensitivity emulsions capable of detecting traces of particles with ionization ≥ 2 keV per 1 micron of path (protons with an energy of 50-100 MeV);
- Emulsions of high sensitivity, registering traces of particles with minimal ionization (0.55 keV per 1 micron).

The emulsions currently used to register traces of charged particles differ from conventional photoemulsions in two ways:

- The ratio of the amount of silver halide to gelatin in a nuclear emulsion is approximately eight times greater than in a conventional one;

- The thickness of the nuclear emulsion layer exceeds, as a rule, 10-100 times the thickness of an ordinary emulsion. In addition, in modern conditions, nuclear emulsions are often used in the form of separate layers devoid of a glass substrate.

One of the main nuclear photoemulsions used is the BR-2 type emulsion, which provides sensitivity up to relativistic single-charge particles and gives a minimum of ionization losses. The main characteristics of this emulsion are given in Table 1.

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 emulsion (composition of BR-2 nuclear photoemulsion; relative humidity 58%)

In addition to the main type of BR-2 emulsion, its modifications with a reduced grain size (fine-grained) and a reduced concentration of AgBr nuclei (diluted) have also been widely used in recent years. The addition of certain substances to the emulsion makes it selectively sensitive to certain nuclear reactions. (For example, the addition of ^{10}B makes the emulsion an extremely sensitive neutron detector). The choice of the type of emulsion depends on its intended application. The sensitivity of the emulsion should be large enough to provide the grain density necessary to register the trace of the particle. With excessive sensitivity, the density of the grains may be so large that individual grains will become indistinguishable and they cannot be counted.

The photoemulsion technique makes it possible to register all charged particles in the cleavage, as well as to determine the area responsible for their formation. The nuclear emulsion method is quite adequate for studying the global characteristics of the phenomenon of fragmentation of the projectile nucleus due to the very high spatial resolution, the observability of the collision act in the 4π geometry of the experiment, the comparative ease of measuring fragment charges and the possibility of registering very small excitations of the target nucleus, which is important for studying the correlation between the fragmentation products of the projectile and the target. These advantages of the photometode are the more noticeable the higher the primary energy of the collision. According to their atomic composition: hydrogen H (~4% of interactions), a group of light nuclei CNO (~26% of interactions) photoemulsions allow us to obtain the characteristics of nuclei far apart in atomic weight.

The technique of nuclear emulsions has always provided overview observations on the physics of the microcosm due to the high reliability of the observed events, excellent spatial resolution and the most complete observability of traces of charged particles. In a number of important cases, it allows you to measure momentum, identify particles. Therefore, it seems to be an effective way to study the processes of relativistic fragmentation due to the high resolution of emulsions and the possibility of observing reactions in full geometry. A particular advantage is the observation of neutron-deficient nuclei in emulsions, due to the more complete observability of reaction products.

The heyday of the use of emulsions occurred in the fifties, when pioneering results in elementary particle physics were obtained. First of all, the problem of obtaining thick layers of emulsion (600 microns), which allowed to obtain threedimensional images of events, was solved. And the high uniformity of the irradiated material has opened up the possibilities of spectrometry and particle identification.

A positive feature of studying the process of fragmentation of nuclei using an emulsion is that traces of particles in gelatin remain forever and the researcher can study them again and again, which cannot be done by machine method.

Also, not the least important positive feature of the emulsion is its cheapness. For the study of high-energy physics, the emulsion has a huge advantage in economic terms compared to other methods.

I.2 Image development

The most significant feature of the photographic process using silver halide emulsions is that when processing such emulsions with a special reducing solution ("developer"), those grains on which there were suitable "centers of manifestation" turn into particles of metallic silver. The physico-chemical processes associated with such a transformation turn out to be very complex and are the subject of numerous studies. Apparently, there are a significant number of competing mechanisms, each of which can be significantly modified by slightly changing the composition of the developing solutions. Silver can be deposited at the interface between the bromide crystal and the "sensitivity region" or at the boundary between this region and the solution. In the latter case, silver is released due to Ag^+ ions in solution, and such a process is strongly influenced by silver bromide solvents, such as, for example, halide compounds of alkali metals.

The structure and shape of the grains of the released silver also strongly depend on the specific conditions of development. These grains may consist of clusters of tiny microcrystals or of the same crystals, but interconnected in thin flat filaments. However, at the current stage of photomethod elaboration, such details - although they are of considerable interest – do not have any practical significance when registering traces, since the sizes of silver grains are on the order of the wavelength of visible light, as a result of which the nature of their structure has little effect on the image observed in the microscope.

It should be noted that silver halide salts play an extremely important role in photography precisely because of their ability to be exposed to development, since no other compound has such properties to a comparable extent. Many substances can undergo changes under the influence of light or other radiation, and the resulting changes may be relatively stable, but none of these substances has a sensitivity approaching that of silver bromide, and only a few of them have the ability to development.

After the development, the silver halide emulsion is placed in a second, so-called "fixing" bath, in which the unchanged halide grains are dissolved, after which only black particles of metallic silver remain in the gelatin. The combination of a very large number of such particles forms a visible black image – an ordinary photographic negative. In conclusion, the plate is washed and dried.

I.3 Method of nuclear photoemulsion

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.

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 essence of the method of nuclear photographic emulsions is as follows: a charged particle passing through a photoemulsion activates silver halide crystals on its way and makes them capable of development. After special treatment of the emulsion layers, traces of particles appear in them in the form of a chain of developed grains, clearly visible under the microscope. Physicists such as L.V. Mysovsky, A.P. Zhdanov, S. Powell, D. Parkins, P. Fowler played a significant role in the development of this technique.

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 sensitivity time of nuclear emulsions is practically determined by their exposure time, which can be on the order of several weeks. During this time, the nuclear emulsion registers all charged particles passing through it. Due to the high spatial resolution of the photo, the method is successfully used to determine the angles of separation of particles and nuclei formed as a result of nuclear interaction. In terms of the accuracy of measuring small angles, the method of nuclear emulsions has no equal. During conducting experiments on accelerators, the photometode does not require a large amount of accelerator operation time. Hardware costs are also relatively low. Among the numerous advantages of the method, however, there are a number of disadvantages.

The complexity of the composition of the photoemulsion substance does not allow us to unequivocally answer the question with which nucleus the interaction of the incoming particle occurred. It is eliminated by introducing additional elements and introducing criteria for selecting processed events. A significant disadvantage is the low speed of radiation treatment. And as a consequence, the need for a long time to set statistics. However, as a rule, this is compensated by the result obtained, thereby allowing the planning of electronic experiments.

The exact determination of the emulsion composition significantly affects the measurement accuracy, which can be achieved using a photometer and which is required for the accurate determination of the energy of a homogeneous group of particles by their average runs. For this reason, it would be highly desirable to know exactly the composition of the emulsion under real conditions of its irradiation.

One of the difficulties encountered in determining the chemical composition of emulsions is that gelatin can quickly exchange water with a gaseous or liquid medium in contact with it. So, for example, if you put a drop of immersion oil on the surface of the emulsion and leave it for a few minutes, and then wipe it off, you can notice the swelling of the gelatin surface area that was in contact with the oil. The described effect is explained by the absorption of a small amount of water contained in the oil; the resulting slight deformation of the surface quickly disappears as soon as the plate comes back into equilibrium with the surrounding atmosphere.

I.4 Mechanism of tracks formation

In the process of formation of traces of charged particles in the emulsion, the occurrence of δ-electrons (electrons knocked out of atoms during ionization and, in turn, capable of ionizing the atoms of the medium through which they move) plays a decisive role, in the presence of which an amount of energy can be released in a given grain that far exceeds the maximum value that would be possible if the energy losses of particles were evenly distributed along its path. On the other hand, the path of a δ-electron with an energy of less than 5 keV turns out to be so short, and its trajectory is so curved due to scattering, that when such an electron occurs inside the grain, it can stop without going beyond the latter. Thus, a much larger amount of energy will be released in individual grains, which can be spent on the formation of a hidden image. As a result of the described effect, it turns out that in almost all emulsions, grains will become capable of manifestation after passing through them a single particle, the specific ionization of which is close to minimal; however, for the formation of a trace sufficiently clearly distinguishable under a microscope, the number of such grains per unit of trajectory length should be quite large compared to the general "background".

Traces left by charged particles in a nuclear emulsion are formed as a result of energy transfer from a moving particle to the atoms of photosensitive grains. A charged particle moving in any material medium participates in a number of interactions with the fields of atoms and nuclei through which it passes; the emulsion retains the trace of each particle and thus makes visible the "record" of these interactions. The characteristics of the trace depend on the type of particle and its velocity. Since these characteristics can be measured, it becomes possible to identify the particle. In addition to nuclear reactions that may occur when a particle passes through the field of action of nuclear forces, a moving charged particle loses energy to excite or ionize atoms along its path.

I.5 Track classification

During analyzing data in photoemulsion experiments, the following classification of particles is used. All secondary charged particles are divided into three classes depending on the velocity β, which is determined by ionization or mileage:

s-particles (rainwater) are single-charged relativistic particles with a velocity $\beta > 0.7$ and relative ionization $J / J_0 < 1.4$, where J_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;

g-particles (gray) are fast fragments of the target nucleus with ionization $J / J_0 > 1.4$ and a range of more than 3 mm; these are mainly protons with energy $E_p > 26$ MeV;

b-particles (black) - slow fragments of the target core with a range of less than 3 mm;

h-particles are a group of all fragments of the target, including g- and b-particles (i.e. $N_h = N_b + N_g$).

In fact, tracks of single- and double-charged particles (relativistic and gray, respectively) are visually clearly distinguishable. Numerically, this can be confirmed by counting the manifested grains on a fixed unit of length. Figure 1 shows the corresponding grain number distributions for single- and double-charged particles.

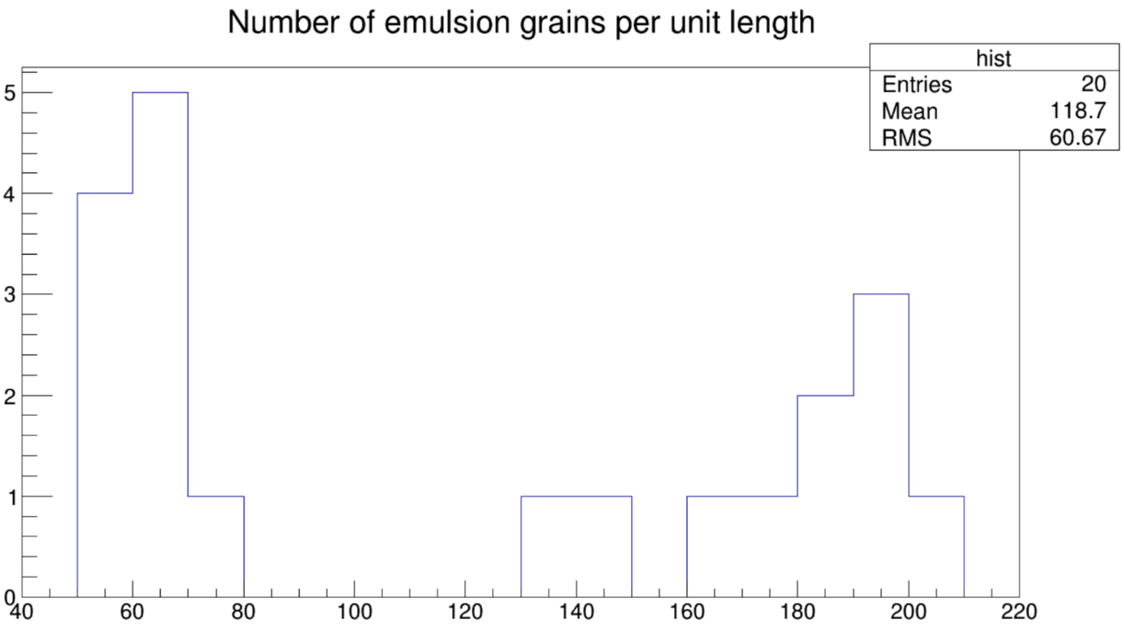

Figure 1 – Number of emulsion grains per unit length

The left area of the distribution corresponds to single–charged particles, the right - to double-charged particles.

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.

II. Experiment BECQUEREL at Accelerator Complex NUCLOTRON/NICA

II.1 The physical program of the experiment

The BECQUEREL (**Be**ryllium **C**lustering **Que**st in **Rel**ativistic Multifragmentation) 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 ^{8}Be nucleus is described as 2αBEC, and the ^{12}C(0^{+}_{2}) excitation or Hoyle state (HS) as 3αBEC. Decays $^{8}\mathrm{Be} \rightarrow 2\alpha$ and $^{12}\mathrm{C}(0^{+}_{2}) \rightarrow {}^{8}\mathrm{Be}\alpha$ 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 $^{16}\mathrm{O}(0^{+}_{6}) \rightarrow \alpha^{12}\mathrm{C}(0^{+}_{2})$ or $^{16}\mathrm{O}(0^{+}_{6}) \rightarrow 2^{8}\mathrm{Be}(0^{+}\ )$. 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.

The consideration of αBEC as an invariant phenomenon indicates possibility of its search in the relativistic fragmentation. A practical alternative is provided by NTE layers longitudinally exposed to relativistic nuclei. In them, the invariant mass of ensembles of He and H fragments can be determined from emission angles in the approximation of conservation of momentum per nucleon of a parent nucleus. Owing to extremely small energies and widths, the ^{8}Be and HS decays, as well as $^{9}\mathrm{B} \rightarrow {}^{8}\mathrm{Be}p$, are identified in fragmentation of light nuclei by an upper constraint on the invariant mass.

The main task of the forthcoming stage of the project is to clarify the relation between the appearance of ^{8}Be and HS and α-ensemble multiplicities and search on this basis for decays of the ^{16}O(0^+_6) state. In this regard, the BECQUEREL experiment aims to measure multiple channels of ^{84}Kr fragmentation below 1 GeV per nucleon. There are a sufficient number of NTE layers, transverse scanning of which on the motorized microscope Olympus BX63 makes it possible to achieve required statistics.

II.2 Dissociation of relativistic nuclei

The relativistic fragments are concentrated up to $\sin\theta_{fr} = p_{fr}/P_0$, where p_{fr} = 0.2 GeV/c is a quantity characterizing the Fermi momentum of nucleons in a projectile nucleus, and P_0 is its momentum per nucleon. Resolution is no worse than 10^{-3} rad at 1 mm base. The transverse momentum P_T of a fragment with a mass number A_{fr} is defined as $P_T \approx A_{fr}P_0 \sin\theta$ in the approximation that it conserves P_0. Tracks of relativistic fragments He and H are identified visually. Approximate conservation of a projectile charge by fragments is used to select few percent peripheral interactions. In fragmentation of NTE nuclei, b-particles (α-particles and protons with energies below 26 MeV), g-particles (protons with energies above 26 MeV), as well as s-particles (produced mesons) can be observed. The most peripheral interactions, called coherent dissociation or “white” stars, are not accompanied by fragmentation of the target nuclei and the production of mesons (s-particles).

Assignment of mass numbers to H and He fragment is possible the mean Coulomb scattering angle. The use of this time-consuming method is justified in special cases for a limited number of traces. In the case of dissociation of stable nuclei, it is sufficient to assume that He - ^{4}He and H - ^{1}H correspond. This simplification is especially true in the case of extremely narrow ^{8}Be and ^{9}B decays. The invariant mass of a system of relativistic fragments is defined as the sum of all products of 4-momentums $P_{i,k}$ of fragments $M^{*2} = \sum(P_i \cdot P_k)$. The subtraction of the mass of the initial nucleus or the sum of the masses of the fragments $Q = M^{*} - M$ is a matter of convenience of presentation. The components $P_{i,k}$ are determined in the fragment conservation approximation P_0. Reconstruction from the invariant mass of decays of relativistic unstable nuclei ^{8}Be and ^{9}B, mastered in the BECQUEREL experiment, confirmed this approximation validity. The most accurate measurements of angles are provided with KSM-1 microscopes (Carl Zeiss, Jena) using the coordinate method. The measurements are carried out in the Cartesian coordinate system. An NTE layer is rotated so that direction of an analyzed primary track coincides with the OX axis of a microscope stage with deviation of up to 0.1-0.2 mkm per 1 mm length. Then the OX axis of the system coincides with direction of projection of a primary track onto a layer plane, and the OY axis on it is perpendicular to a primary track. The OZ axis is perpendicular to a layer plane. For OX and OY, measurements are made by horizontal movement micro screws, and for OZ - by a depth-of-field micro screw. Coordinates are measured on primary and secondary tracks at lengths from 1 to 4 mm with a step of 100 mkm, by linear approximation of which angles are calculated.

II.3 The motorized microscope Olympus BX63

The project aims to intensify application of a proven approach based on automation of measurements provided by state-of-the-art microscopes. However, such microscopes are quite expensive and should be tools of intensive collective use. According to a request supported by the PAC for NP, at the end of 2021, delivery of the motorized microscope Olympus BX63 for the BECQUEREL experiment took place. Thus, prerequisites arise for accelerating proven 19 procedures for searching for and measuring interactions in NTE. In addition to increasing productivity, remote control and analysis is feasible on this microscope, which allowing involving experts in nuclear physics and programming in the project.

The motorized microscope makes it possible to export data and images to collaborating institutes and universities. It can be used for beam diagnostics by the methods NTE and solid-state track detectors, as well as for solving applied problems. Mastering the capabilities of this microscope will allow one to move on to solving problems of automatic search with recognition of characteristic images.

For the near future, the BECQUEREL experiment focuses on the analysis of exposure ^{84}Kr nuclei at 950 MeV per nucleon to study amplification and search for unknown unstable states. Acceleration of accumulation of statistics of events of multiple α-particle fragmentation is provided by transverse scanning of the NTE layers and using of the motorized microscope Olympus BX63. The correction for deceleration in the calculation of the invariant mass occurs according to the position of the vertices in order to use the most part of the NTE volume. As a development, it is highly desirable to expose NTE to heaviest nuclei at few GeV per nucleon.

III. Experiment

III.1 Search for events of nuclear interactions Kr+*Em*

Chemically developed plates of nuclear track emulsion are scanned by means of the microscope MBI-9. The procedure for searching for events of nuclear interactions is divided into 3 types: viewing along the track (the most precise); by area and by stripes (the fastest). The millimeter grid is applied throughout the plate help to fix the position of the interaction vertex. Each cell is numbered.

In this work, nuclear track emulsion layers exposed by Kr was scanned by strips using lens magnification of 20x15. Viewing is carried out in the area (strip) of the emulsion layer. The width of the viewing area is selected depending on the irradiation conditions (nucleus type, energy) and the process under study. A set of event statistics in this way is carried out by tracing the secondary track to the interaction vertex. The mutual configuration of the group of secondary tracks, which is preserved at a sufficiently large distance from the interaction vertex and observed in the fields of view adjacent to the vertex, makes it possible to quickly find interactions of the reaction types under study. The length of the secondary tracks should be much larger than the step (strip width). The advantage of the “by stripes” viewing method is the accelerated collection of event statistics for one selected reaction channel in comparison with other methods. Thus, 88 "stars" of nuclear interaction Kr+*Em* were discovered. Figure 2 shows an image of one of them.

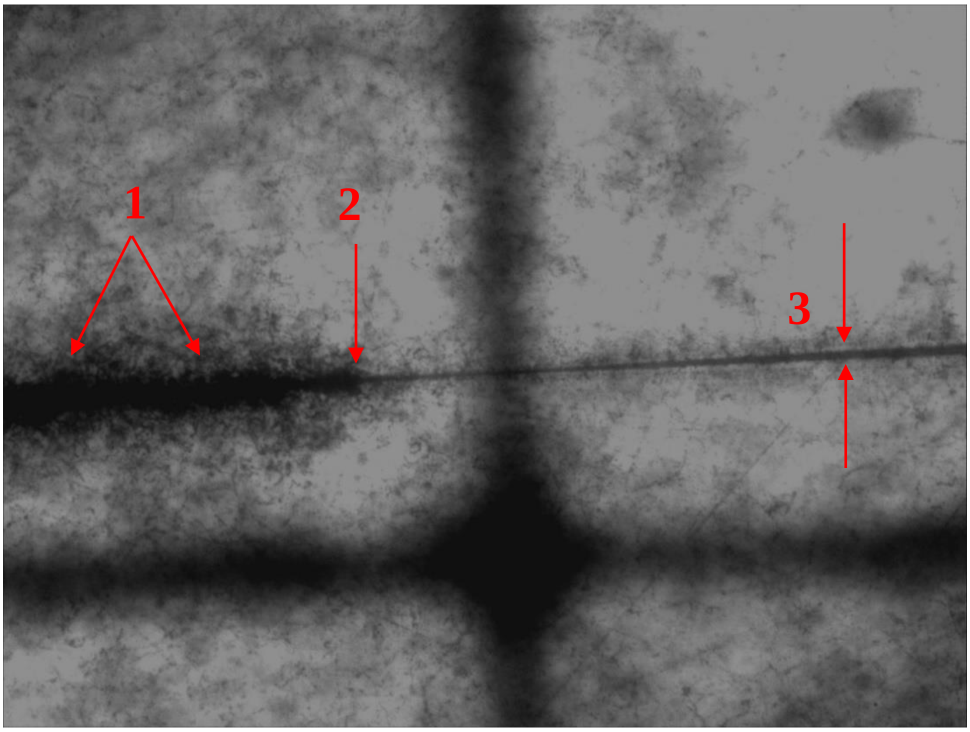

Figure 2. Sample of multiple fragmentation of Kr nucleus at 950A MeV in NTE. From the left side: 1) track of the primary Kr nucleus, 2) interaction vertex and 3) jet of secondary fragments. The image was made by means of microscope MBI-9 with the optical magnification of x40.

Let us describe the observed event in Figure 2. From the left side it's clearly to see the primary track of Kr nucleus. Thickness (blackness) of the track are defined by the number of produced δ-electrons and proportional to the charge squared of the ion (Z_{Kr}=36). The interaction vertex is clearly visible at point (2). Primary nucleus decays into the narrow jet of single- and double-charged particles (3), as a result of which the observed thickness of the tracks is noticeably. Simply to say that primary nucleus with the ionization Z^2 decays onto secondary fragments with ionization Σz^2. The jet of secondary fragments are concentrated in the forward cone with open angle defined by $sin\theta = P_F/p_0$. Tracks of secondary fragments remain in the nuclear emulsion layer for a sufficiently long time, which makes it possible to carry out metric measurements on a large base (~5cm.). It should be noted that the method of nuclear emulsions makes it possible to distinguish well the tracks of fragments with an extremely narrow divergence angle. For example, in emulsion layers, it is easy to distinguish pair of tracks of α-particles from the decay of a relativistic ^{8}Be nucleus (see Figure 3).

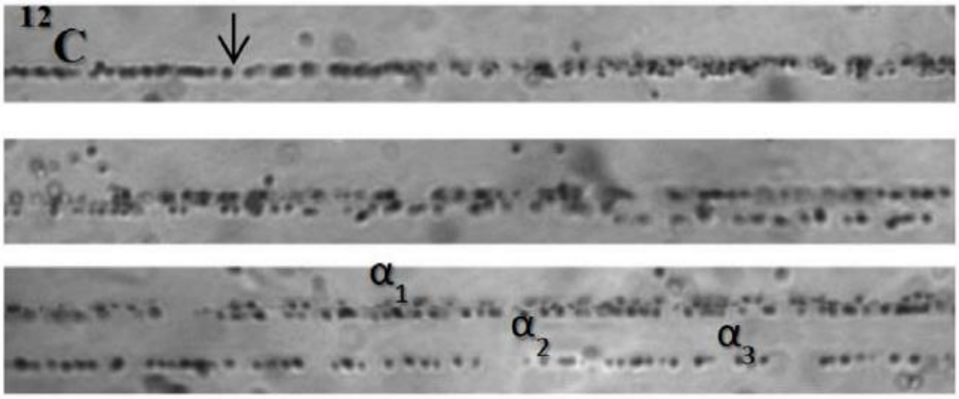

Figure 3. Consecutive frames of coherent dissociation $^{12}C \rightarrow 3\alpha$ at 1 *A* GeV/c; arrow indicate interaction vertex. Tracks of α_1 and α_2 particles were formed from ^{8}Be decay.

Conclusion

This report gives a detailed definition of nuclear photoemulsion method. The procedure for using the method of nuclear photoemulsions and its application is also described. The classification of tracks formed during fragmentation of emulsion nuclei is presented. The positive and negative features of the study of the process of fragmentation of nuclei using an emulsion are given. Also, the short description of the BECQUEREL experiment and its methods and facilities is given. The results of viewing a plate irradiated with krypton nuclei are demonstrated.

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