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Veksler and Baldin laboratory of High Energy Physics

FINAL REPORT ON THE START PROGRAMME

Analysis of the topology of fragmentation in a nuclear emulsion in the interaction of hadrons with 7 GeV/c

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Abstract

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 NTE, 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.

The aim of this work

Accumulation of statistics and analysis of the event topology of nuclear fragmentations from nuclear emulsion induced by hadrons for a planned analysis of correlations involving stopped alpha particles.

Introduction

The BECQUEREL (**Be**ryllium **C**lustering **Que**st in **Rel**ativistic Multifragmentation) [http://becquerel.jinr.ru/] 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 $^{8}Be \rightarrow 2\alpha$ and $^{12}C(0^{+}_{2}) \rightarrow {}^{8}Be\alpha$ 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 $^{16}O(0^{+}_{6}) \rightarrow \alpha^{12}C(0^{+}_{2})$ or $^{16}O(0^{+}_{6}) \rightarrow 2^{8}Be(0^{+})$. 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.

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 ^{8}Be and HS states based on this information

Track classification

For each event found, 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/I_0 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 $I/I_0 \geq 7.0$ and $\beta < 0.23$, where I_0 is the ionization on the tracks of relativistic particles 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 ≤ 3 mm;

Group 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.

Nuclear photographic emulsions 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). 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 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 emulsion (composition of BR-2 nuclear NTE; 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. $1 \leq nh \leq 6$, $nb \geq 1$ and $Lb > 80$ μm

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

Irradiation

The irradiation of nuclear emulsion samples was conducted using the experimental setup HIPERON-M [1] located in channel No. 18 of the U-70 accelerator complex. This channel is used to create a secondary beam of positively charged hadrons (π – 60%, p – 35%, K – 5%)

with an impulse of 7 GeV/c. The target is placed in a vacuum chamber covered by dipole magnet No. 35 of the U-70 ring. The energy of the proton beam is 70 GeV. The magnet provides an initial deflection of particles born on the target towards channel No. 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 irradiated during the spring session in 2018. A total of 2 stacks, each consisting of 10 plates with an emulsion layer thickness of 100 μm, were used for irradiation, along with 1 stack with an emulsion thickness of 200 μm. The total flux of hadrons passing through the nuclear emulsion stacks was 2×10^6 particles. During irradiation, the stack of nuclear emulsions was oriented perpendicular to the beam direction. Such irradiation makes it possible to load a vigorous emulsion with a relatively large flow of particles. In the subsequent analysis, plates with an emulsion layer thickness of 100 μm were selected.

Search for interactions and results

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

Fig. 1. Photo of MBI-9 optical microscope.

The area of the photosensitive part of the nuclear photographic emulsion plates is 9x12 cm^2, 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.

Fig. 2. Photo of plate №. 4/6.

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.

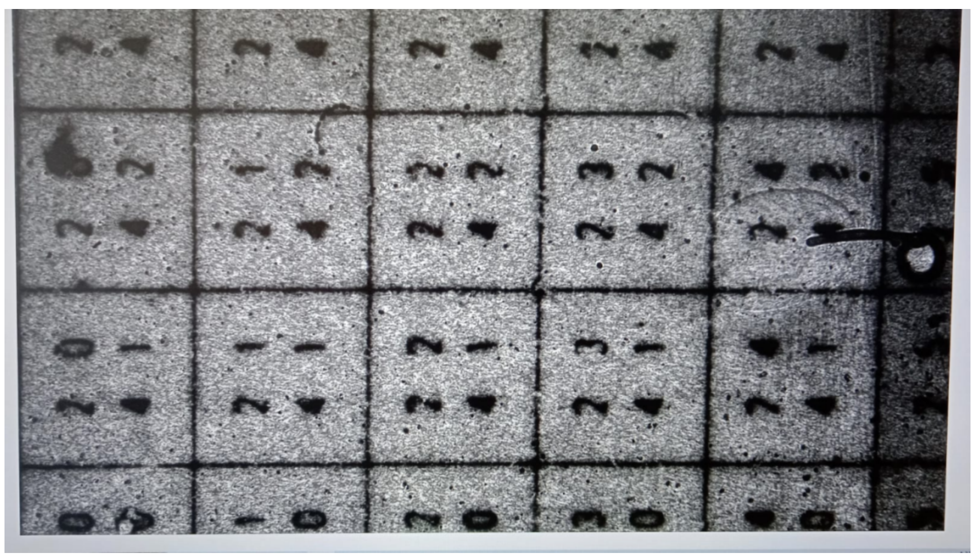


Fig. 3. Image of the coordinate grid on the surface of a nuclear photographic emulsion obtained with an Olympus BX63 optical microscope. The side of one square is 1 mm. The numbers indicate the coordinate of the position of this square in the XY plane.

During the 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 cm^2 and a thickness of 100 microns was selected (figure 3). The table 2 shows the scan results. The total viewing area was 70 mm^2 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 main criterion for selecting events during viewing was that the top 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 nuclear emulsion plate. The events found can be divided into 3 groups of events according to the number of observed particle tracks: interaction on hydrogen, on light CNO nuclei, and on heavy AgBr nuclei. Average number of b-particles ($N_h>0$, $N_h\leq6$ and $N_h\geq7$) 3.3±0.23, g-particles 0.3±0.11, s-particles 0.5±0.16.

	$\langle n_b \rangle$	$\langle n_g \rangle$	$\langle n_s \rangle$	$\langle N_h \rangle$	№ events
$N_h>0$	3.3±0.23	0.3±0.11	0.5±0.16	3.6±0.26	36
$N_h\leq6$	3.26±0.23	0.28±0.1	0.46±0.16		35
$N_h\geq7$	6	2	2		1

Table 2 – average particle multiplicities for events with different numbers of strongly ionizing particles $N_h = n_b + n_g$ for plate 4/6

Relative correlations are shown in the figures 4. The impact of events on light nuclei is 97.2 %, on heavy ones - 2.8 %. For comparison, in the works [2] in the interactions of protons with energies of 4.5 6.2 and 22 GeV/c in a nuclear emulsion, the contributions were 0.5%, 2.2% and 3.2%, respectively.

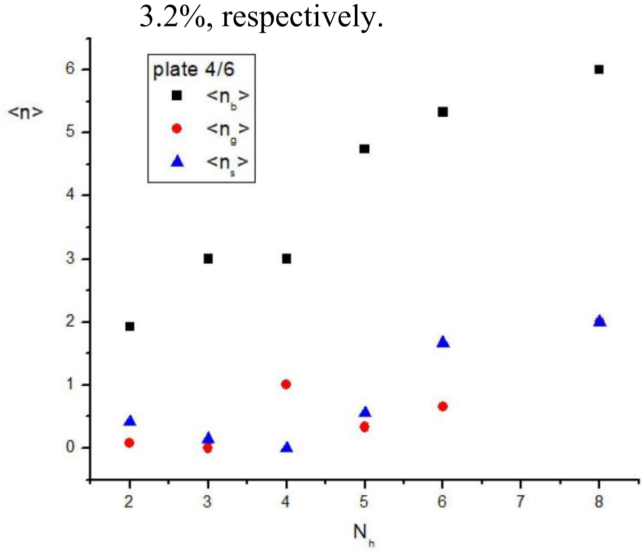


Fig. 4. Correlation between n_b, n_g and n_s from N_h for plate 4/6.

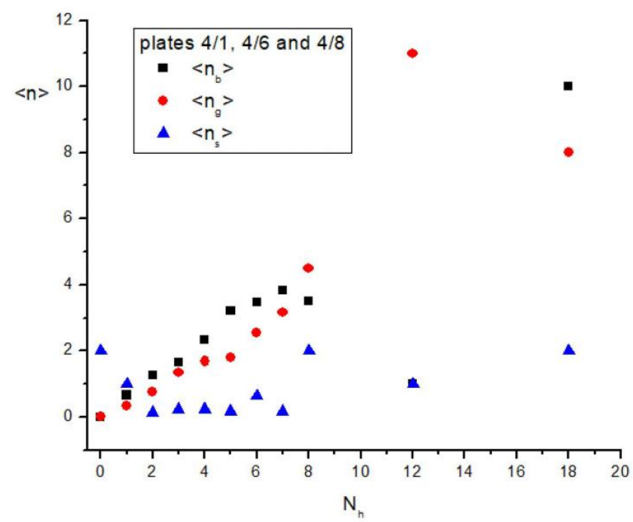


Fig. 5. Correlation between n_b, n_g and n_s from N_h for plates 4/1, 4/6 and 4/8.

при $Nh\geq7$
$\langle nb \rangle=4.583$
$\langle ng \rangle=6.667$
$\langle ns \rangle=1.29$

For a complete analysis with more statistics of events, the viewing logs (see Appendix) of records No. 4/1 and 4/8 are available. The total viewing area for all plates was 3760 mm^2, with a depth of field of 70 µm. Matrix 1 – 4 shows the multiplicities of charged particles from the events found.

N_h / n_s	0	1	2	3	4	5	6	7	8
0			10	6	4	7	1		
1				1					
2			1			1	1		1
3			1			1	1		

Matrix 1 – Matrix distribution by multiplicity n_s – N_h for plate 4/6

n_g / n_b	0	1	2
0			
1		1	
2	11		2
3	7		1
4	2	1	
5	7	2	
6	1		1

Matrix 2 – Matrix distribution by multiplicity n_b – n_g for plate 4/6

N_h / n_s	0	1	2	3	4	5	6	7	8
0			115	82	44	132	8	5	1
1		3	9	14	11	18	4	1	1
2			2	5	1	1	1		1
3	2		1			2	1		
4							1		
5									1

Matrix 3 – Matrix distribution by multiplicity n_s – N_h for plates 4/1, 4/6 and 4/8.

n_g / n_b	0	1	2	3	4	5	6	7	8	9	10	11
0	3	1	32	21	6	9						
1	2	31	23	8	21	1						1
2	64	27	17	20	2	2	2					
3	30	12	29	5	1							
4	13	27	4	1	1							
5	47	2	1									
6	1		1									
7	1											
8												

9												
10									1			

Matrix 4 – Matrix distribution by multiplicity n_b – n_g for plates 4/1, 4/6 and 4/8.

Average number of b-particles (N_h<0, N_h≥6 and N_h≥7) 2.23±0.073, g-particles 1.47±0.069, s-particles 0.24±0.028. Relative correlations are shown in the figures 5. The impact of events on light nuclei is 97.4 %, on heavy ones - 2.6 %.

	$\langle n_b \rangle$	$\langle n_g \rangle$	$\langle n_s \rangle$	$\langle N_h \rangle$	№ events
$N_h>0$	2.23±0.073	1.47±0.069	0.24±0.028	3.7±0.75	470
$N_h\leq6$	2.18±0.071	1.39±0.063	0.22±0.026		458
$N_h\geq7$	4±0.76	4.67±0.85	1±0.42		12

Table 3 – average particle multiplicities for events with different numbers of strongly ionizing particles $N_h = n_b + n_g$ for plates 4/1, 4/6 and 4/8.

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.

№ plate	Viewed squares	3*b*	4*b*	5*b*	<=2*b*	>5*b*	All stars∑
4/6	70	8	3	9	14	2	36

Table 4. Topology of events found as a result of scanning plates No. 4-6 irradiated in a hadron beam at the Hyperon facility.

Examples of events found as a result of viewing the plates are shown in Figure 4.

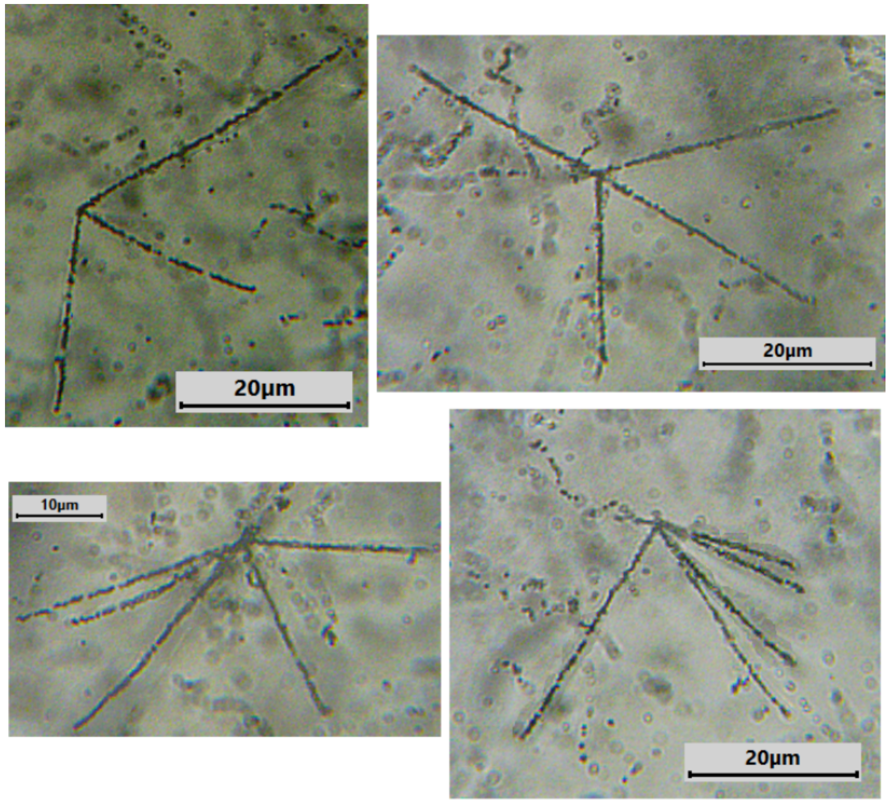


Fig. 6. Images of events with the formation of tracks of b-particles during the interaction of hadrons with nuclei from the composition of a nuclear emulsion.

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 5 shows the histogram results.

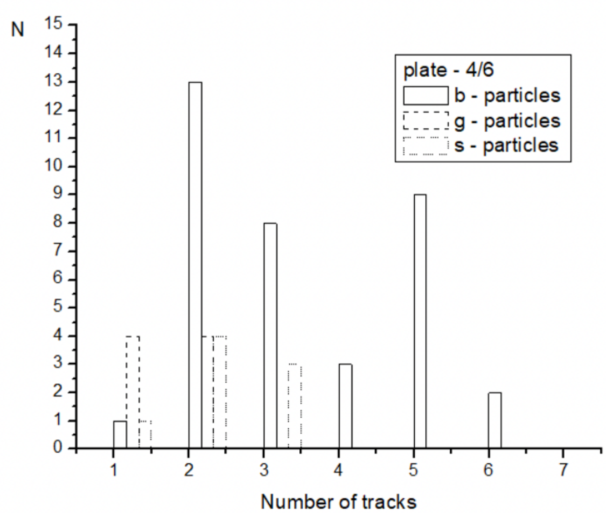
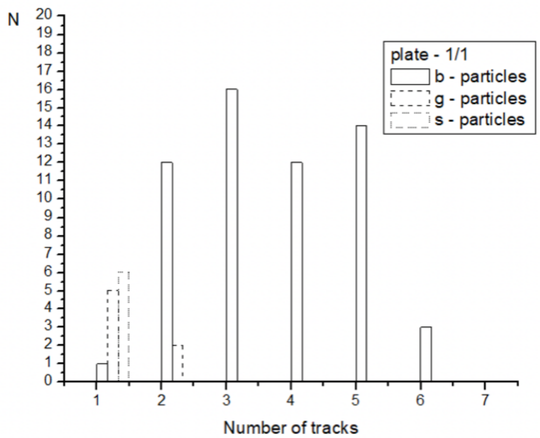


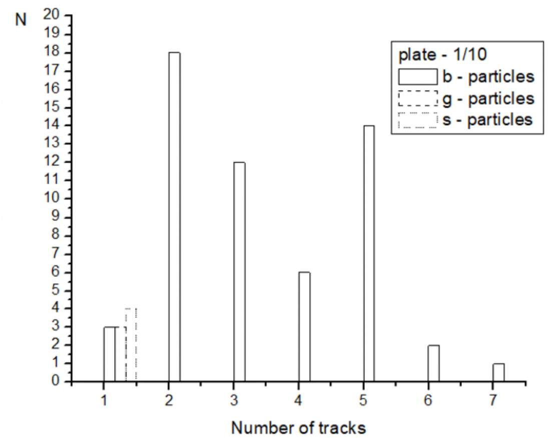
Fig. 7. Distribution by Nuclear Track Emulsion for plate 4/6

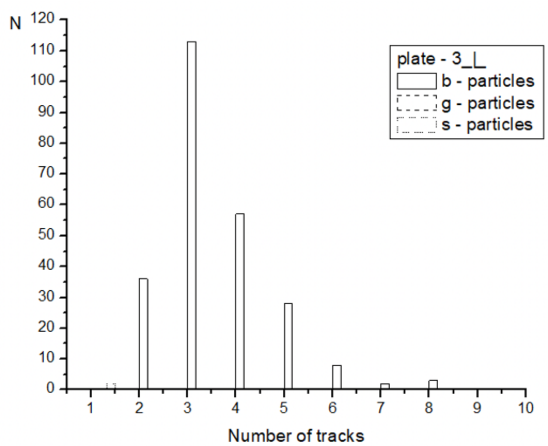
№ plate	Viewed squares	3*b*	4*b*	5*b*	<3*b*	<5*b*	All stars ∑

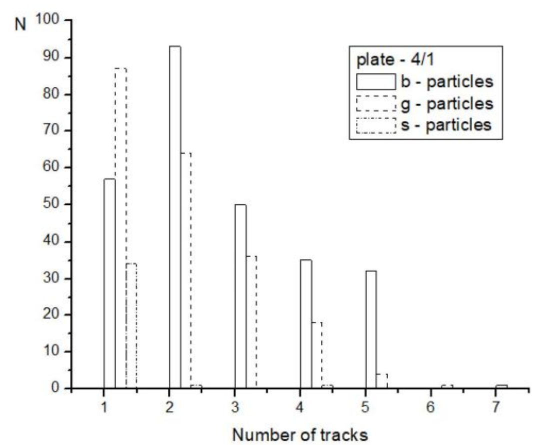
1/1	400	16	12	14	13	41	58
1/10	300	12	6	13	21	39	56
3⊥	1400	114	57	26	37	208	249
4/1	1200	50	35	32	150	235	228
4/8	800	19	8	9	57	84	78
TOTAL	**3760**	**219**	**121**	**103**	**248**	**24**	**705**

Table 5. Topology of events found as a result of scanning plates№. 1/1, 1/10, 3⊥, 4/1 and 4/8 irradiated in a hadron beam at the Hyperon facility.









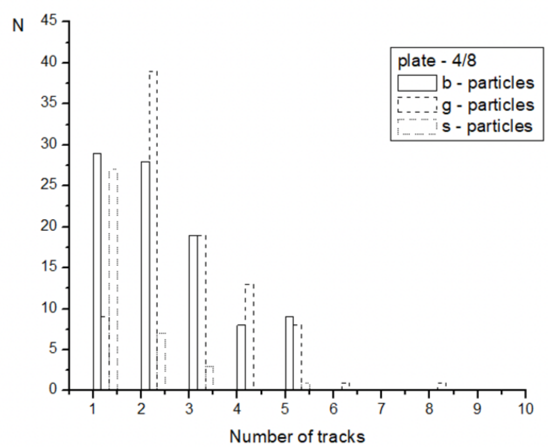


Fig. 7. Distribution by Nuclear Track Emulsion for plates 1/1, 1/10, 3⊥, 4/1 and 4/8.

Conclusion

The analysis carried out confirms the promise of using irradiated layers to study the interactions of hadrons on nuclei at high energies in order to obtain information about the characteristics of relativistic and slow charged particles.

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