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METHOD OF GRAIN COUNTING FOR IDENTIFICATION OF NUCLEAR TRACKS IN DILUTED PHOTOGRAPHIC EMULSION

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Introduction

For the last decades a class of nuclei track solid state detectors (NSSTD) has been considerably widened and nuclear photographic emulsions are now of less importance as, for example, ten years ago. However, there is a number of problems the solution of which requires photographic materials still remaining as a unique device. Such problems include the search of superheavy elements (SHE) in cosmic irradiation. To solve this problem, C.S.Bogomolov (1975) proposed the method for grain counting over track cross-section for heavy relativistic nuclei in diluted photographic emulsion. The validity for track interpretation in the above method is determined by the level of the evolution for a theoretical description of the processes for forming track parameters to be measured among other factors.

In the present paper we consider the experiment on heavy nuclei identification by the method of grain counting in photographic emulsions exposed on board a space ship as early as 1974. Since the moment of carrying out the experiment, the theory of detection has undergone a considerable evolution, and in the present paper based on this experiment it is traced how the theory evolution influences its interpretation.

The proposed consideration of the experiment is already the third one on the ground of the new theoretical approach (Ditlov V., 1980). The first one was made in 1975 (Bogomolov C.S., 1975), the second one in 1976 (Bogomolov C.S., Ditlov V.A., 1978). At the end of the paper to be considered the results for counting are proposed and discussed for further experiments on heavy and superheavy nuclei identification.

Methodology of the experiment (Bogomolov C.S., 1975)

By means of a microscope we count the number of developed grains in two rectangular long parallelepipeds-bars located parallel to the track axis at the same distances from it (see Figs.1 and 3).

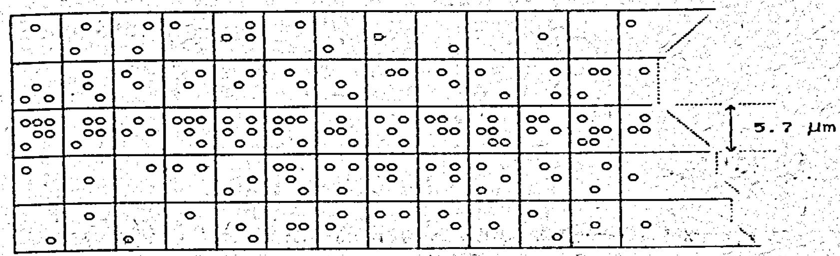


Fig.1. Geometry of the method for grain counting in emulsions, type R2x8. Grain counting was done in squares located at a distance of 2.85 μm from the nucleus trajectory

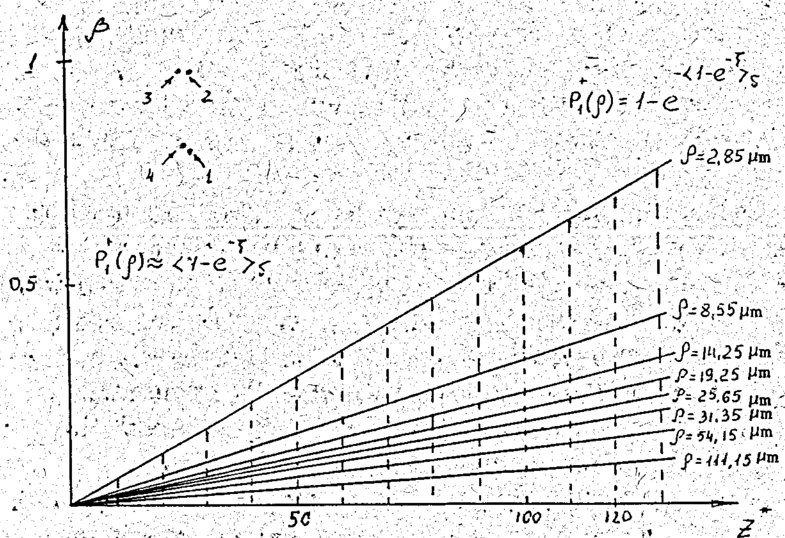


Fig.2. Family of straight lines at which it takes place $\langle 1 - e^{-\xi} \rangle \sim 0.1$ for a distance set from the track axis. "•" - points of four tracks necessary to be identificated in diluted emulsion R2x8

To study the possibility for application of this procedure for nuclei identification, the experiment using extra-atmospheric exposures was carried out (Bogomolov C.S., 1975). To select optimum photographic

materials and their dilutions, laboratory samples of layers, types RK, RKx4, RKx6, RKx8, RKx32, R, Rx4,...Rx32, and then the same series with original emulsions, types M and LD, were prepared. /Numerals mean the degree of emulsion dilution/. The thickness of photographic layers, series R and M, was 400 μm, and series RK and LD - 200 μm, and the format 9x12 cm^2.The characteristics for original emulsions are given in Table 1.

Table 1. Characteristics of original non-diluted emulsions

Type of emulsion	Mean diameters of microcrystals, μm	Density of tracks for relativistic electron, Grains/100μm
RK	0.44	40
R	0.28	45
M	0.14	32
LD	0.10	no tracks

Thirty layers of the above types were irradiated on board a space ship, series "Soyuz". The results for the observation of developed layers on a microscope were provided by the following conclusions:

1. Ultra-fine grain nuclear emulsions are not very suitable for the given purpose, as fine developed grains are semi-transparent and their counting is exhausting.

2. Coarse grain emulsions, especially with strong exposures, result in a large inner light diffusion making the observation difficult.

3. Non-diluted emulsions show very strong diffusion in the particular experiment (overirradiation).

4. Dilutions, types x16 and x32, are too high.

5. Dilutions, type Rx8, are to be considered as optimum photolayers to study multicharged relativistic particles by the method for grain counting in areas parallel to the nucleus path.

In the layer of emulsion Rx8 four traces of particles were detected, their belonging to an iron group being the most probable. More dense traces were not observed, and less dense layers were not suitable to carry out the given experiment procedure.

Based on the supposed traces of iron nuclei, an optimum procedure for grain counting was chosen from the point of view of information capacity. It is characterized by geometry shown in Fig.1. A square eyepiece grid was set so that the particle trace axis was at an equal distance from the horizontal sides of the squares. The grains in squares where the trace passed were not subjected to counting. All grains located in adjacent squares on both sides from the central ones were counted. The grid cell size was 5.7x5.7 μm^2. The observation depth was selected as 5.0 μm which corresponds to 5.7 μm of an undeveloped layer accounting for shrinkage. Grain counting in squares more remote from the nucleus path was not done due to prevalence of background in them. The results for grain counting in four selected traces are given in Table 2. The numbers of grains N in measured trace segments ΣN evaluated per 100 μm relate to trace "bars" shown in Fig.3.

Table 2. Results for grain counting in tracks for nuclei of iron group

№№ tracks	Horizontal projection of measured segment L_h μm	Vertical projection of measured segment L_v μm	Length μm	Whole grain number in segment	Grain number per 100 μm
1	456	193	496	385	77.6
2	1311	350	1360	714	52.5
3	211	315	376	168	44.2
4	570	350	667	506	75.8

Theoretical interpretation of the results for grains counting

The following approximate approach was used in the first interpretation (Bogomolov C.S., 1975). For distances from the track axis less than one tenth of the complete range R(w) of delta-electron with initial energy W, it was supposed that it was moving along the straight line and the number of microcrystals N having obtained the ability for development at the initial rectilinear section of its path, length ρ, is

given by the expression:

$$N = N_o \cdot \varphi(s); \quad s = R(w) - \rho . \quad (1)$$

Here N_o is the number of microcrystals per path unit, $\varphi(s)$ the probability for a microcrystal to obtain developability after passing an electron with residual range s through it which for a one-hit model was written as follows:

$$\varphi(s) = 1 - e^{-\xi(s)}; \quad \xi(s) = w_r \cdot \frac{\Delta E(s)}{\Delta E_r}, (2)$$

where w_r is the frequency of effective ionization acts made by an electron in relativistic ionization minimum, $\Delta E(s)$ effective energy losses of electrons in a microcrystal, ΔE_r effective electron energy losses in relativistic minimum.

For distances larger than 0.1 of the delta-electron range, an approximate calculation for multiple scattering due to which their paths are accidental curves was made (Bogomolov C.S., 1975). For this purpose the function for photographic effect distribution over the electron range projection upon its initial movement direction found from the experiment was used.

The repeated interpretation of this experiment was made in 1976 (Bogomolov C.S.and Ditlov V.A., 1977) . Thereby, the probability for emulsion grain development at some point $\vec{r}$ was supposed to be equal to the integral over δ-electrons spectrum from the probability for obtaining developability by a grain after passing a separate δ-electron with residual range S through it:

$$P(\vec{r}) = \pi a_0^2 \int_u^{W_{max}} \frac{dn}{dw} dw \int_0^{R(w)} \varphi(s) ds \int_0^{2\pi} f(\vec{r}, \vec{v}, s) d\vec{v} . \quad (3)$$

Here $f(\vec{r}, \vec{v}, s)$ is the differential function for an electron flow along the spatial coordinate $\vec{r}$, residual run s and over the directions of electrons movement $\vec{v}$;

dn/dw describes the energetic spectrum of emitted δ-electrons;

a_o is the radius of an undeveloped emulsion microcrystal.

The inner double integral was found by the Spencer method (Spencer L.V., 1955, Jensen M. et al., 1976, Jacobson L., 1973). However, the solution of only a flat task was used with electron irradiation of a 100 keV energy perpendicular to the source plane; $\varphi(s)$ is the function described by formula (2). The results for the second interpretation are presented in columns 5-6 of Table 3.

In spite of some simplification of the task such as neglecting the emission angle dependence on the initial energy of δ-electron, this theoretical interpretation of the experimental results included new principal statements. For the first time the spatial distribution of dissipated energy for a δ-electron flow (Katz R. and Kobetich E.J., 1968; Jacobson L. et al.,1973; Jensen M. et al., 1976) was not used for the calculation of spatial local response distributions in a track of multi-charged nuclei, and the probability for emulsion grain development at some point $\vec{r}$ was supposed to be equal to the integral over the δ-electron spectrum from the probability for obtaining developability by a grain when a separate δ-electron passes through it. As shown in our work (Ditlov V.A. 1980), this supposition is valid for small densities of a δ-electron flow. In the case of type R nuclear emulsion the space distribution of local responses is described by the expression :

$$P_1^+(\vec{r}) = 1 - e^{-\langle 1 - e^{-\xi(s)} \rangle}, \qquad (4)$$

where :

$$\langle 1-e^{-\xi(s)} \rangle = \pi a_o^2 \int_U^{w_{max}} \frac{dn}{dw} dw \int_o^{R(w)} (1-e^{-\xi(s)})\, ds \int_o^{2\pi} f(\vec{r},\vec{v},s)\, d\vec{v}. \qquad (5)$$

We adapted the Spencer method for the reconstruction of spatial distributions of quantities $\langle \xi^k(s) \quad e^{-\xi(s)} \rangle$, which allows us to find spatial local response distributions $P_1^+(\vec{r})$.

So, we can see now that equation (3) is the private case of (4) rewritten for the small flow of δ-**electrons** when:

$$\langle 1-e^{-\xi} \rangle_\delta \ll 1 \qquad (6)$$

Let us check its feasibility in relation to the experiment to be done. For the considered emulsion, type R2x8, the calculated values of average atom charge, atomic weight and ionization potential are as follows:

$$\bar{Z} = 5.521; \quad \bar{A} = 11.082; \quad \bar{U} = 131.35 \text{ эВ}. \qquad (7)$$

For the calculated value of emulsion weight density we obtain ρ=1.94g/cm^3. For a constant multiplier in the Bete-Bloch expression (Brandt H.L. et al.,1948) it is possible to find:

$$PL = 2\pi\, n\, r_o^2\, m_o c^2 (Z^*)^2 = 0.014857\ (Z^*)^2 \text{ keV}/\mu m, \qquad (8)$$

$$dE/dx = PL\, f(\beta)/\beta^2. \qquad (9)$$

With the help of (8) and (9) we find out that the distance from the track axis to the nearest bar edge equal to 2.85 μm can be overcome in the experiment by δ-electrons with energy more than 15 keV. To evaluate the complete number of electrons which are able to pass through the microcrystal surface, πa_o^2, located on the above bar edge, the following equation can be written:

$$n_\delta \approx (Z^*)^2 \frac{PL\, \pi a_o^2}{\beta^2} \frac{1}{2\pi\rho} \int_o^\infty \frac{1}{w^2} d\,w \approx 0.34\ 10^{-5} \frac{(Z^*)^2}{\beta^2}. \qquad (10)$$

Assuming that $P_1^+(\rho|1) \sim 1$ this value coincides with the power low exponent in the probability for the one-hit response model (Ditlov V.,1980):

$$n_\delta \cdot P_1^+(\rho|1) = \langle 1-e^{-\xi} \rangle_\delta \approx 0.3410^{-5} \frac{(Z^*)^2}{\beta^2}. \quad (11)$$

Thus, for nuclei of the iron group with $Z \sim 26$ we obtain:

$$\langle 1-e^{-\xi} \rangle_{\delta,\, z=26} \sim \frac{0.23\ 10^{-2}}{\beta^2}. \quad (12)$$

From this evaluation for nuclei of the iron group it follows that condition (6) is fulfilled only for relativistic velocities, and for $\beta \le 0.1$ its value is already comparable to unit

$$\langle 1-e^{-\xi} \rangle_\delta \ge 0.23.$$

If we consider more multi-charge muclei, for example, the transurane element with Z=114, then we obtain from (9):

$$\langle 1-e^{-\xi} \rangle_{\delta,\, z=114} \sim \frac{0.044}{\beta^2}. \quad (13)$$

For the transurane nucleus the value is greater than 0.23 already at $\beta \le 0.44$. Generally speaking, from (11) it is possible to find the equation for straight line at which $\langle 1-e^{-\xi} \rangle_\delta = 0.1$ and which divides the areas of expansion applicability (4)$\longrightarrow$(3):

$$\beta \sim 0.00583\, Z^*. \quad (14)$$

In Fig.2 this dependence is shown by a straight line for the distance from the track axis ρ=2.86 μm. The relative increase of expansion (3) on the straight line itself is already ~ 5 %. At the point (Z,ρ) over this straight line inequality takes place:

$$\langle 1-e^{-\xi} \rangle_\delta < 0.1. \quad (15)$$

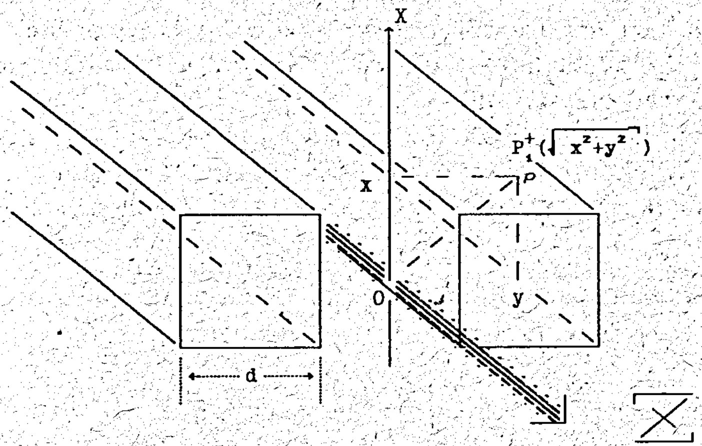
Hence, in this area the use of approximation (3) is acceptable and vice versa at the points (Z,ρ) lying under the straight line tolerance (14) is considerable and exceeding 5 %.

If we neglect the dependence of conditional probability $P^+(\rho,|q=1)$ on the velocity of the registered nucleus, β, then from (11) for parameter pairs (N_n, N_m) of two different tracks (Z_n, β_n) and (Z_m, β_m) one can write :

$$\frac{N_n}{N_m} = \left(\frac{Z_n^*}{Z_m^*} \cdot \frac{\beta_m}{\beta_n} \right)^2. \quad (16)$$

This relation is often used (Bogomolov C.S., 1975) not only in grain counting but also during the measurement of optical densities D in track cross-section (Jensen M. et al., 1976). In this case, optical densities D_m should be used instead of N_m . The applicability area of formula (16) coincides with that of (3) but here β_n and β_m should be rather close here in oder to fulfill the condition of $P_1^+(\rho,q=1)$ independence of velocity β.

As it was found in the paper of Bogomolov C.S. and Ditlov V., (1977) for Z=26 and β=1 in emulsion, type R2x8, the calculated N_{26} = 48.3 for the grain sum in two bars (Fig.1). The parameters for registered nuclei (see Table 3, columns 5 and 6) were obtained using eq. (16). In Fig.2 their values are marked by symbols ".". As seen from the figure, these points are located much higher than straight line (14) for five-percent errors, formula (16) for them has a good accuracy and integration of probabilities over the spectrum of δ-electrons is right (Bogomolov C.S., 1975). Possible interpretation mistakes are necessary to be connected only with a simplified character of solving the tasks for the theory of multiple scattering: when integrating over energetic spectrum of δ-electrons in expressions for radial response distributions, the Spencer ratios found for the task with a flat electron source at E_o=300 keV emitted at a right angle to its surface were used. Our approach (Ditlov V., 1980) allows a more accurate interpretation to be given.



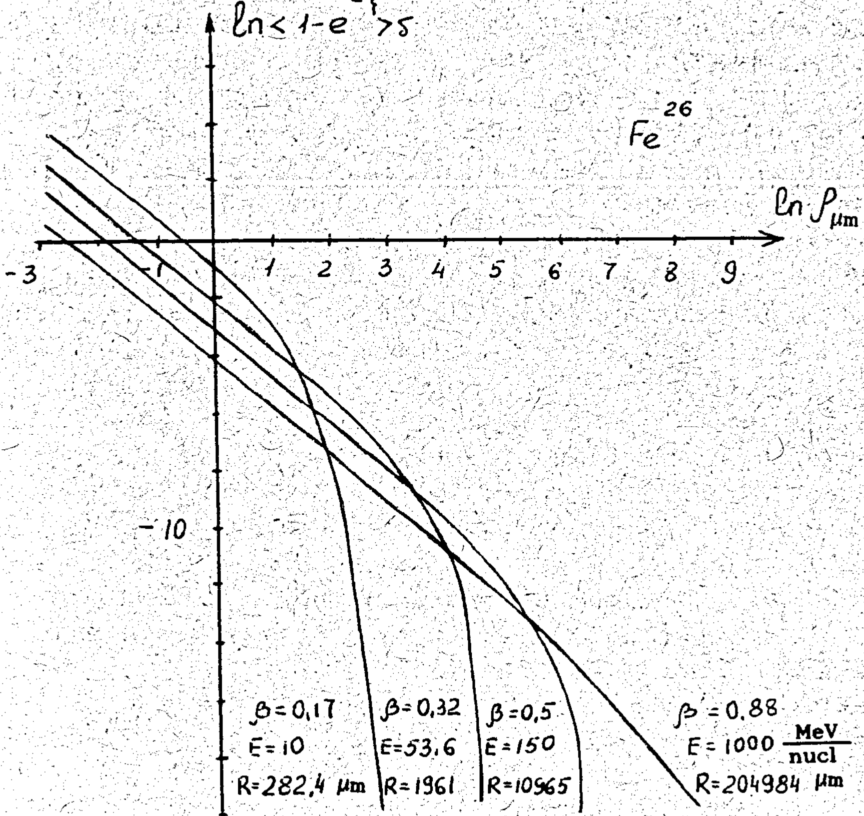


Fig.3. Scheme for integration (17) over bar cross-section in the method for grain counting

Estimation for the dependence of the number of developed grains in two bars on their distances to the track axis

According to Fig.3, the complete number of developed grains in two bars located equally from the track axis is described by the integral:

$$N(\rho) = 4\, n_o L \int_o^{d/2} dx \int_{\rho-d/2}^{\rho+d/2} P_1^+(\rho=\sqrt{x^2+y^2})\,dy \qquad (17)$$

For emulsions, series type R2, the response probability described by one-hit model is given by expression (4). Fig.4 gives the estimated relationships (5), calculated by a computer, for four cross-sections of the iron nucleus track. Integral (17) was calculated by the formula of Simpson parabolas.

Fig.5 presents the estimated dependences $\ln[N(\rho)]$ for eight cross-sections of the iron nucleus track with β=0.177, 0.264, 0.325, 0.374, 0.415, 0.51, 0.69 and 0.87. All points (Z,β) - 1 + 8 of these cross-sections lie above the straight line for five-percent errors of Fig.2, and so with equal β and different Z relation between numbers N takes place at the same remoteness from the track axis ρ :

$$\frac{N_i}{N_k} = \left(\frac{Z_i^*}{Z_k^*}\right)^2 \qquad (18)$$

With the help of this expression it is easy to come from relationships $N(\rho)$ for the iron nucleus (Fig.4) to analogous ones for other nuclei above the straight line of five-percent errors (Fig.2).

Fig.4. Estimated relationships $\langle 1-e^{-\xi}\rangle_\delta$ calculated by a computer, for four cross-sections of the iron nucleus track in emulsion R2x8

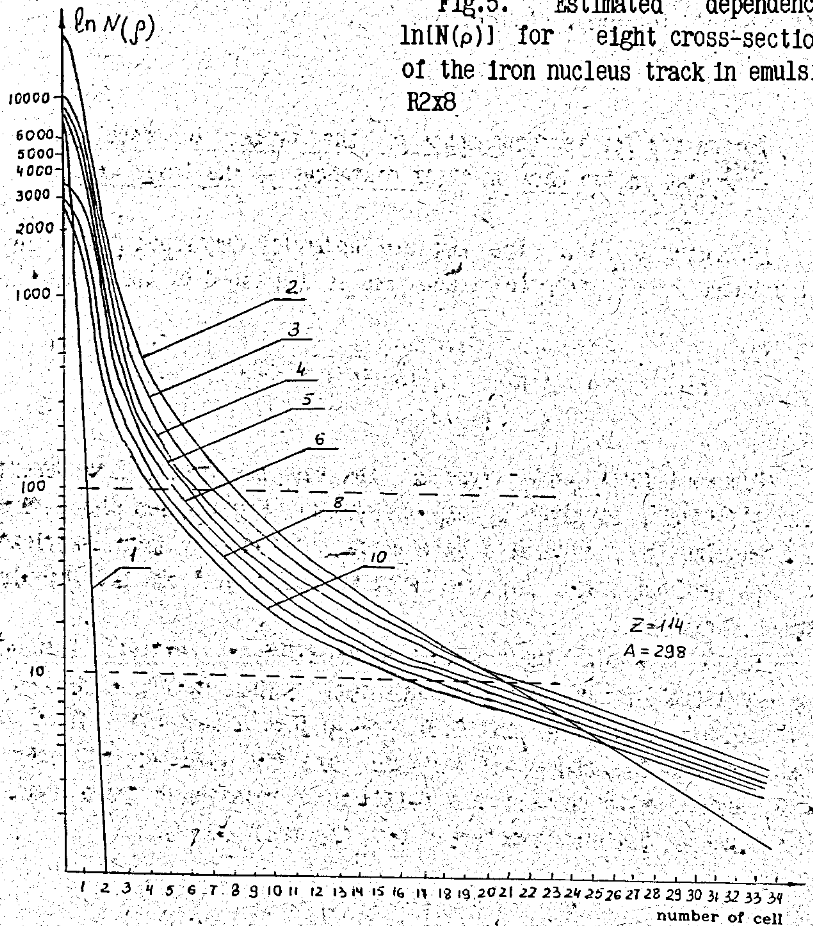


Fig.5. Estimated dependences ln[N(ρ)] for eight cross-sections of the iron nucleus track in emulsion R2x8

Relationships N(ρ) (Fig.5) are estimated for a large interval of values of the coordinate ρ, but the method for grain counting has some limitations considerably narrowing the working range. So, if the number of developed grains in measured bars is N ≥ 100, then it becomes difficult to distinguish grains from each other. If vice versa it is little and comparable to the contribution N_{fog}, then the difficulty for fog extraction appears. Limitations from the top are determined by the possibilities of a device or eyesight, and a limitation from the bottom is connected with the properties of an emulsion layer. So, in accordance

with TU-6, for an undiluted emulsion of the type R2 three fog grains are per 10 cm^3 of the volume that is within a two bar 3x3x200 μm^3 volume with n_o=49.9μm^{-3} for which N_{fog} = 19.5. Hence, the working range for the method of counting in this emulsion is 40÷100 grains. The recalculation of the fog of emulsion, type R2, to the fog of diluted emulsion, type R2x8, for which n_o = 8.24 μm^{-3} gives N_{fog} ~ 4 grains determining a wider working range for the method of counting (20÷100).

In Fig.5 this range is shown by two horizontal shaded lines. As seen from the figure, the iron nucleus with β=0.177 does not make a contribution to the second cell of the eyepiece grid located at a distance of 11.4 μm from the track axis. We obtain N ~ N_{fog} for this cell with relativistic nucleus velocities β ≥ 0.86 close to the nearest border of the working range. This very case was observed for all four detected tracks of iron group nuclei. In Fig.6 the family of curves for relationship N(β) at the point ρ=5.7 μm is given for a set of nuclei with Z, changing from 10 to 30, for the first cell with ρ=3 μm. Relativistic nuclei with Z≤10 give N smaller than a low border of the working interval and with Z ≥ 30 already near the top. If one of the parameters Z or β is known for the nucleus to be studied, then from Fig.6 another parameter β or Z can be easily found for the measured number of grains $N_{5.7}$. But if both parameters are unknown, then the measured value of $N_{5.7}$ makes it only possible to plot a curve for the dependence of possible values of the nucleus Z on possible values of velocity β. In Fig.7 such four dependences are presented for the measured values of N(ρ) (see Table 3, column 2). These curves are easily obtained by recalculating the estimated results in Figs.5 and 6. Already from the general character of the above dependences it is possible to draw conclusions resulting in a decrease of the range of possible values of Z and β. Firstly, in the second cell of the eyepiece grid all four tracks had a small number of grains at the level of background. According to Fig.5 it can be observed, either with β ≤ 0.177 or with β ≥ 0.8. Iron nuclei with β = 0.177 have a range R=282 μm in an emulsion of the type R2x8 while the tracks in emulsion were much larger in length exceeding layer sizes. Hence, the observed tracks are formed by relativistic nuclei, and the version with β ≤ 0.177 is taken away. But in this case (see Fig.7), the upper limit is Z =30 for tracks № 1 and № 4, and Z = 26 for № 2, and Z=23 for № 3. If tracks № 1 and № 4 are related to the iron nucleus, then from Fig.7 it

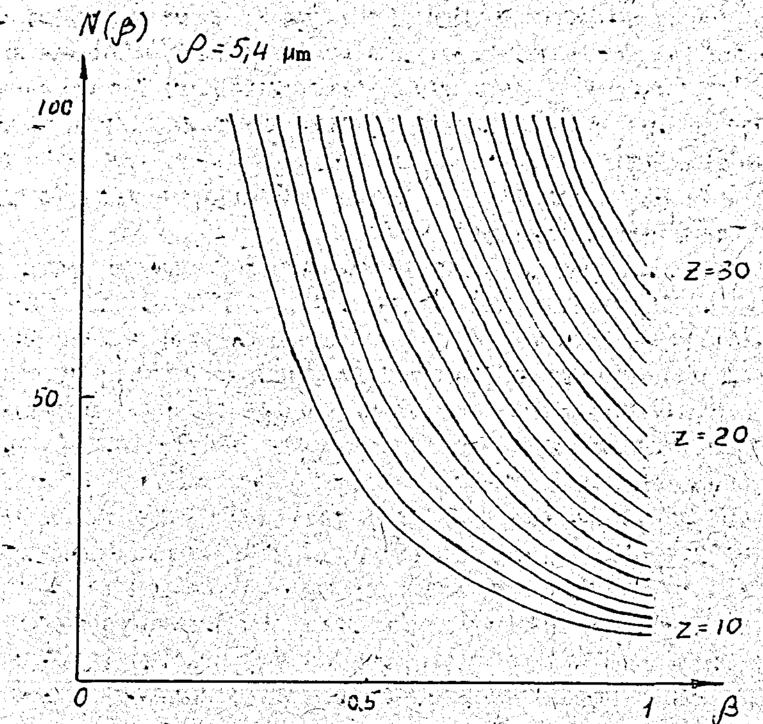


Fig.6. Family of curves for the calculated functions $N(\beta)$ for ρ=5.4 μm and for a set of nuclei with Z, changing from 10 to 30

is possible to obtain β_1=0.845 and β_4=0.855, respectively. At a velocity close to these values for tracks № 2 and № 3 Z=22, β_2=0.86 and Z_3=20, β=0.845. Thus, the new interpretation based on a more accurate consideration of the task differs from the first one (Bogomolov C.S., 1975) by the fact that it gives a lager discrepancy in the values of Z and a smaller one - in β. Besides, the new interpretation shows that the values for pairs (Z,β) of the first interpretation are impossible as they lie apart from the curves for possible values (see Fig.7).

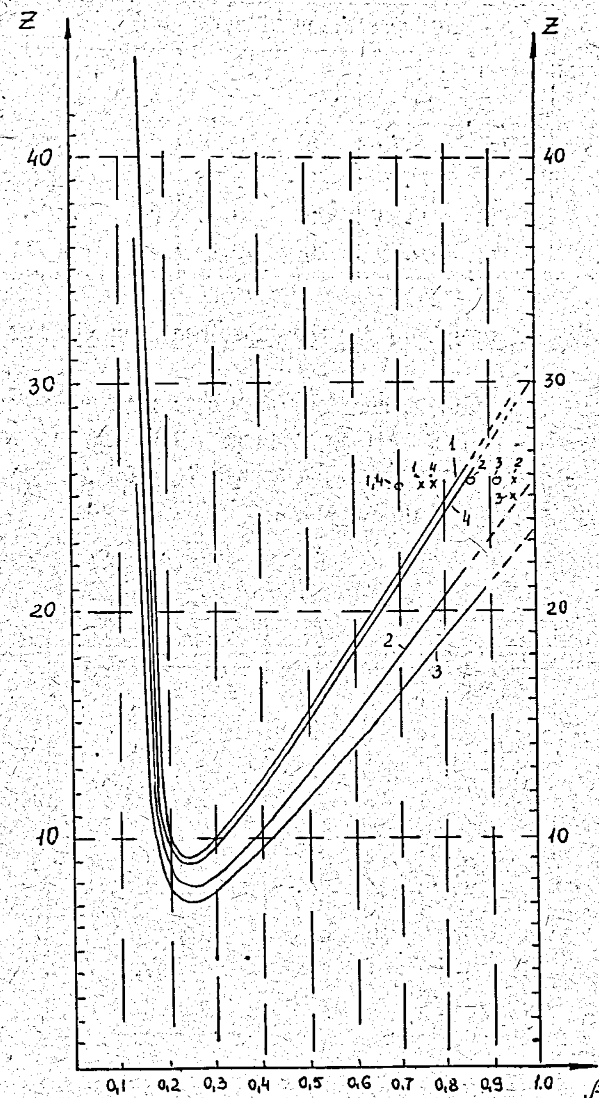


Fig.7. Curvartures of atomic numbers Z and velocities β on the plane (Z,β) possible for set of numbers N :
1 - $N_{5.7}$= 77.6; 2 - $N_{5.7}$=52.6; 3 - $N_{5.7}$=44.2; 4 - $N_{5.7}$= 75.8

Table 3.

№№ of tracks	Number of grains per 100μm	Interpretation of nuclei tracks					
		1975		1976		1991	
		Z	β	Z	β	Z	β
1	77.6	26	0.70	26	0.78	26	0.84
2	52.5	26	0.86	26	0.96	22	0.86
3	44.2	26	0.93	25	0.96	20	0.84
4	75.8	26	0.70	26	0.79	26	0.85

Grain counting and prognosis for the experiment for SHE search

The increase of atomic number for the working range of registered nuclei for values of ρ will be shifted to large values and widened. Fig.8 presents the calculated results of relationship $N(\rho)$ for SHE (Z=114) for velocities and energies given in Table 4.

Table 4.

№	E MeV/nucl	β	R μm	dE/dR keV/μm
I	10	0.1454	199.877	19106.2
2	120	0.1454	2731.35	9550.39
3	230	0.59743	6941.29	6673.64
4	340	0.68073	12426.20	5458.88
5	450	0.738561	18862.6	4798.57
6	560	0.781062	26026.0	4388.74
7	670	0.813508	33756.6	3919.06
8	780	0.838976	41927.9	3919.87
9	890	0.859402	50453.6	3779.06
10	1000	0.876074	59255.1	3674.41

The working range seen in Fig.8, is about 200 cells for this nucleus and changes from 22.8 μm to 140 μm. Hence, the method for grain counting as related to SHE is more informative than for iron group nuclei and makes it possible to determine simultaneously Z and β from the radial distribution of a separate track cross-section. Relationships $N(\rho)$ are shown in Fig.8 on a natural scale for the working ranges $10 \le N(\beta) \le 100$

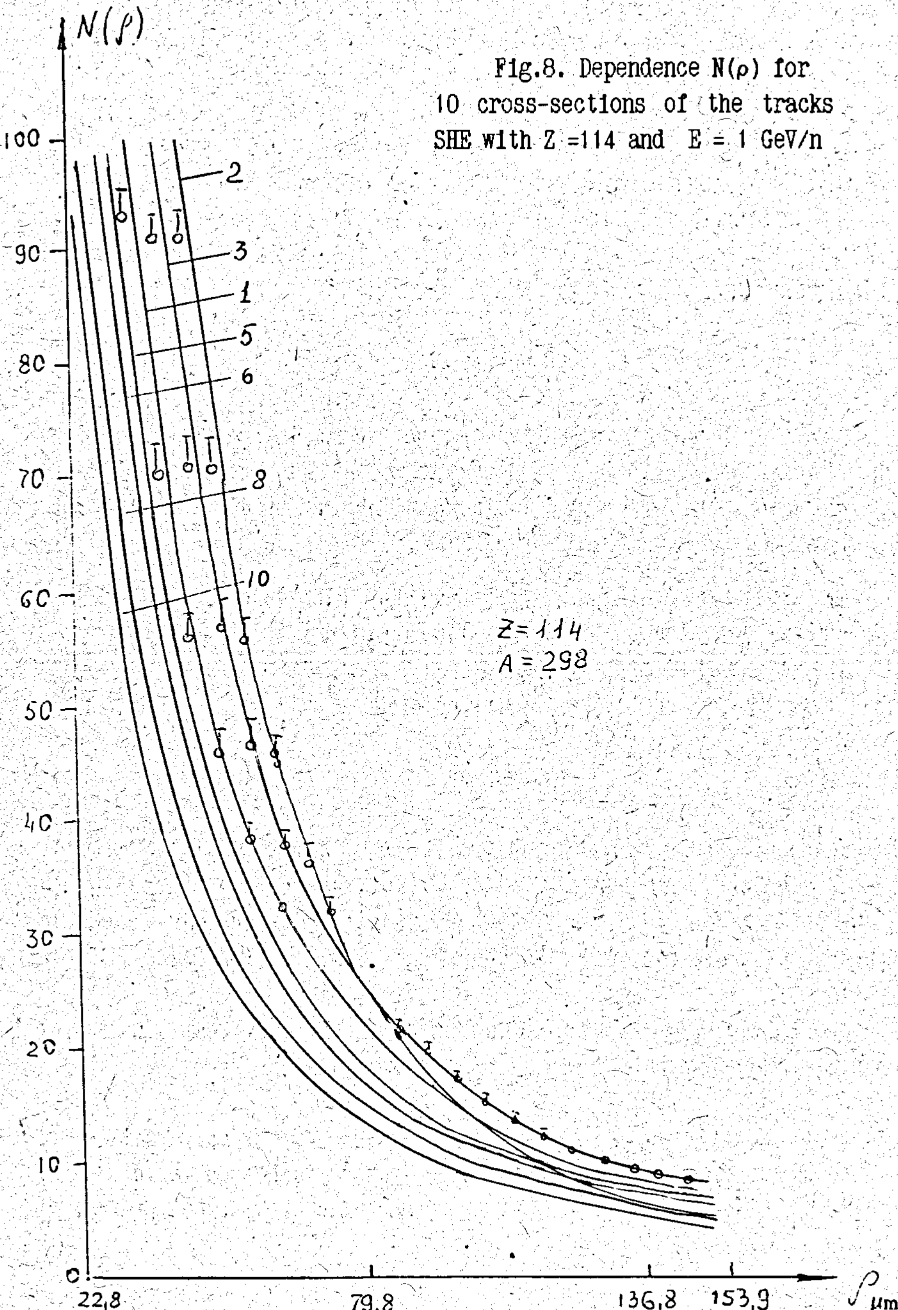


Fig.8. Dependence $N(\rho)$ for 10 cross-sections of the tracks SHE with Z =114 and E = 1 GeV/n

and 22.8 $\mu m \le \rho \le 150$ μm. SHE Z=114 with energy E=10 MeV/nucl forms $N(\rho)$ outside these ranges in accordance with which the curve for cross-section № 1 is absent in this figure. Symbols "·" show the calculated results of $N(\rho)$ for SHE Z=110 for three values of energy: E=120, 230 and 340 MeV/nucl. Vertical lines show different values of $N(\rho)$ for Z=114 and Z=110 which can reach a value of 5 within a distance range of 35-55 μm. At large distances ρ SHE with Z=110 and Z=144 become practically indistinguishable. The resolution of the grain counting method for these nuclei decreases with increasing their velocity.

Conclusions

A more accurate consideration of four relativistic tracks for iron group nuclei shows that the discrepancy in velocities for four registered nuclei appears to be lower than in the previous evaluations. At the same time the high discrepancy in Z is obtained.

The method of grain counting has good possibilities for searching a heavy component of the cosmic irradiation spectrum.

The working ranges of distances from track axis for heavy relativistic nuclei including SHE are determined.

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