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NUCLEAR SIZES AND INTRANUCLEAR MATTER DISTRIBUTION — FROM HADRON-NUCLEUS COLLISIONS

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Размеры ядер и распределение внутриядерной материи — из адрон-ядерных столкновений

Найден и разработан метод исследований внутриядерной материи адронными зондами. Он опробован на случаях ядерных столкновений пион-ксенон.
Определен размер ядра-мишени и построены распределения плотности нуклонов в нем. Они описаны с помощью формул, подсказанных экспериментом.

Работа выполнена в Институте атомной энергии в Сверке и в Лаборатории высоких энергий ОИЯИ.

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Nuclear Sizes and Intranuclear Matter Distribution — from Hadron-Nucleus Collisions

The method of intranuclear matter studies by hadronic projectiles is found and worked out. It is tested on the pion-xenon nucleus collision events.
Target-nucleus size and nucleon density distrubutions in it were estimated and described by formulas prompted experimentally.

The investigation has been performed at the Institute of Atomic Energy in Świerk and in the Laboratory of High Energies, JINR.

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1. INTRODUCTION

About 40 years ago a large amount of experimental data has been accumulated [1–3,4], which contained information with regard to the sizes of the atomic nuclei and the density distribution of the intranuclear matter. This was presented systematically and interpreted in terms of such parameters as nuclear radius, thickness of nuclear surface layer, etc. [4].

At that time the evidences were based on electron scattering, on electrostatic energy shifts, on scattering of nuclear particles, and on the total energy of nuclei. Main experimental facts were obtained by Hofstadter and his associate at Stanford; since he used beams of electrons, his investigation gave information only about the intranuclear protons distributions. It was hoped that soon similar beams of pions and K mesons will tell as much and more about the intranuclear neutrons.

At that time, physicists found right from the start that it is necessary to distinguish between the distributions of protons and of neutrons, and they came to the following conclusions [4]:

1. The proton distribution has a core of constant density surrounded by a surface region in which the density decreases outwards to zero. The evidence is clearest in the surface region and establishes with considerable accuracy the maximum density, the thickness of the surface region and the radial distance at which the density has fallen its maximum value. It is clear in the interior, where the possibility of a slight decrease of the density towards the centre of the nucleus cannot be excluded. The thickness of the surface region varies little for different nuclides and the so-called half-way radius is roughly proportional to $A^{1/3}$.

2. There is inadequate direct evidence on the neutron distribution, and what there is, is not conclusive. However, the indications are quite strong that the neutron distribution does not differ by much from the proton distribution.

3. Assuming that both the nucleons — protons and neutrons — have the same density distributions, then the maximum nuclear density is quite remarkably constant as a function of the mass number A.

It appeared that the knowledge about the intranuclear matter distribution is substantial, but similarly large and substantial is the ignorance of this problem. But, many aspects about the intranuclear matter distribution were at that time so firmly established that it has been possible to apply them in order to investigate other physical quantities.

A few years later, one of the authors of this paper (Z.S.) applied the pion distribution emitted from the hadron-xenon nucleus collision for the neutron/proton ratio determination at the surfacial region of the xenon nucleus periphery [5–7]. Further, a series of experimental investigations of the relations between the characteristics of the fast (≈20–500 MeV kinetic energy) nucleon emission has been performed. It has been shown that the nucleon emission intensity or multiplicity in hadron-nucleus collision is determinated by the target nucleus geometry — by the target nucleus size and the nucleon density distribution in it.

2. ON THE PROCEDURE OF EXPERIMENTAL STUDY OF THE INTRANUCLEAR MATTER PROPERTIES

Investigations of properties of the intranuclear matter involve interaction of the nucleus with nuclear or electrical probe particles. The electric charge and matter distribution inside nuclei is an object of studies first of all, therefore. The probe — for intranuclear matter interactions can be of either an electromagnetic or a nuclear nature, therefore.

The knowledge about the electromagnetic forces is much more conclusive than about nuclear ones. The relationships between charge and magnetic moment distributions and the electromagnetic potentials due to these are well known — as given by Maxwell's equations; the nuclear equivalent of such equations, if exists, remains to be find at yet. The electrically charged probe particles (e.g., electrons, muons) allow one to obtain information about the intranuclear proton distribution only.

In fact, there are actually two distributions — of protons and of neutrons to be under studies. The nuclear or exactly hadronic probes (e.g., mesons, nucleons) should be applied which will tell much more about the intranuclear matter as a whole than the electromagnetic probes.

By such obstacles, we are inclined to employ some specifically «nuclear» effects or facts which manifest themselves in various nuclear effects — obviously, if deeply and conclusively experimentally recognised. The natural relations of these effects with the nuclear matter properties may tell much more about the intranuclear matter and about the target nucleus as a whole. The «effects» should manifest themselves in the hadron-nucleus collisions first of all. Accurate analysis of these collisions may provide information about intranuclear matter distribution and other its properties, about the topic in question: on nuclei sizes and matter distribution in them, about the neutron/proton ratios radial dependencies in atomic nuclei.

In such procedure, the accurate recognition of the yields from the collision processes is of the first importance [8–10].

In the next section, it will be shown that it is possible to realise such programme in practice. Let us start the investigations with the nucleon density distribution in target

nuclei from the multiplicity or intensity distribution of fast nucleons emitted from the target-nucleus.

In studying various collision events, during the xenon bubble chambers photographs scanning, and in performing quantitative analysing of the selected classes of the events registered, many experimental facts were found out. Special exhaustible studies of such facts have been done [8–16]. The results are so firmly established that they may be applied in other physical investigations in question. The mostly appreciated and important here were the data on the hadron passages through nuclei [8–10, 14–16].

The hadron passage through intranuclear matter is a nuclear analogy of the well known electromagnetic process — of the passage of a fast charge particle through layers of materials [8,9]. Usually this nuclear process is covered in hadron-nucleus collisions at energies over the pion production threshold by the particle production effects in the track detectors. But, in the xenon bubble chambers, where γ quanta from the decays of the produced neutral pions as well are registered with the efficiency of nearly 100%, it is possible to distinguish [8–10] the hadron passages in their pure form — without causing the production of observable newly created hadrons — mainly pions. In such cases of traversing atomic nuclei (or intranuclear matter layers, in other words), hadronic projectiles cause emission from the target nuclei of fast nucleons (≈20–500 MeV kinetic energy). The number n_N of the emitted nucleons is equal to the number of the nucleons inside the target-nucleus met by the hadron around its trajectory at the distances equal to or smaller than to the nuclear interaction (force) range R_h, which is nearly as long as the nucleon diameter D_0 is [8–10]. The intensity of the emitted nucleons does not depend on the energy and identity of the hadronic projectile if its energy is large enough for covering the distances in intranuclear matters larger than the target-nuclei diameters are. The range-energy relation for the hadron projectile in intranuclear matter has been observed and determined [17,18].

The energy — and angular — distributions of the emitted fast protons (nucleons) are independent of the identity and energy of the hadronic projectiles at energies high enough (approximately larger than the pion production threshold).

Hadronic projectiles in colliding with atomic nuclei may cause the fast nucleon emission from the target-nuclei in its pure form — without particle production. The particle (hadron) creation process does not influence the nucleon emission process. Two cases of the nuclear collisions can be distinguished in experiments: a) the hadron-nucleus collisions in intranuclear matter leading to the fast nucleon emission only from the target-nucleus [10]; b) the hadron-nucleus collisions in intranuclear matter causing the particle generation process as well. It is convenient to call the first of them a) peripheral or mild hadron-nucleon collisions; in the second case b) it is proposed to call them the hard hadron-nucleon collisions, they may be central hadron-nucleon collisions in intranuclear matter.

It is stated experimentally that particles (hadrons) are created via some intermediate states, or objects, or generons, which, being created inside the target-nucleus, are decaying after having left it — into (usually observed) the so-called generated or created secondary hadrons [11–13]. The generons behave themselves in passing through intranuclear matter as usual hadrons do it [13]. The particle creation process does not influence the nucleon emission and nuclear fragment evaporation process [14], therefore.

A definite simple relation exists between the hadron (pion) deflection angle and the thickness of the intranuclear matter layers traversed by this hadron (pion) [15]. The deflection angle increases in a definite manner with increasing the thickness of the intranuclear matter layer covered by this hadron. The average longitudinal and transverse momenta and kinetic energy of the emitted protons (nucleons) do not depend on the hadron deflection angle [15].

3. THE METHOD

Information about the hadron passage through layers of intranuclear matter obtained experimentally is conclusive and tested accurately [10, 16]. This process is deeply recognized [8,9]. The local character of hadron-nucleus collisions — the definite cylindrical region of the nucleus around the projectile course is involved only — with the radius as large as the nucleon diameter D_0 is, and definite properties of the fast nucleon emission process accompanying hadron passages through intranuclear matter [19] suggests that the distributions $N(n_N)$ or $N(n_p)$ only, of the nucleon n_N and proton n_p multiplicities are in fact the distributions of the intranuclear matter in the cylinders with volumes $V = \pi D_0 \lambda$ at various distances d from the diameter D of the target-nucleus, or at various collision impact parameters d. The distribution $N(n_N)$ or $N(n_p)$ of the emitted fast nucleons contains total information about the matter density distribution in target-nucleus.

The versatile (universal) study of various cases of the fast nucleon (proton) emission intensity is the first mostly important element of the method of determination of the nuclei sizes and matter density distributions by means of hadronic probes. The second important element is the recognition of the physical meaning of various forms of the distributions $N(n_n)$, $N(n_p)$.

It follows from the $N(n_p)$ distributions that the maximum number or multiplicity n_p (or n_N) of the fast protons or nucleons is in fact the diameter or thickness of the target nucleus measured in n_p (or n_N) nucleons per $\pi D_0^2 = S$ area units [nucleons/S].

From experimental studies of the fast nucleon emission intensity or multiplicity distributions $N(n_N)$ in hadron passages through nuclei in their pure form (without causing secondary hadron creation) [10] it follows that:

The number n_N or intensity n_N of the emitted nucleons in covering by the hadronic projectile a definite intranuclear matter layer thickness λ in [nucleons/S] units is always constant, but the proton/neutron ratio in the n_N nucleons fluctuates according to the newtonian binomial distribution [10] with the average value of this ratio

$n_p / n_n = Z/(A-Z)$; D_0 is the nucleon diameter or the strong forces range $D_0 \approx R_h$, A and Z are the mass and charge numbers of the target nucleus.

In fact, it means that there are not two distributions of intranuclear matter, as it was supposed [4], but it is one nucleon- or proton/neutron distribution $N(n_N)$ or $N(n_p / n_n)$. The distributions $N(n_p)$ or $N(n_n)$ are in fact the distributions of nucleons $N(n_N)$, therefore.

Ending this section of the paper, it will be useful to remark that as the measure of the matter thicknesses within nuclei the unit will be used [nucleons/S], [protons/S] or [neutrons/S]. They are the analogies of the units [g/cm^2], used in cosmic ray physics for measuring the thicknesses of matter layers in the Earth atmosphere.

The method is based on experimentally discovered and deeply recognized intranuclear process [8,9] — the passage of a hadron through atomic nuclei, and in general, through layers of intranuclear matter. It may be treated as a nuclear analogy to the well-known electromagnetic process — to the penetration of fast charged particle through layers of materials.

In fact [8]:

1. High energy hadrons can pass through nuclei without causing the particle production; the passage is accompanied by fast nucleon emission in a strictly definite and determined manner; the number of the emitted fast nucleons n_N is $n_N = \lambda S\ (1 - e^{-\lambda/\lambda_t})$, where λ in [nucleons/S] is the intranuclear matter layer thickness covered; λ_t is the hadron mean free path in [nucleon/S], $\lambda_t = 1/\sigma_t$ and σ_t is the total hadron-nucleon cross section in [S/nucl].

2. The nucleon emission in the hadron-nucleus collisions without particle (hadron) production proceeds in the same manner as the emission in any-type collisions when particles are produced, too.

3. The nucleon emission intensity or multiplicity n_N, in hadron-nucleus collisions, is determined by the target-nucleus geometry — by its size and the nucleon density distribution in it.

4. Hadrons, in their passages through intranuclear matter, see the nucleon density distribution in the target nuclei as stable but in which the proton/nucleon ratio fluctuates in definite manner.

5. Hadrons lose their kinetic energy in passing through layers of intranuclear matter; the nucleon emission may be the observed phenomenon related to the energy loss and stopping of the hadrons in intranuclear matter [9].

This analogy is rough enough, but it is an analogy of the nuclear process, when short range forces are acting, to the electromagnetic process — in the wealth of the coulomb forces.

The nuclear process, which is employed as a base for the method, is tested experimentally in many works during about 20 years and it is recognized in detail.

It follows from the nature of this nuclear process that the nucleon multiplicity n_N (or intensity n_N) distribution $N(n_N)$ in the hadron-nucleus collision events is in fact the distribution of intranuclear matter layers thicknesses λ expressed in [nucleons/S] units; this unit is the analogy of the units of material thickness measured in [g/cm^2] — as it is frequently used in cosmic ray physics — for measurements of the Earth atmosphere thicknesses of layers of the atmosphere.

This intranuclear matter distribution is in fact the distribution of average densities of the intranuclear matter within the cylindrical volumes of the radii D_0, centred on the hadronic projectile courses. It is principally possible to transmit these densities into radial densities.

The fluctuation of the neutron/nucleon ratio indicates that in fact in the case of the shortly acting forces it is meaningless to distinguish the distribution of the protons and neutrons in the nuclei. One has to do with one distribution $N(n_N)$; the neutron distributions $N(n_n) = N(n_N\{(A-Z)/Z\})$ and the proton distributions $N(n_p) = N(n_N\{Z/(A-Z)\})$ are its components — neutral and charged.

The method of the matter density distribution determination in nuclei by means of hadronic projectiles is based on very simple relation obtained in our experiments.

The number n_N (or multiplicity) of the emitted fast nucleons from the target nucleus is:

$$n_N = \lambda S(1-e^{-\lambda/\lambda_t}), \qquad (1)$$

where λ in [nucleon/S] and $S = \pi D_0^2 \approx 10[\mathrm{fm}^2]$, D_0 is the nucleon diameter as large as the nuclear force range R_h is; λ_t is the hadron mean free path in intranuclear matter, connected with the hadron-nucleon collision total cross section σ_t as $\lambda_t = 1/\sigma_t$ in [nucleon/S], σ_t is in [S/nucleon]. The formula (1) was tested experimentally [19]. It is valid for pure passage and for any sample of any-type hadron-nucleus collisions.

The relation between the distribution $N(n_N)$ obtained experimentally and the distribution $W(\lambda S) = W(n_N)$ of the matter layer tnickness λ in [nucleon/S] written on the basis of experimental findings is [7,20]:

$$N(n_N) = W(n_N)\cdot(1-e^{-(\lambda S/\lambda_t S)}) = W(n_N)\cdot(1-e^{-(n_N/n_t)}). \qquad (2)$$

where $\lambda_t S = n_t$; $\lambda_t S = n_N$ the exponential coefficient is the opacity of the intranuclear matter for the incident hadron.

More complicated relation can be written for the proton multiplicity n_p distribution $N(n_p)$ and between the intranuclear matter layer thickness λ distributions $W(\lambda) = W(\lambda s = n_N)$:

$$N(n_p) = \sum_{n_N=1}^{n_N=DS} W(n_N)(1-e^{-(n_N/n_t)})C_{n_N}^{n_p}\left(\frac{Z}{A}\right)^{n_p}\left(1-\frac{Z}{A}\right)^{n_N-n_p}. \qquad (3)$$

The last new factor in formula (3) takes into account the fluctuations of the emission intensity of the protons among the definite number of the emitted nucleons n_N, at a definite collision impact parameter; it should be remembered that $n_N = \lambda(n_N)S$, $n_t = \lambda_t S$. The fluctuations were discovered experimentally [10].

The number n_N of nucleons within a tube with the radius D_0 located at a distance d (in nucleons diameter D_0) from the target nucleus diameter is expressed by the relation:

$$n_N = \pi D_0^2 \lambda, \qquad (4)$$

where λ in D_0 diameters is the length of the tube with the radius D_0. This number n_N may be treated as constant at any collision impact parameter d. But, the probability $P(n_p)$ to find the number n_p of protons among n_N nucleons is determined by newtonian binomial formula (distribution):

$$P(n_p) = \binom{n_N}{n_p} p^{n_p}(1-p)^{n_N-n_p}, \qquad (5)$$

where p is the probability for the incident hadron to meet in any time moment a proton in passing through a nucleus. For the xenon nucleus $p = Z/A = 0.412$; n_N is the number (or multiplicity) of the emitted fast nucleons (20–500 MeV kinetic energy). The maximum of the probability $P(n_p)$ lies at n_p from the relation:

$$n_N p + p - 1 \le n_p \le n_N p + p. \qquad (6)$$

4. EXPERIMENTAL DATA

In Figs.1–3, the distributions $N(n_p)$ are done of the multiplicities n_p of the fast protons emitted from the xenon target-nuclei — in various kinds of the collision sample collections from pion-xenon nucleus collisions at 3.5 GeV/c momentum, obtained in 180 litre xenon bubble chamber exposed to the beam of the pions from the accelerator of the Moscow Institute of Theoretical and Experimental Physics [10—12].

In this paper, the data from the xenon bubble chamber will be employed, e.g., the data are shown on three figures.

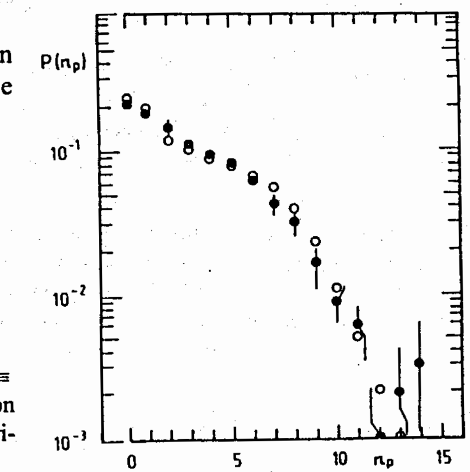

Fig 1. The multiplicity n_p distribution $N(n_p) \equiv P(n_p)$ in pion-xenon nucleus any-type collision events at 3.5 GeV/c momentum; ● — experimental data, O — predictions by formula (3)

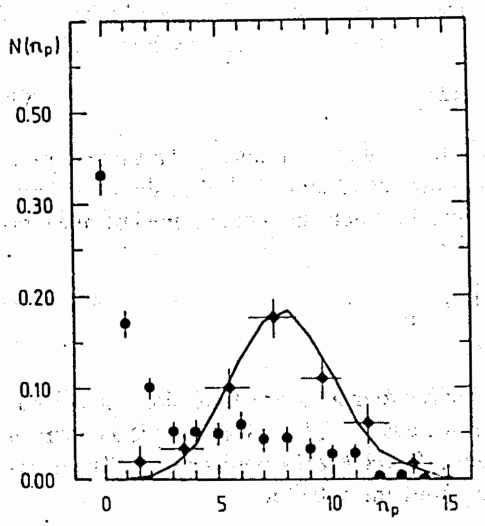

Fig 2. The multiplicity n_p of the protons distribution $N(n_p)$ in the subsample of the pion-xenon nucleus collisions when the incident pion stopped inside the target nucleus; the incident pions are with 3.5 GeV/c momentum. ♦ — experimental data, solid line is the poligon predicted by formula (5) from our former work [10]. ● — experimental data for the subsample of pure passages of the incident pions through the xenon target nuclei

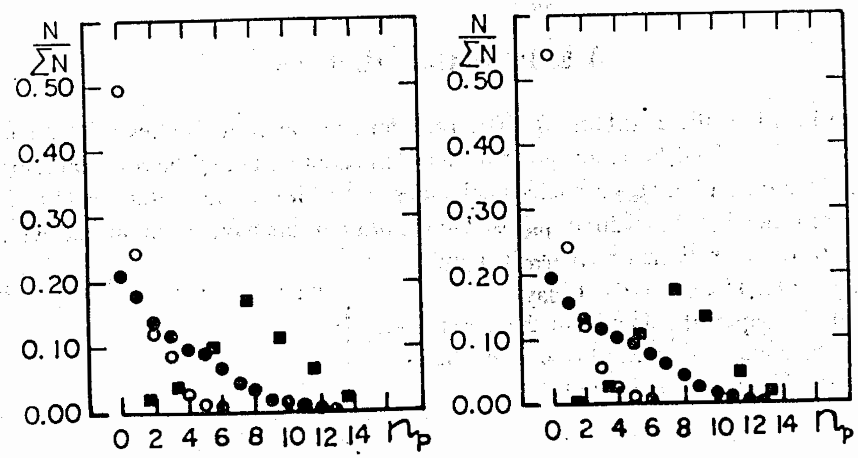

Fig 3. The proton multiplicity n_p distributions $N(n_p) \equiv N/\Sigma N$ in pion-xenon nucleus collisions at 3.5 GeV/c momentum: O — passages, ■ — the stoppings, ● — any-type collision events. Left side — experimental data, right side — predictions given by corresponding formulas (2), (5), (3). N — number of events at a given proton multiplicity [7]

5. RESULTS

The description of the method in section 3 and presentation of adequate experimental data in section 4 allow us to obtain results in question.

5.1. The Target Nucleus Size Estimation

Two evidently possible procedures are for using here:

a) The evident relation between nuclear radius [4] R and the number A of the nucleons in the xenon target nucleus $^{131}Xe_{54}$ is:

$$4/3\pi R^3 = 131 \tag{7}$$

R is in nucleon diameters D_0, $[D_0 \approx R_h]$. Then, $R = 3.15 D_0$ or target nucleus diameter $D = 2R = 6.3 D_0$.

b) The second relation may be employed as well — the value of the nucleus diameter D from the «stopping» events, from Fig.2 [10] is:

$$\pi D_0^2 h = 19, \tag{8}$$

where D_0 is the nucleon diameter in the nucleon diameter units, and h in D_0 units as well is the intranuclear matter layer thickness covered in passing along the target-nucleus diameter in the stoppings. Then, $h = (6.1 \pm 1) D_0$ within the xenon nucleus. It means that the nucleus diameter D in nucleon diameters D_0 is:

$$h = (6.1 \pm 1) D_0, \quad D = (6.05 \pm 1) D_0. \tag{9}$$

Both of the two ways of the nucleus diameter obtaining lead to the same values for the xenon nucleus, within the error of estimation of the value of the quantity h (the length of the intranuclear matter layer thickness along the target-nucleus diameter).

5.2. The Distribution of the Proton/Neutron Ratio inside the Xenon Nucleus

The finding of the proton multiplicity n_p fluctuations at a definite nucleon multiplicity n_N = const in intranuclear matter, at a distance from the nuclear diameter means that there cannot be two distributions $N(n_p)$ and $N(n_n)$ — for the protons and neutrons. It is one distribution of the nucleons $N(n_N)$ in which the ratio n_p / n_n fluctuates in a definite manner; it is experimentally stated, it follows from formulas (3) for $N(n_p)$ distribution; the fluctuations are described by formula (5).

5.3. Proton Multiplicity n_p Distributions $N(n_p)$ in Various Samples of the Pion-Xenon-Nucleus Collision Events

The distributions are expressed by formulas (2), (3), (5) as confronted to corresponding experimental data which are presented on Figs.1,2,3.

5.4. *The Physical Meaning of the Multiplicities* n_N, n_n, n_p *Distributions* $N(n_N)$, $N(n_n)$, $N(n_p)$

The nucleon multiplicity n_N, the neutron multiplicity n_n and the proton multiplicity n_p distributions $N(n_N)$, $N(n_n)$, $N(n_p)$ are in fact distributions of the thicknesses of intranuclear matter tubes lengths λ involved in the hadron-nucleus collisions at various distances from the nucleus diameter; the lengths are expressed in [nucleon/S], [neutron/S] and [proton/S] units. The maximal values of the multiplicities n_N max, n_n max, n_p max are in fact the maximum numbers of the distributed nucleons (along the nuclear diameter D), they correspond to the minimal distances or impact parameters d from the nucleus diameters — to the minimal impact parameters d in nuclear collisions. To the minimal values of the multiplicities in corresponding distributions there correspond the minimal thicknesses of intranuclear matter — on the periphery of the target nucleus.

6. CONCLUSIONS AND REMARKS

Summing up, following mostly important conclusions and remarks may be enumerated:

1. The method of the studies and estimations of the intranuclear matter characteristics by means of hadronic probes is discovered and worked out, and tested in experiments — in the hadron-xenon-nucleus nuclear collisions.

2. The physical meaning of the multiplicities n_N, n_n, n_p distributions $N(n_N)$, $N(n_n)$, $N(n_p)$ is discovered.

3. The additional motivations for the existence of the nuclear analogy for the electromagnetic process of charged particle passage through layers of materials are presented. The hadrons, in passing through layers of intranuclear matter interact locally with this matter — around the hadronic probe course at the distance R_h — as long as the nucleon diameter D_0 is.

4. Only one nucleon multiplicity n_N distribution $N(n_N)$ characterises the matter distribution in nuclei; the neutron/nucleon ratio in this distribution fluctuates according the newtonian binomial distribution. The average value of the n_p / n_N ratio is constant and it equals to Z/A, at any collision impact parameter.

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