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MATTER DENSITY DISTRIBUTION IN ATOMIC NUCLEI AS ILLUMINATED BY HIGH ENERGY HADRONS

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Стругальский З. E1-91-243
Распределение плотности материи в атомных ядрах,
полученное с помощью адронов высоких энергий

Предлагается метод изучения распределения плотности материи в ядрах с помощью адронов высоких энергий. Обнаруженный нами процесс - прохождение адронов через атомные ядра - применяется в качестве физической основы метода; прохождение сопровождается испусканием нуклонов с ядер-мишеней. Распределение интенсивности испускания связано с распределением нуклонов в ядре-мишени, интенсивность испускания нуклонов в данном случае столкновения пропорциональна толщине преодоленного адроном слоя материи в ядре. В качестве примера определено распределение плотности материи в ядре атома ксенона. Распределение материи в ядре не отличается заметно от распределения в нем электрического заряда и не распространяется много вне этого распределения. Кажется, что адронный снаряд видит, при проникании через ядро-мишень, определенное число нуклонов при определенном параметре стролкновения, но число протонов среди нуклонов флуктуирует определенным образом - согласно биномиальному закону; в среднем, это число соответствует соотношению числа нейтронов к числу протонов как (A - Z)/Z.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

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Matter Density Distribution in Atomic Nuclei
as Illuminated by High Energy Hadrons

The method is proposed for the intranuclear matter density distribution study by means of high energy strongly interacting probes. The newly recognized process - the passage of hadrons through atomic nuclei - is employed as the physical basis of the operational principle of the method; the passage is accompanied by the nucleon emission from the target nuclei. The distribution of the nucleon emission intensity is connected with the nucleon density distribution in the target nucleus, and the nucleon emission intensity in a collision event depends simply on the intranuclear matter layer thickness covered by the hadronic projectile. As an example, the matter distribution in the xenon nucleus is determined. The matter distribution in the nucleus does not differ markedly from the charge distribution and does not extend by much beyond it. It seems that the hadronic projectile sees a definite number of nucleons at a definite impact parameter, in passing through the target nucleus, but the number of the protons among the nucleons seen fluctuates according the binomial formula; in average, this number corresponds to the neutron-proton ratio (A-Z)/Z.

The investigation has been performed at the Laboratory of High Energies, JINR.

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1. INTRODUCTION

The subject in this paper is to obtain experimental information about matter density distribution in nuclei by means of hadronic projectiles. The application of high energy hadrons as probes for the intranuclear matter distribution studies has long been a difficult problem [1-3]. A need for such studies arises in attempts to obtain in a direct way some information about the neutron density distribution in nuclei. We now have a precise knowledge of the shapes and sizes of charge distributions in nuclei throughout the periodic table, as a result of the accurate electron scattering experiments by Hofstadter and collaborators in the mid-fifties [4]. The indications are quite strong that the neutron distribution does not differ markedly from the proton distribution [1] and does not extend by much beyond it; there is inadequate direct evidence on the neutron distribution inside nuclei, and what there is, is not conclusive [1,2]. The difficulty in measuring neutron or nucleon distributions is, of course, that the electromagnetic interaction provides little information. After considerations, we were led to the conclusion that the only probes of the whole intranuclear matter distribution must be strongly interacting [2].

But, many methods which have been used, in studying the nuclear structure by means of the strongly interacting probes necessarily involved some model-dependences of the results obtained. Moreover, the collision of a hadron with a nucleus does not distinguish itself by the basic simplicity, similarly as the collision of electrons with nuclei. The hadron-nucleus collision leads, in contrast, to interaction of particles of rather complicated structure - as pion and proton - with nuclei, or as a nucleus with a nucleus.

Thus, some model-independent method should be worked out and more experimental investigations are desired using the method which, in a direct way, will tell us as much and more about the neutrons in nuclei.

Our first attemps to work out some model-independent method have been made before about 30 years [5] and were continued up to last a few years [3,6].

The aim of this work is: a) to describe new appropriate model-independent method of nucleon density distribution determination in nuclei by means of hadronic probes; b) to obtain the distribution for the $^{131}Xe_{54}$ nucleus, as an example; c) to propose to realize similar measurements for various nuclei in beams of hadrons from accelerators.

2. HEURISTIC CONSIDERATIONS

In Hofstadter´s experiments quite remarkably precise information on the distribution of protons in a nucleus was obtained, but it could be discovered anything directly about neutrons - because it relied entirely on electromagnetic information. The information on neutrons can only come from the use of hadronic probes - such as mesons and nucleons. Unfortunately there are here theoretical difficulties which make the interpretation of experimental results very much less certain than in the case of electromagnetic measurements.

In such circumstances, the only way now is to look for appropriate nuclear process in which the outcome in hadron-nucleus collision reaction depends simply and definitely on the nucleon distribution in the target nucleus; this process should be connected with hadron passage through intranuclear matter accompanied by clearly observable and identificable effects. For example, it should be nuclear process something like the well known electromagnetic process - like the passage of electrons through layers of a material. Intuitively, a nuclear analogue of the electromagnetic process should exist in nature, we should observe it sometimes in its pure form - as the passage of high energy hadron through a massive nucleus. Because of the short range of the nuclear forces, such process, if exists, could provide data on nucleon distribution in nuclei localized precisely enough; the expected secondary effects which the passage could be accompanied by should be the emission of nucleons from the target nucleus or nuclear fragments. Such nuclear process - the passage of hadrons through intranuclear matter could be applied as a physical principle of the method for nucleon density distribution determination, if characteristics of the secondary effect, of the nucleon emission - for example, are definitely and clearly dependent on the intranuclear matter layer thickness involved in the hadron-nucleus collisions.

The hadron passage through intranuclear matter - the nuclear analogue of the electromagnetic process - of the passage of electrically charged particle through layers of matter - has been found in our experiments and studied in detail [7-11].

The passage is accompanied by nucleon emission from the target nucleus, and the nucleon emission intensity is related simply to the thickness of the intranuclear matter layer covered by the hadronic projectile.

We employ this nuclear process as physical basis for our method.

The passage of a hadron through intranuclear matter is accompanied by nucleon emission from the target nucleus in a definite manner. All characteristics of the nucleon emission at energies high enough - at a few GeV - are identical in the events of pure passage - when particle production does not occur and in the any-type events - when particles are produced as well in the hadron-nucleus collisions [12]. We may think, therefore, that the passage is a fundamental process in hadron-nucleus collisions, and on the background of it the particle production occurs in some cases. Then, at energies high enough - above a few GeV (about 4 GeV for pion-nucleus and about 8 GeV for nucleon-nucleus collisions), in any of collisions the incident hadron passes through the target nucleus and loses its kinetic energy. The emitted nucleons, which the hadron passage is accompanied by, are the g-track leaving nucleons electrically charged registered in photonuclear emulsions.

The intensity of the nucleons emitted depends simply on the intranuclear matter layer thickness covered by hadronic projectile [13].

The emission of nucleons proceeds in the same manner for all kinds of incident hadrons [13].

3. THE METHOD

The method of the matter density distribution in nuclei determination by means of hadronic projectiles bases on very simple relation, obtained in our experiments [7-13]: The number n_N, or the intensity n_N, of the nucleons emitted from the target nucleus, when a high energy hadron traverses it along a thickness λ, is

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

where λ in nucleons/S, and $S = \pi D_0^2 \approx 10\ fm^2$, is the nucleon diameter as large as the nuclear force range; λ_t is the hadron mean free path in intranuclear matter, connected with the hadron-nucleon total cross-section σ_t as $\lambda_t = 1/\sigma_t$; λ_t is in nucleons/S, σ_t is in S/nucleon. The formula (1) was tested experimentally [8] for the mean intensity $<n_p>$ of the protons emitted in hadron-nucleus collisions at energy interval from about 2 up to about 3500 GeV. The formula (1) is valid for the sample of the pure passage events and for the sample of any-type hadron-nucleus collisions; the independence of the relation of the kind of the incident hadron characterizes it.

On the basis of the formula, it can be stated that:

1. The number of nucleons n_N emitted in any hadron-nucleus collision event, at an incident hadron kinetic energy high enough, provides the information about the thickness λ in nucleons/S of the intranuclear matter layer covered by the projectile hadron in the target nucleus.
2. The mean number $<n_N>$ and the maximum number $n_{N\,max}$ of the emitted nucleons in the sample of hadron-nucleus collisions are simply related to the mean thickness $<\lambda>$ in nucleons/S and maximum thickness λ_{max} in nucleons/S of the target nucleus.
3. The multiplicity n_N, or intensity n_N, distribution $N(n_N)$ of the nucleons emitted in a numerous sample of collisions of a definite hadron with a definite nucleus is in fact the distribution $W(\lambda)$ of the thicknesses λ in nucleons/S of the target nucleus at various distances b from the nuclear diameter, or at various impact parameters b; the thickness $\lambda \equiv \lambda(b)$, where $0 \le b \le R$, and R is the radius of the target nucleus; b and R may be expressed in fm.

On the other hand, the distribution $W(\lambda)$ of the thicknesses $\lambda(b)$ in a nucleus depends simply [14] on the radial distribution [1] $\rho(r)$ in nucleons/fm^3 of the matter density in this nucleus; $0 \le r \le R$.

The relation between the distribution $N(n_N)$ obtained experimentally and the distribution $W(\lambda \cdot S) \equiv W(n_N)$ of the matter layer thicknesses λ in nucleons/S, written on the basis of experimental findings, is [15]:

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

where $\lambda_t = 1/\sigma_t$, σ_t are the above determined quantities, $\lambda_t \cdot S \equiv n_t$, $\lambda \cdot S \equiv n_N$; the exponential coefficient is the opacity of the intranuclear matter for the incident hadron. In formula (2), the values $N(n_N)$ at $n_N = 1$, $n_N = 2, \dots$, $n_N = n_{N\,max}$ are

given from an experiment, σ_t and S are known as well. Then, $W(n_N)$ - the distributions of the intranuclear matter layer thicknesses $\lambda \cdot S \equiv n_N$ - may be evaluated from the $n_N = 1, \dots,$ $\dots, n_{N\,max}$ equations (2).

From the distribution $W(n_N) \equiv W(\lambda \cdot S)$, one can evaluate [16] the radial distribution $\rho(r)$ of the intranuclear matter density in the target nucleus.

Similar, although more complicated, relation can be written for the proton multiplicity n_p distribution $N(n_p)$ and the intranuclear matter layer thicknesses λ distribution $W(\lambda) \equiv$ $\equiv W(\lambda \cdot S \equiv n_N)$, it is [15]:

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

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, at a definite collision impact parameter; it must be remembered that $n_N \equiv \lambda(n_N) \cdot S$, $n_t \equiv \lambda_t \cdot S$. The fluctuations were found experimentally [17].

The mean intensity $<n_p>$, or mean proton multiplicity $<n_p>$, is:

$$<n_p> = \frac{Z}{A} S \cdot <\lambda> \cdot (1 - e^{-\frac{<\lambda>}{\lambda_t}}). \qquad (4)$$

More information about relations between the nucleon emission intensity and the thickness λ in nucleons/S passed by the incident hadron, in various cases of the hadron-nucleus collisions, one can find in our former work [17].

In formula (2), the distribution $W(\lambda(b))$ of the intranuclear matter layer thickness $\lambda(b)$ at any impact parameter b is related simply to the observed distribution $N(n_N)$ of the nucleon emission intensities n_N, which are b-dependent as well $n_N(b) = \lambda(b) \cdot S$. In formula (3), the distribution $W(\lambda(b))$ is related to the distribution $N(n_p)$ of the proton emission intensity n_p.

In fact, relations (2) and (3) are systems of equations - $n_N = 1, 2, 3, \dots, n_{N\,max}$ equations with n_N quantities $W(n_N)$ which should be estimated; similarly, relation (3) is in fact a system of $n_p = 1, 2, \dots, n_{N\,max}$ equations with $n_{N\,max}$ unknown quantities $W(n_N)$.

The method of the matter density distribution determination by means of hadronic projectiles may be used, therefore, in two variants:

1. By solution of the systems of equations (2) or (3) and determination of the radial distribution $\rho(r)$ of the intranuclear matter density from the distribution $W(n_N)$ obtained in solution of the equations.
2. By comparison of the experimental distribution $N(n_N)_{exp}$ or $N(n_p)_{exp}$ with corresponding distributions $N(n_N)_{calc}$ or $N(n_p)_{calc}$ predicted by formulas (2) and (3) correspondingly, when some hypothetical distribution $W(n_N)$ is used in the calculations; the Fermi distribution may be used, for example. The agreement of $N(n_N)_{exp}$ or $N(n_p)_{exp}$ with corresponding $N(n_N)_{calc}$ or $N(n_p)_{calc}$ will indicate that the intranuclear matter density distribution in atomic nucleus used as the target is as the hypothetical one.

Both the analyses may be performed on the sample of pure passages of hadronic projectile through the target nucleus or on the sample of all any-type hadron-nucleus collision events, because the characteristics of the nucleon emission process in pure passages and in the events with particle production are identical [18], at energies larger than about a few GeV.

It can be stated that the distributions $N(n_p)$ or $N(n_N)$ of the emission intensities n_p or n_N of the protons or nucleons emitted in hadron-nucleus collisions contain information about the matter density distribution in target nuclei. Any of experimental arrangements which provides accurate distributions $N(n_p)$ and $N(n_N)$ can be used, therefore, for studies of the matter density distributions in nuclei.

As an example, we present in the next section the results of the matter density distribution determination using 180 litre xenon bubble chamber exposed to pion beams at 3.5 GeV/c momentum.

4. EXPERIMENTAL DATA

The sample of the hadron-nucleus collision reactions, used in this work, included 6301 pion-xenon nucleus collisions at 3.5 GeV/c momentum registered in 180 litre xenon bubble chamber. Among the 6301 any-type

$$\pi^- + Xe \to n_p + n_x + F \qquad (5)$$

collisions (where n_p - number of the emitted protons; n_x - number of produced particles, mainly pions; F - various fragments

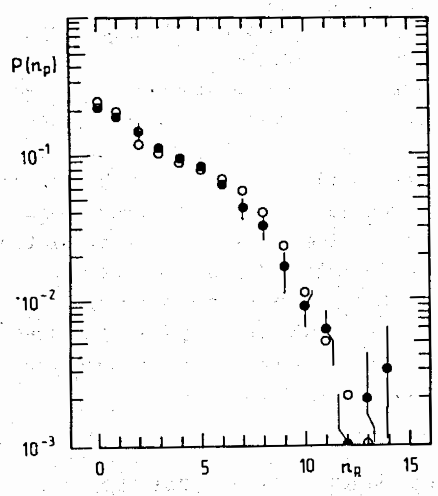

Fig.1. The multiplicity n_p distribution $N(n_p) \equiv P(n_p)$ in pion-xenon nucleus any-type collision events at 3.5 GeV/c momentum; • - experimental data [3], o - predictions by formula (3).

of the target nucleus) 848 events were pure passages of incident pion through the xenon nucleus, of the type

$$\pi^- + Xe \to n_p + F + \pi^- \qquad (6)$$

and

$$\pi^- + Xe \to n_p + F; \qquad (7)$$

in the reaction (7) incident hadrons stopped inside the target nucleus, 78 events were the stoppings. Additional analysis shows [17] that stoppings at 3.5 GeV/c occur in the xenon nucleus at the collision impact parameter near to 0. The sample of the pure passages was enlarged in additional scanning and analysis of selected events, and contained in total about 1000 events of the type (6) and (7) together.

In fig.1, the multiplicity n_p distribution $N(n_p)$ of the protons emitted in the sample of any-type pion-xenon nucleus collisions at 3.5 GeV/c momentum is presented. In fig.2, the distribution $N(n_p)$ is presented in the subsample of the events in which the pion projectile passes through the target xenon

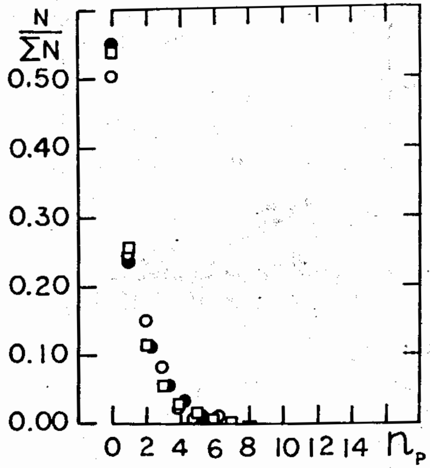

Fig.2. The multiplicity n_p of the emitted protons distribution $N(n_p) \equiv N/\Sigma N$ in the subsample of pion-xenon nucleus collisions without particle production - in which pure passage of the projectile pion through the target xenon nucleus occurs; o - experimental data corrected for inefficiency, □ - experimental data from any-type collision events after taking into account the transparency coefficient for the pionic projectile in the target nuclei, • - calculations by formula (11) from our former paper [15].

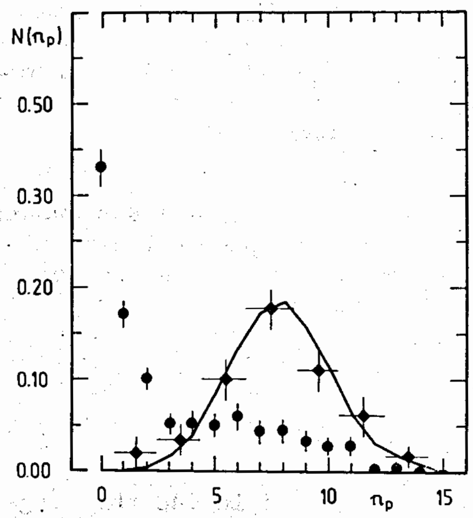

Fig.3. The multiplicity n_p of the protons distribution $N(n_p)$ in the subsample of the pion-xenon nucleus collisions when the incident pion stopped inside the target nucleus; the incident pions are with 3.5 GeV/c momentum. ♦ - experimental data, solid line is the poligon predicted by formula (4) from our former work [17]. ● - experimental data for the subsample of pure passages of the incident pions through the xenon target nuclei.

nucleus without causing particle production. In fig.3, the proton multiplicity n_p distribution is shown in the subsample of incident pion stoppings inside the xenon target nucleus. In fig.4, on the left side, the $N(n_p)$ distributions of the multiplicities n_p of the emitted protons in the any-type events, in the passages, and in the stoppings in collisions of 3.5 GeV/c momentum pions with xenon nucleus are presented together. for comparison.

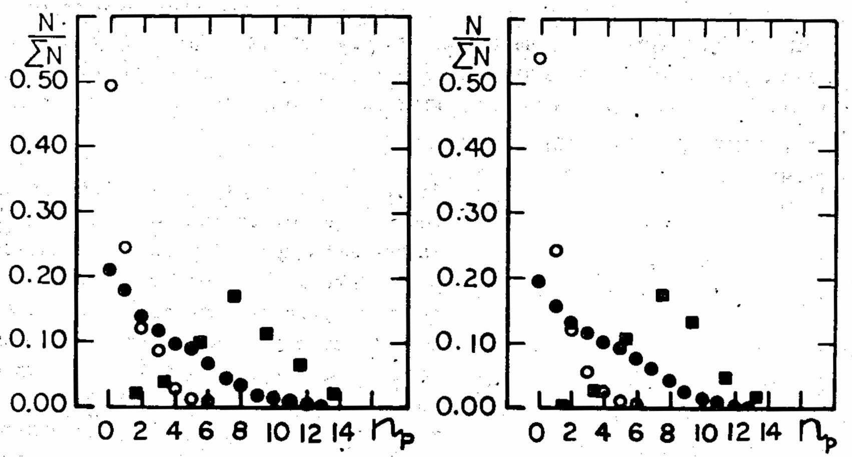

Fig.4. The proton multiplicity n_p distributions $N(n_p) \equiv N/\Sigma N$ in pion-xenon nucleus collisions at 3.5 GeV/c momentum: ○ - passages, ■ - the stoppings, ● - any-type collision events. Left side - experimental data, right side - predictions given by corresponding formulas [15,17]. N - number of events at a given proton multiplicity.

On the distributions obtained experimentally, the distributions expressed by corresponding formulas are superimposed. The comparisons both of the distributions - those from the experiment and the calculated ones - are discussed in the next section.

5. RESULTS AND DISCUSSION

The proton multiplicity n_p distributions $N(n_p)$ for any of the samples of events mentioned above were calculated, using corresponding formulas, under assumption that the intranuclear matter density is distributed according to the distribution [1] - according to the distribution of the electric charge in nuclei. In the formulas used there were not any free parameters, all quantities used in them are from experiments. The results of calculations were compared with corresponding experimental data, figs.1-4.

From the comparisons, it can be stated that:

1. Formulas [15] describe experimental data well enough;
2. From the agreement of the experimental data with appropriate results of the calculations, we are in the position to conclude that the Fermi distribution which describes well the distribution of the protons expresses as well the distribution of all the nucleons, and the distribution of the neutrons - in particular;
3. The number n_p of protons which hadronic projectile sees among n_N nucleons, in traversing the nucleus, at a definite impact parameter b fluctuates according to the binomial formula [17]; in average the ratio $\langle n_p\rangle/n_N = Z/A$.

The agreement is stated within an accuracy of about (10 ÷ ÷15)%.

Similar analysis of the matter density distributions in nuclei was performed for the aluminium and gold nuclei [16], using $N(n_p)$ distributions obtained in studying kaon and pion collisions with the nuclei [19] at 250 GeV/c momentum.

There are of a crucial character the experimental testings of the predictions given by formula (4) for mean values $\langle n_p\rangle$ in various hadron-nucleus collisions at various energies. The testing has been done up to about 3500 GeV/c momentum of hadronic projectiles; the data are in the Table [8]. From the results presented in the Table, agreement well enough should be stated.

In analysing the experimental data, for determination of the matter density distribution in nuclei, we applied only

Table. Mean multiplicities of fast protons $\langle n_p \rangle$ emitted in hadron-nucleus collisions at various energies: experimental data and predicted by formula (4). Experimental data are from Table 2 in our former work [8], where the references for original sources may be found

Reaction	Energy GeV	$\langle n_p \rangle_{exp}$	$\langle n_p \rangle_{calc}$
Pi⁻+ Xe	3.5	3.20 ± 0.01	3.19
Pi⁻+ Em	60	2.04 ± 0.12	*1.90
Pi⁻+ Em	200	2.17 ± 0.10	*1.87
Pi⁺+ Al	250	1.2 ± 0.1	1.23
Pi⁺+ Au	250	3.7 ± 0.3	3.71
K⁺ + Al	250	1.2 ± 0.06	1.09
K⁺ + Au	250	3.3 ± 0.2	3.54
p + Em	6.2	3.58 ± 0.11	**3.01
p + Em	22.5	3.38 ± 0.14	**2.99
p + Em	67	2.66 ± 0.12	**2.99
p + Em	200	2.61 ± 0.18	**2.99
p + Em	300	2.60 ± 0.2	**2.83
p + Em	400	2.90 ± 0.2	**2.85
p + Em	2000	2.62 ± 0.50	**3.03
p + Em	3500	2.6 ± 0.5	*2.29

In calculations, using formula (4), the following quantities were used: $\langle \lambda \rangle$ in protons/S from our work [20]; $\lambda_t = 10.3/\sigma_t$, where σ_t in fm² is from pp or Pip reactions given is Rev. of Particle Properties [21]; for emulsions (Em) the mean values for the charge and mass numbers are $\langle A \rangle = 66.6$ and $\langle Z \rangle = 2.93$. * - calculated for the "average" emulsion, ** - calculated for AgBr composition.

the 2nd variant of the method. We do not use here the 1st variant - the solution of the system of equations, because the data which should be used for this procedure must be more accurate - the sample of the hadron-nucleus collision events should be much more large. We expect the 1st variant of the method will provide more accurate information about the matter density distribution in atomic nuclei.

The method proposed here may be used for the matter density distribution determination in nuclei by means of other detectors - by means of various track detectors and electronic arrangements.

What new is obtained in this work is the experimental finding of the electric charge fluctuation in target nuclei around

the projectile hadron course [17]. The incident hadron, in passing through a definite atomic nucleus at a definite impact parameter b sees always definite number $n_N(b)$ of the nucleons at the strong action range around his course in intranuclear matter, but the number n_p of the protons seen among the nucleons met fluctuates according to the binomial formula [17].

In preparing proposals for the future experiments, one should remember that the distributions $N(n_N)$ or $N(n_p)$ of the multiplicities n_N of the emitted nucleons or n_p of the emitted protons contain information on the matter density distribution in nuclei. Then, any data on the distributions, obtained accurately enough in any of experiments at energies higher than about a few GeV may be used for the investigations in question. Such investigations may be performed on the material from appropriate experiments realized on accelerators by means of track detectors and electronic arrangements in which the nucleons, or the protons only, emitted from the target nuclei in hadron-nucleus collisions are registered with an efficiency near to 100% within 4π solid emission angle.

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