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# THE LAWS OF NUCLEON EMISSION AND TARGET FRAGMENT EVAPORATION IN COLLISIONS OF HIGH ENERGY HADRONS WITH ATOMIC NUCLEI

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## 1. INTRODUCTION

It is commonly known that when atomic nuclei are bombarded by high energy hadrons, of energies above the pion production threshold, the particle production and the emission of nucleons from the target nuclei take place. The presence of events in which intensive emission of nucleons appears without particle production [1,2] leads to the conclusion that the nucleon emission process can proceed independently of the particle production.

Data on the hadron-nucleus collisions obtained during ten last years in our experiments performed by means of the 26 and 180 litre xenon bubble chambers [3,4], and the wealth of data available [1,2,5-9], were laid the foundation of new picture of the collision process which emerged in the attempt to understand these data. The xenon bubble chambers served as 4Pi detectors in which almost all emitted protons and produced particles, in particular electrically charged and neutral pions, were registered, and energies and emission angles of almost all protons and pions were measured with an accuracy high enough in order to obtain a conclusive information about a collision process. The well-known information about the nucleon density distribution in nuclei [10,11] with additional data on the neutron-proton ratio at the periphery of the atomic nucleus [12,13] allowed to treat the target nucleus as a nuclear matter slab, and a sample of hadron-nucleus collision data to treat as a result of interaction of a monoenergetic hadron beam with the nuclear matter slabs of various thickness.

In systematizing the data by a scientist a creation of new additional information occurs as well. All these results of experiments and of the systematization of them can be summarized in a few basic laws. But, when we arrive at scientific laws, another element is introduced: the effect of reflection. The scientific law is not only the expression of a certain quantity of empirical facts, including the facts obtained in systematizing of them, but the thought of the scientist intervenes - selection of facts, comparisons, imagination [14]. These ingredients will be taken into account as well here in our attempt to formulate the laws of the nucleon emission in hadron-nucleus collisions. The nucleon emission process can be treated separately, because the influence on it by other processes taking place in the collision is negligible [15].

This work is arranged as follows: after introduction in section 1, we present the more important definitions in section 2, and we formulate the laws in section 3; the arguments for the laws are presented shortly in section 4; in section 5, conclusions and remarks are given.

## 2. DEFINITIONS, DENOTATIONS, AND UNITS

It is desirable to have a special set of definitions, denotations and units for formulation of the laws in the next section 3. We shall begin our considerations with the short presentation of the set in this section.

We call the kinetic energy of a projectile hadron "high" when it is larger than the threshold for the pion production. The collections of nucleons met in the nature as atomic nuclei we will call "nuclear matter" sometimes.

High energy hadrons, in colliding with atomic nuclei, cause emission of nucleons from the target nuclei, as we can conclude from the usually observed emission of the protons. The nucleons are fast, with kinetic energies from about 20 up to about 400 MeV. Later, we will call them simply protons or nucleons; the protons are distinguished usually as " g-track leaving particles" when the emulsion technique is applied. In any of observed hadron-nucleus collision events $n_N = 0,1,2,...$ nucleons are emitted, and usually we observe $n_p = 0,1,2,...$ protons only. The number $n_N$ of emitted nucleons in a collision event we call the multiplicity of emitted nucleons; the number $n_p$ of emitted protons we call the multiplicity of emitted protons. The mean multiplicity of emitted nucleons per an event in a sample of collision events we denote by $\langle n_N \rangle$, the mean multiplicity of emitted protons we denote correspondingly $\langle n_p \rangle$. The multiplicities $n_N$, $n_p$, $\langle n_N \rangle$, and $\langle n_p \rangle$ we use later as the measures of the nucleon or proton emission intensity.

Any atomic nucleus can be characterized by its maximum thickness $\lambda_{max}$, mean thickness $\langle \lambda \rangle$, and by thickness $\lambda(b)$ at any distance b from its center - at any impact parameter b. It is convenient to express the thickness in units: nucleons per $fm^2$ or protons per $fm^2$, similarly as the thickness of the Earth atmosphere can be expressed in grams per $cm^2$. It is naturally convenient to express the thicknesses of an atomic nucleus in nucleons or in protons per a special area $S = \pi D_0^2$, where $D_0 = 1.81$ fm and $S = 10.30\ fm^2$. We will express, therefore, the thicknesses of the nuclear matter layers in units: nucleons/S, protons/S or, shortly, nucl/S, prot/S.

High energy hadrons in colliding with atomic nuclei may be stopped in them or deflected through various angles without particle production but accompanied by nucleon emission; we call later the events "stopped" and "deflected"correspondingly.



## 3. THE LAWS OF NUCLEON EMISSION AND NUCLEAR FRAGMENT EVAPORATION FROM NUCLEI BOMBARDED BY HIGH ENERGY HADRONS

Now, let us formulate the laws of the nucleon emission and fragment evaporation from nuclei bombarded by high energy hadrons.

<u>Law I.</u> Any hadron of kinetic energy higher than the pion production threshold causes nucleon emission from the target nuclei in traversing them along a path $\lambda$ fm; the number $n_N$ of emitted nucleons equals the number of nucleons contained within the cylindrical volume $v = \pi D_0^2 \lambda\ fm^3$ centered on $\lambda$ in the target nucleus:

$$n_N = \pi D_0^2 \lambda \langle \rho \rangle , \tag{1}$$

where $D_0$ fm is the diameter of the nucleon and $\langle \rho \rangle$ in nucleons/$fm^3$ is the mean density of nucleons inside the volume v.

Relation (1) can be expressed simply and more conveniently for applications:

$$n_N = \lambda \cdot S \tag{2}$$

when $\lambda$ is expressed in nucl/S units, where $S = \pi D_0^2$. Relation (2) allows to conclude additionally that the nucleon emission proceeds monotonically along $\lambda$ nucl/S.

<u>Law II.</u> In passing through nuclear matter, any hadron of kinetic energy larger than the pion production threshold loses monotonically its kinetic energy; the energy $\Delta E_h$ MeV of the hadron lost on the path length $\Delta\lambda$ nucl/S equals:

$$\Delta E_h = \epsilon_h \cdot \Delta\lambda , \tag{3}$$

where $\epsilon_h$ MeV/(nucl/S) depends on the hadron identity. From experiments [16]: for the pions $\epsilon_\pi = 180$ MeV/(nucl/S) and for the protons $\epsilon_p = 360$ MeV(nucl/S).

Independently of the interactions of the incident hadron inside nuclei causing the monotonic nucleon emission and energy losses, its interactions may occur there with nucleons leading to single deflection of the incident hadron through angles large enough and to appearance of the knocked-out nucleons of kinetic energy at which they can cause the nucleon emission in passage through the nucleus in ones turn. This process may disturb markedly the monotonically proceeding emission of nucleons caused by the incident hadron. From the analysis of experimental data, we conclude that the disturbance takes place in about 5-10 percent of collision events.

Law III. Energy and momentum spectra and angular distributions of nucleons appeared in the monotonic nucleon emission process are independent of the projectile energy and identity, in the target nucleus system of reference, and of the number $n_N$ of emitted nucleons and of the number $n_\pi$ of produced pions in hadron-nucleus collisions.

In other words, the nucleon emission process is not effected by the particle production process. It leads to the next law.

Law IV. Any hadron of kinetic energy larger than the pion production threshold causes nucleon emission from the target nucleus in any-type collision with it; the emission goes on in any case monotonically along the hadron course through the thickness $\lambda$ nucl/S of nuclear matter layer the hadron interacted with and its intensity is characterized by

$$n_N = \lambda \cdot S \tag{4}$$

and

$$\langle n_N \rangle = \langle \lambda \rangle S. \tag{5}$$

Results of investigations of the relation between the proton multiplicity and the multiplicity of the fragments evaporated from the target nuclei [17] allow to formulate next law.

Law V. The relations between the mean multiplicity $\langle n_b \rangle$ of evaporated charged fragments and the multiplicity $n_p$ of emitted protons exist:

$$\langle n_b \rangle = 1.25\,(\lambda \cdot S + \frac{A-Z}{Z}) \tag{6}$$

and

$$\langle n_b \rangle / (\langle n_b \rangle + \langle n_p \rangle) = \langle n_b \rangle / \langle n_h \rangle = 0.4\,, \tag{7}$$

where $\lambda S = n_p$ and $\lambda$ is the thickness of the nuclear matter layer involved in the hadron-nucleus collision, measured in prot/S units.

Relations (6) and (7) were derived in one of our previous works [17]: a particular case of these relations was found about 20 years ago [5].

The above formulated laws allow to derive simple formulas for the intensity distribution of nucleon emission; the formulas include the A-dependences of the characteristics of nucleon intensity and their dependences on incident hadron energy and identity [15,17].

## 4. SHORT ARGUMENTATION FOR THE LAWS OF NUCLEON EMISSION AND FRAGMENT EVAPORATION FROM TARGET NUCLEI BOMBARDED BY HIGH ENERGY HADRONS

Let us present new shortly main arguments for the laws formulated in foregoing section. The argumentation is based on few facts stated experimentally in studying hadron-nucleus collisions, in studying pion-xenon nucleus collisions in particular.

Following facts are of a basic importance:

1. Among pion-xenon nucleus collisions at 2.34-9.0 GeV/c momentum a remarkable large sub-class of events can be distinguished in which incident pion does not cause particle production, pion production in particular, but it underwent a deflection only in its passage through the target nucleus, accompanied by fast nucleon emission [1,2].

2. The mean multiplicity $\langle n_p \rangle$ of protons emitted in such "projectile deflection events" at momenta $P_\pi \geq 3.5$ GeV/c is almost constant and equals the mean thickness of the target nucleus $\langle \lambda \rangle$, derived [18] from the distribution of nucleon density in the xenon nucleus [11] and expressed in units prot/S, times S: $\langle n_p \rangle = \langle \lambda \rangle \cdot S$.

3. Among the pion-xenon nucleus collision events without particle production at momenta of the incident pions smaller than about 3.5 GeV/c the cases occur in which incident pion is completely stopped and deposited its kinetic energy in the target nucleus, accompanied by intensive nucleon emission. The probability of the occurrence of such stopped events decreases with the incident pion energy increase [16] - from about 12% at 2.1 GeV up to about 1.5% at 3.3 GeV and to about 0% at 9 GeV.

4. The proton multiplicity $n_p$ distribution $f(n_p)$ in the stopped events at incident pion energy 3.3 GeV is almost symmetrical distribution with sharp maximum at the multiplicity $n_p$ equal [16] to the number of protons contained in the xenon target nucleus within the cylindrical volume SD centered on the nucleus diameter D expressed in units prot/S: $n_p$ = SD and $\langle n_p \rangle$ = = SD; this distribution differs markedly from the distributions when $n_\pi = 1,2,3,\ldots$ pions are produced, fig.1.

5. The mean proton multiplicity $\langle n_p \rangle$ in the stopped events at smaller incident pion energy $E_s$ = 2.1 GeV equals the multi-

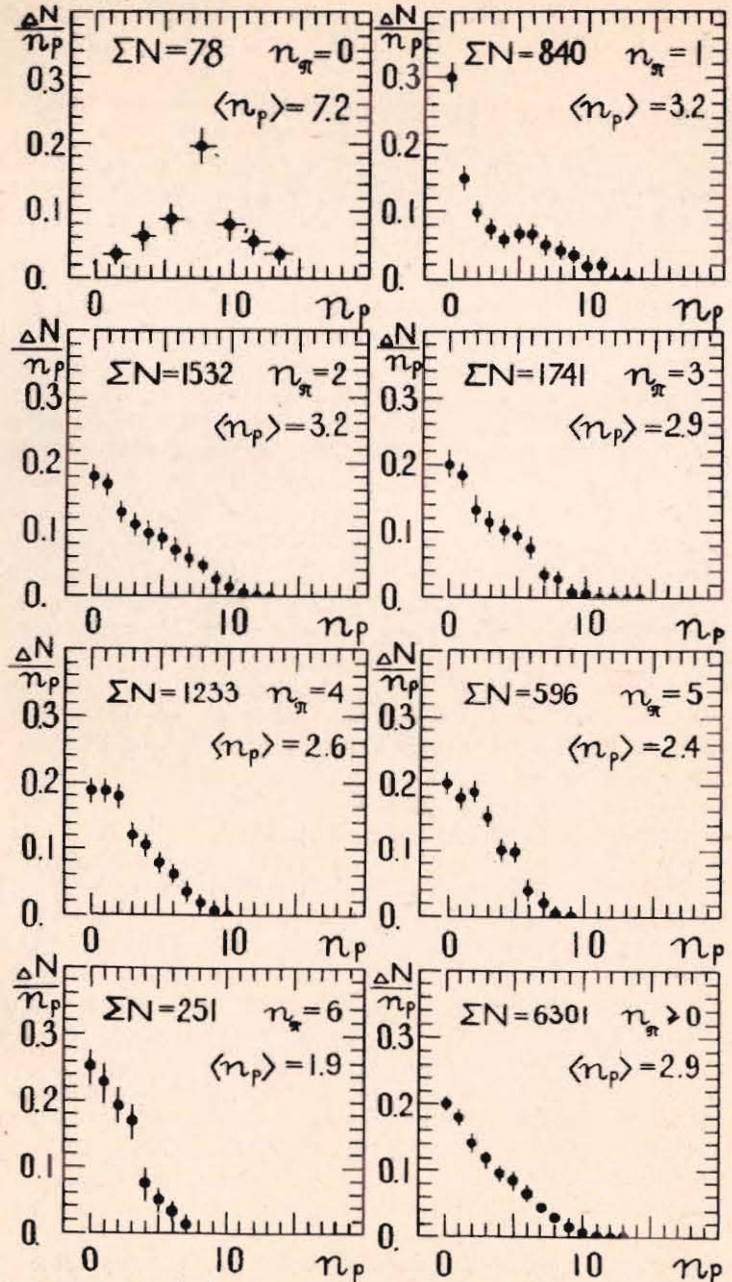



*Fig. 1. Proton multiplicity* $n_p$ *distributions* $f(n_p) = \Delta N/n_p$ *in pion-xenon nucleus collisions with various multiplicities* $n_\pi = 0, 1, 2, \ldots, 6; \geq 0$ *of secondary pions, at 3.5 GeV/c momentum.* $\Sigma N$ - *number of protons in a distribution.*



plicity $\langle n_p \rangle_e$ which is predicted. The prediction has been made by means of simple relation $\langle n_p \rangle_e = E_s/\epsilon_\pi$, where $\langle n_p \rangle_e$ is now the unknown quantity.

6. The mean multiplicity $\langle n_p \rangle$ of protons emitted in any-type hadron-nucleus collisions at energies above ten GeV is almost energy-independent and almost the same as the multiplicity obtained when the average target nucleus thickness $\langle \lambda \rangle$ prot/S is multiplied by S: $\langle n_p \rangle = \langle \lambda \rangle S$; in other words, the mean proton multiplicity $\langle n_p \rangle$ is almost equal to the number of protons contained within the cylindrical volume v centered on the hadron path inside the nucleus [15].

7. At smaller energies of the incident hadron, say at smaller than about 10 GeV, the mean proton multiplicity is energy-dependent [15,19].

8. Energy and momentum spectra, and angular distributions of emitted protons are identical in the sample of events with particle production and in events without particle production - in which incident pion is deflected or absorbed in the target nucleus [20]: the energy spectra in pion-xenon nucleus collisions at 3.5 GeV/c momentum are the same as the energy spectra of emitted protons, or g -track leaving particles, in proton-emulsion nuclei collisions at 4.4 and 400 GeV/c momentum [20]. The angular distribution of protons in pion-xenon nucleus collisions at 3.5 GeV/c momentum is the same as that of protons emitted in proton-emulsion nuclei collisions at 400 GeV/c momentum [21]. The spectra are the same for events with different multiplicities $n_p = 0, 1, 2, \ldots$ of the emitted protons [22].

Faced with the facts which have been written above about, and taking into account many newly discovered properties of the hadron-nucleus collisions [1,2,22], I was in a position to state that: a) The emitted protons cannot be the knocked-out protons; it concerns the emitted nucleons at all, the knocked-out nucleons are met with rarely among the emitted nucleons. b) The nucleon emission process proceeds independently of other processes inside the target nucleus, in particular of the particle production process; moreover, the nucleon emission process is the basic one and against the background of it the particle production process goes on. It is because we can treat the nucleon emission process separately from other processes occurring in hadron-nucleus collisions.

In my opinion, the observed nucleon emission is a secondary phenomenon due to following process: The incident hadrons, in passing through nuclear matter, cause the appearance of secondary low energy pions or maybe kaons which, as of low energy - a few or a few tens MeV, are absorbed by systems of two or more nucleons inside the target nucleus and these systems of relatively low energies decay into the observed nucleons after having left the parent nucleus. The low energy pions may be pulled out from nucleons met inside the target nucleus by the projectile hadron around its path, like electrons are pulled out from atoms by charged projectile in its passage through materials. The appearance of the "slow" pions around the incident hadron course in nuclear matter we call the "pionization" of the nucleons, per analogy to the ionization of atoms by fast charged particles.

Let us discuss now how the laws allow to explain various characteristics of the nucleon emission process. We start with the proton multiplicity distributions. The multiplicity $n_p$ of emitted protons, when the nucleon emission proceeds in its pure form, should be distributed, according to law I, as the distribution $W_0(\lambda \cdot S)$ of the quantities $\lambda \cdot S$ for a target nucleus, where $\lambda$ is the target nucleus thickness expressed in prot/S units. This multiplicity can be evaluated practically for any of atomic nuclei [18]. But, the nucleon emission in its undisturbed form is rarely occurring phenomenon, the distribution $W_0(\lambda \cdot S)$ should be transformed to disturbed form met in experiments, therefore. There are observed collision events in which the nucleon emission is minimally disturbed. The cases should be, for example, the hadron-nucleus collision events without particle production in which incident hadron is deflected only through a small deflection angle, say $\theta_h < 30$ degrees, accompanied by nucleon emission. The proton multiplicity distribution in such cases selected from any-type collision events should be:

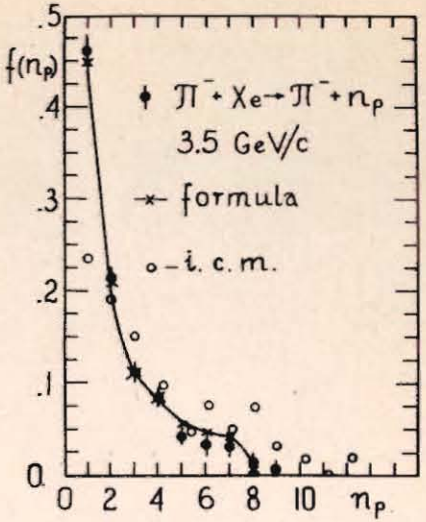
$$f(n_p) = W_0(\lambda S)\, e^{-\lambda/\lambda_{in}}\, e^{-\lambda/\lambda_r}, \qquad (8)$$

where $\lambda_{in}$ prot/S is the mean free path for the particle producing hadron-nucleon collisions connected with the hadron-nucleon inelastic collision cross-section [23]; the $\lambda_r$ is the mean free path for incident hadron deflection through angles larger than a given deflection angle in its passage through nuclear matter, it is expressed in units prot/s and connected with corresponding cross-section $\sigma_r$ for hadron-nucleon elastic collisions leading to deflections of the projectile through angles larger than $\theta_h$. Result of the comparison of the prediction given by formula (8) with corresponding experimental data for pion-xenon nucleus collisions at 3.5 GeV/c momentum is shown in fig.2; agreement well enough is stated.

It is worth-while to emphasize that the A-dependence of the $f(n_p)$ distribution is through A-dependence of $\lambda$ and the energy-dependence is through energy-dependence of $\lambda_r$ and $\lambda_{in}$ which are connected with the energy-dependent corresponding cross-sections $\sigma_r$ and $\sigma_{in}$.



Fig. 2. *Proton multiplicity $n_p$ distribution $f(n_p)$ in pion-xenon nucleus collision events without particle production in which incident pion is deflected through the deflection angle not larger than 30 degrees, at 3.6 GeV/c momentum.* ♦ - *experimental data,* —x— - *predictions given by formula (8), o - predictions given by intranuclear cascade model* [24].




A-dependence and projectile identity-dependence were observed at 37.5 GeV/c momentum hadron-nuclei collisions [25]. The predicted proton multiplicity distribution for these any-type hadron-nuclei collisions should be:

$$f(n_p) = W_0(\lambda \cdot S)\,(1 - e^{-\lambda/\lambda_{in}})\, e^{-\lambda/\lambda_r}, \qquad (9)$$

where the denotations are as in formula (8); $\lambda_r$ in this case can be evaluated experimentally. Formula (9) is valid only for the $\lambda \le D$ or for $n_p \le DS$. The comparison of predictions given by formula (9) with experimental data [25] is shown in fig.3; a satisfactory agreement is stated at proton multiplicities $n_p$ where formula (9) is applicable, at $n_p \le DS$.

Energy-dependence of the mean multiplicity $\langle n_p \rangle$ of protons emitted in proton-tungsten collisions may be described [15], applying laws I and II, by formula

$$\langle n_p \rangle = \langle \lambda \rangle (1 - e^{-\langle \lambda \rangle/\lambda_{tot}}), \qquad (10)$$

where $\lambda_{tot}$ is the mean free path for any-type collision of the incident hadron with a nucleon in nuclear matter, it is determined by corresponding cross-section $\sigma_{tot}$ as $\lambda_{tot} = 1/\sigma_{tot}$, $\langle \lambda \rangle$ and $\lambda_{tot}$ are in units prot/S. The energy dependence in formula (10) is through $\lambda_{tot}$ and through $\langle \lambda \rangle$ as well - because the mean thickness $\langle \lambda \rangle$ of nuclear matter layer the projectile interacted with depends on the projectile energy $E_h$ when $E_h \le \epsilon_h D$, due to energy loss. The A-dependence is through the A-dependent $\langle \lambda \rangle$. The dependence of $\langle n_p \rangle$ on the incident hadron identity is through the projectile identity-dependent $\lambda_{tot}$ and $\epsilon_h$. Comparison of appropriate experimental data [26-28] at

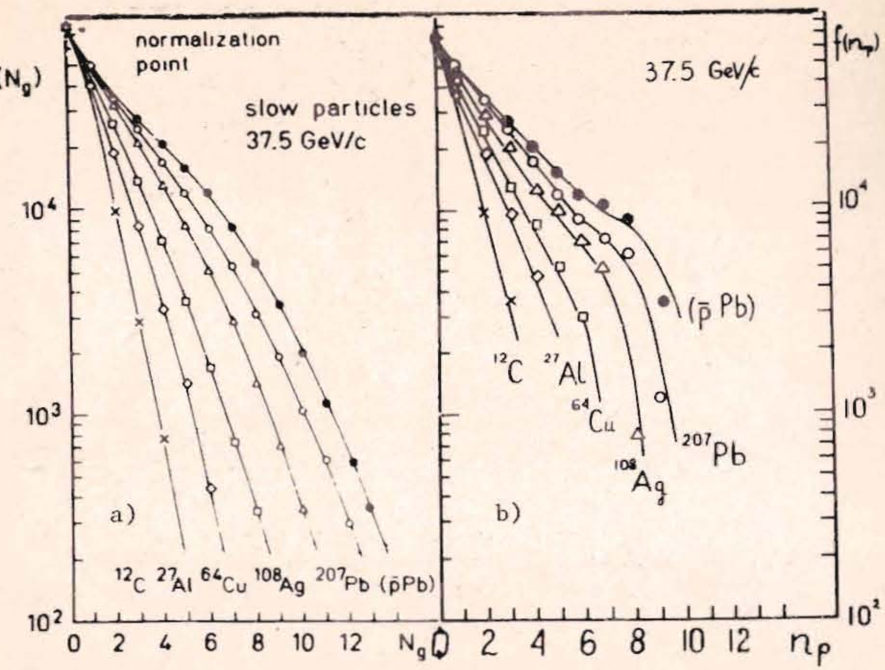



*Fig.3. Proton multiplicity* $n_p = N_g$ *distributions in pion-nuclei and in antiproton-*Pb *collisions at 37-5 GeV/c momentum: a) experimental data* [25]*, b) predicted by formula (9) for* $\lambda \leq$ D.

energies from about 4 up to about 2000 GeV with predictions given by formula (10) shows quantitative agreement [15].

Relations (6) and (7) can be tested using corresponding experimental data [5,28,29] at incident proton energy interval from about 6 up to about 3500 GeV; quantitative agreement is stated [17].

We have seen above that the laws I, II, IV and V help to discover simple physical meaning of the characteristic describing the nucleon emission intensities and target fragment evaporation intensities in hadron-nucleus collisions. In new experiments more data will be obtained which will probably support the formulation of the laws I-V.

In the light of what has been said above, it is possible to estimate the collision impact parameter practically in almost all collisions of a hadron with a target nucleus applying information about the proton multiplicity $n_p$ obtained in a collision event.



## 5. CONCLUSIONS AND REMARKS

It has been proposed above how the experimental information about the nucleon emission and target fragment evaporation in hadron-nucleus collisions at high energies can be summarized in a few basic laws. The laws were deduced for the case when purely nomotonic nucleon emission occurs. But, such pure emission is a rare phenomenon and we observe usually results of a disturbed nucleon emission process. Luckily, the marked disturbance appears in a small portion of collision events, no more than 5-10 percent and it manifests itself clearly in collision events with the multiplicities of the emitted protons $n_p >$ DS, where the diameter D of the target nucleus is expressed in units prot/S. The limit of validity of the laws I, II, IV, and V in applications, is then determined by the relation $n_p \leq$ DS, where D in prot/S.

Relation (6) is for the emitted protons only, and it presents a particular case of the general relation between the mean multiplicity $\langle n_f \rangle$ of evaporated fragments of any electric charge and the multiplicity $n_N$ of emitted nucleons

$$\langle n_f \rangle = 1.25\, \lambda \cdot S, \qquad (11)$$

where $\lambda$ is in nucl/S. The term (A-Z)/Z in relation (6) vanished because it represents the ratio between the neutron and proton numbers within the target nucleus, when only protons were accounted in the nucleon emission.

The laws were tested experimentally within the incident hadron energy interval up to about 2000 GeV, where the nucleon emission intensities were under studies; the constancy of the energy and momentum spectra, and angular distributions of the emitted nucleons was tested up to about 400 GeV. Nevertheless, we hope that the above formulated laws are valid through the total region of projectile energies above the pion production threshold.

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Закономерности процесса испускания нуклонов и испарения ядерных фрагментов из ядер, бомбардированных адронами высоких энергий

Сформулированы закономерности испускания нуклонов и ядерных фрагментов в столкновениях адронов высоких энергий с атомными ядрами. Приводится краткая аргументация приведенных формулировок на базе имеющихся экспериментальных данных.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

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The Laws of Nucleon Emission and Target Fragment Evaporation in Collisions of High Energy Hadrons with Atomic Nuclei

Laws of nucleon emission and target fragment evaporation in collisions of high energy hadrons with atomic nuclei are formulated. An argumentation for these laws is shortly presented on the basis of available experimental data.

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

Communication of the Joint Institute for Nuclear Research. Dubna 1984