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PROTON MULTIPLICITY DISTRIBUTIONS IN HIGH-ENERGY HADRON-NUCLEI COLLISIONS

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Распределение протонов по кратностям в столкновениях адронов высоких энергий с ядрами

Анализируется процесс испускания быстрых протонов в столкновениях адронов высоких энергий с ядрами. Выведена формула, описывающая распределение событий по кратностям протонов.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

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Proton Multiplicity Distributions in High-Energy Hadron-Nuclei Collisions

The fast proton emission process is analysed in high-energy hadron-nuclei collisions. The formula describing the proton multiplicity distributions is derived.

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

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1. INTRODUCTION

A series of investigations has been performed in order to describe the process of fast proton emission in high-energy pion-nuclei collisions [1-3], using the pictures from the 180 litre xenon bubble chamber [4] exposed to the 3.5 *GeV/c* negative charged pion beam. We call "fast" those protons which are of kinetic energies larger than the energy of the evaporated protons, of energies larger nearly than 20 *MeV*. In fact these are protons of energies lying within the value interval 20-400 *MeV* [1-3,5]. Any of the collision events registered has been characterized as completely as it is possible now: all the fast protons and all the pions, including neutral pions of energies equal and larger than zero, have been registered in the 4π solid angle with the registration efficiency being close to 100%. Due to this methodical possibility the class of pion xenon nuclei collisions has been discovered in which intensive fast proton emission is not accompanied by the multiparticle production acts [2].

For explanation of the existence of such events the following working hypothesis has been used: the number of the fast protons emitted by the passage of high-energy pion through an atomic nucleus at some distance from its center is equal to the number of protons met in the neighbourhood of close to the pion path inside the nucleus [3]. The proton multiplicity distribution of the events without multiparticle production calculated on the basis of such hypothesis agrees well with the experimental one within the interval of proton multiplicity values where the comparison can be performed /3/. Then, the existence of the monotonous energy loss of the high-energy pion inside atomic nucleus has been postulated /3/. The argumentation, mainly experimental facts, has been presented later on in favour of the existence of such process and, therefore, of the effect of monotonous braking of high-energy hadrons in nuclear matter /5/. The quantitative characteristic of such braking process has been given /5/.

In this paper we present how it is possible to derive the formula expressing the proton multiplicity distribution of high-energy hadron-nuclei collision events,using the above-mentioned working hypothesis. As we shall see, this formula describes well the experimental data and gives automatically the maximum number of fast protons which may be emitted in such collision processes.

2. *HEURISTIC CONSIDERATIONS*

What happens when the high-energy hadron traverses the atomic nucleus consisting of many nucleons? We know now it undergoes the following main processes: a) the monotonous energy loss accompanied by the fast proton emission; b) the inelastic scattering on the atomic nucleons accompanied by the multiparticle production; c) the quasi-elastic scattering on nucleons. Let this hadron to be pion, it does not cause the applicability limitation of the results of our considerations to other hadrons too.

High-energy pion falling on the atomic nucleus of the radius R and of the nucleon density $\rho(R)$ may traverse it with some probability without causing the multiparticle production - it undergoes only the monotonous energy loss /5/. The energy loss is accompanied by the braking of the pion and by intensive fast proton emission /3,5/. If the incoming pion energy is high enough, it escapes the nucleus, although braked and scattered at some direction. At smaller energy values the pion may stop inside nucleus. At some, definite for given atomic nucleus, energy the pion range in the nucleus may be equal to its diameter 2R. Then, traversing the nucleus along its diameter this pion

causes the emission of all the protons met in the neighbourhood of close to it path, according to our working hypothesis accepted. Such events we have observed just in the xenon chamber exposed to the 3.5 *GeV/c* negative charged pion beam /2/. The number of protons observed in these events, appearing as the peak in the proton multiplicity distribution of the events without multiparticle production and without any secondary pion, equals 8, as exactly as the number of protons met along the xenon nucleus diameter /2,3/.

We observe nearly 12% of the pion-xenon nuclei collision events without multiparticle production - with zero and one secondary pion /2/. The existence of such collision events accompanied by the intensive proton emission without multiparticle production and the absence of the multiparticle production events on nucleons without secondary nucleons indicate this proton emission acts in advance of the multiparticle production process in many cases of pion nuclei collisions. Therefore, in the class of the collision events with the multiparticle production, the high energy pion traversing the nucleus causes the multiparticle production either on the first nucleon met or after passing some path length inside the nucleus along which it undergoes the monotonous energy loss only.

Let us assume any act of multuparticle production to be a result of the pion collision with a single one nucleon inside the nucleus - to be the quasielementary act. We do not know at yet how the multiparticle production is going on, either directly or by some intermediate states, although we know of many its experimental characteristics. Therefore, two possibilities must be consider: a) one, at least, of colliding particles undergoes some strong excitation; the excited states, being of the finite life time, decay into particles commonly observed as the secondaries after escaping the nucleus; b) All the secondaries create simultaneously directly inside the nucleus; they escape it being of different energies and emitted at various angles. How is the process occuring in fact?

There exists no the possibility to give the answer now, if we observe the elementary hadron-hadron collision process; the existing experimental and methodical basis cannot give us adequate experimental information. However, if we observe the collision processes of high-energy hadrons with the atomic nuclei, we are able to distinguish in principle how is the particle creation going on in the nature - the nucleus we may use as an indicator. The possibility to distinguish between the two variants of the particle creation process exists, obviously, if the life time of the hypothetical excited states is long enough they could escape the parent nuclei; at shorter life times there exists no any possibility to know anything. What are the experimental facts speaking about?

It is well known the parent nuclei to be unexpectedly transparent to newly produced particles /6,7/. We must remember, however, that the statement "the particles are created inside the atomic nucleus" has been supported never by any experimental fact. Therefore, it is meaningless to attribute to the secondaries the property to be unusually for particle creation inside the parent nucleus.

Let us suppose now the secondaries to be created inside nuclei. We can see now whether they are able to be monotonously breaked in traversing the nuclear matter or not. We know the braking process to be accompanied by the intensive fast proton emission. We ought to observe therefore the increasing of the average fast proton multiplicity with the growth of the secondary pion number in the hadron-nuclei collisions. In fact we have the independence: nearly constant average number of fast protons emitted is observed at any number of the secondary pions /1,5/. In addition, the maximum number of protons emitted is almost the same in pion-xenon nuclei collisions at 3.5 *GeV/c* /1/ and in pion-argentbromine nuclei collisions at 200 *GeV/c* /8,9/, being nearly 16.

Thus, we meet to much strange properties of the secondaries which we consider to be "created inside atomic nuclei", but there exists no experimental fact showing that they are created just there. We may risk therefore a suggestion here: in high-energy hadron-hadron collisions the particle creation process goes on by some excited states. In hadron-nuclei collisions these states decay into multuparticle channels only after having left the nuclei. Such scheme we use later as the basis for the derivation of the fast proton multiplicity distribution of the hadron-nuclei collision events. We will derive it for the case of pion-xenon nuclei collisions supposing the excited states are undergoing the same monotonous energy loss as the primary pion in traversing the nuclear matter.

3. *DERIVATION OF THE FORMULA DESCRIBING THE FAST PROTON MULTIPLICITY DISTRIBUTION OF THE HADRON-NUCLEI COLLISION EVENTS*

The number n_p of the fast protons emitted by the passage of high-energy hadron through an atomic nucleus of the radius R, at the distance d from the center of this nucleus, is equal to the number of protons met in the neighbourhood of close to the pion path λ:

$$n_p = \pi D_0^2 \frac{Z}{A} \bar{\rho} \cdot \lambda = \pi D_0^2 \frac{Z}{A} \bar{\rho}\, 2\sqrt{(R^2 - d^2)} \qquad (1)$$

according to our working hypothesis; where D_0 is the nucleon diameter, Z is the atomic number, A is the mass number, $\bar{\rho}$ is the average nucleon density along the path length λ. We accept the ratio of the proton number Z inside the nucleus to the number A-Z of the neutrons to be independent on the nucleus radius R; it is not far from the existing data /10,11/.

For convenience, we express later all the lengths taking the nucleon diameter D_0 to be length unity defined by the relation

$$\frac{R}{D_0} = \left(\frac{3A}{4\pi}\right)^{1/3} . \qquad (2)$$

The number n_p of the protons emitted is the function of the impact parameter d: for any definite value n_p one definite value $d(n_p)$ exists for the spherical atomic nucleus of the radius R and of the definite average nucleon density $\bar{\rho}\{\lambda[d(n_p)]\}$ along the path length $\lambda[d(n_p)]$. We write then for the intensity $W(n_p)$ of n_p proton emission:

$$W(n_p) = \pi\{[d(n_p) + D_0]^2 - [d(n_p) - D_0]^2\} \cdot \lambda[d(n_p)], \quad (3)$$

where $\lambda[d(n_p)] = 2\sqrt{(R^2 - d(n_p)^2)}$. So far as $4\pi D_0$ is constant and for the comparison with the experimental data the normalized distribution should be prepared, we use the following expression, instead of the (3) one:

$$W(n_p) = \lambda[d(n_p)] \cdot d(n_p). \quad (3')$$

It gives the series of values W(1), W(2), W(3), ... which, after appropriate normalization, can be compared with the series of the numbers N(1), N(2), N(3), ... of the collision events which could be observed if only monotonous emission of $n_p = 1, 2, 3, ...$ protons takes place in traversing the nucleus by high-energy hadron. The values of $d(n_p)$, $\lambda[d(n_p)]$, $\bar{\rho}\{\lambda[d(n_p)]\}$, and $W(n_p)$ for any number n_p calculated for the xenon nucleus are given in *table 1*. In calculations the spherical nucleus of the radius $R = 9D_0$ and of the nucleon density $\rho(R)$ has been used /3,10/.

Table 1

The values of $d(n_p)$, $\lambda[d(n_p)]$, $\bar{\rho}\{\lambda[d(n_p)]\}$, and $W(n_p)$

n_p	$d(n_p)$	$\lambda[d(n_p)]$	$\bar{\rho}\{\lambda[d(n_p)]\}$	$W(n_p)$
1	4.62	15.45	0.049	71.40
2	3.86	16.26	0.094	62.70
3	2.47	17.30	0.133	42.70
4	2.32	17.95	0.171	41.60
5	1.68	17.70	0.216	29.70
6	0.85	17.91	0.258	15.22
7	0.27	17.99	0.297	4.85
8	0.10	18.00	0.339	1.80

However, high-energy hadrons traversing the nucleus cause the monotonous emission of the fast protons along the total path length $\lambda[d(n_p)]$ only in some part of all the collision events. In the rest part this monotonous emission takes place on some average path length $\bar{\lambda}$. This length $\bar{\lambda}$ fluctuates. If any of the incoming hadrons collides with the nucleus at its any point with the constant probability, we can write for the number I of the collision events in which the hadron undergoes the monotonous energy loss only:

$$I = I_0 \exp\{-\mu \cdot \lambda[d(n_p)] \cdot \bar{\rho}\{\lambda[d(n_p)]\}\}, \quad (4)$$

where I_0 is the number of all collision events, μ is the attenuation coefficient. The proton multiplicity distribution of these I events is described by the function $W(n_p)$ expressed by the formula (3). The rest part $I_0 - I$ of the collision events contains such cases in which some secondary systems were produced. This systems cause the monotonous proton emission too, and the events appear in which the proton multiplicity distribution must be described by the new functions $W'(n_p)$.

Let us derive the function $W'(n_p)$. We divide the path length $\lambda[d(n_p)]$ of the hadron inside the atomic nucleus into some n parts being approximately of a length $\Delta\lambda$ on which nearly one proton could be met. Suppose the hadron traversing the nucleus of the radius R along its diameter meets n protons, then we have for $\Delta\lambda$ the part of the diameter being

$$\Delta\lambda = \frac{2R}{n}. \quad (5)$$

For the xenon nucleus $R = 9D_0$ and $n = 8$. We accept then $\Delta\lambda = 2.5D_0$.

We can write the expressions for the proton multiplicity $W'(n_p)$ which should be observed in experiments, using the following notations $\lambda[d(n_p)] = \lambda(n_p)$, $\bar{\rho}\{\lambda[d(n_p)]\} = \bar{\rho}(n_p)$:

$$W'(1) = I_0 W(1)\cdot \exp[-\mu\cdot\lambda(1)\cdot\bar{\rho}(1)],$$

$$W'(2) = I_0 W(2)\cdot \exp[-\mu\cdot\lambda(2)\cdot\bar{\rho}(2)],$$

$$W'(3) = I_0 W(3)\cdot \exp[-\mu\cdot\lambda(3)\cdot\bar{\rho}(3)] +$$

$$+ I_0 W(2)\cdot\{1-\exp[-\mu\cdot\Delta\lambda\cdot\bar{\rho}(2)]\}\cdot\exp[-\mu(\lambda(2)-\Delta\lambda)\cdot\bar{\rho}(2)],$$

. . . .

$$W'(5) = I_0 W(5)\cdot \exp[-\mu\cdot\lambda(5)\cdot\bar{\rho}(5)] +$$

$$+ I_0 W(4)\cdot\{1-\exp[-\mu\, 3\Delta\lambda\,\bar{\rho}(4)]\}\cdot\exp[-\mu(\lambda(4)-3\Delta\lambda)\bar{\rho}(4)] +$$

$$+ I_0 W(3)\cdot\{1-\exp[-\mu\Delta\lambda\cdot\bar{\rho}(3)]\}\cdot\exp[-\mu(\lambda(3)-\Delta\lambda)\bar{\rho}(3)],$$

. . . .

. . . .

(6)

In general, we have for the proton multiplicity distribution $W'(n_p)$:

$$W'(n_p) = I_0 W(n_p)\cdot\exp[-\mu\cdot\lambda(n_p)\cdot\bar{\rho}(n_p)] +$$

$$+ I_0 \sum_{i=1}^{k} W(n_p-i)\{1-\exp[-\mu(2(n_p-i)-n_p)\cdot\Delta\lambda\cdot\bar{\rho}(n_p-i)]\}\times$$

$$\times \exp[-\mu(\lambda(n_p-i)-(2(n_p-i)-n_p)\Delta\lambda)\cdot\bar{\rho}(n_p-i)], \qquad (7)$$

where k are natural numbers satisfying the relation $k = 2(n_p-i)-n_p$ for $i=1,2,3,\ldots$; $W(n_p-i)$ is the function expressed by the formula (3′) for given n_p and $i = 1,2,3,\ldots$. Similarly, the functions $\bar{\rho}(n_p-i)$ and $\lambda(n_p-i)$ are defined as previously but for the arguments n_p-i, $i=1,2,3,\ldots$. The values of $W(n_p-i)$ are given in *table 1*; for example, the value of $W\{(n_p=4)-1\} = W(n_p=3)$, $W(n_p>8) \approx 0$.

This formula should describe the proton multiplicity distribution of some special cases too, for example, the hadron-nuclei collisions in which multiparticle production does not occur /3/. In such cases new coefficient μ and new path interval $\Delta\lambda$ must be estimated in experiment, however.

4. MAXIMUM NUMBER OF FAST PROTONS EMITTED

Formula (7) gives automatically the maximum number $n_{p\,max}$ of protons emitted. This number we expect to be no larger than the double number of protons packed along the nucleus diameter inside the volume region defined by the relation (1) for $d=0$, in almost all cases and for all energy values. We write then the formula expressing $n_{p\,max}$:

$$n_{p\,max} = 2\pi D_0^2\, 2R\frac{Z}{A} = 3.63\frac{Z\pi^{2/3}}{A^{2/3}}. \qquad (8)$$

This formula should be valid for the nuclei of the atomic number Z larger than $n_{p\,max}$. Therefore, we write the validity conditions of the formula (8), using the relation $Z-n_{p\,max} \geq 0$: a) the expression (8) is valid for the nuclei of the atomic number $A \geq 22$; b) for the smaller atomic numbers $n_{p\,max} = Z$.

It is remarkable the maximum number of the fast protons emitted we expect to be independent of the energy of the incident hadron.

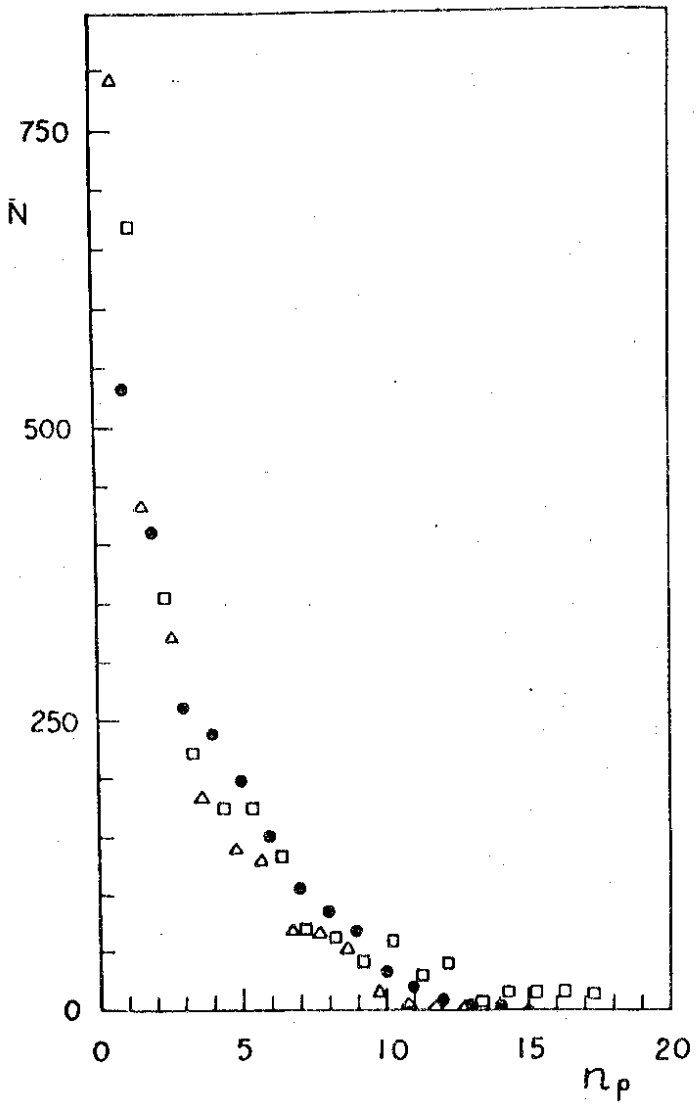
Writing this formula we have used the unifold interaction of incoming hadron inside the nucleus and we have considered the unidimensional picture of the proton emission. In fact, it should be expected that in some part of events at extremely high energies and for the heaviest nuclei the maximum number of the fast protons emitted may be larger than those given by the formula (8). It is not larger, however, than nearly

$$n'_{p\,max} = n_{p\,max} + \pi D_0^2(2R-\bar{\lambda}) = n_{p\,max} + \pi(2R-\bar{\lambda}), \qquad (9)$$

where $\bar{\lambda}$ is the average path length of the hadron inside the atomic nucleus on which the monotonous energy loss occurs.

5. CALCULATIONS OF THE $W'(n_p)$ AND $n_{p\,max}$

Using the formula (7) the calculation of $W'(n_p)$ for the xenon nucleus of $Z=54$ and $A=131$ has been performed.



Comparison of the fast proton multiplicity distributions of hadron-nuclei collisions: ● *- calculated by the formula (7);* Δ *- experimental, from the pion-* AgBr *collisions at 200 GeV* [8,9]; □ *- experimental, from the proton-* AgBr *collisions at 400 GeV* [8,9].

Firstly, the attenuation coefficient μ has been estimated on the basis of the existing experimental data [1,2]. From the total number $N_t = 2800$ of the pion-xenon nuclei collision events at 3.5 *GeV/c* only in $N_i = 2113$ one or more fast protons are emitted. This number N_i corresponds to the number of the pion-xenon interactions with different impact parameters d uniformly distributed on a disc of the radius R. In the sample of 2113 events the number $N = 9$ of such events exists which can be interpreted as the events in which incident pion traversing the xenon nucleus along its diameter undergoes only the monotonous energy loss without multiparticle production [2]. This number N corresponds to the number N_0 of collision events with the impact parameter lying within the disc πD_0^2 and is expressed by the relation

$$\frac{N_0}{N_i} = \frac{\pi D_0^2}{\pi R^2}; \qquad (10)$$

$N_0 = 26$, if $R = 9D_0$ and $D_0 = 1$.

Now, we write the expression

$$\frac{N}{N_0} = \exp\left[-\mu \cdot \lambda[d(n_p = 8)] \cdot \bar{\rho}\{\lambda[d(n_p = 8)]\}\right] \qquad (11)$$

and, using the corresponding values $\lambda = 18$ and $\bar{\rho} = 0.339$, we have:

$$\mu = 0.174. \qquad (12)$$

In *table 2* the calculated values of $W'(n_p)$ are presented. The normalization has been performed to the total number N_i events observed in the experiment [2].

The distribution calculated for the xenon nuclei may be nearly valid for the argent nucleus too, because the nuclear radii R of both these elements are nearly the same. Therefore, we compare the calculated for xenon nucleus distribution with the proton multiplicity distributions of fast protons emitted in the hadron-emulsion nuclei collision events of negative pions of about 200 *GeV* energy and of protons of about 200 *GeV* and 400 *GeV* energy [8,9]. It is shown in the *figure*.

Using the formula (9) the values of $n_{p\,max}$ and $n'_{p\,max}$ were calculated. Results are presented in *table 3*.

Table 2

The calculated proton multiplicity distribution $W'(n_p)$ and the experimental distribution $N(n_p)$ normalized to the total number of events registered

n_p	$W'(n_p)$	$N(n_p)$
1	533	517±23
2	409	411±20
3	261	310±18
4	238	257±16
5	197	217±15
6	151	175±13
7	105	94±10
8	83	76± 9
9	67	29± 6
10	33	12± 4
11	18	12± 4
12	8	1± 1
13	5	0
14	2	1± 1
15	1	0

Table 3

Maximum number of fast protons emitted in hadron-nuclei collisions; $n_{p\,max}$ defined by the formula (8) and $n'_{p\,max}$ defined by the formula (9) for various nuclei

Nucleus	$n_{p\,max}$	$n'_{p\,max}$
$^{12}_{6}C$	6	6
$^{56}_{26}Fe$	14	19
$^{131}_{54}Xe$	16	22
$^{108}_{47}Ag$	16	22
$^{208}_{84}Pb$	18	25

6. *RESULTS AND DISCUSSION*

The distribution calculated corresponds well to the experimental one. In some points the calculation gives larger numbers of events in comparison with the observed numbers, at $n_p = 9$ and $n_p = 8$, for example. But, we must remember that: these experimental points are less accurately estimated, mainly because of the possible mutually covering of the proton tracks in the events with the large numbers of tracks; unidimensional scheme of secondary systems produced inside the nucleus has been used and the interactions of these systems inside nuclei have been supposed to be the same as the interaction of the incident hadron.

We see (the *figure*) our formula describes well enough the proton multiplicity distribution of the events at 200 and 400 *GeV*, both of the pion-nuclei and proton-nuclei collisions.

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