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OBSERVATIONS OF FAST HADRON PASSAGES THROUGH INTRANUCLEAR MATTER

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1. INTRODUCTION

During many years, millions photographs from the xenon bubble chambers: from the 26 litre chamber [1] of the Joint Institute for Nuclear Research and 180 litre chamber [2] of the Institute for Theoretical and Experimental Physics were scanned and analysed. The chambers, especially the second one, are practically total detectors — with spherical 4П solid angle aperture, in which the collision reactions and their products are registered and identified with the efficiency high enough; for example neutral pions with kinetic energy 0 and more than 0 MeV are registered and identified in them with the efficiency near to 100%. More about the characteristics of the chambers as total detectors is published in our former works [3—5].

In scanning and analysing photographs from the xenon bubble chambers exposed to electrically charged pion beams at 2.34, 3.5, 5 and 9 GeV/c momentum, two densely populated classes of the pion-xenon nucleus collision events have manifested themselves clearly and conclusively, figs.1—3.

Two pion-xenon nucleus collision events presented in fig.1 are representative for the two classes I and II.

On the left part on the photograph, one can see the picture of the $Pi^- + Xe$ collision event at 3.5 GeV/c momentum, in which pions are produced — one neutral PiO meson decayed into two gammas initiated electron-photon showers, and two electrically charged pions (long thinner tracks), and a few protons are emitted (short direct thick tracks); one of the secondary charged pions used to collide with the xenon nucleus and produced characteristic «star» with two secondary charged pions and a few protons emitted from the target nucleus. Let this event represents the 1-st class — which the hadron-nucleus collisions in which hadrons are produced are accounted for.

One the right part of the photograph, the collision event is registered of an evidently different nature: there are not pions produced in this case, incident pion is stopped inside the xenon target nucleus only accompanied by the emission of the protons with energies of about 20—400 MeV from the nucleus — such protons (and neutrons) we call «fast» later; the 6 longer tracks are left by the emitted protons, the 4 shorter tracks are from the lower energy protons — evaporated from the residual target nucleus. Let this event represents the II-nd class — which the collision events without hadron production are accounted for.

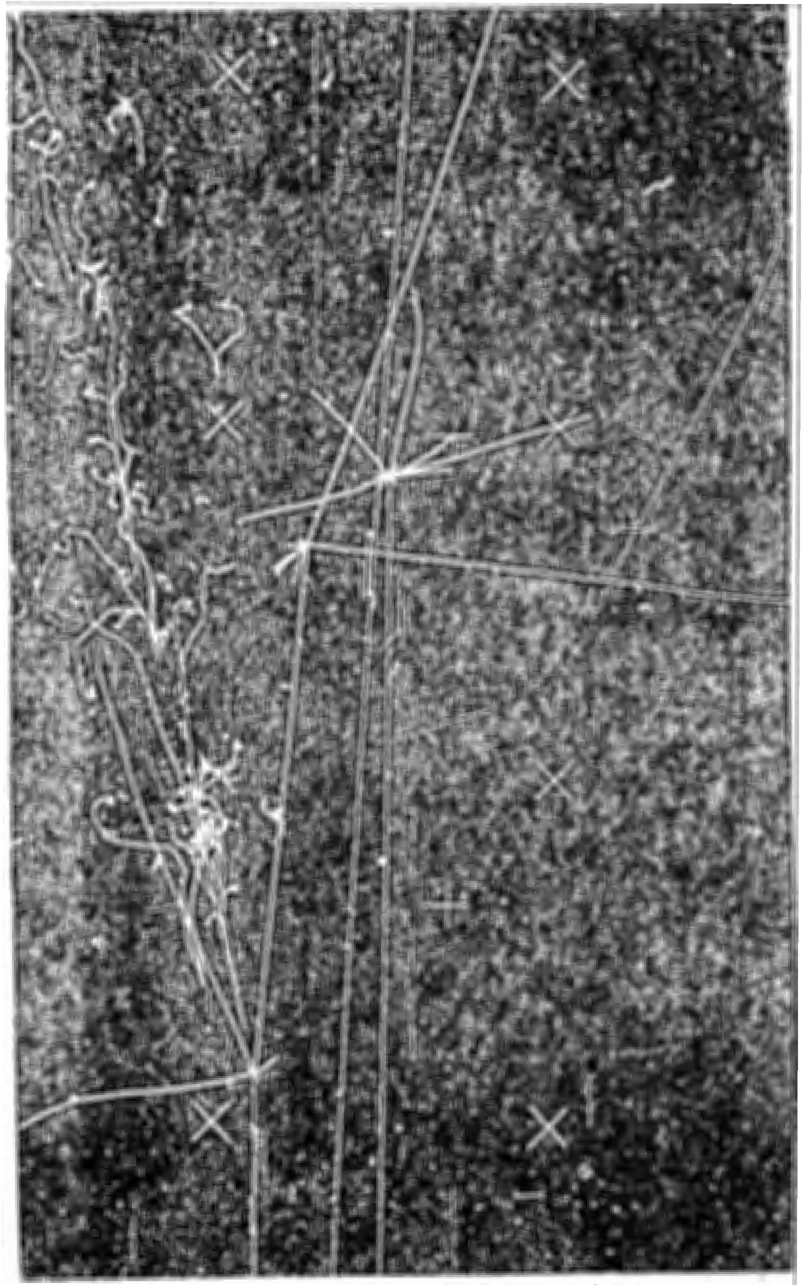


Fig.1. Two classes I and II of pion-xenon nucleus collision events; explanations in the text, sect.1. $Pi^- + Xe$ collisions at 3.5 GeV/c.

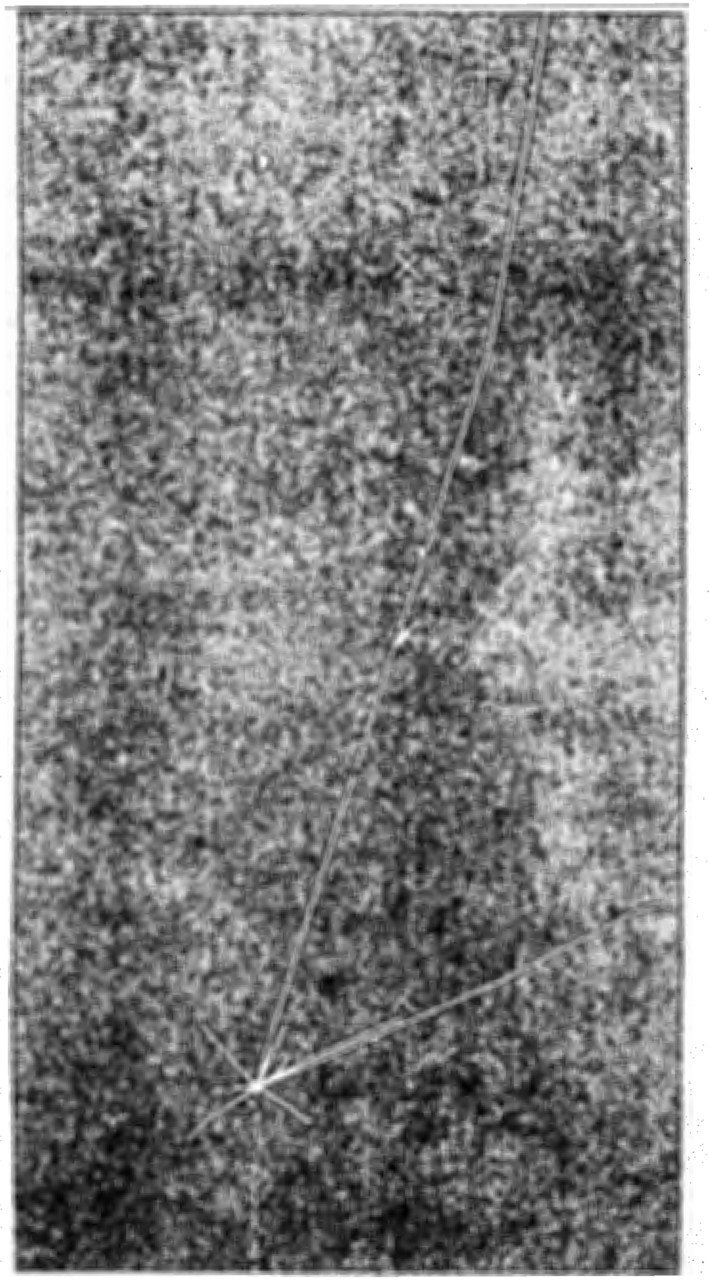


Fig.2. The passage of the incident pion through the target xenon-nucleus; explanation in the text, sect.1. Pi$^-$ + Xe collisions at 3.5. GeV/c.

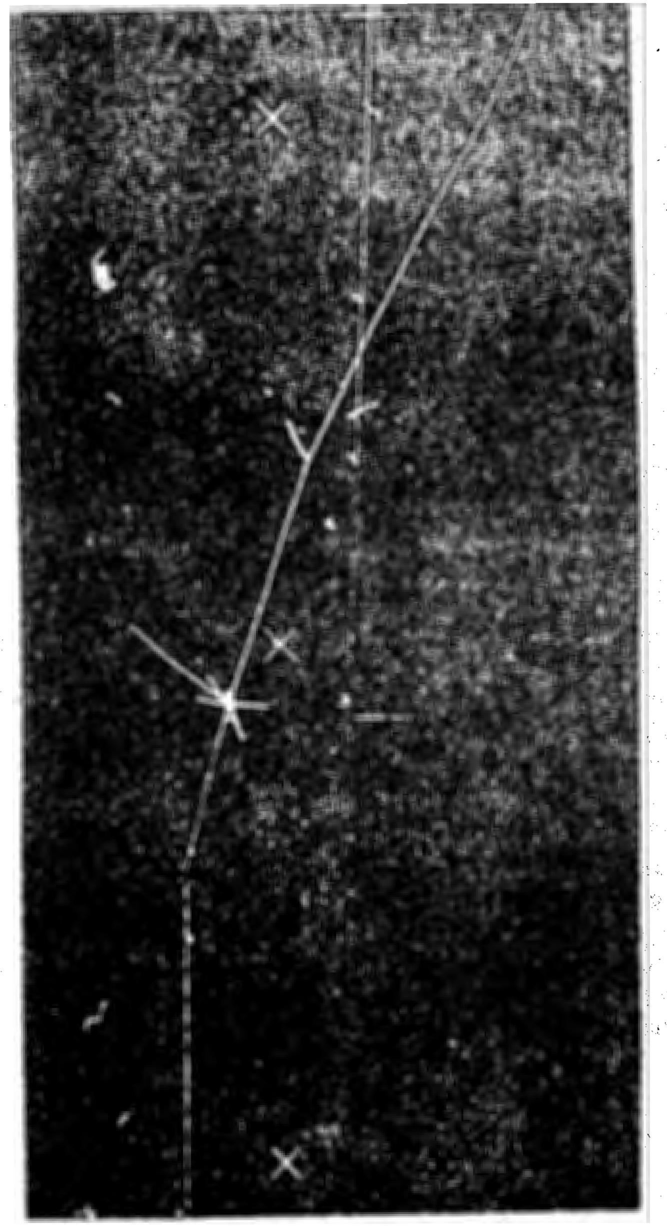


Fig.3. Interactions of the incident pion with three downstream nuclei in the xenon bubble chamber; explanation in the text, sect.1.

On fig.2, a characteristic example of the collision in which the incident pion passed through the target nucleus and left it as bracked and deflected; this passage is accompanied by the emission of the protons from the target nucleus; the evaporated protons are not seen separately — their tracks form a blob in the center of the collision region. This event is representative for the II-nd class of the collision events, as well.

On fig.3, very clear picture of the passage of the incident pion through the xenon nucleus is presented. The pion is deflected at first, probably in the elastic collision with the periphery of the xenon nucleus, and deflected it comes into second collision with the downstream xenon nucleus, passed through it accompanied by nucleon emission — the emitted protons left the 5 tracks, direct; the blob formed by the evaporated protons and other nuclear fragments is seen as well — around the center of the interaction region. The incident pion, deflected slightly second time — in the second collision, collided third time with the third xenon nucleus at its periphery — in result one proton is emitted from the target, seen as the short thick track. This event is representative for the II-nd class of the collision events as well.

For an explanation of the events similar to the presented on photographs, fig.1—3, the working hypothesis has been formulated [6,7]. Expressed here, in a shorter form, it is: The collision events without hadron (particle) production are simply the passages of the incident hadrons though the target nuclei in the purest form; high energy hadron traversing the intranuclear matter layer undergoes «fluent» energy loss accompanied by the emission of «fast» nucleons from the target nucleus; this process (the passage of hadrons through nuclei) is fundamental in the hadron-nucleus collisions and on the background of which other various processes occur sometimes.

The subject matter in this work is a systematization of the experimental material in question, collected in many works [6—14] and discussion of it on the basis of the new data obtained in additional testing analysis performed lately. In result, conclusive data and final physical interpretation based on them is presented here. Majority of the works have been performed by E.Strugalska-Gola in preparing of hers PhD thesis.

2. INVESTIGATION PROCEDURE

The investigation procedure of the two classes I and II of the hadron-nucleus collision events is based on our now-day experimental data on the collisions — obtained from the total detectors, and on the experimental knowledge about sizes of the atomic nuclei and nuclei density distribution in them [15—17].

The set of the data on the outcome from the nuclear collisions obtained by means of the xenon bubble chambers is almost complete [6—14,18—20]. Many aspects about the nuclear sizes and nucleon density distribution in them are now so firmly established [15—17] that it has been possible to use them in order to investigate other physical quantities [17]. The projectile is defined completely [21]. Characteristics of the atomic nuclei employed as targets in high energy nuclear collisions — as maximal and mean thicknesses of the nuclei, and the thicknesses at any distance from nuclear center are determined [13] on the basis of experimental data [15—17].

The investigation procedure consists in comparison of experimental data characterizing the outcome from hadron-nucleus collisions with corresponding expected data obtained from calculations based on the experimental information about the target nucleus size and nucleon density distribution in it and on the incident hadrons as projectiles.

3. EXPERIMENTAL DATA

A systematization and short review of experimental data in question are presented in this section.

3.1. Registration Probability of the Collision Events without Particle Production in Pi + Xe Reactions

Below, in table 1, there are presented: the registration probability P_{wpp} of the events without particle production; the registration probability P_{pass} of the events in which the incident pion passed through the target nucleus without particle production; the registration probability P_{ab} of the events in which the incident pion is absorbed in the xenon target nucleus without causing particle production. The nucleon emission from the target is observed only.

Table.1. The probabilities P of the appearance of various Pi + Xe nuclear collision events without particle production (*wpp*) in which the incident pion is absorbed (*ab*) inside the target nucleus or passed (pass) through it, at definite initial momentum p_π [GeV/c].

p_π [GeV/c]	2.20	3.20	4.85	8.85
P_{wpp} [%]	35.0±5.0	15.0±4.0	8.0±2.0	3.0±1.0
P_{pass} [%]	24.0±4.0	13.0±3.0	7.0±2.0	2.5±0.5
P_{ab} [%]	11.0±3.0	2.0±1.0	1.0±1.0	0.5±0.5

From the data, it follows that: a) The absorption probability P_{ab} of the incident pion decreases with increase of its incident momentum p_π, at its value larger than about 3.2 GeV/c the absorption practically does not appear. It may be simply the manifestation of the relatively large spherical volume of the massive nuclear target. b) The probability P_{pass} of the incident pion passage through the target nucleus decreases as well with the incident pion momentum increase, but it does not disappear at higher momentum values. This decrease can be qualitatively explained as the manifestation of the hadron-nucleon elastic collision cross section decrease with the incident hadron momentum increase, within the values from about 1 to about 10 GeV/c [22].

It is clear, therefore, that due to these facts the passages in their pure form may be observed plentifully at the incident pion momentum values of about a few GeV/c. At higher momenta the pure passages should be relatively rare phenomena — in a few percet only; the expectation might be given from behaviour of the elastic pion-nucleon collision cross-section. P_{wpp} of the appearance of the events without particle production decreases with the incident pion momentum value increase.

3.2. Characteristics of the Nucleon Emission which the Collision Events without Particle Creation Are Accompanied by

As the measure of the nucleon emission intensity we use the multiplicity n_N of the emitted nucleons in an event; as the measure of the proton emission intensity the proton multiplicity n_p is used.

The main property of the observable proton emission is: The energy, momentum, and angular distributions are the same in the events accounted for

Table 2. The mean $\langle n_p \rangle$ and maximal values $n_{p\max}$ of the multiplicities n_p of the emitted protons observed in Pi + Xe collisions at various momenta p_π GeV/c.

Reaction p_π	$\langle n_p \rangle$			$n_{p_{\max}}$		
	pass	stop	total	pass	stop	total
Pi^+ + Xe 2.2	1.9±0.4	4.1±1.0	2.4±0.3	12	10	12
Pi^- + Xe 3.2	3.2±0.3	7.5±0.3	3.3±0.3	15	15	16
Pi^- + Xe 4.8	—	—	3.4±0.6	—	—	16
Pi^- + Xe 8.8	—	—	3.3±0.4	—	—	17

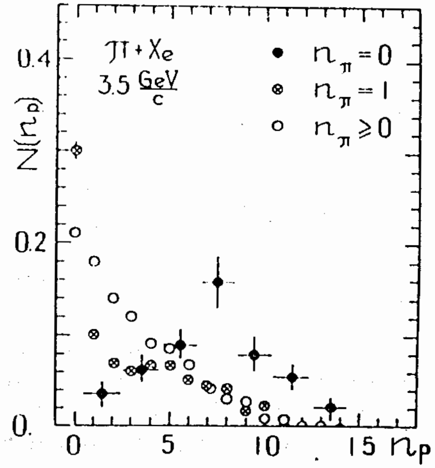


Fig.4. The distributions $N(n_p)$ of the multiplicity n_p of the emitted protons in Pi^- + Xe collision events at 3.5 GeV/c momentum: for stoppings — $n_\pi = 0$, for passages — $n_\pi = 1$, for any-type collisions — $n_\pi \geq 0$.

any of the classes I and II. The spectra are the same for the events with any number $n_p = 1,2,3,...$ of the emitted protons; the distributions are practically the same for the events with any number $n_\pi = 0,1,2,3,...$ of produced pions.

The shapes of the proton multiplicity n_p distributions $N(n_p)$ are practically the same for the events at the momenta of the incident pions $p_\pi \geq 3.2$ GeV, for $n_\pi \geq 2$.

The mean $\langle n_p \rangle$ and maximum $n_{p_{\max}}$ values of the proton multiplicity are presented in table 2, in collision events with various incident pion momentum.

The distributions $N(n_p)$ of the proton multiplicities n_p in samples of the passages, stoppings, and any-type events in Pi^- + Xe collisions at 3.5 GeV/c are shown in fig.4.

The distributions presented in fig.4 provide additional motivation for distinguishing two classes of collision events I and II.

3.3. Distribution of Intranuclear Matter Layer Thicknesses in the Target Nucleus Obtained on the Basis of Corresponding Experimental Data

The distribution of the intranuclear matter layer thicknesses at various distances from the center of the target nucleus can be simply evaluated [13] on the basis of corresponding experimental data [15—17].

For the xenon nucleus the mean thickness λ — the mean thickness of the intranuclear matter layer in nucleons/S (where $S = \Pi R^2 \cong \Pi D^2 \doteq 10\ fm^2$ and R is the nuclear interaction range which is approximately as large as the nucleon diameter D_0) is $\langle \lambda \rangle = 8.5$ nucleons/S which corresponds to 3.5 protons/S.

The maximal thickness $\lambda_{max} = 18.6$ nucleons/S or 7.7 protons/S.

It is a reason to state that the mean thickness $\langle \lambda \rangle = 3.5$ protons/S is the same as the mean multiplicity $\langle n_p \rangle = 3.2 \pm 0.3$ obtained experimentally for the sample of passages and the sample of any-type events. It indicates that the number of the emitted protons equals to the number of the protons met by the incident hadron in its passage through the layer of intranuclear matter as thick as the mean thickness is of the target nucleus; these protons are contained within the cylinder volume as large as $\langle \lambda \rangle \cdot \Pi D_0^2$.

For the stoppings the mean number of the emitted protons obtained experimentally is $\langle n_p \rangle = 7.5 \pm 0.3$ which corresponds to the maximum thickness of the xenon target nucleus $\lambda_{max} = 7.7$ protons/S evaluated [13] on the basis of the data on nucleon distribution in nuclei [17].

3.4. The Energy Loss of the Incident Hadron for Emission of One Nucleon

At 3.5 GeV/c momentum of the incident pion the stopping appears when the intranuclear matter layer thickness covered is as large as the nucleus diameter is — $\lambda \cong D \cong 18.6$ nucleons/S (where D is the nucleus diameter). Then, the mean value $\langle \varepsilon_\pi \rangle$ of the incident pion momentum lost for the emission of one nucleon is

$$\langle \varepsilon_\pi \rangle = \frac{p_\pi}{\lambda_{max}} \cong \frac{p_\pi}{D} \cong \frac{3.2}{18.6} \cong 0.172\ \frac{\text{GeV/c}}{\text{nucleon}} \cong 170\ \frac{\text{MeV/c}}{\text{nucleon}}.$$

If the range-momentum relation exists in intranuclear matter, then the expected number $n_{N_{max}}$ of the emitted nucleons at 2.2 GeV/c momentum in the stoppings in Pi + Xe nucleus collisions will be:

$$n_{N_{max}} \cong \frac{2.2\ \text{GeV/c}}{0.17\ \text{GeV/c}} \cdot \text{nucleon} = 12.8 \text{ nucleons};$$

for 12.8 nucleons is the maximal number of the emitted protons $n_{p_{max}} = 12.8 \cdot \frac{Z}{A} = 12.8 \cdot \frac{54}{131} = 5.2$ protons. This value does not contradict the experimental one, $\langle n_p \rangle = 4.1 \pm 1.0$, in the stoppings observed in collisions at 2.2 GeV/c.

It should be emphasised that to the xenon nucleus $\langle \lambda \rangle = 3.5$ protons/S corresponds the mean number $\langle n_p \rangle = 3.3 \pm 0.3$ protons, in any-type of pion-xenon collisions at the incident pion momenta not smaller than 3.2 GeV/c. It indicates that even when the particles are produced, the number of the emitted nucleons corresponds to the thickness of the intranuclear matter layer which could be covered by the incident pion (hadron) in the case of pure passage. It means that some state created after the particle producing collision continues the incident hadron course. It supports additionally, that the particle production goes via some intermediate state, which decays, after having left the target nucleus, into observed produced hadrons.

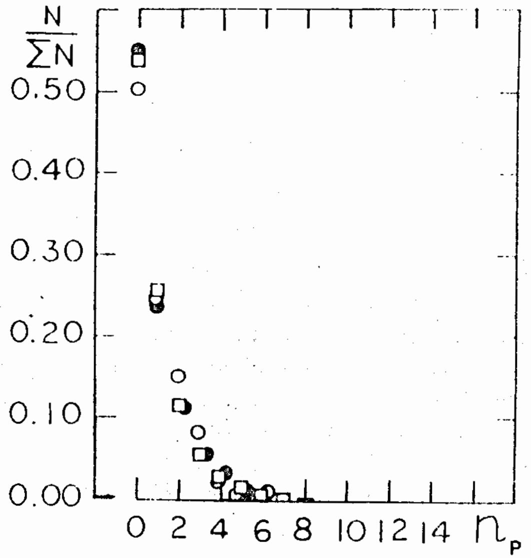
3.5. The Relation between Proton Multiplicity n_p Distribution $N(n_p)$ and the Distribution $N(\lambda)$ of the Intranuclear Matter Layer Thickness λ in the Target Nucleus

The relation between the observed characteristics of the intensity n_N of the nucleon emission which the hadron passage through intranuclear matter is accompanied by and the size of the target nucleus and nucleon density distribution in it can be revealed in confronting the distribution $N(\lambda)$ of the intranuclear matter layer thicknesses to corresponding distribution $N(n_N)$ of the intensity n_N of the emitted nucleons; $N(n_p)$ may be used instead of $N(n_N)$.

In fig.5, the distribution $N(n_p) = N/\,\Sigma N$ obtained experimentally for the sample of the passages of the incident pion at 3.5 GeV/c through the xenon target nucleus is confronted to the distribution $N(\lambda)$ of the intranuclear matter layer thicknesses covered by the hadron in the collisions without particle production and to the distribution $N(n_p)$ of the emitted proton multiplicity n_p from the data on the target nucleus size and nucleon density distribution in it, using corresponding formulas [13,23].

From fig.5, it is clear that: a) Simple relation exists between the intensity n_p distribution $N(n_p)$ of the emitted protons and the size of the target nucleus and the distribution $N(\lambda)$ of the thicknesses λ in nucleons/S in it. b) The protons are emitted from the regions near to hadron course, from the volume $\lambda \Pi D_0^2$,

Fig.5. The distributions $N/\Sigma N$ of the mutiplicities n_p of the emitted protons: O — in the sample of the passages singled out in scanning and measurements: □ — in the sample of passages, obtained from the distribution $N(n_p)$ for any-type collisions; ● — calculated from the data on the target nucleus size and nucleon density dustribution in it, using corresponding formulas [13,23]. (In fact the last distribution is the distribution of the intranuclear matter layer thicknesses λ in protons/S covered in the passages).



where D_0 is the nucleon diameter or the strong interaction range. The emission of the nucleons is the same in the events from the classes I and II.

4. RESULTS AND COMMENTS

Let us sum up the main results obtained in this work:

1. A series of photographs has been completed on which the passages are simply and directly observed. Two classes of hadron-nucleus collision events, I and II, are observed clearly and conclusively.

2. The energy and angular characteristics of the proton emission which the collisions are accompanied by are the same in both the classes of events, I and II.

3. The crucial relations were obtained: At energies high enough, the mean number of nucleons (protons) $\langle n_N \rangle$ ($\langle n_p \rangle$) emitted in total sample of collisions equals the mean thickness $\langle \lambda \rangle$ of the target nucleus expressed in nucleons/S (protons/S).

4. Definite range-energy relation exists for hadrons in intranuclear matter, similarly as such relation for charged particles in materials.

5. The passages may be observed plentifully in their pure form only at definite energy interval — at about 1 to about 10 GeV; at higher energies the passages are relatively rare phenomenon.

The passage of the hadron through layers of intranuclear matter accompanied by the nucleon (proton) emission is a fundamental process in the

hadron-nucleus collisions, on the background of it other processes occur. This process may be a physical basis for direct method of intranuclear matter studies. In particular — single massive atomic nucleus can be used as special «track»-detector of the nuclear and particle processes realized within the distances of about 10^{-13} cm at time intervals of about 10^{-24} sec.

The samples of the passages in the pure form may be used for direct investigations of the nuclear forces — from the angular distributions of the scattered hadrons.

In traversing the target nucleus, the incident hadron causes the nucleon emission from the nucleus in a definite manner; the nucleons (protons) cannot be considered as the knocked out protons.

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Стругальска-Голя Э., Стругальский З. E1-94-296

Наблюдения проникновений быстрых адронов через внутриядерную материю

Описываются дополнительные данные, касающиеся процесса проникновения адронов высоких энергий через внутриядерную материю. Обсуждаются свойства испускания нуклонов, сопутствующего проникновению адрона. Проникновение адронов через слои внутриядерной материи является ядерным аналогом электромагнитного процесса проникновения заряженных частиц через слои материалов.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

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Observations of Fast Hadron Passages through Intranuclear Matter

Additional data on high-energy hadron passages through layers of intranuclear matter are presented. Properties of the nucleon emission which the passages are accompanied by are described. The energy-dependence of the hadron passage properties is discussed. The observed passages of fast hadrons through layers of intranuclear matter are nuclear analogue of the well known electromagnetic process — of the passages of electrically charged particles through layers of materials. The hadron passages are observed plantifully in hadron-nucleus collisions at a few GeV.

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

Communication of the Joint Institute for Nuclear Research. Dubna, 1994