сообщения
объединенного
института
ядерных
исследований
дубна

E1-84-268

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NEW WAY FOR INTERPRETATION OF HADRON-NUCLEUS COLLISION DATA

1984

1. INTRODUCTION

One can notice a general tendency during the last ten years: many physicists used to attach an importance to represent experimental results on high energy hadron-nucleus collisions in terms of the "average number $\langle\nu\rangle$ of collisions in the target nucleus"[1-7]. In order to calculate the average number of collisions, suffered by the incident hadron inside the target nucleus, Gurtu et al.[1] have used the Glauber theory[8]. If P_ν is the probability for the incident hadron to have suffered ν_A collisions in a nucleus with the mass number A, then[1]

$$\langle\nu_A\rangle = (\sum_\nu \nu P_\nu)/(\sum_\nu P_\nu) = (A\sigma_{in})/\sigma_{in}(A),$$

where σ_{in} and $\sigma_{in}(A)$ are the hadron-nucleon and hadron-nucleus inelastic cross-sections respectively. In other words, $\langle\nu_A\rangle$ is the average number of inelastic collisions, a hadron h would make with nucleons inside the nucleis if, following each collision, it remained as a single hadron[2] h.

The suggestion has been presented that the number of fast protons - with kinetic energies from ~30 up to ~400 MeV - emitted in hadron-nucleus collisions can be used as a good measure of the number of collisions inside the nucleus[3,5]. The basis of this "suggestion" comes from the "fact" that the fast target protons "may be related to the recoiling nucleons"[3]. Although, the only argumentation which I could find in support for this "fact" is: "the forward peaked behaviour supports the assumption that grey particle (fast protons - Z.S.) are knock-on recoils"[4].

But, the fast protons cannot be regarded as the knock-on recoils[9,10] and the mean number $\langle\nu_A\rangle$ of collisions of a hadron inside the target nucleus cannot be observed and measured[5]. Things that cannot be observed and measured should have no actual physical existence; we should never take too seriously the quantities introduced in any model by our imagination, and not in the least in experimental physics.

The atomic nucleus used as the target in hadron-nucleus collisions provides the only tool available which allows in a direct way the experimental study of such topics as the space-time development of the particle production, the interaction of short living systems with nucleons, and perhaps even the interactions of almost free constituents of nucleons, and therefore to observe new states of matter - in other words, the target nucleus may be used as a detector. The idea of using atomic nuclei both as targets and as indicators of properties of produced states in hadron-nucleon and in hadron-nucleus collisions has been discussed by many authors[11-23]. The emission of fast nucleons, of fast protons in particular, in hadron-nucleus collisions is the phenomenon which can be applied as the basis for target nucleus operation as the detector[23].

For this reason I have decided to investigate the applicability of the quantity $<\nu>$ for hadron-nucleus data representation, and to test whether the emitted fast protons are knock-on recoils or not. But, the questions "How does the fast nucleon emission process proceed"? and "How is the quantity $<\nu_A>$ related to the multiplicity n_p of fast protons emitted?" must find their answers primarily in experiments.

Faced with new experimental facts, in investigating experimentally hadron-nucleus collisions, I am in a position to discard the current view on the mechanism of the fast nucleon emission and, therefore, on the relation between the quantity $<\nu_A>$ and the number n_p of fast emitted protons. For this reason I am taking the liberty to propose to reject the $<\nu_A>$ quantity from the analysis of experimental data, as unmeasurable one. Instead of this quantity $<\nu_A>$ I propose to use the measurable quantity λ which is the thickness of the nuclear matter layer involved in a hadron- nucleus collision, measured in (nucleons/fm^2) or in (protons/fm^2); the new quantity λ is measurable one because it is related simply to the number (or multiplicity) n_p of fast protons emitted in a hadron-nucleus collision, as we have shown it[24-26]. Experimental data analysed in terms of this new quantity exhibit a new and clear physical meaning.

In the light of this new interpretation of the quantity the target nucleus becomes in fact a detector[23] - it is possible then to estimate the impact parameter in the majority of the hadron-nucleus collision events.

The aim of this work is to clarify out new viewpoint, in analysing appropriate experimental data.

2. THE MULTIPLICITY n_p OF FAST EMITTED PROTONS AS A MEASURE OF THE THICKNESS OF THE NUCLEAR MATTER LAYER INVOLVED IN HADRON-NUCLEUS COLLISIONS

In the study of pion-xenon nucleus collisions in 26 litre[27] and 180 litre[28] xenon bubble chambers, at 2.34 and 3.5 GeV/c momentum, we were able to identify events in which incident pions were completely stopped and deposited its energy in the target nucleus[29,30]. Taking into account the energy loss by

ionization, of the primaries in liquid xenon, the incident pion energies were practically ~2.1 and ~3.2 GeV. The stopping is accompanied by intensive emission of fast nucleons, as it can be concluded from intensive emission of observed fast protons; no any particles are produced in these collisions, in particular pions are not produced;the evaporation of nucleons and target fragments accompanies the stopping as well. Such events we call "stopped" events later on. The probability of the occurrence of stopped events depends on the kinetic energy of the incident pion, and it decreases with the energy increase; at ~2.1 GeV the stopped events occur in ~12% of all the observed pion-xenon nucleus collisions, at ~3.2 GeV they occur in ~2%, at ~5 and ~9 GeV they do not occur practically.

The existence of the stopped events allows to conclude that pions lose a large fraction of their energy by causing fast nucleon emission and target fragment evaporation. The observed energy dependence of the probability of the appearance of these events indicates that range-energy relation may take place in nuclear matter for pions, and probably for all hadrons as well. The extent of the fast nucleon emission and target fragment evaporation caused by a pion may depend then on the number of nucleons it meets on one length unit along its path in nuclear matter and on the way in which it hits them. Energy loss should manifest itself in energy-dependences of emission of fast nucleons in hadron-nucleus collisions. We have shown that in fact high energy pions and protons, of kinetic energy larger than the pion production threshold, lose monotonically their kinetic energy in their passage through atomic nuclei[24,25].

The most important characteristic of the stopped events is the distribution $N(n_p)$ of multiplicities n_p of emitted fast protons. The distribution of proton multiplicities $N(n_p)$ in the stopped pion-xenon nucleus collisions at 3.5 GeV/c momentum exhibits evident peak at the proton multiplicity $n_p \simeq <n_p> = 7.4$, and the multiplicities are distributed symmetrically around this peak value, fig.1. The observed symmetry can occur when the collisions are predominantly along the diameter D of the target nucleus of some spherical symmetry; the sample of the stopped events under consideration does not contain collisions with a markedly large impact parameter - much larger than 0.

At the incident pion energy 2.1 GeV the mean multiplicity $<n_p>$ of emitted fast protons is evidently smaller, $<n_p> = 4.1$.

The observed difference between the mean multiplicities $<n_p>$ at 2.1 and 3.2 GeV indicates that a definite relation between the proton multiplicity $<n_p>$ and the mean path length of the incident hadron in nuclear matter $<\lambda>$ may exist; such relation may exist between n_p and λ as well. If a definite relation between λ and n_p exists in fact, the observed value $<n_p> = 7.4$ in pion-xenon collisions at 3.2 GeV may be simply the number of

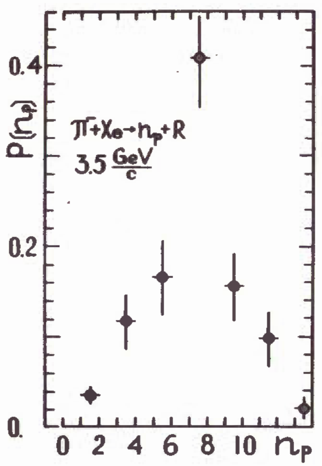

Fig.1. Frequency distribution $P(n_p)$ of the multiplicities n_p = = 0,1,2,3,... of the fast protons emitted in the stopped pion-xenon nucleus collision events at 3.5 GeV/c momentum.

protons which incident pion meets along its path in the xenon nucleus, i.e., along the xenon nucleus diameter D.

Now many aspects about the nuclear matter distribution in atomic nuclei are so firmly established that it has been possible to use them in order to investigate other physical quantities /31/. Measurements of the ratio between the proton number N_p and the neutron number N_n at the periphery of the atomic nucleus /32/, together with the information about proton distribution within the nucleus allow one to conclude that this ratio is almost radially independent and amounts nearly $Z/(A-Z)$. It is possible, therefore, to estimate the number of protons contained within any cylindrical volume centered on the hadron course in an atomic nucleus; it is possible to estimate as well the number of protons met by a hadron along its path λ in nuclear matter or, in other words, the number of protons inside the cylindrical volume $\pi D_0^2 \lambda$ centered on the path λ, where D_0 is the nucleon diameter. We evaluate without difficulties that in the xenon nucleus $n_p = 7.7$ protons are contained within the cylindrical volume $\pi D_0^2 D$, what is just as we observe, $\langle n_p \rangle = 7.4$.

We find, therefore, in this particular case that the mean number $\langle n_p \rangle$ of fast protons emitted equals the number of the protons contained within the cylindrical volume $\pi D_0^2 D$ centered on the target nucleus diameter:

$$\langle n_p \rangle = \pi D_0^2 D \langle \rho \rangle \frac{Z}{A}, \qquad (1)$$

where $\langle \rho \rangle$ is the mean nucleon density along the target nucleus diameter D, D_0 is the nucleon diameter, Z and A are the charge and the mass numbers of the target nucleus.

Formula (1) can be rewritten as more simple one, and more convenient for applications:

$$\langle n_p \rangle = \lambda \frac{Z}{A}, \qquad (1')$$

where instead of D is used the path length λ in (nucleons/S) and $S = \pi D_0^2 \simeq 10\ fm^2$. We note that the observed mean proton multiplicity $\langle n_p \rangle$, according to our finding, is just $\langle n_p \rangle$ (protons/S) and it indicates that the nuclear matter layer of the thickness λ (nucleons/S) = D (nucleons/S) or $\lambda \frac{Z}{A}$ (protons/S) was involved in the hadron-xenon nucleus collision process.

The question arises: "Is the relation (1′) of a general nature or it expresses some particular case?" The answer should be found in experiments.

If the relation (1′) is true generally, it should manifest itself in various characteristics of the fast proton emission process obtained experimentally. The simplest and directly measurable of these characteristics is the energy dependence of the proton multiplicity distribution $N(n_p)$ in the stopped collision events. In fact, if the relation (1′) is generally valid, then having the mean value of the incident pion energy loss ϵ_h in nuclear matter by fast nucleon emission and target fragment evaporation per length unit $\lambda = 1$ (proton/S) the mean number $\langle n_p \rangle$ of emitted fast protons can be estimated for any stopped hadron-nucleus collision at the projectile energy E_h by simple relation $\langle n_p \rangle = E_h/\epsilon_h$ (protons/S). The quantity ϵ_h for incident pions at 3.2 GeV energy was estimated /24/, $\epsilon_h = \epsilon_\pi$ = = 440 (MeV/(proton/S)). Experimental data on the stopped pion-xenon nucleus collisions are available /30/ at 2.1 GeV: $\langle n_p \rangle_{exp}$ = = 4.2±0.3 (protons/S). The predicted value for $\langle n_p \rangle_{pred}$ = = 4.8 (protons/S), in good agreement with the experimental one. This simple direct experimental testing provides a first indication that formula (1′) may be generally valid, at least in the class of the stopped events. Similar testing of the generality of the relation (1′) may be performed using experimental data on the stopped events at other various incident pion energies E_h. Such a testing will provide an accurate experimentally stated relation between the multiplicity $\langle n_p \rangle$ in (protons/S) of the emitted fast protons and the thickness λ in (protons/S) of the nuclear matter layer involved in the stopped collisions in dependence on the projectile energy E_h. The testing presented above, at $E_h = 2.1$ GeV, indicates that this relation is almost independent of E_h, at least at 2.1-3.2 energy interval.

We would like to know whether the relation (1′) is valid or not for any hadron-nucleus collision - not for the stopped only. This newly arised question will find its answer in experiments as well. But, before many observable effects can be analysed from the point of view presented in this paper, a short survey of properties of the fast proton emission process found experimentally should be presented here.

In studying the total sample of pion-xenon collision events at 2.34-9 GeV/c momentum, and in analysing various available /3-5, 33-36/ data on hadron-nucleus collisions /24, 25/ at various projectile energy from a few GeV up to a few thousand GeV, we state that:

1. We observe an astonishing independence of the produced pion multiplicity n_π : the mean values of the fast proton kinetic energy $\langle E_{kp}\rangle$, longitudinal momentum $\langle P_{Lp}\rangle$, transverse momentum $\langle P_{Tp}\rangle$, emission angle $\langle \cos\theta_p\rangle$ and their normalized dispersions $D/\langle E_{kp}\rangle$, $D/\langle P_{Lp}\rangle$, $D/\langle P_{Tp}\rangle$, $D/\langle \cos\theta_p\rangle$; values of these quantities are the same for the stopped collision events and for any-type collision events in which pions are produced intensively (see, for example, fig.2). This property is independent of the incident hadron energy E_h and of its identity as well [24,25].

2. The energy and angular distributions of the fast emitted protons do not depend on the multiplicity n_p of these protons and are the same in the stopped collision events [9,10].

3. The multiplicity n_p distribution $N(n_p)$ of the fast protons emitted in hadron-nucleus collisions exhibits a dependence on the multiplicity n_π of produced pions at incident hadron energy E_h smaller than a few GeV; at higher energies it is energy-independent [24,25].

4. The energy-dependence of the multiplicity distribution of the fast protons emitted at incident hadron energies smaller than a few GeV can be explained quantitatively [25] in terms of our knowledge about the incident hadron energy loss in nuclear matter [24].

5. The observed fast protons cannot be the knock-on recoils [9,10]; the knock-on recoils may appear among them in a small (~10%) portion of the collision events. It is reasonable to think that fast neutrons emitted in hadron-nucleus collisions are not the knock-on recoils, too.

6. The fast nucleon emission in hadron-nucleus collisions comes from definite cylindrical region $\pi D_0^2 \lambda$ inside the target nucleus centered on the hadron path λ.

A short conclusion from the above presented survey will be useful: the fast nucleon emission process may be analysed separately and independently of the particle production process, because not produced particles (pions in particular) are responsible for the characteristics of the fast nucleon emission process, and because the stopped events occur.

Now we are ready to start an analysis of various characteristics of the fast nucleon emission process (of the fast proton emission in particular) in which the relation (1′) manifests itself. In the light of the physical meaning of the multiplicity n_p of the fast protons emitted in hadron-nucleus collisions, following conclusion may be deduced from the relation (1′), if

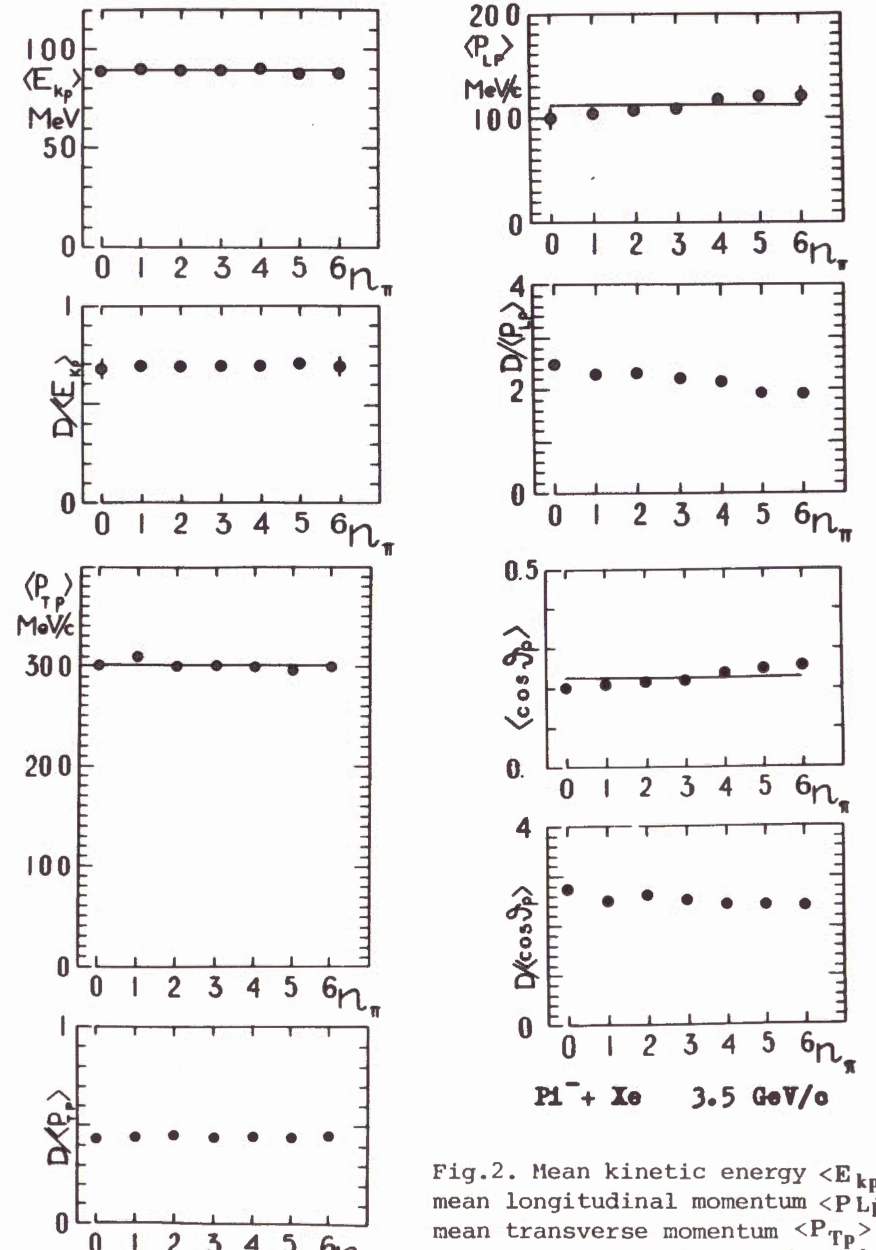

Fig.2. Mean kinetic energy $\langle E_{kp}\rangle$, mean longitudinal momentum $\langle P_{Lp}\rangle$, mean transverse momentum $\langle P_{Tp}\rangle$, mean emission angle $\langle\cos\theta_p\rangle$ of fast protons emitted in pion-xenon nucleus collisions at 3.5 GeV/c momentum, in dependence on the multiplicity n_π of produced pions, and normalized dispersions $D/\langle E_{kp}\rangle$, $D/\langle P_{Lp}\rangle$, $D/\langle P_{Tp}\rangle$, $D/\langle\cos\theta_p\rangle$ of the means.

this relation is valid generally: The mean multiplicity $\langle n_p \rangle_A$ of the fast protons emitted in collisions of a hadron with an atomic nucleus A is almost as large as the mean thickness [26] $\langle \lambda \rangle_A$ of the target nucleus measured in (protons/S) unit:

$$\langle n_p \rangle_A \simeq \langle \lambda \rangle_A . \qquad (2)$$

But, the fast nucleon emission may occur when a hadron interacts with nucleons met along its path in nuclear matter. Therefore, the correct relation between $\langle n_p \rangle_A$ and $\langle \lambda \rangle_A$ should be:

$$\langle n_p \rangle_A = \langle \lambda \rangle_A \cdot (1 - e^{-\langle \lambda \rangle / \langle \lambda \rangle_{tot}}), \qquad (3)$$

where $\langle \lambda \rangle_{tot}$ is the mean free path for interaction of the incident hadron with the nucleon in nuclear matter measured in (protons/S) units, and related to the total cross-section for the hadron-nucleon collision σ_{tot} as $\langle \lambda \rangle_{tot} = 1/\sigma_{tot}$, where σ_{tot} is in (S/nucleon) units.

The mean proton multiplicity $\langle n_p \rangle_A$ expressed by formula (3) is A-dependent and energy-dependent. The A-dependence is due to the A-dependence of the mean thickness $\langle \lambda \rangle_A$ of the atomic nucleus [26, 31]. The energy-dependence at the incident hadron energy larger than a few [24] GeV is due to the dependence of the total cross-section σ_{tot} on the incident hadron energy; at incident hadron energy smaller than a few [24] GeV the "effective" mean thickness of the nuclear matter layer involved in the collision is smaller than $\langle \lambda \rangle_A$, because of the energy loss [25] of incident hadron in nuclear matter. A slight dependence of $\langle n_p \rangle_A$ on the incident hadron identity is expected as well, according to formula (3), because of such dependence of the cross-section σ_{tot}. The dependences of $\langle n_p \rangle_A$ on the hadron energy and identity are observed in fact and formula (3) reflects them quantitatively well [25]. At the incident hadron energy E_h smaller than a few [24] GeV the energy dependence is very sharp, at higher energies it is very weak [25].

The experimental testing of formula (3) has been performed at incident hadron energies from about 1 up to about 3500 GeV, and details concerning corresponding calculations were described [24, 25]. It was not found necessary to repeat here this description. We limit ourselves here, therefore, to a presentation of some results obtained, fig.3-5.

One can test without difficulties that satisfactory agreement between experimental data and predictions given by formula (3) cannot be achieved when instead of the mean free path for any-type collision $\langle \lambda \rangle_{tot}$ the mean free path $\langle \lambda \rangle_{tot}$ for inelastic collisions is used.

In future experiments physicists will obtain new experimental data which may be used for more accurate and complete tes-

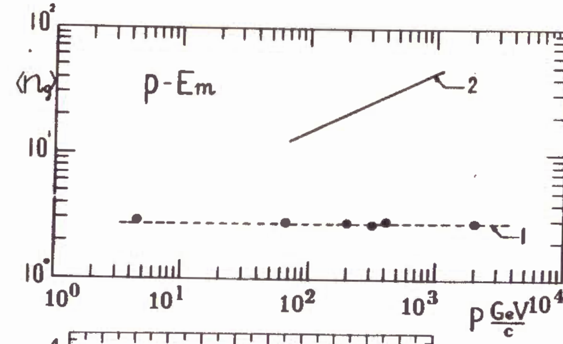

Fig.3. The mean multiplicity $\langle n_g \rangle$ of the grey-track leaving particles in dependence on the incident proton momentum P in proton-emulsion nuclei collisions. • - experimental data [5,34,37], 1 - predicted by formula (3), 2 - predicted by intranuclear cascade model [38].

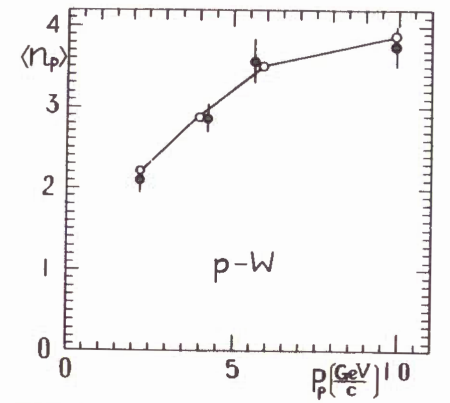

Fig.4. The mean multiplicity $\langle n_p \rangle$ of the fast protons emitted in proton-tingsten nucleus collisions at incident proton momentum P_p 2 - 10 GeV/c. -o- - calculations by formula (3), • - experimental data [39].

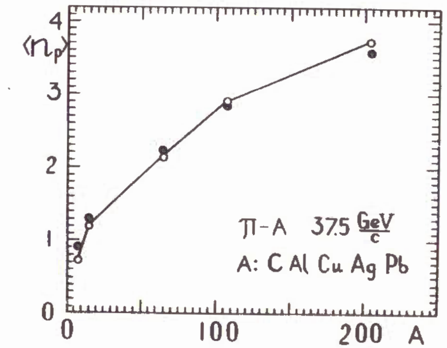

Fig.5. A-dependence of the mean multiplicity $\langle n_p \rangle$ of fast protons emitted in pion-nucleus collisions at 37.5 GeV/c momentum. • - experimental data [40], -o- - calculations using formula(3).

ting of the conception presented here, but at yet we can state that this conception found decisive support in the experimental data available up to now.

We related above the mean proton multiplicity $\langle n_p \rangle$ to the mean thickness $\langle \lambda \rangle$ of the layer of nuclear matter involved in hadron-nucleus collisions, sometimes we related $\langle n_p \rangle$ simply to λ. The meaning of the relation (1) allows to conclude that n_p and λ should obey as well the relation

$$n_p = \pi D_0^2 \lambda \langle \rho \rangle \frac{Z}{A} \qquad (4)$$

or

$$n_p = \lambda \frac{Z}{A}, \qquad (4')$$

where in formula (4) λ and D_0 are expressed in fm, $\langle\rho\rangle$ – the mean nucleon density in the target nucleus along λ in (nucleons/fm^3); in formula (4′) λ is in (nucleons/S) units.

But, in accordance with the meaning of formula (1) λ is always smaller than D or equal to D. But, in experiments we observe proton multiplicities $n_p > D$ (protons/S) only in a small fraction of collisions (less than about 10%). It may find an explanation [41] in "straggling" of $\langle n_p\rangle$ and in secondary fast proton emission caused by rarely occurring knock-on recoils.

3. CONCLUSION AND SUMMARY

A short conclusion may be useful and give a summary of results obtained in section 2:

I. The multiplicity n_p of fast protons observed in hadron-nucleus collisions reflects simply the thickness λ in (protons/S) of the nuclear matter layer involved in the collision.

II. The multiplicity n_p of fast protons emitted in hadron-nucleus collision and the thickness λ in (protons/S) of the nuclear matter layer involved in the collision obey the relations:

$$n_p = \lambda \text{ (protons/S)} \qquad (5)$$

and

$$\langle n_p\rangle = \langle\lambda\rangle \text{ (protons/S)}; \qquad (6)$$

the first is valid for predominant number (90%) of hadron-nucleus collision events, when $\lambda \leq D$ (protonts/S), where D is the diameter of the target nucleus.

III. At incident hadron energies high enough, higher than a few GeV, the multiplicity n_p of the emitted fast protons is related to the thickness λ in (protons/S) of the target nucleus at the impact parameter d at which the hadrom falls on the nucleus; the relation is an analogy to the relation (3):

$$n_p = \lambda(1 - e^{-\lambda/\langle\lambda\rangle_{tot}}), \qquad (3')$$

when $n_p < n_p(D)$ and where $n_p(D)$ is the number of protons contained within the volume $\pi D_0^2 D$ centered on the target nucleus diameter D.

IV. The mean number $\langle n_p\rangle$ of fast protons corresponding to a given nuclear matter layer thickness λ exhibits a definite "straggling" (fig.1).

V. The observed multiplicity n_p of fast protons emitted in hadron-nucleus collisions cannot be related simply to the average number of inelastic collisions the incident hadron would make with nucleons in the nucleus if, following each collision, it remained as a single hadron and, therefore, n_p or $\langle n_p\rangle$ cannot be related simply to the average number $\langle\nu\rangle$ of inelastic collisions inside the target nucleus, defined by formula (1).

The clarification of the physical meaning of the observed multiplicity of fast protons emitted in hadron-nucleus collisions, presented in this paper, provided new possibilities for a new interpretation of the data obtained in hadron-nucleus collision studies. In particular, the information about the thickness of nuclear matter layer the hadron fell on in a collision gives the possibility of determining the collision impact parameter, what in turn allows to treate [26] the target nucleus as "nuclear matter slab". Such a treatment of the target nucleus allows one to consider results of investigations of a sample of hadron-nucleus collisions as results obtained in an absorption experiment in which a beam of incident hadron fell on the sheets of nuclear matter [26] of definite thicknesses $\lambda = 1,2,3,\ldots,n_p(D)$ (protons/S), of definite mean thickness $\langle\lambda\rangle$ (protons/S), and definite maximum thickness λ_{max} (protons/S), where $n_p(D)$ is the mean proton multiplicity when a hadron traverses the target nucleus along its diameter D.

It is obvious from what has been said that: 1) we found a new way leading to a derivation of relations between the input and output data in hadron-nucleus collisions in terms of the hadron-nucleon data. 2) We obtained new information about fast proton multiplicity applicable in a formulation of the operation principle of the target nucleus as a detector [23].

For these reasons, I propose to use the new interpretation of the information about the multiplicity of the emitted fast protons instead the currently used, connected to the quantity λ.

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Received by Publishing Department
on April 20, 1984.

Стругальский З. E1-84-268
Новый способ интерпретации результатов исследований столкновений адрон-ядро

Анализ результатов исследований столкновений адрон-ядро позволяет заключить, что кратность испущенных быстрых /~20-400 МэВ/ протонов является хорошей мерой толщины слоя ядерной материи /выраженной в числе протонов на некоторую площадку Фм^2/, вовлеченного в столкновение. Сведения о толщине слоя ядерной материи, с которым взаимодействует налетающий адрон в данном столкновении, позволяют рассматривать набор событий столкновения адрон-ядро как набор, полученный в абсорбционном эксперименте - когда пучок налетающих адронов падал на слой ядерной материи определенной толщины.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

Сообщение Объединенного института ядерных исследований. Дубна 1984

Strugalski Z. E1-84-268
New Way for Interpretation of Hadron-Nucleus Collision Data

Results of the analysis of data on the hadron-nucleus collisions allow one to conclude that the multiplicity of emitted fast (~20-400 MeV) protons is a good measure of the nuclear matter layer thickness (expressed in protons per some area fm^2) involved in a collision. The information about the thickness of the nuclear matter layer, the hadron interacted with in a collision, provides a possibility of considering a sample of hadron-nucleus collisions as a sample obtained in an absorption experiment in which a beam of incident hadrons fell on the sheets of nuclear matter of definite thicknesses.

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

Communication of the Joint Institute for Nuclear Research. Dubna 1984