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Монотонное торможение адронов высоких энергий
в ядерной материи

Приводятся аргументы в пользу существования монотонных потерь энергии высокоэнергетичными адронами, проходящими через атомные ядра.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна 1979

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Monotonous Braking of High Energy Hadrons
in Nuclear Matter

An argumentation is presented in favour of the postulated existence of the monotonous energy loss which undergo high energy hadrons traversing the atomic nuclei.

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

Preprint of the Joint Institute for Nuclear Research. Dubna 1979

1. INTRODUCTION

In investigating of the pion xenon nuclei interactions, using the pictures from an exposure of the 180 litre xenon bubble chamber to a negative pion beam of 3.5 *GeV/c* momentum, the existence of such events has been shown in which the fast primary causes the emission of protons only without multiparticle production /1,2/. The protons emitted, being of energies from about 20 *MeV* to about 400 *MeV*, we call the "fast" protons to distinguish them from the evaporation protons. The methodical possibilities of the xenon bubble chamber technique enable us to state that the usually observed secondary pions, the negative of kinetic energy values larger than 10 *MeV* and the positive and neutral of energies equal and larger than 0 *MeV*, do not create in such events. Taking into account the average energy value of these protons, being $E_p \doteq 80$ *MeV*, and the average proton multiplicity, being $\bar{n}_p \doteq 8$, we may state too that the multiparticle creation process could occur in principle in such events, being not forbidden energetically, as accompanying the proton emission.

In order to explain the existence of such events, and to calculate the proton multiplicity distribution in them, being in agreement with the experimental one, the following working hypothesis has been suggested: high energy hadron traversing the nuclear matter causes the monotonous emission of the fast protons in numbers being equal to the numbers of protons met in the neighbourhood of close to its path inside the nucleus /3/. Accepting this hypothesis as a point of departure, owing to the agreement of the proton multiplicity distribution calculated with the experimental one, and taking into account the properties of the energy and angular spectra of the protons emitted, the existence of the monotonous energy loss of hadrons in traversing the atomic nuclei has been postulated [3]. These energy losses, being similar in some phenomenological respect with those of charged particle monotonous energy losses in traversing materials, may exist due to the strong interactions of the hadron with the nucleons inside the atomic nucleus.

The purpose of this paper is two-fold: firstly, to provide a simple, but more detailed, argumentation in favour of the existence of the monotonous energy loss which undergoes fast hadron traversing the atomic nuclei; secondly, to characterize this phenomenon as accurate as it is possible up to now.

2. DISCUSSION

In order to facilitate the consideration, we formulate precisely the working hypothesis: High energy pion traversing the nuclear matter undergoes the monotonous energy losses and, consequently, the successive breaking being the result of its interaction with the nucleons inside the atomic nuclei; the energy losses are accompanied by the emission of fast protons. This hypothesis is the consequence of the above mentioned one [3].

We present now an argumentation, mainly the experimental facts, in favour of the existence of such phenomenon in nature, and we give some more important characteristics of this process. We must now come back to the existing experimental facts which are summarized in *figures 1-4*, characterizing the proton emission process in high energy pion-nuclei collisions [1-4]. These data concerning the proton multiplicity distribution, proton energy spectra, and proton angular distribution are mainly the results of our experimental investigations of the pion-xenon nuclei collisions using the xenon bubble chamber exposed to pion beam at 3.5 *GeV/c* [1,2,4]. In these investigations the protons of kinetic energies (20-300) *MeV*,

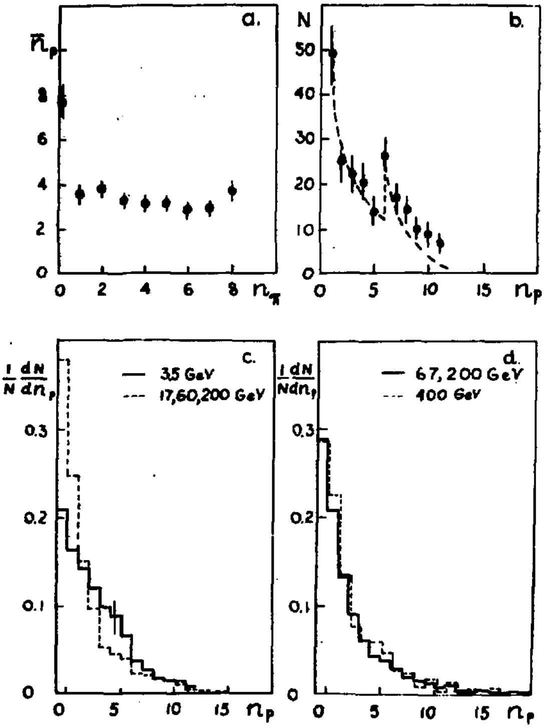

Fig. 1. Proton multiplicity distributions: a) the dependence of the average proton multiplicity $\bar{n}_p$ on the number n_π of secondary pions produced in pion-xenon nuclei collisions at 3.5 GeV/c /1/; *b) the proton multiplicity distribution of the events with zero and one secondary pion without multiparticle production* /2/: *the dotted line presents the calculated distribution* /3/: *c) the proton multiplicity distribution of the pion-xenon* /4/ *(solid) and the pion-argentbromine* /1/ *(dotted) collisions at different energies; d) proton multiplicity distributions in the proton-argentbromine nuclei collisions at different energies* /1/.

positive charged pions of energies (0-100) *MeV*, negative charged pions of energies (10-100) *MeV*, and neutral pions of energies equal and larger than 0 *MeV* are recorded with nearly 100% efficiency in the total 4π solid angle.

The experimental facts being closely connected with the problem under discussion are:

1. The high energy pion-nuclei collisions without multiparticle production exist being accompanied by the intensive fast proton emission only; such events amount nearly 11% including the cases with zero and one secondary pion and any number of fast protons emitted [2].

2. The pion-xenon collision events not accompanied by any secondary pion exist making up nearly 1.3% of all collision reactions observed [2]. Peak is observed in the proton multiplicity distribution of such events at proton number $n_p \doteq 8$.

3. The characteristic inmonotonous proton multiplicity distribution of the events without multiparticle production can be described well (*fig. 1b*) under the assumption that monotonous emission of protons takes place along the pion path inside the nucleus, and the number of the fast protons emitted equals to the number of protons met in the neighbourhood of close to this path [3]. The inmonotony appearing in this distribution, being situated at the proton multiplicity value $n_p = 6$, corresponds to some point on the pion path inside the nucleus from which enlarged proton emission starts, after passing some average for the monotonous emission path length $\bar{\lambda}$ in nuclear matter [3].

4. The formula describing the fast proton multiplicity distribution of all hadron-nuclei collision events has been derived on the basis of our working hypothesis [5]. It agrees well with the experimental data at 3.5 *GeV/c* and it describes the fast proton multiplicity distributions of pion-nuclei collisions and proton-nuclei collisions at wide range of energies, 200 *GeV* and 400 *GeV* [5].

5. The average energy value $\bar{E}_p$ of the protons emitted in any pion-nuclei collision does not depend neither on the secondary pion number n_π nor on the number n_p of protons emitted, being nearly $\bar{E}_p = 80$ *MeV* [1].

6. The energy spectra of protons are of the same shape, *fig. 2c)* for the classes of pion-nuclei collision events with different number of proton emitted [1].

7. The energy spectra of protons emitted are of the same shape, *fig. 2d)*, for the classes of pion-nuclei collisions with different numbers of pions generated, charged and neutrals [1].

8. The distributions of proton emission angles in pion-nuclei collision events with different numbers of pions produced, *fig. 3b)*, are the same /1/.

9. The distributions of proton emission angles in pion-nuclei events with different numbers of protons emitted, *fig. 3a)*, are the same /1/.

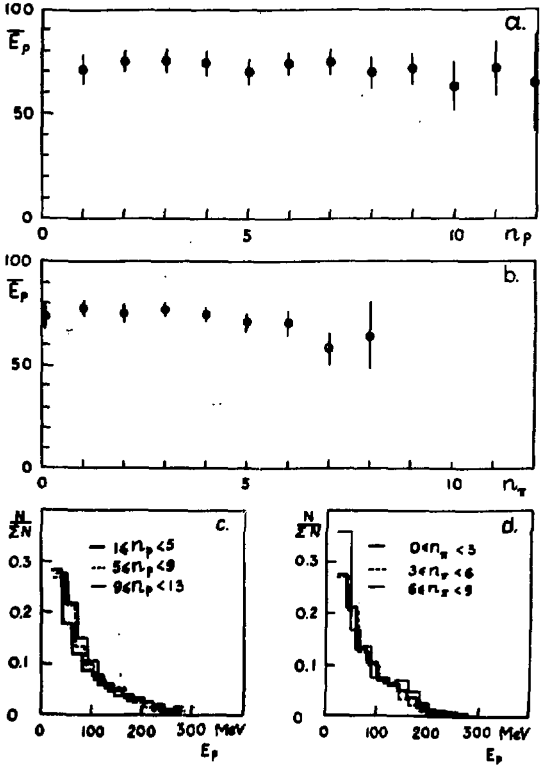

Fig. 2. Energy characteristics of the protons emitted in the pion-xenon nuclei collisions at 3.5 GeV/c; a) average energy of the protons in dependence on the proton multiplicity n_p /1/; *b) average energy of the protons in dependence on the numbers* n_π *of pions generated* /1/; *c) energy spectra of protons in the classes of pion-xenon nuclei collision events with different numbers* n_p *of the protons emitted* /1/; *d) energy spectra of protons in the classes of events with different numbers* n_π *of pions generated* /1/.

10. The average transverse momenta of protons emitted do not depend on the number of charged secondaries appearing in pion-nuclei collisions, being in average nearly 300 *MeV/c* /4/.

11. The proton multiplicity distribution of pion-xenon nuclei collisions at 3.5 *GeV/c* and the of pion-argent-bromine nuclei collisions at 17, 60, 200 *GeV/c* /6,7/ bear a great resemblance to each other, *fig. 1c)*.

12. The proton multiplicity distributions of the proton-argentbromine nuclei collision events are identical at different energies: 67, 200, and 400 *GeV, fig. 1d)*.

It is convenient to think of two classes of facts above mentioned: firstly, the facts being indicative of the exis-

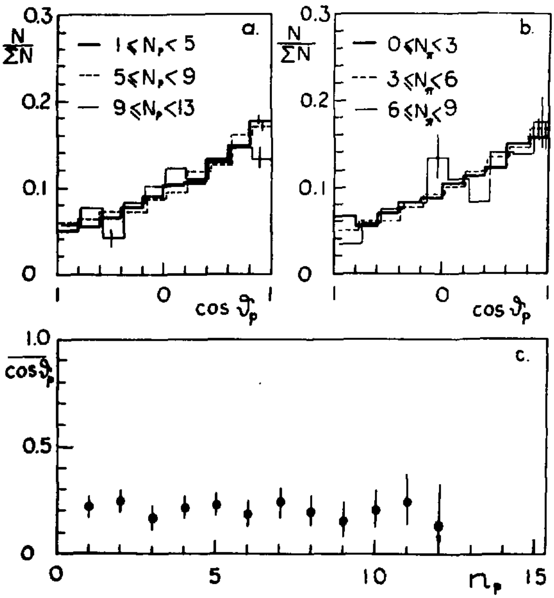

Fig. 3. Angular characteristics of the protons emitted in the pion-xenon nuclei collisions at 3.5 GeV/c /1/: *a) distributions of the emission angles* θ_p *of protons in the classes of collision events with different numbers* N_p *of protons emitted; b) distributions of the emission angles of protons emitted in the collision events with different numbers* N_π *of the pion generated; c)* $\overline{\cos\theta_p}$ *in dependence on the* n_p.

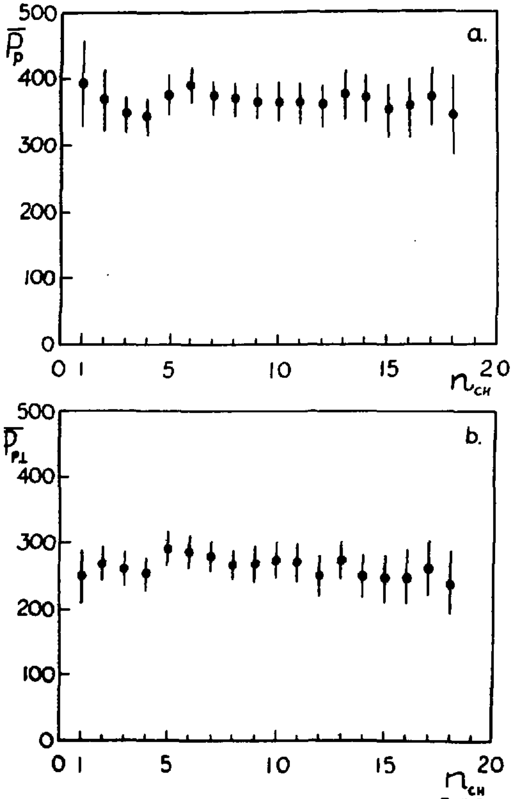

Fig. 4. Average total $\overline{P_p}$ *and transverse* $\overline{P_{p\perp}}$ *momenta of the protons emitted in the pion-xenon nuclei collision events at 3.5 GeV/c with different numbers* n_{ch} *of secondaries* /4/.

tence of the fast hadron monotonous braking in nuclear matter; secondly, the facts, giving possibility to draw some picture of such process and to characterize it in more detail. To the facts of the first class are belonging these numbered off as 1-4; to those of the second class the numbered by 5-12 are attributed. We shall now attempt to interpret these facts on the basis of the hypothesis suggested.

Let us imagine that high energy hadron comes into collision with an atomic nucleus and traverse it along its diameter undergoing the monotonous braking. Suppose this hadron to be of energy being high enough to pass the path length λ inside nucleus just as long as the nuclear diameter $2R$ is. Then, accepting our hypothesis to be conformable to the reality and supposing the protons are capable to escape the nucleus, we shall observe some line in the proton multiplicity distribution at a number n_p proportional to the number N_p of protons lying in the neighbourhood of close to the nucleus diameter:

$$n_p = kN_p . \qquad (1)$$

In the case, when each of such protons interacts with the hadron traversing the nucleus, the coefficient k is equal to one, $k = 1$.

The kinetic energy of the incoming hadron can be matched of such value to make up the path length λ just as long as the nucleus diameter is. At this energy value the hadrons traversing the nucleus at some distances d from its center escape it and the collision events shall be accounted to those with one secondary pion. The case like that we observe just in one of our experiments in which the xenon bubble chamber is exposed to the negative pion beam of 3.5 *GeV/c* momentum /2/; in the class of collision events without secondary pion a peak is seen at $n_p = 8$ in the proton multiplicity distribution /2/.

If we use our working hypothesis, we can calculate accurately the number of protons n_p emitted along the path length $\lambda = 2R$ using the simple formula:

$$n_p = k\pi D_0^2 \frac{Z}{A} 2R, \qquad (2)$$

where D_0 is the diameter of the nucleon, R is the radius of the nucleus in nucleon diameter length units, Z is the atomic number, A is the mass number. In this formula we accept the ratio of the proton number Z to the neutron number $A - Z$ being constant inside the total volume of the nucleus which is commonly used /8,9/. Using corresponding values for the xenon nucleus, $A = 131$, $Z = 54$, we have for $n_p = k8$. This value corresponds to the experimentally estimated one. Then, we conclude $k = 1$. The scheme presented above is obviously oversimplified, but it seems to give correct qualitative and quantitative explanation of the peak observed at $n_p=8$ in the proton multiplicity distribution.

Let us consider now the correspondence of our working hypothesis to the facts numbered as 3 and 4. We have reported that the proton multiplicity distribution has been calculated on the basis of this hypothesis and it agrees well with the experimental one /3/. We have mentioned too that the formula describing the fast proton multiplicity distribution of the hadron-nuclei collision events has been derived on the basis of this hypothesis /5/, it is in agreement with the experimental data within wide energy interval.

Does there exist any other possibility to explain these facts in the frames of the existing models of the hadron-nucleus collision process in such simple manner? Then, we incline at yet to accept ou hypothesis to be correct and corresponding to the reality, and we shall try to apply it to explanation of other facts concerning the hadron-nucleus collisions later on.

The intensive proton emission caused by fast pion traversing the nuclear matter is combined with the intensive monotonous energy loss by this hadron. Because of the independence of the energy and angular distributions of protons emitted neither on the proton nor on the charged secondaries multiplicity, we may think the energy loss mechanism does not depend too neither on the proton nor on the charged secondaries multiplicities. Then, according to our hypothesis we must postulate the existence of pion energy loss in traversing nuclear matter; high energy pion traversing an atomic nucleus undergoes energy loss in comparatively small portions - monotonously along its path inside the nucleus. Similar process, although being of fundamental difference in its nature, we know well as the ionization losses of charged particle by its passing through materials.

The energy loss process and the corresponding braking of pions in nuclear matter preceds the multiparticle production process; the secondaries appearing, if created inside nucleus, must undergo such energy loss too. Really, we observe the intensive emission of protons in pion-nuclei collisions [2] but we observe never the multiparticle production process in pion-nucleon collisions without nucleon emission, in agreement with the baryon conservation law. Such braking process should be peculiar to any hadron; however, it must be tested in future experiments, as it has been done for the pion here. Fast hadron, after passing some average path length $\bar{\lambda}$ inside the nucleus along which the monotonous energy loss takes place only, undergoes the inmonotonous energy loss. This is indicated by the inmonotony in the proton multiplicity distribution in the pion-xenon nuclei collisions with one single secondary pion, *fig. 1b)*; in the more complicated cases of pion-nuclei collisions this inmonotony corresponds to the multiparticle production acts.

3. THE CHARACTERISTICS OF THE HADRON BRAKING PROCESS IN NUCLEAR MATTER

Let us try to reveal some characteristics of the pion braking process on the basis of the second group of the experimental facts denoted by the numbers 5-12. These facts are complete enough to be the basis for evaluation of the most important average quantities describing the braking process: an average path length $\bar{\lambda}$ which must be overcome by the monotonously braked pion inside the atomic nucleus before to cause a multiparticle production act; an average energy $\bar{\epsilon}$ which must be lost for emission of some single nucleon in such braking process. Both of these quantities $\bar{\lambda}$ and $\bar{\epsilon}$ can be estimated as yet for the braking of the pions of the energy being nearly 3.2 *GeV*; the energy of the beam pions equals 3.5 *GeV*, but, as we know from many investigations, the effective energy of the pion interacting with a nucleus in the centre of the chamber is smaller because of the electromagnetic energy loss in traversing by the pion some thickness of the material inside the chamber.

We wish to estimate the quantity $\bar{\lambda}$ now. As it has been shown in experiment, the average proton multiplicity in pion-xenon nuclei collision events at 3.2 *GeV/c* momentum equals $\bar{n}_p = 3.9$, being independent on the number of secondary pions generated /1/. To this average number there corresponds the average value of the pion path length inside the nucleus $\bar{\lambda}$ determined by the relation

$$\bar{n}_p = \pi D_0^2 \bar{\lambda} \frac{Z}{A}, \tag{3}$$

resulting obviously from our considerations. Taking $D_0 = 1$ we have:

$$\bar{\lambda} = \frac{\bar{n}_p A}{\pi Z}; \tag{4}$$

for the xenon nucleus $\bar{\lambda} = 2.98 D_0 \approx R$.

We shall estimate the quantity $\bar{\epsilon}$ now. We know the proton emission is accompanied by the neutron emission too; the number of those being determined by the relation

$n_n = \frac{A - Z}{Z} n_p$. Then, in any emission process both the nucleons are emitted in the numbers $n = n_p + n_n$. We know too, as it has been shown, that pions of the energy being nearly 3.2 *GeV* cause the emission of $n_p = 8$ protons, and, therefore, $n_n = 12$ neutrons in traversing the xenon nucleus along its total diameter length. The total kinetic energy $T_\pi = E_\pi - m_\pi$ of the pion traversing the nucleus along its diameter is lost in the braking process. Then, the average energy $\bar{\epsilon}$ is expressed by the formula

$$\bar{\epsilon} = \frac{T_\pi}{n_p + n_n}; \tag{5}$$

in the case being under consideration $\bar{\epsilon} = 153$ *MeV/nucleon.*

The mean values of the quantities $\bar{\lambda}$ and $\bar{\epsilon}$ may change in dependence on the incoming hadron energy and on the sort of the hadron as well.

The fascinating property of the braking process appears in the characteristics of the fast protons emitted which are listed as the facts numbered 5-9. Their average energy, their energy spectra, and their angular distributions do not depend on the numbers of the protons emitted and on the numbers of secondary pions, i.e., these characteristics do not depend on the number of secondary products emitted in pion-nuclei collisions. The energy values of the fast protons emitted in the forward direction and of the emitted in the backward direction are lying within practically the same intervals 20-250 *MeV*.

If we attempt to explain these properties in terms of the existing hadron-nuclei collision models, we meet the insuperable difficulties. But, the key to an understanding clearly may lie in the following picture of the proton emission process. Let us imagine that the protons emitted do not appear as the knocked out by the hadron traversing the nucleus but they are a result of a decay of some systems composed of some numbers of nucleons, at least of two nucleons. We have said that the average energy of the protons emitted is nearly of the half pion rest mass. We are able, therefore, to suppose the protons to be appearing as a result of absorption of the low energy pions by two-nucleon systems and of their decays later on. These slow pions are generated by the fast hadron along its path inside the nucleus monotonously. We postulate this process to be existing in the nature. This postulated proces s of the monotonous generation of the slow pions by the fast hadrons in nuclear matter we propose to call the pionization in analogy with the ionization one.

Previously we have estimated the value of the average energy which is needed for the emission of the single nucleon. Now we estimate the average energy ϵ_π which should be lost by the fast hadron for generation of one single pion of the low energy in traversing the nucleus, if the pionization process exists. This energy should be expressed by the formula

$$\bar{\epsilon}_\pi = 2\bar{\epsilon}. \qquad (6)$$

Using the value $\bar{\epsilon}$ = 165 *MeV/nucleon* we stimate $\bar{\epsilon}_\pi$ = 306 *MeV/pion*. The low energy pions being absorbed cause the emission of protons of the average energies being nearly 70-80 *MeV* per each, therefore, we must suppose the total energy of the pion absorbed to be nearly 140-160 *MeV*. Then, the energy U_π which must be lost for the pion extraction in our postulated pionization process is nearly 150 *MeV*, i.e., $U_\pi \doteq m_\pi$. The energy U_π is an analog for the ionization potential in ionization process.

Accepting this picture we may expect to find some irregularities in the energy spectra of the fast protons emitted in the hadron-nuclei collisions. Such irregularities should be looked for in the most simple cases of collisions like those without multiparticle production /2/. We shall try to find the expected irregularities in our future experiments.

None of the experimental facts listed above is in contradiction with this picture, and, what is more, the set of this facts can be qualitatively understood on the basis of such scheme of the proton emission process.

We have a big similarity of the proton multiplicity distributions in the pion-xenon nuclei collision events at 3.5 *GeV/c* and in the pion-argentbromine nuclei collision events at 200 *GeV/c*. It indicates the characteristics of this process may be energy independent within this wide energy interval. Some differences observed in both proton multiplicity distributions may be due to the different methods of investigation and different starting values of the energies of the protons: the energies of the protons included to the distribution of the pion-xenon collision events are larger than 20 *MeV*, the energies of the protons included to the distribution of the pion-argentbromine collision events are larger than nearly 40 *MeV* /6/.

Our picture of the proton emission process is based on the analysis of the characteristics of protons emitted in the pion-nuclei collisions. But, we have indications such scheme to be valid for the proton-nuclei collisions too. Namely, we observe the identity of the proton multiplicity distributions of the proton-argentbromine collision events at 200 and 400 *GeV*.

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