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NUCLEON EMISSION INDUCED BY HIGH ENERGY HADRONS TRAVERSING NUCLEAR MATTER

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1. INTRODUCTION

The purpose of this paper is to provide a simple experimental argumentation in favour of the existence of nucleon emission induced monotonously by high energy hadrons along their paths in traversing atomic nuclei.

The first experimental indication that such emission may exist emerged from our studies of the nucleon emission process in high energy hadron-nucleus collisions [1-3] performed mainly by means of the 26 and 180 litre xenon bubble chambers. Properties of these chambers are of great convenience in detailed studies of the hadron-nucleus collision events; the 180 litre chamber is almost ideal detector of the 4π solid angle aperture for nearly all secondaries appearing in such reactions, and might provide new experimental information [4].

Long ago we have observed in these chambers such collisions of pions with xenon nuclei at 3.5 GeV/c momentum in which fast protons, of energies from nearly 20 to 400 MeV, are intensively emitted without multiparticle creation [1]. In order to explain the existence of such events, and to describe qualitatively and quantitatively the proton multiplicity distribution in them, a simple working hypothesis has been suggested [3,5,6]: high energy hadron traversing nuclear matter causes the monotonous emission of fast nucleons along its path; the number of ejected nucleons equals the number of nucleons met in the neighbourhood of the path of this hadron - in particular, the number of emitted protons equals the number of the protons met. This hypothesis allowed one to explain many of characteristics of the proton emission process in hadron-nucleus collision events observed in experiments [3,5,6]. It enables us to suppose that this hypothesis may correspond to the reality and the monotonous nucleon emission induced by high energy hadrons traversing nuclear matter exists in the nature.

2. HEURISTIC CONSIDERATIONS

In attempts to show that high energy hadron traversing nuclear matter causes along its path the monotonous emission of nucleons, we must establish that: a/ Nucleons are ejected from some vessel-shape spatial region situated along the hadron course inside the target-nucleus; b/ The number of ejected nucleons is proportional to the path length of the projectile hadron inside target-nucleus. Appropriate argumentation might be provided by the observation of the most complete pictures of the hadron-nucleus collisions in various detectors. We start therefore with the analysis of such pictures recorded in the track detector giving the mostly full information - in the xenon bubble chamber, for example.

Let us consider such situation in which we observe the emission of nucleons from a massive atomic nucleus, from spherical microobject roughly of a 10^{-13} cm in diameter consisting of many nucleons, bombarded by high energy hadrons. In observing this phenomenon we meet in various cases with a variety of pictures. But, let us limit our consideration to the simplest class of observed images - let us single out such events only in which the projectile appears to be undergoing a deflection from the straight line course through any deflection angle in traversing the target-nucleus, with accompaniment or not by the nucleon emission. We know such cases exist in the nature[1,2]. We see that even in such extremely simplified situation we cannot state immediately either the emission is going on from the total volume of the bombarded object or the nucleons are emitted from some its part only.

Despite these obstacles and these apparent to be insuperable difficulties, we shall try to receive an answer to the question where the nucleon ejection is going from, using various characteristics of the emission process: the nucleon multiplicity distribution of the observed collision events, the angular and energy distributions of the emitted nucleons.

We know that ratio between the neutron number A-Z and the proton number Z may be accepted to be constant inside a target-nucleus[7,8]. We may restrict therefore our consideration to the characteristics of emitted protons only; such restriction eliminates easily the troubles with the neutron effective observation impossibility, without any applicability limitation of the conclusions arising from our heuristic deliberations.

We know from our experiment[2] too that in such collisions the deflection angles θ_h of the projectile, from its initial straight line course, are usually smaller than nearly 20 degrees. But, many cases exist as well in which much larger angles θ_h , being up to about a 150 degrees, are met; in such class of events enlarged proton emission is often observed[2]. The projectile deflections which we meet with in our observations are caused in traversing by it the nuclear matter of a finite thickness; they may be caused in any case either by a single collision or by many subsequent collisions of the projectile with some elements inside the target-nucleus. It can be proved that large deflections are more likely to occur in single collisions, while small deflections are generally caused by many collisions. In such single collisions the recoil nucleons appear of energies large enough they could cause the monotonous emission of nucleons as well in traversing nuclear matter; we think it to be the cause for the appearance of the enlarged nucleon emission intensity in the hadron-nucleus collision events in which the projectile hadrons undergo the deflections through large angles without causing the multiparticle creation.

We must distinguish, in considering this property of the nucleon emission in such simple events, among two different possibilities: the nucleons are emitted from the total volume of the target-nucleus or they are emitted from the limited vessel-shape space inside it, located coaxially with the projectile hadron course. If the first possibility takes place in the nature, we should not expect definite interconnections between the numbers of emitted nucleons and the projectile deflection angles and, therefore, any irregularities in the proton multiplicity distribution of collision events; we should not expect the anisotropy in the azimuth distribution of the proton emission directions too. We would like to show that irregularities may be expected if the second case takes place in the nature. In fact, from our experiments we know that ratio f between the number N_f of protons emitted in the forward direction and the number N_b of those emitted in the backward direction is evidently lerger than 1. For example, for the pion-xenon nucleus collisions at 3.5 GeV/c $f = 1.7 \pm 0.2$, in the events without any secondary pion, and $f = 1.8 \pm 0.1$, in the sample of events with one secondary pion /5/. In the light of the experimental facts which we have spoken above about we may expect then two different kinds of the azimuth distribution of the proton emission directions: a/ The isotropic azimuth distribution, in the case if this emission goes on from the total target-nucleus volume; b/ The anisotropic azimuth distribution, if this emission goes on from some part of the target-nucleus volume draving along the projectile path. It might be stated therefore that the azimuth distribution of the proton emission directions in the hadron-nucleus collisions without multiparticle creation might provide the information whether the nucleon emission is going on from the whole target-nucleus volume or from its parts along the projectile and recoil nucleon paths; in the second case the azimuth anisotropy should increase with increasing the projectile hadron deflection angle.

We would like to give now some predictions concerning the effects which should arise in experiments due to possible proportionality of the number of emitted protons to the projectile path length inside the target nucleus.

In the frames of the picture of the projectile hadron deflection through large deflection angles θ_h ,in the events without multiparticle creation,when the fast recoil nucleon appears being able in ones turn to cause monotonous nucleon emission, we may expect to find an irregularity in the proton multiplicity distribution of such collisions. Really, we show it to be true. Suppose that single collisions go on with the intensity being proportional to the nuclear matter thickness, and accept that the projectile hadron, and the recoil nucleon as well, cause the monotonous nucleon emission, before deflection and after it. If only such events are selected in which multiple scattering occurs and monotonous nucleon emission along the projectile hadron takes place, the proton multiplicity distribution $W(n)$ in them should be defined by the dimensions of the spherical target-nucleus of the radius R and of the radial nucleon density distribution $\rho(r)$ in it, and is expressed by:

$$W(n) = W_0(n) e^{-\mu_s \cdot \bar{\lambda}(n) \cdot \bar{\rho}(n)} , \qquad (1)$$

where $W_0(n) \doteq \bar{d}(n)$ is a function defined for a target-nucleus; $\bar{d}(n)$ is the impact parameter corresponding to the path length $\bar{\lambda}(n)$ inside the target-nucleus on which n protons are met, for a given target-nucleus impact parameter $\bar{d}(n)$ is determined by the nuclear radius R and by $\rho(r)$; $\bar{\rho}(n)$ is the nucleon density along the path length $\bar{\lambda}(n)$ which can be estimated simply by $\rho(r)$; μ_s is the attenuation coefficient accounting the single scattering acts, it must be estimated from experiment [6].

When the events with the single scattering acts are taken into account, the proton multiplicity distribution should change; it can be expressed by the formula:

$$W_1(n) = W_0(n) e^{-\mu_s \cdot \bar{\lambda}(n) \cdot \bar{\rho}(n)} +$$

$$+ \sum_{i=1}^{i=\Sigma(\frac{n-1}{2})} K\{[n-i] \to n\} W_0(n-i) \{1 - e^{-\mu_s \cdot \bar{\lambda}(n-i) \cdot \bar{\rho}(n-i)}\} \times$$

$$\times \{1 - e^{-\mu_s [n-2i] \cdot \Delta\lambda(n-i) \cdot \bar{\rho}(n-i)}\} e^{-\mu_s \cdot i \cdot \Delta\lambda(n-i) \bar{\rho}(n-i)} , \qquad (2)$$

where $i = 1,2,\ldots, E(\frac{n-1}{2})$; $\Delta\lambda(n)$ is the piece of the length $\bar{\lambda}(n)$ on which nearly one proton is met; $K\{[n-i]\to n\}$ is the coefficient accounting the probability that the recoil nucleon traverses appropriate thickness of the nuclear matter and causes the emission of i protons.

It may be proved that the formula (2) contains the term describing the inmonotony in the proton multiplicity distribution when μ_s is large enough; we may prove that it occurs, for example, when the xenon nucleus is used as a target and μ_s is nearly 0.5 - for the sample of events with zero and one secondary pion, without multiparticle creation [2,6].

We might conclude therefore that if the events are considered in which the multiparticle creation does not take place and the nucleon emission intensity is proportional to the projectile hadron path length inside the nuclear matter, the simple formula (2) should describe the proton multiplicity distribution in them; particularly, the first term in this formula, expressed separately by (1) too, should describe precisely the proton multiplicity distribution in the class of events in which the projectile deflection angle is small enough, and the fast recoil nucleons do not appear.

It should be emphasized that the same formula (2), but with a different coefficient μ_s , should describe the total sample of the hadron-nucleus collision events: both - the events with the multiparticle creation act and those without it together, if we accept that the multiparticle creation goes on via some intermediate states decaying into observed many particles after having left the target-nucleus and behaving themselves as any hadron does in traversing nuclear matter [6].

In concluding this section, we state that the experimental characteristics of the nucleon emission process in the hadron-nucleus collision events should contain information whether this emission is going on along the projectile path inside the nuclear matter - with the intensity being proportional to the length of this path, or not.

The energy and angular distributions of the emitted protons might provide, in addition, the information concerning the physical process leading to such nucleon emission in traversing nuclear matter by high energy hadrons.

3. EXPERIMENTAL EVIDENCE

The existence of such high energy hadron-nucleus collision events in which the nucleon emission goes on independently, not as an accompaniment of the multiparticle creation act, provides the first weighty and indispensable experimental argument which allows us to be able to assume that the monotonous nucleon emission might take place along the projectile path inside the target-nucleus. Such collisions we observe in more than 12% of all the pion-xenon nucleus collisions at 3.5 GeV/c momentum; these are the events without any and with only one secondary pion and any number of accompanying nucleons, exactly speaking - of the observed protons [1,2]. These collisions are highly accurate identified, due to the 4π solid angle aperture of the detector used in our experiments. The contamination of these events with those in which secondary negative pions stopping inside the chamber are confused with the stopping protons is no more than nearly 1%, as we have estimated using the information on the positive charged and neutral pions decaying inside the chamber in similar events and effectively identified in their kinetic energy value interval over O MeV.

The second experimental fact in support of possible existence of the monotonous nucleon emission is the asymmetry observed in the proton emission direction azimuth angle distribution in our pion-xenon nucleus collision events without multiparticle creation with only one secondary pion deflected through any angle θ_π. This asymmetry, expressed by the ratios a_1 and a_2:

$$a_1 = \frac{N(0 \pm \Delta\phi)}{1/2\{N(90 \pm \Delta\phi) + N(270 \pm \Delta\phi)\}}, \quad a_2 = \frac{N(180 \pm \Delta\phi)}{1/2N\{N(90 \pm \Delta\phi) + N(270 \pm \Delta\phi)\}} \qquad (3)$$

is characterized in Table 1; $N(0 \pm \Delta\phi)$, $N(180 \pm \Delta\phi)$, $N(90 \pm \Delta\phi)$, and $N(270 \pm \Delta\phi)$ are the numbers of protons emitted within the azimuth angle value limits $\pm \Delta\phi$, starting from 0, 90, 180, and 270 degrees correspondingly; $\Delta\phi$ is some segment of the azimuth angle accepted to be constant. We see (table 1) that both the values a_1 and a_2 change in definite manner with the increasing of the projectile deflection angle θ_π. The statistical confidence level of these data is still low but they might be accepted as an indication that the proton emission goes on from a limited part of the target-nucleus; it can be observed the asymmetry a_2 due to the fast recoil nucleon. The observed behaviour of the asymmetries a_1

Table 1

Azimuth asymmetries a_1 and a_2 in the proton emission directions distribution, in the pion-xenon nucleus collision events at 3.5 GeV/c, with any number of protons emitted and without multiparticle creation, when the projectile pion deflects through the angle θ_π. Symbols and denotations are explained in the text: the angular segment $\Delta\phi$ = 22.5 degrees. The data presented here are based on the same experimental material which we have spoken about [2].

θ_π deg	Asymmetry a_1	Asymmetry a_2
$\geq$ 0	0.93 $\pm$ 0.17	1.33 $\pm$ 0.23
$\geq$ 10	1.09 $\pm$ 0.23	1.39 $\pm$ 0.29
$\geq$ 30	1.12 $\pm$ 0.28	1.23 $\pm$ 0.30
$\geq$ 60	1.13 $\pm$ 0.38	1.33 $\pm$ 0.42
$\geq$ 90	1.30 $\pm$ 0.23	1.73 $\pm$ 0.29

and a_2 with increasing the deflection angle of the projectile hadron indicates too that the nucleon emission follows the hadron path.

Some additional experimental facts should be mentioned here too[1,2]: a/ The observed proton multiplicity distribution of the pion-xenon collisions without multiparticle creation is inmonotonous[2] - two different smooth parts may be distinguished in it, one within the proton multiplicity values from 0 to 5 and the second one at the multiplicities n_p larger than 5: this inmonotony disappears when the projectile deflection angle decreases - at $\theta_\pi \leq 30$ degrees the distribution is smooth. b/ The peak is visible, over a roughly constant background level, in the proton multiplicity distribution of the events without any secondary pion - at $n_p = 8$; we note that such number of protons is met by the projectile in traversing the xenon-nucleus along its diameter[3]. c/ The sample of collisions with multiparticle creation, in which the events with zero and one secondary pion are not presented, does not contain practically the events with n_p larger than the number of protons n_D = 8 situated in the neigbourhood to the xenon-nucleus diameter: the contamination of such events by those in which $n_p > 8$ is small - less than 1%.

It must be emphasized that the above-mentioned experimental facts are not the arguments of the power being high enough to be able to state either the nucleon emission is going on monotonously along the projectile path or not. For this reason, it must be shown clearly that the observed nucleon emission goes on with the intensity being proportional to the hadron path length inside a target-nucleus. It might be done by comparisions of the appropriate experimental data with the formulas (1) and (2).

But, it is clear that before such comparisons can be carried out an understanding must be achieved what of the experimental proton multiplicity distributions are comparable with the results predicted by the formulas (1) and (2). We would like to discuss now shortly this question. The formula (1) has to describe accurately the nucleon density distribution of such hadron-nucleus collisions in which the projectiles or the intermediate states, by means of which the particle creation is going on, are deflected through relatively small angles in traversing nuclear matter; the meaning of the word "small" should be determined from the experimental data. In the case of the collisions without multiparticle creation and with the projectile deflected through angles θ_h these angles should be smaller than the maximum deflection angle $\theta_{h\,max}$ at which the inmonotony in the proton multiplicity distribution does not appear still; we have seen from our experiment that it happens at $\theta_{h\,max} = 30$ degrees. In the class of events with multiparticle creation the absence of events with large deflection angles of both the projectile hadrons and the intermediate states may be accepted in the cases in which the number of emitted protons is less than $n_D = 8$.

Now we can carry out the comparison of appropriate experimental proton multiplicity distributions with the predicted ones, given by the formulas (1) and (2). The results are presented in Table 2 and in Table 3; we state precise agreement of the experimental data with the predicted ones. The formula (2) reproduces, well enough, even the irregularity observed in the class of events without multiparticle creation, Table 3.

It should be noted too that our formula (2) reproduces good enough as well the grey track multiplicity distribution in the samples of the pion-nucleus and proton-nucleus collisions observed in photonuclear emulsions exposed to 200 and 400 GeV energy particle beam[5,6].

Such precise reproduction of the experimental proton multiplicity distributions by the formulas (1) and (2) shows that the nucleon emission is in fact going on with the intensity being proportional to the hadron path length inside atomic

Table 2

Comparison of the experimental[1,2] proton multiplicity distribution in pion-xenon nucleus collisions at 3.5 GeV/c in which pure monotonous nucleon emission occurs with the distributions predicted by the formula /1/. Normalization is performed to the total number of the experimentally collected events.

n_p	Collisions without multiparticle creation acts		Collisions with multiparticle creation acts	
	Experiment	Prediction	Experiment	Prediction
1	33 $\pm$ 6	33	457 $\pm$ 21	470
2	15 $\pm$ 4	18	378 $\pm$ 19	373
3	8 $\pm$ 3	10	279 $\pm$ 17	299
4	7 $\pm$ 3	6	232 $\pm$ 15	236
5	3 $\pm$ 2	3	200 $\pm$ 14	186
6	5 $\pm$ 2	2	146 $\pm$ 12	135
7	2 $\pm$ 1	1	71 $\pm$ 8	73
8	0	0	60 $\pm$ 8	48

nucleus, because these formulas were derived in assumption according to which the monotonous nucleon emission goes on in such a way that the number of ejected protons is proportional to the hadron path length in nuclear matter.

4. MECHANISM OF THE MONOTONOUS NUCLEON EMISSION PROCESS

In order to try to discover the mechanism of the monotonous nucleon emission induced by high energy hadrons in traversing nuclear matter, we must analyse various possible characteristics of the emitted protons; first of all their angular and energy distributions.

Let us start with the presentation of the experimental angular distributions of the emitted protons for 3.5 GeV/c momentum pion-xenon nucleus collisions. We see that: a/ The proton emission angle θ_p distributions in the classes of events with various proton numbers n_p are the same[1]; b/ The proton emission angle distributions in the classes of events with various numbers of secondary pions are the same[1]; c/ The average values of the proton emission angles $\bar{\theta}_p$ are almost independent of the proton multiplicities n_p[1]. Many protons are emitted to the backward hemisphere, as it is presented in Table 4.

Table 3

Comparison of the experimental proton multiplicity distributions[1,2] in pion-xenon nucleus collision events at 3.5 GeV/c, in which single scattering of the projectile hadron or of the intermediate state with nucleons inside target nuclei may occur, with the predictions given by the formula /2/. Normalization is performed to the total number of registered events.

n_p	Collisions without multiparticle creation acts		Collisions with multiparticle creation acts	
	Experiment	Prediction	Experiment	Prediction*
1	60 ± 8	67	517 ± 23	509
2	33 ± 6	37	411 ± 20	405
3	31 ± 5	28	310 ± 18	334
4	25 ± 5	23	157 ± 16	249
5	17 ± 4	20	217 ± 15	216
6	29 ± 5	26	175 ± 15	160
7	23 ± 5	23	94 ± 10	88
8	16 ± 4	16	76 ± 9	73
9	12 ± 3	12	29 ± 6	29
10	8 ± 3	5	12 ± 4	16
11	7 ± 3	3	12 ± 4	14
12	0	1	1 ± 1	11
13	0	0	0	6
14	1 ± 1	0	1 ± 1	0

*Experimental conditions were taken into account.

According to our information on the monotonous nucleon emission, the events with larger number of protons should correspond to those cases in which the projectile hadrons or the fast recoil nucleons traverse large thickness of the nuclear matter inside massive atomic nuclei, like the xenon nucleus. Thus, if the existence of the protons emitted to the backward hemisphere is a result of their multiple, plural or single scattering in nuclear matter, the decrease of the $f = \frac{N_f}{N_b}$ values with the increasing the proton multiplicities should be observed. It is not observed in experiment, Table 4; starting from $n_p = 3$ the ratio f is constant. Thus, we may conclude that the appearance of the protons emitted to the backward hemisphere cannot be explained only in terms of the multiple

Table 4

The ratio f between the number of protons emitted to the forward hemisphere N_f and those emitted to the backward hemisphere N_b, in various classes of the pion-xenon collision events /1,2/ at 3.5 GeV/c, in dependence on the proton multiplicity n_p.

n_p	$f = \frac{N_f}{N_b}$	
	All pion-xenon nucleus collision events	Pion-xenon nucleus collision events without multiparticle creation acts
1	2.90 ± 0.53	3.25 ± 1.31
2	2.46 ± 0.23	1.62 ± 0.59
3	1.98 ± 0.17	1.43 ± 0.47
4	2.14 ± 0.18	2.30 ± 0.61
5	1.87 ± 0.15	1.33 ± 0.42
6	2.00 ± 0.17	1.94 ± 0.44
7	2.02 ± 0.21	2.16 ± 0.59
8	2.01 ± 0.22	2.54 ± 1.24
Total	2.05 ± 0.07	1.80 ± 0.20

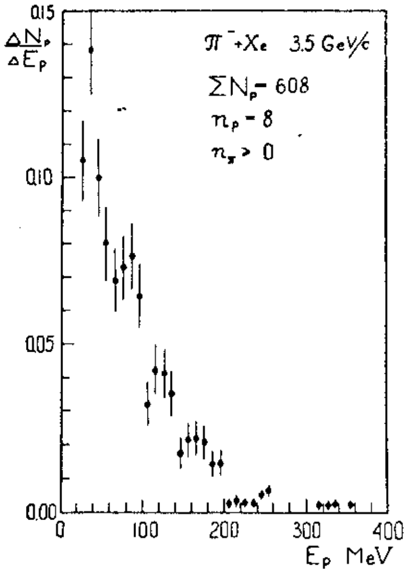
scattering of these protons inside the target-nucleus, and we must take into account some other mechanism of the backward ejection of the protons in the hadron-nucleus collisions at high energies.

Let us pass now to the analysis of energy spectra of the emitted protons. We see that: a/ The average proton kinetic energy $\bar{E}_p$ does not depend on the proton multiplicity n_p [1] ; b/ It does not depend on the number of produced pions n_π too ; c/ The shapes of the energy spectra of these protons are independent of the proton multiplicities n_p and of the number of secondary pions n_π [1] . The accurate analysis of the energy spectrum shapes in the sample of events without multiparticle creation indicates that wide peaks exist in these spectra at the proton kinetic energy values lying nearly to 40, 140, and 220 MeV [2,9]. If we accept that the monotonous nucleon emission mechanism leads to the observed peaks, we can suppose that the best conditions for those peaks observation in experiment in the total sample of events with multiparticle creation should be in the class of such events with the proton multiplicity $n_p = n_D = 8$, when the projectile hadron and generated intermediate states traverse the target-nucleus mainly along and around its diameter, and undergo the single deflections only in very small part of events, less than nearly a few per cent. In this case the best conditions exist for the observation of almost total sample of these peaks. We present such energy srectrum in the figure.

We do not intend to give precise analysis of this spectrum here, it will be the subject of our special work. But, we may conclude, on the basis of the figure that it cannot be excluded the existence of the peaks in the presented spectrum nearly at 40, 80, 120, and 160 MeV.

The absence of any visible changes of the ratio f at $n_p \geq 3$ in various classes of pion-xenon collisions, and the independence of the shapes of the angular and energy spectra neither on n_p not on n_π indicates that the observed protons may be a product of some many nucleon intermediate states being formed when high energy hadrons traverse nuclear matter and decay after having left the target-nucleus [10]; such possible mechanism can lead to the observed peaks in the proton energy spectra as well.

In the distribution, done in section 3, it was shown that the nucleon emission intensity is proportional to the path length of the hadron traversing the target-nucleus. But, such situation may occur when the two or more nucleon intermediate systems do not cause the monotonous nucleon emission in tra-



Energy spectrum of protons emitted in pion-xenon nucleus collisions with proton multiplicity $n_p = 8$.

versing the parent nucleus, as being of the kinetic energies less than the energy necessary for these systems to induce the monotonous nucleon emission. It could indicate that the nuclear matter may be transparent for the many nucleon systems of energies being less than the minimal energy at which the monotonous nucleon emission could start. This could indicate the possibility for existence of some discrete energy levels for the monotonous nucleon emission; these levels should be overcome for this emission to start.

5. CONCLUSION

As a conclusion, we might summarize the whole discussion in a few sentences:

1. We have experimental arguments that high energy hadrons traversing nuclear matter cause monotonous nucleon emission; the number of emitted nucleons is proportional to the path length of the hadron, it equals to the number of nucleons met in the neighbourhood to this path.

2. We have experimental indications that the monotonous emission goes on via some two or more nucleon systems.

3. The mechanism of the nucleon emission is still unclear for us. One possible mechanism could be such that along the projectile hadron path mesons are generated in nuclear matter, of such energies at which they are absorbed simply by two or more nucleons; the systems formed in such a way of relatively small kinetic energies might move inside the target-nucleus without causing nucleon emission in ones turn and decay, after having left it, into nucleons.

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