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STOPPING AND ENERGY DEPOSITION OF HADRONS IN TARGET NUCLEI

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1. INTRODUCTION

In collisions of fast hadrons, of kinetic energies above the pion production threshold, events may occur in which incident particle or particles created by it in its interaction inside the target nucleus are completely stopped and deposited their energy in the nucleus. Such kind of collisions we treat later on as "stopped" events in which some excited state of nuclear matter may be generated; various levels of excitation may be presented. An increase of the incident particle energy would result in a higher excitation, providing that it has enough stopping power. There should be an optimum incident energy for generation of highly excited states, however, because target nuclei would become transparent at an energy high enough.

The problem arises: "Whether and how we can produce high enough excited states of nuclear matter?". In order to obtain an answer for this question we have used pictures from 26 and 180 litre xenon bubble chambers without magnetic field [1,2] exposed to pion beams of 2.34-9 GeV/c momentum. The 180 litre chamber was exposed to 3.5 GeV/c momentum negatively charged pions, the 26 litre chamber - to 2.34 GeV/c momentum positively charged pions and to 5 and 9 GeV/c momentum negatively charged pions. Expositions were performed in the Moscow Institute of Theoretical and Experimental Physics and in High Energy Laboratory of the Joint Institute for Nuclear Research in Dubna.

It is the purpose of the present paper to put on record the results of our investigations.

2. METHOD

The characteristics of the xenon bubble chambers and detailed information about the experimental procedure can be found in many publications [1-5]; we limit ourselves here to the presentation of the most important information, therefore.

In the 180 litre, 103 cm long and 41 cm wide and 41 cm high chamber the protons of kinetic energies from nearly 20 up to nearly 200 MeV, the secondary pions: the negatively charged of kinetic energy over about 10 MeV, the positively charged of energy from 0 MeV, and the neutral pions of energy from 0 MeV, are recorded with the efficiency near to 100% within the total solid angle 4 Pi. Protons of kinetic energies smaller than

200 MeV, negatively and positively charged pions of kinetic energies smaller than about 100 MeV stop inside the chamber, when appear in the chamber central area of 40x10x10 cm^3 and emitted through any emission angles; protons of energies smaller than 350 MeV stop inside the chamber when emitted through emission angles smaller than 60 degrees and larger than 120 degrees. The energies of the stopped charged particles can be estimated with a mean accuracy of roughly 3% using the range-energy relation. The accuracy of the neutral pion energy estimation is in average 10%, by total track length of electrons in the electron-photon showers produced by gamma quanta from neutral pion decays. Emission angles of charged secondaries can be estimated with an accuracy of 1-3 degrees and those of the neutral pions - with an accuracy of about 1 degree. It has been estimated that over 90% of all protons emitted in reactions are stopping within the chamber, the V-particles - lambdas and neutral kaons are recorded and identified in the chamber as well. The scanning efficiency for collision events is better than 99.5%.

3. DEFINITIONS

Using the 180 litre xenon bubble chamber we were in the position to define the "stopped" events as follows: We identify the hadron-nucleus collision events as stopped when the projectile is absorbed inside the target nucleus, accompanied by nucleon emission and nuclear fragments evaporation, without causing particle production, pion production in particular.

This definition differs markedly from the definition used in electronic experiments, for example - from the definition used in the work of Nakai et al. /6/: The definition of the "stopped" events here is the events with "high-multiplicity" and "no forward particle".

Our, above formulated definition of the "stopped" events is adequate one. The sufficiency for the requirement of the "stopped" events selection of the definition being in use in electronic experiments should be tested in appropriate conditions - in the 180 litre xenon bubble chamber, for example. Let us test it before to start a description of results obtained in our experiments. In order to perform it, we select two classes of events registered in the chamber, similarly as it has been done in the work of Nakai et al. /6/: a) Events in which pions are ejected through the emission cone no more than 10 degrees, with any number of emitted protons (g-track leaving particles - according to the terminology used in the emulsion technique) and evaporated nuclear fragments (b-track leaving particles in nuclear emulsions) registered at any emission angle. b) Events in which pions are ejected through the emission angles more than

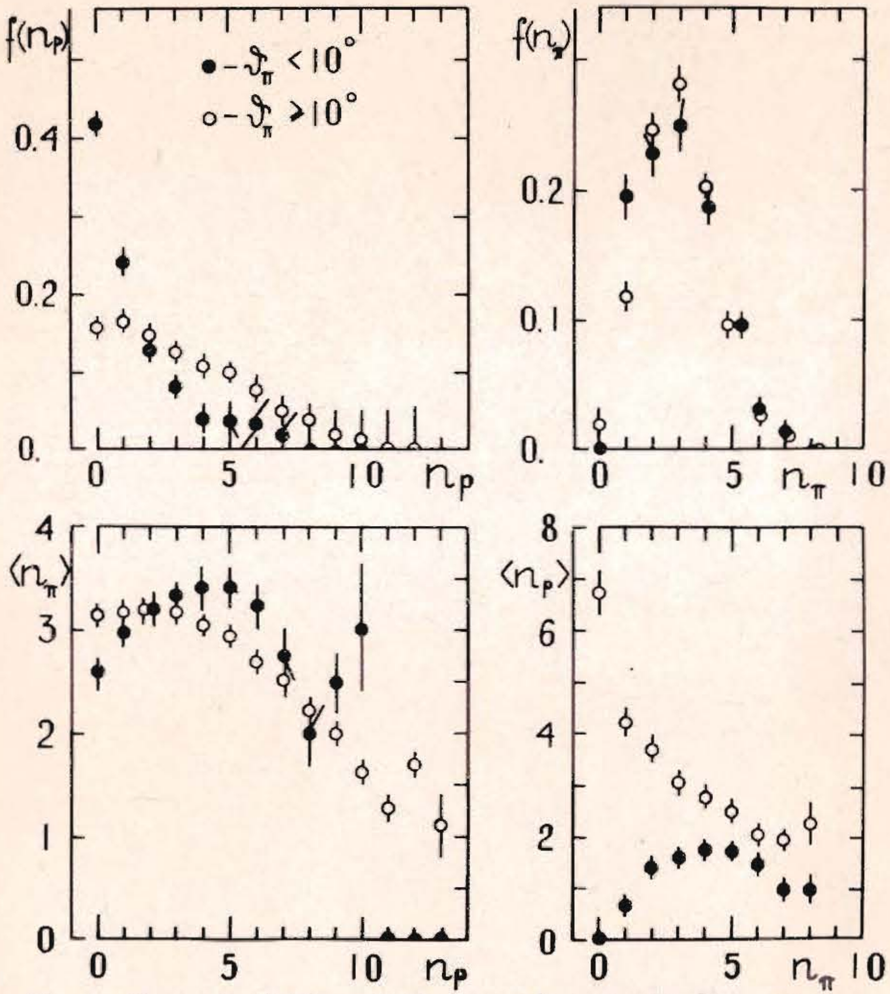

Fig.1. Characteristics of the two classes of pion-xenon nucleus collision events at 3.5 GeV/c momentum: a) when pions are ejected through angles θ_π smaller than 10 degrees; b) when pions are ejected through angles θ_π not less than 10 degrees. Denotations used: $f(n_p)$ *-distribution of the proton multiplicity* n_p, $f(n_\pi)$ *-distribution of the multiplicity* n_π *of the pions with any electric charge,* $\langle n_\pi \rangle$ *- the mean multiplicity of ejected pions,* $\langle n_p \rangle$ *- the mean multiplicity of emitted protons.*

10 degrees, with any number of protons and nuclear fragments ejected at any angle. We construct characteristics of these events: proton multiplicity n_p distributions $f(n_p)$, pion mul-

Table I

Quantities characterizing the proton multiplicity n_p and pion multiplicity n_π distributions in pion-xenon nucleus collisions at 3.5 GeV/c momentum in two cases: a) when the pion emission angles Θ_π in an event are smaller than 10 degrees; b) when pion emission angles Θ_π are no less than 10 degrees

Pion emission angle Θ_π	Quantity	Value of the quantity
$\Theta_\pi < 10$ deg.	$\langle n_p \rangle$	1.46
	r.m.s.	1.87
	skewness	1.66
	kurtosis	3.04
	$\langle n_\pi \rangle$	2.91
	r.m.s.	1.45
	skewness	0.54
	kurtosis	-0.15
$\Theta_\pi \geq 10$ deg.	$\langle n_p \rangle$	3.29
	r.m.s.	2.68
	skewness	0.79
	kurtosis	0.19
	$\langle n_\pi \rangle$	2.98
	r.m.s.	1.37
	skewness	0.34
	kurtosis	0.01

tiplicity n_π distributions $f(n_\pi)$, dependences of the proton mean multiplicity $\langle n_p \rangle$ on the pion multiplicity n_π, and dependences of the pion multiplicity $\langle n_\pi \rangle$ on the proton multiplicity n_p. Data are presented in fig.1 and in table 1. Similarly, we construct the characteristics for two similar classes of events, but with the emission angle for pions limited by 15 degrees. Results do not differ principally from the results presented in fig.1 and in table I.

It follows, from the distribution $f(n_\pi)$ of the produced pion multiplicity n_π, fig.1 and table 1, that at energies about 3 GeV pions are ejected intensively through large angles, much larger than about 10 degrees, and the $f(n_\pi)$ distributions are practically the same when the ejection angles are smaller than 10 degrees and when the angles are larger than 10 degrees. The dependence of the average number $\langle n_\pi \rangle$ of the produced pions on the multiplicity n_p of emitted protons shows that the intensity of the pion production at higher ($\sim 4 \div \sim 8$) multiplicities of emitted protons n_p does not differ markedly in both the cases - when the pion ejection angles are smaller and larger than 10 degrees. Moreover, the maximum intensity of emitted protons, measured by the maximum mean proton multiplicity $\langle n_p \rangle_{max}$ appears when the produced pion multiplicity $n_\pi = 0$, fig.1; in these events only the bombarding hadrons are completely stopped and deposited their energy in target nuclei.

This result leads to the conclusion that the definition of the stopped events used in electronic experiments[6] is inadequate; it cannot be used for a correct selection of the "stopped" events, therefore. It is worthwhile to communicate that the authors of the above cited work[6] performed by means of the electronic arrangement explain that ".... the "stopping" does not necessarily mean stopping of the projectile particle but stopping of its energy flow"[7].

So, we shall use our definition of the "stopped" events for the selection of them in scanning on the bubble chamber photographs.

4. EXPERIMENTAL DATA

About 150000 photographs of the 180 litre chamber exposed to 3.5 GeV/c momentum pion beam were scanned and rescanned[8] for pion-xenon nucleus collisions of the type:

$$\pi + Xe \to n_p + f \qquad (1)$$

which could occur in the fiducial region of nearly $42 \times 10 \times 10$ cm^3 volume situated coaxially and centered inside the chamber of $103 \times 41 \times 41$ cm^3 volume; $n_p = 0,1,2,3,...$ denotes the number of emitted protons and f denotes residual nuclear fragments. Similarly, events of type (1), occurring inside a fiducial region in the 26 litre xenon bubble chamber were selected[9] out of about 50000 photographs at 2.34, 5.0 and 9 GeV/c momentum of incident pions. The sample of 6301 events of any-type pion-xenon nucleus collisions at 3.5 GeV/c momentum was collected as well and analysed in detail. The precentage P_a of the selected "stopped" events in the sample of any-type collisions,

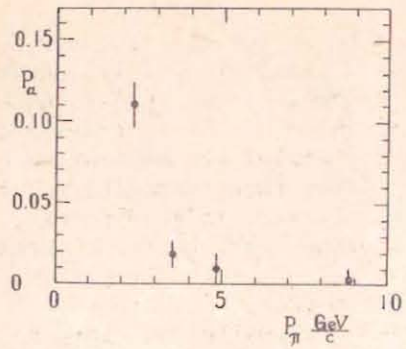

Fig.2. Probability P_a *of the appearance of the pion-xenon nucleus collision events in which incident pion is stopped inside the target nucleus, in dependence on the incident pion momentum* P_π.

in dependence on the incident pion momentum P_π is shown in fig.2. It decreases rapidly - from $P_a \simeq 12\%$ at 2.34 GeV/c up to $P_a \simeq 2\%$ at 3.5 GeV/c and $P_a \simeq 0$ at 9 GeV/c momentum.

Later, we analyse in detail 96 "stopped" events registered in the 180 litre chamber at 3.5 GeV/c momentum, as the sample of totally observed "stopped" events obtained in the best registration and scanning conditions. For comparisons of various characteristics of the "stopped" events, data on 6301 any-type pion-xenon collision events /10/ at 3.5 GeV/c momentum were used as well.

In fig.3, the multiplicity n_p distribution $f(n_p)$ of emitted protons in the stopped events is shown. Its shape differs markedly from the shape of the distribution $f(n_p)$ for any-type collision events /4/, fig.3 and table II. The distribution for the stopped events is almost symmetrical, with the maximum at about $\langle n_p \rangle = 7.4 \pm 0.7$. Such symmetry can be obtained when the stopping occurs predominantly in central pion-xenon nucleus collisions. It is remarkable that the mean number of emitted protons equals the number of protons, $n_p = 7.6$, contained in the target xenon nucleus within the cylindrical volume $\pi D_0^2 D$, where D_0 is the nucleon diameter in fm and D is the xenon nucleus diameter /11/ in fm.

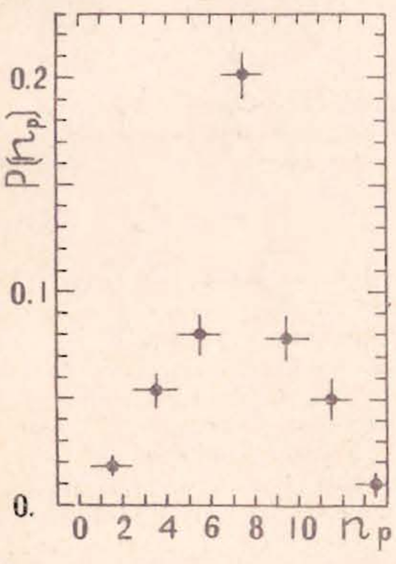

Fig.3. Proton multiplicity n_p *distribution* $P(n_p)$ *in pion-xenon nucleus collision events in which incident pion is absorbed in the xenon target nucleus, at 3.5 GeV/c momentum.*

Table II

Characteristics of the proton multiplicity n_p *distributions in pion-xenon nucleus collision events without particle production, when* $n_\pi = 0$, *and in any-type events, when* $n_\pi \geq 0$

Quantity	$n_\pi = 0$	$n_\pi \geq 0$
$\langle n_p \rangle$	7.40	3.46
r.m.s.	3.45	2.64
skewness	-0.0013	0.92
kurtosis	-0.13	0.41

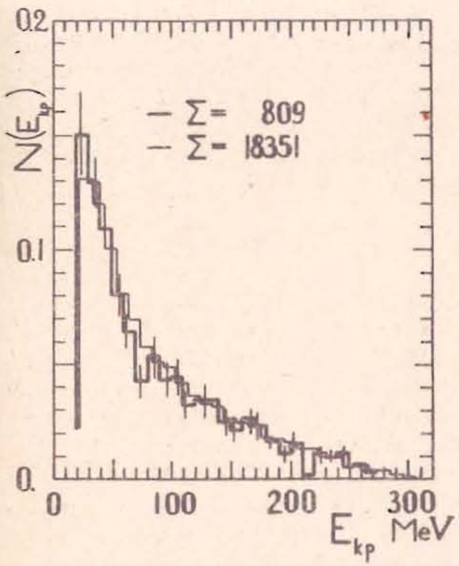

Fig.4. Kinetic energy E_{kp} *spectrum* $N(E_{kp})$ *of protons emitted in pion-xenon nucleus collision events at 3.5 GeV/c momentum in which incident pion is stopped inside the target nucleus without producing any particles - thick line; thin line - in any type collisions, with any number of produced pions; Σ - number of protons in a histogram.*

To the incident pion momentum 3.5 GeV/c corresponds an effective kinetic energy of about 3.3 GeV at the centre of the chamber. The equality of the obtained mean value of the proton multiplicity $\langle n_p \rangle$ in the stopped events at this energy to the number of protons contained within the volume $v = \pi D_0^2 D$ allows to estimate the mean energy loss $\langle \epsilon_\pi \rangle$ of incident pions in nuclear matter per the length unit being one nucleon/S, where $S = \pi D_0^2$. In fact, to the observed 7.4 protons in average inside the volume $v = \pi D_0^2 D$ centered on the target nucleus diame-

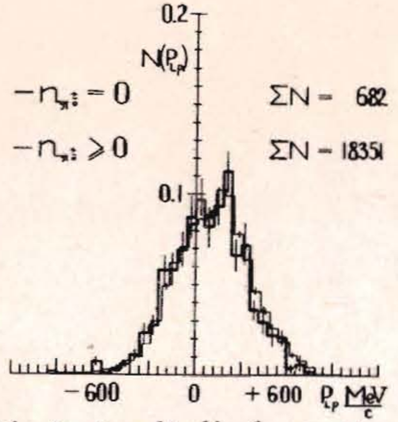

Fig. 5. Longitudinal momentum P_{Lp} *distribution* $N(P_{Lp})$ *of protons emitted in the stopped pion-xenon nucleus collision events at 3.5 GeV/c momentum - thick line; the momentum distribution for the sample of collision events with any number of produced pions, at 3.5 GeV/c momentum - thin line.* ΣN *- number of protons in a histogram.*

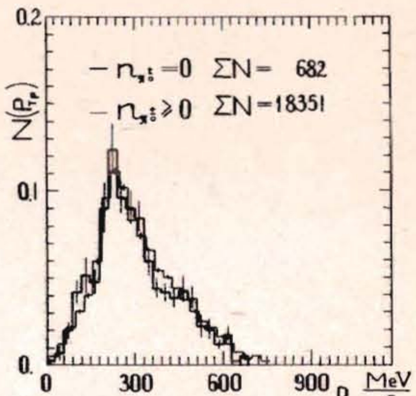

Fig. 6. Transversal momentum P_{Tp} *distributions* $N(P_{Tp})$ *for protons emitted in the stopped pion-xenon nucleus collision events at 3.5 GeV/c momentum - thick line; for protons emitted in any-type pion-xenon nucleus collision events at 3.5 GeV/c momentum - thin line.* ΣN *- number of protons in a distribution.*

ter D corresponds 7.4 $k \simeq 10.8$ neutrons emitted from the xenon nucleus, where $k = (A - Z)/Z$. The energy loss per the length unit one nucleon/S is then $\langle\epsilon_\pi\rangle = 3.3/18.2 \simeq 0.184$ GeV/(nucleon/S).

The energy lost in the target nucleus, when the incident hadron stopped inside it, manifests itself in the nucleon emission mainly. The characteristics of the emitted protons may throw the light on the energy loss mechanism, therefore. Let us, then see the energy, momentum and angular spectra of the emitted protons. In figs. 4-7 the spectra are shown in comparison with corresponding spectra for the sample of any-type collision events. From these data, it can be concluded that: a) Energy spectra of emitted protons are the same in the stopped events and in any-type events; b) Distributions of the longitudinal momenta P_{Lp} of emitted protons in the stopped events and in the any-type events are the same; c) Transverse momenta of emitted protons P_{Tp} in the stopped events and in the any-type events are the same; d) Distributions of cosine of the proton emission angle θ_p, $N(\cos\theta_p)$, are the same in the stopped events and in the any-type collision events. It indicates that the mechanism of the nucleon emission in stopped events and in any-type events is

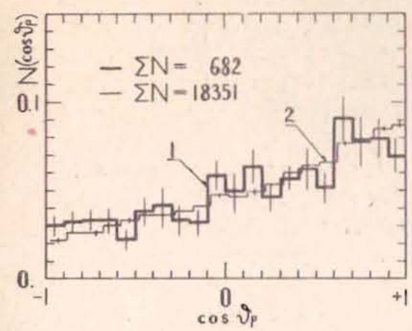

Fig. 7. Distributions $N(\cos\theta_p)$ *of cosine of the emission angle* θ_p *of protons emitted in pion-xenon nucleus collisions at 3.5 GeV/c momentum: 1 - for the stopped events; 2 - for any-type events.* ΣN *- number of protons in a histogram.*

the same. It is worth-while to mention here that it has been shown [13] that the proton mean multiplicity $\langle n_p\rangle$ in any-type hadron-nucleus collisions at energies above nearly 10 GeV is practically equal to the mean thickness $\langle\lambda\rangle$ of the nuclear matter layer in protons/S times the value of S.

It would be very useful to see how the energy loss of the incident hadron is proceeding in traversing nuclear matter. The simplest expected case would be when the energy losses increase linearly with the distance covered by the hadron in nuclear matter. In order to test it, we predict the mean number $\langle n_p\rangle$ of emitted protons at a smaller energy E_π of incident pion and compare it with the observed mean $\langle n_p\rangle$ at this energy. Thus, pions of kinetic energy $E_\pi = 2.12$ GeV, used in one of our experiments, should stop on the nuclear matter layer in average $E_\pi/\epsilon_\pi = 4.6$ protons/s. The observed mean number of the emitted protons is $\langle n_p\rangle = 4.1 \pm 0.3$ what is almost the same as 4.6 protons predicted. It indicates that in fact the energy loss of the incident hadron may increase linearly with the increase of the nuclear matter layer thickness.

5. CONCLUSIONS

Based on the present experimental data, we conclude that: a) The number of observed stopped events in pion-xenon nucleus collisions decreases with incident hadron energy increase; at energy above nearly 4 GeV the stopped events in the pion-xenon nucleus collisions do not occur practically. b) Proton multiplicity n_p distribution $f(n_p)$ of the emitted protons in the sample of the stopped events differs in full from the distributions in any other type of the pion-xenon nucleus collision events. c) Energy and momentum spectra, and angular distributions of the protons emitted in the stopped events do not differ from corresponding spectra in any-type collision events.

As it can be concluded, from the energy dependence of the percentage of the proton-emulsion nuclei collisions without s-tracks and with any number of g- and b-tracks [14-15], the stopped events at energies 4 GeV are rather rare cases and they do not appear practically at incident proton energy above ~ 8 GeV.

Our data on the probability of occurrence of the stopped events are in disagreement with the results presented in the work of Nakai et al. [6]; this disagreement is caused by application of different selection criteria of the stopped events. But, faced with experimental results presented above, obtained by means of 4Pi detector, we are in the position to state that the new definition of the stopped events, applied in present work, is more adequate.

In our opinion, the selection criteria for the stopped events used iu the electron experiments up to now cannot be applied later on, especially when the problems concerning the possible production of the highly excited states of nuclear matter are in question.

REFERENCES

1. Kanarek T.I. et al. Proc.Intern.Conf.High Energy Accel. and Instrumentation, CERN, 1959, Dubna, 1983.
2. Kusnetsov E.V. et al. Sov.Journ. PTE, 1970, 2, p. 56.
3. Strugalski Z. et al. Nuclear Phys., 1971, B27, p. 429.
4. Strugalski Z., Pluta J. Sov.Journ. of Nucl.Phys., 1974, 27, p. 504.
5. Peryt W. et al. JINR, E1-81-803, Dubna, 1983.
6. Nakai N. et al. Phys.Lett., 1983, 121B, p. 373.
7. Shibata T.A. et al. Nuclear Phys., 1983, A408, p.525.
8. Strugalski Z., Pawlak T., Pluta J. JINR, E1-82-841, E1-82-718, E1-82-719, Dubna, 1982; E1-83-234, Dubna, 1983.
9. Strugalski Z. et al. JINR, E1-81-578, Dubna, 1981; Wosinska K. Thesis Institute of Physics, Warsaw Technical University, Warsaw, 1983.
10. Strugalski Z. et al. JINR, R1-83-68, R1-83-237, R1-83-564, R1-83-568, Dubna, 1983.
11. Strugalski Z. JINR, E1-11976, Dubna, 1978.
12. Strugalski Z., Nuclear Phys., 1966,87, p. 280; Strugalski Z. Miller K. JINR, E1-81-781, Dubna, 1981.
13. Strugalski Z. JINR, E1-84.268, Dubna, 1984.
14. Sumbera M., Vokal S. Acta Physica Slov., 1982, 32, p. 256.
15. Winzeler H. Nuclear Phys., 1965, 69, p. 661.

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Стругальский З., Павляк Т., Плюта Я. E1-84-855
Остановки и потери энергии адронов в ядре мишени

Исследовались такие случаи столкновений адронов с тяжелыми атомными ядрами при импульсах 2-9 ГэВ/с, в которых налетающий адрон останавливается в ядре мишени и теряет в нем свою энергию. Число наблюдаемых "остановок" быстро уменьшается с ростом энергии налетающего адрона. Адроны теряют свою энергию при прохождении через ядерную материю пропорционально длине пройденного пути.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

Сообщение Объединенного института ядерных исследований. Дубна 1984

Strugalski Z., Pawlak T., Pluta J. E1-84-855
Stopping and Energy Deposition of Hadrons in Target Nuclei

Collision events in which incident hadron is stopped and deposited its energy inside massive target nucleus were studied at 2-9 GeV/c momentum. The number of observed "stopped" events decreases rapidly with incident hadron energy increase. Hadrons lose their kinetic energies in passing through nuclear matter proportionally to their paths in it.

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

Communication of the Joint Institute for Nuclear Research. Dubna 1984