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RETARDATION OF HADRONS IN PASSING THROUGH INTRANUCLEAR MATTER

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1. INTRODUCTION

In the Philosophical Magazine of July 1905, Ernest Rutherford gave an account of some preliminary experiments on the retardation of the velocity of the alpha particles from radium C in passing through matter[1]. His further papers on this subject appeared during 1906[2-4]. Eight years later, Niels Bohr started his theory of the decrease of velocity of moving electrified particles in passing through matter[5,6]. In quantum mechanics, this problem was discussed by many authors[7-15].

In passing through matter, an electrified particle loses its kinetic energy due to: a) excitation and ionization of the atoms met, b) bremsstrahlung. These processes are of electromagnetic nature - electromagnetic interactions are involved in them.

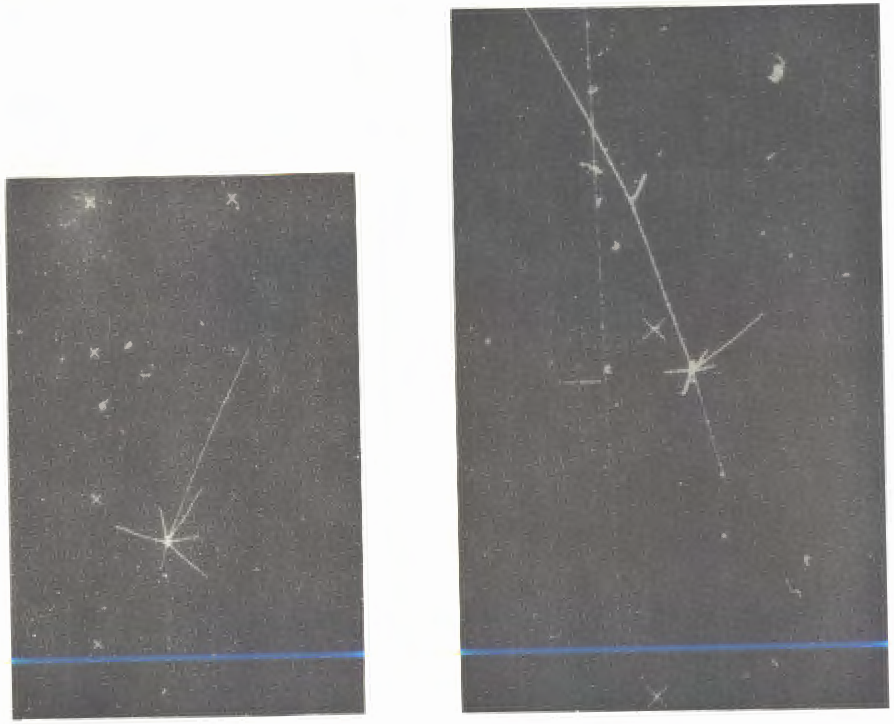
Now, on the basis of our experiments and observations performed during about last 15 years[16-21], I am in a position to announce that the strongly interacting particles - hadrons - lose their kinetic energies in passing through intranuclear matter - due to the strong interactions, similarly as electrified particles do it in passing through materials - due to the electromagnetic interactions.

The subject matter in this paper is to show it shortly.

2. THE EFFECTS OBSERVED

The collisions of high energy hadrons with atomic nuclei give rise to a great variety of phenomena - the nucleon emission from the target nuclei, resonance and particle creation, and nuclear fragment evaporation are the most frequently occurring and observed in them. The kinetic energies of hadronic projectiles we call "high" if larger by much than their rest masses.

The expressive and rather complicated picture of the hadron-nucleus collisions can be recognized in detail in some total experiments only - when all the produced particles, including neutrals (as neutral pions) and all the emitted nucleons are recorded and identified. Now it is possible to inves-



a) b)

Fig.1. The passages of negatively electrified pions with kinetic energies of about 3 GeV through $^{131}\mathrm{Xe}_{54}$ *nuclei: a) The incident pion (thin track) traverses the nucleus accompanied by nucleon emission (short straight tracks are left by the emitted protons) and leaves it reduced in velocity - as it can be concluded from its track (the longest track among the secondaries). b) The incident pion traversed firstly one xenon nucleus accompanied by neutron emission (the neutrons did not left tracks) and left it retarded and deflected; after covering some distance it traverses second xenon nucleus accompanied by nucleon emission (straight short tracks are left by the emitted protons) and left it reduced in velocity (as it is seen from the larger ionization produced); after covering some distance it passed through the third xenon nucleus. In both the cases presented, particles are not created.*

tigate the hadron-nucleus collision processes under conditions desired - it can be realized by means of heavy liquid bubble chambers and nuclear emulsions, for example. It can be done in the xenon bubble chambers as well, where almost all the produced particles, including neutral pions with kinetic energies equal 0 or larger than 0, are detected and recorded effectively enough[16,17].

Such well nigh on total experiments were performed[16,17] by means of the 26 and 180 litre xenon bubble chambers exposed to beams of electrified pions with momenta 2.34, 3.5, 5, and 9 GeV/c from the accelerators of the Joint Institute for Nuclear Research at Dubna and of the Institute of Theoretical and Experimental Physics in Moscow.

It was possible, in such experiments, to distinguish three general classes of the collision events: I. The class of events in which particles are produced - the pions in particular, we call them the particle-producing-collisions. II. The class of events in which the hadronic projectiles pass through the target nuclei without causing particle production - without visible pion production in particular, we call them the passages. III. The class of events in which the hadronic projectiles are absorbed inside the target nuclei without causing the particle production, we call them stoppings. The collisions accounted for any of the classes I - III proceed accompanied by intensive fast nucleon emission; "fast nucleons" means the nucleons with kinetic energies from about 20 up to about 400 MeV. The momentum and angular characteristics of the fast nucleons are the same for nucleons emitted in events included to any of the classes I - III and they are independent of the energy and identity of the projectile. The example of photographs of the passages through $^{131}\mathrm{Xe}_{54}$ nucleus by beam pions are presented in fig.1.

The sample of events containing all the three classes I - III together we call the class IV - the class of any-type collision events.

The percentage of stoppings decreases with increasing the momentum of the incident hadron. For pions falling on xenon nuclei, we obtained that at 2.34 GeV/c momentum stoppings are in about 12% of the any-type collision events, at 3.5 GeV/c momentum stoppings are in about 2%, at 5 GeV/c and 9 GeV/c the percentage is practically 0. It leads to the conclusion that some range-energy relation may hold for hadrons in intranuclear matter - similarly as the range-energy relation holds for electrified particles in materials.

3. SOME QUALITATIVE AND QUANTITATIVE RELATIONS

The number n_N of the emitted fast nucleons is related to the intranuclear matter layer thickness λ covered by a hadron:

$$n_N = \lambda \cdot S(1 - e^{-\lambda/\lambda_t}), \qquad (1)$$

where λ is number of nucleons over the area $S = \pi \cdot D_0^2 \simeq 10.3$ fm^2, D_0 is the nucleon diameter /22/; λ_t in nucleons/S units is the mean free path for hadrons in intranuclear matter, related to the hadron-nucleon total cross section σ_t measured in S/nucleon as $\lambda_t = 1/\sigma_t$. In these units, $\lambda \cdot S$ expresses the number of nucleons over S in intranuclear matter layer λ nucleons/S, and $\lambda_t S$ expresses the number of nucleons over S in the intranuclear matter layer as thick as the mean free path λ_t in nucleons/S.

It should be noted that in experiments only protons are usually registered effectively enough among the emitted nucleons.

At incident hadron energies high enough, above a few GeV, the approximated expression

$$n_N \simeq \lambda \cdot S \qquad (2)$$

can be in use, instead of (1), because the term in parentheses in formula (1) is almost constant and near to 1.

Relation (1) holds for all the classes I – IV of the hadron-nucleus collision events.

The energy and momentum spectra and angular distributions of the emitted nucleons seem to be independent of the energy and identity of the incident hadrons; they are independent as well of the multiplicity of the emitted protons and of the ejected pions – if the particle production occurs. Such properties of the nucleon emission process indicate that the nucleons are not the knocked out ones, they are rather products of some many-nucleon systems formed inside target nuclei and decaying after having left the parent nuclei.

Range – energy, $R_h - E_h$, relation for hadrons h in intranuclear matter has been observed /19/:

$$E_h = \epsilon_h \cdot R_h, \qquad (3)$$

where E_h in GeV, R_h in nucleons/S, ϵ_h – the energy of a hadron h lost on the path λ as long as 1 nucleons/S; for pions $\epsilon_h = \epsilon_\pi = 0.18$ GeV/(nucleon/S), for protons $\epsilon_h = \epsilon_p = 0.36$ GeV/(nucleon/S).

Table

Mean and maximal energies of pions and protons lost in passages through intranuclear matter; kinetic energies E_h *of the incident hadrons are larger than* $E_h = \epsilon_h D$*, where* D *in nucleons/S is the target nucleus diameter and* ϵ_h *in GeV per nucleons/S is the energy lost by a hadron on the intranuclear matter layer as thick as 1 nucleon/S,* $S \simeq 10.3$ *fm*^{2}*; for pions* $\epsilon_h = \epsilon_\pi = 0.180$ *GeV/nucleons/S, for protons* $\epsilon_h = \epsilon_p = 0.360$ *GeV/(nucleons/S).*

Reaction	Energy GeV	Energy lost GeV	
		mean	maximum
Pi + C	≥ 1.5	0.5	1.5
Pi + Al	≥ 1.7	0.7	1.7
Pi + Cu	≥ 2.5	1.1	2.5
Pi + W	≥ 3.8	1.8	3.8
Pi + Ta	≥ 3.8	1.8	3.8
Pi + Pb	≥ 4.0	1.9	4.0
p + C	≥ 2.1	1.0	2.1
p + Al	≥ 3.4	1.5	3.4
p + Cu	≥ 5.0	2.2	5.0
p + W	≥ 7.6	3.6	7.6
p + Ta	≥ 7.6	3.5	7.6
p + Pb	≥ 7.9	3.7	7.9

The mean $\langle\lambda\rangle$ and maximal λ_{max} thicknesses of nuclei in nucleons/S can be determined on the basis of data on nuclear sizes and nucleon density distributions in them /22, 23/ . It allows one to determine, using relation (3), mean and maximal energy losses in target nuclei of hadrons with kinetic energies higher than $\epsilon_h \cdot \lambda_{max} = \epsilon_h \cdot D$ traversing them, where D in nucleons/S is the nucleus diameter. Some data are given in the Table.

The decrease of the incident hadron energy, due to energy loss in intranuclear matter, is observed evidently at projectile energies of a few GeV – the decrease of the momentum of the produced pions with increase of the intranuclear matter layer thickness involved in the particle producing collisions has been registered (fig.2).

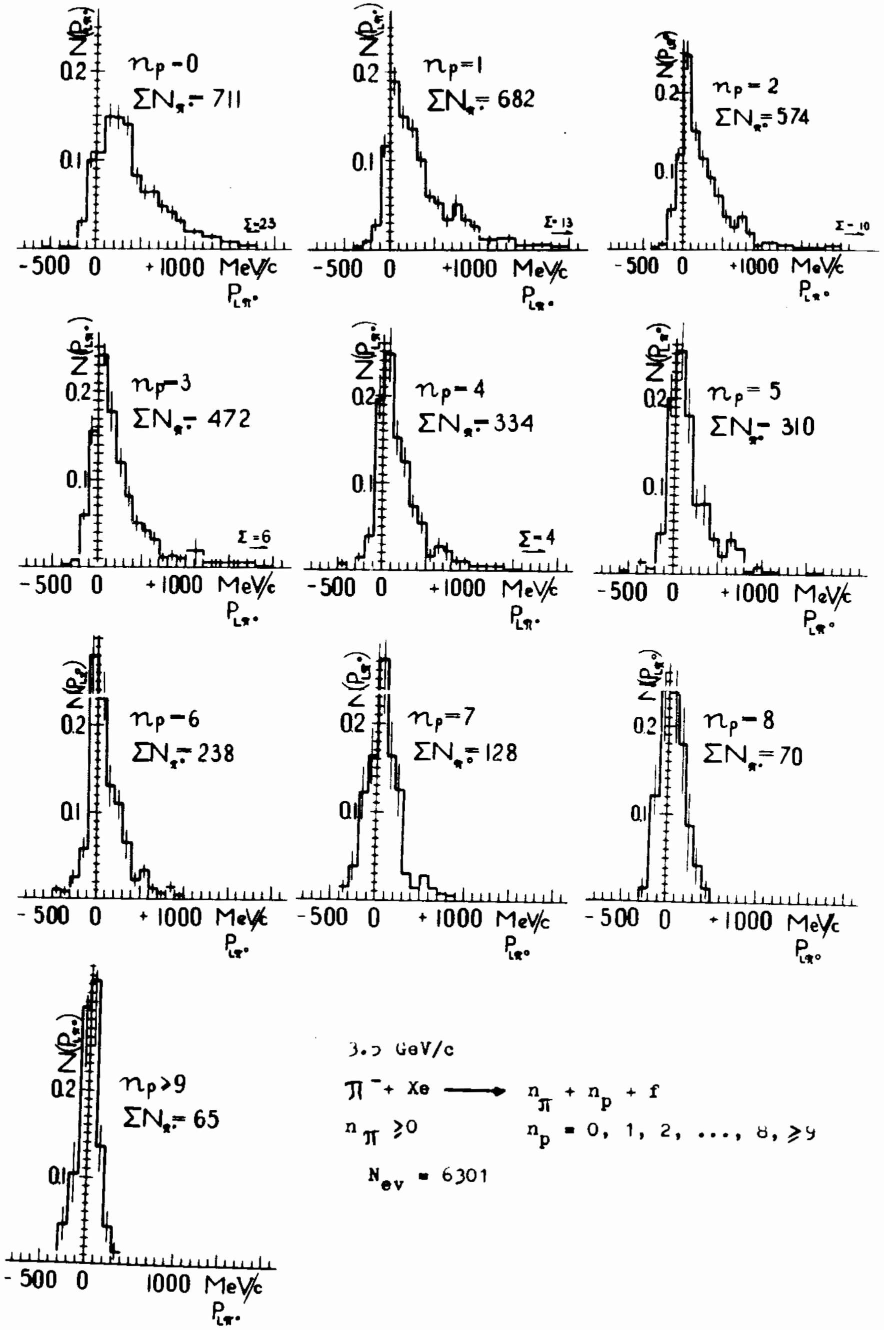


Fig.2. The decrease of the longitudinal momentum $P_{L\pi^0}$ *of the produced neutral pions, in pion-xenon nucleus collisions at 3.5 GeV/c momentum, with increase of the thickness of the intranuclear matter layer involved - higher values of the multiplicity* n_p *of the emitted protons correspond to larger thicknesses,* $n_p = 8$ *corresponds to the diameter of the target nucleus* /19/; ΣN_{π^0} *are numbers of events in a histogram.*

The observed decrease of the occurrence of the stoppings with increase of the incident hadron energy, in collisions of definite hadron with a definite target nucleus, can be described quantitatively by means of simple formula based on relations (1) and (3), and on the data on the target nucleus size and nucleon density distribution in it /19/.

4. CONCLUSIONS AND REMARKS

The above described experimental data have clearly brought out the fact that hadrons lose their energies in passing through layers of intranuclear matter - similarly as electrified particles do it in traversing materials. There can be no doubt that hadrons are reduced in velocity by their passage through layers of intranuclear matter - due to the action of the strong forces.

The hadron energy loss is accompanied by the emission of observed fast nucleons - similarly as energy loss of electrified particles in materials is accompanied by ejection of observed electrons. But, how far this analogy holds? The ejected electrons are knocked out, the emitted nucleons are not of this nature - they are rather decay products of some two- or more-nucleon systems formed inside target nucleus and decaying after having left it. From the values of the mean kinetic energies of the observed protons, which are nearly as large as half of the pion mass, it can be concluded that these systems can be produced when low energy pions - of kinetic energies near to zero - are absorbed by two or more nucleons inside the target nucleus; such pions could be "knocked out" from nucleons along the paths of hadrons in intranuclear matter, and they cannot be observed directly - as absorbed in intranuclear matter with large efficiency. Such low energy pions could be trated as corresponding to electrons knocked out from atoms by electrified particles in materials.

Additional investigations of this hypothetical analog are in progress now. It is hoped that this hypothesis, made in one of our works/24/, might correspond to reality. Preliminary calculations on some mean characteristics of the emitted fast protons, performed on the basis of above hypothesis, seem to give reasonable results.

The hadron energy loss process proceeds independently of the particle production process - energy and momentum spectra and angular distributions of the emitted nucleons are the same for events without particle production and for those with particle production. On the background of the above described fluent nucleon emission induced by hadrons traversing atomic nuclei the particle production process occurs sometimes.

One more important thing which has been found in these investigations is a strictly causal relation in the intranuclear world - within the atomic nucleus: a certain cause is followed by definite effect. In the case under discussion, to a definite impact parameter in a definite hadron-nucleus collision there corresponds strictly determined number of the emitted fast nucleons and definite energy loss of the projectile. This finding allows one to hope that: a) massive target nucleus will serve as precise detector of the properties of the particle creation process in statu nascendi; b) any atomic nucleus can be treated as a layer of one-nucleon-thin "foils" of intranuclear matter; c) it may form a basis for a new branch of physics - "The Intranuclear Physics".

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REFERENCES

1. Rutherford E. Some Properties of the Alpha Rays from Radium.Philosophical Magazine, vol.10, ser.6, 1905,p.163.
2. Rutherford E. Some Properties of the Alpha Rays from Radium. Philosophical Magazine, vol.11,ser.6, 1906,p.166.
3. Rutherford E. The Retardation of the Velocity of the Alpha Particles in Passing Through Matter. Philosophical Magazine, vol.11, ser.6, 1906, p.553.
4. Rutherford E. Retardation of the Alpha Particle from Radium in Passing Through Matter. Philosophical Magazine, vol.12, ser.6, 1906, p.134.
5. Bohr N. On the Theory of the Decrease of Velocity of Moving Electrified Particles in Passing Through Matter. Philosophical Magazine, vol.25, 1913, p.10.

6. Bohr N. On the Decrease of Velocity of Swiftly Moving Electrified Particles in Passing through Matter. Philosophical Magazine, vol.30, 1915, p.581.
7. Moller Ch. - Ann.d. Physik, 1932, 14, p.531.
8. Bethe H. - Handb. d. Physik, 1933, 24, p.1.
9. Williams E.J. - Proc. Roy. Soc., 1932, A135, p.108; 1933, A139, p.163; 1939, A169, p.531.
10. Williams E.J. - Phys. Rev., 1940, 58, p.292.
11. Bloch F. - Ann.d.Physik, 1933, 16, p.285.
12. Bloch F. - Zs.f. Physik, 1933, 81, p.363.
13. Livingston M.S., Bethe H.A. - Rev. Mod. Phys., 1937, 9, p.245.
14. Rossi B., Greisen K. - Rev. Mod. Phys., 1941, 13, p.240.
15. Heitler W. The Quantum Theory of Radiation. Clarendon Press, Oxford, 1954.
16. Strugalski Z., Pluta J. - Sov.Journ. of Nuclear Phys., 1974, 27, p.504.
17. Strugalski Z., Pawlak T., Pluta J. JINR Communications E1-82-718, E1-82-719, E1-82-841, Dubna, 1982; E1-83-234, Dubna, 1983; E1-85-888, Dubna, 1985.
18. Strugalski Z. Degradation of Hadron Energy Through Nuclei. Second International Conference of Nucleus-Nucleus Collisions, Visby, Sweden, 10-14 June, 1985; Proc.ed. by B. Jacobson and K.Aleklett, vol.1, p.107.
19. Strugalski Z. JINR Communications E1-83-850, Dubna,1983; E1-86-579, Dubna, 1986.
20. Strugalski Z. Hadron Passage through Nuclear Matter. 20-th International Cosmic Ray Conference, August 2-15, Moscow,USSR,1987, Proc. vol.5,p.46, "Nauka", Moscow,1987.
21. Strugalski Z. et al. Experimental Study of Hadron Passage through Intranuclear Matter. JINR Communications E1-88-211, Dubna, 1988.
22. Elton L.R.B. - Nuclear Sizes. Oxford University Press, 1961.
23. Pawlak T. et al. Characteristics of Atomic Nuclei Employed as Targets in High Energy Nuclear Collisions. JINR Communications E1-86-643, Dubna, 1986.
24. Strugalski Z. Monotonous Braking of High Energy Hadrons in Nuclear Matter. JINR Communications E1-12086, Dubna, 1979.

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Стругальски З. E1-88-639
Торможение адронов при прохождении
через внутриядерную материю

Скорости адронов уменьшаются при прохождении через внутриядерную материю - из-за сильных взаимодействий, аналогично тому, как скорости заряженных частиц уменьшаются при прохождении через материалы - из-за электромагнитных взаимодействий. Наблюдаемые потери энергии адронов во внутриядерной материи можно принимать за аналог хорошо знакомых потерь энергии заряженных частиц в материалах.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

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Strugalski Z. E1-88-639
Retardation of Hadrons in Passing
through Intranuclear Matter

Hadrons are reduced in velocities by their passages through layers of intranuclear matter - due to strong interactions, similarly as electrified particles are reduced in velocities by their passages through layers of materials - due to electromagnetic interactions. The observed hadron energy loss in intranuclear matter can be treated as an analog of the well-known energy loss of electrified particles in materials.

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

Communication of the Joint Institute for Nuclear Research. Dubna 1988