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MECHANISMS OF ENERGY TRANSFER FROM HADRONIC AND NUCLEAR PROJECTILES INTO TARGET NUCLEI IN COLLISIONS AT HIGH ENERGIES

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1. INTRODUCTION

The mechanisms of energy transfer from hadronic and nuclear projectiles into target nuclei, in collisions at high energies, are determined by the hadron-nucleus and nucleus-nucleus collision mechanisms, described in our recent works [1,2].

In hadron-nucleus collisions, two general channels of the energy transfer may be distinguished: 1) The transfer to the intranuclear matter — to the nucleon assemblage bound naturally as the atomic nucleus with definite mass number A and charge number Z; 2) The energy transfer to single nucleons which, this way, continue their existence during relatively short lifetime — of about 10^{-22} s — as intermediate objects or generons through which the particles are generated.

The first channel manifests itself as the fast nucleon emission which the hadron passage through intranuclear matter is accompanied by, about 0.360 GeV/(nucleon/S) energy must be lost for any of nuclei; the hadron passage through target nucleus is localized within the pipe of $2R_h$ diameter, centered on the hadron course; $S = \pi D_0^2 \approx 10.3$ fm^2, $R_h \approx D_0$ is the strong interaction range as long as the nucleon diamater D_0 is.

The amount of the projectile nucleon energy transferred by this channel into target nucleus is limited, being of 0.36 GeV/(nucleon/S) along definite length of the hadron in intranuclear matter not larger than about 20 nucleon/S — for the heaviest nuclei.

The second channel manifests itself as the particle production. The particle production, as we know experimentally [1,2], is realized through the intermediate objects or generons; it seems not to be some limits for the energy which could be transferred this way. The particles are created in $2 \rightarrow 2$ type endoergic reaction; in particular, there may be the nucleon-nucleon $2 \rightarrow 2$ type reactions. In such reactions, into nucleon might be pumped practically unlimitedly high energy. The quasi-unidimensional cascade of the intermediate objects may develop along the hadron course in the target nucleus massive enough [2]. This way, the intranucleon matter might be highly excited — it is not observed any limit for energy transfer from a hadronic projectile to the nucleon target.

In nucleus-nucleus collisions both the channels of the energy transfer should be in operation. It becomes to be clear whether and how might be

possible to produce the quark-gluon plasma phase of the intranuclear matter or no.

The subject matter in this paper is to describe the method of the energy transfer processes investigations and to present experimental results obtained by this method.

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2. INVESTIGATION PROCEDURE

The mechanisms of the energy transfer from hadronic and nuclear projectiles to nuclear targets may be revealed experimentally only. Naturally, they are dependent on the hadron-nucleus and nucleus-nucleus collision mechanism. They should be known on experience before to analyse the energy transfer processes.

The collision reactions were studied exprimentally first, therefore [1,2]; the studies based on experimental material complete enough — from almost total expriment [1,2] performed by means of 26 and 180 litre xenon bubble chambers; the chamber data were supplemented with appropriate data from other detectors: nuclear emulsions, electronic arrangements, hybrid detectors [1,2]. Information was collected for various nuclear targets, at wide value interval of the projectile momenta.

In results, it was stated, among other facts, that [1,2]:

2.1. In hadron-nucleus collisions:

a) The relatively small volume ν of the target nucleus is involved

$$\nu = \pi \cdot R_h^2 \cdot \lambda, \tag{1}$$

with the radius as long as the strong interaction range R_h is ($R_h \approx D_0$, where D_0 is the nucleon diameter) centered on the hadron path λ in the nucleus [3], $\pi R_h^2 = S \approx 10$ fm^2. When λ is in nucleons/S ν may be expressed in number n_N of nucleons contained in it, $\nu = S\lambda$ — in nucleons [3].

b) The hadrons can pass through layers of the intranuclear matter without causing the particle production, in some cases [4]. In passing, they induce the emission of nucleons (visible proton emission) in a definite manner, anyhow — the number of the emitted nucleons is equal approximately to the number n_N of the nucleons contained inside the volume ν (1) covered on its length λ

nucleons/S: precise formulas in question were published in our former works [5—7].

c) The particle production process goes through intermediate objects or generons [8] in 2 → 2 type collision reactions of the incident hadron with downstream nucleons, on the background of the hadron passage throught layers of intranuclear matter [1,2]. It was found exprimentally that the particle production process does not influence the nucleon emission and fragment evaporation processes [9].

d) In result of the collision of a hadron with a target nucleus massive enough, the rest of the damaged nucleus uses to evaporate nuclear fragments and decay into stable parts [7].

2.2. In nucleus-nucleus collisions:

a) The nuclear projectile may be treated as collimated beam of weakly bound nucleons which collide with the target nucleus. In interaction of the beam nucleons with layers of the intranuclear matter, they behave themselves as hadrons usually do it in.

b) The outcome in a nucleus-nucleus collision is a composition of the outcome in hadron-nucleus collisions at various parameters [2].

The information about the hadron-nucleus and nucleus-nucleus collisions, presented above, is conclusive enough, in order to state, on the basis of it that:

The energy transfer in hadron-nucleus and nucleus-nucleus collisions might be realized through: 1) the energy loss of hadron in its passage through layers of intranuclear matter, mainly for the nucleon emission induced; 2) the energy loss of the incident hadron in the particle-producing collisions with downstream nucleons, in passing through the intranuclear matter.

The nucleon emission and the particle production processes go independently one of the another. It will be enough to determine the energy balance in both the independent processes. It has been done, to no small degree, in our former works [10—14].

Summing up, the search procedure consisted in accurate experimental investigation of the hadron-nucleus and nucleus-nucleus collision mechanisms and then of the energy balance in the main of energy transfer processes — in the nucleon emission process the hadron passage through intranuclear matter is accompanied by, and in the particle-producing process.

3 EXPERIMENTAL RESULTS

In the light of the hadron-nucleus and nucleus-nucleus collision mechanisms revealed in experiments and described in our recent works [1,2], following pictures of the energy transfer into the target nucleus emerge — as prompted in experience:

1. Hadrons and beams of nucleons, i.e. accelerated atomic nuclei, lose their kinetic energy due to strong interactions in passing through layers of intranuclear matter, proportionally to the layer thickness λ covered — similarly as electrically charged particles lose their energy in materials due to the electromagnetic interactions [14]. The hadron energy loss

$$\Delta E_h = \varepsilon_h \cdot \lambda, \tag{2}$$

where ε_h is the hadron h energy loss in GeV/(nucleon/S) — for pions $\varepsilon_h = \varepsilon_\pi = 0.180$ GeV/(nucleon/S) and for protons $\varepsilon_h = \varepsilon_p \approx 0.360$ GeV/(nucleon/S), $S \approx 10.3$ fm^2; λ is in nucleons/S. For the mean thickness $\langle \lambda \rangle$ in nucleons/S of the target nucleus, the mean energy loss is:

$$\langle \Delta E_h \rangle = \varepsilon_h \cdot \langle \lambda \rangle. \tag{3}$$

For the maximum thickness λ_{max} in nucleons/S of the target nucleus — when a hadron h passes through the nucleus along its diameter D:

$$\Delta E_{h_{max}} = \varepsilon_h \cdot \lambda_{max} = \varepsilon_h \cdot D. \tag{4}$$

The observable effect which the hadron energy loss is accompanied by is the emission of the fast nucleons from the target nuclei in hadron's passage through intranuclear matter. The measurable well mean number of the emitted protons $\langle n_p \rangle$ in all hadron-nucleus collisions, h — A, equals:

$$\langle n_p \rangle = \frac{Z}{A} \cdot \langle \lambda \rangle \cdot S \left(1 - e^{-\frac{\langle \lambda \rangle}{\langle \lambda_t \rangle}} \right), \tag{5}$$

where $\langle \lambda \rangle$ in nucleons/S is the mean thickness of the target nucleus [15,16]. $\langle \lambda_t \rangle$ in nucleons/S equals $1/\sigma_t$ and σ_t is the total hadron-nucleon cross section in S/nucleon. The relation (5) holds for all the hadrons up to energies met in experiments, when accelerator beams or cosmic ray particles are applied [14].

It is worth-while to use the table in which the mean and maximum energy loss $\langle \Delta E_h \rangle$ and ΔE_{max} of pions and protons in their passages through target nuclei are presented [14].

It should be emphasized that the energy transfer to the nucleus as a collection of weakly bound nucleons is limited by the range-energy relation for hadrons in intranuclear matter [10] — similar to the range-energy relation for electrically charged particles in materials [10].

At energies lower than a few GeV this energy loss is tangible, at energies higher by much — higher than tens GeV it is imperceptible.

The energy loss process by the nuclear breaking of hadrons in their passage through intranuclear matter is localized within the target nucleus at relatively small region determined above — by formula (1).

Then, at energies high enough, over a few GeV, this mechanism of the energy transfer cannot be taken into account as ineffective one which the hadronic projectiles could transfer their energy to the target nucleus by.

The accelerated nuclei — as the nuclear projectiles — can be treated as the beams of hadrons — of nucleons. The observation of the nucleus-nucleus collisions performed in various detectors — streamer chambers, bubble chambers, nuclear emulsion indicate that collimated beams of nucleons appear in outcome of the nuclear collisions [2]. It can be concluded, from this phenomenon, that nucleons from the projectile nuclei behave themselves as any hadron do it in passing through the layers of intranuclear matter. Then, the total energy loss by the nucleon emission from the target nucleus should be expressed by the sum of the energy loss in hadron-nucleus collisions at various impact parameters b:

$$\Delta E_{\mathrm{nuc}} \approx \sum_{b=r_t}^{b=0} n(b)\cdot \Delta E_h(b), \qquad (6)$$

where $n(b)$ — the number of collisions with impact parameter b, parameter b changes from $b = 0$ up to $b = r_t$ the radius of the target nucleus.

We are then now in a position to state that: Only limited part of the hadronic or nuclear projectile energy can be transferred to the target nucleus; such energy transfer is accompanied by the emission of nucleons from target nucleus induced by hadronic or nuclear projectile. It is not possible to pump this way unlimitedly much of the energy into target nucleus as such; the target nuclei are disintegrated into nucleons, in the collisions — the utter disintegration into nucleons may occur as well sometimes — in head on collisions of nuclei with near values of their mass numbers.

2. Hadrons and nuclei or beams of nucleons accelerated to energies high enough by much higher than the pion profuction threshold lose their energies as well in particle-producing collisions with downstream nucleons in intranuclear matter.

According to the mechanisms of the particle production processes in hadron-nucleus and nucleus-nucleus collisions [1,2] — prompted experimentally, in the 2 → 2 type collision reactions

$$h_1 + h_2 \to g_1 + g_2 \tag{7}$$

of two hadrons h_1 and h_2 two intermediate objects or generons g_1 and g_2 are created first; there is not any limit for the energy transfer from the projectile to the produced generons — not only as the kintetic energy of the generons, but as their internal energy of excitation. After the lifetime of about $\tau_g \approx 10^{-22}$ s the generons decay into «created» particles and resonances.

It is not excluded that the intermediate objects are the excited states of nucleons — the inner structure of nucleons manifests itself in the existence of generons [19]; the intermediate objects or generons could be treated as the excited quark-gluon matter bags. The process of the intermediate objects creation is localized within the relatively small volume v (1), of the shape of the tube with the diameter $D_0 = 2R_h$. The generons, in passing through intranuclear matter, approximatelly along the incident hadron course [2] may collide with downstream nucleons and create new intermediate objects, and the quasi-unidimensional cascade of the intermediate objetcs may develop in the target nucleus massive enough [2]; the generons escape the nucleus and decay into resonances and particles after lifetime of about 10^{-22} s.

In the generon collisions, quark-gluon bags may be created massive enough; this way, objects of highly excited quark-gluon matter may be created. In such objects the quark-gluon plasma state could be obtained. And so, this is the unique and real way for creation of the highly excited state of the intranucleon matter — which might be treated as bags with excited quark-gluon matter; the outcome of the bags explosion is simply observable and often observed — as the decays of generons into families of jets at appropriately high energies, for example [1,17,18].

The search for the mechanism of the bags formation is the only tool for possible discovery of the intranucleon matter phase transition. The existence of the intranuclear matter phase transitions depends on the possibility to fuse the generons throughout the target nucleus. Is it possible? The answer should be found in experiments.

The projectile kinetic energy E_h which could be transferred to intranucleon matter Δ is then:

$$\Delta = E_h - \Delta E_h , \tag{8}$$

where ΔE_h is the part of energy transferred to intranuclear matter by the incident hadron in its passage through the target nucleus — for the fast nucleon emission; ΔE_h is determined in the table, for a few nuclei.

Table. Mean and maximum energies of pions and protons lost in their passage through intranuclear matter; the kinetic energy E_h of the incident hadrons is larger than $E_h = \varepsilon_h D$, where D in nucleons/S is the target nucleus diameter and ε_h in GeV/nucl/S is the energy lost by a hadron on the intranuclear matter layer as thick as 1 nucl/S, $S \approx 10$ fm^2; for pions $\varepsilon_h = \varepsilon_\pi = 0.180$ GeV/(nucl/S), for protons $\varepsilon_h = \varepsilon_p \doteq 0.360$ GeV/(nucl/S)

Reaction	Energy GeV	Energy lost GeV	
		mean	max
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	1.9	4
p + C	≥ 2.1	1	2.1
p + Al	≥ 3.4	1.5	3.4
p + Cu	≥ 5	2.2	5
p + W	≥ 7.6	3.6	7.6
p + Ta	≥ 7.6	3.5	7.6
p + Pb	≥ 7.9	3.7	7.9

4. CONCLUSIONS AND REMARKS

As the result of the projectile energy transfer to target nucleus investigations described above, following mostly important assertions may be stated, for the target nucleus at rest in the laboratory:

1. In the hadron-nucleus collisions the projectile energy is transferred into the target nucleus in its passage through layers of the intranuclear matter, anyhow; this energy transfer depends on the path length covered by the projectile and its successors; in the passage, definite tube-shaped relatively small volume of the target nucleus is involved only. The energy transfer realized this way is limited and independent of the projectile energy, at energies high enough, and amounts no more than about 8 GeV for the proton projectiles — it is as twice higher as for the pionic projectiles.

Often, on the background of the projectile passage, the energy is transferred to the downstream nucleons in some particle-producing collisions. As a result of this collision,intermediate objects, or generons, are created in 2 → 2 type endoergic reaction. If the target nucleus is massive enough, the generons may collide with the downstream nucleons and produce new — secondary generons in ones turn. This way the intranuclear cascade of generons may be initiated localized around the incident hadron course within the tube (1). This energy transfer is not limited, it depends on the projectile energy only.

The intermediate objects decay, after having left the parent nucleus, into «created» resonances and particles, jets may appear plentifully.

2. In the nucleus-nucleus collisions, i.e. in the collisions of weakly bound nucleons beam with the target nucleus, the energy transfer process is similar for any of the beam nucleons treated as the projectile in hadron-nucleus collision. The outcome in nucleus-nucleus collision is then a composition of appropriate nucleon nucleus collisions at various impact parameters; the screening should be taken into account.

And so, the mechanism of the projectile energy transfer to the target nucleus, prompted by experiment, suggests some ways to production of the expected highly excited states of intranuclear matter and to realization in experiments the quark-gluon phase transitions.

It should be remembered that the energy transfer to the atomic nucleus goes through the intermediate objects or generons produced only, however. But generons escape the parent nucleus and use to decay into resonances and particles after about 10^{-22} s.

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