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THE ENERGY OVERCOMPENSATING DISINTEGRATIONS OF RESIDUAL TARGET NUCLEI DAMAGED IN HADRON-NUCLEUS COLLISIONS

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Энергетически сверхкомпенсирующие дезинтеграции остаточных ядер-мишеней, поврежденных в адрон-ядерных столкновениях

Массивные ядра-мишени, поврежденные в столкновениях с адронами высоких энергий, распадаются на ядерные фрагменты. Во многих случаях выделяется некоторая порция ядерной энергии; эта порция иногда может быть сверхкомпенсирующей энергию, использованную на повреждение ядра.

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The Energy Overcompensating Disintegrations of Residual Target Nuclei Damaged in Hadron-Nucleus Collisions

Massive target nuclei damaged in hadron-nucleus collisions at high energies use to disintegrate into nuclear fragments. In many cases such breakup is egzoergic — some portion of nuclear energy is released; this portion should be overcompensating the energy used for the nucleus damage, in some cases.

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

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1. INTRODUCTION

In the series of our recent works [1—7] conclusive and based experimentally information has been obtained about the mechanisms of the hadron-nucleus collision processes, of the energy transfer from hadronic and nuclear projectiles into target nuclei in the nuclear collisions, and about the damages of the target nuclei and their transitions into some unstable states.

The damaged nuclei cannot exist long time in such an unstable nucleon configuration, and some their fragments must be evaporated or they should decay into stable parts. This way, at the end of the collision process the breakup or disintegration of the residual nucleus into lighter fragments should occur. In some cases, this disintegration may be egzothermic — some portion of the nuclear energy of the nucleus should be released. The released energy may be overcompensating the energy used for the nuclei damage adequate for the occurrence of the energetic useful breakup. Such, incident hadron induced breakups or disintegrations could be applied as elementary nuclear energy sources in some energy devices, e.g. — some energy nuclear multipliers.

And so, a possibility of extracting nuclear energy with the help of fast induced nuclear breakup — in hadron-nucleus collisions — appeares, it is a new possibility. Probably, nuclei of any of elements with the mass numbers large anougth, larger than about > 100 may in principle undergo such a fission stimulated by fast hadrons. This statement is supported by our experimental data on the target nucleus damages in the nuclear collisions [3]; any of nuclei may be penetrated up to a definite deep or pierced by a hadron with corresponding kinetic energy high enough.

In such breakup reactions, as the nuclear fuel, nuclei of any of sufficiently heavy elements might be applied in the energy nuclear amplifiers. The amplifiers may work at the intensive hadronic beams from accelerators — especially at pion beams [6]. Therefore, the practical usefulness of this method should be analysed from the economical point of view; the energy and financial balances should be taken into account. In doing it, the quantitative data on the energy transfer from hadronic projectiles into target nuclei [2] and on the mechanisms of the target nuclei damages [3] should be used.

Now, nuclear reactors constitute a major source of energy being in use, and they are likely to continue to be so in a foreseable future. But, they are not without various problems, and alternative approaches to energy extraction from atomic nuclei are of great interest. It was a sufficient motivation for me in doing this work.

The paper is arranged as follows: after the introduction in section 1, section 2 presents the short and simple description of the hadron-nucleus collision reaction mechanism, section 3 contains the description of the residual target nucleus breakup, in section 4 the conditions for the energy overcompensating collisions are given, in section 5 possible applications of the induced breakup in an energy multipliers are described shortly, section 6 closes the paper with the conclusions and remarks; many references are added.

2. THE HADRON-NUCLEUS NUCLEAR COLLISION REACTION MECHANISMS

The results on the collision mechanism were presented widely in our former works [1,8], here only some parts of the descriptions are rewritten — adequately to the problem in question.

In hadron-nucleus collisions the interaction of the incident hadron is localized in relatively small cylindrical volume with the radius as large as the strong interaction range R_s is, centered on the hadron course within the target nucleus.

Four main processes are usually occurring when hadrons collide with atomic nuclei: a) The passage of the incident hadron through intranuclear matter, accompanied by the emission of nucleons with kinetic energy from about 20 up to about 400 MeV from the interaction region, we call them the «fast» nucleons later; the emission of the nucleons is induced by the incident hadron in its passage through intranuclear matter. b) The production of hadrons. On the background of the projectile passage through layers of intranuclear matter, the particle-producing head on collisions of the projectile with one of the downstream nucleons occur; particles are produced through intermediate objects in 2 → 2 type endoergic reactions of the hadron and its successors with downstream nucleons. The intermediate objects, as the hadron successors, may use to collide with the next of the downstream nucleons and create new intermediate objects; the linear intranuclear cascade of generons may develop along the incident hadron course this way in intranuclear matter. c) The evaporation of the target nuclear fragments, including the target nucleons of kinetic energy smaller than about 10—20 MeV. d) The breakup of the residual target nucleus into nuclear fragments.

In any case, whether the particles are produced or not, any projectile hadron causes the emission of nucleons in passing through atomic nucleus. This nucleon emission should not be confused with the nucleon evaporation with clearly different energy and angular distributions. The number n_N of the emitted «fast» nucleons equals the number of nucleons contained within the volume

$$V = \pi R_s^2 \lambda = \pi D_0^2 \lambda , \qquad (1)$$

centred on the hadron path λ in intranuclear matter, where D_0 is the diameter of the nucleon, as large as the strong interaction range is. The particle production process does not affect the nucleon emission [9].

The particle creation process goes on the background of the incident hadron passage through intranuclear matter and it is localized along the projectile course in intranuclear matter within the tube of the radius R_s as large as the strong interaction range R_s is, centered on the hadron cource. Hadrons are created through some intermediate objects formed inside the tube in the target nucleus and they use to decay after having left the nucleus, after lifetime of about $\tau_g = 10^{-22}$ s, into commonly known «produced» particles and resonances; the intermediate objects are in fact the hadrons in statu nascendi [10]. In collisions with nuclei massive enough, at energies high enough, the intermediate objects may use to collide in ones turn with the downstream nucleons — the intranuclear cascade may develop of the intermediate objects along the incident hadron course through the volume [1]. The multiplicity n distribution $f(n, A, E_h)$ of the electrically charged hadrons produced in a collision of a hadron with an atomic nucleus A at the incident hadron energy E_h is [11,12] a composition of some number $m = 1,2,3,...$ of statistically independent outcomes which could be observed separately in elementary hadron-nucleon collisions at incident hadron energy E_h/m.

The evaporation process was studied experimentally in nuclear photoemulsions mainly; the evaporation products leave characteristic black tracks in the emulsions — the tracks of nuclei with the charge number $Z = 1$ to $Z = 2$ predominantly [13,14]. It was obtained that: 1. The black track leaving particles exhibit an almost isotropic distribution [14,15]. 2. The mean number of the black track leaving particles $<n_b>$ is not related to the number of generated pions [14], at energies of the incident hadron over a few GeV; this number $<n_b>$ is weakly energy dependent at smaller energies [14,16]. 3. Mean kinetic energy of the emitted black track leaving particles is about 20 MeV and stays within incident hadron energy change; it is independent as well of the identity of the impinging particle [17]. 4. The ratio N_F/N_B between the number N_F of the black track leaving particles directed into forward hemisphere and the number N_B of the particles directed into backward hemisphere amounts about 1.1 ± 0.1; it does not depend on n_b and it is the same for pion-nucleus collisions at about 60 and 200 GeV [17]; it is reasonable to accept that N_F/N_B is practically independent of the energy and identity of the impinging hadron.

In experiments performed by means of photonuclear emulsions, the relations between characteristics of the black track leaving particles and the gray track leaving ones were investigated [13,14,16—18]; among the gray track leaving particles are the fast protons predominantly — with energies of about 20 to 500 MeV. Experimental relations in question allow one to conclude that [19]: 1. A large difference between mean energies of the fast protons, $<E_g>$, and of the black track leaving particles, $<E_b>$, is independent of the energy and mass of the projectile and of the target mass as well [16]. 2. A large difference between angular distributions of the b- and g-track leaving particles is independent of the energy and identity of the impinging hadron, and of the target nucleus mass number as well. 3. The range and angular distributions of the gray track producing particles do not change with incident hadron energy change, as it has been proved at energies larger than about 2 GeV. Still less correlated with the energy are the black track, their number n_b is proportional to n_g. 4. The dependence of the mean number of the black tracks $<n_b>$ on the number n_g of gray tracks has the same behaviour through the energy range 6.2 GeV to 400 GeV [15,18], one linear function describes it well [15]. This linear function for proton-AgBr nuclei collisions passed near the dirigin $<n_b> = 1.21\, n_g + 1.49$; this correlation is completely independent of the number of produced pions [18]. Even if the shower particle multiplicity increases from 2.8 to 16.8 no change is observed in the mean black and gray track multiplicities. 5. The differential frequency distributions for the stars as function of $n_h = n_g + n_b$, for proton-emulsion nuclear collisions at 6.2—3500 GeV exhibit only small irregularities and differences [15]. 6. The multiplicities n_g and n_h obey the relation [15]:

$$<n_g/n_h> = <n_g>/<n_h> = \text{constants} = 0.39\,. \qquad (2)$$

It indicates proportionality between $<n_g>$ and $<n_h>$, and hence between $<n_b>$ and $<n_g>$; this relation is energy independent.

3. THE RESIDUAL TARGET NUCLEUS DISINTEGRATION

The picture of the target nucleus breakup process has been presented in detail in our former work [3]; some of the mostly important fragments of this picture will be given once more here adequately to the problem under study. Lately, in our experimental studies of hadron-nucleus collisions at projectile kinetic energy larger than the pion production threshold, a new physical motivation has been obtained for the induced breakup or disintegration of the colliding nuclei [8,20,21].

The mechanism of the colliding nucleus splitting into some nuclear fragments is of a simple newly known nature and experimentally based. A nucleus involved in a hadron-nucleus collision at energy high enough is pierced by the hadronic projectile, along its course in intranuclear matter; in passing through the nucleus, the hadron involves the intranuclear matter into strong interactions within the channel with the diameter $D = 2R_s$ centered on the hadron course, $R_s \approx D_0$ is the strong interaction range as large approximately as the nucleon diameter D_0 is. Range-energy relation, $R_h - E_h$ is known for hadrons in intranuclear matter [22]:

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

where the path R_h in intranuclear matter in nucleons/S, ε_h in GeV/(nucleon/S), $S = 10.3\ \mathrm{fm}^2$, the hadron energy E_h in GeV; $\varepsilon_h = \varepsilon_\pi = 0.180$ GeV/(nucleon/S), $\varepsilon_h = \varepsilon_p = 0.360$ GeV/(nucleon/S). In passing through intranuclear matter, the incident hadron is accompanied by the nucleons emitted from the target nucleus with energies from about 20 up to about 500 MeV; the number of the emitted nucleons is equal to the number of the nucleons contained inside the nucleus inside of the channel centered on the hadron course. Obviously, the target nucleus is destroyed this way at the part of it which is involved into the collision reaction. Such destroyed nucleus does not exist in the excited state and it should decay into heavier stable nuclear fragments. It may be expected that the decay or evaporation process should be determined by the collision impact parameter — first of all. But, the answer to the question «How is the desintegration of the colliding nuclei processing?» should be find in observations and experiments. Experiments were performed. Relations important for the subject in question were collected in our former works [3,15,19,23,24]. Some of the results are presented here once again: 1. The mean multiplicity $<n_p>$ of the emitted protons is

$$<n_h> = <\lambda_A> \cdot S\,, \tag{4}$$

where $<\lambda_A>$ is the mean thickness of the target nucleus in protons per S units, and $S = \pi D_0^2 \approx 10\ \mathrm{fm}^2$. The approximate relation holds as well: $n_p \approx \lambda \cdot S$, where λ in protons/S is the thickness of the intranuclear matter covered by the hadron. 2. The angular distribution of the emitted fast protons is independent of the impinging hadron [26,27]. 3. The kinetic energy spectra of the emitted protons are practically independent of energy and identity of the impinging hadron [28]. 4. The mean value of the kinetic energy of the emitted protons is almost as large as one half of the Pi meson rest mass [28]. The kinetic energy of the protons emitted to the backward hemisphere is almost as large as one half of the Pi meson rest mass [29]. 5. The dependence of the mean number $<n_b>$ of the black track leaving particles on the number n_g of the gray tracks exhibits the same behaviour through the energy range from 6.2 to 400 GeV and practically one function describes it well [15,18,19]; this function is:

$$<n_b> = 1.25\,\left(n_p + \frac{A - Z}{Z} \right), \tag{5}$$

where A and Z are the mass and charge numbers. This function (5) is valid for the incident hadron energy larger than $D \cdot \varepsilon_h$, where D is the diameter of the target nucleus in nucleons/S, ε_h is the energy lost by the hadron in its passage through intranuclear matter in GeV/(nucleon/S).

In result of the emission of fast nucleons from the target nucleus a damage appears in it. On the walls of such damages the equilibrium of interactions acting on nucleons in the atomic nucleus is disturbed, and the nucleus becomes to be in some unstable state, and it should decay into stable fragments. This decay happens a long time after the passage of the incident hadron, after about 10^{-17} s. The emission of the fast nucleons happened after about 10^{-23} s after the collision starting.

4. THE CONDITIONS FOR OCCURRENCE OF THE ENERGY OVERCOMPENSATING COLLISION REACTIONS

Let us start this section with the definition of the energy overcompensating collision reaction.

4.1. The Energy Overcompensating Collision Reaction

It is known from experiments that in any hadron-nucleus collision reaction two stages may be distinguished: 1. The fast stage in which the target nucleus is destroyed by the incident hadron in its passage through layers of intranuclear matter, the destruction is happening in a definite manner [3]; the passage is accompanied by the emission of fast nucleons and the produced objects which are having left the parent nucleus; the target nucleus becomes to be damaged. 2. The slow stage in which the damaged nucleus uses to transit itself into some stable state or decay into stable fragments — slow evaporated nucleons, light evaporated nuclei, low energy nuclear fragments.

The first stage occurs due to the energy los of the incident hadronic projectile, the second stage is pure nuclear process — it occurs due to the inner nuclear energy release in the induced breakup of the damaged residual target nucleus — the breakup closes the unstable existence of the target nucleus damaged in the collision.

Let us denote the energy loss of the incident hadron for the target nucleus damage by ΔE_i and the nuclear energy released by the residual target nucleus breakup ΔE_d. We define the hadron-nucleus nuclear collision reaction as energy overcompensating if $\Delta E_d > E_i$.

4.2. The Conditions of Occurrence of the Energy Overcompensating Hadron-Nucleus Nuclear Collisions

First of the conditions is the preparation of an occurrence of large enough target nucleus damages adequately to the nucleus breakup induced by hadronic projectiles.

The second condition is to apply the heaviest target nuclei in the hadron-nucleus collisions; the binding energy of the nucleons in such nuclei should be as large as possible, and it might be released in the breakup process.

The third is that the target-nucleus damage occurring in the collision should be deep enough for the induced breakup starting; the depth as large as 4 nucleons/*S* should be well for it. For such a damage the kinetic energy of the incident pions should be about 700 MeV; for the incident nucleons it should be twice larger.

The fourth condition is to apply such incident hadrons which are losing the smallest energy per one nucleon emission from the target nucleus in their passage through it.

Taking into account all our experience in working with the hadron-nucleus collisions, we are in the position to state that: In order to obtain the energy overcompensating collision reactions the beams of the negatively charged incident pions with kinetic energies of about 700 MeV should be applied in the nuclear collisions with the heavy nuclei; the mostly convenient shall be the nuclei of Hg, Pb, Au, Th, U. At such conditions the overcompensation of the incident pion beam energy, with the density 10^{12} pions/cycle, may be of the order of about 1000 MeV per one hadron-nucleus collision. The energy supply for obtaining the incident beam has not been taken into account here; the accelerator efficiency is accepted as 100%, here.

5. POSSIBLE APPLICATION OF THE INDUCED DISINTEGRATION

Information about the hadron-induced breakup of the target nucleus in nuclear collisions should find various applications, especially in the future energetics. Now, there may be mentioned two important applications:

1. The application of the induced breakup as the physical basis for the «nuclear amplifiers of energy» [6].

2. Application of the hadron induced nuclear breakup and its properties as physical phenomenon which should be taken into account in employing «calorimeters» as an energy producing device in «... nuclear energy production driven by a particle beam accelerator» [30].

But, I am afraid of very small possibility of using this phenomenon in practice now, because of very low energetic efficiency in hadronic beams production at the existing accelerators.

6. CONCLUSION AND REMARKS

No doubt should be made that the energy overcompensating hadron-nucleus nuclear reactions are occurring. What concerns the possible application of them in practice, is now rather a doubtful problem. Maybe, when special sources of hadron beams, mainly neutrons and protons with kinetic energies of about 3—6 GeV could be constructed in the future.

The existence of the energy overcompensating nuclear reactions at high energies should be taken into account in constructing of the calorimetric nuclear amplifiers of energy [30].

But, this phenomenon — the energy overcompensating collision reactions at GeV region of energies is very interesting from the physical point of view.

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