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THE MECHANISM OF NUCLEAR ENERGY RELEASE IN NUCLEUS-NUCLEUS COLLISIONS

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I. INTRODUCTION

This work is a continuation of our previous one [1] in which the nuclear energy release was considered in hadron-nucleus collisions. It has been stated there that some portion of the internal energy of the residual target nucleus (damaged and instable, therefore) is released when the locally damaged nucleus is transiting itself into light nuclear fragments (nucleons, *D, T*) and a lighter, finally stable nucleus or some number of the stable lighter nuclei.

The energy release depends on the number of the emitted light fragments first of all; the mean intensity $\langle n_b \rangle$ (or mean multiplicity $\langle n_b \rangle$) of the emitted light nuclear fragments depends on the damage surfaces inside the locally damaged nucleus.

For that reason, the regions of the locally occurring damages in the colliding nuclei and the surfaces of these damages inside the residual nucleus or nuclei should be recognized as accurately as possible, before to start a discussion about the light nuclear fragment evaporation from the residual nucleus or nuclei in nucleus-nucleus collisions. If this will be done, the estimation of the nuclear energy release might be realized. The characteristics of the damaged regions in the colliding nuclei may be determined on the basis of the nuclei disintegration mechanism obtained from the nucleus-nucleus collision experimental data at high energies. Our earlier former works [2,3] were designed for the problems in question; we use results contained in them in the considerations here — in this work.

2. THE PICTURE OF THE NUCLEI DISINTEGRATION MECHANISMS — FROM HADRON-NUCLEUS AND NUCLEUS-NUCLEUS COLLISIONS EXPERIMENTAL DATA

2.1. Hadron-Nucleus Collisions. The following, interesting and mostly important facts about the hadron-nucleus collisions have just been discovered:

1. The interaction of the incident hadronic projectile in intranuclear matter is localized within the cylindrical volume centered around the projectile course at a distance as large as the strong interaction range R_s is [4,5,6,7].

2. The hadronic projectile passage through the intranuclear matter is accompanied by the emission of fast nucleons (with kinetic energies from ≈ 20 up to ≈ 500 MeV); the number of the emitted nucleons equals the number of the nucleons met by the hadronic projectile [4—7].

3. The emitted fast protons are correlated, the clustering is evidently observed when multiplicities of the protons are smaller than $k < 8$ [8].

4. Hadrons (pions, e.g.) are produced via some intermediate objects (we called them *«generons»*), on the background of the incident hadron passage through a target nucleus [9-11]. The intermediate objects are decaying into the «generated» resonances and hadrons — after having left the parent nucleus [9,10].

5. The hadron production process does not influence the fast nucleon emission and fragment evaporation processes [12].

6. Fast nucleons emitted from the target nucleus memorize the mechanism of the hadron-nucleus collision in which the nucleons were emitted [13].

7. The average multiplicities $\langle n_b \rangle$ of the slow protons and light charged nuclear fragments (the so-called evaporated protons and light charged nuclear fragments) are correlated with the multiplicities n_p of fast nucleons emitted from the target nucleus [14]:

$$\langle n_b \rangle = 1.25(n_p + (A - Z)/Z), \qquad (1)$$

where A and Z are the mass- and charge-numbers of the target nucleus.

2.2. Nucleus-Nucleus Collisions. A fast nucleus projectile with the kinetic energy per nucleon high enough (higher by much than the pion production threshold) may be treated as a sharply collimated beam of nucleons bound together — as in any of atomic nuclei. In passing through a track detector (bubble chamber or photographic emulsion, e.g.), a nucleus leaves a characteristic track caused by ionization in the detector working medium.

After a collision of the nucleus with a nucleus in a track detector working medium, especially after the central or quasicentral collision with a target nucleus of similar mass number, the projectile nucleus suffers a splitting into nucleons — a slightly dispersed beam of the nucleons appears, it is the beam of freely moving nucleons along their courses in the parent projectile nucleus. The protons of them leave visible tracks, the neutrons are not observed usually. Although, in the main part of the colliding nuclei (or the nucleon collimated beams) only peripheral parts of them are involved in the collision reactions — the main part of the colliding nuclei collide peripherally. They will be not sufficiently disturbed to be disrupted totally, and the nuclear fragments emerging from the encounter will appear at the fast stage of the collisions (during about $10^{-24} - 10^{-22}$ s) — one with the velocity little different of the incoming nucleus, and the second almost at rest — as damaged residual target nucleus, and a few fast ($\approx$ 20–500 MeV) nucleons emitted from it. The residual and unstable target nucleus will suffer a transmutation at rest into stable fragments, through the «evaporation» of nucleons and light target fragments (D, T, α particles) — during the slow stage of the intranuclear reaction

($\approx 10^{-22} - \approx 10^{-16}$ s) [2,3]. The damaged projectile nucleus will suffer similar transmutation in its flight.

The nucleus-nucleus collisions occur at various impact parameters — the distances between the centres of the colliding nuclei. The picture of a peripheral nucleus-nucleus collision when the target nucleus is resting in the lab. coordinate system was presented above. In the case of the nucleus-nucleus collision in the centre of mass of the colliding nuclei, the picture is similar but both of the colliding nuclei (residual and damaged) transmute into nucleons and nuclear fragments as moving oppositively in the c.m. system bodies. At the impact parameters $d \approx 0$, the total splitting of both the nuclei into nucleons occurs — two oppositively directed beams of the nucleons are observed. When the initial energy of the head-on colliding nuclei is high enough in the c.m. system (over tens GeV/nucleon, e.g.), the beams are strongly collimated. The above-described picture is presented in the series of drawings, in many works.

2.3. Some Experimental Facts from Obsrvations and an Analysis of the Nucleus-Nucleus Collisions. The following interesting and mostly important facts about the nucleus-nucleus collisions have just been discovered:

1. Three main phenomena are observed when a nucleus collides with a nucleus:

a. The passage of one of colliding nuclei through the second nucleus;

b. The particle production process;

c. Slow nucleons and light nuclear fragments (D, T, α-particles) evaporation [15].

The passage is accompanied by the emission of «fast» ($\approx$ 20–500 MeV) nucleons from the overlapping parts of the colliding nuclei.

The particle (hadron) production in the nucleus-nucleus collisions occurs; indication exists that this production proceeds similarly as in hadron-nucleus collisions and the outcome from such collisions is a composition of the outcomes in the binary nucleon-nucleon collisions [15].

The slow nucleons ($\leq$ 20 MeV) and light nuclear fragments (D, T, α) evaporation characteristics were obtained experimentally [16-23]. The main of them are:

a. The angular distributions of the fragments and nucleons in the projectile nucleus rest frame is close to the isotropy;

b. The «slow» nuclear fragments and single evaporated nucleons differ evidently from the «fast» nucleons emitted from colliding nuclei with energies of about 20 up to about 500 MeV in the rest frame of each of the colliding nuclei;

c. The momentum components of the fragments, in the rest frame of the projectile nucleus, have a Gaussian shape with st.dev. (a width) from about 50 to 200 MeV/c, depending only on the masses of the fragmenting nucleus and on the fragment, and not on the target nucleus and the beam energy. The above experimental data suggest [24] that the fragmentation can be viewed as a decay of an excited nucleus. Therefore, as the delayed process it keeps little or even no memory of the nucleus excitation mechanism formation which started the excitation;

d. The fragmentation process of the colliding nuclei can be considered as a composition of the fragmentations of the target-nuclei initiated by hadrons projectiles;

e. The colliding nuclei can be treated as colliding beams of sharply collimated beams monoenergetic nucleons; in central nucleus-nucleus collisions "the colliding nuclei split into freely oppositively moving nucleons; the protons in them are observable well enough; the higher is the velocity of the moving nuclei the higher is the collimation of the nucleon beams;

f. The fragmentation of the residual target-nucleus damaged in the hadron-nucleus collision or in nucleus-nucleus collision can be viewed as a decay of an excited nucleus [1].

3. MECHANISMS OF THE EXCITATION OF NUCLEI IN NUCLEUS-NUCLEUS COLLISIONS

We are in a position to state, on the basis of experimental data, that the excitation of nuclei in nucleus-nucleus collisions goes through local damages of the colliding nuclei.

Experimental information [3] about the mechanism of the nucleus-nucleus collision process is following:

1. Only a limited regions of the colliding nuclei in nucleus-nucleus collisions are involved — the overlaping ones. It occurs in a predominant portion of the collision events — it is the observable phenomenon, statistically motivated for the collisions of objects as atomic nuclei with some limited sizes. Such information was known many years ago — as obtained from cosmic ray studies by photographic method [24].

Now it is evidently supported in works performed on ion accelerators. In some small portion of events the head-on central collisions of nuclei occur.

2. When the colliding nuclei are of similar mass numbers, and their energy is high enough (about a few GeV/nucl), the total splitting of the nuclei into nucleons occurs, in the head-on collisions. This phenomenon is observable one [25], and it is applicable for the neutron beams construction from ion accelerators [26] — monochromatic and highly collimated, with regulation of the energy. The residual nuclei occurring in the peripheral nucleus-nucleus collisions are locally damaged and instable, therefore. The sizes of the local damages depend on the collision impact parameter and on the colliding nuclei diameters [27], and they may be

determined — similarly as the damage sizes in hadron-nucleus collisions — from the number of fast nucleons emitted in a collision.

3. The damage occurs in the fast stage of a collision — during the passage of a hadronic or nuclear projectile through the target nucleus. At energies high enough, the projectile energy lost for the target nucleus damage in the fast stage of the collision is limited and determined.

4. The passage of a projectile through the target nucleus is accompanied by the fast (≈ 20–500 MeV) nucleon emission. On the background of this passage, particle (hadron) production may occur in projectile-nucleons collisions with downstream nucleons in the target nucleus. The hadron production process does not disturb the projectile passage through the target nucleus (at energy high enough).

5. The residual target nucleus is locally damaged — all the nucleons involved in the collision are ejected from the target nucleus, the projectile has left the nucleus as well, during the fast stage of the collision — during the passage of the projectile through the nucleus.

6. Such residual target nucleus, although damaged locally only, is instable and should transit itself into a stable stage — through the evaporation of nuclei and light nuclear fragments, and at least through decay into larger nuclear fragments. It should happen in the second (slow) stage of the intranuclear reaction induced in the nucleus-nucleus collision.

7. The slow stage, starting just after the fast stage ending, lasts about $10^{-22} - 10^{-16}$s, as it can be estimated [3].

So, the target nucleus damage mechanism revealed experimentally appears as a complicated nuclear process induced inside the target nucleus in a nucleus-nucleus collision, developing in time and space in intranuclear matter of the target nucleus. This process consists of at least three mutually related stages which last together about $\approx 10^{-24} - 10^{-16}$ s after the collision starting. At the first stage, which lasts about $10^{-24} - 10^{-22}$ s, the target nucleus is (or the colliding nuclei are) locally damaged and fast nucleons (≈ 20–500 MeV kinetic energy) are ejected from the damaged nucleus (or from colliding nuclei) region (regions). The projectile hadron or projectile beam of nucleons involved in nucleus-nucleus collision and accompanied by the emitted fast nucleons left the target nucleus. At the second stage of the intranuclear reaction, lasting about $10^{-24} - 10^{-16}$s, the damaged in the first stage target nucleus uses to evaporate the black track leaving particles — mainly nucleons, *D, T*. At the final stage of the intranuclear reaction, the residual target nucleus splits into two or more relatively massive nuclear fragments. The reactions in the second and the third stages are realized due to the inner nuclear energy — the projectile particle or nucleus does not have at yet any contact with the residual target nucleus.

The disintegration mechanism of the residual target nucleus may be successfully investigated experimentally — by means of the method for intranuclear processes studies using any massive target nucleus as subnuclear detector — like subnuclear bubble or spark chambers.

4. THE MECHANISM OF ENERGY RELEASE IN REACTIONS INDUCED BY NUCLEUS-NUCLEUS COLLISIONS AT HIGH ENERGIES

In the light of the experimental facts, the intranuclear energy may be released from the colliding nuclei only in one of possible cases: when the damaged (and instable, therefore) residual target nucleus transits itself from an excited stage into some one stable final stage or a few stable final fragments (or stages) [1].

The emission of fast nucleons from the target nucleus and the projectile-producing processes cannot be treated as such in which the nuclear energy could be released [1]. The local damage of the target and its instability is a consequence of the collision. But, the damaged and instable residual-target nucleus may release energy in transiting itself into some stable final stages.

The mechanism of the energy release in this case is simple and obvious: the internal energy of the damaged residual target nucleus may be high enough, and a portion of it may be released in some conditions when it is possible to split the residual target nucleus into some parts. The decrease in binding energy per nucleon in nuclei with increasing their mass numbers means that a heavy nucleus can break up into lighter fragments with the release of a substantial amount of energy. The probability of occurence of the spontaneous fission is very small, but any nuclear deformation may be sufficient to permit the separation of the nucleus into fragments. The intranuclear reactions, induced by nucleus-nucleus collisions may lead to release of a portion of intranuclear energy ΔE_R. If this portion is larger than the energy E_I used to induce this reaction by nucleus-nucleus collisions, this reaction is the energy overcompensating one. Such reactions may occur, really; they should be searched for, especially in heavy nuclei collisions — at energies of the nuclei high enough — preliminarly, higher than about 0.5—1 GeV/nucleon. This way, some new nuclear fuels might be obtained — for accelerator driven energy plants.

5. CONCLUSIONS AND REMARKS

The above presented mechanism of nuclear energy release in intranuclear reactions induced by nucleus-nucleus collisions at high energies (over about 0.5 GeV/nucleon) is prompted experimentally.

One basical physical process in this mechanism is the fission of the residual target nuclei damaged locally in the first stage of the nucleus-nucleus collision. The energy release occurs in transitions of the damaged (excited) nucleus into a stable stage or stages.

The qualitative information about this mechanism and the qualitative data on the hadron-nucleus and nucleus-nucleus collision mechanism [1-27] allow one to understand the experimental data which are published in works on transmutation of radioactive waste with the help of relativistic heavy ions [28,29]. It is possible as well to predict yields from such and similar experiments — on this basis.

It will be worth while to write that some higher probability to obtain the energy-overcompensated reactions in nucleus-nucleus collisions is in collisions of the mostly heavy nuclei.

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