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Z.Strugalski[1,2], E.Strugalska-Gola[2]

ENERGY CHANGES IN MASSIVE TARGET-NUCLEI, INDUCED BY HIGH-ENERGY HADRONIC PROJECTILES

Permanent addresses:
[1]Warsaw University of Technology, Institute of Physics ul.Koszykowa 75, 00-662 Warsaw, Poland
[2]Institute of Atomic Energy, 05-400 Otwock-Swierk, Poland

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1. INTRODUCTION

In investigating experimentally the hadron-nucleus collision reactions, conclusive information has been obtained about the mechanisms of the nuclear collisions and of the nuclear reactions induced in them — of the energy transfer from hadronic projectiles into target-nuclei, of the target-nuclei damages and excitations, and of their transitions into some unstable states, and, at least, their disintegrations into nucleons and heavier nuclear fragments [1—6].

The investigations were performed mainly by means of the 26 litre Xenon bubble chamber of the JINR, Dubna and the 180 litre bubble chamber of the ITEPh, Moscow. The smaller chamber was exposed at Dubna synchrophasotron to 2.34, 5 and 9 GeV/c charged pion beams, the larger chamber was exposed to 3.5 GeV/c beam of positively charged pions from the Moscow ITEPh accelerator [1—6]. Additionally, for studies of the target nuclei disintegrations and transitions, mainly, appropriate experimental data from emulsion experiments were used [7—11].

On the basis of such experimental data obtained in the studies [1—6,12], the hadron-nucleus collision reaction appears as some complicated process in which no less than three stages may be distinguished easily [13]: a) The first, fast stage which lasts from about 10^{-24} s up to about 10^{-22} s in which the target-nucleus becomes to be locally damaged and nucleons with energies from about 20 up to about 500 MeV are emitted; b) The second, slow stage, when the damaged nucleus uses to transit itself from the instable state to some more stable state — by evaporating the light target fragments — as protons, deuterons, tritons: this stage lasts from about 10^{-22} s up to about 10^{-17} s; c) The third, final stage is such in which the residual target nucleus uses to decay into two or more relatively large stable fragments.

Now, it seems to be real to estimate, by experiments, the energy changes in massive target-nuclei induced by high energy hadronic projectiles.

The subject matter in this work is to obtain quantitative estimations of the energy changes in intranuclear matter (or in a target-nucleus) at each of the stages of the hadron-nucleus collision nuclear reaction.

2. STATEMENTS — EXPERIMENTALLY BASED

Experimental results on the hadron-nucleus collision mechanism were obtained in series of our investigations [1—6,13]. The set forth below [14] are selected adequately to the problem in question.

2.1. *On the Hadron-Nucleus Collision Mechanism*

The results of the collision mechanism were presented widely in our former works, here only some parts of the descriptions are rewritten, adequately to the problem in question [13].

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 around 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 500 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 $2 \to 2$ 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

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

centered 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.

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 around 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 the lifetime of about $\tau_g \geq 10^{-22}$ s, into commonly known «produced» particles and resonances; the intermediate objects are in fact the hadrons in statu nascendi [14]. 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 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 emulsion — the tracks of nuclei with the charge number $Z = 1$ to $Z = 2$ predominantly. 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 $\langle n_b \rangle$ is not related to the number of generated pions, at energies of the incident hadron over a few GeV; this number is $\langle n_b \rangle$ weakly energy dependent at smaller energies; it depends clearly on n_p — the multiplicity of the emitted fast protons; $n_p = n_g$ in the emulsions [6].
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.
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; 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; 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:

1. A large difference between mean energies of the fast protons, $\langle E_g \rangle$, and of the black track leaving particles, $\langle E_b \rangle$, is independent of the energy and mass of the projectile and of the target mass as well.

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 tracks, their number n_b is proportional to n_g.

4. The dependence of the mean number of the black tracks $\langle n_b \rangle$ on the number n_g of gray tracks has the same behaviour through the energy range 6.2 GeV to 400 GeV; one linear function describes it well. This linear function for proton-AgBr nuclei collisions passed near the dirigin $\langle n_b \rangle = 1.21 n_g + 1.49$; this correlation is completely independent of the number of produced pions [8]. 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 [11].

5. The differential frequency distributions for the stars as a function of $n_h = n_g + n_b$, for proton-emulsion nuclear collisions at 6.2—3,500 GeV exhibit only small irregularities and differences.

6. The multiplicities n_g and n_h obey the relation [8]:

$$\langle n_g/n_h \rangle = \langle n_g \rangle / \langle n_h \rangle = \text{constants} = 0.39. \quad (2)$$

It indicates proportionality between $\langle n_g \rangle$ and $\langle n_h \rangle$, and hence between $\langle n_b \rangle$ and $\langle n_g \rangle$; this relation is energy independent.

2.2. *On the Energy Balance in the Collision Process*

In the hadron-nucleus nuclear collision reactions induced by high-energy hadronic projectiles, which mechanism was described above (in section 2.1), the

hadron-nucleus nuclear collision act in its true sense lasts shortly, about 10^{-24}—10^{-22} s, from the impact of the colliding objects up to leaving of the target-nucleus by the projectile. During this short time-lag, some energy from the projectile to the target nucleus may be transfered only. The next stages of the nuclear reaction induced in the collision may occur only either due to the target energy excitation (if any) during the collision act or due to an inner energy surplus in the damaged target nucleus. In the collision act, the target-nucleus, as locally damaged, is driven out from its equilibrium state; the transition to a new equilibrium state (a new equilibrium nucleon configuration) may be exoergic.

So, one is in a position to consider firstly the energy balance in the hadron-nucleus nuclear collision act only — only in the fast stage of the hadron-induced nuclear reaction separately.

Let us follow the method of the energy balance estimation used in one of our former works [15].

The subject matter here is to discuss the energy losses and energy depositions of high energy hadrons in target nuclei; we call «high» the energies if higher than the pion production threshold. The question «How do hadrons deposit their kinetic energy in intranuclear matter?» must find its answer primarily in experiments. For that reason, in order to investigate experimentally the energy loss and energy deposotion of hadrons in target nuclei, one should use such a sample of hadron-nucleus collisions in which projectile-hadron passage through the target-nucleus occurs in the purest form. Such a sample can be selected, in fact, as the sample of events in which the passage accompanied by fast nucleon emission occurs without particle production [15,16].

In this type of hadron-nucleus collisions, the events were singled out for the analysis in question in which the incident hadron (pion) is completely stopped and lost its energy E_h in the target xenon nucleus [17]. At about 3.2 GeV of the pion-projectiles kinetic energies, stoppings of them inside the target nucleus are observed at the intranuclear matter layer thicknesses as large as the diameter D of the xenon target nucleus is. In fact, the incident pion energies are 3.5 GeV, but effectively the collisions are at 3.2 GeV, because a small portion, ≈ 0.3 GeV, of the incident charged hadrons is lost by ionization inside the chamber.

In result of such a collision, in average $\langle n_p \rangle \approx 7.4$ fast protons and $\langle n_n \rangle = [(A-Z)/Z] \langle n_p \rangle$ fast neutrons, or simply; $\langle n_N \rangle = (A/Z) \langle n_p \rangle$ fast nucleons n_N are emitted (with energies from about 20 MeV up to about 500 MeV) accompanying the projectile passages. The mean number of nucleons $\langle n_N \rangle$ fluctuates in a known manner [17], but we do not take this fluctuation into account here, for simplicity; the simplification shall not influence our final results.

The mean kinetic energy $\langle E_k \rangle$ of the emitted $\langle n_N \rangle$ fast nucleons is:

$$\langle \Sigma E_{kN} \rangle \approx A/Z \langle n_p \rangle \langle E_{kp} \rangle, \tag{3}$$

where $\langle n_p \rangle$ and $\langle E_{kp} \rangle$ are measurable quantities — the mean number of fast protons and the mean kinetic energy of the protons; $\langle n_p \rangle = 7.4$, $\langle \Sigma E_{kp} \rangle \approx$ ≈ 90 MeV. Then, $\langle \Sigma E_{kN} \rangle \approx 1615$ MeV.

So, the portion ΔE_h^{I} of the hadron kinetic energy which is taken away from the target nucleus by the emitted fast nucleons, defined by formula (3) is in average 1,615 MeV. It gives a shortage ΔE_h^{II} of the total incident hadron energy E_h, where we have: $\langle \Delta E_h^{II} \rangle = E_h - \langle \Sigma E_{kN} \rangle - \langle n_N \rangle 8 = 3200 - 1615 - 144 =$ $= 1441$ MeV. The last term in the formula is for binding energy of the emitted nucleons in the target nucleus. This fraction of the energy lost in the target nucleus cannot be explained simply, it does not manifest itself in any simple manner — as target fragments evaporation or additional fast nucleon emission; it is to large portion of E_h which could be lost without a trace.

The decay of the locally destroyed unstable residual target into smaller stable fragments proceeds due to an unstable nucleon configuration, caused in the hadron-nucleus collision fast stage — after having left the target nucleus by the incident hadron or its successors and after fast nucleon emission; in the cases in consideration here the incident hadrons are stopping within the target nucleus — because of such their kinetic energy applied in the experiment [13].

For this reason, the fraction of energy lost by the incident hadron should find its explanation in another way. Let this explanation be firstly treated as some working hypothesis; finally its physical meaning must be found in an experiment. This working hypothesis was used qualitatively in our former works [19,20]. Now, we try to give the most probable explanation, from the point of view of additional experimental information about the emission of the fast protons (nucleons) [18]. In conclusion, from the results of the analysis [18] it should be stated that the clusterization of the emitted fast protons is an experimental fact, outside the limits of statistical errors. This result can be extrapolated and for the emitted part of neutrons — for all the emitted fast nucleons [18].

It is known from observations and experiments that emitted fast nucleons should be treated not as knocked out simply from the target nucleus, but as a result of decays of two- or more-nucleon systems formed inside the target nucleus when slow pions are absorbed by two or more nucleons [15, 19—21]. The slow pions appear inside the target nucleus around the incident hadron course, and it is very probable that the fraction ΔE_h^{II} of the incident hadron energy is used for the low energy pion extraction in nuclear matter [19].

Let us estimate an energy used for this hypothetical effect — for low energy pion extraction. In average, in the «stopping» events under discussion, $\langle n_N \rangle \approx 18$ fast nucleons are emitted. These nucleons appear from decay of $\langle n_N \rangle / 2$ pairs of nucleons. Each of the pairs is formed in result of the absorption of one pion, then $\langle n_N \rangle / 2$ pions appear in average, and the energy ε for an extraction of one pion is:

$$\varepsilon = \Delta E_h^{II} / (\langle n_N \rangle / 2) \approx 1441/9 \approx 160 \text{ MeV}. \tag{4}$$

This energy is not very much lager than the pion rest mass; the extracted pions should be therefore with low kinetic energies. Maybe, the small anisotropy of the emitted fast nucleons is due to this kinetic energy of the absorbed pions by pairs of nucleons.

The pion extraction energy, or the pion extraction potential may be treated as an analogue to the ionization potential in charged particle interaction with an atom.

Taking into account this pion extation energy $\langle \Delta E_h^{II} \rangle$, the mean portion $\langle \Delta E_{h\,\text{pas}} \rangle$ of the incident hadron energy lost in intranuclear matter in passing through the target nucleus may be expressed as:

$$\langle \Delta E_{h\,\text{pas}} \rangle = (A/Z) \langle n_p \rangle \{ \langle E_{kp} \rangle + (1/2)\varepsilon \} = \langle \Delta E_h^{I} \rangle + \langle \Delta E_h^{II} \rangle, \tag{5}$$

where $\langle \Delta E_h^{I} \rangle$ is the mean kinetic energy of the emitted fast nucleons and $\langle \Delta E_h^{II} \rangle$ is the mean energy of the slow pion extraction from intranuclear matter, per one collision event under analysis. This energy (5) is lost, in average, in the target nucleus for its damage in the collision fast stage, during about 10^{-24}—10^{-22} s.

In result, the unstable configuration of nucleons in the residual target nucleus is caused by the projectile hadron. The damage is memorized by the target nucleus during no less than about from 10^{-22} s up to 10^{-17} s — up to evaporation of protons and light nuclear fragments from the surfaces of the damage in the nucleus [6].

So, in the light of the experimental facts, and the working hypothesis which is a consequence of these facts, it may be stated:

In the fast collision stage, definite portion of the incident high energy hadron defined by formula (5) is used only for the nucleus local damage.

The discussion above is performed for the special specimen of the events (the events without particle production). But, the investigations of the particle production process and its possible influence on the hadron passage through the target nuclei provide information that the statement expressed above is valid for all the collision events, without and with particle production [22]. The particles are produced via some intermediate objects which take away from the parent nucleus the energy lost for the hadron production, because they use to decay into observed «created» particles outside the parent nucleus — after having left it [21,22].

The local damage and some unstable configuration of nucleons in the target nucleus is produced only in high energy hadron-nucleus collisions. This unstable configuration of nucleons causes its transition to some new stable configuration, and this tendency to an equilibrium configuration uses to lead to the light fragment evaporation process in the next slow stage of the collision nuclear reaction initiated by the projectile hadron.

In the light of such mechanism, taking into account the short-range of very strong nuclear interaction, the evaporation process should be analysed additionally in some future works.

2.3. *On the Energy Balance at Various Stages of the Nuclear Reactions Induced by Hadronic Projectiles*

The energy balances at various stages of the nuclear reactions induced by high energy hadronic projectiles shall be described in a new manner, corresponding to experimental facts on the collision process mechanism and on the hadron-induced nuclear reactions.

I. The energy balance in the first, fast, stage of the nuclear reaction induced in a hadron-nucleus collision

At the stage before the impact, the binding energy of nucleons in the target nucleus was:

$$E_b = A\langle \varepsilon_b \rangle, \tag{6}$$

where $\langle \varepsilon_b \rangle$ is mean binding energy per nucleon, $\langle \varepsilon_b \rangle \approx 8$ MeV. After the collision, when the projectile hadron or its successors leaved the target nucleus — after about 10^{-22} s from the impact, the binding energy of the residual target nucleus containing $A - n_N$ nucleons is less:

$$E_b^{\mathrm{I}} \approx (A - n_N)\langle \varepsilon_b \rangle, \tag{7}$$

where n_N is the number of the emitted fast nucleons.

No any larger energy than defined by formula (7) may be released in any nucleon configuration transitions from the damaged residual target nucleus.

II. The energy balance in the second, slow stage of the nuclear reaction induced in a hadron-nucleus collision

The second stage lasts during a time interval from about 10^{-22} s up to about 10^{-17} s and it is the slow period in the course of the process in a hadron-nucleus-collision-induced nuclear reactions.

At the beginning of this stage, the energy of the damaged residual-target-nucleus is defined by the formula (7). The transformation of the unstable residual nucleon configuration starts to transit itself into a new — more stable one. This transition is accompanied mainly by the evaporation of light nuclear fragments, as nucleons, deuterons, tritons, α-particles. The mean intensity or multiplicity $\langle n_f \rangle$ of these fragments depends on the intensity or multiplicity n_N of the emitted fast nucleons [5]:

$$\langle n_f \rangle = 1.25\, n_N = 1.25\, \lambda S\left[1 - e^{-\frac{\lambda}{\langle \lambda_0 \rangle}}\right], \tag{8}$$

for $n_N = 1,2,3,\ldots,$ $DS = \lambda_{max}$; S is the area $\pi D_0^2 \approx 10$ fm^2; λ is the intranuclear matter layer covered by the incoming hadron in the collision in nucleons/S, $\langle \lambda_0 \rangle$ is the mean free path of the hadron in intranuclear matter in nucleons/S [23]; n_f is for the evaporated low-energy nuclear fragments $n_f = n_b + n_0$; where n_0 is for neutral nuclear fragments; D is the target-nucleus diameter in nucleons/S.

The mean numbers $\langle n_f \rangle$ of the evaporated light fragments are determinable in experiments, e.g., in nuclear emulsions; the kinetic energies may be determined experimentally as well — with an accuracy high enough for a given target nucleus [7].

The energy taken away from the damaged target-nucleus by the light fragments is defined by the formula:

$$E_{evap}^{\mathrm{I}} = \langle n_f \rangle \bar{\varepsilon}_{ev}, \tag{9}$$

where $\langle n_f \rangle$ is from the formula (8) and $\bar{\varepsilon}_{ev}$ is the mean evaporation energy per a light fragment, it is a measurable quantity [24], e.g..

After evaporation of the light fragments — from the surfaces of the damage in the target nucleus, the binding energy of the residual nucleus should be evidently smaller:

$$E_b^{\mathrm{II}} \approx E_b^{\mathrm{I}} - \langle n_f \rangle \bar{\varepsilon}_{ev}, \tag{10}$$

where E_b^{I} is defined by the formula (7).

After evaporation of the light fragments, the residual target nucleus contains smaller number of nucleons A_r and smaller number Z_r of protons.

The estimations give:

$$A_r \approx A - n_N - \langle n_{Nf} \rangle, \tag{11}$$

where $\langle n_{Nf} \rangle$ is the mean number of nucleons in evaporated light fragments, A is the mean mass number of the target nucleus before collision.The value $\langle n_{Nf} \rangle$ may be evaluated from the emulsion data, e.g.[7].

For the charge number Z_r we have:

$$Z_r \approx Z - n_p - \langle n_{pf} \rangle, \tag{12}$$

where Z is the charge number of the target nucleus before the collision and $\langle n_{pf} \rangle$ is the mean number of protons in the evaporated light fragments.

The binding energy of the nucleons in the residual target nucleus shall be then:

$$E_{br}^{\mathrm{II}} \approx (A - n_N - \langle n_{Nf} \rangle) \langle \varepsilon_b \rangle. \tag{13}$$

3. CONCLUSIONS AND REMARKS

In the previous section, the energy balance was estimated in the fast stage of the hadron-nucleus-collision reaction, as it should be done, in the light of the mechanism of the collision at this stage. Approximate formulas are proposed for the energy balance at the end of the second, slow stage, after light nuclear fragment evaporation from the damaged target nucleus.

But, after the evaporation the residual nucleus may be as one, but unstable at yet, collection of constrained nucleons or as some number of the smaller nuclei. In the first case, this collection may decay into some parts with release of some portion of the nucleon binding energy. In the second case, some number of the smaller, maybe, stable nuclei appeared during the slow reaction stage with release of some portion of the residual target nucleus as well.

It should be done an accurate quantitative energy balance, on the basis of the above presented scheme, which should be treated as preliminary one of possible treatments of the problem in question.

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Энергетические перемены в массивных ядрах-мишенях,
возбужденные адронами высоких энергий

Оказалось реальным экспериментально оценить энергетические перемены в массивных ядрах-мишенях, возбужденные адронными снарядами высоких энергий. Предметом этой статьи является описание результатов количественной оценки этих энергетических перемен в разных стадиях ядерной реакции столкновения адрон-ядро. Приводятся соответствующие формулы энергетических балансов, полученные на базе механизма столкновения адрон-ядро и основанные на экспериментальных данных.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

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Strugalski Z., Strugalska-Gola E. E1-97-130
Energy Changes in Massive Target-Nuclei,
Induced by High-Energy Hadronic Projectiles

Now it turned out that it is real to estimate by experiments the energy changes in massive target-nuclei, induced by high-energy hadronic projectiles. The subject matter in this work is to present results of the quantitative estimations of the energy changes in intranuclear matter at various stages of hadron-nucleus collision reactions. Appropriate formulas are proposed for the energy balances — as following from the experimentally based mechanism of the hadron-nucleus collision reactions.

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

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