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THE PICTURE OF THE NUCLEI DISINTEGRATION MECHANISM — FROM HADRON-NUCLEUS AND NUCLEUS-NUCLEUS COLLISIONS EXPERIMENTAL INVESTIGATIONS AT HIGH ENERGIES

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I. INTRODUCTION

Mechanism of atomic nuclei disintegration — the mechanism of nuclei breaking up into smaller pieces — may be revealed on the basis of conclusive experimental information about the hadron-nucleus collision mechanism [1].

It has been shown in many of our observations and experimental investigations of the hadron-nucleus collision processes that the nuclear collision reaction mechanism may be revealed and its characteristics may be known conclusively. Experiments were performed with 26 and 180 litre xenon bubble chambers exposed to beams of electrically charged pions — mainly the negatively charged π^--mesons have been used [1-29].

During many years, millions of photographs from the xenon bubble chambers — from the 26 litre chamber of the Dubna, Joint Institute for Nuclear Research [1] and the 180 litre of the Moscow Institute for Theoretical and Experimental Physics [2], exposed to beams of pions with 2.34, 3.5, 5 and 9 Gev/c momentum — were scanned and analysed.

Additionally, adequate results from experiments of other physicists, by different methodics, and our observations of various events were used for analysis in question — as supplement each other and mutually complementing them perfectly [30-36].

The nuclei disintegration mechanism revealed experimentally appears as a complicated nuclear process developing in time and space in intranuclear matter, consisting of at least three connected related stages which last together about $10^{-24} \div 10^{-17}$ s after the collision starting. At the first stage, which lasts about $10^{-24} \div 10^{-22}$ s, the target nucleus is locally damaged and fast nucleons — with energies of about 20 up to about 500 MeV — are ejected from the target-nucleus region involved in the collision; the projectile hadron accompanied by the emitted fast protons left the target nucleus. At the second stage, lasting about $10^{-22} \div 10^{-17}$ s, the damaged in the first stage target-nucleus uses to evaporate the black track leaving particles — mainly nucleons (protons are visible well enough). At the final stage, the residual target-nucleus uses to split into two or more nuclear fragments.

In applying the subnuclear detector, the disintegration mechanism may be successfully investigated experimentally; in developing in time of the collision reaction under study.

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ЯДЕРНЫХ ИССЛЕДОВАНИЙ
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2. STATEMENTS — EXPERIMENTALLY BASED

Let us start the description of the results, obtained from the experiments in question, with the overlook of the total sample of the hadron-nucleus collision events under consideration.

2.1. *The Time Development of the Nuclear Reaction Induced by Hadronic Projectiles*

It is known experimentally that the nuclear reaction induced by a projectile-hadron in a hadron-nucleus nuclear collision is passing gradually in time through various stages [1]. With every of the sequence of the stages the damage of the nucleus changes and grows.

The first stage, the «fast» one, in which the projectile is interacting with intranuclear matter lasts

$$\Delta\tau = \lambda / c \tag{1}$$

from about 10^{-24} s up to about 10^{-22} s; λ is the path length of the hadron in intranuclear matter, c is the light velocity. After this time interval after the impact, the incident hadron and its possible successors leave the target-nucleus accompanied by nucleon emission with kinetic energies of about 20 up to about 500 MeV. The target-nucleus is left as piersed at a collision impact parameter and damaged. The damage is local — it involves the part of the nucleus within a cylindrical volume centered by the projectile course, with the diameter as large as two strong interaction ranges $2R_h$, or two nucleon diameters D_0, because $R_h \approx D_0$. The intensity of the emitted nucleons is defined — the number of nucleons equals the number of nucleons contained in the target-nucleus in this cylindrical volume.

The incident hadron energy lost in the first stage of the collision — in passing through the target nucleus and damaging it — is strongly defined — only a definite part of the incident hadron energy may be used [11] in this process.

The residual nucleus is unstable and it must transit itself into some stable state or states. The second stage of the nuclear reaction starts the transition of the damaged unstable nucleus into stable state or states. This process is due to the internal energy of the nucleus, because the interaction of the incident hadron with the target nucleus takes no place more here. In this stage the transition goes through the evaporation of light fragments of the damaged nucleus — mainly protons, deuterons and tritons, and α-particles [32—36]. This stage of the nuclear reaction lasts about:

$$\Delta\tau \geq h / \Delta E \tag{2}$$

seconds, where h is the Planck constant and ΔE is the energy of the evaporated fragments; ΔE is practically from about 0 MeV up to about 30 MeV with the mean

$\langle \Delta E \rangle \approx 8$ MeV. Then, $\Delta\tau$ can be as about 10^{16}—10^{-17} s; similar value for the time interval for this stage one can find in references, e.g., [36].

The mechanism of the *b*-track leaving particle ejection appears as experimentally revealable one. It is determined by the local damage of the target-nucleus left by the incident hadron passage through intranuclear matter. The evaporation of the light nuclear fragments (p, D, T) is determined by the surface layers of the damage in the target nucleus. The damaged target nucleus memorizes information about the collision during relatively long period — not smaller than from about 10^{-23} s up to about 10^{-16} s — from the ending of the first («fast») stage of the hadron-nucleus collision [27].

The relation $\langle n_b \rangle = f(n_p)$, where $n_p \simeq n_g$ is derived simply on the basis of experimental information [27]:

$$\langle n_b \rangle = 1.25 \quad \{ n_p + (A - Z)/Z \}. \tag{3}$$

Simultaneously, with the light fragment evaporation process, the ejection of heavy fragments of the damaged target nucleus may be observed. Some of them may be the unstable fragments as well. These fragments may transit into stable ones — at least. This transition may be treated as the third stage of the nuclear reactions under consideration. Some adequate experimental data might be obtained about — by means of radiochemical methods. It may be that the observed deviation from the formula (3) at higher numbers n_p of the emitted «fast» protons is due to some time-overlapping of both the last stages — of the second and third stages in the damaged target-nucleus disintegration mechanism.

In this section, the picture of nuclei disintegration mechanism in high energy hadron-nucleus collision nuclear reactions is drawn as appearing from experimental investigations.

2.2. *A View Overlooking the Total Sample of the Hadron-Nucleus Nuclear Collision Events Observed in the Xenon Bubble Chambers*

In scanning and analysing photographs from the xenon bubble chambers irradiated in beams of pions with from ~ 2 up to ~ 9 GeV/c momentum, large sample of any-type of collisions was collected.

Among this total sample pion-xenon-nucleus (hadron-nucleus) nuclear collision events there are two, I and II, densely populated classes of the events manifesting themselves clearly and conclusively; Figs.1-3 in the work cited here [21] are illustrating them enough:

1. The pion-xenon nuclear collision events in which secondary hadrons (mainly pions) are produced and observed clearly are accounted for class I. The pion-xenon nuclear collision events in which secondary hadrons are not produced

are accounted for class II. At the incident pion (hadron) momenta less than about 3.5 GeV/c, events were observed, in class II, when incident pion (hadron) is passing through the target-nucleus or it is stopped and absorbed in it. At the incident pion momenta higher than about 3.5 GeV/c the incident hadron did not stop in the target-nucleus, all the incident hadrons are passing through the nuclei as braked and deflected through various, predominantly small, angles relatively to the projectile initial course.

2. The collisions accounted for any of classes I and II are accompanied by the emission of «fast» protons (nucleons) from the target nucleus with energies from about 20 up to 500 MeV. The energy and angular spectra of the protons are identical in both of the samples I and II of the nuclear collision events. They are independent of the identity and energy of the projectile, and stay constant in its energy range from about 2 up to about 400 GeV (and may be more).

The particle creation process goes on the background of the incident hadron passage through the target-nucleus, and it is localized along its course within the nucleus. Particles are created via intermediate objects or «generons» in $2 \to 2$ endoergic collisions. Generons use to decay into commonly known «produced» particles and resonances, after lifetime $\tau_g \approx 10^{-22}$ s — after having left the parent nucleus [3,4,15]. The projectile energy lost for the generon production is not transferred to the target nucleus, because they escape the parent nucleus and use to decay into created particles outside the nucleus. The hadron-nucleus interaction is switched off at the moment when the hadronic projectile or its sucessor or successors (generon or generons) escaped the nucleus. Corresponding time interval which lasts from about 10^{-24} s up to about 10^{-22} s depends on the projectile kinetic energy and the collision impact parameter. This stage of the nuclear reaction induced by the hadronic projectile can be treated as its first, «fast» stage in which target nucleus is damaged; the nucleus is pierced at some collision impact parameter — the projectile left a channel of the radius as large as strong interaction range, centered around its course in intranuclear matter. The number of «fast» nucleons emitted in this stage of the collision reaction equals the number of nucleons contained in the channel before the incident hadron passage.

It can be stated, therefore: the interaction of the projectile hadron with the target nucleus lasts about 10^{-24}—10^{-22} s and it leads to the target nucleus damage and the emission of the «fast» nucleons. All the further nuclear transmutations are going on account of the target-nucleus inner energy changes.

3. The evaporation of the nucleons and various light fragments from the target nucleus is determined by the target-nucleus damage described above. The evaporation starts after about 10^{-23} s after the hadron-nucleus collision starting and lasts up to about 10^{-17}—10^{-16} s [27,36]. This stage of the nuclear reaction

can be named the «slow» stage one. The mean number $\langle n_b \rangle$ of the evaporated protons and light nuclear fragments is expressed by the relation (3).

4. The evaporation goes mainly from the surface of the damaged parts of the target nucleus [27]. The nucleus transforms itself from the unstable state to some more stable residual nucleus. But this nucleus may be not stable at yet, and the decay of it into some parts may start. The decay of the unstable nucleus may occur into its relatively large parts, into a few stable parts of the residual nucleus.

So, the disintegration of the target-nucleus in a hadron-nucleus nuclear collision reaction is taking its course through a few stages: the local damage of the target-nucleus during hadron passage through the nucleus — just after the impact. The passage is accompanied by the emission of fast nucleons from the target-nucleus with the intensity which equals the number of nucleons contained in intranuclear matter around the projectile course within the strong interaction range R_h:

$$n_N = \pi R_h^2 \lambda \langle \rho \rangle \approx \pi D_0^2 \lambda, \tag{4}$$

where D_0 in fm is the diameter of the nucleon, $D_0 \approx R_h$, λ in fm is the length of the path of the hadron in the nucleus. This stage lasts about 10^{-24}—10^{-22} s, depending on the length λ, $\langle \rho \rangle$ in nucleons/fm^3 is the mean density of nucleons along λ. At projectile energies high enough, the target nucleus is pierced through at a collision impact parameter. The possible particle production process does not disturb the nucleus damage — it is the same whether the particles are created or not. The energy loss of the incident hadron, for the nucleus damage is limited [22]. The hadron-nucleus nuclear interaction incident hadron having left the taregt-nucleus.

3. QUANTITATIVE CHARACTERISTICS OF THE NUCLEI DISINTEGRATION MECHANISM

The characteristics of the nucleus disintegration process and its mechanism are much exposed preliminarily in section 2. Here, additionally, more important and conclusively stated properties of it were raported shortly.

3.1. The Region of the Target Nucleus Involved in Hadron-Nucleus Collisions

The first, «fast» stage of the nuclear collision reaction is localized within the target-nucleus. The volume v of it:

$$v = \pi R_h^2 \lambda \tag{5}$$

is involved only.

1. The number n_N of nucleons involved in the reaction is:

$$n_N = \nu\langle\rho\rangle = \pi R_h^2 \lambda \langle\rho\rangle, \tag{6}$$

where $\langle\rho\rangle$ is the mean density of the nucleons in the target-nucleus, in the nucleons/volume unit (nucleons/fm^3).

The intensity n_N may be expressed more simply:

$$n_N = \pi R_h^2 \lambda \langle\rho\rangle = S\lambda \langle\rho\rangle = S\Lambda, \tag{7}$$

where $S = \pi D_0^2 \approx \pi R_h^2 \approx 10$ fm^2, $\Lambda = \lambda \langle\rho\rangle$ is hadron path length in the nucleus in nucleons/S $\approx$ nucleons/10 fm^2. More exact formulas for n_N and additional information about hadron passage through intranuclear matter one can find in one of previous works [5,8,9,12].

2. 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 nuclear analog of the well-known energy loss of electrified particles in materials [14]. Range-energy reaction, $R_h - E_h$, for hadrons h in intranuclear matter has been observed [14]:

$$E_h = \varepsilon_h R_h, \tag{8}$$

where E_h in GeV, R_h in nucleons/S, ε is the energy of a hadron h lost on the path λ as long as 1 nucleon/S; for pions $\varepsilon_h = \varepsilon_\pi \approx 0.180$ GeV/(nucleon/S), for protons $\varepsilon_h = \varepsilon_p \approx 0.360$ GeV/(nucleon/S). Mean and maximal values of energies of pions and protons lost in passages through intranuclear matter are given for pion-nucleus and proton-nucleus collisions, for various target nuclei in the table on page 5 in our previous work [14].

3. It was found that the particle (hadron) production process does not influence the nucleon emission and fragment evaporation processes [37].

4. As a result of investigations of the projectile energy transfer to the target nucleus, the following mostly important assertions may be stated, for the target at rest in the lab.system:

a. 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 $2 \rightarrow 2$ type collision 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 localized around the incident hadron course within the tube (5) may be initiated. This energy transfer to the cascade is not limited, it depends on the projectile energy only, as it can be suspected [22].

But, the intermediate objects decay into «created» resonances and particles after having left the parent nucleus.

It should be remembered that the energy transfer to the atomic nucleus goes through the energy loss by the hadron passage and by the intermediate objects produced, however. The first channel is for limited transfer of the projectile energy, the second is unlimited, but the intermediate objects escape the parent nucleus and use to decay into resonances and particles after about 10^{-22} s — outside the parent nucleus.

It should be expected, therefore, that the target nucleus excitation in the first — «fast» — stage of the collision is always limited, independent of the energy of the hadronic projectile. The maximal and mean energy values which may be transferred to the target nucleus, in passing of the projectile through the nuclei were estimated experimentally [14].

b. The strong interaction of the hadronic projectile within the target nucleus lasts from about 10^{-24} s up to about 10^{-22} s, after the inpact — depending on the projectile velocity and the collision impact parameter.

5. The projectile kinetic energy E_h which can be transferred to intranuclear matter Δ is:

$$\Delta = E_h - \Delta E_h, \tag{9}$$

where ΔE_h is the part of energy transferred to intranuclear matter for the fast nucleon emission. ΔE_h has been determined [22] for a few nuclei.

4. DISCUSSION

The above presented picture of nuclei disintegration mechanism, based on the results from hadron-nucleus and nucleus-nucleus collisions experimental investigations, should be treated as experimentally prompted one. Three stages may be distinguished in the nuclear reaction initiated in the collisions: I-III (sec.1). The expeirmental information about the various stages is mostly complementary for the first one — about the fast stage. Less complementary, but conclusively enough, is the experimental information about the second stage — the slow one. This concerns the third stage — the stage ending the nuclear collision reaction, when residual target nucleus may split into two or more fragments which use to fly away, with relatively large kinetic energies.

Most of experimental data, not analysed from the point of view in question, are collected in the publications of various groups of physicists. Appropriate data should be analysed once more. Investigations of them on the basis of the today knowledge on the hadron-nucleus collision mechanisms presented here and in our former publications [1—29], may provide some additional and new experimental facts and information about the fast and the slow stages of the collisions. As concerns the last (the ending or third) stage of the residual nucleus disintegration process, new information should be looked for in some new experiments with photoemulsion methods and radiochemical spectroscopy methods.

Summing up, it can be stated that: The experimental indications and evidences are quite strong that the nucleus disintegration process initiated in the hadron-nucleus collisions is as described above in the fast and in the slow stages of it, however.

No conclusive data were analysed in our works on the last stage of the residual nucleus disintegration into two or more fragments.

In this paper, the mechanism of the nuclei disintegration in nucleus-nucleus collisions is not described; the description of nuclei disintegrations in those collisions will be done in one of our next works.

The above-presented experimentally based picture of the nuclei disintegration mechanism in hadron-nucleus collision reaction provides new possibilities for studies in nuclear and particle physics,

Conclusive knowledge of the hadron-nucleus collision reaction mechanism, based experimentally opens new possibilities, e.g.: for deeper understanding the hadron-induced nuclear disintegration processes; for the most effective and efficient use of the target nuclei as the subnuclear fine indicators (or detectors) in particle physics [3,4]; for estimations of the intranuclear energy changes in fast hadron-collision-induced nuclear reactions [22]; for search for the energy compensating fast hadron incident nuclear reactions; for discovering of the spallation mechanism and for other topics; for application in works concerning new generation of the nuclear energetics.

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Стругальска-Голя Э., Стругальски З., Хмеловски В. E1-97-129

Картина механизма дезинтеграции ядер — из экспериментальных исследований столкновений адрон-ядро и ядро-ядро при высоких энергиях

Экспериментально раскрыт механизм процесса дезинтеграции ядер в столкновениях адронов высоких энергий с ядрами. Дезинтеграция является сложным ядерным процессом, протекающим во времени и пространстве внутри ядра. Она проходит по крайней мере три стадии в течение промежутка времени около $10^{-24} \div 10^{-17}$ с.

В первой стадии, длящейся около $10^{-24} \div 10^{-22}$ с, обильно испускаются быстрые нуклоны и ядро-мишень подвергается локальному повреждению. Во второй стадии, длящейся около $10^{-22} \div 10^{-17}$ с, поврежденное и нестабильное ядро испаряет легкие ядерные фрагменты — в основном нуклоны, дейтроны, протоны, α-частицы. В третьей, конечной стадии, остаточное ядро-мишень иногда делится на две или больше частей (фрагментов).

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Strugalska-Gola E., Strugalski Z., Chmielowski W. E1-97-129

The Picture of the Nuclei Disintegration Mechanism — from Hadron-Nucleus and Nucleus-Nucleus Collisions Experimental Investigations at High Energies

The mechanism of the nuclei disintegration process in collisions of high-energy hadrons with nuclei is revealed experimentally. The disintegration appears as a complicated nuclear process developing in time and space in intranuclear matter, consisting at least of three stages which last together about $10^{-24} \div 10^{-17}$ s after the impact. At the first stage, which lasts about $10^{-24} \div 10^{-22}$ s, fast nucleons are densely emitted and the target-nucleus is locally damaged. At the second stage, lasting about $10^{-22} \div 10^{-17}$ s, the damaged and unstable residual target nucleus uses to evaporate light fragments — mainly nucleons, deuterons, tritons, α-particles. At the final stage, the residual target-nucleus uses to split sometimes into two or more nuclear fragments.

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

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