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THE HADRON-NUCLEUS COLLISION REACTION MECHANISM MEMORIZED BY FAST NUCLEONS EMITTED FROM TARGET NUCLEI

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1. INTRODUCTION

Commonly accepted meaning is that the history of the hadron-nucleus collision reaction process is memorized by fast nucleons emitted from the target nucleus. The nucleon emission process in hadron-nucleus collisions starts just at the time when the projectile hadron uses to pass through the target nucleus. Usually only the electrically charged component is observed simply and effectively — the protons emitted within the kinetic energy range from about 20 up to about 400 MeV; these energy values cover all the emitted protons, and probably all the neutrons.

The fast protons, observable as proton-tracks in bubble chambers or as the gray track leaving particles in emulsions, are emitted during a short time after the passage of the incident hadron or its successors through the target nucleus; the emission process is initiated in intranuclear matter during about 10^{-23} second after the collision reaction started. Many physicists expect therefore them to memorize a part of the history of the collision reaction process, of its first stage — from the starting [1] of the collision up to having covered by the incident hadron the intranuclear matter layer involved in the collision.

What is more, many aspects about nuclear sizes and the nuclear matter density distribution in them are now so firmly established [2] that it is possible to use them in order to investigate other physical quantities [3]. The characteristics of the proton emission process are known experimentally with an accuracy high enough [4—14] as well.

Relations between characteristics of nuclei (nuclear sizes and nucleon density distribution in them) and some characteristics of the nucleon emission process (or the proton emission process only) may be discovered and investigated experimentally.

This way, the information about the history of the hadron-nucleus collision reaction process may be obtained as experimentally based; a position is for an use when any of freely fabricated hypotheses may be avoided — as the fruits of human fantasy, and all what has to be stated will be based and motivated experimentally.

It has been found in experiments [4,5] as well that definite relations exist between the intensities of the fast proton emission and the intensities of the nuclear fragments evaporation — the evaporation of the low energy singly and multiply electrically charged fragments; the last are emitted a long after the passage of the incident hadron, after about 10^{-17} second and are leaving the black tracks in emulsions [5]. So, the information about the fragment evaporation process may be obtained as experimentally based, as well.

In this work, we would like to find an answer to the question: How is the hadron-nucleus nuclear collision process going on during the time interval from about 10^{-23} up to about 10^{-17} second? The answer should be find primarily in experiments. Appropriate experimental information was obtained in many experiments. The subject matter in this work is to use it for elucidation of the problems in question.

This paper is arranged as follows: after the introduction in section 1, in section 2 the characteristics of the target nucleus are presented adequately to the problems under discussion; in section 3 appropriate characteristics of the fast nucleon emission from the target nucleus are presented; in secion 4 relations between characteristics of the target nuclei and fast nucleon emission process are revealed as based experimentally; in section 5 the picture of the damaged target nucleus is presented — as prompted experimentally; section 6 treats about the transitions of the damaged nucleus into stable elements; section 7 closes the publication — with the conclusions and remarks.

2. SIZES OF ATOMIC NUCLEI AND NUCLEON DENSITY DISTRIBUTION IN THEM

It has been shown that in hadron-nucleus collisions the target nucleus may be conveniently and successfully treated as a «slab» of the intranuclear matter, e.g. [15—18], and the sample of the homogeneous nuclear collisions may be considered as an interaction of a beam of identical monoenergetic hadrons with intranuclear matter slabs with various thicknesses [15,18,19].

It is necessary, therefore to characterize adequately and precisely the incident hadronic projectile — by its absorption properties in layers of intranuclear matter, and the incident hadronic beam as some composition of a number or identical hadronic projectiles. It is realized in fact, when as adequately numerous sample of collisions of identical hadrons with identical nuclei is considered as the interaction of the hadronic beam with the nucleus or intranuclear matter slabs.

The hadronic projectile and the hadronic projectiles beam may be characterized by the hadron mean free path $\langle \lambda_0 \rangle$ in intranuclear matter [20,21]; it is measurable quantity [20,21], the method was proposed [21], and the measurements were performed [20].

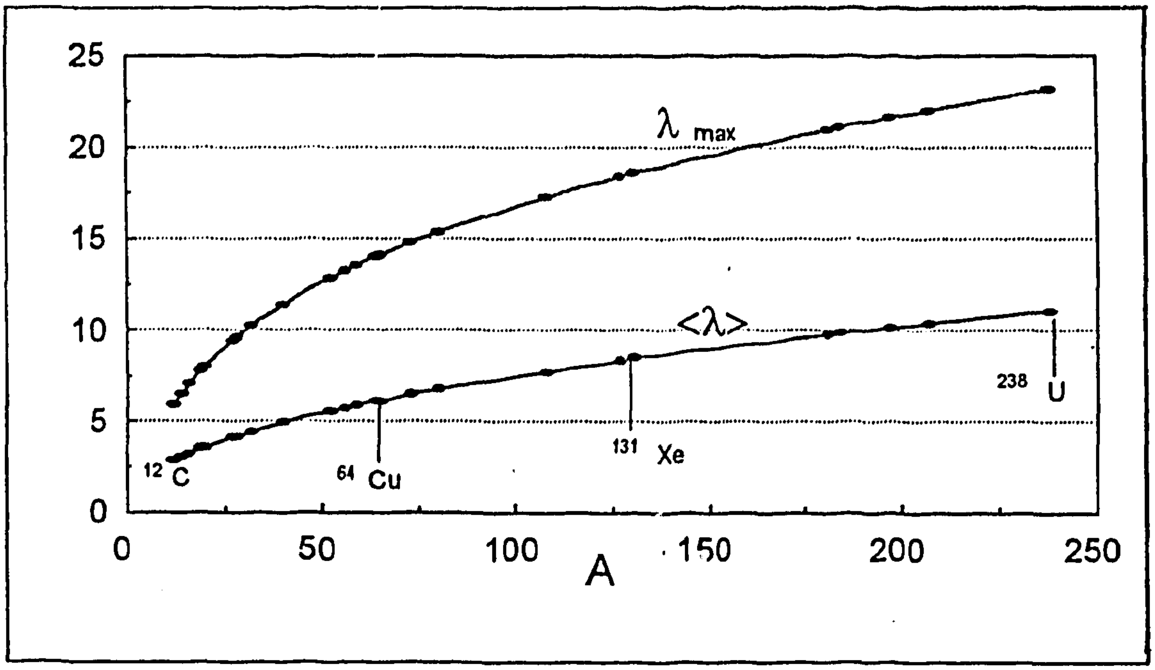

Fig. 1. The A-dependence of the maximum λ_{max} and the mean thickness $\langle \lambda \rangle$ in nucleons/S for various atomic nuclei; $S \approx 10.3\ \mathrm{fm}^2$

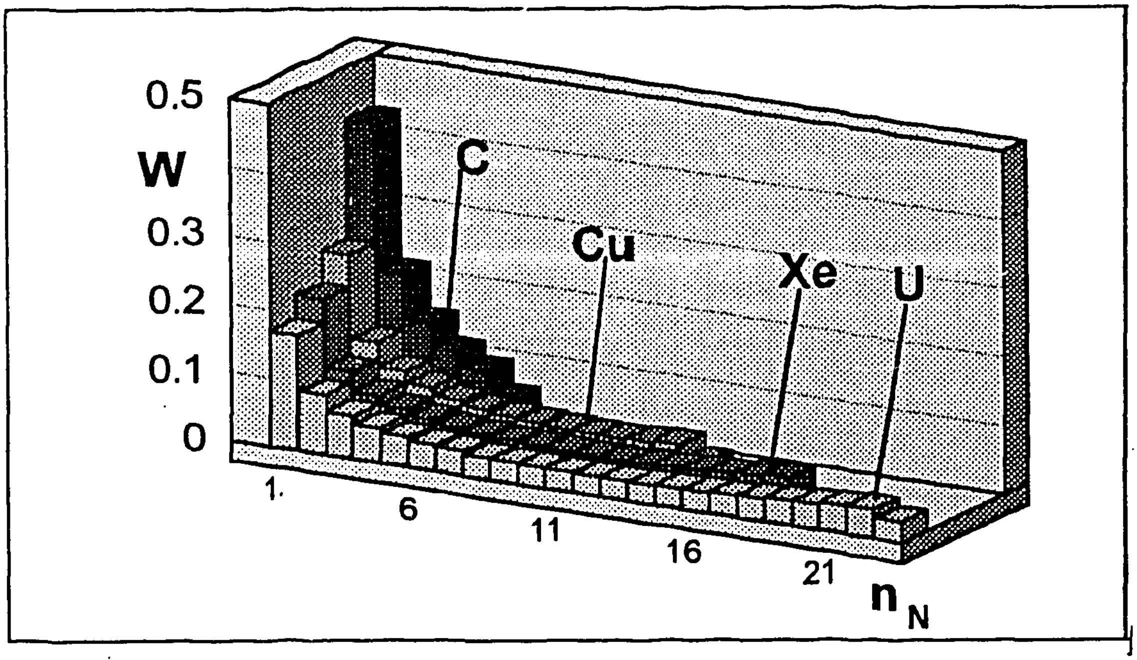

Fig. 2. The distributions $W(n_N)$ of the intranuclear matter layers with thicknesses n_N nucleons/S, for C, Cu, Xe, and U nuclei

The atomic nucleus may be characterized generally by the maximum thickness of the intranuclear matter layer $\lambda_{\max}$ in it, the mean thickness $\langle \lambda \rangle$, and the potential thikcness $\lambda(b)$, corresponding to a given collision impact parameter b, expressed in numbers of nucleons over some area S, in nucleons/S [22,23], where $S = \pi R_h^2 \approx \pi D_0^2 \approx 10.3$ fm^2, R_h is the strong interaction range, D_0 denotes the nucleon diameter; $R_h \approx D_0$. The unit is defined per analogy to the unit grams/cm^2 commonly used in Cosmic Ray Physics; the unit protons/S is in use as well [15,18].

The representations of the projectile hadron and the target nucleus correspond strictly to the experimental situation in all the hadron-nucleus collision experiments.

The values of $\lambda(b)$, $\langle \lambda \rangle$, $\lambda_{\max}$ are given in our former works [22,23] for many atomic nuclei: $^{12}_{6}$C, $^{14}_{7}$N, $^{16}_{8}$O, $^{19}_{7}$F, $^{20}_{10}$Ne, $^{27}_{13}$Al, $^{28}_{14}$Si, $^{32}_{16}$S, $^{40}_{18}$Ar, $^{52}_{24}$Cr, $^{54}_{26}$Fe, $^{59}_{27}$Co, $^{64}_{29}$Cu, $^{65}_{30}$Zn, $^{73}_{32}$Ge, $^{80}_{35}$Br, $^{108}_{47}$Ag, $^{127}_{33}$I, $^{134}_{54}$Xe, $^{197}_{74}$Au, $^{207}_{82}$Pb, $^{238}_{92}$U.

As the example, in Figs.1 and 2, the dependences $\langle \lambda \rangle$ and $\lambda_{\max}$ on the atomic mass number A, and the distributions W of thicknesses $\lambda(n_N)$ are presented.

3. CHARACTERISTICS OF THE FAST NUCLEON EMISSION PROCESS

The fast nucleon emission is characterized by its intensity, energy and angular spectra of the emitted nucleons, and by corresponding distributions of these quantities in various samples of the hadron-nucleus nuclear collision reactions. It is known — from experiments [24]: two general classes of hadron-nucleus nuclear [12] collision events, I and II, are observed clearly and conclusively: I — is the class where the hadron-nucleus collisions in which hadrons are produced are accounted for; II — is the class where the collision events without hadron production are accounted for — pure passage of the projectile through the target nucleus is visible. Many subclasses of the events may be distinguished as well [9—15].

In the context of this work, some of the characteristics of the nucleon emission process will be discussed only here [25]:

1. A series of photographs of the hadron-nucleus nuclear collisions has been completed on which the passages of the projectiles through the target nuclei are simply and directly observed [24]; in the passages a definite part of the hit nucleus is involved — the tube $\pi R_s^2 \lambda$ with the diameter $2R_s$ determined by the

strong interaction range R_s centered on the hadron path λ in intranuclear matter; the passages may be observed plentifully in their pure form at definite projectile energy interval only — at about 1 to 10 GeV [24], at higher energies the pure passages are relatively rarely identified.

2. Any hadron with kinetic energy higher than the pion production threshold causes nucleon emission from the target nuclei in traversing them along the path λ fm; the number of nucleons n_N emitted equals the number of nucleons contained within the cylindrical volume $v = \pi R_s^2 \lambda$ fm^3 centered on λ in the target nucleus:

$$n_N = \pi R_s^2 \lambda \langle \rho \rangle \approx \pi D_0^2 \lambda \langle \rho \rangle , \tag{1}$$

where D_0 fm is the diameter of the nucleon, R_s — the strong interaction range as large approximately as $D_0 \approx R_s$; the relation [1] can be expressed simpler and more conveniently for applications

$$n_N = \lambda S \tag{2}$$

when λ is expressed in nucleons/S units, and $S = \pi D_0^2 \approx$ 10.3 fm.

3. The passage of the incident hadron through layers of intranuclear matter, accompanied by the nucleon (proton) emission from the target nucleus is a fundamental process in the hadron-nucleus nuclear collisions, on the background of it other processes occur; the observable effect of this process is the emission of nucleons (protons) with kinetic energies from about 20 up to about 400 MeV. This process is memorized by the target nucleus during relatively long period — from about 10^{-23} up to about 10^{-17} s, what can be concluded from definite relation between nucleon (or proton only) emission intensity (or multiplicity) n_N (or n_p), and the mean intensity or multiplicity $\langle n_b \rangle$ of the black track leaving in emulsions particles [26]; the hadronic projectile leaves «a track» in intranuclear matter, memorized relatively long in it — from about 10^{-23} up to about 10^{-17} s.

4. The emitted fast nucleons (fast protons or gray track leaving particles in emulsions) in the kinetic energy range of about 20 to about 400 MeV in *p*- and Pi-nucleus collision reactions at about 2 to about 400 GeV exhibit a differential energy spectrum of the form [5,13,25,27]:

$$N(E)dE \sim E^{-\gamma} dE, \tag{3}$$

where $N(E)$ is the number of protons per event and MeV; γ has the value 1.09±0.02 [27]. The energy spectrum of the emitted protons is identical in both the classes I and II of the collision events.

5. The angular distribution is close to the form

$$\frac{1}{\sigma}\frac{d\sigma}{d(\cos\theta)} \sim e^{0.96\cos\theta}, \tag{4}$$

and stays constant in the energy range 2 — 400 GeV of the p- and Pi-projectiles. The angular distribution is identical in both the classes I and II of collision events.

6. The mean emission intensity $\langle n_b \rangle$ of the black track leaving (in emulsions) particles is determined by the intensity n_N (or n_p) of the emitted fast protons (nucleons) [26]. The black track leaving are low-energy singly and multiply electrically charged fragments of the damaged target nucleus: p, d, t, with $E_{\rm kin} \lesssim 30$ MeV/nucleon and ^{4}He, ^{3}He with $E_{\rm kin} \lesssim 300$ MeV/nucleon, they are mainly the evaporated particles; they exhibit isotropic angular distribution [27].

The $\langle n_b \rangle - n_p$ relation is completely independent of the number of the produced hadrons in the hadron-nucleus collision reactions, which means that the produced hadrons in intranuclear matter by the projectile objects do not transfer any significant energy to the target nucleus. Even if the produced particle multiplicity increases about ten times — from about 2 up to about 17 particles — no change is observed in the mean black track $\langle n_b \rangle$ and gray track n_g multiplicities (or in $\langle n_b \rangle$ and n_p multiplicities) [14].

7. At energies high enough, over a few GeV (the table in our former work) [28], the mean number $\langle n_N \rangle$ of fast nucleons (protons $\langle n_p \rangle$) emitted in a sample of any type collision events equals the mean $\langle \lambda \rangle S$, where $\langle \lambda \rangle$ is the mean thickness of the target nucleus in nucleons/S, $S \approx 10.3$ fm^2.

8. Definite range-energy relation in intranuclear matter exists for hadrons, similarly as such relation for charged particles in usual materials [29,30].

4. RELATIONS BETWEEN CHARACTERISTICS OF THE TARGET NUCLEI AND THE CHARACTERISTICS OF THE FAST NUCLEON EMISSION PROCESS

The relations between characteristics of the target nuclei and the characteristics of the fast nucleon emission process are obtained experimentally, based on the results of the series of hadron-nucleus collision interactions studies performed by means of the intranuclear detectors [31,32] — i.e., by means of the target nucleus employed as a fine detector [18,31,32].

Two main phenomena related to the problem in question manifest themseves conclusively in the nuclear collisions:

1. The hadron-nucleus nuclear collision reactions are localized in relatively small cylindrical region inside the target nucleus of the radius as large as the strong interaction range R_s is, centered on the incident hadron course in intranuclear matter.

2. The projectile and its successors produced by it pass through layers of intranuclear matter accompanied by fast nucleon emission from the target nucleus; the intensity and other characteristics of the nucleon emission do not depend on whether hadrons are produced in the collision reactions or not [14,25].

It is known [25], the relation exists between the number n_N of the nucleons (or n_p of the protons), emitted from the target nucleus and the number n_N of nucleons contained within the target nucleus region $\pi R_s^2 \lambda$ centered on the hadron course λ inside intranuclear matter; this number n_N is determined [22,23] from the Hofstadter's experiments data [2,3].

The relation may be written [10]:

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

where $\lambda_t = \frac{1}{\sigma_t}$ is the hadron mean free path in nucleons/S, σ_t is the total hadron-nucleon cross section in S/nucleon, λ is the intranuclear matter layer thickness in nucleons/S covered by the incident hadron in the target nucleus; some approximate relation may be written as well:

$$n_p \approx \frac{Z}{A} \cdot \lambda \cdot S, \tag{5'}$$

where λ is the intranuclear matter layer covered by the incident hadron, $S \approx 10.3\ \mathrm{fm}^2$

Moreover, the crucial relations were obtained: at incident hadron energies E_h high enough, at $E_h \gtrsim \varepsilon_h \cdot D$ (where D is the target nucleus diameter in nucleons/S), ε_h in GeV/(nucleons/S) is the energy lost by a hadron on the intranuclear matter layer as thick as 1 nucleon/S and $S \approx 10.3\ \mathrm{fm}^2$; for pions $\varepsilon_h = \varepsilon_\pi = 0.180$ GeV/(nucleon/S), for protons $\varepsilon_h = \varepsilon_p = 0.360$ GeV/(nucl/S) the mean number of nucleons (protons) $\langle n_N \rangle (\langle n_p \rangle)$ emitted in total sample of collisions equals $\langle \lambda \rangle S$, where $\langle \lambda \rangle$ is the mean thickness (in nucleons/S) of the target nucleus:

$$\langle n_N \rangle \approx \langle \lambda \rangle \cdot S, \tag{6}$$

$$\langle n_p \rangle \approx \frac{Z}{A} \langle \lambda \rangle \cdot S. \tag{6'}$$

Simple relation exists between the intensity n_p distribution $N(n_p)$ of the emitted fast protons and the size of the target nucleus and the distribution $N(\lambda)$ of the thicknesses λ in it [11,24], (Fig.5 in our former work [24]).

In other words: the target nucleus is pierced by the incident hadron in a definite manner, and the fast nucleons emitted memorize and indicate the collision impact parameter and the localization and size of the region in intranuclear matter involved in the collision. This process of the destruction of the target nucleus on the first stage of the collision happens during about 10^{-24}—10^{-23} s, and it is memorized during relatively long period — of about 10^{-23} up to 10^{-17} s. This time interval is determined by the nuclear fragment evaporation process, which takes place after about 10^{-17} s after the starting of the collision reaction [5]; the relation between the mean intensity $\langle n_b \rangle$ of the emission of the low-energy singly and multiply electrically charged nuclear fragment evaporation and the intensity n_p of the fast protons emitted during about 10^{-24}—10^{-23} s was derived as well [26] and tested experimentally.

5. THE DAMAGE OF THE TARGET NUCLEUS IN THE HADRON-NUCLEUS COLLISIONS

In colliding with a target-nucleus, a hadronic projectile and its successors — the products of its nuclear interactions with downstraem nucleons in intranuclear matter are traversing the nucleus, along the intranuclear matter layer thikcness λ, during the time from about D_0/c up to about D/c, where D_0 is the nucleon diameter and D is the nucleus diameter. During this time interval — from about 10^{-24} up to about 10^{-23} s, the nucleus is damaged — fast nucleons from the interacting region as large as $\pi D_0^2 \lambda$ are emitted; some damaged region appeared, on the walls of which the equilibrium between nucleons is destroyed and the residual nucleus should transit into some stable state as a whole or in some its stable fragments. The main role should play in this process the electromagnetic interactions — as of the long range of action; the transition time should be of the order of 10^{-17}—10^{-16} s, therefore. The transition should start on the surface of the damaged region.

It is qualitative, some naive, picture which may be mostly corresponding to the physical scenario in question inside the damaged target nucleus. But, what is in fact? The answer to this question should be find primarily in an experiment. The key for the solving may lie in the relation between the mean intensity $\langle n_b \rangle$ of the nuclear fragments evaporation and the intensity of the fast nucleon (proton) emission intensity $n_N(n_p)$; such relation is known experimentally [4,5], the explanation of it may throw some light on the mechanism of the transition of the residual nucleus from its damaged state to the final stable state or stable final fragments.

This explanation has been done quantitatively in assumption that the evaporation of the nuclear fragments goes from the walls of the damaged regions in the target nucleus [26].

6. TRANSITIONS OF THE DAMAGED TARGET NUCLEUS INTO STABLE STATES

The transmutation of the target nucleus into stable smaller nuclei or nucleus does not start before the evaporation of the singly or multiply charged fragments from the damaged region walls, because the $\langle n_b \rangle - n_p$ relation seems to be determined by the damaged surfaces [26]. When and how is the transmutation of the damaged nucleus into stable nucleus or nuclei going on? — it should be found experimentally — it is the last stage of the hadron-nucleus nuclear collision process. Some mass-spectrometrical methods should be used for such experimental analysis. The transmutation time interval should be larger by much than the lifetime of the damages in the target nucleus after the collision process.

7. CONCLUSIONS AND REMARKS

Taking into account all the above-written, we are in the position to state that:

there is a lot of information memorized by the target nucleus about the hadron-nucleus nuclear collision process.

All this what is expressed as characteristics of the passage of the incident hadron through the target nucleus and of the characteristics of the fast nucleon emission the passage is accompanied by contains the information about the hadron-nucleus nuclear collision process. The characteristics are simple observables, obtained usually in the hadron-nucleus collision experiments. The simplicity of the mechanism of the hadron-nucleus collision process — from the starting of the collision up to the target-nucleus transmutation into stable lighter nuclei, and simple observability of it in such a clear and conclusive manner is impressible, really!

Now it is clear how it is possible to use single target nucleus as a fine detector — the «intranuclear detector» — something like the intranuclear track chamber.

With the descovery of the hadron passage through layers of intranuclear matter accompanied by the fast nucleon emission, the possibility for experimental studies of the nuclear interactions or nuclear forces on the new level becomes to be directly realizable

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