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Z.Strugalski*

THE EVAPORATION OF SINGLY AND MULTIPLY ELECTRICALLY CHARGED SLOW TARGET FRAGMENTS IN HADRON-NUCLEUS COLLISION REACTIONS

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*Addresses for correspondence: Warsaw University of Technology, Institute of Physics, ul.Koszykowa 75, PL 00-662 Warsaw, Poland
and
Institute of Atomic Energy, PL 05-400 Otwock-Swierk, Poland

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1. INTRODUCTION

Results on target-nuclei fragmentations induced by high energy hadronic projectiles are mainly from hadron-nuclei nuclear collisions studies in emulsions, e.g. [1—8].

The intensities or multiplicities n of singly and multiply electrically charged particles, with $\beta = \frac{v}{c} < 0.7$, were named in emulsion experiments n_h-intensities of the heavy track leaving particles; the intensities or multiplicities n of the produced singly charged particles with $\beta > 0.7$ were named n_s-intensities of the shower track leaving particles. The heavy track particles are usually divided into two groups: the gray track leaving particles with intensities or multiplicities n_g and the black track leaving particles with intensities or multiplicities n_b; $n_h = n_b + n_g$.

The gray track leaving particles are mainly protons within the kinetic energy range from about 30 up to about 400 MeV. Studies of them are of special interest due to the fact that they are emitted during or shortly after the passage of the incident hadron and their successors through the target nucleus — during about 10^{-24} up to about 10^{-23} s. Many suspect them to memorize the history of the hadron-nucleus collision reaction — from its initial stage up to a starting of the target fragment evaporation process, during about 10^{-23} up to about 10^{-17} s.

The black track leaving particles are low-energy singly and multiply electrically charged fragments — protons, deuterons, tritons with kinetic energies $E_{\mathrm{kin}} \lesssim 30$ MeV/nucleon and ^{3}He, ^{4}He with $E_{\mathrm{kin}} \lesssim 300$ MeV/nucleon. They are emitted a long time after the passage of the incident hadron — about 10^{-17} s [4]; they are mainly evaporated particles, with almost isotropic angular distribution [8].

The dependence of the mean number $\langle n_b \rangle$ of the black tracks on the number n_g of the gray tracks has been stated experimentally clearly and conveniently [3,4]. It exhibits the same behaviour throughout the energy range from about 6 to about 400 GeV as is stated well enough in experiments [4], and may be up to about 3500 GeV — as prompted some other data [3]. Indications are strong enough that the correlation does not depend on the nature of the projectile hadron [4]; only the number n_p or n_g of the emitted fast protons (nucleons) determines the mean excitation energy of the residual target-nucleus. The correlation is not depending on the number of produced pions.

The subject matter in this paper is to study the $\langle n_b \rangle - n_g$ correlation, to present some physical basis for it, and to derive the experimentally known dependences on the basis of our knowledge on the hadron-nucleus collision reaction process, and to perform quantitative experimental verification of the correctness of presented description.

The paper is arranged as follows: after the introduction in section 1, in section 2 some heuristic considerations are presented; in section 3 the derivation of the $\langle n_b \rangle - n_g$ relation is described; in section 4 experimental data are presented shortly; in section 5 experimental data are described; conclusions and remarks close section 6. This publication is the next from the series of papers on the problem under discussion [9—12].

2. HEURISTIC CONSIDERATIONS

Two processes in hadron-nucleus nuclear collision events, related simply to the ejection of single nucleons or heavier nuclear fragments from the target nuclei, which manifest themselves clearly, are: a) The emission of fast nucleons (gray track leaving particles if registered in emulsions); b) The evaporation of the black track leaving particles. The difference in energy and angular distributions of both the groups of the particles ejected from the target nuclei is indicative of a two-stage of the heavy track leaving particles (both of the two sorts a) and b) of the particles ejected from the nuclei) emission; two different processes occur rather, although the mean intensity $\langle n_b \rangle$ of the black track leaving particles is determined by the intensity $n_g = n_p$ of the gray track leaving particles — by the relations stated experimentally [3,4,10,13].

The mechanisms of the h-track leaving particles ejections may be revealed in experiments, first of all, and they should be determined by the damages of the target nuclei left by the incident hadrons passages in the nuclear collisions [14]. The discovery in experiments of the relations between the fast nucleon emission intensity or multiplicity n_N ($n_N = n_p + n_n$, where p is for protons, n is for neutrons, and $n_p = n_g$ if in emulsions) and the intranuclear matter layer thickness λ in nucleons/S involved in the hadron-nucleus collisions, together with the experimentally obtained [3,4] $\langle n_b \rangle - n_g$ and $\langle n_b \rangle - n_h$ relations between the mean intensity $\langle n_b \rangle$ of the black track leaving particles and the intensity $n_g = n_p$ of the emitted fast protons (gray track leaving particles — in emulsions) provided a starting point for the deduction of some picture of the nuclear fragment evaporation mechanism in hadron-nucleus nuclear collisions; $S = \pi R_s^2 \approx \pi D_0^2 \approx 10.3$ fm^2, where R_s is the strong interaction range, $R_s \approx D_0$ — the nucleon diameter.

So, the based experimentally picture of the damaged target nucleus is: a) Any high energy hadron in nuclear collision with an atomic nucleus involves definite region of the nucleus — the tube with the radius as large as the strong interaction range R_s is ($R_s \approx D_0$, where D_0 is the nucleon diameter) centered on the hadron path λ nucleons/S in intranuclear matter; to the length λ there corresponds the intranuclear matter layer thickness λ nucleons/S involved in the collision. b) The thickness λ covered by the incident hadron is determined by the range R_s-energy relation in intranuclear matter [17]:

$$\lambda = \frac{E_h}{\varepsilon_h}, \tag{1}$$

where E_h GeV — the incident hadron energy, $\varepsilon_h = \varepsilon_\pi = 0.180$ GeV/(nucleon/S) for the incident pion and $\varepsilon_h = \varepsilon_p = 0.360$ GeV(nucleon/S) for the incident proton.

When the incident hadron energy $E_h \geq \varepsilon_h \cdot \lambda = \varepsilon_h D$, where D in nucleons/S is the nucleus diameter, the target nucleus is pierced by the hadron in any of the nuclear collisions. The hadron passage along the path λ is accompanied by the emission of the number n_N of the fast nucleons contained within the volume $\pi D_0^2 \lambda$; to the n_N nucleons it corresponds $n_p = \frac{Z}{A} n_N$ fast protons, where Z and A are the atomic charge and the mass numbers, correspondingly. The fast nucleon emission occurs no later than about 10^{-23}—10^{-22} s after starting of the collision. This way the target nucleus is damaged. The localization of the damages is such that for various nuclei of about $A = 100$, as for the Ag nucleus, in nearly 90% of collisions the damaged part of the residual target nucleus is localized near to the nucleus surface [10].

The nucleons on the damaged part of the target nucleus surface are not in the equilibrium state — similarly as the nucleons on the rest of the surface of the residual target nucleus, and they should evaporate, therefore. After the emission of the fast nucleons and the evaporation of the slow target fragments, the residual target nucleus is yet remaining in the instable state and then it must decay into stable nuclear fragments. The decay process should proceed in expense of the inner nuclear energy of the residual instable nucleus.

A definite relation exists between the hadron path λ in intranuclear matter and the number n_N of the emitted fast nucleons (or n_p — of the emitted fast protons), and definite relation between $\langle n_b \rangle$ and n_p is observed, then some pure geometrical relations inside the damaged target nucleus may lead to a discovering of some physical meaning of the $\langle n_b \rangle - n_p$ and $\langle n_h \rangle / \langle n_p \rangle$ relations, and this way, to throw a light on a mechanism of the evaporation process.

Let us start the analysis with some simple working hypothesis.

3. THE WORKING HYPOTHESIS

The quantitative intercorrelations $\langle n_b \rangle = f_1(n_g)$ and $\langle n_g \rangle = f_2(n_h)$ obtained experimentally [3]: a) f_1 — between the mean value $\langle n_b \rangle$ of the intensity n_b of the black track leaving particles and the intensity n_g of the gray track leaving particles; b) f_2 — between the mean intensity $\langle n_h \rangle$ of the heavy track leaving particles and of the mean intensity $\langle n_g \rangle$ of gray track leaving particles, are both determined by simple geometrical relations between the volumes and surface layers at definite regions of the nuclei involved and damaged in the hadron-nucleus nuclear collisions.

It is worth-while here to remind that the b-track leaving in emulsions particles are low-energy simply and multiply charged nuclear fragments p, d, t with the kinetic energy $E_{\text{kin}} \lesssim 30$ MeV/nucleon and ^{4}He, ^{3}He with $E_{\text{kin}} \lesssim 300$ MeV/nucleon; the gray track leaving particles are mainly protons in the kinetic energy range of about 30 up to about 400 MeV; $n_h = n_g + n_b$.

4. DERIVATION OF THE $\langle n_b \rangle - n_g$ AND $\langle n_g \rangle - \langle n_h \rangle$ INTERCORRELATIONS

Let us now derive the relations f_1 and f_2, on the basis of the above formulated working hypothesis, owing to the heuristic considerations presented in section 2; let start with the f_1 function.

According to the working hypothesis, the ratio $\langle n_b \rangle / n_g$ in any of the hadron-nucleus collisions should equal the ratio between volumes $v_1 = \pi[(1.50D_0)^2 - D_0^2]\lambda$ and $v_2 = \pi D_0^2 \lambda$. It gives

$$\langle n_b \rangle = \nu_1 / \nu_2 = 1.25 n_g \, . \tag{2}$$

When $n_g = 0$, the incident hadron still interacts with $(A - Z)/Z$ nucleons to which there correspond $\langle n_b \rangle = 1.25(A - Z)/Z$ evaporated electrically charged fragments. In result, we have

$$\langle n_b \rangle = 1.25 \left(n_g + \frac{A - Z}{Z} \right), \tag{3}$$

for $n_p = 0, 1, 2, 3, \ldots$; n_g is in fact the multiplicity n_p of the emitted fast protons, $n_g \equiv n_p$. But, n_p may be expressed as $n_p = \lambda S \cdot Z/A \cdot [1 - \exp(-\lambda/\langle \lambda_0 \rangle)]$, what gives:

$$\langle n_b \rangle = 1.25 \left[\lambda(A, Z) \cdot \frac{Z}{A} \cdot S \left\{ 1 - e^{-\frac{\lambda(A, Z)}{\langle \lambda_0 \rangle}} \right\} + \frac{A - Z}{Z} \right] . \tag{4}$$

Taking into account that $\lambda(A, Z) \cdot \frac{Z}{A} \cdot S\,(1 - \exp[-\lambda(A, Z))/\langle \lambda_0 \rangle])$ equals the number n_p of the emitted fast protons, we obtain

$$\langle n_b \rangle = 1.25 \left(n_p + \frac{A - Z}{Z} \right). \tag{5}$$

For the ${}^{108}_{47}\mathrm{Ag}$ target nucleus the value $1.25 \cdot \frac{A - Z}{Z} = 1.62$; for the ${}^{80}_{35}\mathrm{Br}$ it equals 1.61. Then, for the heavy elements in the emulsions, the fomula is:

$$\langle n_b \rangle = 1.25 \cdot n_g + 1.61; \tag{6}$$

$n_g \equiv n_p = 0, 1, 2, \ldots\ldots, \frac{Z}{A} \cdot D \cdot S$, where D in nucleons/S is the target nucleus diameter; for ${}^{108}_{47}\mathrm{Ag}$ $n_{p_{\max}} \approx 8$.

Let now start to derive the f_2 relation. According to the heuristic considerations and the working hypothesis

$$\frac{\langle n_p \rangle}{\langle n_h \rangle} = \frac{\langle n_g \rangle}{\langle n_h \rangle} = \frac{\pi D_0^2 \lambda}{\pi (1.50 D_0)^2 \lambda} = 0.44 = \mathrm{const.} \tag{7}$$

Formulas (6) and (7) are practically the same as the obtained experimentally by H.Winzeler [3].

The agreements between the derived values and the corresponding data from experiments are exclusively good. It allows, therefore, to derive

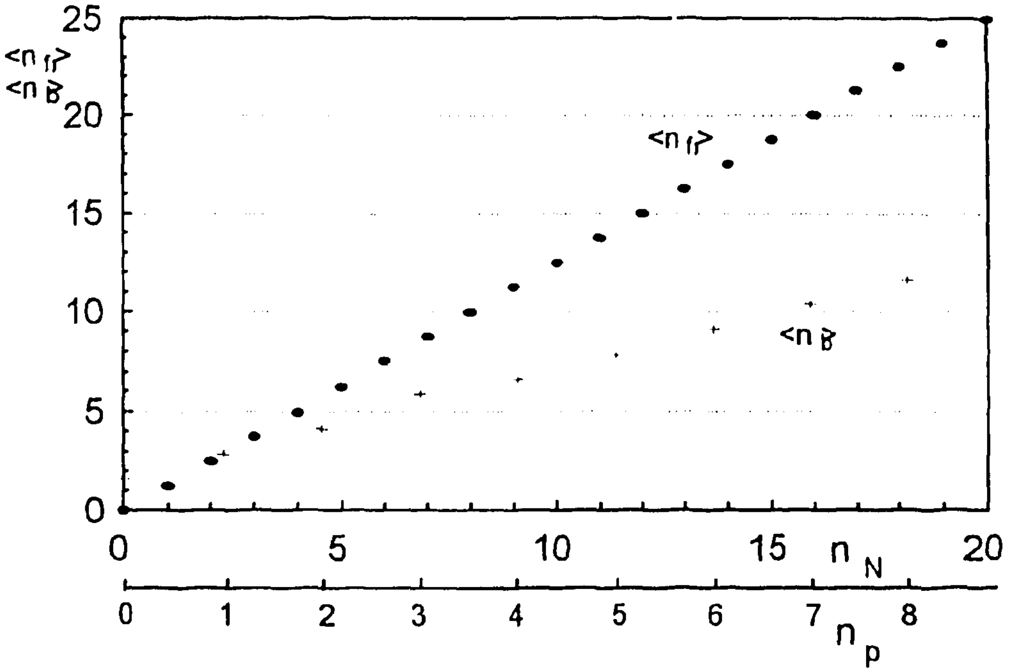

Fig. 1. The derived $\langle n_{fr} \rangle - n_N$ and the $\langle n_b \rangle - n_p$ dependences (formulas (8) and (5)), for Ag and Br targets in emulsions. $\langle n_{fr} \rangle$ — the mean number of the heavy fragments — both neutral and electrically charged together, n_N = 0,1,2,...... the multiplicity of the emitted fast nucleons, with kinetic energies of about 20 up to about 500 MeV, $\langle n_b \rangle$ — the mean number of the black track leaving charged fragments; n_p = 0,1,2,3,...., the multilplicity of the emitted fast protons

corresponding formulas for hadron-nucleus collisions in the case when all the low-energy heavy fragments — neutral and charged are registered. In such a situation, the formulas, derived per analogy, are:

$$\langle n_f \rangle = 1.25 n_N = 1.25 \cdot \lambda \cdot S \cdot \left[1 - e^{-\frac{\lambda}{\langle \lambda_0 \rangle}} \right] \qquad (8)$$

for $n_N = 1,2,3,\ldots, D \cdot S = \lambda_{\max} \cdot S$; λ is the intranuclear matter layer covered by the incoming hadron in the collision, $\langle \lambda_0 \rangle$ is the mean free path of the hadron in intranuclear matter [18]; n_f is for the evaporated low-energy nuclear fragments $n_f = n_b + n_0$, where n_0 is for neutral nuclear fragments.

The $\langle n_f \rangle - n_N$ dependence is shown in Fig.1.

5. EXPERIMENTAL VERIFICATION

Only in a few investigations there have been published the results on the evaporation of black track leaving particles which are applicable in this paper for verification of the formulas derived above, [1—8].

Let us start this section with short review of some of the experimental results, therefore.

5.1. Some Experimental Data

In the table, some of appropriate data from the work of H. Winzeler [3] are presented.

The intensities of the n_g- and n_b-track leaving particles are intercorrelated. The $\langle n_b \rangle - n_g$ correlation [3] is presented in Fig.2. The author [3] proposed the relation:

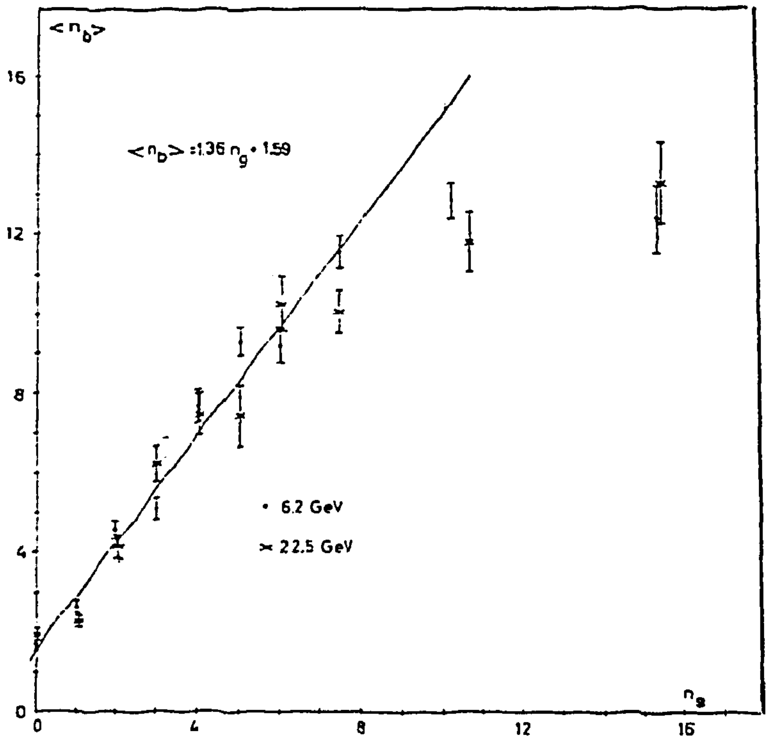

Fig.2. The $\langle n_b \rangle - n_g$ correlation obtained experimentally by H.Winzeler [3]. $\langle n_b \rangle$ is the mean number of the black track leaving particles — the mean number of the charged nuclear fragments; $n_g = 0,1,2,3,\ldots$ the multiplicity of the emitted fast protons, mainly with kinetic energies from about 20 up to about 500 MeV

Table. Data on heavy track leaving particles in emulsions, adopted from the work of H.Winzeler [3]

Incident proton energy GeV	$\langle n_h \rangle$ all n_s	$\langle n_g \rangle$ all n_s	$\langle n_b \rangle$ all n_s	$\frac{\langle n_g \rangle}{\langle n_h \rangle}$
6.2	9.25±0.18	3.58±0.11	5.68±0.21	0.39±0.01
22.5	8.60±0.25	3.38±0.14	5.22±0.29	0.35±0.01
3500	6.8±1.00	2.6±0.5	4.2±1.1	0.38±0.02

Denotes: $\langle n_h \rangle$ — heavy tracks mean intensity, $\langle n_g \rangle$ — gray tracks mean intensity, n_b — black tracks multiplicity, n_g — gray track intensity, n_s — shower track intensity or multiplicity; $n_h = n_g + n_b$, n_h — heavy track intensitry or multiplicity

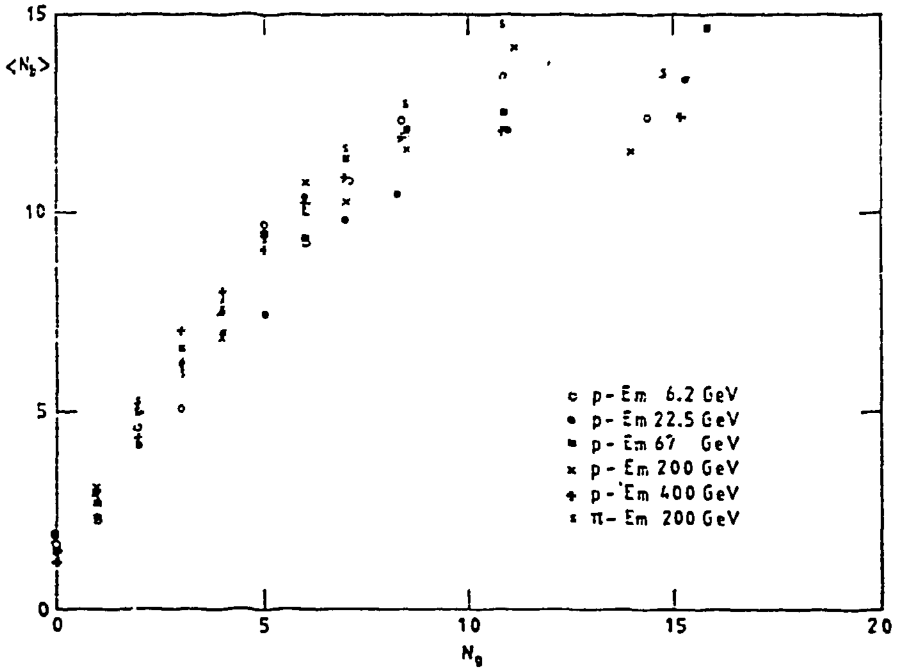

Fig.3. The $\langle n_b \rangle - n_g$ correlation at various incident hadron energies; the data collected by I.Otterlund et al. for p-emulsion and π-emulsion nuclear collisions [4].

$$\langle n_b \rangle = 1.21 n_g + 1.49, \tag{9}$$

valid for the number $n_g = n_p$ of the fast protons emitted from the target nucleus, from $n_g = 0$ up to $n_g = 8$; at higher values of n_g a deviation from linearity — from the function (9) — manifests itself clearly [3].

Simple relation is observed for $\langle n_g \rangle / \langle n_h \rangle$ ratio as well, it is [3]:

$$\langle n_g / n_h \rangle = \frac{\langle n_g \rangle}{\langle n_h \rangle} = 0.39 \pm 0.02, \tag{10}$$

for total range of the incident hadrons energy — for 6.2, 22.5, 3500 GeV of the proton energy.

The relations $\langle n_b \rangle - n_g$ for incident proton energies 6.2, 22.5, 67, 200, 400 GeV and for the incident pions at 200 GeV are presented in Fig.3 [4].

5.2. Comparison of the Experimental Results with the Predictions by the Formulas

In confronting the experimental data against the derived formulas, we are in a position to state that:

1. The derived $\langle n_b \rangle - n_g$ relation, expressed by the formula (3) is practically the same as the relation obtained experimentally [3] and expressed by the formula [9], what seems to support the working hypothesis formulated above.

2. The derived relation (7) is practically the same as the relation (10) — obtained experimentally [3]. This agreement is in support of the working hypothesis, as well.

The deviation from both the dependences (3) and (9) — from the derived (3) and from the experimentally obtained one (9) — is caused by some well-known phenomenon described in one of our former works, e.g. [19,20]. Namely, it has been stated that [19,20]: An incident hadron, in passing through atomic nucleus parallely and nearly to its diameter D, sees always the same number $n_N(D)$ = constants of the nucleons around its path within the $\pi D_0^2 D = \pi R_s^2 D$ region, but the number n_p of the protons met among the n_N nucleons fluctuates as

$$n_p = C_{n_N}^{n_p} \left(\frac{Z}{A} \right)^{n_p} \left(1 - \frac{Z}{A} \right)^{n_N - n_p}, \tag{11}$$

where

$$C_{n_N}^{n_p} = n_N!/\,[n_p!(n_N - n_p)!\,], \tag{12}$$

Z and A are the mass and charge numbers of the target nucleus. In other words, the thickness of the intranuclear matter layer measured in nucleons/S is only correct measure of the intranuclear matter layer thickness involved in the collision, especially at larger thicknesses of the layers. But, the larger thicknesses involved in the hadron-nucleus collisions with heavy nuclei, $A \gtrsim 90$ are in no more than about 15% of the collision events.

Owing to the above formulated statement, we should conclude: The mostly corrected analysis of the $\langle n_b \rangle - n_g$ dependence should be performed on the basis of the $\langle n_b \rangle - n_N$ dependence, where n_N is the intensity of fast nucleon, not only protons emitted; the $\langle n_b \rangle - n_g$ or the $\langle n_b \rangle - n_p$ dependence may be analysed only at $n_g = 0,1,2,\ldots, \frac{Z}{A} \cdot D \cdot S$, where D in nucleons/S is the target nucleus diameter, $S = 10.3\ \mathrm{fm}^2$.

6. CONCLUSIONS AND REMARKS

The mechanism of the h-track leaving particle ejection appeares 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 damage is localized within a channel with the diameter which is equal to two strong interaction ranges $R_s \approx D_0$, centered on the incident hadron course. In most of the collision cases, the damage happens at the outer part of the target-nucleus.

The evaporation of the light nuclear fragments is determined by the surface layers of the damage in the target nucleus. The damaged target nucleus memorized an information about the collision during relatively long period — not smaller than from about 10^{-23} s up to about 10^{-16} s — from the starting of the collision up to the starting of the residual target nucleus transition into stable fragments.

The above-described behaviour of the intranuclear matter, after the incident hadron passage through it, indicates its relatively hard consistency.

Taking into account our knowledge about the hadron passage through atomic nuclei and the $\langle n_b \rangle - n_p$ correlation stated experimentally, I am in a position to write that now we are ready for experimental studies of the intranuclear matter phase in the hadron-nucleus collision reactions. In other words, the intranuclear matter consistency may be studied experimentally in hadron-nucleus collisions.

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