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Z.Strugalski *

MECHANISMS OF HIGH ENERGY HADRON-NUCLEUS AND NUCLEUS-NUCLEUS COLLISION PROCESSES

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*Permanent address: Warsaw University of Technology,
Institute of Physics, ul. Koszykowa 75, 00-662 Warsaw, Poland

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1. INTRODUCTION

When one nucleus, a «projectile» nucleus, passes close enough to the second nucleus, to the «target» nucleus, so that the two interact appreciable anyhow, the collision of the nuclei occurs. If the distance between the centers of the colliding nuclei — the impact parameter d is larger than the sum of the radii R_1 and R_2 of the nuclei, and the diameter D_0 of the nucleon, $d > R_1 + R_2 + D_0$, then they interact electrically; if $d \lesssim R_1 + R_2 + D_0$, the nuclear interaction is taking place; D_0 is as large as the strong interaction range R_s; the gravitational interaction may be without taking into account — as of comparatively small constant. This definition holds if one of the colliding nuclei is a hadron; obviously, it is clear for the simplest case — for the smallest nucleus — the nucleus of Hydrogen.

The subject matter here are the nuclear interactions at different impact parameters $0 \leq d \leq R_1 + R_2 + D_0$; the mechanism of the nuclear collision process will be here of interest — first of all. Photographs of the nucleus-nucleus collision reactions, taken in various track detectors, yield information about the collision mechanism and the dynamics of the interaction. This information cannot be revealed, however, just simply in the cases of two heavy nuclei collision — because of very many of nucleons from both the colliding nuclei are involved simultaneously in the collisions. In my opinion, in allowing the picture of the collision mechanism to be seen, which is usually kept covered on the photographs, one should start from the analysis of the simplest collision events: of the hadron-nucleus collision events, or nucleus-hadron collision events, or the collision of the simplest atom Hydrogen nucleus with a heavy nucleus.

Many of our previous works have been devoted to discussing the analysis of the hadron-nucleus collision mechanism [1—12]. The experimental data described in them will be used in this work.

Let us start this work with a short description of the hadron-nucleus collision mechanism as prompted experimentally in our hadron-nucleus collision studies.

2. EXPERIMENTAL BASIS FOR THE PICTURES OF THE COLLISION MECHANISM

A number of examples from the history of classical Physics and contemporary Physics teach that to an understanding of a physical phenomenon first of all true qualitative picture of this phenomenon should be created — on the basis of facts known experimentally.

The picture of the hadron-nucleus collision mechanism is to be drawn now, in the next section, and is based on our experimental data obtained in almost total experiments [1—8] in studying the hadron-nucleus collisions at 2.34 — 9 GeV energy [1—8] and on the results of our analysis of accelerator and cosmic ray data available at higher incident hadron energies [1—13] — up to about 10000 GeV.

The picture of the nucleus-nucleus collision mechanism emerges from the data on hadron-nucleus collisions and on the information from experiments performed on ion accelerators and ion colliders [14,15].

2.1. Experimental Facts in Hadron-Nucleus Collisions

Four main phenomena are usually observed 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 400 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; c) The evaporation of target fragments including the target nucleons of kinetic energy smaller than about 10÷20 MeV; d) The fission of residual target nucleus into nuclear fragments.

2.1.1. The Passage of the Incident Hadron through Intranuclear Matter

Two classes of the nuclear collision events should be simply distinguished: I. The collisions in which the hadron production occurs; II. The collisions in which the hadron production does not occur. The emission of nucleons manifests itself in any of the nuclear collisions at the impact parameter smaller than the target nucleus radius. In both of the two classes the nucleon emission proceeds in the same manner, as one can conclude from its characteristics — from the identity of the angular and energy spectra of the emitted fast protons in both of the classes.

From the analysis of the bubble chamber data on pion-xenon nucleus collisions at various incident pion energies [16,17], from about 2 up to about 9 GeV/c momentum, and of other data available, presented in many works [18—51], it should be concluded that any hadron with kinetic energy higher than the pion production threshold may pass through some layer of intranuclear matter before to come into particle-producing reaction in it with one of the downstream nucleons [9]. Events were observed in which incident hadrons with energies of a few GeV traversed target nuclei or are stopped in them without causing particle production.

In any case, whether are the particles 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 spectra. The number n_N of the emitted «fast» nucleons equals the number of nucleons contained within the volume

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

centered on the hadron path λ in intranuclear matter, where D_0 is the diameter of the nucleon, or the strong interaction range. The particle production process does not effect an influence on the nucleon emission [34]. In particular, the mean multiplicity $\langle n_p \rangle$ of the emitted protons is:

$$\langle n_p \rangle = \langle \lambda_A \rangle \cdot S, \qquad (2)$$

and $\langle \lambda_A \rangle$ is the mean thickness of the target nucleus in protons/S units, and $S = \pi D_0^2 \doteq 10\ \mathrm{fm}^2$. Both the formulas (1) and (2) are verified quantitatively using appropriate experimental data [18—34].

2.1.2. The Production of Hadrons

In studying the hadron-nucleus collision processes, using the target nucleus as an indicator of the properties of the hadron-nucleon and hadron-nucleus collisions [35], experimental facts were stated of general importance [4—8,11]:

1. 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, centered on the hadron course. At incident hadron energies larger enough — larger than a few GeV, the particle production process does not disturb the process of the «fast» nucleon emission.

2. Hadrons are created through some intermediate objects [39] formed inside the target nucleus and decaying outside it into usually observed «produced» particles.

3. The multiplicity n distribution $f(n, A, E_h)$ of the electrically charged hadrons produced in a collision of a hadron h with an atomic nucleus A at the incident hadron energy E_h is [11,17]:

$$f(n, A, E_h) = e^{-\frac{\langle \lambda \rangle}{\langle \lambda_0 \rangle}} \sum_m (1 - e^{\frac{\langle \lambda \rangle}{\langle \lambda_0 \rangle}})^{m-1} P_m(n), \tag{3}$$

where $P_m(n)$ is the composition of the m statistically independent distributions of the charged particle multiplicities n [17]. The relation (3) represents 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.

2.1.3. The Evaporation of the Target Fragments

The evaporation products were studied experimentally using the nuclear photoemulsions mainly, these products leave characteristic black tracks in the emulsion [18,21,36]. It was obtained that:

1. The black track leaving particles exhibit an almost isotopic distribution [21,36].

2. Mean number $\langle n_b \rangle$ of the black track leaving particles is not related to the number of generated pions [36], at energies of the incident hadrons over a few GeV.

3. Mean number $\langle n_b \rangle$ of the black track leaving particles is energy independent at projectile energies higher than a few GeV, at smaller energies it may be weakly energy dependent [36,37].

4. Mean kinetic energy of the emitted black track leaving particles is about 20 MeV and stays with incident hadron energy change; it is independent as well of the impinging particle [38].

5. 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 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 [38]. It is reasonable to accept that N_F / N_B is practically independent of the energy and identity of the impinging hadron.

2.1.4. Relations between Characteristics of the *b*-Track and *g*-Track Leaving Fragments Emission Process

Experimental investigations of the relations in question allow to conclude that [40]:

1. A large difference between mean energies of the gray track leaving particles $\langle E_g \rangle$ 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 [37].

2. A large difference between angular distributions of *b*- and *g*-track leaving particles are independent of the energy and identity of the impinging hadron, and on 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 primary energy are the black tracks, their number n_b is proportional to n_g.

4. The dependence of the mean number of black tracks $\langle n_b \rangle$ on the number n_g of grey tracks has the same behaviour through the energy range 6.2. GeV to 400 GeV [21,27] and one linear function describes it well [21]. This linear function for proton-AgBr nuclei collisions passes near the dirigin $\langle n_b \rangle = 1.21 n_g + 1.49$; this correlation is completely independent of the number of produced pions [27]. Even if the shower particle multiplicity increases from 2.8. to 16.8 no change is observed in the mean black and grey track multiplicites.

5. The differential frequency distributions for the stars as function of $n_h = n_g + n_b$, for proton-emulsion nuclei collisions at 6.2 — 3500 GeV exhibit only small irregularities and differences [21].

6. The multiplicities n_g and n_h obey the relation [21]:

$$\langle n_g / n_h \rangle = \langle n_g \rangle / \langle n_h \rangle = \text{const.} = 0.39.$$

It indicates proportionality between n_g and n_h, and hence between n_b and n_g; this relation is energy-independent.

2.2 Experimental Facts in Nuclear Collisions

Three main phenomena, simply observable, are usually seen when a nucleus collides with a nucleus: a) The passage of one of nucleus or its fragments through the second nucleus; b) The particle production; c) The fragmentation of the colliding nuclei. Depending on the coordinate system, the observed picture changes, but the main processes can be distinguished simply and recognized in experiments. One more — the fourth process might occur — the phase transition in the intranuclear matter in colliding nuclei, we do not discuss it here now, however, this phenomenon will be discussed later.

2.2.1. The Passage of one Nucleus or its Fragments through the Second Nucleus

The passages should be accompanied by the emission of «fast» nucleons from the overlapping parts of the colliding nuclei.

From early studies, in cosmic rays, indications were obtained that in most collisions not all nucleons from the colliding nuclei are involved. It seems to many investigators that the geometrical overlap of the colliding nuclei defines the participant part of the nuclei; the parts lying outside the overlap region are the spectator only and continue their initial motion almost undisturbed. A theoretical justification for such a simple picture provided relative proportion between de Broglie wave length and the internucleon distance; at about 1 GeV the wave length is about 1.8 fm. It follows from it that a nucleon of a projectile nucleus sees the target nucleus as a collection of individual nucleons. A simple physical justification is such that the strong interaction range is approximately as long as the nucleon diameter, and the bonds of nucleons in atomic nuclei are relatively low — about 8 MeV/nucleon.

Similar argumentation may be used for observed break up of the overlapping parts of the colliding nuclei into many single nucleons; it is evidently observed on the photographs of the collision events registered in track detectors — streamer chambers and bubble chambers. Indeed, the numbers of the nucleons involved in a collision can be determined separately for projectile and target nuclei — by simple counting of corresponding nucleons emitted from the target — and that from the projectile-nucleus. The number of the nucleons emitted from the target and projectile separately were used in experimental investigations of the nuclear collisions for selection of evens with different impact parameters at Berkeley and Dubna [41].

Summarizing the results from all the information given above, one can be led to a conclusion that the fragmentation process of the colliding nuclei can be considered as a composition of the fragmentation processes of the target nucleus initiated by hadronic projectilles; the colliding nuclei can be treated as colliding beams of the nucleons.

2.2.2. Particle Production

Any of rapidly moving nuclei can be treated as a collimated beam of monoenergetic nucleons. From many works, from reviews for example and publications cited in them [42—46], it can be concluded that:

1. The colliding nuclei can be treated as a collision of the collimated monoenergetic nucleon beams.

2. The hadron production in such colliding beams proceeds as in hadron-nucleus collisions, and the outcome from such a collision is a composition of the outcomes of the nucleon-nucleon collisions. Generally, in fact the collision between two nuclei is a composition of binary nucleon-nucleon collisions. In other aspects, the beam collision reaction is depending on the sizes of the colliding nuclei and on the collision impact parameter.

2.2.3. Nuclear Fragmentation

Nuclear fragmentation accounts for a few per cent among the total inelastic processes cross-section, starting from about GeV up to maximal cosmic ray energies registered in observeations and experiments. The basic characteristics of the fragmentation processes were established experimentally [47—50]:

1. The momentum components of the fragments, in the rest frame of the projectile nucleus have a Gaussian shape with st. dev. (a width) from about 50 to 200 MeV/c, depending only on the masses of the fragmenting nucleus and the fragment, and not on the target nucleus and the beam energy. The momentum spectra, in this rest frame, indicate an effective temperature of 8—10 MeV — very low excitation. The isotope production rates are approximately target- and energy-independent.

2. The angular distribution of the fragments in the projectile rest frame is close to isotropy.

3. As it is concerning the nuclear fragmentation, the above experimental facts suggest [51] that the fragmentation can be viewed as a decay of an excited nucleus, therefore, as a delayed process it keeps little or no memory of the excitation mechanism formation which started the excitation.

4. The low energy nuclear fragments, including single evaporated nucleons, differ evidently from the nucleons emitted from colliding nuclei with kinetic energy of about 20 up to 500 MeV in the rest frame of each of the colliding nuclei — from the «fast» nucleons; the emission of such fast nucleons we observed in the hadron-nucleus collisions, subsect. 2.1.2. Here, the «fast» nucleon emission behaviour was discussed shortly in the cases of nucleus-nucleus collision reactions, subsect. 2.2.1.

3. THE PICTURE OF THE HADRON-NUCLEUS COLLISION PROCESS

In any of the hadron-nucleus collision events, the general process observed is the passage of the hadronic projectile or its successor(s) — generon(s) —

through intranuclear matter accompanied by the fast nucleon emission from the target nucleus; it may be seen in the lab coordinate system, in which the nucleus is at rest, or in the antilab system, in which the hadron is resting.

The projectile hadron with energy large enough may traverse the target nucleus without causing secondary hadron production, as it is known experimentally [6]; the interaction region of the hadron in intranuclear matter is limited to the cylindrical volume of the radius R_s centered on the projectile course, R_s is the strong interaction range — as large approximately as the nucleon diameter D_0 is. Often, in passing through layers of the intranuclear matter, the hadronic projectile may come into particle-producing collision with one of the downstream nucleons met at any depth in the layer. In the passage hadron loses always almost fluently its kinetic energy, the energy lose the successors of the projectile as any hadron does it as well. In passing through the intranuclear matter the projectile is usually, at lower energies, deflected slightly from its initial course; the deflection is a result of the multiple scattering through small — a few degrees — angles of the hadron from objects in intranuclear matter.

The particle production in hadron-nucleus collisions starts in result of the particle-producing collision of the hadron with one of downstream nucleons in intranuclear matter.

The particle production in hadron-nucleon collisions, in particular in nucleon-nucleon collisions, is mediated by intermediate objects created first in a $2 \rightarrow 2$ type endoergic reaction in the early stage of the collision. The intermediate objects — generons — move predominantly along the incident hadron course and behave themselves in intranuclear matter as usual hadrons do it [39], before the decaying into finally observed particles and resonances after having left the parent nucleus. The lifetime of generons is large enough, $\tau_g \gtrsim 10^{-22}$ seconds, them to be possible to traverse the most massive atomic nuclei.

In traversing layers of the intranuclear matter, generons can collide with the downstream nucleons and produce new generons — giving rise, this way, to a development of quasi-unidimensional cascade of the generons in intranuclear matter. In such cascading process, the kinetic energy of the incident hadron is distributed between generons created; it is a reason to suppose an equipartition in this distribution, in average. It may be formulated the law for the particle production process in hadron-nucleus collisions, therefore:

- Various characteristics of the outcome in a hadron-nucleus collision at an energy E are the composition of corresponding statistically independent characteristics of the outcome in some number m of hadron-nucleon collisions at the energy of E/m in average.

In result of the collision, the destroyed target nucleus decays ito fragments — at least into stable fragments.

The fast nucleon emission process and the incident hadron deflection process can be described by means of simple formulas — in terms of the target nucleus size and the nucleon density distribution in it [4,16,17].

The data on the particle production in hadron-nucleus collisions are described quantitatively, on the basis of this picture, in a convincing manner in terms of corresponding hadron-nucleon data and the information about the target nucleus, without any free parameters [11,17].

4. THE PICTURE OF THE NUCLEUS-NUCLEUS COLLISION PROCESS

In the light of the facts described above, sect.2.1 and 2.2., stated in hadron-nucleus collisions, and in nucleon-nucleus collisions in particular, it can be concluded that: In a head on collision of two identical massive enough nuclei, at energy high enough — over a few GeV/nucleon in the center of their mass coordinate system, the nucleons in one of the nuclei pass through the second nucleus. The passage is the general phenomenon, but it occurs rarely in its pure form. On the background of it, the particle production occurs often in the nuclei collisions. The production goes through intermediate objects — the generons — created first in $2 \rightarrow 2$ nucleon-nucleon endoergic collision reaction. In the coordinate system accepted here, many generons may become to be at rest, and use decay into the usually observed «produced» hadrons, after the lifetime of about 10^{-22} seconds. In such configuration, simple picture appeares: Two beams of the collimated monoenergetic nucleons with energies practically as large as the energies of the nucleons in the colliding nuclei, in GeV/nucleon, will escape from the collision region into opposite sides. From the center of the collision region many generated hadrons will be ejected through total 4π solid angle; many of the ejected hadrons will be organized into collimated spurts of hadrons — jets. The fragments of colliding nuclei will not appear, both nuclei are totally desintegrated into nucleons. It happens due to the laws of fast nucleon emission induced by a hadron in its passage through layers of the intranuclear matter — any of nucleons involved in the interaction with the incident hadron is emitted from the target nucleus.

It should be possible to imagine the picture of such nucleus-nucleus collisions at various impact parameters $0 < d \lesssim D$, where D is the diameter of the colliding nuclei.

Depending on whether it is possible to join the generons one to another, some excited quark-gluon matter or quagma might be created this way — only through some junction of the generons. But, what is in fact? The answer should be lucked for in experiments and observartions.

In the collisions of identical massive nuclei, the head on events can be simply distinguished — as the collisions without the colliding nuclei fragments.

It is not excluded that collision events without the opposite beams of nucleons appear; the ejection of the generated particles from the center of the collision region will be observed only. In such type of events the quagma should be looked for — first of all.

From experiments, performed mainly by means of the intranuclear detector in hadron-nucleus collisions, and observations, and qualitative analysis of the nucleus-nucleus collision events, it is possible to formulate a general rule of the nucleus-nucleus collision process.

At energies over a few GeV/nucleon, the outcome from a collision of two massive nuclei is a composition from some number of statistically independent outcomes in nucleon-nucleus collisions at the same energy of the incident nucleon with the target nucleus, at all the possible impact parameters.

5. CONCLUSIONS AND REMARKS

In my opinion, based on results from the series of hadron-nucleus investigations performed by means of the intranuclear detector — i.e. by means of the target nucleus employed as a fine detector — three main phenomena manifest themselves conclusively in the collisions:

1. The hadron passage through layers of intranuclear matter accompanied by fast nucleon emission;
2. The hadron generation through intermediate objects — generons — decaying after having left the parent nucleus into the usually observed «produced» particles and resonances;
3. The localization of the reactions of the incident hadron in small cylindrical region in intranuclear matter of the radius as large as the nuclear interaction range is, centered on the hadron course in the target nucleus.

The manifestation of these phenomena is clear as well in the nucleus-nucleus collisions of the massive enough nuclei at momenta over a few GeV/c/nucleon.

In this work, all the three phenomena were qualitatively depicted. They are known for us from long time ago and were quantitatively analyzed in the works cited here and in the publications cited in them.

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Механизмы процессов столкновений адрон-ядро и ядро-ядро
при высоких энергиях

Механизмы процессов столкновений адрон-ядро и ядро-ядро описаны качественно, как подсказанные в экспериментах. Взаимодействие налетающего адрона локализовано во внутриядерной материи в малом цилиндрическом объеме, радиусом равным радиусу действия ядерных сил и с осью вдоль траектории адрона. Адрон возбуждает эмиссию нуклонов из ядра мишени; частицы рождаются через промежуточные объекты в реакциях столкновения типа 2 → 2 во внутриядерной материи. Выход из реакции столкновения ядро-ядро является композицией выходов из статистически независимых столкновений адрон-ядро при разных параметрах столкновения. Обсуждаются наблюдаемые эффекты, связанные с обнаруженным на опыте механизмом реакции.

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Mechanisms of High Energy Hadron-Nucleus
and Nucleus-Nucleus Collision Processes

Mechanisms of high energy hadron-nucleus and nucleus-nucleus collision processes are depicted qualitatively, as prompted experimentally. In hadron-nucleus collisions the interaction of the incident hadron in intranuclear matter is localized in small cylindrical volume, with the radius as large as the strong interaction range is, centered on the hadron course in the nucleus. The nucleon emission is induced by the hadron in its passing through the nucleus; particles are produced via intermediate objects produced in 2 → 2 endoergic reactions of the hadron and its successors with downstream nucleons. In nucleus-nucleus collisions, the outcome of the reaction appears as the composition of statistically independent hadron-nucleus collision outcomes at various impact parameters. Observable effects supporting such mechanisms are discussed.

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

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