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Z.Strugalski*

PHYSICAL MEANING OF THE YIELDS FROM HADRON-NUCLEON, HADRON-NUCLEUS, AND NUCLEUS-NUCLEUS COLLISIONS OBSERVED IN EXPERIMENTS

*Permanent address: Warsaw University of Technology, Institute of Physics, ul.Koszykowa 75, 00-662 Warsaw, Poland
or Institute of Atomic Energy PL 05-400 Otwock-Swierk, Poland

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1. INTRODUCTION

A physical meaning of the outcomes from hadronic collision processes is discussed during a long period; the nucleon-nucleon collision reactions are of special interest in this context. The theoretical interpretations are centered mainly on the candidate theory for strong interactions, Quantum Chromo Dynamics — QCD, applied at varying levels of mathematical rigour [1—5]. Large majority of the results obtained this way are theoretically and hypothetically biased, and based on some sorts of beliefs — commonly accepted, however.

In this work, I would like to present unbiased, experimentally based results of investigations of the outcomes from the hadron-nucleon, hadron-nucleus, and nucleus-nucleus collisions. Experimental works [6—15], which the conclusions presented here are based on, were performed in a total experiment using the 26 litre and 180 litre xenon bubble chambers exposed to pions beams at 2.34—9 GeV/c momentum, supplemented by results from experiments realized by means of other detectors: nuclear emulsions, electronic arrangements, streamer chambers exposed to pion, kaon, proton and nuclear beams from accelerators at various energies, and from cosmic rays [16—19].

In my opinion, the physical meaning of the collision reactions outcomes may be revealed on the basis of the experimentally discovered pictures of the collision processes. The mechanisms of the collisions may be found out experimentally using the intranuclear detector [6] — the target nucleus serves as the detector [9,19—21], which could provide information about the processes localized within the space regions as large as 10^{-13}–10^{-12} cm and within time intervals of about 10^{-23}–10^{-22} seconds. Such detector — we called it the intranuclear detector [6] — has been used in our investigations during about ten last years [6,9,21].

The mechanisms of the hadronic and nuclear collision processes have been studied using the xenon intranuclear detector.

The intranuclear detectors, for example the xenon intranuclear detector, the lead intranuclear detector, the uranium intranuclear detector and others may be treated as some subnuclear detectors — like the macroscopic track detectors — as bubble chambers, streamer chambers or nuclear photoemulsions.

Let us start the considerations here with the description of the investigation procedure. Firstly, I would like to state that many of the processes which have been «observed» in the xenon intranuclear detector are passing in strictly causal manner, e.g., the hadron passage through intranuclear matter accompanied by the nucleon emission from the target nucleus — the number of the nucleons emitted corresponds to the number of the nucleons met inside the nucleus along the projectile course, within the strong interaction range [9,19].

2. THE INVESTIGATION PROCEDURE

In order to reveal the physical meaning of the outcomes from hadron-nucleon, hadron-nucleus, and nucleus-nucleus collisions observed in detectors, one should discover at first the mechanisms of the collision processes and then the mechanisms of the energy transfer from the hadronic and nuclear projectiles into the target nuclei. It should be remembered that the answers to the question's: how are the collision processes going on?, how is the energy transfer from the projectiles to the nuclear targets going on?, what is observed in the final states of the collisions? should be found experimentally. Any freely fabricated hypotheses or models are intolerable on any level of the investigating procedure — as the fruits of human fantasy; all what is stated must be based experimentally and motivated in experiments. It could be a wrong direction of the search singled out and accepted by others, in other way, and be in use during relatively long period.

It is possible to realize the investigations in accordance with the desiderata formulated above; it will be when the experiments which the conclusions have to be used from are the total experiments. Usually, it can be achieved in some of track detectors — as the heavy liquid bubble chambers, when, as the supplemented, data from other detectors are employed — as those from electronic arrangements, streamer chambers, nuclear emulsions. Very effective, for the experiments in question, are the intranuclear detectors — single massive atomic nuclei employed as fine detectors for indications and analysis of the processes within the space regions with sizes of about 10^{-13}–10^{-12} cm in diameters and in time intervals of about 10^{-23}–10^{-22} seconds [6—9,12,13,18,19].

Interesting, original and conclusively based on experimental data pictures of the processes under study emerge when a complete series of appropriate data, total and clearly motivated on experience is used — as the basis for the conclusions formulations.

In applying such investigation procedure, during over ten years, the pictures, prompted experimentally, of the hadron-nucleon, hadron-nucleus, nucleus-nucleus collision processes and of the energy transfer processes from the projectiles to the target nuclei in them were revealed [6—9]. We do not repeat the description of the investigation procedure at that level, and I am taking the liberty to propose some of our recent works where the investigation methods are described [3—13].

In the next section 3, a presentation of main results obtained in those works is given; the results interesting and important for our further considerations in question are given in section 4.

3. EXPERIMENTAL RESULTS ON COLLISION MECHANISMS

In all the collision processes: 1) in hadron-nucleon (in nucleon-nucleon in particular), 2) in hadron-nucleus (in nucleon-nucleus in particular), 3) in nucleus-nucleus the particle production occurs in head-on 2 → 2 type collision reactions of the incident hadrons with the nucleons. In the hadron-nucleus and nucleus-nucleus collisions the emission of the nucleons from the nuclei involved predominates, however; the emitted nucleons are with the kinetic energies of about 20—400 MeV, the emission does not depend on the energy and identity of the impinging projectiles, and whether the particle creaction occurs or not [6—8]. The particle production goes through intermediate objects created first in the 2 → 2 type endoergic reactions and decaying into observed particles and resonances after the lifetime of about 10^{-22} s.

In the hadron-nucleon collisions the projectile energy is transferred to the target nucleon, in the hadron-nucleus and in the nucleus-nucleus collisions the projectile energy is transferred partly to the target nucleus and partly to the nucleons involved in the particle producing collision reactions with the projectile within the target nucleus. The energy transfer to the target nucleus is limited, and it is no larger than about a few GeV per the incident nucleon; the energy transfer from the hadronic projectile to the downstream nucleon in the particle creating collision reaction is practically unlimited.

Below, the phenomena, the collision reactions are accompanied by, will be considered from the point of view of the physical interpretation of the observed outcomes from the collision reactions under studies.

3.1. Hadron-Nucleon Collisions

From our former investigations [6,9,13,20,21], the experimentally based conclusions may be stated: in hadron-nucleon (in nucleon-nucleon in particular) collisions at high energies the particles are produced through intermediate objects created first in 2 → 2 type endoergic reaction and decaying into finally observed resonances and particles after the lifetime $\tau_g \geq 10^{-22}$ s; these objects were called «generons» [9]. The appearance of the well-collimated spurts of hadrons, or jets, in the final state of the collision reaction, and of the large transverse momenta are therefore naturally a simple and indispensable consequence of such mechanism of the perticle production process. Generons are formed in head-on collisions [9].

In forming the intermediate objects, or generons, in a hadronic head-on collision, large energy is transferred from the projectile to the target, e.g., from a hadron to a nucleon; at energies high enough, this energy transfer may be practically unlimited. As a measure of this energy transfer in the particle-producing collisions, the intensity or multiplicity of the particles may be used.

The pions are the mostly intensive component among the products at high energies, kaons and baryon-antibaryon pairs appeare about ten times rarer.

The main properties of the nucleon-nucleon particle-producing collisions are: The mean intensity or multiplicity of the produced particles increases logarithmically with the projectile momentum — from about 5 at about 10 GeV/c up to about 18 particles at about 1000 GeV/c. The mean transverse momentum of the particles is $p_T \approx 0.4$ GeV/c, independently of the incident particle energy value. The longitudinal component of the momentum, expressed in the Feynman variables, $X_F = p_l / p_{max}$ is with almost constant exponential distribution, independently of the collision reaction energy.

3.2. Hadron-Nucleus Collisions

In hadron-nucleus collisions the interaction of the incident hadron (nucleon) is localized in relatively small cylindrical volume with the radius as large as the strong interaction range is, centered on the hadron course within the target nucleus.

Four main phenomena are usually observed when hadrons collide with atomic nuclei: a) The passage of the incident hadron through intranuclear matter, accompained 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. On the background of the projectile passage through layers of intranuclear matter, the particle-producing head-on collisions of the projectile with one of the downstream nucleons occur; particles are produced through intermediate objects in 2 → 2 type endoergic reactions of the hadron and its successors with downstream nucleons. The intermediate objects as the hadron successors may use to collide with the next of the downstream nucleons and create new intermediate objects; the linear intranuclear cascade of the generons may develop along the incident hadron course in intranuclear matter, this way. c) The evaporation of the target nuclear fragments, including the target nucleons of kinetic energy smaller than about 10—20 MeV. d) The fission of the residual target nucleus into nuclear fragments.

In any case, whether the particels are produced or not, any projectile hadron causes the emission of nucleons in passing through atomic nucleus. This nucleon emission should not be confused with the nucleon evaporation with clearly different energy and angular distributions. The number n_N of the emitted «fast» nucleons equals the number of nucleons contained within the volume

$$V = \pi R_s^2 \lambda \approx \pi D_0^2 \lambda \tag{1}$$

centered on the hadron path λ in intranuclear matter, where D_0 is the diameter of the nucleon, as large approximately as the strong interaction range is. The particle production process does not effect an influence on the nucleon emission [22]. In particular, the mean multiplicity n_p of the emitted protons is:

$$\langle n_p \rangle \approx \langle \lambda_A \rangle \cdot S, \tag{2}$$

where $\langle \lambda_A \rangle$ is the mean thickness of the target nucleus in protons/S units, and $S = \pi D_0^2 \approx 10\ \mathrm{fm}^2$.

The particle creation process goes on the background of the incident hadron passage through intranuclear matter and it is localized along the projectile course in intranuclear matter within the tube of the radius R_s as large as the strong interaction range R_s is, centered on the hadron course. Hadrons are created through some intermediate objects formed inside the tube in the target nucleus and they use to decay after having left the nucleus, after about lifetime $\tau_g = 10^{-22}$ s into commonly known «produced» particles and resonances; the intermediate objects are in fact the hadrons in statu nascendi [13]. In collisions with nuclei massive enough, at energies high enough, the intermediate objects may use to collide in ones turn with the downstream nucleons — the intranuclear cascade may develop of the intermediate objects along the incident hadron course through the volume (1). The muliplicity n distribution $f(n, A, E_h)$ of the electrically charged hadrons produced in a collision of a hadron with an atomic nucleus A at the incident hadron energy E_h is [21,23]:

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

where P_m is the composition of the m statistically independent distributions of the charged particle multiplicities n [21]. The relation (3) represents a composition of some number $m = 1, 2, 3, \ldots$ of statistically independent outcomes which could be observed separately in elementary hadron-nucleon collisions at incident hadron energy E_h / m.

The evaporation process was studied experimentally in nuclear photoemulsions mainly; the evaporation products leave characteristic black tracks in the emulsions

— the tracks of nuclei with the charge number $Z = 1$ to $Z = 2$ predominantly [24,25]. It was obtained that: 1. The black track leaving particles exhibit an almost isotropic distribution [15,25]. 2. The mean number of the black track leaving particles n_b is not related to the number of generated pions [25], at energies of the incident hadron over a few GeV; this number $\langle n_b \rangle$ is weakly energy dependent at smaller energies [25,26]. 3. 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 identity of the impinging particle [27]. 4. The ratio N_F / N_B betwen the number N_F of the black track leaving particles directed into forward hemisphere and the number N_B of the particles directed into backward hemisphere amounts about 1.1 ± 0.1; it does not depend on n_b and it is the same for pion-nucleus collisions at about 60 and 200 GeV [27]; it is reasonable to accept that N_F / N_B is practically independent of the energy and identity of the impinging hadron.

In experiments performed by means of photonuclear emulsions, the relations between characteristics of the black track leaving and gray track leaving particles emission characteristics were investigated [16,24,25—27]; among the gray track leaving particles are the fast protons predominantly — with energies of about 20 to 500 MeV. Experimental relations in question allow one to conclude that [28]: 1. Large difference between mean energies of the fast protons, $\langle E_g \rangle$, and of the black track leaving particles, $\langle E_b \rangle$, is independent of the energy and mass of the projectile and of the target mass as well [26]. 2. A large difference between angular distributions of the b- and g-track leaving particles is independent of the energy and identity of the impinging hadron, and of the target nucleus mass number as well. 3. The range and angular distributions of the gray track producing particles do not change with incident hadron energy change, as it has been proved at energies larger than about 2 GeV. Still less correlated with the primary energy are the black tracks, their number n_b is proportional to n_g. 4. The dependence of the mean number of the black tracks $\langle n \rangle$ on the number n_g of gray tracks has the same behaviour through the energy range 6.2 GeV to 400 GeV [15,16], one linear function describes it well [15]. This linear function for proton-AgBr nuclei collisions passed near the dirigin $n_b = 1.21 n_g + 1.49$; this correlation is completely independent of the number of produced pions [16]. Even if the shower particle multiplicity increases from 2.8 to 16.8 no change is observed in the mean black and gray track multiplicities. 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 [15]. 6. The multiplicities n_g and n_h obey the relation 15:

$$\langle n_g / n_h \rangle = \langle n_g \rangle / \langle n_h \rangle = \text{constans} = 0.39. \quad (4)$$

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

3.3. Phenomena Observed in Nucleus-Nucleus Collisions

Three main phenomena, simply observable, are seen when a nucleus collides with a nucleus: a) The passage of nucleus or its fragments through the second nucleus; b) The particle production process; c) The fragmentation of the colliding nuclei and nucleon evaporation.

The passage should be accompanied by the emission of «fast» nucleons from the overlapping parts of the colliding nuclei. The fragmentation process of the colliding nuclei can be considered as a composition of the fragmentations of the target nuclei initiated by hadronic projectiles. The colliding nuclei can be treated as colliding beams of the nucleons — any rapidly moving nucleus can be treated as a collimated beam of monoenergetic nucleons.

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 in the nucleon-nucleon collisions. In fact, generally, 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. The basic characteristics of the fragmentation processes were established experimentally [29—36], the most important here are: a) 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 very low effective temperature of 8—10 MeV, very low excitation in other words. The isotope production rates are approximately target- and energy-independent. b) The angular distribution of the fragments in the projectile rest frame is close to the isotropy. c) As it is concerning the nuclear fragmentation, the above experimental facts suggest [37] 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. d) 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; the emission of such fast nucleons we observed in the hadron-nucleus collisions.

4. THE PHYSICAL MEANING OF THE COLLISION REACTION OUTCOMES

It may be concluded, from the experimental data presented above, that what is observed in our investigations in the lab. system, and described in our publications, and in the works cited in them is: The hadron-nucleus collision processes at high energies (at above the pion creation energy threshold) proceed in two clearly different stages; the fast stage, during about 10^{-23}–10^{-22} seconds, is the passage of the incident hadron through the layers of the intranuclear matter inside the target nucleus. At this stage, the incident hadron uses to start the «fast» nucleon emission process from the target and the particle creation process in head-on collisions with some of down-stream nucleons, in passing through the intranuclear matter layer involved. The relatively small part of the nucleus is taking part in the collision only — the tube of the volume $\pi D_0^2 \lambda$, where $D_0 \approx R_h$, is the strong interaction range as large approximatelly as the nucleon diameter is, λ is the intranuclear matter layer thickness. Depending on the hadron energy and on the collision impact parameter, the target nucleus may be pierced; at energies higher than a few GeV the target nucleus is pierced anyhow.

From this stage, the fast nucleon emission is distinguishable — it differs by much from the nucleon evaporation, the emitted fast nucleons are recognized as not knocked out ones, as well. The observed, so-called «produced», particles are in fact decay products of produced intermediate objects or generons — created first and decayed into observed «created» hadrons after having left the parent target nucleus; the lifetime of the generons is about 10^{-22} seconds.

The target nucleus at this stage is pierced and becomes to be instable, and should undergo some transmutation into some stable parts — nuclear fragments, smaller nuclei. The second stage of the collision process starts. This stage can be named slow one.

At the second stage, the duration of which may be determined arbitrarily only — e.g., from the end of the projectile passage through the target nucleus up to the decay of the pierced nucleus into stable fragments and nucleons.

In the particie-producing hadron-nucleon collisions, the secondary hadrons are created via intermediate objects or generons, similarly as in the hadron-nucleus collisions.

In the nucleus-nucleus collisions, in the lab. system, the projectile nucleus may be imagined as collimated beam of monoenergetic nucleons. The nucleus-nucleus collision of two moving nuclei is in fact the collision of two collimated monoenergetic nucleons beams: the outcome in this case is expected to be a composition of the nucleon-nucleus collisions.

In conclusion, what can be stated is: From the facts presented above, that what is observed in our works, and in the works of other authors in which similar processes are investigated, is that the hadron creation goes through intermediate objects called generons. The hadronic jets are created through the intermediate objects — as their decay products. The intermediate objects behave themselves as usual hadrons do it in passing through intranuclear matter, and convert into hadronic jets or hadrons after about 10^{-22} seconds — after having left the parent nucleus.

Now many believe, however, that quarks do not appear as such but they materialize or convert into observed well collimated spurts of particles, which have been named jets. And so, according to this belief, the intermediate objects or generons may be regarded to be partons or quarks, systems of quarks or partons, quark or parton bags. It can be stated, therefore, that in the experiments discussed here these objects are observed by means of atomic nuclei employed as intranuclear detectors; the behaviour of these objects in their passage through layers of intranuclear matter is observed, as well.

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Физический смысл выходов из адрон-нуклонных, адрон-ядерных и ядро-ядерных столкновений, наблюдаемых в экспериментах

Рассматривается физическое значение выходов из адронных и ядерных процессов столкновения, как подсказанное экспериментально. Различается быстрая и медленная стадия в процессах столкновения. Адроны рождаются посредством промежуточных объектов, наблюдаемых на опыте в столкновениях адрон-ядро. Промежуточные объекты можно трактовать как группы кварков или кварковые мешки.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

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Strugalski Z. E1-95-23
Physical Meaning of the Yields from Hadron-Nucleon, Hadron-Nucleus, and Nucleus-Nucleus Collisions Observed in Experiments

A physical meaning of the outcomes from hadronic and nuclear collision processes at high energies is presented, as prompted experimentally. The fast and slow stages in hadron-nucleus collisions are distinguished. Hadrons are produced via intermediate objects observed in hadron-nucleus collisions. The intermediate objects may be treated as the groups of quarks or the quark bags.

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

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