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Z.Strugalski

JETS IN HIGH ENERGY NUCLEON-NUCLEON COLLISIONS

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1. INTRODUCTION

In this paper I present a new picture of the particle-producing collision of two accelerated strongly interacting particles, in particular of two nucleons; it arose from our experimental studies - from the studies of hadron-nucleon collisions /1,2/ in which massive target-nucleus served as a detector /3/ of the properties of the particle production process in its early stage.

Our experimental results allowed one to conclude that the particle production in hadron-nucleon collisions is mediated by intermediate objects created at first; we have called these objects "generons" /2/. The usually observed many-particle final states are the outcome of the decays in flight of these objects into commonly known resonances and particles; a particle-producing collision may be therefore treated in its early stage as a two-particle final state 2 → 2 endoergic reaction: $a_1 + a_2 \to a_3 + a_4$, where a_1 and a_2 are the colliding particles of the rest energies $M_1 = m_1c^2$ and $M_2 = m_2c^2$, a_3 and a_4 are the reaction product particles of the rest energies $M_3 = m_3c^2$ and $M_4 = m_4c^2$, which obey the relations $M_1 + M_2 < M_3 + M_4$, and $M_1 < M_3$ and $M_2 < M_4$; m_i are the rest masses of the particles, where $i = 1,2,3,4$.

The appearance of the well-collimated spurts of particles, or jets, in the final state of the collision is therefore a simple and indispensable consequence of such mechanism of particle production.

Because this picture differs much from that accepted now, it was found necessary: a) to look briefly over the experimental foundation which the picture almost commonly used now is based on; b) to present new experimental facts having an influence on our present point of view which is to be described here; c) to derive experimentally testable kinematical relations between various jet characteristics as a consequence of the newly known particle production mechanism.

2. DEFINITIONS, DENOTATIONS AND TERMINOLOGY

Let us list main definitions of the quantities characterizing a particle-particle collision and its outcome, and fix adequate and convenient terminology. In doing this, we take into account the definitions and terms used within the frames of the current picture.

In many cases the observed two-particle collisions are produced in collisions of two beams of particles moving along parallel courses. The course of the particle in the center of the beam is called the beam axis; the direction of the motion of the particles along the beam axis is called the beam axis direction.

As a result of the head-on collision of two hadrons, protons for example, of high enough energy, many reaction product particles emerge finally; the number of particles increases with increasing the relative kinetic energy of the colliding hadrons. We call the kinetic energy of a particle "high" if this energy is large enough for pion production; usually, here we will have to do with particle´s kinetic energy E_k which is much higher than their rest mass m; in other words, the particle rest energy $M = mc^2 \ll E_k$ where c is the velocity of light; we call such particles, as usually, relativistic particles. In this paper we consider predominantly the collisions of particles of kinetic energies above tens GeV; in this case almost all reaction product particles are relativistic.

The most convenient variables expressing the state of motion of an i-th relativistic particle are the components of the energy-momentum four-vector $(E_i, \vec{p}_i c)$ or four-momentum, where E_i is the total energy - the sum of rest energy $M_i = m_i c^2$ and kinetic energy E_{ki} of the particle, $\vec{p}$ is the space part of four-momentum or momentum simply.

The number N of all particles, neutral and electrically charged, emerged in two-particle collisions is called the particle multiplicity of the collision. The angle θ_i between the beam axis and the emission direction of an i-th secondary particle is called the particle emission angle.

At high energies the finally emerged particles in a collision event are not randomly scattered in all direction, but they are generally organized into well-collimated spurts of particles, which have been called jets. A jet can be tentatively defined[4] as a set of hadrons with limited transverse momenta, typically $\langle p_T \rangle \approx 0.35$ GeV/c, with respect to global momentum $\vec{p}_j$ of the set and having longitudinal momenta $\vec{p}_L = x\vec{p}_j$ distributed in a scaling way, where the x distribution[6] being independent of $\vec{p}_j$. We call the straight line, on which the vector $\vec{p}_j$ lies, the jet axis. The angle θ_{Ji} between the axis of an i-th jet and the beam axis is referred to as the jet emission angle.

The number N_J of jets emerged in a collision event is called the jet multiplicity of the event.

In decays of the intermediate objects a_3 and a_4 into resonances and, consequently, the resonances into finally observed particles, the jet structure of the outcome is formed - two or more jets can emerge which may be observed. We call the jets j_{a_i1}, j_{a_i2}, j_{a_i3}, j_{a_ik}, where $k = 1,2,3,4,\ldots$ and $i = 3$ or $i = 4$, the related jets.

The algebraic sum of electric charges q_i of all i charged particles in a jet $Q_j = \sum_i q_i$, we call the charge of a jet. Jets with electric charge $Q = 0$ we call neutral jets; jets with electric charges $\pm 1, \pm 2, \pm 3, \ldots$ we call positively or negatively charged jets, correspondingly.

As usual, the collision of two particles a_1 and a_2 may be considered in various frames of reference or coordinate systems: The centre-of-momentum system, CMS, is defined by the relation $\vec{p}^{\,*}_{a_1} + \vec{p}^{\,*}_{a_2} = 0$; in this system quantities are denoted by an asterisk. The target system, TS, is defined by the relation $\vec{p}_{a_2} = 0$. The beam system, BS, is defined by $\vec{p}_{a_1} = 0$. The colliding beam system, CBS, is defined as the system of reference in which two particles of equal rest mass, $m_{a_1} = m_{a_2}$, and equal absolute value of momentum, $|\vec{p}_{a_1}| = |\vec{p}_{a_2}|$, collide so that their momenta form some angle $\pi - \Theta$, where Θ is an angle between the axes of the beams. The bisector of the angle Θ is referred to as the collision axis. For colliding beam experiments the CBS coincides with the LS, and for $\Theta = 0$ it even coincides with the CMS. The collision axis in the CMS is the straight line along which the colliding particles, treated as point-like, move from opposite sides to the point of impact. The collision axes in the BS and in the TS are the straight lines along which the point-like projectiles come to the point-like target.

3. ON EXPERIMENTAL FOUNDATION OF THE CURRENT PICTURE OF HIGH ENERGY PARTICLE-PRODUCING COLLISION PROCESS

Now, there is a compelling evidence that many of the known particles are not point-like elementary objects, but they are of a composed structure. In particular, nucleons are composed[6,7] from constituents called either quarks[8-11] or partons[12]. In fact, there are now three fundamental conclusions based on purely experimental facts concerning the nucleon structure: a) From elastic electron-nucleon scattering - nucleons are not point-like particles; they have a fuzzy boundary finite size with an average radius of about $8\cdot10^{-13}$cm. b) The magnetic structures of the neutron and the proton are almost identical but the magnitude of scattering from each is proportional to the magnetic properties of each particle as found from static experiments; the distribution of electric charge within the proton is directly related to the magnetic structure. c) From inelastic electron-nucleon scattering experiments - the internal structures from which inelastic scattering takes place are much smaller than the nucleons[8]; these small and hard objects, called partons[12], are embedded within the proton; attempts have been made to identify partons with quarks[10,11]. This fine structure should become visible only when a violent collision of the composed particles gives rise to the emission of debris; it seems it should be easy to knock out one of the constituents. When it is attempted, however, by bombarding a hadron with high energy particles, the fragments that emerge are not quarks or partons but ordinary hadrons, constituted, as one thinks, of the standard combinations of quarks; no one has yet isolated a quark or a parton.

A wide array of collision processes are considered to be of kinematical features which are typical of reactions involving hadron constituents acting independently of one another. It is believed [4,13,14] that quarks do not appear as such but they materialize as observed well-collimated spurts of particles, which have been named jets.

From such a point of view, it is commonly believed that when two accelerated particles, in particular two nucleons, are made to collide head on the particles do not merely become apart; instead much of their energy goes into creating new particles, often dozens of them, which fly away from the point of impact - like debris from an explosion; the appearance of fragments with a large transverse momentum, in particular of the observed jet almost perpendicularly directed to the collision line is due to the hard scattering[15] of constituents [4,14].

But, in my opinion, this belief has been never supported by some kind of adequate experiments; nobody has observed the particle-producing collision process in its early stage and proved experimentally that the particles observed in the final state of the head-on collisions of two accelerated hadrons, of two nucleons for example, are in fact produced in such a way. It can be not excluded, on the basis of present-day known experimental data, the following a priori possible mechanism of particle production: Two colliding nucleons, a_1 and a_2, are turned first into some new two objects, generons a_3 and a_4, each of some rest energy larger than that of the projectile and of some finite lifetime, which move along the courses allowed for the reaction products of the two particle final state andoergic collisions and decay in flight into finally "produced" particles and resonances. Such a picture is namely prompted by an experiment in which a massive target is used as a detector of the properties of the particle production process [1-3], in its early stage (section 4 of this paper).

What has been observed at energies high enough is: when two protons, for example, collide head on, the emitted particles are in the CMS of the collision almost always confined to two narrow cones centered on the axis defined by two colliding beams. Occasionally, however, particles emerge from the point of impact roughly perpendicular to the beam axis; if one such particle is detected, at least several more usually accompany it. What is the most intriguing is that when a fragment is shot to the side in this way, the particles are not scattered randomly in all directions, instead they are generally organized into jets; four-jet structures have been found.

As concerns the four-jet events, it has been found that[13]: a) The spectator jets[13] are present in the collisions with a large transverse momentum object produced; the spectator jets do not follow exactly the line of flight of incoming protons but deviate slightly in the away direction. b) Trigger jets[13] and away jets[13] do exist; the away jet transverse momentum does not balance that of a trigger jet. c) A rather high rate of resonance production in jets is observed. d) The average transverse momentum of jet fragments with respect to the jet axis is $\langle q_T\rangle \approx 0.5$ GeV/c, this value does not depend on the jet momentum.

We limited here the considerations to the nucleon-nucleon collision processes only, because a possibility exists now to test simply experimentally just these collisions, using the available hadron-nucleon collision data [13,14,16]. The mechanism of particle production in electron-electron, electron-nucleon, neutrino-nucleon collision process may be tested experimentally later on, applying the method worked out here for testing the particle production mechanism in nucleon-nucleon collisions.

4. EXPERIMENTAL BASIS OF THE NEWLY PRESENTED PICTURE OF HIGH ENERGY PARTICLE-PRODUCING COLLISION PROCESS

Two possible extreme variants of the particle production mechanism were tested experimentally[1,2] using nuclear targets as detectors of the properties of hadron-nucleon collision process, exactly speaking, of nucleon-nucleon collision process: a) The particles and resonances usually observed in the final state of hadron-nucleon collisions are created immediately. b) The production of particles and resonances in collisions of two hadrons a_1 and a_2 is mediated by intermediate objects a_3 and a_4 created at first in the hadron-nucleon two particle final state endoergic reaction, $a_1+a_2 \rightarrow a_3+a_4$, which decay, after some time, into finally observed particles and resonances; the lifetime of these objects has been supposed to be as long as it is needed for them to cover distances as long as the diameters of the most massive target-nuclei. It has been supposed as well that the intermediate objects a_3 and a_4 behave themselves in passing through the target-nuclei as the nucleons do it; in particular, they can create such objects in collision with downstream nucleons.

The expected outcome of the collision of definite hadron with definite target-nucleus, at definite momentum of the bombarding particle, can be determined in both cases a) and b). In the case a) the expectations come from the intranuclear cascade model[17-19]; in the case b) the expected outcome can be determined using the free-parameter-less model worked out by the author some years ago[20-22], in which the final state of hadron-nucleus collisions is described by simple formulas[1,2,20-22] in terms of known data on hadron-nucleon collisions and the size of the target-nucleus and nucleon density distribution in it.

The comparison was made of the predictions obtained in both cases a) and b) with appropriate experimental data at a wide energy value of the bombarding hadron, from about a few GeV up to about 1500 GeV, and results were published[1,2]. We found not necessary to repeat these results, they can be summarized here briefly only.

The experimental verification of the predictions given by the intranuclear cascade model shows that the case a) must be refused[1]. But, the experimental verification of the simple formulas[1,2,20-22] derived for the case b) shows a quantitative agreement of the predictions with available experimental data at the wide energy region of the bombarding hadrons, where the data exist[2].

Summing up, as a result of our investigations of the particle production process[1,2,20-22] in hadron-nucleon collision using nuclear targets as detectors[3], it should be concluded: Particle production in hadron-nucleon collisions proceeds through the intermediate objects a_3 and a_4 created first in a 2 → 2 endoergic reaction, $a_1+a_2 \rightarrow a_3+a_4$, and decaying then into finally observed particles and resonances. In the nucleon-nucleon collisions two such identical objects should be created because of identical conditions for both colliding nucleons. The average lifetime of these objects, called generons, is $\tau_g \gtrsim 10^{-22}$ s[1-3].

5. SUGGESTIONS OF EXPERIMENTAL TESTING

The simplest method of a further experimental testing of both the pictures of the particle production process, of the commonly used now[4,13,15] and of the new one[1,2], is to investigate the jet structure of the outcome in the head-on collision of two nucleons. In practice, this can be done in proton-proton colliding beam experiments, for example. Each of the two pictures leads to the expected characteristics of the outcome from the nucleon-nucleon collisions which are much different.

The differences in expectations of jet production characteristics become to be evident when corresponding schemes of the four-jet structures resulting from nucleon-nucleon collisions in the CMS, as seen within the frames of both particle production process pictures, are confronted, fig.1.

According to the hard scattering picture (fig.1b), left side). two constituents q_1 and q_2, of the nucleons a_1 and a_2, respectively, scatter elastically and, as scattered with large transverse momenta denoted by q_3 and q_4, show up as two jets of hadrons. One of them is used as a trigger jet, JTT, and the other one is an away jet, AJ. Two incoming hadrons, each with one constituent removed by the hard scattering, create two spectator jets or a target jet, TJ, and a beam jet, BJ. In my opinion, such scheme has been never tested experimentally adequately.

According to the new scheme (fig.1b), right side), two colliding protons a_1 and a_2 undergo the two-particle final state 2 → 2 endoergic reaction in which as reaction products two new objects a_3 and a_4 emerge that decay, after some time, into resonances and particles forming, in this way, the finally observed jets. We named these objects "intermediate" or "generons", which in the case of nucleon-nucleon collisions were

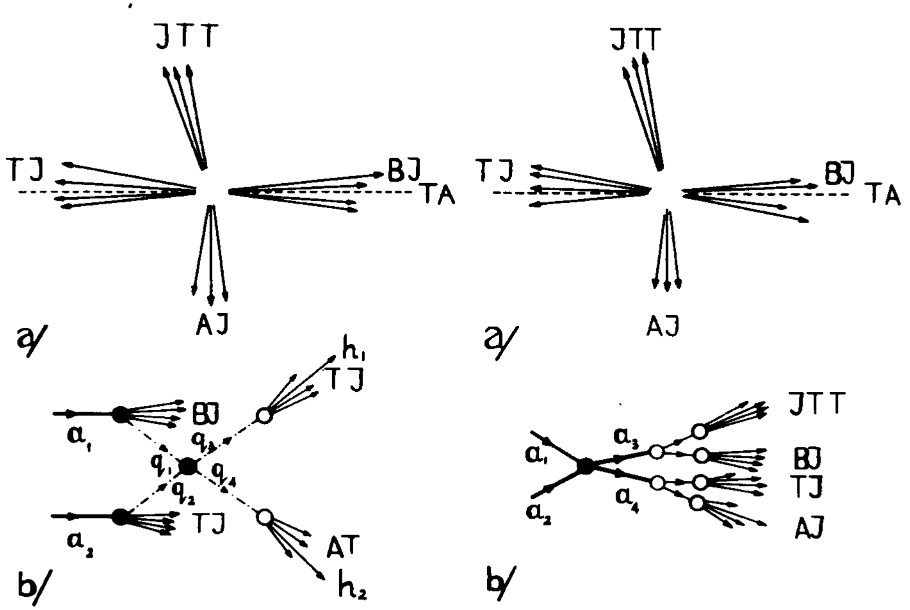

Fig.1. a) Illustrations of the four-jet structure resulting from a beam proton a_1 collision with a target proton a_2 in the CMS of colliding protons: left side - current picture; right side - new picture. b) Illustrations of the underlying structures of the large p_T processes: left side - $a_1 + a_2 \rightarrow q_1 + q_2 + X_1 + X_2 \rightarrow$ jets; right side - $a_1 + a_2 \rightarrow a_3 + a_4 \rightarrow$ jets. Denotations: TJ - target jet, JTT - jet towards trigger, BJ - beam jet, TA - towards away, AJ - away jet, q_1 and q_2 - scattering constituents, q_3 and q_4 - the constituents after scattering, $X_1 \equiv$ BJ, $X_2 \equiv$ TJ, h_1 - trigger hadron, h_2 - one of away jet hadrons.

identified with Weisskopf's "excited nucleon states"/24/. Obviously, the $a_1 + a_2 \rightarrow a_3 + a_4$ endoergic reaction can be regarded simply as a quasielastic 2 → 2 collision at energy high enough, in its early stage.

It was not found necessary to demonstrate that the relations between characteristics of jets, in the four-jet events, predicted on the basis of both schemes will differ at all. Certainly, some relations between characteristics of jets may follow from the current hard-scattering picture, we are not sure it is the case, however, we do not try to derive them

here. It is not possible to distinguish any related jets in the hard scattering picture. But, simple and experimentally testable relations should exist, if the new scheme is true. We present some of these relations here for testing in future experiments.

Suppose that all the particles, neutral and electrically charged, emerged in the final state of head-on proton-proton collisions, in which four jets can be distinguished, are detected and their four-momenta are determined in the CMS of the colliding protons. Then, the four-momenta P_{ji}, $i = 1,2,3,4$, of each of the jets are determined. Later we omit asterisks distinguishing the variables in the CMS. Moreover, according to our picture of the particle production process, corresponding two pairs of related jets are from the decay of the two intermediate objects a_3 and a_4 into two decay products. Then, combining four of the observed jets into pairs of the related jets, momenta and masses of generons a_3 and a_4 can be determined. There are six possible combinations into pairs from the four jets registered, but the combinations of pairs of the related jets will be correctly correlated the four momenta of which obey the kinematical relations for the 2 → 2 reactions. In some cases, depending on the energy of the colliding protons, the corresponding related jet-pairs can be found simply, almost visually - the related jets may be spatially distinguished.

Let us denote the four-vectors describing the collision products a_3 and a_4 as $P_{a_3} = (\vec{p}_{a_3}, iE_{a_3})$ and $P_{a_4} = (\vec{p}_{a_4}, iE_{a_4})$, where $\vec{p}_{a_3}$ and $\vec{p}_{a_4}$ are the space parts of the four-momenta, and E_{a_3} and E_{a_4} are energies. Simple, experimentally testable relations between $\vec{p}_{a_1}$, $\vec{p}_{a_2}$, $\vec{p}_{a_3}$, $\vec{p}_{a_4}$, E_{a_1}, E_{a_2}, E_{a_3}, E_{a_4} can be written in the CMS of the colliding protons:

$$\begin{gathered} \vec{p}_{a_1} + \vec{p}_{a_2} + \vec{p}_{a_3} + \vec{p}_{a_4} = 0, \\ E_{a_1} + E_{a_2} = E_{a_3} + E_{a_4} = E = \text{constant}, \end{gathered} \tag{1}$$

and

$$\vec{p}_{a_3} + \vec{p}_{a_4} = 0, \tag{1'}$$

as a consequence from the energy and momentum conservation relations for the 2 → 2 type collisions;

$$[[\vec{p}_{a_1} \cdot \vec{p}_{a_3}] \cdot [\vec{p}_{a_2} \cdot \vec{p}_{a_4}]] = 0 \tag{2}$$

expressing the coplanarity of the four vectors $\vec{p}_{a_i}$, where $i = 1, 2, 3, 4$ and[ ] denotes the vector product;

$$[\vec{p}_{a_1} \cdot [\vec{p}_{a_{31}} \cdot \vec{p}_{a_{32}}]] = 0 \qquad (3)$$

and

$$[\vec{p}_{a_2} \cdot [\vec{p}_{a_{41}} \cdot \vec{p}_{a_{42}}]] = 0, \qquad (3')$$

expressing the coplanarity of the triplets of vectors $\vec{p}_{a_2}$, $\vec{p}_{a_{41}}$, $\vec{p}_{a_{42}}$ and $\vec{p}_{a_1}$, $\vec{p}_{a_{31}}$, $\vec{p}_{a_{32}}$, where $\vec{p}_{a_{31}}$, $\vec{p}_{a_{32}}$, $\vec{p}_{a_{41}}$, $\vec{p}_{a_{42}}$ are the space parts of the four-vectors of the two related jets, 1 and 2, appearing when the objects a_3 and a_4 decay into two-component states.

We remember that the relations (1)-(3') are valid only for the four-jet events. It would be useful to find out some experimentally testable relations for collision events when more than four jets emerge in the final state; this can be done in fact.

Let us suppose that, according to our new picture of the particle production process, the jets observed are in fact the product of the decays of the generons a_3 and a_4. It is known from many experiments that the part of the total energy of the collision reaction transformed into the rest energy of the particles finally appearing is small; at about tens GeV nearly a few per cent, and it decreases with increasing the incident particle kinetic energy. Therefore, the kinetic energy of the objects a_3 and a_4 increases with increasing the kinetic energy of the colliding protons a_1 and a_2; at extremely high energies of the projectile particles the decays of the objects a_3 and a_4 into many jets will be observed as the transition of a_3 into one jet and of a_4 into another one. Therefore, we are able to expect that at extremely high energies of the colliding particles, the collision events will look like two-jet events; only a special analysis of the jet structure may show that the obserbed single jets are in fact composed of two or more jets; the finally emitted particles will be usually confined to two narrow cones centered on the axis defined by the two colliding beams. Occasionally, however, the common axis of the two jets observed will be at relatively large angle θ to the beam axis. In other words, two jet events will be observed in which jets are emitted at large angles θ_{j1} and θ_{j2} obeying the relation: $\theta_{j2} = 180° - \theta_{j1}$, fig.2. It should be emphasized that such large-jet-emission-angle events may be rarely occurring phenomenon.

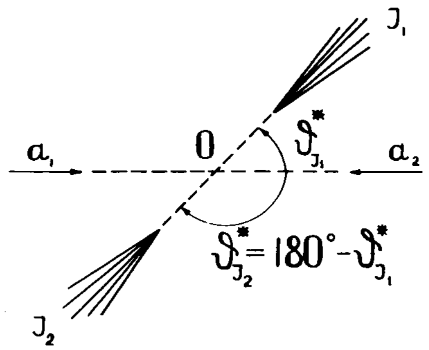

Fig.2. Possible two-jet events at ultra-high energies of colliding nucleons a_1 and a_2. J_1 and J_2 - produced jets, o - point of impact, $\theta^*_{J_1}$ and $\theta^*_{J_2}$ - jet emission angles.

One more important expectation, testable experimentally, following from the above presented considerations, is: The jet structure picture observed in the outcome of proton-proton collisions will change with increasing the colliding particle energy in the CMS, starting from some GeV up to extremely high energies. At energies of some GeV the jet structure cannot be practically visible, without special analysis. At higher energies, at tens GeV, many-jet events will appear. At energies larger than about some thousands GeV two-jet events will appear only. The change of the observed picture can be predicted simply quantitatively on the basis of the two-particle final state kinematics, with increasing the kinetic energy of the colliding particles.

We do not expect such properties of the jet structure of the proton-proton collision outcome within the frames of the current picture, where the hard scattering of the nucleon constituents is taken into account.

6. CONCLUSIONS AND REMARKS

Let us sum up the consequences from our consideration presented above.

Experimental studies of the early stage of the particle production process, performed by means of nuclear targets used as detectors of the properties of this process, lead to the conclusion that particles are produced via intermediate objects created at first in a 2→2 type endoergic reaction; these objects decay in flight into finally observed resonances and particles after the lifetime $\tau_g \geq 10^{-22}$s. From this picture of the particle production process it follows that:

1. The jet structure of the outcome in nucleon-nucleon collisions is a simple and indispensable consequence of the par-

ticle production mechanism prompted by experiments in which nuclear targets are used as detectors.

2. The picture of the jet structure of the collision outcome observed in the CMS of the colliding nucleons depends on the energy of the colliding nucleons; the simply visible many-jet events should appear within a definite energy interval only, outside this interval many-jet structure may be detected only by means of some special analysis.

3. The newly experimentally discovered scheme of particle production in nucleon-nucleon collisions (fig.1b, right side) differs by much from the currently being in use hard-constituent-scattering scheme (fig.1b), left side).

4. Using relations (1)-(3′), it is possible to distinguish experimentally which of the two schemes, the current or the new one, corresponds to reality.

In many works the jet structure of the outcome in nucleon-nucleon collisions is proposed to use for nucleon structure studies[25,26]. But, in the light of the above presented conclusions, it should be emphasized that before the information on the jet structure of nucleon-nucleon collision events could be used for the nucleon structure elucidation, the information about the particle production mechanism in the early stage of nucleon-nucleon collisions should be taken into account.

In my opinion, all particle-producing collision schemes being currently in use when the collision of any sort of particles is considered[4,14,27] should be tested experimentally in a similar way, as it is possible to do it in the case of the nucleon-nucleon collisions.

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Струи в нуклон-нуклонных столкновениях при высоких энергиях

Экспериментальные исследования адрон-нуклонных и нуклон-нуклонных столкновений при высоких энергиях, с использованием ядерных мишеней как детекторов, приводят к заключению, что частицы рождаются посредством промежуточных объектов, рожденных сперва в эндоэргической реакции типа 2 → 2. Эти объекты, называемые генеронами с временами жизни $\tau_g \geq 10^{-22}$ с, распадаются на лету на обычно наблюдаемые частицы и резонансы. Струйная структура выхода в нуклон-нуклонных столкновениях является прямым и необходимым следствием такого механизма рождения частиц. Картина струйной структуры конечных состояний в столкновениях, наблюдаемая в СЦМ сталкивающихся нуклонов, зависит от энергии этих нуклонов. Предлагается новая схема процесса образования частиц, проверяемая на опыте; предлагаются простые соотношения между характеристиками сталкивающихся нуклонов и образованных струй для экспериментальной проверки.

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Jets in High Energy Nucleon-Nucleon Collisions

From our experimental studies of high energy hadron-nucleon and nucleon-nucleon collisions, by means of nuclear targets applied as detectors, it follows that particles are produced via intermediate objects created first in a 2 → 2 type endoergic reaction. These objects, called generons, decay in flight into finally observed particles and resonances after their lifetime $\tau_g \geq 10^{-22}$ s. The jet structure of the outcome in nucleon-nucleon collisions is a simple and indispensable consequence of this particle production mechanism. The picture of the jet structure in the collision outcome observed in the CMS of the colliding nucleons depends on the energy of these nucleons. New particle production scheme is proposed, which can be tested experimentally; corresponding simple relations between characteristics of colliding nucleons and of produced jets are proposed for a testing.

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

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