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Z.Strugalski

FREE-PARAMETERLESS MODEL OF HIGH ENERGY PARTICLE COLLISIONS WITH ATOMIC NUCLEI

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1. INTRODUCTION

In this paper I present a new view of high energy hadron-nucleus collision process or, in general, of the process of interaction of high energy particles with nuclear matter.

We call "high" the kinetic energies of the projectiles if larger than the threshold energy for pion production; by the term "nuclear matter" a spherical collection of nucleons is called, of definite size and nucleon density distribution, known in the nature as the atomic nucleus.

My belief is that a major breakthrough has occurred due to complex experimental study of hadron-nucleus collisions[1-8] and that within a relatively short period we are going to achive a depth of understanding and quantitative description of the particle-nucleus collision, and of the hadron-nucleus collision in particular, that a few years ago I did not expect to see. I present my view of the process as prompted to me by experiments performed during the last fifteen years with my co-workers[1-8].

What does it mean "to understand and describe the particle-nucleus collision process quantitatively"?

A number of examples from the history of classical physics and quantum mechanics teach the general procedure by which we acquire physical understanding, creating finally physical models and theories. Three elements are prerequisite to a quantitative understanding of a physical phenomenon: a) a qualitative picture of this phenomenon; b) a precise knowledge of the behaviour of the variables characterizing the phenomenon; c) the boundary conditions. Many models and theories were constructed in such a way.

A qualitative picture is usually based on a few selected experimental results which are first oversimplified and codified for introduction into model or theory that may contain a good deal of additional human invention springing from the physicists imagination, and not from direct experimental facts. On this, sometimes neither too precisely nor too logically specified, basis a theoretical system is built and quantitative predictions are made. If these predictions are checked by experiments with sufficient accuracy, the model or theory is considered to be good, at least as a point of departure, otherwise, the model or theory is just good for the waste basket.

Generalizing from commonly applied procedure for the process discussed here, it can be concluded that this process will be regarded as understood and described quantitatively when characteristics of the outcome observed in the final states of the particle-nucleus collisions will be expressed in terms of corresponding characteristics of the outcomes in the final states of corresponding particle-nucleon collisions and of the data on target-nuclei sizes and nucleon density distributions in them.

This procedure influenced the composition of this work in which free-parameterless model of the particle-nucleus collision process is presented; the outcome of hadron-nucleus collisions is expressed in it in terms of data on hadron-nucleon collisions and of data on the target-nuclei size and nucleon density distributions in them in a convincing manner. The paper is arranged as follows: after short introduction, in section 1, we start, in section 2, with the presentation of the picture of the hadron-nucleus collision process and of the behaviour of fundamental characteristics of this process; in section 3, entitled "The Description Procedure", our model is described; in this section various predictions of the model are presented in the form of simple formulas testable experimentally. In section 4 results of preliminary experimental testing of the model, performed till now, are resummed shortly. Remarks, in section 5, end this work.

2. THE PICTURE OF THE HADRON-NUCLEUS COLLISION PROCESS

The picture is to be drawn now was seen in studying experimentally the nucleon emission process accompanying the hadron-nucleus high energy collisions [1,2,9-11].

2.1. Experimental Facts

In result of our experimental studies [9-11] and of the analysis [3,4,9,10,12-18] of various experimental data available [9-11,19,20] it can be concluded that: a) Interactions of an incident hadron with nuclear matter, leading to "fast", of kinetic energy from about 20 to about 400 MeV, nucleon emission and particle production, are localized predominantly to a narrow cylindrical volume [3,14] of the diameter as large as nearly two nucleon diameters D_0 situated coaxially along the hadron course [3,4,9,10,15-18]. b) The emission of fast nucleons, in particular of the usually observed fast protons, proceeds independently of the particle production process [9]; events occur in which incident pion, of energy much higher than the threshold for pion production, is deflected only through some angle in an accompaniment of the nucleon emission but without pion production [1,2,5]. c) A definite simple relation exists between the hadron deflection angle and the thickness of the nuclear matter layer traversed by this hadron[21]. d) Any high energy hadron induces monotonously the nucleon emission of fast nucleons from the target-nucleus when passes through it [11]; definite and simple relation exists between the nucleon emission intensity, measured by the multiplicity n_N of emitted nucleons, and the nuclear matter layer thickness λ traversed by the hadron[10]: $n_N = \pi D_0^2 \cdot \lambda \cdot \bar{\rho}$, where $\bar{\rho}$ is the average nucleon density along λ. e) The particle-producing interactions of the incident hadrons with nuclear matter occur in result of collisions of the hadrons with single nucleons inside target-nuclei[12]. f) The particle production in hadron-nucleon collisions, in nucleon-nucleon collisions in particular, is mediated by intermediate objects created first in a 2 → 2 type endoergic reaction in the early stage of the collision [12,13]; these objects behave themselves in passing through nuclear matter as usual hadrons do it [18] and decay in flight after having left the most massive target-nuclei, as of the lifetime large enough[13,17] - of $\tau_g \geq 10^{-22}$ s. g) Many of predictions given by the orthodox intranuclear cascade model[22] disagree with experimental data at incident hadron energies where an agreement is expected [6,12]. h) The proton density distribution in atomic nuclei is known[23]; the ratio of the neutron number N_n to the proton number N_p in atomic nuclei is almost constant within them, being $N_n/N_p \approx A/Z$, where A is the mass number and Z is the atomic number [7,8,23]. i) Any target-nucleus can be characterized by its thickness $\lambda = \lambda(b)$ at any impact parameter b, its maximum thickness λ_{max}, and its average thickness $\langle\lambda\rangle$, measured in units of the proton number n_p per the area $S = \pi D_0^2 = \pi\, 1.81^2$ fm^2. j) The number n_p, or the multiplicity n_p, of the emitted fast protons in any hadron-nucleus collision event with $n_p \leq n_p(D)$ is the measure of the thickness λ of the nuclear matter layer which a collision occurs with [24,25], if λ is expressed in units of the number n_p of protons per the area $S = \pi D_0^2$; $n_p(D)$ is the number of protons emitted when an incident hadron causes monotonous nucleon emission in its passage along the target-nucleus diameter D. k) Any projectile-particle can be characterized by the mean free path in nuclear matter for a given type of a particle-nucleon collision [24,25]; the mean free path can be determined experimentally [24], it is connected simply with corresponding cross-section σ_0 for appropriate particle-nucleon collision[24-26-28]. $\langle\lambda_0\rangle = 1/(\bar{\rho}\sigma_0)$, where $\bar{\rho}$ is the average density of nucleons in nuclear matter along the particle path.

The above presented conclusions, which may be regarded as experimental facts, allow one to create a picture of the hadron-nucleus collision process, or in general of the particle-nucleus collision process, which differs by much from any of pictures being currently in use.

I would like to present now this picture, limiting at first the considerations to hadron-nucleus collisions only.

2.2 The Picture of the Hadron-Nucleus Collision Process

When a high energy hadron is incident on an atomic nucleus, it may undergo various processes as it interacts with nuclear matter. This hadron, as is known from experiments[1,3,9], can traverse the target-nucleus without causing particle production or it can come into particle-producing collision with one of the downstream nucleons met at any depth. In passing through a layer of nuclear matter a hadron losses monotonously its energy and is deflected from its initial course; the passage is always accompanied by fast nucleon emission.

The hadron energy losses[29] manifest themselves just in the monotonous nucleon emission[11]; about $\epsilon \approx 160$ MeV losses a pion per one of nucleons emitted from the target-nucleus[29]. The emission is not a result of simple knocking out of nucleons by the projectile in its passage through nuclear matter[11]. The mechanism of the nucleon emission is still unclear. One the most probable possible mechanism could be such that along the projectile-hadron path in nuclear matter slow mesons monotonously appear, of such energies at which they are absorbed simply by two or more nucleon groups; the excited many-nucleon systems formed in such a way, of relatively small kinetic energies, can move inside the target without causing nucleon emission in ones turn and decay, after having left it, into nucleons[11].

In most of cases the hadron deflection angles θ_h are smaller than nearly 30 degrees[3,4], however, many events exist in which larger angles are observed; in such large-deflection-angle events enlarged proton emission is evidently seen[3,4]. The deflection that the projectile-hadron undergoes in traversing nuclear matter layer of finite thickness may be caused either by a single collision or by many collisions with nucleons; it can be proved that large deflections are more likely to occur in single collisions, while the small ones are generally a result of many collisions. The result of a single collision is referred to as a single scattering; the result of a small number of collisions, as plural scattering; the result of a large number of collisions, as multiple scattering. We think the reason for the existence of events in which small deflection angles occur to be the multiple subsequent collisions resulting deflections through small angles; the reason for the existence of the events in which large deflection angles are observed to be such that single collisions occur. In such single collisions the recoil nucleons may appear of energies large enough they could cause the monotonous emission of nucleons from the target as well as in traversing it; we think it to be the cause for the appearance of the enlarged nucleon emission intensity in the hadron-nucleus collision events without particle production in which the projectile-hadrons underwent the deflection through large angles.

The hadron-nucleus collision events without particle production are relatively rare phenomenon. Events in which particles are intensively produced occur predominantly. The particle production is a result of some particle-producing head-on collision of the incident hadron with one of the nucleons inside the target-nucleus. Such collision may happen with any of nucleons met by the incident hadron along its path in nuclear matter which it has to overcome. In many cases the deflection and the energy losses of the projectile-hadron, and the monotonous fast nucleon emission accompanying hadron passage through nuclear matter, may occur in advance of the particle-producing collision with one of nucleons.

The particle-producing hadron-nucleon collision is of the type 2 → 2 endoergic reaction in an early stage of the collision. In result of some collision of such a type two intermediate objects, called generons, are created which decay into finally observed particles and resonances after some lifetime. Their liftetime /12,13,17/ is $\tau_g \geq 10^{-22}$ s, which is large enough them to be possible to traverse as large thickness λ of nuclear matter layers as the diameters of the most massive atomic nuclei are.Before decays, these objects behave themselves identically as usual hadrons do it /12,13/: they cause monotonous nucleon emission and they can undergo the particle-producing collisions with single nucleons in atomic nucleus, resulting the appearance of new intermediate objects. When a high energy hadron or intermediate object collides head on, the emitted in the early stage of the collision two intermediate objects are almost always confined to narrow angle centered on the axis defined by the two colliding particles.

In collisions of high energy hadrons, of energy much higher than the threshold for pion production, with massive target-*nuclei, almost unidimensional* cascades of the intermediate objects develop in nuclear matter. The commonly observed outcome in hadron-nucleus collisions - many particles and resonances - is in fact a result of almost simultaneous decay of a few *intermediate objects emerged outside the* target-nucleus into these particles and resonances. The outcome of the decay of any one of the intermediate objects can be treated as statistically independent of the outcomes in decays of all the rest intermediate objects.

In the cascading process the kinetic energy of the incident hadron is distributed between the intermediate objects created; it is a reason to suppose an equipartition in this distribution.

It may be formulated, therefore, the theorem concerning the particle production process in hadron-nucleus collisions: 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 being in average E/m. This theorem is a simple consequence of the mechanism of the particle production process in hadron-nucleus collisions and is testable in experiments. It is of great importance as a basis for quantitative description of the particle production process in hadron-nucleus collisions and, in general, in any sort of particle-nucleus collisions.

3. THE DESCRIPTION PROCEDURE

What is the common feature in the sample of hadron-nucleus collision events collected in experiments performed using any technique - bubble chambers, nuclear photoemulsions, electronic detectors? One common feature can be recognized, and we think it crucial: in games of chance in the collision processes we find events repeating themselves again and again. They are mass phenomena or repeative events; this unlimited repetition, this "mass character" is typically present in the case of all the events under studies.

In fact, as usually is practiced, the observable characterictics correspond to definite reactions - to the sample of collisions of definite identical hadrons with definite identical target-nuclei, at definite energies. We have, therefore, in experiments a practically unlimited sequence of uniform observations. The rational concept of probability applies both to problems in which either the same event repeats itself again and again, or a great number of uniform elements are involved which may be treated as occurring at the same time. True, in any collision the target-nucleus is destroyed, but in any collision identical projectile-hadron and identical target-nucleus are always involved. It enables us, in attempts to describe the hadron-nucleus collision process quantitatively, to treate the sample of collision events as interaction of a homogeneous monoenergetic beam of parallelly moving hadrons with a "slab" of nuclear matter. The way this problem is formulated is similar to that in absorption experiments, when the interaction of a particle beam with a slab of material is studied, for example - when the absorption of gamma rays by matter is studied/30/.

3.1. The Methematical Formalism

We can conclude, therefore, from the above-presented consideration, that the theory of probability and statistics/31,32/ is the mathematical foundation naturally suitable to provide mathematical formalism adequate for a quantitative description of the hadron-nucleus collision processes, especially of the particle production phenomenon in them.

Any of events registered in an experiment is characterized by its measurable properties, or measurable quantities, which can vary from one individual to another. There are known such properties as, for example, the number n_p of emitted protons - or the proton multiplicity, the number n_π of produced pions - or the produced pion multiplicity, the kinetic energy E_{ks} and emission angle θ_s of various secondaries, and others. A measurable quantity which can vary from one individual to another is called, in the theory of statistics/31/, a variable.

Usually some hundreds of thousands of values of a variable are noted merely in the arbitrary order in which they occur in experiments, the mind cannot properly grasp the significance of the record. The data are condensed, therefore, by some method of ranking or classification before their characteristics can be comprehended. A manifold classification may be made as numerous as we please/31/. Numerical measurements lend themselves with peculiar readiness to a manifold classification, for the class limits can be conveniently and precisely defined by assigned values of the variable. For convenience, the values of the variable chosen to define the successive classes are usually equidistant, so that the numbers of observations in different classes are comparable. The interval chosen for classifying is called the class-interval, and the frequency in a particular class-interval is called a class-frequency. The manner in which the class-frequencies are distributed over the class-intervals is spoken of as the frequency-distribution of the variable. It is often convenient to present the frequency-distribution by means of diagrams: frequency-poligons and histograms.

There are a few quantities characterizing frequency-distributions. But, two characteristics in which similar frequency-distributions may differ are of most importance: 1) The position, i.e., the value of the variable round which they centre; 2) The extent to which the observations are dispersed about the central value. Of less importance are the commonly known characteristics comprising differences in skewness, peakedness, and so on.

Measures of the position or location are generally known as averages; measures characterizing the extent to which the observations are dispersed about the average are termed measures of dispersion.

Precise definitions and properties of various measures of the position and of various measures of dispersion can be found in any book devoted to the theory of probability and statistics. We omit here these definitions and we found not necessary to discuss here the properties of averages and dispersion-measures, as commonly known.

After the above-presented short discussion about general behaviour of the characteristics of the outcome in hadron-nucleus collisions, it is possible to start now to show how to express quantitatively the results of these collisions in terms of corresponding data on the outcome in hadron-nucleon collisions and on the target-nucleus size and nucleon density distribution in it.

It is reasonable to start with a presentation of the input and the output data.

3.2. Input and Output Data

According to an analogy of the hadron-nucleus collision experiments, in which nuclear targets are treated as nuclear matter "slabs", to the particle absorption experiments, in which incident particles collide with material slabs, it is simply to determine adequate set of input data. This set should consist of three subsets: a) Determining an ability of projectile-hadrons to their interaction with nuclear matter. b) Describing target-nuclei as nuclear matter "slabs". c) Expressing appropriate characteristics in hadron-nucleon outcome.

3.2.1. The Projectile-Hadron

The intensity of an occurrence of some sort of hadron-nucleus collisions, for example - collisions in which some number n_π of produced pions emerge in the final state, is determined by appropriate mean free path $\langle\lambda_0\rangle$ of the hadron in nuclear matter before to come into collision of this sort.

It is known /24/ that the mean free path $\langle\lambda_0\rangle$ is determined simply by appropriate cross-section σ_0 for corresponding hadron-nucleon collisions /12,24/. It is natural to express this quantity in units of nucleons per the area $S = \pi D_0^2$, because the number of nucleons per this area is a natural measure of nuclear matter layer thickness /24,26/. We have then:

$$\langle\lambda_0\rangle\left[\frac{\text{nucl.}}{S}\right] = \frac{1}{\sigma_0}, \qquad (1)$$

where σ_0 is expressed in units of S per nucleon.

In experiments nuclear matter layer thickness is naturally to express in units of protons per S, because protons are simply detectable with an efficiency near to 100% and the observed proton multiplicity $n_p \leq n_p(D)$ is a measure of the nuclear matter layer thickness involved in a collision as well /12,13/.

Taking into account that neutron-proton ratio in atomic nuclei is almost radially-independent, being of about A/Z for any nucleus, $\langle\lambda_0\rangle$ can be expressed in units of protons per S as:

$$\langle\lambda_0\rangle\left[\frac{\text{protons}}{S}\right] = \langle\lambda_0\rangle\left[\frac{\text{nucleons}}{S}\right]\cdot\frac{Z}{A} = \frac{Z}{\sigma_0 A} = \langle\lambda_0(A,Z)\rangle . \qquad (1')$$

The quantity $\langle\lambda_0\rangle$ expressed in nucleons per S is independent of A, but the expressed in protons per S is A-dependent, because Z/A varies with A.

3.2.2. The Target-Nucleus as Nuclear Matter Slab

Any target-nucleus used as nuclear matter "slab" is determined by the maximum thickness λ_{max}, the average thickness $\langle\lambda\rangle$, and the thickness $\lambda(b)$ corresponding to an impact parameter b. It is natural to express all these quantities in units of protons per the area S. All they are determined by the experimentally known quantities describing any atomic nucleus of a given A and Z: the nucleon density radial distribution $\rho(r)$ and the neutron-proton ratio distribution $N_n/N_p = (A-Z)/Z$ = constants /7,8,23/.

We omit here detailed definitions of the quantities λ_{max}, $<\lambda>$, and $\lambda(b)$ because it has been done in our former work for many atomic nuclei /24,25/.

3.2.3. Characteristics of the Outcomes in Hadron-Nucleon Collisions

The outcome in any sort of hadron-nucleon collisions is expressed by means of various frequency-distributions, corresponding averages and measures of dispersions. Usually, these frequency-distributions are simply the produced particle multiplicity distributions, for example - pion multiplicity distributions, the spectra of kinetic energy of any sort of produced particles, the longitudinal P_L and transverse P_T momentum distributions of various secondaries, secondary particle emission angle distributions θ_s, rapidity distributions, and many other various characteristics. In principle, all the frequency-distributions and corresponding moments can be obtained in hadron-nucleon collision experiments at any hadron energy E.

3.2.4. Remarks and Comments

Ending this sub-section 3.2., I would like to emphasize that: a) All the input data are obtained experimentally; in many cases sets of input data exists now and can be used for descriptions of the outcomes obtained in various hadron-nucleus collision experiments. b) Not any free parameters are involved. c) Any of predicted frequency-distributions and corresponding moments are testable experimentally.

Frequency-distributions and corresponding moments are not available now for hadron-nucleon collisions at any incident hadron energy E, but many exist now at such energies that it is possible to perform approximate calculations of expectations for corresponding hadron-nucleus outcomes with an accuracy high enough for comparison with existing hadron-nucleus collision data.

Information about the projectile-hadron and about the target-nucleus, as given in sub-sections 3.2.1 and 3.2.2., forms a set of the boundary conditions in our model. In other words, the boundary conditions in hadron-nucleus collisions are defined by: the sort of incident particle and its energy; the mass number A and the atomic number Z of the targetnucleus.

3.3. Quantitative Predictions

Three main processes should be described quantitatively in terms of the input data: a) Nucleon emission from atomic nuclei induced by high energy hadrons traversing them. b) Hadron deflection in its passage through layers of nuclear matter. c) Particle production caused by high energy hadrons falling on atomic nuclei. All these processes occur with definite cross-sections at any incident hadron energy E.

Let us start from expressions for a relation between a cross-section for hadron-nucleon collision and corresponding cross-section for hadron-nucleus collision.

3.3.1. The Cross-Sections

Let us treate many hadron-nucleus collisions as a collision of a beam of hadrons with a nucleus or a nuclear matter "slab".

When a beam of hadrons of intensity high enough is incident on a nucleus, or, in other words, on a lens-shaped nuclear matter "slab" of the A-depending radius $R(A)$, some of the hadrons in passing through it cause the monotonous nucleon emission and are deflected through various deflection angles only, the other undergo as well such interactions with nucleons inside the "slab" which lead to the particle production.

The cross-sections for both the processes occurring together equal the geometrical cross-section $\sigma_{hA\ geom.} = \pi R^2(A)$. But, in experiments, especially in those when the cases of hadron absorption due to the particle-producing collisions are registered only, the cross-section for the hadron-nucleus collisions is smaller than the geometrical one. Cross-sections σ_{hA} for any sort of the hadron-nucleus collisions can be determined when appropriate mean-free-paths $<\lambda_0>$ are known.

Let us consider, as an example, the cross-section for the particle-producing hadron-nucleus collisions $\sigma_{hA\ in}(E, A)$ at a definite hadron energy E; corresponding mean-free-path in nuclear matter we denote by $<\lambda_0(E, A)>_{in}$ in units of protons per S. We can write:

$$\sigma_{hA\ in}(E, A) = 2\pi \int_0^{b_{max}} b\left(1 - e^{-\frac{2\sqrt{R^2(A) - b^2}}{<\lambda_0(E,A)>_{in}}}\right) db = T_1 - T_2. \qquad (2)$$

The first term T_1 in relation (2) expresses the geometrical cross-section for hadron-nucleus collisions, the second term T_2 expresses the cross-section for incident hadron to pass through the "slab" without inelastic interactions.

The cross-section $\sigma_{hA}(E, A)_f$ for a given inclusive reaction can be obtained from formula (2) by replacing $<\lambda_0>_{in}$ by appropriate fractional mean-free-path $<\lambda_0>_f$.

3.3.2. Nucleon Emission from Target-Nuclei

The most often discussed characteristic of high energy hadron-nucleus collisions is the frequency-distribution of events with definite number n_N of nucleons emitted when a hadron of kinetic energy E collides with atomic nucleus of the mass number A. In experiments the frequency $f(n_p, E, A)$ of events with definite number n_p of emitted protons is usually studied, instead of the events with definite n_N, because neutrons cannot be registered in many cases.

According the statements from points d) and h) in subsection 2.1., the number n_p of monotonously emitted fast protons along the path λ in nuclear matter is:

$$n_p = \pi D_0^2 \lambda \cdot \bar{\rho} \cdot \frac{Z}{A} . \qquad (3)$$

This relation is true when $n_p \le n_p(D)$, and it can be written: $\lambda[\frac{\text{prot.}}{S}] \equiv n_p[\frac{\text{prot.}}{S}]$.

It has been shown how can be approximate formulas for the frequency-distribution $f(n_p, A, E)$ derived /10,16,27/; derivation is based on experimental information about the proton emission process.

This frequency-distribution can be expressed naturally as

$$f(n_p, A, E) = f_1(n_p', A, E) + f_2(n_p'', A, E) , \qquad (4)$$

where the proton multiplicity $n_p = 0, 1, 2, 3, \ldots = n_p' + n_p''$ and $n_p' = 0, 1, 2, \ldots, n_p(D)$, $n_p'' = 0, 1, 2, \ldots$. In the first term f_1 events, in which monotonous nucleon emission occurs only, are taken into account, in the second term f_2 events, in which "secondary" monotonous nucleon emission caused by recoil nucleons of energy high enough is present, are taken into account.

It is almost impossible to express simply the term f_2, but the first term f_1 can be expressed by simple formulas for wide special classes of hadron-nucleus collisions observed in experiments. The most simple expression is for the case when hadrons, in passing through a nuclear matter "slab", do not undergo deflection through large angles, larger than about 30 degrees, and do not come into particle-producing collisions with downstream nucleons. Then, the frequency-distribution $f_1(n_p, A, E) = f_1(n_p, A, E)_d$ is obviously:

$$f_1(n_p, A, E)_d = W_0(n_p, A)\, e^{-n_p/\langle\lambda_0\rangle_r} , \qquad (4')$$

for $n_p \le n_p(D)$. $W_0(n_p, A)$ is defined by the target-nucleus size and nucleon density distribution in it, it can be found in our former work /26/; $\langle\lambda_0\rangle_r$ $[\frac{\text{prot.}}{S}]$ is the mean-free-path for a collision in result of which incident hadron is deflected through an angle larger than 30 degrees.

Per analogy, similar formula may be written for the frequency-distribution $f_1(n_p, A, E) = f_1(n_p, A, E)_{in}$ in the sample of events when particle-producing collisions take place without events in which the incident hadron is deflected through an angle larger than 30 degrees, before to come into collision with one of downstream nucleons, and without events in which at least one of the intermediate objects created underwent the deflection through an angle larger than 30 degrees:

$$f_1(n_p, A, E)_{in} = W_0(n_p, A)\left(1 - e^{-n_p/\langle\lambda_0\rangle_{in}}\right) e^{-n_p/\langle\lambda_0\rangle_r} , \qquad (4'')$$

where $n_p \leq n_p(D)$, $\langle\lambda_0\rangle_{in}$ and $\langle\lambda_0\rangle_r$ are mean-free-paths for corresponding processes - particle production and hadron deflection through large angles, both expressed in units of protons per S.

3.3.3. Incident Hadron Deflection in Its Passage Through Nuclear Matter

According to our picture, the deflection of an incident hadron in passage through nuclear matter can be considered as the multiple scattering. In treating this scattering quantitatively we are able to consider a nuclear matter "slab" as consisted of uniformly distributed nucleons. In this case we can write for the mean deflection $\langle\Theta_h\rangle$ of a hadron in passing through a thin "foil" of nuclear matter of a thickness λ measured in number of nucleons per the area S:

$$\langle\Theta_h\rangle = \langle\theta_h\rangle \cdot \lambda^{1/2} , \qquad (5)$$

where $\langle\theta_h\rangle$ is the average deflection, in degrees, which a hadron undergoes in passing through a thickness of the nuclear matter layer $\lambda = 1$ nucleon/S; for pions $\langle\theta_\pi\rangle$ is about 8.5 degrees per $\lambda = 1$ nucleon/S.

Formula (5) is similar to formula used by Thomson for the mean deflection of alpha particles in their passage through this foils of metal /34/.

3.3.4. Particle Production

We consider now the particle production process in hadron-nucleus collisions at any incident hadron energy E. All what is seen as an outcome in a collision is a composition of some number m of statistically independent outcomes which could be observed separately in elementary hadron-nucleon and nucleon-nucleon collisions at incident particle energy values of about E/m. The quasi-elementary collisions occur when the incident hadron and the produced generons come into collisions with nucleons and the quasi-unidimensional intranuclear cascade of generons develops. The quantity m depends on the nuclear matter layer thickness λ [protons/S] which incident hadron has to overcome in a collision. It is possible, as we show later, to derive exact formulas for the average value $<m>$ and for the probability $P(m, t)$ that a value m will appear when a hadron is incident on nuclear matter "slab" of a thickness $t = \lambda / <\lambda_0>$.

Let us treat meantime $P(m, t)$ and $<m>$ as known and apply our theorem formulated in section 2. In the theory of probability and statistics there are simple relations between a composition of m statistically independend frequency-distributions and its moments and the component distributions and their moments. We use these relations and write similar ones for the frequency-distributions, average values $<v>$ of variables v and for normalized dispersions $Z = (<v^2> - <v>^2)^{1/2} / <v>$ in the case under consideration.

The relation between a frequency-distribution $F_{hA}[v_{hA}(E, h, t)]$ of a variable $v_{hA}(E, h, t)$ characterizing some process in hadron h collision with nuclear matter layer of a thickness t in a target-nucleus of the mass number A and the atomic number Z, at an energy E, and frequency-distributions $f_{hN}[v_{hN}(E', h, N)]$ of corresponding variable $v_{hN}(E', h, N)$ characterizing corresponding process in collisions of this hadron h with nucleons N, at energies $E' = E/m < E$, can be written:

$$F_{hA}[v_{hA}(E, h, t)] = \sum_{m=1}^{m=k} P(m, t)\, \Phi_m \{ f_{hN}[v_{hN}(\frac{E}{m}, h, N)] \}, \qquad (6)$$

where: $k = 1, 2, 3, \ldots$; $\Phi_m \{ f_{hN}[v_{hN}(\frac{E}{m}, h, N)] \}$ is the composition of m statistically independent frequency-distributions $f_{hN}[v_{hN}(\frac{E}{m}, h, N)]$, including adequate normalization coefficient. This composition can be evaluted simply, if f_{hN} are known /26-28,31,32,35/.

For the average values of variables we can write:

$$<v_{hA}(E, h, t)> = <m> \cdot <v_{hN}(\frac{E}{<m>}, h, N)> ; \qquad (7)$$

for the normalized dispersion:

$$Z_{hA}[v_{hA}(E, h, t)] = \frac{1}{\sqrt{<m>}} Z_{hN}[v_{hN}(\frac{E}{<m>}, h, N)] . \qquad (8)$$

The quantity $t = \lambda/\langle\lambda_0\rangle$ can be related either to the average thickness of atomic nucleus, when instead of λ the $\langle\lambda\rangle$ [prot/S] = $\langle n_p\rangle$ [prot/S] is used, or to a thickness $\lambda(b)$, corresponding to any distance b from the target-nucleus centre, when instead of $\lambda(b)$[prot/S] = $n_p(b)$ [prot/S] is used. In the first case particle-production-characteristics are related to the total sample of collision events - with any proton multiplicity $n_p \leq n_p(D)$, in the second case they are related to the collision events with a definite number n_p of emitted protons only.

It is of principal importance now to derive the distribution $P(m,t)$ and to express the average value $\langle m\rangle$ in terms of λ[prot/S] $\equiv n_p$[prot/S] or $\langle\lambda\rangle$ [prot/S] $\equiv \langle n_p\rangle$ [prot/S] and of the mean-free-path $\langle\lambda_0\rangle$.

According to our picture of the particle production process in hadron-nucleus collisions, we should solve first a decidedly oversimplified problem, which nevertheless serves to indicate the essential nature of the desired distribution: The probability that in traversing thickness dt one particle is converted into two is just dt. If one particle enters a sheet of thickness t, what is the probability $P(n,t)$ that n particles will emerge? This problem was considered by W.H.Furry [38], we use his results here. The incoming particle may be an incident hadron in the case under discussion, and the n particles which will emerge can be n generons produced.

The probability in question is:

$$P(n,t) = e^{-t}(1 - e^{-t})^{n-1}, \tag{9}$$

the most probable number of generons is 1, the mean number $\langle n\rangle = e^{t}$.

In formulas (6)-(8) not the distribution $P(n,t)$ and the average number $\langle n\rangle$ is used but the distribution $P(m,t)$ and the average number $\langle m\rangle$ of all generons produced and interacted in the particle-producing collisions in nuclear matter. It is possible to obtain corresponding formulas for $P(m,t)$ and $\langle m\rangle$ by replacement the average mean-free-path $\langle\lambda_0\rangle$ in the quantity $t = \lambda/\langle\lambda_0\rangle$ by $3\langle\lambda_0\rangle$, because on the length equal to three mean-free-paths no less than about 95% of all the generons produced will interact; the outcomes of collisions of the generons produced with nucleons inside the target-nucleus provide just the component-frequency-distributions at the energies $E' = E/m$. We can write, therefore:

$$P(m,t) = e^{-t}(1 - e^{-t})^{m-1} \tag{10}$$

and

$$\langle m\rangle = e^{t}, \tag{11}$$

where $t = \lambda / 3 \langle \lambda_0 \rangle$. These $P(m, t)$ and $\langle m \rangle$ should be used in formulas (6)-(8).

4. ON AN EXPERIMENTAL TESTING OF THE MODEL

An accurate experimental testing of this free-parameterless model will be subject of our next work. Here we can state only that: a) In any case when predictions of this model were preliminarily confronted [12,13,20-28] to corresponding experimental data available, within a wide energy region - from a few GeV to about 1500 GeV, a quantitative agreement was found. b) The energy-, A-, and n_p-dependences of various characteristics of the outcomes in hadron-nucleus collisions are naturally explained within the frames of this model.

5. REMARKS

It should be emphasized that: 1) Any of the processes taking place when a hadron passes through a nucleus can be described in this free-parameterless model in terms of the data on hadron-nucleon collisions and on the data on target-nucleus size and nucleon density distribution in it. 2) Main processes taking part when a hadron collides with an atomic nucleus can be described in a convincing manner by means of a few simple relations botween hadron-nucleus and hadron-nucleon collision data: (2)-(8). 3. There are not any limitations for the incident particle energy; the model is able to describe particle-nucleus collisions at any energy higher than the threshold for pion production. 4) The model can be applied for any sort of particles interacting with atomic nuclei, not for hadrons only.

In this paper a rather preliminary and general form of the free-parameterless model of the particle-nucleus collision process is presented. We try to show our way in which we have built this new model, relying not on abstract reason, but deciphering the secret language of Nature from Nature's documents - the facts of experience.

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Работа выполнена в Лаборатории высоких энергия ОИЯИ.

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The outcome of the hadron-nucleus collisions is described in a convincing manner in terms of the hadron-nucleon collision data by means of simple formulas.

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

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