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ON STUDIES OF THE HADRON-NUCLEUS COLLISION PROCESSES

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Об исследованиях процессов столкновения адронов с ядрами

Описан новый способ экспериментального исследования процесса адрон-ядерных столкновений. Он базируется на свойствах процесса проникновения адронов высоких энергий через слои внутриядерной материи. Проникновение адронов через атомные ядра является ядерным аналогом хорошо известного электромагнитного процесса - проникновения электрически заряженной частицы через слои материалов. Описывается подсказанная экспериментально картина механизма адрон-ядерного столкновения.

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On Studies of the Hadron-Nucleus Collision Processes

A new way of hadron-nucleus collision process investigations in experiments is described. It is based on the properties of the hadron passage through layers of the intranuclear matter. The passages are a nuclear analog of the well-known electromagnetic processes - the passages of electrically charged particles through layers of materials. The picture of the hadron-nucleus collision mechanism, as prompted experimentally, is presented.

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

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1. INTRODUCTION

Let us examine how experimental investigations of the hadronic and nuclear collision processes are actually carried out. The collisions, taken as a whole, are much too complex phenomena and go beyond our direct observation and comprehension. We analyse them, dividing into various components and examining, and explaining them one by one. The observations of the collisions and measurements of various observable quantities, made bit by bit, yield a raw material or data characterizing the final state of these processes; the obtained data we call the observational and experimental information. But, the real collision process - from its beginning up to the appearance of the final products of it - is not directly perceptible to us. We do not know the mechanism of the collision, and it is the unknown quantity in our investigations - the obscurity of a fundamental character. In order to avoid this serious lack of the information, we replace the unobservable mechanism of the process by a physical model of it, which is more or less adapted to our appropriate knowledge and to the observational and experimental information.

But the simplest models, drawn from our knowledge and experience on a human scale are not acceptable for the interpretation of subatomic facts. Something else must be invented: a human imagination, and a new vocabulary - new words and abstract symbols, and notions, and categories. In general, the imagination and vocabulary should contain the elements which correspond to a measurable quantities - corresponding to measurements that could be effected in laboratories. It was experienced many times in scientific activity that the general statement: "each word in the vocabulary should correspond to a measurable quantity" is more and more difficult to apply as one goes deeper and deeper into the infinitely small /1/. Yes, it is difficult but it is not impossible. Our efforts to penetrate into processes within "infinitely" small space-time regions is more and more successful - not all methodical possibilities were exhausted at yet. At least now we are able to obtain experimentally the information about the picture of the hadron-nucleus collision process within the target-nucleus region /2/.

It is possible to do it on the basis of new experimental data on the hadron passage through nuclei[3-12].

The way the high energy nuclear physics, or the physics of the hadron-nucleus and nucleus-nucleus collisions is commonly doing now is to postulate models of the hadron-nucleus collision processes and then carry out calculations with the aid of computers, using various sets of parameters for the interaction processes. The simulated data are then compared with the data obtained experimentally, and thus the optimum model parameters are extracted from the experimental data. Detailed results cannot be obtained this way, because so many parameters have to be taken into account in any of nowadays models. Moreover, data obtained in many experiments are very poor, because of insufficient statistics of the events under study, and of a low quality due inadequate apparatuses applied in the experiments.

And so, as things stand now, we do not dispose of a commonly known reasonable experimental picture of the mechanism of the hadron-nucleus collisions, regardless of many experimental investigations were performed. We are in a position to state, therefore, that we should investigate experimentally the hadron-nucleus collisions in a new way: the only physical quantities involved in the considerations about the phenomena under studies or in efforts to prepare corresponding adequate model or theory are those which can be measured or observed, or for which a measuring or observing operation can be stated. Similar method, named operational, emphasized repeatedly by Bridgman, is a very safe guide, but it is very difficult to follow, however, in the subatomic physics[1]. Yes, indeed, but it is possible it to follow in the case under our considerations.

The subject matter in this work is to describe some of our results obtained in investigations of the hadron-nucleus collision mechanism, on the way proposed above.

The new method should be based on some nuclear phenomenon taking place inside the target nucleus and accompanied by some secondary effects visualized for observations and measurements. Such phenomenon - the hadron passage through layers of intranuclear matter - has been discovered in our experiments[3-12]. The passage is accompanied by the emission of target nucleus, the intensity of the emission corresponds to the intranuclear matter layer thickness covered by a hadron. Let us start our considerations with a description of the method.

2. ON THE METHODS OF INVESTIGATIONS

What does it mean "to understand and describe the hadron-nucleus collision process quantitatively ?". Generalizing from commonly applied procedure for the processes 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 state of the hadron-nucleus collision will be expressed in terms of corresponding known characteristics of the outcomes in the final states of corresponding hadron-nucleon collisions and of the data of target nuclei sizes and nucleon density distributions in them[13]. There is no place for any free parameters.

The conditions of being possible to investigate the hadron-nucleus collision process experimentally on the new and higher level, adequately to the desiderata formulated above, are existing in laboratories at present. Really, many aspects about the intranuclear matter, or nucleons inside nuclei, distribution are now so firmly established that it has been possible to use them in order to investigate other physical quantities[14-17]. The mean free paths for reactions of hadrons in intranuclear matter are directly measurable quantities[18]. The data on hadron-nucleon collisions, and the cross-sections for various reactions are known[19]. The collisions of hadrons with nuclei may be investigated by means of the 4Pi geometry detectors, in almost total experiments[2-12]. Free-parameterless model of the high energy hadron-nucleus collisions may be created[13].

A typical set of data used for such a model is: 1. The picture of the mechanism of the collision reaction; 2. The nucleon or matter distribution inside the target nucleus; 3. The incident hadron-nucleon collision reactions cross-sections; 4. The mean free paths for various hadron-nucleon collisions inside the target nucleus; 5. The hadron-nucleus impact parameter or the thickness of the intranuclear matter layer involved in a collision; 6. The data on particle production in hadron-nucleon collisions (at least of the pion production). The picture of the hadron-nucleus collision reaction mechanism should be prompted by experiment and contain information about the main phenomena which the collisions are accompanied by: about the nucleon emission from the target nucleus, about the particle production reactions inside the target nucleus, and about the target fragment ejection. In this picture some uncertainties may appear, this shortage should be supplemented by something which is a creation of our imagination; the supplement should be treated as our working hypothesis which is to be the object for future experimental testing. Any of the rest of the imput data - of the quantities or characteristics must be determined by measurements. The working hypothesis will be the only free and unknown "parameter" in the model.

The expressive and rather complicated picture of the hadron-nucleus collisions can be recognized in detail in some total experiment only - when all the produced particles, including neutrals (as neutral pions) and all the emitted nucleons are recorded and identified. Now it is possible to investigate the hadron-nucleus collisions under conditions desired - it can be realized by means of heavy liquid bubble chambers and by some hybrid arrangements containing detectors with nuclear emulsions, for example. Such total experiment can be realized using the xenon bubble chambers as well, where almost all the produced particles including neutral pions with kinetic energies equal to 0 or larger than 0, are recorded and detected effectively enough/4,20,21/. The description of the method of the chamber data analysis can be fond in our works cited above.

Our investigations of the hadron-nucleus collision process have been performed by means of the 26 litre xenon bubble chamber of the Joint Institute for Nuclear Research at Dubna and of the 180 litre xenon bubble chamber of the Institute for Theoretical and Experimental Physics at Moscow. The first one was exposed to pion beams at 2.34, 5, and 9 GeV/c momentum, the second chamber was exposed to 3.5 GeV/c negatively charged pions; the mostly accurate and complete analysis of the chamber photographs has been done on the sample of pictures at 3.5 GeV/c momentum. This experiment can be treated as the well nigh on a total experiment.

In the next section 3, the experimental data on the collisions under study will be presented and the picture of the hadron-nucleus collision process obtained experimentally will be described.

3. AN EXAMPLE OF THE SET OF DATA FROM A TOTAL EXPERIMENT

Hundreds thousand of chamber photographs were scanned and rescanned for the pion-xenon nucleus collision events which could occur in a chosen central relatively small region inside the chambers exposed to 2.34, 3.5, 5.0, and 9.0 GeV/c momentum P_h pion beams. A part of the pictures, without any physi-

Table

General characteristics of the experimental material

Reaction	Chamber volume (litre)	P_h (GeV/c)	N_f	N_{ev}
$\pi^- + Xe$	26	2.34	20000	6100
$\pi^- + Xe$	180	3.50	80000	6301
$\pi^- + Xe$	26	5.00	6000	1468
$\pi^- + Xe$	26	9.00	9000	1994

P_h - incident hadron momentum, N_f - number of photographs, N_{ev} - number of events analysed.

cal selection, was analysed by measurement (Table). The mostly accurate and full analysis was perfomed for the sample of events at 3.5 GeV/c momentum, and these data will be the subject of our discussion here, predominantly.

Any sharp change in the straight line track of any beam pion was considered as an indication that the pion undergoes the collision with the xenon nucleus. The end or deflection point of any beam track we accepted to be the pion-xenon nucleus collision location. In fact we were able to detect the collision events in which the beam pion track ends off or deflects at an angle of no less than 2 degrees, in accompaniment or not by any number of tracks outgoing from the place of interaction.

The secondary neutral pions of any kinetic energy, including 0, are recorded and identified in our chamber by the simply visible tracks of the negaton-positon conversion pairs and by the observed electron-photon showers created by the gamma quanta appearing in the neutral pion decay process. The minimum energy value of the gamma quanta detected with the constant efficiency amounts nearly 5 MeV. The positive pions stopped within the chamber are identified simply by the characteristic track sequence left by the charged secondaries emerged in the decay process. We meet some difficulties in attempts to identify the negatively charged pions stopping inside the chamber, namely - to distinct them from the stopping protons. But, we estimate the content of the stopping pion tracks in the sample of tracks accepted as being left by the stopping protons. Stopping kaons are identified without difficulties as well. Similarly, we can identify hyperons if they decay inside the chamber. The neutrons which are in the collision process interact with the xenon nuclei frequently leaving characteristic "neutral stars".

Tracks of the length larger than nearly 5 mm are visible well and detectable with the constant efficiency which is close to 100%. To this minimum length there corresponds the minimum kinetic energy of the registered protons of nearly 20 MeV and of the registered charged pions of nearly 10 MeV. The tracks of smaller lengths are visible as well, but in this case the detection efficiency is not constant. The protons of energies from nearly 20 up to nearly 200 MeV, the secondary pions: the negatively charged of kinetic energy from 0 up to nearly 100 MeV, positively charged of kinetic energy from 0 up nearly 100 MeV, and the neutral pions of any kinetic energy, including 0 MeV, are recorded with the efficiency being near to 100% within the total 4Pi solid angle. The kinetic energy of protons emitted within the 60 degrees and stopping inside the chamber is no more than nearly 350 MeV.

The scanning efficiency for all pion-xenon nucleus collisions registered in our experiment was better than 99.5%. In nearly 6% of the events the tracks of stopped negatively charged pions were indistinguishable from those of the proton tracks;it amounts roughly 2% of all the proton tracks. This estimation follows from the analysis based on the experimental data from the studies of nuclear collisions in nuclear emulsions exposed to the negative pion beam/22/. The contamination of the sample of all the tracks considered to be left by protons with the tracks of deuterons, tritons, and alpha particles was estimated to be no larger than 10%. But, in the majority of cases, the tracks of such heavy particles are shorter than 5 mm; in this experiment we analyse the particles which leave tracks longer than 5 mm.

The accuracy of the proton energy measurement, using the range-energy relation, is 10% for the protons of 15 MeV kinetic energy and 1% for those of 200 MeV kinetic energy/23/. The proton emission angles were measured with an accuracy of 1-8 degrees. In most cases the average accuracy of the proton energy measurement is roughly 4% and that of the emission angle estimation is nearly 3 degrees. The accuracy of the neutral pion energy estimation is nearly 12%, in average/24/. The accuracy of the pion emission angle estimation, for the charged and neutral pions, is about 1 degree.

We have estimated that over 90% of all emitted protons are stopping inside the chamber.

A sample of 6301 pion-xenon nucleus collision events with any number of secondaries were selected in scanning of about 80000 chamber photographs. This sample of events forms the experimental basis of this work.

It was possible in this sample of events, obtained in our very nigh on total experiment, to distinguish two general classes of hadron-nucleus collision events: I. The class of events in which the hadronic projectiles pass through the target nuclei without particle production - without causing ejection of particles which could be produced, without ejection of produced pions in particular; we called such events the passages, in some of such events the projectile stopped inside the target nucleus. II. The class of events in which particles are produced - the pions in particular; we called them the particle producing collisions. In both of the classes intensive emission of nucleons from the target nuclei is observed; the emitted protons are registered in the chamber with an efficiency of about 100%. In any of events from any of the classes some fragments of the target nucleus may be observed. Latter, we distinguish the III class of events, consisting of the two classes I and II together, we call it the total sample of collision events.

Let us consider firstly the sample of events from the class I.

3.1. Hadron Passages through Nuclei

We obtained that a sample of the 6301 any-type collision events contains 848 events which could be treated to be without particle production, they may be described by the reactions:

$$\mathrm{Pi}^- + \mathrm{Xe} \longrightarrow \mathrm{Pi}^- + n_p + f, \qquad (1)$$

and

$$\mathrm{Pi}^- + \mathrm{Xe} \longrightarrow n_p + f, \qquad (2)$$

where n_p = 0, 1, 2, ... denotes the multiplicities or intensity of the emitted protons, and f denotes residual nuclear fragments. The percentage of the collision events of the type (1) and (2) together which could imitate the true passages and stoppings was estimated, it equals 0.2%. Among the 848 events 78 are such in which uncident pion might be absorbed inside the target nucleus, in 588 events incident pion might pass through the target nucleus, and in 182 events incident pion charge exchange was registered. Thus, the pion passage through the target nucleus without particle production occurrence might happen in 10.6±0.5% of all the pion-xenon nucleus collisions at 3.5 GeV/c momentum. This percentage is larger by much than the percentage of the events which may be accepted wrongly as the passages of the incident pions through nuclear matter without causing particle production, which is 0.2%.

It can be concluded that the passage of the incident hadron through massive xenon nucleus is observed evidently in its pure form; in passing through intranuclear matter the hadron causes intensive emission of the observed protons from the target nucleus. It is reasonable to think that fast neutrons are emitted intensive as well, but they are not registered effectively enough in the chamber, and we do not analyse them here. This observation could not be done in other experiments where all neutral mesons and other neutral particles produced were not observed effectively enough.

The occurrence of the stoppings depends on the incident pion energy. In scanning of photographs from the 26 litre chamber, we obtained that at 2.34 GeV/c momentum stoppings are in about 12%; at 3.5 GeV/c momentum, in about 2%, at 5 and 9 GeV/c momentum the percentage is practically 0. It leads to the conclusion that some range-energy relation exists for hadrons in intranuclear matter; at 3.5 GeV/c momentum this range is as large approximately as the xenon nucleus diameter is.

The passage of the hadrons through nuclei has been studied, results are described in many of our works/2-10,25/. On the basis of the experimental data, we are in a position to state: We observe the passages of hadrons through layers of intranuclear matter; the passage is nuclear process which may be regarded as an analogy of corresponding electromagnetic process - of the passage of electrically charged fast particle through layers of materials.

3.2. The Particle Production Process

The only tool available now to realize experiments in which the mechanism of the particle producing process will be revealed is to apply single massive target nucleus as a fine detector/4,12,26,27/. The particle production process has been studied by means of the $^{131}Xe_{54}$ nuclear detector, using the sample of events in which particles are produced - the events from the class II. From the experimental investigations

we may conclude/12/: 1. In hadron-nucleus collisions particles are produced via some intermediate objects which decay after having left the parent nucleus; the objects we called "generons". 2. Indications were obtained that particle production in elementary hadron-nucleon collisions, in nucleon-nucleon collisions in particular, goes through such objects as well; the objects decay into commonly observed resonances and particles after lifetime of 10^{-23} to 10^{-22} s. The intermediate objects can produce new objects in collisions with downstream nucleons in intranuclear matter in ones turn, and this way an intranuclear cascade of the intermediate objects may develop inside parent nucleus; in most cases this cascade is collinear with the incident hadron course. 4. It has been shown that the above-described mechanism of the particle production process allows one to derive formulas for frequency distributions of various quantities describing hadron-nucleus collisions in terms of frequency distributions of corresponding quantities in elementary hadron-nucleon collisions/12,28-30/.

3.3. The Emission of Nucleons from Target Nuclei

Careful attention has been payed to the studies of the emission of nucleons from target nuclei in hadron-nucleus collisions; in our experiments the data were obtained mainly by means of the xenon buble chambers/2-8,10,20,21,31-34/, in almost total experiments.

The data obtained allows us to state that: 1. The nucleon emission may accompany any of the hadron-nucleus collisions; its intensity seems to be depending on the collision impact parameter - in a first sight, in the scanning. 2. The passage of hadrons through intranuclear matter is accompanied by fast nucleon emission; the nucleons are in fact that leaving g-tracks if in photonuclear emulsions. 3. The nucleon emission in the collisions without particle production proceeds in the same manner as the emission in any-type collisions - when particles are produced. 4. The nucleon emission intensity is determined by the target nucleus geometry - by the target nucleus size and nucleon density distribution in it. 5. Hadrons lose their energy in passing through intranuclear matter/10/, the nucleon emission is the observable effect related to the energy loss. 6. Hadrons, in their passages through intranuclear matter see the nucleon density as stable at a definite impact parameter, but the proton-nucleon ratio for the emitted nucleons fluctuates in any of events according to the binomial formula/6/.

Formulas for description of the nucleon emission intensity in hadron-nucleus collisions, in terms of the data on the target nucleus size and nucleon density distribution in atomic nuclei, are obtained on the basis of experimental data available. The formulas presented are not simple fittings of the data, they are based on physical motivation only, and do not contain free parameters. Formulas contain A-, energy-, and hadron identity dependences, and are valid at incident hadron energy over the pion production threshold/31/.

3.4. The Emission of Target Fragments in Hadron-Nucleus Collisions

The evaporation of the nuclear fragments proceeds independently of the particle production process. In collisions only an active part of the nucleus is destroyed, around the incident hadron course within the strong interaction range, predominantly near to the nucleus outer part. The mean multiplicity $\langle n_b \rangle$ of the evaporated fragments obeys simple relation $\langle n_b \rangle = 1{,}25 \cdot \{S \cdot \lambda(A,Z) + \frac{A-Z}{Z}\}$, where $\lambda(A,Z)$ is the mean thickness of the target nucleus in protons per some area S fm², $S = \pi D_0^2$ and D_o is the nuclear interaction range/35/.

3.5. Hadron Deflection in Its Passage through Intranuclear Matter

From the analysis of experimental data on hadron passages through intranuclear matter, it can be concluded/36/: 1. The observed deflection angle distribution of the projectile is a result of two sorts of deflections in intranuclear matter - one is due to a multiple scattering from objects of the rest mass as large approximately as the pion rest mass, the second is due to a single scattering from massive objects of the rest mass as large approximatelly as the rest mass of the nucleon. 2. The result of the multiple scattering is described quantitatively by simple formula/36/.

4. THE PICTURE OF THE HADRON-NUCLEUS COLLISION PROCESS

Now we are ready to describe the picture of the hadron-nucleus collision process, as emerging from experimental data obtained in the total experiment in which the target nucleus was

used as a fine detector of properties of the collision reaction in its initial stage. This picture, as deduced from experimental data, should be treated as experimental fact/4,6,8,12,2/.

When a high energy hadron is incident on an atomic nucleus or, in other words, on a intranuclear matter layer of a given thickness, it may undergo various processes as it traverses this layer. The incident hadron, as it is known experimentally, can traverse this layer without causing particle production or it can come into particle-producing collision with one of the downstream nucleons met at any depth in the intranuclear matter. In the passage, a hadron always loses monotonously its kinetic energy and is deflected from its initial course; this deflection is a result of the multiple scattering through small, a few degrees, angles of the hadron from objects in intranuclear matter of the rest mass as large approximatelly as the pion rest mass. Such a passage is always accompanied by "fast" nucleon emission - by the emission of nucleons with kinetic energies from about 20 up to about 500 MeV. Because the observed number of emitted fast nucleons equals the namber of nucleons met by the hadron around its course at distances as large as the nuclear forces range, it should be concluded that the nucleon emission accompanying the passage starts from the cylindrical region situated coaxially with the hadron course in intranuclear matter.

The fast nucleon emission is a phenomenon occurring independently of the occurrence of the particle-producing collisions and in many cases nucleon emission proceeds in advance of the particle-producing hadron-nucleon collision in intranuclear matter. The fast nucleon emission and hadron deflection are the phenomena on background of which the particle-producing hadron-nucleon collisions in intranuclear matter occur. The particle-producing reaction in intranuclear matter starts in result of collision of the projectile hadron with one of the downstream nucleons.

The particle production in hadron-nucleon collisions, in nucleon-nucleon in particular, is mediated by intermediate objects created first in a $2 \to 2$ type andoergic reaction in the early stage of the collision.

The intermediate objects, we call them generons, move predominantly along the incident hadron course in intranuclear matter and behave themselves in it, before the decay into finally observed particles and resonances after having left the parent nucleus, as usual hadrons do it; the lifetime of generons is large enough, about 10^{-22} s, them to be possible to traverse the mostly massive atomic nuclei. In traversing intranuclear matter, generons can collide with downstream nucleons and produce new generons, giving rise this way to the development of quasi-unidimensional cascade of the generons in intranuclear matter.

In the cascading process the kinetic energy of the incident hadron is distributed between generons created; it is a reason to suppose an equipartition in this distribution in average. It may be formulated the law: Various characteristics of the outcome in a hadron-nucleus collision at an energy E are the compositions of corresponding statistically independent characteristics of the outcome in some number m of hadron-nucleon collisions at the energy E/m in average.

5. DISCUSSION AND RESULTS

The picture of the mechanism of the hadron-nucleus collision process presented above was used as the physical basis for the free-parameterless model/13,29,31/. In this model characteristics of the outcome observed in the final states of the hadron-nucleus collisions are expressed in terms of corresponding characteristics of the outcomes in the final states of corresponding hadron-nucleon collisions and of the data on target nuclei sizes and nucleon density distributions in them. Some predictions of this model/13,29,31/ expressed by formulas without any free parameters were tested experimentally, agreements with corresponding experimental data are obtained/30/.

The picture of the mechanism of hadron-nucleus collision process described here differs by much from the picture used in other models.

The model may be tested using the wealth of published experimental data/37/, as well.

The picture of the hadron-nucleus collision process may be used for the analysis of the extensive Air showers produced by high energy cosmic rays. It may be useful as well for creation of edequate model of nucleus-nucleus collision processes.

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