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HADRON-NUCLEUS COLLISIONS. I. PICTURE, DESCRIPTION PROCEDURE, CROSS-SECTIONS

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1. INTRODUCTION

The hadron-nucleus collisions at high energies have attracted in the last ten years increasing interest, both experimental[1-5] and theoretical[6-9]. There are at least two reasons. The first is of a general nature: the attempts are made to work out the theory of the process of the hadron interaction with nuclear matter. The second one is of the practical nature: the nuclear reactions offer the unique possibility for experimental study, in a direct way, of the particle production process and its space-time development; the target-nucleus can serve as "a detector".

Many models exist[9], but presently there is no model which in a convincing manner can account for all hadron-nucleus collision data in terms of our knowledge of hadron-nucleon interactions.

On the other hand, the newly performed experimental investigations of the pion-nucleus collisions[10-13], using the xenon bubble chambers, and the qualitative analysis of the total sample of existing hadron-nucleus data[1-5,10-13] provide the picture of the collision process which differs by much from the pictures applied in any of now existing models.This picture will be discussed in the next section; it seems to be useful for a simple quantitative description of the hadron-nucleus collision data.

The purpose of the series of our articles, started from the present paper, is to show how it is possible to reproduce on the basis of this picture the existing data on hadron-nucleus collisions in terms of our knowledge of hadron-nucleon interactions, the target nuclear sizes, and radial distribution of nucleon density in nuclei.

Although the hadron-nucleon interaction is a complex phenomenon not yet satisfactorily described by any theory, there are well known experimentally determined cross-sections, σ, for most important types of elastic, σ_{el}, inelastic, σ_{inel}, and both together - total, σ_{tot}, hadron-nucleon collisions at a wide energy value interval[14]; the multiplicity distributions, angular and energy spectra of secondaries in various types of these elementary collisions are known as well. These data seem to be complete enough and applicable in a description of the hadron-nucleus collision data.

Many aspects about nuclear sizes and the nuclear matter distribution are now so firmly established [15,16] that it has been possible to use them in order to investigate other physical quantities.

The hadron-nucleus collision process we shall consider generally as the process of the passage of high energy hadrons through nuclear matter, like the process of high energy particle passage through a material, for example, through a slab of a metal; the target-nucleus plays a role of the "slab" of nuclear matter.

We call as "high" the energies of the projectile hadrons larger than the minimum energy below which the pion production cannot take place, i.e., larger than the threshold value of the kinetic energy; often the term "high" is applied arbitrarily for the energy values of the order of 10 GeV and more. The term "nuclear matter" we apply for the many-nucleon conglomerate of limited size and definite proton-neutron ratio, existing in the nature in its natural form - as the atomic nucleus; often this term is applied for the unlimitedly large atomic nucleus of definite constant proton-neutron ratio in it [17].

We start our considerations with the qualitative description of our picture of the hadron-nucleus collision process.

2. QUALITATIVE PICTURE OF THE HADRON-NUCLEUS COLLISION PROCESS

The picture is to be drawn now has been seen in studying the nucleon emission process accompanying the hadron-nucleus high energy collisions. We find not necessary to repeat here the reasons which have been put forward for it, limiting ourselves to provide references to former papers.

In drawing this picture, we present first, without unnecessary complications, the most important and distinguished experimental data which it is based on and, subsequently, we shall give various details of it.

Following facts are peculiar to high energy hadron-nucleus collisions:

1) In result of the hadron-nucleus collisions particles are produced, nucleons of kinetic energies above the so-called "evaporation energy", of nearly 20 to 400 MeV, are intensively emitted, and fragments of the target-nuclei are ejected.

2) The nucleon emission accompanying the hadron-nucleus collision proceeds independently on the particle creation acts; in many cases it starts to go in advance of the particle creation act [18].

3) There are events in which incident hadron undergoes the deflection only, in passing through the target-nucleus, in accompaniment of intensive nucleon emission without particle creation [10-13].

4) The nucleon emission process starts in some narrow cylindrical region localized along the high energy hadron course inside the target-nucleus [11,18-23].

5) The particle creation process is localized along the projectile hadron course in nuclear matter [9,11-13,18-23].

6) Pions are created through some intermediate or excited states formed inside the target-nucleus and decaying outside it; this fact, we have not written former directly about, is provided in analysing neutral pion creation in pion-xenon nucleus collisions at 3.5 GeV/c.

Most of these facts were treated in our former works [10-13,18-24] as rather experimental indications.They have been found mainly in experiments performed by means of the xenon bubble chambers exposed to pion beams of 2.34-9 GeV/c momentum, but we extrapolate them to be valid for the total high energy region,and for any hadron.The justification for such extrapolation depends,apart from internal consistency,on the agreement of the finally predicted results in our description scheme with experimental ones.

Let us create some picture which could be suitable to these, above-mentioned, features of the hadron-nucleus collision process. We shall use this picture later as the working hypothesis in our description formalism. Some first draft of it we have presented in former papers [18-24].

In order to do this, we shall consider what might happen when high energy hadron comes into collision with the atomic nucleus; let the target-nucleus consists of a large number of nucleons. As a result of the collisions we observe, in the bubble chamber for example, large variety of pictures: the events in which the projectiles are deflected through various angles θ_h, with accompaniment or not by the emitted nucleons [10-13]; the cases in which many various particles are ejected - pions, kaons, hyperons, nucleons, and nuclear fragments. But what happens there, inside the target-nucleus, we do not know; we may put forward some conjectures only, as it currently is practiced.

Taking into account the total sample of the existing experimental facts, it is reasonable to draw following picture of the collision process:

1) When hadrons are incident upon nuclei, they start to pass through nuclear matter and interact with it.

2) Any high energy hadron induces monotonously nucleon emission from the target-nucleus in passing through it; the emission intensity can be described by simple formula which we shall present later [21].

3) The nucleon emission process leads to monotonous energy loss of the hadron in traversing the target-nucleus [24].

4) Any hadron may undergo other various processes as well in passing through nuclear matter: a) It can undergo monotonously the deflection from initial course through relatively small deflection angles; this process is accompanied by the monotonous nucleon emission from the nucleus. b) Sometimes it may undergo the deflection through relatively large angle; in such cases the recoil nucleons appear of kinetic energy large enough them to be able to cause monotonous nucleon emission in ones turn. c) Sometimes it may undergo such collision with one of the nucleons which leads to the particle creation process.

5) The particle creation proceeds through some "intermediate or excited state" formed in hadron-nucleon elementary collision inside the target-nucleus; this "state" follows the incident hadron course.

6) The "excited or intermediate states" are of properties most likely similar to that of the incident hadrons; they can undergo any of the processes numbered above as 1)-4); their life time τ is long enough them to be possible to leave the target-nucleus before to undergo the decay into observed particles.

7) If the thickness of the nuclear matter layer is large enough, some quasi-unidimensional intranuclear cascade of these "intermediate states" shall develop along incident hadron course inside the target-nucleus. In result of such cascading many "intermediate states" may go outside the target and decay into the observed so-called "created particles".

8) The cross-sections for the inelastic hadron-nucleon collisions in nuclear matter are the same as the cross-sections for the elementary collisions of hadrons with free nucleons; the cross-sections for the "excited state" -nucleon collisions are the same as for corresponding hadron-nucleon collisions. The hadron-nucleon collision mean free path in nuclear matter is in simple relation to the corresponding cross-section for elementary hadron-nucleon collision [25].

9) Both the main processes - the nucleon emission and the particle creation proceed independently one on another and are localized along the incident hadron course in nuclear matter. The monotonous nucleon emission is disturbed sometimes by the appearance of recoil nucleons of kinetic energies high enough to be able to cause the monotonous emission as well [21,22]. In result of the collision the target-nucleus undergoes a destruction and remains in some unstable state which goes subsequently into stable fragments.

It should be noted that all these above-mentioned processes may interlace in the sequence with the exception of the transition of the residual target-nucleus into stable fragments; in any case the monotonous nucleon emission takes place regularly, however.

We can start now to work out the method of description of the hadron-nucleus collision process, using as the basis this above presented simple picture.

3. QUANTITATIVE DESCRIPTION

The problem which will be considered in this section is that of the quantitative description of the experimental data within the frames of the qualitative picture presented. We should be careful not to forget that we would like to express and account various hadron-nucleus collision characteristics in terms of our knowledge of elementary hadron-nucleon interactions and of the data on nuclear sizes and nucleon density distributions in nuclei.

3.1. Method of Description

The characteristics of the hadron-nucleus collision process provided by experiments are of the statistical nature. As a rule, they are a result of quantitative analysis of very big number of events registered in experiments. As usually is practiced, the characteristics correspond to definite reactions - to the sample of collision events of definite hadrons with definite target-nuclei, at definite energy. It enables us, in attempts to describe these characteristics quantitatively, to treate the sample as the interaction of the homogeneous monoenergetic beam of parallelly moving hadrons with a "slab" of nuclear matter. Really, it is possible to consider, for a convenience, a large number of identical target-nuclei, the hadrons are interacting with, in the total sample of events, as one nuclear matter "slab" which remain undemolished after any collision. In fact in any collision the target-nucleus is destroyed, bit in any of collisions in the sample

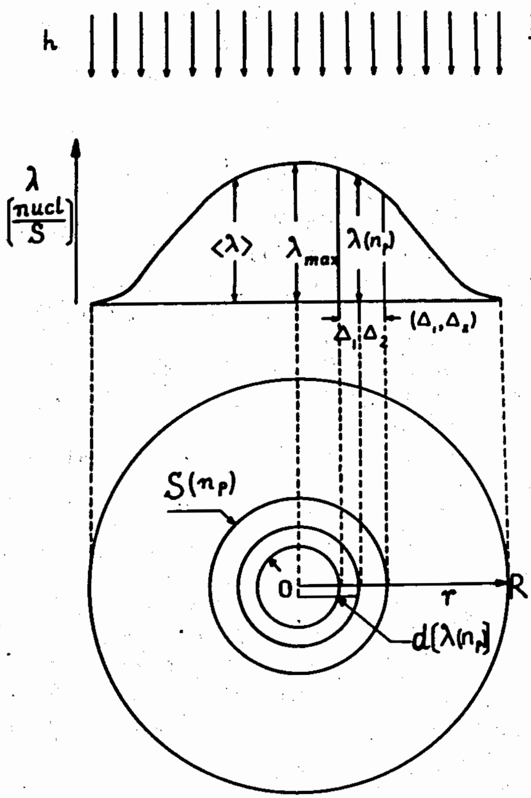

Fig.1. Schematic representation of the target-nucleus as a nuclear matter "slab". λ - nuclear matter layer thickness; λ_{max} and $<\lambda>$ - maximal and average thicknesses of the "slab", $\lambda(n_p)$ - "average" thickness of the nuclear matter layer, corresponding to the impact parameter values $d(n_p)^{+\Delta_2}_{-\Delta_1}$; $S(n_p)=S(A,n_p)$ is a ring corresponding to these impact parameter values; R is the target-nucleus radius; h - hadron beam.

identical projectile hadron and target-nucleus are always involved.

The way this problem is formulated is similar to that in absorption experiments, when the interaction of particles with a slab of material is studied.

Thicknesses of slabs in absorption experiments are usually given in units of grams per square centimeter of absorber. Incident beams are characterized by absorption coefficients for various processes which beam particles are undergoing. Similarly we shall characterize the thicknesses of the nuclear matter "slabs" in units of nucleon numbers per some area S. The projectile hadrons belonging to the hadron "beam" we shall characterize by corresponding absorption coefficients; when inelastic collisions will be considered, we will express such coefficient as the mean free path for inelastic hadron-nucleon collision in nuclear matter. Various mean free paths $<\lambda_0>$ correspond to various types of reactions which the hadrons can be undergone. It is convenient to express this quantity in units of the number of nucleons, or of the number of protons, per some area S in nuclear matter.

The nucleon density decreases towards the periphery of the nucleus; any target-nucleus might be considered then as some wedge-shaped circular "slab" of nuclear matter (fig.1). Such slab should be characterized by the maximal, λ_{max}, average, $<\lambda>$, and local, $\lambda(r)=\lambda(n_p)$, nuclear matter thicknesses (fig.1). Now it is possible to characterize any target-nucleus by means of these quantities with an accuracy high enough for the analysis of the existing hadron-nucleus collision data. Definitions of all the three quantities and the descritpion of the method for their estimation are presented in one of our works [25].

Values of mean free paths in nuclear matter for various hadron-nucleon collisions in it are dependent on corresponding cross-sections for the elementary collisions in definite manner[25]. In particular, simple relation exists between the mean free path for inelastic hadron-nucleon collisions in nuclear matter and appropriate cross-section for collisions of hadrons with free nucleons[25].

The pictures of hadron-nucleus collision events observed in experiments, in the bubble chambers or in the photonuclear emulsions, for example, are a result of the hadron passage through nuclear matter. This passage might be described in terms of the quantities defined above, characterizing the target-nucleus and the projectile hadron.

We would like to present mathematical formulation of such description, in the next section.

3.2. Mathematical Formulation of a Description of Hadron-Nucleus Collision Processes

When a hadron is incident on a nuclear matter slab of thickness λ and traverses it without undergoing a collision leading to the particle creation act or the deflection through large deflection angle, θ_h, leading to the appearance of the recoil nucleon of such energy at which this nucleon could cause the nucleon emission in passing through nuclear matter, it causes pure monotonous nucleon emission only [18-23], according to the working hypothesis, section 2, point 2) on page 4. In this case, the number n of emitted nucleons depends simply on the nuclear matter layer thickness λ [18-23]:

$$n=\pi\cdot D_0^2\cdot\lambda\cdot\bar{\rho}\,, \qquad (1)$$

where D_0 is the nucleon diameter which we use later as the length unit, $\bar{\rho}$ is average nucleon density along the hadron path λ. This path λ is expressed in units of the nucleon diameter D_0, $\bar{\rho}$ in units of nucleons per πD_0^3. The number n_p

of emitted protons is expressed simply as:

$$n_p = \pi \cdot D_0^2 \cdot \lambda \cdot \bar{p} \cdot \frac{Z}{A} . \qquad (1')$$

The expressions (1) and (1') are valid as well for the case when an incident hadron undergoes the collision in which intermediate state is created and passes through the target-nucleus along the hadron course, without undergoing the deflection through large deflection angle θ_h, according to the working hypothesis, section 2, points 4), 5) and 6) on page 4.

When the hadrons undergo deflections through large angles, the simple dependences (1) and (1') are disturbed[19,22], but, as we know, such cases are relatively rare[13,21].

Then, in the light of the relation (1'), it is natural to express λ by the number of protons, corresponding to this λ, per $S = \pi D_0^2$. If λ is measured in such units, then

$$\lambda = \lambda(n_p) \equiv n_p , \qquad (2)$$

where n_p is the number of protons met by the hadron along and in the neighbourhood to its course in nuclear matter[18,19,22]. As we have shown in former works[18,19,22] n_p can be treated to be equal to the proton multiplicity observed in a hadron-nucleus collision events in experiments. It has been shown, in one of our papers[13,21], that the relation (2) should take place for most part of events in the total sample of the inelastic hadron-nucleus collisions. The disturbance of the monotonous nucleon emission takes place primarily in the small part of events in which $n_p = \lambda(n_p) \geq \lambda(n_p)_{max}$; this part consists usually of nearly 2-6% of the total number of events within wide energy interval of incident hadrons, from a few GeV to 400 GeV[21,26,27].

Therefore, in calculating various characteristics of the hadron-nucleus collision process, the proton multiplicities $n_p = \lambda(n_p) \leq \lambda(n_p)_{max}$ will be applied as the measure of the nuclear matter layer thickness in the nuclear matter "slabs".

The emission of n_p protons happens when hadron collides with the target-nucleus at the impact parameter being not strictly $d(n_p) = d/\lambda(n_p)/$ but at $d(n_p)^{+\Delta_2}_{-\Delta_1} = d/\lambda(n_p)/^{+\Delta_2}_{-\Delta_1}$, where $d(n_p)$ is an "average" value of this parameter, Δ_1 and Δ_2 are small intervals[22]. The parameter $d(n_p)$ and the intervals Δ_1 and Δ_2 are simply determined using the data on the nuclear sizes and the nucleon density distribution in nuclei[22]. Then, the probability $W_0(n_p)$ for a hadron to collide with the target-nucleus at such impact parameter at which n_p protons could be emitted is:

$$W_0(n_p) = \frac{2\pi}{\pi R^2} \int_{d(n_p)-\Delta_1}^{d(n_p)+\Delta_2} r\, dr = \frac{\Delta_2^2 - \Delta_1^2}{R^2} + \frac{2}{R^2} / \Delta_1 + \Delta_2 / d(n_p) . \qquad (3)$$

The formulas (1), (2), (3) form a basis on which the nucleon emission intensity and, in particular, the proton emission intensity might be described.

Let us consider now the formalism which we shall use for the description of the particle creation process. It should be emphasized that, according to our qualitative picture and the points 4c) and 5) of the working hypothesis, the creation act might start in collision of the projectile hadron with any of nucleons lying along the path λ in nuclear matter. When it happens, the "excited state" is created which might start the quasi-unidimensional cascade development of these states. This cascade should be described now.

In efforts to describe it, we solve first a decidedly oversimplified problem, which nevertheless serves to indicate the essential nature of the distribution of these states. Namely, we suppose that all these states are created just at the surface of the target being in front of it for the projectile. Now we formulate the problem as follows: The probability that in traversing thickness dt one state "converts" into two, in colliding with a nucleon, is just dt. If one state enters a sheet of thickness t, what is the probability $P(m,t)$ that m states will emerge?

This problem has been originally discussed by Furry[28]. Therefore, it was not found necessary to repeat the derivation of appropriate formulas; we write, using the Farry's data, that: a) The probability $P(m,t)$ is expressed by[28]

$$P(m,t) = e^{-t} (1-e^{-t})^{m-1} ; \qquad (4)$$

b) The most probable number of "excited states" emerging is one, the mean number of these states is

$$\langle m \rangle = e^{t} . \qquad (5)$$

Thus the expression (4) can be written as

$$P(m,t) = (\langle m \rangle)^{-1} \{1 - (\langle m \rangle)^{-1}\}^{m-1} . \qquad (4')$$

The thickness t can be expressed by the values of $\lambda(n)$ and $\langle\lambda_0\rangle$ as $t=\frac{\lambda(n)}{\langle\lambda_0\rangle}$ and we can write

$$\langle m\rangle = e^{\frac{\lambda(n)}{\langle\lambda_0\rangle}} \quad \text{or} \quad \langle m\rangle = e^{\frac{\lambda(n_p)}{\langle\lambda_0\rangle}} \qquad (5')$$

and

$$P(m,t) = \left(e^{\frac{\lambda(n)}{\langle\lambda_0\rangle}}\right)^{-1}\left\{1-\left(e^{\frac{\lambda(n)}{\langle\lambda_0\rangle}}\right)^{-1}\right\}^{m-1}. \qquad (4'')$$

The quantities $\lambda(n)$ and $\langle\lambda_0\rangle$ are expressed in units of the number of nucleons per $S=\pi D_0^2$ or in units of the number of protons per S. The mean free path $\langle\lambda_0\rangle$ is connected to the hadron-nucleon cross-section σ_{hN} by the relation[25]:

$$\langle\lambda_0\rangle = \frac{\pi}{k\cdot\sigma_{hN}}\left[\frac{\text{nucleons}}{S}\right], \qquad (6)$$

where $k=0.45$, σ_{hN} in $\frac{D_0^2}{\text{nucleon}} = \frac{5.04\,\text{fm}^2}{\text{nucleon}}$.

The formulas (4)-(6) form mathematical basis for the description of any characteristic of the particle creation process in hadron-nucleus collision. We show how this description can be realized.

Let us derive first the formula for the hadron-nucleus collision cross-sections.

4. HADRON-NUCLEUS COLLISION CROSS-SECTIONS

The method worked out for a description of the hadron-nucleus collisions, presented in foregoing section, should allow to derive a simple formula for the cross-sections. Let us, for example, derive it for the inelastic collisions.

In any of collisions nucleons are emitted, in particular the simply observed protons; the proton multiplicities $n_p=0,1,2,\ldots$ are represented, corresponding to "average" collision impact parameters $d(n_p)$. To any $d(n_p)$ corresponds the "average" path $\lambda(n_p)=\lambda[d(n_p)]$ in nuclear matter. The number of collision events with a given proton multiplicity n_p, or with a given collision impact parameter $d(n_p)^{+\Delta_2}_{-\Delta_1}$, in a complete sample of events, with any n_p, is then determined by the ring $S(n_p)$ (fig.1). The values of the impact parameters depend on the mass number A, then we should write $S(n_p) = S(A,n_p)$.

The probability for a projectile to undergo the inelastic collision along $\lambda(n_p)$ is $(1-e^{-\lambda(n_p)/\langle\lambda_0\rangle})$, where $\langle\lambda_0\rangle$ is corresponding mean free path determined by the formula (6).

Therefore, we might write obviously for the hadron-nucleus collision cross-sections:

$$\sigma_{hA} = \sum_{n_p=n_p(\lambda_{min})}^{n_p=n_p(\lambda_{max})} S(A,n_p)\left(1-e^{\frac{\lambda(n_p)}{\langle\lambda_0\rangle}}\right), \qquad (7)$$

where $n_p(\lambda_{max})$ and $n_p(\lambda_{min})$ are the proton multiplicities corresponding to the minimal and maximal values of the nuclear matter layer thicknesses in the "slab"; the λ_{min} corresponds to the target-nucleus radius R. The sum of all rings, for all values of n_p, should be equal to πR^2. The quantities $\lambda(n_p)$ and $\langle\lambda_0\rangle$ can be applied in units of the numbers of nucleons per $S=\pi D_0^2$ area, the $S(A,n_p)$ - in millibarns. The $S(A,n_p)$ are determined by the nuclear sizes and nucleon density distributions in nuclei. The disturbance of the monotonous nucleon emission, caused by possible single elastic scatterings of hadrons and "intermediate states" from nucleons in nuclear matter through large angles θ_h, might be obviously not taken into account in the formula (7).

It should be noted that in the formula (7) the rings S(A,n) corresponding to any number n of nucleons per area πD_0^2, including fractional numbers n, might be used instead of the rings $S(A,n_p)$. Then, the formula (7) should be rewritten as:

$$\sigma_{hA} = \sum_{i=1}^{i=w} S_i(A,n)\left[1-e^{-\frac{\lambda(n)}{\langle\lambda_0\rangle}}\right], \qquad (7')$$

where $i=1,2,3,4,\ldots,w$, and $\Sigma\, S_i(A,n)=\pi R^2$.

The values of the mean free paths for the inelastic pion-nucleus and proton-nucleus collisions are given in our former work[25] and are presented in fig.2. The quantities $S(A,n_p)$ were calculated using the Fermi's distribution ρ_F of the nucleon density in nuclei[16]. The values of nuclear radii R were limited by the condition: $\rho(R)/\rho(0)$ is smaller than 10^{-4}. The values of $S(A,n_p)$ for various nuclei will be given in one of our future works, for example, we give them for the lead nucleus, in πD_0^2 units: S(Pb,0.4)=26.51, S(Pb,1)=2.5, S(Pb,2)=2.02, S(Pb,3)=1.61, S(Pb,4) = 1.57, S(Pb,5)=1.56, S(Pb,6)=1.85, S(Pb,7)=2.21, S(Pb,8)=1.86, S(Pb,9)=2.46.

Using formula (7) cross-sections were calculated for pion-nucleus and proton-nucleus inelastic collisions at energies

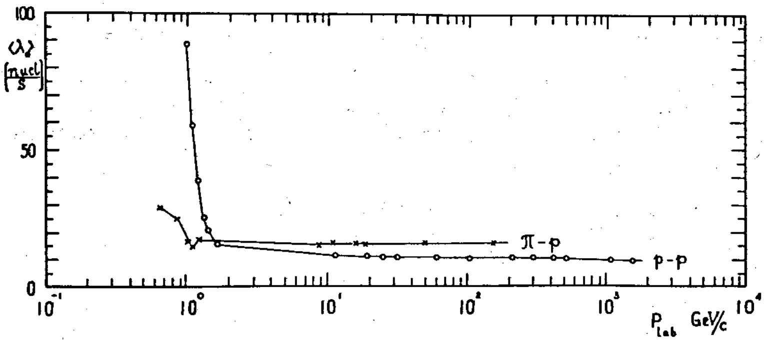

Fig.2. Energy dependences of the mean free path $\langle\lambda_0\rangle$, for pion-nucleon and proton-nucleon inelastic collisions in nuclear matter, expressed in units of a number of nucleons per area $S=\pi D_0^2$.

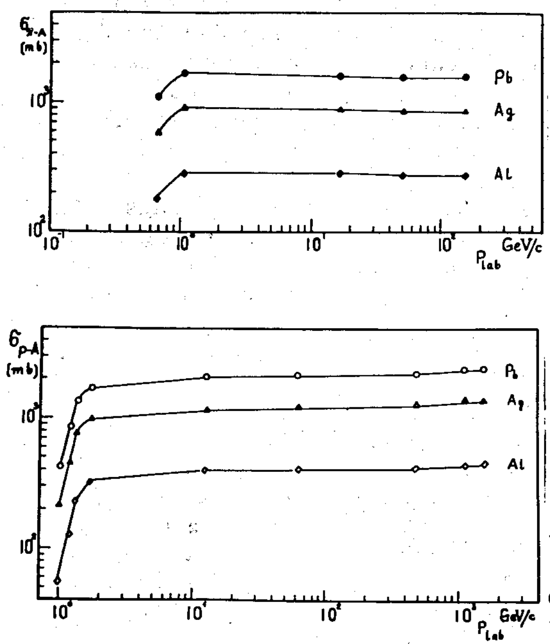

Fig.3.Cross-sections for pion and proton inelastic collisions with Pb , Ag , and Al nuclei in dependence on the projectile momentum, predicted by formula (7).

corresponding to those values at which the data exist on the pion-nucleon elementary inelastic collisions[14]; results are presented in fig.3, for Pb , Ag , Al targets. A-dependence of these cross-sections is determined simply by the nuclear sizes and nucleon density distribution in target-nuclei; in formula (7) it is contained in the terms S (A,n_p).

In order to test predictions given by formula (7) with existing experimental data [1] on the cross-sections A-dependence, cross-sections for inelastic pion-nucleus collisions at 50 GeV/c momentum and for proton-nucleus collisions at 60 GeV/c momentum were calculated. Results are shown in fig.4. For comparison, approp-

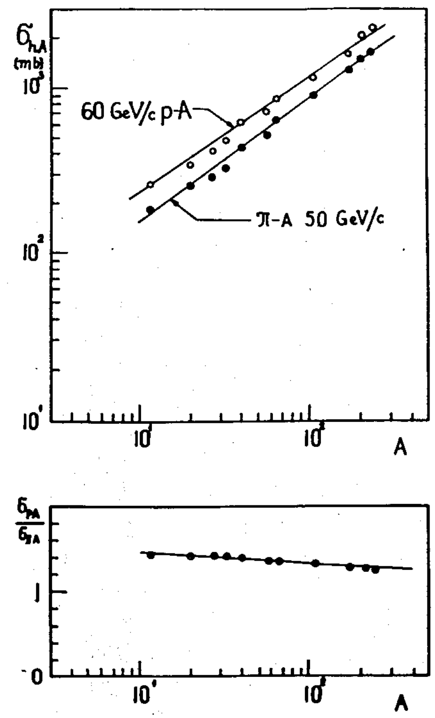

Fig.4. A-dependences of absorption cross-sections for pion-nucleus collisions at 50 GeV/c momentum and for proton-nucleus collisions at 60 GeV/c momentum, predicted by formula (7), points and circles. Lines superimposed on the calculated cross-sections represent experimental data on pion-nucleus and proton-nucleus collisions at 30-70 GeV taken from Busza's review [1]. On the lower figure the calculated ratio between values of cross-sections for proton-nucleus and pion-nucleus collisions at the same energies is shown, in dependence on the mass number of targets.

riate experimental data at 30-70 GeV energy are superimposed on the predicted ones. In this figure the ratios $\sigma_{pA}/\sigma_{\pi A}$ between proton-nucleus and pion-nucleus cross-sections calculated at energy of nearly 60 GeV are presented for various target-nucleus mass numbers A.

It can be stated that formula (7) reproduces well the A-dependence of inelastic pion-nucleus and proton-nucleus cross-sections at nearly 60 GeV/c. It enables us to expect that predicted cross-sections presented in fig.3 will correspond to experimental ones.

The above presented results do not contradict our picture of the hadron-nucleus collision process, it enables us therefore to try to reproduce many other characteristics of this process, provided by experiment, within the frames of this picture, using the method worked out and described in this article.

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