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RESULTS OF SEARCHES FOR THE NUCLEON STRUCTURE DISPLAYS IN HIGH ENERGY HADRON-NUCLEUS COLLISIONS

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1. INTRODUCTION

Recently, the proper basis for discussing hadron-nucleus collisions is predominantly in terms of the constituents of the nucleon - quarks, partons. But, the questions "How is particle production process in hadron-nucleon and hadron-nucleus collisions proceeding?" and "Is the inner nucleon structure manifesting itself in hadron-nucleus processes?" must find their answers primarily in experiments. It is of great importance, therefore, to analyse experimentally the effects which are sensible for the nucleon structure.

There are two, at least, frequently occurring processes in which the nucleon constituents should manifest themselves in hadron-nucleus collisions: a) The incident hadron deflection in its passage through nuclear matter; b) The particle production. Both these processes are observable ones, and can be analysed accurately enough on the basis of the experimental data obtained by means of a variety of experimental techniques.

The subject matter in this paper is to discuss about the effects in question. We start with our own experimental data from 26 and 180 litre xenon bubble chambers exposed to the pion beams at 2.34 and 3.5 GeV/c momentum. The conclusions from an analysis of the experimental material allow to consider properly other experimental data available up to about 8000 GeV/c momentum.

2. EXPERIMENTAL PROCEDURE

We were able, using the xenon bubble chambers, to identify the pion-xenon collision events in which the incident pion is deflected only in passing through the target nucleus or stopped within it [1,2]; the projectile deflections and stoppings are always accompanied by the emission of fast nucleons ($\sim 20 \div \sim 400$ MeV) but the particle production does not occur in these events.

It has been shown experimentally that the number n_p of the fast emitted protons observed in any collision is a good measure of the nuclear matter layer thickness λ measured in protons/S units, where $S = \pi D_0^2 \simeq 10\ fm^2$ and D_0 is the nucleon diameter [3,4]. It is possible, therefore, with the xenon bubble chamber techniques: a) to observe the projectile deflection in dependence on

the thickness λ of the nuclear matter layer the hadron has been passed through it [5,6]; b) to determine experimentally the mean free path for the particle producing hadron-nucleon collisions in nuclear matter, and to relate it to the hadron-nucleon inelastic collision cross-section [7]. The mean free path is determined by the relation

$$I = I_0 e^{-t/\lambda}, \qquad (1)$$

where I_0 is the total number of incident hadrons falling on the nuclear matter layer of the thickness $t \equiv n_p$ protons/S, I - the number of incident hadrons traversed the layer without particle production, λ protons/S is the unknown mean free path.

Using the data on the mean free paths for the particle producing hadron interactions inside the target nuclei, we are in the position to analyse various appropriate available hadron-nucleus data up to the highest energies. We applied the target nucleus as a detector of the properties of hadron-nucleon and hadron-nucleus collision processes, in other words.

One experimentally stated fact is of importance here - we observe that: a) The energy and momentum spectra, and angular distributions of fast protons (fast nucleons as well), emitted in the collisions are the same in hadron-nucleus collisions with and without particle production, and they are independent of the energy and the identity of the impinging hadron; energy and momentum spectra and angular distributions are the same in sub-groups of events with different multiplicities n_p of emitted fast protons [8,9]. b) At incident hadron energy higher than a few GeV the frequency distribution of the multiplicities n_p of the fast emitted protons is energy-independent.

3. EXPERIMENTAL DATA

A. Hadron Deflection in Its Passage through Nuclear Matter

The distributions $\Delta N/\Delta\cos\theta_\pi$ of the incident pion deflection angle θ_π, in pion-xenon nucleus collisions at 2.34 and 3.5 GeV/c momentum, are shown in figs. 1, 2; the mean thicknesses $\langle\lambda\rangle$ protons/S $\equiv \langle n_p\rangle$ protons/S of the nuclear matter layer traversed by the projectiles, on which deflections through the deflection angles θ_π occur, are shown in fig.3.

Three main findings from the data shown on these figures, and from accurate analysis of the data [6], are:

1. Two sorts of projectile deflections manifest themselves evidently - the small angle deflections ($\theta_\pi \leq 30$ degrees) and the large angle deflections (larger than about 30 degrees);

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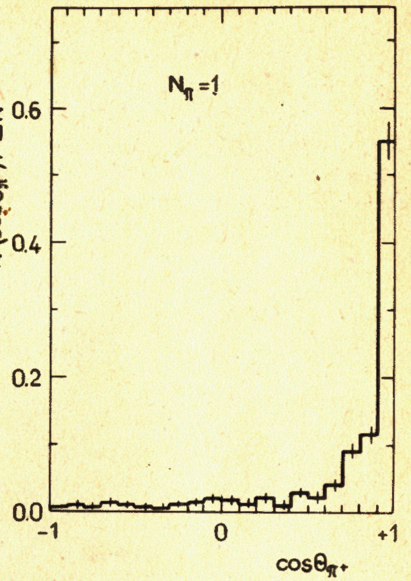
Fig. 1. Pion deflection angle distribution, in $\cos\theta_\pi$, in the pion-xenon nucleus collisions of the type $Pi^+ + Xe \to Pi^+ + kp + F$ at 2.3 GeV/c momentum; k = 0, 1,2,... proton multiplicity, F -target fragments. Data obtained in experiment performed together with K.Wosinska.



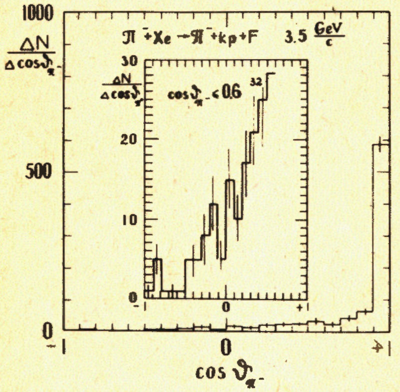
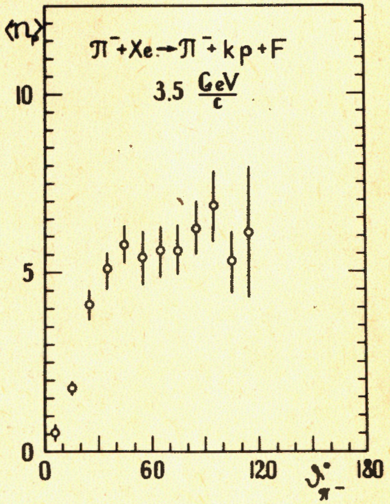


Fig.2. Pion deflection angle distribution, in $\cos\theta_\pi$, in the pion-xenon nucleus collisions of the type $Pi^- + Xe \to Pi^- + kp+F$ at 3.5 GeV/c momentum[6]; k = 0,1,2,... proton multiplicity, F - target fragments.

Fig.3. The dependence of the emitted proton mean multiplicity $\langle n_p \rangle$ on the incident pion deflection angle θ_π in pion-xenon nucleus collision events of the type $Pi^- + Xe \to Pi^- + kp + F$ at 3.5 GeV/c momentum[6]; k = 0,1, 2,... number of emitted protons, F - target fragments.



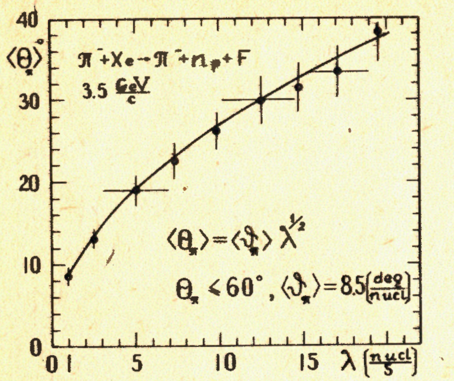


Fig.4. The dependence of the mean incident pion deflection angle $\langle\theta_\pi\rangle$ on the nuclear matter layer thickness λ nucleons/S in the pion-xenon nucleus collisions without particle production at 3.5 GeV/c momentum, when pions are deflected by an angle no larger than 60°. Solid line - prediction given by formula (2).

additional investigation shows[6] that the large deflections occur at any thicknesses λ, from about λ = 1 proton/S up to about λ = 8 protons/S.

2. A definite relation exists between the projectile deflection angle θ_π degrees and the mean thickness of the nuclear matter layer $\langle\lambda\rangle \equiv \langle n_p \rangle$ protons/S; the deflection angle θ_π increases up to about 40-50 degrees with increase of the mean value of $\langle n_p \rangle$ up to $\langle n_p \rangle \simeq n_p(D)$ protons/S, where $n_p(D)$ is the nuclear matter layer thickness corresponding to the nucleus diameter D, fig.3.

3. The deflection angle $\langle\Theta\rangle$ of the projectile can be expressed quantitatively[6] by simple Rayleigh and Thomson formula[10,11]

$$\langle\Theta\rangle = \langle\theta_\pi\rangle \cdot \lambda^{1/2}, \qquad (2)$$

where $\langle\theta_\pi\rangle$ is the mean deflection on the thickness of the nuclear matter layer λ = 1 nucleon/S, fig.4. Formula (2) is valid for the deflection angles $\langle\Theta\rangle$ smaller than about 40 degrees[6].

Experimental investigations of the rest masses of the targets the charge exchange collisions occur with in nuclear matter layers of the thicknesses no more than about 2 nucleons/S allow one to conclude that in almost all events the pions have been colliding with the objects of the rest masses kinematically corresponding to the rest mass of the pion. The values of the deflection angles Θ_{π^0} of the neutral pions are $\Theta_{\pi^0} = 5 \div 15$ degrees[12]. Additional study of the pion deflection angles in $Pi^- + Xe \to Pi^- + p + R$ reactions at 3.5 GeV/c momentum indicate that about 0.9 deflections correspond to $Pi + Pi \to Pi + Pi$ and 0.1 of events can be qualified for the $Pi + p \to Pi + p$ deflections[6], R denotes the residual nucleus and nuclear fragments.

The above presented experimental findings allowed to perform the analysis of the incident hadron deflection phenomenon[7]. From this analysis one can conclude that[6]: Hadrons are undergoing deflections in their passage through layers of nuclear matter; the observed distribution of the deflection angles is a result of two sorts of deflections - one is due to a multiple scattering by objects of the rest mass as large approximately as the pion mass, the second is due to a single scattering by massive objects in nuclear matter of the rest mass approximately as large as the nucleon rest mass.

If we use as a point of departure the nucleon structure of the atomic nucleus, we should think that in the picture of the projectile deflection phenomenon obtained in our experiment the nucleon structure is displayed. The structure of the nucleon appears here as illuminated by fast pions, when the nucleon is influenced by other nucleons in the atomic nucleus. We should imagine the nucleon, as seen by the projectile hadrons in nuclear matter, as consisting of at least two objects:
a) Of a massive heavy object of the rest mass approximately as large as the nucleon rest mass, which probably forms a core.
b) Of lighter constituents, like pions or may be their combinations, bound with the core with a large binding energy - approximately as large as the rest masses of these constituents forming some cloud around the core.

A preliminary and very unprecise estimation, from the relation between the cross-sections for the single and multiple scatterings, indicates that the radius of the core may be about five times smaller as the radius of the nucleon in nuclear matter/6/.

B. The Mean Free Paths

Let us single out firstly the sample of the "projectile deflected" events from all the pion-xenon nucleus collisions at 2.34 and 3.5 GeV/c momentum. In these events the incident pion is deflected only, without particle production, with an accompaniment by $n_p = 0, 1, 2, \ldots, 8, \geq 9$ emitted fast protons. The proton multiplicities $n_p = 0, 1, \ldots, 8$ indicate how thick is the nuclear matter layer on which a given deflection angle occurred/3,4/. Putting in formula (1) the total numbers of the projectile deflected events instead of the quantity I_0 and the numbers of the events in which the projectile is deflected through the deflection angle θ_π smaller than 30 degrees instead of I, at various thicknesses $t \equiv n_p = 0, 1, 2, \ldots, 8$ protons/S of the nuclear matter layers, we estimate corresponding mean free paths λ_s for incident pion deflection through deflection angles larger than 30 degrees. The values of λ_s obtained at various t do not differ markedly; all these estimations give/7/ the mean free path $\lambda_s = 5.29 \pm 0.62$ protons/S. According to our picture of the hadron single deflection, the obtained λ_s characterises the mean free path for the projectile collision with the nucleon core inside nuclear matter.

Because of the appearance of two sorts of collisions - the collisions with lighter constituents and the collisions with heavier nucleon cores, the most accurate determination of the mean free path λ_m for multi-particle production will be achieved when large enough thickness t of the nuclear matter layer will be employed as an absorber/7/. We use therefore for the λ_m determination the sample of any-type pion-xenon nucleus collisions occurred when the projectile fell on the nuclear matter layer of the thickness $t \equiv n_p = 8$ protons/S; the events from this sample correspond to the pion-xenon nucleus collisions occurring almost along the diameter of the target nucleus. From our experiment at 3.5 GeV/c momentum $I_0 = 200 \pm 14$ and $I = 42 \pm 6$, where I is the number of collisions without particle production. In this case formula (1) gives/7/ $\lambda_m = 5.12 \pm 0.70$ protons/S.

But, we can calculate the mean free path λ_i for inelastic hadron-nucleon collisions in nuclear matter using the cross-section σ_{in} for elementary hadron-nucleon inelastic collision; the relation between λ_i and σ_{in} is/7/: $\lambda_i \text{ protons/S} = \frac{1}{\sigma_{in} \frac{S}{\text{proton}}}$

For incident pions at 3.5 GeV/c momentum the ratio between λ_i and λ_m is $\lambda_m / \lambda_i = k = 3.0 \pm 0.3$.

The coefficient $k \neq 1$ which may be interpreted as a display of the nucleon inner structure in hadron-nucleus collisions.

C. Particle Production

One can see that the values for λ_s and λ_m are practically the same, what may indicate that the particle production, pion production in particular, occurs when a projectile collides with the heavy nucleon core. Because the characteristics of the emitted fast nucleons in hadron-nucleus collisions are the same when multiparticle production occurs or not, we can conclude that the secondary "generated" particles appear after some time after the two-body collision, when the reaction products have left the parent nucleus. But, we observe in experiments that the mean multiplicities of produced pions in hadron-nucleus collisions are larger than the mean multiplicities of produced pions in collisions of the same hadrons with free nucleons. We must postulate, therefore, that the struck and excited nucleon (we called it "generon"/13/) may collide with the downstream nucleons in nuclear matter and produce new excited nucleons (new generons). In nuclei large enough the almost one-dimensional cascade of excited nucleons may develop/13/.

4. CONCLUSIONS AND REMARKS

We can conclude, from what has been said above, that the nucleon structure is exhibiting itself in hadron-nucleus collisions. The findings are obtained in pion-xenon nucleus collisions at 2.34 and 3.5 GeV/c momentum, directly. Indirectly, we have proved them as well in proton-nucleus collisions at projectile energies up to some thousands GeV. Namely, on the basis of the picture of the particle production process obtained in our experimental studies, the free-parameterless model of hadron-nucleus collisions was worked out /14/ which allows one to describe quantitatively the hadron-nucleus collision outcome in terms of the hadron-nucleon collision outcomes for a target nucleus with definite size and nucleon density distribution in it.

In the free-parametrless model the relations between the frequency distributions $F_{hA}(v_{hA})$ of variables v_{hA} characterizing some process in hadron h collision with an atomic nucleus A and the appropriate frequency distributions $f_{hN}(v_{hN})$ of variables v_{hN} characterizing this process in collisions of the same hadron with the nucleon are expressed by simple formulas /14/. For example, for the mean values of the variables we can write:

$$v_{hA}(E, h, t) = \langle m\rangle v_{hN}\left(\frac{E}{m}, h, N\right), \qquad (3)$$

where $v_{hA}(E, h, t)$ is a variable v_{hA} when incident hadrons h of energy E collide with nuclear matter layer of the thickness t, $v_{hN}(\frac{E}{m}, h, N)$ is the variable v_{hN} when the same hadrons of energy $\frac{E}{m}$ collide with the nucleon, $\langle m\rangle = e^{t/\lambda}$, and λ is the mean free path for a given process in nuclear matter. For the dispersion D of the variables

$$D^2 = D_1^2 + D_2^2, \qquad (4)$$

where D_1 is definite dispersion of the variable v_{hN} and D_2 is definite dispersion of the quantity /14/ m.

As an example, let us compare predictions of the model for the mean multiplicity $\langle n_{ch}\rangle$ of charged secondaries generated in proton-nucleus collisions in nuclear emulsion with corresponding experimental data. Calculations have been performed by Sredniawa and Strugalska, figs. 5-7. Experimental data are from various works /15-17/. We can state the agreement of the experimental data with the predictions of the model.

The above presented results allow one to conclude that the nucleon structure manifests itself in proton-nucleus collisions within a wide energy interval as well. The predictions of the

Fig.5. The mean multiplicity $\langle n_s\rangle$ of shower particles produced in proton p collisions with atomic nuclei in emulsions Em at various projectile momentum P_p GeV/c. Points - experimental data as complied in the work of Gurtu et al. /16/, solid line - calculations.

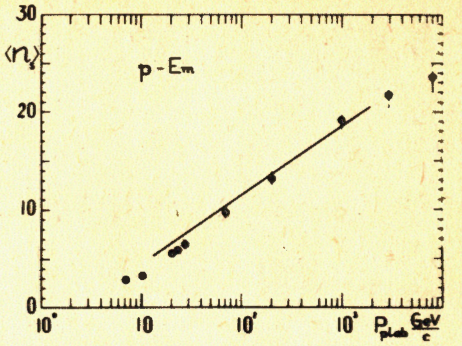


Fig.6. Dispersion D of the multiplicity $\langle n_s\rangle$ of the shower particles produced in proton-nucleus collisions in emulsions in dependence on the projectile momentum P_p GeV/c. Solid line- calculations, points - data as complied in the work of Tsai-Chü et al. /17/.

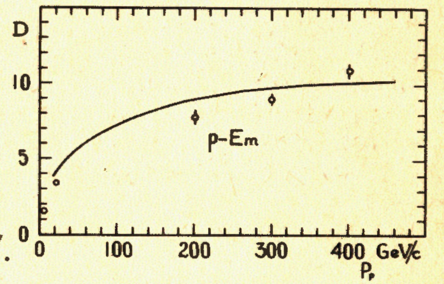
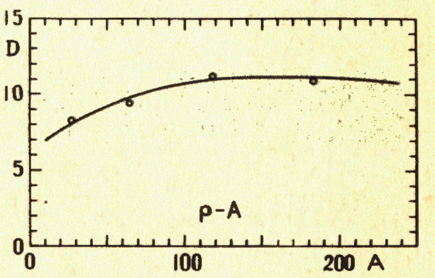


Fig.7. Dispersion D of the multiplicity of the shower particles produced in proton-nucleus collisions at 400 GeV/c momentum in dependence on the target mass number A. Solid line - calculation, points - data from the work of Fumuro et al. /15/.



model for the mean multiplicities of produced pions agree with corresponding data for pion-nucleus collisions as well, up to incident pion energy of about 150 GeV where the data are available. It is reasonable to conclude, therefore, that the structure of the nucleon manifests itself in hadron-nucleus collisions starting from the incident hadron energy of about 2 GeV.

In connection with our results concerning the particle production mechanism, it is worth-while to mention the model of particle production given by V.F.Weisskopf /18,19/, in which spectra of the energy states of the excited nucleon are considered.

The quark fireball model for hadron production, developed by T.R.Mongan[19], should be mentioned here as well.

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Результаты поиска проявлений структуры нуклона в адрон ядерных столкновениях при высоких энергиях

Проводился анализ экспериментальных данных по адрон-ядерным столкновениям при энергиях от нескольких ГэВ до нескольких тысяч ГэВ с целью обнаружения эффектов проявления структуры нуклона в этих столкновениях. Обнаружено, что структура нуклона проявляется в процессе отклонения налетающего адрона при прохождении через атомное ядро и в процессе множественного рождения частиц при энергиях свыше 2 ГэВ. Распределение углов отклонения содержит две составляющие, средний свободный путь для рождения частиц приблизительно в три раза больше обычного ожидаемого. Эти эффекты могут быть интерпретированы как проявление структуры нуклона.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

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