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ELASTIC HADRON SCATTERING AND NUCLEON STRUCTURE

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The problem of confinement in QCD concentrates our consideration on the **dynamics** of strong interaction at long distances. The effective constant of QCD grows at long distances, and now no microscopic theory does exist in this region. The QCD sum rules [1,2] permit one to investigate some dynamical properties of hadrons. However, the elastic hadron scattering cannot be investigated on the basis of this method. Therefore different models for description of hadron interactions at large distances are developed which are based on the general quantum field theory principles(analyticity, unitarity, and so on). They must take into account basic information about the hadron **structure** as a compound system with a central part region where the valence quarks are concentrated and a long-distance region where the coulor-singlet quark-gluon field occurs.

We want to note that full summation of long-distance contributions must be carried out because of a large magnitude of the strong-interaction coupling constant. The most consistent solution of this problem can be done on the basis of the Logunov-Tavkhelidze quasipotential method [3].

In this paper we shall investigate high-energy pion-nucleon and kaon-nucleon scattering in a wide region of momentum transfers. It will be shown that taking long-distance effects into account permits us to determine from an unique point of view the amplitude of $\pi^{\pm}p$ and $K^{\pm}p$ scattering. As a result, different properties of high energy meson-nucleon scattering are explained and the corresponden-ce to nucleon-nucleon scattering is shown. All this permits us to conclude that a unique picture is obtained for the hadron processes at high and superhigh energies on the basis of the model of hadron interaction which takes into account the nucleon structure at long distances. Let us investigate the t -channal singularity structure of the scattering amplitude in oder to define diagrams which determine the high energy dynamics of strong interaction at long distances.

The Born term of the scattering amplitude can be represented as a sum of t and u -channal contributions:

$$T(s,t,u) = T(s,t) + T(s,u), \tag{1}$$

where $T(s,t)$ and $T(s,u)$ have diffraction maxima at forward and backward direction, respectively. Amplitudes (1) decrease rapidly with growing $|t|$ and $|u|$. This permits us to represent them in the following integral form:

$$T(s,t) = \int_0^\infty dx\, \rho_t(s,x)\, e^{xt},$$
$$T(s,u) = \int_0^\infty dx\, \rho_u(s,x)\, e^{xu}. \tag{2}$$

In this case for hard processes the region of small $0 < x < 1$ GeV^{-2} is essential. For soft processes the main contribution comes from the region $x \gtrsim 1$ GeV^{-1}. We can take into account only the t -channal contribution in (1) when $|t|/s \ll 1$.

The density function $\rho_t(s,x)$ can be calculated by using the inverse Laplace transformation:

$$\rho_t(s,x) = \frac{1}{2\pi i}\int_{-i\infty}^{i\infty} dt\, e^{-xt}\, T(s,t).$$

The integration contour can be removed to the positive t -region. As a result, we have:

$$\rho_t(s,x) = \frac{1}{\pi}\int_{t_0}^{\infty} dt\, e^{-xt}\, \mathrm{Im}_t T(s,t) + \text{(pole term contributions)}. \tag{3}$$

Representation (3) can be easily obtained from the dispertion relations for the scattering amplitude at fixed s .

It may be considered as a sum rule for determining the soft part of the density function with the use of the calculated imaginary part of the amplitude $T(s,t)$ on the t -channel cut. In the region of t-fixed, defined by the particle interaction at distances of an order of the hadron size, the density function is essentially contributed by $x \gtrsim 1$ GeV^{-2}. The factor exp $(-xt)$ permits us to take into account only the nearest t -channel singularities. So, in the unitarity condition we take account only of two-pion elastic contributions. Keeping the pole term in one amplitude in the unitarity condition and the asymptotic term in other, we obtain that the essential contribution to $\mathrm{Im}_t T(s,t)$

comes from triangle diagrams (Fig.1). They are connected with the pion meson-cloud of hadron and determined by the hadron structure at large distances. It can be shown from (3) that the triangle contribution completely determines the eikonal phase behaviour at distances $\rho \gtrsim 5$ GeV^{-1}.

Of course, at distances $\rho \lesssim 1/2\mu_\pi \sim 4$ GeV^{-1} we must take into account the inelastic contributions with four, six, and more pions in the t -channal and the contributions with heavy mesons. The estimations of these effects are very difficult. But they have a central character and their contribution can be determined as a function with free parameters.

So, the scattering amplitude can be decomposed into two parts:

$$T(s,t) = T_c(s,t) + T_p(s,t), \tag{4}$$

where T_c contans a central part of interaction and is determined phenomenologically, T_p is a peripheral part of interaction determined by the triangle contributions with two-meson exchange in the t -channal. The simplest spinless variant of this model describes all known properties of hadron scattering in a wide momentum transfer region at ISR energies/5/ in a unique way. The model leads to the scattering amplitude which is an analytic function of t . It leads to the energy and t -dependence of the diffraction peak slope at small t . The differential cross section in the model has one diffraction minimum. The small slope of differention cross sections at large t is determined by the radius of the central part of interaction which is of order 0.5 fm. In the case of πp -scattering at P_L = 200 GeV the model predicts the diffraction minimum at $3.5 < |t| < 4.2$ GeV^2. This result was confirmed experimentally/6/.

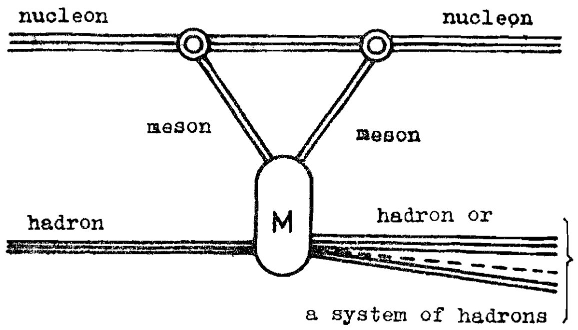
The model generalization to the spin particles was done in/7/ (meson-nucleon case). It was shown that in this case in diagram (1) there appears the term with additional $\sqrt{s}$.

In this case we have for the helicity meson-nucleon amplitude in the Born approximation:

$$T_{++}(s,t) \sim b(s,t)\,;\; T_{+-}(s,t) \sim \frac{\sqrt{|t|}}{\sqrt{s}}\left[\sqrt{s}\,\alpha(s,t) + a(s,t)\right] \underset{s\to\infty}{\sim} \sqrt{|t|}\,\alpha(s,t), \tag{5}$$

where $b(s,t)$, $\alpha(s,t)$, $a(s,t)$ slowly depend on energy.

Thus, the strong interaction at long distances leads to the dynamical mechanism of the slow energy dependence of spin effects. The dimensional parameters determining the magnitude of these spin effects are masses of an intermidiate nucleon state and masses of scattering nucleons which contribute to the $\alpha(s,t)$ amplitude /7/. When we calculate another reaction only the amplitude M in diagram of Fig. 1 is changed. So, we conclude that the structure of the meson-cloud contribution to the helicity-flip amplitude (5) is similar for different hadron reactions, and the terms containing an additional $\sqrt{s}$ factor must be in the amplitude of any reactions, independently of the t -channal exchange in amplitude M (Fig.1).



F i g. 1. The contribution of two-pion exchange into the hadron-hadron interaction at long distances.

As a result, the slow energy dependence in polarization must hold in a wide class of hadron reactions, including the charge exchange processes $\pi^- p \to \pi^0 n$, $\pi^- p \to \eta n, \ldots$, inclusive hadron reactions e.g. $pp \to \Lambda X$, and so on. The slowly energy-dependent polarization is observed experimentally in inclusive reactions. However, further theoretical and experimental investigations in this direction are necessary.

Summation of long-distance effects on the basis of quasipotential equation leads to the eikonal representation for the meson-nucleon helicity amplitudes:

$$T_{++}(s,t) = ip \int_0^\infty \rho d\rho \, J_0(\rho\Delta)\left[1 - e^{-\chi(\rho,s)}\right], \quad (6)$$

$$T_{+-}(s,t) = p \int_0^\infty \rho d\rho \, J_1(\rho\Delta)\, \chi_1(\rho,s)\, e^{-\chi(\rho,s)},$$

where the expressions for the eikonal phases $\chi(\rho,s)$ and $\chi_1(\rho,s)$ contain the quasipotentials $b(s,r)$, $a(s,r)$, $\alpha(s,r)$ and a growing as $\sqrt{s}$ term in $\chi(\rho,s)$ /7/.

The eikonal representation (7) will be used for the description of experimental data for $\pi^\pm p$ and $K^\pm p$ scattering. The estimations show that because of smallness of $\alpha(s,r)$ the growing as $\sqrt{s}$ term in the eikonal phase $\chi(\rho,s)$ is essential at $\sqrt{s} \gtrsim 200$ GeV and unimportant at experimentally available energies. The contribution $a(s,t)$ determines the decreasing with energy part of the helicity-flip amplitude. This term can be omitted at $E_L > 50$ GeV. As a result, in the energy region $50 \lesssim E_L \lesssim 400$ GeV in which we analyse the meson-nucleon scattering only the amplitude $T_{++}(s,t)$ can be taken into account. This amplitude has a standard form (6) with

$$\chi(\rho,s) = \chi_c(\rho,s) + \chi_p(\rho,s).$$

Let us approximate the calculated in the model peripheral part of the eikonal phase χ_p by the form which is similar to that of pp -scattering:

$$\tilde{\chi}_p(\rho,s) = h_p\left(b_p^2(s)+\rho^2\right)\left[e^{-M_p(s)\sqrt{b_p^2(s)+\rho^2}} + h_{as}e^{-M_{as}(s)\sqrt{b_p^2(s)+\rho^2}}\right]. \quad (7)$$

The parameters in (7) depend on energy as follows:

$$M_p(s) = M_1/\ae(s); \quad b_p(s) = b_1/\ae(s); \quad M_{as}(s) = M_2/\ae(s)$$
$$\ae(s) = \left[1 + \alpha(\ln s - i\pi/2)\right]^{1/2}. \quad (8)$$

From the model calculations we have obtained the following values for the effective masses M_1 , M_2 , effective radius b_1 and constant h_p and h_{as}

M_1 = 1.17 GeV; M_2 = 0.44 GeV; b_1 = 2.32 GeV^{-1}
h_p = 0.11 GeV^2 h_{as} = 0.2.

The parameter α determines the total cross section growth. In our model $\alpha = 0.1$. This is an average value for different reactions.

The contribution of heavy nucleon states to diagram (Fig. 1) will be taken into account phenomenologically by including the parameter g_p into the peripheral part of the eikonal phase:

$$\chi_p^{\pi p} = g_p^{\pi p}\, \widetilde{\chi}_p .$$

The central part contribution to the eikonal phase is determined as in the proton-proton case and has the form[8]:

$$\chi_c(\rho, s) = h_c \exp\left(-\mu_c(s)\sqrt{b_c(s)+\rho^2}\right), \qquad (9)$$

where the effective mass μ_c and effective radius b_c have the same energy dependence as μ_p and b_p. Most of the experimental data are in a low-energy region. **To obtain a quantitative description** of these data, we must include in our consideration the $1/\sqrt{s}$ part of the helisity-non-flup amplitude, For simplicity we assume that the cross-odd and cross-even terms of $1/\sqrt{s}$ part of the eikonal phase are similar and determined by the peripheral effects. As a result, we obtain:

$$\chi_{1/\sqrt{s}}^{\pi^+ p} = \frac{A+iB}{\sqrt{s}}\,\widetilde{\chi}_p \quad ; \quad \chi_{1/\sqrt{s}}^{\pi^- p} = \frac{B+iA}{\sqrt{s}}\,\widetilde{\chi}_p . \qquad (10)$$

The parameters of the central part of interaction and parameters A and B were calculated from the experimental data on $\pi^\pm p$ reaction[9-13] $(\chi^2/\overline{\chi}^2 = 1{,}03)$:

$$A = (25{,}05 \pm 2{,}3)\,GeV \quad ; \quad B = (31{,}85 \pm 2{,}5)\,GeV$$

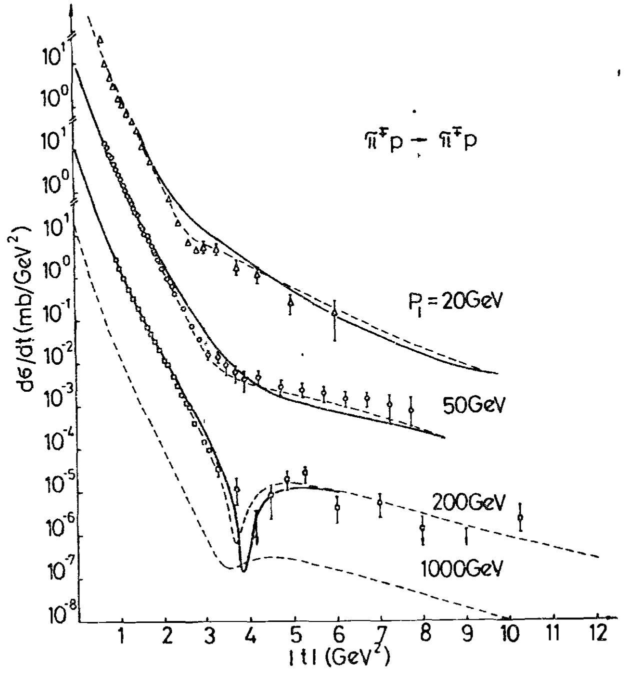
$$h_c = 3{,}07 \pm 0{,}23 \quad ; \quad g_p^{\pi p} = 1{,}07 \pm 0{,}04 \qquad (11)$$

$$\mu_c = (1{,}047 \pm 0{,}03)\,GeV \; ; \; b_c = (1{,}83 \pm 0{,}08)\,GeV^{-1}.$$

In the case of kaon-nucleon scattering the long-distance part of interactions is determined from the same diagram (Fig. 1) with the amplitude $M_{\pi K}$. So, we have **approximately:**

$$\chi_p^{Kp} = g_p^{Kp}\, \widetilde{\chi}_p . \qquad (12)$$

Let us assume that the central part of χ_c^{Kp} is in form similar to $\chi_c^{\pi p}$. As a result, in the case of Kp -scattering from the analysis of experimental data only the effective constant h_c^{Kp} in (9), coefficient g_p^{Kp} (12) and parameters A', B' in (10) were determined. Quantitative description of experimental data[11-13] ($\chi^2/\overline{\chi}^2$ = 1,27 for the number of experimental point N = 230) was obtained for the following parameters.

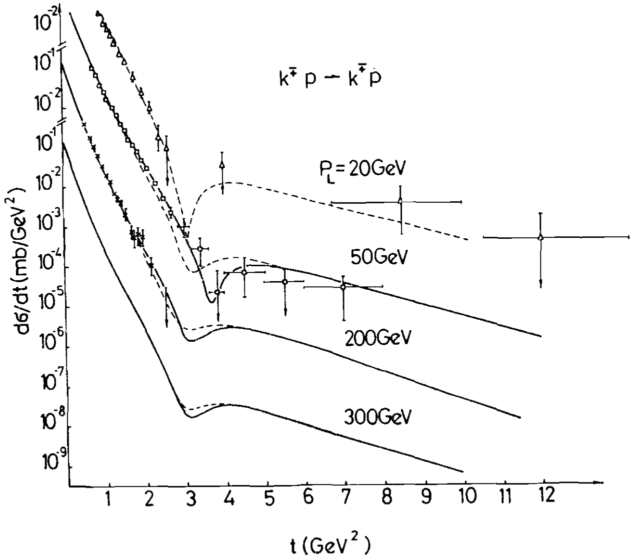


F i g. 2. The differential cross sections of $\pi^\pm p$ elastic scattering. – – – – - fit for $\pi^- p$, P_L = 50 GeV, 200 GeV. ; and predictions for P_L = 20 GeV and P_L = 1000 GeV. ——————— -predictions for $\pi^+ p$-scattering (experimental data for $\pi^- p$ -scattering[9,10].

$$A = (5.67 \pm 0.06)\,GeV \qquad B = (15.27 \pm 0.16)\,GeV$$

$$h_c = 3.73 \pm 0.05 \qquad g_p^{Kp} = 0.63 \pm 0.012 .$$

Thus, consistent account of the interaction at long distances permits a quantitative description of $\pi^\pm p$ and $K^\pm p$ scattering.



F i g. 3. The dirrerential cross sections for $K^{\pm}p$ -elastic scattering. ——— - fit for $K^{+}p$, p =50 GeV, P_L = 200 GeV and predictions for P_L = 20 GeV and P_L= 300 GeV. – – – – - predictions for $K^{-}p$ -scattering. (Experimental data: Δ - $K^{-}p$(P_L = 20 GeV); $\square$ - $K^{+}p$ (P_L = 50 GeV); $*$ - $K^{+}p$(P_L = 200 GeV)).

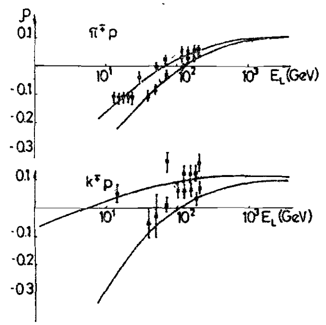
If can be seen (Fig. 2,3) that the diffraction minima are in the same momentum-transfer region $|t| \sim 4\ GeV^2$ for both meson -nucleon reactions. This result is due to the same form of the eikonal phase obtained in the model for pion-nucleon and kaon-nucleon reactions. The crossing-odd part of $1/\sqrt{s}$ term of the eikonal phase is different in $\pi^{\pm}p$ and $K^{\pm}p$ scattering. This part is sufficiently small in $\pi^{\pm}p$ and large in $K^{\pm}p$ - scattering. The ratio of crossing-odd and crossing even parts of $1/\sqrt{s}$ terms of the scattering amplitudes are the following

$$R^{\pi^{\pm}p} = -0.15; \qquad R^{K^{\pm}p} = 0.46.$$

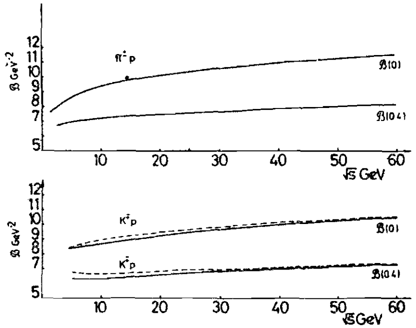
As a result, we arrive at a different behaviour of the ratio

$$\rho(s,0) = Re\,T(s,0)/Jm\,T(s,0)$$

(see Fig.4) and differential cross-sections at the diffraction-minimum region for $\pi^{\pm}p$ and $K^{\pm}p$ scattering (Fig.s.2 and 3).



F i g. 4. The ratio of the real and imaginary parts of the elastic forward amplitude.



F i g. 5. The slope of the diffraction peak.

The behaviour of the diffraction peak slope parameter is universal for all hadron reactions. The diffraction peak slope depends on s and t in the whole momentum transfer region for meson-nucleon and nucleon-nucleon reaction.

So, we can conclude that a self-consistent picture of the meson -nucleon and nucleon-nucleon scattering has been found in this paper on the basis of the dynamical model which takes into account the nucleon structure at long distances. As a result, the quantitative description of different properties of hadron elastic reactions is obtained.

We hope that consistent summation of the long-distance contribution to the hadronic interaction with the particle spin taken into account permits us to explain different effects in other high-energy hadron scattering processes at amall angles.

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Голоскоков С.В., Кулешов С.П., Селюгин О.В. E2-86-495

Упругое рассеяние адронов и структура нуклона

Рассмотрено упругое пион-нуклонное и каон-нуклонное рассеяние при высоких энергиях в широкой области передач импульса. Показано, что учет взаимодействия на больших расстояниях позволяет с единой точки зрения определить амплитуды $\pi^{\pm}p$ и $K^{\pm}p$-рассеяния. В результате объяснен широкий круг экспериментальных явлений в высокоэнергетических мезон-адронных реакциях и показано их соответствие нуклон-нуклонному рассеянию. Это позволяет сделать вывод о получении единой картины адронных процессов при высоких и сверхвысоких энергиях в рамках предложенной модели адрон-адронного взаимодействия, учитывающей структуру нуклона на больших расстояниях.

Работа выполнена в Лаборатории теоретической физики ОИЯИ.

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Goloskokov S.V., Kuleshov S.P., Selyugin O.V. E2-86-495

Elastic Hadron Scattering and Nucleon Structure

High-energy pion-nucleon and kaon-nucleon scattering is investigated in a wide range of momenum transfer. It is shown that taking into account of long-distance effects permits to determine from a unique point of view the amplitude of $\pi^{\pm}p$ and $K^{\pm}p$ scattering. As a result, different properties of high energy meson-nucleon scattering are shown. All that permits to conclude that a unique picture is obtained for the hadron processes at high and superhigh energies on the basis of the model of hadron interaction which makes allowance for the nucleon structure at long distances.

The investigation has been performed at the Laboratory of Theoretical Physics, JINR.

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