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S.V.Goloskokov

SPIN MECHANISM OF TOTAL-CROSS-SECTION GROWTH AND POLARIZATION PHENOMENA IN MESON-CLOUD MODEL

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At present no theory of strong interactions does exist in which the high energy particle scattering at small angles can be investigated, and therefore different models for the scattering are developed[1].

Important results have been found in the dynamical model of particle scattering which takes into account the internal structure of the particles[2]. The model permits us to calculate the effects of large distances connected with meson cloud concentrated around the hadron centre. On the basis of this model a quantitative description was obtained of known properties of meson-nucleon and nucleon-nucleon scattering at high energies in a wide region of momentum transfers[2,3].

Taking into account the spins of interacting particles, we arrive at the anomalous behaviour of the scattering amplitude[4]. It leads to a weak energy dependence of spin effects. The quasipotential equation[5] permits us to sum up these terms. As a result, we obtain the new spin mechanism of the total-cross-section growth[6].

In this paper we discuss the spin effects in nucleon-nucleon scattering within the meson cloud model. The model assumes the central part of a nucleon to exist, where valence quarks are concentrated surrounded by a meson cloud, that at large distances consists of π mesons only.

The contribution from scattering of central part of one hadron on the meson cloud of the other can be written as follows[2,4]:

$$T_p(s,t) = \frac{g^2}{i(2\pi)^4} \int d^4q\, M_{\pi p}(s',t)\, \phi[(k-q)^2, q^2]\, \phi[(p-q)^2, q^2] \times$$
$$\times \frac{\bar{u}(\vec{p})\gamma_5 (\hat{q}+m)\gamma_5 u(\vec{k})}{(q^2-m^2+i\epsilon)[(k-q)^2-\mu^2+i\epsilon][(p-q)^2-\mu^2+i\epsilon]} . \qquad (1)$$

Here m and μ are nucleon and meson masses, respectively,

$$s' = (k+k'-q)^2$$

$u(k)$ and $\bar{u}(p)$ are free spinors describing nucleons before and after interaction. They are normalized by the condition

$$u^+(\vec{p})u(\vec{p}) = 1 .$$

The distribution of matter inside the nucleon is taken into account by the vertex functions ϕ in (1)$^{/4/}$. We suppose that these functions are proportional to the electric form-factor of proton chosen in the dipole form. $M_{\pi p}(s', t)$ is the relativistic invariant meson-nucleon scattering amplitude:

$$M_{\pi p}(s', t) = \bar{u}(-\vec{p})[\frac{1}{2}\sqrt{s'}\,A(s', t) + (\frac{\hat{p} + \hat{k}}{2} - \hat{q})B(s', t)]\,u(-\vec{k}),$$

where A and B are scalar functions weakly dependent on energy. The integrals (1) can be calculated.

The proton-proton scattering amplitude at large distances connected with the meson-cloud contribution has the form$^{/4/}$:

$$T_p(s, t) = \bar{u}(-\vec{p})\bar{u}(\vec{p})\{\tilde{a}_p(s, t) + \tilde{b}_p(s, t)[\hat{n}(-\vec{\ell}) \otimes \hat{I} + \hat{I} \otimes \hat{n}(\vec{\ell})] + \\ + d_p(s, t)\,\hat{n}(-\vec{\ell}) \otimes \hat{n}(\vec{\ell})\}\,u(-\vec{k})u(\vec{k}), \tag{2}$$

$$\hat{n}(\vec{\ell}) = \gamma_0 - \vec{\gamma}\vec{\ell}/|\vec{\ell}|; \quad \vec{\ell} = (\vec{p} + \vec{k})/2.$$

Here the amplitudes $\tilde{a}_p(s,t)$ and $\tilde{b}_p(s,t)$ contain the anomalous terms

$$\tilde{a}_p(s, t) = \alpha_p(s, t)\frac{\sqrt{s}}{2} + a_p(s, t),$$

$$\tilde{b}_p(s, t) = \beta_p(s, t)\frac{\sqrt{s}}{2} + b_p(s, t), \tag{3}$$

where α, a, β, b logarithmically depend on energy. The amplitudes (3) lead to the spin effects slowly changing with energy. The calculation shows that

$$\alpha_p(s, t) \sim \beta_p(s, t) \ll 1. \tag{4}$$

We can calculate the high energy scattering amplitude at small angles by the quasipotential equation$^{/7/}$ using the amplitude (2) as a quasipotential. Provided the conditions (4) are fulfilled we have$^{/6/}$:

$$T_{++,++}(s, t) = i\int \rho\, d\rho\, J_0(\rho\Delta)[1 - e^{\tilde{\chi}_0(\rho,s)}],$$

$$T_{++,+-}(s, t) = \int \rho\, d\rho\, J_1(\rho\Delta)\chi_1(\rho, s)e^{\tilde{\chi}_0(\rho,s)},$$

$$\tilde{\chi}_0(\rho, s) = -\frac{2}{i}\int_{-\infty}^{\infty}\{D(r, s) - \frac{\sqrt{s}}{2}[\beta^2(r, s) + \frac{1}{16}\alpha^2(r, s)]\}\,dz =$$

$$= \chi_0(\rho, s) + \frac{\sqrt{s}}{2}\chi_{an}(\rho, s),$$

$$\chi_1(\rho, s) = \frac{1}{2i}\int_{-\infty}^{\infty} d(\beta(r, s))/d\rho\, dz. \tag{5}$$

The eikonal phases χ_0 and χ_1 are expressed through the quasipotential in coordinate space. The quasipotential D(r, s) contains the interactions of central parts of hadrons together with the peripherical part:

$$D(r, s) = d_c(r, s) + d_p(r, s). \tag{6}$$

The quasipotentials a and b do not contribute to the leading terms of the scattering amplitude. The double spin-flip amplitude is suppressed as a power.

Expressions (5) have an eikonal form, however, $\tilde{\chi}_0$ contains the term growing as $\sqrt{s}$ proportional to α^2 and β^2. It leads to the total cross section growth at superhigh energies caused by spin effects.

Really the main contribution to the non-spin-flip amplitude at superhigh energies comes from the terms with double change of the spin of one or two particles proportional to $\beta^2(r, s)$ and $\alpha^2(r, s)$, when the quasipotential (2) contains the anomalous terms. The quasipotential equation permits us to sum up these terms. As a result, they become exponential and contribute to the eikonal phase χ_0. It can be shown that the anomalous terms are unimportant in χ_0 at $\sqrt{s} \lesssim 100$ GeV. In this energy range the behaviour of the eikonal phase χ_0 is determined by the quasipotential D(r, s).

In the meson cloud model the peripheral part of the eikonal phase has an exponential form:

$$\chi_p(\rho, s) = -\frac{2}{i}\int_{-\infty}^{\infty} d_p(r, s)\,dz \underset{\rho \to \infty}{\sim} e^{-\mu\rho}$$

with $\mu \sim 0.6$ GeV$^{/2/}$.

It reproduces the behaviour of the eikonal phase at large distances$^{/8/}$. The total eikonal phase contains the central effects (6)

$$\chi_0(\rho, s) = \chi_c(\rho, s) + \chi_p(\rho, s)$$

due to hadron-centres interaction. It can be approximated by the expression$^{/2/}$:

$$\chi_0(\rho, s) = -\,h\,e^{-\mu(s)\sqrt{\rho^2 + b^2(s)}}. \qquad (7)$$

The anomalous terms have the peripheral character. When (4) is fulfilled, the main contribution to the eikonal phase $\tilde{\chi}_0$ is from the quasipotential $\beta(r, s)$

It can be approximated as follows

$$\beta(r, s) \sim H e^{-M\sqrt{r^2 + C^2}}, \qquad (8)$$

where

$$M \sim 0.5 \div 0.6 \text{ GeV}; \quad C \geq 10 \text{ GeV}^{-1}. \qquad (9)$$

As a result the total eikonal phase with inelastic effects/9/ taken into account can be written in the form:

$$\tilde{\chi}_0(\rho, s) = -\,e^{-\mu(s)\sqrt{\rho^2 + b^2(s)}}\left(1 - \gamma e^{-\mu(s)\sqrt{\rho^2 + b^2(s)}}\right) \times$$

$$\times \left(h + \frac{A + iB}{\sqrt{s}}\right) - (1 - i)\,2\sqrt{s}\,H^2\sqrt{C^2 + \rho^2}\,K_1\!\left(2M\sqrt{C^2 + \rho^2}\right); \qquad (10)$$

$$\mu(s) = \mu_0/\kappa(s); \quad b(s) = b_0 \cdot \kappa(s); \quad \kappa(s) = \sqrt{1 + \alpha\left(\ln s - \frac{i\pi}{2}\right)}\,.$$

In (10) the hypothesis of geometrical scaling is used to determine the energy dependence of the main term of the eikonal phase and the form of $1/\sqrt{s}$ term. The $s \to u$ crossing symmetry of the main asymptotic term of the eikonal phase is employed too. It is connected with the asymptotical equality of pp and $p\bar{p}$ differential cross sections. As in the previous paper/9/ the parameter γ was chosen equal to unity. The mass of the anomalous term was defined in accordance with (9):

$M = 0.56$ GeV.

Other parameters were obtained from the analysis of experimental data on σ^{pp}_{tot} and $\sigma^{p\bar{p}}_{tot}$ at $5 \text{ GeV} < \sqrt{s} < 62 \text{ GeV}$/10/ and $d\sigma/dt\,(pp)$ at $\sqrt{s} = 52.8$ GeV/11/ and $\sqrt{s} = 27.4$ GeV/12/.

The anomalous term β being small leads to the small value of spin-flip amplitude which can be eliminated by the data analysis.

A quantitative description of experimental data ($\chi^2/N = 1.3$) was obtained when

$h = 5{,}052 \pm 0{,}03$; $\mu_0 = (0{,}663 \pm 0{,}007)$ GeV;

$b_0 = (1{,}919 \pm 0{,}02)\,\text{GeV}^{-1}$; $\alpha = 0{,}062 \pm 0{,}004$;

$A = (6{,}42 \pm 0{,}28)$ GeV; $B = (17{,}01 \pm 0{,}73)$ GeV;

$H = (24{,}2 \pm 0{,}73)\,\text{GeV}^{-1}$; $C = (13{,}9 \pm 0{,}3)\,\text{GeV}^{-1}$.

Note that the parameters of the main term of the eikonal phase correspond to parameters found in/9/.

The anomalous term of the scattering amplitude is small and its radius is in accordance with the model (9). The theoretical curves are plotted in figs.1,2. The pp and $p\bar{p}$ total cross sections are shown up to the CERN $p\bar{p}$ collider energy in fig.2.

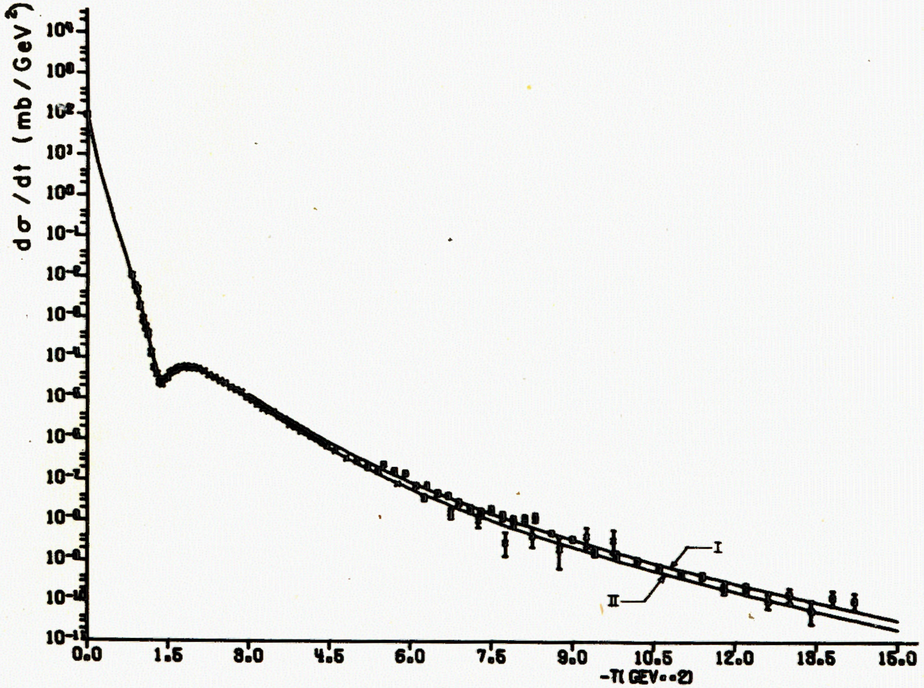


Fig.1. Description of $d\sigma/dt$ obtained in the model: I – $\sqrt{s}$ = = 27.4 GeV; II – $\sqrt{s}$ = 52.8 GeV.

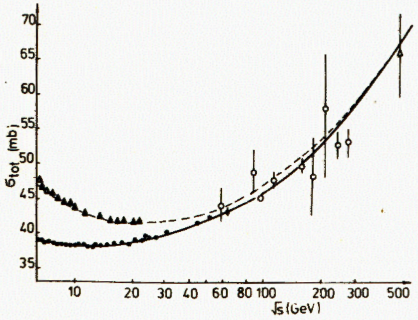


Fig.2. Description of pp and $p\bar{p}$ total cross sections (data from/10,15,16/).

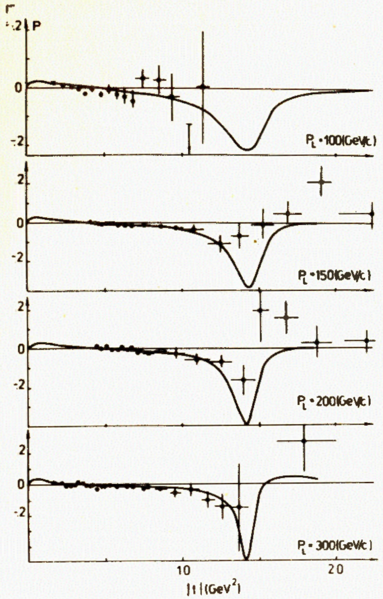
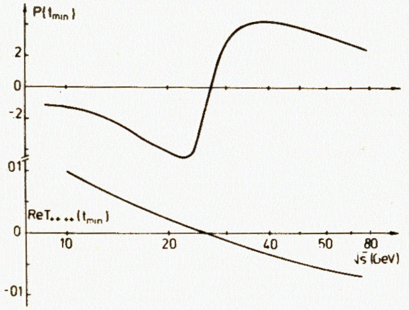


Fig.3. Predictions for the polarization (data from [17]).

Fig.4. Energy dependence of $\mathrm{Re}T_{++,++}$ and the polarization at the diffraction minimum.



In the energy region $\sqrt{s} \lesssim 100$ GeV the standard mechanism connected with the interaction-radius growth is responsible for the total-cross-section growth. At higher energies the spin mechanism leads to the rapid cross section growth [6] which does not contradict the Froissart bound [13]:

$$\sigma_{tot} \leq \frac{C}{m_\pi^2} \ell n^2 s .$$

Its contribution to σ_{tot} at $\sqrt{s} = 540$ GeV is approximately equal to 10 mb. The ratio $\mathrm{Re}T(s,0)/\mathrm{Jm}T(s,0)$ calculated in the model for pp and $p\bar{p}$ scattering is in good agreement with the data at $\sqrt{s} \gtrsim 7$ GeV.

Using the parameters obtained from the data fitting and helicity amplitudes (5) we can calculate the polarization. Predictions of the model are in good agreement with experimental data (fig.3). A similar behaviour was derived in [14] for the same energy region.

Note that the imaginary part of the non-spin-flip amplitude equals zero at the diffraction minimum; thus, the sign of polarization is determined by the sign of the real part of $T_{++,++}$.

The energy behaviour of $\mathrm{Re}T_{++,++}(t_{min})$ is shown in fig.4. The real part of $T_{++,++}$ changes sign at $\sqrt{s} \sim 28$ GeV. This phenomenon explains the small magnitude of the differential cross section at the diffraction minimum in a vicinity of this energy [11].

$$\frac{d\sigma}{dt}\Big|_{t_{min}} (\sqrt{s} = 30.4\,\mathrm{GeV}) \sim 6\cdot 10^{-6}\ \mathrm{mb/(GeV)^2} .$$

As a result the polarization changes sign at the same energy (fig.4). So, the model predicts a rapid change in the polarization behaviour at $P_L \gtrsim 400$ GeV. Predictions for the polarization in this energy region are shown in fig.5.

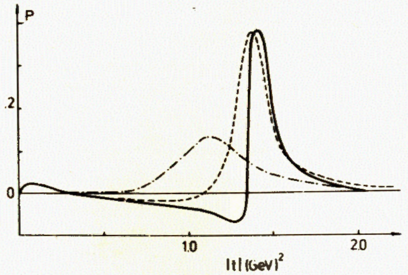
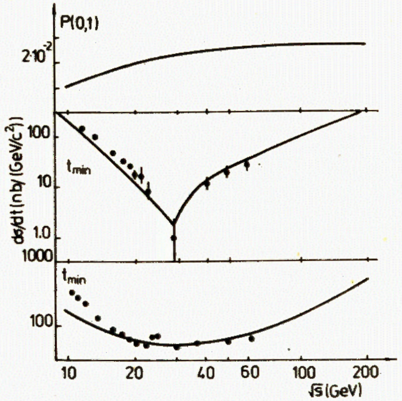


Fig.5. Predictions for the polarization at high energies. —— $\sqrt{s} = 30$ GeV; - - - $\sqrt{s} = 50$ GeV; — · — $\sqrt{s} = 200$ GeV.

Fig.6. Energy dependence of the polarization at $|t| = 0.1$ GeV and the differential cross section at the diffraction minimum and maximum.



A large magnitude of the polarization at high energies is due to the anomalous behaviour of the spin-flip amplitude:

$$\frac{|T_{++,+-}(s,t)|}{|T_{++,++}(s,t)|}\Big|_{t\text{ - fixed}} \sim \text{const} .$$

In this case the polarization at $|t|$ fixed should be approximately energy-independent. This can be observed in fig.6.

A strong energy dependence of the eikonal phase $\chi_0(\rho, s)$ (10) leads to a rapid change of the differential cross sections at the diffraction minimum and maximum (fig.6). As a result, the diffraction structure almost disappears at CERN $p\bar{p}$ collider energies. The experimental observation of the effects discussed here will give evidence for the spin mechanism of the total-cross-section growth. With a consistent consideration of the results of the meson cloud model [8] we can reduce the number of free parameters. However, the main conclusions will be the same.

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Голоскоков С.В. E2-83-313
Спиновый механизм роста полных сечений
и поляризационные явления при высоких энергиях
в модели мезонной "шубы" адрона

На основе модели мезонной "шубы" адрона показано, что спиновый механизм роста полных сечений важен при энергиях $p\bar{p}$ коллайдера ЦЕРНа. Модель позволяет описать данные по дифференциальным сечениям pp -рассеяния при энергиях ISR. Ее предсказания для поляризации находятся в согласии с экспериментом при энергиях 100 ГэВ $\leq P_L \leq$ 300 ГэВ.

Работа выполнена в Лаборатории теоретической физики ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна 1983

Goloskokov S.V. E2-83-313
Spin Mechanism of Total-Cross-Section Growth
and Polarization Phenomena in Meson-Cloud Model

On the basis of the meson cloud model it is shown that the spin mechanism of the total-cross-section growth is important at CERN $p\bar{p}$ collider energies. The model permits us to describe the differential cross sections of pp scattering ISR energies. Its predictions for polarization are in good agreement with the experimental data at energies $100 \leq P_L \leq 300$ GeV.

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

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