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SPIN EFFECTS IN pp- AND $\bar{p}p$-SCATTERING AT $\sqrt{s}$ < 100 GEV

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At present interest in the elastic hadron reactions is caused by the spin phenomena both in the range of small and large scattering angles. At distances of an order of the hadron size 1 fm. the constant of strong interaction grows and the methods of perturbation theory of QCD became inapplicable. Thus, a large number of models with different conceptions of the hadron structure and the role of contributions of the interacting components, etc., were suggested for the consideration of concrete processes including the interactions at large distances[1].

The investigation of spin phenomena in the high energy nucleon-nucleon scattering is an important verification of the applicability of the model approaches and basic principles of QCD.

At present there is no theoretical model that can unite all the obtained material of various sorts and expose the underlying physical processes (see, e.g.[2,3]).

Note that most of modern conceptions allow us to conclude that the physics of spin phenomena of high energies and limited transfer momenta is related to the dynamics of strong interactions at large distances. In this range the methods, based on the dynamical equations for a physical quantity[3], prove to be the most effective. For the investigation of the properties of high energy hadron scattering at small angles a dynamical model taking into account the hadron structure at large distances was developed[4].

It is shown[5] that in the model the spin-flip amplitude appears naturally and doesn't disappear with growing energy. The summation of large-distance contributions by the Logunov-Tavkhelidze quasipotential method makes it possible to modify the eikonal representation and in the eikonal phase there appear the terms growing as $\sqrt{s}$, which we call anomalous. This effect changes the dynamics of strong interactions at superhigh energies and gives rise to a new "spin" mechanism of hadron interactions. The obtained results were used to describe the meson-nucleon and nucleon-nucleon scattering in a wide range of transfer momenta[6].

In this work the size of the contribution of anomalous terms of the eikonal phase of the spin-flip scattering amplitude was determined by analysing the experimental data of the proton-proton scattering. On this basis we obtained predictions for polarization effects and considered the proton-antiproton scattering. Special attention is paid to the behaviour of the differential-cross sections around the diffraction minimum.

The model assumes the nucleon to consists of a central part, where valence quarks are concentrated and the perturbation theory of QCD is valid, and a large cloud of a quark-gluon field, singlet in colour.

It has been shown that at small angles the form of the amplitude of interaction of this field of one interacting nucleon with the central part of the other is described by a triangular dyagram with the exchange of the lightest constituents, π -mesons[4]. If spins of interacting hadrons are taken into account in this model, there appear spin-flip amplitudes, which do not disappear with growing energy. And the interaction quasipotential can be represented in the following general form[5]:

$$\hat{V}(\vec{r},s) = \frac{\sqrt{s}}{2}\,\alpha_p(\vec{r},s) + a_p(\vec{r},s) + [\hat{I}\otimes\hat{n}(-\vec{e}) + \hat{n}(\vec{e})\otimes\hat{I}] \times \left[\frac{\sqrt{s}}{2}\,\beta_p(\vec{r},s) + b_p(\vec{r},s)\right] + \hat{n}(\vec{e})\otimes\hat{n}(-\vec{e})\,d_p(\vec{r},s); \quad (1)$$

where $\vec{e} = \frac{\vec{P}+\vec{P}'}{2}$, $\hat{n}(\vec{e}) = \gamma_0 - \frac{\vec{e}\,\vec{\gamma}}{|\vec{e}|}$,

and α, a, β, b, d are scalar functions weakly (logarithmically) dependent on energy.

The summation of large-distance contributions of form (1) carried out in the framework of the quasipotential method leads to the following form of the eikonal pheses for spin-non-flip scattering amplitudes:

$$\chi_p(\rho,s) = -\frac{2}{i}\left[\int_{-\infty}^{\infty} d_p(\vec{r},s)\,dz - \frac{\sqrt{s}}{2}\int_{-\infty}^{\infty}\beta_p^2(\vec{r},s)\,dz\right] = \tilde{\chi}_p(\rho,s) + \frac{\sqrt{s}}{2}\,\chi_{an}(\rho,s) \quad (2)$$

and for spin-flip scattering amplitudes:

$$\chi_1(\rho,s) = \frac{1}{2i}\frac{d}{d\rho}\int_{-\infty}^{\infty}\beta_p(\vec{r},s)\,dz = \frac{d}{d\rho}\,\tilde{\chi}_1(\rho,s). \quad (3)$$

As the model-calculated expressions of the eikonal phases χ_p and χ_1 are rather cumbersome for calculations, we employ the folloging approximation in analysing the experimental data:

$$\tilde{\chi}_p(\rho,s) = h_p(b_p^2(s)+\rho^2)\left[e^{-\mu_p(s)\sqrt{b_p^2(s)+\rho^2}} + h_{as}\,e^{-\mu_{as}(s)\sqrt{b_p^2(s)+\rho^2}}\right] \quad (4)$$

$$\chi_{an}(\rho,s) = (1-i)\,H^2(B^2+\rho^2)^{1/2}\,K_1\left(M\sqrt{B^2+\rho^2}\right). \quad (5)$$

Here the cross-symmetric combination ($1-i$) has been introduced because of the account of $s\to u$ cross-symmetric diagram in the scattering amplitude. This leads to the asymptotic equality of the pp - and $\bar{p}p$ cross-sections as $s\to\infty$.

The total eikonal phase contains the central effects due to the hadron-centre interaction, which we put on a distinct status and approximate as follows:

$$\chi_c(\rho,s) = h_c\,\exp\left(-\mu_c(s)\sqrt{b_c^2+\rho^2}\right), \quad (6)$$

where $\mu_c(s)$ and b_c are the effective mass and radius of the interaction of central parts of hadrons.

The use of the maximal accessible experimental data allows a more accurable determination of the contribution of the anomalous terms, the spin-flip scattering amplitude and the prediction of the polarization phenomena and differential cross-sections at high and superhigh energies.

To determine the energy dependence ofthe effective masses and interaction radius, we have used the hypothesis of geometrical scaling[7] which must be fulfilled approximately in the energy range of ISR[8] and the local dispersion relations[9,10]. As a result, for $\tilde{\chi}_p(\rho,s)$ we have:

$$\tilde{\chi}_p(\rho,s) = \tilde{\chi}_p(\rho^2/b_p^2(s)); \quad b_p(s) = b_0\cdot\varkappa_1(s); \quad \varkappa_1(s) = \left(1+\alpha_1\left(\ln s - \frac{i\pi}{2}\right)\right)^{1/2}. \quad (7)$$

But for $\chi_c(\rho,s)$ we consider the energy dependence only for the effective mass:

$$\mu_c(s) = \mu_c^0 / \varkappa_2(s) \; ; \; \varkappa_2(s) = (1 + d_2(\ln s - \tfrac{i\pi}{2}))^{1/2}.$$

In the model the form of the peripheral part of $1/\sqrt{s}$ term of the eikonal phase resembles (4). This permits us to use for the $1/\sqrt{s}$ term the same form of the eikonal phase. As a result, for the total eikonal phase of the spin-non-flip scattering amplitude we have:

$$\chi(\rho,s) = \chi_c(\rho,s)(1 - \gamma\chi_c(\rho,s)) + g_1\tilde{\chi}_p(\rho,s) + g_2^2\frac{\sqrt{s}}{2}\chi_{an}(\rho,s)$$

$$+ \frac{A + iB}{\sqrt{s}}(\chi_c(\rho,s) + \chi_p(\rho,s)) \qquad (8)$$

and for the phase with spin-flip which slowly changes with energy:

$$\chi_1(\rho,s) = g_2\rho H M K_0(M\sqrt{B^2+\rho^2}). \qquad (9)$$

The coefficients g_1 and g_2 take into account a possible deviation of the eikonal phase due to other exchange effects, and the coefficient γ in (8) is determined by the inelastic interaction of the central part of the hadron.

For the falling with energy terms of the spin-flip amplitude we use the simplest Gaussian form:

$$|T_{sf}(s,t)|^2 = \frac{|t|}{s} h^2_{1/\sqrt{s}} e^{2b_{1/\sqrt{s}}t}.$$

The free parameters in (8,9) were obtained from the analysis of the pp -differential cross-sections in the energy range

$$4{,}5\,GeV \le \sqrt{s} \le 540\,GeV \quad (\chi^2/\bar{\chi}^2 = 0{,}98 \; ; \; N_{exp} = 1227)$$

(see Table I).

μ_c^0	= (0.751 ± 0.007) GeV;	b_c	= (2.252 ± 0.017) GeV^{-1};
α_p	= (0.126 ± 0.006);	α_c	= (0.045 ± 0.0015);
B	= (4.341 ± 0.04) GeV;	A	= (2.02 ± 0.02) GeV;
h_c	= (4.91 ± 0.06);	γ	= (0.222 ± 0.002);
g_1	= 1.0	g_2	= 0.85.

As is seen from Table II, in the energy range of ISR the idea of approximately geometrical scaling is really correct:

$$\frac{B(0)}{\sigma_{tot}} \simeq const \; ; \; \frac{d\sigma/dt|_{second\ max.}}{\sigma^2_{tot}} \simeq const.$$

However, at energy $\sqrt{s}$ = 540 GeV essential difference is already observed, especially, for the second relation.

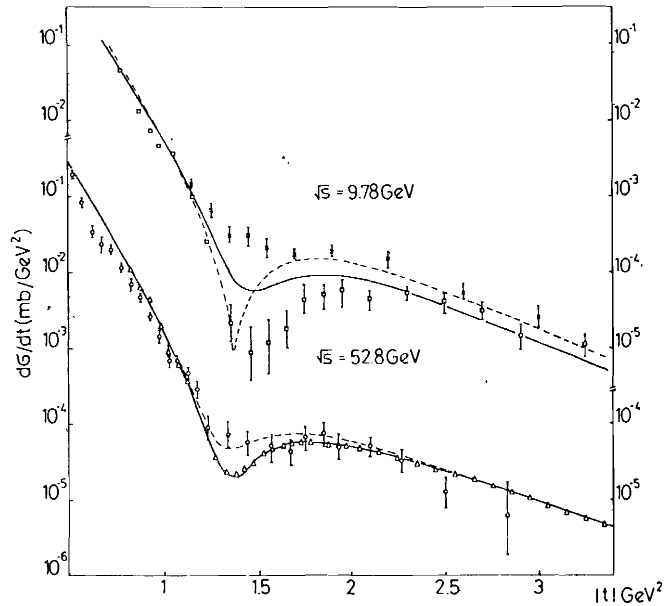
Despite that the contribution of the anomalous term was appreciable only in the range 0.8 $\le |t| \le$ 3 GeV when analysing the experimental data by formula (8), the constant of this term is determined sufficiently correctly, with a 5% accuracy, which confirms the presence of this term in the eikonal phase.

The contribution to the differential cross sections is near $1\cdot10^{-5}$ mb at $\sqrt{s}$ = 62.2 GeV, i.e. approximately 30%. This result permit us to extend the predictions of the model to much higher energies, where the contribution of the anomalous term is large, and in the range of the diffraction minimum it becomes dominant.

An important property of this model is that it can be applied to the proton-antiproton scattering at sufficiently low energies. Really, the obtained $s \to u$ crossing amplitudes of $\bar{p}p$ -scattering are in agreement with the recent experimental data on $p\bar{p}$ -scattering at P_L = 50 GeV /12/ and P_L = 1850 GeV /16/ (Fig.1). Note that they have a sharp diffraction minimum at $\sqrt{s}$ = 9.78 GeV and a slightly marked, in contrast to the pp -cross-section, minimum at $\sqrt{s}$ = 52.8 GeV. This is due to the fact that we have used the local dispersion relations and the real part of $\bar{p}p$ -amplitude is less than that of pp - amplitude when $\sqrt{s}$ = 9.78 GeV, but larger at $\sqrt{s}$ = 52.8 GeV, both at t = 0 and in the range of diffraction minimum. Then we have the following ratios for differential cross-sections in the range of the diffraction minimum:

$$\left.\frac{(d\sigma/dt)^{pp}}{(d\sigma/dt)^{\bar{p}p}}\right|_{\sqrt{s}=9{,}78\,GeV} \simeq 2 \; ; \; \left.\frac{(d\sigma/dt)^{pp}}{(d\sigma/dt)^{\bar{p}p}}\right|_{\sqrt{s}=52{,}8\,GeV} \simeq \frac{1}{2}$$

that are in agreement with the experimental data.

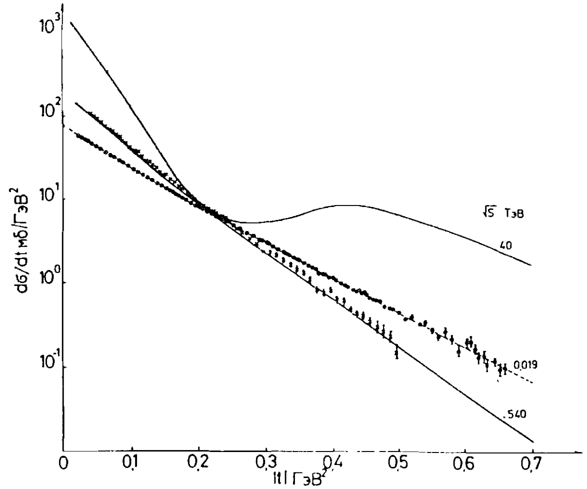


F i g. 1. The differential cross sections pp - and $\bar{p}p$ -scattering in the range of large transfer momenta :
———————— for pp -scattering
- - - - - - - - - predictions for $\bar{p}p$ -scattering.

The compatibility of the model predictions with the experimental data on proton-antiproton scattering is an indication of the small contribution of the spin-flip amplitude to the differential hadron cross-sections in a wide range of transfer momenta.

As is seen from Fig. 2. the model quite well reproduces the differential nucleon-nucleon cross-sections not only at large but also at small transfer momenta. Now let us examine the model predictions for the polarization phenomena at $P_L \gtrsim 100$ GeV. As is noted above, the spin effects falling with energy is incssential in this energy range and the behaviour of the spin-flip amplitude and, consequently, the polarization is defined by the anomalous term of the quasipotential $\beta(\rho, s)$.

The predictions obtained in the model for the polarization phenomena, based on the parameters determined by analysing the differential cross sections, are shown in Fig. 3a (for $P_L = 100$ and 300 GeV). On the whole, they correctly reproduce the whole picture of the behaviour of the experimental data. Note that the polarization is positive at small $|t|$ and changes sign at $|t|$ = 0.4 - 0.5 GeV^2. The change of sign of the polarization in this transfer-momentum range is observed experimentally at P_L = 45 GeV and that sign remains at higher energies.



F i g. 2. The differential cross sections in the range of small transfer momenta : - - - - - - - - - pp - scattering; ———————— predictions for $\bar{p}p$ -scattering.

In the considered model this effect is caused by the passage, through zero, of the leading asymptotic term of the spin-flip amplitude which is essentially determined by an anomalously growing part of the quasipotential.

In the range of low energies the contribution of $1/\sqrt{s}$ terms of the spin-flip amplitude leads to positive polarization at $|t| \leq 1$ GeV^2.

The predictions of the model for the proton-antiproton polarization at P_L = 100 and 300 GeV are shown in Fig.3 and from the Figure it is clear that already at these energies the polarization of $\bar{p}p$ - scattering is similar to the polarization of pp -scattering and with futher growing energy they will coincide.

The model predictions for the polarization at higher energies are shown in Fig. 3c. Note that a weak energy dependence of the polarization at fixed $|t| \sim 0.18$ GeV^2 (Fig. 4) is due to the behaviour of the spin flip-amplitude by the calculated potential $-\beta(s, z)$).

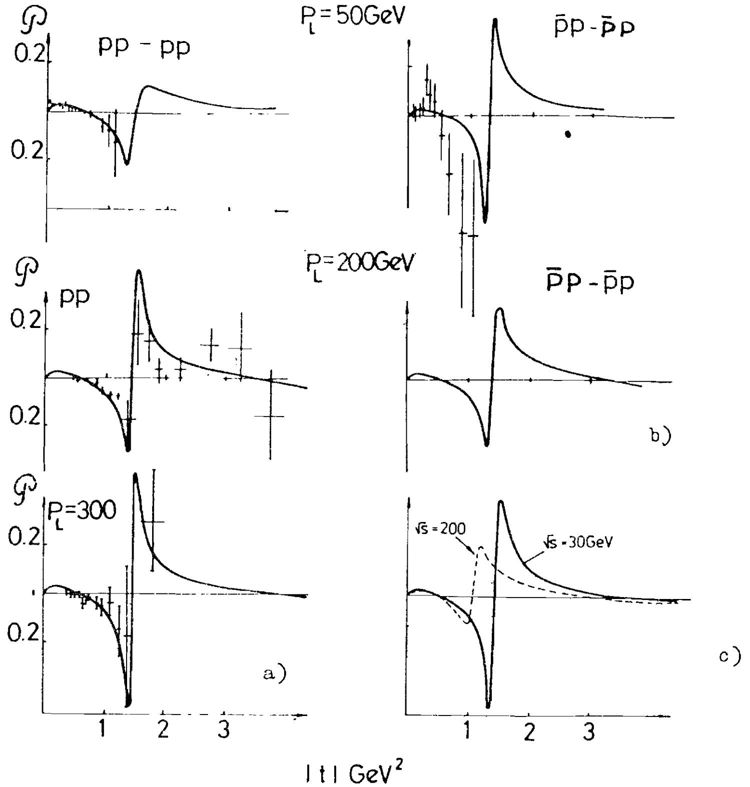
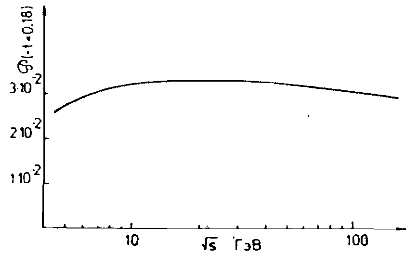


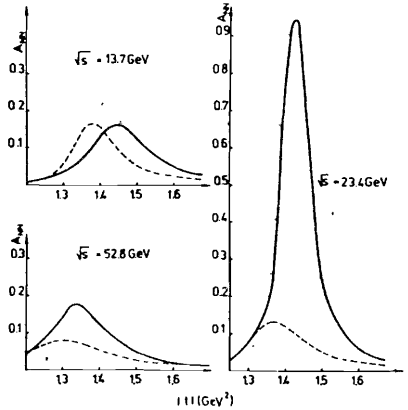
Fig.3. Comparison of dynamical-model prodictions for polarization with experiment: a) pp-scattering for P_L 50; 200 and 300 GeV; b) $\bar{p}p$ -scattering for P_L 50 GeV and 200 GeV; c) $pp(\bar{p}p)$-scattering for $\sqrt{s}$= 30 GeV and $\sqrt{s}$ = 200 GeV.

In the range of transfer momenta corresponding to the position of the diffraction minimum the predicted spin correlation parameter A_{NN} becomes essentially large. It is seen from Fig. 5 that for pp -scattering A_{NN} reaches its limiting value at P_L = 500 GeV, i.e. in the range where the diffraction minimum is most deep. Such a large size of A_{NN} allows a sufficiently reliable experimental check of our model predictions. Ahd, accordingly, further

essential information is obtained about the size of the potential $\beta(r,s)$ at relatively low energies.



F i g. 4. The behavious of the polarization of the energy at $|t|$ = 0.18 GeV^2.



F i g. 5. The model predictions for A_{NN}: ——— pp-scattering; - - - - - $\bar{p}p$ -scattering.

T a b l e 1.

Interval at $\lvert t\rvert$ (GeV)^2	0.03– 0.5	0.07– 1.03	0.035– 2.85	0.02– 3.5	0.05 14.2	0.5 10.0	0.03 0.5	0. (σ_{tot})
Interval at $\sqrt{s}$ (GeV)	4.5– 9.3	9.78	13.6 18.17	19.4	23.4 30.5	44.5 62.1	540	4.5 62.1
$\chi^2/\overline{\chi^2}$	1.16	0.79	0.9	1.02	0.95	1.05	0.92	0.87
Number of experimental points	95	58	123	170	316	290	84	91

T a b l e 2.

$\sqrt{s}$, GeV	9.28	13.4	19.4	30.5	62.1	540
$\beta(s,0)/\sigma_{tot}$	0.29	0.3	0.31	0.32	0.32	0.28
$\frac{(d\sigma/dt)_{2\text{-th max.}}}{\sigma^2_{tot}}$	5.9	4.0	3.15	3.0	3.3	48.3

Thus, the dynamical model leads to a lot of predictions concerning the behaviour of spin correlation parameters at high energies to be verified experimentally at an energy P_L = 500 GeV. Since the obtained results are in good agreement with experimental data in the investigated energy range, we may conclude that in the model the quasipotential $\beta(r,s)$ has been calculated exactly. Just it defines the spin contribution to the eikonal phase $\chi(\rho,s)$, the spin-non-flip amplitude, and may essentially change the behaviour of the cross sections at superhigh energies. Note that in the range of small transfer momenta the model leads to a smooth change of the slope with growing $|t|$. It is a common behaviour of the slope of the diffraction peak for different reactions at high energies, which is confirmed experimentally at P_L = 70 GeV (Serpuchov), P_L = 200 GeV (FNAL), and $\sqrt{s}$ = 540 GeV (CERN). Thus, the dynamical model developed here, which takes into account the effects of the meson cloud of hadrons and spins of the interacting particles, allows us to reproduce all the known properties of high energy hadron scattering in a wide momentum transfer region. A consequence of the model is small in size anomalous terms of the scattering amplitude which lead to the spin effect slowly changing with growing energies.

It should be emphasized that a self-consistent picture can be obtained only in the case of a large interaction radius of the anomalous quasipotential $\beta(s,r)$. This verifies the conclusion of the model about the peripheral origin of the part of this interaction quasipotential rapidly growing with energy.

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Голоскоков С.В., Кулешов С.П., Селюгин О.В. E2-86-496
Спиновые эффекты в pp- и $\bar{p}$p-рассеянии при $\sqrt{S}$ < 100 ГэВ

Исследовано влияние взаимодействия на больших расстояниях с учетом спинов частиц на процессы высокоэнергетического адрон-адронного рассеяния в области малых углов. На основе анализа данных по протон-протонному рассеянию определены вклады "спинового" механизма в дифференциальные сечения при высоких и сверхвысоких энергиях. Получены предсказания для поляризационных явлений протон-протонного и протон-антипротонного рассеяния. Особое внимание уделено поведению дифференциальных сечений в области дифракционного минимума.

Работа выполнена в Лаборатории теоретической физики ОИЯИ.

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Goloskokov S.V,, Kuleshov S.P., Selyugin O.V. E2-86-496
Spin Effects in pp- and $\bar{p}$p-Scattering at $\sqrt{S}$ < 100 GeV

The influence of long-distance interaction with the account of spins of particles on the processes of high-enegry hadron-hadron scattering at small angles is investigated. The contribution of "spin" mechanism into different cross sections is determined at high and superhigh energy by analysing the experimental data on the proton-proton scattering. On this basis predictions are obtained for polarization effects and proton-antiproton scattering. Special attention is paid to the behaviour of the differential cross sections around the diffraction minimum.

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

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