Hadron structure and spin effects in elastic hadron scattering at NICA energies

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Abstract

The spin effects in the elastic proton-proton scattering are analysed at NICA energies. It is shown the importance the investigation of the region of the diffraction minimum in the differential cross sections. Some possible estimation of spin effects are given for the different NICA energies in the framework of the new high energy generalized structure (HEGS) model.

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Introduction

One of the most important tasks of modern physics is the research into the basic properties of hadron interaction. The dynamics of strong interactions finds its most complete representation in elastic scattering. It is just this process that allows the verification of the results obtained from the main principles of quantum field theory: the concept of the scattering amplitude as a unified analytic function of its kinematic variables connecting different reaction channels were introduced in the dispersion theory by N.N. Bogoliubov[1]. Now many questions of hadron interactions are connected with modern problems of astrophysics such as unitarity and the optical theorem [2], and problems of baryon-antibaryon symmetry and CP-invariance violation [3]. The main domain of elastic scattering is small angles. Only in this region of interactions can we measure the basic properties that define the hadron structure. Their values are connected, on the one hand, with the large-scale structure of hadrons and, on the other hand, with the first principles that lead to the theorems on the behavior of scattering amplitudes at asymptotic energies [4, 5].

Modern studies of elastic scattering of high energy protons lead to several unexpected results reviewed, e.g., in [6, 7]. Spin amplitudes of the elastic NN scattering constitute a spin picture of the nucleon. Without knowledge of the spin NN-amplitudes it is not possible to understand spin observable of nucleon scattering off nuclei. In the modern picture, the structure of hadrons is determined by Generalized Distribution functions (GPDs), which include the corresponding parton distributions (PDFs). The sum rule [8] allow to obtain the elastic form factor (electromagnetic and gravitomagnetic) through the first and second integration moments of GPDs. It leads to remarkable properties of GPDs - some corresponding to inelastic and elastic scattering of hadrons. Now some different models examining the nonperturbative instanton contribution lead to sufficiently large spin effects at superhigh energies [9, 10]. The research of such spin effects will be a crucial stone
for different models and will help us to understand the interaction and structure of particles, especially at large distances. There are large programs of researching spin effects at different accelerators. Especially, we should like to note the programs at NICA, where the polarization of both the collider beams will be constructed. So it is very important to obtain reliable predictions for the spin asymmetries at these energies. In this paper, we extend the model predictions to spin asymmetries in the NICA energy domain.

The NICA SPD detector bounded a very small momentum transfer. If in the first steps the angles start from 16 mrad, then the minimum momentum transfer, which can be measured is more than $-0.01\ \text{GeV}^2$. Hence it is needed to exclude the Coulomb-nuclear interference region, where the real part of the spin-non-flip amplitude can be determined. We should move our researches on the region of the diffraction minimum, where the imaginary part of the spin-non-flip amplitude changes its sign. Note that in some models the absence of the second diffraction minimum is explained by the contribution in the differential cross section of the spin-flip amplitude \cite{11}. The interference of the hadronic and electromagnetic amplitudes may give an important contribution not only at very small transfer momenta but also in the range of the diffraction minimum \cite{12}. However, for that one should know the phase of the interference of the Coulombic and hadronic amplitude at sufficiently large transfer momenta too.

Using the existing model of nucleon elastic scattering at high energies $\sqrt{s} > 9\ \text{GeV} - 14\ \text{TeV}$ \cite{13, 14}, which involves minimum of free parameters, we are going to develop its extended version aimed to describe all available data on cross sections and spin-correlation parameters at lower energies down to the SPD NICA region. The model will be based on the usage of known information on generalized parton distributions in the nucleon, electro-magnetic and gravitomagnetic form factors of the nucleon taking into account analyticity and unitarity requirements and providing compatibility with the high energy limit, where the pomeron exchange dominates.

1 HEGS model and spin effects in the dip region of momentum transfer

The differential cross sections of nucleon-nucleon elastic scattering can be written as a sum of different helicity amplitudes:

$$
\frac{d\sigma}{dt} = \frac{2\pi}{s^2}(|\Phi_1|^2 + |\Phi_2|^2 + |\Phi_3|^2 + |\Phi_4|^2 + 4|\Phi_5|^2).$$

(1)
\begin{align*}
AN \frac{d\sigma}{dt} &= -\frac{4\pi}{s^2} [\text{Im}(\Phi_1(s,t) + \Phi_2(s,t) + \Phi_3(s,t) - \Phi_4(s,t))\Phi_5^*(s,t)] \quad (2) \\
A_{NN} \frac{d\sigma}{dt} &= \frac{4\pi}{s^2} [\text{Re}(\Phi_1(s,t)\Phi_2^*(s,t) - \Phi_3(s,t)\Phi_4^*(s,t)) + |\Phi_5(s,t)|^2] \quad (3)
\end{align*}

The HEGS model \cite{13, 14} takes into account all five spiral electromagnetic amplitudes. The electromagnetic amplitude can be calculated in the framework of QED. In the high energy approximation, it can be obtained \cite{15} for the spin-non-flip amplitudes:

\begin{equation}
F_{\text{em}}^1(t) = \alpha f_1^2(t)\frac{s - 2m^2}{t}; \quad F_{\text{em}}^3(t) = F_{\text{em}}^1; \quad (4)
\end{equation}

and for the spin-flip amplitudes: with the electromagnetic and hadronic interactions included, every amplitude \( \phi_i(s,t) \) can be described as

\begin{equation}
\phi_i(s,t) = F_{\text{em}}^i \exp (i\alpha \varphi(s,t)) + F_{h}^i(s,t), \quad (5)
\end{equation}

where \( \varphi(s,t) = \varphi_C(t) - \varphi_{Ch}(s,t) \), and \( \varphi_C(t) \) will be calculated in the second Born approximation in order to allow the evaluation of the Coulomb-hadron interference term \( \varphi_{Ch}(s,t) \). The quantity \( \varphi(s,t) \) has been calculated at large momentum transfer including the region of the diffraction minimum \cite{16, 17, 12} and references therein.

Let us define the hadronic spin-non-flip amplitudes as

\begin{equation}
F_{\text{em}}^{h}(s,t) = [\Phi_1(s,t) + \Phi_3(s,t)] / 2; \quad (6)
\end{equation}

The model is based on the idea that at high energies a hadron interaction in the non-perturbative regime is determined by the reggenized-gluon exchange. The cross-even part of this amplitude can have two non-perturbative parts, possible standard pomeron - \( (P_{2np}) \) and cross-even part of the 3-non-perturbative gluons \( (P_{3np}) \). The interaction of these two objects is proportional to two different form factors of the hadron. This is the main assumption of the model. The second important assumption is that we choose the slope of the second term four times smaller than the slope of the first term, by analogy with the two pomeron cuts. Both terms have the same intercept.

The form factors are determined by the Generalized parton distributions of the hadron (GPDs). The first form factor corresponding to the first momentum of GPDs is the standard electromagnetic form factor - \( G(t) \). The second form factor
is determined by the second momentum of GPDs \( A(t) \). The parameters and \( t \)-dependence of GPDs are determined by the standard parton distribution functions, so by experimental data on deep inelastic scattering and by experimental data for the electromagnetic form factors (see [18]). The calculations of the form factors were carried out in [19]. The final elastic hadron scattering amplitude is obtained after unitarization of the Born term. At large \( t \) our model calculations are extended up to \(-t = 15 \text{ GeV}^2\). We added a small contribution of the energy independent part of the spin flip amplitude in the form similar to the proposed in [20] and analyzed in [21].

\[
F_{sf}(s, t) = h_{sf} q^3 F_1^2(t) e^{-B_{sf} q^2}.
\]  

The energy dependent part of the spin-flip amplitude is related to the main amplitude but with an additional kinematic factor and the main slope taken twice more, conformity with the paper [22, 23]. The form factors incoming in the spin-flip amplitude are determined by the GPD functions \( H(s, t, x) \) and \( E(s, t, x) \), which include the corresponding PDF distributions. The model is very simple from the viewpoint of the number of fitting parameters and functions. There are no any artificial functions or any cuts which bound the separate parts of the amplitude by some region of momentum transfer.

Now we shall restrict our discussion to the analysis of \( A_N \) as there are some experimental data in the region of NICA energies. In the standard pictures the spin-flip and double spin-flip amplitudes correspond to the spin-orbit (LS) and spin-spin (SS) coupling terms. The contribution to \( A_N \) from the hadron double spin-flip amplitudes already at \( p_L = 6 \text{ GeV}/c \) is of the second order compared to the contribution from the spin-flip amplitude. So with the usual high energy approximation for the helicity amplitudes at small transfer momenta we suppose that \( \Phi_1 = \Phi_3 \) and we can neglect the contributions of the hadron parts of \( \Phi_2 - \Phi_4 \). Note that if \( \Phi_1, \Phi_3, \Phi_5 \) have the same phases, their interference contribution to \( A_N \) will be zero, though the size of the hadron spin-flip amplitude can be large. Hence, if this phase has different \( s \) and \( t \) dependencies, the contribution from the hadron spin-flip amplitude to \( A_N \) can be zero at \( s_i, t_i \) and non-zero at other \( s_j, t_j \). The experimental data \( (\sum \chi^2/n_{dof} = 1.24) \).

Now let us examine the form of the differential cross section in the region of the momentum transfer where the diffractive properties of elastic scattering appear most strongly - it is the region of the diffraction dip. The form and the energy dependence of the diffraction minimum are very sensitive to different parts of the scattering amplitude. The change of the sign of the imaginary part of the scattering amplitude determines the position of the minimum and its movement with changing energy. The contributions of the real part of the spin-non-flip scattering amplitude and the
Figure 1: The model calculation of the diffraction minimum in $d\sigma/dt$ of $pp$ scattering [left] at $\sqrt{s} = 30.4$ GeV; [right] for $pp$ and $p\bar{p}$ at $\sqrt{s} = 52.8$ GeV [24] scattering.

Figure 2: The model calculation of the diffraction minimum in $d\sigma/dt$ of $pp$ at $\sqrt{s} = 13.4; 16.8; 30.4; 44.7$ GeV; (lines, respectively, long dash; solid; thin-solid, and short - dash ); and experimental data [24], respectively, - the triangle down, the circles (solid), triangle up, and circles )
The square of the spin-flip amplitude determines the size and the energy dependence of the dip. Hence, this depends heavily on the odderon contribution. The spin-flip amplitude gives the contribution to the differential cross sections additively. So the measurement of the form and energy dependence of the diffraction minimum with high precision is an important task for future experiments.

The HEGS model reproduces $d\sigma/dt$ at very small and large $t$ and provides a qualitative description of the dip region at $-t \approx 1.6$ GeV$^2$, for $\sqrt{s} = 10$ GeV and $-t \approx 0.45$ GeV$^2$ for $\sqrt{s} = 13$ TeV. Note that it gives a good description for the proton-proton and proton-antiproton elastic scattering or $\sqrt{s} = 53$ GeV and for $\sqrt{s} = 62.1$ GeV (Fig.2a).

The dependence of the position of the diffraction minimum on $t$ is determined in most part by the growth of the total cross sections and the slope of the imaginary part of the scattering amplitude. Figures 2b and 3 show this a dependence obtained in the HEGS model at different energies.

In Fig.3, the description of the diffraction minimum in our model is shown for NICA energies. The HEGS model reproduces sufficiently well the energy dependence and the form of the diffraction dip. In this energy region the diffraction minimum reaches the sharpest dip at $\sqrt{s} = 30$ GeV near the final NICA energy. Note that at this energy the value of $\rho(s, t = 0)$ also changes its sign in the proton-proton scattering.

The calculated analyzing power at $p_L = 6$ GeV/c is shown in Fig.4a. One can see that a good description of experimental data on the analyzing power can be reached only with one hadron-spin-flip amplitude.

The experimental data at $p_L = 11.75$ GeV/c seriously differ from those at $p_L = 6$ GeV/c but our calculations reproduce $A_N$ sufficiently well (Fig.4b). It is shown
that our energy dependence of the spin-flip amplitudes was chosen correctly and we may hope that further we will obtain correct values of the analyzing power and other spin correlation parameters.

From Fig. 4 we can see that in the region $|t| \approx 0.2 \div 1$ GeV$^2$ the contributions from the hadron spin-flip amplitudes are most important. At last, Fig. 5a shows our calculations at $p_L = 200$ GeV/c.

At this energy, the contributions of the phenomenological energy independent part of the spin-flip amplitude is compared with the energy dependent part. The spin effect is sufficiently large and has a specific form, which is determined by the form of the differential cross section in the diffraction dip domain.
2 Conclusions

The Generalized parton distributions (GPDs) make it possible to better understand the thin hadron structure and to obtain the hadron structure in the space frame (impact parameter representations). It is tightly connected with the hadron elastic hadron form factors. The research into the form and energy dependence of the diffraction minimum of the differential cross sections of elastic hadron-hadron scattering at different energies will give valuable information about the structure of the hadron scattering amplitude and hence the hadron structure and the dynamics of strong interactions. The diffraction minimum corresponds to the change of the sign of the imaginary part of the spin-non-flip hadronic scattering amplitude and is created under a strong impact of the unitarization procedure. Its dip depends on the contributions of the real part of the spin-non-flip amplitude and the whole contribution of the spin-flip scattering amplitude. In the framework of HEGS model, we show a deep connection between elastic and inelastic cross sections, which are tightly connected with the hadron structure at small and large distances.

The HEGS model reproduces well the form and the energy dependence of the diffraction dip of the proton-proton and proton antiproton elastic scattering [30]. The predictions of the model in most part reproduce the form of the differential cross section at $\sqrt{s} = 13$ TeV. It means that the energy dependence of the scattering amplitude determined in the HEGS model and unitarization procedure in the form of the standard eikonal representation satisfies the experimental data in the huge energy region (from $\sqrt{s} = 9$ GeV up to $\sqrt{s} = 13$ TeV. It should be noted that the real part of the scattering amplitude, on which the form and energy dependence of the diffraction dip heavily depend, is determined in the framework of the HEGS model only by the complex $\bar{s}$, and hence it is tightly connected with the imaginary part of the scattering amplitude and satisfies the analyticity and the dispersion relations. Quantitatively, for different thin structures of the scattering amplitude, a wider analysis is needed. This concerns the fixed intercept taken from the deep inelastic processes and the fixed Regge slope $\alpha'$, as well as the form of the spin-flip amplitude. Such an analysis requires a wider range of experimental data, including the polarization data of $A_N(s,t)$, $A_{NN}(s,t)$, $A_{LL}(s,t)$, $A_{SL}(s,t)$. The obtained information about the sizes and energy dependence of the spin-flip and double-flip amplitudes will make it possible to better understand the results of famous experiments carried out by A. Krish at the ZGS to obtain the spin-dependent differential cross sections [31, 32] and the spin correlation parameter $A_{NN}$ and at the AGS [33] to obtain the spin correlation parameter $A_N$ showing the significant spin effects at large momentum transfer.
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