Properties of the Spin-flip Amplitude of Hadron Elastic Scattering and Possible Polarization Effects at RHIC

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Abstract. With relation to the RHIC spin program we research the polarization effects in elastic proton-proton scattering at small momentum transfer and in the diffraction dip region. The calculations take into account the Coulomb-hadron interference effects including the additional Coulomb-hadron phase. In particular we show the impact of the form of the hadron potential at large distances on the behavior of the hadron spin-flip amplitude at small angles. The $t$-dependence of the spin-flip amplitude of high energy hadron elastic scattering is analyzed under different assumptions on the hadron interaction.

I INTRODUCTION

Several attempts to extract the spin-flip amplitude from the experimental data show that the ratio of spin-flip to spin-nonflip amplitudes can be non-negligible and may be only slightly dependent on energy [1,2].

For the definition of new effects at small angles and especially in the region of the diffraction minimum one must know the effects of the Coulomb-hadron interference with sufficiently high accuracy. The Coulomb-hadron phase was calculated in the entire diffraction domain taking into account the form factors of the nucleons [3]. Some polarization effects connected with the Coulomb hadron interference, including some possible odderon contribution, were also calculated [4].

The model-dependent analysis based on all the existing experimental data of the spin-correlation parameters above $p_L \geq 6$ GeV allows us to determine the structure of the hadron spin-flip amplitude at high energies and to predict its behavior at superhigh energies [6]. This analysis shows that the ratios $\text{Re } \phi_h^p(s,t)/(\sqrt{|t|} \text{Re } \phi_1^p(s,t))$ and $\text{Im } \phi_h^p(s,t)/(\sqrt{|t|} \text{Im } \phi_1^p(s,t))$ depend on $s$ and $t$ (see Fig.1 a,b). At small momentum transfers, it was found that the slope of the

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“residual” spin-flip amplitudes is approximately twice the slope of the spin-non-flip amplitude. The obtained spin-flip amplitude leads to the additional contribution to the pure CNI effect at small \( t \) (Fig. 1 c).

The dependence of the hadron spin-flip amplitude on \( t \) at small angles is closely related with the basic structure of hadrons at large distances. We show that the slope of the so-called “reduced” hadron spin-flip amplitude (the hadron spin-flip amplitude without the kinematic factor \( \sqrt{|t|} \)) can be larger than the slope of the hadron spin-non-flip amplitude, as was observed long ago [5].

**II THE SLOPE OF THE HADRON AMPLITUDES**

For an exponential form of the amplitudes this coincides with the usual slope of the differential cross sections divided by 2. At small \( t \) (\( \sim 0 \div 0.1 \text{GeV}^2 \)), practically all semiphenomenological analyses assume: \( B_{1+}^+ \approx B_{1-}^+ \approx B_{2+}^- \approx B_{2-}^- \). If the potentials \( V_{++} \) and \( V_{+-} \) are assumed to have a Gaussian form in the first Born approximation \( \phi_h^+ \) and \( \phi_h^- \) will have the same form \( \phi_h^+(s, t) \sim \exp(-B \Delta^2) \), \( \phi_h^-(s, t) \sim q B \exp(-B \Delta^2) \). In this special case, therefore, the slopes of the spin-flip and “residual” spin-non-flip amplitudes are indeed the same. A Gaussian form of the potential is adequate to represent the central part of the hadronic interaction. The form cuts off the Bessel function and the contributions at large distances. If, however, the potential (or the corresponding eikonal) has a long tail (exponential or power) in the impact parameter, the Bessel functions can not be taken in the approximation form and the full integration leads to different results.

If we take \( \chi_i(b, s) \sim H e^{-a \cdot b} \), we obtain

\[
F_{int}(s, t) = \frac{a}{(a^2 + q^2)^{3/2}} \approx 1/[a\sqrt{a^2 + q^2}] \exp(-Bq^2) 
\]  

(1)
with $B = 1/a^2$. For the “residual” spin-flip amplitude, on the other hand, we obtain [8]

$$\sqrt{|t|} \tilde{F}_{sf}(s,t) = (3 a q)/[(a^2 + q^2)^{5/2}] \approx (3 a q B^2)/((\sqrt{a^2 + q^2}) \exp(-2 Bq^2)). \quad (2)$$

In this case, therefore, the slope of the “residual” spin-flip amplitude exceeds the slope of the spin-non-flip amplitudes by a factor of two. A similar behaviour can be obtained with the standard dipole form factor [8].

### III THE DETERMINATION OF THE STRUCTURE OF THE HADRON SPIN-FLIP AMPLITUDE

Note that if the “reduced” spin-flip amplitude is not small, the impact of a large $B^-$ will reflect in the behavior of the differential cross section at small angles [7]. The method gives only the absolute value of the coefficient of the spin-flip amplitude. The imaginary and real parts of the spin-flip amplitude can be found only from the measurements of the spin correlation coefficient.

Let us take the spin nonflip amplitude in the standard exponential form with definite parameters: slope $B^+$, $\sigma_{tot}$ and $\rho^+$. For the “residual” spin-flip amplitude, on the other hand, we consider two possibilities: equal slopes $B^- = B^+$ and $B^- = 2B^+$. The results of these two different calculations are shown in Fig.2. It is clear that around the maximum of the Coulomb-hadron interference, the difference between the two variants is very small. But when $|t| > 0.01 \text{ GeV}^2$, this difference grows. So, if we try to find the contribution of the pomeron spin-flip, we should take into account this effect. As the value of $A_N$ depends on the determination of the beam polarization, let us calculate the derivative of $A_N$ with respect to $t$, for example, at $\sqrt{s} = 500 \text{ GeV}$.

If we know the parameters of the hadron spin non-flip amplitude, the measurement of the analyzing power at small transfer momenta helps us to find the structure of the hadron spin-flip amplitude. There is a specific point of the differential cross sections and of $A_N$ on the axis of the momentum transfer, - $t_{re}$, where $|ReF^{++}_c| = |ReF^{++}_h|$. This point $t_{re}$ can be found from the measurement of the differential cross sections [9]. At high energies at the point $t_{re}$ [8] we obtain for $pp$-scattering

$$ReF^h_{sf}(s,t) = \frac{-1}{2(ImF^h_{nf}(s,t) + ImF^c_{nf}(t))} A_N(s,t) \frac{d\sigma}{dt} - ReF^c_{sf}(t). \quad (3)$$

We can again take the hadron spin-nonflip and spin-flip amplitudes with definite parameters and calculate the magnitude of $A_N$ by the usual complete form while the real part of the hadron spin-flip amplitude is given by (3). Our calculation by this formula and the input real part of the spin-flip amplitude are shown in Fig. 2 c. At the point $t_{re}$ both curves coincide. So if we obtain from the accurate measurement of the differential cross sections the value of $t_{re}$, we can find from $A_N$...
the value of the real part of the hadron spin-flip amplitude at the same point of momentum transfer.

IV THE MODEL PREDICTIONS

The model [10] takes into account the contribution of the hadron interaction at large distances and leads to the high-energy spin-flip amplitude. The model gives the large spin effects in the $hh$-elastic scattering and predicts non-small effects for the $PP2PP$ experiment at RHIC especially in the diffraction dip domain [11]. The additional pure CNI effects can be calculated using the Coulomb-nuclear phase [3]. These polarization effects will be present at RHIC energy, even though $F^h_{++} \to 0$ at high energy. Our model calculations show on Fig.3 for both cases.

The model gives the standard $t$-dependence of $ReF_h^{++}$ and $ImF_h^{++}$. Instead of it, in a convenient parameterization of both the modulus and the phase one can obtain the alternative case, in which $ImF_h(s,t)$ has the zero at small $t$ (for details,
FIGURE 4. (a) $A_{NN}^{CN}$ at $\sqrt{s} = 50$ GeV and small $t$ for two models. (b) and (c) $A_{NN}^{CN}$ at $\sqrt{s} = 50$ GeV and $\sqrt{s} = 500$ GeV in the region of the dip (the solid line corresponds to the model I with zero of $\Im F_h$ at dip; the dashed line shows the variant II, with the zero of the $\Re F_h$ at the dip).

see [12]). Such an approach enables one to specify the elastic hadron scattering amplitude $F_h(s,t)$ directly from the elastic scattering data. The difference between the phases leads either to central or peripheral distributions of elastic hadron scattering in the impact parameter space. The obtained form of $A_{NN}^{CN}$ at small momentum transfers differs for the two variants beginning at $|t| > 0.05$ GeV$^2$ (Fig.4 a). The difference reaches $2\%$ at $-t = 0.15$ GeV$^2$ and, in principle, can be measured in an accurate experiment. Now let us calculate the Coulomb-hadron interference effect $- A_{NN}^{CN}$ in the two alternatives for higher $|t|$: (i) the diffraction dip is created by the “zero” of the $\Im F_h(s,t)$ part of the scattering amplitude and $\Re F_h(s,t)$ fills it; (ii) the diffraction dip is created by the “zero” of the $\Re F_h(s,t)$ part of the scattering amplitude and $\Im F_h(s,t)$ fills it. The results are shown in Fig. 4 (b) for $\sqrt{s} = 50$ GeV and in Fig. 4 (c) at $\sqrt{s} = 500$ GeV.

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