EFFECTS OF ABSORPTION IN SMALL-ANGLE SCATTERING OF POLARIZED PROTONS*

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We investigate the single-spin asymmetry, $A_{\mathrm{N}}(t)$, arising from Coulomb-nuclear interference (CNI) in the small-angle elastic scattering of polarized protons. Previous theoretical predictions failed to explain the non-trivial t dependence of A_{N} in elastic proton–gold scattering, measured recently at RHIC. We found that the absorptive corrections make the Coulomb amplitude of pA elastic scattering significantly different from eA scattering, leading to dramatic changes in the t dependence. Moreover, we also found the absorptive corrections being significant for the analysis of data for polarized pp elastic scattering, which previously revealed a zero spin-flip part of the Pomeron. We concluded with an essentially non-zero hadronic spin-flip.

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1. Introduction

The measurement of small-angle elastic scattering, *i.e.*, in the Coulomb-nuclear interference (CNI) region, was presented in [1, 2] as an optimal way to measure the single-spin asymmetry, $A_{\mathrm{N}}(t)$. The measurement of the single-spin asymmetry allows one to study spin-flip hadron interaction of the Pomeron [3]. This topic is becoming more actual with the new results on $A_{\mathrm{N}}(t)$ from the HJET measurement [4–6] and the STAR experiment [7] at RHIC.

However, in the HJET experiment corresponding to the RHIC fix target configuration, the energies $E_{\mathrm{lab}} = 100$ and 255 GeV might be not sufficiently high to eliminate the Reggeon contributions. Note, the Regge phenomenol-

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ogy can describe pp interactions at low energies via exchange of ω, f, ρ and a_2 Reggeons, where the last two are the iso-vector Reggeons, which are predominantly spin-flip.

The effective method to suppress the iso-vector Reggeons is to use nuclear targets, which either completely eliminate such Reggeons, or suppress by a factor $(1 - Z/A - 1)$. Although the first calculations of nuclear effects [2, 8] well reproduced data for $A_{\rm N}$ in proton–carbon elastic scattering, measurements on heavier targets, especially gold, revealed an unexpected t dependence [4].

The magnitude of spin-flip hadronic interaction can be studied in single-spin asymmetry by introducing a ratio of spin-flip to the imaginary part of the non-flip hadronic elastic amplitudes, r_5,

$$r_5 \equiv \frac{m\phi_+^h}{q\phi_5^h}\,, \tag{1}$$

where ϕ_+^h and ϕ_5^h are hadronic spin-flip and non-flip amplitudes, respectively. This parameter can be extracted from the difference between experimental data and theoretical predictions with the spin-flip interaction of Coulomb origin only.

However, the t dependence of $A_{\rm N}(t)$ in the proton–gold elastic interaction measured recently in the HJET measurement [4] revealed a dramatic disagreement with theoretical expectations [2].

2. Absorptive corrections

The source of the problem turns out to be the nuclear electromagnetic form factor, used in [2, 8], which needs to be corrected. It was assumed to be the same as in electron-nuclear scattering, *i.e.* given by Fourier transform of the nuclear thickness function, $T_A(b) = \int_{-\infty}^{\infty} {\rm d}z \rho_A(b,z)$, the integral of the nuclear density along the trajectory of the incoming proton.

However, in pp, pA scattering, two strongly interacting particles are present. Although elastic scattering at large distances, $b \gg R$, where R is the nuclear radius, the interaction is pure electromagnetic, at small impact parameters, $b < R$, the strong interaction matters and can break-up the colliding hadrons. The corresponding absorptive corrections can be expressed in the eikonal (Glauber) model via the multi-Pomeron exchanges, as is illustrated in Fig. 1.

Note, in the case of the hadronic interaction, the absorptive corrections are not necessary, since they are a natural part of the usual Glauber formula.

The absorptive correction can be implemented as a convolution of the Coulomb form factor with the probability of no hadronic interaction $S(b)$. In more detail, one assumes that the Coulomb amplitude has the form of

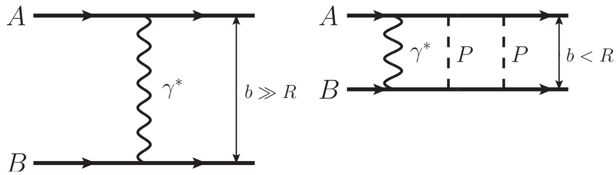

Fig. 1. At large interaction distances, only the Coulomb interaction applies. Nevertheless, when at small impact parameters, besides the photon exchange, there is a high probability of the additional Pomeron exchanges.

$$f^{\mathrm{em},pA}(q) = \sqrt{\pi} Z \alpha_{\mathrm{em}} \left[\frac{2}{q^2} + \frac{\mu_p - 1}{m_N q}\right] F_A^{\mathrm{em}}\left(q^2\right) e^{i\delta_{pA}\left(q^2\right)}, \tag{2}$$

where Z is the number of protons, m_N is the nucleon mass, μ_p is the anomalous magnetic moment and $\delta_{pA}(q^2)$ is the Coulomb phase. The probability of no hadronic interaction can be expressed using the Glauber formula as

$$S(b) = e^{-\frac{1}{2}\sigma_{\mathrm{tot}}^{pp} T_A(b)}. \tag{3}$$

Since the absorptive correction is a function of impact parameter, first, one has to perform the Fourier transformation (FT) of (2) from the momentum space to impact parameters, then multiply by the absorptive factor $S(b)$, and Fourier transform back to the momentum space. This procedure leads to the result (after some algebraic simplifications)

$$f^{\mathrm{em},pA}(b) = \sqrt{\pi} Z \alpha_{\mathrm{em}} \left[2F_1\left(b^2\right) + \frac{\mu_p - 1}{m_N} F_2\left(b^2\right)\right], \tag{4}$$

$$F_1\left(q^2\right) = 2\pi \int_0^\infty \mathrm{d}b\, b\, J_0(qb) S(b) \int_0^\infty \mathrm{d}q'\, J_0\left(q'b\right) \frac{1}{q'} F_A^{\mathrm{em}}\left(q'^2\right) e^{i\delta_{pA}\left(q'^2\right)}, \tag{5}$$

$$F_2\left(q^2\right) = 2\pi \int_0^\infty \mathrm{d}b\, b\, J_0(qb) S(b) \int_0^\infty \mathrm{d}q'\, J_0\left(q'b\right) F_A^{\mathrm{em}}\left(q'^2\right) e^{i\delta_{pA}\left(q'^2\right)}, \tag{6}$$

where $J_0(x)$ is the Bessel function.

2.1. Absorptive corrections in pp scattering

The above procedures should be also applied to proton–proton elastic collisions, where only the absorption factor is different

$$S(b) \equiv 1 - f_{\mathrm{el}}(b), \tag{7}$$

where $f_{\rm el}(b)$ is well-known pp elastic hadronic amplitude in the impact parameter space

$$f_{\rm el}(b) = \frac{\sigma_{\rm tot}^{pp}}{4\pi B} e^{-\frac{b^2}{2B}}\,, \tag{8}$$

where B is the slope parameter.

3. Results

Comparison of the theory with $r_5 = 0$ and the absorption-corrected Coulomb form factor (4) (dashed green line) with experimental data for proton–gold scattering presented in Fig. 2, demonstrates essential improvements in the t dependence. Nevertheless, the data description leaves space for other nuclear corrections. We have evaluated some of them, the Gribov corrections and NN correlations, and found only insignificant modifications. Variations of r_5 did not lead to any significant improvements either. The most important correction is still missed in our calculations. The measured results include not only the elastic channel but also quasi-elastic channels with nuclear excitations, which are difficult to get rid of experimentally, and correspondingly difficult to account for theoretically either.

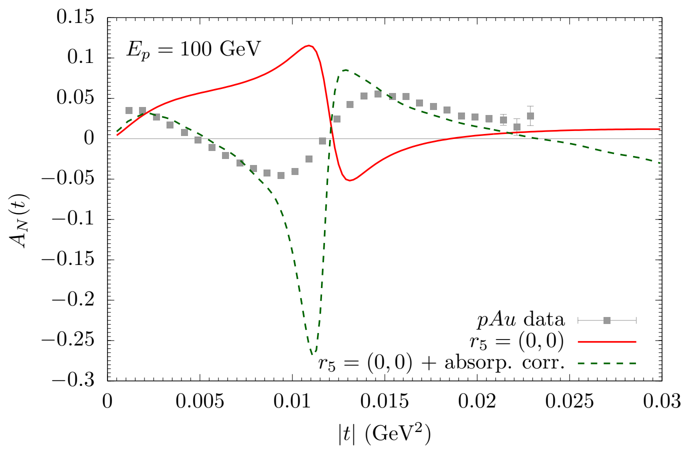

Fig. 2. (Color online) $A_{\rm N}(t)$ calculation with zero r_5 with and without absorptive corrections for Coulomb nuclear form factor for pAu at $E_{\rm lab} = 100$ GeV *versus* HJET data [4].

The absorption corrections applied to pp elastic scattering are found to be significant, especially for STAR data. The absorption free calculations describe the data well with $r_5 = 0$, *i.e.*, without hadronic spin-flip, as demonstrated in Fig. 3 (solid red line). However, $r_5 = 0$ is completely excluded after introducing of absorption, as is shown by the dashed green line in Fig. 3.

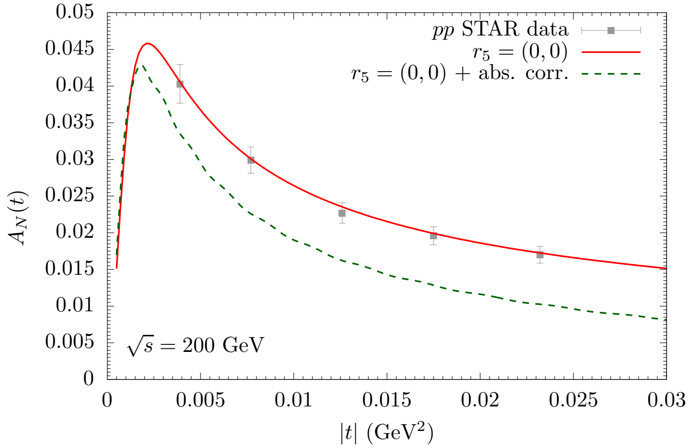

Fig. 3. (Color online) $A_{\rm N}(t)$ calculation with zero r_5 with *versus* without absorptive corrections to the Coulomb form factor for pp at $\sqrt{s} = 200$ GeV *versus* STAR data [7].

4. Conclusions

Summarizing, we introduced absorptive corrections to the Coulomb form factor in elastic pA and pp scattering. These corrections are important for the study of spin effects in the CNI region of small t. Notably, the absorptive corrections shed light on the description and interpretation of the single-spin asymmetry $A_{\rm N}(t)$ in elastic pp and pA collisions.

Moreover, as follows from Eqs. (4)–(6), the Coulomb form factor is not universal, but is different for spin-non-flip and spin-flip amplitudes. The absorptive corrections can be tested in the forthcoming measurements by the STAR experiment at 510 GeV.

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