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Evaluation of the elastic *pp* single-flip helicity amplitude at low momentum transfer and high energies

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We report on the evaluation of the single-flip helicity amplitude by analyzing proton-proton elastic polarization data in the four-momentum-transfer $-t$ region from 1.5×10^{-3} to 0.6 $(\mathrm{GeV}/c)^2$. Recent results around 200 GeV/c in the low $|t|$ range, where the interference of the electromagnetic and hadronic amplitudes is significant, allow a more reliable evaluation of the single-flip hadronic helicity amplitude ϕ_5^h. Within the experimental errors, our analysis indicates a small and negative real part (-1 to -4 %) and a positive imaginary part (8 to 30 %) for the reduced hadronic single-flip helicity amplitude $(m/\sqrt{-t})\phi_5^h$ with respect to the helicity-averaged hadronic nonflip amplitude. To study the stability of these results, we have also considered data at 45–300 GeV/c in the 0.057–0.6 $(\mathrm{GeV}/c)^2$ momentum transfer range in conjunction with the aforementioned data.

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Elastic pp ($\bar{p}p$) scattering allows the study of the diffraction process at the highest available energies. A large fraction of the data from the CERN Intersecting Storage Rings (ISR), Super Proton Synchrotron (SPS), and Fermilab Tevatron colliders on total and differential cross sections at small $|t|$ values ($|t| \leq 1\,(\mathrm{GeV}/c)^2$) is well represented by the exchange of a Pomeron ($\mathcal{P}$) trajectory with an intercept higher than 1 (≈ 1.086) and a slope of about 0.25 [1].

The special role of the elastic channel, contributing more than 20% of the total cross section, is generally interpreted in terms of the optical theorem as a shadow of the many inelastic channels present at high energies. Thus the dominant amplitude is expected to be mainly imaginary and helicity conserving. This reflects in the phenomenological features of simple $\mathcal{P}$ exchange, with a vanishing helicity single flip, leading one to expect a polarization asymmetry decreasing as the inverse square root of the center-of-mass energy, $s^{-1/2}$. This simple picture might however be more complicated at higher energies and larger momentum transfers. Multiple-$\mathcal{P}$ exchanges might be needed at extremely high energies to properly recover unitarity. The behavior of the differential cross sections at larger $|t|$ values also requires multiple exchanges to describe the dip region and beyond.

When the difficulty of simple Regge models to explain polarization data resulted in the introduction of absorption corrections in the 1970s, interest in these models diminished at the same time. At present, however, the framework is quite different and much theoretical effort has succeeded in relating Regge phenomenology to QCD concepts [2], by associating $\mathcal{P}$ exchange with the exchange of $n \geq 2$ (nonperturbative) gluons [3]. For the case $n = 2$ ($C = +1$), this mechanism generates a *bare* Pomeron $\mathcal{P}_0$; while for $n = 3$, containing both $C = \pm 1$, the $C = -1$ amplitude leads to the *bare* odderon ($\mathcal{O}_0$), corresponding to an odd-signature partner of $\mathcal{P}$ [4].

Polarization results (both for pp and $\bar{p}p$) in the very high energy domain could probe this complex structure of the Pomeron at the level of helicity amplitudes. For example, an additional $\mathcal{O}$ exchange might provide the necessary phase difference with $\mathcal{P}$ to obtain an essentially energy-independent spin asymmetry [5].

Until now, polarization measurements in elastic scattering have only been performed with fixed targets up to 300 GeV/c ($\sqrt{s} \approx 24$ GeV). There are future projects involving acceleration of polarized protons at the RHIC (the Relativistic Heavy Ion Collider at Brookhaven National Laboratory) (pp up to $\sqrt{s} \approx 500$ GeV) and at Fermilab ($\bar{p}p$ up to $\sqrt{s} \approx 2000$ GeV).

However, as outlined in this Brief Report, some new information can already be extracted by considering the behavior of existing elastic pp asymmetry data in the laboratory momentum range between 45 and 300 GeV/c. This is an interesting transition region, where the total cross section reaches a minimum just above 50 GeV/c, followed by a rising behavior characteristic of the highest energies, and the dip structure in the differential cross section appears around 200 GeV/c, close to the energy where ρ, the real-to-imaginary ratio of the dominant nonflip helicity amplitude, crosses zero.

Here we focus on the contribution of the hadronic single-flip helicity amplitude by studying the single-spin asymmetry and properly accounting for the Coulomb-nuclear interference (CNI) terms [6]. In the s-channel helicity formalism for pp elastic scattering we can express the transverse single-spin asymmetry A_N as

$$A_N = -\frac{2\,\mathrm{Im}\{(\phi_1 + \phi_2 + \phi_3 - \phi_4)\,\phi_5^*\}}{|\phi_1|^2 + |\phi_2|^2 + |\phi_3|^2 + |\phi_4|^2 + 4|\phi_5|^2}. \quad (1)$$

We assume as usual additivity of the hadronic and electromagnetic amplitudes ($\phi_i = \phi_i^h + e^{i\delta}\phi_i^e$, $i = 1, \ldots, 5$) with δ, the Coulomb phase shift ($\delta = -\alpha \ln|bt/2 + 4t/\Lambda^2| - 0.577\alpha$) and $\Lambda^2 = 0.71\,(\mathrm{GeV}/c)^2$ the dipole Sachs form factor parameter. It is generally considered that ϕ_2, ϕ_4, and $\phi_1 - \phi_3$ are all negligible in the region of study; this is certainly true for electromagnetic amplitudes and is very likely to be true for the hadronic. Thus $\phi_1 \approx \phi_3$ and ϕ_5 are the most significant amplitudes for A_N.

The denominator of Eq. (1) with proper normalization corresponds to the pp elastic differential cross section which, at low momentum transfers, is usually parametrized by neglecting spin-dependent terms as

$$\frac{d\sigma}{dt} = \frac{4\pi\alpha^2}{t^2} + \frac{\sigma_{\mathrm{tot}}^2}{16\pi}\left(1+\rho^2\right)e^{bt} + \frac{e^{bt/2}}{t}\alpha\sigma_{\mathrm{tot}}(\delta+\rho) \quad (2)$$

where α is the fine structure constant and b is the nuclear slope parameter. For higher values of $|t|$ we will include the contribution from the helicity single-flip amplitude as in Eq. (4). The total cross section is written in terms of the imaginary part of the hadronic nonflip helicity amplitudes according to the optical theorem as

$$\mathrm{Im}(\phi_1^h + \phi_3^h)\,|_{t=0} = \frac{1}{4\pi}[s(s-4m^2)]^{1/2}\sigma_{\mathrm{tot}} \quad (3)$$

where m is the proton mass.

The elastic pp polarization measurements performed at $|t|$ values [$0.15 \leq |t| \leq 2.5\,(\mathrm{GeV}/c)^2$] at 100–300 GeV/$c$ beam momenta [7–10] and other lower energy experiments [11,12] show the following general features.

(1) A positive analyzing power A_N at small $|t|$ values [$0.1 \leq |t| \leq 0.4\,(\mathrm{GeV}/c)^2$] decreases like $\sim 1/\sqrt{s}$ up to $s \approx 50\,\mathrm{GeV}^2$, with a possible flattening around values of a few percent up to the highest energies.

(2) For $s \geq 50\,\mathrm{GeV}^2$, A_N changes sign around $|t| \approx 0.3$ to $0.4\,(\mathrm{GeV}/c)^2$ from positive to negative and reaches a negative minimum followed by a sharp zero crossing in the region where the diffractive dip in the differential cross section develops around $|t| \approx 1.2\,(\mathrm{GeV}/c)^2$ and possibly remains positive at larger $|t|$ values.

These features have stimulated a number of speculations on the existence of a hadronic helicity single-flip contribution, ϕ_5^h, that does not necessarily decrease as $s^{-1/2}$.

Recent elastic pp scattering results at very small angles from Fermilab help to advance our understanding of the hadronic single-flip helicity amplitude. By using the polarized proton beam at Fermilab and scattering on a recoil-sensitive scintillator target, it was possible for the first time to measure the analyzing power of pp scattering at very small $|t|$ values [$1.5 \times 10^{-3} \leq |t| \leq 5.0 \times 10^{-2}\ (\mathrm{GeV}/c)^2$] around 200 GeV/$c$ [13]. This momentum transfer range was not accessible in other experiments that used unpolarized beams and polarized targets at comparably high energies. The data set around 200 GeV/c that we are considering in this study spans $1.5 \times 10^{-3} \leq |t| \leq 0.6\ (\mathrm{GeV}/c)^2$. Over this region, the asymmetry can be expressed as

$$A_N = \frac{\sqrt{-t}}{m}\,\frac{(\mu-1)z - 2zI + 2(\rho I - R)(1+t/\tau)}{1 + (\rho - z)^2 - \frac{t}{2m^2}\{[(\mu-1)z - 2R]^2 + 4I^2\}} \quad (4)$$

where $z = t_c/|t|$, $t_c = 8\pi\alpha/\sigma_{\mathrm{tot}} \approx 1.8 \times 10^{-3}\,(\mathrm{GeV}/c)^2$, and $\mu = 2.793$ is the magnetic moment of the proton [14]. The Coulomb phase may be omitted as its inclusion does not alter values of parameters significantly. I and R are the ratios of the imaginary and real parts of the reduced helicity single-flip $\tilde{\phi}_5^h = (m/\sqrt{-t})\,\phi_5^h$ to the imaginary part of the averaged nonflip amplitudes, respectively, and defined as

$$R + iI = \lim_{-t \to 0} \frac{2\tilde{\phi}_5^h}{\mathrm{Im}\,(\phi_1^h + \phi_3^h)} \quad (5)$$

where the $m/\sqrt{-t}$ term originates from angular momentum conservation at $t = 0$ constraining the asymmetry to vanish at least as $\sqrt{-t}$ there.

We parametrize the asymmetry in the higher part of the $|t|$ region of interest with the factor $(1+t/\tau)$ in the last term of Eq. (4) to reflect the t dependence of the hadronic contribution. We do not attach such a t behavior to any one of ρ, I, or R in particular, but to all in combination. The parameter τ is related to the zero-crossing position of the asymmetry around -0.3 to $-0.4\,(\mathrm{GeV}/c)^2$. In the region where $|t| \geq 0.6\,(\mathrm{GeV}/c)^2$ this parametrization should be augmented to represent the second zero crossing at about $-t \approx 1.2\,(\mathrm{GeV}/c)^2$ from negative to positive after reaching a negative minimum, possibly due to a near vanishing of the spin-averaged amplitude at this value of momentum transfer [1]. However, in the region of the present analysis, $|t| \leq 0.6\,(\mathrm{GeV}/c)^2$, and given current data, our linear parametrization describes the A_N behavior with sufficient precision.

Table I shows the results of fitting the expression in Eq. (4) to various combinations of available elastic pp asymmetry data (see Fig. 1). All three parameters R, I,

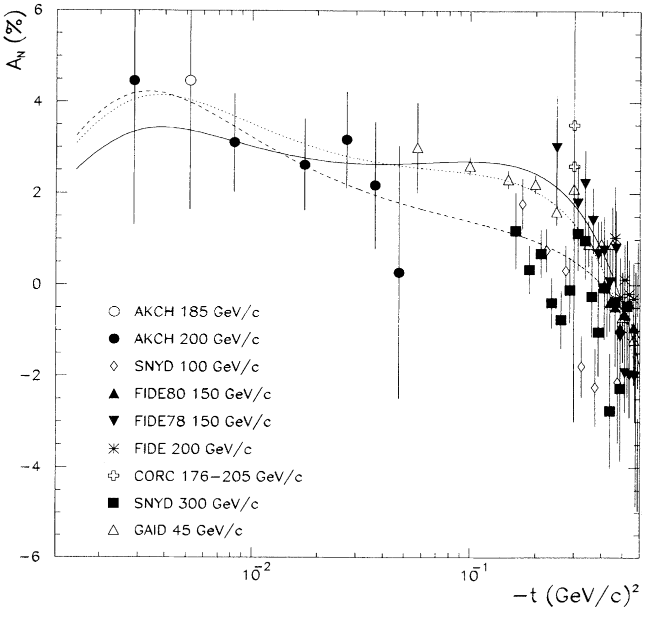

FIG. 1. The three curves represent the fits to the pp asymmetry data in the $1.5 \times 10^{-3} \leq |t| \leq 0.6\ (\mathrm{GeV}/c)^2$ range we have considered (see Table I). The solid line corresponds to 1, dashed to 2, and dotted to 3.

TABLE I. Results of the evaluation of the single-flip helicity amplitude for *pp* elastic scattering, see Eq. (4). We take $\sigma_{\rm tot} = 39$ mb and when an error equals zero it implies that the variable is fixed to a constant value in minimization.

No.	R	I	τ [(GeV/c)^2]	ρ	P_L range (GeV/c)	Refs.	No. data pts.	$\chi^2/N_{\rm DF}$
1	-0.044 ± 0.013	0.295 ± 0.207	0.440 ± 0.018	-0.02	150–205	[7–9,13]	37	30.13/33
2	-0.010 ± 0.004	0.082 ± 0.138	0.285 ± 0.036	-0.02	150–300	[7–10,13]	53	66.64/49
3	-0.037 ± 0.022	0.078 ± 0.182	0.389 ± 0.017	-0.10	45–205	[7,8,10,12,13]	51	73.35/47
4	-0.025 ± 0.039	0.145 ± 0.311	0.450 ± 0.000	-0.02	185–200	[13]	7	0.671/3
5	-0.041 ± 0.002	0.000 ± 0.000	0.440 ± 0.009	-0.10	45–205	[7,8,10,12]	44	79.19/40
	-0.097 ± 0.002	0.500 ± 0.000	0.433 ± 0.009					74.08/40
	-0.161 ± 0.003	1.000 ± 0.000	0.424 ± 0.012					70.52/40

and τ were allowed to vary and ρ was fixed to the values known from measurements and dispersion relation estimates at the appropriate energies. In the first entry of Table I, we have considered all the available data in the range of 150 to 205 GeV/c including the only existing small-angle data at 185 and 200 GeV/c. We find that R is small and negative (-0.044 ± 0.013) and I is positive albeit with a substantial error (0.29 ± 0.20). In entries 2 and 3, we have added data at 300 and at 45–100 GeV/c, respectively, in the larger $|t|$ region and found that R remained consistently small and negative (-1 to -4%), and I had positive values (8 to 30%), compatible with each other within relatively large errors.

From Eq. (4) we observe that when $|\rho|$ is small, as is the case for the energies studied, I contributes to A_N mostly in the CNI region ($z \approx 1$). The corresponding real part R, however, features prominently at larger momentum transfers ($z \approx 0$) as reflected by the parametrization.

In order to test the relative weights of these contributions and the stability of the results discussed above we consider data in the low and higher $|t|$ regions separately. We first fit the data only in the CNI region by fixing the A_N zero-crossing position at $\tau = 0.45$ (GeV/c)^2 in Eq. (4) (see entry 4 in Table I). Second, we suppress the electromagnetic terms in Eq. (4) by setting $z = 0$ and fitting the data only in the higher $|t|$ range. Since the expression in Eq. (4) with $z = 0$ reveals that I and R are highly correlated, we fixed I at various values (0.0, 0.5, and 1.0) for these sets of fits as shown in item 5 of Table I. Under such conditions, we still found that R remained consistent with the results of the other fits as shown by the entries 1, 2, and 3. Also note that, under the same set of conditions, a reduced imaginary part of the single-flip helicity amplitude as large as the helicity-averaged nonflip amplitude (I=1) or vanishing small (I=0) would appear to be equally acceptable. These results are presented here mainly to emphasize the significance of the small $|t|$ data for obtaining more definitive results in fully evaluating the single-flip hadronic amplitude.

Some years ago [15], an attempt was made to extract the behavior of $\tilde{\phi}_5^h$ from cross section and polarization data and $\tilde{\phi}_5^h$ was found to be comparable to $(\phi_1^h + \phi_3^h)/2$ at $t = 0$. However the data available at that time were limited to $|t| \geq 0.15$ (GeV/c)^2 and the CNI contribution was neglected in this kinematical range. In [16], it was suggested that diffractive scattering with exchange of two pions could become important at large s. This mechanism can cause a nonvanishing hadronic single-flip contribution because one of the pions can couple with spin-flip, while the other does not. The reduced single spin-flip contribution with respect to the nonflip one could be therefore higher than 30%. Also the impact model [17] based on the rotating matter picture [18] for a polarized proton provides a helicity-flip contribution through the spin-orbit coupling at the level of 10–20% [19]. In a different study [20], it was pointed out that ϕ_5^h might remain nonzero at high energies if the nucleon contains a dynamically enhanced component with a compact diquark. In this case the effect is expected to be 5–10%. In [21], it is argued that the effects at large distances are largely determined by the meson cloud of hadrons and this results in a dominant contribution to the single-flip amplitudes of different exclusive processes at high energies and fixed transfer momenta. In [22], for example, the small-angle polarization is discussed in terms of nonperturbative instantonlike contributions of the gluonic field.

In conclusion, we have performed an evaluation of the elastic *pp* single-flip helicity amplitude by making use of the relatively scarce asymmetry data available in the low to medium momentum transfer range. The results of this study give, for the single-flip helicity amplitude, an indication of a small and negative reduced real part, and a positive and appreciable reduced imaginary part though with relatively large errors, which appear to be sufficiently stable over the entire momentum range considered (45 to 300 GeV/c). From our analysis, it is evident that in order to clarify the issue of diffractive (Pomeron) helicity single-flip amplitude we need to have more, and more precise polarization data in the $|t|$ region where we have carried out the analyses. There is no measurement to this day in the range of $0.05 \leq |t| \leq 0.15$ (GeV/c)^2 at energies higher than 50 GeV. A newly approved experiment [23] at RHIC plans to perform a thorough study of *pp* elastic scattering with polarized proton beams. This experiment can provide the high precision polarization data over the full kinematical range $4 \times 10^{-4} \leq |t| \leq 2$ (GeV/c)^2, and $50 \leq \sqrt{s} \leq 500$ GeV, required to perform a more refined analysis of near forward elastic proton-proton high energy interactions.

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[14] It is worth noting here that the ratios of the electromagnetic amplitudes to the imaginary helicity nonflip hadronic amplitude, when expanded in powers of t, beginning with t^{-1} due to the photon pole term, $\phi_1^e/\mathrm{Im}\,\phi_1^h = t_c\{t^{-1} - b/2 + 4/\Lambda^2 - (\mu - 1)/2m^2 + \cdots\}$ and $(m/\sqrt{-t})\phi_5^e/\mathrm{Im}\,\phi_1^h = \frac{1}{2}(\mu - 1)t_c\{t^{-1} - b/2 + 4/\Lambda^2 - (\mu - 2)/4m^2 + \cdots\}$, indicate that form factor effects cancel to a large extent. It is therefore sufficient to keep the leading t^{-1} terms in these ratios.

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