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Theoretical Models for Proton-Proton Elastic Polarization*

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Abstract

We apply various models - Regge models, the Chou-Yang-Durand-Lipes model and an optical model - to proton-proton elastic polarization for $|t| \leq 6(\text{GeV}/c)^2$. Only the last model correctly predicted the regular sequence of double zeros, as is now observed in the recent polarization measurements at 12.33 GeV/c.

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Due to the discovery of several unexpected phenomena¹ at CERN Intersecting Storage Ring energies (such as rising σ_{tot} , the change of slope in $d\sigma/dt$ at $t \approx -0.2$ (GeV/c)² and a dip at $t \approx -1.5$ (GeV/c)²), proton-proton scattering has recently become one of the most exciting scattering processes. This is in sharp contrast to the general feeling previously held about pp scattering at much lower energies, where σ_{tot} is flat and $d\sigma/dt$ comparatively smooth. The new wide-angle polarization data² for pp elastic scattering at 5.15, 7.0 and 12.33 GeV/c now reveals that even at these low energies - in spite of the fact that σ_{tot} is flat and $d\sigma/dt$ is smooth - many exciting things are happening. In particular, the new 12.33 GeV/c data, together with some earlier data^{3,4} at 10, 12 GeV/c at small t , show (see Fig. 1) a regular sequence of dips (or "double zeros") in the polarization, located at $t \approx -0.8$ -2.4 and $-(4 \rightarrow 5)$ (GeV/c)². It is clearly important to try and understand this new structure in the polarization: it is presumably providing us with a sensitive clue about the amplitudes in this region. In this paper, we briefly examine various theoretical models - some Regge models,^{5,6,7} the Chou-Yang⁸-Durand-Lipes⁹ model, and an optical model developed some time ago by Chu and Hendry¹⁰ - and compare them with the data. We note at the outset that this very surprising type of structure in the polarization was in fact predicted¹⁰ some time ago by the optical model.

For brevity, we shall concentrate on the 12.33 GeV/c data - it covers the largest t -range, and it is at this, the highest of the three energies, that the dip structure is cleanest.

We start first with a consideration of Regge models. Any significant structure at all in pp elastic polarization is of course somewhat surprising from the simplest kinds of traditional Regge models, where the diffractive Pomeron is smooth and the usual ideas of s-channel exoticity and exchange degeneracy (EXD) make the other amplitudes also smooth in t . However, Regge models can be made to give rise to dips in the pp polarization by breaking EXD, and indeed several specific models of this kind have been developed.

Regge A (Austin et al.⁵) Here the t -channel helicity amplitudes are parametrized in terms of 3, 4 and 5 ($P, P', P'', \omega, \omega'$) poles, with various kinds of ghost-killing mechanisms. We show in Fig. 1a(R1) their 4-pole fit (Fig. 7(e) of their paper⁵) at 12 GeV/c. (As with other fits in the present paper, $d\sigma/dt$ and σ_{tot} are also fit simultaneously, but we do not show them here.) It has a slight dip at $t \approx -0.4$ (GeV/c)², but for large $|t|$ it falls off rapidly, showing no evidence of the subsequent large oscillations of the data. Variation of their parameters can improve the fit ((R2) of Fig. 1a) but the oscillations are somewhat contrived.

Regge B (Parry et al.⁶) Parry et al. suggest a parametrization with linear EXD breaking:

$$\mathcal{P} = \frac{C}{p_{lab}} \left(-\frac{t^*}{4M^2} \right)^{\frac{1}{2}} \cos \theta_s [1 + B t^* \cos \pi \alpha(t)] \exp(-5t^*) \left(\frac{s}{s_0} \right)^{\alpha(t)}$$

where C, B are constants, $t^* = -tu/s$ and $\alpha(t) = \alpha_0 + \alpha' t$. Oscillations in the polarization clearly arise from the factor $[1 + B t^* \cos \pi \alpha(t)]$, where $B = 0$ for exact EXD. A typical fit (R3) with this is also shown in Fig. 1a, with $B = 1.0$ and $\alpha(t) = 0.5 + t$.

Regge C. Another possible way of achieving oscillations in the polarization is to use cyclic residues⁷. We have considered three such models. In each case, we took the (structureless) non-flip amplitude as

$$N = 1 \left[\beta_1(t) \left(\frac{s}{s_0} \right)^{\alpha_1(t)} + \beta_2(t) \left(\frac{s}{s_0} \right)^{\alpha_2(t)} \right]$$

where each $\beta(t) = B \exp(Ct)$, and each $\alpha(t) = \alpha_0 + \alpha' t$. The first part in this expression is the usual Pomeron contribution giving the forward diffraction peak, while the second part is necessary to allow for the flattening of $d\sigma/dt$ beyond $|t| \approx 1.0 \text{ (GeV/c)}^2$. For the flip amplitude, we took

$$F = \sqrt{\frac{-t}{4M^2}} \gamma_R(t) C(t) \left(\frac{s}{s_0} \right)^{\alpha_R(t)}$$

where $\gamma_R(t) = g \exp(ht)$ and $C_1(t) = \sin^2 [\pi \alpha_R(t)/2]$, $C_2(t) = \sin^2 [\pi \alpha_R(t)/2] \cos^2 [\pi \alpha_R(t)/2]$, $C_3(t) = \cos^2 [\pi \alpha_R(t)/2]$.

The double zero locations are determined by the Regge trajectory $\alpha_R(t)$. Typical fits are shown in Fig. 1b, and $\alpha_R(t) = 0.77 + 1.1 t$, $0.4 + 0.58 t$ and $-0.23 + 1.1 t$ for the three cases (R4), (R5), (R6) respectively.

None of the Regge fits above is very satisfactory. Trajectory and residue functions can indeed be chosen to get the polarization double zeros at the correct places, but typically the magnitude dies away rapidly for larger $|t|$. Moreover, none of the above models give the correct energy dependence for the polarization at fixed t . It does not seem to be clear how to modify these models (e.g., by means of cuts etc.) to get better agreement with the data.

We turn now to a basically different kind of model, namely the optical or geometric model. The major difference between Regge and optical models is that in the latter, the (s-channel) diffraction amplitude really has a set of single zeros, just as in classical optics. Double zeros in the polarization then come about from the coincidence (or near coincidence) of the zeros in the diffraction amplitude and a corresponding set in the single flip amplitude. The latter property implies that the single flip amplitude must be substantially peripheral.

We shall briefly describe two optical models, in terms of the partial wave expansions

$$k^2 N(s, t) = \sum (\ell + \frac{1}{2}) n_\ell d_{00}^\ell(\theta_s)$$

$$k^2 F(s, t) = \sum (\ell + \frac{1}{2}) f_\ell d_{10}^\ell(\theta_s)$$

for the nonflip and flip amplitudes respectively.

Optical A (Chou-Yang⁸, Durand-Lipes⁹). In this model, perhaps the best known in the optical category, the collision is envisaged as coming about from the overlap of the two proton mass distributions, each mass distribution being taken proportional to the proton electromagnetic form factor. Taking $G_p(t) = (1 - t/\mu^2)^{-2}$ with $n_\ell = i(1 - S_\ell)$ and $f_\ell = S_\ell \rho'_\ell$, one finds⁹

$$S_\ell = \exp \left[A \left(\frac{\mu}{2k} \right)^3 Q_\ell^{(3)} \left(\cosh \frac{\mu}{k} \right) \right], \quad \rho'_\ell = -C \ell \left(\frac{\mu}{2k} \right)^4 Q_\ell^{(3)} \left(\cosh \frac{\mu}{k} \right)$$

where $\mu^2 = 0.71 \text{ (GeV/c)}^2$ and $\text{Re } A$ is adjusted to fit $\sigma_{\text{tot}}(pp)$.

This parametrization at present is unable to fit the new polarization data (even if μ^2 is varied). This can actually be seen directly from Figs. 1, 2 of the original Durand-Lipes paper⁹: the imaginary part of the nonflip amplitude has only two zeros (at $t = -1.4$ and -5.8 (GeV/c)^2) while the flip amplitude has only one zero (at $t = -0.9 \text{ (GeV/c)}^2$) for $0 < \theta_s < 90^\circ$. Thus, while it is possible to arrange for a dip in the polarization around $t \approx -1 \text{ (GeV/c)}^2$, one does not generate the subsequent dips.

By examining, for example, n_l and f_l as functions of l , or better still as functions of b , the impact parameter, one can easily see that the lack of recurring zeros in $N(s,t)$, $F(s,t)$ is a consequence of $n(b)$, $f(b)$ having too much low - b component; both of them need to be more peripheral.

Optical B (Chu-Hendry¹⁰). This model is based upon direct parametrization of the impact parameter distributions $n(b)$, $f(b)$: schematically

$$n(b) = D(b) + P_n(b), \quad f(b) = P_f(b)$$

where $D(b)$ is a Fermi distribution in b (which gives rise to the diffraction), and $P_n(b)$, $P_f(b)$ are Gaussian distributions in b centered around the periphery $b = R$. One can then get a fit such as shown in Fig. 1c. The oscillations of $\text{Im } N$ and $\text{Re } F$ approximately coincide, yielding a sequence of double zeros in the polarization.

The essential features of this model may be more clearly understood if we examine the gray disk approximation. With $D(b) = i D$ for $b \leq R$ and $D(b) = 0$ for $b > R$, and with $P(b) = P \delta(b-R)$, one gets in the classical limit

$$N(s,t) \sim i J_1(R\sqrt{-t})/R\sqrt{-t}, \quad F(s,t) \sim J_1(R\sqrt{-t}).$$

This yields a polarization proportional to $[J_1(R\sqrt{-t})]^2/R\sqrt{-t}$, with double zeros located at the zeros of the J_1 Bessel function. With $R \approx 0.9F$, these occur at $t \approx -0.7, -2.5, -5.2, \dots (\text{GeV}/c)^2$. These features remain even when a smooth Fermi distribution is used for the central b-region and Gaussians are used for the peripheral piece.

It seems remarkable that a relatively simple optical type of approach produced the kind of polarization that is observed. It is generally agreed¹ that the dip which is observed in $d\sigma/dt$ at ISR energies, is highly indicative of optical diffraction: the new elastic polarization data at 12.33 GeV/c seems to strongly indicate that optical phenomena may very well be occurring also at considerably lower energies.

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Figure Caption

Fig. 1 Model fits to the 12 GeV/c elastic proton-proton polarization data. (R1) Austin et al., quoted in Ref. 5; (R2) Austin et al.,⁵ with different values of the parameters; (R3) Parry et al.,⁶; (R4), (R5), (R6) as in text with cyclic residues, (Opl) fit with Chu-Hendry¹⁰ optical model. Data are from Ref. 2 (ϕ) at 12.33 GeV/c, Ref. 3 (ϕ) at 12.0 GeV/c and Ref. 4 (ϕ) at 10.0 GeV/c.