Table I. Observed wavelengths and computed values of $\alpha(z)/\alpha(\text{lab})$ for some radio galaxies.

Object	z	λ_{ob}	λ_{ob}	$\alpha(z)/\alpha(\text{lab})$
Laboratory	0.0	4958.9	5006.8	...
3C 219	0.17	5823.1	5880.4	1.009
3C 234	0.18	5875.2	5932.3	1.003
3C 26	0.21	6003.2	6060.1	0.990
3C 171	0.24	6140.6	6200.5	1.005
3C 79	0.26	6230.0	6289.7	0.996

lengths of the O III lines in five radio galaxies with appreciable red shifts. Given the observed wavelenths, the ratio $\alpha(z)/\alpha(\text{lab})$ can be computed from the relation $[\alpha(z)/\alpha(\text{lab})]^2 = (\delta\lambda/\lambda)_{\text{ob}} \times (\delta\lambda/\lambda)_{\text{lab}}^{-1}$. Here $\delta\lambda$ is the fine-structure splitting and λ is the weighted mean wavelength, weighted according to $(2J+1)$. We find from Table I that

$$\alpha(z\approx 0.2)/\alpha(\text{lab}) = 1.001 \pm 0.002 \text{ probable error}$$

considering only statistical errors. The hypothesis[1] that α is proportional to cosmic time requires $\alpha(z\cong 0.2)/\alpha(\text{lab}) \approx 0.8$ and hence is ruled out by the above results.

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CROSSOVER AND POLARIZATION PHENOMENA IN HIGH-ENERGY SCATTERING. CUTS, CONSPIRACIES, AND SECONDARY REGGE POLES

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The usual interpretation, in Regge-pole models, of the change in signs of the cross section differences $d\sigma(\bar{A}B)/dt - d\sigma(AB)/dt$ at $t \sim -0.15$ (GeV/c)^2 observed in elastic πN, KN, and NN scattering is inconsistent with recent data on the reaction $\gamma p \to \pi^0 p$. It is pointed out that this contradiction is direct evidence for the existence of contributions to the high-energy scattering amplitudes in addition to those of the leading Regge poles. Alternative explanations of the crossover phenomena which avoid the foregoing difficulty are proposed, and their implications are discussed.

A common experimental feature of high-energy $\pi^{\pm}p$, $K^{\pm}p$, $\bar{p}p$, and pp elastic scattering is the change in the sign of the cross section differences[1]

$$D(AB) = d\sigma(\bar{A}B)/dt - d\sigma(AB)/dt \qquad (1)$$

at momentum transfers $t = t_c \sim -0.15$ (GeV/c)^2. This "crossover" phenomenon is usually explained in Regge-pole models for these reactions by supposing that the signs of the helicity-nonflip residue functions for the ρ- and ω-exchange amplitudes change sign at this point.[2,3] This explanation is inconsistent with recent data[4] on the reaction $\gamma p \to \pi^0 p$, thought to be dominated by ω exchange,[5] as will be discussed below.

In the Regge exchange model, $D(AB)$ can be expressed as

$$D(AB) = 2\,\text{Re}\sum_{[\lambda]} T_{[\lambda]}{}^* V_{[\lambda]}, \qquad (2)$$

where $[\lambda]$ labels the particle helicities in the t channel. The amplitude $T_{[\lambda]}$ is a sum of amplitudes for exchanges even under charge conjugation $(P, P', A_2, \cdots)$. Similarly, $V_{[\lambda]}$ is a sum of amplitudes odd under charge conjugation $(\rho, \omega, \cdots)$. It is commonly assumed that the dominant terms in $T_{[\lambda]}$ for $t \sim 0$ are those for no helicity flip, and that these terms are predominantly imaginary (diffraction scattering). Partial justification for these assumptions may be found in the following experimental results: (i) The ratio of the real part of the forward-scattering amplitude to the imaginary part is small for $\pi^{\pm}p$, pp, and $\bar{p}p$ elastic scattering.[6] (ii) The elastic differential cross sections show no sign of the flattening or the dip at $t=0$ which would result from a large helicity-flip amplitude. (iii) The sum of the polarized cross sections $(Pd\sigma/dt)_{\pi^+p} + (Pd\sigma/dt)_{\pi^-p}$ for $\pi^{\pm}p$ scattering is small.[7] Since $|t_c|$ is rather small, the imaginary part of the helicity-nonflip T amplitude is presumably still the most important individual term in the complete scattering amplitude at that point. Thus, $D(AB)$ may be approximated as

$$D(AB) \sim 2 \sum_{\text{nonflip}} \operatorname{Im} T_{[\lambda]} \operatorname{Im} V_{[\lambda]}. \qquad (3)$$

Since $\operatorname{Im} T \neq 0$, the change in the sign of $D(AB)$ must correspond to a change in the sign of the imaginary part of the helicity-nonflip V amplitude for $t \sim t_c$.

In the usual Regge-pole model for elastic scattering,[2,3] the only $C=-1$ exchanges considered are those corresponding to the ρ and ω mesons [the coupling of the φ meson to nucleons is apparently very weak; φ exchange is therefore neglected]. In the case of $\pi^{\pm}p$ elastic scattering, only ρ exchange is present. The crossover condition can be satisfied only if the residue of the helicity-nonflip ρ-exchange amplitude vanishes at $t=t_c$. This implies, of course, that both the real and imaginary parts of this amplitude vanish at t_c. It should be noted that this result is a consequence of the assumption that only a single exchange is present. The crossover condition would place essentially no restriction on the real part of the V amplitude if additional $G=+1$, $C=-1$ contributions were present.

A similar situation is encountered in the usual description of the crossover phenomena in $K^{\pm}p$ and $\bar{p}p$ and pp scattering.[2,3] Although ρ and ω exchange are both allowed, the ω-exchange contributions are found empirically to be by far the larger. As a consequence, the residue for the helicity-nonflip ω-exchange amplitude is required to change sign at $t=t_c$. This explanation of the crossover in NN scattering becomes particularly restrictive when combined with the factorization theorem for the Regge residues and the requirement of real analyticity for the unfactored residues: It can then be shown that the ω-exchange residue functions vanish at $t=t_c \sim -0.15$ $(\text{GeV}/c)^2$ for every helicity amplitude in every reaction.[3] Thus, if the usual explanation for the crossover in $\bar{p}p$ and pp scattering were correct, striking dips would appear at $t=t_c$ in all reactions in which ω exchange gives the dominant contribution. The assumption of SU(3) symmetry for the Regge residues would lead to analogous results for the ρ-exchange amplitudes, more restrictive than those derivable from the $\pi^{\pm}p$ scattering data alone.

The foregoing conclusion is inconsistent with recent data on the reaction $\gamma p \to \pi^0 p$.[4] The only particle exchanges expected in this reaction are ω, ρ, and B. The ρ-exchange contribution is generally thought to be small compared with the ω-exchange contribution because of the relatively weak $\rho\pi\gamma$ and $\rho\bar{N}N$ couplings.[5] The B meson, if it exists, lies on a rather low trajectory. Its contribution to the cross section consequently decreases rapidly with increasing photon energy, and should be quite small in the multi-GeV region. It is therefore expected that ω exchange will be the dominant process in this reaction.[5] However, there is no sign of a dip in the measured differential cross sections at $t=t_c \sim -0.15$ $(\text{GeV}/c)^2$. We therefore conclude that the usual explanation of the crossover in $\bar{p}p$ and pp scattering is very likely incorrect. Support for this conclusion can also be obtained from data on the reactions $K^{\pm}p \to K^{\pm}p$ and $\pi^{\pm}p \to \rho^{\pm}p$. Although the difficulty of separating the π- and ω-exchange contributions to these reactions makes the conclusions less certain,[8] there is again no sign of the expected ω-exchange dip at $t=t_c$. We note, finally, that the SU(3)-symmetric generalization of the ω-crossover model would require that all ρ-exchange residue functions vanish at $t=t_c$, in flagrant contradiction to the data[9] on the $\pi^-p \to \pi^0 n$ charge-exchange reaction: The dominant process in this reaction is ρ-meson exchange. The ρ-helicity-flip amplitude is quite large for $t \sim t_c$.[10]

We wish to emphasize that the foregoing difficulties are a direct consequence of the assumption that the ω Regge pole gives the only significant $C=-1$ contribution to the $\bar{p}p$ and pp elastic scattering amplitudes. We conclude, therefore, that extra ω-type contributions must be present; we will denote these by $\bar{\omega}$. It is evident from Eq. (3) that the crossover in $\bar{p}p$ and pp scattering can be reproduced provided that the helicity-nonflip component of $\mathrm{Im}(\omega+\bar{\omega})$ changes sign at $t=t_c$. Note, however, that the existence of the crossover does not place any significant restriction of either the ω-residue function considered by itself, or the helicity-nonflip components of $\mathrm{Re}(\omega+\bar{\omega})$. As a consequence, the difficulties discussed above are no longer encountered in the description of such reactions as $\gamma p\to\pi^0 p$, provided that $\mathrm{Re}(\omega+\bar{\omega})$ is large for $t\sim t_c$. The ω and $\bar{\omega}$ contributions must therefore differ in phase. The crossover phenomena in $K^{\pm}p$ and $\pi^{\pm}p$ elastic scattering can be explained in an analogous fashion by changes in the sign of the imaginary parts of $\omega+\bar{\omega}$ and $\rho+\bar{\rho}$ contributions, respectively. This model has the attractive feature that the crossover phenomena can be explained in an SU(3)-symmetric fashion. [As noted above, the usual model cannot be formulated with SU(3)-symmetric residues, inasmuch as the ω-helicity–flip amplitude in $K^{\pm}p$ scattering necessarily vanishes at $t=t_c$ in that model, while the ρ-helicity–flip amplitude in $\pi^{\pm}p$ scattering must be large.[3,10]]

From a theoretical point of view, there are numerous possibilities for the $\bar{\omega}$- and $\bar{\rho}$-type contributions.[11] In general, secondary Regge poles, Regge cuts, conspiring poles, and conspiring cuts are all expected to be present. Any one of these contributions, when combined with the ω or ρ amplitude, may explain the crossover phenomenon. A definitive choice of the relevant mechanism [if one mechanism is in fact dominant] must therefore come from successful descriptions of a variety of scattering phenomena. Qualitative evidence for the existence of such extra contributions is already available. For example, the fact that polarization is observed in the reaction[12] $\pi^-p\to\pi^0 n$ indicates that some $\bar{\rho}$ contribution must be present in the charge-exchange amplitude. Weaker evidence is obtained from the partial filling in of the zero predicted in the cross section for $\gamma p\to\pi^0 p$ at the point $t\sim-0.5$ (GeV/c)^2 at which $\alpha_\omega(t)=0$.

It is interesting to speculate as to which of the foregoing possibilities is the most likely on the basis of present data. We note first that data on total cross sections require $\mathrm{Im}(\omega+\omega)$ to be large at $t=0$, while the crossover phenomenon requires that $\mathrm{Im}(\omega+\bar{\omega})$ vanish for $t\sim t_c$. It is therefore evident that any successful explanation of the crossover must permit a rapid relative variation of $\mathrm{Im}\omega$ and $\mathrm{Im}\bar{\omega}$ in the small interval $0\geq t\gtrsim t_c$. The explanation of the crossover in terms of a normal secondary Regge pole seems for this reason to be the least satisfactory. Such an explanation requires the t dependence of the leading and secondary residues to be radically different, whereas a rather similar t dependence would be expected. On the other hand, a rapid relative variation of the ω and $\bar{\omega}$ amplitudes is natural if $\bar{\omega}$ is a conspiring pole or conspiring cut. In such a case, the $\bar{\omega}$ (or $\bar{\rho}$) contribution vanishes $\sim t$ for $t\to 0$ and, hence, may increase rapidly in magnitude in the interval $0>t\gtrsim t_c$. In contrast, the contribution of the ω (or ρ) exchange term would be expected to decrease rapidly away from the forward direction. Furthermore, because of the forward zeros, conspiring contributions to the $\pi^{\pm}p$, $K^{\pm}p$, pp, and $\bar{p}p$ scattering amplitudes would not affect previous analyses of the energy dependence of total cross-section differences, or the successful predictions of the real parts of the forward-scattering amplitudes. At the same time, a conspiring $\bar{\rho}$ leads to a $(-t)^{3/2}$ variation of the polarization in the reaction $\pi^-p\to\pi^0 n$ near $t=0$.[13] Nonconspiring or resonance models for $\bar{\rho}$ lead to a $(-t)^{1/2}$ variation of the polarization. Present data strongly favor the first possibility. It should be noted that conspiracies are also required to explain the behavior of the cross sections and the resonance decay angular distributions in the reactions $\pi N\to\rho N$, $\pi N\to\rho N^*$, $\gamma p\to\pi^+n$, $np\to pn$, and $\bar{p}p\to\bar{N}^*N^*$ at small momentum transfers.[8] The foregoing arguments taken together suggest rather strongly that the conspiracy mechanism is the most likely to give a satisfactory explanation of the crossover and related phenomena.

It is amusing to note that the $V+\bar{V}$ model is consistent with the interpretation of the crossover phenomenon in terms of classical diffraction scattering. The zero in $\mathrm{Im}(V+\bar{V})$ in this model is simply a diffraction zero in the difference between the predominantly imaginary elastic-scattering amplitudes. The amplitude $\mathrm{Re}(V+\bar{V})$ would certainly not be expected to have the same zeros as $\mathrm{Im}(V+\bar{V})$ in the classical picture, and cannot in our model.

In conclusion, we wish to re-emphasize that the observed crossover in $\bar{p}p$ and pp elastic scattering, and the absence of a dip in the cross section for the reaction $\gamma p \to \pi^0 p$ at $t \sim -0.15$ $(\text{GeV}/c)^2$, together provide convincing experimental evidence for the existence of contributions to high-energy scattering amplitudes in addition to those given by the leading Regge poles. We would like also to point out several implications of the $V+\bar{V}$ model:

(i) Since the energy dependence of the V and $\bar{V}$ contributions to the scattering amplitude will in general be different, the crossover point t_c will shift with energy. However, reasonable estimates indicate that this shift is likely to be small in the energy range presently accessible.

(ii) Recent predictions[3] of the polarization in pp and $\bar{p}p$ scattering will be significantly modified. In particular, the change in sign of the ω residue in the usual model led to the prediction of a change in the sign of the polarization in these reactions at $t \sim t_c \sim -0.15$ $(\text{GeV}/c)^2$. This zero is absent in the $(\omega+\bar{\omega})$ model: First, the (presumably small) $\omega+\bar{\omega}$ helicity-flip amplitude need not have a zero at $t=t_c$. Second, since the $P+P'$ amplitude is predominantly imaginary, the contribution of the nonflip $\omega+\bar{\omega}$ amplitude to the polarization depends primarily on $\text{Re}(\omega+\bar{\omega})$, which is nonzero for $t \sim t_c$. Similar remarks apply to the polarization in $K^{\pm}p$ scattering. The predictions[3] for the spin correlation parameter C_{NN} in pp and $\bar{p}p$ scattering are less definitive, since $\text{Im}(\omega+\bar{\omega})$ gives important contributions to this quantity. The zero predicted at $t \sim t_c$ may or may not appear.

(iii) Since the ω and $\bar{\omega}$ contributions differ in phase, nucleon polarization would be expected in the reaction $\gamma p \to \pi^0 p$ at small t. Polarization phenomena are quite sensitive to small terms in the scattering amplitude. As a consequence, the measurement of this polarization would be particularly useful for the determination of the $(\omega+\bar{\omega})\bar{N}N$ helicity-flip coupling, about which essentially nothing is known.

(iv) Careful measurements of the polarization in the reaction $\pi^- p \to \pi^0 n$ for $|t| < 0.1$ $(\text{GeV}/c)^2$ will be useful for differentiation of models based on conspiring and nonconspiring $\bar{\rho}$ contributions.[13]

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