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REGGE POLES: RECENT PROGRESS AND EXPERIMENTAL QUESTIONS

These notes summarize two lectures, given in June 1967, at Dubna, in Laboratory of Theoretical Physics and Laboratory of High Energy Physics

Reproduced directly from the publication
T.P. 295 A.E.R.E., Harwell, England

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1. BACKGROUND.[1]

For a two-body process a + b → c + d (Figure 1), a Regge pole exchange amplitude at high energy has the form[2]

$$T = \beta(t) \frac{1 \pm \exp(-i\pi\alpha(t))}{\sin \pi\alpha(t)} \left(\frac{s}{s_o}\right)^{\alpha(t)} \qquad (1)$$

$\alpha(t)$ and $\beta(t)$ are the trajectory and residue functions; s and t are invariant squares of energy and momentum transfer; s_o is a scale constant. The signature ± determines whether the pole appears in even or odd angular momenta, in the t-channel.

On the Chew-Frautschi plot, the moving pole links t-channel particles ($t>o$) with s-channel scattering ($t<o$), giving a sophisticated kind of single-particle exchange (see Fig.2).

Here are some properties of Regge-exchange.

i) <u>Shrinking.</u> The cross section from one pole has the form

$$\frac{d\sigma}{dt} = F(t)\ (s/s_o)^{2\alpha(t) - 2} \qquad (2)$$

We expect $d\alpha(t)/dt > 0$, so $d\sigma/dt$ falls faster at larger momentum transfers (−t), and the shape becomes narrower as s increases. We can find $\alpha(t)$ directly from the experimental s-dependence of $d\sigma/dt$.

ii) <u>Connection with particles.</u> Values of $\alpha(t)$ found from scattering must be compatible with known particles, on a Chew-Frautschi plot.

iii) <u>Phase-Energy relation.</u> In the scattering region, α and β are real and the phase of T is fixed by α – i.e. by the s-dependence – and by the signature. This phase rule follows, via dispersion relations, from the simple power dependence s^{α}. It is non-trivial. The same α-dependent phase would hold asymptotically for $s^{\alpha}(\ln s)^{-N}$ dependence, but fitting the latter to a set of data would give a different α and hence a different phase.

iv) Spin-flips have same phase. In general $\beta(t)$ is a sum of spin operators, with real coefficients in a suitable convention. First-rank polarization $\mathcal{P}$ (the simple kind, with only one spin measurement) has the form

$$\mathcal{P}\ d\sigma/dt \sim \Sigma\ \mathrm{Im}\ (T_i\ T_j^*) \qquad (3)$$

where the T_i are various spin coefficients of T. For one Regge pole, all T_i have the same phase and $\mathcal{P} = 0$.

v) Leading spin-flips have same s-dependence. The conventional invariant amplitudes for spin-flips have lower s-dependence, but this can be compensated by the spin operators they multiply. In $d\sigma/dt$, the leading spin-flip and non-flip terms have equal s-dependence.

vi) Specific spin-dependence. The spin-dependence of a Regge-pole exchange depends on the quantum numbers: i.e. on the kind of t-channel particles it can give.

vii) Nonsense zeros. $\beta(t)$ contains generalized Clebsch-Gordan coefficients, depending on $\alpha(t)$, which vanish for "nonsense" couplings. "Nonsense" means that α is a negative integer (half-integer for fermions) or that a real particle with spin α and similar quantum numbers (ignoring signature) cannot couple. Since the numerator $\sin \pi \alpha$ also vanishes at nonsense points, T does not vanish unless the signature factor $[1 \pm \exp(-i\pi\alpha)]$ also vanishes. Hence the rule: T has zeros at nonsense points with "wrong" signature (but see also §2).

Consider Regge-ρ exchange in πN scattering. The usual[3] invariant amplitude B is nonsense at $\alpha_\rho = 0$, because scalar meson exchange gives none.

This point also has wrong signature, so B_ρ has a zero. More generally, any coupling to t-channel states with net helicity $\lambda_1 - \lambda_2 = \lambda$ is nonsense for a particle with spin $J < |\lambda|$. In the example given, B corresponds to $\bar{N}N$ helicities $(\frac{1}{2}, -\frac{1}{2})$.

The vanishing of T, or part of T, can give minima in $d\sigma/dt$ and sign changes in interference terms (e.g. in polarization).

viii) Factorization. $\beta(t)$ breaks into factors characterising the two vertices.

$$\beta(t) = \eta_{ac}(t)\, \eta_{bd}(t) \tag{4}$$

Thus different processes are inter-related.

ix) Crossing. Regge pole amplitudes for $a + b \to c + d$ and $\bar{c} + b \to \bar{a} + d$ are simply related, since the corresponding t-channels differ only by interchanging $a \leftrightarrow \bar{c}$. For example, if a and c are spinless, the amplitudes differ by the signature ± 1.

If two Regge poles were identical in all but signature (a case of "exchange degeneracy") we might be tempted to combine them. But the combination would not behave simply under crossing; well-defined signature is essential.

*   *   *

Branch points. The exchange of two or more Regge poles, in diagrams (like Fig.3) that have a third double-spectral function $\rho(s,u)$, gives moving branch-points in angular momentum. For linear trajectories, $\alpha_i(t) = \alpha_i(o) + t\alpha_i'$, the two-pole branch point is at

$$\alpha_{12}(t) = \alpha_1(o) + \alpha_2(o) - 1 + t\,\alpha_1'\alpha_2' \;/\; (\alpha_1' + \alpha_2') \qquad (5)$$

In general, if P is the Pomeranchuk pole (with $\alpha_P(o) = 1$), the (P+i)-exchange branch point coincides with α_i at t=0 and lies above it for $t < o$. The branch points for (many-P + i) - exchange also coincide at t=o and lie still higher for $t < o$. The corresponding branch-out contributions to the scattering amplitude are like continua of Regge pole terms - up to the branch points. Hence, for $t < o$ the branch cuts must ultimately dominate over single poles at very high energy. This is a pity, since cuts have many more unknown parameters.

However, perhaps the poles still dominate at present accelerator energies. This is tacitly assumed in Regge pole theories.

Test cases.

Regge-pole properties are tested convincingly in reactions where only one known pole is allowed. The best case is $\pi^- + p \to \pi^0 + n$, where the selection rules permit only ρ-exchange. There are good $d\sigma/dt$ data up to 18 GeV/c, for $|t| < 1$ $(\text{GeV/c})^2$.

The s-dependence of $d\sigma/dt$ gives a trajectory with positive slope, highly consistent with the spin and mass of ρ (Fig. 5b) - and also with the R and T mesons, if we guess $J^P = 3^-$ and 5^- and extrapolate α linearly (Fig.2). This checks properties (i) and (ii).

Using the optical theorem and charge-independence, the imaginary part of the forward amplitude is found from $\sigma_T(\pi^- p) - \sigma_T(\pi^+ p)$. The deficit in $d\sigma/dt$ (t=o) then gives the real part, and checks the phase rule (iii).

The rise of $d\sigma/dt$ away from t=o suggests a strong spin-flip term (associated with the invariant amplitude B). But we notice $\alpha_\rho = 0$ near $t = -0.6\ (\text{GeV/c})^2$; for B this is a nonsense wrong signature point and we expect B=o here. Sure enough, there is a minimum in $d\sigma/dt$ at this point, checking property (vii).

Through the range $0 \geqslant t > -1\ (\text{GeV/c})^2$, the ratio of spin-flip to non-flip terms in $d\sigma/dt$ fluctuates rapidly but the S-dependence (measured by $\alpha(t)$) does not fluctuate. This checks property (v).

Properties (viii) and (ix) give no predictions here. There remains the equal-phase rule (iv), predicting 'zero polarization'. Non-zero values were recently measured at 6 and 11 GeV/c: see below.

2. RECENT PROGRESS

2.1 Polarization in $\pi^- + p \rightarrow \pi^\circ + n$.

At the 1966 Berkeley conference, new 11.2 GeV/c data were presented suggesting - within big errors - that the polarization previously found at 5.9 GeV/c might even be increasing with energy. Final results[5] are less sensational:

$$\left.\begin{aligned} \mathcal{P} &= 0.16 \pm 0.035 \text{ at } 5.9\ \text{GeV/c} \\ \mathcal{P} &= 0.14 \pm 0.045 \text{ at } 11.2\ \text{GeV/c}, \end{aligned}\right\} \qquad (6)$$

averaging over $0.04 \leqslant -t \leqslant 0.24\ (\text{GeV/c})^2$.

Clearly something must be added to Regge-ρ exchange. Early proposals were to add a second trajectory ρ' (with $\alpha_{\rho'} \approx \alpha_\rho - 1$)[5] or to add Breit-Wigner terms to represent known s-channel resonances.[7] Both predicted $\mathcal{P}$ would fall by about 50% between 6 and 11 GeV/c. The experimental errors above are too big to exclude this completely, but the energy dependence does seem less rapid.

Revised proposals have now been made. Logan et al.[8] suggest a much higher ρ' trajectory (perhaps related to the $\delta(963)$ meson). Since $\mathcal{P} \sim s^{-\Delta\alpha}$, where $\Delta\alpha = |\alpha_\rho - \alpha_{\rho'}| \approx 0.4$, the polarization falls more slowly; s-channel resonances can be added if desired.

Another idea, not yet fully worked out, is that ρ and ρ' trajectories intersect. If so, polarization from ρ-ρ' interference vanishes at this t-value.

Desai et al[10] extrapolate the sequences of known s-channel resonances to include unobserved members with higher spins and masses but also rapidly diminishing elasticity. Their result is that $\mathcal{P}$ stays almost constant between 6 and 11 GeV/c, but ultimately has to fall rather fast. At 18 GeV/c, predicted $\mathcal{P}$ has fallen by nearly 50%, for small t.

Branch cuts are another possibility. The preliminary (and short-lived) report that $\mathcal{P}$ increased with energy was first hailed as a characteristic effect of interference between ρ and a cut, because the cut terms fall less rapidly than the pole term, asymptotically. However, we are dealing with sub-asymptotic energies, where the continuum of Regge-pole-like terms that make up a cut has a mean behaviour somewhat below the asymptotic behaviour. A realistic model calculation[12], with the ρ pole and the (ρ+ Pomeranchuk) cut, shows that polarization should be decreasing even up to 100 GeV/c, in the small-t region above. Polarization vanishes where pole and cut terms have equal phase; at 11 GeV/c this zero may be near $t = -0.5$ $(\mathrm{GeV/c})^2$, but it moves toward t=o as $s \to \infty$ (unlike the fixed zero from intersecting trajectories).

Semi-empirical absorptive corrections to Regge-ρ exchange have also been proposed[13]. They give slowly falling polarization with a moving zero, but seem to lack a solid theoretical foundation.

Polarization data with higher energy and accuracy would reduce the possible explanations. So would spin-parity determinations of the new mesons, to decide if there is a ρ' particle.

2.2 Nonsense zeros.

At the Berkeley conference there were three prize examples.

i) $\pi^- + p \to \pi^0 + n$. The B amplitude for ρ-exchange is nonsense with wrong signature at $\alpha_\rho = o$, and vanishes to give a dip in $d\sigma/dt$ (§1).

ii) $\pi^+ p \to K^+ + \Sigma^+$. We expect $K^*(888)$ and $K^*(1410)$ exchanges, plus perhaps s-channel resonances. The B amplitude for $K^*(888)$-exchange has a zero at $\alpha = o$, just like the ρ case above; $K^*(1410)$ has right signature at $\alpha = o$, so no zero. Data at 3.2 GeV/c show a minimum in $d\sigma/dt$ and a sign change in Σ-polarization, near $t = -0.6$ $(GeV/c)^2$, which can both be correlated with this $K^*(888)$ nonsense zero[14].

iii) $\pi^\pm + p \to p + \pi^\pm$, elastic near 180^0. Here we have fermion Regge-poles in the u-channel; u is the invariant square of exchange-momentum-transfer (replacing t). Consider the N and Δ(1236) trajectories; it is plausible that the nonsense point $\alpha = -\frac{1}{2}$ lies inside the scattering region and near the backward direction, in each case. For N this point has wrong signature and a zero is predicted; but Δ has right signature and no zero[15]. Hence we expect a minimum near the backward direction for the $\pi^+ p$ case (N + Δ exchange) but none for $\pi^- p$ (Δ alone). The data, up to 10 GeV/c, suggest such a situation and were fitted using Regge-exchanges only [16].

Recently it has been claimed [17] that s-channel resonances alone can explain backward $\pi^\pm p$ data, at least up to 5 GeV/c, so case (iii) is not yet established properly.

The simple rule for zeros, formulated in §1, has some curious consequences. Take Compton scattering and consider the helicity non-flip amplitude[18]. In the t-channel, this means coupling to a two-photon state with helicities (+1, -1), which is forbidden for a physical meson with spin $J < 2$. Hence this is a nonsense wrong signature coupling for the Pomeranchuk trajectory at $t = o$, where $\alpha = 1$. We have a zero in the amplitude and no Pomeranchuk term in the total photon cross section, using the optical theorem. Secondary poles give $\sigma_T \sim s^{\alpha_2 - 1}$, with $\alpha_2 < 1$, whereas the integrated

Pomeranchuk contribution to elastic scattering gives $\sigma_{el} \sim 1/(\ln s)$ — apparently greater than σ_T asymptotically! This contradiction can be resolved by cuts from many-Pomeranchuk exchange.

Recent developments have modified the whole theory of nonsense zeros however[19,20]. In general, fixed poles in angular momentum are forbidde but there is an exception; amplitudes can have fixed poles at the nonsens wrong-signature points. One finds that such fixed poles have no direct effect on the asymptotic s-channel scattering, but can have an indirect effect by generating poles in the reduced residues at these nonsense points. If we write the residue function

$$\beta(t) = \beta_o(t)\, C(t) \tag{7}$$

where $C(t)$ is the generalized Clebsch-Gordan part, the statement is that $C(t)$ still vanishes at the nonsense point ($t=t_N$, say), but $\beta_o(t)$ can have a compensating pole at the same point:

$$\beta_o(t) = \gamma(t) + \varepsilon(t)/(t-t_N).$$

In particular, this reinstates the Pomeranchuk term in photon total cross sections[21].

In general,[8] the behaviour of $\beta(t)$ now depends on the strength of pole coefficient $\varepsilon(t)$ compared to $\gamma(t)$. If $\varepsilon(t)$ is weak, it simply <u>displaces the zero</u> of β to a new value near t_N. If $\varepsilon(t)$ is dominant, it <u>removes the zero</u> of β completely. Now the strength of $\varepsilon(t)$ is determi by the third double-spectral function $\rho(s,u)$ – which also determines the strength of branch cuts. We conclude that, if branch cuts are weak, we shall probably expect nonsense zeros as before, but perhaps slightly displaced in t.

2.3 Daughters and conspirators. In general 2-body reactions with unequal mass particles, analyticity suggests that Regge poles occur in families[22]; if $\alpha_o(t)$ is the leading (parent) trajectory, the n^{th} daughter trajectory α_n is correlated at t=o by $\alpha_n(o) = \alpha_o(o) - n$. Successive daughters have alternating signature, but other properties are as for the parent. No physical particles are yet firmly identified as belonging to daughter trajectories; one wonders if the latter do in fact rise rapidly and give particles like the parent, or not.

There is an interesting model calculation by Swift[23]. From an infinite sum of ladder diagrams in perturbation theory, for unequal mass scattering, he extracts both the parent Regge pole and the first daughter. Taking equal internal masses, the daughter trajectory and residue $\alpha_1(t)$ and $\beta_1(t)$ have no two-particle cut (unlike the parent). Taking unequal internal masses, they have two-particle cuts but remain dominated by the three-particle scattering and $\alpha_1(t)$ moves less rapidly than $\alpha_o(t)$.

Conspirators were proposed years ago[24], but have only just become fashionable. They are sets of t-channel Regge poles that choose to satisfy certain s-channel constraints collectively rather than individually; a typical conspiracy includes some trajectories coinciding and some with integer spacings, at t=o. Conspirators have various signatures and spin-parity assignments, but common i-spin and G-parity. Two questions arise. Do any conspiracies happen in nature? And how do they fit in with daughters?

Gribov[25] showed that fermion trajectories meet in pairs at u=o; this is a special case of conspiracy. But among boson Regge poles no conspiracies are yet established. Indeed, in elastic scattering it is known that poles are not conspiring if they contribute to the total cross section (via the optical theorem); this eliminates the best-known poles in the best-known processes.

One possible conspiracy has π and an opposite-parity trajectory as leading members, coinciding at t=o. The second conspirator need not give a 0^+ meson, if it "chooses nonsense" at $\alpha = o$, but will give a 2^+ meson if α reaches 2. The evidence is this. Assuming Regge poles only, without conspiracy the π term in pn and $\bar{p}p$ charge exchange is large and incompatible with experiment. Conspiracy offers a solution[26]. But this is not conclusive, for the data can also be explained by invoking strong cuts[27].

Recent work by Freedman and Wang[28] suggests a connection between daughters and conspirators. When the initial and final t-channel states have pairs of equal-mass particles (like $\pi\pi \rightarrow \bar{N}N$), they prove an O(4) symmetry at t=o. Poles classified according to O(4) give infinite families of Regge poles, with both daughter-type and conspirator-type inter-relations at t=o. The families contain one parent, or a few conspiring parents of different spin-parity classes, plus all their daughters. NN scattering is discussed in detail (t-channel $\bar{N}N \rightarrow \bar{N}N$): here the odd daughters happen to decouple. The possible conspiracies are more restricted than originally supposed[25], but include the pion case above.

2.4 Double-Regge diagrams.

There is recent interest in diagrams like Fig. 5a, with two Regge poles. These are not the only contributions leading to three final particles, but it is interesting to see if they play an important role.

The following properties can be seen[29]:

i) These diagrams can only be important in the central part of the Dalitz plot (the inner triangle in Fig.6). We expect the outer strips to be dominated by resonance production like Fig. 5b.

ii) Each diagram preferentially populates one corner of the Dalitz plot, since the vertices favour low momentum transfer. Diagram 5a populates the corner marked X in Fig. 6; we permute labels 3,4,5 to get other corners.

iii) Longitudinal momenta in the c.m. system are preferentially ordered $p_{L3} > p_{L4} > p_{L5}$ in the direction of particle 1.

iv) At a fixed point in the Dalitz plot, the kinematics become rather rigid, generally giving a peak for the distribution function in any remaining variable.

v) Factorization relates the outer Regge-pole couplings to two-body reactions. In particular, this indicates that baryon exchanges are relatively weak and generally negligible.

vi) Nonsense zeros are expected, as before, with new possibilities at the central vertex.

Chan et al[29] have compared such diagrams with data for $\pi^+ p \to \pi^+ \pi^0 p$ at 8 GeV/c, and $\bar{\pi} p \to K_1^0 K_1^0 n$ at 10 GeV/c, with encouraging results. Similar diagrams are also suggested by some $\bar{p}p \to \bar{p}p\omega$ and $K^- p \to \Sigma^0 \pi^+ \pi^-$ data at 6 GeV/c.[30].

3. EXPERIMENTAL QUESTIONS

3.1 Asymptotic spin-dependence.

Regge-pole property (v) of §1 allows a non-trivial spin dependence at high energy, which one would like to measure. The equal-phase rule destroys first-rank polarization in any case (Eq. 3), but not second-rank effects like the depolarization tensor D_{ij}, which have general form

$$D_{ij}\, d\sigma/dt \sim \sum \mathrm{Re}\,(T_m T_n^*). \qquad (9)$$

So these second-rank tensors are interesting. They require <u>two</u> spin determinations; e.g. for D_{ij}, both initial target polarization and final recoil polarization. For more discussion see refs 31, 32.

3.2 Factorization tests.

Factorization property (viii) of §1 gives famous relations between cross-sections in the Pomeranchuk (one pole) limit, e.g.

$$\sigma_T(\pi\pi) \;\; \sigma_T(NN) \;\; = \;\; [\sigma_T(\pi N)\;]^2, \qquad (10)$$

and a similar relation for $d\sigma/dt$. But pion targets are hard to make; this is more use as a prediction of $\pi\,\pi$ scattering than as a factorization test.

However, factorization includes spin-dependence[33]. Any I=0 Regge pole exchange, that is common to $\pi\pi$, πN, KN and NN scattering, contributes

$$\left.\begin{aligned}
T_{\pi\pi} &= F\,\eta_\pi^2 \\
T_{\pi N} &= F\,\eta_\pi(\eta_N + i\phi_N\,\underset{\sim}{\sigma}\cdot\underset{\sim}{n}) \\
T_{KN} &= F\,\eta_K(\eta_N + i\phi_N\,\underset{\sim}{\sigma}\cdot\underset{\sim}{n}\,) \\
T_{NN} &= F(\eta_N + i\,\phi_N\,\underset{\sim}{\sigma}^{(1)}\cdot\underset{\sim}{n}\,)\;(\eta_N + i\,\phi_N\,\underset{\sim}{\sigma}\cdot\underset{\sim}{n})
\end{aligned}\right] \qquad (11)$$

where $F(s,t,\alpha)$ includes all the common s-dependence, signature and kinematic factors. $\eta_\pi(t)$, $\eta_K(t)$, $\eta_N(t)$ and $\phi_N(t)$ are the vertex couplings to π,K and N (two kinds). Pauli matrices $\underset{\sim}{\sigma}$ operate on rest-frame spinors and $\underset{\sim}{n}$ is the normal to the scattering plane. Going to $\bar{K}N$ and $\bar{N}N$ scattering, odd-signature terms charge sign. For I=1 Regge poles, there are Clebsch-Gordan coefficients for different charge channels.

Thus factorization relates the spin-dependence of πN,KN, $\bar{K}N$, NN and $\bar{N}N$ scattering, and can be tested without reference to $\pi\pi$ (or KK). For example, in the Pomeranchuk limit, all depolarization tensors are equal:

$$D_{ij}(\pi N) = D_{ij}(KN, \bar{K}N) = D_{ij}(NN, \bar{N}N) \quad (12)$$

Eq. (11) also implies internal constraints in NN scattering. One consequence, in the Pomeranchuk limit, is $C_{nn} = K_{nn} = 0$, these being the normal components of the spin-correlation and polarization transfer tensors.[31,34]

When several Regge poles take part, we must first isolate their contributions. This can often be done by taking suitable sums and differences of cross sections, or by exploiting the different energy-dependences. [When fitting Regge poles to data, this is done by computer].

For example, πN scattering is dominated by two vacuum poles P, P' and the ρ pole. If $\mathcal{P}$ is polarization as before, $\mathcal{P}\, d\sigma/dt$ is a sum of PP', Pρ and P'ρ interference terms. Of these, Pρ and P'ρ change sign between π^+p and π^-p, while PP' does not. Experimentally, $\mathcal{P}\, d\sigma/dt$ is approximately anti-symmetric between π^+p and π^-p, so the PP' term is small. From factorization we can show the corresponding PP' terms in KN and NN polarization are also small. Hence, assuming P, P' and ω poles dominate the latter cases, it follows that $\mathcal{P}\, d\sigma/dt$ must be approximately anti-symmetric between K^+p and K^-p, and between pp and $\bar{p}p$.

Thus polarization effects give the best tests.[31,33,34]

Another kind of test is possible if a coupling vanishes somewhere. For example, the cross-over of pp and $\bar{p}p$ differential cross sections near $t = 0.1$ $(GeV/c)^2$ seems to require the ω-residues to change sign here[35]. Factorization then makes the ω residues vanish in other reactions: e.g. a similar cross-over is predicted for K^+p and K^-p, and agrees with data. Similarly, the ω term in $\pi N \to \rho N$ must vanish at the same t-value.

3.3 Tests for cuts.

Almost any branch-cut contribution can be faked by one or more Regge poles. So we must look for terms with energy-dependence and/or spin-dependence that no known poles can give.

i) Unexpected energy-dependence of $d\sigma/dt$. Consider $\pi p \to \pi^* p$, where π^* is a 0^+ state[36]. All the leading Regge poles P, P', ω, ρ, A_2 are parity-forbidden at the $\pi\pi^*$ vertex; the others give rapidly decreasing terms as $s \to \infty$. But the (P + P)-cut includes all spin-parity assignments and is allowed: it gives $d\sigma/dt \sim (\ln s)^{-2}$ at t=0. Unfortunately, no 0^+ resonance production is found experimentally.

Double-charge exchange offers another test[37]. No doubly charged mesons are yet known. Any such Regge poles presumably lie low and give very rapidly decreasing terms, for processes like $\pi^+ n \to \pi^- N^{*++}$, $\pi^- p \to K^+ \Sigma^-$ and $K^- p \to K^+ \Xi^-$. But the $\rho+\rho$, $\rho+K^*$ and $K^* + K^*$ cuts exist, and predict $d\sigma/dt \sim s^{-1.7} (\ln s)^{-2}$, $s^{-2}(\ln s)^{-2}$ and $s^{-2.4}(\ln s)^{-2}$, respectively, at t=0.

A single Regge pole gives shrinking of $d\sigma/dt$. Dominant cuts give no shrinking, (except near t=o where the pole takes over). The strong shrinking in $\pi^- p \to \pi^0 n$, agreeing with the extrapolated ρ trajectory, shows cuts are weak here.

ii) Unexpected energy-dependence of forward scattering amplitude.

The real and imaginary parts of forward non-flip elastic amplitudes are measured by Coulomb interference and by total cross sections, respectively. They approach their asymptotic limits as a power of s, for poles. Branch cut contributions go as $(\ln s)^{-2}$ and $(\ln s)^{-1}$ for the real and imaginary parts. To distinguish the cuts is possible in principle but difficult in practice.

iii) Unexpected energy-dependence of spin effects.

We can exploit the specific spin-dependence of Regge pole terms[36]. Consider $\bar{N}N$ states in the t-channel; they form three distinct classes.

There are singlet states, with $J^{PC} = 0^{-+}, 1^{+-}, 2^{-+}, \ldots$; triplet states with $L=J$ and $J^{PC} = 1^{++}, 2^{--}, \ldots$; triplet states with $L=J\pm1$ and $J^{PC} = 0^{++}, 1^{--}, 2^{++} \ldots$ A Regge pole interpolates states within one class, and has the same kind of spin-couplings. π and B belong to the first class; A_1 belongs to the second; P,P', ω,ρ and A_2 belong to the third. Branch cuts however are not restricted to a single class of state or spin-dependence.

In NN scattering, the leading poles are all of the third class and predict $D_{nn}=1$ asymptotically (D_{nn} is also known as the Wolfenstein D-parameter). Assuming the A_1 and B trajectories lie below 0.5 for $t < 0$, their contributions to $(1-D_{nn})\, d\sigma/dt$ fall faster than s^{-1} as $s \to \infty$. The many-P cut contributions can fall much more slowly.

In $\pi N \to \rho N$ and $KN \to K^*(888)\, N$, the vector meson decay correlations measure some matrix elements of its spin density matrix ρ_{ij}. The leading Regge poles are of the third class and give $\rho_{00} = \rho_{01} = 0$. The pion contributes strongly to these elements, but lies lower on the Chew-Frautschi plot; thus, for poles alone, we expect ρ_{00} and ρ_{01} to tend to zero like some inverse power of s. For dominant branch cuts, they could tend to non-zero constants instead. Present data up to 10 GeV/c seem consistent with Regge poles alone.(27,38)

The most famous test case is $\pi^- p \to \pi^0 n$ polarization. If this effect is pole-cut interference, it is first-order in the cut and therefore more sensitive than either of the two preceding tests. Here poles and cuts have similar spin-dependence, since only the third class of $N\bar{N}$ states is allowed, so we can exploit only the energy-dependence. As discussed in §2, present data are not enough to distinguish between pole and cut effects.

iv) Other phenomena.

It is suggested that wide-angle scattering contains evidence of cuts,(39) and arguments are given for characteristic oscillations.(40)

The pn and $\bar{p}p$ charge exchange data seem to require either a cut[27] or a conspiracy[26]; the latter has physical consequences and may eventually be eliminated.

3.4 Tests for crossing.

Consider the reactions $\pi^+ p \to K^+ \Sigma^+$ and $K^- p \to \pi^- \Sigma^+$, related by crossing; they have the advantage that Σ^+ polarization is measured by the weak decay. Only $K^*(888)$ and $K^*(1410)$ Regge pole exchanges are known; they are odd and even under crossing, respectively. Σ^+ polarization comes from interference between the two poles. Hence $\mathcal{P}\, d\sigma/dt$ must have the same size but opposite signs in the two reactions.

3.5 The region $t > 0$.

There is evidence that trajectories may continue to rise, roughly linearly with t (or u), for a long way in the region $t > o$ $(u > o)$[4,41]. What does this imply?

For a sequence of particles on such a trajectory, mass increases as $J^{\frac{1}{2}}$. The impact parameter in any two-particle channel also increases as $J^{\frac{1}{2}}$. Eventually the impact parameter exceeds the range of forces, and the two-particle partial widths become exponentially small. Hence very high spin members will not appear in elastic scattering, but only in many-body channels. Note that $N^*(3690)$, possibly a spin - 23/2 recurrence of $N^*(1518)$, was found in a study of 8-prong events.[42]

For fermion trajectories, the appropriate variable is really $W=\sqrt{u}$, rather than u. Thus $\alpha(u)$ has two branches, corresponding to the two square roots of u; these appear as a pair of Regge trajectories, coinciding at u=0 and complex conjugate for $u < 0$. In fact, the two branches correspond to the two possible parities for given j, following the MacDowell symmetry. If $\alpha(u)$ were exactly linear, the two branches would coincide, giving pairs of particles with the same mass and opposite parities. When the fermion trajectories starting with N, $N^*(1518)$ and

$\Delta(1236)$ are discussed, only one branch is usually considered[41], but the approximate linearity in u suggests there may be many opposite-parity particles waiting to be discovered. Chiu and Stack[16] parametrized the N trajectory ($J^P = \frac{1}{2}^+, \frac{5}{2}^+, \ldots$) and found that the other branch gave $\frac{1}{2}^-$ and $\frac{5}{2}^-$ particles with masses 0.85 and 1.60 GeV; the former was removed by a zero in the residue, but the latter was identified as the πN $D\frac{5}{2}$ resonance.

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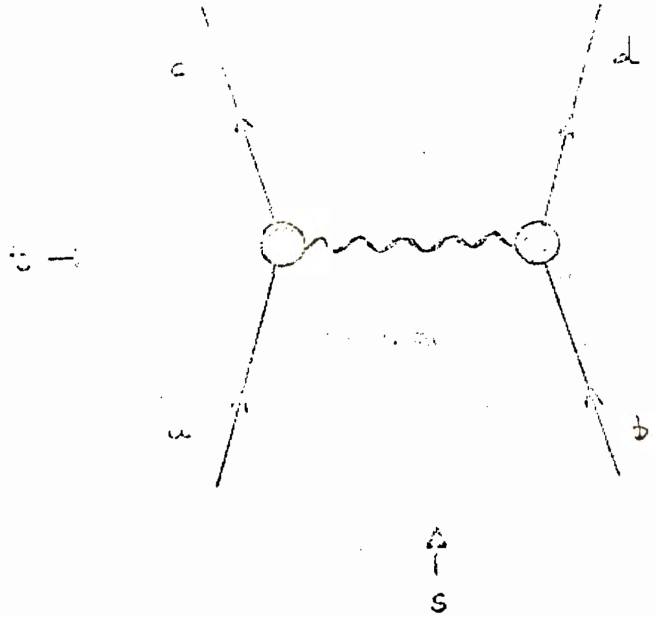

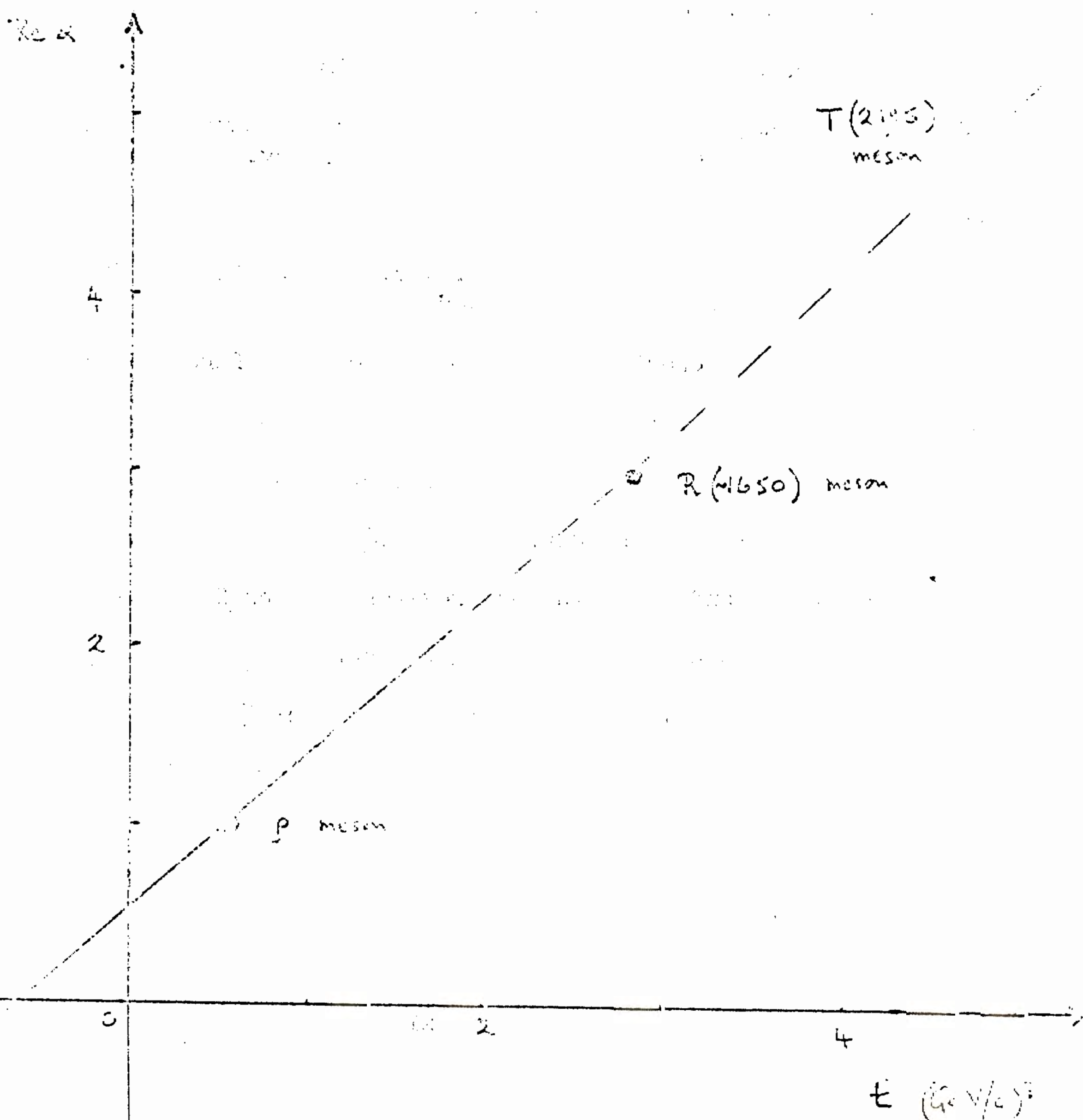

Figure 2
Chew-Frautschi plot for the ρ trajectory

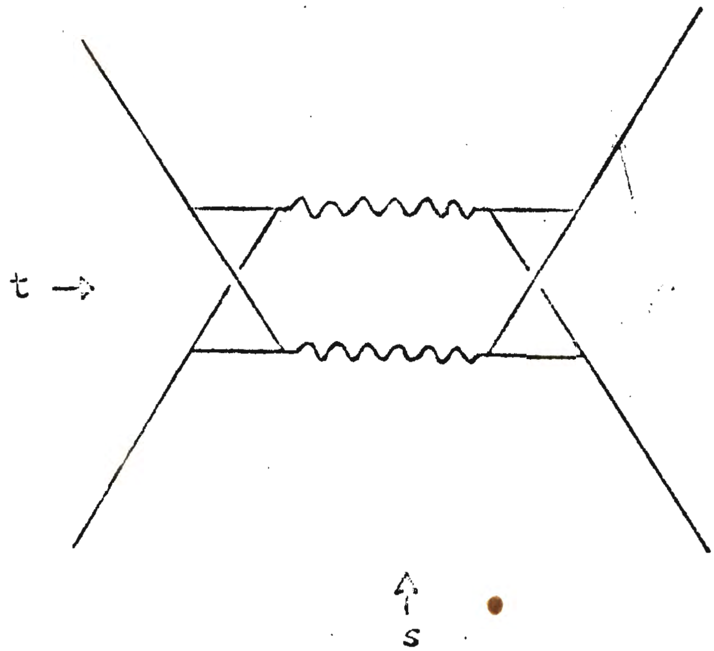

FIGURE 3

Two-Reggeon exchange giving a branch point

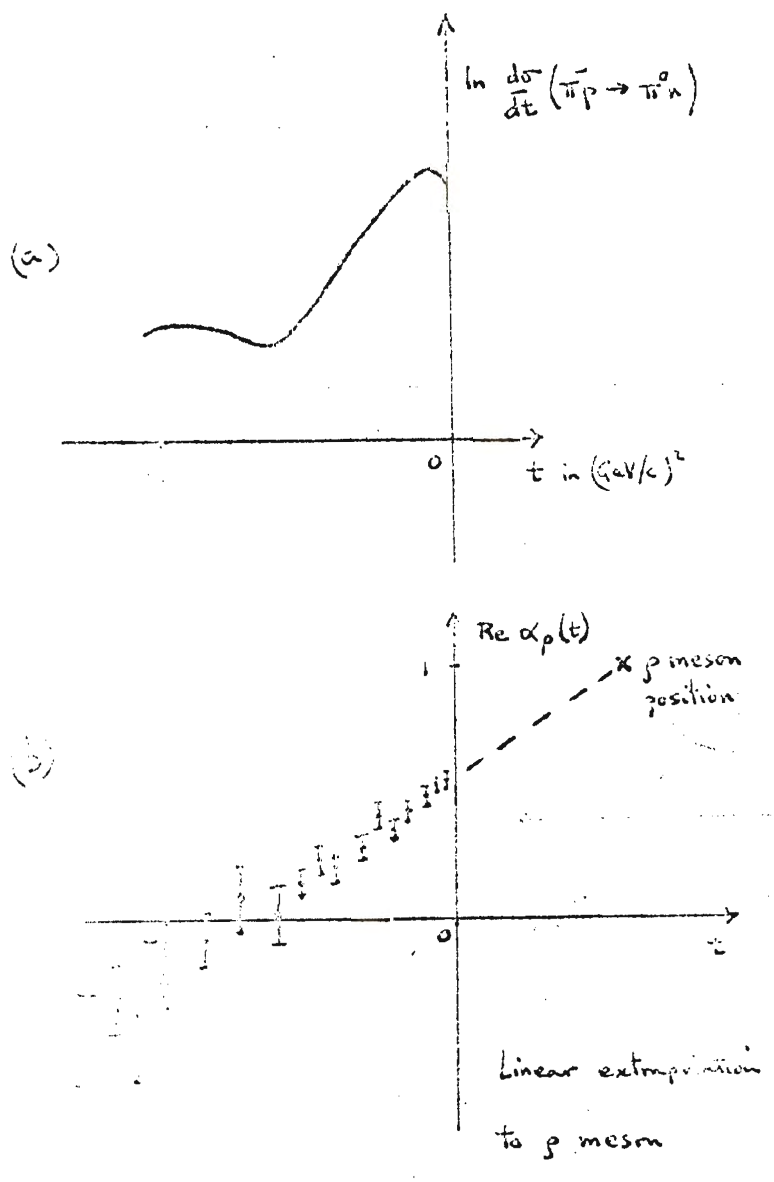

FIGURE 4

πp charge exchange test case.

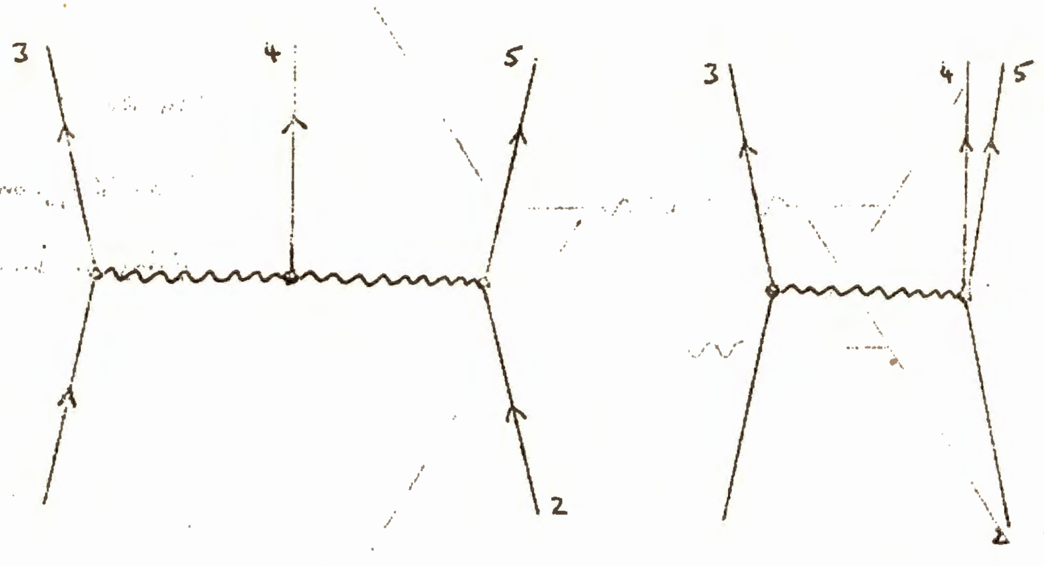

FIGURE 5

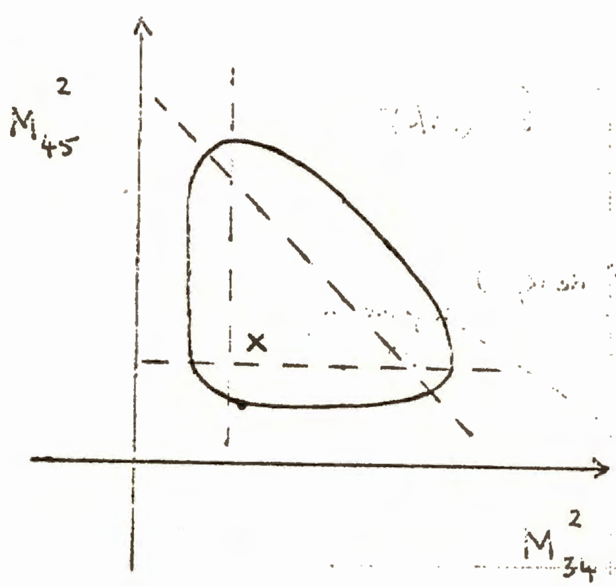

FIGURE 6