Regge-Cut Theory Yields Encouraging Results

The idea that the analytic structure of partial-wave scattering amplitudes as functions of the angular momentum might determine many properties of the complete scattering amplitude has been extremely important in recent studies of high-energy scattering. Tullio Regge, in 1959, originally investigated this idea for potential scattering. In that case the amplitudes have only simple poles (Regge poles) in angular momentum. The positions of these poles are functions of the energy. The resulting Regge trajectories determine both the location and properties of resonances and behavior of scattering amplitudes at large momentum transfers.

The basic ideas of the Regge description of scattering amplitudes have been taken over into high-energy physics. Here the Regge poles determine not only the behavior of resonances in a given channel, say $A + B \rightarrow C + D$ but also the high-energy behavior of scattering amplitude in the crossed channel $A + \overline{C} \rightarrow \overline{B} + D$.

Considerable effort has been devoted over the past nine years to application of simple Regge-pole models to the description of high-energy reactions. The models have been remarkably successful. Among the many successes are:

- Resonances in a given reaction and high-energy behavior in the crossed channel of that reaction are correlated through the trajectory.
- The model generally explains the presence, shape and energy dependence of both forward and backward peaks in a great number of high-energy reactions. In particular, virtually all elastic and inelastic meson–baryon reactions can be described in terms of only a few Regge poles.
- A single trajectory can contribute to several reactions. The contribution of this pole is proportional to its residue, which factors into two pieces. Each piece depends on a given pair of the external particles, and this fact allows correlation of the magnitudes and energy dependencies of the forward and backward peaks in reactions involving the same trajectories and external-particle pairs.
- At certain known values of the trajectory function the contribution of a Regge amplitude vanishes. This disappearance normally leads to dips in the cross section.

These predictions are borne out in many reactions—for example, in meson–baryon reactions near the backward direction. On the other hand, some features of the high-energy data are difficult to explain with a pure Regge-pole model. In order to understand these features of the data, phenomenologists have incorporated another type of angular-momentum singularity, Regge-cuts, into their analysis.

Regge cuts. That such singularities must exist in a relativistic theory, as opposed to potential theory, has been known for some time. In particular, V. N. Gribov and Isaak Y. Pomeranchuk showed on very general grounds that there must be an essential singularity at $j = -1$. Stanley Mandelstam showed this singularity could be put on a second Riemann sheet of the j plane and made harmless if there exist appropriate j-plane cuts. The properties of such cuts have, therefore, been of much theoretical interest.

Work on Regge cuts in both phenomenology and theory has recently been very active, with encouraging results. To examine the phenomenological and theoretical work on Regge cuts a topical conference was held at the University of Wisconsin at Madison, 23–25 April 1969. The conference was arranged to coincide with the last three days of the 1969 Spring Institute for Theoretical Physics at the University of Wisconsin.

The theory of Regge cuts is not as well developed as one might wish. For phenomenological applications one uses rather simple models, not based on very fundamental theory. On the other hand, theoretical studies that have established the existence and some properties of Regge cuts are based primarily on model field theories, and they do not yield predictions specific enough for phenomenology. As might be expected, the conference divided rather clearly into several parts: phenomenological studies,

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model field-theory calculations, and intermediate work that attempts to establish a bridge between the two.

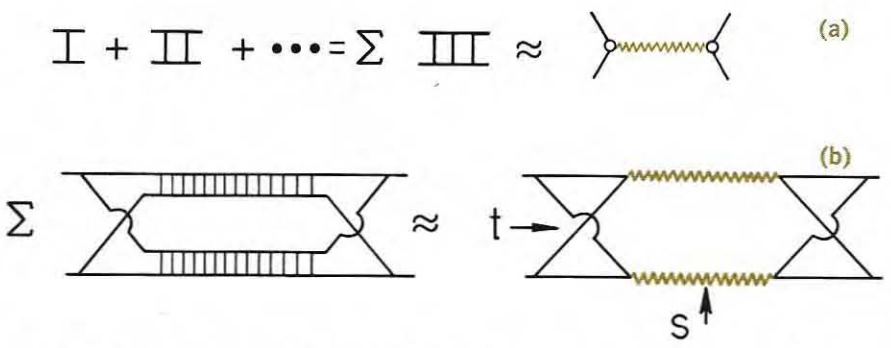
Models. Marc Ross (Michigan) surveyed the commonly used models for Regge cuts and the phenomenological situation. Most theoretical studies employ Feynman-diagram models with crossed lines. Such graphs are nonplanar and require the presence of a third spectral function. These cuts have a definite signature, which is generally believed to be correct and which can correctly shield the Gribov–Pomeranchuk essential singularity. For phenomenological applications, the more commonly used models are based on multiple-scattering theory or absorptive corrections. The theoretical basis for these models is not yet complete. Some of the important features of the data that they must fit are the crossover of particle–particle and particle–antiparticle differential cross-sections, polarization data, loss of exchange degeneracy for residues, and antishrinkage. As we mentioned above, there are striking dips in many differential cross sections in the simple Regge-pole model, because of what are technically known as "nonsense-wrong-signature zeros." Cut-pole interference can also produce dips, and an outstanding task for phenomenology is to distinguish the two mechanisms.

Field theory. In Feynman-graph techniques, surveyed for the conference by Clifford Risk (Michigan), one considers a class of Feynman diagrams, extracts the asymptotic behavior from the Feynman integral, and sums all graphs. One of the more common models is the sum of ladder graphs in ϕ^3 theory, shown in part a of the figure. This sum produces a moving pole in the angular-momentum plane, and consequently ladder sums are a conventional approximation to Regge poles in models for cuts, such as that (due to Mandelstam) illustrated in part b of the figure.

John Polkinghorne (Cambridge) described t-channel iterations of the Mandelstam diagram (figure, b). This calculation produces a result compatible with t-channel unitarity and is necessary in order to remove the Gribov–Pomeranchuk essential singularity at $l = -1$. The asymptotic behavior of the integrated sum differs from the original cut contribution only by a factor $(\log \log)^{-2}$.

For the treatment of certain cut models, as well as for multi-Reggeon exchange amplitudes, it would be useful to have a Feynman-like Reggeon calculus. Ian Drummond (Cambridge) described work on the general vertex function $f(\alpha_1\alpha_2)$ for the coupling of two Reggeons to an elementary particle. These general results were checked in two specific models for the Reggeon lines and their couplings. Related work on the three-Reggeon vertex $F(\alpha_1\alpha_2\alpha_3)$ was described by Peter Landshoff (Cambridge). The result reduces in the appropriate way to $f(\alpha_1\alpha_2)$ and to two-particle–one-Reggeon vertices.

Quantum electrodynamics. These calculations were all limited to spinless-field theories. Calculations in a realistic field theory that incorporates



TWO CLASSES OF FEYNMAN DIAGRAMS in ϕ^3 theory, used as models for a simple Regge pole (in *a*, above) and a Regge cut (in *b*, below). In *a* the sum of all planar diagrams for the exchange of n elementary particles behaves, for large s, as a single t-channel Regge pole. (The Regge pole is represented by the colored wavy line.) Part *b* of the figure shows a model for a moving Regge cut. Here double Regge-pole exchange is required. To produce a cut the diagram must be nonplanar—hence the crossed particle-exchange lines at the ends. As in part *a*, the model for the Regge poles is a sum of ladder graphs.

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spin, namely, quantum electrodynamics, were described by Tai T. Wu (Harvard). The processes $e^-e^- \rightarrow e^-e^-$, $e^-e^+ \rightarrow e^-e^+$, $\gamma e^- \rightarrow \gamma e^-$, $\gamma\gamma \rightarrow \gamma\gamma$ and the scattering of electrons and gammas by an external field have been examined up to order e^8. Because internal electron lines carry spin, one gets asymptotic contributions from certain graphs that are of higher order than one would expect from the spinless theories. For each order in e^2 elaborate cancellations occur in the asymptotic limit between graphs with crossed and uncrossed lines, and one must go to high order to find contributions of the type expected to dominate asymptotically.

Keiji Kikkawa (Wisconsin) described a calculation that produces Regge cuts from duality amplitudes. Such amplitudes are the nontree-diagram generalization of the Veneziano model. The planar graphs were previously found to produce corrections to the linear Veneziano trajectory while maintaining crossing symmetry. Certain classes of nonplanar graphs were shown to produce Regge-cut contributions.

Corrections. Field-theory calculations do not usually lead to simple phenomenological predictions. Absorptive corrections, which produce Regge cuts, are more often used. Frank Henyey (Michigan) discussed the derivation of absorptive cuts from Feynman-diagram models. He focused our attention on the box diagram whose sides are Reggeons. To produce a Regge cut, the ladders that serve as models for the Reggeons must include crossed rungs. Considerable effort is required to obtain a relative pole-cut phase that produces destructive interference.

In a related vein, Antonio Pagnamenta (Rutgers) discussed high-energy scattering in multiple-scattering models. In collisions of particles composed of clusters of two, three, four and infinitely many constituents, the Glauber series converges well. These models fit the proton–proton scattering data, but it is not possible to differentiate the models on experimental grounds. David Harrington (Rutgers) compared, in potential theory, the high-energy limit of the multiple-scattering series with Glauber theory. He showed that the two theories agree because of cancellations in the multiple-scattering series. This

agreement suggests that the Regge cuts predicted by Glauber theory may actually be present, even though they are absent in the complete double-scattering term.

Diffraction models for the high-energy proton–proton differential cross section are able to explain the data fairly successfully in terms of the proton electromagnetic form factor. So it would be desirable to have an expression for the form factor in terms of strong-interaction quantities. An initial step in this direction has been taken by Richard Arnold (Argonne), who described a calculation based on cut dominance and the Fubini–Dashen–Gell-Mann sum rule, which reproduces the relation between the proton–proton cross section and the proton form factor.

Raymond Rivers (Chicago) presented an absorption model based on the inclusion of nonelastic (two-body) intermediate states in the *s*-channel unitarity sum. Absorptive corrections to the Regge amplitude were expressed in terms of certain cross-section ratios. Rudolph Hwa (Stony Brook) described a bootstrap of the Pomeron cut. The model begins with unitarity (saturated by two intermediate-state resonances) and crossing, and it relies on the bootstrap to produce Regge behavior.

Phenomenology. The remainder of the conference was primarily devoted to accounts of fits to data based on Regge-cut models. Because fewer secondary trajectories are used in such models, the number of adjustable parameters may be smaller than in a pure pole model. On the other hand, as the cut contribution is not factorizable, the predictive power of these models may be somewhat weaker.

Arnold gave a survey of fits with Regge cuts and with other models in elastic and charge-exchange scattering. Attention was focused on models that begin with either a fixed or moving l-plane pole in the Born term. The full amplitude containing a Regge cut is generated, for example, by an absorptive calculation such as the eikonal model. Arnold discussed the work of a number of groups who use these methods. In addition, he presented a detailed model incorporating exchange-degenerate Regge poles, which fits the forward-elastic and charge-exchange data and the polarization. Cuts in this model are essen-

tially minor corrections to the pure pole model. In particular, dips are still produced by nonsense-wrong-signature zeros in the pole amplitudes.

Gordon Kane (Michigan) described the results of extensive calculations for inelastic processes with a Regge-exchange plus absorptive-cut model. The absorptive-cut correction term involves an extra adjustable parameter to account for the effect of inelastic absorptive states. The cut contribution in this model, in contrast to that of Arnold, is of a size comparable to the pole contribution. The pole and cut contributions interfere destructively; this interference can produce dips in the cross section; so the data can be fitted without assuming nonsense-wrong-signature zeros as in the pure Regge-pole model. In addition the cut contribution decreases as spin-flip increases; so the dip position depends upon the helicity. A careful examination of the backward-scattering region should be able to distinguish the pole-cut and the pole model. Christopher Michael (Wisconsin), however, described the practical difficulties in distinguishing the pole-cut model from a pure pole model that incorporates additional secondary trajectories. Each model possesses enough freedom in its parameters to fit most reactions. Processes connected by crossing to exotic channels (those in which no single Regge exchange is allowed) provide a possible means of unambiguously detecting cut contributions through their characteristic energy dependence.

Bernard Margolis (McGill) discussed the predictions of various versions of the eikonal approximation—in particular, the Frautschi–Margolis model for proton–proton scattering. The predictions are: The forward peak will eventually shrink; the elastic differential cross section will continue to fall; the total cross section will eventually rise slightly; the forward real-to-imaginary ratio will change sign, and cuts contribute a definite and substantial amount to forward scattering.

Absorptive corrections to the Regge-exchange term can be introduced through the unitarity relation. Henri Navelet (Saclay) described such a calculation and fits to pion–nucleon, kaon–nucleon and nucleon–nucleon elastic-scattering and charge-exchange reactions. The absorptive correction is essentially a Regge-cut term, and good fits were obtained. Ronald Mickens (Massachusetts Institute of

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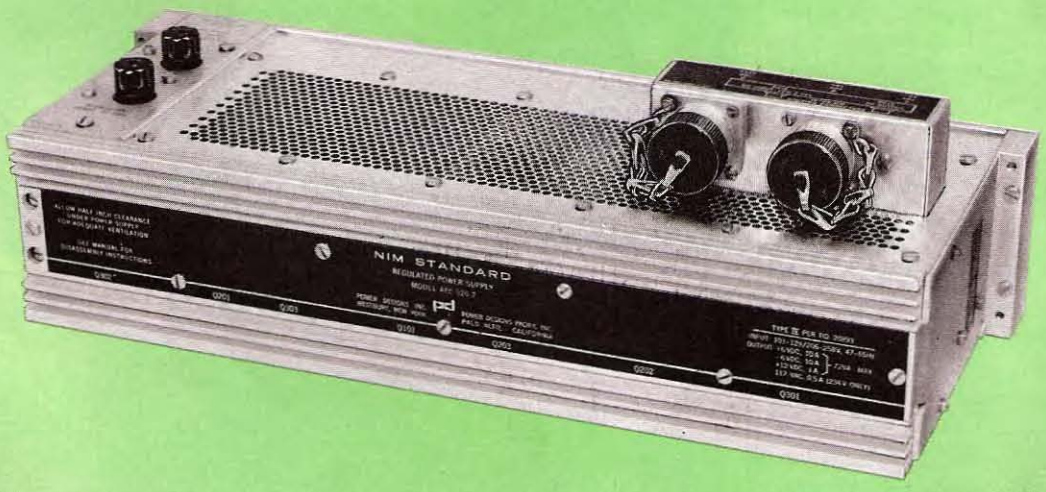

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Technology) suggested that destructive interference between pole and cut is not always necessary. Calculations of the forward real-to-imaginary ratio for both phase choices in Pomeron models were unable to decide which phase is correct.

The current position. In model field theories, the existence of Regge cuts appears to be well established, along with the location of the branch point and the signature. Furthermore, in these models one can find cuts with the properties required to mask the Gribov–Pomeranchuk essential singularity. It is not clear that any other cut properties, in particular the phase relative to the pole, have been rigorously established. In addition, all models consider only limited classes of graphs. Subtle cancellations can occur when one considers larger classes. Much more work is needed to establish firmly the other properties of Regge cuts.

The popular phenomenological Regge-cut models have no outstanding difficulties in fitting data, but the question of whether cuts are required by the present data is somewhat controversial. These models are based in one way or another on absorptive or unitarity corrections. It is certainly clear that such corrections are related to Regge cuts, but none of these models has any rigorous theoretical foundation. In particular, although the absorption models yield a relative pole-cut phase that seems to be verified by experiment, they lack crossing and hence do not produce a signatured contribution. Signature essentially must be put in by hand. Finally, the popular cut models do not even agree on the strength of the cut contribution and have somewhat different physical implications. Firmer theoretical underpinnings would greatly increase the predictive power of these models.

* * *

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