We can alter G_n so that it is positive semidefinite. Consider the form

$$G_n^{(\text{new})}=G_n^{(\text{old})}\left(\frac{n+j+e}{n+j+d}\right). \tag{6.3}$$

This choice should change neither the asymptotic linearity nor the slope. We choose $e=-1$ so that the numerator factor vanishes for $n=1$ and $j=0$, i.e., at the point where $G_n^{(\text{old})}$ is negative. The constant d was arbitrarily chosen to be zero.

These results are shown in Fig. 2. The ghost disappeared because the leading trajectory was found to approach $j=0$ asymptotically. The asymptotic slope of the trajectories differ from Fig. 1 since a different scaling passes the leading trajectory through the ρ mass.

ACKNOWLEDGMENT

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PHYSICAL REVIEW D VOLUME 2, NUMBER 4 15 AUGUST 1970

Crossing Regge Trajectories and Pole-Cut Relationships*

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The general features of typical pole-cut relationships with crossing Regge-pole trajectories are considered. The possible shapes of the resulting physical pole trajectories are described.

I. INTRODUCTION

In a recent paper,[1] we discussed the question of possible left-hand branch lines of Regge-pole trajectories. These branch lines are of interest in connection with diffraction scattering,[1–5] and possibly also for other high-energy properties. Since, *a priori*, one may perhaps think that there are other possibilities, we have pointed out that Regge trajectories can have such branch lines only as a consequence of the crossover of two (or more) *pole* trajectories. The relevant constraint is the condition that these branch points of the trajectory $\alpha(s)$ are not inherited by the continued partial-wave amplitude $F(s,\lambda)$.

From the phenomenological point of view, we may not want to have two trajectories which correspond to different branches of the same analytic function. It was therefore the main point of Ref. 1 to show that one can use fixed or moving branch points in the complex λ plane of $F(s,\lambda)$ in order to remove one of the two crossing Regge trajectories into a secondary sheet with respect to these λ branch lines.[6–8] It is the purpose of this paper to explore the general features of the resulting pole-cut relationships.

Crossing Regge poles and corresponding pole-cut relationships are possible structures in the complex λ plane which may well play an important role in phenomenological calculations, and which may give more concise parametrizations than poles and cuts separately. There is no proof at present that such structures are necessary within the framework of dispersion theory, but there are indications from potential theory,[9,10] relativistic perturbation theory,[11] and certain iteration schemes[12] that they may be relevant.

Suppose we have two Regge trajectories $\alpha_1(s)$ and $\alpha_2(s)$ which are pole surfaces of the continued partial-wave amplitude $F(s,\lambda)$. Then this amplitude has the meromorphic terms

$$F(s,\lambda)=\frac{\beta_1(s)}{\lambda-\alpha_1(s)}+\frac{\beta_2(s)}{\lambda-\alpha_2(s)}+\cdots. \tag{1}$$

* Supported in part by the U. S. Atomic Energy Commission.
[1] R. Oehme, Phys. Letters **30B**, 414 (1969).
[2] P. G. O. Freund and R. Oehme, Phys. Rev. Letters **10**, 450 (1963).
[3] R. Oehme, in *Strong Interactions and High-Energy Physics*, edited by R. G. Moorhouse (Oliver and Boyd, London, 1964), pp. 129–227.
[4] J. S. Ball and F. Zachariasen, Phys. Rev. Letters **23**, 346 (1969).
[5] R. Oehme, Phys. Letters **32B**, 573 (1970).
[6] In two recent papers by Zachariasen and co-workers (Refs. 7 and 8), special models for pole-cut relationships have been discussed which contain two crossing Regge trajectories, and which are therefore of the same general type as those considered in Ref. 1. Unfortunately, these authors refer to our paper in a way which is highly misleading.
[7] P. Kaus and F. Zachariasen, Phys. Rev. D **1**, 2962 (1970); F. Zachariasen, in Proceedings of the 1970 Coral Gables Conference (unpublished).
[8] J. S. Ball, G. Marchesini, and F. Zachariasen, University of Utah report (unpublished); Phys. Letters **32B**, 583 (1970).
[9] R. Oehme, Nuovo Cimento **25**, 183 (1962); Ref. 3, p. 163.
[10] V. Singh, Phys. Rev. **127**, 632 (1962); G. S. Guralnik and C. R. Hagen, *ibid.* **130**, 1259 (1963).
[11] J. D. Bjorken and T. T. Wu, Phys. Rev. **130**, 2566 (1963); R. F. Sawyer, *ibid.* **131**, 1384 (1963).
[12] See, for example, Ref. 7; also G. F. Chew and D. R. Snider, Phys. Letters **31B**, 75 (1970).

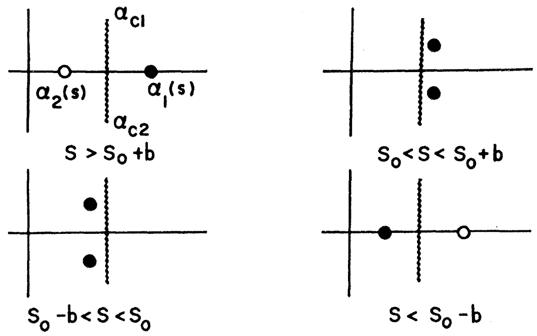

FIG. 1. Relative positions of poles and cut in the complex angular-momentum plane (λ plane) for the case of a real $\alpha(s)$ cut and a complex λ cut. Closed circles, poles in the physical sheet; open circles, poles in the unphysical sheet.

If the trajectories $\alpha_1(s)$ and $\alpha_2(s)$ cross at $s=s_0$, i.e., if $\alpha_1(s_0)=\alpha_2(s_0)$, it is possible (but not necessary) that $\alpha_1(s)$ and $\alpha_2(s)$ are two branches of a two-valued analytic function $\alpha(s)$.[13] In the neighborhood of $s=s_0$, we have then an expansion of the form

$$\alpha_{1,2}(s)=a_0\pm a_1(s-s_0)^{1/2}+\cdots. \quad (2)$$

From Eq. (1) we see that $F(s,\lambda)$ has no branch point at $s=s_0$, provided $\beta_1(s_0)=\beta_2(s_0)$.

In order to remove one branch of the trajectory $\alpha(s)$ from the physical sheet of the λ plane, we introduce a branch cut in $F(s,\lambda)$. This branch cut must, of course, in some way be correlated with the pole trajectories. There are many possibilities, which also depend upon the extent to which we want to remove one of the branches of $\alpha(s)$. In the following, we consider briefly three types of pole-cut relationships. The first two cases are similar to the situation encountered in potential theory with r^{-2}-type potentials,[3,9] but they may just as well be considered in a more general framework with fixed or moving branch points in the λ plane.

II. THREE TYPES OF POLE-CUT RELATIONSHIPS

A. Real $\alpha(s)$ Cut, Complex λ Cut

We suppose that there are two Regge trajectories $\alpha_1(s)$ and $\alpha_2(s)$ which cross at $s=s_0$, where s_0 is real. Then these trajectories can be branches of a two-valued function $\alpha(s)$ with a branch point at $s=s_0$ and a cut which we draw toward the left along the real s axis; it may be finite or infinite. Furthermore, we require that there is a branch cut of $F(s,\lambda)$ in the λ plane such that the pole trajectory $\alpha_2(s)$ never enters into the physical sheet and that $\alpha_1(s)$ never leaves this sheet. Since $\alpha(s)$ and $F(s,\lambda)$ are real analytic functions, the two branches $\alpha_1(s)$ and $\alpha_2(s)$ must be complex conjugates of each other for real $s\leq s_0$ along the cut. Then it follows from our requirements that both poles must be on the boundary between the physical and the unphysical sheet of the λ plane. But this is the same as saying that they must be on the lip of the λ branch cut of $F(s,\lambda)$, and consequently this branch cut must be complex. We see that our assumptions imply complex-conjugate branch points $\alpha_{c1,2}(s)$ in the λ plane for real $s\leq s_0$. These branch points are connected by a cut which coincides with the path of the pole $\alpha(s)$ as s varies along the left-hand cut in the s plane of $\alpha(s)$. For real $s>s_0$, the poles $\alpha_1(s)$ and $\alpha_2(s)$ are both on the real λ axis, with only $\alpha_1(s)$ being in the physical sheet of the λ plane. The branch points $\alpha_{c1,2}(s)$ may become real for these values of s.

In earlier papers,[1,5] we have described explicit models with pole-cut relations of the type considered above. Here we refrain from writing out more extensive formulas. We only illustrate, in Figs. 1 and 2, the characteristic features of these models using a very simple example with branch points at $\alpha_c=a\pm ib$ and a pole trajectory, which, in the physical sheet of the λ plane, is given by

$$\begin{aligned}\alpha_1(s)&=a+[(s-s_0)^2-b^2]^{1/2} \quad \text{for} \quad s>s_0+b\\ &=a-[(s-s_0)^2-b^2]^{1/2} \quad \text{for} \quad s<s_0-b, \end{aligned}\quad (3)$$

with $b>0$, and

$$\mathrm{Re}\,\alpha(s)=a \quad \text{for} \quad s_0-b\leq s\leq s_0+b.$$

For $F(s,\lambda)$ near the point $s=s_0$, we can consider an expression of the form

$$\varphi(s,\lambda)=\frac{s-s_0+[(\lambda-\alpha_{c1})(\lambda-\alpha_{c2})]^{1/2}}{[\lambda-\alpha_1(s)][\lambda-\alpha_2(s)]}. \quad (4)$$

The types of models described in this section are of particular interest for the description of diffraction scattering, because they make it possible to have $\mathrm{Re}\,\alpha(s)=\text{const}$ for $s\leq 0$ without introducing a fixed pole.[2,3] They may have something to do with the possible existence of repulsive forces at small distances in the vacuum channel. The examples discussed in Ref. 5 are of interest in connection with possible violations of the Pomeranchuk theorem. For $\ln t\gg 1$, they have rapid oscillations in $d\delta/ds$.

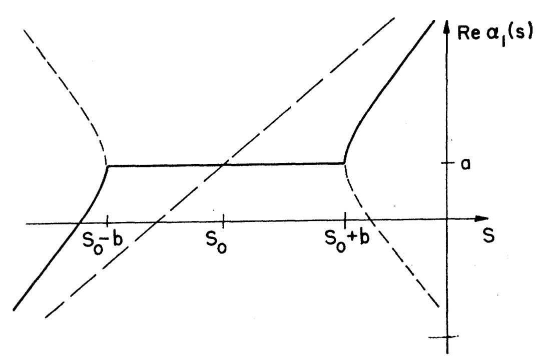

FIG. 2. Typical form of the real part of the physical pole trajectory for pole-cut relationships of the type discussed in Sec. II A.

[13] This is a consequence of the Weierstrass preparation theorem. See also Hung Cheng, Phys. Rev. 130, 1283 (1963).

B. Complex $\alpha(s)$ Cut, Real λ Cut

Let us now consider a situation where the branch points in the λ plane remain on the real axis. We may have a cut from $\lambda=\alpha_c$ to $-\infty$ or a finite cut between α_{c1} and $\alpha_{c2}<\alpha_{c1}$. Again we introduce two crossing pole trajectories $\alpha_1(s)$ and $\alpha_2(s)$ with $\alpha_1(s)$ in the physical sheet and $\alpha_2(s)$ in the unphysical sheet of $F(s,\lambda)$ with respect to the λ cut mentioned above. The trajectories α_1 and α_2 are branches of a two-valued analytic function $\alpha(s)$, and the question is: What kind of cut do we need in the s plane in order to satisfy our requirements? We see that $\alpha(s)$ must move along the real branch cut of $F(s,\lambda)$ in the λ plane as s varies along the relevant cut of $\alpha(s)$ in the s plane. But then the s-plane cut must be complex, with two complex-conjugate branch points. This follows because $\alpha(s)$ is a real, analytic function which has to be real for s on the cut, and it cannot be real for points on a cut along the real axis.

The features of the type of pole-cut relationships described above are illustrated in Figs. 3 and 4 with the help of a simple explicit model. We take the real cut in the λ plane as a straight line connecting the branch points

$$\alpha_{c1,2}=a\pm b,\quad b>0. \tag{5}$$

The pole trajectory is given by

$$\alpha(s)=a+[(s-s_0)^2+b^2]^{1/2}, \tag{6}$$

and the pole in the physical sheet has the functional form

$$\begin{aligned}\alpha_1(s)&=a+[(s-s_0)^2+b^2]^{1/2}\quad\text{for}\quad s\geq s_0+0\\&=a-[(s-s_0)^2+b^2]^{1/2}\quad\text{for}\quad s\leq s_0-0.\end{aligned} \tag{7}$$

We see that the physical trajectory has a discontinuity at $s=s_0$ which is illustrated in Fig. 4. We have

$$\alpha_1(s_0+0)-\alpha_1(s_0-0)=2b. \tag{8}$$

The function $\alpha(s)$ has branch points at $s=s_0\pm ib$. The inverse function is given by

$$s(\lambda)=s_0+[(\lambda-a)^2-b^2]^{1/2}, \tag{9}$$

and, as a function of the angular-momentum variable λ, the physical pole $s=m^2(\lambda)$ is of the form

$$\begin{aligned}m^2(\lambda)&=s_0+[(\lambda-a)^2-b^2]^{1/2}\quad\text{for}\quad \lambda\geq a+b\\&=s_0-[(\lambda-a)^2-b^2]^{1/2}\quad\text{for}\quad \lambda\leq a-b.\end{aligned} \tag{10}$$

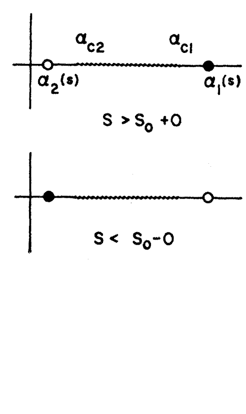

FIG. 3. Relative positions of poles and cut in the λ plane for the case of a complex $\alpha(s)$ cut and a real λ cut. Closed circle, pole in the physical sheet; open circle, pole in the unphysical sheet.

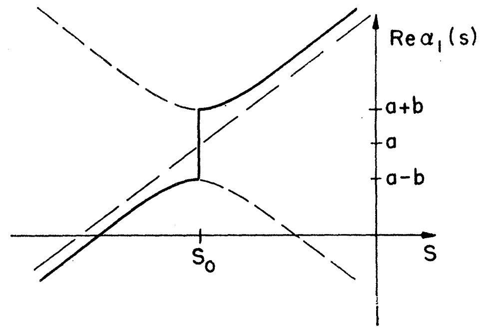

FIG. 4. Typical form of the real part of the physical pole trajectory for pole-cut relationships of the type discussed in Sec. II B.

In the interval $a-b<\lambda<a+b$, the mass (squared) is complex, with $\mathrm{Re}\,m^2(\lambda)=s_0$.

If pole-cut relations of the type considered in this section should actually occur in realistic theories,[14] they could have very interesting phenomenological consequences. In potential scattering,[3,9] the present case corresponds to a situation where there is an attractive potential with an r^{-2} singularity at the origin. For values of the continued angular momentum which lie on the cut in the complex λ plane, the attractive potential overcomes the centrifugal repulsion and gives rise to a "collapse into the center."

C. Real $\alpha(s)$ Cut, Real λ Cut

As a third possibility, we consider again a real branch cut of $F(s,\lambda)$ in the λ plane, but now we also want to insist upon a two-valued Regge-pole trajectory $\alpha(s)$ with a left-hand cut along the *real* s axis for $s\leq s_0$. As in the first case, the branches $\alpha_1(s)$ and $\alpha_2(s)$ must then be complex-conjugate functions for the real points along this cut in the s plane. Since the λ cut is also assumed to be real, we find that it is now *not* possible for the branches of $\alpha(s)$ to be on the boundary of the physical sheet; rather, they must be either in the physical or in the unphysical sheet of the λ plane. For real $s\geq s_0$, the functions $\alpha_{1,2}(s)$ are real and they can be in different sheets, as may be required from the physical point of view. However, with the assumptions made in this section, we will find it difficult to obtain trajectories with $\mathrm{Re}\,\alpha(s)=\text{const}$ for $s\leq s_0$. Special models of this type have been discussed in Ref. 7.

Suppose that only the branch $\alpha_1(s)$ is in the physical sheet for real $s\geq s_0$, and $\alpha_2(s)$ is in the unphysical sheet. We have assumed a real branch point at $\lambda=\alpha_c(s)$ with a cut drawn to the left along the real λ axis toward $-\infty$. This branch cut must be correlated with the poles $\alpha_{1,2}(s)$; its discontinuity contains these poles. Clearly, as real functions for $s\geq s_0$, $\alpha_1(s)$ and $\alpha_2(s)$ can only be in

[14] See, in this connection, the recent paper by Hung Cheng and T. T. Wu, Phys. Rev. Letters **24**, 759 (1970). These authors introduce the term "promotion" for a feature of the trajectory similar to the one discussed in this section.

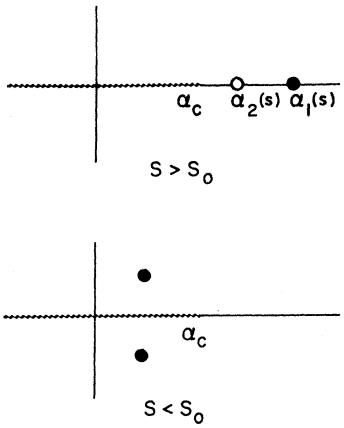

FIG. 5. Relative positions of poles and cut in the λ plane for the case of a real $\alpha(s)$ cut and a real λ cut. Closed circle, pole in the physical sheet; open circle, pole in the unphysical sheet.

different sheets if

$$\alpha_1(s)>\alpha_c(s) \quad \text{and} \quad \alpha_2(s)>\alpha_c(s). \tag{11}$$

(See Fig. 5.) We may want to allow $\alpha_2(s)$ to be on the boundary of the physical sheet for $s>s_0$, but then it must lie on the cut $\lambda\leq\alpha_c(s)$. In view of our assumptions, this is not compatible with the reality properties of $F(s,\lambda)$.

The inequalities (11) imply that we cannot have $\text{Re}\alpha(s)=\text{const}$ for $s\leq s_0$. In order to see this, we consider $\alpha(s)$ and $\alpha_c(s)$ in the neighborhood of $s=s_0$, choosing $s_0=0$ for simplicity of writing. Near the point $s=0$, the branch-point trajectory $\alpha_c(s)$ is analytic and the pole trajectory has a square-root branch point. We write the expansions

$$\begin{aligned}\alpha_c(s)&=\alpha_0+a_c s+\cdots,\\ \alpha(s)&=\alpha_0+as+(\beta_0+bs)s^{1/2}+\cdots,\end{aligned} \tag{12}$$

and from the inequalities (11) we then obtain the condition

$$\beta_0=0 \quad \text{and} \quad a_c<a. \tag{13}$$

With these relations the inequalities are satisfied for $s^{1/2}<(a-a_c)/b$; for larger values of s, higher-order terms must come into play.

It is reasonable to assume that the branch-point trajectory $\alpha_c(s)$ has non-negative slope, i.e., $a_c\geq 0$. Then we find from our conditions that we must at least have $a>0$, which implies already $\text{Re}\alpha(s)\neq\text{const}$ for $s<0$. Of course, there may be higher powers of s in place of the linear terms in Eq. (12), but this would not improve the situation.

We conclude that models with real infinite cuts in the s plane of $\alpha(s)$ and in the λ plane of $F(s,\lambda)$ require trajectories which are nonlinear in $s^{1/2}$. For example, in the neighborhood of the branch point at $s=0$, we may have the expression

$$\alpha_{1,2}(s)=\alpha_0+as\pm bs^{3/2}+\cdots, \tag{14}$$

with $a>0$ and $b>0$. For $s>0$, both branches of the pole surface must remain to the right of the branch point in the λ plane.

The situation becomes different if we have a finite real cut in the λ plane which contracts to a point and extends itself again as s passes through the point $s=0$ where the pole trajectories cross. We do not want to pursue here these and other more complicated possibilities.

III. DISCUSSION

The three types of pole-cut relationships we have discussed are rather simple cases. In general, there are many other possibilities—in particular, if we have moving branch points in the λ plane. Generally, we find that there is no particular connection between the position of the coincidence point of the two pole trajectories in the λ plane [i.e., the point $\lambda=\alpha_1(s_0)=\alpha_2(s_0)$] and the branch point $\alpha_c(s_0)$. It is usually sufficient that the point $\alpha(s_0)$ lies somewhere on the cut in the λ plane, as is the case with our relationships A and B. Only in the example C, where we require real s cuts and real λ cuts, is there a coincidence of $\alpha(s_0)$ and $\alpha_c(s_0)$. Because of the reality conditions, this happens to be the only point where pole and branch-point trajectories can touch. However, even in these models, the existence of a left-hand branch point in the pole trajectory $\alpha(s)$ is only due to the crossover of two pole trajectories. It has, *a priori*, nothing to do with the branch cut in the λ plane, although, in special models, poles and cuts may be intimately connected and interdependent, mainly because the cut is introduced in order to remove one branch of the pole trajectory from the physical sheet of the λ plane.

As we pointed out before,[1] a direct compensation of a branch cut in a single pole trajectory and a branch-point trajectory is generally not possible. It should be noted, in this connection, that the corresponding situation for Regge pole residua is quite different. There can easily be a compensation of s branch cuts between a pole residuum and a branch-cut discontinuity. For example, we may consider the continued partial-wave amplitude

$$F(s,\lambda)\sim\frac{A+[\lambda-\alpha_c(s)]^{1/2}}{\lambda-\alpha(s)}=\frac{A+[\alpha(s)-\alpha_c(s)]^{1/2}}{\lambda-\alpha(s)}+\frac{1}{i\pi}\int_{-\infty}^{\alpha_c(s)}d\lambda'\frac{[\lambda'-\alpha_c(s)]^{1/2}}{\lambda'-\alpha(s)}\frac{1}{\lambda'-\lambda}+\cdots,$$

where the cut due to $[\alpha(s)-\alpha_c(s)]^{1/2}$ is canceled between the pole and the cut term. There are many further examples of this phenomenon in the literature.[1,5,7,15]

As far as the character of the branch points in the

[15] R. Carlitz and M. Kislinger, Phys. Rev. Letters **24**, 186 (1970). Note, however, that in the case of channels like $\pi N\to\pi N$, the continued partial-wave amplitudes do have a branch point at $s=W^2=0$.

λ plane is concerned, we can assume quite generally that they are of the square-root type. Barring branch points with s-dependent character, i.e., terms of the form $[\lambda-\alpha_c(s)]^{\beta(s)}$, we know that those moving branch points which are associated with nonsense, wrong-signature points (Amati-Fubini-Stanghellini–Mandelstam cuts)[16] must be of this type.[17] There are also indications that fixed cuts should be of square-root character.[3] Certainly, for moving as well as fixed branch points, we cannot have straight logarithmic terms of the form $\ln[\lambda-\alpha_c(s)]$ in the expansion of F around $\lambda=\alpha_c$, because then the amplitude would not be bounded for $\lambda\rightarrow\alpha_c(s)$, and in most cases this is inconsistent with the continued unitarity condition.[3,18]

If we had an explicit theory, the actual pole-cut relationship could, of course, be uniquely determined. In the relativistic dispersion scheme, we can only ask which models are possible in view of the known constraints. Perhaps a generalized, quasiphysical description of these relationships in terms of the balance between centrifugal forces and interparticle forces can be helpful. The author hopes to come back to this question elsewhere.

There are also bootstrap schemes and other iteration procedures which can be used for the construction of models with pole-cut relationships.[7]

We have considered, in this paper, the general features of typical pole-cut relationships in the complex λ plane, and we have described possible shapes of the resulting physical Regge trajectories. The actual high-energy properties resulting from these models depend, to some extent, upon the specific *Ansätze* made for $F(s,\lambda)$, and we refer to Refs. 5 and 7 for special examples. Although phenomenological work could be very helpful in restricting the number of possible models, it is apparent that some further theoretical guidance would be desirable.

[16] D. Amati, S. Fubini, and A. Stanghellini, Nuovo Cimento **26**, 896 (1962); S. Mandelstam, *ibid.* **30**, 1127 (1963).
[17] R. Oehme, Phys. Rev. Letters **18**, 1272 (1967).
[18] R. Oehme, Phys. Rev. Letters **9**, 358 (1962).

PHYSICAL REVIEW D VOLUME 2, NUMBER 4 15 AUGUST 1970

Validity of the Relativistic Eikonal Approximation*

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The relativistic eikonal formula for high-energy scattering, discussed recently by a number of authors, rests on a certain technical approximation concerning the high-energy behavior of sums of generalized ladder graphs. This approximation is shown to be justified, in the sense that it preserves the leading energy behavior in the sum over all generalized ladder graphs of a given order.

THE eikonal approximation in nonrelativistic quantum mechanics has long been known to provide a useful description of the scattering of fast particles by smooth potentials.[1] An analogous approximation for the discussion of high-energy scattering in relativistic quantum field theory has more recently been developed by a number of authors.[2] In the context, say, of a Yukawa-like coupling of scalar "nucleons" to scalar "mesons," the relativistic eikonal approximation for nucleon-nucleon scattering consists in the first instance in the selection of a unique subset of Feynman diagrams; namely, generalized ladder graphs with mesons exchanged in every possible way, all vertex corrections, self-energy insertions, and closed nucleon loops being excluded. To order g^{2n} in the coupling constant, this subset is composed of $n!$ distinct graphs. For the selected graphs the additional key approximation involves the systematic dropping of terms quadratic in the meson four-momenta where these appear in the propagators of the nucleons. This allows the use of a remarkable identity that makes it possible to sum up in compact form all $n!$ contributions to the amplitude in order g^{2n}; and one finds for the eikonal approximation to the amplitude in this order[3]

$$M_n^{\mathrm{eik}}(s,t)=ig^2\int d^4x\frac{e^{-i\Delta\cdot x}\Delta_F(x)[i\chi(x,s)]^{n-1}}{n!},\quad(1)$$

* Supported by the U. S. Air Force Office of Research, Air Research and Development Command, under Contract No. AF 49(638)-1545.
[1] See, e.g., M. L. Goldberger and K. M. Watson, *Collision Theory* (Wiley, New York, 1964), pp. 330–339; for a more recent development, see R. Sugar and R. Blankenbecler, Phys. Rev. **183**, 1387 (1969).
[2] The relativistic eikonal formula was obtained by H. D. I. Abarbanel and C. Itzykson, Phys. Rev. Letters **23**, 53 (1969), by functional derivative techniques; essentially the same result was independently derived by M. Lévy and J. Sucher, Phys. Rev. **186**, 1656 (1969), by Feynman-graph methods. Feynman graphs up to sixth order have been discussed by R. Torgerson, *ibid.* **143**, 1194 (1966). Related techniques for exhibiting the high-energy behavior of certain graphs were used by S. J. Chang and S. Ma, Phys. Rev. Letters **22**, 1334 (1969); see also H. Cheng and T. T. Wu, Phys. Rev. **180**, 1852 (1969); **180**, 1868 (1969); **180**, 1873 (1969); **180**, 1899 (1969). For a connection with the droplet model of T. T. Chou and C. N. Yang [*ibid.* **175**, 1832 (1968)], see B. W. Lee, Phys. Rev. D **1**, 2361 (1970).
[3] This is Eq. (3.20) of the paper by M. Lévy and J. Sucher (Ref. 2).