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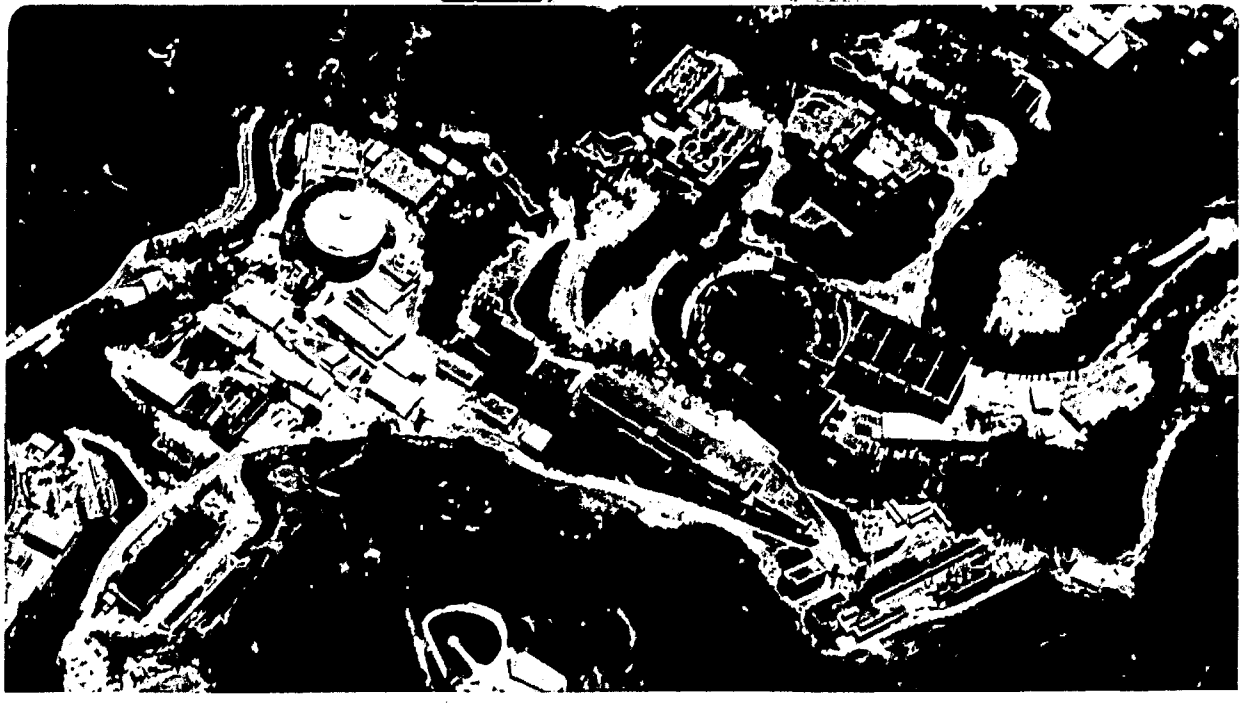
G.F. Chew

July 1985



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PARTICLES AS S–MATRIX POLES; HADRON DEMOCRACY *

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ABSTRACT

A review is given of the 1950's recognition of hadron democracy — an idea emerging from the analytic S matrix.

*Talk delivered at the Fermilab International Symposium on *Particle Physics in the 1950's*, May 1-4, 1985

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The idea of hadron democracy —that all hadrons are "composites" and none fundamental— is not the same as the idea that all physically-observable particles correspond to singularities of an analytic scattering matrix. Nevertheless the history of these two ideas, which both belong to the decade under study at this symposium, is intertwined. I shall in this paper give a personal recollection of the connection.

I am indebted to Jim Cushing for allowing me a look at a preliminary stage of his case study of the S-matrix program. I am forbidden from quoting Jim and take full responsibility for what I shall say here, but his efforts have been helpful in compensating my poor memory.

Let me begin by recalling that, when Murph Goldberger and I worked closely together from 1946 to 48 as students of Enrico Fermi at the University of Chicago, we learned —as did other students of that epoch— that there were a few elementary particles out of which everything was built. Among these were neutrons and protons —the building blocks of nuclei. No one then doubted the elementarity of nucleons and, to me at least, Fermi never expressed a doubt; but by the end of the fifties there was a growing belief that no hadron deserved to be called elementary. Distinction between protons and deuterons had become blurred. I propose here to recall how evolving understanding of the S-matrix contributed to that blurring.

All ingredients for the new S-matrix understanding had been in existence during the forties. As we heard yesterday from Rechenberg [(1)], Heisenberg in the early forties had defined the S-matrix and recognized unitarity and Poincare invariance as key general properties. Kramers had suggested the importance of analyticity and Kronig had connected analyticity with causality. The idea that the S-matrix might be a framework for a complete theory —replacing field theory and circumventing the divergences therein— had been stated by Heisenberg. But where was the S-matrix counterpart of "force" between particles? Yukawa in the mid-thirties had proposed a meson field basis for the force between nucleons. How could the S-matrix, which dealt with asymptotic states where particles are outside regions of interaction, incorporate the equivalent of a Yukawa force? A similar question could be asked about electromagnetic forces.

A decisive S-matrix step of the fifties, mostly occurring after Fermi's death, connected "force" with the singularities of an analytic S-matrix through recognition of the so-called "crossing principle" —that when a particle energy, on which an analytic S-matrix element depends, is continued from positive to negative values an outgoing particle changes into an ingoing antiparticle. This idea was one aspect

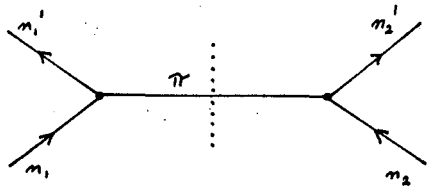

Figure 1:

of the more general principle, recognized by the end of the fifties but not at the beginning, that graphs of the type invented by Feynman for perturbative evaluation of a Lagrangian field theory, are relevant to the analytic S-matrix, independently of any approximation based on a small coupling constant. These graphs describe S-matrix *singularities*, in a manner compatible with crossing (tree graphs correspond to poles and loops to branch points).

Landau seems to have been the first, in his 1959 paper [2], to formalize the connection between Feynman-like graphs and S-matrix singularities, but Landau did not claim to discover the idea —which emerged from the area of theoretical activity that has been called "dispersion relations" and which was reviewed yesterday by Treiman [3] and Pickering [4]. Before attempting to identify historical ingredients in the discovery of graph rules for S-matrix singularities, I show in Fig. 1 the Landau-graph representation of the Yukawa force. Lines in the graph correspond to physical hadrons; there is no renormalization to be considered. This graph denotes the position and residue of a pion pole in a nucleon-nucleon scattering amplitude. The subgraph of Fig. 2 depicts one factor building the pole residue; this factor was called the pion-nucleon coupling constant. During the fifties it gradually dawned on the collective consciousness of a subset of particle theorists that physical consequences from a meson-exchange force such as had been proposed by Yukawa follow if the pole of Figure 1 is present in the nucleon-nucleon scattering amplitude. It furthermore became understood that such a pole *must* be present if the S-matrix is simultaneously to be analytic, unitary and Poincaré invariant.

An experimentally-persuasive part of the story was that the pion-nucleon coupling constant, defined as a factor in a pole residue, could be measured in a variety of different reactions. There was not only nucleon-nucleon scattering (Fig. 1) but

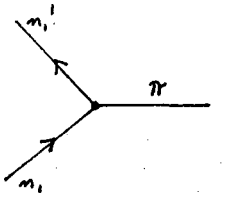

Figure 2:

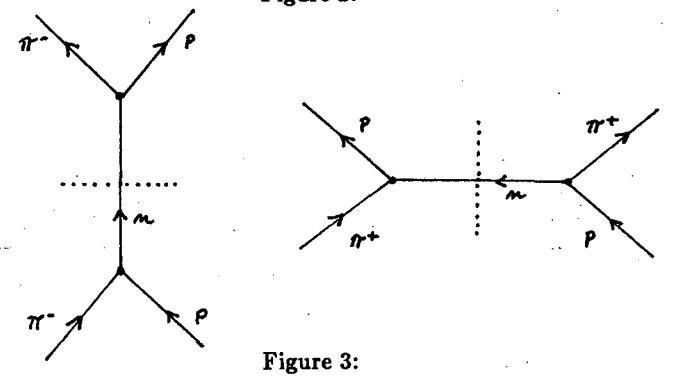

Figure 3:

pion-nucleon scattering (Fig. 3) and photo-pion production (Fig. 4). The latter two processes have been extensively referred to in this symposium. The poles shown here lie close enough to experimentally-accessible regions that careful measurements allowed their residues to be determined. (Sufficiently close to an isolated pole of an analytic function, the pole residue determines the value of the function.) As mea-

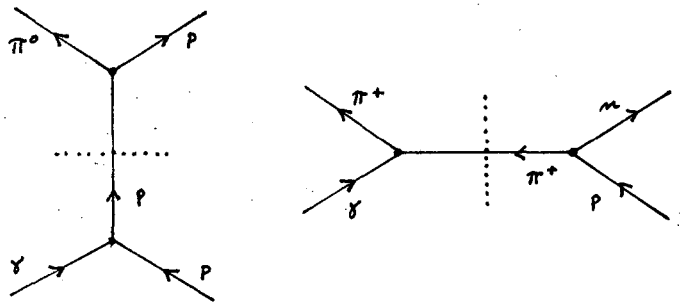

Figure 4:

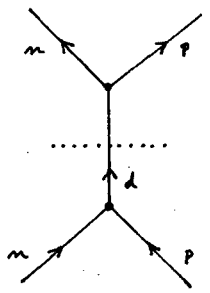

Figure 5:

surements gradually become more and more accurate, the pion-nucleon coupling constant determined by very different experiments converged to a single value. The correctness of the graphical pole-particle correspondence, never "proved" during the fifties from any accepted set of general principles, slowly became compelling. Little by little the idea took hold in some fraction of the particle-physics community that analyticity, together with unitarity and Poincaré invariance, determine the forces acting between particles, once particle quantum numbers have been specified. Incompleteness of proofs based on field theory became uninteresting. (During the sixties an independent axiomatic analytic S-matrix framework was developed, taking off from Landau's 1959 paper [2]).

Heisenberg and other S-matrix enthusiasts of the forties failed to recognize the generality of the pole-particle correspondence. Although they recognized the deuteron as a pole within the neutron-proton scattering amplitude (Fig. 5), they did not appreciate the pion pole of Fig. 1 or the notion that there would be amplitudes in which neutrons and protons themselves appear as poles, e.g., (Figs. 3 and 4). And curiously, although the 1953 dispersion relations formulated by Gell-Mann, Goldberger and Thirring explicitly manifested particle poles, no emphasis at first was given to this feature. It would take several years before pole consciousness would develop.

Before awareness of general graphical rules for S-matrix singularities, Gell-Mann was stressing the dynamical content of dispersion relations. Gell-Mann, Goldberger, Thirring and their followers in the fifties did not speak of an analytic S-matrix but of "dispersion relations". Not until the end of the decade was the connection between these two notions appreciated: Dispersion relations are Cauchy-Riemann formulas expressing an analytic S-matrix element in terms of its singularities. Amazingly,

the S-matrix thinking of the forties had no impact on the dispersion-relations developments of the fifties. "Crossing" was overlooked in the forties; when appreciated in the early fifties the term "S-matrix" was not in vogue. Until 1960 no connection was made between dispersion relations and Heisenberg's work.

The term "crossing" was used first by Gell-Mann and Goldberger [6] in 1954 in connection with dispersion relations, and at the 1956 Rochester conference Gell-Mann [7] stressed the power of this and other general principles, reviving (without awareness of his predecessor) the Heisenberg idea that the S-matrix might replace field theory. Francis Low and I at that point had been working at the University of Illinois on a semirelativistic "static model" of the pion-nucleon interaction where the notion of "force" was explicit in the traditional sense of a Lagrangian theory [8]. We had found a formulation of the model which, by employing analytic functions, allowed more direct contact with experimental data that was usual for field theories of strong interactions. The poles of our analytic functions were the key to such contact; we had associated our pole residue with "force strength" and pole position with particle mass (in this case pion mass). We did not know how to make our model fully relativistic, but were struck by the fact that Goldberger's completely-relativistic dispersion relation for pion-nucleon scattering [9] involved an analytic function whose properties looked similar to those of the function in our model. I had earlier worked closely with Goldberger both at Chicago and in Berkeley before meeting Low, and Goldberger was again close by —at the University of Chicago. It was natural for the three of us to join forces in connecting dispersion relations with the static model, and Goldberger involved Nambu (also at Chicago) in this project. That 1956 collaboration, which led to two papers referred to as CGLN [10] in my recollection yielded the first clear statement that "force" —in the sense of Yukawa— resides in the singularities of an analytic S-matrix. From that point on I never believed the description of interhadronic forces to need a Lagrangian. Mandelstam's paper of 1958 gave powerful reinforcement to this belief [11]. Although I failed to recognize until 1960 that the CGLN papers and that of Mandelstam were dealing with the concept identified by Heisenberg in the early forties, my thinking for two decades starting in 1956 became based on the analytic S-matrix.

Curiously, even people who believed in dispersion relations during the mid-fifties did not with heart and soul always accept the amazing connection of Feynman-like graphs with S-matrix singularities. In 1958 I wrote a paper *conjecturing* that the nucleon-nucleon scattering pole of Fig. 1 could be verified by extrapolation of scattering data [12], but I remember finding it difficult to believe that such would

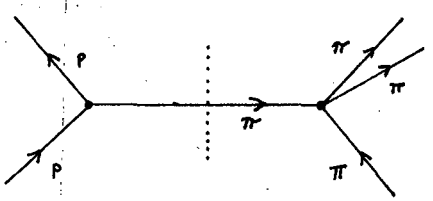

Figure 6:

actually work. (It did.) Slightly later Francis Low and I made a corresponding conjecture about the pole of Fig. 6 [13]. The fact that Francis expected this latter conjecture to be verified was comforting to me; I had enormous respect for Francis' judgement.

In connection with S-matrix poles I recall a remark by Landau made privately to me during the 1959 Kiev Conference. Landau had been scolding me for wasting time on approximate dynamical models and stated that recognition of the pole-particle correspondence was a momentous achievement that should not be blurred by unreliable model calculations. Landau seemed to be giving somebody in the U.S. credit for discovering the general pole-particle correspondence, but it has never been clear me that any individual deserves credit. Maybe somebody at this meeting will stand up and assign priority. Certainly Breit and Wigner have some claim although they did not know about graphs or crossing when they proposed their celebrated 1936 formula [14].

The S-matrix models that I and others spent so much time on in the fifties never (as Landau foretold) achieved a reliable status, but they contributed to a changing attitude about the nature of neutrons, protons and pions. It was found that when other neighboring meson singularities were added to the pion pole of a nucleon-nucleon scattering amplitude, the combined neutron-proton "force" was approximately that needed to bind the deuteron. Earlier Low and I had found that the "force" of Fig 3(b) could generate the Δ resonance as a pion-nucleon bound state [8]. Then in 1959 just before the Kiev Conference, Mandelstam and I encountered a mind-boggling phenomenon[15]. We found that a spin-1 $\pi\pi$ resonance could be generated by a force due to Yukawa-like "exchange" of this same resonance. Later such a resonance was named the ρ meson, and although we did not use the name

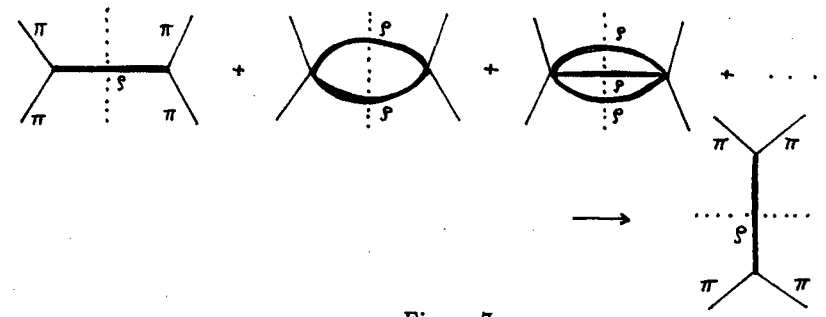

Figure 7:

ρ in 1959, Fig. 7 sketches how the (dispersion relation) summation over an infinite sequence of ρ discontinuities in a $\pi\pi$ elastic amplitude can generate a ρ pole. We here were using a boundary condition that later was associated with the name of Regge. The phenomenon represented in Fig. 7 is analogous to that of generating a bound state through a Schrodinger equation with an attractive potential. (The idea that summing over an infinite sequence of discontinuities in one variable can generate a pole in another variable came in the sixties to be called "duality"). Any particle corresponding to such a pole could be regarded a "bound state" of other particles.

The mechanism typified by Fig. 7 was called "bootstrap" [16] because ρ as a "force" generates ρ as a particle. It did not take long to ask, "Cannot *any* hadron be so regarded as a bound state of other hadrons — due to (Yukawa-like) hadron-exchange forces?" The pole-particle correspondence, following from general S-matrix principles, makes no distinction between elementary and composite particles. The question was, "are observed hadron masses, spins, coupling constants compatible with bound-state status?" Model-based estimates yielded an affirmative answer for all the known hadrons, including neutrons and protons. No methods ever were developed for summing all important S-matrix discontinuities, but S-matrix theorists of the early sixties saw the neutron and proton as bound states in a sense qualitatively similar to that of the deuteron. The puzzle to be resolved was no longer one of elementary hadrons but of the internal quantum numbers carried by hadrons.

Three related but different statements about hadrons were heard at the end of the fifties:

1. There is hadron democracy—all hadrons having an essentially equivalent status.
2. Hadrons are bound states of other hadrons sustained by hadron- exchange forces.
3. Hadrons are self generated by an S-matrix bootstrap mechanism which determines all their properties.

To the present time none of these statements has achieved precise meaning but none has been shown false. The hope kindled in the fifties, that general principles, such as S-matrix unitarity, allow no arbitrariness in particle properties remains very much alive today.

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