QUARK MODELS AND QUARK PHENOMENOLOGY
Invited Talk at Third Symposium on the History of Particle Physics

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September 18, 1992

ABSTRACT

Overwhelming experimental evidence for quarks as real physical constituents of hadrons along with the QCD analogs of the Balmer Formula, Bohr Atom and Schroedinger Equation already existed in 1966. A model of colored quarks interacting with a one-gluon-exchange potential explained the systematics of the meson and baryon spectrum and gave a hadron mass formula in surprising agreement with experiment. The simple quark model dismissed as heresy and witchcraft by the establishment predicted quantum numbers of an enormous number of hadronic states as well as relations between masses, reaction cross sections and electromagnetic properties, all unexplained by other approaches. Further developments leading to QCD included confinement in the large N_c limit, duality, dual resonance and string models, high energy scattering systematics, unified treatment of mesons and baryons, no exotics and no free quarks.

I. PROLOGUE - HOW TO THINK ABOUT QUARKS

1.1 Dedication - Implications of BCS for Quarks

I begin with a tribute to a great physicist who taught me how to think about quarks and physics in general, John Bardeen. A few sentences from John could often teach you more and give more deep insight than ten hours of lectures from almost anyone else. In 1966 when I began to take quarks seriously I was unknowingly thinking about them in the language I had learned from John during two years at the University of Illinois, as quasiparticle degrees of freedom describing the low-lying elementary excitations of hadronic matter. Unfortunately I did not realize how much my own thinking had been influenced by John Bardeen until he was gone. I dedicate this paper to his memory.

Were quarks real? Quarks as real as Cooper pairs would be enough. Quarks leading to anything remotely approaching the exciting physics of BCS would be more than enough. John always emphasized that Cooper pairs were not bosons, and that superconductivity was not Bose condensation. The physics was all in the difference between Cooper pairs and bosons. I was not disturbed when quarks did not behave according to the establishment criteria for particles. The physics might all be in the difference between quarks and normal particles. One had to explore the physics and see where the quark model led.

The arguments of the BCS critics that the theory was not gauge invariant did not disturb John; he knew where the right physics was. Similarly the arguments criticizing quarks as non-relativistic did not disturb me. The model had the right physics. It already in 1966 described so much experimental data not understood by any other model that it had to have the right physics. The formalism would come later and the basis of QCD was already published in 1966[1]. A model of colored quarks interacting with colored gauge bosons in the manner described by a non-Abelian gauge theory had so much of the right physics[2] that it had to lead somewhere. But there are none so blind as those who don't want to see.

1.2 A Historical Perspective

The history of this period can be characterized by repetition at successive levels of the conflict between "Grand Unification" and "Compositeness" approaches to the structure of matter. Each stage began with the belief that the fundamental constituents of matter or "elements" were known. The experimental discoveries of too many elements led on the one hand to attempts to unify the elements while still considering them as elementary, and on the other to build them out of a smaller number of fundamental building blocks. In 1950 the nucleon and pion were considered the fundamental constituents of hadronic matter. Evidence for composite structure was resisted by the establishment who sought to unify the large number of new "elementary" particles with concepts like nuclear democracy or higher symmetry, in which all particles were equally elementary. Today we have come full circle back to square one at a deeper level. All matter is constructed from quarks and leptons. The explanations of the large number of elementary objects using grand unification or compositeness have moved from the nucleon-pion level to the quark-lepton level.

The quark model developed very differently in the Eastern and Western Hemispheres. In the East the model was taken seriously from the beginning and supported by top establishment figures like Bogoliubov, Sakharov, Zeldovich, Gribov, Thirring, Morpurgo and Dalitz. The Western approach was stated explicitly by M. L. Goldberger in introducing a colloquium speaker at Princeton in 1967. "A boy was standing on a street corner snapping his fingers and claiming that it kept the elephants away. When told that there had been no elephants around for many years, his response was 'You see! It works!'. And now our speaker will talk about the quark model."

The approach of Galileo of studying nature by experiments led Eastern physics to the conclusion "The quark model works, and we do not understand it. Therefore it is interesting." Western theorists who seemed to have forgotten Galileo concluded "The quark model works, but it contradicts the established dogma. Therefore it is heresy and witchcraft."

A true perspective requires distinguishing between dogma, phenomenology that contradicts established dogma but works, and phenomenology which contradicts established dogma but does not really work and is nonsense. The quark model really worked and pointed the way toward future new ideas and a new and better understanding of the structure of matter. Two interesting examples in today's physics are high T_c superconductivity and cold fusion. Both surprised everybody when they were first announced. But high T_c really works and demands further investigation for a better understanding. Cold fusion is nonsense and does not work.

Israeli particle physics was at the crossroads between East and West with roots in Moscow Leningrad and London. In 1967-68 when Goldberger referred to the quark model as witchcraft, a group of young junior faculty and postdocs named Rubinstein, Veneziano, Virasoro, Horn, Harari and Rosner who had come to Israel after spending time in the West were putting the new quark model ideas together with accepted S-matrix Reggeism. Thus began a new era in particle physics then called duality which laid the foundations for what is now called string theory [3].

1.3 Weak and Strong SU(3) - Constituent and Current Quarks

Murray Gell-Mann pinpointed an important ingredient in understanding quarks: the difference between "weak" and "strong" SU(3) flavor algebras which led to constituent and current quarks. Two independent breakthroughs were based on quark-like degrees of freedom. That QCD had the right physics to describe strong interaction dynamics was already clear in 1966, with constituent quarks interpreted as quasiparticle degrees of freedom describing elementary excitations. But current quarks then only provided a mathematical basis for current algebra and were not seen as real physical point-like objects until the quark-parton description of SLAC experiments. The relation between constituent and current quarks is expected to come somehow out of QCD, but may well be as difficult as getting BCS out of the Lagrangian of QED.

II. SOME PREHISTORY

2.1 Flavor Symmetry and Composite Models

An early composite model of hadrons was the Fermi-Yang model of a pion as a bound nucleon-antinucleon pair. Its generalization by Sakata to include strange particles and a flavor symmetry generalized from isospin SU(2) to SU(3) was soon seen to be in conflict with experiment[4].

The "Eightfold Way" of Gell-Mann and Ne'eman introduced an SU(3) flavor symmetry and a hadron classification from two different points of view. Gell-Mann's "weak SU(3)" began with the properties of the electroweak currents; Ne'eman's "strong SU(3)" with a gauge theory of strong interactions. Both used octet classifications for baryons and mesons with no theoretical explanation for the octet baryon classification nor any physical interpretation for the fundamental triplet. Goldberg and Ne'eman [5] extended SU(3) to U(3) and included baryon number in a formulation constructing the baryon octet from three fundamental triplets carrying baryon number 1/3. Ne'eman also suggested that SU(3) was an exact symmetry of strong interactions broken by an additional "fifth interaction"[6]. But the fundamental triplets of U(3) were presented only as an algebraic device and not as physical particles.

The "weak" and "strong" approaches to flavor symmetry are parts of two very different lines of development of electroweak and strong interaction physics over the past forty years. Electroweak physics is characterized by the "standard model syndrome", with most experiments either testing a standard model or looking for new physics beyond it. In 1945 the standard model for electroweak physics was the Quantum Electrodynamics in Heitler's book and the Fermi theory of beta decay. Crises when the standard model appeared to be wrong were resolved by either revealing wrong experiments or finding new concepts like parity nonconservation easily fit into the existing framework. The first indications of "physics beyond this standard model" arose in infinities in QED calculations and the Lamb shift experiment and in disagreements between measured beta ray spectra and Fermi theory. The QED difficulties were solved by the new formulation of Feynman, Schwinger and Tomonaga. The difficulties with beta ray spectra went away after better experiments confirmed the Fermi theory. The development through various similar crises to modern electroweak theory was straightforward.

Hadron physics developed very differently with no sensible "standard model" until QCD. Today's picture of QCD proton structure bears no resemblance to accepted models of the 1940's, 50's and 60's. The particle theory establishment clung to old dogma and refused to accept new ideas until forced by experimental data. Concepts now generally accepted like spontaneously broken symmetries, chiral symmetry, the unitary symmetry now called flavor-SU(3), quarks, and the the color degree of freedom were ridiculed by the reactionary establishment as they were dragged kicking and screaming along the path that eventually led to QCD.

At the 1960 Rochester Conference I mentioned to Nambu that I had heard from John Bardeen in Urbana about his very interesting application of ideas from superconductivity to particle physics. Nambu said I was the only person at the conference who had expressed any interest in this work. At the 1962 Rochester conference in Geneva, the prediction that a particle later called the Ω^- should exist, already proposed in a paper by Glashow and Sakurai, was not considered important enough to be mentioned in any invited or contributed talk. It was mentioned in a comment from the floor by Gell-Mann. The paper proposing the existence of quarks was accepted by Physics Letters only because it had Gell-Mann's name on it. The editor said "The paper looks crazy, but if I accept it and it is nonsense, everyone will blame Gell-Mann and not Physics letters. If I reject it and it turns out to be right, I will be ridiculed."

Today we accept Ne'eman's proposal of a non-Abelian gauge theory with exact flavor symmetry for strong interactions and flavor symmetry breaking by a completely different interaction. But the basic degrees of freedom are completely different. The fundamental fermions and gauge bosons are not Ne'eman's baryon and vector meson octets but colored quarks and gluons, with more than three flavors and an additional color degree of freedom.

2.2 $\bar{p}p$ Annihilation - First Evidence for Quarks

Annihilation experiments[7] performed shortly after the antiproton discovery gave results disagreeing with conventional model predictions. A pion multiplicity of 5.3 ± 0.4 was found, much greater than the 2 or 3 predicted by statistical models, while $e^+ - e^-$ pairs were not seen at the level predicted by QED from one-photon annihilation of a pointlike $\bar{p}p$ pair. Pions as quanta of a boson field could be created only after the annihilation of the positive and negative baryon number present in the initial state. No one considered the simple but unacceptably heretical explanation that both mesons and baryons were composite objects made of the same constituents which carried baryon number, rather than being elementary and completely different like photons and electrons, that no annihilation of baryon number was needed and that constituents with opposite baryon number simply rearranged to form "positronium-like" states with a multiplicity related to the number of constituents originally present. Shortly after the quark proposal, such a model showed that a rearrangement of the three quarks and three antiquarks in the proton and antiproton into three mesons[8] gave the observed pion multiplicity. A simple "back-of-the-envelope" calculation for pions produced from three s-wave $q\bar{q}$ pairs with the standard 3:1 statistical factor favoring the spin-triplet ρ which decays into two pions gives $3{\cdot}(3/4){\cdot}2+3{\cdot}(1/4) = (21/4) = 5.25$.

This quark-rearrangement model was ridiculed as nonsense when proposed [8] in 1966. The establishment prejudice against quarks even created serious difficulties for obtaining appointments and promotions for young people in our group. Deans and committees were influenced by pejorative comments in letters from well-known physicists about people who rush into print with such garbage.

2.3 Group Theory
From Physics Without Groups to Groups Without Physics

Until the discovery of the Ω^- the particle physicists believed that group theory was useless for high energy physics, thought of isospin as rotations in some three-dimensional space and knew nothing about unitary groups. They therefore tried rotations in 4, 5, 6, 7 and 8 dimensions with fancy names like global symmetry, cosmic symmetry, etc. before finding that the natural symmetry group to include the $SU(2) \times U(1)$ of isospin and strangeness was $SU(3)$. Perhaps they called it the "Eightfold Way" because it took them eight years (1953-61) to find it.

Soon afterwards the pendulum swung and a flood of papers tried to include flavor SU(3) and space-time in a larger group and produced a number of fancy no-go theorems. I noted immediately[9] that the physics underlying these fancy groups was completely crazy. No sensible interaction could be invariant under transformations generated by operators acting nontrivially both in space-time and in an internal symmetry space. Translation invariance implies that a pion-nucleon scattering experiment at SLAC gives the same results when moved to Fermilab. Isospin invariance implies $\sigma(\pi^- p) = \sigma(\pi^+ n)$. But invariance under transformations acting in space-time like a translation and also transforming nontrivially under isospin can move a pion beam from a SLAC experiment to Fermilab, while leaving the nucleon target at SLAC. Any dynamics invariant under such transformations must obviously have no interactions, no bound states and a continuous mass spectrum. However, no one paid attention to this kind of "low-brow phenomenology" and fancy theorems were published showing that nonsense is nonsense.

III. STATIC HADRON PROPERTIES IN THE QUARK MODEL

The significance of quark model predictions has been confused by model builders who produce an apparently large number of predictions from a specific model without noting that only two or three depend on the model and the rest all follow from model-independent symmetries like angular momentum, isospin and SU(3). They get excellent but meaningless χ^2 fits to data. We avoid the pitfall by considering only those quark model predictions not easily obtained in other ways, and in particular relations between mesons and baryons and the determination of the values of parameters which are left free in SU(3).

3.1 The Very Early Successes

The difference between the quark structures of the meson and baryon octets immediately explained striking regularities in the low-lying hadron spectrum not explained by SU(3); e.g. the baryon octets and decuplets and meson nonets without the ninth baryon suggested by some SU(3) models and no meson decuplets and the spin-parity quantum numbers $J^P = 0^-,\ 1^-, 1/2^+,\ 3/2^+$. Introducing U(3) rather than SU(3) and breaking SU(3) at the quark level by setting $m_s > m_u$ immediately gave the experimentally observed mass inequalities

$$M_\Xi > M_\Sigma \approx M_\Lambda > M_N; \qquad M_\eta > M_{K^+} \approx M_{K^-} > M_\pi \tag{3.1a}$$

instead of the bad baryon mass inequality following from using the same structure for baryon and meson octets.

$$M_\Lambda > M_N \approx M_\Xi > M_\Sigma \tag{3.1b}$$

These regularities still did not influence the establishment to take quarks seriously. Many open questions remained; e.g. the reason for the decuplet classification for the spin-3/2 baryons, rather than octet or singlet, the reason for the $\Lambda - \Sigma$ mass difference and whether the next excited states were orbital excitations or states with additional $\bar{q}q$ pairs,

3.2 The Relevant Degrees of Freedom

Thirty years of experimental hadron spectroscopy have failed to produce any evidence for excitations of any of the additional degrees of freedom proposed for theoretical reasons; e.g. bags, strings, meson clouds, gluons, and a sea of $\bar{q}q$ pairs including strange quarks. All observed hadronic states are described as excitations of the spins and relative co-ordinates of the constituent quarks in the $\bar{q}q$ and $3q$ systems. There is no evidence for excitations describable as relative motion between the center-of-mass of the valence quarks and other constitutents like a bag, cloud or sea. Although the constitutent quark is not believed to be an elementary point-like object but rather a more complicated object with internal structure, there is so far no experimental evidence for low-lying excitations of this structure; i.e. no evidence for "excited constituent quarks." Many model builders have attempted to introduce such additional degrees of freedom, either to satisfy theoretical prejudices or to obtain a "better fit" than the simple constituent quark model to certain experimental data. Any advantages claimed by these models must be scrutinized carefully before acceptance and the absence of any observed low-lying excitations of such degrees of freedom must be explained.

3.3 SU(6) and the Symmetric Quark Model

The great breakthrough in baryon spectroscopy was the application of SU(6) symmetry [10] with the unreasonable assumption that spin 1/2 quarks obeyed Bose statistics. The contradiction was avoided by the introduction of parastatistics[11] or an additional internal degree of freedom [1, 12] later called color. Great progress was made in understanding the baryon spectrum without a fundamental understanding of statistics by the phenomenological "symmetric quark model"[11, 13] which classified the hadron spectrum according to the group $SU(6) \times O(3)$. It described all baryons as three quark states with wave functions satisfying Bose statistics and having orbital and radial excitations with quantum numbers qualitatively described by a harmonic oscillator shell model[11, 14, 15]. An enormous number of baryon resonances fit exactly into this simple potential model beginning with the SU(6) 56 classification of the lowest baryons into a spin 1/2 flavor octet and a spin 3/2 decuplet, the first excited configuration being a 70 of SU(6) with L=1 and the second being an L=2 56. But the overwhelming evidence repeatedly presented by Dalitz et al for this model was consistently[14] dismissed by the establishment.

The successful SU(6) prediction of -3/2 for the ratio of the proton and neutron magnetic moments was again striking evidence for compositeness, since only a composite model gave a simple ratio for *total* moments. In other approaches adding Dirac and anomalous moments was like adding apples and oranges. The anomalous moment was a function of the strong interaction coupling constant; the Dirac moment was not. Meson magnetic moments were not measured directly, but the radiative magnetic dipole transition $\omega \rightarrow \pi\gamma$ is described by the same quark magnetic operators appearing in the proton moment. The successful prediction relating this transition to the proton magnetic moment[16] again confirmed that mesons and baryons were made of the same quarks.

The scale of the nucleon magnetic moments caused confusion since quark magnetic moments were expected to have the scale of the quark mass rather than the hadron mass, while detailed relativistic calculations of hadron properties by the Soviet group [12] gave hadron moments at the right scale. This was resolved [17] by noting that the effective mass appearing in the magnetic moment of a bound Dirac particle depends upon the Lorentz structure of the potential and its scale is set by the particle energy, not its mass, for a world scalar potential. The relativistic calculations [12] effectively assumed a world scalar potential.

3.4 The Pre-History of QCD

Andrei Sakharov was a pioneer in hadron physics who took quarks seriously already in 1966. He asked "Why are the Λ and Σ masses different? They are made of the same quarks!"[18]. His answer that the difference arose from a flavor-dependent hyperfine interaction led to relations between meson and baryon masses in surprising agreement with experiment[2]. Sakharov and Zeldovich *anticipated* QCD by assuming a quark model for hadrons with a flavor dependent linear mass term and a two-body interaction whose flavor dependence was all in a hyperfine interaction

$$v_{ij} = v_{ij}^{o} + \vec{\sigma}_i \cdot \vec{\sigma}_j v_{ij}^{hyp} \qquad (WW3.2)$$

where v_{ij}^{o} is independent of spin and flavor, $\vec{\sigma}_i$ is a quark spin operator and v_{ij}^{hyp} is a hyperfine interaction with different strengths but the same flavor dependence for qq and $\bar{q}q$ interactions. They obtained two relations between meson and baryon masses in surprising agreement with experiment [2, 19],

The mass difference between s and u quarks calculated in two ways from the linear term in meson and baryon masses showed that it costs exactly the same energy to replace a nonstrange quark by a strange quark in mesons and baryons, when the contribution from the hyperfine interaction is removed.

$$(m_s - m_u)_{Bar} = M_\Lambda - M_N = 177\,\mathrm{MeV} \qquad (WW3.3a)$$

$$(m_s - m_u)_{Mes} = \frac{3(M_{K^*} - M_\rho) + M_K - M_\pi)}{4} = 180\,\mathrm{MeV} \qquad (WW3.3b)$$

where the subscripts u, d and s refer to quark flavors. The flavor dependence of the hyperfine splittings calculated in two ways from meson and baryon masses gave the result

$$1.53 = \frac{M_\Delta - M_N}{M_{\Sigma^*} - M_\Sigma} = \left(\frac{v_{ud}^{hyp}}{v_{us}^{hyp}}\right)_{Bar} = \left(\frac{v_{ud}^{hyp}}{v_{us}^{hyp}}\right)_{Mes} = \frac{M_\rho - M_\pi}{M_{K^*} - M_K} = 1.61 \qquad (WW3.4)$$

This striking evidence that mesons and baryons are made of the same quarks and described by a universal linear mass formula with spin corrections in remarkable agreement with experiment was overlooked for amusing reasons [20, 21] and rediscovered only in 1978 [22]. In that same year 1966 Nambu derived just such a universal linear mass formula for mesons and baryons from a model in which colored quarks were bound into color singlet hadrons by an interaction generated by coupling the quarks to a non-abelian SU(3) color gauge field, and spin effects were neglected [1].

The Nobel Prize for QCD might have been awarded to Sakharov, Zeldovich and Nambu. They had it all in 1966. The Balmer formula, the Bohr atom and the Schroedinger equation of Strong Interactions. All subsequent developments leading to QCD were just mathematics and public relations, with no new physics. But the particle physics establishment refused to recognize the beginnings of new physics and had to wait until new fancy names like chromodynamics, color, confinement, etc. were invented together with a massive public relations campaign. Then they claimed that they had discovered it all.

3.5 Color, Confinement and Large N

The color degree of freedom solved the quark-statistics problem for baryons and also provided answers to several puzzles previously unanswered. The observed hadron spectrum indicated that both qq and $\bar{q}q$ interactions were attractive in all possible states of spin and parity. An antiquark should be attracted by the three quarks in a baryon to make a $3q\bar{q}$ bound state. But there were no bound states with "exotic" quantum numbers that could not be made from the $q\bar{q}$ or $3q$ configurations. There was also the meson-baryon puzzle - why qq and $\bar{q}q$ systems are bound but different. No simple meson-exchange model gave these properties.

In 1967 I noted that quarks would be confined in the limit where the number of colors was large, now called the large N_c limit [23]. $\bar{q}q$ pairs were bound into mesons, the meson-meson interaction went to zero, the hadron spectrum was simply systems of non-interacting mesons and free quarks would not be observed. At that time any heretical paper of this type would never be accepted by a reputable refereed journal; I therefore put it into lecture notes. In 1972 I looked at saturation in toy models of nuclei and noted that a nucleon-nucleon isospin-exchange interaction produced by ρ exchange would bind only the deuteron and the isoscalar $N\bar{N}$ system, and that no higher mass bound states would exist. This led naturally to replacing isospin SU(2) by color SU(3) and a model with colored quarks interacting with a color-exchange potential to give the first explanation of the absence of exotics and the observed meson-baryon systematics[24] as well as the relation between qq and $\bar{q}q$ potentials later used in all potential models treating both mesons and baryons.

I was very excited to have found a simple explanation of so much hadron physics for which there was no other explanation, and wrote letters from Israel to several friends including Dick Feynman and Viki Weisskopf. Feynman never answered, but Viki wrote that it was all very interesting but theorists would not like it because it was not renormalizable. This did not bother me as it rather reminded me of the criticisms of BCS as not being gauge invariant. Thinking along the lines of BCS I was sure that I had found interesting physics and that the correct formalism would come later. In fact the discovery of asymptotic freedom came at the same time and it is interesting to compare the situation in the summers of 1972 and 1973. In his summary talk at the 1972 Rochester Conference at Fermilab, Gell-Mann noted that the color degree of freedom was established from electroweak data, that strong interactions were still unknown and would probably arise from exchanges of vector gluons. But there was no suggestion that color played any role in strong interactions. At the SLAC summer school in 1973 I was invited to talk about my work on "Quarks and colored glue" and Gross, Politzer and Wilczek were talking about the great breakthrough of asymptotic freedom.

Someone called my attention to Nambu's old paper [1], the details of which I had forgotten, which had worked out the SU(3) algebra of this interaction, but not investigated the spatial dependence or the implications for exotics. In contrast with the behavior of some of my peers, I immediately rewrote the paper giving Nambu full credit for the work I had independently rediscovered before submitting the paper for publication.

It is rather painful to note the disparaging and untrue criticism of my paper [25] : "Recently this point has been given publicity by Lipkin [24], who treats, however, a Han-Nambu picture ..... We have rejected such a picture." Murray Gell-Mann is a great physicist whose work and ideas have had a tremendous impact on the work and thinking of practically everyone attending this history conference including myself. But the general consensus of those active in the field in 1973 is that there was nothing new nor original in this paper[25]. My paper [24], treats only strong interactions, ignores electromagnetism and the possibility of integrally charged quarks and has nothing to do with Han-Nambu. This irrelevant red herring is discussed below. Their criticism[25] is irrelevant nonsense.

IV. QUARK MODEL PREDICTIONS FOR HADRON REACTIONS

Further evidence for a quark structure of hadrons was found in the additive quark model for hadron reactions, the so-called ideal mixing pattern of vector and tensor mesons, a mysterious topological quark diagram selection rule now called OZI[26, 27, 28] and peculiar systematics in the energy behavior of certain hadron total cross sections.

4.1 The Additive Quark Model, Duality and Dual Resonance Models

The simple additive quark model (AQM) of Levin and Frankfurt[29] explained the ratio of 3/2 between nucleon-nucleon and meson-nucleon scattering and again showed mesons and baryons to be made of the same quarks. Further refinements included flavor dependence of the scattering amplitudes at the quark level[30]. That the total cross sections in channels now called exotic do not have the sharply decreasing behavior found in other channels, was be described in the AQM by attributing all the energy decrease to $\bar{q}q$ annihilation amplitudes [31]. The AQM was combined with a Regge picture attributing this energy behavior to exchange degeneracy of Regge trajectories by using the AQM to relate the couplings of hadrons to exchange-degenerate Regge trajectories[32, 33]. The universality of additive quark couplings to mesons and baryons arose again and again in different contexts in these descriptions.

An S-matrix Regge approach beginning with finite-energy sum rules then led to duality with the same states appearing both as s-channel resonances and t-channel exchanges and then to dual resonance models beginning with the Veneziano model[3]. Although this was not directly related to the quark model, it soon appeared that introducing the quark-model constraints on Reggeon couplings provided a powerful input with predictive power. Thus for example the absence of exotics both as resonances and t-channel exchanges led to the OZI rule, while the exchange degeneracy and the dominance of the energy-dependent part of the cross section by $\bar{q}q$ annihilation led naturally to duality diagrams[34, 35, 33]. The energy independent part of the cross section, later found to be slowly rising, was seen to be related to diffraction, described by Pomeron exchange, with a coupling given by the Levin-Frankfurt quark-counting recipe.

4.2 Neutral Meson Mixing, OZI and the November Revolution

The first use of the additive quark model to obtain OZI relations for neutral mesons[36] was the selection rule forbidding reactions like

$$\sigma(\pi^- p \to N\phi) = 0 \qquad (YY4.1a)$$

and its SU(3) rotation predicting the equality

$$\sigma(K^- p \to \Lambda\omega) = \sigma(K^- p \to \Lambda\rho) \qquad (YY4.1b)$$

The ρ^o and ω mesons are produced in the reactions (YY4.1b) only via their $u\bar{u}$ component and thus are produced equally.

An outstanding failure of a quantitative prediction of an OZI-forbidden process was the experimental discovery of the J/ψ by pure accident while no theorist had predicted the narrow width nor directed experimenters to look for these enormous signals. The big charm-search review paper by Gaillard, Lee and Rosner [37] predicted the vector charmonium state, overestimated its width by a factor of 30, and did not point out the striking signal of a very narrow resonance. The very narrow width caused considerable confusion after the discovery of the J/ψ and was used as evidence against the charmonium interpretation. Feynman insisted that this "crazy Zweig rule" could not give such a large suppression, because it was violated by two-step strong interaction processes where each step was allowed and perturbation theory was certainly not valid. There must be some new symmetry principle with a new conserved quantum number.

This failure to understand the OZI rule led to overestimating the width by a factor of 30. The experimental $\phi \to \rho\pi$ width was used as input[37] and threshold effects were disregarded. But the $\phi \to \rho\pi$ decay is dominated by the two-step transition $\phi \to K\bar{K} \to \rho\pi$ for which the OZI-allowed $K\overline{K}$ channel is open. The use of the experimental $\phi \to \rho\pi$ width as input can give only an upper bound for the width of the J/ψ decay where no OZI-allowed channel is open and the $D\overline{D}$ channel analogous to $K\overline{K}$ in $\phi \to \rho\pi$ is closed. The distinction between open on-shell and closed off-shell intermediate states is now known to be significant because the physically observable transitions to open on-shell channels are related by unitarity to the OZI-forbidden processes [38] and because the amplitudes via on-shell intermediate states cannot be canceled by off-shell contributions. But there still is no real answer to Feynman's argument against the narrowness of the J/ψ. Hand-waving arguments suggest that second order processes are cancelled by contributions from different intermediate states. But there is still no rigorous QCD argument supported by calculations.

The GLR paper [37] contains a note attributed to me, suggesting $e^+ - e^-$ as the best place to look for charm, since the charge $+2/3$ gave a much larger relative cross section. The most striking signal would be a large increase in the number of strange particles, since charm would decay to strangeness. Half of the hadronic events above charm threshold would contain strange particles. My argument was correct but the signal was not seen. At the 1975 Lepton-Photon Conference Haim Harari resolved the paradox, by noting that the excess of strange particles was not observed because of the unexpected appearance near charm threshold of the tau lepton. The nonstrange hadrons from τ events compensated for the strangeness excess from charm. At that time the existence of the τ as well as the identification of the J/ψ as charmonium were still controversial.

V. ABSENCE OF FREE QUARKS AND FRACTIONAL CHARGES

Much of the resistance of the particle physics establishment to the quark model was based upon their fractional charge and upon the failure of experimenters to find free quarks. Both points are red herrings.

5.1 Why There Are No Free Quarks

Why should anyone expect to find free quarks? A so called "free electron" is a very complicated object containing a cloud of virtual photons and $e^+ - e^-$ pairs. The hydrogen atom is much more than a point electron and a point proton,. The other constituents are observed in Lamb shift and other experiments. Theorists describe this complicated structure only by using infinite renormalizing constants. Pulling the hydrogen atom apart into an electron and a proton, each containing its own infinite cloud of junk, was possible because the vacuum polarization between the electron and proton was small when they were separated. The energy required to excite and ionize the hydrogen atom was less than the rest mass of an electron-positron pair by a factor of order 10^5.

But suppose the excitation energy of the first excited state of the hydrogen atom was more than double the mass of positronium. The excited states would decay almost immediately by emitting positronia and isolated electrons would not have been discovered. Hitting the electron with a photon having enough energy to move it far away from the proton would polarize the vacuum and create a string of electron-positron pairs, which would quickly recombine into neutral positronia. Atomic collisions could well produce "electron jets" of neutral atoms and positronia and no free electrons). Free constituents would not be easily found for hadrons whose spectrum indicated a structure with the energy of the first excited state already greater than twice the pion mass. The energy required to move these constituents from their lowest orbit into the first excited orbit was already greater than double the rest mass of the lowest bound state. Thus pumping energy into the proton would simply create pions and other bound states. The forces and vacuum polarization created by trying to remove a quark from a proton were much too great to allow the quark to be removed like the electron from a hydrogen atom.

Already in the late 1960's the hadron spectrum suggested that hitting a quark produced a string of pairs, and that the excitation spectrum looked like the spectrum of a string [3]. One does not have to invent fancy names like confinement and chromodynamics to understand this simple physics. But the establishment refused to budge from its reactionary position. The party line that nothing was more elementary than neutrons and protons was sacrosanct and heretics were ridiculed.

5.2 Who Needs Integrally Charged Quarks

The prejudice against fractional charge led to a number of proposals of models with integrally charged quarks and a series of useless proposals for experiments to measure the quark charge. The basic fallacy in the arguments for and against integral charge is seen by noting that the electromagnetic current must have a color octet component in all models with integrally charged quarks, and that all matrix elements of color octet operators vanish between color singlet states. Thus all experiments involving only color singlet hadrons can measure only the color singlet component of the quark charge and will give the fractional charge[39].

If quarks really have integral charge but color octet hadrons exist only at the Planck mass, there is no way to observe the integral charge at reasonable energies and therefore no way to kill the integrally charged models. Looking for evidence for integrally charged quarks is useless far below the threshold for producing color octet states. The only sensible answer to the proposal that quarks might have integral charge is "Who needs them"? Why bother shooting down such models? One can paraphrase Pauli's remark about hidden variables: "Integrally charged quark models are like mosquitoes - the more you kill, the more there are."

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