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My Perspectives on Particle Physics: Summary of Orbis Scientiae, 1976

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I. INTRODUCTION - EXCUSES AND APOLOGIES

When my old teacher and friend, Syd Meshkov, called me some weeks ago to ask if I would summarize the conference, I happened to be rereading a letter Vicki Weisskopf received from his teacher at the time of the discovery of parity violation -- another era of excitement and rapid progress in particle physics. It was fascinating reading, because the writer was musing on many of the problems that we are trying to unravel and understand even today. But I am not here to elaborate on Pauli's insight; what inspired me to accept this challenging task was the last sentence in this historical document,[1] which was

"Viele Fragen, keine Antworten."

That is, in the summary talk I don't have to answer any profound questions, but I need only summarize questions raised in the conference! This is what gave me the courage to accept the challenge.

It would be dishonest if one were to attempt to summarize talks and discussions one did not understand. I know my shortcomings, and will have to pass unmentioned some topics. I apologize to those concerned for this unavoidable slight.

Lastly, I must quote Dick Feynman[2] verbatim: "As is conventional in summary talks, I'm not going to summarize what happened during today, the last day of the conference. The excuse usually is, of course, that you've just heard it.

But I have just discovered the real reason, for the summarizer didn't attend today's sessions, because he [was] busy preparing his summary."

II. ULTIMATE THEORY - IMPOSSIBLE DREAM?

It seems to me that an ultimate theory should encompass all known interactions, gravitational as well as strong, weak and electromagnetic interactions. I do not know much about supergauge theories developed and explained here by Peter Freund, nor a different formulation by Arnowitt, Nath and Zumino,[3] but I consider them as an important first step toward such ambitious undertakings. More immediately, scalar mesons some people seem to want may find a natural setting in such a theory.

An ultimate theory would have only one dimensional constant, the Planck mass, and perhaps a cosmological constant. All other physical quantities should be computable. It must explain all natural phenomena -- from galaxies to quarks and beyond.

A revision of quantum mechanics may also be necessary. As my mentor Chen Ning Yang[4] often emphasized to me, an essential difference between classical and quantum mechanics is that the underlying algebras of the two mechanics are real and complex, respectively. The view that one should be able to choose the phase of a complex wave function independently at every space-time point then naturally leads us to the concept of gauge fields -- a single overwhelming theme of this conference.

Are there other algebras that could be, or should be brought into physics?[4] Are there other symmetries (other than those associated with complex algebra: time reversal/charge conjugation and U(1) gauge invariance) that may be due to more complex underlying algebraic structures?[4] Feza Gürsey, I believe, has made an important observation in this connection, by finding a natural setting for the perfect color SU(3) symmetry in the octonion quantum theory. We will discuss this matter later.

III. PATI-SALAM THEORY - A VIABLE ALTERNATIVE

Pati made an impassioned case for a unified theory of leptons and integrally charged Han-Nambu quarks. The Pati-Salam model is a viable alternative to the more popularly held quantum chromodynamics. It is consistent with all known experimental facts.

If it turns out theoretically that color cannot be confined, and if fractionally charged quarks are not to be found experimentally, then the Pati-Salam model will be in a much stronger position as the unified gauge theory of strong, weak and electromagnetic interactions. If the lifetimes of quarks are of order $10^{-11} \sim 10^{-12}$ sec., as Pati estimates, emulsion exposures may prove to be the most rewarding hunting grounds for live quarks.

Frankly, I like quantum chromodynamics (QCD hereafter) better, because it seems to me richer in mathematical beauty and complexity, and more intricate in its physical implications. Here, though, I must admit that I am guilty of scientific prejudice; for most of us, it's a matter of taste, and fashion. The following discussions are mostly in the framework of QCD.

IV. QUANTUM CHROMODYNAMICS - CENTRAL DOGMA

Murray Gell-Mann presented a beautiful introduction to this subject and I need only list a few important features (central dogma) of the theory:

(1). Strong, weak and electromagnetic interactions are described by a non-Abelian gauge theory based on a simple group $\mathcal{G}$. Therefore, there is only one gauge coupling constant. The super group $\mathcal{G}$ decomposes into *

$$\mathcal{G} \supset SU_c(3) \otimes G_{flavor}$$
$$\supset SU_c(3) \otimes U_W(2)$$

where $SU_c(3)$ is the exact $SU(3)$ color symmetry associated with strong interactions, which can be described by an asymptotically free gauge theory (in the narrow sense, this is QCD), and $U_W(2)$ is the spontaneously broken symmetry of

*The super symmetry, or supersymmetry $\mathcal{G}$ hereafter has nothing to do with the supergauge theories discussed in the last section.

weak (and electromagnetic) interactions.

(2). Main ingredients of the theory are:

Gauge bosons:

a. confined color gluons.

b. weak bosons and photon; other massive bosons which carry flavor.

c. diquarks/leptoquarks which carry both color and flavor.

Fermions:

Leptons, and confined quarks. They appear in common multiplets of the super group $\mathscr{G}$.

In addition there may be fundamental scalars responsible for spontaneous breakdown of $\mathscr{G}$ down to $SU_C(3) \otimes U_W(2)$ and/or of $U_W(2)$.

In this general framework there are a number of questions that have been discussed in this conference. I will again list them, with the names of speakers who addressed each question:

(1). What is the supergroup $\mathscr{G}$? (Gürsey)

(2). How is color confined? (Appelquist, Cornwall, Wilson)

(3). Leptonic interactions of hadrons. (DeRujula, Politzer)

(4). Hadronic weak interactions. (Minkowski, Zee)

(5). Phenomenological description of hadrons as confined quarks and gluons in a "bag" (Johnson). I must stress here that the MIT bag model was first conceived as a fundamental theory of hadrons. I am taking the liberty of interpreting it as a reasonable phenomenological description of confined quarks and gluons in an asymptotically free QCD.

(6). Higgs meson phenomenology.

(7). Magnetic monopole (Dirac, Goldhaber, Hagen). Dr. Hagen clarified for us the difficulties in the operator formulation of magnetic monopole theory.

(8). "Stability of the Proton" (Gell-Mann).

(9). The origin of quark masses, Cabibbo angle and CP violation (Glashow, Zee).

(10). Solitons (Neveu). The relevance of quantum solitons in QCD is not entirely clear to me. The theory of solitons is an interesting subject on its own right; important progress is being made here, and our general understanding of quantum field theory is deepened thereby.

Before summarizing my understanding of some of these topics, let us list the experimental discoveries that have been made during the past year or so at a breathtaking rate.

V. EXPERIMENTAL DEVELOPMENTS - FACTS?

(1). Discoveries of J, $\psi(3.7)$, and the physics of the psion family, including possibly five resonances in the range 4.0 - 4.5 GeV; μe events as possible signal of heavy lepton production (Chen, Oberlach, Tannenbaum; Gilman).

(2). Structure of the neutral current (Sciulli; Minkowski).

(3). Dimuon effects in ν- and $\bar{\nu}$-induced reactions (Mann; DeRujula).

(4). Production of large $p_\perp$ leptons,[5] and $\ell/\pi \sim 10^{-4}$.

(5). Apparent $\Delta Q = -\Delta S$ neutrino interaction at BNL.[6]

(6). $Ke^+\mu^-$ events in ν-induced reactions in Gargamelle and at Fermilab.[7]

(7). High y and low x anomaly in $\bar{\nu}$-(and possibly ν-) induced reactions (Mann; DeRujula).

(8). Scaling breakdown in μp scattering.[8]

(9). ISR production of Kp, πp resonances (Sassoms).

(10). Magnetic monopole (Price, Ross) - my impression on this is that there is a candidate, but the evidence is far from conclusive.

Let me summarize items (1), (2), (3) and (7) above that have been discussed at this conference.

VI. PSION PHYSICS - PUZZLES.

We have heard excellent reviews from three experimentalists and a theorist. It is silly for me to try to summarize the vast amount of data and possible inferences. I will instead list my own inferences and puzzles.

(1). The spectrum of the psion family is unmistakably that of a $Q\bar{Q}$ system, where Q is a spin ½ fermion.

(2). The electric charge of Q is not known: the VMD phenomenology based on SU(4) is ambiguous, because we do not know to what quantity [$1/\gamma_V$, or $(M_V)^N/\gamma_V$, where $1/\gamma_V$ is the photon-vector meson coupling and N is some integer, say] SU(4) should be applied; inferences based on the saturation of a Weinberg sum rule ought to take into account not just J(3.1), but $\psi(3.7)$ and resonances in the range 4.0 - 4.5 GeV.

(3). Radiative decay widths of the P states, and of ψ' into the P states are not in accord with charmonium estimates. It may indicate that the charmonium wave functions used are not good enough, and/or the charge of Q is -1/3, rather than 2/3, in which case theoretical estimates of E1 moments should be reduced by a factor of 4. In any case, if the psion family can be described in a nonrelativistic approximation, the dipole sum rule ought to hold:

$$\sum_f |\langle i|\vec{x}|f\rangle|^2 (E_f - E_i) = \frac{2}{m_Q} \quad .$$

This should be used extensively as a diagnostic tool to determine what the charge of Q is, and to see whether there should be large E1 transition rates from the 4.0 - 4.5 GeV region and continuium states to the P states.

(4). 20 - 25% of decay modes of ψ' are unaccounted for. There are two possibilities again: some or all branching ratios are underestimated, and/or there are undiscovered decay modes, such as $\psi' \to X'(2^1S_0) + \gamma$. In the latter case, which is an M1 transition, Q may have a large anomalous magnetic moment.

(5). Charm searches at SPEAR and DORIS have so far yielded negative results. Why? Let us speculate.

(5.a). Psions are bound ($b\bar{b}$) states where $Q_b = -1/3$. The "bottom" quark decays nonleptonically by the scheme

$$b \rightarrow u\bar{u}d \quad ,$$

and there will be no "strangeness-signal" in the final states of the ($b\bar{q}$), ($\bar{b}q$) meson decays, where q is a light quark, u or d.

(5.b). The usual charm scheme is right as to charmed meson production in e^+e^- collisions, for example:

$$e^+e^- \rightarrow \gamma \rightarrow D^+D^- \quad ,$$

but D mesons decay predominantly into a heavy lepton[9] ($\pi\mu$ puzzle all over again!):

$$D^+ \rightarrow U^+ + \nu_U$$

$$\begin{aligned} U^+ &\rightarrow \mu^+\nu_\mu\bar{\nu}_U \\ &\rightarrow e^+\nu_e\bar{\nu}_U \\ &\rightarrow \bar{\nu}_U + \text{mostly nonstrange hadrons.} \end{aligned}$$

This hypothesis is viable, I believe,[10] if the D meson decay constant f_D is much larger[11] than $f_\pi \approx f_K$ ($f_D \approx 10f_\pi$, say) and $M(U) \approx 1.8$ GeV.

(5.c). The charm quark decays mostly into a u-quark with emission of a gluon.[12] The D^+, D^0 mesons decay mostly into nonstrange hadrons.

(5.d). There is nothing wrong with the orthodox (i.e., conventional[13]) charm phenomenology. SPEAR and DORIS have been very, very unlucky.

Lest any of you misunderstand, let me say that I am not advocating that the psions are bound states of the bottom quark and its anti-quark. Rather, I am provoking you to come up with a plausible indication that the charge of Q is indeed 2/3.

VII. NEUTRAL CURRENT - A MILD SURPRISE

Frank Sciulli presented an analysis of the spin structure of the weak neutral current based on the Caltech-Fermilab experiment. His group used the Fermilab dichromatic beam, and consequently had some control over incident neutrino energy.

Instead of reviewing the analysis, let me summarize their result in the framework of the minimal (Weinberg-Salam) theory of weak interactions. We can parametrize the neutral current interactions of hadrons in an effective Lagrangian:

$$\frac{G_F}{\sqrt{2}} \, x \, \bar{\nu}\gamma_\mu(1-\gamma_5)\nu\left[V_3^{\ \mu} - A_3^{\ \mu} - 2\sin\Theta_W j^\mu_{e.m.}\right] \quad .$$

What his group found is that

$$x \approx 1 \quad ,$$

$$\sin^2\Theta_W \approx 0.3 \sim 0.4 \quad .$$

I would like to call your attention to the parameter x . It is a measure of the relative strength of neutral current to charged ones; it takes the value

$$x = \frac{m_W^2}{m_Z^2 \cos^2\Theta_W} = 1$$

only in the most naive version of the theory in which the spontaneous symmetry breakdown occurs in the doublet Higgs system. That this prediction is borne out is a mild surprise to me, because I expected the pattern of spontaneously broken symmetry to be more complicated, but perhaps not to Steve Weinberg and Abdus Salam and to most of you. There is a lesson for me somewhere here; I know not what, though.

VIII. DIMUON EVENTS AND HIGH y, LOW x ANOMALY

"Peripheral Collisions Just Study Fluffs. Lepton Scattering Gets at The Guts." - usually attributed to R.R. Wilson

Al Mann reported on two results of the Harvard-Pennsylvania-Wisconsin-Fermilab neutrino experiments.

(1). Dimuon Events. Through extensive discussions with members of the collaboration at Fermilab, I am convinced that dimuon events are genuine, in the sense that second muons in most of these events are not from π/K decays, and they are not due to accidental coincidences. Further, the Pais-Treiman test shows that most of them do not come from the production and decay of a neutral heavy lepton, $L^0 \to \mu^- \mu^+ \nu$.

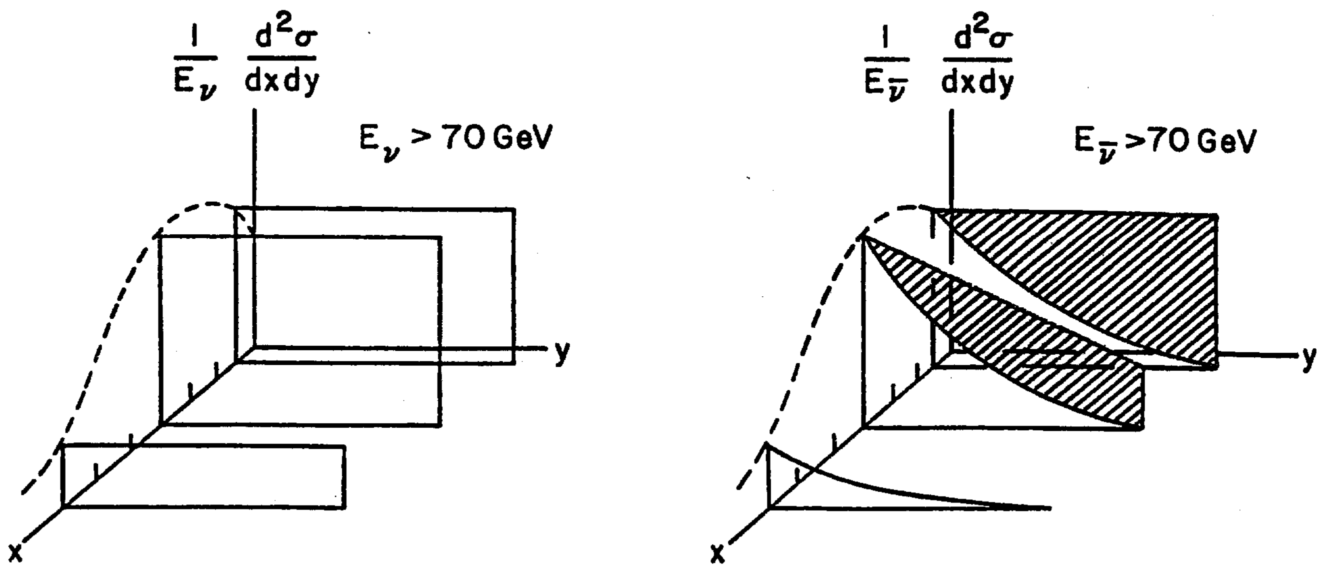
Basic characteristics of these events are: for incident ν, μ^- is almost always fast, μ^+ slow; <u>mutatis</u> <u>mutandis</u> for incident $\bar{\nu}$;

$$\frac{\sigma(\nu\to\mu^-\mu^+)}{\sigma(\nu\to\mu^-)} \approx 10^{-2}, \quad \frac{\sigma(\bar{\nu}\to\mu^+\mu^-)}{\sigma(\nu\to\mu^-\mu^+)} \approx 0.8 \pm 0.6$$

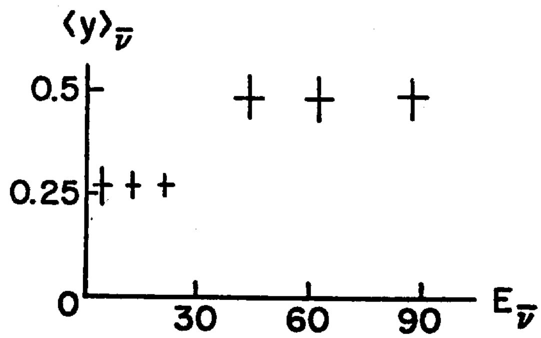
and

$$\frac{\sigma(\nu\to\mu^-\mu^-)}{\sigma(\nu\to\mu^-\mu^+)} \approx 10^{-1}$$

(2). High y and low x anomaly: Al Mann elaborated on the high y anomaly in the deep inelastic $\bar{\nu}$ scattering data that they have accumulated for some time; the phenomenon is most pronounced for $E_{\bar{\nu}} > 70$ GeV, although the trend is already apparent in $30 \text{ GeV} < E_{\bar{\nu}} < 70$ GeV. I will present below schematic diagrams (a theorist's conception) of their $d^2\sigma/dxdy$ for E_ν and $E_{\bar{\nu}} > 70$ GeV:



In the antineutrino case, the crosshatched portions are excesses over the naive parton model expectation. The excesses are concentrated in small x and large y. On the other hand, the neutrino data seem, more or less to agree with the parton model expectation. A more dramatic demonstration of the anomaly is to plot the average value of y, $\langle y\rangle_{\bar{\nu}}$, against $E_{\bar{\nu}}$:



Again, the plot is my impression of the data Mann presented; for the real data, please refer to him. The naive (valence) parton model expectation is 1/4, which agrees with the low energy data. The effective threshold for the anomaly appears to be somewhere between 30 and 50 GeV.

I shall postpone possible theoretical interpretations of these phenomena until we have examined various models for flavors.

IX. MODELS OF WEAK INTERACTIONS - HOW MANY FLAVORS?

With the existence of neutral currents now generally accepted, the most popular gauge theory of weak and electromagnetic interactions is that based on the group $SU(2) \otimes U(1)$. There phenomenological requirements that both $\Delta S = 0$ and $\Delta S = 1$ β decays are V-A , and the relative phases of the $\Delta I = \frac{1}{2}$ and $\Delta I = 3/2$ amplitudes in $K \to 2\pi$ and $K \to 3\pi$ agree with experiment.[14]

There are several motivations for the vectorlike theory; I have discussed them at the SLAC Conference at some length, but let me briefly repeat them here.

(1). Aesthetics: A vectorlike theory is asymptotically symmetric with respect to $L \leftrightarrow R$, asymptotically in the sense of neglecting fermion masses. Consequently, such a theory is automatically anomaly-free. Further, such a theory affords the possibility of interrelating or "deriving" CP violation, the Cabibbo angle and fermion masses in a natural way. Shelly Glashow gave an example of the first two (i.e., the Cabibbo angle and CP violation); Tony Zee the last two. (As Glashow mentioned, it is also possible, as shown by Pakvasa and Sugawara,[15] and more recently by Maiani,[16] to introduce CP violation "naturally" in a six-quark model which makes use only of V-A currents).

(2). Octet enhancement, some proponents argue, comes out more naturally in the six-quark model. Further, the "embarassment" of what I shall call the "P_6 problem", namely that $K^0 \to \pi\pi$ is forbidden in the SU(3) limit in conventional models (and in the minimal model) does not arise in this vectorlike model. I shall come back to these points presently.

It is worth emphasizing that in any vectorlike model, the hadronic, electronic and muonic neutral currents are always vector (therefore there are no parity violating effects in atomic physics). On the face of it, this seems to contradict Sciulli's report. However, proponents of the vectorlike theory in the audience, take heart! His results are only two standard deviations away from a pure vector theory.

X. $\Delta I = \frac{1}{2}$ RULE AND ALL THAT

As Cabibbo and Gell-Mann pointed out many years ago, the parity-violating octet part of the hadronic weak interactions in V-A theory transforms like λ_6 , and consequently, the decay $K^0 \to \pi\pi$ is forbidden in the SU(3) limit. This is the P_6 problem. I personally do not consider it a problem. In all dynamical models I have examined, the suppression factor due to this is typically $(m_K^2 - m_\pi^2)/m_K^2$; it is zero in the SU(3) limit, but in reality it is about 1. If the strangeness-changing nonleptonic weak interactions arise from the product of a V-A and a V+A current, the parity violating octet part transforms like λ_7 , and it is true that there is no "no-go" theorem even in the symmetry limit to worry about.

There are several explanations which have been advanced recently for the observed, approximate $\Delta I = \frac{1}{2}$ rule, and more generally the octet enhancement rule. Let me review them.

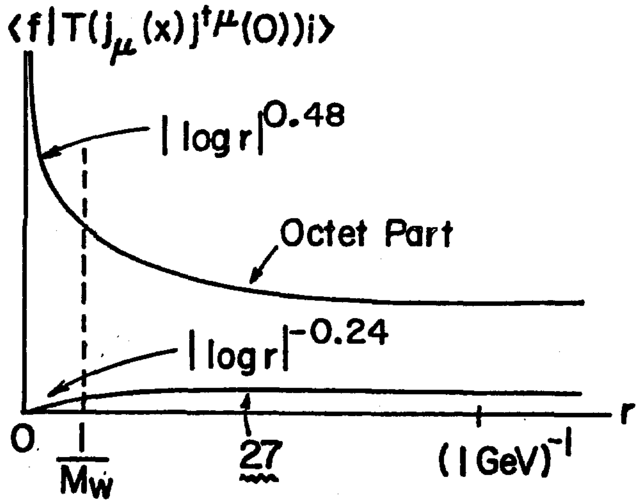
(1). In the minimal theory, it was observed that the short distance behavior of the product of two V-A currents is more singular for an octet part[17] than for the $\underset{\sim}{27}$ part if the effects of strong interactions are described by QCD. The weak transition amplitude is described by

$$\int \left[d^4x\right]_E \frac{e^{-m_W r}}{r^2} \langle f|T(j_\mu(it,\vec{\underset{\sim}{x}})j^{\dagger\mu}(0))|i\rangle \;, r^2 = \underset{\sim}{x}^2 + t^2 \;. \tag{1}$$

What matters therefore is the size of the matrix element at short distances of order $1/m_W$. Using the Wilson operator product expansion, one finds

$$T(j_\mu(x)j^{\dagger\mu}(0)) \approx |\log \mu r|^{\alpha}\mathcal{O} + |\log \mu r|^{\alpha'}\mathcal{O}' \qquad \text{for } \mu r << 1 \tag{2}$$

where the operator $\mathcal{O}$ is an octet and $\mathcal{O}'$ is a mixture of $\underset{\sim}{8}$ and $\underset{\sim}{27}$; μ is a scale parameter. The exponents α and α' are computable in QCD: with four four flavors and three colors $\alpha = 0.48$, $\alpha' = -.24$. Murray Gell-Mann and the Caltech group consider this short distance enhancement negligible; Mary K. Gaillard and I stated[17] that the short-distance enhancement was not big enough. We felt that there had to be additional enhancement of matrix elements of $\mathcal{O}$ and suppression of matrix elements of $\mathcal{O}'$. I can now make this statement a little more quantitative: for finite r we can estimate the size of the matrix element $\langle f|T(j_\mu(x)j^{\dagger\mu}(0))|i\rangle$ by inserting a complete set of intermediate states between the two currents. For r of order (1 GeV)$^{-1}$, only a well-defined set of states makes important contributions, and these contributions are mostly octet. As r decreases, the matrix element of the left-hand side of (2) must match that of the right-hand side. Thus the following picture emerges:



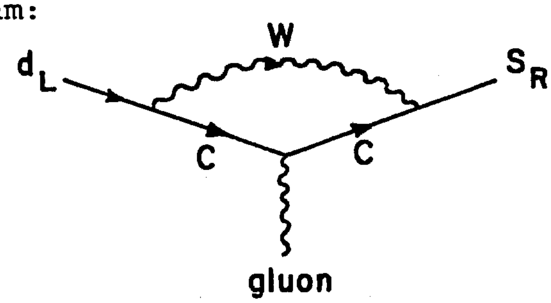
Even though my collaborators and I have not completed the detailed computation, I am not convinced yet that this picture, the cooperative enhancement of the octet channel both at long- and short-distances, cannot explain the observed validity of the $\Delta I = \frac{1}{2}$ rule.

(2). Tony Zee reported on the work of the Princeton group on this issue. The vectorlike theory contains the piece that looks like, in the local limit,

$$\sim \frac{G_F}{\sqrt{2}} \sin \Theta_C : \bar{s}_R \gamma_\mu c_R \bar{c}_L \gamma^\mu d_L : \quad . \tag{3}$$

This is the product of a V-A and a V+A current; it transforms like λ_6 for p.c., and λ_7 for p.v. part. In QCD, the above interaction is multiplied (enhanced) by a factor $(\log \frac{M_W}{\mu})^{\alpha}$. But here α is bigger than in the minimal theory: as a rule α is bigger for $(V+A)\times(V-A)$ than for $(V-A)\times(V-A)$; the more flavors, the bigger α (up to a point). On the other hand, they argue, and I agree, that the operator in (3) will not have matrix elements of appreciable size. It is, however, just a feeling, intuition you might say, based on a naive quark model (i.e., there are not many c-quarks in a hadron.) Note, however, that the product of the two V-A currents discussed in the last section does get larger enhancement from a larger α in a vectorlike theory.

(3). Peter Minkowski presented a new idea on the subject based on his work in collaboration with Harold Fritzsch. The idea is a very attractive one. It is best expressed by a Feynman diagram:



that is, the weak interaction takes place effectively through $s \to d$ + gluon:

$$\sim \frac{G_F}{\sqrt{2}} \sin \Theta_c m_c \log\left(\frac{m_W}{m_c}\right) \bar{s}\, \sigma_{\mu\nu} \underset{\sim}{\lambda}_c (1-\gamma_5) d \cdot \underset{\sim}{G}^{\mu\nu} + \text{h.c.} \; ; \tag{4}$$

it has the same SU(3) transformation properties as (3). As far as I can tell, the matrix element $\langle f | \bar{s}_R \sigma_{\mu\nu} \underset{\sim}{\lambda}_c d_L \cdot \underset{\sim}{G}^{\mu\nu} | i \rangle$ will have an appreciable size. While this model is much too new for me to give it a clean bill of health, I do not see anything wrong so far. I do not think that this model is grossly in conflict with the small $K_L K_S$ mass difference.

We have discussed two models whose structure of effective nonleptonic weak interactions is of the form $S_6 + P_7$. As emphasized both by Minkowski and Zee, radiative decays of hyperons ($\Xi^- \to \Sigma^- \gamma$, $\Xi^0 \to \Lambda\gamma$, $\Sigma^+ \to p\gamma$) will prove to be testing grounds for P_6 vs. P_7. Theoretical expectations[18] on asymmetry parameters in these decays based on $S_6 + P_6$ have not so far been borne out by experiments of limited statistics.

XI. DIMUON EVENTS -SIGN OF CHARM?

As we have seen, the theory of nonleptonic weak decays is in a state of flux. Even in the minimal theory it is possible that the initial estimates[13] of nonleptonic branching ratios of charmed particles are in error, and I am now pursuaded[19,20] that the inclusive muon branching ratio of a generic charmed particle could be as much as 20%.

The dimuon events can be explained, then, in the framework of the minimal theory.[21] They can also be explained in the vectorlike model discussed above, with somewhat different conclusions, but let me just concentrate on the former. (For the latter, please recall Alvaro DeRujula's discussion).

In the parton model, in addition to the valence quarks, there are strange quarks and their antiquarks in the sea, their contributions to the F_2 function being, say, about 5%. There are three processes that can produce charmed quarks in the final states:

1. $\nu + d \rightarrow \mu^- + c$ (Cabibbo-suppressed, but off valence and sea quarks),
2. $\nu + s \rightarrow \mu^- + c$ (Cabibbo-favored, but off sea quarks),
3. $\bar{\nu} + \bar{s} \rightarrow \mu^+ + \bar{c}$ (Cabibbo-favored, but off sea quarks).

The processes (1) and (2), summed together, would contribute about 10% to the total ν cross-section well above threshold. The process (3) would also contribute 15% to the total $\bar{\nu}$ cross-section: recall that $\sigma_{\bar{\nu}}/\sigma_{\nu}$ for non-charm production reactions is about 1/3.

The x distribution of the charm producing ν-reactions will have two components:[22] one concentrated about $x = 0$, representing charm production off sea quarks; the other having a normal x distribution, representing charm production off valence quarks. In the $\bar{\nu}$ case, there is only the small-x component. The y distribution is flat in either case, except near $y=0$, where threshold effects may manifest themselves. With the generic branching ratio into μ channels of order 10%, one estimates

$$\frac{\sigma(\nu\to\mu^-\mu^+)}{\sigma(\nu\to\mu^-)} \approx \frac{\sigma(\bar{\nu}\to\mu^+\mu^-)}{\sigma(\bar{\nu}\to\mu^+)} \approx 1 \sim 2\% \quad .$$

The dimuon events of the same sign are problematical, but not too serious. Charmed pair production of about 1% of the total cross-section both in ν and $\bar{\nu}$ induced reactions would explain them comfortably. As a comparison, I recall for you that strange pair production in the $\bar{\nu}$ interactions might be as high as 20%.[23] In the vectorlike model, there is the additional possibility of $D^0\bar{D}^0$ mixing, producing dimuon events of the same sign.

XII. NEW PARTICLE PRODUCTION AND SLOW SCALING

For the following discussion, I shall assume Mann's data on high y, low x anomaly are quantitatively correct. My trusted colleague, Robert Shrock, and I have pondered over the data for the last month or two, and we have tentatively concluded that they cannot be understood by charm production and logarithmic scaling breaking that QCD predicts, alone; in particular, the jump in $\langle y\rangle_{\bar{\nu}}$ they observe is about twice (or even thrice, according to the experimenters) bigger than we can account for.

Alvaro DeRujula reported on, I believe, Michael Barnett's work on the interpretation of this anomaly in the framework of the vectorlike theory and slow scaling; to the latter David Politzer addressed himself very eloquently. But before embarking on that, let me take the 6 quark vectorlike model, and derive the most naive expectations for new particle production in ν- and $\bar{\nu}$-induced reactions, in order to illustrate the necessity of a slow approach to scaling.

In the vectorlike model, there are two new elementary processes for new particle production which are Cabibbo-favored and which take place off valence quarks:

$$\nu + d_R \to \mu^- + t_R \quad ,$$

$$\bar{\nu} + u_R \to \mu^+ + b_R \quad .$$

The other processes are either Cabibbo suppressed or off sea quarks, and I shall ignore them. To simplify our argument, we shall assume $m(t) > m(b)$, so that the effective threshold for the former has not been reached. The second process, which takes place only in the $\bar{\nu}$ case, will have a flat y distribution. We then expect $\langle y \rangle_{\bar{\nu}}$ to jump from 1/4 to 7/16 at the effective threshold. This is in excellent agreement with observation.

However, there are two problems in this naive approach. One is that the x distribution of the new particle production in $\bar{\nu}$-induced reactions is expected to be normal; we have been told that it peaks near $x = 0$. The second, and equally serious problem, is that $\sigma_{\bar{\nu}}/\sigma_{\nu}$, which is 1/3 at low energies, must jump to 4/3 above the effective threshold if b alone is excited, and to 1 if both t and b are excited; at the currently available highest energy, this ratio is at most 1/2.

Politzer described his work with Howard Georgi. First he described what he means by the mass of a confined (and therefore asymptotically inaccessible) quark. Second, he discussed the operator product expansion which takes into account the finite quark masses to all orders, but the gluon coupling constant g to lowest order. This study culminates in a new scaling law:

$$\nu W_2(\nu,q^2) = F_2(\xi)$$

where the variable ξ is a rather complicated function of ν, q^2 and the initial and final quark masses m_I and m_F. I shall not write it down here; suffice it to say that in the case $m_I = m_F = 0$, it reduces to the usual scaling variable x. What is the meaning of ξ? Feza Gürsey tells me that he and Orfanides noticed some years ago that the Clebsch-Gordan coefficients of the Poincaré group become functions of the scaling variable ξ alone in the limit $q^2 \to -\infty$.

For our purpose, the most relevent case is $m_I \approx 0$ and m_F large (in the scale of hadron physics: 1 GeV, say), which is the case considered by Barnett. In this case

$$\xi \approx x + \frac{m_F^2}{2mE_\nu y} ,$$

which can be readily understood in the parton model. Note that x and y are restricted by the condition

$W^2 = 2mEy(1-x) > W^2_{\text{Threshold}}$.

According to Barnett's analysis, which I saw for the first time here, the x distribution of new particle production is squashed toward x = 0, because $x \lesssim \xi$; the approach to the asymptotic value of $\langle y \rangle_{\bar{\nu}}$ as a function of $E_{\bar{\nu}}$ is not very slow; the approach to the asymptotic value of $\sigma_{\bar{\nu}}/\sigma_{\nu}$ is very slow (I must confess that I do not understand this difference intuitively at the moment; it must be that it requires a numerical computation to reproduce it).

So much for phenomenology. Let me now turn to more abstract aspects of theoretical physics.

XIII. SUPER SYMMETRY - EXCEPTIONAL GROUPS AND OCTONIONS

The octonion algebra is a noncommutative, nonassociative division algebra (i.e. ax + b = 0 implies a unique x), with seven imaginary units $e_i^2 = -1$, i = 1 to 7. Suffice it to say that the e's are closed under multiplication. The automorphism group of the octonion algebra is G_2, the first exceptional group, just as it is SU(2) for the quarternion algebra.

Feza Gürsey's general philosophy on octonion quantum theory is eloquently described in his Baltimore lectures.[24] Octonion quantum theory is not a closed subject - it still needs to be developed. The novel feature in Gürsey's philosophy is that, say, e_7 has to be used to describe temporal development of a quantum mechanical system, i.e., $e^{-iEt} \rightarrow e^{-e_7 Et}$, and the automorphism group relevant to the internal symmetry of fundamental fields is a subgroup of G_2 which leaves $(1,e_7)$ invariant -- $SU_c(3)$! Only the color singlet operators correspond to observables. Colored quarks, for example, lie in a fictitious octonionic Hilbert space; the physical Hilbert space, which is a subspace, consists of color-neutral states. The crucial question, to me, is then whether the physical Hilbert space is a subspace of the bigger fictitious Hilbert space which is automatically invariant under the action of the S-matrix by the very nature of as-yet-to-be-formulated octonion quantum field theories, or this must be arranged by a special dynamical mechanism.

In any case, let our fancy take a flight! It turns out that 3×3 hermitian matrices with octonionic entries (more technically, octonions over real, complex, quartenion and octonion algebras, i.e., Rozenfeld algebras) are power associative (i.e., $A^2A = AA^2 = A^3$, etc.), and satisfy the properties of observable density matrices. The automorphism groups of these matrices comprise the rest of exceptional simple Lie groups, F_4, E_6, E_7 and E_8. Gürsey proposed to consider these groups as candidates for the super unified group $\mathcal{G}$.

Much work has been done along these lines by Gürsey and collaborators, and by Gell-Mann. A remarkable feature of all these groups is that they contain a maximal subgroup

$SU_c(3) \otimes G_{flavor}$: for E_6, E_7 and E_8, the G_{flavor} are, respectively, $SU(3) \otimes SU(3)$, $SU(6)$, and $SU(3) \otimes SU(3) \otimes SU(3)$. [Incidentally these maximal subgroups are the little groups of $(1, e_7)$].

Let me illustrate the use of these groups in the case of E_6: the smallest nontrivial representation is $\underset{\sim}{27}$, which decomposes under $SU_L(3) \otimes SU_R(3) \otimes SU_c(3)$ as

$$(3,\bar{3},1^c) \oplus (3,1,3^c) \oplus (1,\bar{3},\bar{3}^c) \quad :$$

the nine color-singlets are leptons, some of which may be Majorana neutrals; the middle factor consists of three flavors of left-handed colored quarks; the last, three flavors of left-handed antiquarks (i.e., antiparticles of the right-handed quarks). In order to implement the GIM scheme, one has to postulate another $\underset{\sim}{27}$. The Weinberg-Salam $SU_W(2) \otimes U(1)$ is a subgroup of $SU_L(3) \otimes SU_R(3)$ where the $SU_W(2)$ is embedded in $SU_L(3)$.

There are other candidates for $\mathscr{G}$ that have been discussed in the literature, for example, SU(5) of Georgi and Glashow,[25] and SO(10) in connection with the vectorlike model.[26] It may or may not be relevant that SU(5) is isomorphic to E_4 (the groups in the E series are all exceptional except E_4; E_4 fails to be exceptional because of this isomorphism). Incidentally, all these groups are anomaly-free.

XIV. STABILITY OF THE PROTON

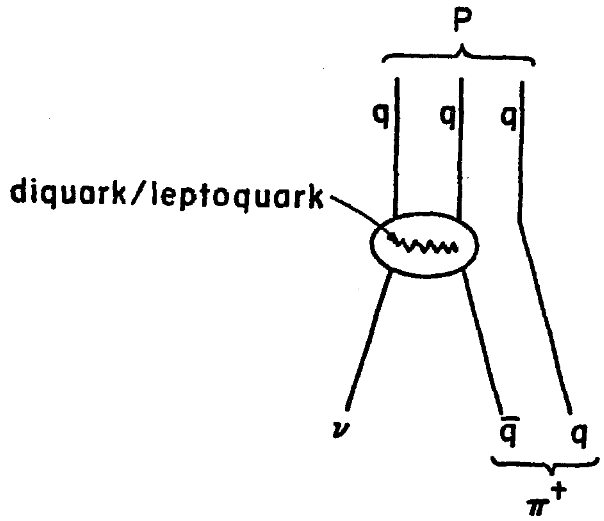
The lifetime of the proton is at least 10^{30} years. This is to be compared with the age of the universe, about $10^{11\pm1}$ years. All supergroup scheme contains a germ for instability of the proton, and let me explain this.

In the usual picture, the proton consists of three quarks, completely antisymmetric in color. Therefore any two of them are antisymmetric in color (these are the diquarks): they transform like $\bar{3}^c$ and are bosonic. They cannot go into an antiquark, but they can go into $\bar{q} + \ell$ (leptoquark) because the lepton ℓ is color-singlet, and the leptoquark is bosonic:

$$\begin{array}{ccc} \text{Diquark} & \leftrightarrow & \text{Leptoquark} \\ (qq)_{\text{antisym}} & & (\bar{q}\ell) \end{array} .$$

Of course this group-theoretic argument is true whether or not there is a supergroup $\mathscr{G}$. It is just that in schemes where leptons and quarks belong to separate multiplets, there is no agent which can mediate this transition.

In super-unified schemes though, some of the gauge bosons corresponding to the coset $\mathscr{G}/\left[SU_c(3) \otimes G_{\text{flavor}}\right]$ carry the quantum numbers of diquarks/leptoquarks. Thus we cannot avoid, unless something intervenes, there being a process like $p \to \pi^+ + \nu$ which I picture as



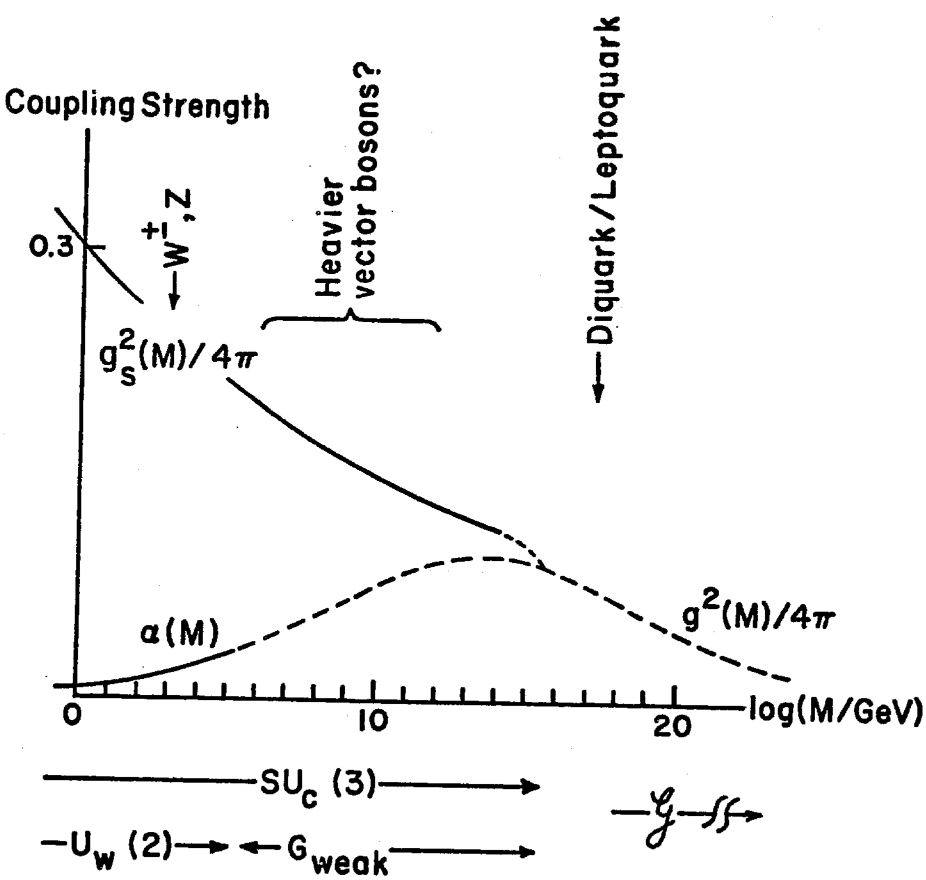
Murray Gell-Mann suggested three "cures" for this. We can arrange the dynamics so that this process is "postponed" to higher orders in G_F, or we can make the masses of these gauge bosons very massive, of the order of the Planck mass. Lastly, define the baryon number N as $N_{local} + N_{global}$, where N_{local} is associated with a local gauge invariance, N_{global} with a global gauge invariance; arrange the matters (presumably through vacuum expectation values of the Higgsians) so that each is violated, but not the sum, which is the physical baryon number.

It is intriguing (and mind-boggling) to speculate on what would happen to this issue if we had a respectable octonion field theory. You see, the coset $\mathscr{G}/\left[SU_c(3) \times G_{flavor}\right]$ does not leave e_7 invariant, the e_7 which is the analogue of the i in quantum mechanics, and the gauge bosons associated with this coset may have a completely different physical significance.

XV. HIERACHICAL SYMMETRY BREAKING AND HIGGSIANS

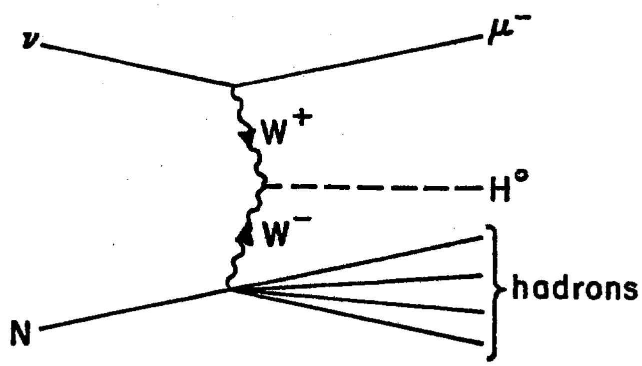
How does the supersymmetry $\mathcal{G}$ break down to the "observed" symmetry $SU_c(3) \otimes U_W(2)$? According to a more conservative picture in which all spontaneous breakdowns are due to Higgs phenomena the scenario is something like the following;[27] we have to bear in mind in this discussion the theorem due to Tom Appelquist and Jim Carazzone,[28] which states that in studying a phenomenon on the mass scale M, effects of particles of masses $>> M$ may be completely neglected.

Let M be the running mass scale in the sense of the renormalization group analysis. In the regime $M \gtrsim 10^{19}$ GeV or the Planck mass, there is a manifest supersymmetry $\mathcal{G}$, and the associated unified coupling constant $g(M)$, which presumably becomes logarithmically weaker with increasing M. In the intermediate range 10^3 GeV$<M<<10^{19}$ GeV the effects of diquark/leptoquarks may be neglected and the apparent symmetry is that of $SU_c(3) \otimes G_{weak}$. Below $M \approx 10^3$ GeV, the presently observed pattern sets in, with a broken $U_W(2)$ describing weak and electromagnetic interactions, and an exact $SU_c(3)$ describing strong interactions. The former is described by an infrared fixed-point theory, the latter by a ultraviolet fixed-point (asymptotically free) theory. I have sketched in the following figure how various coupling strengths vary as the running mass scale varies. Dotted portions in the figure are conjectural. They depend on what the groups in question are, and how many fermions and relevant Higgs mesons there are at each mass scale.



The Higgs meson(s) responsible for the spontaneous breakdown of $U_W(2)$, if it exists, is relevant to today's observational physics. The phenomenology of the Higgsian meson was recently surveyed by Ellis, Gaillard and Nanopoulos.[29] Steve Weinberg[30] has, more recently, shown that the mass of the Higgs meson is $\gtrsim$ 4 GeV.

Dave Cline[31] argues that the best way of producing Higgs mesons (H^0) may be in the ν-N scattering via the following mechanism:



A naive estimate of the H^0 production ratio gives[32] about 10^{-5} in neutrino interactions.

While these topics were not dealt with in this conference, they form an integral part of my own perspective on particle physics.

XVI. MAGNETIC MONOPOLE

The beautiful Maxwell equations can be improved upon in at least two ways. Professor Dirac told us how he came upon the magnetic monopole. He wanted a more symmetric system of equations, a system symmetric with respect to $E \leftrightarrow B$. The compatibility of this system with quantum mechanics, specifically the single-valuedness of wave functions, led to electric charge quantization.

The second way is to embed the local gauge invariance of the Maxwell theory in a compact non-abelian simple group, say SO(3), and devise a system of equations which is covariant under the local non-abelian gauge transformations. This second approach leads to the Yang-Mills theory. In this scheme electric charge quantization is automatic, since the topology of the U(1) associated with electric charge conservation is compact.

There is a strong connection between these two approaches. On the one hand, Polyakov and 't Hooft have shown that in a SO(3) gauge theory with scalar fields, there is a soliton-like solution which exhibits all the characteristics of a Dirac magnetic monopole. This monopole is very massive, $M \sim 10^4$ GeV.

On the other hand, Fred Goldhaber showed us another connection. If we follow Dirac's original line of thought, we see the correspondence between the quantized quantity eg and a component of the angular momentum, where g is the magnetic charge

Goldhaber proposed to interpret it as the third component of the isospin, and to modify the Hamiltonian (by adding more gauge fields and interactions amongst them) so as to make it commute with all three components of the isospin. The outcome is the Yang-Mills theory. Fred gives credit to Henri Poincaré for this insight; I am sure he is being very modest.

I believe that magnetic monopoles do exist (but it is just a belief, nothing more), perhaps at a very large mass, because such a beautiful mathematical construct must have a counterpart in nature. I would at this juncture call your attention to a series of papers by Wu and Yang[33] on the connection among gauge theories, magnetic monopoles, and the branch of mathematics known as fibre bundles. (The "bundle" here has nothing to do with the same word used in Professor Dirac's lecture).

XVII. QUARK CONFINEMENT - PERTURBATIVE APPROACH

The hope for quark confinement in QCD arises from the following circumstance. The massless gluon theory has a severe infrared disease; the effective coupling is getting stronger as the mass scale M goes to zero. It may be that the theory circumvents this difficulty by allowing only colorless objects as asymptotically observable particles; in configuration space, two quarks cannot be separated by a macroscopic distance, because the force acting between them grows progressively as the separation gets bigger.

There has always been a stumbling block in pursuing this idea, and it is known as the Kinoshita-Lee-Nauenberg theorem. Since I am more familiar with the work of T.D. Lee and Nauenberg, let me cast the discussion in their language. Suppose we have a Hamiltonian $H(\mu)$, which exhibits a degenerate spectrum in the limit $\mu \to 0$. We consider an inclusive cross section $\sigma^{(n)}(\mu)$, computed in the n-th order in the coupling constant. The inclusiveness of the cross section entails summing over ensembles of initial and final states which would become degenerate if μ were zero. The theorem states that

$$\lim_{\mu \to 0} \sigma^{(n)}(\mu) = \text{finite} \quad .$$

Superficially this seems to imply that it is not possible to find signs of quark confinement in perturbation theory.

Tom Appelquist reported on a long calculation performed by him, Jim Carazzone, Hannah Kluberg-Stern and Mike Roth, the latter three at Fermilab, to lowest nontrivial order, to verify this theorem. A related calculation was also performed by Ed Yao at Michigan. Both groups confirm the Kinoshita-Lee-Nauenberg theorem in a non-abelian gauge theory. In particular, the former group shows that with a detector of finite energy resolution which does not see color, it is possible, for example, to detect a quark by its fractional charge -- this if perturbation theory makes sense.

On the other hand, Mike Cornwall reported on his rather extensive and painstaking work with George Tiktopoulos, which indicates that color confinement does occur in QCD, and the S-matrix elements involving external colored objects are strongly damped to zero as $\mu \to 0$. I cannot vouch for the technical correctness of their calculation. I can say, however, that there is no contradiction between Cornwall's and Appelquist's discussions. The UCLA group arranges the calculation so that they sum over leading $\log \mu$ terms to all orders in perturbation theory first, and then let the parameter μ vanish: in other words, they are calculating in principle the following:

$$\sigma = \lim_{\mu\to 0} \sigma(\mu) = \lim_{\mu\to 0} \left[\sum_{n}^{\infty} \sigma^{(n)}(\mu) \right] .$$

The inference that I draw from these discussions is that the summation and the limiting process $\mu\to 0$ do not commute.

I shall argue that the Cornwall-Tiktopoulos strategy is a plausible one if color confinement is anything like a phase transition in many body problems, in the next section. In the meantime, please note that the finite μ serves two purposes. They put in μ^2 in the Feynman-gauge gluon propagator by hand;

$$g_{\mu\nu} \frac{1}{k^2+i\varepsilon} \to g_{\mu\nu} \frac{1}{k^2-\mu^2+i\varepsilon} .$$

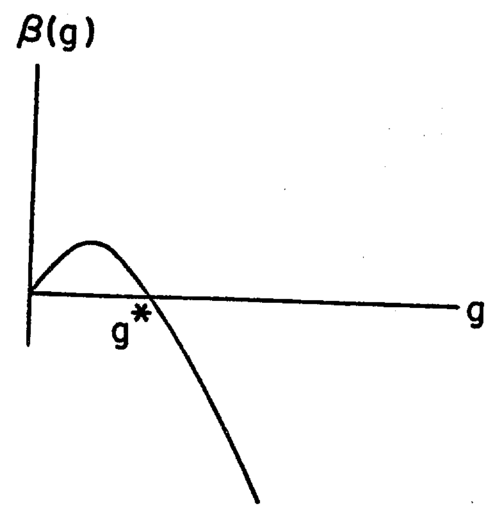
It is an infrared cutoff, and it is also a device to break gauge invariance explicitly. I will make use of this observation in the next section.

XVIII. QUARK CONFINEMENT AS A CRITICAL PHENOMENON

Ken Wilson described the progress he has made in the lattice gauge theory. In previous versions of the theory, he succeeded in establishing color confinement as long as the lattice constant a was kept finite. In the new formulation which resembles the block spin method in statistical mechanics, the S-matrix is in principle a-independent and covariant. We all await eagerly his final numerical results - meson and baryon masses, cross-sections, decay rates, etc.

In the last month or two, I have been very fortunate to have my two esteemed friends -- Jean Zinn-Justin and Bill Bardeen -- explain to me their views on quark confinement as a critical phenomenon, and interpret for me the views of Wilson, Kogut and Susskind, and Migdal[34] and Polyakov.[35] I would like to describe to you my understanding of the subject; for my misunderstanding or misrepresentations I alone am responsible.

To circumvent the infrared catastrophe, let us work in $4 + \varepsilon$ dimensions, $\varepsilon > 0$. The β function of the renormalization group looks like the following figure:



The ultraviolet fixed point $(g^*)^2$ is of order ε. For $g < g^*$, the perturbation expansion probably makes sense at least as an asymptotic expansion. Note that the gauge Lagrangian $\mathscr{L}(A_\mu, g)$ can be written as

$$\mathscr{L}(A_\mu, g) = \frac{1}{g^2}\,\mathscr{L}(gA_\mu, 1)$$

and the analogy between g^2 and kT in statistical mechanics is complete: g^{*2} corresponds to the critical temperature T_c. Beyond g^*, the theory is in a different phase, and perturbation theory is no help at all here.

There is a way of overcoming this impasse. For example, in a ferromagnetic system it is only necessary to turn on an external magnetic field (in which case there is no critical point in correlation functions) in order that a perturbation series make sense. Another example, perhaps more familiar to particle physicists, is the σ model:

$$L_\sigma = \tfrac{1}{2}\left((\partial_\mu\sigma)^2 + (\partial_\mu\pi)^2\right) - \frac{\mu^2}{2}(\sigma^2+\pi^2) - \frac{\lambda}{4}(\sigma^2+\pi^2)^2 \quad .$$

As long as $\mu^2 (\sim T-T_c)$ is positive the expansion in λ makes sense. To go the the other phase (the Goldstone phase), one first adds to the Lagrangian a symmetry-breaking term, $c\sigma$ (the analogue of external magnetic field), next develops a new perturbation series in λ (with $\lambda\langle\sigma\rangle^2$ fixed), then continues μ^2 to a negative value, and finally lets c go to zero.[36] One obtains in this way Green's functions valid in the Goldstone phase. These procedures are based on an assumed theorem (which has been proved in some simple cases, and is known as the Simon-Griffiths theorem) that as long as there is an explicit symmetry breaking, Green's functions or correlation functions are analytic (or at least asymptotic) in the dominant couplings when subsidiary parameters are suitably chosen.

The procedure Cornwall and Tiktopoulos adopted, it seems to me, is a variation of this general strategy. They break the gauge symmetry explicitly, resume the perturbation series and then, and only then, remove the explicit symmetry breaking, to reach the "high temperature" phase.

Zinn-Justin and Edouard Brézin[37] have studied, as have Migdal and Polyakov, as I understand, the nonlinear σ-model, in $2 + \varepsilon$ dimensions. It bears a striking resemblance to the gauge theory in many ways. One is that at $\varepsilon = 0$, the nonlinear σ-model, in which $\sigma + i\underset{\sim}{\tau}\cdot\underset{\sim}{\pi} = f_\pi \exp(i\underset{\sim}{\tau}\cdot\underset{\sim}{\phi}/f_\pi)$, and which may be considered as a description of the Goldstone phase, has a bad infrared disease; the second is that the β-function has the same behavior as in the gauge theory. They have succeeded, by the aforementioned strategy, in reaching the normal phase in which $\langle\sigma\rangle = 0$.

Actually, the resemblance between the nonlinear σ-model and the gauge theory is more than skin-deep. The lattice gauge theory is invariant under $\prod_n \left[SU_c(3)\right]_n$, where n labels lattice sites: the gauge linkage $U_{n,\hat{\mu}} = \exp\left[iga\, \lambda\cdot A_\mu(n)\right]$ in Ken Wilson's lattice theory[38] is a nonlinear realization of $\left[SU_c(3)\right]_n \otimes \left[SU_c(3)\right]_{n+a\hat{\mu}}$, just as $f_\pi \exp(i\tau\cdot\phi/f_\pi)$ is a nonlinear realization of $\left[SU(2)\right]_L \otimes \left[SU(2)\right]_R$. Bill Bardeen is investigating the dynamical circumstances in which $U_{n,\hat{\mu}}$ takes a form other than the one written down above.

As $\varepsilon \to 0_+$, we expect to recover the real physical situation. From the work of Brézin and Zinn-Justin, it seems clear to me that the σ-model has only the normal phase in 2 dimensions, thus obviating the Coleman theorem which proscribes Goldstone bosons in 2 dimensions. By an obvious extention, I suspect that an asymptotically free gauge theory has only phases in which colored objects are confined.

There are several immediate questions on which we debate hotly. First, what is the order parameter in QCD, which heralds the onset of a new phase? How does a bag picture of hadrons arise in a confinement phase? What happens to the super gauge theory based on $\mathcal{G}$ on a lattice, and are there other ways of breaking $\mathcal{G}$ down to $SU_c(3) \otimes G_{weak}$ in this setting? There are myriads of questions we can raise, or haven't thought about.

XIX. EPILOGUE

There are questions I haven't even begun to summarize, but I am using up very fast the allotted time. I feel a

Voltaire tapping on my shoulder and whispering to me "Cela est bien dit, mais il faut cultiver notre jardin." [39] In contemporary American, I think it means "Shut your trap and go back to work."

We are living in an exciting era. Let's all get back to work. Thank you.

I thank Robert Shrock for his help in the preparation of the manuscript.

FOOTNOTES

These footnotes are personal annotations to the text. They are not intended to be, nor should they be used as, a bibliography. Please refer to individual talks for authoritative references.

[1] See, W. Pauli, Collected Scientific Papers, edited by R. Kronig and V. Weisskopf, (Interscience Publishers, New York, 1964), pp xiii xvi.

[2] R.P. Feynman, in Neutrino-1974, edited by C. Baltay (American Institute of Physics, New York, 1974), pp 299 - 319.

[3] See P. Nath's and B. Zumino's contributions to the Proceedings of the Conference on Gauge Theories and Modern Field Theory at Northeastern University, September, 1975 (to be published by the MIT Press).

[4] For public pronouncement, C.N. Yang, "Some Concepts in Current Elementary Particle Physics," in The Physicist's Conception of Nature, edited by J. Mehra (D. Reidel Publishing Co., Dordrecht, Holland, 1973), pp 447 - 453.

[5] See the summary of Leon Lederman in the forthcoming Proceedings of the Photon/Lepon Symposium at SLAC, 1975.

[6] E.G. Cazzoli, et al., Phys. Rev. Lett., 34, 1125 (1975).

[7] H. Deden, et al., Phys. Lett., 58B, 361 (1975); J. von Krogh, at the Irvine Conference, December 5 (1975); G. Blietszhau, et al., TCL/Int.758, CERN preprint; J. von Krogh, et al., Wisconsin preprint. I wish to thank J. von Krogh and members of the Wisconsin-Berkeley-CERN-Hawaii collaboration

for making available to me their data prior to publication.

[8] Y. Watanabe, et al., Phys. Rev. Lett., 35, 898 (1975);

L. Hand informed me that, to about ±7∿8% absolute accuracy, the Berkeley-Cornell-Michigan State group data fit the empirical formula

$$F_2(\omega,Q^2) = F_2^{SLAC}(\omega')\left(\frac{\omega}{\omega_0}\right)^{b\left[\ln Q^2/(3\ \mathrm{GeV}^2)\right]}$$

where

$$b = .090 \pm .018$$
$$\omega_0 = 6.1(+3.9,-2,4), \qquad \text{(statistical errors)}$$

for $Q^2 \geq 3\ \mathrm{GeV}^2$. The best fit is obtained if the Stein fit in ω' is used for F_2^{SLAC} [(S. Stein, et al., Phys. Rev. D12, 1884 (1975)]. I wish to thank Lou Hand for presenting the data in a form that I can digest.

[9] I. Karliner, "The effect of Heavy Lepton on Charmed Particles Decays", IAS preprint (1975).

[10] I. Karliner and B.W. Lee, private discussion.

[11] See in this connection, J. Kandaswam, J. Schecter and M. Singer, "Possible Enhancement of the Leptonic Decays of Charmed Pseudoscalars," Syracuse preprint (1975).

[12] See Peter Minkowski's talk in these Proceedings, and the discussion in a later section.

[13] See for example M.K. Gaillard, B.W. Lee and J.L. Rosner, Revs. Mod. Phys. 47, 277 (1975).

[14]E. Golowich and B. Holstein, Phys. Rev.Lett. 35, 831 (1975).

[15]Pakvasa and H. Sugawara, Hawaii preprint (1975).

[16]L. Maiani, "CP Violation in Purely Lefthand Weak Interactions," Rome preprint (1975).

[17]M. K. Gaillard and B.W. Lee, Phys. Rev. Lett., 33, 108 (1974). G. Altarelli and L. Maiani, Phys. Lett., 52B, 351 (1974).

[18]My recent readings on this subject include: G. Farrar, Phys. Rev. D4, 212 (1971); M.K. Gaillard, Nuovo Cimento 6A, 559 (1971). For a more complete bibliography see the papers A. Zee cited.

[19]This is a tribute to M.K. Gaillard. I thank her for intense discussions on this point during the SLAC Photon/Lepton Symposium in 1975. See also footnote 20 below, especially the note added in proof.

[20]J. Ellis, M.K. Gaillard, and D.V. Nanopoulos, Nuclear Physics B100, 313 (1975).

[21]I believe the following points were first made in the literature by M.K. Gaillard, "Charm," in *The Proceedings of the Xth Rencontre de Moriond*, edited by J. Tran Thanh Van, (CRNS publication, 1975); see also A. Pais and S.B. Treiman, Phys. Rev. Lett., 35, 1556 (1975); talks of L. Wolfenstein and C. Llewellyn-Smith at the SLAC Photon/Lepton Symposium, 1975.

[22]The characteristic x and y distributions of the dimuon events in the charm scheme were emphasized in B.W. Lee, "Dimuon Events," in the forthcoming *Proceedings of the Conference on Gauge Theory and Modern Field Theory* (to be published by the MIT Press).

[23]See the talk of B. Roe in the forthcoming Proceedings of the Photon/Lepton Symposium at SLAC, 1975.

[24]F. Gürsey, "Color Qaurks and Octonions," in The Johns Hopkins University Workshop on Current Problems in High Energy Particle Theory, 1974. G. Domokos and S. Kövesi-Domokos, (eds.) pp 15-42 (Physics Department, The Johns Hopkins University).

[25]H. Georgi and S.L. Glashow, Phys. Rev. Lett., 32, 438 (1974).

[26]H. Fritzsch, M. Gell-Mann and P. Minkowski, Phys. Lett., 59B, 256 (1975).

[27]H. Georgi, H.R. Quinn and S. Weinberg, Phys. Rev. Lett., 33, 451 (1974).

[28]T. Appelquist and J. Carazzone, Phys. Rev. 11, 2856 (1975).

[29]J. Ellis, M.K. Gaillard and D.V. Nanopoulos, "A Phenomenological Profile of the Higgs Boson," CERN preprint (1975).

[30]S. Weinberg, "Mass of the Higgs Boson," Harvard preprint.

[31]D. Cline, in a luncheon conversation.

[32]M.K. Gaillard, private communication.

[33]T.T. Wu and C.N. Yang, "Concept of Nonintegrable Phase Factors and Global Formulation of Gauge Fields" and "Some Remarks about Unquantized Non-Abelian Gauge Fields," to be published; C.N. Yang, Phys. Rev. Lett., 33, 445 (1974).

[34]A.A. Migdal, "Gauge transitions in Gauge and Spin Lattice Systems," L.D. Landau Institute for Theoretical Physics preprint (1974).

[35]A.M. Polyakov, Phys. Lett. 59B, 79 (1975).

[36]See for example, B.W. Lee "Chiral Dynamics," (Gordon and Breach, New York, 1972).

[37]E. Brézin and J. Zinn-Justin, "Renormalization of the Nonlinear

σ-model in 2 + ε Dimension -- Application to the Heisenberg Ferromagnets," a private note.

[38]The best reference may be K. Wilson's lectures in the forthcoming Proceedings of the Erice Summer School, 1975.

[39]Voltaire, in Candide, ou l'Optimisme.