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THE NEW ORTHODOXY: HOW CAN IT FAIL?

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I. Progress

During this last decade, neutrino-physics has evolved from its crude beginnings into a highly quantitative branch of particle physics. And during this decade, particle-physics itself has developed extremely rapidly and fruitfully into a state which is far reaching, surprisingly rigid, and broadly accepted. In fact it is only in about the last five years that the concepts central to the present orthodoxy really took hold and began to dominate our picture of particle interactions. All the concepts were actually in place in 1974, even before the November Revolution. Provided one's copy of the 1974 London Conference has not completely disintegrated, one need only refer back to John Iliopoulos' talk there[1)] to find a remarkably complete exposition of the contemporary orthodoxy. And by this I mean the whole works: grand unified SU(5) and almost all its ramifications.

In the interim this nascent orthodoxy was sorely tested. Even after the discovery of the ψ there ensued two years delay and confusion in the firm establishment of the charm quantum-number. There were the problems of the high-y anomaly and ν-induced trileptons, the perplexing role of the τ-lepton, the $\mu \to e\gamma$ rumors, confusion in the atomic-physics neutral-current experiments, and the shift in the value of $\sin^2\theta_W$ from ~0.3-0.4 to ~0.2. These perturbations on the orthodoxy have provided us with a measure of the elastic constant of the basic gauge structure. It has been found that the elastic constant is quite low: given a new phenomenon, a gauge-theory (or more often many gauge theories) can be found which accounts for the purported effect. In addition one has found that this gauge-theory structure is not only elastic and "soft" but is critically damped; upon removal of such external stimuli the theory quickly returns to the equilibrium orthodox state, with a minimum of reverberations.

We have now reached a quiet time. Other than some residual confusion among the atomic parity-violation experiments, the smallest feasible gauge-theory-structure [$SU(2) \otimes U(1)$ for electro-weak, SU(3) for strong, and SU(5) for grand unification] accounts very well for the observations[2)]. The situation really is remarkably satisfactory. It is no wonder that, after the false alarms and relatively extravagant theoretical responses of the past few years, there is at present such a mood of minimalism and complacency. Theorists now tend to shave their theories with Ockham's Razor: there shall be three generations of fermions, one neutral Higgs boson, the $W^{\pm}$ and Z; and then nothing new until 10^{15} GeV. Measure the proton lifetime, the parameters of the quark mass-matrix, find the Higgs boson (mass 10.6 GeV?), find $W^{\pm}$ and Z^{o}, and that's it.

There is good reason for this attitude. Although neither QCD nor the gauge-theory aspects of $SU(2) \otimes U(1)$ are at all solidly established experimentally, one will hear plenty of reasons at this meeting for taking the orthodoxy very seriously. And it is a heady business to even be able

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to consider seriously an extrapolation of particle-physics concepts by 10 to 15 orders of magnitude, enabling one even to consider at a scientific level the origin of baryon-asymmetry in the Big Bang at temperatures of $\sim 10^{15}$ GeV. Some might call this attitude either arrogance or wild optimism, but I don't agree. After all, the theories of gravitation and electromagnetism have been extrapolated 20 to 30 orders of magnitude beyond the original distance-scales for which they were formulated. Given their equally fundamental character, why not QCD and the electro-weak SU(2) ⊗ U(1)?

But whatever the pros and cons for accepting the orthodoxy, there are the attendant dangers common to any orthodoxy. With the risk of being banal, I feel compelled to express what I see as the biggest danger, which is that experiments become too sharply focused. While searches for what is predicted by the orthodoxy will proceed, searches for phenomena outside the orthodoxy will suffer. Even more important, marginally significant data which support the orthodoxy will tend to be presented to — and accepted by — the community, while data of comparable or even superior quality which disagrees with the orthodoxy will tend to be suppressed within an experimental group — and even if presented, will not be taken as seriously. I do not mean to impugn experimentalists by such statements. I think this bias is just an inevitable consequence of Big Science and the natural conservatism which emerges from the committee-like processes present in collaborations involving a large number of people and even institutions, as well as large amounts of money and time.

All this is a cliche, and perhaps an insult to the reader's intelligence and sensibilities. Nevertheless, even while being swept along by the present excitement, I do feel we must resist this bias, search for alternatives, and check with great care that we are on the right track.

But how? Random searches for crazy phenomena are a hard way to live. We have to make use of what is known. Various approaches present themselves. One is to build beyond the present orthodoxy in the same way that SU(5) grand unification builds on QCD and electroweak unification. The supersymmetry-supergravity program is the prime example at present[3)]. There is so far not enough success — or focus — to suggest a very definite line of experimental attack, although searches for gluinos and gravitinos have been considered and discussed[4)].

Another attack consists of perturbing or enriching the orthodoxy without really touching the foundations. Yet another, so conservative that it becomes radical, is to critically examine what is the minimal amount of theory needed to interpret the data (or at least most of it), keep that much, throw away the rest, and rebuild.

These options will be discussed in the next sections. None of these ways may suffice; sometimes the more profound, discontinuous change (like from the bootstrap to the quark model) is needed to get on the right path. I won't discuss that. I wish I could.

II. Gentle Heresies

Without even describing the orthodoxy (that is done in many other places[5)]) we go on to a catalogue of variations on the theme. These will help, if nothing else, to elucidate many of the unanswered questions present within the orthodoxy:

(1) More Generations

Is it 1,2,3,... infinity or does the replication of generations stop? Astrophysical arguments[6] limit the number of sequential, massless two-component neutrinos, and bounds on radiative corrections[7] to the relation $m_W/m_Z = \cos\theta_W$ limit the mass-differences between members of weak doublets to less than a few hundred GeV. More generations also tend to mess up the "standard" SU(5) grand-unification scenario; three is preferred[8]. Nevertheless a fourth generation is a possibility.

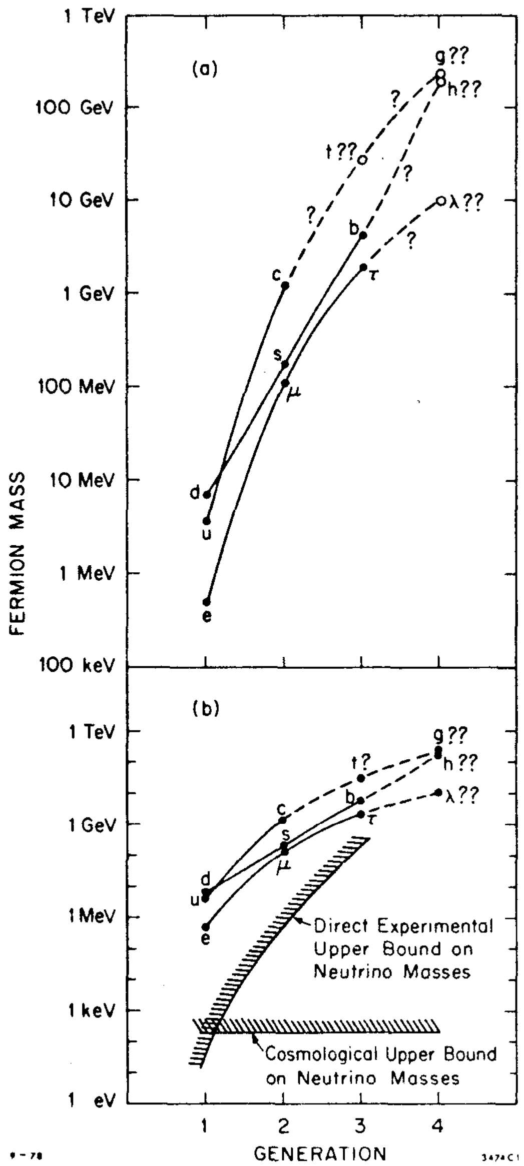

Fig. 1. Hypothetical spectrum of fermion masses.

My own favorite wild guess[9] for the fourth-generation masses is shown in Fig. 1. It is simply phenomenological curve-fitting. Toponium lies at 50-60 GeV and out of range of PEP/PETRA, but a fourth generation lepton λ with $m_\lambda \sim$ 10-15 GeV should be seen. The fourth generation quarks $Q = g,h$ could be roughly degenerate in mass, with $m_Q \sim$ 100-200 GeV. They would be splendid particles. They might be produced by pp or $p\bar{p}$ collisions at Fermilab or Isabelle with nanobarn cross sections, and would be very visible, inasmuch as they decay into W + quark leading to 6-jet final states, with each jet carrying $\gtrsim$ 30 GeV of momentum:

$$p\bar{p} \rightarrow Q + \bar{Q} + \ldots$$

$\bar{Q} \rightarrow W + \bar{q}$, with $W \rightarrow q + \bar{q}$

$Q \rightarrow W + q$, with $W \rightarrow q + \bar{q}$

Such quarks would be coupled to a Higgs-boson more strongly than to the photon and almost as strongly as to a gluon.

(2) Surprises in the Mass Matrix

Given the orthodoxy, it is a regrettable fact of life that most of the parameters of the mass matrix of quarks (and leptons) are input and not derived. Thus there may be some surprises. The most accessible surprise would involve the bottom quark, leading to either an abnormally long lifetime or curious decay modes. For example, Derman[10)] uses permutation symmetry to relate masses and mixings of different fermion generations and ends up with very peculiar decay modes of the bottom-quark, such as

$$b \rightarrow q\mu e$$

We should not forget that the mass and mixings of the quarks are very poorly understood. The prevailing expectation that the bottom quark lifetime is very short rests on the presumption that CP violation originates in the quark mass matrix. This is a quite indirect line of reasoning dependent on the most fragile structure in the theory — that of the Higgs sector.

(3) <u>More Intermediate Bosons</u>

Georgi and Weinberg showed[11)] that any electroweak gauge theory of the form $SU(2) \otimes U(1) \otimes G$ and with an appropriate Higgs structure reproduces the low-energy phenomenology. <u>Any</u> such extension will bring with it extra neutral gauge-bosons which mix with Z^o and consequently modify the predicted Z^o mass. Georgi and Weinberg further showed that at least one of these neutral bosons must have a mass less than the standard mass of ~94 GeV. That is a reassurance to LEP and other accelerator builders. Nevertheless, it still might make a difference in the planning of machines if there were two Z^o's at masses of 60 GeV and 120 GeV instead of one at 94 GeV.

(4) <u>Right-Left Symmetry: Neutrino Oscillations</u>

The familiar right-left symmetric models[12)] based on $SU(2)_L \otimes SU(2)_R \otimes U(1)^N$ can be made a special case of the above scheme. They also emerge from grand unification based on SO(10). A most characteristic feature of such schemes is that parity-conservation is intrinsic; parity-violation is included by spontaneous symmetry breaking. Neutrinos are now four-component objects, and there is no particular reason why they shouldn't have mass and mix. Thus in this case neutrino-oscillations are a credible phenomenon. On the other hand, theory is hard put to explain why such a neutrino mass, while nonvanishing, is so tiny.

(5) <u>Replication of the Fermion Generations Breaks Down</u>

Maybe there are only two generations, and the b is a singlet under $SU(2)_L$. Then it decays via an unknown mechanism, with unknown lifetime and decay modes. Is this credible? Within a grand-unified scheme[13)] based on the exceptional group E6 it is: the representation-content is such that there are only u and c as $|Q| = 2/3$ quarks, while there are four $|Q| = 1/3$ quarks d,s,b and h. There are also extra heavy leptons, neutral and charged. This scheme originally have trouble with the value of $\sin^2\theta_W$; a number closer to 3/8 was preferred. However, by directly breaking E6 to $SU(3) \times SU(2) \times U(1)$ near the grand unifying mass-scale, a value of $\sin^2\theta_W \sim .25$ can be obtained[13)].

(6) More Higgs Particles

There is no particular reason to proliferate Higgs-bosons. There is also no reason to expect the Higgs-sector to be less rich than the fermion sector. Thus one should search[14)] for charged Higgs-bosons and their effects, as well as for Higg's more strongly coupled than one expects for the orthodox h^o. This is a rather undisciplined business, with theory providing only crude and overly flexible guidelines.

From the point of view of the orthodoxy, proliferation of Higgs-bosons endangers the satisfactory condition of "natural" flavor conservation[15)] which exists for only one Higgs-boson: one must be careful that $K^o - \bar{K}^o$ mixing is not too large.

(7) Connections Between Generations

The replication of generations is very suggestive of a symmetry relating them. If this is a continuous symmetry, then we can expect it to be gauged[16)]. If there are gauge bosons X connecting the generations, it is hard to avoid flavor-changing neutral currents; hence reactions such as

$$\mu \rightarrow e\gamma$$

$$K_L \rightarrow \mu e$$

$$K^{\pm} \rightarrow \pi^{\pm}\mu e$$

ought to proceed via X-exchange. The branching-ratio varies typically as the fourth power of m_X, which for a typical ($O(\alpha)$) coupling constant of X to fermions puts $m_X \gtrsim 20$ TeV. With no theoretical guide that bounds m_X from above, it is rather discouraging to invoke this mechanism in urging experimentalists to improve the limits on flavor-changing processes such as $K_L \rightarrow \mu e$. Nevertheless, given the obscurity of the origin of generations and of the Cabibbo mixing between them, it is an important goal.

(8) Existence of Fractionally Charged Hadrons

This may seem like a radical perturbation on the orthodoxy, but it need not be so[17)]. If we give the octet of QCD gluons a small mass (say, via the Higgs-mechanism) the short-distance properties of the theory (including the option of grand unification and all that) should remain unchanged — and the theory should still exist. What in the theory changes? There could exist real quarks (and perhaps gluons) of large mass and large size; as the gluon mass tends to zero the mass and size of the unconfined quark should tend to infinity. It is a challenge for QCD theorists to estimate an upper bound on the bare-gluon-mass which is consistent with data. (My own guess is $\lesssim 20$ MeV.)

How to search for such real quarks is an uncertain business. Production cross sections are utterly unknown, as are the interaction of unconfined quarks in matter. The most stable fractionally charged hadron might even have large baryon number, and in any event an unconfined quark may accrete nucleons at it traverses matter[18)].

(9) No Fractionally-Charged Quark Model At All

The leading alternative to fractionally-charged constituents is a gauged version of the Han-Nambu three-triplet model[19]. This has been most consistently pursued by Pati and Salam[20]. The Pati-Salam scheme has had difficulty[21] with the nonobservability of a predicted $\tilde{U}$-boson which mixes with the photon. If overt colored particules exist in the charm region, the $\tilde{U}$ should have a mass less than 4 GeV and a large leptonic width. Pati and Salam have recently pushed the scale of any overt color higher; the mass of the $\tilde{U}$ is now asserted to be over 7 GeV. The mechanism invoked[22] appears to have considerable resemblance to that of deRujula, Giles and Jaffe[23].

One might expect that as the threshold for production of physical colored states is pushed to infinity, the model reverts to the standard fractionally charged quark model. This is true in any process involving a single gauge boson. When two (or more) are simultaneously involved, there are differences. The most accessible tests[24] seem to be using the decays $\eta \to \gamma\gamma$ and $\eta' \to \gamma\gamma$. The predicted differences between integer and fractionally charged sources are typically a factor ~2. Data[25] supports fractional charge; however ambiguity in the strong-interaction parts of the problem still leaves the test less than decisive[26].

We may also note that it is not clear how to fit the τ lepton and b quark into the Pati-Salam scheme. It would have been easier were the number of quark flavors to have stopped at 4.

III. Composite Degrees of Freedom and Other Heresies

The orthodoxy presumes elementarity of the degrees of freedom (fermions, gauge-bosons, Higgs-particles) even at distances comparable to the Planck-length. This is evidently an extremely strong assumption, and we may question what happens if it is relaxed.

(1) Higgs-Bosons

The Higgs-sector is the ugly duckling of electroweak or grand-unified theories. There are several sources for this:

(a) The Higgs self-couplings and Yukawa couplings (as normally introduced) have nothing to do with gauge-couplings or gauge theories. Imagine the (grand-unified) world with the gauge coupling (that means α, α_s, and α_{wk}) set to zero. In a true pure gauge theory we would expect this limit to correspond (at most) to collections of free fermions and gauge-quanta. But what happens in the orthodox world? We are apparently left with a self-interacting Higgs sector coupled via Yukawa couplings to fermions; this Higgs-sector also contains massless Goldstone-bosons. Unless the Higgs-couplings themselves are somehow radiatively induced[27], one is left with something of a mess. In the orthodox SU(5), there are between one dozen and two dozen undetermined parameters[28].

(b) Higgs-boson self-masses are quadratically divergent; parameters in the Lagrangian must be fine-tuned[29] to make the masses of W and Z 10-15 orders of magnitude smaller than the grand-unifying scale.

(c) Radiative corrections, such as W-pair exchange, necessarily couple superheavy Higgs bosons of mass ~ Planck mass (e.g., the 24 of SU(5)) with those (e.g., the 5 of SU(5)) responsible for giving m_W and m_Z their mass[30]. This tends to equalize the two mass-scales, and again fine-tuning is necessary to maintain order.

(d) Were the Higgs 5 and 24 to be nearly decoupled, there would emerge extra pseudogoldstone bosons of the 5 with leptoquark quantum numbers. These pseudogoldstone bosons also induce proton decay and have to be made superheavy. There is a potential problem in finding a mechanism for giving them a very big mass while at the same keeping m_W and m_Z with very small mass[31].

(e) Despite many ingenious and partially successful attempts, Cabibbo mixings and the hierarchy of fermion masses (e.g., the large value of $m_\tau/m_e \sim 3000$ or $m_t/m_u > 2000$) are in the main unexplained.

To cope with these problems, it is an attractive — some[29] would say compelling — idea to make the Higgs-bosons composites of fermion-anti-fermion pairs, bound together by a new kind of strong interaction — hopefully some other nonabelian gauge theory. This is an old hope[32], and it has recently undergone revival and rejuvenation, with considerable progress made[33]. The main problem (if it is one) is that it seems hard to account for the rich structure in the fermion mass-matrix without introducing a rather ponderous, extravagant set of new gauge-groups and fermion representations. Ockham is not well served.

The main experimental implication of this approach is that the Higgs-sector contains a new class of strong interactions and attendant strongly interacting quanta. The natural setting is a TeV mass-scale (and above). Entry into such a world would require multi-TeV colliding beams — probably pp or $p\bar{p}$. But it is a problem whether the ordinary quarks and gluons which predominate in p and $\bar{p}$ beams are coupled to this new sector strongly enough — and with some clean identifiable signature — that this sector can be discovered, even if it is there[14]. Were the aforementioned 100-200 GeV superheavy quarks to exist, it might make the problem easier.

(2) Fermions

This option, while obviously desirable, given the proliferation of flavors and leptons, seems to be hard to implement. If the quarks are on the same footing as leptons, then one must consider composite neutrinos along with everything else. And that's hard to consider.

Aside from any detailed theory, probably the most direct test for compositeness is, for quarks, to search for power-law violation of deep inelastic scaling. For leptons, one may look for gross violation of QED (or electroweak theory) in $e^+e^- \to \mu^+\mu^-$ or Bhabha scattering.

Harari[34] has made a brave foray into this area, building all fermions from threefold composites of two spin-1/2 "rishons" of charge 0 and 1/3. Higher generations are, somehow, dynamical excitations of the lowest generation. Gluons, $W^\pm$ and Z^0 are composites of six (!) rishons. Gauge-theory strong and electroweak dynamics as we know it is scuttled. But Ockham is well served.

(3) Gauge-Bosons

To consider gauge bosons composite (on a distance scale large compared to the grand-unified scale) is real heresy. There is then apparently little meaning left to the grand-unification idea at all. Nevertheless, although much less attractive, it is possible to take such a position[35,36]. The success of the Weinberg-Salam effective Lagrangian in describing low-energy weak processes does not imply the full $SU(2) \otimes U(1)$ gauge theory. The alternative could be exchange of ungauged intermediate bosons, as discussed in detail by Hung and Sakurai[37]. These bosons probably interact strongly with each other at sufficiently high energies. The best hopes of a test lie in measuring m_W and m_Z. In such a generalization, they need not take the standard values. However, m_W is constrained to be smaller than 37 GeV/$\sin^2\theta_W \sim 175$ GeV. Another test is to measure $\sigma(e^+e^- \to W^+W^-)$ above threshold to check for the expected gauge-theory cancellations which are supposed to keep the cross section relatively small[38].

I, and independently Shei and Glashow[39], even tried to eliminate $W^\pm$ and Z completely by going back to the old Kummer-Segre idea of constructing the weak interaction out of exchange of a pair of spinless bosons. In this case each boson carries weak-isospin of unity. Up to a point, the idea works. Structurally, one obtains the Weinberg-Salam effective Lagrangian. However, the idea falters when one tries to find parameters which give $\sin^2\theta_W \sim 0.2$. The reason the idea does not survive easily is that, whatever the weak quanta are, one <u>must</u>, according to quite general arguments[36], copiously produce them in e^+e^- annihilation. "Copiously" means a value of

$$R = \frac{\sigma(e^+e^- \to \text{weak quanta})}{4/3\, \pi \alpha^2 s^{-1}}$$

which, when averaged over energy is large compared to 10. [The contribution in the orthodox theory is the Z^o resonance.] The puny contribution of $R = 1/4$ from a pair of spinless charged quanta just doesn't have the clout. The message of this exercise is that if one wants composite objects to mediate the weak interaction it is difficult to restrict them to pairs of spin-zero and/or spin 1/2 objects. Such constituents do not provide enough e^+e^- colliding beam cross section to satisfy the general constraints on R. A strongly-interacting system (bootstrap?) of W's and Z's seems to be the most viable alternative left.

IV. Summary and Comments

The reader will have noticed that most of the excursions away from the orthodoxy of grand-unified SU(5) only tend to make matters worse without providing much of intrinsic benefit. Nevertheless, the "gauge-hierarchy" problems in the SU(5) scheme — namely the smallness of m_W and m_Z relative to the grand-unification scale, the pattern of large mass-ratios of fermions and the plethora of poorly-understood mixing angles — create a serious credibility problem for the orthodoxy. Perhaps one can have the best of both worlds by accepting SU(5) as the appropriate symmetry at the very short distance scale, along with its breaking (via the $\underline{24}$) into $SU(3) \otimes SU(2) \otimes U(1)$, but by rejecting any claim of understanding the origin of quark masses <u>and</u> the masses of W and Z (in other words everything to do with the Higgs 5). This is not to say there is no "low-mass" ($\lesssim 1$ TeV) Higgs-sector; in the gauge-theory framework the longitudinal components of W and Z at any distance-scale small compared to m_W^{-1} must be elements of some kind of Higgs-system. We only mean to plead ignorance regarding its nature.

What is retained and what is lost by this tactical retreat? One retains the prediction of $\sin^2\theta_W \approx 0.2$, the neat, efficient classification of fermions into SU(5) representations, and the estimates of proton lifetime. One loses the prediction of the ratio of m_b to m_τ. This may not be bad inasmuch as the same argument gives a poor number for m_d/m_e and a marginally acceptable one for m_s/m_μ.

Accepting this situation[40)] we can look again at our list of heresies to see which look the most credible. A most important one is that of intergeneration relationships, implying hot pursuit of $\mu \to e\gamma$, $K_L \to \mu e$, etc. Another is a hunt for the heaviest possible quark (or lepton) as a promising way of gaining access to the Higgs-sector. Heavy unconfined quarks might signal a small, nonvanishing gluon mass, providing another handle on the origin of mass-generation. Existence of neutrino oscillations might signal a right-left symmetric variant of the theory emergent from a grand-unifying SO(10). The remaining heresies (e.g., neutral leptons, exotic quark color or flavor representations, W's and/or Z's with the wrong mass or self-interaction) could signal more radical departures from the orthodoxy. But no matter what is the right answer, there is no room for complacency. The possibilities are as rich as ever, and we must continue to look everywhere we can to try to uncover them.

V. Acknowledgements

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