ADDENDUM

SUMMARY TALK[*][†]

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I. Introduction

Several years ago, the task of summarizing a high-energy-physics conference used to be extremely difficult. There was very little (or no) relationship among topics such as strong interaction phenomenology, hadron spectroscopy, weak interaction processes, etc. A coherent discussion of all of these subjects was almost impossible. One of the remarkable achievements of the last few years of theoretical and experimental work is the emerging unity of all of these topics. All interactions seem to be described by gauge theories which are testable by an ever-increasing number of experimentally feasible measurements. Attempts to unify the fundamental interactions, while not yet entirely successful, are already at the stage of providing us with interesting analogies and with connections between different basic forces and building blocks of matter. These developments enable us to discuss the various topics presented in this Summer Institute as components of a general overview of the field of high energy physics. This summary will therefore be presented as a "tourist guide" over a "road map" of the fundamental interactions (Fig. 1). We will describe the scenery at each significant road or junction on our map, and try to use their recent history in order to predict possible future developments. A summary talk should always emphasize the open, unsolved problems which we face. There is no shortage of such problems, and we will discuss them along the way.
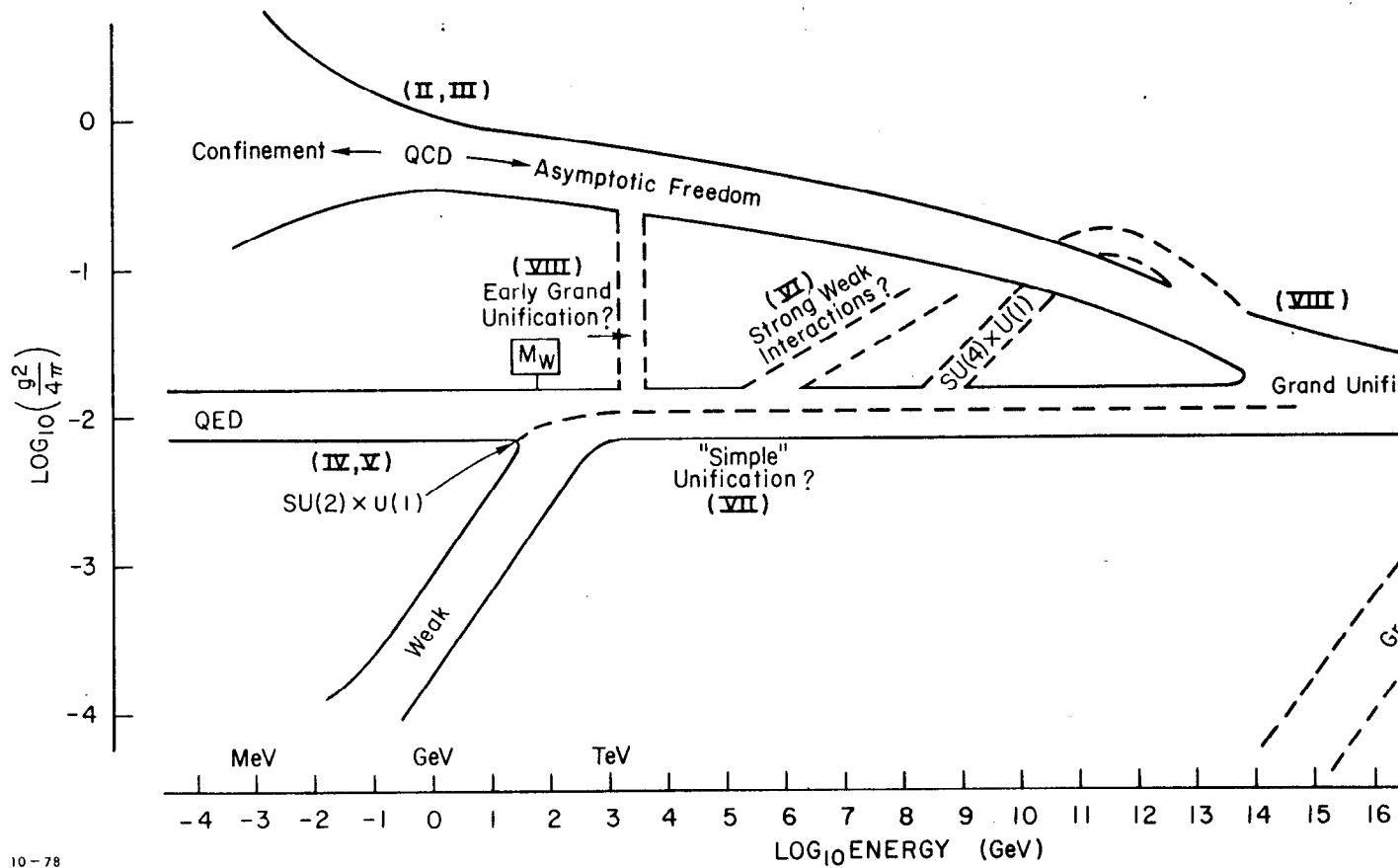
Fig. 1: A "map" of the fundamental interactions. The coupling strengt[h] versus energy on a log-log scale. The weak interactions and QED merge [around the mass of the W, but "true" unification is not achieved. QCD [has loga]rithmically decreasing strength, merging with the electro-weak interact[ion at the "grand] unification" mass. Speculative possibilities include "early grand unif[ic]ation", strong weak interactions, electro-weak groups larger than [SU(2)×U(1) and] finally extended supergravity. The sections in which each topic is dis[cussed are] marked on the "map".

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II. QCD--A Theory of Strong Interactions

Quantum Chromo-Dynamics is the leading candidate theory for the strong interactions of quarks and gluons. It has recently enjoyed so much popularity that we tend to forget that the <u>direct</u> experimental evidence for it is meager, at best. The high momentum behaviour of the theory is reasonably well understood. The low momentum regime is far from being fully analyzed.

At <u>high momenta</u>, QCD exhibits asymptotic freedom.[1] Its effective coupling "constant" diminishes logarithmically, and the use of perturbation theory is probably justified. Well-defined predictions can be made for a large number of high momentum processes such as deep inelastic scattering, large p_T processes, e^+e^- collisions, Drell-Yan processes, etc. There is no difficulty in deriving such predictions concerning quarks and gluons. The "only" difficulty is the translation of these predictions into a language involving measurable hadronic quantities. Nevertheless, using simple parton-model ideas, at least some of the predictions can be translated into experimentally meaningful statements. The most direct prediction of asymptotically free QCD involves the pattern of scaling violation in deep inelastic processes. We will briefly return to them in our next section.

The <u>low-momentum</u> domain of QCD has been the subject of elaborate analysis. Rich and beautiful nonperturbative phenomena have been discovered,[2] but their direct connection with the experimental world, has not yet been firmly established. We suspect that the large distance, low-momentum, behavior of QCD is not governed by the rules of perturbation theory. We know that the vacuum of the theory has a much richer structure than anyone had suspected several years ago. However, we do not know whether quark and gluon confinement are a direct logical result of QCD, and no one has yet succeeded in computing the general pattern of low energy hadron spectroscopy, starting from a general QCD framework.

Thus, at present, the main attraction of QCD is in its elegant mathematical structure, in its analogy to the successful gauge theories of the other interactions and in the lack (so far) of any reasonable alternative. Its experimental verification still lies ahead.

In testing QCD, it is important to distinguish between several levels of hypotheses. We usually assume that:

    (i)   Quarks are hadronic constituents.

    (ii)   Quarks come in three colors.

   (iii)   Gluons are hadronic constituents.

    (iv)   Gluons are vector particles.

    (v)   The interactions of quarks and gluons are $SU(3)_C$-symmetric.

    (vi) $SU(3)_C$ is a local gauge symmetry, leading to asymptotic freedom, etc.

It is important to realize that only tests of assumption (vi) can be regarded as convincing tests of QCD. Some alleged QCD tests probe only assumptions (i)-(iv). Other tests probe even less!

A particularly interesting system which enables us to study the different domains of QCD is Quarkonium.[3] The nonrelativistic quark-antiquark potential can be probed by observing the properties of different energy levels of different systems such as $c\bar{c}$ (ψ-family), $b\bar{b}$ (T-family) and similar systems involving future heavier quarks. The short distance behavior of the potential is presumably Coulomb-like. The large distance behavior is apparently determined by the low momentum, nonperturbative aspects of QCD. The potential may be rising linearly at large distances. It may also have other, indefinitely rising, functional forms. However, none of this has been proven, so far, either theoretically or experimentally. As additional levels of Quarkonium are studied, we gain better understanding of wider ranges of the quark-antiquark potential. However, we are very far from a convincing complete description of all nonrelativistic $q\bar{q}$ forces.

III.   QCD--Experimental Tests

The strongest available experimental evidence for the validity of QCD comes from the q^2-dependence of deep inelastic structure functions. The asymptotic freedom property of QCD tells us that the hadronic structure functions in deep inelastic electron, muon and neutrino scattering obey approximate scaling, with logarithmic deviations. The precise form of the logarithmic q^2-dependence

requires a knowledge of the quark and gluon distributions inside the hadron. However, some of its qualitative features are clear. For instance, at fixed x near x = 1, the inelastic hadron structure functions $F_2(x,q^2)$ should decrease at large q^2, while near x = 0 it should increase. The rate of fall is more and more pronounced as x approaches 1, but the leading term is always given by a power of $(\log q^2)$. Some successful phenomenological fits to the data have been obtained and the qualitative trend is certainly in agreement with QCD.[4]

A more impressive test which depends on a relatively small number of assumptions involves the anomalous dimensions of the moments of the F_3 structure function in inelastic νN and $\bar{\nu} N$ scattering. Defining the Nth moment of F_3 as:

$$M_3(N,q^2) = \int_0^1 dx \; x^{N-1} \; F_3(x,q^2)$$

we know that, to leading order in $\log q^2$:

$$M_3(N,q^2) \;\propto\; (\log q^2)^{-d_N}$$
$$q^2 \to \infty$$

where d_N is completely determined by QCD. Each d_N depends on N_f, the number of quark flavors, but ratios of d_N's are independent of N_f. A plot of $\log M_3(N_1,q^2)$ versus $\log M_3(N_2,q^2)$ enables us to find the experimental value of d_{N_1}/d_{N_2}, thus providing us with a direct test of QCD. Such a test has now been performed by the BEBC group[5] and the results are in good agreement with the prediction of QCD. Other tests of QCD are less definitive, either because of lack of data at sufficiently high momenta or because of theoretical ambiguities in translating predictions concerning quarks and gluons into statements concerning detectable hadrons.

Some of the possible areas of QCD tests are:

(a) Large transverse momentum phenomena in hadronic collisions.

(b) High mass lepton-pair production in hadronic collision.

(c) Energy dependence of R = $\sigma(e^+e^- \to hadrons)/\sigma(e^+e^- \to \mu^+\mu^-)$.

(d) Studies of transitions forbidden by the Zweig-Iizuka rule and their dependence on the number and momenta of exchanged gluons.

(e) Properties of hadronic jets in e^+e^- collisions and in
decays of Quarkonium systems.

(f) Possible observation of "glueballs."

In all of these fields much more experimental and theoretical work is needed before we can reach definite conclusions on the validity of QCD as the correct theory of strong interaction physics.

IV. SU(2) × U(1)--A Theory of Weak and Electromagnetic Interactions

We now have a successful "standard" gauge theory of the weak and electromagnetic interactions, based on the Weinberg-Salam SU(2) × U(1) model,[6] and including three generations of quarks and leptons. The gauge bosons are W^+, W^-, Z^0 and the photon. All left-handed quarks and leptons are in doublets. All right-handed quarks and leptons are in singlets. The assignments of the fermions are:

(I) $\begin{pmatrix} u \\ d \end{pmatrix}_L$ $\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L$; $(u)_R$ $(d)_R$ $(e^-)_R$

(II) $\begin{pmatrix} c \\ s \end{pmatrix}_L$ $\begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L$; $(c)_R$ $(s)_R$ $(\mu^-)_R$

(III) $\begin{pmatrix} t \\ b \end{pmatrix}_L$ $\begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$; $(t)_R$ $(b)_R$ $(\tau^-)_R$

Not all of these assignments are equally well-established. Some of the open questions are:[7,8]

(a) A set of three Cabibbo-like angles and one phase define the mixing matrix among the left-handed quarks of the three generations. All we know about these angles, at present, is:

$$\theta_1 = 13^\circ; \quad \theta_2 < 30^\circ; \quad \theta_3 < 16^\circ; \quad \delta > 0.3^\circ.$$

It is important to determine the angles and test for self-consistency.

(b) We have no direct evidence for the classification of right-handed fermions beyond the first generation. The assignments of c_R, s_R, t_R, b_R to singlets follows from the requirement of "natural" flavor conservation by

neutral currents together with the known classification of u_R, d_R. The assignment of μ_R and τ_R to singlets is based on wishful thinking.

(c)   The assignment of e_R to a singlet is based on the SLAC polarized ed experiment.[9] Other assignments for e_R are probably, but not certainly, excluded. ·

(d)   Needless to say, the t-quark and the τ-neutrino are yet to be discovered.

(e)   We do not yet know whether all or some of the neutrinos are massless. If any neutrino has a mass, it would have a right-handed component.

Modulo the above remarks, the SU(2) × U(1) model has been extremely successful,[10] and all noncontroversial data agrees with it, provided that the Weinberg angle θ_W obeys:

$$\sin^2\theta_W \sim 0.22$$

We must remember, however, that SU(2) × U(1) is not a truly unifying theory of weak and electromagnetic interactions. The independent weak and electromagnetic coupling constants are re-expressed in terms of two parameters, not one! There is no way of computing θ_W within SU(2) × U(1). This is why we left a dashed dividing line in the common road of weak and electromagnetic interactions (Fig. 1). We will return to this point in Section VII.

It is interesting to ask whether the third generation of quarks and leptons is the last one, or whether additional generations will be discovered. Neither the SU(2) × U(1) theory nor QCD are equipped to answer such a question. We have cosmological limits on the number of flavors of massless neutrinos. We have a distant upper limit of sixteen quark flavors, if we want QCD to retain its asymptotic freedom property at arbitrarily high momenta. However, we have no good arguments for the necessity of any given number of quark or lepton flavors, or for determining the number of generations of fermions.

An important symmetry which is only beginning to be explored, is the explicit symmetry between different generations of fermions in the Lagrangian for weak, electromagnetic and strong interactions. For n generations we have at least a discrete permutation symmetry under S_n (the symmetric group)[11] and at most a full gauge symmetry under a U(n) algebra, whose generators connect different generations

of fermions.[12] The properties of these symmetry groups are closely related to the important question of determining the fermion masses and the Cabibbo-like angles.

Thus, even if SU(2) × U(1) is eventually established as the correct theory for the weak and electromagnetic interactions, there is still a long series of fundamental questions which will remain unanswered.

But what is the experimental evidence for SU(2) × U(1)?

V. SU(2) × U(1): Experimental Tests

The Weinberg-Salam SU(2) × U(1) theory has passed its first round of tests with amazing success. All neutral-current phenomena seem to agree well with the predictions of the theory,[10] leading to a unique classification of all first-generation left-handed and right-handed quarks and leptons, and to a unique value of $\sin^2\theta_W$. The only remaining experimental controversy relates to the atomic physics search for parity violation. It is important to note that not only $\sin^2\theta_W$ is determined in a self-consistent way by many experiments, but a second free parameter can be determined. The ratio:

$$\rho = \frac{M_W^2}{M_Z^2 \cos^2\theta_W}$$

which should be equal to one for the simplest allowed Higgs structure of the theory, is now determined to be:

$$\rho = 0.98 \pm 0.05$$

It is therefore very likely that the phenomenology of low energy neutral current phenomena is correctly described by the SU(2) × U(1) model,[10] with left-handed fermion doublets, right-handed fermion singlets and Higgs doublets.

However, in order to prove the validity of the full structure of the theory, several extremely important tests are still missing.

The first step, hopefully to be accomplished within the next few years, would be to discover indirect evidence for the existence of the $W^\pm$ and Z boson, at their predicted masses. Such evidence may come from the energy dependence of the forward-backward asymmetry in $e^+e^- \rightarrow \mu^+\mu^-$ at PETRA and PEP energies. It may also come

from the observation of deviations from linearly rising neutrino or anti-neutrino total cross sections at high energies.

If such effects are discovered, they would only represent an intermediate step towards the actual discovery of the Z^0 and $W^{\pm}$. Only a <u>direct</u> observation of these particles, at their predicted mass values (around 90 and 80 GeV, respectively) would constitute direct evidence for the validity of the basic ideas of the SU(2) × U(1) gauge theory.

Another crucial aspect of the theory involves the Higgs mesons which are instrumental in the process of spontaneous symmetry breaking and mass generation for the gauge bosons and the fermions. So far, we do not have the slightest piece of experimental evidence for the existence of the Higgs particles. We have no reliable estimate of their masses or even their number. A direct observation of these particles or, at least, some indirect evidence for their existence, will probably be the last crucial test of the theory.

VI. Weak Interactions above 100 GeV

Let us assume that all electromagnetic and weak phenomena at energies below 100 GeV or so, are correctly described by the Weinberg-Salam SU(2) × U(1) theory. What happens at higher energies?

The Higgs particles may have masses below, say, 100 GeV. In such a case, either the particles themselves or some indirect evidence for their existence may be discovered by the time we reach 100 GeV. However, if the Higgs masses are larger than, say, 300 GeV an entirely new set of possibilities emerge. Interactions among such heavy Higgs particles may become strong.[13] Perturbation theory may fail. The weak interactions may become as complex and as uncalculable as the strong interactions are, with the possible existence of bound states of Higgs particles. Such bound states may even be much lighter than the Higgs particles themselves. With the QCD coupling constant decreasing, we may even find ourselves with strong weak interactions and weak strong interactions.

A similar situation of strong weak interactions may also emerge if quarks and leptons exist at masses of 500 GeV or more.[14]

Such a possibility is not so far off. If each quark flavor is three times heavier than its predecessor, the ninth or tenth flavor of quarks will reach a mass of 500 GeV.

The above situations to not have to materialize. However, they are not revolutionary at all. They simply indicate that the weak interactions above a few hundred GeV may be rich, complex, and strong!

Another possibility involves the enlargement of the weak gauge group. The simplest[15] such extension of SU(2) × U(1) would be SU(2)$_L$ × SU(2)$_R$ × U(1). This would introduce three additional gauge bosons W_R^+, W_R^-, Z_R^0 with masses anywhere above 300 GeV. If such bosons are indeed heavy, and if all right-handed fermions are in doublets of SU(2)$_R$, we will have right-handed charged currents whose strength is of the order of less than one (or a few) percent of the strength of left-handed currents. To the level of a few percent, the standard SU(2) × U(1) low energy phenomenology will be correct. Only at energies of several hundred GeV we will recognize the importance of the additional right-handed currents. Speculations concerning SU(2)$_L$ × SU(2)$_R$ × U(1) are particularly attractive in view of the fact that, unlike SU(2) × U(1), such a theory conserves parity prior to the spontaneous symmetry breaking. The violation of parity is then introduced by the different mass-scales of the gauge bosons of SU(2)$_L$ and SU(2)$_R$, respectively. Note that the SLAC polarized ed experiment[9] rules out a possibility[16] which was very popular until recently: An SU(2)$_L$ × SU(2)$_R$ × U(1) model with heavy $W_R^\pm$ but two "light" Z-bosons. However, the possibility that all three SU(2)$_R$ gauge bosons are heavy, remains open.

At higher energies, even larger extensions of the weak gauge group may emerge. Various candidates include SU(4) × U(1)[17] as well as SU(N) groups for N-flavors. Different hierarchies of weak gauge bosons are possible, each leading to a different pattern of the weak interactions in the region above 100 GeV.

VII. "Simple" Unification of Weak and Electromagnetic Interactions

We have already remarked that the successful Weinberg-Salam SU(2) × U(1) theory does not provide us with a "true" unification of the weak and electromagnetic interactions. The relative strengths of the two interactions are determined by the free parameter θ_W which cannot be determined from the theory.

A natural question to ask is whether, at higher energies, we can reach a true unification. That would require the embedding of SU(2) × U(1) in a simple gauge group G or a direct product of isomorphic simple groups having identical couplings. The latter possibility is sometimes called "pseudosimple." Such a "simple unification" scheme[7,18] will enable us to calculate the Weinberg angle θ_W and to relate all weak and electromagnetic phenomena to each other without any arbitrary parameters (except for particle masses and Cabibbo-like angles). A "simple unification" scheme would not accommodate quarks and leptons in the same multiplet. However, it would explain the relationship between the quantization of the electric charges of leptons and quarks.

What we are looking for is a gauge group G such that:

    (i)   G ⊃ SU(2) × U(1)

    (ii) G commutes with SU(3)$_C$

(iii) G is simple or "pseudosimple".

Such a gauge group will necessitate several new vector bosons with masses above 100 GeV. The masses of these bosons would then set the scale for "simple unification" of the weak and electromagnetic interactions with a unique value of θ_W. If we achieve "simple unification" we can then eliminate the dashed line which divides the weak and electromagnetic interactions in our road map (Fig. 1).

Unfortunately, the attractive idea of "simple unification" runs into problems. It is not difficult to show[7,18] that "simple unification" can be achieved only with groups of the form SU(3N) or SU(3N) × SU(3N), and that all such schemes lead to unacceptable values of θ_W--either $\sin^2\theta_W = 0.75$ or $\sin^2\theta_W = 0.375$. It is unlikely that renormalization corrections would modify these $\sin^2\theta_W$ values in a substantial way, unless the mass scale of "simple unification" is around, say, 10^{15} GeV or more. However, unlike the case of "grand unification" (Section VIII), there is here no

reason to expect such a mass scale. Another unattractive feature of all "simple unification" schemes is the total absence of any similarity between their quark multiplets and lepton multiplets. Such a similarity is observed at the lower level symmetry of SU(2) × U(1) as well as at the higher level of a "grand unification" symmetry, but it cannot be achieved at the "simple unification" level.

We therefore conclude that our present understanding enables us to reach an acceptable "true" unification of the weak and electromagnetic interactions, only when they are combined with the strong interactions of QCD, under a "grand unification" scheme. We now turn to this subject.

VIII. Grand Unification

According to QCD the "running coupling constant" decreases logarithmically[1] at large momenta. At some high energy value, it would reach the order of magnitude of the weak and electromagnetic coupling constants. It is attractive to envisage an overall "grand unification" symmetry,[19] which would be valid above that high energy value, and which would be spontaneously broken into the different fundamental interactions at lower energies. Such a "grand unification" group G will include SU(2) × U(1) × SU(3)$_C$ as a subgroup. If G is simple or pseudosimple, all coupling constants are related to each other and the Weinberg angle is determined. The gauge bosons of G include the eight gluons, the photon, W^+, W^-, Z^0 and at least a dozen (possibly many more) additional bosons, sometimes known as "leptoquarks." These are color-carrying bosons capable of converting a lepton into a quark or vice versa. The mass scale for the "grand unification" can be estimated by computing the momentum in which the QCD coupling strength decreases to the order of magnitude of α. The relevant equations for the three coupling constants g_3, g_2, g_1 of SU(3)$_C$, SU(2) and U(1), respectively, are:

$$g_i^{-2}(\mu) = G^{-2}(M) + 2b_i \ln\left(\frac{M}{\mu}\right)$$

where i = 1,2,3; G is the common coupling constant at the "grand unification" mass M, μ is the "running" mass parameter and b_i are the known coefficients of $g_i{}^3$ in the β-functions for the appropriate gauge groups. The typical values of M, obtained from these equations, are around 10^{15} GeV or even higher.[20] This is reflected in our "road map" (Fig. 1), where "grand unification" is achieved at these extremely high energies. All "grand unification" schemes assign quarks and leptons to the same multiplet of G. Consequently, baryon number is not conserved[19] and the proton becomes unstable. It decays by the virtual emission of "leptoquarks," yielding an estimate for the "leptoquark" mass which is, again, around 10^{15} GeV or more.

The most attractive "grand unification" schemes are based on the gauge groups SU(5)[21] and SO(10).[22] Both predict $\sin^2\theta_W = 0.375$. However, this value is applicable only at the "grand unification" mass above 10^{15} GeV. Its value at present energy is renormalized downwards and is estimated[23] around 0.2 for SU(5) and 0.28 for SO(10). Both values are encouraging, especially the first.

An intriguing possibility is "early grand unification." A model[24] based on an extended color group $\left[SU(3)_L \times SU(3)_R\right]_C$ may lead to the relation:

$$\frac{1}{2}\, g_3{}^{-2}(M) = g_2{}^{-2}(M) = g_1{}^{-2}(M).$$

The factor 1/2 comes from the "chiral color" group. It essentially tells us that the logarithmic decrease of g_3 will have to reach 2α rather than α. This happens at a much lower energy (see Fig. 1). Unfortunately, the renormalization correction to $\sin^2\theta_W$ are correspondingly smaller and its predicted value at present energies is around 0.35, unacceptably high.

Another amusing speculation involves a "grand unification" scheme which includes the usual SU(3)$_C$ but an enlarged weak-electromagnetic group such as SU(4) × U(1). In such a case the logarithmic μ-dependence of g_i will be such that at masses below the "grand unification" mass M, the "weak" SU(4) coupling will be larger than the "strong" SU(3) coupling. (See Fig. 1.)

IX. The Ultimate Unification: Extended Supergravity

By the time we reach 10^{15} GeV or more, we cannot avoid con-
sidering the last fundamental interaction: gravity. A convincing
unification scheme involving gravity as well as the strong, weak
and electromagnetic interactions is still far ahead. However,
recent work on supergravity[25] has led to some preliminary attempts
in this direction. The one we mention here is the "extended super-
gravity" theory incorporating the $J = 2$ graviton, $J = 3/2$ gravi-
tinos, $J = 1$ vector bosons, $J = 1/2$ fermions and $J = 0$ Higgs fields
into one supermultiplet. The resulting theory will be a super-
symmetric theory of gravity, with well defined couplings for the
vector gauge bosons of the weak, strong and electromagnetic
interactions.

However, in addition to all the usual theoretical problems
which face the theory of supergravity, this extended scheme runs
into a serious phenomenological obstacle. The largest "extended
supergravity" group, which does not admit spins larger than two,
is SO(8). However, SO(8) cannot accommodate[26] the known existing
vector bosons and fermions. It has no room for W^+, W^-, μ, ν_μ, τ,
b. Whether this deficiency can be rectified only time will tell.

X. Conclusion

We have taken a brief tour through the world of fundamental
interactions. All interactions are described by gauge theories.
Many intriguing similarities exist between the different inter-
actions. Various levels of unification have been studied in the
last few years, and they appear to offer a great promise for the
future. Experimental verification of QCD still lies ahead, and
direct confirmation of SU(2) × U(1) awaits the discovery of the
W and Z bosons. Nevertheless, we seem to be on the right track!

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