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FUNDAMENTAL TESTS AND MEASURES OF THE STRUCTURE OF MATTER AT SHORT DISTANCES*

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ABSTRACT

Recent progress in gauge field theories has led to a new perspective on the structure of matter and basic interactions at short distances. It is clear that at very high energies quantum electrodynamics, together with the weak and strong interactions, are part of a unified theory with new fundamental constants, new symmetries, and new conservation laws. A non-technical introduction to these topics is given, with emphasis on fundamental tests and measurements.

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1. INTRODUCTION

In the past few years there has been extraordinary progress in the understanding of the structure and interactions of matter at short distances. The most important theoretical progress has been in the area of non-Abelian gauge theories which are now leading toward a unified description of the weak, strong, and electrodynamic interactions. It is now evident that quantum electrodynamics is just one manifestation of a larger unified theory. In this review I will emphasize the areas where fundamental tests and precision measurements are crucial to the development of basic theory. Many previously-believed conservation laws, such as baryon and lepton number conservation, are now open to question or in fact are predicted to be violated. High precision tests, including searches for very rare processes, are thus essential in order to definitively test the theories.

2. QUANTUM ELECTRODYNAMICS

One of the most fundamental questions in physics is whether we have actually identified the fundamental constituents of matter.[1] In quantum electrodynamics, the leptons e, μ, and τ are elementary point-like carriers of the electromagnetic current, each with a Dirac coupling to the electromagnetic field. High energy ($\sqrt{s} = E_{c.m.} \leq 32$ GeV) measurements of the reactions $e^+e^- \to e^+e^-$, $\mu^+\mu^-$, $\tau^+\tau^-$, and $\gamma\gamma$ at the PETRA storage ring have placed severe limits on any deviation from the predicted Dirac structure or any internal lepton structure. For example, measurements of electron-positron annihilation into muon pairs by the Mark-J collaboration [2] lead to lower limits (95% confidence level)

$$\Lambda_- > 160 \text{ GeV}, \qquad \Lambda_+ > 120 \text{ GeV} \tag{1}$$

for modifications $1/Q^2 \to 1/Q^2 \mp 1/(Q^2 - \Lambda_\pm^2)$ of the proton propagator or the electron or muon vertex. Alternatively, this result demonstrates that the electron and muon are effectively point-like down to distances $R \sim \Lambda^{-1} \lesssim 2 \times 10^{-16}$ cm.

Surprisingly, the strongest limits on possible internal lepton structure in some models come from the precise measurements of the gyromagnetic ratios of the electron and muon--measurements at the limit of zero momentum transfer. The most precise published value is [3] $\frac{1}{2} g_{e^-}^{ext} = 1.001\ 159\ 652\ 200\ (40)$. The QED prediction has now been computed through order $(\alpha/\pi)^4$ [ninth order in perturbation theory!] by Kinoshita and Lindquist.[4] The result is $\frac{1}{2} g_e^{th} = 1.001\ 159\ 652\ 504\ (182)$. The $(\alpha/\pi)^4$ calculations require the evaluation of 891 Feynman diagrams. The uncertainty reflects the limit of error on 10-dimensional numerical integrations, as well as the uncertainties in the determination of α. Since there is no a priori reason why a spin 1/2 system must have $g \sim 2$ in general (witness the nucleons), it is extraordinary that QED correctly predicts g_e to 10 significant figures!

Let us now consider the possibility that the electron is composite with an intrinsic radius R.[1,5] The natural size of the magnetic moment of a charged extended system is $\mu \sim eR$, which would imply a contribution to the gyromagnetic ratio $\Delta g_e \sim m_e R$ (barring cancellations). Alternatively, one can compute the magnetic moment of any system from the general relationship between the anomalous moment $a = 1/2(g-2)$ of a system and its excitation spectrum (the Drell-Hearn-Gerasimov sum rule). For a spin 1/2 system one has

$$a^2 = \frac{m^2}{2\pi^2\alpha} \int_{s_{th}}^{\infty} \frac{ds}{s} \left[\sigma_P^\gamma(s) - \sigma_A^\gamma(s)\right] \tag{2}$$

where $\Delta\sigma = \sigma_P^\gamma - \sigma_A^\gamma$ is the difference between the spin parallel and spin antiparallel total photoabsorption cross sections. Barring special cancellations, $\Delta\sigma \sim \mathcal{O}(\alpha R^2)$ at energies where the compositeness of the target is manifest. For a composite electron this again gives the estimate $\Delta a_e \sim m_e R$. The agreement between theory and experiment $|\Delta a_e| < 10^{-9}$ then implies that any internal size scale of the electron is limited to exceedingly small distances $R \lesssim 10^{-20}$ cm, $R^{-1} \gtrsim 10^6$ GeV. (The limits for the muon are comparable.)

It is, however, possible to construct specific models for composite leptons which give a smaller correction to the magnetic moment than the general estimate given above. For example, in a model in which the constituent fermions have mass m_F much less than the intrinsic momentum scale R^{-1} of the system, one obtains the quadratic relationship $\Delta a \sim m_e m_F R^2$. In fact, one can evidently conceive of the electron as a tightly bound composite system (radius $\lesssim 10^{-16}$ cm) of permanently confined but light mass ($m_F \lesssim 100$ MeV) fermion constituents, without violating any high energy or low energy constraint. The dynamics of such models are, however, far from clear. A light mass fermion constituent also seems to be required in order to understand the small mass of the electron. It is also interesting to note that a very complex theory can appear to be simple and renormalizable at low momentum scales $Q^2 << R^{-2}$ even though the particles are composite at short distances.

3. WEAK INTERACTIONS AND QUANTUM ELECTRODYNAMICS

Before the advent of the Glashow, Weinberg, Salam SU(2) × U(1) theory [7] of the weak and electrodynamic interactions, there was no satisfactory way of computing the weak interaction corrections to QED predictions. Previous models, besides violating unitarity at high energies, gave logarithmically-divergent corrections to the lepton magnetic moments and even quadratically-divergent contributions to neutrino charge radii. It is, however, now clear that QED and the weak interactions are unified as part of a more general, completely calculable, renormalizable theory. In particular, the weak interaction contributions to the muon moment in the SU(2) × U(1) theory as shown in Fig. 1 are readily calculable:[9]

$$\Delta a_\mu^{wk} \sim \alpha m_\mu^2/M_W^2 \sim G_F\, m_\mu^2 \sim 2 \times 10^{-9}$$

compared to the present experimental uncertainty of $\sim 11 \times 10^{-9}$.

Let us briefly review the main features of the GWS "standard model" [7]: In its intital stage the theory begins with the assumption of an exact internal symmetry SU(2) analogous to isospin, with doublets of massless (negative helicity or "left-handed") leptons and quarks, and triplets of massless vector bosons; e.g.

$$\psi_\ell \sim \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L , \quad \psi_q \sim \begin{pmatrix} u \\ d \end{pmatrix}_L , \quad \vec{W} \sim \begin{pmatrix} W^+ \\ W^0 \\ W^- \end{pmatrix} \tag{3}$$

The interactions of this theory (see Fig. 2) generalize the Dirac coupling of QED and preserve the SU(2) rotational invariance:

$$g_2 \, \bar{\psi}_\ell \, \vec{\not{W}} \, \psi_\ell + g_2 \, \bar{\psi}_q \, \vec{\not{W}} \, \psi_q + \ldots \tag{4}$$

where $\vec{W}^\mu = \sum_{i=1}^{3} W_i^\mu \vec{T}_i$ and the $\vec{T}_i$ are the set of 2 × 2 traceless matrices. In fact the entire theory, including the W self couplings, is invariant under rotations $\psi \to e^{i\vec{\Lambda}(x)}\psi$ where $\vec{\Lambda}(x)$ is an arbitrary 2 × 2 matrix function of space and time. This ("non-Abelian") local gauge invariance is a generalization of the (Abelian) local phase or U(1) gauge invariance of QED, and insures the renormalizability of the theory. One can also define an additional conserved "charge" Y (= −1/2 for leptons, 1/6 for quarks) which reflects the fact that the lepton and quark currents are separately conserved. The coupling of the weak hypercharge current $g_1 Y \bar{\psi}\gamma^\mu\psi$ to an additional zero mass vector boson B_μ then has an exact $\psi \to e^{i\Lambda(x)Y}\psi$ local U(1) gauge symmetry.

The theory discussed thus far has little resemblance to the observed weak interactions. However, if one introduces an extra doublet of interacting scalar bosons $\phi = \begin{pmatrix}\phi^+\\ \phi^o\end{pmatrix}$ with non-zero expectation value in the ground state, then the exact SU(2) gauge invariance of the theory will be "broken" while still retaining the renormalizability of the theory in the ultraviolet domain. What emerges at low energies is (1) a massive charged vector boson $W^{\pm}$, (2) a massive neutral vector boson $Z^{\circ}_{\mu} = \sin\theta_W B_{\mu} - \cos\theta_W W^{\circ}_{\mu}$, and (3) a massless neutral vector boson $A_{\mu} = \sin\theta_W B_{\mu} + \cos\theta_W W^{\circ}$ coupled to the electrodynamic current. One can then identify the electric charge $e = g_2 \sin\theta_W$ and the Fermi constant $G_F/\sqrt{2} = e^2/8M_W^2 \sin^2\theta_W$, where the weak mixing angle is given by $\tan\theta_W = g_1/g_2$. The weak interactions at low momentum transfer $Q^2 << M_W^2$ then have the form:

$$\mathscr{L}^{wk}_{eff} = \frac{G_F}{\sqrt{2}} J^{\dagger Z}_{\mu} J^{\mu}_{Z} + \frac{G_F}{2\sqrt{2}} J^{\mu\dagger}_{W} J^{W}_{\mu} \qquad (5)$$

with

$$J^{\mu}_{W} = \sum_{q,\ell} \bar{\psi} \left[\gamma^{\mu}(1 + \gamma_5)T^{+}\right]\psi \qquad (6)$$

and

$$J^{\mu}_{z} = \sum_{q,\ell} \bar{\psi} \left[\gamma^{\mu}(1 + \gamma_5)T^{3} - 2q \sin^2\theta_W\right] \psi \qquad (7)$$

The form and relative normalization of the charged and neutral weak interactions predicted by (7) have now been checked in many neutrino and weak/electromagnetic interference experiments--in many cases to better than 1% precision. One of the most precise experiments is the SLAC-Yale [10] measurement of parity violation in deep inelastic polarized electron e^-p scattering. The interference between the electromagnetic and weak neutral currents (see Fig. 3) leads to an asymmetry $(\sigma_L - \sigma_R)/(\sigma_L + \sigma_R)$ in the $e^-p \to e^-X$ cross section and thus to a determination of $\sin^2\theta_W$. A combined analysis of the various neutral current experiments gives (see Fig. 4): [11]

$$\sin^2\theta_W = 0.229 \pm 0.009(\pm 0.005) \tag{8}$$

and

$$\kappa = \frac{\left(J_\mu^Z \; J_Z^\mu\right)_{\text{expt}}}{\left(J_\mu^Z \; J_Z^\mu\right)_{\text{predicted}}} = 0.992 \pm 0.017(\pm 0.011) \tag{9}$$

where the error in parentheses indicates errors due to theoretical uncertainties (radiative corrections, etc.).

Thus far there is no discrepancy with the predictions of the $SU(2) \times U(1)$ model, although other models (such as those which are parity symmetric at large momentum transfer) are not ruled out. The most critical test of this model will be the experimental confirmation of the $W^{\pm}$ and $Z°$ vector bosons at the predicted mass

$$\begin{aligned} M_W &= 82.0 \pm 2.4 \text{ GeV} \\ M_Z &= 93.0 \pm 2.0 \text{ GeV} \end{aligned} \tag{10}$$

The width of the $Z°$ is particularly interesting since it signals the number of neutrinos. Confirmation of $SU(2) \times U(1)$ model will also require the identification of the Higgs scalars, the origin of symmetry-breaking in the theory. It is however possible that these particles are themselves composites [12] rather than new additional elementary-field degrees of freedom.

The fermions in the higher generations enter the SU(2) × U(1) multiplets in parallel to (2); i.e.:

$$\psi_\ell = \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L , \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L , \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$$

$$\psi_q = \begin{pmatrix} u \\ d \end{pmatrix}_L , \begin{pmatrix} c \\ s \end{pmatrix}_L , \begin{pmatrix} t \\ b \end{pmatrix}_L \tag{11}$$

However, as first noted by Cabibbo, the quarks which appear in the weak interaction theory are not necessarily the mass eigenstates of the full theory, including strong interactions. In the case of three generations, the mass eigenstates

$$q_m = \begin{bmatrix} A_{mn} \; u_n \\ d_m \end{bmatrix}_L \tag{12}$$

are related by 3 rotation angles and one CP violating phase ϕ to the weak interaction eigenstates. The angle of the mixing between the first two generation quarks is the Cabibbo angle, which has been determined to considerable accuracy $\theta_c \sim 13.17° \pm 0.64°$ from analyses of strangeness-changing weak interactions.

The fact that the mixing of three generations leads in a natural way to CP and T violation is a very interesting result.[13] By parametrizing present data for CP violating effects in terms of the phase angle ϕ, one can predict a non-zero value for the neutron electric dipole moment:

$$(D/e)_n \cong 10^{-30} \text{ cm}$$

compared to the present limit $\sim 10^{-26}$ cm. If the e, μ, and τ neutrinos are massive then one expects a similar mixing pattern for the lepton sector, and a non-zero value for the electron dipole moment. [9]

4. THE STRONG INTERACTIONS [14]

The successful application of local gauge theories to weak and electrodynamic interactions has led to an even more fundamental advance in the case of the strong interactions--the development of quantum chromodynamics. In QCD the fundamental degrees of freedom of hadrons and their interactions are the quanta of quark and gluon fields which obey an exact internal SU(3) "color symmetry." Each quark "flavor" q = u,d,s,c,b,... is represented as a color triplet

$$\psi = \begin{pmatrix} q_R \\ q_Y \\ q_B \end{pmatrix}$$

interacting with an octet of gluon fields $\tilde{G}^\mu = \sum_{a=1}^{8} G^\mu_a \tilde{\lambda}_a$ where the λ_a are the set of 3 × 3 traceless matrices. The interactions

$$g_3 \bar{\psi} \tilde{\not{G}} \psi$$

together with the gluon self couplings (see Fig. 5) preserve an exact local gauge symmetry for arbitrary rotations $\psi \to e^{i\tilde{\Lambda}(x)\psi}$ in the SU(3) color space. The gluons are massless and theory is renormalizable. The lowest energy states are the color-singlet baryons $|q_R q_Y q_B\rangle$ and mesons $1/\sqrt{3}|q_R\bar{q}_R + q_B\bar{q}_B + q_Y\bar{q}_Y\rangle$. In addition, bound states of gluons $|gg\rangle$ and $|ggg\rangle$ as well as $|q\bar{q}g\rangle$ states are predicted.

It now seems possible that quantum electrodynamics is <u>the</u> theory of the strong interactions in the same sense that quantum electrodynamics accounts for electromagnetic interactions. It is well known that the general structure of QCD meshes remarkably well with the facts of the hadronic world, especially quark-based spectroscopy, current algebra, the approximate point-like structure of large momentum transfer lepton-hadron reactions, and the logarithmic violation of scale-invariance in deep-inelastic reactions. The theory is particularly successful in predicting the features of electron-positron annihilation into hadrons: the magnitude and scaling of the total cross section, the production of hadronic jets with a pattern conforming to elementary quark and gluon processes, and heavy quark phenomena. The empirical results are consistent with the basic postulates of QCD, that the charge and weak currents within hadrons are carried by the quarks, and that the strength of the quark-gluon couplings becomes weak at short distances (asymptotic freedom).

Although it is simplest to define the coupling constant in QED at zero momentum transfer, this choice is in a sense arbitrary since the one-photon exchange interactions can be computed at any Q^2 by including the vacuum polarization insertions to all orders:

$$\alpha(Q^2) = \frac{\alpha(Q_0^2)}{1 + \alpha(Q_0^2)\left[\pi(Q^2) - \pi(Q_0^2)\right]} \tag{13}$$

For $Q^2 >> m_e^2$, $\pi(Q^2) \sim -(1/3\pi) \log Q^2/m_e^2$ so the effective coupling $\alpha(Q^2)$ increases at large Q^2. In the case of QCD the vacuum polarization diagrams involving gluon self-coupling (see Fig. 6) actually reverse the sign of $\pi(Q^2)$:

$$\pi_{QCD}(Q^2) \cong \frac{1}{6\pi}\left[\frac{33}{2} - n_f\right] \log Q^2 \tag{14}$$

as long as the number of quark flavors (n_f) is less than 17. Thus for very large Q^2, the strong interaction coupling constant $\alpha_s = g_3^2/4\pi$ is given by ($Q^2 >> \Lambda^2$)

$$\alpha_s(Q^2) = \frac{4\pi}{\left(11 - \frac{2}{3}\, n_f\right) \log \frac{Q^2}{\Lambda^2}} \tag{15}$$

The fact that the coupling constant decreases at large Q^2 (see Fig. 7) implies that we can use perturbation theory for calculating hadronic processes at short distance. Conversely, the increase of the effective coupling at large distances is consistent with the expectation that the theory strongly confines particles of non-zero color.

The fundamental parameters of QCD are the coupling constant α_s and the quark masses. The actual measurement of these quantities is complicated by the fact that only bound states of quarks and gluons are accessible, and there can be large and uncertain corrections from non-perturbative, binding, and other higher-order effects. In addition, the specification of $\alpha_s(Q^2)$ depends on the momentum scale chosen to express the leading order results and the choice of normalization scheme.

At this time the most precise determination of the QCD coupling constant is given by an analysis of the decay of the upsilon, Υ, the lowest energy bound state of b and $\bar{b}$ quarks with $J^{PC} = 1^{--}$ at M_Υ = 9.46 ± 0.01 GeV. The hadronic width of the upsilon can be computed in lowest order perturbation theory from the 3 gluon decay amplitude (see Fig. 8) in analogy to orthopositronium decay into 3 photons. The QCD prediction, including first order radiative corrections as recently computed by Lepage and Mackenzie,[15] is

$$\Gamma_{\Upsilon \to 3g} = |\psi_{NR}(\vec{0})|^2 \frac{\alpha_s^3(M_\Upsilon^2)}{M_\Upsilon^2} (\pi^2 - 9) \frac{160}{81} \left[1 + C_{3g} \frac{\alpha_s}{\pi}\right] \tag{16}$$

with

$$C_{3g} = 3.8 \pm 0.5.$$

The lepton decay rate is

$$\Gamma_{\Upsilon \to e^+e^-} = |\psi_{NR}(\vec{0})|^2 \frac{16\pi \left(\frac{1}{3}\right)^2 \alpha^2}{M_\Upsilon^2} \left[1 - \frac{16}{3} \frac{\alpha_s}{\pi}\right] \tag{17}$$

The measured ratio for $\Gamma_{\Upsilon \to had}/\Gamma_{\Upsilon \to e^+e^-}$ then implies $\alpha_s(Q^2 = M_\Upsilon^2)$ = 0.14 ± 0.01 where the error indicates 1σ accuracy.

The determination[2] of α_s from $e^+e^- \to q\bar{q}g \to 3$ jets also gives values in the range $\alpha_s(Q^2 \sim 1000\ \mathrm{GeV}^2) \sim 0.15$ to 0.23 although there are large corrections from hadronization and higher order effects. It is also in principle possible to determine α_s from exclusive processes[16] such as ratios of meson form factors: $F_\pi(Q^2)/F^2_{\pi\gamma}(Q^2)$, and from radiative corrections to deep inelastic lepton-hadron scattering.

Considering that new phenomena still continue to be discovered in QED and atomic physics, it is likely that we have only touched the surface of much more complex QCD phenomena. Thus far there have been many semi-quantitative tests of the theory, including the verification of scale-invariant quark-quark interactions from the behavior of meson and baryon form factors at large momentum transfer. There is, however, only a rough qualitative understanding of the basic properties of hadrons, such as their masses, magnetic moments, charge radii. Detailed answers to such questions require an understanding of the hadronic wavefunctions as well as their multiparticle Fock state structure (see Ref. 5). Perhaps the most dramatic confirmation of QCD would be the observation of gluonium $|gg\rangle$ and $|ggg\rangle$ states. It should also be emphasized that the reported observation of fractional charge systems by Fairbank et al.[17] reopens the fundamental question of whether quarks are really confined in QCD—i.e.: whether QCD is an exact local gauge theory or is spontaneously broken so that the gluons have a finite mass and the confinement potential has finite range. Alternatively, these results could signal the existence of color singlet fractional charged particles, or bound states of zero charge color anti-triplets $\bar{3}_c$ with quarks, or even fractionally charged subconstituents of the quarks themselves.

5. UNIFIED THEORIES OF THE STRONG, WEAK, AND ELECTROMAGNETIC INTERACTIONS[11,7]

Thus far our discussion had led to no real understanding of the quark ↔ lepton parallelism, especially why the proton and electron charges are equal and opposite to within parts in 10^{20}. This could be understood if (a) quarks and leptons have common subconstituents, and/or (b) quarks and leptons are in the same representation of a fundamental symmetry group. The latter possibility is the central motivation for many grand unified theories, as exemplified by the SU(5) gauge theory model of Georgi and Glashow.[18] In this model the 15 fermions of the first generation (see Fig. 9) are identified members of the $\underline{5}$ and $\underline{10}$ representation of SU(5), e.g.,

$$\psi_{\underline{5}} \sim \begin{pmatrix} \bar{d}^R \\ \bar{d}^Y \\ \bar{d}^B \\ e^- \\ \nu_e \end{pmatrix}_L \qquad (18)$$

and $\psi_{\underline{10}}$ is an antisymmetric 5×5 matrix with entries for e^+_L, $(u,d)_L$ and $(\bar{u})_L$. The gauge bosons correspond to the set of (24) 5×5 traceless matrices

$$\tilde{A} = \left(\begin{array}{c|cc} \text{gluons} & X^{R,Y,B} & Y^{R,Y,B} \\ \hline \bar{X}^{R,Y,B} & Z^{0},\gamma & W^+ \\ \bar{Y}^{R,Y,B} & W^- & Z^0 \end{array}\right) \qquad (19)$$

The X and Y vector bosons have color and fractional charge and couple quarks to leptons! Since charge is a generator of SU(5), $\bar{\psi}Q\psi$ = tr Q = 0, and the sum of the charges of the constituents in any representation must be zero; i.e., $3Q_d + Q_{e+} = 0$; this naturally explains the equality of lepton and baryon charges.

The basic scenario of SU(5) is then as follows (see Fig. 10). At momentum transfers Q^2 much larger than M_X^2 and M_Y^2, all particles can be treated as massless and SU(5) is an exact gauge symmetry. At lower energies this symmetry is broken (by a Higgs scalar vacuum expectation value) leaving symmetries corresponding to the subgroups $SU(3)_C \times SU(2) \times U(1)$. Finally, at much lower energies, $Q^2 \gtrsim M_W^2, M_Z^2 \sim 10^2$ GeV^2 the theory is again broken (as in Section 3) and the exact gauge symmetries that remain are the $SU(3)_C$ (massless gluon octet) and U(1) symmetry of QED (massless photons). From analysis of observed mass scales, and the fact that the U(1) coupling constant is increasing and the SU(2) and $SU(3)_C$ coupling constants are logarithmically decreasing one can estimate that the grand unified scale (where the coupling constants coincide $\alpha_1 = \alpha_2 = \alpha_3 = \alpha_5$) is $\sim 10^{15}$ GeV (see Fig. 11). (This also gives an estimate for M_X, M_Y.) In fact, $\alpha_{GUT}(Q^2 \sim 10^{15}$ GeV$^2) \cong 1/42$ now becomes the fundamental coupling constant, not $\alpha \cong 1/137$.

The SU(5) model leads to two critical predictions:

(1) The weak mixing angle is fixed to be $\sin^2\theta_W = 3/8$ at the grand unified scale. One can however use an extrapolation determined by the renormalization group (over 13 decades!) to compute $\sin^2\theta_W = 0.209 \pm 0.006$ at $Q^2 = M_W^2$. This is not far from the experimental value[10,11] $\sin^2\theta_W =$ $0.229 \pm 0.009(\pm 0.005)$.

(2) Because of the X and Y couplings, baryon number is not conserved, although baryon number minus lepton number is still a conserved quantity in SU(5). The proton is thus unstable, and will decay into channels such as $p \rightarrow e^+\pi^\circ$ (see Fig. 12). The predicted proton decay rate is proportional to the grand unified scale to the fourth power and thus has a large uncertainty: $\tau_p \sim 10^{31 \pm 2}$ years. The present experimental limit is $\tau_p \gtrsim 10^{30}$ years; in fact, four large-scale experiments now under construction will have a sensitivity to $\tau_p \sim 10^{33}$ years, so a decisive test of SU(5) appears possible. This is especially true since the most recent evaluation[15] of the QCD scale constant $\Lambda_{\overline{MS}} \sim 100$ MeV in Eq. (15) leads to the lowering of the grand unified scale mass and hence lower predicted values for τ_p.

In addition to SU(5) other grand unified theories have been proposed. All such models have profound implications for the evolution of the early universe,[19] which would be expected to trace through the various symmetry phases, starting with a hot soup of massless quarks, gluons, W, X, etc. A possible connection of the baryon excess $n_B - n_{\overline{B}}$ in the universe to CP violation is also possible.[20,7,11] The grand unified models also evidently predict large rates for the production of free magnetic monopoles in the early universe.

In many grand unified theories, there is no natural or compelling reason why neutrinos should be massless, and the determination of the neutrino masses is now a topic of intense experimental activity.[21] In analogy to the quark case, the mass eigenstates ν_m may be linear combinations of ν_e, ν_μ, and ν_τ. This means that the neutrino ν_μ^L produced at time $t = 0$ in $\pi^+ \to \mu^+\nu_\mu^L$ decay will at $t > 0$ be a linear combination of ν_μ^L, ν_μ^R (chirality non-conservation), and ν_e^L (neutrino "oscillations").

If a neutrino has mass, it also follows that it can have an anomalous magnetic moment;[9] diagrams such as Fig. 15 give contributions of order $a_\nu \sim m_\nu m_f G_F$. One can thus imagine inducing a neutrino helicity flip using external magnetic fields. If a neutrino is self-conjugate $C|\nu\rangle = \pm|\nu\rangle$ and there are charged right-handed currents so that $W^- \to e^-\nu_L$ and $W^- \to e^-\nu_R$ are possible, then double β-decay processes $nn \to pp\, e^-e^-$ in nuclei are possible (see Fig. 14). In some models $n \leftrightarrow \bar{n}$ oscillations are also predicted.

6. CONCLUSIONS

The concept of a grand unified theory has led to an extraordinary new perspective on the structure of matter at short distances. It is clear that at very high energies, QED together with the weak and strong interactions are part of a unified theory with new fundamental constants, new symmetries, and new conservation laws. The prediction that baryon and lepton number are no longer individually conserved should lead us to question all of presently accepted conservation laws and symmetries. This new gauge field theory perspective also makes it evident that the numerical value of parameters such as α_{QED} at zero momentum transfer is not significant in itself, considering the dependence of the coupling on resolution scale Q^2 and normalization scheme. Questions concerning the possible time variation of the fundamental constants such as α_{QED} are now seen to be connected with the evolution from the early universe.

Although gauge field theories and grand unified theories are leading to answers to many fundamental questions, one must acknowledge that countless others remain, such as the origin of a vast ratio of mass scales: $M_X/M_W \sim 10^{13}$, the origin of the fermion masses (e.g., why is $M_p < M_n$?), the possible compositeness of leptons and quarks, and the ultimate role of gravity ($M_{Planck} \sim 10^{19}$ GeV). It is clear that high precision experiments, searches for rare new processes, as well as detailed high energy measurements, will be crucial for continuing progress in these areas.

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REFERENCES

1. For examples of fundamental theories with composite leptons and quarks, see J. G. Pati and A. Salam, Phys. Rev. D10, 275 (1974), H. Harari, Phys. Lett. 86B, 83 (1979), and I. Bars, Yale preprint, YTP-81-19 (1981).
2. D. P. Barber et al., Phys Rev. Lett. 43, 1915 (1979). For a review of the PETRA results, see G. Wolf, DESY 80/13 (1980).
3. R. S. Van Dyck, Jr., P. B. Schwinberg, and H. G. Dehmelt, Phys. Rev. Lett. 38, 310 (1977). For a review of anomalous moment measurements and theory, see J. H. Field, E. Picasso and F. Combley, Sov. Phys. UZP 22, 198 (1979).
4. T. Kinoshita and W. B. Lindquist, report to this conference. For recent progress in the analytic evaluation of the anomalous moment through order $(\alpha/\pi)^3$ see M. Levine and R. Roskies (report to this conference). A review of other precision measurements in QED is given by G. P. Lepage and D. R. Yennie (report to this conference).
5. The analysis discussed here follows S. J. Brodsky and S. D. Drell, Phys. Rev. D22, 2236 (1980). See also G. L. Shaw, D. Silverman, and R. Slansky, Phys. Lett. 94B, 57 (1980).
6. S. Dimopoulos, S. Raby and L. Susskind, Nucl. Phys. B173, 208 (1980). I. Bars, Ref. 1.
7. For reviews and references to electroweak theory see P. Langacker, SLAC-PUB-2544 (1980), L.-F. Li, NSF-ITP-81-25 (1981), and the proceedings of the Cornell Z° Theory Workshop, CLNS-81-485 (1981).
8. See, e.g., S. J. Brodsky and J. D. Sullivan, Phys. Rev. 156, 1644 (1967), and references therein.

9. B. W. Lee and R. Strock, Phys. Rev. D17, 2410 (1978) and references therein.

10. C. Y. Prescott et al., Phys. Lett. 84B, 524 (1979).

11. J. Ellis, CERN TH.2942 (1980), and references therein.

12. L. Susskind, Phys. Rev. D20, 2619 (1979).

13. M. Kobayashi and M. Maskawa, Prog. Theor. Phys. 49, 652 (1973).

14. For recent reviews of QCD see, A. J. Buras, Rev. Mod. Phys. 52, 1 (1980), A. H. Mueller, CU-TP-192 (1981), E. Reya, DESY 79/88 (1979), S. J. Brodsky and G. P. Lepage, SLAC-PUB-2447 (1979).

15. G. P. Lepage and P. Mackenzie, Cornell preprint CLNS/81-498 (1981).

16. S. J. Brodsky and G. P. Lepage, Phys. Rev. D22, 2157 (1980).

17. C. S. Larue, W. M. Fairbank, J. D. Phillips, Phys. Rev. Lett. 42, 142 (1979).

18. H. Georgi and S. L. Glashow, Phys. Rev. D6, 429 (1972).

19. See, e.g., A. Guth and E. J. Weinberg, Phys. Rev. D23, 876 (1981).

20. A. D. Sakharov, JETP Lett. 5, 27 (1967).

21. For reviews, see S. M. Bilensky and B. Pontecorvo, Phys. Reports 41, 1 (1978), and B. Kayser, SLAC-PUB-2685 (1981), and references therein.

FIGURE CAPTIONS

1. Weak interaction contributions to the muon magnetic moment.
2. SU(2) couplings of leptons and quarks.
3. Interfering weak and electromagnetic contributions to deep inelastic lepton-proton scattering.
4. Values of $\sin^2\theta_W$ and κ from a phenomenological analysis of neutral current data. The limit curve corresponds to a confidence level of 68%. From Ref. 11.
5. Quark-gluon couplings in SU(3) color.
6. Vacuum-polarization contributions to quark-quark scattering.
7. Variation of the strong and electromagnetic coupling strengths with momentum transfer.
8. Leading contributions to the hadronic and leptonic decays of the upsilon.
9. The 15 fundamental fermions of the first generation. The subscript L and R indicates particle helicity.
10. The approach to equality of the SU(3), SU(2), and U(1) gauge couplings in the SU(5) grand unified theory.
11. Symmetry breaking pattern in SU(5).
12. Origin of the baryon decay in SU(5).
13. Diagram leading to double β-decay in nuclei.
14. Weak interaction contribution to the magnetic moment of a massive neutrino.

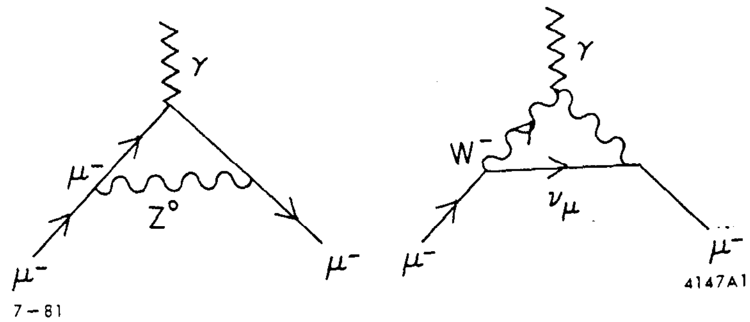


Fig. 1

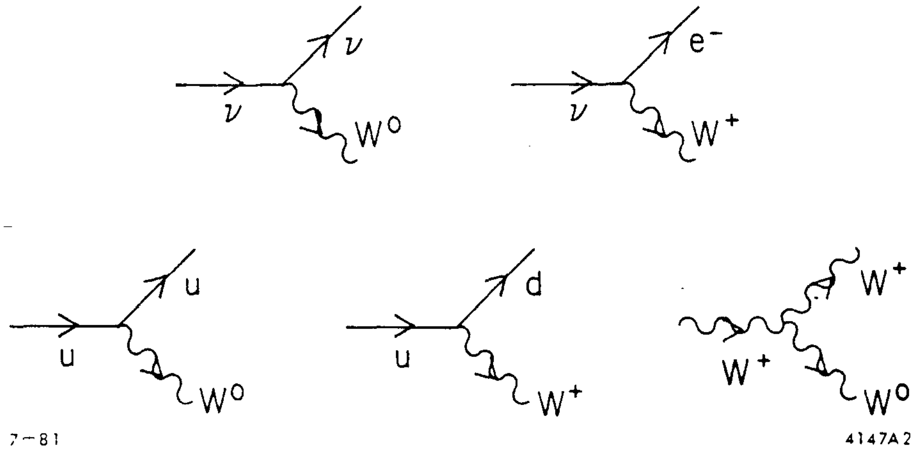


Fig. 2

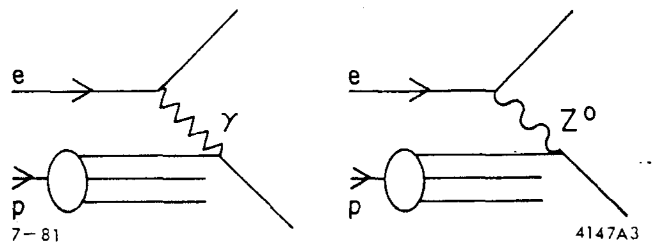


Fig. 3

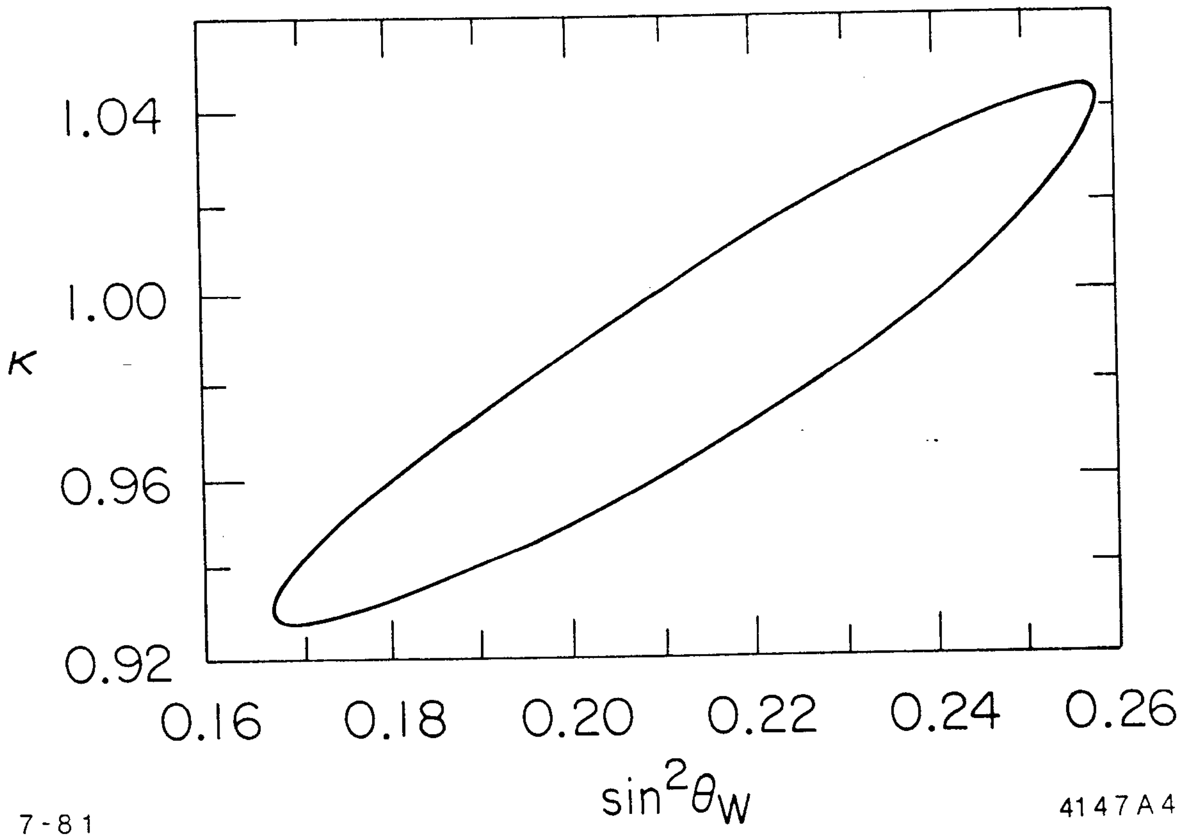


Fig. 4

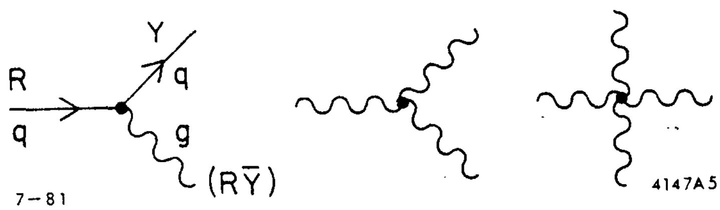
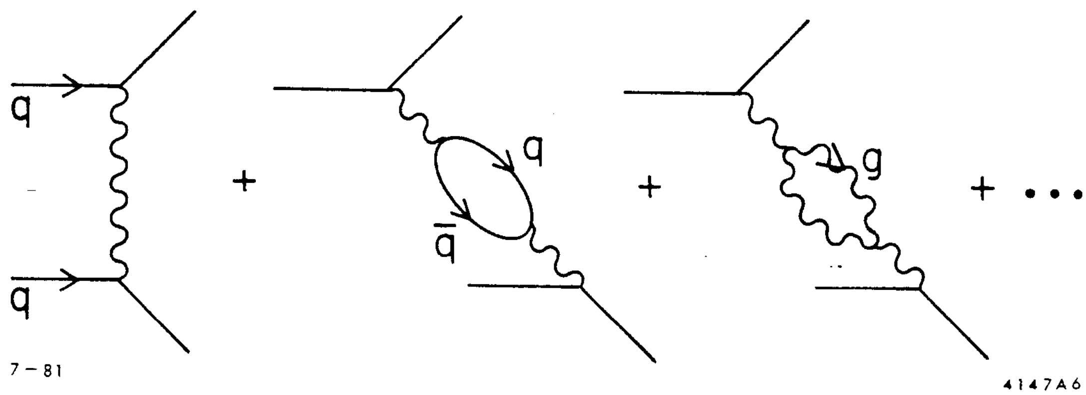


Fig. 5



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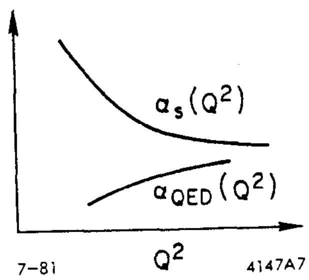

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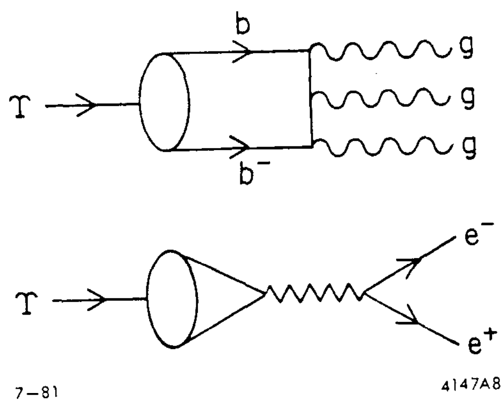

Fig. 8

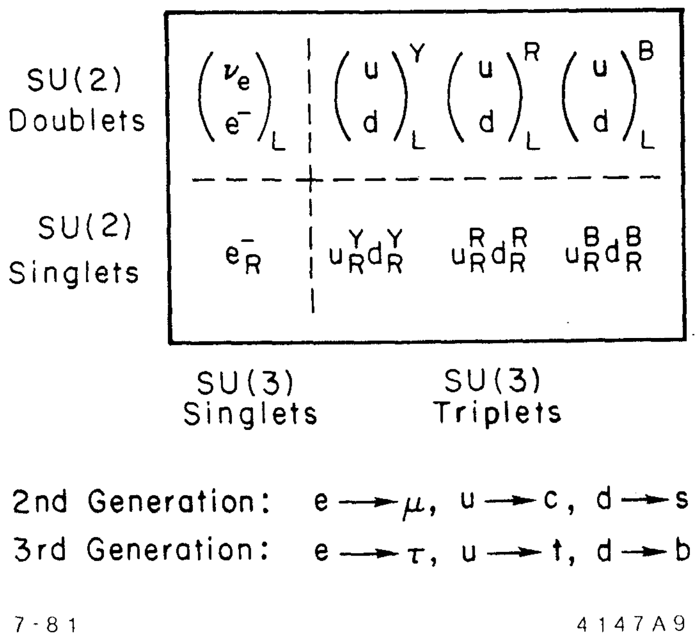
SU(2) Doublets
SU(2) Singlets
$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L$
$\begin{pmatrix} u \\ d \end{pmatrix}_L^Y$ $\begin{pmatrix} u \\ d \end{pmatrix}_L^R$ $\begin{pmatrix} u \\ d \end{pmatrix}_L^B$
e^-_R
$u^Y_R d^Y_R$ $u^R_R d^R_R$ $u^B_R d^B_R$
SU(3) Singlets
SU(3) Triplets
2nd Generation: e → μ, u → c, d → s
3rd Generation: e → τ, u → t, d → b
7-81
4147A9

Fig. 9

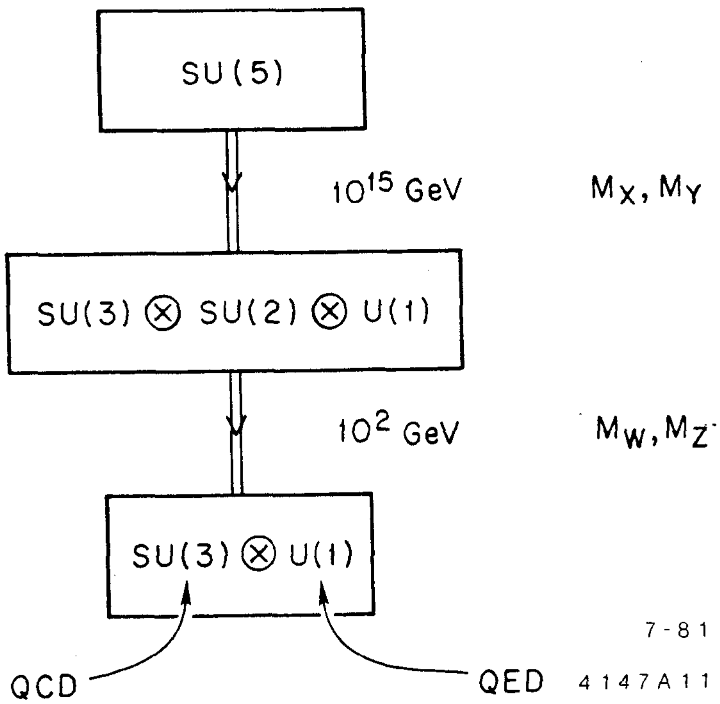
SU(5)
10^15 GeV
M_X, M_Y
SU(3) ⊗ SU(2) ⊗ U(1)
10^2 GeV
M_W, M_Z
SU(3) ⊗ U(1)
QCD
QED
7-81
4147A11

Fig. 10

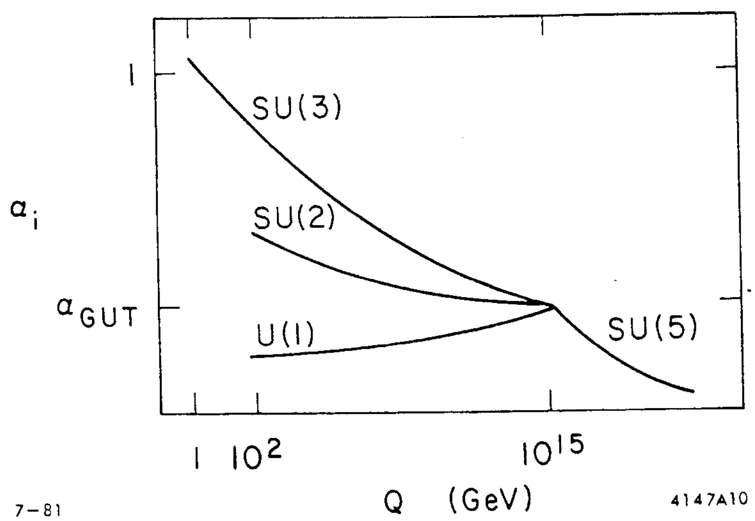

Fig. 11

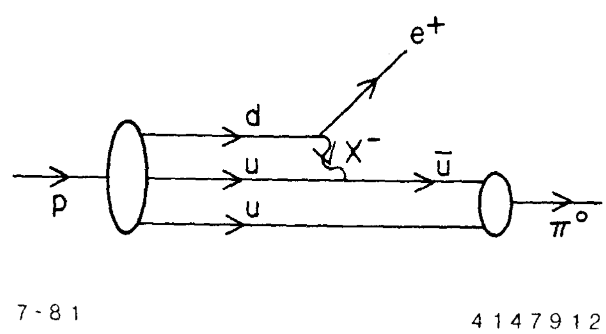

Fig. 12

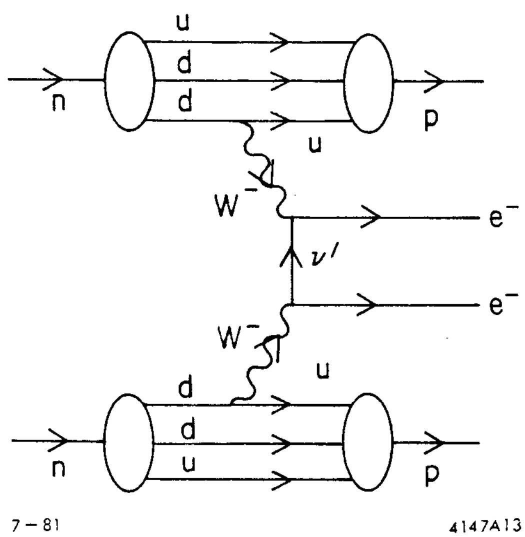

Fig. 13

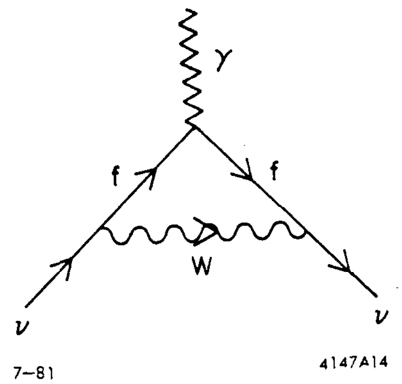

Fig. 14