Note regarding the observation of quark-type fractional electric charges

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Expansion of the charge spectrum of quarks and leptons leads to grand unified models whose electroweak sector contains a second neutral boson with a mass $\lesssim 90$ GeV. This boson may already be of experimental interest. A method is suggested for measuring the masses of new, heavy quarks and leptons.

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Fractional electric charges, $Q \approx \pm 1/3$ electron charge, may have been observed experimentally by LaRue *et al.*[1]

If their results are confirmed, it will be necessary to expand the charge spectrum of quarks and leptons (under the assumption of strict confinement). Their results[1] can be explained by assuming the existence of some new leptons $L(1^c)$ with electric charges $\pm 1/3 \pm n$ and/or quarks $r(3^c)$ with charges n, where $n = 0, 1, 2, \ldots$. As a result, charges $\pm 1/3, \pm 2/3, \ldots$, would be exhibited by not only leptons (L) but also hadrons [SU(3)^c singlets, 1^c] : $\bar{q}r$ (mesons), qqr, and qrr (baryons) (q represents an ordinary quark). We must evidently assume that these particles are quite heavy: $m \gg 1$ GeV. The lightest among them should be stable; they might have formed in an early cosmological epoch, survived to the present, entered matter, and manifested themselves in experiments like those of Ref. 1.

Although the introduction of new quarks r and leptons L presents no difficulties in ordinary SU(3)$^c \otimes$ SU(2) $\otimes$ U(1), there is the question of just which grand unified models would contain these particles along with the quarks and leptons which have already been discovered.

In this letter we will consider only those grand unified models which have intermediate SU(5) systematics for the three known generations of quarks and leptons.[2] In the general case of a group SU(n) $\supset$ SU(5) $\otimes$ SU(n - 5) $\otimes$ U(1), the charges would be written in the fundamental representation $[n = (5, 1) + (1, n - 5)]$ as follows:

$$(Q_c,\ Q_c,\ Q_c,\ Q_{l_1},\ Q_{l_2};\ Q_{f_1},\ \ldots\ Q_{f_{n-5}}),\quad \sum_i^n Q_i = 0,$$

where the charges Q_c, Q_{l_1}, and Q_{l_2} correspond to the representation $5 = (3^c, 1) + (1^c, 2)$ of the group SU(5) $\supset$ SU(3)$^c \otimes$ SU(2) $\otimes$ U(1), and the charges $Q_{f_1}, \ldots, Q_{f_{n-5}}$ are of family symmetry. In higher representations containing quarks and leptons, these family charges may lead to an "anomalous" distribution of electric charges for some of these particles (r and L). From the condition that all three families ($u, d; \nu_e$,

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e), ($c, s; \nu_\mu, \mu$), and ($t?, b; \nu_\tau, \tau$) have an observable ($\overline{5} + 10$) structure corresponding to SU(5) (Ref. 2) we conclude that

$$3Q_c + Q_{l_1} + Q_{l_2} = 0, \quad Q_{f_i} = 0 \ (i = 1, 2, 3), \quad \sum_{k=1}^{n-8} Q_{f_{3+k}} = 0.$$

We then find that the grand unified models in which we are interested should have an SU(n) symmetry with $n \geqslant 10$ and a "supercharge" symmetry SU($n-8$), which shifts the charges of r and L from their standard values.

We will be publishing elsewhere a detailed analysis of a "minimum" theory with local SU(10) symmetry and spontaneous breaking which leads to the discrete charge spectrum of r and L required by the experiments of Ref. 1. In the present letter we would like to discuss the electroweak sector of a prebroken grand unified model with a remaining symmetry SU(2)⊗U(1)⊗U(1)$'$ in the general case of SU(n). The ordinary quarks and leptons are singlets according to U(1)$'$. The quarks (r) and leptons (L), which have acquired large masses [$m \approx M$, where M is the mass of the SU(n) grand unification] as a result of breaking, have an additional quantum number, "supercharge," which is related to U(1)$'$ [this quantum number has the values ±1/3 in the SU(10) model]. A further breaking of SU(2)⊗U(1)⊗U(1)$'$ to U(1)$_{\text{em}}$ results from the presence of two scalar Higgs doublets: the Weinberg-Salam scalar ϕ, $\langle\phi\rangle = \binom{0}{\lambda}$, and a new scalar χ [a nonsinglet according to U(1)$'$], $\langle\chi\rangle = \binom{\eta}{0}$. These doublets follow from different scalar multiplets of SU(n). Finally, we find the following expressions for the electric charge and the field of the photon ($c_{1,2} \equiv \cos\theta_{1,2}$, $s_{1,2} \equiv \equiv \sin\theta_{1,2}$): $e = g_1 c_1$ and

$$A_\mu = (c_1, s_1 c_2, s_1 s_2)\begin{pmatrix} B_\mu \\ W_{3\mu} \\ V_\mu \end{pmatrix}, \quad c_1 = \left[1 + \left(\frac{g_1}{g_2}\right)^2 + \left(\frac{g_1}{g_3}\right)^2\right]^{-1/2},$$

$$c_2 = \left[1 + \left(\frac{g_2}{g_3}\right)^2\right]^{-1/2},$$

where the constants and fields (g_1, B_μ), ($g_2, W_{3\mu}$), and (g_3, V_μ) are related to U(1), SU(2), and U(1)$'$, respectively. The charged ($W^\pm$) and neutral (Z_1 and Z_2) bosons acquire masses. We can estimate these masses from the existing data on neutral currents in neutrino-hadron processes.[3] In our case the effective four-fermion Lagrangian is written as follows:

$$\mathcal{L}_{NC} = 2\sqrt{2}\, G_F (1 + \Delta) \bar{\nu} \gamma_\mu (1 + \gamma_5) \nu \left[I_{3\mu} - \frac{1}{2} Q_q J_\mu s_1^2 (1 + c_2^2) \right]_q,$$

where $I_{3\mu}$ is the current of the third component of the weak isospin, J_μ is the electromagnetic current of quark q with charge Q_q ($q = u_L, d_L, u_R, d_R$), and $\Delta \equiv \eta^2/\overline{\lambda}^2$. The constants g_1, g_2, and g_3 can be found by the standard procedure from the equations of the renormalization group in the SU(n) theory if α_s and α_{em} are known at low energies. In the SU(10) model with α_s (10 GeV) ≈ 0.16 they are ($\alpha_i \equiv g_i^2/4\pi$)

$$\alpha_1 \approx 0{,}01, \quad \alpha_2 \approx 0{,}04, \quad \alpha_3 \approx 0{,}105, \quad s_1^2 \approx 0{,}25, \quad c_2^2 \approx 0{,}72.$$

Now comparing $\mathscr{L}_{\mathrm{NC}}$ with a model-independent analysis of the data of Ref. 3, we find $\Delta \lesssim 0.1$, and for the masses of the weak bosons we then find (in GeV)

$$m_W \approx 88, \quad 95 \lesssim m_{Z_1} \lesssim 98, \quad m_{Z_2} \lesssim 87.$$

An experimental search for a second neutral boson with a mass $\lesssim 90$ GeV and a total width $\Gamma_{Z_2} \approx s_2^2\, m_{Z_1}/m_{Z_2}\, \Gamma_{Z_1} \lesssim 600$ MeV ($\Gamma_{Z_1} \approx 2.4$ GeV) would thus be a critical test of the entire scheme.

Let us examine the cosmological aspects of the existence of heavy r and L (with $m \approx 10^{14-15}$ GeV). Standard cosmology[4] yields an unacceptably high number density for these particles, $f \equiv n/n_\gamma \approx mG^{1/2} \approx 10^{-18} m$ (where m is in GeV). The number density of r and L may turn out to be acceptable ($f_{\mathrm{expt}} \lesssim 10^{-30}$, Ref. 4) if the conditions during the expansion of the universe and the temperature dependence $T(t)$ were different from those of standard cosmology in the early stages, at times near the Planck time. Thus we conclude that, first, the curvature must satisfy the condition $\max R^{\sigma}_{\mu\nu\lambda}(t)\,| = l^{-2} \ll m^2$, so that there will be a suppression [of the type $f \sim (m^2 G)^{3/4} e^{-2ml}$] on the production of $\bar{r}r$ (or $\bar{L}L$) by the varying gravitational field. Second, the condition $\max T(t) = T_0 \ll m$ must be satisfied, so that $f \sim e^{-m/T_0}$ will be sufficiently small ($f \approx f_{\mathrm{expt}}$, $m/T_0 \approx 70$, $T_0 \approx 10^{12-13}$ GeV). Finally, there must be "initial" conditions with $f(t_{\mathrm{in}}) \lesssim f_{\mathrm{expt}}$. No cosmological observation, which has been made to date, contradicts these "minimum" but necessary changes in the standard picture.

We conclude with a suggestion for experimentalists. Heavy hadrons ($\bar{q}r$, qqr) entering matter would probably become attached to nuclei (with binding energies ≈ 1–10 MeV) and would continue to exist in this form in the matter. The corresponding heavy atoms would be bound at lattice sites with a binding energy $\epsilon \approx 1$ eV. Heavy leptons, in contrast, might be in deep Bohr orbitals (for L^-) or in interstitial positions (for L^+), also with an energy $\epsilon \approx 1$ eV. Accordingly, an acceleration of the corresponding object of magnitude $a \gtrsim \epsilon\,(sm)^{-1}$, where s represents atomic dimensions, would cause a heavy r (or L^-) atom (or a lepton L^+ itself) to move between lattice sites and thus be expelled from the object. For masses $m > 10^{12}$ GeV, the accelerations required are $a \approx 10^{18}/m$ (where a is in meters per square second and m is in GeV), comparable to those currently attainable in the laboratory. Accordingly, shaking a sample containing heavy charges (one of the balls from the experiments of Ref. 1, for example) by fast vibrations or centrifuging might be a successful method for measuring the masses of the r and L particles, provided that they lie in an appropriate mass corridor.

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