Long-lived *t* quark

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A long-lived t quark with $T_t \gtrsim 10^{-10}$ s is consistent with grand unified theories and useful for explaining experimental data on extensive air showers. The expected mass of the t quark is about 40 GeV.

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Experimental discovery of the t quark is an important problem in the physics of elementary particles. The CERN $p\bar{p}$ collider presents an opportunity for the corresponding search, and a priliminary analysis of the experimental data has already begun.[1] Estimates in Ref. 1, for example, indicate the existence of a t quark with a mass of about 40 GeV. From the standpoint of the grand unified theory, the discovery of the t quark is a necessary step which must be taken in order to formulate the first principles of the theory. In particular, the discovery of a short-lived t quark with $T_t \lesssim 10^{-16}$ s and a charge of 2/3 would confirm the hypothesis of "generations" and the Kobayashi--Moshawa mechanism[2] for CP violation for the standard grand unified models. On the other hand, some difficulties hav arisen. For many years new, long-lived, massive particles ($T^x \gtrsim 10^{-10}$ s, $M_x \gtrsim 20$ GeV) have been observed in the cosmic rays[3] and interpreted as hadrons. A long-lived t quark would furnish a logical explanation for these obsevations, but it would also mandate changes in the standard grand unified model.

There are grand unified models in which the t quark is long-lived[4] but has a charge of 1/3 (Refs. 4 and 5). This t-quark charge is characteristic of grand unified models in which the hypothesis of generations has a limited meaning and does not lead to a doubling of the multiplets of particles which determine the low-energy properties of the theory. Here the t quark is a heavy analog of the b quark, generalizaing the GIM mechanism,[6] which has been proposed for the u and c quarks. For the model of Ref. 4 this "duality" also extends to the lepton sector, stimulating the prediction of several more new heavy leptons. The lightest, the θ lepton (the "dual" of the τ lepton), should have a mass on the order of 20–40 GeV. Today the grand unified model with a long-lived t quark,[4] along with a standard theory [the SU (5) theories, for example], does not seem paradoxical, and it even appears preferable in the light of experiments on cosmic rays and extensive air showers. Furthermore, when supplemented with the requirement of asymptotic freedom,[8] this SU (5) theory has only a small number of "adjustable" parameters and thus considerable predictive power. In particular, the non-observability of exotic decays of the τ lepton is linked directly by the SU (5) model[4] to the existence of the long-lived t quark, which is requird to explain the data on extensive air showers. A parity-nonconservation effect has also been detected in atomic physics, for heavy atoms; for the SU (5) grand unified models under discussion, this parity-nonconservation effect must be at the level of the predictions of the Weinberg–Salam model.

An asymptotically free SU (5) theory was proposed in 1976 by E. S. Fradkin and the present author. the discovery of the τ lepton (which was in fact predicted by this theory) refined several of the theoretical parameters, but considerable latitude remained in the choice of parameters until recently. In particular, we did not know much about the physics of the b quark, and some uncertainty remained in the parameters determining the spectroscopy of the new leptons and quarks. Today, we can make several refinements. Analysis of recent experiments shows that the primary decay of the b quark involves not a u quark but a c quark. In the SU (5) model[4] the necessary current results from a (b, s) interference,

$$j_\mu = \mathrm{tg}\,(\widehat{b, s})\,\bar{b}\,\gamma_\mu O c \tag{1}$$

and its amplitude is on the order of 1/4. The important point, however, is that for the SU (5) theory this assertion is sufficient to establish the physics of the t quark essentially unambiguously. The primary decay of th t quark in the model of Ref. 4 is now determined by a current involving the u quark,

$$j_\mu = \mathrm{tg}(\widehat{t, d})\,\bar{u}\,\gamma_\mu O t \tag{2}$$

and it is important to note that the (t, d) mixing angle in (2) is extremely small. After the choice (1) is made, the (t, d) mixing angle is not arbitrary but determined by the particular multiplet structure adopted in the theory, by which the mixing angles for the leptons and quarks are correlated. In particular, if we retain the standard structure of the $\Psi_R\,(\Psi^L)$ and $\partial_R\,(\partial^L)$ multiplets, and if we choose the η and ζ multiplets in Ref. 4 to satisfy (1) and (2),

$$\eta = \begin{pmatrix} t_i^c \\ \tau \\ N_\tau \end{pmatrix} \; ; \quad \zeta = \begin{pmatrix} b_i \\ \theta \\ N_\theta \end{pmatrix} , \tag{3}$$

then we find that the (t_L, d_L) and (e_R, π_R) mixing angles are unambiguously related,

$$\mathrm{tg}\,(\widehat{e_R, \tau_R}) = \left(\frac{q_1 \rho}{\sqrt{2}}\right)\frac{1}{m_\tau} \; ;$$

$$\mathrm{tg}\,(\widehat{t_L, d_L}) = \left(\frac{q_1 \rho}{\sqrt{2}}\right)\frac{1}{m_t} \; . \tag{4}$$

Since the $(e_R\,\tau_R)$ mixing angle (which determines the exotic decays of the τ lepton) is known[9] [$tg(e_R\,\tau_R) \lesssim 4.10^{-2}$], expressions (4) can be used to find the (t_L, d_L) interference angle:

$$\mathrm{tg}\,(\widehat{t_L, d_L}) \approx \frac{m_\tau}{m_t}\,\mathrm{tg}\,(\widehat{e_R, \tau_R}) \lesssim 2.2 \times 10^{-3}, \tag{5}$$

under the assumption that the mass of the t quark is on the order of 40 GeV, in accordance with the choice of parameters for the SU (5) theory made in Ref. 4. The small (t_L, d_L) mixing angle has two consequences: The t quark is long-lived, and parity-nonconservation effects in heavy atoms should be observable at the level predicted by the Weinberg–Salam model.

In the standard grand unified theories, the t quark lives for about 10^{-16}s. Because of the effective mixing (in particular, mixing with the b quark by virtue of the Kobayashi–Moshawa CP-violation mechanism[2]), the t quark cannot be long-lived if it has a mass of about 40 GeV. In the model of Ref. 4, with estimate (5), the lifetime of the t quark increases,

$$T_t \approx (10^3)^2 (T_t)_{\text{stand}} \approx 10^{-10}\ \text{s}, \tag{6}$$

and in principle it can increase to 10^{-8}s if exotic decays of the τ lepton are not observed at the level of $10^{-2}\%$. A long-lived t quark of this sort is extemely pertinent to a theoretical interpretation of the experimental data from extensive air showers, since it could furnish a natural explanation for the production of new hadrons in $N+N$ collisions and in $\pi+p$ reactions at $E_L \gtrsim 1$ TeV in the atmosphere at altitudes 5–20 km. The lifetime of such hadrons is estimated experimentally to be 10^{-8}–10^{-10}s at a mass on the order of [10]20–40 GeV.

If the current determining the primary weak decay of the b quark is chosen in form (1), we get rid of the uncertainty of the model of Ref. 4 regarding the predicted magnitude of the parity nonconservation in heavy atoms. As long as no such current has been detected for the b quark, there have been several possibilities,[11] in particular, those which lead to SU (5) predictions substantially different from the predictions of the Weinberg–Salam model. The essential point is that the magnitude of the "weak" charge Q_W, which determines the angle through which the polarization plane rotates, depends in the nonstandard grand unified models on not only $\sin^2\Theta_w$ but also the two parameters C_L and s_R:

$$Q_W = [(A-2Z)\left(-\frac{1+c_L^2}{2} + 2\sin^2 Q_W\right) - 3A\left(-\frac{1+c_L^2}{2} + \frac{2}{3}\sin^2\theta_W\right)](1-s_R^2) \tag{7}$$

The predictions of this theory can be changed by choosing these parameters appropriately. Having fixed (1), however, we are forced to choose the parameters $s^2{}_L + \sin^2(d_L t_L)$ and $s^2{}_R = \sin^2(e_R, \tau_R)$ to be small (on the order of 10^{-4} or smaller). In the Weinberg--Salam model these parameters are strictly zero, but it is clear, according to Ref. 7, that an assignment of values on the order of 10^{-4} to these parameters would not make the predictions of this SU (5) model different from those of the standard model. Although experiment has not yet unambiguously answered this question in favor of the Weinberg–Salam model, a recent trend in this direction is becoming obvious.

The agreement between this SU (5) grand unified model and experimental data from extensive air showers is impressive, but it is not an absolute validation of the theory. We must not overlook the existence of standard SU (5) models which predict a t quark of probably the same mass but with very different properties. The discovery of this quark is an urgent matter for the grand unified models, although the existence of the long-lived hadrons observed in the extensive air showers is not an ordinary possibility for the standard grand unified models, and in this sense difficulties are unavoidable. The success of the hypothesis of generations (if a t quark with a charge of 2/3 is discovered) will undoubtedly become a major victory of the grand unified models, but the standard SU (5) theory, like the model of Ref. 4, must be revised. Long-lived quarks with $T \sim 10^{-10}$s and a mass on the order of 40–60 GeV seem to be a necessary element of the future theory.

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