Superheavy fermions and proton lifetime

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The grand unification models can contain superheavy fermions ($m \approx 10^{15}$ GeV) in addition to superheavy vector and scalar bosons. An introduction of multiplets with such fermions changes the unification energy and the proton lifetime (τ_p). Specifically, it makes it possible to increase τ_p in the SU_5 model by two to three orders of magnitude.

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The hierarchy of particle masses is an important feature of grand unification models.[1] One multiplet of vector bosons (this also pertains to scalar bosons) includes both light particles with masses $m \lesssim 100$ GeV ($W^{\pm}$, Z^0) and superheavy particles: $m \sim 10^{14}$–10^{15} GeV. Do superheavy fermions exist together with the light fermions?

The structure of fermion multiplets in the examined (SU_5, SO_{10}) models is such that the gauge-invariant interaction of fermions with Higgs multiplets that have large vacuum expectations ($v \approx 10^{15}$ GeV) cannot be constructed and also the ordinary mass terms cannot be introduced. The fermion masses (m_f) arise here as a result of interactions with the scalar multiplets that acquire vacuum expectations of ~ 300 GeV, where $m_f \lesssim 250$ GeV.[2]

Using the SU_5 model we examine in this paper some consequences of introducing superheavy fermions, focusing attention first on their effect on the proton lifetime. This is of special interest for the SU_5 model, since the most probable predictions based on this model,[3] $\tau_p = 10^{30 \pm 2}$ years, are already at the lower experimental limits, $\tau_p \gtrsim 10^{30}$ years,[4] and the implementation of new projects in the next few years involving the search for proton instability[5] will make it possible to increase the lower limits to 10^{33}–10^{34} years. Moreover, the most recent estimates of the QCD parameter, $\Lambda = 0.20 \pm 0.06$ GeV[6] (see also Ref 7), give $\tau_p = (0.6\text{–}7.0)\times 10^{29}$ years, consistent with that in Ref. 3, which indicates that the standard SU_5 model must be modified.

Note that the superheavy fermions can play a specific role in forming baryon asymmetry in the universe annd also in further unifying the particles and interactions (unification of fermion generation, inclusion of gravitation).

1. *The superheavy fermions in* SU_5. The simplest possibility is an additional (one or generally several), two-sides 5-multiplet $\Psi_{L(R)} = (q_1, q_2. q_3. l^+, l^0)_{L(R)}$. The general form of interactions that give mass to the particles in Ψ is

$$h \bar{\Psi}^{\alpha}_{L} \Psi_{R\beta} \Phi^{\beta}_{\alpha} + M \bar{\Psi}^{\alpha}_{L} \Psi_{R\alpha} + \lambda.c., \tag{1}$$

where Φ^{α}_{β} is the Higgs 24-multiplet with vacuum expectations $\langle \Phi^{\alpha}_{\alpha} \rangle_0 = (2v, 2v, 2v, -3v, -3v)v \sim 10^{15}$ GeV. Thus, we obtain from Eq (1)

$$m_{l^0} = m_{l^+} = M - 3hv \qquad m_q = M + 2hv . \tag{2}$$

By combining the parameters in Eq. (2) we can obtain arbitrary relationships between the masses m_l and m_q.

As a result of a lepton-quark transition due to X or Y boson exchange, the heavier components of the 5-multiplet experience a fast, three-particle decay: for example, for $m_q \ll m_l \approx m_x \approx 10^{15}$ GeV $l^+ \to qX \to quu$ with $\tau \approx 192\pi^3 [\alpha_{GU} m_x N]^{-1} \approx 10^{-36}$ sec ($N = 12$ is the number of decay channels X).

The light components of the 5-multiplet are stable: for $m_l > m_q$ they are the q quarks which form stable hadrons with $m \gtrsim m_q$, and $m_q > m_l$ it is the l lepton. The cosmological exclusions of these particles and the upper limits for their masses[8] are missing if they are mixed with the known light fermions (for example, q with d quarks) and hence they experience weak decays ($q \to ue\nu_e$). Such mixing occurs in the SU_5 model by introducing an additional 45-multiplet of the Higgs particles. $\tau_q = 192\pi^3 [G_F^2 m_q^5 s^2 N]^{-1} \approx 10^{-18}$ sec for the mixing parameter $s = 0.01$ and $m_q \approx 100$ GeV.

2. *Behavior of constants, unification point* (q_{GU}), *and proton lifetime.* The introduction into a unified model of additional fermion or Higgs multiplets Ψ with small mass splitting: $m_{\max}/m_{\min} \approx 1$ changes q_{GU} very little (a special case of this is the independence of q_{GU} of the fermion generation number). If, however, there is a large splitting within the multiplet $m_{\max}/m_{\min} \gg 1$, then the additional contributions from Ψ to the different coupling constants in the region $m_{\min} < q < m_{\max}$ will be different and the unification energy will change. Thus, for the 5-multiplet with $m_q \ll m_l$ a slowing down in the decrease of α_c (SU_3^c constant) is greater as q increases due to the q-quark effects at $m_q < q < m_l$ than the additional increase of α_{em}, since there is no contribution from the l^+ lepton in this region, and hence the unification point of the α_c and α_{em} constants $[\alpha_{em}(q_{GU}) \approx 3/8 \alpha_c(q_{GU})]$ is shifted in the direction of higher energies. At $m_q \gg m_l$ the opposite occurs: q_{GU} and τ_p decrease.

Generally, a variation of the unification energy q^n_{GU} of the α_c, α_{em}, and $\tau^n_p (\tau_p - q^4_{GU})$ constants as a result of introduction of n 5-multiplets:

$$\lg\frac{q^n_{GU}}{q^0_{GU}} = \frac{1}{4}\lg\frac{\tau^n_p}{\tau^0_p} = \frac{2}{33}\left|\lg\frac{m_l}{m_q}\right|\frac{n\epsilon}{1-\frac{2}{33}n\epsilon}$$

$$\epsilon = \begin{cases} +1 & m_l > m_q \\ -1 & m_l < m_q \end{cases}. \tag{3}$$

We shall assume that $\max(m_l,m_q)\approx q_{GU}\sim 10^{15}$ GeV. At $n=1$, $m_{\min}\sim 100$ GeV we have from Eq. (3): $q^n_{GU}/q^0_{GU} = 6.8$ and $\tau^n_p/\tau^0_p = 10^{\pm 3}$. The unification point and τ_p can vary continuously by decreasing the mass splitting (for example, by increasing $m_{\min}$). For $n = 1$ $\lg g_{GU}/m_{\min} \approx 3.9 \lg(\tau^1_p/\tau^0_p)$ and a variation of τ_p by an order of magnitude corresponds to $m_{\min}\approx 10^{11}$ GeV and by two orders of magnitude, to 10^7 GeV.

The discussed 5-multiplets also modify the behavior of α_w/q and hence the predictions for $\sin^2\theta_w$:

$$\Delta\sin^2\theta_W \equiv \sin^2\theta_W\big|_n - \sin^2\theta_W\big|_0 = \frac{2}{99}\left(1-\frac{8}{3}\,\frac{\alpha_c^{-1}(m_{\min})}{\alpha_{\mathrm{em}}^{-1}(m_{\min})}\right)\frac{n\epsilon}{1-\frac{2}{33}n\epsilon}$$

$$\approx \frac{11}{3\pi}\,\alpha_{\mathrm{em}}(m_{\min})\ln\frac{q^n_{GU}}{q^0_{GU}} \approx 0.0056\lg\frac{\tau^n_p}{\tau^0_p}. \tag{4}$$

As seen in Eq. (4), a variation of $\sin^2\theta_w$ is directly related to the variation for q_{GU} or τ_p. The experimental values of $\sin^2\theta_w$ (0.19–0.25) give an upper limit to a possible increase of τ_p in the SU_5 model using the superheavy fermions. Since $\tau_p = 10^{29}$–10^{30} years in the standard time model corresponds to $\sin^2\theta_w\approx 0.21$, a permissible decrease of $\Delta\sin^2\theta_w = 0.015$–$0.020$ gives [see Eq. (4)] $\tau^n_p/\tau^0_p\sim 10^3$ and $\tau^n_{p_{\max}}\sim 10^{32}$–$10^{33}$ years. Such an increase of τ_p, according to Eq. (3), can be achieved by introducing a single 5-multiplet with $m_q\sim 100$ GeV and $m_l\sim 10^{15}$ GeV. The same result can be reproduced for τ_p and $\sin^2\theta_w$ by increasing the numbr of 5-multiplets n fold and by concurrently decreasing the mass splitting m_l/m_q. In the case of three 5-multiplets (one for each generation of known particles) $m_q\sim 10^{11}$ GeV.

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