Supersymmetric unified theories

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A supersymmetric generalization of the SU(3)×SU(2)×U(1) model is analyzed. At low energies (≤ 1 TeV), the Higgs sector essentially has to contain two SU(2) doublets H and H' and a neutral singlet G. The supersymmetry is broken spontaneously. Operators with $d = 5$ do not lead to a rapid decay of the proton, while operators with $d = 6$ lead to $\tau_0 \approx 10^{34}$ yr.

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Several recent papers[1-5] have examined the consequences of a low-energy supersymmetry which is broken at an energy ~100 GeV. This low-energy supersymmetry puts the question of hierarchies in a new light, and it has the attractive features of mathematical elegance and the prediction of a new physics at $E \sim 100$ GeV.

Analyzing the Dimopoulos-Georgi model,[2] Weinberg[4] noted that in it the operators with $d=5$ lead to a rapid decay of the proton ($\tau_p \approx 10^{28}$ yr). In this model the supersymmetry is broken manually (by deliberate intervention). Our purpose in the present paper is to construct a model with a spontaneous breaking of the supersymmetry. We will see that the operators with $d=5$ do not lead to the decay of the proton; the proton has a long lifetime (as it usually does in supersymmetric schemes[5]) and decays because of operators with $d=6$ in 10^{34} yr.

The quarks and leptons form chiral supermultiplets. The SU(2) composition of one family is

$$\begin{pmatrix} U \\ D \end{pmatrix}_L (Q_L),\ U_R,\ D_R\ ;\begin{pmatrix} \nu \\ E \end{pmatrix}_L (L_L),\ E_R\ , \tag{1}$$

where the large letters denote chiral multiplets, and $U=(u, su)$, where su is a scalar u quark. The gauge fields form vector supermultiplets. The masses give the quarks and leptons two Higgs superdoublets[3,4]:

$$H_L = \begin{pmatrix} H_0 \\ H_- \end{pmatrix}_L\ ,\quad H'_L = \begin{pmatrix} H'_+ \\ H'_0 \end{pmatrix}_L\ , \tag{2}$$

where $H_0 = (\mathrm{H}_0, \lambda_{H_0})$. For a self-consistent description we need a Higgs singlet $G = (\mathrm{G}, \lambda_G)$. In addition to those already mentioned, there are fields with a mass $\sim 10^{15}$ GeV which are not included directly in the low-energy description. The Lagrangian of the mass fields in (1) contains a kinetic term and an interaction with Higgs fields:

$$\mathcal{L} = f_u [H'_L\, \epsilon\, Q_L U_R^*\ ]_F + f_d [H_L \epsilon\, Q_L D_R^*\ ]_F + f_e\ [H_L\ \epsilon\, L_L E_R^*\ ]_F\ , \tag{3}$$

where the Yukawa constants f determine the masses of the spinor fields, and ϵ is the antisymmetric symbol of the SU(2) group. Before we take up the interaction of the Higgs fields, we wish to make a comment regarding the scalar partners of the mass fields. Their precipitation is inadmissible. The minimum potential must therefore be reached at zero mass fields. We will accordingly seek the minimum potential of the Higgs fields, and we will construct the potential of the scalar mass fields manually in the appropriate manner, giving the corresponding particles masses ~100 GeV.

We can write the Lagrangian for the Higgs fields as follows (without the kinetic term):

$$\mathcal{L} = \mu [H'_L \epsilon H_L]_F + h [H'_L \epsilon H_L G_L]_F + s [G_L]_F . \tag{4}$$

In the Lagrangian of the gauge fields, we include the U(1) term ζD_B. The interaction potential of the scalar Higgs fields is

$$V(\mathbf{H}, \mathbf{H}', \mathbf{G}) = F^+_H F_H + F^+_{H'} F_{H'} + {}^1/_2 \, (\mathrm{D}_{SU(2)})^2 + {}^1/_2 D^2_B . \tag{5}$$

To conserve the U(1) symmetry, we require $h^2 < g^2/2$; then the potential in (5) reaches a minimum at

$$< \mathbf{H} > = \begin{pmatrix} \eta/\sqrt{2} \\ 0 \end{pmatrix}, \quad < \mathbf{H}' > = \begin{pmatrix} 0 \\ \eta'/\sqrt{2} \end{pmatrix}. \tag{6}$$

We can rewrite (5) in terms of (6) and $\langle \mathbf{G} \rangle = G$:

$$V(\eta, \eta', G) = (\mu + hG)^2 \frac{\eta^2 + \eta'^2}{2} + \frac{g^2}{32} (\eta'^2 - \eta^2)^2 + {}^1/_2 [\zeta + {}^1/_4 g' (\eta'^2 - \eta^2)]^2 + [s - \frac{h}{2} \eta \eta']^2 . \tag{7}$$

It is necessary to introduce G because without it the minimum in (7) would be reached at η or $\eta' = 0$. The minimum of (8) is reached at

$$\eta \eta' = \frac{2s}{h} \quad (8a), \quad \eta^2 - \eta'^2 = \frac{4\xi g'}{g^2 + g'^2} \quad (8b), \quad \chi = -\frac{\mu}{h} \quad (8c).$$

It is clear from (8) that the term $\mu \, [H' \epsilon H]_F$, which leads to the Majorana mass λ_w and to a rapid decay of the proton because of the operators with $d = 5$, does not yield the Majorana mass λ_w in our model because of the cancellation with the term $h \, [H' \epsilon H \chi]_F$:

$$(\mu + h < \mathbf{G} >) \lambda_H \epsilon \lambda_{H'} = 0. \tag{9}$$

The proton decay results from the operators with $d = 6$, and for a discussion in specific terms we must supplement our model with a high-energy superstructure. As this superstructure we adopt that version of the SU(5) Dimpoulos-Georgi model in which there is a 24-plet of superheavy Higgs fields, while the doublets H and H' are included in an SU(5) quintet. At an energy of 10^{15} GeV there is a breaking SU(5) $\to$ SU(3) $\otimes$ SU(2) $\otimes$ U(1), which conserves the supersymmetry. We assume that the field G is an SU(5) singlet. The proton lifetime is different from the standard estimates because of the change in M_{GUT} caused by the large number of additional light particles. Using $\Lambda_{\mathrm{QCD}} = 100$ MeV, we find

$$M_{GUT} = 5 \times 10^{15} \text{ GeV}, \quad \tau_p = 10^{34} \text{ yr}. \tag{10}$$

In summary, the model proposed here is based on a low-energy SU(3) ⊗ SU(2) ⊗ U(1) supersymmetry. At ~100 GeV there is a spontaneous breaking of the supersymmetry and of the SU(2) ⊗ U(1) symmetry because of the U(1)D_B term. The coefficient ξ in this term, like the quantity s, of dimensionality M^2, is introduced into the theory manually (from the standpoint of Ref. 1, these terms, of scale $e^{-1/g^2}M_{\text{GUT}}$, must be generated dynamically); then the problem of hierarchies is solved. This model necessarily contains a singlet field in addition to the two doublets of Higgs fields. The proton does not decay because of the operators with $d = 5$; its decay time is 10^{34} yr. At an energy of 100 GeV there is an interesting new physics. The scalar partners of the mass fields constitute a deficiency of this model. By virtue of the Dimopoulos-Georgi theorem (the appearance of light scalars), these fields must manually be given masses ~100 GeV in this step. This is not an esthetically attractive procedure, although it does not damage the hierarchies.[6]

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