NEW SUPERSYMMETRIC STANDARD MODEL WITH STABLE PROTON

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We discuss a supersymmetric extension of the standard model with an extra U(1) gauge symmetry. In this model, the proton stability is guaranteed by the gauge symmetry without invoking R parity. The gauge symmetry breakdown automatically generates an effective µ term and large Majorana masses for right-handed neutrinos. The supersymmetry-soft-breaking terms for scalar fields could be universal at a very high energy scale, and the electroweak symmetry is broken through radiative corrections.

The supersymmetric standard model (SSM) is considered to be one of the most plausible extensions of the standard model (SM). In particular, the minimal SSM (MSSM) is usually treated as the standard theory around the electroweak scale. However, this MSSM suffers one potentially serious problem. The proton may decay through baryon-number-violating couplings of dimension four, and thus its lifetime could become unacceptably short. In order to forbid those dangerous couplings, therefore, an ad hoc discrete symmetry is imposed on the model through R parity. In the SM, on the other hand, the interactions which induce the proton decay are not allowed by gauge symmetry. The SSM would become more plausible, if the proton can be protected from decay more naturally.

In this report, we present a new SSM, in which the proton stability is guaranteed by an extra U(1) gauge symmetry, within the framework of a model coupled to N = 1 supergravity. This model also provides natural explanations for the µ parameter and neutrino masses which are merely put by hand in the usual SSM.

Keeping the extension of the SM as minimal as possible, the particle contents of the model are taken as shown in Table 1. The extra U(1) gauge symmetry is denoted by U′(1), for which the charges of superfields are expressed as Q, QUc, etc. The index i (= 1, 2, 3) of the superfields for quarks and leptons stands for the generation, while the indices j (= 1 · · · nj) of H1 and H2, k (= 1 · · · nk) of S, and l (= 1 · · · nl) of K and Kc are attached for possible multiplication.

In addition to the superfields of the MSSM, our model has SM gauge singlets Nc and S for, respectively, right-handed neutrinos and Higgs bosons to break the U′(1) symmetry. The superpotential is then required to contain the couplings H2LNc and SNcNc for giving non-vanishing but tiny masses to the ordinary neutrinos. The µ term in the MSSM is replaced by SH1H2. New colored superfields K and Kc are incorporated to cancel a chiral anomaly. Their fermion components can receive masses from SKKc.

The hypercharges of K and Kc, the U′(1) charges of all the superfields, and the numbers nj, nk, and nl are determined by chiral and trace anomalies and necessary couplings of superfields. Barring irrational hypercharges for K and Kc, we obtain YK = ±1/2 and nj = nk = nl = 3. The superfields with the same quantum numbers are all trip-
Table 1. Particle contents and their quantum numbers. \( i = 1, 2, 3; j = 1, \ldots, n_i; k = 1, \ldots, n_k; l = 1, \ldots, n_l \).

| \( i \)  | \( SU(3) \) | \( SU(2) \) | \( U(1) \) | \( U'(1) \) |
|-------|-----------|-----------|-----------|-----------|
| \( Q^i \) | 3 | 2 | \( \frac{1}{3} \) | \( Q_Q \) |
| \( U^{ci}_i \) | 3* | 1 | \(-\frac{1}{2} \) | \( Q_{U^c} \) |
| \( D^{ci}_i \) | 3* | 1 | \( \frac{1}{3} \) | \( Q_{D^c} \) |
| \( L^i \) | 1 | 2 | \(-\frac{1}{2} \) | \( Q_L \) |
| \( N^{ci}_i \) | 1 | 1 | 0 | \( Q_{N^c} \) |
| \( E^{ci}_i \) | 1 | 1 | 1 | \( Q_{E^c} \) |
| \( H^1_i \) | 1 | 2 | \(-\frac{1}{2} \) | \( Q_{H^1} \) |
| \( H^2_i \) | 1 | 2 | \( \frac{1}{2} \) | \( Q_{H^2} \) |
| \( S^k \) | 1 | 1 | 0 | \( Q_S \) |
| \( K^l \) | 3 | 1 | \( Y_K \) | \( Q_K \) |
| \( K^{cl}_l \) | 3* | 1 | \(-Y_K \) | \( Q_{K^c} \) |

Table 2. \( U'(1) \) charges of the superfields.

| \( Q_Q \) | \( Q_{U^c} \) | \( Q_{D^c} \) | \( Q_L \) | \( Q_{N^c} \) | \( Q_{E^c} \) |
|-----------|-----------|-----------|-----------|-----------|-----------|
| \( Q_{H^1} \) | \( Q_{H^2} \) | \( Q_S \) | \( Q_K \) | \( Q_{K^c} \) |
| \(-\frac{1}{3} \) | \(-\frac{2}{3} \) | \(-\frac{1}{3} \) | \(-\frac{1}{3} \) | \(-\frac{1}{3} \) |

The superpotential is given by

\[
W = \eta_u \mathcal{H}_2 \mathcal{Q}^i \mathcal{U}^{ck} + \eta_d \mathcal{H}_1 \mathcal{Q}^i \mathcal{D}^{ck} + \eta_e \mathcal{H}_2 \mathcal{L}^j \mathcal{N}^{ck} + \eta_e \mathcal{H}_1 \mathcal{L}^j \mathcal{E}^{ck} + \lambda_{N}^{ijk} \mathcal{S}^{ij} \mathcal{N}^{ck} + \lambda_{H}^{ijk} \mathcal{S}^{ij} \mathcal{H}_1 \mathcal{H}_2^k + \lambda_{K}^{ijk} \mathcal{S}^{ij} \mathcal{K}^3 \mathcal{K}^{ck},
\]

where all the couplings allowed by gauge symmetry and renormalizability are contained. The couplings are all cubic, and there is no mass parameter.

The model is coupled to \( N = 1 \) supergravity, which breaks supersymmetry softly in the observable world. The Lagrangian contains, as well as supersymmetric terms, mass terms for scalar bosons and gauge fermions, and trilinear couplings for scalar bosons. In the ordinary scheme, the mass-squared and trilinear coupling constants for the scalar bosons have universal values \( m_3^2/2 \) and \( A \), respectively, at the energy scale a little below the Planck mass. Hereafter, the scalar components of the superfields \( H_1, H_2, \) and \( S \) are expressed by \( \mathcal{H}_1, \mathcal{H}_2, \) and \( \mathcal{S} \).

The parameter values of the model change according to the relevant energy scale. The mass-squared of \( \mathcal{H}_2^3 \) receives large negative contributions through quantum corrections, owing to a large coefficient \( \eta_u \) of \( H_2^3 Q^3 \mathcal{U}^{c3} \) related to the top quark mass. As a result, this mass-squared becomes small around the electroweak scale, leading to non-vanishing vacuum expectation values (VEVs) for \( \mathcal{H}_1^3 \) and \( \mathcal{H}_2^3 \). The electroweak symmetry is broken through radiative corrections. On the other hand, for the first two generations, quantum corrections to the masses-squared of \( \mathcal{H}_1^1 \) or \( \mathcal{H}_2^1 \) are not large, so that the VEVs of these scalar bosons vanish. If a coefficient \( \lambda_K \) of \( S^3 K^3 \mathcal{K}^{c3} \) is large, the mass-squared of \( \mathcal{S}^3 \) is also driven small. A non-vanishing VEV is induced for \( \mathcal{S}^3 \), and the \( U'(1) \) symmetry is broken spontaneously.

The scalar potential is numerically analyzed at the electroweak scale to examine
the parameter regions which give a vacuum consistent with experimental results. In particular, the $U'(1)$ symmetry predicts a new neutral gauge boson $Z'$, for which stringent constraints are obtained on the mass and the mixing with the $Z$ boson of the SM. We assume that $\tilde{H}_3^1$, $\tilde{H}_3^2$, and $\tilde{S}^3$ of the third generation have non-vanishing VEVs, which are denoted by $v_1$, $v_2$, and $v_s$. It is shown that sizable regions are allowed for the mass-squared parameters $M^2_{\tilde{H}_1}$, $M^2_{\tilde{H}_2}$, and $M^2_{\tilde{S}}$ of the Higgs bosons. The coefficient $\lambda_H$ of $S H_1 H_2$ should be around $0.1 - 0.4$. Owing to the constraints from the $Z'$ boson, $M^2_{\tilde{H}_1}$ is mostly larger than $(1 \text{ TeV})^2$. The value of $M^2_{\tilde{H}_2}$ is generally smaller than $M^2_{\tilde{H}_1}$ in magnitude, and $M^2_{\tilde{S}}$ is always negative. The VEV of $S$ is larger than $1 \text{ TeV}$.

The term $\lambda_H S H_1 H_2$ assumes the $\mu$ term of the SSM. The effective $\mu$ parameter is given by $\lambda_H v_s/\sqrt{2}$, which has an appropriate magnitude for the electroweak symmetry breaking. The terms $S N^c N^c$ induce large Majorana masses for the right-handed neutrinos. The ordinary neutrinos have non-vanishing masses approximately given by $|\eta_\nu|^2 v^2_S/2\sqrt{2} |\lambda_N| v_s$. Taking for $\lambda_N \sim \lambda_H$, the neutrino masses become very small if the coupling constants $\eta_\nu$ for the neutrino Dirac masses are of the order of that for the electron $\eta_e$. A typical mass scale of squarks and sleptons is given by the universal value $m_{3/2}$ for the scalar boson masses, which is around $M_{\tilde{H}_1}$ and thus of order 1 TeV. Then, the smallness of the neutron and the electron electric dipole moments, which is another problem in the MSSM, can be explained.

In this model, the lightest Dirac fermion $\psi_K$ in the $K$ and $K^c$ system is stable, having both color and electric charges. In the early universe, after going out of thermal equilibrium, this fermion is bound to become a color-singlet particle. Since its mass is large, the decoupling occurs much earlier than for the up and down quarks. Therefore, the bound state is mainly formed by $\psi_K$ and its anti-particle. This is an electrically neutral meson, and eventually decays into lighter particles. The remnants for $\psi_K$ could exist in the present universe, and may be explored by non-accelerator experiments. However, its relic density depends on various uncertain factors, making a definite prediction difficult.

The energy dependencies of the model parameters are quantitatively described by renormalization group equations. The coupling constant $\eta_u$ for the top quark mass should be around unity at the electroweak scale, which is obtained for $\eta_u > 0.1$ at the high energy scale. The coupling constant $\lambda_K$ evolves similarly. If both $\eta_u$ and $\lambda_K$ are larger than 0.1 at the high energy scale, the mass-squared parameters $M^2_{\tilde{H}_2}$ and $M^2_{\tilde{S}}$ receive large quantum corrections. Taking the universal values as $m^2_{3/2} \sim (1 \text{ TeV})^2$ and $A \sim 1$ for the mass-squared parameters and the trilinear coupling constants, the values of $M^2_{\tilde{H}_2}$ and $M^2_{\tilde{S}}$ become small enough at the electroweak scale to induce SU(2)×U(1)×U'(1) gauge symmetry breaking. The quantum corrections to these parameters also become large, if the gauge fermion is heavy. On the other hand, the energy dependence of $M^2_{\tilde{H}_1}$ is weak and its value is not much different from the universal value. It is shown that there are reasonable parameter regions at the high energy scale, with the masses and trilinear coupling constants for scalar bosons being universal, which give parameter values at the electroweak scale consistent with phenomena. Unfortunately, however, the gauge coupling constants are not unified at an energy scale for possible grand unification, unless the particle contents of the model are modified.

References

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