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A heterotic standard model

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Abstract

Within the context of the $E_8 \times E_8$ heterotic superstring compactified on a smooth Calabi–Yau threefold with an $SU(4)$ gauge instanton, we show the existence of simple, realistic $N = 1$ supersymmetric vacua that are compatible with low-energy particle physics. The observable sector of these vacua has gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$, three families of quarks and leptons, each with an additional *right-handed neutrino*, *two* Higgs–Higgs conjugate pairs, a small number of uncharged moduli and *no exotic matter*. The hidden sector contains non-Abelian gauge fields and moduli. In the strong coupling case there is *no exotic matter*, whereas for weak coupling there are a *small number* of additional matter multiplets in the hidden sector. The construction exploits a mechanism for "splitting" multiplets. The minimal nature and rarity of these vacua suggest the possible theoretical and experimental relevance of spontaneously broken $U(1)_{B-L}$ gauge symmetry and two Higgs–Higgs conjugate pairs. The $U(1)_{B-L}$ symmetry helps to naturally suppress the rate of nucleon decay.

The discovery of non-vanishing neutrino masses indicates that, in supersymmetric theories without exotic multiplets, a right-handed neutrino must be added to each family of quarks and leptons [1]. It is well known that this augmented family fits exactly into the **16** spin representation of $Spin(10)$, making this group very compelling from the point of view of grand unification and string theory. Within the context of $N = 1$ supersymmetric $E_8 \times E_8$ heterotic string vacua, a $Spin(10)$ group can arise from the spontaneous breaking of the observable sector E_8 group by an $SU(4)$ gauge instanton on an internal Calabi–Yau threefold [2]. The $Spin(10)$ group is then broken by a Wilson line to a gauge group containing $SU(3)_C \times SU(2)_L \times U(1)_Y$ as a factor [3]. To achieve this, the Calabi–Yau manifold must have, minimally, a fundamental group $\mathbb{Z}_3 \times \mathbb{Z}_3$.

Until now, such vacua could not be constructed since (a) Calabi–Yau threefolds with fundamental group $\mathbb{Z}_3 \times \mathbb{Z}_3$ were not known and (b) it was unknown how to find $SU(4)$ gauge instantons on such manifolds. Recently, the first problem was rectified

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in [4]. We have now solved the second problem, exhibiting a large class of $SU(4)$ gauge instantons on the Calabi–Yau manifolds presented in [4]. Generalizing the results in [5,6], these instantons are obtained as connections on stable, holomorphic vector bundles with structure group $SU(4)$. The technical details will be given elsewhere [7]. In addition to these considerations, we also use a natural method for "splitting" multiplets that was introduced for general bundles in [6]. In this Letter, we present the results of our search for realistic vacua in this context.

The results are very encouraging. We find $N = 1$ supersymmetric vacua whose minimal observable sector, for both the weakly and strongly coupled heterotic string, has the following properties.

- Observable sector. Weak and strong coupling.
  1. Gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$.
  2. *Three families* of quarks and leptons, each with a *right-handed neutrino*.
  3. *Two* Higgs–Higgs conjugate pairs.
  4. *Six* geometric moduli and a *small number* of vector bundle moduli.
  5. *No exotic matter fields*.

These are, to our knowledge, the first vacua in any string theory context whose observable sector contains no exotic matter. We emphasize that, although very similar to the supersymmetric standard model, our observable sector differs in three significant ways. First, there is an extra right-handed neutrino in each family. Closely related to this is the appearance of an additional gauged $B–L$ symmetry. Finally, we find, not one, but two Higgs–Higgs conjugate pairs.

The structure of the hidden sector depends on whether one is in the weakly or strongly coupled regime of the heterotic string. In the strongly coupled context, we find the following minimal hidden sector.

- Hidden sector. Strong coupling.
  1. Gauge group $E_7 \times U(6)$.
  2. A *small number* of vector bundle moduli.
  3. *No matter fields*.

Again, note that this hidden sector has no exotic matter. Combining this with the above, we have demonstrated, within the context of the strongly coupled heterotic string, the existence of realistic vacua containing no exotic matter fields. We emphasize that the hidden sector gauge group $E_7 \times U(6)$ is sufficiently large to allow acceptable supersymmetry breaking via condensation of its gauginos.

In the weakly coupled context, we find the following minimal hidden sector (this is also a valid vacuum in the strongly coupled case).

- Hidden sector. Weak coupling.
  1. Gauge group *Spin*(12).
  2. A *small number* of vector bundle moduli.
  3. *Two* matter field multiplets in the **12** of *Spin*(12).

Note that, in this case, there are a small number of exotic matter multiplets in the hidden sector. Again, the hidden sector gauge group *Spin*(12) is sufficiently large to allow acceptable supersymmetry breaking via gaugino condensation.

The vacua presented above are the result of an extensive search within the wide context made precise in [7]. They appear to be the minimal vacua, all others containing exotic matter fields, either in the observable sector, the hidden sector, or both, usually with a large number of Higgs–Higgs conjugate pairs. We have been unable to find any vacuum in this context with only a single pair of Higgs–Higgs conjugate fields. Furthermore, to our knowledge, phenomenological vacua in all other string contexts [6,8,10–12] have substantial amounts of exotic matter, both in the observable and hidden sectors. For all these reasons, we refer to the class of vacua presented in this Letter as a *heterotic standard model* and speculate that it may be of phenomenological significance. In particular, it would seem to motivate renewed interest, both theoretical and experimental, in its characteristic properties; namely, (1) the physics of a $U(1)_{B-L}$ gauge symmetry spontaneously broken at, or above, the electroweak scale and (2) the physics of two pairs of Higgs–Higgs conjugate fields, particularly their experimental implications for flavor changing neutral currents. It is immediately clear that the $B–L$ symmetry will help to naturally suppress the rate of nucleon decay. This potentially resolves a long-standing problem in phenomenological string vacua. At the least, our results go a long way toward demonstrating that realistic particle physics can be the low-energy manifestation of