Phenomenology and Cosmology of Extra Generations of Higgs Bosons

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If the Higgs sector (like the fermion sector) in a supersymmetric model consists of several generations, then a basis in which only one generation gets vacuum values can be chosen. The other generations have been largely ignored, but can be interesting. For example, in the minimal model, if tree-level flavor-changing neutral currents are eliminated by some symmetry, then the lightest of these scalars is stable and the second lightest is only slightly more massive. The lightest is a superb dark-matter candidate, and if light enough, gives an unusual and detectable signature at the SLAC Linear Collider or the CERN e^+e^- collider LEP.

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One of the attractive features of supersymmetric models is that they treat scalar bosons and fermions in the same framework, and allow for the possibility of placing the Higgs boson(s) of the standard model in the same representation as the fermions. Yet, in spite of the fact that the fermion sector of the standard model is mysteriously replicated twice, the possible replication of the Higgs sector of the minimal model has been largely ignored. In the popular "superstring-inspired" E_6 models,[1] the Higgs bosons are, in fact, placed in the same representation as the fermions, and thus the minimal Higgs sector is replicated twice. However, even here the phenomenology of these additional Higgs bosons has attracted relatively little attention.[2,3]

The Higgs structure of the minimal supersymmetric model[4] consists of two doublets of opposite hypercharge. If there are many such pairs of doublets, then one can choose a basis in which only one pair acquires a vacuum expectation value (VEV). The other pairs do not acquire VEV's. In this work, it will be shown that, under a very general set of assumptions, these other scalars have a very interesting phenomenology: The lightest such boson may be stable, may constitute the dark matter of the Universe, and may be detectable in the immediate future at the SLAC Linear Collider (SLC) and the CERN e^+e^- collider LEP. Since these extra scalars come from replication of the Higgs sector, but are not strictly associated with spontaneous symmetry breaking, we will refer to them as "pseudo Higgs" bosons.

We will first consider the simplest extension of the minimal supersymmetric model. Only two assumptions will be made: (i) We assume that the Higgs sector of the minimal supersymmetric model (H and $\bar{H}$) is extended to include a number of such pairs of doublets, H_i and $\bar{H}_i$, and (ii) it is assumed that there are naturally no tree-level flavor-changing neutral currents (FCNC). Note that we are not including SU(3)×SU(2)×U(1) singlets, which may exist in the low-energy theory in E_6 models, although the effects of singlets will be discussed later. From these two assumptions,[5] many interesting consequences will follow. We will first show that the lightest pseudo Higgs boson is absolutely stable, that the second lightest is only a few hundred MeV heavier, and that both, if under 40 GeV, could be detected in the near future at SLC and LEP *if* the unusual signature is looked for. We then discuss the cosmology of the stable pseudo Higgs boson and find that its relic cosmological abundance is naturally in the range needed to supply the dark matter known to exist in galactic halos. Finally, we discuss the effects of including singlets on our qualitative and quantitative conclusions.

The minimal supersymmetric model has two doublets of opposite hypercharge, H and $\bar{H}$. We assume that there are two replications of this structure, H_i and $\bar{H}_i$ ($i=1,2,3$). The most general gauge-invariant superpotential is

$$W=m_{ij}H_i\bar{H}_j+\lambda_{ijk}Q_iU_jH_k+\lambda'_{ijk}Q_iD_j\bar{H}_k+\lambda''_{ijk}L_iE_j\bar{H}_k\ ,$$

where Q_i, U_i, D_i, L_i, and E_i are the quark and lepton superfields. We will assume that there are no tree-level FCNC (in either the quark or lepton sector). As shown by Glashow and Weinberg[6] and by Paschos[6] this implies that a basis can be chosen in which only one generation, which we label H_3 and $\bar{H}_3$, couples to fermions. If this occurs naturally, i.e., without fine tuning, this means that some symmetry exists under which the third-generation Higgs fields have different quantum numbers from the other generations. The precise nature of this symmetry will not be relevant. The most general scalar potential (ignoring the dependence on scalar quarks and leptons) is

$$V=m_{H_i}^2|H_i|^2+m_{\bar{H}_i}^2|\bar{H}_i|^2-m_{ij}B(H_i\bar{H}_j+\text{H.c.})+\frac{g^2}{8}\sum_a\left|\sum_i(H_i^*\tau_aH_i+\bar{H}_i^*\tau_a\bar{H}_i)\right|^2+\frac{g'^2}{8}\left|\sum_i(|H_i|^2-|\bar{H}_i|^2)\right|^2,\qquad(1)$$

where B is an arbitrary soft-supersymmetry-breaking parameter. (We have not exhibited crossterms of the form $H_i^\dagger H_j$+H.c. in this expression.) Since the third-generation fields have different quantum numbers under the above symmetry from the other generations, the m_{13}, m_{23}, m_{31}, and m_{32} terms all vanish. As a result there are no quadratic terms mixing H_3 and $\bar{H}_3$ with the other generations, and so when H_3 and $\bar{H}_3$ get VEV's, the other generations will not. (Crossterms mixing the first and second generations can exist but will be irrelevant in what follows.) Furthermore, in minimal supergravity models, all scalar mass-squared parameters are equal at some unification scale, so that $m_{H_1}^2 = m_{\bar{H}_1}^2$ at that scale. This equality is not broken by radiative corrections, since there are no Yukawa couplings, and thus it is valid at the electroweak scale. Therefore, the first-generation fields cannot get VEV's.[7] This also applies to the second-generation fields. Thus, the H_1, $\bar{H}_1$, H_2, and $\bar{H}_2$ fields do not get VEV's.

Including all remaining terms, it is easy to see that the Lagrangian has a symmetry $H_1,\bar{H}_1,H_2,\bar{H}_2 \to -H_1,-\bar{H}_1,-H_2,-\bar{H}_2$. As a result, the lightest pseudo Higgs boson must be stable.[8]

From the above potential, the mass matrix of the neutral scalar fields can be calculated. The H_3 and $\bar{H}_3$ fields have no mixing with the others, and have mass matrices given by the usual matrices in the minimal supersymmetric model.[4] For each generation of pseudo Higgs bosons, there are four neutral scalars. The mass matrix will divide into two separate matrices, corresponding to the "scalar" and "pseudoscalar" sectors (these terms refer to their couplings to fermions, if such couplings existed). For simplicity, we write the matrices corresponding to a single generation of pseudo Higgs bosons, taken to be H_1 and $\bar{H}_1$. The matrix corresponding to the scalar sector is

$$\begin{pmatrix} m_{H_1}^2 - \frac{1}{2} m_Z^2 \cos(2\beta) & -m_{11}B \\ -m_{11}B & m_{\bar{H}_1}^2 + \frac{1}{2} m_Z^2 \cos(2\beta) \end{pmatrix}, \tag{2}$$

where $\tan\beta \equiv \langle H_3\rangle/\langle \bar{H}_3\rangle$. The matrix corresponding to the pseudoscalar sector is

$$\begin{pmatrix} m_{H_1}^2 - \frac{1}{2} m_Z^2 \cos(2\beta) & m_{11}B \\ m_{11}B & m_{\bar{H}_1}^2 + \frac{1}{2} m_Z^2 \cos(2\beta) \end{pmatrix}. \tag{3}$$

Note that these matrices are identical except for the sign of the off-diagonal term. The eigenvalues are thus identical. If the H_2 and $\bar{H}_2$ pseudo Higgs bosons are included, the matrices are 4×4, but will also only differ in the sign of the even-odd off-diagonal terms. As a result, the eigenvalues will still be degenerate at tree level. Because of the sign difference, however, this degeneracy will be split at one-loop order (see Ref. 9). We see that the second-lightest pseudo Higgs boson will have a mass larger than the lightest by approximately $(\alpha/\pi)M_W$ or between a couple of hundred MeV and a couple of GeV. The lightest pseudo Higgs boson will be denoted ϕ_S, and the second lightest will be denoted ϕ_P. ϕ_S will be related to the weak eigenstates by rotating the mass matrix: $\phi_S = H_1^0 \cos\theta_S + \bar{H}_1^0 \sin\theta_S$, where H_1^0 and $\bar{H}_1^0$ are the neutral components of H_1 and $\bar{H}_1$. If there are more generations of pseudo Higgs bosons, there will be a more complicated set of angles in the diagonalization; but since θ_S is completely arbitrary, this expression can be used without loss of generality—θ_S is simply the angle which rotates the weak-eigenstate basis into ϕ_S.

How does this stable particle, ϕ_S, interact? Since it has no VEV, it does not interact through a vector-vector-scalar interaction (this $Z \to Z^* + \phi_S$ cannot occur). It will have no interaction with fermions. It does interact through four-point couplings with itself, heavier pseudo Higgs bosons, Higgs bosons, W's, and Z's, as well as through a three-point coupling to the neutral Higgs bosons. Some of these interactions are crucial in determining the cosmological abundance; however, the most important interaction of immediate phenomenological interest is the $Z\phi_S\phi_P$ interaction. The vertex is given by $(g/2\cos\theta_w)\cos(\theta_S+\theta_P)(p+p')^\mu$, where θ_P diagonalizes the mass matrix which contains the second-lightest pseudo Higgs boson (θ_P) and θ_W is the weak mixing angle. From the structure of these matrices, however, one can see that $\theta_S = -\theta_P$, and thus the arbitrary rotation angle θ_S will drop out. This result is also independent of the number of pseudo Higgs-boson generations.[9]

If the θ_S has a mass below 40 GeV, then the Z will decay into an ϕ_S and a ϕ_P (recall that the mass of the ϕ_P is 0.2 to 2 GeV more than that of the ϕ_S). The ϕ_S only interacts weakly and is stable, so it disappears. The ϕ_P will decay into the ϕ_S, which disappears, through a virtual Z, into a fermion pair. The $Z \to \phi_S + \phi_P$ branching ratio is

$$\frac{\Gamma(Z \to \phi_S + \phi_P)}{\Gamma(Z \to \nu\bar{\nu})} = \frac{1}{2}\left(1 - 4\frac{m_S^2}{M_Z^2}\right)^{3/2}, \tag{4}$$

where we have approximated $m_S \approx m_P$. For light ϕ_S, this branching ratio is enormous, and would occur in roughly 1 in 30 Z decays. The signature is missing transverse momentum (due to the vanishing ϕ_S bosons) and a low-energy fermion pair. The energy of this fermion pair in the ϕ_P rest frame is 0.2 to 2 GeV, which could be boosted as high as 20 GeV in the laboratory frame. The lifetime of the ϕ_P should be (given the limited phase space available) quite long, $\sim 10^{-10\pm 3}$ sec; thus the fermion pair might not point back to the original beam-beam interaction point. The backgrounds to such a low-energy fermion pair (a μ pair is probably the easiest to see) might be large, but the signal is also very large. Other phenomenological signals for heavier ϕ_S bosons are currently under investigation.[9]

The fact that the lightest pseudo Higgs boson is stable means that some fraction of the ϕ_S particles thermally created in the early Universe must survive until today. In fact, since these particles do not have the Z or squark couplings typical of stable supersymmetric particles (such as the photino or neutralino) one might worry that their present density exceeds the critical density and that, therefore, they are inconsistent with observation. However, pairs of ϕ_S particles can annihilate efficiently via the exchange of "ordinary" Higgs scalars. (In the model under consideration, there are two neutral scalar Higgs bosons, one of which is less massive than the Z, and a neutral pseudoscalar which is heavier than the lightest scalar.[4] By convention, the lightest scalar is denoted h_2 and the pseudoscalar h_3.) For example, the Feynman rule for the $\phi_S\phi_S h_2 h_2$ vertex is $ig^2\cos(2\theta_S)\times\cos(2\alpha)/(4\cos^2\theta_W)$ and for the $\phi_S\phi_S h_2$ vertex is $igm_Z\cos(2\theta_S)\cos(\alpha+\beta)/(2\cos\theta_W)$, where α and β are mixing angles associated with the ordinary Higgs and gaugino sectors. See Ref. 4 for the conventions used and a detailed discussion of Higgs bosons in supersymmetric models. Other couplings also contribute but these will be displayed elsewhere.[9] These couplings and the couplings of Higgs bosons to fermions allow s-channel annihilation to take place into a pair of fermions and, when phase space permits, also into a pair of scalar Higgs bosons, a pair of pseudoscalar Higgs bosons, and a pseudoscalar Higgs boson plus a Z. For example, the annihilation cross section into a pair of bottom quarks via exchange of the lightest Higgs boson (in the nonrelativistic limit) is

$$\sigma v = \frac{3\pi\alpha_{\rm em}^2\cos^2(2\theta_S)\sin^2\alpha\sin^2(\alpha+\beta)m_b^2(1-m_b^2/m_S)^{1/2}}{4\sin^4\theta_W\cos^4\theta_W\cos^2\beta[(4m_S^2-m_{h2}^2)^2+m_{h2}^2\Gamma_{h2}^2]}, \tag{5}$$

where m_{h2} and m_b are the masses of the lightest scalar Higgs boson and bottom quark, Γ_{h2} is the width of h_2, $\alpha_{\rm em}$ is the fine-structure constant, and v is the relative velocity of the annihilating pseudo Higgs bosons. We have also found cross sections for the annihilation into the other fermions and the other channels mentioned above[10] (as well as t-channel exchanges) but these results will be given in Ref. 9.

Using Eq. (5) plus its equivalent for the other channels, the relic abundance of ϕ_S can be found by the "Lee-Weinberg" calculation.[11] Defining the relic abundance today as Ω_S, the ratio of average ϕ_S density to critical density, and the Hubble parameter $H=100h$ km/sec Mpc, we plot in Fig. 1 contours of constant $\Omega_S h^2$ in the m_{h2}-m_S plane. The free parameters of the model are m_S, m_{h2}, and θ_S, as well as $\tan\beta$. The values of $\Omega_s h^2$ on the contours are marked. (Note that observation constrains h to $0.5\leq h\leq 1$.) Taking $\cos 2\theta_S=1$ and a typical value of $\tan\beta=2$, we note that for much of parameter space we predict an abundance of ϕ_S particles between 10 and 10^{-2}. Recalling that the observed density of stars and luminous matter gives $\Omega_{\rm lum}\approx 0.01$, and

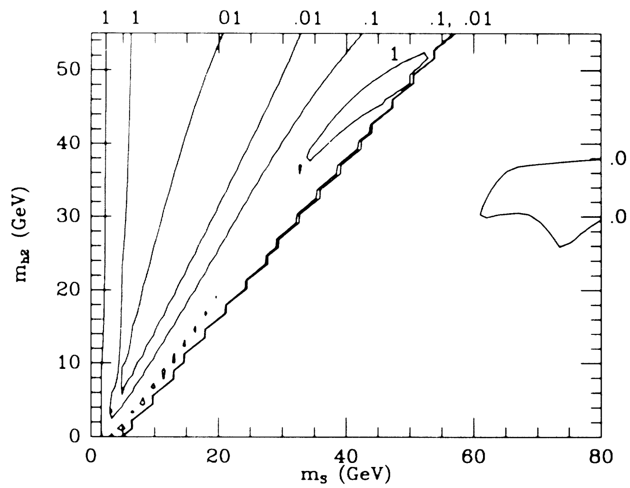

FIG. 1. Contours of constant pseudo-Higgs-boson relic abundance for model parameter values of $\tan\beta=2$ and $\cos^2 2\theta=1$. The values of $\Omega_S h^2$ along the contours are marked.

that the dark-matter (DM) abundance is roughly $0.025\leq\Omega_{\rm DM}\leq 1$, we predict that if stable ϕ_S particles exist they very likely contribute substantially to the dark matter in our galactic halo, and may well provide the bulk of it. Of course, limits on this type of dark matter from direct detection can be found.[9] Finally, we note that if $\cos(2\theta_S)$ is less than 1, σv decreases proportionally and $\Omega_S h^2$ increases (roughly) proportionally, so that a value of $\cos(2\theta_S)\approx 10^{-3}$ would cause $\Omega_S > 1$ for almost all of parameter space (and would therefore be inconsistent with astronomical observation). Here we have displayed only one possible example. Further details and a more complete exploration of parameter space will be presented in Ref. 9.

It has been assumed that the lightest pseudo Higgs boson is lighter than its supersymmetric partner, the pseudo Higgsino. If this is not true, then one can examine the pseudo-Higgsino mass matrices, and find that the two lightest neutral pseudo Higgsinos are, at tree level, degenerate in mass, as before. One difference is that the lightest charged pseudo Higgsino, $\tilde\phi^+$, is *also* degenerate in mass, at tree level. If this degeneracy is not broken by radiative corrections, then there is a stable charged particle, which rules out the scenario. If it is broken (and the charged pseudo Higgsino is heavier), then the $\tilde\phi^+$ could be pair produced in Z decays, or in e^+e^- collisions at the KEK collider TRISTAN. Each $\tilde\phi^+$ would decay into a ϕ_S-ino and an (e,ν_e) or (μ,ν_μ) pair of very low energy. One would see low-energy $e\mu$ events with missing p_T, possibly located too far from the collision point to be τ's. The phenomenology of these particles is currently under investigation.[9]

Throughout this work, we have ignored the possibility of $SU(3)\times SU(2)\times U(1)$ singlets. Such singlets, called N and ν^c, appear in the 27-dimensional representation of

E_6, and thus may exist in the low-energy theory which comes from such models. How would their inclusion affect the results? First, one can now have a $\lambda_{ijk}^N H_i \overline{H}_j N_k$ term (as well as N^3, N^2, and N terms) in the superpotential. Now, one must choose the properties of the N_k under the symmetry. If N_3 transforms as a Higgs boson, then there is a possibility that the pseudo Higgs boson could acquire a VEV. For example, if λ_{123} is large and λ_{213} is small, then the equality $m_{H_1}^2 = m_{\overline{H}_1}^2$ is broken by radiative corrections and one can arrange parameters so that the pseudo Higgs boson acquires a VEV. If $N_{1,2}$ transform as a Higgs boson, then a λ_{131} term will result in Higgs-boson–pseudo-Higgs-boson mixing if $N_{1,2}$ gets a VEV.[12] (Such mixing would cause the pseudo Higgs boson to decay like a Higgs boson.) Drees and Tata[13] have shown that a simple discrete symmetry will eliminate this mixing; also, as pointed out in Ref. 2, such mixing can be eliminated very naturally in most models, even without a discrete symmetry. Thus, the stability of the pseudo Higgs boson and the elimination of mixing does, strictly speaking, require an additional assumption, albeit a very natural one. One still must worry about an $\overline{H}L\nu^c$ term, where ν^c is the right-handed neutrino.[14] If the ν^c is lighter than the pseudo Higgs boson, then the pseudo Higgs bosons will decay into $\nu + \nu^c$, eliminating the possibility that they are the dark matter and that they can be detected (other than through the width measurement of the Z). Even if the ν^c is heavier, some models have a $Dd^c\nu^c$ term, where D is an exotic quark. If the D were lighter, the pseudo Higgs boson could decay through this interaction. Thus, the stability of the pseudo Higgs boson can still exist in such models, but does require additional assumptions.

Suppose that these assumptions are made. Then the pseudo-Higgs-boson mass matrix will decouple from the Higgs-boson mass matrix, as before. The matrices are fully exhibited in Ref. 2, and one can see there that the degeneracy in the eigenvalues is no longer present. The ϕ_S will now no longer be slightly lighter than the ϕ_P. The phenomenological signal, in Z decays, will then only occur if both turn out to be lighter than about 40 GeV, and the virtual Z in the decay of the ϕ_P will decay into a fermion pair with much more energy. The lifetime will then be so short that the fermion pair will point directly back to the vertex (and there will certainly be enough energy to produce hadrons). This signal might actually be easier to see, since the missing p_T is much larger, but the fraction of parameter space in which both particles are light enough is much smaller.

In conclusion, we have found that pseudo Higgs particles, which occur in a wide class of models and which have been largely ignored, can be very interesting. Striking signatures at SLC and LEP can occur and the lightest one is a fine candidate for the 90%–99% of the mass of the Universe whose nature is still unknown.

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[2] J. Ellis, D. V. Nanopoulos, S. Petcov, and F. Zwirner, Nucl. Phys. **B283**, 93 (1987), give an extensive discussion.

[3] M. Drees, Int. J. Mod. Phys. A **4**, 3635 (1989).

[4] See J. F. Gunion and H. E. Haber, Nucl. Phys. **B272**, 1 (1986), for an extensive review.

[5] Strictly speaking, we are also assuming that the supersymmetric partner of the lightest pseudo Higgs boson is heavier than the lightest pseudo Higgs boson. If this assumption is relaxed, the phenomenological and cosmological consequences are not qualitatively affected as will be discussed later.

[6] S. Glashow and S. Weinberg, Phys. Rev. D 15, 1958 (1977); E. A. Paschos, Phys. Rev. D **15**, 1966 (1977).

[7] See A. B. Lahanas and D. V. Nanopoulos, Phys. Rep. **145**, 1 (1987). From Fig. 13 in that article, one can see that in the limit of $m_1^2 = m_2^2$ there can be no SU(2)×U(1) breaking.

[8] Note that this symmetry is actually a global U(1) symmetry. It should also be pointed out that due to the stringent constraints on stable charged particles, the lightest pseudo Higgs boson must be neutral. It can be shown that there is a large region of parameter space in which the lightest is, in fact, neutral.

[9] K. Griest and M. Sher (to be published).

[10] We have ignored the possibility that annihilation takes place into super-symmetric particles; see Ref. 9.

[11] For a description of the method used and references see K. Griest and D. Seckel, Nucl. Phys. **B283**, 68 (1987); **B296**, 1034(E) (1988).

[12] If the symmetry is global, this would give an unacceptable Goldstone boson; however, the presence of an N^2 term could make the symmetry discrete, avoiding this problem.

[13] M. Drees and X. Tata, Phys. Rev. Lett. **59**, 528 (1987).

[14] As pointed out by Drees and Tata (Ref. 13), if there is a single discrete symmetry, then the absence of Dirac neutrino masses will force this term to exist.