ELECTROWEAK BARYOGENESIS IN A SUPERSYMMETRIC MODEL
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1 Introduction and Formalism of the NMSSM

It is well known that there is difficulty in sustaining the hypothesis of baryogenesis at the electroweak phase transition in the minimal standard model. To overcome these difficulties attention has been given to extensions of the minimal standard model, involving the addition of extra scalars. Prominent among these is the minimal supersymmetric standard model, MSSM, where the Higgs sector is just two doublets. Here we shall discuss, with a perturbative treatment, the next-to-minimal model, NMSSM, which has additionally one singlet Higgs scalar. In the absence of hard information we have to adopt a hypothesis on the SUSY breaking scale and on the spectrum of the particles, and ours is the simplest possible. We follow a paper of recent years in taking the SUSY breaking scale, MS, to be of the order of 1 TeV; we take perfect supersymmetry above that scale. Then at MS the quartic couplings are fixed by the gauge couplings and two more parameters. We then use the renormalization group equations to run down the quartic couplings to the electroweak scale, where we investigate the nature of the phase change. There are also cubic and quadratic supersymmetry breaking couplings, and there results a space of variable parameters in which we investigate what proportion leads to a first order electroweak phase change, and so is compatible with electroweak baryogenesis.

There has been quite considerable previous work on the electroweak phase change in the MSSM. We are not aware of so much on the NMSSM. The work of Pietroni has pointed out that the NMSSM, in contrast to the MSSM, has cubic terms in the scalar field potential at tree level leading to the possibility of a potential barrier in radial directions even at tree level. That work uses a unitary gauge which we consider to be not so secure a basis for the consideration of phase changes as the Landau gauge which we use.

We start with the tree level potential which is

\[ V_0 = \frac{1}{2}(\lambda_1 (H^1_1 H_1)^2 + \lambda_2 (H^2_1 H_2)^2) + \]

\[ \lambda_3 \lambda_4 (H^1_1 H_1)(H^2_1 H_2) - \lambda_4 |H^1_1 H_2|^2 + \]

\[ (\lambda_5 H^1_1 H_1 + \lambda_6 H^2_1 H_2)N^* N + (\lambda_7 H_1 H_2 N^* + hc) + \]

\[ \lambda_8 (N^* N)^2 + (|\mu|^2 + (\lambda N^* N + hc))(H^1_1 H_1 + H^2_1 H_2) + m^2 H^1_1 H_1 + m^2 H^2_1 H_2 + m^2 N^* N - \]

\[ ((m_4 H_1 H_2 N + \frac{1}{3} m_5 N^3 - \frac{1}{2} m^2 N H_1 H_2 - m^2 N^2) + hc) \]

where \( H^1_1 H_1 \), \( H^2_1 H_2 \), \( H^0_1 H^0_2 - H^1_1 H^1_2 \) are the terms involving \( \mu \) from the \( \mu \) term in the superpotential. The last two terms comprise all possible soft supersymmetry breaking terms. \( V_0 \) is a function of 10 real scalar fields, \( \phi_1, \phi_2, \ldots, \phi_{10} \), for each of the Higgs doublets and 2 for the singlet, N.

For simplicity, and to automatically ensure real VEVs, we shall follow the usual practice and take the parameters real. The boundary values at MS of the quartic couplings are given by

\[ \lambda_1 = \lambda_2 = \frac{1}{4}(g_2^2 + g_1^2), \lambda_3 = \frac{1}{4}(g_2^2 - g_1^2), \lambda_4 = \lambda^2 - \frac{1}{2} g_2^2, \]

\[ \lambda_5 = \lambda_6 = \lambda^2, \lambda_7 = -\lambda k, \lambda_8 = k^2 \]

and are developed down to MW, by using the appropriate RG equations, \( \lambda \) and k, from the superpotential, are free parameters at MS. However they are linked to the one important Yukawa coupling \( a, g_i \), by 3 simultaneous RG equations; in developing from high energy down to MS their values there should not be such that they correspond to divergent or unnaturally large values at high energy. The \( m^2, m^2, m^2 \) are standard mass parameters and are to be specified in terms of the VEVs and other parameters by the usual requirement that \( V_0(\phi) \), \( \phi_1, \phi_2, \ldots, \phi_{10} \), with the parameters \( \lambda_i \) assumed renormalized at the electroweak scale, be a minimum at the neutral VEVs:

\[ \langle H_1 \rangle = \begin{pmatrix} v_1 \\ 0 \end{pmatrix}, \langle H_2 \rangle = \begin{pmatrix} 0 \\ v_2 \end{pmatrix}, \langle N \rangle = x \]

(1)

where \( v_1, v_2 \) and x are real and \( v = \sqrt{v_1^2 + v_2^2} = 174 GeV \). The scalar mass-squared matrix gives rise to 7 massive physical particles and 3 zero mass would-be Goldstone bosons. We can now discuss the other parameters in \( V_0 \).

Firstly there are the terms involving \( \mu \) which arise from the \( \mu \) term in the superpotential. This raises the mu-problem (first noted in the MSSM). \( \mu \) would naturally be expected to take on a value of the order of magnitude of the fundamental scale of the theory, whereas

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We are not considering large \( \tan \beta \) here.
In the work reported here we have adopted the values of Ref. [1] in taking \( k = .1, \lambda = .65 \). For other parameters we have searched in the regions \( 1 < \tan \beta < 3, 200 < M_{\chi} < 300\, \text{GeV}, -5 < m_{W}^{2} < 5, -5 < m_{S}^{2} < 5, -1 < \frac{m_{h}^{2}}{M_{\chi}} < 1 \), while for \( x \) we have used \( x = 174\, \text{GeV} \), having found that values significantly bigger or smaller greatly restricted the range of the other parameters compatible with the \( T = 0 \) criteria. Considerations on the special parameter \( \mu \) are given below, where we now outline our current results:

1. \( \mu = 0 \): A search over a grid of 200,000 sets of parameters found a basis space of about 20,000 giving an acceptable broken \( T = 0 \) electroweak vacuum. The curvature criterion gave about 10% of this basis space compatible with baryon number preservation with \( T_{\text{crit}} = T_{0} \) mostly in the range 50-150 GeV. The lightest Higgs scalar was of the order of 100 GeV, and the lightest Higgsino was of a similar mass.

2. \( \mu \neq 0 \): In the region close to the previous successful cases, sets of parameters exist with values of \( \mu \) of magnitude up to 40 GeV with negative values preferred.

3. Conclusions: We confirm, and quantify, previous results that electroweak baryon preservation is compatible with the NMSSM and we additionally find that a \( \mu \) parameter of moderate magnitude is acceptable.

The investigation of the parameter space is not complete and is continuing.

References

1. A.G. Cohen, D.B. Kaplan and A.E. Nelson, Ann. Rev. Nucl. Part. Sci. 43 (1993) 27.
2. M. Dine, P. Huet, R. Leigh and A. Linde, Phys. Lett. B283 (1992) 319; Phys. Rev. D46 (1992) 550.
3. G.W. Anderson and L.J. Hall, Phys. Rev. D45 (1992) 2685.
4. A.T. Davies, C.D. Froggatt, G. Jenkins and R.G. Moorhouse, Phys. Lett. B336 (1994) 464.
5. J. Gunion, H.E. Haber, Nucl. Phys. B272 (1986) 1.
6. A. Brignole, J.R. Espinosa, M.Quiros and F. Zwirner, Phys. Lett. B324 (1994) 181.
7. M. Pietroni, Nucl. Phys. B402 (1993) 27.
8. L. Dolan and R. Jackiw, Phys. Rev. D9 (1974) 3320.
9. T. Elliott, S. F. King and P. L. White, Phys. Lett. B305 (1993) 71; Phys. Rev. D49 (1994) 2435.
10. S. A. Abel, S. Sarker and P. L. White; these Proceedings.