I review the status of the strength of the electroweak phase transition, and electroweak baryogenesis in the Minimal Supersymmetric Standard Model (work done with K. Kainulainen and M. Joyce). The emphasis is on new brane-inspired ideas about electroweak baryogenesis, and improvements in the semiclassical treatment of CP violation at a first order electroweak phase transition.

PRESENTED AT

COSMO-01
Rovaniemi, Finland,
August 29 – September 4, 2001
1 Introduction

I have given a similar talk in ref. [1] in 2000, so I will not repeat material that was presented there. Rather I will emphasize what is new since that time. The main new results fall under the categories of (1) effects of brane cosmology, (2) nonthermal production of sphalerons by preheating, and (3) refinements of the computation of electroweak baryogenesis in the MSSM.

2 Brane-world implications for Baryogenesis

In the context of large (ADD [2]) extra dimensions, it has already been noted that baryogenesis is difficult because of the extremely low reheat temperature that is needed to keep light Kaluza-Klein gravitons out of thermal equilibrium, since they would distort the cosmic gamma ray background [3]. A warped extra dimension à la Randall and Sundrum (RS) [4] however provides an interesting possibility: the Friedmann equation is modified to the form [5]-[7]

\[ H^2 = \frac{8\pi G}{3}\rho \left(1 + \frac{\rho}{\Lambda}\right) \]

where \( \Lambda \) is the tension of the brane on which we are presumed to be living. If \( \Lambda \) is sufficiently small, then the expansion rate could be significantly increased at the time of the electroweak phase transition [8], making it possible for sphalerons to go out of equilibrium as is required for electroweak baryogenesis, without having to add new physics for the purpose of strengthening the electroweak phase transition. Unfortunately the modified Friedmann equation (1) is specific to the RS-II model in which there is a just a single brane; in the two-brane version that was invented to solve the hierarchy problem, the \( O(\rho^2) \) correction has the wrong sign for helping with baryogenesis [4]. It would be interesting to find other brane-world models which had the desired behavior.

On a more general note, it could be expected that cosmology at the TeV scale (or perhaps 100 GeV if we push the parameters) might be rather radically altered in the RS-I model, since the TeV brane on which we live in that model should cease to exist as we know it at temperatures exceeding this scale [10]-[12]. At sufficiently high temperatures the TeV brane is hidden behind a horizon in the extra dimension. Its emergence is associated with a phase transition in the conformal field theory corresponding to the bulk graviton degrees of freedom. If this coincides with the electroweak phase transition, the situation could be richer than is normally assumed.

3 Preheating Effects

One of the holy grails in electroweak baryogenesis is satisfying the sphaleron bound: the rate of sphaleron interactions per unit volume must be less than \( H^4 \) once the baryon...
asymmetry has been created in order to avoid its relaxation back to negligible levels. I mentioned eq. (1) as one new idea for achieving this. Another which has gotten some attention recently is related to preheating. If inflation occurs with a low reheat temperature \( T \ll 100 \text{ GeV} \) (as one would like for the large extra dimension scenarios), then sphalerons could not be created by normal thermal processes. However they might be produced by nonequilibrium conversion of the coherent field energy of the inflaton near the end of inflation, as has been discussed by A. Rajantie in these proceedings [13] and in the references [14].

In order to make this idea work, one can couple the inflaton to the Higgs field in the manner of hybrid inflation, through an interaction of the form

\[
V = \lambda(H^2 - v^2)^2 + \frac{1}{2}m^2\sigma^2 + g^2\sigma^2H^2
\]

but the COBE observations require that \( m_{\sigma} \sim 10^{-10} \text{ eV} \), which is unstable against radiative corrections [15]. The problem can be ameliorated in inverted hybrid inflation models[16], in which the inflaton \( \sigma \) rolls away from \( \sigma = 0 \) instead of towards it, due to the addition of some nonrenormalizable operators to \( V \). The number of counterterms which need to be fine tuned to keep \( V \) sufficiently flat in this model is much smaller than in the ordinary hybrid model. Nevertheless, this discussion underscores the difficulties in constructing a convincing or natural realization of low temperature baryogenesis.

4 Electroweak Baryogenesis in the MSSM

It has become standard to compute the baryon asymmetry due to sphalerons in three steps [17]-[22]: first compute the source term that appears in diffusion equations for the various species which couple to left-handed quarks (since these are the particles which ultimately bias sphalerons); then solve the diffusion equations for the chemical potentials of the left-handed quarks. This is easily fed into the sphaleron rate equation to compute the baryon asymmetry. Because the network of diffusion equations is complicated, it was also standard to employ some simplifying approximations, one of which was to assume that the sum of the chemical potentials for the two Higgs fields \( H_1 \) and \( H_2 \) is driven to zero by interactions involving the top quark Yukawa coupling. In this approximation one considers only the source for the difference between the two, and this turns out to be suppressed by the fact that the ratio \( H_1/H_2 \) remains quite constant within the bubble walls that form during the electroweak phase transition [23, 24]. However, it was pointed out by us [25] that the assumption of top Yukawa equilibrium is not realistic, and that the source term for \( H_1 + H_2 \) is much larger than that for \( H_1 - H_2 \), since it is not suppressed by the constancy of \( H_1/H_2 \) inside the wall, nor is it very strongly suppressed by the top Yukawa interactions.

Despite this enhancement, we still find that the baryon asymmetry is small, and it is rather difficult to tune the parameters of the MSSM to get an acceptably large
baryon asymmetry. Our results are in contrast to those of [18, 21, 26], who find larger values. The difference comes from our respective derivations of the source term in the diffusion equations, which we do starting from the semiclassical CP-violating force acting on Higgsinos in the bubble wall [19, 20]. From this force, one can derive the diffusion equations from the Boltzmann equation in a controlled and rigorous fashion.

It should be emphasized that if we were simply making rough order-of-magnitude estimates of the baryon asymmetry based on the semiclassical formalism, our results would be in better agreement with those of [18, 21, 26]. The suppression comes from the detailed properties of our source term for the Higgsinos, which looks like

\[
S_H = \frac{v_w D_{\tilde{H}}}{2 \langle v^2 \rangle T} \left\langle \left| \frac{p_z}{E^3} \right| \right\rangle \left( m^2 \theta' \right)^{''}
\]

(3)

where \( v_w \) is the bubble wall velocity, \( D_{\tilde{H}} \) is the Higgsino diffusion coefficient, \( \langle \cdot \rangle \) denotes thermal averaging, and \( me^{\theta(x)} \) is the locally varying Higgsino mass inside the wall. The salient feature is that this source is close to being a total derivative, and it must be integrated in the solution of the diffusion equations. Its integral is much smaller than its typical values, which we would have used had we been doing an order-of-magnitude estimate. This can be seen from Fig. 1(a), which shows \( S_H \) as a function of distance in the wall, and Fig. 1(b), the left-handed quark chemical potential. The latter is several orders of magnitude smaller than the former due to the large cancellations which take place in integrating the diffusion equations.

Figure 1: (a) Higgsino source term versus distance \( \times \) temperature in wall. (b) Left-handed quark chemical potential over \( T \), versus distance \( \times T \).
As a result, we are forced to take the CP violating phase of the \( \mu \) parameter to be close to maximal, and to assume that the wall velocity \( v_w \) and \( \tan \beta \) are close to their optimal values, as shown in fig. 2. The required value of \( v_w \) is not unlikely \([27]\), but such large phases require the squarks to be quite heavy in order to suppress the loop contributions to the EDM of Mercury \([28]\). Moreover, we need to take the chargino and Higgsino mass parameters \( |\mu| \) and \( m_2 \) to be nearly degenerate, as shown in fig. 3.

\[
\begin{align*}
\text{Figure 2: Baryon-to-photon ratio } & \times 10^{10} \text{ as a function of (a) wall velocity and (b) } \tan \beta = \langle H_2 \rangle / \langle H_1 \rangle. \\
\end{align*}
\]

In addition to the tunings of parameters already mentioned, one needs for the right-handed stop mass to be very light \([29, 30, 24]\) and the left-handed stop to be heavy. Therefore electroweak baryogenesis in the MSSM is not yet ruled out, but it is close to being so. Life is easier in the NMSSM though, where the MSSM is supplemented by a singlet field. Not only is it easy to make the electroweak phase transition stronger \([31]\), but the CP violation can occur transitionally and thus be relatively free from experimental constraints \([32]\). The semiclassical analysis of the source term in this model has been carried out in \([33]\).

References

[1] J. M. Cline, “Status of electroweak phase transition and baryogenesis,” Pramana 54, 1 (2000) [Pramana 55, 33 (2000)] [arXiv:hep-ph/0003029].
Figure 3: Baryon-to-photon ratio contours in the plane of chargino mass parameters for two different wall velocities. Shaded regions are excluded by LEP II.

[2] N. Arkani-Hamed, S. Dimopoulos and G. Dvali, Phys. Lett. B429 (1998) 263 [hep-ph/9803315]; Phys. Rev. D59 (1999) 086004 [hep-ph/9807344].

[3] K. Benakli and S. Davidson, “Baryogenesis in models with a low quantum gravity scale,” Phys. Rev. D 60, 025004 (1999) [arXiv:hep-ph/9810280].

[4] L. Randall and R. Sundrum, “A large mass hierarchy from a small extra dimension,” Phys. Rev. Lett. 83, 3370 (1999) [hep-ph/9905221]; L. Randall and R. Sundrum, “An alternative to compactification,” Phys. Rev. Lett. 83, 4690 (1999) [hep-th/9906064].

[5] P. Binetruy, C. Deffayet and D. Langlois, “Non-conventional cosmology from a brane-universe,” Nucl. Phys. B 565, 269 (2000) [hep-th/9905012].

[6] C. Csaki, M. Graesser, C. Kolda and J. Terning, “Cosmology of one extra dimension with localized gravity,” Phys. Lett. B 462, 34 (1999) [hep-ph/9906513].

[7] J. M. Cline, C. Grojean and G. Servant, “Cosmological expansion in the presence of extra dimensions,” Phys. Rev. Lett. 83, 4245 (1999) [hep-ph/9906523].

[8] G. Servant, “A way to reopen the window for electroweak baryogenesis,” arXiv:hep-ph/0112209.

[9] J. M. Cline and J. Vinet, “Order $\rho^2$ corrections to Randall-Sundrum I cosmology,” arXiv:hep-th/0201041.
[10] N. Arkani-Hamed, M. Porrati and L. J. Randall, JHEP 0108, 017 (2001) [hep-th/0012148].

[11] A. Hebecker and J. March-Russell, Nucl. Phys. B 608, 375 (2001) [hep-ph/0103214].

[12] P. Creminelli, A. Nicolis and R. Rattazzi, [hep-th/0107141].

[13] A. Rajantie, “Baryogenesis at the end of hybrid inflation,” arXiv:hep-ph/0111200.

[14] J. Garcia-Bellido and A. D. Linde, Phys. Rev. D 57, 6075 (1998) [arXiv:hep-ph/9711360]; J. Garcia-Bellido, D. Y. Grigoriev, A. Kusenko and M. E. Shaposhnikov, Phys. Rev. D 60, 123504 (1999) [arXiv:hep-ph/9902449]; L. M. Krauss and M. Trodden, Phys. Rev. Lett. 83, 1502 (1999) [arXiv:hep-ph/9902420]; J. M. Cornwall and A. Kusenko, Phys. Rev. D 61, 103510 (2000) [arXiv:hep-ph/0001058]; J. M. Cornwall, D. Grigoriev and A. Kusenko, Phys. Rev. D 64, 123518 (2001) [arXiv:hep-ph/0106127]; J. Garcia-Bellido and D. Y. Grigoriev, JHEP 0001, 017 (2000) [arXiv:hep-ph/9912513]; G. N. Felder, J. Garcia-Bellido, P. B. Greene, L. Kofman, A. D. Linde and I. Tkachev, Phys. Rev. Lett. 87, 011601 (2001) [arXiv:hep-ph/0012142]; A. Rajantie, P. M. Saffin and E. J. Copeland, Phys. Rev. D 63, 123512 (2001) [arXiv:hep-ph/0012097].

[15] D. H. Lyth, “Constraints on TeV-scale hybrid inflation and comments on non-hybrid alternatives,” Phys. Lett. B 466, 85 (1999) [arXiv:hep-ph/9908219].

[16] E. J. Copeland, D. Lyth, A. Rajantie and M. Trodden, “Hybrid inflation and baryogenesis at the TeV scale,” Phys. Rev. D 64, 043506 (2001) [arXiv:hep-ph/0103231].

[17] P. Huet and A. E. Nelson, “Electroweak baryogenesis in supersymmetric models,” Phys. Rev. D 53, 4578 (1996) [arXiv:hep-ph/9506477].

[18] M. Carena, M. Quiros, A. Riotto, I. Vilja and C. E. Wagner, “Electroweak baryogenesis and low energy supersymmetry,” Nucl. Phys. B 503, 387 (1997) [arXiv:hep-ph/9702409].

[19] J. M. Cline, M. Joyce and K. Kainulainen, “Supersymmetric electroweak baryogenesis in the WKB approximation,” Phys. Lett. B 417, 79 (1998) [Erratum-ibid. B 448, 321 (1998)] [arXiv:hep-ph/9708393].

[20] J. M. Cline, M. Joyce and K. Kainulainen, “Supersymmetric electroweak baryogenesis,” JHEP 0007, 018 (2000) [arXiv:hep-ph/0006119]. Erratum: [arXiv:hep-ph/0110031].

[21] M. Carena, J. M. Moreno, M. Quiros, M. Seco and C. E. Wagner, “Supersymmetric CP-violating currents and electroweak baryogenesis,” Nucl. Phys. B 599, 158 (2001) [arXiv:hep-ph/0011053].
[22] S. J. Huber, P. John and M. G. Schmidt, Eur. Phys. J. C 20, 695 (2001) [arXiv:hep-ph/0101249].

[23] J. M. Moreno, M. Quiros and M. Seco, “Bubbles in the supersymmetric standard model,” Nucl. Phys. B 526, 489 (1998) [arXiv:hep-ph/9801272].

[24] J. M. Cline and G. D. Moore, “Supersymmetric electroweak phase transition: Baryogenesis versus experimental constraints,” Phys. Rev. Lett. 81, 3315 (1998) [arXiv:hep-ph/9806354].

[25] J. M. Cline and K. Kainulainen, “A new source for electroweak baryogenesis in the MSSM,” Phys. Rev. Lett. 85, 5519 (2000) [arXiv:hep-ph/0002272].

[26] N. Rius and V. Sanz, “Supersymmetric electroweak baryogenesis,” Nucl. Phys. B 570, 155 (2000) [arXiv:hep-ph/9907460].

[27] G. D. Moore, “Electroweak bubble wall friction: Analytic results,” JHEP 0003, 006 (2000) [arXiv:hep-ph/0001274].

[28] T. Falk, K. A. Olive, M. Pospelov and R. Roiban, “MSSM predictions for the electric dipole moment of the Hg-199 atom,” Nucl. Phys. B 560, 3 (1999) [arXiv:hep-ph/9904393].

[29] M. Carena, M. Quiros and C. E. Wagner, “Opening the Window for Electroweak Baryogenesis,” Phys. Lett. B 380, 81 (1996) [arXiv:hep-ph/9603420].

[30] J. M. Cline and K. Kainulainen, “Supersymmetric Electroweak Phase Transition: Beyond Perturbation Theory,” Nucl. Phys. B 482, 73 (1996) [arXiv:hep-ph/9605233].

[31] A. T. Davies, C. D. Froggatt and R. G. Moorhouse, “Electroweak Baryogenesis in the Next to Minimal Supersymmetric Model,” Phys. Lett. B 372, 88 (1996) [arXiv:hep-ph/9603388].

[32] S. J. Huber, “Singlets and the electroweak phase transition,” arXiv:hep-ph/9902323.

[33] S. J. Huber and M. G. Schmidt, “Electroweak baryogenesis: Concrete in a SUSY model with a gauge singlet,” Nucl. Phys. B 606, 183 (2001) [arXiv:hep-ph/0003122].

[34] K. Kainulainen, T. Prokopec, M. G. Schmidt and S. Weinstock, “First principle derivation of semiclassical force for electroweak baryogenesis,” JHEP 0106, 031 (2001) [arXiv:hep-ph/0105295].