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CONFLICTS BETWEEN B VIOLATING PHENOMENA IN
SUPERGRAVITY MODELS

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A B S T R A C T

We show that there is an incompatibility between matter stability and cosmological baryon production in standard $N=1$ supergravity models. This discrepancy emerges from the bound on the reheating temperature $T_{rh} < 10^{10}$ GeV which comes from the restriction on the gravitino decay after inflation. Some weird possibilities to bypass the controversy are also analyzed.

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The analyses of proton decay in global and local supersymmetric theories have been extensively discussed in the literature^{1),2)}. However, the somewhat correlated problem of cosmic baryon asymmetry has not attracted much attention because one naively expects that there would not be a significant difference between predictions from ordinary and supersymmetric grand unified theories.

Contrary to this general expectation, we show that a very serious problem of consistency between these two manifestations of baryon violating interactions arises in the $N = 1$ supergravity theories that have been constructed so far^{1*}. Indeed, we shall prove that only exotic particles at an intermediate mass scale (10^9 - 10^{10} GeV) can guarantee an adequate cosmological baryon production while preserving the matter stability at the same time.

It is well known that the major danger for too fast a proton decay in supersymmetric theories comes from dimension five operators¹⁾. It was shown that these operators are sufficiently suppressed only if⁴⁾

$$\frac{m_{sq}^2 \cdot m_{\tilde{H}_3}}{m_{\tilde{W}}} \geq (0.4 \sim 4) \cdot 10^{18} \text{ GeV}^2 \quad (1.a)$$

$$\frac{m_{sg}^2 \cdot m_{\tilde{H}_3}}{m_{\tilde{g}}} \geq (4 \sim 40) \cdot 10^{18} \text{ GeV}^2 \quad (1.b)$$

where m_{sq} , $m_{\tilde{W}}$, $m_{\tilde{g}}$, and $m_{\tilde{H}_3}$ denote the squark, wino, gluino and colour-triplet Higgsino masses, respectively (Fig.1). In order to avoid resurrection of the hierarchy problem m_{sq} should not largely exceed 100 GeV. Then we obtain from (1)

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Similar conclusions have been reached in Ref. 3) where alternative scenarios with a superheavy or superlight gravitino have been proposed.

$$m_{\tilde{H}_3} > 10^{16} \text{ GeV} \quad (2)$$

On the other hand, if $m_{\tilde{H}_3}$ is so large, the colour-triplet Higgs scalar (the superpartner of $\tilde{H}_3$) cannot be used to produce the final baryon asymmetry through its decays into ordinary fermions in the framework of $N = 1$ supergravity models.

The point is the following. The standard cosmology forbids⁵⁾ the gravitino mass in the region $1 \text{ KeV} < m_{3/2} < 10^4 \text{ GeV}$. On the other hand, the recent application²⁾ of supergravity to relate the $SU(2) \times U(1)$ breaking scale and the mass splittings of the observable sector favour the gravitino mass around 100 GeV which falls in the forbidden region of the gravitino mass. In this case one has to rely on the inflationary universe scenario so that most of the gravitinos are sufficiently inflated away⁶⁾. However, the universe must be reheated to produce baryons to a high temperature T_{rh} . If T_{rh} is too high, gravitinos are reproduced by two-body reactions $a+b \rightarrow c+\text{gravitino}$. From the recent calculation⁷⁾ on the amount of the gravitino produced after the inflation using the $N = 1$ supergravity interaction⁸⁾, one can tolerate $T_{rh} < 10^9 - 10^{10} \text{ GeV}$ from the study of nucleosynthesis and background radiation spectrum.

Since a previous baryon asymmetry is washed out also by inflation and T_{rh} is less than $10^9 - 10^{10} \text{ GeV}$, any heavy particle whose decays are responsible for the cosmological baryon asymmetry must have a mass $\lesssim 10^{10} \text{ GeV}$. The bound (2) on $m_{\tilde{H}_3}$ coming from proton decay rules out the possibility of using the traditional coloured Higgs triplets for this job.

The possibility of introducing more Higgs triplets and then trying to "rotate away" the proton decay presents some general difficulties due to the non-negligible mixing between heavy and light generations^{1*)}. In order to generate a baryon asymmetry, therefore it appears unavoidable to introduce new exotic particles, i.e., particles which are not contained in the $SU(5)$ spectrum.

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We thank A.Yu. Smirnov for discussions on this problem.

Before considering these new particles, we present some general considerations on baryogenesis in supersymmetric theories. It has already been noticed in Ref. 9) that it is possible to get a non-vanishing cosmological baryon production in a regime of unbroken supersymmetry. The point is the following. The one-loop diagram which is relevant for baryogenesis (Fig.2) gives an effective D-term and thus it is not forbidden to arise radiatively even in the case of exact supersymmetry. The diagram is finite and so we do not have a sort of "cut-off" suppression. If we call μ the $H-\bar{H}$ mixing, the interference diagram is^{1*} proportional to $(\mu/M_H)^4$. On the other hand, as we have emphasized, the dangerous dim.5 operators which are responsible for p-decay presents an $H-\bar{H}$ propagator (Fig.1) and so they are suppressed by a factor $(\mu/M_H) \cdot M_H^{-1}$. If $M_H \lesssim 10^{10}$ GeV, then we need $(\mu/M_H) \lesssim 10^{-6}$ to respect the condition (1) and then n_B/n_γ turns out to be hopelessly small.

Alternatively, one can try to think that the H_3 decay takes place when supersymmetry has already been broken. Then one can introduce a supersymmetry soft breaking term

$$\mu^2 S_{H_3} S_{\bar{H}_3}$$

where S_{H_3} ($S_{\bar{H}_3}$) denotes the scalar component of the H_3 ($\bar{H}_3$) superfield. In this case, the one-loop interference diagram in components is exactly the same as in the usual non-supersymmetric grand unified models with the exception of the μ mixing. The contribution to ΔB is proportional to $(\mu/M_H)^2$ and so we see that again the suppression of the dim.5 operators in Fig. 1 rules out any possibility of getting enough n_B/n_γ , if $m_H \lesssim 10^{10}$ GeV. If one wants the coloured Higgs for the job of baryon number generation, the only way out we can envisage would be to have different μ mixings at the time of H_3 ($\bar{H}_3$) decay at $T \sim 10^{10}$ GeV and today. If μ is of order m_H at $T \sim m_H$ and of order $m_{3/2} = O(M_W)$ today, then it is possible to get a compatibility between cosmological baryon production and matter stability. Such a scenario, however, is not easily implementable.

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A detailed calculation can be found in Ref. 3).

Let us now turn our attention to the possibility of introducing new particles at $10^9 \sim 10^{10}$ GeV. Clearly, the above difficulty concerning the coloured Higgs triplets $(3^*, 1, 1/3)$ can be readily generalized to include additional scalars responsible for four fermion $\Delta B = 1$ processes, i.e., $(3, 1, -4/3)$ and $(3, 3, -1/3)$ also, for the case of the supersymmetric minimal $SU(3) \times SU(2) \times U(1)$ model. Therefore, we claim that, in the $N = 1$ supergravity $SU(5)$ and the minimal^{1*} $SU(3) \times SU(2) \times U(1)$ models with $m_{3/2} \sim O(M_w)$, it is impossible to obtain a sufficient cosmological baryon asymmetry, barring the possibility of an extremely large $H-\bar{H}$ mixing at high T with a quite small mixing at zero temperature. As we shall see in a moment, this statement also applies to a large class of grand unified theories including $SO(10)$ and E_6 for instance, since the only heavy particles which can be used in the process of baryon generation have rather weird $SU(3) \times SU(2) \times U(1)$ quantum numbers and, moreover, they must lie at a scale much below the grand unification scale. These suggest the absence of grand unification and the presence of some particles with weird quantum numbers at the scale $\lesssim 10^9 - 10^{10}$ GeV.

We proceed to analyze what these weird particles can be. We envisage two possibilities: heavy scalars and heavy fermions.

Given the ban on proton mediating scalars, one can think of using decays of heavy weird scalars with at least two channels with different baryon numbers. The candidates are $(3, 2, 1/6)$, $(3, 2, 7/6)$, $(3, 1, 2/3)$, $(6, 1, 1/3)$, $(6, 3, 1/3)$, $(6, 1, 4/3)$, $(6, 1, -2/3)$, and their complex conjugates. The major difficulty is that the p decay triggering scalars must be absent also in the internal loops but we need an effective baryon number violation in the loop for baryogenesis. If one wants an efficient interference already at the one-loop level, it seems unavoidable to introduce at least one non-standard fermion. The simplest example is given in Fig. 3, where the $SU(3) \times SU(2) \times U(1)$ singlet N with a mass of order $10^9 \sim 10^{10}$ GeV is introduced for the one-loop interference. One can easily see that one physical CP violating phase remains after using the phase freedom of the

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"Minimal" means the particle spectrum of superfields of ordinary quarks, leptons and Higgs doublets, but with complete freedom of introducing $\Delta B \neq 0$ Yukawa couplings by coloured Higgs fields $(3, 1, -1/3)$, $(3, 1, -4/3)$, etc.

complex fields. The decaying scalar transforms as $(3^*, 2, -1/6)$ under $SU(3)_C \times SU(2)_L \times U(1)_Y$ and hence it does not mediate proton decay as mentioned before^{1*}. In the loop we exchange the familiar Higgs doublet $(1, 2, 1/2)$ and $(1, 2, -1/2)$. Combination of N and Higgs doublets have the B violating effect in this case. The N must be lighter than the $(3^*, 2, -1/6)$ scalar since it has to be on mass shell to get a non-vanishing contribution to the absorptive part of the one-loop interference. We insert in Fig. 3 a soft supersymmetry breaking through the μ term¹²⁾ $\sim Am_{3/2}W$. The usual low energy $H_1 H_2$ soft breaking proportional to $m_{3/2}$ would lead to a too small n_B/n_γ and so we must invoke temperature effects which are responsible for $H_1 H_2$ mixing proportional to T^2 .

The decay of weird heavy scalars led us to introduce non-standard fermions in order to get non-vanishing contributions at one loop level. It is obvious then to examine the possibility of using superheavy fermions themselves to produce baryons through their decays¹³⁾. It is straightforward to classify all the possible superheavy fermions which can decay into three ordinary fermions (Fig.4). Some of them also decay into the two-body final states, e.g., into a standard fermion and a Higgs doublet.

Again in the case of superheavy fermions, it is easy to find one-loop interference diagrams for baryogenesis if we allow the presence of p-decay mediating scalars as intermediate states^{13),4)}. At first sight one might imagine that the presence of these superheavy objects [mass $> 10^{15}$ GeV, see Eq. (2)] in the decay of heavy fermions (mass $< 10^{10}$ GeV) does not prevent origin of a sufficient baryon asymmetry. We show that contrary to this naive expectation, the net baryon asymmetry is diluted too much in the decay of such heavy fermions. An exhaustive analysis of this problem can be found in the first of Ref. 13) (the same notation shall be used here). We just summarize here the major points. For a fermion F whose mass m_F is $\lesssim 10^{10}$ GeV, the decoupling temperature T_D is roughly

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This kind of particle can appear in extended grand unified theories. See Ref. 11).

$$T_D \cong m_F \left[\ln \left\{ \left(\frac{g^2}{4\pi} \right)^2 \left(\frac{1}{8\pi^3 N} \right)^{1/2} \frac{M_{Pl}}{m_F} \right\} \right]^{-1} \quad (4)$$

where $N = 228.75$ are the light degrees of freedom of the minimal supersymmetric standard model, and $g^2/4\pi$ denotes a typical coupling strength. Since the scalar in Fig. 4 is much heavier than F , F cannot decay at $T = m_F$. At $T \approx m_F/3N$, the Universe is matter dominated by F until it decays at a much lower decaying temperature

$$T_\Gamma = 0.1 \left(\frac{\lambda^2}{4\pi} \right)^{4/3} \left(\frac{m_F}{m_{H_3}} \right)^3 \left(m_{H_3} M_{Pl}^2 \right)^{1/3} \left(\frac{n_F}{n_\gamma} \Big|_{T_D} \right)^{-1/3} \quad (5)$$

where

$$\frac{n_F}{n_\gamma} \Big|_{T_D} \cong \left(\frac{4\pi}{g^2} \right)^2 \left(8\pi^3 N \right)^{1/2} \frac{m_F}{M_{Pl}} \quad (6)$$

Since the Universe is matter dominated by the rest mass of F 's, their decay reheats the Universe up to a temperature T_a :

$$T_a \cong \left(\frac{m_F T_\Gamma^3}{3N} \frac{n_F}{n_\gamma} \Big|_{T_D} \right)^{1/4} \quad (7)$$

Consequently, the baryon asymmetry produced before the F decay is diluted by a factor

$$d \cong \left(\frac{T_\Gamma}{T_a} \right)^3 \cong \left(\frac{3N T_\Gamma}{m_F} \right)^{3/4} \left(\frac{n_F}{n_\gamma} \Big|_{T_D} \right)^{-3/4} \quad (8)$$

From (5), (6) and (8), we obtain

$$d \cong 0.2 \left(\frac{\lambda^2}{4\pi} \right) \left(\frac{g^2}{4\pi} \right)^2 (3N)^{3/4} (8\pi^3 N)^{-1/2} \left(\frac{m_F}{m_{H_3}} \right)^2 \left(\frac{M_{Pl}}{m_F} \right)^{3/2} \quad (9)$$

Therefore, the baryon asymmetry ratio is given by¹³⁾

$$\frac{n_B}{n_\gamma} \cong \left[0.28 \frac{1}{N} \left(\frac{f^2}{4\pi} \right) \cdot \varepsilon \cdot \text{Im } I \right] \cdot \left[0.2 (3N)^{3/4} \cdot \left(\frac{\lambda^2}{4\pi} \right) \left(\frac{m_F}{m_{H_3}} \right)^2 \left(\frac{M_{Pl}}{m_F} \right)^{1/2} \right] \quad (10)$$

where the first factor is the usual one encountered in baryogenesis with an order of 10^{-5} - 10^{-9} . Therefore, the second factor in Eq. (10) can be at most as small as 10^{-4} . However, for $m_F < 10^{10}$ GeV, $M_{H_3} > 10^{15}$ GeV, and $(\lambda^2/4\pi) \approx 0.1$, the second factor is less than 10^{-5} , and no appreciable baryon asymmetry is produced by such a process.

The remaining possibility is that all the intermediate scalars have a mass which is $\sim m_F \lesssim 10^{10}$ GeV. This means that we must avoid the use of p-decay mediating scalars. In this case there does not exist one-loop interference diagrams which can give rise to n_B/n_γ . Going to higher loops encounters the problem of more suppression and we have not analyzed these contributions.

In conclusion, the desperate supersymmetric excursion into the world of exotic particles which can give rise to a net baryon number produced at $T \lesssim 10^9 \sim 10^{10}$ GeV shows that it is not impossible, in particular for the decay of weird scalars, to obtain a reasonable n_B/n_γ . However, it seems quite awkward to propose the existence of these particles at 10^{10} GeV, while the usual p-decay mediating colour triplets should be much heavier or not be present at all.

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R E F E R E N C E S

- 1) N. Sakai and T. Yanagida, Nuclear Phys. B197 (1982) 533;
S. Weinberg, Phys.Rev. D26 (1982) 223.
- 2) For reviews on N=1 local supersymmetric models, see, for instance:
R. Barbieri and S. Ferrara, Surv. in HEP 4 (1983) 33;
J. Ellis, Cornell Conference (1983), CERN preprint TH.3718 (1983);
D.V. Nanopoulos, CERN preprint TH.3699 (1983);
H.P. Nilles, University of Geneva preprint UGVA-DPT 1983/12-412
(1983), to be published in Physics Reports.
- 3) J. Ellis, K. Enqvist, G. Gelmini, C. Kounnas, A. Masiero,
D.V. Nanopoulos and A.Yu. Smirnov, CERN preprint TH.3902 (1984).
- 4) J. Ellis, D.V. Nanopoulos and S. Rudaz, Nuclear Phys. B202 (1982) 43.
- 5) H. Pagels and J.R. Primack, Phys.Rev.Letters 48 (1982) 223;
S. Weinberg, Phys.Rev.Letters 48 (1982) 1303.
- 6) J. Ellis, A.D. Linde and D.V. Nanopoulos, Phys.Letters 118B (1982) 59;
D.V. Nanopoulos, K.A. Olive and M. Srednicki, Phys.Letters 127B (1983)
30.
- 7) J. Ellis, J.E. Kim and D.V. Nanopoulos, CERN preprint TH.3839 (1984).
- 8) E. Cremmer, B. Julia, J. Scherk, P. van Nieuwenhuizen, S. Ferrara, and
L. Girardello, Phys.Letters 79B (1978) 231;
E. Cremmer, S. Ferrara, L. Girardello and A. Van Proeyen, Nuclear Phys.
B212 (1983) 413.
- 9) D.V. Nanopoulos and K. Tamvakis, Phys.Letters 114B (1982) 235;
H.E. Haber, Phys.Rev. D26 (1982) 1317.
- 10) L. Girardello, M.T. Grisaru and P. Salomonson, Nuclear Phys. B194
(1982) 65.
- 11) J.E. Kim, Phys.Letters 121B (1983) 46.
- 12) J.E. Kim and H.P. Nilles, Phys.Letters 138B (1984) 150.
- 13) R. Barbieri, A. Masiero and D.V. Nanopoulos, Phys.Letters 98B (1981)
191;
T. Yanagida and M. Yoshimura, Phys.Rev.Letters 45 (1980) 71;
J. Harvey, E. Kolb, D. Reiss and S. Wolfram, Caltech preprint CALT-68-
784 (1980);
A. Masiero and R.N. Mohapatra, Phys.Letters 103B (1981) 343.
In the supersymmetric context, see:
A. Masiero, D.V. Nanopoulos, K. Tamvakis and T. Yanagida, Z.Phys. C17
(1983) 33.

FIGURE CAPTIONS

Figure 1 : SU(5) diagrams for dimension 5 operators.

Figure 2 : Baryon generating interference diagram in the supersymmetric SU(5).

Figure 3 : Baryogenesis diagram by a weird scalar with a heavy neutral lepton singlet.

Figure 4 : Baryogenesis by a superheavy fermion F . There must exist at least two channels with different baryon numbers of light fermions f .

Fig. 1

Fig. 2

Fig. 3

Fig. 4