Ref.TH.2966-CERN

COSMOLOGICAL BARYON PRODUCTION THROUGH SUPERHEAVY FERMIONS

R. Barbieri^{*)} and D. V. Nanopoulos

CERN -- Geneva

and

A. Masiero

Max Planck Institute
for Physics and Astrophysics, Munich

A B S T R A C T

Cosmological effects of superheavy fermions present in a wide class of grand unified models are discussed. An interesting outcome is that long-lived superweakly interacting fermions may be the only source of surviving baryon asymmetry generated at temperatures possibly as low as 1 TeV.

^{*)} Also at Scuola Normale Superiore, Pisa, Italy.

1. Superheavy fermions might exist if some new physics indeed occurs at a mass $M \gg M_W$ beyond the standard $SU(3) \times SU(2) \times U(1)$ model, as advocated for example in grand unified models¹⁾. In searching for physical effects due to their presence, one is naturally led to consider their possible rôle^{*)} in cosmology during the cooling of the early Universe. On general grounds, two different kinds of heavy fermions may occur: those being able to decay into "light" matter only through the exchange of superheavy bosons with typical grand unification masses $M \sim 10^{15}$ GeV (cat. A), as opposed to the heavy fermions with a direct coupling to "light" fields (cat. B). The classical example of cat. B fermions is the $SO(10)$ right-handed neutrino which can, for example, decay in the left-handed neutrino and a neutral Higgs.

In this letter we want to point out that - unlike cat. B fermions - heavy long-lived fermions F of cat. A may play an important rôle in the production of a baryon asymmetry $|n_B/n_Y| > 0$ at temperatures much lower than any standard scale, medium or superheavy, for interesting B violating interactions. Their history during the cooling of the early Universe might be the following. At some temperature T_* , when their interaction rates fall below the expansion rate of the Universe $H(T)$, they decouple from equilibrium. For the range of masses that we shall consider, $10^{11} \text{ GeV} \leq m_F \leq 10^{14} \text{ GeV}$, it is $0.1 \leq T_*/m_F \leq 1$. Up to some temperature $T_*^{(1)} \approx 10^{15} \text{ GeV}$, when their possibly B violating interactions were still in equilibrium, they are likely to have washed out any pre-existent baryon asymmetry. Since their decay goes through the exchange of a superheavy boson, (see Fig. 1), their lifetime Γ_F^{-1} can be much longer than the decoupling time. After decoupling of F 's, which thereafter behave as a collisionless gas, the decay of some superheavy Higgs particle may create a baryon asymmetry at temperatures $T \gtrsim 10^{12} \text{ GeV}$ ³⁾, which in turn may, or may not subsequently get destroyed by some medium heavy bosons with B violating interactions in equilibrium. What is important for us is that finally, at some temperature $T_F \ll m_F$, at which $\Gamma_F \approx H(T_F)$, the fermions F will decay, again producing a net n_B of size comparable to the one produced in Higgs decays. This might be the only source of surviving baryon asymmetry. As observed by Harvey et al.⁴⁾, from the decays of the F particles a large amount of entropy might also be produced which may dilute $|n_B/n_Y|$ itself below the observed value. This is because of the conversion of the large F energy density ρ_F , given essentially by the rest mass $\rho_F \approx m_F n_F$, which dominates the energy density of the Universe for $T_F < T \ll m_F$. Avoiding too big a dilution factor fixes a minimum decay temperature $T_F \gtrsim 10^3 \div 10^4 \text{ GeV}$, and in turn a minimum mass $m_F \gtrsim 10^{11} \div 10^{12} \text{ GeV}$.

*) The possibility of creating a baryon asymmetry through superheavy fermions was originally suggested in Ref. 2).

The fact that T_F may be as low as ~ 1 TeV makes the F decays an interesting mechanism for production of B asymmetry, particularly in the physical situation when other B violating phenomena take place at medium heavy energy, making hard the survival of any pre-existent baryon (or antibaryon) excess^{*)}. This is especially true if the medium energy phenomena, as in the case of $\Delta B = 2$, $\Delta L = 0$ $N-\bar{N}$ oscillations, do not conserve some linear combination $B + aL$ of baryon and lepton numbers, which would still protect the baryon asymmetry from being washed out⁵⁾.

Unlike the long-lived superweakly interacting fermions (cat. A), the short-lived heavy fermions with direct coupling to "light" matter (cat. B) do not seem to be able to produce any important cosmological effect⁶⁾. In particular, one can put no lower limit on their mass simply based on cosmological considerations⁴⁾.

2. On general grounds, the following theorem is readily established: the standard $SU(3) \times SU(2) \times U(1)$ model with Higgs doublets conserves baryon number, no matter how one complicates the fermion matter multiplets^{**)} . Dominant B violating decays of heavy fermions will then be described by four-fermion effective interactions of one F with three other "light" fermion fields, generated in a renormalizable theory by superheavy boson exchanges (Fig. 1). Classifying all the possible $SU(3) \times SU(2) \times U(1)$ invariant couplings of the above kind, one indeed finds fermions F having at least two couplings with different B numbers, as well as left- and right-handed fermions F_L and F_R having the same $SU(3) \times SU(2) \times U(1)$ transformation properties, but different B and $B-L$ numbers^{***)}.

*) We thank R. Mohapatra and L. Susskind for a discussion on this point.

**) The same is obviously not true for the lepton number, which can be broken by introducing a neutral heavy lepton.

***) As is well known, the possible breaking of $B-L$ through four-fermion interactions is a peculiarity of fermions which are not chiral under $SU(3) \times SU(2) \times U(1)$ and are therefore naturally superheavy. In models with superheavy fermions $B-L$ is indeed generally broken. The irreducibility of their fermionic representation (per generation) leads actually to no globally conserved number; this property is particularly desirable from a cosmological point of view, since otherwise an initial baryon asymmetry $n_B \sim n_\gamma$ could not be washed out. On the other hand, through heavy fermions, whose decays do not conserve any linear combination $B + aL$, the theoretically interesting possibility exists of creating B and L asymmetries substantially different between themselves, although both small relative to the entropy density.

In general, the two-body interactions mediated by a superheavy boson, with rates $\sim (g^2/4\pi)^2 T^5/M^4$, will remain in equilibrium up to a temperature

$$T_*^{(1)} \simeq M \left(\frac{1.6 N^{1/2}}{(g^2/4\pi)^2} \frac{M}{M_P} \right)^{1/3} \simeq 10^{15} \text{ GeV} \quad (1)$$

where the expansion rate of the Universe $H = 1.6 T^2 N^{1/2}/M_P$ becomes dominant. Here $M_P = 1.22 \times 10^{19}$ GeV, $N \simeq 10 \div 100$ is the suitably weighted number of all particles with masses $< T_*^{(1)}$ and $g^2/4\pi$ is a typical unified fine structure constant $\simeq 0.02$. Since some of these interactions will in general be B violating, one expects no baryon (or antibaryon) survival up to $T_*^{(1)}$. After $T_*^{(1)}$, if they are not singlets under $SU(3) \times SU(2) \times U(1)$, the fermions F will still be kept in equilibrium even below their mass by annihilations and Compton-like scatterings with "light" gauge bosons with interaction rates $n_F \sigma v \sim n_F (g^2/4\pi)^2 / m_F^2$. By equating these rates with $H(T)$, taking into account the Boltzmann distribution $n_F \sim (m_F T)^{3/2} \exp(-m_F/T)$, one gets the decoupling temperature T_* . An approximation for $m_F \lesssim 10^{13}$ GeV gives

$$T_* \simeq m_F \left[\lg Q + \frac{1}{2} \lg \lg Q \right]^{-1} \quad (2)$$

$$Q \equiv \left(\frac{g^2}{4\pi} \right)^2 \left(\frac{\pi}{8N} \right)^{1/2} \frac{1}{\pi^2} \frac{M_P}{m_F}$$

as well as the relative number density

$$\left. \frac{n_F}{n_\gamma} \right|_{T_*} \simeq Q^{-1} \lg Q \quad (3)$$

For later times, until they decay, the relative number density of the F 's remains constant, with their energy density being dominated by their rest mass, $\rho_F \approx n_F m_F$. Actually, at $T \sim m_F/3N$, this same energy will start dominating the full energy density in the Universe up to the temperature T_F of their decays. By assumption, these decays proceed through diagrams of the kind of Fig. 1, with some channels having $\Delta B \neq 0$ and non-negligible branching ratios. By exchanging a Higgs scalar with an average universal coupling λ and a mass $M \approx 10^{15}$ GeV, the width is given by

$$\Gamma_F \approx \left(\frac{\lambda^2}{4\pi} \right)^2 \frac{m_F^5}{12\pi M^4} \quad (4)$$

which becomes comparable to

$$H = \left(\frac{8\pi}{3M_P^2} g \right)^{1/2} \approx \left(\frac{8\pi}{3M_P^2} \frac{m_F T^3}{\pi^2} \frac{n_F}{n_\gamma} \Big|_{T_*} \right)^{1/2} \quad (5)$$

at

$$T_F = 0.1 \left(\frac{\lambda^2}{4\pi} \right)^{4/3} \left(\frac{m_F}{M} \right)^3 (HM_P^2)^{1/3} \left(\frac{n_F}{n_\gamma} \Big|_{T_*} \right)^{-1/3} \quad (6)$$

In these decays a generation of baryon asymmetry is expected. In fact, through typical interference diagrams of the type of Fig. 2, one gets

$$\left| \frac{\tilde{n}_B}{n_\gamma} \right| \approx 0.28 \frac{N_F}{N} \frac{n_F}{n_\gamma} \Big|_{T_*} \left(\frac{g^2}{4\pi} \right) \in \text{Im } I \quad (7)$$

where N_F is the number of helicity states of all fermions F , ϵ is a phase angle characterizing the average strength of CP violations in the interactions of F with scalar bosons and $\text{Im}I$ is the imaginary part of the typical diagram. As in the case of Higgs decays, from Eq. (7) one can give the estimate³⁾

$$\left| \frac{\tilde{n}_B}{n_\gamma} \right| \simeq (10^{-9} \text{ to } 10^{-3}) \frac{n_F}{n_\gamma} \Big|_{T_*} \quad (8)$$

Before discussing whether these values overlap the ones allowed by astronomical observations, $|n_B/n_\gamma| \simeq 10^{-10}$ to 10^{-8} , one should keep in mind that, since $\rho(T_F)$ is dominated by the rest mass of the F 's, their decay will also reheat the Universe up to a temperature T'_F so that

$$\rho(T_F) \simeq \frac{m_F T_F^3}{\pi^2} \frac{n_F}{n_\gamma} \Big|_{T_*} \simeq \frac{3N T_F'^4}{\pi^2} \quad (9)$$

and in turn dilute the baryon asymmetry by a factor

$$d \simeq \left(\frac{T_F}{T'_F} \right)^3 = \left(\frac{3N T_F}{m_F} \right)^{3/4} \left(\frac{n_F}{n_\gamma} \Big|_{T_*} \right)^{-3/4} \quad (10)$$

The final observed asymmetry will then be given by

$$\begin{aligned} \left| \frac{n_B}{n_\gamma} \right| &= \left| \frac{\tilde{n}_B}{n_\gamma} \right| d \simeq (10^{-9} \text{ to } 10^{-3}) \left(\frac{3N T_F}{m_F} \right)^{3/4} \left(\frac{n_F}{n_\gamma} \Big|_{T_*} \right)^{1/4} \equiv \\ &\equiv (10^{-9} \text{ to } 10^{-3}) d' \end{aligned} \quad (11)$$

Demanding that the factor d' should not be less than 10^{-5} , using Eqs. (3), (6), (10) and (11) puts a lower limit on m_F as well as on T_F

$$m_F \gtrsim 10^{11} \div 10^{12} \text{ GeV}$$

$$T_F \gtrsim 10^3 \div 10^4 \text{ GeV}$$

where a typical value $\lambda^2/4\pi = 10^{-4} \div 10^{-5}$ has been taken. At $T_F \approx 10^5 \div 10^6 \text{ GeV}$, corresponding to a mass $m_F \approx 10^{13} \text{ GeV}$, an over-all asymmetry $|n_B/n_Y| \approx 10^{-13}$ to 10^{-7} can be obtained. This region of temperatures, from 1 up to 10^3 TeV , is below any of the standard scales, medium or superheavy, for interesting B violating interactions⁵⁾. On the other hand, although possibly as small as 1 TeV, the minimal decay temperature is high enough not to disturb in any way the hadronic era as well as the nucleosynthesis.

Coming now to the heavy fermions with a direct coupling to "light" matter⁶⁾ (cat. B), their B violating interactions are also necessarily of the type of Fig. 1, whereas their main decay normally proceeds much more quickly through a two-body process, necessarily B conserving, with a relative branching ratio

$$B \approx \frac{\lambda^2}{4\pi} \left(\frac{m_F}{M} \right)^4 \frac{1}{12\pi} \quad (12)$$

Two differences obviously emerge. In order for them to be able to produce any baryon asymmetry, the non-equilibrium condition requires a lower bound for their mass as well as for the minimum temperature, which should both be greater than $(\lambda^2/4\pi)(1/1.66N^{1/2})M_P \gtrsim 10^{12} \text{ GeV}^*$. Furthermore, the fact that the relative rate for their B violating processing is normally suppressed with respect to the main decay mode makes it unlikely that the B asymmetry produced by them be sizeable, even if m_F is not too much lighter than M itself. On the other hand, in the case where no B asymmetry is produced in their decays, their relatively short lives make them avoid any sensible lower bound on their masses based on cosmological considerations.

*) Such a limit is obtained by imposing the non-equilibrium condition at the temperature where the total decay rate becomes comparable to $H(T)$. In some instances, this may not be necessary⁷⁾.

REFERENCES

- 1) R. Barbieri and D.V. Nanopoulos, Phys. Lett. 91B (1980) 369; *ibid.* 95B (1980) 43.
- 2) H. Georgi and D.V. Nanopoulos, Nucl. Phys. B155 (1979) 52.
- 3) A.D. Sakharov, Pis'ma Zh. Eksp. Teor. Fiz. 5 (1967) 32;
M. Yoshimura, Phys. Rev. Lett. 41 (1978) 28;
D.V. Nanopoulos, Proc. 6th Int. Workshop on Weak Interactions with Very High Energy Beams, eds. K.E. Lassila and B.L. Young, (Iowa University 1978), pp. 964 and 991;
D.V. Nanopoulos, The Baryon Number in the Universe, Invited talk given at the CalTech Workshop on High-Energy Physics, February 1979 (unpublished);
S. Dimopoulos and L. Susskind, Phys. Rev. D18 (1978) 4500;
D. Toussaint, S.B. Treiman, F. Wilczek and A. Zee, Phys. Rev. D19 (1979) 1036;
J. Ellis, M.K. Gaillard and D.V. Nanopoulos, Phys. Lett. 80B (1979) 360;
A.D. Sakharov, Zh. Eksp. Teor. Fiz. 76 (1979) 1172;
S. Weinberg, Phys. Rev. Lett. 42 (1979) 850;
D.V. Nanopoulos and S. Weinberg, Phys. Rev. D20 (1979) 2484.
- 4) J.A. Harvey, E.W. Kolb, D.B. Reiss and S. Wolfram, CalTech preprint CALT-68-784 (1980).
- 5) S. Weinberg, Harvard preprint HUTP-80/A093 (1980).
- 6) G. Branco, J.P. Derendinger, P. Hut, F. Klinkhamer and A. Masiero, UGVA preprint, in preparation;
For a different point of view, see:
T. Yanagida and M. Yoshimura, Phys. Rev. Lett. 45 (1980) 71.
- 7) A. Masiero and R.N. Mohapatra, in preparation.
See also T. Yanagida and M. Yoshimura, Ref. 6).

FIGURE CAPTIONS

- Fig. 1 : A four-fermion interaction between a heavy fermion (double line) and "light" fermions (simple full line) mediated by a heavy boson exchange.
- Fig. 2 : A typical interference diagram for the decays of heavy fermions into three "light" fermions leading to a possible B asymmetry. The dotted (wavy) line denotes a scalar (vector) boson exchange.

FIG.1

FIG.2