Ref.TH.2737-CERN

BOUNDS ON THE BARYON / PHOTON RATIO DUE TO OUR EXISTENCE

D.V. Nanopoulos
CERN - Geneva

A B S T R A C T

The existence of human beings to measure the ratio n_B/n_γ necessarily imposes severe bounds on it :

$$10^{-11} \simeq \theta((m_e/m_{\text{Planck}})^{\frac{1}{2}}) \leq n_B/n_\gamma \leq \sigma(\alpha^2) \simeq 10^{-4}$$

Then in a large class of grand unified theories the existence of six flavours becomes an unavoidable necessity.

Ref.TH.2737-CERN

20 September 1979

We exist. We believe that thanks to the efforts of human beings during the last three-hundred years, we have a fairly detailed picture of how the Universe probably evolved into its present state. The picture is called the "standard hot big bang model" ¹⁾ of the Universe. This model, despite its remarkable successes, namely the discovery of the 3K microwave background ²⁾, the ~25% (by mass) of He⁴ abundance ³⁾, etc., had, until recently, a problem. The baryon to photon ratio, which governs the whole course of cosmic evolution, which is observed to be ⁴⁾

$$\frac{n_B}{n_\gamma} \simeq 10^{-9 \pm 1} \quad (1)$$

remained unexplained. It had to be introduced as an ad hoc initial condition.

During the last year or so, in a successful amalgamation of grand unified theories (GUTS) ⁵⁾ (theories that unify weak electromagnetic and strong interactions) with the big-bang model, mechanisms have been proposed ^{6),7)} for the creation of more matter than antimatter. Remarkably enough, detailed calculations ⁷⁾ have shown that the ratio n_B/n_γ which may be given in terms of purely microscopic quantities, is in accord with the observed value (1). Since the ratio n_B/n_γ is such a fundamental quantity and since it plays such an important rôle in the cosmic evolution, we may consider as a must the existence of all the basic ingredients that are necessary for its determination.

In this note I shall show that these remarks are strengthened considerably by the simple fact that our existence (actually the existence of any kind of life !) puts rather strong limits on the ratio n_B/n_γ .

In the "standard" picture the suitable conditions for nucleogenesis (H¹, He⁴, ...) are satisfied around $T \sim 10^9$ K and the remarkable result of 25% (by mass) of He⁴ abundance has its deep roots in the following facts ^{1),3)} :

a)

$$\rho_{\text{matter}}(10^9 \text{ K}) \leq \rho_{\text{radiation}}(10^9 \text{ K}) \quad (2)$$

where ρ is the energy density,

b)

$$G_F^2 m_e^3 \simeq G_N^{1/2} \quad (3)$$

where, as usual G_F and G_N are the Fermi and Newton (gravitational) constants, respectively, and m_e is the electron mass ; and

c) there are no more than three kinds of massless stable neutrinos ⁸⁾.

Since

$$\rho_{\text{matter}}(T) \sim m \left(\frac{n_0}{T_0^3} \right) T^3 \quad (4)$$

and

$$\rho_{\text{radiation}}(T) \sim T^4 \quad (5)$$

(in our units $k_{\text{Boltzmann}} = 1$, i.e., $1 \text{ ev} \simeq 11600 \text{ }^\circ\text{K}$) where m is the proton mass and n_0 and T_0 the present baryon density ($\sim 10^{-5} - 10^{-7}$ baryons/cm³) and photon temperature ($\sim 3\text{K}$), respectively, Eq. (2) implies :

$$\frac{n_B}{n_\gamma} \sim \frac{n_0}{T_0^3} \leq 10^{-4} \sim \alpha^2 \quad (6)$$

The importance of this bound is obvious for our existence : too much He^4 would imply too little H^1 , i.e., too little water and also completely different stellar evolution, presumably inappropriate for anything interesting to happen, which is also the case for too little He^4 .

After a primordial element formation, the matter and the radiation continued to interact thermally through frequent ionization and recombination of atoms, keeping each other at the same temperature, i.e., the thermal equilibrium was maintained. Then, as the Universe expanded and cooled down, two interesting things happened :

d) the Universe ceased to be radiation-dominated and became matter-dominated :

$$\rho_{\text{matter}}(T) \geq \rho_{\text{radiation}}(T) \quad (7)$$

which implies :

$$T \leq T_m \equiv \sigma \left(m \frac{n_0}{T_0^3} \right) \quad (8)$$

- e) the photons ceased to be energetic enough to keep hydrogen atoms ionized, so the electrons and the protons quickly recombined ; then we certainly need :

$$T \leq T_r \equiv \sigma \left(\alpha^2 m_e \right) \quad (9)$$

Recombination of the plasma was crucial because it brought an end to the interaction and thermal equilibrium between radiation and matter ("decoupling") perhaps the simplest prerequisite for something at all to happen. Before plasma recombination, the photon pressure prevented the uniform matter from condensing into stars, galaxies or clusters of galaxies. However, after recombination, the photon pressure was gone and condensation could begin. Small perturbations in the matter density, perhaps dating back to the beginning of expansion, began to grow larger and larger, etc.

It is then obvious, and not too much to ask, that anything interesting (including our existence) has happened sometime after the phases d) and e) [or e) and d] occurred. This simple fact is going to set a lower bound on n_B/n_V . Since a priori we do not know what is the time-order between the phases d) and e) we consider the two cases.

I. - $\underline{T_m \leq T_r}$

Immediately through Eqs. (8) and (9) $T_m < T_r$ implies

$$\frac{n_0}{T_0^3} < \sigma (\alpha^4) \quad (10)$$

and also $t_m > t_r$, where $t^{-1} \sim ((32\pi G_N \rho)/3)^{\frac{1}{2}}$. So it is enough to demand that the present age of the universe,

$$t_0 \sim \left(\frac{1}{G_N m^2} \right) \frac{1}{m_e} \quad (11)$$

satisfy the condition

$$t_0 > t_m \quad (12)$$

Then since

$$t_m^{-1} \sim (G_N m^2)^{1/2} m \left(\frac{n_0}{T_0^3} \right)^2 \quad (13)$$

Eq. (12) implies :

$$\frac{n_0}{T_0^3} \geq \mathcal{O} \left(\left(\frac{m_e}{M_{\text{Planck}}} \right)^{1/2} \right) \quad (14)$$

where, as usual, $M_{\text{Planck}} \equiv G_N^{-1/2}$. Then, in this case, we get :

$$\mathcal{O} \left(\left(\frac{m_e}{M_{\text{Pl}}}} \right)^{1/2} \right) \leq \frac{n_0}{T_0^3} \leq \mathcal{O}(\alpha^4) \quad (15)$$

which are rather severe limits if we compare them with the actual value as given by Eq. (1). [It is worth remembering that $n_Y(T) \simeq 20 T^3 (^{\circ}\text{K})$ and that $n_B(T)/n_Y(T)$ remains essentially constant during the period of interest here.]

II. - $T_r \geq T_m$

Again, in this case, we get immediately through Eqs. (8) and (9) the limit :

$$\frac{n_0}{T_0^3} \geq \mathcal{O}(\alpha^4) \quad (16)$$

Of course, it is now enough that $t_0 > t_r$, but with the bound of Eq. (16), this inequality is immediately satisfied. So, using Eqs. (6) and (16), we get

$$\mathcal{O}(\alpha^4) \leq \frac{n_0}{T_0^3} \leq \mathcal{O}(\alpha^2) \quad (17)$$

which provides non-trivial bounds on the baryon to photon ratio.

In any case we have

$$\mathcal{O}\left(\left(\frac{m_e}{M_{Pl}}\right)^{1/2}\right) \leq \frac{n_0}{T_0^3} \leq \mathcal{O}(\alpha^2) \quad (18)$$

which is our main result.

Here are some comments.

- 1) Equation (18) is the result of the simple fact that anything interesting has happened after the phases d) and e) have occurred (lower bound) and that nucleogenesis occurred during the radiation-dominated era (upper bound).
- 2) It is worth emphasizing that such a minimal set of prerequisites for our existence puts such severe limits on n_0/T_0^3 :

$$\mathcal{O}(10^{-11}) \leq \frac{n_0}{T_0^3} \leq \mathcal{O}(10^{-4}) \quad (19)$$

Actually, another way to derive the lower bound in Eq. (19) is to notice that T_m [as given by Eq. (8)] has to be smaller than the present-photon temperature T_0 ($\sim 3^\circ\text{K}$), i.e.,

$$\mathcal{O}\left(m \frac{n_0}{T_0^3}\right) < \mathcal{O}(3^\circ\text{K})$$

This fact, in turn, puts rather strong constraints on the basic ingredients that have been used to explain this fundamental ratio and makes their existence a kind of an unavoidable necessity.

- 3) Looking at Eqs. (15) and (17), it becomes less unexpected that

$$\frac{n_0}{T_0^3} \sim \mathcal{O}(\alpha^4) \quad (20)$$

and that $T_m \sim T_r$, as have been measured experimentally.

4) It is amazing to notice that using Eqs. (12), (13) and (20), we get

$$t_0 > \mathcal{O} \left(\frac{1}{G_N m_e} \cdot \frac{1}{m} \right) \quad (21)$$

which is not dramatically smaller than the actual value, as given in Eq. (11). Here the message is that if observers exist to measure the age of the Universe, then necessarily t_0 has to satisfy (21). It is not a coincidence, it is a necessity.

5) It is astonishing that the lower bound on n_0/T_0^3 as given by (14), contains the ratio of the smallest (m_e) and largest (M_{Pl}) masses known in the realm of particle physics. Then it is interesting to notice that since ⁵⁾ $M_X \sim \alpha^2 M_{\text{Planck}}$, where X denote the superheavy bosons present in grand unified theories and which are responsible for baryon creation, we get

$$\frac{n_0}{T_0^3} \sim \mathcal{O} \left(\left(\frac{m_e}{M_X} \right)^{1/2} \right) \quad (22)$$

The fundamental ratio n_0/T_0^3 is given in terms of the ratio of the masses of the lightest (m_e) and heaviest (M_X) particles available in grand unified theories.

6) It is worth mentioning that the baryon number violating interactions (responsible for baryon creation) are also responsible for the desintegration of matter. (Interactions which once worked toward our creation are driving us to extinction. That is our destiny.) Namely they mediate proton decay and, in the simplest grand unified theories, the proton lifetime is given by ⁵⁾

$$\tau_p \sim \frac{1}{\alpha^2} \cdot \frac{M_X^4}{m^5} \quad (23)$$

Obviously the condition for something interesting to happen is

$$\tau_p > t_m \quad (24)$$

which, by the use of Eqs. (13), (20) and (22) implies

$$M_X > \mathcal{O}(\alpha^{-4} m) \quad (25)$$

Use of the inequality $\tau_p > t_0$ gives the bound

$$M_X > O(\alpha^{-5} m) \quad (26)$$

These bounds are rather non-trivial and are satisfied by the actual values ($\sim 10^{15}$ GeV, $\tau_p \sim 10^{30}$ years) as determined in grand unified theories ⁵⁾.

We now turn to the implications of the bounds (18) on the structure of the present theories of particle physics, namely on grand unified theories. Let us recall that the three key ingredients for the creation of more baryons than antibaryons are ⁶⁾ :

- 1) baryon number violation,
- 2) C and CP violation, and
- 3) departures from thermal equilibrium.

In general, by putting quarks, antiquarks and leptons in the same multiplet, grand unified theories lead to a natural and experimentally acceptable violation of the baryon number. Furthermore, baryon number violating interactions in spontaneously broken grand unified theories may generate the observed baryon number when the expansion and cooling of the universe creates the necessary departures from thermal equilibrium. So, the unification of all basic interactions, plus the expansion of the universe, may be a necessity.

What about CP violation ? Here things are more complicated. Of course, CP violation has been observed in the K system and it would be nice to find that the same CP violating mechanism that is responsible and necessary for the creation of baryons, also triggers $K_L \rightarrow 2\pi$. As is well known, the two competing mechanisms of CP violation in gauge theories are the K-M mechanism ⁹⁾, i.e., the existence of at least six quarks, and the mechanism ¹⁰⁾ that involves multi-Higgs systems with suitably tuned parameters. In grand unified theories, there is a tendency which seems more natural that all Higgs bosons become superheavy ¹¹⁾ ($\sim 10^{15}$ GeV). We have difficulties in keeping even the one, which is responsible for the spontaneous breakdown of the standard weak interactions, light ¹²⁾. So, if we use multi-Higgs systems as a source of CP violation, it seems quite difficult to explain both the low energy CP violation (K system) and the necessary super-high energy CP violation (baryon creation) in a unified way.

The fact that we already have seen 5 (and hopefully very soon 6) quarks makes the K-M mechanism more probable at low energies. Still, there is another complication. It has been found ¹³⁾ that in grand unified theories, even with four quarks, there is CP violation at super-high energies, but not at low energies. Then, it is possible to satisfy the criterion for baryon creation and leave low energies without CP violation. In the simplest mechanism of baryon creation ¹⁴⁾, it is the decay of super-heavy Higgs bosons to light fermions that is responsible for the effect ¹⁴⁾. It is not surprising that the magnitude of the asymmetry will be proportional to the Yukawa couplings, i.e., to the fermion masses. Incidentally, this shows the important rôle of the super-heavy Higgs bosons. Their existence in grand unified theories might not be accidental and boring. Do they just only provide the Higgs mechanism, or is it the opposite? Does the Higgs mechanism come as a second *raison d'être* of Higgs bosons? The magnitude of the effect, given the mass spectrum of the known four quarks, is too small, not only to explain the observed n_B/n_γ value [Eq. (1)], but it even violates our bounds (18). Then, this possibility is out.

If this is the case, the existence of at least six quarks - to provide both low energy CP violation and heavy masses for generating enough baryon asymmetry - is a necessity. Consequently, we have a rather natural and unified explanation of CP violation at low and super-high energies. Here it is appropriate to recall some other arguments for six quarks.

- 1) The observed He^4 abundance demands for its natural explanation no more than three kinds of massless stable neutrinos ⁸⁾ [see c]. Because of the equal footing of quarks and leptons in grand unified theories, this fact implies no more than six flavours. It should be strongly stressed here that, despite recent differing claims ¹⁵⁾, it is virtually impossible ¹⁶⁾, in grand unified theories, to bypass this limit by invoking a large number of electronic neutrinos ($n_{\nu_e}/n_\gamma \sim 1$). As pointed out in Ref. 16), in the framework of grand unified theories, an accidental and unnatural ratio $n_{\nu_e}/n_\gamma \sim 1$, will make the natural explanation of the baryon to photon ratio look chimeric. Furthermore ¹⁶⁾, the exciting possibility of understanding the highly homogeneous and isotropic structure of the universe, as well as the deviations from this strict homogeneity and isotropy (with interesting consequences on galaxy formation) will be totally lost.
- 2) Grand unified theories provide natural quark lepton mass relations ¹⁷⁾, which are sensitive to the number of flavours ¹⁷⁾. It is amazing that agreement with the observed quark-lepton mass spectrum demands no more than

six flavours ¹⁷⁾. Actually, in order to get all the correct quark-lepton mass relation, a bit more complicated Higgs system (than the simplest possible one) is needed ¹⁸⁾. As it has turned out from detailed calculations ⁷⁾, this system was also needed for getting the observable value of the $n_{\bar{p}}/n_{\gamma}$.

Putting all these pieces of information together, we come to the conclusion that there are only six flavours and that their existence is necessary for our existence (or the existence of anything interesting at all). Here lies the most important point. It is a fact that the first generation (u,d,e, ν_e) is certainly and undoubtedly enough for almost all cosmic and biological evolution. It seems though that the existence of the other two generations is unavoidably necessary to support the survival of suitable amounts of the first generation, which are enough to create an interesting universe. I hope that this is a straight answer to Glashow's "flavour" anxieties ¹⁹⁾.

If we accept this line of thinking, it seems that unification of all interactions, expansion of the universe and the existence of six quarks are a must. Furthermore, using the fundamental dogma that nature always uses the most economical way to do things, we see that theories with "grand plateau" ¹¹⁾ (or "desert"), i.e., with nothing happening between 300 GeV and 10^{15} GeV, become highly favourable. They are the simplest theories containing all the basic ingredients of the creation and evolution of the universe as we now see it.

Needless to say, we do not have any satisfactory "flavour" theory yet, or any unified theory of everything. It has not escaped my notice that further unification with the "flavour" group and/or gravity may explain (or demand) the existence of six flavours. If this conjecture turns out to be the case, all my previous remarks may be used a posteriori to explain the fact that under the known form of the laws of physics the existence of an "undull" universe was unavoidable. Once more, to a greater extent than was imagined, things simply must be as they are.

REFERENCES

- 1) See, for example :
P.J.E. Peebles - "Physical Cosmology", Princeton University Press (1971) ;
S. Weinberg - "Gravitation and Cosmology", J. Wiley, N.Y. (1972), Ch. 15.
- 2) A.A. Penzias and R.W. Wilson - *Astrophys.J.* 142, 419 (1965).
For the most recent measurements of the "microwave background" spectrum
see :
D.P. Woody and P.L. Richards - *Phys.Rev.Letters* 42, 925 (1979).
- 3) R.W. Wagoner, W.A. Fowler and F. Hoyle - *Astrophys.J.* 148, 3 (1967).
- 4) G. Steigman - *Ann.Rev.Astron.Astrophys.* 14, 339 (1976).
- 5) For a review of grand unified theories, see :
D.V. Nanopoulos - "Protons are not Forever", Harvard Preprint
HUTP-78/A062 (1978), and "The World According to GUTS", CERN
Preprint in preparation (1979) and references therein.
- 6) M. Yoshimura - *Phys.Rev.Letters* 41, 281 (1978) ; 42, 746(E) (1979) ;
S. Dimopoulos and L. Susskind - *Phys.Rev.* D18, 4500 (1978) ;
B. Toussaint et al. - *Phys.Rev.* D19, 1036 (1979) ;
J. Ellis, M.K. Gaillard and D.V. Nanopoulos - *Phys.Letters* 80B, 360 (1979) ;
S. Weinberg - *Phys.Rev.Letters* 42, 850 (1979).
- 7) D.V. Nanopoulos and S. Weinberg - Harvard Preprint HUTP-79/A023 (1979).
- 8) V.F. Shvartsman - *JETP Letters* 9, 184 (1969) ;
G. Steigman et al. - *Phys.Letters* B66, 202 (1977) ;
J. Yang et al. - *Astrophys.J.* 227, 697 (1979).
- 9) M. Kobayashi and K. Maskawa - *Progress Theor.Phys.* 49, 652 (1973).
- 10) T.D. Lee - *Phys.Rev.* D8, 1226 (1973) ;
S. Weinberg - *Phys.Rev.Letters* 37, 657 (1976).
- 11) H. Georgi and D.V. Nanopoulos - *Nuclear Phys.* B155, 52 (1979).
- 12) S. Weinberg - *Phys.Letters* 82B, 387 (1979) ;
J. Ellis, M.K. Gaillard, D.V. Nanopoulos and C. Sachrajda - *Phys.Letters*
83B, 339 (1979).
- 13) J. Ellis, M.K. Gaillard and D.V. Nanopoulos - Ref. 6), and CERN Preprint
TH 2749 (1979).
- 14) S. Weinberg - Ref. 6) ; see also Ref. 7).
- 15) A.D. Linde - *Phys.Letters* 83B, 11 (1979) ;
S. Dimopoulos and G. Feinberg - Columbia University Preprint UC-TP-159
(1979).

- 16) D.V. Nanopoulos, D. Sutherland and A. Yildiz - Harvard Preprint HUTP-79/A038 (1979) ;
D. Schramm and G. Steigman - University of Chicago Preprint (September 1979).
- 17) A.J. Buras, J. Ellis, M.K. Gaillard and D.V. Nanopoulos - Nuclear Phys. B135, 66 (1978) ;
D.V. Nanopoulos and D.A. Ross - Nuclear Phys. B157, 273 (1979).
- 18) H. Georgi and C. Jarlskog - Harvard Preprint HUTP-79/A026 (1979) ;
H. Georgi and D.V. Nanopoulos - Harvard Preprint HUTP-79/A039 (1979).
- 19) S.L. Glashow - Harvard Preprints HUTP-79/A029 (1979) and HUTP-79/A059 (1979), and numerous private violent discussions.