CERN-TH.4057/84

THE COSMOLOGY OF DECAYING GRAVITINOS

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ABSTRACT

We consider the cosmological constraints on unstable particles with masses $O(m_W)$. Constraints from the energy density during primordial nucleosynthesis, from subsequent entropy generation, and from perturbations of the microwave background are not as restrictive as bounds from the dissociation of light elements. Most restrictive is the need to avoid over-production of D and ^3He through the photo-dissociation of ^4He . When applied to gravitinos, this bound imposes an upper limit of $O(10^8)$ GeV on the reheating temperature after inflation, which could create problems for baryosynthesis in supersymmetric theories. These problems can be avoided if the photino is heavier than the gravitino.

1. - INTRODUCTION

Standard Big Bang cosmology imposes severe constraints on the masses and lifetimes of unstable particles¹⁾. Of particular relevance to supersymmetric theories are bounds on particles weighing $O(10 \text{ to } 10^3) \text{ GeV}$ which decay after primordial nucleosynthesis. This is because the gravitino generally has only gravitational couplings with ordinary matter, which are suppressed by $O(1/M)$: $M \equiv (8\pi)^{-\frac{1}{2}} M_P \approx 2.43 \times 10^{18} \text{ GeV}$. Therefore the gravitino will have a very long lifetime $\tau \sim O(M^2/M_W^3)$ if its mass is $O(M_W)$ and there is a lighter supersymmetric particle into which it can decay. Conversely, if the gravitino is lighter than the other supersymmetric particles, their decays into it will be comparably slow. Supersymmetric theories therefore motivate a study²⁾⁻⁵⁾ of cosmological constraints on particles with masses $O(M_W)$ which decay after nucleosynthesis, though the results should be of more general interest.

Let us first review the types of constraint that can be considered. The first²⁾ is on the mass density of such particles during primordial nucleosynthesis itself. If it were too large, the resulting increase in the rate of expansion of the Universe during that epoch would invalidate the successful standard calculations^{6),7)} of light element abundances. The success of these calculations also depends on the assumed baryon-to-entropy ratio, which is not very different from the range allowed by present-day observations. The resulting upper limit²⁾ on entropy generation between nucleosynthesis and the present day provides a second constraint on such unstable particles. The third class³⁾ of constraint results from consideration of the individual cosmological fates of the stable decay products, namely γ , ν , $e^\pm$ and $p, \bar{p}$. There are no restrictive constraints on ν , e or p decay products, while $e^\pm$ pair-annihilate to give γ . Therefore the important constraints are those obtained by considering γ and $\bar{p}$. These are generally tighter than the previous constraints from mass density and entropy generation. Several such constraints have been proposed previously in the literature, notably from bounds on the photodissociation of deuterium (D)³⁾, and from the $\bar{p}$ -dissociation of helium (^4He)⁵⁾, based on the good agreement between the calculated and observed abundances of D and of ^4He respectively. Also proposed³⁾ have been constraints derived from upper limits on non-blackbody perturbations on the microwave background radiation.

In this paper we review and revise constraints based on the above considerations, and develop a new constraint which is surer and more stringent than the previous ones. It is based on the photodissociation of ^4He , which produces D and

^3He , either directly or through intermediate ^3H . The mass abundance of ^4He is very large and well known to be $23 \pm 2\%$, while the combined mass abundance of D and ^3He can only be very small ($\sim 10^{-4}$)⁷⁾. Therefore only a very small fraction of ^4He could have been photo-disintegrated without overproducing D and ^3He . In the case of gravitinos, this bound translates into an upper bound on the primordial gravitino abundance:

$$n_{3/2} / n_\gamma < 6.1 \times 10^{-14} (m_{3/2} / 100 \text{ GeV})^{-1} \quad (1)$$

Combined with calculations³⁾ of gravitino regeneration after inflation, this corresponds to a bound

$$T_R < 2.5 \times 10^8 \text{ GeV} (m_{3/2} / 100 \text{ GeV})^{-1} \quad (2)$$

on the reheating temperature T_R after inflation. Such a low value of T_R is difficult to reconcile with baryosynthesis in supersymmetric theories⁸⁾. However, the dilemma can be avoided⁹⁾ if the gravitino is the lightest supersymmetric particles, and hence stable. In this case, there is a bound analogous to (1) on the next-to-lightest sparticle, probably the photino $\tilde{\gamma}$. However, this bound is easy to satisfy, since the stronger interactions of the $\tilde{\gamma}$ enable¹⁰⁾ it to annihilate before nucleosynthesis and freeze out at an acceptably low density.

2. - MASS DENSITY AND ENTROPY GENERATION

Most of our constraints are obtained from upper bounds on deviations from the canonical big bang model of nucleosynthesis^{6),7)}. This assumes that the Universe was radiation-dominated by photons and three types of light ($m_\nu \ll 1 \text{ MeV}$) two-component neutrinos during the epoch of primordial nucleosynthesis ($t_{\text{ns}} \sim 10^2 \text{ sec}$), and predicts yields of the light elements D, ^3He , ^4He and ^7Li in good agreement with observation. The presence during primordial nucleosynthesis of an additional massive particle, such as a heavy neutrino or a gravitino, increases the synthesized abundances¹¹⁾, though not in the same way as an additional species of light neutrino, because the temperature dependence of its energy density is different ($\propto m_\nu T^3$ instead of T^4). Kolb and Scherrer¹¹⁾ have studied these modified effects in detail, by including the energy density ($\rho_\nu \propto m_\nu^{-1.85}$ for $m_\nu \gg 1 \text{ MeV}$) of a massive neutrino in the numerical code for primordial nucleosynthesis. They find that for $m_\nu > 20 \text{ MeV}$, ρ_ν is small enough to keep the

primordial mass abundances of ${}^4\text{He}$ and $\text{D}+{}^3\text{He}$ below the observationally inferred upper bounds⁷⁾: $Y_p({}^4\text{He}) < 0.25$, $X_p(\text{D}+{}^3\text{He}) < 1.5 \times 10^{-4}$. Therefore we require the heavy particle energy density to be less than that of a 20 MeV neutrino¹¹⁾, namely:

$$\rho_X(T_\gamma) = m_X n_X(T_\gamma) < 3.8 \times 10^{-2} \text{ MeV}^4 (T_\gamma/\text{MeV})^3, \quad (3)$$

for $T_\gamma < m_e$.

This result can be expressed equally well as an upper limit on the ratio between the number densities of heavy particles and of photons:

$$n_X / n_\gamma < 1.6 \times 10^{-6} m_{100}^{-1}, \quad (4)$$

where $m_{100} \equiv m_X/100 \text{ GeV}$. Equivalently, one can express the constraint (3) as the condition that the heavy particle does not matter-dominate the Universe at a temperature T_m higher than that at which a 20 MeV neutrino would matter-dominate in the presence of three other light ($m_\nu \ll 1 \text{ MeV}$) neutrinos. One derives T_m from the relation

$$\rho_X(T_m) \equiv N_F (\pi^2/15) T_m^4, \quad (5)$$

where $N_F \approx 1.681$ if the photon and three light neutrinos are the sole relativistic degrees of freedom. The constraint (3) corresponds to

$$T_m < 3.4 \times 10^{-2} \text{ MeV}. \quad (6)$$

This differs slightly from the value quoted in Ref. 3), because there a 25 MeV neutrino was deemed acceptable in order to have had a negligible effect on elemental abundances¹¹⁾, while only two light neutrinos were assumed to be present. However, a small effect on the abundances can indeed be observationally tolerated, and it has been recently argued¹³⁾ that ν_τ must also be light. The results (3)-(6) are exhibited in Table 1, together with the corresponding maximum reheating temperature after inflation which is allowed if the heavy particles are

assumed to be gravitinos, viz.

$$T_R < 9.3 \times 10^{15} m_{100}^{-1} \text{ GeV}. \quad (7)$$

This reheating temperature T_R has been calculated from the result (4) using the calculation of Ref. 3) for the gravitino number density regenerated by particle collisions after inflation:

$$n_{3/2}(T_\gamma) \simeq 8.63 \times 10^{-13} T_\gamma^3 T_{R9} (1 - 0.018 \ln T_{R9}), \quad (8)$$

where $T_{R9} \equiv T_R/10^9 \text{ GeV}$.

A more restrictive bound^{2),3)} arises from the consideration that the decay of a massive particle after nucleosynthesis would change the baryon-to-photon number ratio $\eta \equiv n_B/n_\gamma$, destroying the present good agreement between the predicted and observed abundances of ^4He . The increase in η is restricted because the observational upper bound^{7),12)} $Y_p(^4\text{He}) < 0.25$ imposes an upper bound on η during nucleosynthesis (called η_{ns}), while observations of luminous baryonic matter ($\Omega_B > 0.01$) set a lower limit on η today (called η_0). Any generation of entropy subsequent to nucleosynthesis should not have changed η by more than a factor $\eta_{ns}/\eta_0 \simeq 2$ to 10, as argued previously^{11),13)} in the case of massive neutrinos. We make the simplifying assumption that all the unstable massive particles decay simultaneously when the Universe is of age equal to the particle lifetime τ , and has a temperature T_d given by¹³⁾:

$$\tau = \left(\frac{5}{2\pi^3 N_F} \right)^{1/2} \frac{M_P}{T_m^2} \left[\left(\frac{T_m}{T_d} - 2 \right) \left(\frac{T_m}{T_d} + 1 \right)^{1/2} + 2 \right]. \quad (9)$$

This formula takes into account the fact that the heavy particle mass density is not negligible by comparison with the energy density of relativistic particles. If we denote by f the fraction of the heavy particle density converted into photons, then the maximum allowable temperature of matter-domination is

$$T_m \simeq 7.2 \times 10^{-1} \text{ MeV} (\tau/\text{sec})^{-1/3} f^{-1/2}, \quad (10a)$$

if $T_m > 10^{-2} \text{ MeV}$, and

$$T_m \simeq 6.2 \text{ MeV} (\tau/\text{sec})^{-1/2} f^{-3/4}, \quad (10b)$$

if $T_m \lesssim 10^{-2} \text{ MeV}^*$). These values are obtained by extending the calculations of Ref. 13) for the case when three light neutrinos are present and the two regimes correspond to whether or not the massive particle contributes significantly to the energy density before it decays. The corresponding upper bounds on the massive particle density obtained using Eq. (5) are

$$\rho_X < 7.9 \times 10^{-1} \text{ MeV}^4 (\tau/\text{sec})^{-1/3} f^{-1/2} (T_\gamma/\text{MeV})^3, \quad (11a)$$

if $t_{\text{ns}} \lesssim \tau < 3.8 \times 10^5 f^{-3/2} \text{ sec}$, and

$$\rho_X < 6.9 \text{ MeV}^4 (\tau/\text{sec})^{-1/2} f^{-3/4} (T_\gamma/\text{MeV})^3, \quad (11b)$$

if $\tau > 3.8 \times 10^5 f^{-3/2} \text{ sec}$, while the corresponding upper limits on n_X/n_γ are displayed in Table 1. In the case of gravitinos, two likely decay modes are $3/2 \rightarrow \gamma + \tilde{\gamma}$ and $3/2 \rightarrow g + \tilde{g}$, with partial lifetimes³⁾

$$\tau(3/2 \rightarrow \gamma + \tilde{\gamma}) \simeq 4 \times 10^8 (\text{sec}) m_{100}^{-3}, \quad (12)$$

for $m_{\tilde{\gamma}} \ll m_{3/2}$;

$$\tau(3/2 \rightarrow \gamma + \tilde{\gamma}, g + \tilde{g}) \simeq 4.4 \times 10^7 (\text{sec}) m_{100}^{-3}, \quad (13)$$

for $m_{\tilde{\gamma}}, m_{\tilde{g}} \ll m_{3/2}$.

In the first case, $f \simeq \frac{1}{2}$, whereas $f \simeq 0.8$ in the second case. Thus the short-lived case (10a, 11a) is only applicable to gravitinos which are somewhat heavier than 100 GeV. Using the result (8) for gravitino production, we find

$$T_R < \begin{cases} 3.5 \times 10^{14} \text{ GeV} & , \text{ for } 7.4 \gtrsim m_{100} \gtrsim 7.2, \\ 1.3 \times 10^{14} m_{100}^{1/2} \text{ GeV} & , \text{ for } 7.2 > m_{100}, \end{cases} \quad (14)$$

*) Including a realistic exponential distribution of decay times would yield values of T_m only about 10% higher¹⁴⁾.

if only the $\gamma + \tilde{\gamma}$ decay mode is available, and

$$T_R < \begin{cases} 5.8 \times 10^{14} \text{ GeV}, & \text{for } 35 \gtrsim m_{100} \gtrsim 4.4, \\ 2.8 \times 10^{14} m_{100}^{1/2} \text{ GeV}, & \text{for } 4.4 > m_{100}^{(15)}, \end{cases}$$

if the $g + \tilde{g}$ decay mode is also available. While more restrictive than the bound (7) coming from the mass density during primordial nucleosynthesis, the results (14) and (15) are less restrictive than the corresponding limit quoted in Ref. 3) for two reasons. One is the more conservative allowance made for entropy increase, and the other is the inclusion of the massive particle energy density in the time-temperature relationship (9).

3. - PHOTOFISSION OF LIGHT ELEMENTS

The most restrictive bounds on heavy unstable particles come from considering the effects of their decay products on the light elements synthesized prior to their decay. An unstable massive particle may create high-energy photons either directly (e.g., $3/2 \rightarrow \gamma + \tilde{\gamma}$), or indirectly by decaying into light charged particles (e.g., $\nu_H \rightarrow e^+ e^- \nu_e$) which can Compton-scatter the thermal background photons to high energies¹³⁾. Such photons in turn initiate electromagnetic cascades in the thermal background plasma, creating many lower energy ($\sim$ few MeV) photons capable of photodissociating the primordially synthesized D, ^3He , ^4He and ^7Li ¹⁵⁾. In particular, by constraining the depletion of the most weakly bound nucleus, D, to be less than a factor 0(3), a severe restriction on the abundance of unstable gravitinos decaying into $\gamma + \tilde{\gamma}$ ($n_{3/2}/n_\gamma \lesssim 4.8 \times 10^{-3} \eta m_{100}^{-1}$) was obtained in Ref. 3). However, unstable massive particles may also produce¹⁶⁾ significant numbers of $p\bar{p}$ pairs (perhaps $\approx \frac{1}{2}$ pair per $3/2 \rightarrow g + \tilde{g}$ decay, for example). Some $\bar{p}$ could then annihilate on ^4He nuclei to produce additional D and ^3He ¹⁷⁾. Assuming reasonable values for the relevant cross-sections and arguing that D should not be produced in excess of the observational limit, Khlopov and Linde⁵⁾ have obtained the bound $n_{3/2}/n_\gamma < 4.6 \times 10^{-3} \eta$. While this bound is inapplicable to particles without hadronic decay modes (e.g., if $3/2 \rightarrow \gamma + \tilde{\gamma}$ alone), and it would be an unlikely accident if the photodissociation and $\bar{p}$ creation of D occurred at precisely equal rates, we are disturbed that the rates of destruction and creation of D could be approximately equal, thus invalidating both the bounds of Ref. 3) and of Ref. 5). Hence we re-examine this problem and derive new and

more severe bounds on heavy particle abundances from two new arguments, namely that the photodissociation of ${}^4\text{He}$ should neither (a) deplete ${}^4\text{He}$ excessively, nor (b) create excessive D and ${}^3\text{He}$ in the process.

(a) To estimate the maximum factor by which ${}^4\text{He}$ could have been depleted, we must put an upper bound on the mass fraction synthesized primordially, and compare it with the observational lower bound¹²⁾ $Y_p({}^4\text{He}) > 0.21$. In so doing, we shall not demand agreement with the observed abundances of D, ${}^3\text{He}$ and ${}^4\text{He}$, since it is conceivable that all the D and ${}^3\text{He}$ were created by the photofission of ${}^4\text{He}$. To bound the primordial $Y({}^4\text{He})$ from above, we need an upper bound on η . A conservative lower bound on the age of the Universe, $t_0 \gtrsim 10^{10}$ yr, implies that $\Omega h^2 \lesssim 1$ in the standard Friedmann-Robertson-Walker cosmology with zero cosmological constant¹⁸⁾, where $\Omega = \rho_0/\rho_c$ and the present Hubble parameter $H_0 = h \cdot 10^2 \text{ km sec}^{-1} \text{ Mpc}^{-1}$. Then $\eta \approx 2.8 \times 10^{-8} \Omega_B h^2 (T_0/2.7^\circ\text{K})^{-3} < 3.2 \times 10^{-8}$ for a present blackbody temperature $T_0 > 2.6^\circ\text{K}$, since the baryon density $\Omega_B < \Omega$. Using $\eta < 3.2 \times 10^{-8}$, we find from Ref. 7) that $Y_{ns}({}^4\text{He}) < 0.29$, so that $Y({}^4\text{He})$ could not have been decreased by a factor greater than $0.29/0.21 \sim 1.4$. Following Ref. 15), we calculate the depletion factor for $t_{ns} < \tau < t_{\text{recombination}} (\approx 10^{13} \text{ sec})$ to be

$$\frac{Y_{ns}}{Y_p} \simeq \exp \left[\frac{1}{n_e} \int N(E_0) dE_0 \int_{Q({}^4\text{He})}^{E_0} \frac{dn}{dE_\gamma} \cdot \frac{\sigma({}^4\text{He})}{\sigma_T} \cdot dE_\gamma \right], \quad (16)$$

where dn/dE_γ is the differential energy spectrum of photons in the electromagnetic cascades triggered by a photon of energy E_0 , $N(E_0)$ is the spectrum of photons generated by massive particle decay, $\sigma({}^4\text{He})$ is the cross-section for ${}^4\text{He}$ photofission¹⁹⁾ which has its threshold at $Q({}^4\text{He}) \approx 20 \text{ MeV}$, σ_T is the total cross-section for photon energy degradation by Compton scattering and by pair-production on the thermal background ions and electrons²⁰⁾, and $n_e \approx (7/8)n_B$ is the thermal electron density. We do not include pair-production on the thermal background photons, since the threshold $E_c \sim m_e^2/T_\gamma$ for this process is far above the energy of $O(30) \text{ MeV}$ where $\sigma({}^4\text{He})$ peaks, for T_γ in the interesting range below 10^{-2} MeV (corresponding to $\tau \gtrsim 10^4 \text{ sec}$). However, this process does determine the upper cut-off on E_γ and hence fixes the overall normalization of dn/dE_γ , as discussed below. We take dn/dE_γ from Aharonian et al.²¹⁾, who have performed Monte Carlo simulations of electromagnetic cascades generated by high-energy

photons in non-relativistic radiation-dominated plasmas. In the limit of large optical depth, the differential spectrum of secondary photons obeys a power law with slope -1.5 from low energies ($\sim 0.1 m_e$) up to the photon-photon pair production threshold $E_c \sim m_e^2/T_\gamma$. After appropriate normalization, we have

$$\frac{dn}{dE_\gamma} \simeq 10^2 \left(\frac{T_\gamma}{\text{MeV}} \right)^{1/2} \left(\frac{E_\gamma}{\text{MeV}} \right)^{-3/2} \left(\frac{E_0}{100 \text{ MeV}} \right) \text{ MeV}^{-1}, \quad (17)$$

and hence obtain

$$\int_{Q(^4\text{He})}^{E_c} \frac{dn}{dE_\gamma} \cdot \frac{\sigma(^4\text{He})}{\sigma_T} \cdot dE_\gamma \equiv \beta_{^4\text{He}}(T_\gamma) E_0/E_*, \quad (18)$$

where $E_* = 100 \text{ MeV}$ and $\beta_{^4\text{He}}$ is a slowly-varying function listed in Table 2. Then Eq. (16) becomes

$$Y_{ns}/Y_p \simeq \exp \left[m_x n_x f \langle \beta_{^4\text{He}} \rangle / n_e E_* \right], \quad (19)$$

where we have used $\int E_0 N(E_0) dE_0 \simeq f m_x n_x$. We therefore require that for $\tau \gtrsim 10^4$ sec:

$$\begin{aligned} n_x/n_\gamma &\simeq \ln(Y_{ns}/Y_p) (7\eta E_* / 8 f m_x \langle \beta_{^4\text{He}} \rangle) \\ &< 4.6 \times 10^{-10} f^{-1} m_{100}^{-1}, \end{aligned} \quad (20)$$

where we have taken the upper bounds on Y_{ns}/Y_p and η , and used $\langle \beta \rangle \approx 0.02$. Correspondingly, we obtain

$$\rho_x < 1.1 \times 10^{-5} f^{-1} (T_\gamma/\text{MeV})^3 \text{ MeV}^4, \quad (21)$$

and

$$T_m < 1.0 \times 10^{-5} f^{-1} \text{ MeV}. \quad (22)$$

In the case of gravitinos decaying into $\gamma + \tilde{\gamma}$ alone, for which $f \approx 0.5$, we have for $m_{100} \lesssim 34$ corresponding to $\tau \gtrsim 10^4$ sec:

$$T_R < 4.6 \times 10^{12} m_{100}^{-1} \text{ GeV}. \quad (23)$$

These limits improve by a factor 0(10 to 1000) on the constraints from entropy generation after nucleosynthesis.

(b) However, a much more stringent limit comes from bounding the photoproduction of D and ^3He . Since ^4He is $0(10^4)$ times more abundant than D or ^3He , even a small depletion of its abundance by photofission: $\gamma + ^4\text{He} \rightarrow n + ^3\text{He}$, or $\rightarrow p + ^3\text{H}$ ($^3\text{H} \rightarrow ^3\text{He} + e^- \bar{\nu}_e$), or $\rightarrow p + n + D$ would have created a huge amount of D and ^3He . As we check explicitly below, the ^4He abundance changes negligibly in the process, so we must impose the observationally inferred^{7),12)} limit $Y_p(^4\text{He}) < 0.25$. This implies⁷⁾ that $\eta < 6 \times 10^{-10}$ so that a minimum mass fraction $X_{ns}(D + ^3\text{He}) > 6.7 \times 10^{-5}$ would have been synthesized primordially. Observational data suggest⁷⁾ a very conservative upper limit $X_p(D + ^3\text{He}) < 2.1 \times 10^{-4}$, if D burning in stars creates ^3He , a fraction $g > 1/4$ of which survives subsequent stellar processing. Therefore $X(D + ^3\text{He})$ could not have been increased by more than a factor of ~ 3 . The balance equation for the D + ^3He abundance is^{*})

$$\begin{aligned} \frac{d}{dt} X(D + ^3\text{He}) \simeq & \int \frac{N(E_0) dE_0}{\eta_e} \frac{d\eta_x}{dt} \\ & \cdot \left[X(D) \int_{Q(D)}^{E_0} \frac{dn}{dE_\gamma} \cdot \frac{\sigma(D)}{\sigma_T} \cdot dE_\gamma + X(^3\text{He}) \int_{Q(^3\text{He})}^{E_0} \frac{dn}{dE_\gamma} \cdot \frac{\sigma(^3\text{He})}{\sigma_T} \cdot dE_\gamma \right. \\ & \left. - r Y(^4\text{He}) \int_{Q(^4\text{He})}^{E_0} \frac{dn}{dE_\gamma} \cdot \frac{\sigma(^4\text{He})}{\sigma_T} \cdot dE_\gamma \right], \end{aligned} \quad (24)$$

where $r = [(3/4)\sigma\{\gamma^4\text{He} \rightarrow n^3\text{He}, p^3\text{H}\} + (1/2)\sigma\{\gamma^4\text{He} \rightarrow pnD\}]/\sigma\{\gamma^4\text{He} \rightarrow \text{anything}\} \approx 0.5$. Using the cross-sections compiled in Refs. 22) and 23), we calculate from expressions isomorphic to Eq. (18) the values of $\beta_D(T_\gamma)$ and $\beta_{^3\text{He}}(T_\gamma)$ listed in Table 2, using $Q(D) = 2.225 \text{ MeV}$ and $Q(^3\text{He}) \approx 6.5 \text{ MeV}$ for the respective photofission

^{*}) Since the thermalization time-scale is $\ll$ the expansion time-scale, the red-shifting of the photons need not be taken into account.

thresholds. Since $\langle \beta_D \rangle \approx \langle \beta_{4\text{He}} \rangle \gtrsim \langle \beta_{3\text{He}} \rangle \approx 10^{-2*}$, it is obvious that the rate of destruction of D and ^3He by photofission is actually negligible compared to the rate of their creation by photofission of ^4He [recall $Y(^4\text{He}) \sim 10^4 X(\text{D} + ^3\text{He})$]. Therefore, to a very good approximation

$$\frac{d}{dt} X(\text{D} + ^3\text{He}) \approx -Y(^4\text{He}) \frac{\tau_f m_x}{n_e} \cdot \frac{d\eta_x}{dt} \cdot \frac{\langle \beta_{4\text{He}} \rangle}{E_*}, \quad (25)$$

and so

$$X_p(\text{D} + ^3\text{He}) - X_{ns}(\text{D} + ^3\text{He}) \approx \frac{Y_{ns}(^4\text{He}) \tau_f m_x \eta_x \langle \beta_{4\text{He}} \rangle}{(7\eta/8) n_\gamma E_*}. \quad (26)$$

Using $\langle \beta_{4\text{He}} \rangle \approx 0.02$ for $\tau > 10^4$ sec, we find

$$n_x/n_\gamma < 3.1 \times 10^{-14} m_{100}^{-1} f^{-1}, \quad (27)$$

corresponding to

$$\rho_x < 7.5 \times 10^{-10} f^{-1} (T_\gamma/\text{MeV})^3 \text{MeV}^4, \quad (28)$$

or

$$T_m < 6.8 \times 10^{-10} f^{-1} \text{MeV}. \quad (29)$$

*) Lindley¹⁵⁾ obtained $\langle \beta_D \rangle \sim 0.2$, an apparent overestimate of the D breakup by a factor ~ 10 . We believe this was due to his neglect of pair-production by $\gamma\gamma$ collisions which resulted in incorrect secondary photon spectrum, compounded with an overestimate of the photofission cross-section close to threshold.

In the case of a gravitino with $f \approx 0.5$ and $m_{100} \lesssim 34$, we get^{*)}

$$T_R < 2.5 \times 10^8 m_{100}^{-1} \text{ GeV}. \quad (30)$$

The bounds (27) to (30) are our key results, which are considerably more restrictive than those given previously, though based on very conservative^{**)} assumptions. There are other less restrictive bounds, which we now mention briefly.

4. - OTHER CONSTRAINTS

If the heavy unstable particle can decay into hadrons, as mentioned before, it will probably give¹⁶⁾ $r_{\bar{p}} \approx \frac{1}{2}$ $p\bar{p}$ pair per decay, and these could yield¹⁷⁾ D and ${}^3\text{He}$ via $\bar{p}$ annihilation on ${}^4\text{He}$. The cross-section for ${}^3\text{He}$ production has recently been measured²⁴⁾ at LEAR, so that the fraction of antimatter, $R = n_{\bar{p}}/n_B$ in the early Universe is restricted by $R < (4/3) X({}^3\text{He})/Y({}^4\text{He})f_{3\text{He}}^{\text{eff}}$, where $f_{3\text{He}}^{\text{eff}} = \sigma(\bar{p}{}^4\text{He} \rightarrow {}^3\text{He} \text{ or } {}^3\text{H} + \text{anything})/\sigma_{\text{tot}} = 0.237 \pm 0.014$. Balestra et al.²⁴⁾ assume the abundances $X({}^3\text{He}) = (4.2 \pm 2.8) \times 10^{-5}$, $Y({}^4\text{He}) = 0.23 \pm 0.02$, to obtain $R < (1.03 \pm 0.07) \times 10^{-3}$. However, to extract a conservative upper limit, we adopt the same worst-case scenario as in the previous section, viz. $\Delta X({}^3\text{He}) < 1.5 \times 10^{-4+}$, $Y({}^4\text{He}) < 0.25$, $\eta < 6 \times 10^{-10}$, to obtain $R \lesssim 3.4 \times 10^{-3}$. Then

$$n_x / n_y = R \eta / r_{\bar{p}} < 2 \times 10^{-12} r_{\bar{p}}^{-1}. \quad (31)$$

For the gravitino decay mode into gluinos ($r_{\bar{p}} \approx 0.5$) we finally obtain

*) If we adopt the even more conservative upper bound¹²⁾ $X(D + {}^3\text{He}) < 5 \times 10^{-4}$, which assumes that ${}^3\text{He}$ is completely destroyed in stars, then the limit on T_R changes to $T_R < 7.7 \times 10^8 m_{100}^{-1} \text{ GeV}$.

***) Somewhere to the right of Mrs. T.

+) The minimum synthesized abundance of ${}^3\text{He}$ is⁷⁾ $X_{\text{ns}}({}^3\text{He}) > 2.5 \times 10^{-5}$ [for $\eta < 6 \times 10^{-10}$ corresponding to $Y_p({}^4\text{He}) < 0.25$], while the maximum primordial abundance suggested by observations is⁷⁾ $X_p({}^3\text{He}) < 1.8 \times 10^{-4}$, assuming that a fraction $g > 1/4$ of ${}^3\text{He}$ survives stellar processing.

$$T_R < 1.8 \times 10^{10} \text{ GeV}, \quad (32)$$

which is less restrictive by a factor ≈ 70 than the constraint from photo-production (Eq. 30). It should be noted that the constraints in Eqs. (30) and (32) have been derived under the same conservative assumptions about primordial elemental abundances.

Similar constraints can be obtained from the observed lack of non-blackbody perturbations in the microwave background spectrum. Massive particle decay would create a non-thermal population of photons which would thermalize by Compton scattering, thus distorting the background thermal photon spectrum to a Bose-Einstein form, $n_\gamma \propto [\exp \{h\nu/kT+\mu\}-1]^{-1}$, with negative chemical potential, μ ²⁵⁾. Radiative processes such as double-Compton scattering or bremsstrahlung would reduce even large values of μ to zero very rapidly, if the decay occurred before $t \sim 10^4\text{--}10^5 \text{ sec}$ ^{13),25)}. For late decays, only small perturbations $\Delta\rho_\gamma/\rho_\gamma \approx f m_x n_x / \rho_\gamma \ll 1$ are permissible, and these would result in distortions that persist until the present day with $\mu \approx 1.4 \Delta\rho_\gamma/\rho_\gamma$ ²⁵⁾. Recent data on the microwave background are well fitted by a pure blackbody spectrum with $T_0 \approx 2.74 \pm 0.07^\circ\text{K}$ ^{26),28)} except that an excess flux corresponding to $T_0 = 2.96 \pm 0.08^\circ\text{K}$ has been reported near the Wien peak by Woody and Richards²⁷⁾. A global fit to these data then allows for a small chemical potential²⁶⁾, $\mu = (5 \pm 3) \times 10^{-3}$ [for $\Omega_B h^2 = 0.025$, as suggested by primordial nucleosynthesis⁷⁾]. Assuming that the Universe is essentially radiation-dominated before massive particle decay (as required by the previous constraints), we then obtain, for $\tau \gtrsim 10^5 \text{ sec}$,

$$\rho_x / T_\gamma^3 \simeq 0.76 f^{-1} (\tau/\text{sec})^{-1/2} (\Delta\rho_x / \rho_\gamma), \quad (33)$$

or,

$$\rho_x < 2.7 \times 10^{-3} f^{-1} (\tau/\text{sec})^{-1/2} (T_x/\text{MeV})^3, \quad (34)$$

corresponding to

$$n_x/n_\gamma < 1.1 \times 10^{-7} f^{-1} (\tau/\text{sec})^{-1/2} m_{100}^{-1} \quad (35)$$

Inserting the appropriate values of τ and f for the two decay modes [Eqs. (12) and (13)] of a gravitino, we obtain

$$T_R < 5.1 \times 10^{10} m_{100}^{1/2} \text{ GeV}, \text{ when } m_{100} \lesssim 16, \quad (36)$$

for $3/2 \rightarrow \gamma + \tilde{\gamma}$;

$$< 9.7 \times 10^{10} m_{100}^{1/2} \text{ GeV}, \text{ when } m_{100} \lesssim 8, \quad (37)$$

for $3/2 \rightarrow \gamma + \tilde{\gamma}, g + \tilde{g}$.

It has been suggested²⁸⁾ that the data of Woody and Richards²⁷⁾ suffers from a calibration error and indeed, a recent independent measurement at the Wien peak gives $T_0 = 2.73 \pm 0.04^\circ\text{K}$ ²⁹⁾, in agreement with the blackbody temperature at lower frequencies. A global fit to the new data would reduce the upper limit on μ by a factor ~ 5 -10 and improve the constraints above [Eqs. (34)-(37)] by the same factor. [Similar results have been independently obtained in Ref. 30).]

The constraints above are applicable if the massive particle decays before (re)combination of hydrogen, which occurs at a redshift $z_{\text{rec}} \sim 10^3$ ³¹⁾, corresponding to a time $t \approx 2 \times 10^{13} \text{ sec}$ ^{*}). If radiative decays occur subsequently, the decay photons would remain unthermalized and would be red-shifted by a factor $< 10^3$ to contribute to the diffuse extragalactic radiation background today. From a recent review³²⁾, we find that a conservative upper limit to the radiation spectrum for the wide range $E_\gamma \sim 1 \text{ keV}$ to $\sim 1 \text{ GeV}$ can be conveniently expressed as a power law, $N(E_\gamma) < 10^2 (E_\gamma/\text{keV})^{-2} \text{ photons/cm}^2 \cdot \text{sec} \cdot \text{st. keV}$, from which we construct the invariant ratio

$$F(\geq E_\gamma) \equiv \rho(\geq E_\gamma) / \rho_{\text{BB}}(T_0 = 2.7^\circ\text{K}) \quad (38)$$

$$< 1.7 \times 10^{-4} (E_\gamma/\text{keV})^{-1}$$

^{*}) Assuming that the epochs of recombination and matter-domination by baryons approximately coincide (i.e., for $\Omega_B h^2 \lesssim 0.025$).

Therefore, in order that the red-shifted energy density of the decay photons should not exceed that of the radiation background today, we require

$$\left[f \rho_x / \rho_\gamma \right]_{T=T_d} < F (\geq E_0 T_0 / T_d) , \quad (39)$$

where $T_d \approx 9.3 \times 10^{-8} \text{ MeV } (\tau/10^{14} \text{ sec})^{-2/3}$ is the blackbody photon temperature at decay, and E_0 is the initial energy of the decay photons.

Combining the above restrictions, we then find the very restrictive limit

$$\frac{n_x}{n_\gamma} < 1.7 \times 10^{-19} f^{-1} m_{100}^{-1} (E_0/100 \text{ GeV})^{-1} (\tau/10^{14} \text{ sec})^{-4/3} . \quad (40)$$

This limit is, however, not directly relevant to gravitinos, since they cannot have such a long lifetime without being almost degenerate in mass with the photino.

Finally, we note that if the photofission bound [Eq. (27)] is satisfied, the present density of relic photinos from gravitino decay will be much lower than the present baryon density, and no useful bound [cf. Ref. 4)] can be extracted from a consideration of the relic photino mass density.

5. - IMPLICATIONS FOR SUPERSYMMETRIC COSMOLOGY

The bound Eq. (30) is an embarrassment for conventional supersymmetric cosmology³³⁾, in which the cosmological baryon asymmetry is generated by the decays of particles with baryon-number violating interactions which must weigh 10^{11} GeV or more³⁴⁾. Since the baryon asymmetry can only be produced during or after reheating, this bound implies that a thermal Boltzmann distribution for the heavy particles responsible for baryosynthesis would yield far too few of them. Therefore, the only hope is some sort of non-thermal mechanism for their production. However, it is not easy to reconcile the lower limits on the masses of the Higgs and hence of the inflaton with the observational upper limits on $\delta\rho/\rho$ in such a scenario. While it may indeed be possible³⁵⁾, this sort of epicycle on the standard scenario for baryosynthesis does not enthuse us, so we propose another way of avoiding cosmological embarrassment.

Suppose the gravitino is actually lighter than the photino, rather than heavier as we have previously supposed. In this case, the gravitino would be

stable, and most of our previous constraints must now be applied to the unstable photinos. The most stringent constraint on the gravitino would therefore be that on its mass density today:

$$m_{3/2} n_{3/2} (T_0 = 2.7^\circ\text{K}) < 1.05 \times 10^{-2} \text{ MeV cm}^{-3}, \quad (41)$$

which corresponds, using Eq. (8), to a reheating temperature

$$T_R < 1.3 \times 10^{12} m_{100}^{-1} \text{ GeV}. \quad (42)$$

This is compatible with baryosynthesis by the decays of thermally-produced heavy Higgs bosons with masses $O(10^{11})$ GeV. What of the unstable photinos? The most stringent constraints on their density are those from photoproduction of D and ^3He , namely Eqs. (27) to (29). It is easy to satisfy these constraints, since the electroweak interactions of photinos enable them to annihilate efficiently¹⁰⁾, leaving behind an acceptably small density. An approximate expression for the relic photino density after annihilation is¹⁰⁾

$$\rho_{\tilde{\gamma}} \approx \frac{2.3 \times 10^{-9}}{\tilde{b}} \text{ MeV cm}^{-3} ; \quad \tilde{b} \approx 0.014 \left(\frac{m_{\tilde{\gamma}}^2 \times \text{GeV}^2}{\tilde{m}^4} \right) \quad (43)$$

where $\tilde{m}$ is an assumed common mass for the squarks and sleptons. We see from Eq. (43) that if we choose a representative photino mass of 10(20) GeV, the relic photino density will respect all the cosmological constraints if $\tilde{m} < 25(40)$ GeV. A gravitino lighter than the photino is therefore a viable cosmological scenario, as is a heavy gravitino of mass above $O(10^4)$ GeV which decays before nucleosynthesis²⁾. Either of these possibilities can be realized in supergravity models with non-minimal kinetic terms for the chiral and/or vector superfields^{9),36)}.

We have seen here how the constraints summarized in Table 1 are important for supersymmetry, but they would also be relevant in other theoretical contexts where long-lived but unstable particles appear.

ACKNOWLEDGEMENTS

We thank Amanda Cooper for help with the computations.

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$\rho_x / (T_x / \text{MeV})^3 \text{ [MeV}^4]$	n_x / n_γ	$T_m \text{ [MeV]}$	$T_R \text{ [GeV]}$	Constraint
$< 3.8 \times 10^{-2} *$	$< 1.6 \times 10^{-6} m_{100}^{-1} *$	$< 3.4 \times 10^{-2} *$	$< 9.3 \times 10^{15} m_{100}^{-1}$ for $m_{100} < 50$	Mass density during primordial nucleosynthesis
$< 7.9 \times 10^{-1} (\tau / \text{sec})^{-1/3} f^{-1/2}$ for $t_{ns} \lesssim \tau < 3.8 \times 10^5 f^{-3/2}$ $6.9 (\tau / \text{sec})^{-1/2} f^{-3/4}$ for $\tau > 3.8 \times 10^5 f^{-3/2}$	$< 3.3 \times 10^{-5} m_{100} (\tau / \text{sec})^{-1/3} f^{-1/2}$ for $t_{ns} \lesssim \tau < 3.8 \times 10^5 f^{-3/2}$ $< 2.8 \times 10^{-4} m_{100}^{-1} (\tau / \text{sec})^{-1/2} f^{-3/4}$ for $\tau > 3.8 \times 10^5 f^{-3/2}$	$< 7.2 \times 10^{-1} (\tau / \text{sec})^{-1/3} f^{-1/2}$ for $T_m > 10^{-2}$ $< 6.2 (\tau / \text{sec})^{-1/2} f^{-3/4}$ for $T_m < 10^{-2}$	(a) $< 3.5 \times 10^{14}$ for $74 > m_{100} > 7.2$ $< 1.3 \times 10^{14} m_{100}^{1/2}$ for $m_{100} \lesssim 7.2$ $< 5.8 \times 10^{14}$ for $35 > m_{100} > 4.4$ $< 2.8 \times 10^{14} m_{100}^{1/2}$ for $m_{100} \lesssim 4.4$ (b)	entropy generation after primordial nucleosynthesis
$< 1.1 \times 10^{-5} f^{-1} *$	$< 4.6 \times 10^{-10} f^{-1} m_{100}^{-1} *$	$< 1.0 \times 10^{-5} f^{-1} *$	$< 4.6 \times 10^{12} m_{100}^{-1}$ for $m_{100} \lesssim 34$	Photodissociation of ^4He
$< 7.5 \times 10^{-10} f^{-1} *$	$< 3.1 \times 10^{-14} f^{-1} m_{100}^{-1} *$	$< 6.8 \times 10^{-10} f^{-1} *$	$< 2.5 \times 10^8 m_{100}^{-1}$ for $m_{100} \lesssim 34$	Photoproduction of D and ^3He
$< 5.0 \times 10^{-8} \tau_p^{-1} m_{100} *$	$< 2 \times 10^{-12} \tau_p^{-1} *$	$< 4.5 \times 10^{-8} \tau_p^{-1} m_{100} *$	$< 1.8 \times 10^{10}$ for $m_{100} \lesssim 50$	Creation of ^3He by $p \bar{p}$ annihilation
$< 2.7 \times 10^{-3} f^{-1} (\tau / \text{sec})^{-1/2} \S$	$< 1.1 \times 10^{-7} f^{-1} (\tau / \text{sec})^{-1/2} m_{100}^{-1} \S$	$< 2.5 \times 10^{-3} f^{-1} (\tau / \text{sec})^{-1/2} \S$	(a) $< 5.1 \times 10^{10} m_{100}^{1/2}$ for $m_{100} \lesssim 16$ $< 9.7 \times 10^{10} m_{100}^{1/2}$ for $m_{100} \lesssim 8$ (b)	Spectral distortions in microwave blackbody background
$< 4.2 \times 10^{-15} f^{-1} *$ $\bullet (E_0 / \text{GeV})^{-1} (\tau / 10^{14} \text{sec})^{-4/3}$	$< 1.7 \times 10^{-19} f^{-1} m_{100}^{-1} *$ $\bullet (E_0 / \text{GeV})^{-1} (\tau / 10^{14} \text{sec})^{-4/3}$	$< 3.8 \times 10^{-15} f^{-1} *$ $\bullet (E_0 / \text{GeV})^{-1} (\tau / 10^{14} \text{sec})^{-4/3}$		Intensity of X-ray and γ -ray background
$*$) - for $\tau \gtrsim t_{ns} \sim 300 \text{ sec}$	$+$) - for $\tau \gtrsim 10^4 \text{ sec}$	$\S$) - for $t_{rec} \sim 10^{13} \text{ sec} \gtrsim \tau \gtrsim 10^5 \text{ sec}$	$\#$) - for $\tau \gtrsim t_{rec}$	
a) - for $3/2 \rightarrow \gamma + \tilde{\gamma}$	b) - for $3/2 \rightarrow \gamma + \tilde{\gamma}, g + \tilde{g}$			

Table 1

T_γ (MeV)	10^{-6}	10^{-5}	10^{-4}	10^{-3}	10^{-2}	10^{-1}
$\beta_4\text{He}$	2.3×10^{-3}	7.4×10^{-3}	2.3×10^{-2}	7.4×10^{-2}	8.9×10^{-2}	--
$\beta_3\text{He}$	8.6×10^{-4}	2.7×10^{-3}	8.6×10^{-3}	2.7×10^{-2}	7.2×10^{-2}	--
β_D	2.3×10^{-3}	7.2×10^{-3}	2.3×10^{-2}	7.0×10^{-2}	2.1×10^{-1}	5.9×10^{-2}

Table 2