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HADRONIC DECAYS OF COSMOLOGICAL GRAVITINOS

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Abstract

We discuss a variety of effects due to the thermalisation and possible annihilation of relativistic protons and antiprotons from the decay of cosmological gravitinos. For a rather narrow range of gravitino mass around 250 GeV, the photons produced by inverse 'Compton' scattering of nucleons off the thermal radiation are of the right energy to photodissociate helium 4, creating deuterium and helium 3. In a supersymmetric inflationary universe, this leads to a maximum reheating temperature of about 1.2×10^7 GeV for this particular gravitino mass.

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If a massive gravitino decays into a photon and a stable photino, the destructive effect of the energetic photon on the cosmologically synthesized light elements leads to a strong limit on the allowed density of gravitinos, and thence to an upper limit on the temperature to which the universe reheats at the completion of the inflationary phase transition [1,2]. The strongest limit comes from requiring that destruction of ^{4}He does not create excessive amounts of ^{3}He or D [2]. In addition, Khlopov and Linde [3] have shown that if the gravitino decays into gluinos, which then condense into hadronic particles, the possible annihilation of antiprotons with ^{4}He nuclei can similarly overproduce the lighter elements.

For plausible gravitino masses, any protons and antiprotons from decay will be extremely relativistic, and will most likely lose energy by scattering before annihilating (protons, of course, can simply come to rest at a typical thermal energy). Inverse 'Compton' scattering (high energy proton colliding with thermal photon) has a cross-section only of order microbarns, since a factor $(m_p/m_e)^2$ is lost compared to the standard value for electron-photon scattering; although this is much smaller than the typical cross-sections, of the order of barns, for nucleons scattering off thermal nucleons or electrons, inverse Compton losses are important because thermal photons outnumber nucleons and electrons by a factor of 10^9, which more than compensates for the smaller cross-section. In what follows we discuss the cooling of energetic protons and antiprotons, and estimate the destructive effect of the secondary photons. First we need to review the cosmological behavior of the photons themselves.

The threshold for photodissociation of ^4He is about 20 MeV, so any photons of interest here must be more energetic than this. However, there is more [1]; photons, in this cosmological setting, lose energy by a variety of means, and helium dissociation occurs only occasionally even when above threshold. If the competition is between photodissociation and Compton scattering off thermal electrons, then helium destruction occurs at a small but interesting rate. If, however, the photon is energetic enough that pair production by scattering off thermal photons is above threshold, then the relative frequency of photodissociation is beaten down by a factor of 10^9 and becomes quite insignificant. If helium is to be destroyed, the photon energy ε must be not only above 20 MeV, but simultaneously below a temperature-dependent threshold for photon-photon pair-production, estimated in [1] as $\varepsilon < 0.02\ \mathrm{MeV}^2/kT$. In deriving this inequality, it is essential to notice that even when $\varepsilon kT < m_e c^2$ there may still be enough photons in the exponential tail of the distribution for pair-production to dominate over Compton scattering: hence the numerical factor. For $kT > 10^{-3}$ MeV, the two thresholds overlap, so no photons are capable of destroying helium. In a standard cosmology, with $kT = (t/1.32s)^{-1/2}$ MeV, this temperature occurs at cosmic age $t = 1.32{\times}10^6$s, and only after this is helium vulnerable. Helium 3 and deuterium have lower photodissociation thresholds, and therefore become vulnerable earlier; here we will only be concerned with ^4He, but a complete discussion, from which the foregoing is taken, can be found in ref [1].

If the gravitino mass is m_{100} (in units of 100 GeV), its lifetime including the gluino decay channel is [2] $\tau = 4.4{\times}10^7 m_{100}{}^{-3}$ s, and the cosmological temperature when it decays is then $kT_D = 1.73 \times 10^{-4}\ m_{100}^{3/2}$ MeV. An upper limit on m_{100} comes from requiring that $kT_D < 10^{-3}$ MeV; this gives $m_{100} < 3.2$. Gravitinos undergoing hadronic decay will produce pairs of protons and antiprotons, with average energy $E_p = 100fm_{100}$ GeV, f being some factor less than one. Inverse Compton scattering of these nucleons off thermal photons of typical energy $3kT_D$ will be in the non-relativistic (Thomson) regime provided $3kT_D E_p < m_p^2$, or approximately $m_{100} < 100$ if f is not too different from unity. The maximum energy of the inverse Thomson scattered photons is $12\gamma^2 kT_D$ [1], where $\gamma = E_p/m_p = 100fm_{100}$. This gives a lower limit to m_{100} if the scattered photons are to be above 20 MeV and so able to destroy helium 4. Expressing E_p and kT_D in terms of m_{100}, one finds a limit $m_{100} > 0.99f^{-4/7}$; this is $m_{100} > 1.5$ if $f = 1/2$.

This means that gravitinos in only a very small range of mass, from 150 GeV to 320 GeV, produce protons and antiprotons and thence scattered photons capable of destroying ^{4}He. If the gravitino is too light, the photons are below 20 MeV, and if too heavy, it decays early, while helium is protected from dissociation by photon-photon scattering. On the other hand, this range of masses includes values of interest in supersymmetric models, and so the argument is worth pursuing.

As an example, let us take a gravitino of 250 GeV mass, and assume that it decays into a proton and antiproton, each of energy 125 GeV. Its lifetime is 2.8×10^6s, and the cosmological temperature when it decays is 6.8×10^{-4} MeV; the energy below which photon-photon scattering is negligible is $0.02\text{MeV}^2/kT_D = 29$ MeV, meaning that any photons between 20 MeV and 29 MeV may destroy helium. Because the scattered photons are much lower in energy than the proton or antiproton, the inverse Thomson spectrum can easily be estimated in a discretized approximation. The average energy of scattered photons is one-third the maximum, namely $\varepsilon = 4\gamma^2 kT_D$. If a proton γ loses this energy, it is left with $\gamma' = \gamma(1-4\gamma kT_D/m_p)$, and the next scattered photon has energy $\varepsilon' = 4\varepsilon'^2 kT_D$. The energy interval between these two photons is $\varepsilon-\varepsilon' \approx 8\gamma kT_D/m_p = 4\varepsilon^{3/2}(kT_D)^{1/2}/m_p$, and since there is one photon in this interval, the spectrum must be roughly

$$n(\varepsilon)d\varepsilon = m_p d\varepsilon/(4\varepsilon^{3/2}(kT_D)^{1/2}) \tag{1}$$

The total number of photons between two energies ε_a and ε_b is then

$$N_\gamma = m_p(1/\sqrt{\varepsilon_b} - 1/\sqrt{\varepsilon_a})/(2(kT_D)^{1/2}) \tag{2}$$

In our example, this number turns out to be $N_\gamma = 725$ photons between 20 MeV and 29 MeV. To find the number of helium nuclei destroyed, we follow again ref [1]. For a single photon of energy ε, the probability of its photodissociating helium, rather than simply scattering off an electron, is just the ratio of mean free paths $p(\varepsilon) = n_4\sigma_4/n_e\sigma_e$. To be accurate, one should take the photon spectrum (1) and integrate its product with $p(\varepsilon)$ from 20 MeV to 29 MeV; instead, we shall simply multiply the number of photons by an estimated average value of $p(\varepsilon)$. The number of helium nuclei destroyed is then

$$\Delta N_4 = N_\gamma(n_4/n_e)\ (\sigma_4/\sigma_e)_{av} \tag{3}$$

For a helium abundance of 22% by weight, n_4/n_e is 0.06, and an optical estimate of the ratio of cross-sections gave a value of 0.03. This means that a proton or antiproton of initial energy 125 GeV may be expected to destroy ΔN_4 = 1.3 nuclei of ^{4}He. For photon energies, as here, just above threshold, almost all the photodissociations produce ^{3}He or ^{3}H, which instantly decays to ^{3}He: very little deuterium is created.

So far, we have assumed that energetic protons and antiprotons thermalise only by inverse Thomson scattering: nuclear reactions with background particles have been ignored. This turns out to be only a marginally acceptable assumption. Experiments measuring the cross-section for proton or antiproton on proton, at around 100 GeV (fast particle onto target) yield results around 100mb [4]: the measurements are fairly uncertain, and the difference between pp and $p\bar{p}$ scattering is, for our purposes, insignificant. For a proton γ, the mean energy loss per inverse Thomson collision is $d\gamma = -4\gamma^2 kT_D/m_p$ in a mean free path $(n_\gamma\sigma_{Th})^{-1}$, where the proton Thomson cross-section is $\sigma_{Th} = 0.67(m_e/m_p)^2$b = 0.16μb. The energy loss rate with distance travelled is then

$$d\gamma/dx = -4n_\gamma\sigma_{Th}\gamma^2 kT_D/m_p \tag{4}$$

Let p(x) be the probability that a proton travels a distance x without suffering a nuclear collision. The probability that it travels a further distance dx without collision is $1-n_p\sigma_{pp}dx$, so

$$p(x+dx) = p(x)(1-n_p\sigma_{pp}dx). \tag{5}$$

This gives $dp/p = -n_p\sigma_{pp}dx = \Gamma d\gamma/\gamma^2$, where $\Gamma = n_p\sigma_{pp}m_p/4n_\gamma\sigma_{Th}kT_D$. Integrating this, we find $p(\gamma)$, the probability that a proton of initial energy γ_0 survives at least down to an energy γ without nuclear collision, to be $p(\gamma) = \exp(-\Gamma(1/\gamma-1/\gamma_0))$. (We are assuming here that σ_{pp} is constant over the energy range of interest). The probability $P(\gamma)d\gamma$ that a proton survives exactly down to energy γ, and then suffers a nuclear collision, is the product of $p(\gamma)$ and $n_p\sigma_{pp}dx = \Gamma d\gamma/\gamma^2$, the latter being the probability that the proton, of energy γ, encounters a background proton. One could therefore calculate the typical energy to which a proton survives as

$$\bar{\gamma} = \int_0^{\gamma_0} \Gamma\exp(-\Gamma(1/\gamma-1/\gamma_0))d\gamma/\gamma \tag{6}$$

but the accuracy of our estimate hardly warrants the trouble of doing this integral numerically. Instead, we take $\bar{\gamma}$ to be the solution of $\Gamma(1/\bar{\gamma}-1/\gamma_0) = 1$, when $p(\gamma)$ falls to e^{-1}.

In our example, with $m_{100} = 2.5$ and with $\sigma_{pp} = 100$mb, we find $\Gamma = 110$, and then $\bar{\gamma} \approx 60$. By the time the proton energy has fallen this far, the typical inverse Thomson photon has energy $4\gamma^2kT_D \approx 10$ MeV, below the helium threshold. Although, for individual events, inverse Thomson scattering is three or four orders of magnitude more important than nuclear collisions, the photons produced are soft, and the two energy loss rates are comparable. In this simple picture of thermalisation, protons and antiprotons lose somewhat more than half of their initial energy in photons which may destroy helium, but then collide with background protons. In such collisions, a large number of fragments, mostly pions, is produced, and we will assume that the remnants are of insufficient energy to have any further effect on element abundances.

There are two other effects we should worry about. The high energy nucleon may collide not with a proton but with a nucleus of ^{4}He, and the antiproton must eventually annihilate, which likewise it will do sometimes not on a proton but on a helium nucleus. In either case, ^{3}He or D may result. However, for a ^{4}He abundance of 22%, the relative numerical density of helium nuclei, $n_4/(n_4+n_p)$, is 0.07 and, according to [3], only about a tenth of such collisions will yield either of the lighter elements (complete disruption being the usual outcome). We expect therefore that nuclear collisions will create only about 0.007 ^{3}He or D nuclei per proton or antiproton, compared to the 1.3 that we estimated to result from the inverse Thomson photons.

Finally, it is not reasonable to imagine that gravitino decay leads only to hadronic particles; there will be some proportion of decays to a photon and a photino. The photon will typically have half the available energy, 125 GeV in our case, and its destructive effect on helium can be estimated from the calculations of ref [1]. There, the cascade of photons and electrons resulting from the thermalisation of a single high energy photon was approximately calculated, and the number of helium nuclei destroyed was found by integrating the cascade over the appropriate ratio of cross-sections. This yielded a quantity $\Sigma_4(\varepsilon)$, ε being photon energy, with the number of nuclei destroyed given by $\Delta N_4 = \Sigma_4(\varepsilon)n_4/n_e$. For high energies, Σ_4 becomes proportional to ε; its value at 100 MeV (and for a cosmological temperature of $kT_D = 6.85\times10^{-4}$ MeV) is about 0.01. For a single photon of energy 125 GeV, we therefore expect the number of helium nuclei destroyed to be

$$\Delta N_4 = \frac{125\mathrm{GeV}}{100\mathrm{MeV}}\,\Sigma_4(100\mathrm{MeV})\,\frac{n_4}{n_e} = 0.75 \qquad (7)$$

This is in contrast to our estimate of $\Delta N_4 = 2.6$ per proton-antiproton pair of the same energy. If each of these decay modes occurs with equal rate, the average ΔN_4 per decay is just 1.7.

All of the ^{4}He photodissociations will produce ^{3}He or D, and if we demand that the combined abundance of the two must be less then 10^4 of the baryon density, we have $\Delta N_4 n_{3/2} < 10^{-4}n_B$, or

$$n_{3/2}/n_\gamma < 10^{-4}n_B/\Delta N_4 n_\gamma = 5\times10^{-14}/\Delta N_4, \qquad (8)$$

where a standard baryon to photon ratio of 5×10^{-10} has been assumed [5]. From [2], we discover

$$n_{3/2}/n_\gamma = 2.35\times10^{-13}T_{R9}\ln(1-0.018T_{R9}) \qquad (9)$$

where T_{R9} is the reheating temperature in a supersymmetric inflationary cosmology. Using $\Delta N_4 = 1.7$, we find

$$T_R < 1.2\text{x}10^7\text{GeV} \qquad (10)$$

for a gravitino of 250 GeV decaying equally into proton-antiproton pairs or into a photon and a photino. This compares with the limit derived in [2] which gives, for this gravitino mass, $T_R < 10^8$GeV.

On the basis of this rough calculation, we conclude that the most important effect of the hadronic decay mode may be the 'soft' inverse Thomson photons produced by the thermalisation of energetic protons and antiprotons. Furthermore, this may cause more helium destruction than direct decay photons. However, in our example, the gravitino mass was artfully chosen to put the soft photons in the peak of the helium photodissociation cross-section; outside a very small (though interesting) gravitino mass range the effect will disappear. In addition, the calculation is uncertain because we are close to a number of thresholds, and because the importance of proton energy loss by nuclear scattering is hard to gauge. Despite these doubts, it seems that another small area in the parameter space of gravitino mass and reheating temperature may be crossed out.

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References

[1] D. Lindley, Ap. J., 294, 1 (1985)

[2] J. Ellis, D. V. Nanopoulos and S. Sarkar, Nucl. Phys. B, 259, 175 (1985)

[3] M. Yu. Khlopov and A. D. Linde, Phys. Lett. B, 138, 265 (1984)

[4] D. R. Ward et al, Phys. Lett. B, 62, 237 (1976)

[5] J. Yang, M. S. Turner, G. Steigamn, D. N. Schramm and K. Olive, Ap. J., 281, 493 (1984)