Thermal Gravitino Production and Collider Tests of Leptogenesis

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Considering gravitino dark matter scenarios, we obtain the full gauge-invariant result for the relic density of thermally produced gravitinos to leading order in the Standard Model gauge couplings. For the temperatures required by thermal leptogenesis, we find gaugino mass bounds which will be probed at future colliders. We show that a conceivable determination of the gravitino mass will allow for a unique test of the viability of thermal leptogenesis in the laboratory.

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INTRODUCTION

The smallness of the neutrino masses can be understood naturally in terms of the see-saw mechanism once the Standard Model is extended with right-handed neutrinos which have heavy Majorana masses and only Yukawa couplings. For a reheating temperature after inflation, $T_R$, which is larger or not much smaller than the masses of the heavy neutrinos, these particles are produced in thermal reactions in the early Universe. The CP-violating out-of-equilibrium decays of the heavy neutrinos generate a lepton asymmetry that is converted into a baryon asymmetry by sphaleron processes. This mechanism, known as thermal leptogenesis, can explain the cosmic baryon asymmetry for $T_R \gtrsim 3 \times 10^9\text{GeV}$. \cite{peebles}

One will face severe cosmological constraints on $T_R$ if supersymmetry (SUSY) is discovered. An unavoidable implication of SUSY theories including gravity is the existence of the gravitino $\tilde{G}$ which is the gauge field of local SUSY transformations. As the spin-3/2 superpartner of the graviton, the gravitino is an extremely weakly interacting particle with couplings suppressed by inverse powers of the (reduced) Planck scale $M_P = 2.4 \times 10^{18}\text{GeV}$.

In the course of spontaneous SUSY breaking, the gravitino acquires a mass $m_{\tilde{G}}$ and the couplings of the spin-1/2 goldstino which become dominant for small $m_{\tilde{G}}$. Depending on the SUSY breaking scheme, $m_{\tilde{G}}$ can range from the eV scale up to scales beyond the TeV region. Gravitinos can be produced efficiently in the hot primordial plasma. Because of their extremely weak interactions, unstable gravitinos with $m_{\tilde{G}} \lesssim 5\text{TeV}$ have long lifetimes, $\tau_{\tilde{G}} \gtrsim 100\text{sec}$, and decay after big bang nucleosynthesis (BBN). The associated decay products affect the abundances of the primordial light elements. Demanding that the successful BBN predictions are preserved, bounds on the abundance of gravitinos before their decay can be derived which imply $T_R \lesssim 10^8\text{GeV}$ for $m_{\tilde{G}} \lesssim 5\text{TeV}$. Thus, the temperatures needed for thermal leptogenesis are excluded.

We therefore consider SUSY scenarios in which a gravitino with $m_{\tilde{G}} \gtrsim 10\text{GeV}$ is the lightest supersymmetric particle (LSP) and stable due to R-parity conservation. These scenarios are particularly attractive for two reasons: (i) the gravitino LSP is a compelling dark matter candidate and (ii) thermal leptogenesis can still be a viable explanation of the baryon asymmetry.

THERMAL GRAVITINO PRODUCTION

Assuming that inflation governed the earliest moments of the Universe, any initial population of gravitinos must be diluted away by the exponential expansion during the slow-roll phase. We consider the thermal production (or regeneration) of gravitinos in the radiation-dominated epoch that starts after completion of reheating at the temperature $T_R$. Gravitinos with $m_{\tilde{G}} \gtrsim 10\text{GeV}$ are not in thermal equilibrium with the primordial plasma after inflation because of their extremely weak interactions. At high temperatures, gravitinos are generated in scattering processes of particles that are in thermal equilibrium with the hot SUSY plasma. The calculation of the relic density of these thermally produced gravitinos, $\Omega_{\tilde{G}}^{TP}$, requires a consistent finite-temperature approach. A result that is independent of arbitrary cutoffs has been derived for SUSY quantum chromodynamics (QCD) in a gauge invariant way. Following this approach, we provide the complete $\text{SU}(3)_c \times \text{SU}(2)_L \times \text{U}(1)_Y$ result to leading order in the couplings.

We compute $\Omega_{\tilde{G}}^{TP}$ from the Boltzmann equation for the gravitino number density

$$\frac{dn_{\tilde{G}}}{dt} + 3H n_{\tilde{G}} = C_{\tilde{G}}.$$  

The term proportional to the Hubble parameter $H$ accounts for the dilution by the cosmic expansion. The collision term $C_{\tilde{G}}$ describes the production and disappearance of gravitinos in thermal reactions in the primordial plasma. Since the phase space density of the gravitino is significantly below those of the particles in thermal equilibrium, gravitino disappearance processes can be neglected. Thus, $C_{\tilde{G}}$ is given by integrating the thermal gravitino production rate.

Considering a primordial plasma with the particle content of the minimal SUSY Standard Model (MSSM) in...
the high-temperature limit, we calculate the thermal production rate of gravitinos with $E \gtrsim T$ using the Braten–Yuan prescription [9] and hard thermal loop (HTL) resummation [11]. With the systematic treatment of screening effects in the plasma, we obtain a finite result in a gauge-invariant way. Moreover, in contrast to previous estimates [11, 12], our result does not depend on arbitrary cutoffs. The explicit form of the thermal gravitino production rate and the detailed derivation will be presented in a forthcoming publication [13].

After numerical integration of the thermal gravitino production rate, we obtain the SU(3)$_c \times$SU(2)$_L \times$U(1)$_Y$ result for the collision term:

$$C_G = \frac{3}{16\pi^2}\sum_{i=1}^{3} \frac{3\zeta(3)T^6}{M_P^2} \left(1 + \frac{M_i^2}{3m_G^2}\right) c_i g_i^2 \ln\left(\frac{k_i}{g_i}\right),$$

where the gaugino mass parameters $M_i$, the gauge couplings $g_i$, and the constants $c_i$ and $k_i$ are associated with the gauge groups U(1)$_Y$, SU(2)$_L$, and SU(3)$_c$ as given in Table I. In expression (2) the temperature $T$ provides the scale for the evaluation of $M_i$ and $g_i$. Note that HTL resummation [9, 10] requires weak couplings, $g_i \ll 1$, and thus high temperatures $T \gg 10^6$ GeV.

Our result $k_3 = 1.271$ for the SU(3)$_c$ contribution is larger than 1.163 obtained from [8]. This results from an analytical disagreement [13]: We find a cancellation of the term $T^3(N + n_f)|L_2(-e^{-E/T} - \pi^2/6)$ given as part of $I_{BFR}$ in (C.14) of Ref. [8].

Assuming conservation of entropy per comoving volume, the Boltzmann equation (1) can be solved analytically [8, 14]. With the collision term (2), we find

$$\Omega_{G}^{TP} h^2 = \sum_{i=1}^{3} \omega_i g_i^2 \left(1 + \frac{M_i^2}{3m_G^2}\right) \ln\left(\frac{k_i}{g_i}\right) \times \left(\frac{m_G}{100 \text{ GeV}}\right) \left(\frac{T_R}{10^{10} \text{ GeV}}\right),$$

with the Hubble constant $h$ in units of 100 km Mpc$^{-1}$ s$^{-1}$ and the constants $\omega_i$ given in Table I. Here $M_i$ and $g_i$ are understood to be evaluated at $T_R$. With our new $k_3$ value, we find an enhancement of about 30% of the SU(3)$_c$ contribution to the relic density.

TABLE I: Assignments of the index $i$, the gauge coupling $g_i$, and the gaugino mass parameter $M_i$ to the gauge groups U(1)$_Y$, SU(2)$_L$, and SU(3)$_c$ and the values of the associated constants $c_i$, $k_i$, and $\omega_i$.

| gauge group   | $i$ | $g_i$ | $M_i$ | $c_i$ | $k_i$ | $\omega_i$ |
|---------------|-----|-------|-------|-------|-------|-----------|
| U(1)$_Y$     | 1   | $g'$  | $M_1$ | 11    | 1.266 | 0.018     |
| SU(2)$_L$    | 2   | $g$   | $M_2$ | 27    | 1.312 | 0.044     |
| SU(3)$_c$    | 3   | $g_s$ | $M_3$ | 72    | 1.271 | 0.117     |

FIG. 1: The relic gravitino density from thermal production, $\Omega_{G}^{TP} h^2$, as a function of $T_R$. The solid and dashed curves show the SU(3)$_c \times$SU(2)$_L \times$U(1)$_Y$ results for universal ($M_{1,2,3} = m_{1/2}$) and non-universal ($0.5M_{1,2} = M_3 = m_{1/2}$) gaugino masses at the GUT scale, respectively. The dotted curves show our result of the SU(3)$_c$ contribution for $M_3 = m_{1/2}$ at $T_{GUT}$. The gray band indicates the dark matter density $\Omega_{DM}$.

Figure II shows $\Omega_{G}^{TP} h^2$ as a function of $T_R$ for $m_{GUT} = 10$, 50, and 300 GeV. With $m_{1/2} = 400$ GeV, the solid and dashed lines are obtained respectively for universal ($M_{1,2,3} = m_{1/2}$) and non-universal ($0.5M_{1,2} = M_3 = m_{1/2}$) gaugino masses at the GUT scale, respectively. The dotted curves show our result of the SU(3)$_c$ contribution for $M_3 = m_{1/2}$ at GUT. The gray band indicates the dark matter density $\Omega_{DM}$.

We find that electroweak processes enhance $\Omega_{G}^{TP}$ by about 20% for universal gaugino masses at $T_{GUT}$. In non-universal cases, $M_{1,2} > M_3$ at $T_{GUT}$, the electroweak contributions are more important. For $0.5M_{1,2} = M_3$ at $T_{GUT}$, they provide about 40% of $\Omega_{G}^{TP}$.

COLLIDER PREDICTIONS OF LEPTOGENESIS

Thermal leptogenesis requires $T_R \gtrsim 3 \times 10^9$ GeV [2]. This condition together with the constraint $\Omega_{G}^{TP} \leq \Omega_{DM}$ leads to upper limits on the gaugino masses. The SU(3)$_c$ result for $\Omega_{G}^{TP}$ implies limits on the gluino mass [8, 10]. With our SU(3)$_c \times$SU(2)$_L \times$U(1)$_Y$ result, the limits on the gluino mass $M_3$ become more stringent because of the new $k_3$ value and the additional electroweak contributions. Moreover, as a prediction of thermal leptogenesis,
we obtain upper limits on the electroweak gaugino mass parameters \(M_{1,2}\). At the Large Hadron Collider (LHC) and the International Linear Collider (ILC), these limits will be probed in measurements of the masses of the neutralinos and charginos, which are typically lighter than the gluino. If the superparticle spectrum does not respect these bounds, one will be able to exclude standard thermal leptogenesis.

Figure 2 shows the gaugino mass bounds for \(T_R = 10^9\), \(3 \times 10^9\), and \(10^{10}\) GeV evolved to \(M_{\text{GUT}}\), i.e., in terms of limits on the gaugino mass parameter \(m_{1/2}\). Here \(\Omega_{\text{DM}}^{\text{max}} h^2 = 0.126\) is adopted as a nominal 3\(\sigma\) upper limit on \(\Omega_{\text{DM}} h^2\). With the observed superparticle spectrum, one will be able to evaluate the gaugino mass parameters \(M_{1,2,3}\) at \(M_{\text{GUT}}\) using the SUSY renormalization group equations \([17, 18, 19]\). While the determination of \(M_{1,2}\) at low energies depends on details of the SUSY model that will be probed at colliders \([8]\), the bounds shown in Fig. 2 depend mainly on the \(M_R\) relation at \(M_{\text{GUT}}\). This is illustrated by the solid and dashed curves obtained with \(M_{1,2,3} = m_{1/2}\) and \(0.5 M_{1,2} = M_{3} = m_{1/2}\), respectively. The dotted curves represent the \(SU(3)_c\) limits for \(M_{3} = m_{1/2}\) at \(M_{\text{GUT}}\) and emphasize the importance of the electroweak contributions.

**DECAYS OF THE NEXT-TO-LIGHTEST SUPERSYMMETRIC PARTICLE**

With a gravitino LSP of \(m_{\tilde G} \gtrsim 10^{10}\) GeV, the next-to-lightest SUSY particle (NLSP) has a long lifetime of \(\tau_{\text{NLSP}} \gtrsim 10^{30}\) s \([20, 21]\). After decoupling from the primordial plasma, each NLSP decays into one gravitino LSP and Standard Model particles. The resulting relic density of these non-thermally produced gravitinos is

\[
\Omega_{\tilde G}^{\text{NTP}} h^2 = \frac{m_{\tilde G}}{m_{\text{NLSP}}} \Omega_{\text{NLSP}} h^2 ,
\]

where \(m_{\text{NLSP}}\) is the mass of the NLSP and \(\Omega_{\text{NLSP}} h^2\) is the relic density that the NLSP would have today, if it had not decayed. As shown below, more severe limits on \(m_{1/2}\) are obtained with \(\Omega_{\text{NTP}}^{\text{NTP}} h^2\) taken into account. Moreover, since the NLSP decays take place after BBN, the emitted Standard Model particles can affect the abundance of the primordial light elements. Successful BBN predictions thus imply bounds on \(m_{\tilde G}\) and \(m_{\text{NLSP}}\) \([20, 21]\). From these cosmological constraints it has been found that thermal leptogenesis remains viable only in the cases of a charged slepton NLSP or a sneutrino NLSP \([16, 22]\).

Note that the cosmological constraints from BBN can become much weaker with entropy production after decoupling of the NLSP and before BBN. For example, large parts of the parameter region disfavored by BBN constraints on charged slepton NLSP scenarios become allowed with a moderate amount of entropy production \([23]\). In addition, such an entropy production dilutes both the generated baryon asymmetry and the thermally produced abundance of gravitinos. Therefore, upper limits on the gaugino masses will still allow us to probe the viability of thermal leptogenesis. However, the \(T_R\) labels of the curves in Fig. 2 will change to higher values.

**COLLIDER TESTS OF LEPTOGENESIS**

Thermal leptogenesis will predict a lower bound on the gravitino mass \(m_{\tilde G}\) once the masses of the Standard Model superpartners are known. With a charged slepton as the lightest Standard Model superpartner, it could even be possible to identify the gravitino as the LSP and to measure its mass \(m_{\tilde G}\) at future colliders \([24, 25, 26]\). Confronting the measured \(m_{\tilde G}\) with the predicted lower bound will then allow us to decide about the viability of thermal leptogenesis.

In order to explain our method, we do now consider an exemplary SUSY model. Let us assume that the analysis of the observed spectrum \([10]\) will point to the universality of the soft SUSY breaking parameters at \(M_{\text{GUT}}\) and, in particular, to the minimal supergravity (mSUGRA) scenario with the gaugino mass parameter \(m_{1/2} = 400\) GeV, the scalar mass parameter \(m_0 = 150\) GeV, the trilinear coupling \(A_0 = -150\) GeV,
a positive higgsino mass parameter, \( \mu > 0 \), and the mixing angle \( \tan \beta = 30 \) in the Higgs sector. A striking feature of the spectrum will then be the appearance of the lighter stau \( \tilde{\tau}_1 \) with \( m_{\tilde{\tau}_1} = 143.4 \) GeV as the lightest Standard Model superpartner \[27\]. In the considered gravitino LSP case, 10 GeV \( \lesssim m_{\tilde{G}} < m_{\tilde{\tau}_1} \), this stau is the NLSP and decays with a lifetime of \( \tau_{\tilde{\tau}_1} \gtrsim 10^6 \) s into the gravitino. For the identified mSUGRA scenario and the considered reheating temperatures, the cosmological abundance of the \( \tilde{\tau}_1 \) NLSP prior to decay can be computed from \( \Omega_{\text{NLSP}}h^2 = \Omega_{\tilde{G}}h^2 \approx 3.83 \times 10^{-3} \), which is provided by the computer program micrOMEGAs \[28\]. For given \( m_{\tilde{G}} \), this abundance determines \( \Omega_{\tilde{G}}h^2 \) and the release of electromagnetic (EM) and hadronic energy in \( \tilde{\tau}_1 \) NLSP decays governing the cosmological constraints \[21\] \[21\].

Figure 3 allows us to probe the viability of thermal leptogenesis in the considered mSUGRA scenario. From the constraint \( \Omega_{\tilde{G}}^{\text{TP}} + \Omega_{\tilde{G}}^{\text{NTP}} \leq \Omega_{\text{DM}}^{\text{max}} \), we obtain the solid curves which provide the upper limits on \( m_{1/2} \) for \( T_R = 10^9, \ 3 \times 10^9, \) and \( 10^{10} \) GeV. The dashed line indicates the \( m_{1/2} \) value of the considered scenario. The vertical solid line is given by \( m_{\tilde{\tau}_1} = 143.4 \) GeV which limits \( m_{\tilde{G}} \) from above. In the considered scenario, the \( m_{1/2} \) value exceeds the \( m_{1/2} \) limits for \( T_R \gtrsim 10^{10} \) GeV. Thus, temperatures above \( 10^{10} \) GeV can be excluded. Temperatures above \( 3 \times 10^9 \) GeV and \( 10^9 \) GeV remain allowed for \( m_{\tilde{G}} \) values indicated by the dark-shaded (dark-green) and medium-shaded (light-green) regions, respectively. The \( m_{\tilde{G}} \) values indicated by the light-shaded region are excluded by BBN constraints for late \( \tilde{\tau}_1 \) NLSP decays.

Here thermal leptogenesis, \( T_R \gtrsim 3 \times 10^9 \) GeV, predicts \( m_{\tilde{G}} \gtrsim 130 \) GeV and thus a \( \tau_{\tilde{\tau}_1} \) lifetime of \( \tau_{\tilde{\tau}_1} > 10^{11} \) s \[20\] \[21\]. If decays of long-lived \( \tilde{\tau}_1 \)'s can be analyzed at colliders giving evidence for the gravitino LSP \[24\] \[26\], there will be the possibility to determine \( m_{\tilde{G}} \) in the laboratory: From a measurement of the lifetime \( \tau_{\tilde{\tau}_1} \) governed by the decay \( \tilde{\tau}_1 \rightarrow \tilde{G} \tau \), \( m_{\tilde{G}} \) can be extracted using the supergravity prediction for the associated partial width,

\[
\tau_{\tilde{\tau}_1} \approx \Gamma^{-1}(\tilde{\tau}_1 \rightarrow \tilde{G} \tau) = \frac{48\pi m_{\tilde{G}}^2 M_W^2}{m_{\tilde{\tau}_1}^5} \left( 1 - \frac{m_{\tilde{G}}^2}{m_{\tilde{\tau}_1}^2} \right)^{-4} \tag{6}
\]

as obtained for \( m_{\tilde{\tau}} \rightarrow 0 \). Moreover, for \( m_{\tilde{G}} \gtrsim 0.1 m_{\tilde{\tau}_1} \), \( m_{\tilde{G}} \) can be inferred kinematically from the energy of the tau, \( E_{\tau} \), emitted in the 2-body decay \( \tilde{\tau}_1 \rightarrow \tilde{G} \tau \) \[24\] \[26\]:

\[
m_{\tilde{G}} = \sqrt{m_{\tilde{\tau}_1}^2 - m_{\tilde{\tau}}^2} - 2m_{\tilde{\tau}} E_{\tau} \tag{7}
\]

While \( m_{\tilde{G}} \) within the dark-shaded (dark-green) region will favor thermal leptogenesis, any \( m_{\tilde{G}} \) outside of the medium-shaded (light-green) region will require either non-standard mechanisms lowering the \( T_R \) value needed for thermal leptogenesis or an alternative explanation of the cosmic baryon asymmetry.

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1 Considering bound-state effects of long-lived negatively charged particles on BBN, it has recently been claimed that the stau NLSP abundance for \( \tau_{\tilde{\tau}_1} \gtrsim 10^7 - 10^{11} \) s is severely constrained by the observed \( ^6 \)Li abundances \[24\] \[33\]. If the associated bounds are confirmed, the considered mSUGRA scenario will be cosmologically allowed only with late-time entropy production \[23\].

2 Thermal leptogenesis requires right-handed neutrinos and thus an extended mSUGRA scenario. This could manifest itself in the masses of the third generation sleptons \[17\]. Since the effects are typically small, we leave a systematic investigation of extended scenarios for future work.

3 We use the conservative BBN bounds considered in \[21\]. The average EM energy release in one \( \tilde{\tau}_1 \) NLSP decay is assumed to be \( E_{\tau}/2 \), where \( E_{\tau} \) is the energy of the tau emitted in the dominant 2-body decay \( \tilde{\tau}_1 \rightarrow \tilde{G} \tau \) (cf. Fig. 16 of Ref. \[21\]). With an EM energy release below \( E_{\tau}/2 \), the light-shaded band can become smaller. For less conservative BBN constraints and/or enhanced EM energy release, the excluded \( m_{\tilde{G}} \) region becomes larger.
CONCLUSION

We provide the full SU(3)_c × SU(2)_L × U(1)_Y result for the relic density of thermally produced gravitino LSPs to leading order in the gauge couplings. Our result is obtained in a consistent gauge-invariant finite-temperature calculation and thus independent of arbitrary cutoffs. With this result, new gravitino and gaugino mass bounds emerge as a prediction of thermal leptogenesis. If supersymmetry is realized in Nature, these bounds will be accessible at the LHC and the ILC. In particular, with a charged slepton NLSP, there will be the exciting possibility to identify the gravitino as the LSP and to measure its mass. Confronting the measured gravitino mass with the predicted bounds will then allow for a unique test of the viability of thermal leptogenesis in the laboratory.

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