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Thermal Production of Gravitinos

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Abstract

We evaluate the gravitino production rate in supersymmetric QCD at high temperature to leading order in the gauge coupling. The result, which is obtained by using the resummed gluon propagator, depends logarithmically on the gluon plasma mass. As a byproduct, a new result for the axion production rate in a QED plasma is obtained. The implicatons for the cosmological dark matter problem are briefly discussed, in particular the intriguing possibility that gravitinos are the dominant part of cold dark matter.

1 Introduction

Supersymmetric theories, which contain the standard model of particle physics and gravity, predict the existence of the gravitino [1], a spin-$\frac{3}{2}$ particle which aquires a mass from the spontaneous breaking of supersymmetry. Since the couplings of the gravitino with ordinary matter are strongly constrained by local supersymmetry, processes involving gravitinos allow stringent tests of the theory.

It was realized long ago that standard cosmology requires gravitinos to be either very light, $m_{\tilde{G}} < 1\,\text{keV}$ [2], or very heavy, $m_{\tilde{G}} > 10\,\text{TeV}$ [3]. These constraints are relaxed if the standard cosmology is extended to include an inflationary phase [4, 5]. The cosmologically relevant gravitino abundance is then created in the reheating phase after inflation in which a reheating temperature T_R is reached. Gravitinos are dominantly produced by inelastic $2 \to 2$ scattering processes of particles from the thermal bath. The gravitino abundance is essentially linear in the reheating temperature T_R.

The gravitino production rate depends on $m_{\tilde{g}}/m_{\tilde{G}}$, the ratio of gluino and gravitino masses. The ten $2 \to 2$ gravitino production processes were considered in [5] for $m_{\tilde{g}} \ll m_{\tilde{G}}$. The case $m_{\tilde{g}} \gg m_{\tilde{G}}$, where the goldstino contribution dominates, was considered in [6]. Four of the ten production processes are logarithmically singular due to the exchange of massless gluons. As a first step this singularity can be regularized by introducing either a gluon mass or an angular cutoff [5]. The complete result for the logarithmically singular part of the production rate was obtained in [7]. The finite part depends on the cutoff procedure.

To leading order in the gauge coupling the correct finite result for the gravitino production rate can be obtained by means of a hard thermal loop resummation. This has been shown by Braaten and Yuan in the case of axion production in a QED plasma [8]. The production rate is defined by means of the imaginary part of the thermal axion self-energy [9]. The different contributions are split into parts with soft and hard loop momenta by means of a momentum cutoff. For the soft part a resummed photon propagator is used, and the logarithmic singularity, which appears at leading order, is regularized by the plasma mass of the photon. The hard part is obtained by computing the $2 \to 2$ scattering processes with momentum cutoff. In the sum of both contributions the cutoff dependence cancels and the finite part of the production rate remains. For the gravitino production rate the soft part has been considered in [10] and the expected logarithm of the gluon plasma mass has been obtained.

Constraints from primordial nucleosynthesis imply an upper bound on the gravitino number density which subsequently yields an upper bound on the allowed reheating temperature T_R after inflation [11]-[15]. Typical values for T_R range from $10^7 - 10^{10}$ GeV, although considerably larger temperatures are acceptable in some cases [16]. In models of baryogenesis where the cosmological baryon asymmetry is generated in heavy Majorana neutrino decays [17], temperatures $T_R \simeq 10^8 - 10^{10}$ GeV are of particular interest [18]. Further, it is intriguing that for such temperatures gravitinos with mass of the electroweak scale, i.e. $m_{\tilde{G}} \sim 100$ GeV can be the dominant component of cold dark matter [7]. In all these considerations the thermal gravitino production rate plays a crucial role. In this paper we therefore calculate this rate to leading order in the gauge coupling, extending a previous result [7] and following the procedure of Braaten and Yuan [8].

The paper is organized as follows. In section 2 we summarize some properties of gravitinos and their interactions which are needed in the following. In order to illustrate how the hard thermal loop resummation is incorporated we first discuss the axion case in section 3. The most important intermediate steps and the final result for the gravitino production rate are given in section 4. Using the new results the discussion in [7] on gravitinos as cold dark matter is updated in section 5, which is followed by an outlook in section 6. The calculation of the hard momentum contribution to the production rates is technically rather involved. We therefore give the relevant details in the appendices.

2 Gravitino interactions

In the following we briefly summarize some properties of gravitinos which we shall need in the following sections. More detailed discussions and references can be found in [19, 20, 21].

Gravitinos are spin-3/2 particles whose properties are given by the lagrangian for the vector-spinor field $\psi^\alpha_\mu(x)$,

$$\mathcal{L} = -\frac{1}{2}\varepsilon^{\mu\nu\rho\sigma}\overline{\psi}_\mu\gamma_5\gamma_\nu\partial_\rho\psi_\sigma - \frac{1}{4}m_{\tilde{G}}\overline{\psi}_\mu[\gamma^\mu,\gamma^\nu]\psi_\nu - \frac{1}{2M}\overline{\psi}_\mu S^\mu \; . \qquad (1)$$

Here $m_{\tilde{G}}$ is the gravitino mass, $M = (8\pi G_N)^{-1/2}$ is the Planck mass and S_μ is the supercurrent corresponding to supersymmetry transformations. ψ_μ and S_μ are Majorana fields, so that $\overline{\psi}_\mu S^\mu = \overline{S}_\mu\psi^\mu$.

Free gravitinos satisfy the Rarita-Schwinger equation,

$$-\frac{1}{2}\varepsilon^{\mu\nu\rho\sigma}\gamma_5\gamma_\nu\partial_\rho\psi_\sigma - \frac{1}{4}m_{\tilde{G}}[\gamma^\mu,\gamma^\nu]\psi_\nu = 0 \; , \qquad (2)$$

which, using

$$\gamma^\mu\psi_\mu(x) = 0 \; , \quad \partial^\mu\psi_\mu(x) = 0 \; , \qquad (3)$$