Gravitational violation of $R$ parity and its cosmological signatures

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Discrete $R$ parity ($R_P$) is usually imposed in the minimal supersymmetric standard model (MSSM) as an unbroken symmetry. In this paper we study very weak gravitationally induced $R$-parity breaking, described by nonrenormalizable terms inversely proportional to the Planck mass. The lightest supersymmetric particle, a neutralino, is unstable but its lifetime exceeds the age of the Universe and thus it can serve as a dark matter (DM) particle. The neutralino lifetime is severely constrained from below due to the production of positrons and antiprotons, diffuse gamma radiation, etc. The violation of $R_P$ generated gravitationally by dimension-five operators in the MSSM is shown to violate these constraints if they are suppressed only by the Planck scale. A general theoretical analysis of gravitationally induced $R_P$ violation is performed and two plausible and astrophysically consistent scenarios for achieving the required suppression are identified and discussed.

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I. INTRODUCTION

A discrete symmetry, called $R$ parity ($R_P$) is usually imposed [1] on the minimal supersymmetric standard model (MSSM) [2]. This assumption makes the lightest supersymmetric particle (LSP) stable. The most natural candidate for the LSP in the MSSM is a neutralino. Indeed, in the MSSM with soft supersymmetry-(SUSY-)breaking terms and radiatively induced electroweak symmetry-breaking calculations one can show that one of the neutralinos is the LSP in a wide range of allowed parameters. Moreover, the relic density of neutralinos in this scenario satisfies the requirements for cold dark matter density in large areas of SUSY parameter space [3].

The hypothesis of the neutralino as a dark matter (DM) particle is amenable to experimental verification [3]. The neutralinos can be detected directly through their elastic scattering off nuclei [4]. The annihilation of neutralinos can produce remarkable indirect signals in the form of high-energy neutrino radiation from the Sun and Earth [5], in the form of galactic antiprotons and positrons [6], and some others.

If $R_P$ is very mildly broken instead of being exactly conserved then the LSP can be a DM particle, but an unstable one. Naively one would expect that a neutralino with a lifetime of the order of the age of the Universe could provide the DM. But specific neutralino decay channels, e.g., containing positrons, antiprotons, pions, are severely constrained from observations. They typically require the neutralino lifetime to be much larger than the age of the Universe [7].

While it is possible for $R_P$ to remain unbroken on technical grounds, there is no deep theoretical reason for $R_P$ to be a symmetry of nature. In fact many models of $R_P$ violation have been proposed [8] but in the absence of fine-tuning they lead to large $R_P$ violation inconsistent with the LSP as a dark matter particle. Only very weak violation of $R_P$ can make the decaying neutralino a realistic dark matter particle. Such a possibility was studied in [9] in the context of a specific mechanism [10] of spontaneous $R_P$ violation through a right handed sneutrino vacuum expectation value (VEV) close to the weak scale and a very tiny $\nu^c/H_2$ Yukawa coupling.

A more natural possibility is given by $R_P$ violation due to gravitational effects. In fact, it is well known that quantum gravity effects, associated with worm holes or “virtual” black holes violate all nongauge symmetries including the discrete ones and $R_P$ in particular [11–17]. In this paper we shall describe a gravitational breaking of $R_P$ by nonrenormalizable terms inversely proportional to the Planck mass. We shall discuss also the relevance of these terms to the wormhole effects.

Although the gravitational violation of $R_P$ seems to be a realistic possibility, one cannot ignore the alternative case of exactly conserved $R_P$ in the presence of all gravitational effects. Such theories were indeed constructed [18–22]. A discrete symmetry is respected by all interactions including quantum gravity if it is a remnant of a spontaneously broken gauge symmetry. In the case of $R_P$, the matter parity $[\equiv \pm (-1)^{3B-L}]$ forms a discrete subgroup of the gauged $B-L$ symmetry. Hence in the presence of a gauged $B-L$ symmetry, $R_P$ could arise as a discrete gauge symmetry [21,22] in the low-energy theory if the breaking of $B-L$ is accomplished by a Higgs fields with appropriate values of $B-L$ [19,20]. In this case $R_P$ is exactly conserved.

Another example is given [23] in a SU(5)×SU(5) model where $R_P$ is conserved in the presence of nonrenormalizable Planck scale terms.