Lifetime Limit of LSP from Cosmological Light Elements

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Abstract. From the present cosmic abundance of the light elements, one can obtain a lifetime bounds of LSP. From the consideration of deuterium, we obtain \( \tau_\chi \geq 10^6 \) s [1].

INTRODUCTION

More than 20 years have passed since the Lee-Weinberg bound on the stable heavy neutrino was proposed [2]. It applies to an absolutely stable particle which needs a conserved quantum number. The decaying particle cosmology was proposed around the same time [3]. But the decaying particle cosmology has been extensively applied for the gravitino [4]. In this talk, we focus on the decay of the lightest supersymmetric particle (LSP), \( \chi \). For \( \chi \) to decay, the R-parity must be broken.

In supergravity, there can be nonrenormalizable interactions for the R-parity violation, but we neglect these compared to the renormalizable ones. There can be also R-violating bilinear terms, of the form \( L_i H_2 \), which can be rotated away at the superpotential level. However, in the presence of soft terms some bilinear terms cannot be rotated away. But for decay processes, this subtle point is not important. Thus we consider the R-violating trilinear terms,

\[
W = \frac{1}{2} \lambda_{ijk} L_i L_j E^{ck} + \lambda'_{ijk} L_i Q_j D^{ck} + \frac{1}{2} \lambda'' D^{ci} D^{cj} D^{ck}
\]  

which are allowed by (i) supersymmetry and (ii) gauge symmetry. Therefore, it is reasonable to consider the phenomenology of R-parity violation. With the above superpotential present, the lepton number and/or baryon number are broken. That

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is the reason for requiring the $R = (-1)^{3B+L+2S}$ conservation. Anyway, with the R-parity violation, we expect neutrino oscillation, proton decay, and other abnormal processes. From laboratory experiments, the single bounds on the couplings are not very strong, e.g. $\lambda_{121} < 0.05, \lambda_{122} < 0.05, \lambda_{111}' < 0.001, \lambda_{112}' < 0.02, \lambda_{112}'' < 10^{-6}$, and $\lambda_{113}'' < 10^{-5}$. However, a combined bound from lower limit of the proton decay lifetime is very strong

$$\lambda' \lambda'' < 10^{-24}. \quad (2)$$

If a universal strength for the R-violating couplings are assumed, then these couplings are very small. For example, if a singlet scalar field $\phi$ carrying odd R-parity develops a VEV, $\langle \phi \rangle \equiv \epsilon M_P$, then the R-parity is spontaneously broken. At low energy, these effects are represented by $\lambda, \lambda'$, and $\lambda''$ couplings which carry negative R-parity. These may arise from nonrenormalizable interactions containing $\phi$ field. In this case, these couplings can be of the same order.

Thus, to allow reasonably large R-violating couplings, one usually forbid $\lambda'$ or $\lambda''$ completely.

In general, laboratory experiments give upper bounds on the couplings. However, the cosmological bounds depend on the region of couplings. It is schematically shown in Fig. 1. In this talk, I am interested in the region $\tau_\chi \sim 10^{-6}$ s.

**THE LIFETIME OF LSP**

The neutralino is a mixture of the neutral gauginos and neutral Higgsinos,

$$\chi = N_1 \tilde{B} + N_2 \tilde{W} + N_3 \tilde{H}_1^0 + N_4 \tilde{H}_2^0. \quad (3)$$

The decay can occur, for example, through $\chi \rightarrow Q + \tilde{q}$ where the virtual $\tilde{q}$ transforms to $L + D^c$. For this process, the interaction is given by

![FIGURE 1. A schematic view of allowed windows for the $\chi$ lifetime. Our interest is near the point marked by the grey upward arrow.](image-url)
\[
- \frac{\lambda'_{ijk}}{M_f^2} \left( gN_2 + \frac{1}{3}g_1N_1 \right) \int d^4\theta U^{aj} \chi E^a D^ck + \text{h.c.}
\] (4)

For the $\chi \rightarrow u^c + d + e^+$ decay, there exist 9 diagrams. The possible diagrams increase very rapidly if one considers colored final states. Kinematically excluding $tt^c$ final states, there are 1,080 diagrams. Thus, we assume the universal sfermion mass to simplify the expression. Then the $\chi$ decay rate is given by

\[
\Gamma_{\text{tot}} = \frac{g^2 m^5_\chi}{256 \pi^4 M_f^4} \cdot \left\{ \sum |\lambda_{ijk}|^2 \left( \frac{1}{8} N_2^2 + \frac{3}{8} N_1^2 \tan^2 \theta_W \right) + \sum_{j \neq 3} |\lambda'_{ijk}|^2 \left( \frac{3}{4} N_2^2 + \frac{7}{12} N_1^2 \tan^2 \theta_W \right) + \sum |\lambda''_{ijk}|^2 \left( \frac{3}{8} N_2^2 + \frac{7}{24} N_1^2 \tan^2 \theta_W - \frac{1}{2} N_1 N_2 \tan \theta_W \right) \right\}
\] (5)

where the overall coefficient in front of the curly bracket is $1.8 \times 10^{15}$ s$^{-1}$ for $M_f = 1$ TeV and $m_\chi = 30$ GeV.

**COSMOLOGICAL BOUND ON $\tau_\chi$**

**The decoupling temperature $T_D$**

The last moment when the heavy particles are in equilibrium with photons is the decoupling temperature $T_D$. For the neutralino, it is determined by a competition between the universe expansion rate and $\chi$ destruction rate. The destruction rate is a function of sfermion mass for the $t$-channel process $\chi + \chi \rightarrow f + f^c$. If there exists a significant Higgsino component, i.e. $(N_1^2 + N_2^2)/|N_3^2| > (M_2^2/M_f^2)^2$, then the s-channel $Z$ exchange diagram dominates. It is the easiest way to estimate the decoupling temperature. However, we also include the sfermion exchange diagrams in the numerical estimation. Nevertheless, the decoupling temperature does not depend on these parameters very much. Let us introduce a decoupling factor $d$

\[
d = \frac{m_\chi}{T_D}.
\] (6)

The decoupling factor $d$ is given for various parameter sets in Ref. [1]. For example, $M_f = 300$ GeV, $m_\chi = 60$ GeV, $\tan \beta = 10$, and the gaugino dominated neutralino $(N_1 = 0.9 - 1, N_2 = 0.1 - 0.5, \text{ and } N_3 = N_4 = 0)$ give $d = 21 - 22$. For a wide range of parameters, $d$ is in the range 15–30.

In particular, we note the following. Higgsino dominated $\chi$ gives a little bit smaller decoupling temperature and hence a lower $\chi$ density. The $t$ and $u$ channel processes are important for $N_{3,4} > 0.1$ if $M_f > 300$ GeV. However, the decoupling temperature is rather insensitive to $\tan \beta$. In the numerical analyses, we further assumed the relations $m_{A,h_1,h_2}/m_\chi = 1/3$ and $\Gamma_{A,h_1,h_2} = 1/500$. We note, however, that the cross section and the decoupling temperatures are not sensitive to these assumptions.

In the next section, we are interested in relatively light neutralino case, which excludes the possibility of producing $t, W, Z, H$ in the $\chi\chi$ annihilation.
The $\chi$ lifetime bound

If $\chi$ decays after 1 s, it affects the nucleosynthesis in a way of destroying the already manufactured light elements. Note that our $\chi$ lifetime is $10^{-15}/|\lambda|^2$ s and the cosmic time scale in the radiation dominated era is $t = 0.3N^{-1/2}M_P/T^2$.

Requiring that $E_{\chi} < \text{(energy of relativistic particles)}$, we obtain $\tau_{\chi} < 4.8 \times 10^{10} \, (\text{GeV}/m_{\chi})^2$ s, which gives a $|\lambda|$ bound of order $10^{-13}$.

A more stringent bound comes from the dissociation of light elements, in particular the D dissociation [4,5]. The $\chi$ decay products degrade very rapidly by scattering with background photons. We are interested in the photons with $E > 2.225$ MeV. But $e^+e^-$ production from scattering on the background radiation turned out to be important also [5]. In this analysis, another important temperature parameter $T_*$ is introduced. At $T_*$, the rates for the Compton scattering and the $e^+e^-$ production are comparable. The critical photon energy $E_*$ corresponding to $T_*$ is given by $E_* T_* = (1/50) \, \text{MeV}^2$. Then we note that $10^{-9}$ (with respect to the photon number) photons with $\omega > 25T_*$ can be used to produce $e^+e^-$. In this case, the $e^+e^-$ scatter off the background radiation to transfer the energy to photons which can dissociate D. Therefore, the maximum allowable lifetime $\tau_{\max}$ is determined by the condition that if it decayed later than $\tau_{\max}$, the probability for photon to scatter with $e$ is negligible, namely it mostly scatter off with D to dissociate it. Therefore, $\chi$ must decay before $\tau_{\max}$. The equation for $\tau_{\max}$ is

$$
2 \frac{n_\chi}{n_e} \epsilon \sum (\epsilon, T) e^{-t/\tau_{\max}} \frac{dt}{\tau_{\max}} = 1 \quad (7)
$$

where

$$
\sum (\epsilon, T) = \int_{Q_D}^{\omega_1} \frac{\sigma_D}{\sigma_{KN} + \sigma_{pp}} 2 \left( 1 - \frac{\omega}{\omega_m} \right) \frac{d\omega}{\omega_m}. \quad (8)
$$

Here $\epsilon$ is the photon energy in the fraction of $\chi$ mass, $\omega$ is the photon frequency, $\sigma_D$, $\sigma_{KN}$, and $\sigma_{pp}$ are the deuteron dissociation cross section, Klein-Nishina cross section, and $pp$ production cross section, respectively. The maximum scattered photon energy is $12\gamma T$.

We calculated $\tau_{\max}$ from the above formula to obtain

$$
\tau_{\max} = (2.2 - 2.5) \times 10^6 \, \text{s}. \quad (9)
$$

For $\delta_B \approx 5 \times 10^{-10}$ and 60 GeV photino-like (bino-like) neutralino, the combination of R-violating couplings is bounded as

$$
\sum 0.12(0.05)|\lambda_{ijk}|^2 + \sum 0.31(0.07)|\lambda'_{ijk}(j \neq 3)|^2 + \sum 0.04(0.04)|\lambda'_{3jk}|^2 \\
+ \sum 0.23(0.12)|\lambda''_{ijk}(i < j, k \neq 3)|^2 > 7.7 \times 10^{-24} \quad (10)
$$
CONCLUSION

Thus the sum of the R-violating couplings is bounded from below to a few times $10^{-12}$, the details of which depends on the nature of the neutralino. We studied the lifetime region around $10^6$ s in Fig. 1. Of course, our bound is most meaningful if the R-violating couplings are of the same order. It is interesting to note that there is a allowed lifetime window between $10^3$ s and $10^6$ s.

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FIGURE 2. The maximum allowable lifetime of $\chi$ for $M_f = 300$ GeV, $N_1 = 0.99$, $N_2 = 0.14$, and $N_3 = N_4 = 0$. 