Non-thermal Production of Neutralino Cold Dark Matter from Cosmic String Decays

R. Jeannerot\textsuperscript{1}, X. Zhang\textsuperscript{2,1} and R. Brandenberger\textsuperscript{3}

\textsuperscript{1}International Centre for Theoretical Physics (ICTP), POB 586, Strada Costiera 11, 34014 Trieste, Italy;
\textsuperscript{2}CCAST (World Laboratory), P.O. Box 8730, Beijing 100080, P.R. China, and Institute of High Energy Physics, Academy
Simica, Beijing 100039, P.R. China;
\textsuperscript{3}Department of Physics, Brown University, Providence, RI 02912, USA
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We propose a mechanism of nonthermal production of a neutralino cold dark matter particle, \( \chi \), from the decay of cosmic strings which form from the spontaneous breaking of a \( U(1) \) gauge symmetry, such as \( U_{B-L}(1) \), in an extension of the minimal supersymmetric standard model (MSSM). By explicit calculation, we point out that with a symmetry breaking scale \( \eta \) of around \( 10^8 \) GeV, the decay of cosmic strings can give rise to \( \Omega \chi \approx 1 \). This gives a new constraint on supersymmetric models. For example, the dark matter produced from strings will overclose the universe if \( \eta \) is near the electroweak symmetry breaking scale. To be consistent with \( \Omega \chi \leq 1 \), the mass of the new \( U(1) \) gauge boson must be much larger than the Fermi scale which makes it unobservable in upcoming accelerator experiments. In a supersymmetric model with an extra \( U_{B-L}(1) \) symmetry, the requirement of \( \Omega \chi \leq 1 \) puts an upper bound on the neutrino mass of about \( 30 \text{eV} \) provided neutrino masses are generated by the see-saw mechanism.

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I. INTRODUCTION

In spite of the increasing evidence that cold matter (matter with pressure \( p = 0 \)) makes up less than the critical density \( \rho_c \) for a spatially flat Universe, equally strong evidence for the existence of a substantial amount of cold dark matter (CDM) remains. The best current estimates give \( \Omega_{CDM} \sim 0.3 \) \[1\] whereas \( \Omega_B < 0.1 \) \[2\] (here, \( \Omega_B = \rho_B/\rho_c \) denotes the fractional contribution of \( X \) matter to \( \rho_c \), and \( B \) stands for the contribution of baryons).

The leading candidates for cold dark matter are the axion and the neutralino. The axion is a neutral spin-zero pseudogoldstone boson associated with the spontaneous breaking of the global \( U_{PQ}(1) \) symmetry, which was introduced by Peccei and Quinn \[3\] as a solution to the strong CP problem. At zero temperature the axion mass is given by

\[
m_a \sim 6 \times 10^{-6} eV \left( \frac{10^{12} \text{GeV}}{f_a} \right)
\]

where \( f_a \) is Peccei-Quinn symmetry breaking scale and \( N \) is a positive integer which describes the color anomaly of \( U_{PQ}(1) \). Axions can be produced by three different mechanisms: vacuum alignment, axion string decay and axion domain wall decay \[4\]. Cosmology yields an upper limit on \( f_a \) of \( f_a \lesssim 10^{12} \) GeV.

The neutralino is an electrically neutral hypothetical particle which arises in supersymmetric models. In many such models, e.g. in the MSSM (the minimal supersymmetric standard model), the lightest supersymmetric particle (LSP) is stable, unless R-parity violating interactions are included. The LSP is generally thought to be the lightest neutralino \( \chi \). The neutralinos in the Universe today are in general assumed to be a relic of an initially thermal neutralino distribution in the hot early Universe. Based on this thermal production mechanism, there have been many calculations of the LSP abundance (for a review, see e.g. \[5\]) as a function of the MSSM parameters. These studies show that there exists a domain of parameter space in the MSSM which is consistent with all of the present experimental constraints and for which the \( \chi \) has a relic mass density \( \Omega_{\chi} \sim 1 \). However, cosmology also imposes limits on the LSP mass. In the case of a Bino-like LSP, the calculation of Refs. \[6\] yields \( M_{\tilde{B}} \lesssim 300 \text{GeV} \). A recent study \[7\] relaxes this upper bound to about 600 GeV by including the \( B \) coannihilations with the \( \tilde{e} \) and \( \tilde{\mu} \).

In this paper, we propose a new non-thermal production mechanism of the LSP. We consider models with an extra \( U(1) \) gauge symmetry in extensions of the MSSM. This \( U(1) \) symmetry could be \( U_{B-L}(1) \), where \( B \) and \( L \) are respectively baryon and lepton numbers. Such models explain the neutrino masses via the see-saw mechanism. Another possibility is that the new \( U(1) \) corresponds to a \( U(1) \)’ from string theory or grand unified theories \[8\].

The basic idea of our mechanism is as follows. When the extra \( U(1) \) symmetry which we have introduced gets broken at a scale \( \eta \), a network of strings is produced by the usual Kibble mechanism \[9\]. The initial separation of the strings is microscopic, of the order \( \lambda^{-1} \eta^{-1} \) (where \( \lambda \) is a typical Higgs self coupling constant of the \( U(1) \) sector of the theory) which implies that a substantial fraction of the energy density of the Universe is trapped in strings. After the symmetry breaking phase transition, the defect
network coarsens. In the process, string loops decay. If, as we assume, the fields excited in the strings couple to the neutralino $\chi$, then a non-thermal distribution of $\chi$ particles will be generated during the process of string decay. The total energy density in $\chi$ particles will depend on the scale $\eta$ of $U(1)$ symmetry breaking. The presence of our alternative generation mechanism for $\chi$ particles relaxes the constraints on the mass of the $\chi$. Even if the usual thermal generation mechanism is too weak to generate $\Omega_\chi \sim 1$, our new non-thermal mechanism may, for appropriate values of $\eta$, be able to lead to $\Omega_\chi \sim 1$. In fact, we find that if $\eta < 10^9\text{GeV}$ and $M_\chi \sim 100\text{GeV}$, then our mechanism will lead to $\Omega_\chi > 1$, unless the couplings of the $U(1)$ sector to $\chi$ are small. Note that there are similarities between our non-thermal production and the mechanism based on preheating proposed in [10].

To begin with, we consider a general case and calculate the relic mass density of the LSP, then we will move on to a discussion of some implications.

II. LSP PRODUCTION VIA STRING DECAY

Local cosmic strings form at a phase transitions associated with the spontaneous symmetry breaking of a gauge group $G$ down to a subgroup $H$ of $G$ if the first homotopy group of the vacuum manifold $\pi_1(\mathbb{C}^G)$ is nontrivial. We suppose the existence of such a phase transition which is induced by the vacuum expectation value (vev) of some Higgs field $\Phi$, $\langle \Phi \rangle = \eta$, and takes place at a temperature $T_c$ with $T_c \simeq \eta$. The strings are formed by the Higgs field $\Phi$ and some gauge field $A$ of $G$ whose generator is broken by the vev of $\Phi$. We assume that the generator of $G$ associated with $A$ is diagonal so that the strings are abelian. The mass per unit length of the strings is given by $\mu = \eta^2$.

During the phase transition, a network of strings forms, consisting of both infinite strings and cosmic string loops. After the transition, the infinite string network coarsens and more loops form from the intercommuting of infinite strings. Cosmic string loops loose their energy by emitting gravitational radiation. When the radius of a loop becomes of the order of the string width, the loop releases its final energy into a burst of $\Phi$ and $A$ particles. Those particles subsequently decay into LSP, which we denote by $\chi$, with branching ratios $\epsilon$ and $\epsilon'$. For simplicity we now assume that all the final string energy goes into $\Phi$ particles. A single decaying cosmic string loop thus releases $N \simeq 2\pi \lambda^{-1} \epsilon$ LSPs which we take to have a monochromatic distribution with energy $E \sim T_c^{-1}$.

In such scenarios, we thus have two sources of cold dark matter which will contribute to the matter density of the universe. We have CDM which comes from the standard scenario of thermal production; it gives a contribution to the matter density $\Omega_{therm}$. And we also have non-thermal production of CDM which comes from the decay of cosmic string loops and gives a contribution $\Omega_{nonth}$. The total CDM density is $\Omega_{CDM} = \Omega_{therm} + \Omega_{nonth}$. During the temperature interval between $T_c$ and the LSP freezeout temperature $T_\chi$, LSPs released by decaying cosmic string loops will thermalise very quickly with the surrounding plasma, and hence will contribute to $\Omega_{therm}$, which should not sensitively deviate from the value calculated by the standard method [3,4]. However, below the LSP freezeout temperature, since the annihilation of the LSP is by definition negligible, each CDM particle released by cosmic string decays will contribute to $\Omega_{nonth}$. We obviously must have

$$\Omega_{nonth} < 1.$$  

(1)

This will lead us to a constraint (a lower bound) on the cosmic string forming scale. We now calculate $\Omega_{nonth}$.

We assume that the strings evolve in the friction dominated regime so that the very small scale structure on the strings has not formed yet. The network of strings can then be described by a single length scale $\xi(t)$ [11]. In the friction dominated period, the length scale $\xi(t)$ has been shown to scale as [12]:

$$\xi(t) \sim \xi(t_c) \left( \frac{t}{t_c} \right)^{3 \lambda \eta^{-1}}$$  

(2)

where $\xi(t_c) \sim (\lambda \eta)^{-1}$ and $\lambda$ is the Higgs self quartic coupling constant. The number density of cosmic string loops created per unit of time is given by [11]:

$$\frac{dn}{dt} = \nu \xi^{-4} \frac{d\xi}{dt}$$  

(3)

where $\nu$ is a constant of order 1. We are interested in loops decaying below $T_\chi$.

The number density of LSP released from $t_{lsp}$ till today is given by:

$$n_{lsp}^{nonth}(t_0) = N \nu \int_{\xi_F}^{\xi_0} \left( \frac{t}{t_0} \right)^{\frac{3}{2}} \xi^{-4} d\xi$$  

(4)

where the subscript 0 refers to parameters which are evaluated today. $\xi_F = \xi(t_F)$ where $t_F$ is the time at which cosmic string loops which are decaying at time $t_\chi$ (associated with the LSP freezeout temperature $T_\chi$) have formed. Now the loop’s average radius shrinks...
at a rate $\frac{d\eta}{dt} = -\Gamma_{\text{loops}} G\mu$, where $\Gamma_{\text{loops}}$ is a numerical factor $\sim 10 - 20$. Since loops form at time $t_F$ with an average radius $R(t_F) \approx \lambda^{-1} G\mu M_{pl}^{\frac{3}{2}}$, they have shrunk to a point at the time $t \approx \lambda^{-1} \Gamma_{\text{loops}}^{-1} M_{pl}^{\frac{3}{2}} t_F$. Thus $t_F \sim (\lambda \Gamma_{\text{loops}} M_{pl}^{\frac{3}{2}}) t_0^2$. Now the entropy density is $s = \frac{2\pi^2}{45} g_* T^3$ where $g_*$ counts the number of massless degrees of freedom in the corresponding phase. The time $t$ and temperature $T$ are related by $t = 0.3 g_*^{\frac{1}{2}} (T) M_{pl}$ where $M_{pl}$ is the Planck mass. Thus using Eqs. (4) and (5), we find that the LSP number density today released by decaying cosmic string loops is given by:

$$Y_{\text{LSP}}^{\text{nonth}} = \frac{n_{\text{LSP}}^{\text{nonth}}}{s} = \frac{6.75 \pi}{h} \lambda^2 \Gamma_{\text{loops}} g_{*T} g_{*T, X} M_{pl}^2 \frac{T^4}{T_0^4},$$

where the subscript on $g^*$ refers to the time when $g^*$ is evaluated.

The LSP relic abundance is related to $Y_{\chi}$ by:

$$\Omega_{\chi} h^2 \approx M_\chi Y_{\chi} (s(t_0) \rho_{\text{c}}(t_0))^{-1} h^2 \approx 2.8 \times 10^8 Y_{\chi}^{\text{tot}} (M_{\chi}/\text{GeV})$$

where $h$ is the Hubble parameter and $M_{\chi}$ is the LSP mass. Now $Y_{\chi}^{\text{tot}} = Y_{\chi}^{\text{therm}} + Y_{\chi}^{\text{nonth}}$; hence by setting $h = 0.70$, Eqs. (2) and (3) lead to the following constraint:

$$5.75 \times 10^8 Y_{\chi}^{\text{nonth}} (M_{\chi}/\text{GeV}) < 1.$$ (7)

We thus see that Eqs. (2) and (3) lead to a lower bound on the cosmic string forming temperature $T_c$.

Recent measurements of cosmological parameters from the cosmic microwave background radiation combined with Type IA supernovae show evidence for a cosmological constant. In such a scenario, the relic matter density satisfies $\Omega_{m} h^2 \simeq 0.35$.

In Fig. 1, we have plotted the bound on $T_c$ as a function of $\frac{\epsilon h^2}{M_{\chi}}$ for both $\Omega_{\chi} h^2 = 1$ and $\Omega_{\chi} h^2 = 0.35$. We have set $g_{*T,c} = 250$, $g_{*T} = 90$, $T_c = \frac{m_{\nu}}{2\lambda}$, $M_{pl} = 1.22 \times 10^{19}$ GeV, and the cosmic string parameters $\nu = 1$, $\lambda = 0.5$ and $\Gamma = 10$. The region above each curve corresponds to $\Omega_{\chi} h^2 < 1 (\Omega_{\chi} h^2 < 0.35$ respectively), and the region below to $\Omega_{\chi} h^2 > 1 (\Omega_{\chi} h^2 > 0.35$ respectively); this region is excluded by observations. We see that if there is a cosmological constant, a slightly stronger bound on $T_c$ is obtained.

### III. IMPLICATIONS FOR PHENOMENOLOGY

Our results have important implications for supersymmetric extensions of the standard model with extra $U(1)'s$ (or grand unified models with an intermediate $SU(3)_c \times SU(2)_L \times U(1)_{Y} \times U(1)'$ gauge symmetry).

Most importantly, the requirement $\Omega_{\text{nonth}} < 1$ imposes a new constraint on supersymmetric model building and rules out many models with a low scale of a new symmetry breaking which produces defects such as cosmic strings.

Consider, for example, the model with an extra $U_{B-L}(1)$ gauge symmetry. In this model, the spectrum of the standard model is extended to include right-handed neutrinos $N_i$. The light neutrinos receive masses via the see-saw mechanism and the matter-antimatter asymmetry of the universe is generated by the out-of-equilibrium decay of these right-handed neutrinos. In the latter case, leptogenesis can occur by the decay of cosmic strings associated with the spontaneous breaking of the $U_{B-L}(1)$ gauge symmetry $\left[14\right]$. In the supersymmetric version of this model, the strings will release not only right-handed neutrinos $N_i$, but also their superpartners $\tilde{N}_i$. The heavy neutrinos $N_i$ and their scalar partners $\tilde{N}_i$ can decay into various final states including the LSP. The superpotential relevant to the decays is $W = H_1 \epsilon L_y E^c + H_2 \epsilon L_y N^c$.

where $H_1, H_2, L, E^c$ and $N^c$ are the chiral superfields and $y_L, y_E$ are Yukawa couplings for the lepton and neutrino Dirac masses, $m_1 = y_L v_1, m_D = y_E v_2$, with $v_12$ being the vacuum expectation values of the Higgs fields. At tree level, the decay rates of $N_i$ into s-lepton plus Higgsino and lepton plus Higgs are the same and they are smaller than the rate of $\tilde{N}_i$ decaying into s-lepton plus Higgs and Higgsino plus lepton by a factor of 2. If the neutralino is higgsino-like, the LSP arise directly from the decays of the $N_i$ and $\tilde{N}_i$. If the neutralino is bino- or photino-like, subsequent decays of s-lepton into binos or photinos plus leptons will produce the LSP. For reasonable values of the parameters, we estimate the branching ratio $\epsilon$ of the heavy particle decay into LSP to be between 0.1 and 0.5. From Eq. (4) it follows that string decays can easily produce the required amount of LSP. However too many LSPs will be generated unless the $B - L$ breaking scale, $\Lambda_{B-L}$ is higher than about $10^8$ GeV. In turn, this will set a lower limit on the neutrino masses generated by the see-saw mechanism, $m_{\nu} \sim m_{\tau}^2/\Lambda_{B-L}$. Inserting numbers and taking $m_D \sim m_\tau \sim 1.8$ GeV, one obtains that $m_\nu \lesssim 30$ eV.

In models with spontaneous breaking of a $U_{B-L}(1)$ gauge symmetry, upper and lower bounds on the $B - L$ breaking scale have already been derived from considerations of cosmic rays from string decay $\left[14\right]$ and from leptogenesis $\left[14\right]$, respectively. Our lower bound on the $B - L$ breaking scale is independent of leptogenesis.

Our lower limit on the $B - L$ symmetry breaking scale in gauge $B - L$ models and in general models with an extra $U(1)'$ pushes the mass of the new gauge boson far above the Fermi scale, rendering it impossible to test the new physics signals from the extra $Z'$ in accelerators.

To summarize, we have pointed out a new production mechanism for neutralino dark matter which can be effective in many models beyond the MSSM, models with
Tc
χ
region below correponds to Ω
χ
branching ratio and the LSP mass for Ω
χ
and Ω
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corresponds to Ω
mass density Ω
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the nonthermal production of LSPs from string decays. Similarly, one could consider LSP production from other
topological defects. We have calculated the relic LSP mass density Ω
month as a function of the string scale, the freezeout temperature and the mass of the LSP. The LSP mass density has two contributions, one from thermal production which has been calculated by many authors in the literature before, another is the non-thermal produc-
tion which has been calculated by many authors in

One important caveat must be made concerning our calculations. Cosmic strings arising in supersymmetry models are generically superconducting [17]. In this case, the string dynamics may be very different from that of ordinary strings, the dynamics assumed in this paper, and thus the corresponding constraints on particle physics model building would be quite different. Nevertheless, the main point that cosmic string decay in extensions of the MSSM can yield a new production mechanism for dark matter remains unaffected.

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