Late decaying axino as CDM and its lifetime bound

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Abstract

The axino with mass in the GeV region can be cold dark matter (CDM) in the galactic halo. However, if R-parity is broken, for example by the bilinear terms $\mu_\alpha$, then axino($\tilde{a}$) can decay to $\nu + \gamma$. In this case, the most stringent bound on the axino lifetime comes from the diffuse photon background and we obtain that the axino lifetime should be greater than $3.9 \times 10^{24} \Omega_{\tilde{a}} h^2$ s which amounts to a very small bilinear R-parity violation, i.e. $\mu_\alpha < 1$ keV. This invalidates the atmospheric neutrino mass generation through bilinear R-violating terms within the context of axino CDM.

[Key words: dark matter, axino, R-parity violation, detection of CDM]
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The observed rotation curve of the halo stars [1] requires to fill the galactic halo with cold dark matter (CDM) such as axion [2–4], the lightest supersymmetric particle (LSP) [5], the axino LSP [6,7], and wimpzilla [8]. The axion is motivated from the solution of the strong CP problem *a la* Peccei and Quinn (PQ) [9], which is required to be very light [10]. The LSP is motivated from *R-parity conservation* in the supersymmetric solution of the gauge hierarchy problem, where R-parity is defined as \((-1)^{3B+L−2S}\). For the LSP to be CDM, its mass is around 100 GeV [11]. The wimpzilla is $10^{12−13}$ GeV stable particle.

The possibility of axino dark matter, which is our interest in this paper, has been suggested from time to time as the hot DM, the warm DM and the cold DM possibilities [12]. Theoretically, it arises in SUSY theories with a spontaneously broken PQ symmetry. In supergravity it is necessary to have a period of inflation to dilute the very weakly interacting gravitinos. But it is thermally produced in significant numbers even after the inflation, which requires a low reheating temperature, $\leq 10^9$ GeV [13]. A similar study for axino requires a much lower reheating temperature of order TeV in which case O(GeV) axino mass is allowed. Then axino can be a DM candidate [6,7]. Here, we focus our attention on this CDM axino. Since there is no reliable constraint on the axino mass [14,7], the axino is assumed to be the LSP. Then, the most important question is whether the LSP(axino) is absolutely stable (due to R-parity conservation) or unstable. Since the stable axino case has been extensively studied [7], we restrict our attention on the R violating case.

If a CDM candidate is proposed, it is of utmost importance to devise a scheme to prove its existence experimentally as in the cases of the very light axion [15,16] and the LSP [5,11]. The axino CDM lacks this kind of possible detection mechanism due to its extremely weak interaction strength if R-parity is conserved. However, if R-parity is broken, it may be possible to detect its decay products. Therefore, it is worthwhile to study possible decay mechanisms of CDM axino. The detection possibility by the axino decay relies on the axino lifetime around $> 10^{13}$ s after the galaxy formation era.

The R-parity conservation seems to be an attractive proposal for proton stability. However, R-parity is not dictated from any deep theoretical principle. For example, if there
exists an $SU(3) \times SU(2) \times U(1)$ singlet superfield $N$ which is needed from the see-saw mechanism $L_\alpha NH_2$ where $L_\alpha$ is the lepton doublet of the $\alpha$-th family and $H_i$ is the Higgs doublet ($i = 1, 2$), we may write a renormalizable superpotential, $W_N = mN^2 + fN^3$. From the coupling to the observable sector fields for the Dirac mass coupling, $N$ is required to carry $-1$ unit of the R-parity quantum number. But this R-parity is broken by the $N^3$ term. Also, $N$ obtains a vacuum expectation value $-2m/3f$ which is too large for neutrino phenomenology. Namely, R-parity conservation is not guaranteed \textit{a priori} at the SM level. Thus, if a singlet $N$ is introduced, one should impose (at least an approximate) R-parity conservation, namely we should impose $f = 0$ in this example. If R-parity is broken, it must be done so very weakly. In this paper, for simplicity of the discussion, we restrict our attention on the bilinear R-violating terms,

$$\mu_\alpha L_\alpha H_2$$

where $\alpha = 1, 2, 3$. $\mu_\alpha$ is bounded by the eV order neutrino mass. Without an explicit statement, this bound applies to the heaviest SM neutrino, presumably the tau neutrino. With the R-parity violation, the $\nu_\tau$ mass arises from the see-saw type diagram with an intermediate zino line with two insertions of the R-parity violating $\langle \tilde{\nu} \rangle$. Also, it can get a contribution from the intermediate $\tilde{H}_2^0$ line with two insertions of $\mu_3$. These give similar conclusions and we discuss the $\mu_3$ case for an explicit illustration. Then, $\mu_3$ is bounded as

$$|\mu_3| \leq M_{\tilde{H}_2^0,\text{TeV}}^{1/2} \text{ MeV}$$

where $M_{\tilde{H}_2^0,\text{TeV}}$ is neutral Higgs mass in units of TeV. In this paper, we introduce dimensionless numbers: for a small coupling $\epsilon$, $\epsilon_{-n}$ represents it in units of $10^{-n}$, for MeV order masses $m_{\text{MeV}}$ in units of MeV, for GeV order masses $m_{\text{GeV}}$ in units of GeV, for large mass $m_{[n]}$ in units of $n$ GeV, and for super large mass $F_{12}$ in units of $10^{12}$ GeV.

The bilinear R-violating parameters have been extensively discussed in regards to the neutrino oscillation \cite{17} within the above bound (\cite{3}). In this paper, we will draw a conclusion that this is not consistent with the CDM axino, already from the observed diffuse gamma ray background.
With the bilinear R-parity violation, we expect the following decay modes of the axino

\[ \tilde{a} \rightarrow \nu + \gamma (\text{or } l^+ l^-), \quad \tilde{a} \rightarrow \nu + a, \quad \tilde{a} \rightarrow \tau^+ + \pi^-, \text{ etc.} \quad (3) \]

where \( m_{\tilde{a}} > m_\tau + m_\pi \) is assumed.

To estimate the partial decay widths, let us assume the following R violating axino interaction

\[ \mathcal{L}_{\tilde{a} \rightarrow \nu} = \epsilon_0 \phi \tilde{a} \psi, \quad \text{or} \quad i \epsilon_1 \frac{\alpha_{em}}{F_a} F^\mu\nu \tilde{a} \gamma_5 [\gamma_\mu, \gamma_\nu] \psi \]

where \( F_a \) is the axion decay constant (including the division by the domain wall number \( N_{DW} \)), \( F_\mu\nu \) is the field strength of a spin-1 field \( A_\mu \), \( \phi \) is a scalar field and \( \psi \) is a fermion field (Dirac or Majorana field). Then, the lifetime of axino becomes

\[ \tau_{\tilde{a}} = n_\psi m_{\tilde{a}, GeV}^{-1} \left( 1.32 \epsilon_0^2 \cdot P_0, \text{ or } 2.57 \times 10^{-5} \epsilon_1^2 F_{a,12}^{-2} m_{\tilde{a}, GeV}^2 \cdot P_1 \right)^{-1} \text{[sec]} \quad (5) \]

where \( n_\psi = 1, 2 \), respectively for the Dirac and Majorana \( \psi \); we neglected \( m_\phi \), and \( P_{0,1} \) are phase space factors. For a massive final fermion, \( P_{0,1}^{-1} = (1 - m_\psi^2/m_{\tilde{a}}^2)^{-1}(1 + m_\psi/m_{\tilde{a}})^{-2} \). Let us proceed to discuss several possibilities of O(GeV) axino decay.

Firstly, for the \( \tilde{a} \rightarrow \nu + a \) decay, we note that the axion multiplet couples to the standard model chiral fields, below the PQ symmetry breaking scale, as \( \exp(2iQA/F_a)W_Q \) where \( W_Q \) carries \(-Q\) units of the Peccei-Quinn(PQ) charge, and \( A \) is the axion supermultiplet. The heavy quark axion models [2] do not allow these tree level couplings since the SM fields are neutral under the PQ symmetry, but the lepton-coupling type models [3] can lead to this kind of couplings. Our interest is on the superpotential for the axino-neutrino coupling, \( m_\nu \nu \nu \exp(2iQ_\nu A/F_a) \) where \( Q_\nu \) is the PQ charge of the neutrino, and \( \mu_\alpha L_\alpha H_2 e^{iQA/F_a} \). Setting \( Q_\nu = 1/2, Q = 1/2 \), we obtain \( W = m_\nu \nu \nu e^{iA/F_a} \) and \( \mu_\alpha L_\alpha H_2 e^{iA/F_a} \) from which we obtain the relevant terms for the axino decay \( -(m_\nu A^2/2F_a^2)\nu \nu \) and \( -(\mu_\alpha A^2/2F_a^2) L_\alpha H_2 \), respectively. The R-parity violation by the vacuum expectation value of a sneutrino, \( \nu_\tilde{\nu} \equiv \langle \tilde{\nu} \rangle \), or by \( \mu_\alpha \) allow the following Yukawa couplings

\[ \mathcal{L}_{\tilde{a} \rightarrow \nu \nu} = \left( \frac{m_\nu \nu \nu}{F_a^2}, \text{ or } \frac{\mu_\alpha \nu_2}{F_a^2} \right) \times a \nu \tilde{a} \]

(6)
from which we estimate $\epsilon_0 \simeq 10^{-33}m_{\nu,eV}v_{\nu,\text{GeV}}/F_{a,12}^2$ and $10^{-25}\mu_{a,\text{MeV}}v_{2,[100]}/F_{a,12}^2$, respectively, and $v_2 = \langle H^0_2 \rangle$. Thus, in view of Eq. (3) $\epsilon_0$ is too small (i.e. $\tau_\tilde{a} \sim 10^{28}$ s) and the decay mode $\tilde{a} \rightarrow \nu + a$ is not important cosmologically.

Second, the decay $\tilde{a} \rightarrow \tau^+\pi^+$ occurs through the bilinear R-parity violating term $\mu_3 L_3 H_2$ with $\alpha = 3$, given in Eq. (1), which allows the mixing of $\tilde{\tau}$ and $H^-_1$. Then, the coupling $(m_\tau/F_a)\tilde{\tau}^+\tau a$ and the Yukawa coupling $\sim (m_d/v_1)qd^c H^-_1$ give an effective interaction (4) with

$$\epsilon_0 = \frac{m_\tau f_\pi m^2_\tau}{F_a v_1} \frac{1}{M^2_\tau} \Delta M^2_{R\text{PV}} \frac{1}{M^2_{H^-_1}}$$

(7)

where $\Delta M^2_{R\text{PV}}$ is the $\tilde{\tau}$--$H^-_1$ mixing parameter. The effective interaction (4) with $\psi = \tau$ and $\phi = \pi^+$ arises from the tree diagram with the $\tilde{\tau} - H^-$ mixing insertion in the intermediate scalar propagator with the four external fermions, $\tilde{a}$, $\tau$, $\bar{d}$, and $u$. In estimating $\epsilon_0$, we used the PCAC relation in obtaining the matrix element $\langle 0 | \bar{d}_R u_L | \pi^+ \rangle \sim f_\pi m^2_\pi / m_d$. The superpartner masses for the gauge hierarchy solution are around 100 GeV. The bound on the stau-charged Higgs mixing parameter $\Delta M^2_{R\text{PV}}$ is bounded from the tau neutrino mass bound, $m_\nu < 1$ eV. For the R-parity violating bilinear coupling $\mu_3 L_3 H_2$, the mixing parameter is estimated as $\Delta M^2_{R\text{PV}} = 2\mu_3^2$. Using Eq. (2), we obtain $\Delta M^2_{R\text{PV}} < 2\mu_{\text{TeV}} M_{H_2^\text{a,TeV}}^{1/2}$ GeV$^2$. Then, we estimate $\epsilon_0 < 3.71 \times 10^{-25}[\cos \beta]^{-1} F_{a,12}^{-1} M_{H^-_1,[100]}^{-2} M_{H^-_1,[100]}^{-2} M_{H_2^\text{a,TeV}}^{1/2}$ for the $\tau\pi$ decay mode, and the axino lifetime must satisfy a bound

$$\tau_\tilde{a} \geq 0.959 \times 10^{27} [\text{sec}] \frac{M^4_{\tau,\text{TeV}} M^4_{H^-_1,\text{TeV}}}{m_{\tilde{a},\text{GeV}} \mu_{\text{TeV}}^{2} M_{H_2^\text{a,TeV}}^{1/2}} P^{-1}_0$$

(8)

where the MSSM parameter $\tan \beta = v_2/v_1$, and we assume that $P_0$ is nonzero, i.e. the O(GeV) axino has mass $m_{\tilde{a}} > 1.92$ GeV.

Third, we note that the interaction $\nu\tau\tilde{\tau}a$, arising from stau intermediate state and R-parity violating insertion of neutrino--$\tilde{B}/\tilde{W}$ mixing, is not important.

Finally, we note that the decay $\tilde{a} \rightarrow \nu + \gamma$ (or $l^+l^-$) occurs through the anomaly term

$$\mathcal{L}_{a\gamma\nu} = \frac{i c_{a\gamma\nu} \alpha_{em}}{16\pi F_a} \cdot \frac{c_\mu a}{\mu} \cdot \bar{\nu}_\alpha \gamma_5 [\gamma^\mu, \gamma^\nu] \tilde{a} F_{\mu\nu}$$

(9)
where $c_{a\gamma\gamma}$ is the axion-photon-photon coupling which depends on models \[18\], and $F_{\mu\nu}$ is the photon field strength, and the photino-neutrino mixing parameter $c'\mu_{\alpha}/\mu$ has been introduced. Note that $c'$ is O($<1$) and $\mu_\alpha$ is O($<\text{MeV}$). It turns out that this photon mode constitutes the most important contribution in the axino decay. The gluon anomaly term can be considered, but it is not important since we must consider intermediate gluino and squark lines. From the interaction Eq. (9), we estimate

$$\epsilon_1 = 1.99 \times 10^{-7} c_{a\gamma\gamma} c' \mu_{\alpha,\text{MeV}} \mu^{-1}_{\text{[100]}},$$

(10)

giving the axino lifetime

$$\tau_{\tilde{a}} \simeq 9.8 \times 10^{17} \text{[sec]} \ c_{a\gamma\gamma}^{-2} c'^{-2} \mu_{\alpha,\text{MeV}}^{-2} \mu^{-1}_{\text{[100]}} F_{a,12}^2 m_{\tilde{a},\text{GeV}}^{-3}.$$  

(11)

The RHS of Eq. (11) can fall in the cosmologically interesting scale for $F_{\tilde{a}}$ slightly smaller than $10^{12}$ GeV and $m_{\tilde{a}} = \text{O(GeV)}$.

This leads us to the estimation of the cosmological abundance of axino. The decoupling temperature of axino is of order the PQ symmetry breaking scale \[12\,7\]. Thus, for an O(GeV) axino, inflation must end below the PQ symmetry breaking scale so that axinos produced at the decoupling temperature is sufficiently diluted. However, if the reheating temperature after inflation were high enough, a significant number of axinos would have been reproduced thermally and can constitute cold dark matter. Here, we are interested in this thermally produced axinos after inflation. In this scenario, the number density depends on axino mass and reheating temperature $T_R$. For O(GeV) axino in R-conserving theories the reheating temperature bound is $T_R \leq 100 - 1000$ GeV from the condition that the thermally produced axinos do not exceed the critical energy density as estimated in Ref. \[7\]. On the other hand, if there exists R-violating terms, then the lightest neutralino decays to $l^-l^+\nu$ within 1 s for $\mu_\alpha/\mu < 10^{-6}$, which occurs through the diagram $\chi^0_1 \to W^\mp \chi^\pm$ and the mixing of $\chi^\pm$ and $l^\mp$. Namely, a neutralino predominantly decays to SM particles, which is harmless at a later epoch. Thus, to produce O(GeV) axino copiously in R-violating theories, reheating temperature must be raised.
In the present estimation of reheating temperature $T_R$, we ignore the gluino decay to axino since R-parity is broken. Taking into account the photon thermalization after the decay of MSSM SUSY particles and $e^+e^-$ annihilation, the axino energy density at present is $\rho_{\tilde{a}}(T_{\gamma}) = m_{\tilde{a}}(2\pi^2/45) \cdot (43/11) \cdot T_{\gamma}^{3Y_{\tilde{a}}^{TP}}(T_R)$ where the thermal production of axino $Y_{\tilde{a}}^{TP}$ is calculated just from the scattering processes. Thus, representing $\rho_{\tilde{a}} = \Omega_{\tilde{a}} \times$ (the critical energy density), we have $m_{\tilde{a}}Y_{\tilde{a}}^{TP} \simeq 0.72\,\text{eV}(\Omega_{\tilde{a}}h^2/0.2)$. For $F_a \sim 10^{11}\,\text{GeV}$, $\Omega_a \sim 0.3$ and O(GeV) axino, $Y_{\tilde{a}}^{TP} \sim 0.5 \times 10^{-9}$ and we can read $T_R$ at around 200 GeV from Fig. 1 of Ref. [7]. In this region, if one considers the gluino decay in R-conserving theories, $T_R$ should be a factor $\sim 2$ smaller. The neutralino decay in R-conserving case is not important in this region, but can be very important for $T_R < 100\,\text{GeV}$ [7].

The present dark matter density in the galactic halo requires a significant amount of dark matter. In the present case, there is the other candidate for dark matter, the axion. For the axion CDM, we are restricted to $F_a \sim 10^{12}\,\text{GeV}$. But with the CDM axino, $F_a$ can be lower as far as $F_a > 10^9\,\text{GeV}$. If the axino lifetime is of order the age of the universe, then there remains a significant number of axinos which can be detected in experiments in search of proton decay. The interesting decay mode for axino detection is the $\nu\gamma$ mode.

For $10^3\,\text{sec} < \tau_{\tilde{a}} < t_{\text{rec}}$ where $t_{\text{rec}}$ is the time at the recombination, there can be an allowed region $\tau_{\tilde{a}} > t_{\text{min}}$ so that the decay products are not copious enough to dissociate the light nuclei. After the time of recombination, photons are not effective to scatter off the neutral particles, and hence $t_{\text{min}} \leq t_{\text{rec}}$. Since we are considering the axino lifetime $> 10^{13}\,\text{s}$, the late decaying axino is safe from destroying light nuclei.

If axino decays to $\nu + \gamma$, the underground neutrino detectors can detect the photon. The photon energy($\equiv E_{\gamma}$) of 10 GeV, i.e. axino mass of 20 GeV, is the boundary for using different search types for the Cherenkov rings. If $E_{\gamma} < 10\,\text{GeV}$, the Compton scattering on an atomic electron kicks out a high energy electron whose Cherenkov radiation can be detected. If $E_{\gamma} > 10\,\text{GeV}$, then $e^+e^-$ pair production off nucleus dominates and the Cherenkov rings from these pair can be detected.

From the super-K detector, one establishes the proton lifetime bound of $10^{33}\,\text{seconds}$
These detectors use baryons in water, \( n_B = N_A/cm^3 \) where \( N_A = 6.023 \times 10^{23} \). On the other hand axino as CDM now has the local number density of order \( n_{\tilde{a}} = 0.3m_{\tilde{a},GeV}^{-1}/cm^3 \), giving the ratio \( n_{\tilde{a}}/n_B \sim 5 \times 10^{-25}m_{\tilde{a},GeV}^{-1} \). If we require the detection rate of axino decay the same as that of proton decay, we obtain \( (\tau_p/n_{\tilde{a}}/\tau_{\tilde{a}}n_p) \simeq 1 \). Thus, axinos are detectable at the rate of counting proton decay debris with proton lifetime of \( 10^{33} \) seconds \[19\] if 

\[
\tau_{\tilde{a}} \simeq \frac{1.6 \times 10^{16}}{m_{\tilde{a},GeV}} \text{[sec]}. \tag{12}
\]

Since we have not observed this kind of events, we obtain \( \tau_{\tilde{a}} > 1.6 \times 10^{16}m_{\tilde{a},GeV}^{-1} \text{ sec}^{-1} \).

However, the most stringent bound comes from the diffuse gamma ray background. The classical study on this effect has been published more than 20 years ago \[20\]. The observed flux \( F_\gamma \) is bounded by \[21\] 

\[
\frac{dF_\gamma}{d\Omega} \leq (10^{-3} \sim 10^{-5}) \ E_{GeV}^{-1} \ cm^{-2}sr^{-1}sec^{-1} \tag{13}
\]

where \( E \) is the decay photon energy at present. The figure \( 10^{-3} \) is for the conservative bound applicable to the whole observed range of \( E \). For \( E = 1\text{MeV} \sim 10\text{GeV} \) where we are interested, \( 10^{-5} \) gives a good fit to the data.

On the other hand, the decay of axinos produces the diffuse photon flux at present, for \( 0 \leq E \leq m_{\tilde{a}}/2 \)

\[
\frac{dF_\gamma}{d\Omega} = \frac{3n_{\tilde{a}}}{8\pi} \left( \frac{E}{E_0} \right)^{3/2} e^{-(E/E_0)^{3/2}} \tag{14}
\]

where \( E_0 = (m_{\tilde{a}}/2)(\tau_{\tilde{a}}/t_0)^{2/3} \) and \( t_0 \) is the age of the universe (\( \sim 4 \times 10^{17} \) s).

For \( t_{\text{rec}} < \tau_{\tilde{a}} < t_0 \), most axinos have decayed and the flux has a peak at \( E = E_0 \) with a value \( n_{\tilde{a}}/8\pi e \). Assuming the critical axino density, we have a condition that the photons from axinos decay do not exceed the observed flux,

\[
(\tau_{\tilde{a}}/t_0)^{2/3} < 1.4 \times 10^{-7} \Omega_0 h^2 \tag{15}
\]

which is inconsistent with the condition \( \tau_{\tilde{a}} > t_{\text{rec}} \) (\( \sim 10^{15} \) s).

For \( \tau_{\tilde{a}} > t_0 \), axino decays are increasing at present and the maximum flux is \( (3n_{\tilde{a}}/8\pi)(t_0/\tau_{\tilde{a}})e^{-t_0/\tau_{\tilde{a}}} \) at \( E = m_{\tilde{a}}/2 \). Comparing this with Eq. \[13\], we obtain
\[ \tau_{a,ec} > 3.9 \times 10^{21-26} \Omega_a h. \]  

For the region satisfied by Eq. (16), the bound on \( \mu_\alpha \) is very stringent, i.e. less than \( O(10^{2-3} \text{ eV}) \), hence the idea for neutrino mass generation via bilinear R-parity violation is not consistent with CDM axino. A very conservative upper bound on \( \mu_\alpha \) is 1 keV.

In conclusion, we searched for the detection possibility of axinos as CDM with \( T_R \sim 200 \text{ GeV} \). The diffuse gamma ray background gives a very strong bound on bilinear R-parity violating parameter \( \mu_\alpha \). Even if \( \mu_\alpha \) is of order keV, it can be detected by diffuse gamma ray background observation. On the other hand, with \( O(\text{keV}) \) \( \mu_\alpha \) SUSY generation of neutrino oscillation parameters through bilinear R-parity violation is not achievable with CDM axino.

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