Axinos as Cold Dark Matter

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We show that axinos produced in the early Universe in the decay of the lightest neutralinos are a compelling candidate for *cold* dark matter. We argue that axinos may well provide the main component of the missing mass in the Universe because their relic density is naturally of the order of the critical density. [S0031-9007(99)09187-5]

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Axinos are predicted to exist in models involving low-energy supersymmetry (SUSY) and the Peccei-Quinn (PQ) solution [1] to the strong CP problem. They are supersymmetric partners of axions [2–4]. SUSY is widely considered as perhaps the most attractive framework in which the Fermi scale can be naturally connected with physics around the Planck scale. The Peccei-Quinn mechanism, which invokes a global, chiral U(1) symmetry group spontaneously broken at some high energy scale $f_a \sim 10^{11}$ GeV remains the most compelling way of solving the strong CP problem.

Axinos are thus very strongly motivated. Despite this, they have received much less attention in the literature than other SUSY partners. Of particular importance to both experimental searches and cosmology is the lightest supersymmetric particle (LSP). Axinos, being massive as well as electrically and color neutral, are an interesting candidate for the LSP. One of the most important consequences of supersymmetry for cosmology in the presence of unbroken R parity is the fact that the LSP is stable and may substantially contribute to the relic mass density in the Universe. If the contribution is of the order of the critical density $\rho_{\rm crit}$, such a particle is considered an attractive dark matter (DM) candidate. Current models of the formation of large structures as well as the measured shape of their power spectrum strongly suggest that a dominant contribution to the dynamical component of the total mass-energy density is that from cold DM [5].

In the minimal SUSY model (MSSM), the LSP is usually *assumed* to be the lightest of the four neutralinos. The lightest neutralino χ is a mixture $\chi = Z_{11}\widetilde{B} + Z_{12}\widetilde{W}_3 + Z_{13}\widetilde{H}_b^0 + Z_{14}\widetilde{H}_t^0$ of the respective fermionic partners (denoted by a tilde) of the electrically neutral gauge bosons B and W_3, and Higgs bosons H_b and H_t. It is well known that the neutralino's relic density ρ_χ is often of order $\rho_{\rm crit}$. At high temperatures in the early Universe a thermal population of neutralinos remains in equilibrium with the thermal bath. When their annihilation rate into ordinary matter becomes smaller than the expansion of the Universe, they decouple from the thermal bath, or "freeze-out" [5]. The freeze-out temperature is typically small compared to the neutralino's mass, $T_f \sim m_\chi/20$ [5]. Relic neutralinos are therefore always nonrelativistic, or cold, DM candidates [6,7].

Many bounds on the neutralino mass and the parameter space of SUSY models have been derived by requiring that the neutralino abundance does not "overclose" the Universe. This requires satisfying the condition $\Omega_\chi h^2 \lesssim 1$ [5], where $\Omega_\chi = \rho_\chi/\rho_{\rm crit}$ and h is related to the Hubble parameter, $H_0 = 100h$ (km/sec)/Mpc. This condition comes from considering the evolution of a thermal population of LSPs in the expanding Universe and, in particular, their annihilation cross section at decoupling. The annihilation has to be efficient enough to deplete the LSP number density to acceptable values. Cosmological properties of the neutralino as the LSP and DM are often taken into account in many studies of SUSY, including present and future collider and DM searches.

In this Letter we will show that this standard paradigm changes dramatically if one assumes that it is the axino, rather than the lightest neutralino, which is the LSP. This assumption is well justified. Experimental searches at LEP have now pushed the neutralino mass limit considerably, above about 28 GeV in the MSSM [8]. In more restrictive, and perhaps more motivated, models the bound can be much higher. For example, in the constrained MSSM (CMSSM) [9], also known as the effective minimal supergravity model, it is already around 42 GeV [10]. On the other hand, it is worth noting that these bounds strongly depend on the (well-motivated) assumption that the masses of the gauginos (the fermionic partners of the gauge bosons) are equal at a grand-unified scale. In the absence of this condition one recovers a robust model independent bound $m_\chi \gtrsim 3$ GeV [11] coming from requiring $\Omega_\chi h^2 \lesssim 1$—a neutralino version of the so-called Lee-Weinberg bound [5].

In contrast to the neutralino, the mass of the axino, $m_{\tilde{a}}$, remains not only virtually unconstrained experimentally but also theoretically easily imagined in the few to tens of GeV range which we are interested in [12]. This is illustrated by the following examples. In the supersymmetric version of the heavy quark axion model [the

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Kim-Shifman-Vainstein-Zakharov (KSVZ) model [3]], the axino mass can arise at a one-loop level with a SUSY breaking A-term insertion at the intermediate heavy squark line. Then, we expect $m_{\tilde{a}} \sim (f_Q^2/8\pi^2)A$ where f_Q is the Yukawa coupling of the heavy quark to a singlet field containing the axion. In a straightforward SUSY version of the Dine-Fischler-Srednicki-Zhitnitskii (DFSZ) [4] model axino mass is typically rather small, $m_{\tilde{a}} \sim \mathcal{O}(\text{keV})$ as has been pointed out in Ref. [13]. However, in addition to the above inevitable contributions to the KSVZ and DFSZ axino masses, there can be other contributions from superpotentials involving singlet fields. For example, if the PQ symmetry is assumed to be broken by the renormalizable superpotential term (KSVZ or DFSZ models) $W = fZ(S_1S_2 - f_a^2)$ where f is a coupling, and Z, S_1, and S_2 are chiral fields with PQ charges of 0, $+1$, and -1, respectively, then the axino mass can be at the soft SUSY breaking mass scale. The axino mass arises from the mass matrix of $\tilde{S}_1$, $\tilde{S}_2$, and $\tilde{Z}$,

$$\begin{pmatrix} 0, & m_{\tilde{a}}, & ff_a \\ m_{\tilde{a}}, & 0, & ff_a \\ ff_a, & ff_a, & 0 \end{pmatrix}. \tag{1}$$

Certainly, the tree level axino mass is zero if $\langle Z \rangle = 0$. However, with soft terms included, there appears a linear term in Z, $V = |f|^2(|S_1|^2 + |S_2|^2)|Z|^2 + (AfS_1S_2Z + \text{H.c.})$; thus $\langle Z \rangle$ is of order A/f, and the axino mass can arise at the soft mass scale. A complete knowledge of the superpotential is necessary to pin down the axino mass [12,14]. Therefore, generically it is not unreasonable to consider the axino mass scale of order tens of GeV.

One severe bound of $m_{\tilde{a}} \lesssim 2$ keV has been derived by Rajagopal, Turner, and Wilczek [13]. This bound arises from requiring that the "primordial" axinos, produced along with the axions in the very early Universe when the PQ symmetry becomes broken around the scale $f_a \sim 10^{11}$ GeV, do not contribute too much to the total relic abundance of the Universe, $\Omega_{\tilde{a}}h^2 < 1$. As was noted in Ref. [13], the bound $m_{\tilde{a}} \lesssim 2$ keV (which would make the axino a *warm* dark matter candidate) can be evaded by assuming that, at temperatures below f_a, the Universe underwent a period of inflation and that the temperature of subsequent reheating was sufficiently below f_a. These assumptions are not too radical and have now become part of the standard cosmological lore [5]. The same remedy is also usually used to solve the analogous problem with primordial gravitinos [15].

Once the number density of the primordial axinos has been diluted by inflation, they can again be produced in the decays of heavier particles [16]. Since axino's couplings to matter are strongly suppressed by $1/f_a$, all heavier SUSY partners first cascade decay to the next-to-lightest SUSY partner (NLSP). A natural candidate for the NLSP is the lightest neutralino. As stated above, the neutralino freezes out at $T_f \sim m_\chi/20$. If it were the LSP, its comoving number density n_χ after freeze-out would remain nearly constant. In the scenario considered here, the neutralino, after decoupling from the thermal equilibrium, will subsequently decay into the axino via, e.g., the process

$$\chi \to \tilde{a}\gamma\,. \tag{2}$$

This process was already considered early in Ref. [16] (see also [13]) in the limit of a photino NLSP and only for both the photino and the axino masses assumed to be very low, $m_{\tilde{\gamma}} \leq 1$ GeV and $m_{\tilde{a}} \leq 300$ eV, the former bound now excluded by LEP searches. In that case, the photino lifetime was typically much larger than 1 sec thus normally causing destruction of primordial deuterium produced during nucleosynthesis by the energetic photon. Avoiding this led to a lower f_a-dependent bound on the mass of the photino in the MeV range [16].

In this Letter, we show that the conclusions and bounds of Refs. [13,16] can be evaded if one considers both the axino and the neutralino in the GeV mass range. In this regime the neutralino decays into the axino typically before nucleosynthesis, thus avoiding the problems considered in Refs. [13,16]. The resulting nonthermally produced axino will be a *cold* DM candidate.

NLSP freeze-out.—The effective coupling of the neutralino with the axino is very much weaker than that of its interactions with other matter. Therefore the neutralino's decoupling is not different from the case when it is the LSP. The freeze-out temperature T_f is determined by the annihilation cross section $\sigma(\chi\chi \to \text{ordinary matter})$ and is normally well approximated by iteratively solving the equation for $x_f = T_f/m_\chi$

$$\frac{1}{x_f} = \ln\left[\frac{m_\chi}{4\pi^3} M_P \sqrt{\frac{45x_f}{N_F}} \langle \sigma v_{\text{rel}} \rangle (x_f)\right], \tag{3}$$

where $M_P = 1.22 \times 10^{19}$ GeV, N_F is the effective number of relativistic degrees of freedom, and $\langle \sigma v_{\text{rel}} \rangle$ is the averaged product of annihilation cross section and the annihilating neutralinos' relative velocity [6]. The iterative procedure Eq. (3) is typically well justified by the smallness of the scaled freeze-out temperature x_f [$x_f = \mathcal{O}(1/20)$ [5]]. Without further decay, the neutralino comoving number density n_χ would have remained basically constant.

Neutralino decay into axino.—In the scenario considered here, the NLSP neutralino comoving number density after freeze-out will continue to decrease because of its decay (2) into the axino LSP. This is presented in Fig. 1. At $T/m_\chi \equiv x < x_f$ and for $\Gamma_\chi \ll H$, n_χ is roughly given by

$$n_\chi(x) \simeq n_\chi^{\text{eq}}(x_f) C(x) \exp\left[-\int_x^{x_f} \frac{dx'}{x'^3} \frac{\langle \Gamma_\chi \rangle_{x'}}{H(m_\chi)}\right], \tag{4}$$

where $C(x)$ takes into account the temperature difference between the photons and the decoupled neutralinos and $\langle \Gamma_\chi \rangle_x$ is the thermally averaged decay rate for the neutralino at x, while $H(m_\chi) = \sqrt{(2\pi)^3 N_F/45}\, m_\chi^2/M_P$.

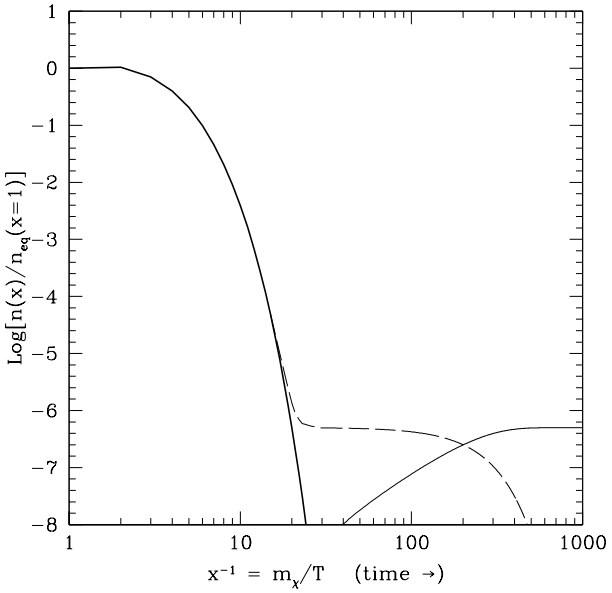

FIG. 1. A schematic of the behavior of the comoving number density: thermal equilibrium (thick solid), NLSP neutralino (dash), and LSP axino (thin solid).

The interaction of the axino and the gaugino component of the neutralino is given by the term $\alpha_Y C_{aYY}/(4\pi \times \sqrt{2} f_a)[(\Phi B_\alpha B^\alpha)_{\theta\theta} + (\Phi^* \bar{B}_{\dot\alpha} \bar{B}^{\dot\alpha})_{\bar\theta\bar\theta}] + \alpha_2 C_{aWW}/(4\pi \times \sqrt{2} f_a)[B \to W_3]$, where Φ is the chiral supermultiplet containing the axion and the axino, while the vector multiplet B (W_3) corresponds to the $U(1)_Y$ [$SU(2)_L$] gauge group with a coupling strength α_Y (α_2). The coefficients C_{aYY} and C_{aWW} are model dependent. Usually, one performs chiral transformations so that there is no axion-$W_{\mu\nu}\tilde{W}^{\mu\nu}$ coupling. This is equivalent to giving vanishing Peccei-Quinn charges to left-handed doublets. In this case, $C_{aWW} = 0$ and $C_{aYY} = C_{a\gamma\gamma}$. In the DFSZ model with (d^c, e) unification $C_{aYY} = 8/3$, and in the KSVZ model for $e_Q = 0$, $-1/3$, and $2/3$, $C_{aYY} = 0$, $2/3$, and $8/3$, respectively [17]. Below the QCD chiral symmetry breaking scale, $C_{a\gamma\gamma}$ and C_{aYY} are reduced by 1.92.

We first concentrate on the dominant decay channel (2) which is always allowed as long as $m_{\tilde a} < m_\chi$. We will comment on other channels below. The decay rate for the process (2) is given by

$$\Gamma = \frac{\alpha_{em}^2 N^2}{256\pi^3} C_{a\chi\gamma}^2 \frac{m_\chi^3}{f_a^2} \left(1 - \frac{m_{\tilde a}^2}{m_\chi^2}\right)^3, \qquad (5)$$

where α_{em} is the electromagnetic coupling strength, $C_{a\chi\gamma} = (C_{aYY}/\cos\theta_W) Z_{11}$, and N is a model dependent factor [$N = 1(6)$ for the KSVZ (DFSZ) model].

In the theoretically most favored case of a nearly pure B-ino [9,18], the neutralino lifetime can be written as

$$\tau \simeq 0.76 \text{ sec} \frac{1}{C_{aYY}^2} \left(\frac{f_a/N}{10^{11} \text{ GeV}}\right)^2 \left(\frac{100 \text{ GeV}}{m_\chi}\right)^3, \qquad (6)$$

where the phase space factor from Eq. (5) has been neglected.

A comment is in order regarding a plausible range of f_a [19]. A somewhat model dependent lower bound $f_a \gtrsim 10^9$ GeV comes from astrophysical considerations, most notably from requiring that axions do not overly affect processes in globular clusters, in red giants, and in supernova 1987A. An upper limit of $\sim 10^{12}$ GeV is quoted in the context of cold axion energy density. A range $10^{9-10} \lesssim f_a \lesssim 10^{12}$ GeV gives cosmologically interesting values for the relic density of axions.

There are hard photons produced in the χ decay (2) but these thermalize via multiple scattering from background electrons and positrons ($\gamma + e \to \gamma + \gamma + e$) [16,20]. The process proceeds rapidly for electromagnetic background temperatures above 1 MeV at which point background $e - \bar e$ pairs annihilate. To ensure efficient thermalization and to avoid problems with photodestruction of light elements produced during nucleosynthesis, we require that the neutralino lifetime Eq. (6) is sufficiently less than about 1 sec (which also coincides with temperatures of about 1 MeV). A modest requirement $\tau \lesssim 10^{-1}$ sec leads, in the case of the neutralino with a large B-ino component (a neutralino is never a *pure* B-ino state), to an upper bound on f_a which depends on m_χ. At larger m_χ additional decay channels open up, most notably $\chi \to Z\tilde a$. We can see that, for large enough values of the B-ino mass, the decay (2) will take place almost entirely before nucleosynthesis.

The case of Higgsino-dominated neutralino as the NLSP is probably less attractive and also more model dependent. First, the lifetime (6) is now typically significantly larger, easily extending into the period of nucleosynthesis and beyond. This is caused by the suppression of the B-ino component through which the decay proceeds. [See the form of $C_{a\chi\gamma}$ below Eq. (5).] Much lower values of f_a could be considered as a remedy for much larger Higgsino masses and/or additional (model dependent) decay channels involving Higgs in the final state.

In the MSSM, the Higgsino relic abundance in the mass range allowed by LEP is typically very small, thus leading to even smaller $\Omega_{\tilde a} h^2$. One possibility would be to consider rather obese Higgsino masses, above roughly 500 GeV, where $\Omega_\chi h^2 \gtrsim 1$ again. A resulting value of $\Omega_{\tilde a} h^2$ would then depend on the actual size of the Higgsino component in the decaying neutralino, as well as on the axion/axino model which would determine the couplings of the decay channels to the Higgs final state. One could also allow for a Higgs singlet and assume that its fermionic partner is mostly the NLSP.

The resulting axino relic abundance today is simply given by

$$\Omega_{\tilde a} h^2 = \frac{m_{\tilde a}}{m_\chi} \Omega_\chi h^2 \qquad (7)$$

since all the neutralinos have decayed into axinos. The axino will normally be produced relativistic (except when the ratio of the neutralino-axino mass difference to the axino mass is small) but will later redshift due to the

expansion of the Universe and become cold by the time of matter dominance. It is worth noting that the neutralinos will not dominate the energy density of the Universe before decaying; to see this we have to compare its lifetime, given by Eq. (6), with the time when the equality $\rho_\chi = \rho_{\rm rel}$ takes place. This time is easily computed neglecting the decay and amounts to 10^6–10^7 sec; we see therefore that the neutralinos never dominate the energy density and matter domination starts only after the produced axinos become nonrelativistic.

With the neutralino lifetime (6) significantly larger than 10^{-6} sec they escape from the high-energy detectors. Thus SUSY phenomenology remains basically unchanged from the usual case where the neutralino is the LSP. In particular, accelerator mass bounds on supersymmetric particles apply. But cases previously excluded by the constraint $\Omega_\chi h^2 < 1$ can now be allowed via Eq. (7). This leads to a possibly dramatic relaxation of the parameter space of SUSY models. For example, in the MSSM the region of large Higgsino masses mentioned previously has been considered as cosmologically excluded but now can again be allowed if one takes a sufficiently small ratio $m_{\tilde{a}}/m_\chi$. In the gaugino region it is normally reasonable to expect that, in order to satisfy $\Omega_\chi h^2 \lesssim 1$, there should exist at least one sfermion with mass roughly below 500 GeV [18]. In the CMSSM, the same requirement often provides upper bounds on the unified, or common, scalar and gaugino masses of order 1 TeV [9] over a large range of parameters. Both bounds which hold for a gaugino-like LSP away from annihilation resonances can now be readily relaxed.

So far we have considered the neutralino as the NLSP. This assumption can easily be relaxed to accommodate any other superpartner, either neutral or carrying an electric or color charge, provided that its effective coupling with the axino is of order $\sim 1/f_a$. All one needs to require is that the NLSP decays into the axino and that the thermalization of an accompanying ordinary particle takes place before nucleosynthesis. If this can be achieved then cases previously believed to be excluded as corresponding to non-neutral LSPs can now again be allowed.

In conclusion, we have shown that the axino can easily be the LSP with a mass in the GeV range. Such an axino would be a *cold* dark matter candidate for a natural range of the Peccei-Quinn scale f_a. It is not impossible that, with or without its nonsupersymmetric partner, the axino could dominate the matter in the Universe.

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