

Fermionic partner of Quintessence field as candidate for dark matter

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(Dated: March 25, 2002)

Quintessence is a possible candidate for dark energy. In this paper we study the phenomenologies of the fermionic partner of Quintessence, the Quintessino. Our results show that, for suitable choices of the model parameters, the Quintessino is a good candidate for cold or warm dark matter. In our scenario, dark energy and dark matter of the Universe are connected in one chiral superfield.

Recent data from type Ia supernovae [1] and cosmic microwave background (CMB) radiation [2] have provided strong evidences for a spatially flat and accelerated expanding universe at the present time. In the context of Friedmann-Robertson-Walker cosmology, this acceleration is attributed to the domination of a scalar, dubbed dark energy [3]. The simplest candidate for dark energy seems to be a remnant small cosmological constant. However, many physicists are attracted by the idea that dark energy is due to a dynamical component, such as a canonical scalar field $\phi$, named Quintessence [4]. The data from WMAP [2] indicate that the potential of the Quintessence field around present epoch should be very flat. Consequently its effective mass will be extremely small, $m_{Q} \lesssim H_{0} \sim 10^{-33}$ eV.

When coupled to the ordinary matter, Quintessence boson will induce a long range force and cause the physical constant vary with time. The current experiments have put strong limits on these couplings. In Ref. [5], Carroll considered a possibility of suppressing such couplings by imposing an approximate global shift symmetry, $Q \to Q + C$, where $C$ is a constant. In this case, Quintessence behaves like a Pseudo-Goldstone boson. With this approximate symmetry, Carroll [5] further explicitly proposed an interaction of the form

$$\mathcal{L}_{Q\gamma\gamma} = \frac{c}{M_{pl}} QF_{\mu\nu} \tilde{F}^{\mu\nu} , \quad (1)$$

where $F_{\mu\nu}$ is the electromagnetic field strength tensor and $\tilde{F}_{\mu\nu}$ is its dual. The current data do not strongly constrain the coefficient $c$, $c \lesssim 3 \times 10^{-2}$, which interestingly opens a possibility to detect the effects of Quintessence on the rotation of the plane of polarization of light coming from distant sources in the near future.

From the point of view of particle physics, fundamental interactions, as widely believed, may be supersymmetric (SUSY) beyond the TeV scale. In a SUSY theory, the Quintessence boson will be accompanied by a 2-component neutral fermion ($\tilde{Q}$), Quintessino, and a scalar ($\sigma_{\gamma}$), the Squintesson. The Quintessence, as argued above, is taken as a pseudo-Goldstone boson, so one would expect its fermionic superpartners also light. A naive dimensional analysis in a model independent way indicates $m_{\tilde{Q}} \sim \mathcal{O}(M_{SUSY}^{2}/\Lambda)$, where $\Lambda$ corresponds to the decay constant of the Pseudo-Goldstone boson, the Quintessence here. It may be possible, however, in the similar way as for axino [6] and Majorino [7] that the Quintessino receives a large mass in a specific model. In this paper we will study the phenomenologies of Quintessino and, for our discussions, we take its mass as a free parameter.

In the minimal supersymmetric standard model (MSSM) with a conserved R-parity, the lightest SUSY particle (LSP), taken usually as the lightest neutralino, $\chi_{0}^{0}$, is stable and serves as an ideal candidate for cold dark matter (CDM). However, if the Quintessino is lighter than $\chi_{0}^{0}$, the interaction in Eq. (1) with $c \sim 10^{-2}$ leads the $\chi_{0}^{0}$ decay away so that the neutralino can not serve as CDM, unless the coefficient $c$ is smaller than $c < 10^{-6}$ and the neutralino is actually stable. We further study the possibility that the $\chi_{0}^{0}$ decay product, the Quintessino, forms dark matter of the Universe. However, the released electromagnetic energy from the neutralino decay will be too much to be compatible with the Big Bang nucleosynthesis (BBN) [8] and CMB [9] data. To resolve the conundrum, we introduce new couplings between the Quintessence and the matter fields. We will show that the Quintessino can serve as a good candidate for cold or warm dark matter for suitable choices of the parameters. In our model, the dark energy, Quintessence, and dark matter, Quintessino, are unified in one chiral superfield, similar to the quark and lepton in the same representation of a gauge group in the unified theory.

We start our discussions with supersymmetrizing Eq. (1). The relevant part of the Lagrangian responsible for the neutralino decay is given by

$$\mathcal{L}_{\tilde{Q}\gamma\gamma} = \frac{c}{M_{pl}} \bar{\tilde{Q}} \gamma^{5} \sigma^{\mu\nu} \tilde{F}_{\mu\nu} . \quad (2)$$

Taking the neutralino to be Bino-like, a simple calculation gives its decay width

$$\Gamma(\tilde{B} \to \tilde{Q} \gamma) = \frac{1}{2\pi} \left( \frac{c}{M_{pl}} \right)^{2} \cos^{2} \theta_{W} m_{\tilde{B}}^{3} (1 - x^{2})^{3} , \quad (3)$$

with $x = \frac{m_{\tilde{Q}}}{m_{\tilde{B}}}$. Taking the coefficient $c$ to be $3 \times 10^{-2}$, $m_{\tilde{B}}$ around the electroweak scale and assuming $m_{\tilde{Q}}$ smaller than $m_{\tilde{B}}$, the lifetime of the Bino will be in the range of $10^{7} - 10^{12}$ sec, which is much shorter than the age of the Universe. To stabilize the Bino, so that it forms the CDM of the Universe, the coupling constant $c$ has to be smaller than $10^{-6}$. In this case, however, it may become impossible to detect the Quintessence effect in the polarization studies, as suggested by Carroll.
We now study the possibility whether Quintessino can form the dark matter (DM). A similar mechanism for gravitino and graviton DM produced in the weakly interacting massive particle (WIMP) decays has been studied in Ref. [10]. For the process $\bar{B} \to \bar{Q}\gamma$, taking place long after BBN, the total energy release in photons is severely constrained by the BBN observation [11]. The CMB data also constrain the energy injection in form of photons in order not to distort the Planckian CMB spectrum [12]. The electromagnetic energy released from the Bino decay can be written as

$$\xi_{EM} = \epsilon_{EM} N_B = 1.5 \times 10^{-9} \text{GeV} \frac{1 - x^2}{x}, \quad (4)$$

where $\epsilon_{EM}$ is the initial electromagnetic energy released in each Bino decay and $N_B = n_B/n_{BG}$ is the number density of Binos normalized to the number density of the background photons. Demanding Quintessino gives the correct DM density, $\Omega_{DM} = 0.23$, $N_B$ is given by [10] $N_B = 3.0 \times 10^{-12} \frac{\tau_{\bar{B}}}{m_{\bar{Q}}} \left[ \frac{\Omega_{DM}}{0.23} \right]$. Taking $c = 3 \times 10^{-2}$, the lifetime and the energy release are generally greater than $10^9$ sec and $10^{10}$ GeV respectively, which are, unfortunately, excluded by the BBN [8] and CMB [9] constraints (see the excluded region in the Figs. 4 and 5). Note that the axino dark matter particles are mainly produced by the anomalous interactions [12] similar to Eq. (4). The argument and calculations show the differences between the axino and Quintessino.

To evade the BBN and CMB constraints, we introduce new interactions between Quintessence and ordinary matter. The shift symmetry, $Q \to Q + C$, implies that the interactions of the Quintessence with matter should involve derivatives. In terms of an effective Lagrangian there are generally two classes of operators at dimension 5, one with fermions $f$ [11] and the other one with Higgs boson $H$ of the standard electroweak theory

$$\mathcal{L}_{QFF} = \frac{1}{\Lambda} \partial_{\mu} Q (c_{ij}^{\mu} f_{jR}^\dagger \gamma^\mu f_{jR} + c_{iL}^{\mu} f_{iL}^\dagger \gamma^\mu f_{jL}) \quad (5)$$

$$\mathcal{L}_{QHH} = \frac{c_{H}}{\Lambda} i \partial_{\mu} Q \left( H^\dagger D^\mu H - (D^\mu H)^\dagger H \right) \quad (6)$$

where $\Lambda$ represents the cutoff energy scale and $D^\mu$ is the gauge covariant derivative. Several constraints are set on the cutoff scale $\Lambda$. First, since the Quintessence is very light, the coupling in the forms above will lead to an energy-loss channel for stars. The cutoff is bounded below, $\Lambda \gtrsim 2 \times 10^9 \text{GeV}$, in order not to lead conflict with the observational limits on the stellar-evolution time scale [12]. The SN 1987A observation also constrains this “invisible channel” and leads to $\Lambda \gtrsim 6 \times 10^9 \text{GeV}$ [12]. The interactions in Eq. (5) also induce lepton flavor changing decay $\mu \to e + Q$ with the branching ratio given by $\text{Br}(\mu \to eQ) = \frac{1}{\Lambda^2} \left( \frac{c_{ij}^{\mu}}{m_{\mu}/m_{\tau}} \right)^2$ for $c_{ij}^{\mu} = c_{iL}^{\mu} = 1$. The familon search experiments set the bound on the cutoff scale as $\Lambda \gtrsim 4 \times 10^9 \text{GeV}$ [14]. The operator in Eq. (6) gives rise to a mixing between the Quintessence and the gauge boson $Z_\mu$, which induces an effective coupling of the Quintessence to the light fermions [13]. The astrophysical experiments put a limit $\Lambda \gtrsim 3 \times 10^9 \text{GeV}$. In a word, the present astrophysical and laboratory experimental limit on the energy scale $\Lambda$ of an axion-like pseudoscalar coupling with matter is around $10^{10} \text{GeV}$ [15].

We supersymmetrize the interactions above by introducing the gauge and supersymmetric invariant Lagrangian

$$\mathcal{L} = \frac{c}{\Lambda} \bar{Q} \Phi^\dagger e^{2gV} \Phi |_{\theta \gamma h0} + h.c., \quad (7)$$

where $\bar{Q} = (\sigma_i + iQ) + \sqrt{2} \theta \bar{Q} + \theta F$ is the chiral superfield containing Quintessence $Q$ and its fermionic partner $\bar{Q}$, $\Phi$ is any matter superfield in the MSSM and $V$ is the vector superfield. We notice that this Lagrangian possesses the shift symmetry, i.e., $Q \to Q + iAC$. When expressing it in terms of the component fields, we obtain the needed couplings in Eqs. (5) and (6). Taking $\Phi$ in Eq. (7) to be the Higgs superfield, the Bino can decay via a new channel, $\bar{B} \to h \bar{Q}$, with $h^0$ the lightest CP-even Higgs boson and the relevant coupling given by

$$\mathcal{L}_{Bh\bar{Q}} = \frac{c}{\Lambda} \frac{v}{\sqrt{2}} g' \cos(\alpha + \beta) \bar{Q} h^0 \quad (8)$$

where $v = 246 \text{GeV}$ is the vacuum expectation value (VEV) of the Higgs field, $g'$ is the gauge coupling of $U(1)_Y$, $\tan \beta = v_2/v_1$ is the ratio between the two VEVs, and $\alpha$ is the mixing angle between the neutral Higgs bosons. The decay width is given by

$$\Gamma(\bar{B} \to h\bar{Q}) \approx \left( \frac{c}{\Lambda} \right)^2 \frac{\sin^2 \theta_W}{8\pi} M_Z m_{\bar{B}} \gamma (1 - x_Q)^2 - x_h^2 \frac{1}{2} ((1 + x_Q)^2 - x_h^2) \frac{1}{2}, \quad (9)$$

where we have taken the limit of large $M_\phi$ and large $\tan \beta$, with $x_Q = m_{\bar{Q}}/m_\phi$ and $x_h = m_{h^0}/m_\phi$.

If the cutoff scale $\Lambda$ is near the present experimental limit, for example, $\Lambda \sim 10^{12} \text{GeV}$, we have the decay time $\tau \sim 10^{-5} \text{sec}$ for $m_{\bar{B}} = 1 \text{TeV}$, which means that the neutralino decays shortly after it freezes out, and much before the BBN. In this case, the constraint from BBN is quite weak. The Quintessino, if still relativistic, will contribute to the energy density and change the expanding rate of the Universe during BBN. This energy contribution, in general, can be expressed in terms of the effective number of extra generations of neutrinos, defined by $\delta N_v \equiv \rho_\nu/\rho_\nu$, where $\rho_\nu$ and $\rho_\nu$ are the energy density of Quintessino and one species of neutrino, respectively. In order not to affect the Universe’s expansion too much during BBN, $\delta N_v$ is constrained to be less than 0.2—0.5 [16]. For $\Lambda$ around $10^{12} \text{GeV}$ and $m_{\bar{B}} = 1 \text{TeV}$, we obtain $\delta N_v \sim 10^{-5}$, which is much below the limit.

The property of Quintessino dark matter produced non-thermally may be characterized by the comoving free streaming scale, $\lambda_{FS}$, which represents a quantity of crucial relevance to the formation of the large scale cosmic
structure. The density fluctuations on scales less than $\lambda_{FS}$ would be severely suppressed. We calculate the free streaming scale of Quintessino dark matter asootnote{We have integrated the red-shifted velocity of Quintessino, $v/a$, from the time when it is produced, $\tau$, to $t_{EQ}$ when the matter begins to dominate the Universe and $y \equiv \tau/t_{EQ}$. In Fig. 1, we show the curves of constant $\lambda_{FS}$ in the ($\log_{10}(x_Q)$, $\log_{10}(\tau/sec)$) space. We can see that the free-streaming scale of Quintessino, taking $\tau \sim 10^{-5}$ sec and $x_Q \sim 10^{-3}$, is much shorter than 0.1 Mpc, which means it serves as a good candidate for cold dark matter.}

$$\lambda_{FS} = \int_{t_{EQ}}^{t_{10^4}} \frac{v(t')}{a(t')} dt' \approx 143.2 \text{ Mpc ln} \left( \frac{W + \sqrt{1 + W^2}}{W} \right),$$

with $W = 2x_Q/\sqrt{(1 + x_Q)^2 - x_h^2}(1 - x_Q^2 - x_h^2)y$. We have integrated the red-shifted velocity of Quintessino, $v/a$, from the time when it is produced, $\tau$, to $t_{EQ}$ when the matter begins to dominate the Universe and $y \equiv \tau/t_{EQ}$. In Fig. 1, we show the curves of constant $\lambda_{FS}$ in the ($\log_{10}(x_Q)$, $\log_{10}(\tau/sec)$) space. We can see that the free-streaming scale of Quintessino, taking $\tau \sim 10^{-5}$ sec and $x_Q \sim 10^{-3}$, is much shorter than 0.1 Mpc, which means it serves as a good candidate for cold dark matter.

As the cutoff scale gets higher, the constraints from BBN and CMB will come into action. In the following, we will take $\Lambda = M_{pl}$ for a detailed discussion.

For $\Lambda = M_{pl}$, the neutralino decays long after BBN, so we have to study the constraints from BBN and CMB on the electromagnetic energy release in the decay. In general, the electromagnetic energies are released through the Higgs cascade decays. The $h^0$ decays dominantly into $bb$ and $\tau\tau$. We have calculated the averaged electromagnetic energy released in the Higgs boson decay using the Jetset7.4 Monte Carlo event generator package\footnote{We have calculated the averaged electromagnetic energy released in the two body decay $\chi_i^0 \rightarrow Q\overline{Q}'$. We fix $x_h = 0.1$.} in the decoupling limit. We get $\epsilon_{EM} \approx 0.8E_{h^0}$, ignoring possible electromagnetic energy carried by neutrinos via the process, such as, $\nu\nu \rightarrow e^+e^-$. Since the present constraint on the hadronic energy release is only sensitive to the decay time $\tau \lesssim 10^4$ sec\footnote{We plot the decay lifetime and electromagnetic energy release for a range of $(m_{\tilde{B}}, x_Q)$. We notice that some parameter space is excluded by the BBN and CMB constraint, but the region with $m_{\tilde{B}} \sim 400 GeV - 1.2 TeV$ and $x_Q \sim 0.4 - 0.8$ remains viable. The best fit point $(\tau, \xi_{EM}) = (3 \times 10^8$ sec, $10^{-9}$ GeV) is marked in the figure, which corresponds to such a point that $^7\text{Li}$ is destroyed to the level of the present observation while keeping the concordance between CMB and BBN determination of the baryon number $\eta$ from other light elements. The $^7\text{Li}$ underabundance may be an evidence supporting the late time WIMPs decay\footnote{In our scenario, this point corresponds to taking $m_{\tilde{B}} \approx 500 GeV$ and $x_Q \approx 0.7$.}}$, we will not consider the constraint from the hadronic energy release. In Fig. 2, we plot the decay lifetime and electromagnetic energy release for a range of $(m_{\tilde{B}}, x_Q)$. We notice that some parameter space is excluded by the BBN and CMB constraint, but the region with $m_{\tilde{B}} \sim 400 GeV - 1.2 TeV$ and $x_Q \sim 0.4 - 0.8$ remains viable. The best fit point $(\tau, \xi_{EM}) = (3 \times 10^8$ sec, $10^{-9}$ GeV) is marked in the figure, which corresponds to such a point that $^7\text{Li}$ is destroyed to the level of the present observation while keeping the concordance between CMB and BBN determination of the baryon number $\eta$ from other light elements. The $^7\text{Li}$ underabundance may be an evidence supporting the late time WIMPs decay\footnote{In our scenario, this point corresponds to taking $m_{\tilde{B}} \approx 500 GeV$ and $x_Q \approx 0.7$.}. In our scenario, this point corresponds to taking $m_{\tilde{B}} \approx 500 GeV$ and $x_Q \approx 0.7$. Finally, we consider the case that the NLSP is Higgsino.
gsino. In the hyperbolic branch of the mSUGRA parameter space, the lightest Higgsino is the LSP and gives correct relic density even the neutralino mass is large, due to the rapid coannihilation processes\textsuperscript{20}. In this case, for $\mu > 0$ and $c = 1$, the relevant coupling is given by

$$\mathcal{L}_{\tilde{\mu}\tilde{h}_Q} = - \frac{1}{2} \frac{\mu}{M_{pl}} \left[ C_S \tilde{H}_S \tilde{Q} - i C_A \tilde{H}_A \gamma^5 \tilde{Q} \right] h^0, \quad (11)$$

with $C_{S,A} = \sin \alpha \mp \cos \alpha$ and $\tilde{H}_{S,A} = (\tilde{H}_1 \mp \tilde{H}_2)/\sqrt{2}$ being the CP-even(odd) Higgsino. For $\mu < 0$, $C_S$ and $C_A$ interchange, which become equal in the limit of large tan $\beta$. In Fig. 3 we plot the lifetime and energy release of the CP-even (left-panel) and CP-odd (right-panel) Higgsino decay for a range of $(\mu, x_Q)$ for $\mu < 0$. For the CP-even Higgsino we get the best fit point by taking $\mu \approx -600 GeV$ and $x_Q \approx 0.7$. For the CP-odd Higgsino this point is reached when $\mu \approx -2 TeV$ and $x_Q \approx 0.7$.

From Fig. 4 we can see that the free-streaming scales are in the range $\tilde{L}_{FS} \sim 0.1 - 1.0$ Mpc for $\tau \sim 10^6$ sec and $x_Q \sim 0.4 - 0.8$. So, for this parameter space, the Quintessino has the properties similar to that of warm dark matter (WDM), which has been proposed to resolve the difficulties with the conventional WIMPs CDM model on subgalactic scales\textsuperscript{17, 21}. However, the WDM scenario is constrained severely by the evidences for early galaxy and star formation. The high optical depth of reionization found by WMAP data\textsuperscript{2} implies an early star formation at $z > 10$. If this result is confirmed, there would be no room for the presence of significant WDM\textsuperscript{22}. We leave the detailed investigation of the effects of Quintessino DM and superWIMP\textsuperscript{10} DM on the large scale structure and CMB for the future study\textsuperscript{23}.

In summary, we have studied the cosmological phenomenologies of models with supersymmetric interaction of Quintessence and matter. We proposed new interactions between Quintessence and matter, and examined the constraints by the current astrophysical and laboratory experimental data. We then studied their implications in Quintessino dark matter. Our results show that Quintessino can be a good candidate for CDM or WDM through the late-time decay of the NLSP of ordinary superparticle, which can be the Bino or Higgsino-like neutralino. In our model, the present acceleration of the Universe is driven by the dynamics of Quintessence and, at the same time, the superpartner of Quintessence, the Quintessino, makes up the dark matter of the Universe\textsuperscript{24}.

**Acknowledgments**

We would like to thank B. Feng, J. Feng, Y.N. Gao, P. Gondolo and R. Mohapatra, for comments and discussions. This work is supported in part by the NSF of China under the grant No. 10105004, 19925523, 10047004 and also by the Ministry of Science and Technology of China under grant No. NKBRSF G19990754.

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[24] Note that the axion dynamics will not be able to drive the Universe acceleration. Furthermore, for axion and axino they both are dark matter particles.