Dark energy and neutrino mass limits from baryogenesis

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In this Brief Report we consider the coupling of a dark energy scalar such as quintessence to neutrinos and discuss its implications in studies on the neutrino mass limits from baryogenesis. During the evolution of the dark energy scalar, the neutrino masses vary; consequently the bounds on the neutrino masses we have here differ from those obtained before.

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There is strong evidence that the Universe is spatially accelerating at the present time [1]. The simplest account of this cosmic acceleration seems to be a remnant small cosmological constant; however, many physicists are attracted by the idea that a new form of matter, usually called dark energy [2], is causing the cosmic accelerating. A simple candidate for dark energy is quintessence [3–6], a scalar field (or multiscalar fields) with a canonical kinetic term and a potential term in the Lagrangian. Another one is called in the literature k essence [7,8]. Differing from quintessence, for k essence the accelerating expansion of the Universe is driven by its kinetic rather than potential energy. Being a dynamical component, the scalar field dark energy is expected to interact with ordinary matter. In the literature there have been a lot of studies on the possible couplings of quintessence to baryons, dark matter, and photons [9–13]. For example, in Refs. [11,14] it was shown that introducing an interaction between quintessence and dark matter provides a solution to the puzzle of why Ω_{DM} and Ω_{DE} are nearly equal today. Specifically the authors of Ref. [15] recently considered a model of interacting dark energy with dark matter and in their scenario the mass of dark matter particle χ depends exponentially on the dark energy field scalar $Q, M_\chi(Q) = \bar{M} e^{-\lambda Q/M_{pl}}$. During the evolution of the dark energy scalar field the mass of the dark matter particle varies, consequently the parameters of the dark matter model, such as the minimal supersymmetric standard model (MSSM), differ drastically from the results where no connection between dark energy and dark matter is present. Recent data on the possible variation of the electromagnetic fine structure constant reported in [16] have triggered interest in studies related to the interactions between quintessence and the matter fields. For this case, one usually introduces an interaction of form $\sim Q F_{\mu\nu} F^{\mu\nu}$ with $F_{\mu\nu}$ being the electromagnetic field strength tensor.

In recent years we [17] have studied the possible interactions between the dark energy scalars, such as quintessence or k essence, and the matter fields of the standard electroweak theory and have shown that during the evolution of these scalar fields *CPT* symmetry is violated and the baryon number asymmetry required is generated. The mechanism for baryogenesis and/or leptogenesis proposed in Refs. [17,18] provides a unified picture for dark energy and baryon matter of our Universe. In this Brief Report we consider possible couplings of quintessence to the neutrinos and study its effects on the neutrino mass limits from baryogenesis.

We start with an examination on the neutrino mass limits required by avoiding the washing out of the baryon number asymmetry [19]. Consider a dimension five operator

$$L_{\not{L}} = \frac{2}{f} l_L l_L \phi\phi + \text{H.c.}, \tag{1}$$

where f is a scale of new physics beyond the standard model which generates the $B-L$ violations, l_L, ϕ are the left-handed lepton and Higgs doublets, respectively. When the Higgs field gets a vacuum expectation value $\langle\phi\rangle \sim v$, the left-handed neutrino receives a Majorana mass $m_\nu \sim \frac{v^2}{f}$. If this interaction in the early universe is strong enough, combined with the electroweak Sphaleron effect it will wash out any baryon number asymmetry of the Universe.

At finite temperature, the lepton number violating rate induced by the interaction in Eq. (1) is [20]

$$\Gamma_{\not{L}} \sim 0.04 \frac{T^3}{f^2}. \tag{2}$$

The survival of the baryon number asymmetry requires this rate to be smaller than the Universe expansion rate $H \sim 1.66 g_*^{1/2} T^2 / M_{pl}$, which gives rise to a T-dependent upper limit on the neutrino mass

$$\Sigma m_{\nu i}^2 = \left[0.2 \ \text{eV} \left(\frac{10^{12} \ \text{GeV}}{T} \right)^{1/2} \right]^2. \tag{3}$$

For instance, taking T around 100 GeV for one type of neutrino it gives $m_\nu < 20$ keV; however, for $T \sim 10^{10}$ GeV, a typical leptogenesis temperature, this bound reduces to 2 eV.

Now we introduce an interaction between the neutrinos and the quintessence

$$\beta \frac{Q}{M_{pl}} \frac{2}{f} l_L l_L \phi\phi + \text{H.c.}, \tag{4}$$

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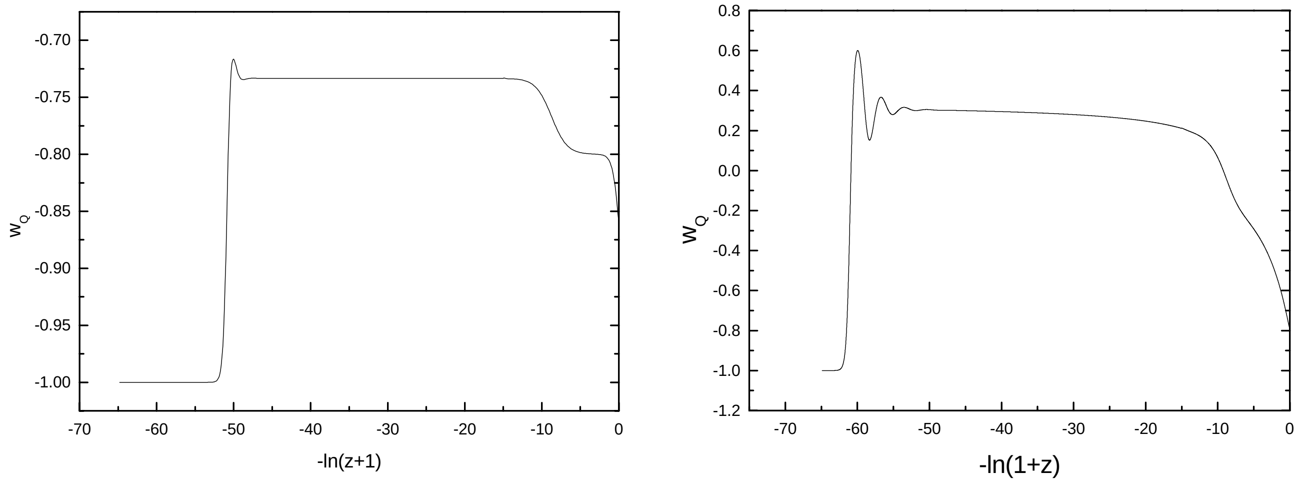

FIG. 1. Plot of w_Q as a function of $-\ln(1+z)$. The left one is for the quintessence model given by Eq. (9); the right one is for the quintessence model given by Eq. (12).

where β is the coefficient which characterizes the strength of the quintessence interacting with the neutrinos and generally one requires $\beta < 4\pi$ to make the effective Lagrangian description reliable. Combining Eq. (1) and Eq. (4) we have an effective operator for quintessence-dependent neutrino masses

$$L_{\not{L}}(Q) = \frac{2C(Q)}{f} l_L l_L \phi\phi + \text{H.c.}, \tag{5}$$

where $C(Q) = 1 + \beta Q/M_{pl}$.

In the early universe the $B-L$ violating interaction rate now becomes

$$\Gamma_{\not{L}} \sim 0.04 \frac{T^3}{f^2} C^2(Q).$$

Correspondingly the formula for the neutrino mass upper limit in Eq. (3) changes to

$$\sum m_{\nu i}^2 = \left[0.2 \ \text{eV} \left(\frac{10^{12} \ \text{GeV}}{T} \right)^{1/2} \frac{C(Q_0)}{C(Q_T)} \right]^2,$$

where Q_0 is the value of the quintessence field at the present time and Q_T the quintessence evaluated at the temperature T. In general $C(Q_0)/C(Q_T)$ will not be one, so one expects a change on the neutrino mass limit for a given temperature T.

To evaluate $C(Q)$ we need to solve the following equations of motion of the quintessence, which for a flat Universe are given by

$$H^2 = \frac{8\pi G}{3} \left[\rho_B + \frac{\dot{Q}^2}{2} + V(Q) \right], \tag{6}$$

$$\ddot{Q} + 3H\dot{Q} + V'(Q) = 0, \tag{7}$$

$$\dot{H} = -4\pi G[(1+w_B)\rho_B + \dot{Q}^2], \tag{8}$$

where ρ_B and "w_B" represent, respectively, the energy density and the equation-of-state of the background fluid, for example, $w_B = 1/3$ in radiation-dominated and $w_B = 0$ in the matter-dominated Universe.

For numerical studies, we consider a model of quintessence with an inverse power-law potential [3],

$$V = V_0 Q^{-\alpha}. \tag{9}$$

This model is shown [3,6] to have the property of tracking behavior. For a general discussion on the tracking solution, one considers a function $\Gamma \equiv V''V/(V')^2$, which when combined with Eqs. (6) and (7), is given by

$$\Gamma = 1 + \frac{w_B - w_Q}{2(1+w_Q)} - \frac{1 + w_B - 2w_Q}{2(1+w_Q)} \frac{\dot{x}}{6+x} - \frac{2}{(1+w_Q)} \frac{\ddot{x}}{(6+\dot{x})^2}, \tag{10}$$

where $x \equiv (1+w_Q)/(1-w_Q)$, $\dot{x} \equiv d \ln x / d \ln a$, and $\ddot{x} \equiv d^2 \ln x / d \ln a^2$. If $w_Q < w_B$, $\Gamma > 1$ and Γ is nearly constant [i.e., $|d(\Gamma-1)/Hdt| \ll |\Gamma - 1|$] [6], the model has the tracking property.

In the tracking region,

$$\Gamma - 1 = \frac{w_B - w_Q}{2(1+w_Q)} = \frac{1}{\alpha}, \tag{11}$$

then $w_Q = (\alpha w_B - 2)/(\alpha + 2)$. The WMAP gives that $w_{Q0} < -0.78$ [21], which requires a small value of α for this model. In Fig. 1 we show the evolution of w_Q with time, for parameters $\alpha = 0.5$, $\Omega_{Q_0} \simeq 0.7$.

In Fig. 2 we plot the evolution of quintessence field as a function of redshift z. The values of quintessence field at the present time Q_0 is $0.143 M_{pl}$.

Defining $\Sigma \equiv (\Sigma m_{\nu i}^2)^{1/2} = [C(Q_0)/C(Q_T)]\Sigma_T$, where $\Sigma_T = 0.2 \ \text{eV}(10^{12} \ \text{GeV}/T)^{1/2}$, we plot in Fig. 3 the Σ as a function of the temperature T for different values of parameters

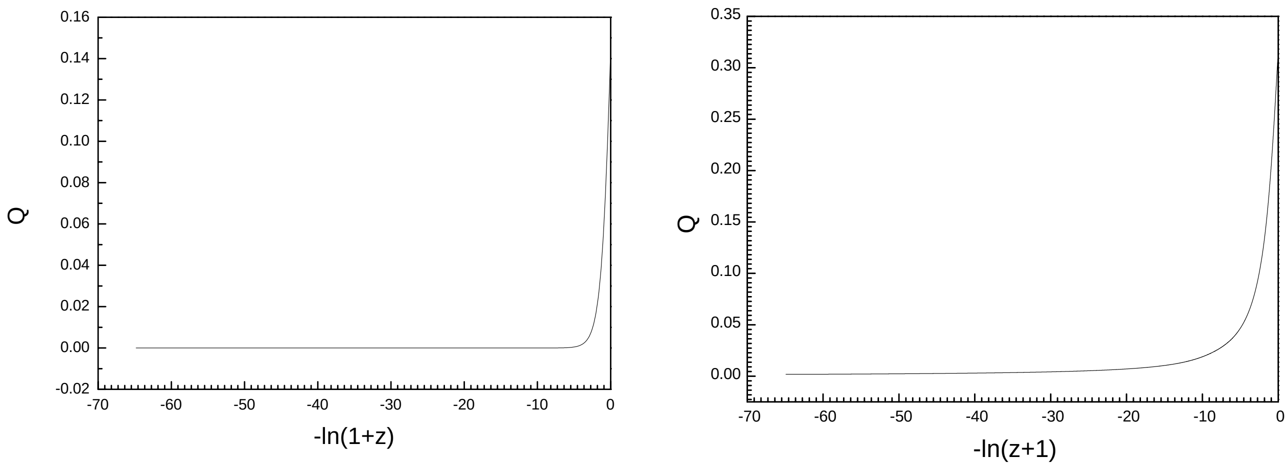

FIG. 2. Plot of Q expressed in units of M_{pl} as a function of $-\ln(1+z)$. The left one is for the quintessence model given by Eq. (9); the right one is for the quintessence model given by Eq. (12).

β. $\beta=0$ corresponds to the case when no interaction between the quintessence and the neutrinos exist. One can see from the figure that the difference between $\beta=0$ and $\beta\neq 0$ increases as the temperature decreases.

Numerically we find at $T\sim 100$ GeV, for one type of neutrino the mass bound which is 20 keV for $\beta=0$ changes to 29 keV for $\beta=3$ and 11 keV for $\beta=-3$. At $T\sim 10^{10}$ GeV, these mass limits are 2.9, 2, and 1.1 eV for $\beta=3,\ 0,\ -3$, respectively.

Our limits on the neutrino masses depend on the quintessence model. For an illustration, we consider another quintessence model [6]

$$V(Q)=V_0\exp(\lambda/Q). \tag{12}$$

In Fig. 1 we show the evolution of ω_Q with time. We take $\lambda=0.5M_{pl}$ which gives rise to $\omega_Q\simeq -0.8$ at present time, consistent with the WMAP limit. The behavior of the quin-

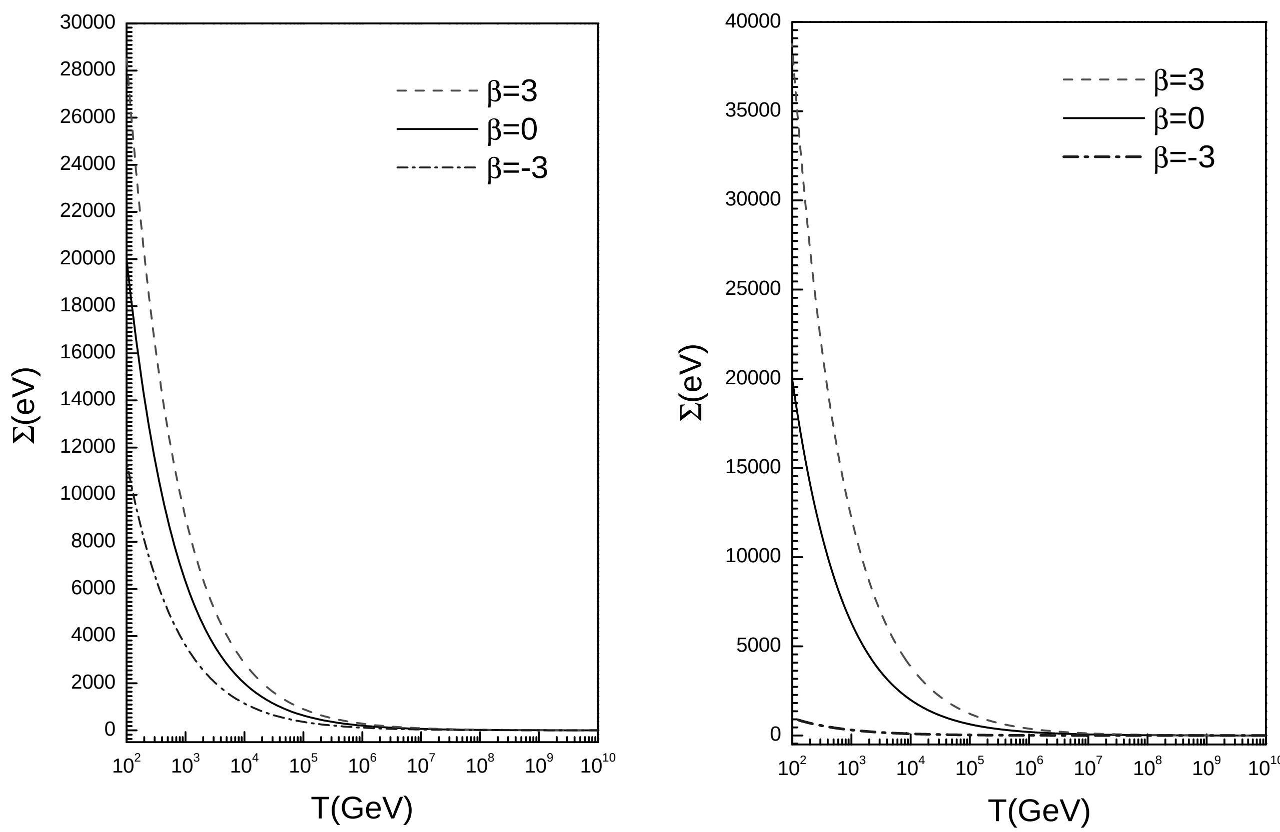

FIG. 3. Plot of Σ for different values of β as a function of temperature T. The left one is for the quintessence model given by Eq. (9); the right one is for the quintessence model given by Eq. (12).

tessence field for this model as shown in Fig. 2 is different from the model we studied above. Consequently the neutrino mass limits will also be different. From Fig. 3 one can see that for this model the neutrino mass limits differ drastically from that obtained in the absence of the quintessence interacting with neutrinos. For example, taking $T = 100$ GeV, Σ are 39, 20, and 1 keV for $\beta = 3,0$, and -3 and at $T = 10^{10}$ GeV $\Sigma = 3.9$, 2, and 0.1 eV, respectively.

In summary we have considered in this Brief Report a scenario where neutrino masses vary during the evolution of the dark energy scalars, such as quintessence, and studied its implications in baryogenesis. We assume that the neutrino masses are from a dimension five operator in Eq. (1) and the interaction form of the quintessence with the neutrinos is given by Eq. (4). The operator (1) is not renormalizable, which in principle can be generated by integrating out the heavy particles. For example, in the model of the minimal seesaw mechanism [23] for the neutrino masses

$$L = h_{ij}\overline{l_{Li}}N_{Rj}\phi + \tfrac{1}{2}M_{ij}\overline{N^c_{Ri}}N_{Rj} + \text{H.c.}, \tag{13}$$

where M_{ij} is the mass matrix of the right-handed neutrinos and the Dirac mass of neutrino is given by $m_D \equiv h_{ij}\langle\phi\rangle$. Integrating out the heavy right-handed neutrinos will generate the operator in Eq. (1), however, to have the light neutrino masses varied there are various possibilities, such as by coupling the quintessence field to either the Dirac masses or the Majorana masses of the right-handed neutrinos or both. Qualitatively because of these interactions the neutrino mass limits from leptogenesis [22] are expected to be changed, however, to quantify these changes one needs to specify the details of these couplings and the quintessence models. Numerical studies on leptogenesis in the minimal seesaw model show that the neutrino mass is bounded from above which for three degenerated neutrinos is $m_\nu < 0.12$ eV [24]. Interaction of the quintessence with the neutrinos can change this upper bound. Note that the cosmological limit on the neutrino mass from WMAP gives $m_\nu < 0.23$ eV [21]. Interestingly a recent study on the cosmological data showed a preference for neutrinos with degenerated masses around 0.21 eV [25].

Our studies in this Brief Report can be generalized into models of electroweak baryogenesis in the discussions of the constraints on the model parameters, such as the Higgs boson mass.

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[1] S. Pelmutter *et al.*, Astrophys. J. **483**, 565 (1997).
[2] M.S. Turner, astro-ph/0108103.
[3] B. Ratra and P.J.E. Peebles, Phys. Rev. D **37**, 3406 (1988).
[4] C. Wetterich, Nucl. Phys. **B302**, 302 (1988).
[5] J.A. Frieman, C.T. Hill, A. Stebbins, and I. Waga, Phys. Rev. Lett. **75**, 2077 (1995).
[6] I. Zlatev, L. Wang, and P.J. Steinhardt, Phys. Rev. Lett. **82**, 896 (1999); P.J. Steinhardt, L. Wang, and I. Zlatev, Phys. Rev. D **59**, 123504 (1999).
[7] C. Armendariz-Picon, V. Mukhanov, and P.J. Steinhardt, Phys. Rev. Lett. **85**, 4438 (2000); Phys. Rev. D **63**, 103510 (2001).
[8] T. Chiba, T. Okabe, and M. Yamaguchi, Phys. Rev. D **62**, 023511 (2000).
[9] S.M. Carroll, Phys. Rev. Lett. **81**, 3067 (1998).
[10] R.D. Peccei, hep-ph/0009030; C. Kolda and D.H. Lyth, Phys. Lett. B **458**, 197 (1999).
[11] L. Amendola, Phys. Rev. D **62**, 043511 (2000).
[12] P.J.E. Peebles, astro-ph/0208037.
[13] R. Horvat, Mod. Phys. Lett. A **14**, 2245 (1999); J. High Energy Phys. **08**, 031 (2002).
[14] L. Amendola and D. Tocchini-Valentini, Phys. Rev. D **66**, 043528 (2002); M. Gasperini, F. Piazza, and G. Veneziano, *ibid.* **65**, 023508 (2002); M. Pietroni, *ibid.* **67**, 103523 (2003).
[15] D. Comelli, M. Pietroni, and A. Riotto, hep-ph/0302080.
[16] J.K. Webb *et al.*, Phys. Rev. Lett. **87**, 091301 (2001).
[17] M. Li, X. Wang, B. Feng, and X. Zhang, Phys. Rev. D **65**, 103511 (2002); M. Li and X. Zhang, hep-ph/0209093.
[18] A. DeFelice, S. Nasri, and M. Trodden, Phys. Rev. D **67**, 043509 (2003).
[19] M. Fukugita and T. Yanagida, Phys. Rev. D **42**, 1285 (1990); S.M. Barr and A. Nelson, Phys. Lett. B **246**, 141 (1991).
[20] U. Sarkar, hep-ph/9809209; W. Buchmuller, hep-ph/0101102.
[21] WMAP Collaboration, D.N. Spergel *et al.*, astro-ph/0302209.
[22] M. Fukugita and T. Yawagida, Phys. Lett. B **174**, 45 (1986); P. Langacker, R.D. Peccei, and T. Yanagida, Mod. Phys. Lett. A **1**, 541 (1986); M.A. Luty, Phys. Rev. D **45**, 455 (1992); R.N. Mohapatra and X. Zhang, *ibid.* **46**, 5331 (1992).
[23] M. Gell-Mann, P. Ramond, and R. Slansky, in *Supergravity*, edited by P. van Nieuwenhuizen and D. Freedman (North-Holland, Amsterdam, 1979); T. Yanagida, in *Proceedings of Workshop on Unified Theories and Baryon Number in the Universe*, edited by O. Sawada and A. Sugamoto (KEK, Tokyo, 1979); R.N. Mohapatra and G. Senjanovic, Phys. Rev. Lett. **44**, 912 (1980); S.L. Glashow, Caraese lectures, 1979.
[24] W. Buchmuller, P.D. Bsri, and M. Plumacher, hep-ph/0302092.
[25] S.W. Allen, R.W. Schmidt, and S.L. Bridle, astro-ph/0306386.