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# Dark energy and neutrino $CPT$-violation

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**Abstract.** In this paper we study dynamical $CPT$-violation in the neutrino sector as induced by the dark energy of the universe. Specifically we consider a dark energy model where the dark energy scalar derivatively interacts with the right-handed neutrinos. This type of derivative coupling leads to cosmological $CPT$-violation during the evolution of the background field of the dark energy. We calculate the induced $CPT$-violation of left-handed neutrinos and find that the $CPT$-violation produced in this way is consistent with the present experimental limit and sensitive to future neutrino oscillation experiments such as the neutrino factory.

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## 1 Introduction

The recent observational data from type Ia supernova [1], cosmic microwave background (CMB) radiation [2, 3] and large scale structure (LSS) [4, 5] determinations have provided strong evidence for a spatially flat and accelerated expanding universe at the present time. In the context of the Friedmann–Robertson–Walker cosmology, this acceleration is attributed to the domination of a component dubbed dark energy [6]. 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 quintessence [7–11], the K-essence [12–14], and the phantom [15] and the quintom [16–20].

Being a dynamical component, dark energy is expected to interact with matter. Recently there has been a lot of interest in the literature [21–37] in the study of possible interactions between the neutrinos and the dark energy. An interesting prediction of these models is that the neutrino masses are not constant but vary as a function of time and space [23, 24]. This prediction of variation of the neutrino masses can be verified in the present and in future experiments. For example, the neutrino mass evolution with time can be tested in a measurement of the time delay of the neutrinos emitted from short gamma ray bursts [38]. Another interesting possibility is to detect the neutrino mass variation in space via neutrino oscillations [24, 25, 39–41]. In this paper we study the possibility of $CPT$-violation in the neutrino sector induced by the evolution of a dark energy scalar field.

In [21, 22] the authors have made a proposal for the dynamical $CPT$-violation by introducing a derivative coupling of the dark energy scalar to the left-handed fermions of the standard model:[1]

$$\mathcal{L}_{\rm eff} \sim \partial_\mu \phi \bar{l}_{\rm L} \gamma^\mu l_{\rm L} \,, \tag{1}$$

where $\phi$ is the dark energy scalar, for instance quintessence; $l_{\rm L}$ by gauge invariance of $\mathrm{SU}(2)_{\rm L} \times \mathrm{U}(1)_Y$ is the doublet of the left-handed lepton $l_{\rm L} = (\nu_{\rm L}, e_{\rm L})^{\rm T}$. During the evolution of the universe the time derivative of the scalar field does not vanish, $\dot{\phi} \neq 0$, which gives rise to $CPT$-violation. This type of $CPT$-violation, as shown in [21, 22], helps us to understand the matter–antimatter asymmetry of the universe; however, since the experimental limit on $CPT$-violation in electrons found in the laboratory is so stringent, the induced $CPT$-violation in the neutrino sector will be far below the sensitivity of the current and of future experiments. Phenomenologically, a comparably large neutrino $CPT$-violation is helpful to explain the possible $CPT$-violating neutrino oscillations. For example, the neutrino $CPT$-violation has been proposed [45–49] to account for the LSND anomaly [50], which can be tested at the upcoming MiniBooNE experiment [51]. It is noteworthy that, whether the LSND result is confirmed or not by future experiments, the possibility of $CPT$-violation consistent with the other neutrino oscillation experiments [52–54] is intriguing and can be tested in the future neutrino factory experiment [54, 55].

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[1] There are several other papers that deal with $CPT$-violation originating from spacetime-varying scalars [42–44].

In this paper we consider specifically a model in which the dark energy scalar couples derivatively to the right-handed neutrino and calculate the induced $CPT$-violation in left-handed neutrinos due to mixing between the right-handed neutrinos and the left-handed neutrinos. Our results show that with an appropriate choice of the model parameter the $CPT$-violation in the neutrino sector is consistent with the present experimental data and can be tested in a future neutrino factory experiment without conflicting with the experimental limit on the electron $CPT$-violation.

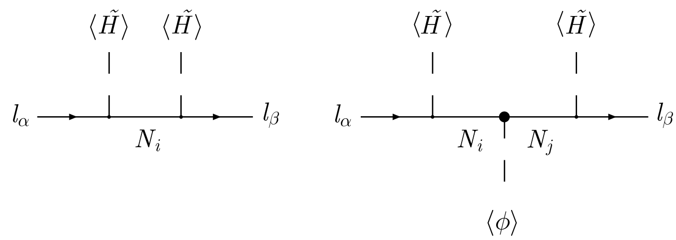


**Fig. 1.** Seesaw mechanism (*left diagram*) and $CPT$-violation in neutrinos (*right diagram*) at tree level

## 2 Model of neutrino $CPT$-violation

The model under investigation in this paper includes a scalar field $\phi$ that drives the acceleration of the universe and derivatively couples to the right-handed neutrinos $N_i = \nu_{\mathrm{R}i} + \nu_{\mathrm{R}i}^{\mathrm{C}} \sim \frac{f_{ij}}{\Lambda} \bar{\nu}_{\mathrm{R}i} \partial_\mu \phi \gamma^\mu \nu_{\mathrm{R}j}$ $(i, j = 1, \dots)$, with the $f_{ij}$ the parameters that characterize the strength of this type of interaction, expected to be of order $\mathcal{O}(1)$, and $\Lambda$ the energy scale characterizing the dynamics which generates this effective interaction. In our model, the right-handed neutrinos, being a part of the dark energy sector, are taken to be at the $\mathcal{O}(\mathrm{eV})$ scale, and $\Lambda \ll M_W$ is to give observable $CPT$-violating effects. Similar $\mathcal{O}(\mathrm{eV})$ scale right-handed neutrino models are studied in [24, 25]. The derivative coupling will lead to cosmological $CPT$-violation in the right-handed neutrino sector during the evolution of the background dark energy field. Mixing between the left-handed neutrino and the right-handed neutrino is induced through a gauge invariant and renormalizable Yukawa interaction, $y_{\alpha j} \bar{l}_{\mathrm{L}\alpha} \widetilde{H} \nu_{\mathrm{R}j}$ ($\alpha = e, \mu, \tau$ denotes the flavor indices), where the $y$ are the Yukawa couplings, and $l$ and $\widetilde{H}$ are the SM lepton doublet and Higgs doublet, respectively.

The relevant Lagrangian can be written

$$\begin{aligned} -\mathcal{L} &= y_{\alpha j} \bar{l}_{\mathrm{L}\alpha} \widetilde{H} \nu_{\mathrm{R}j} + \frac{1}{2} M_i \bar{\nu}_{\mathrm{R}i}^{\mathrm{C}} \nu_{\mathrm{R}i} + \mathrm{h.c.} \\ &\quad + \frac{f_{ij}}{\Lambda} \bar{\nu}_{\mathrm{R}i} \partial_\mu \phi \gamma^\mu \nu_{\mathrm{R}j} - \frac{1}{2} \partial_\mu \phi \partial^\mu \phi + V(\phi) \\ &= y_{\alpha j} \bar{l}_{\mathrm{L}\alpha} \widetilde{H} N_j + \mathrm{h.c.} + \frac{1}{2} M_i \bar{N}_i N_i + \frac{1}{2} \bar{N}_i A_{\mu ij} \gamma^\mu N_j \\ &\quad + \frac{1}{2} \bar{N}_i S_{\mu ij} \gamma^\mu \gamma_5 N_j - \frac{1}{2} \partial_\mu \phi \partial^\mu \phi + V(\phi) \,, \end{aligned} \tag{2}$$

with $V(\phi)$ the potential for $\phi$. We have adopted the following definition in (2):

$$A_\mu = \frac{1}{2} (f - f^{\mathrm{T}}) \frac{1}{\Lambda} \partial_\mu \phi \,, \tag{3}$$

$$S_\mu = \frac{1}{2} (f + f^{\mathrm{T}}) \frac{1}{\Lambda} \partial_\mu \phi \,, \tag{4}$$

so the matrix $A_\mu$ is antisymmetric, while $S_\mu$ is symmetric.

Integrating out the right-handed Majorana neutrinos, we obtain

$$-\mathcal{L}_\nu = \frac{1}{2} \bar{\nu}_\alpha m_\nu^{\alpha\beta} \nu_\beta + \frac{1}{2} \bar{\nu}_\alpha a_\mu^{\alpha\beta} \gamma^\mu \nu_\beta + \frac{1}{2} \bar{\nu}_\alpha s_\mu^{\alpha\beta} \gamma^\mu \gamma_5 \nu_\beta \,, \tag{5}$$

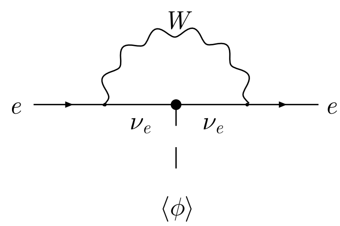


**Fig. 2.** $CPT$-violation in electrons at one loop level

with

$$m_\nu = -m_D \frac{1}{M} m_D^{\mathrm{T}} \,, \tag{6}$$

$$a_\mu = \frac{1}{2} \left( b_\mu - b_\mu^{\mathrm{T}} \right) \tag{7}$$

and

$$s_\mu = -\frac{1}{2} \left( b_\mu + b_\mu^{\mathrm{T}} \right) , \tag{8}$$

where $\nu = \nu_{\mathrm{L}} + \nu_{\mathrm{L}}^{\mathrm{C}}$ is the left-handed Majorana neutrino. Here $M = \mathrm{diag}(M_1, M_2, \dots)$, $m_D = yv$ with $v \simeq 174\,\mathrm{GeV}$ and $b_\mu$ is defined by

$$b_\mu = m_D \frac{1}{M} (A_\mu - S_\mu) \frac{1}{M} m_D^\dagger \,. \tag{9}$$

We can see that the last two terms in (5) will produce $CPT$-violation in the neutrinos for a non-vanishing $\dot{\phi}$. It is easy to show that the $CPT$-violating term above can be given in the simple form [55–59]

$$\mathcal{L}_{CPT\mathrm{V}} = -\bar{\nu}_{\mathrm{L}\alpha} b_\mu^{\alpha\beta} \gamma^\mu \nu_{\mathrm{L}\beta} \,. \tag{10}$$

For the electron $CPT$-violation is induced by the $W$ and neutrino loop.[2] The coupling between the axial vector background and the electron current, $c_\mu \bar{e} \gamma^\mu \gamma_5 e$, is strongly constrained by present experiments [61]. For $\Lambda \ll M_W$, we obtain

$$c_\mu \simeq \frac{1}{8\pi} \frac{\alpha}{\sin^2 \theta_{\mathrm{W}}} \frac{\Lambda^2}{M_W^2} s_\mu \,, \tag{11}$$

where the loop integral was cut off at $\Lambda$, as the effective theory is only valid below $\Lambda$ [60], $\alpha \simeq \frac{1}{137}$ is the fine structure

[2] $\widetilde{H}$–$N$ exchange also contributes to $CPT$-violation in electrons and neutrinos [60] but is, however, strongly suppressed in our model, since the masses of the right-handed Majorana neutrinos and also the Yukawa couplings are very small.

constant, $\sin^2\theta_{\rm W} \simeq 0.23$ is the square sine of the Weinberg angle, and $M_W \simeq 80$ GeV is the mass of the $W$ gauge boson.

Taking the $CPT$-violating parameters $a_\mu$ and $s_\mu$ to be much smaller than the masses of the left-handed Majorana neutrinos, which will later be shown to be the actual case, we can simplify (9) as follows:

$$b_\mu \sim \tilde{b}\frac{m}{M}\frac{1}{\Lambda}\partial_\mu\phi\,, \qquad (12)$$

and similarly for (11) we have

$$c_\mu \sim \tilde{c}\frac{1}{8\pi}\frac{\alpha}{\sin^2\theta_{\rm W}}\frac{\Lambda^2}{M_W^2}\frac{1}{\Lambda}\partial_\mu\phi \sim 1.3\times10^{-3}\tilde{c}\frac{\Lambda}{M_W^2}\partial_\mu\phi\,, \qquad (13)$$

where $m$ and $M$ denote the mass scale of the left- and right-handed Majorana neutrinos, and $\tilde{b}$ and $\tilde{c}$ are two dimensionless parameters. It should be noted that the magnitudes of $\tilde{b}$ and $\tilde{c}$ are of the same order as $f \sim \mathcal{O}(1)$ in (2).

For the homogeneous scalar field, we can express the time component of $\partial_\mu\phi$ in the following way:

$$\dot{\phi} = [(1+w_\phi)\rho_\phi]^{1/2}, \qquad (14)$$

with the equation of state defined by

$$w_\phi = \frac{\frac{1}{2}\dot{\phi}^2 - V(\phi)}{\frac{1}{2}\dot{\phi}^2 + V(\phi)}\,, \qquad (15)$$

and the energy density by

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + V(\phi)\,. \qquad (16)$$

The values of $w_\phi$ and $\rho_\phi$ are constrained by cosmological observations [2, 3], $w_\phi < -0.78$ and $\rho_\phi \simeq 73\%\rho_{\rm c}$, with $\rho_{\rm c} \simeq 4.2\times10^{-47}\,{\rm GeV}^4$ the critical energy density of the Universe at present. Accordingly we have for $\dot{\phi}$

$$\dot{\phi} \leq 2.6\times10^{-24}\,{\rm GeV}^2. \qquad (17)$$

The $CPT$-violating parameters of the neutrinos and the electrons are now given by

$$b_0 \sim \tilde{b}\frac{m}{M}\frac{1}{\Lambda}\dot{\phi} \qquad (18)$$

and

$$c_0 \sim 1.3\times10^{-3}\tilde{c}\frac{\Lambda}{M_W^2}\dot{\phi}\,. \qquad (19)$$

## 3 Experimental test for $CPT$-violation

Neutrino $CPT$-violation can be tested in neutrino oscillation experiments. So we begin our discussion with the effective Hamiltonian that governs the propagation of neutrinos. The evolution of neutrinos is determined by the Schrödinger equation,

$$\mathrm{i}\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} \simeq H_{\rm eff}(x)\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}, \qquad (20)$$

where the Hamiltonian can be written [56]

$$\begin{aligned} H_{\rm eff}(x) &= \frac{1}{2|\mathbf{p}|}\left(m_\nu m_\nu^\dagger\right) + \frac{1}{|\mathbf{p}|}\left(b_\mu p^\mu\right) + \sqrt{2}G_{\rm F}{\rm diag}(N_e(x),0,0) \\ &\simeq \frac{1}{2p^0}\left(m_\nu m_\nu^\dagger\right) + b_0 - |\mathbf{b}|\cos\theta + \sqrt{2}G_{\rm F}{\rm diag}(N_e(x),0,0)\,, \end{aligned} \qquad (21)$$

with $m_\nu$ and $b_\mu = (b_0, -\mathbf{b})$ defined in (6) and (9), respectively. $p^\mu = (p^0, \mathbf{p})$ is the four momentum of the neutrinos, $\theta$ is the angle between $\mathbf{p}$ and $\mathbf{b}$, and $\sqrt{2}G_{\rm F}N_e(x)$ is the usual MSW term [62, 63].

We define the $b_i$ to be the eigenvalues of the matrix $b_0$ and $\delta b_{ij} = b_i - b_j$. Then $\delta b_{21}$ is constrained by fitting the data from the solar neutrino experiments and the KamLAND reactor neutrino experiment [52], which gives

$$\delta b_{21} < 3.1\times10^{-20}\,{\rm GeV}\,. \qquad (22)$$

In addition, the bound of $\delta b_{32}$ is also obtained from the Super-K and K2K data [53, 54]

$$\delta b_{32} < 5\times10^{-23}\,{\rm GeV}\,. \qquad (23)$$

It has been shown that the future neutrino factory experiment [54, 55] will be sensitive to a $\delta b_{32}$ as small as

$$\delta b_{32} \sim 3\times10^{-23}\,{\rm GeV}\,. \qquad (24)$$

From cosmological observations [2, 3] and the experimental results on neutrino oscillations [64–69], we take the parameters of our model as $\rho_\phi \sim 3\times10^{-47}\,{\rm GeV}^4$ and $w_\phi \sim -0.9$ and the mass scale of the neutrinos as $m \sim 10^{-2}$ eV. For the mass of the right-handed neutrino (dark fermion) we take, for example, $M = 1$ eV [24]. One can see that the values of the $CPT$-violation parameters $\delta b_{21}$ and $\delta b_{32}$ are predicted to be

$$\delta b_{21} \sim \delta\tilde{b}_{21}\left(\frac{m}{M}\right)\frac{1}{\Lambda}[(1+w_\phi)\rho_\phi]^{1/2} \sim \delta\tilde{b}_{21}\left(\frac{\rm MeV}{\Lambda}\right)1.7\times10^{-23}\,{\rm GeV}\,, \qquad (25)$$

and

$$\delta b_{32} \sim \delta\tilde{b}_{32}\left(\frac{m}{M}\right)\frac{1}{\Lambda}[(1+w_\phi)\rho_\phi]^{1/2} \sim \delta\tilde{b}_{32}\left(\frac{\rm MeV}{\Lambda}\right)1.7\times10^{-23}\,{\rm GeV}\,. \qquad (26)$$

As shown in (12), the parameters $\delta\tilde{b}_{32}$ and $\delta\tilde{b}_{21}$ are $\mathcal{O}(1)$. The equations above indicate that it is quite possible to have $CPT$-violating effects consistent with the present experimental data and detectable in the future neutrino factory experiment with $\Lambda$ no larger than MeV. It should be noted that if the value of the quintessence field $\phi$ is of the order of $M_{\rm Pl}$, the mass of the right-handed neutrinos should be shifted greatly by (2). However, in the dark energy models [24, 70, 71] where the value of $\phi$ is much lower than $M_{\rm Pl}$, and even lower than $\Lambda$, our model is consistent.

We now estimate the corresponding $CPT$-violation in the electron sector. For the parameters taken above, we have $c^0 \sim \tilde{c}\, 3.5\times10^{-34}$ GeV. The present experimental limit is $c^0 < 5\times10^{-25}$ GeV [55, 60]. We see that the $CPT$-violation of the electron in our model is well within the present limit.

## 4 Conclusion

In summary, we study the neutrino $CPT$-violation induced by the dark energy sector. Specifically we consider a dark energy model including a scalar boson and right-handed neutrinos, and we introduce a derivative coupling between the boson and the neutrinos. This derivative coupling leads to cosmological $CPT$-violation during the evolution of the dark energy field. We calculate the induced $CPT$-violation in the left-handed neutrinos due to their mixing with the right-handed neutrinos and also the loop contribution to the $CPT$-violation of the electron. Our calculations show that the $CPT$-violation in both neutrinos and electrons is well within the present experimental limits. Furthermore, neutrino $CPT$-violation can be tested in future neutrino oscillation experiments such as the neutrino factory. Our study in this paper shows that the neutrino oscillations may provide us with a non-gravitational way to probe the properties of dark energy.

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