Detecting dark energy in long baseline neutrino oscillations*

GU Pei-Hong(顾佩洪)[1;1)] BI Xiao-Jun(毕效军)[2;2)] FENG Bo(冯波)[3,4;3)]
YOUNG Bing-Lin(杨炳麟)[5;4)] ZHANG Xin-Min(张新民)[1;5)]

1 (Theoretical Physics Division, IHEP, Chinese Academy of Sciences, Beijing 100049, China)
2 (Key Laboratory of Particle Astrophysics, IHEP, Chinese Academy of Sciences, Beijing 100049, China)
3 (National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China)
4 (Research Center for the Early Universe(RESCEU), Graduate School of Science,
The University of Tokyo, Tokyo 113-0033, Japan)
5 (Department of Physics and Astronomy, Iowa State University, Ames, Iowa 50011, USA)

Abstract In this paper, we discuss a possibility of studying properties of dark energy in long baseline neutrino oscillation experiments. We consider two types of models of neutrino dark energy. For one type of models the scalar field is taken to be quintessence-like and for the other phantom-like. In these models the scalar fields couple to the neutrinos to give rise to spatially varying neutrino masses. We will show that the two types of models predict different behaviors of the spatial variation of the neutrino masses inside the Earth and consequently result in different signals in long baseline neutrino oscillation experiments.

Key words dark energy, neutrino oscillation

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1 Introduction

There are growing evidences from various cosmic observations, including type Ia supernova (SNIa)[1], cosmic microwave background (CMB)[2], large scale structures (LSS)[3, 4], and so on, that support for a spatially flat and accelerating universe at the present epoch. In the context of Friedmann-Robertson-Walker cosmology, this acceleration is attributed to the so-called dark energy. The simplest candidate for the dark energy seems to be a remnant small cosmological constant. However, many physicists are attracted to the idea that the dark energy is due to a dynamical component in the evolution of the universe, such as the quintessence[5—9], the K-essence[10—12], the phantom[13], or the quintom[14—17].

Recently there have been a lot of work[18—37] which study the possible connections between neutrinos and the dark energy, generally referred to as the neutrino dark energy. One of the predictions of the class of models of neutrino dark energy is that the neutrino masses are not constant, but can vary as a function of space and time. This general prediction can be tested with Short Gamma Ray Burst[26], CMB and LSS[28], and much more interestingly and directly in neutrino oscillation experiments[21, 22, 38—42]. In this paper we make a concrete study of the possibility of probing the property of dark energy and differentiating its dynamic origin in the very long baseline neutrino oscillations.

In general for the models of neutrino dark energy, the Lagrangian is given by

$$\mathcal{L}=\mathcal{L}_{\nu}^{\rm SM}+\mathcal{L}_{\phi}+\mathcal{L}_{\rm int}\ , \qquad (1)$$

where $\mathcal{L}_{\nu}^{\rm SM}$ is the Lagrangian of the standard model describing the physics of the left-handed neutrinos,

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1) E-mail: guph@mail.ihep.ac.cn
2) E-mail: bixj@mail.ihep.ac.cn
3) E-mail: fengbo@resceu.s.u-tokyo.ac.jp
4) E-mail: young@iastate.edu
5) E-mail: xmzhang@mail.ihep.ac.cn

$\mathcal{L}_\phi$ is for the dynamical dark energy scalar ϕ such as quintessence or phantom, and $\mathcal{L}_{\rm int}$ describes the sector that mediates the interaction between the dark energy scalar and neutrinos, and gives rise to variations of the neutrino masses.

At energy much below the electroweak scale, the relevant Lagrangian for the neutrino dark energy can be written as

$$\mathcal{L}=\mathcal{L}_\nu+\mathcal{L}_\phi-c\sum_j m_j(\phi)\bar{\nu_j}\nu_j \ , \tag{2}$$

where $\mathcal{L}_\nu$ is the kinetic term of neutrinos, c is a coefficient which takes the value of 1 for a Dirac neutrino and 1/2 for a Majorana neutrino, $m_j(\phi)$ is the scalar field dependent mass of the j-th neutrino that characterizes the interaction between the neutrino and the dark energy scalar.

The authors of Ref. [34] have used the recently released SNIa data to constrain the coupling of the scalar ϕ to neutrinos and the property of the dark energy scalar. They found that the model with a phantom scalar is mildly favored. However, the data do not rule out the possibility of the quintessence scalar coupled to neutrinos. In this paper we will show that these two models predict different spatial variations of neutrino masses inside the Earth and consequently result in different signals in the very long baseline neutrino oscillations.

This paper is organized as follows: in Section 2 we present our mechanism for the neutrino mass variation; in Section 3 we study quantitatively the mass-varying effect in the long baseline neutrino oscillations; Section 4 is a brief summary.

2 Mechanism for variations of neutrino masses

In the Standard Model of particle physics, a typical term for the neutrino masses can be described by a lepton violating dimension-5 operator

$$-\mathcal{L}_{\not{L}}=\frac{2}{f}l_{\rm L}l_{\rm L}HH+{\rm h.c.}, \tag{3}$$

where f is a scale of new physics beyond the standard model which generates the B-L violations, l and H are the lepton and Higgs doublet, respectively. Here we neglect the lepton generation symbol. When the Higgs field gets a vacuum expectation value, $\langle H\rangle=v\approx174$ GeV, the left-handed neutrino receives a Majorana mass $\sim\dfrac{v^2}{f}$. In Ref. [20] the authors proposed a model where the dark energy scalar ϕ couples to the dim-5 operator. In this model the neutrino masses vary along with the evolution of the universe and the neutrino mass limit imposed by baryogenesis is modified.

The dimension-5 operator above is not renormalizable. It can be generated from physics beyond the standard model which involves very heavy particles interacting with the Standard Model particles. At low energies the heavy particles can be integrated out and thus resulting in effective, nonrenormalizable terms. For example, in the model of the minimal see-saw mechanism, we have the neutrino mass term,

$$-\mathcal{L}=\sum_{ij}h_{ij}\bar{l}_{Li}H\nu_{Rj}+\frac{1}{2}\sum_{ij}M_{ij}\bar{\nu}^{\rm C}_{Ri}\nu_{Rj}+{\rm h.c.}, \tag{4}$$

where M_{ij} are the Majorana mass matrix elements of the right-handed neutrinos and h_{ij} the Yukawa couplings. The Dirac masses of the neutrinos are given by $m_{Dij}=h_{ij}v$. Now integrating out the heavy right-handed neutrinos ν_{Rj}, one will generate a dim-5 operator as stated above. As pointed out in Ref. [20], there are various possibilities to have the light neutrino masses varied, such as by coupling the quintessence field to either the Dirac masses or the Majorana masses of the right-handed neutrinos, or to both.

In this paper we consider the case where the variation of the neutrino masses is caused by a coupling of the dark energy scalar ϕ to the right-handed neutrinos. With the Majorana masses of the right-handed neutrinos varying, M_{ij} becomes a function of the dark energy scalar field ϕ, $M_{ij}=M_{ij}(\phi)$. Furthermore, we assume a linear relationship between the Majorana mass and ϕ. Then the relevant Lagrangian can be written as

$$-\mathcal{L}=h_{ij}\bar{l}_{Li}H\nu_{Rj}+\frac{1}{2}g_{ij}\phi\bar{\nu}^{\rm C}_{Ri}\nu_{Rj}+{\rm h.c.}\mp\frac{1}{2}\partial_\mu\phi\partial^\mu\phi+V(\phi)\ , \tag{5}$$

where g_{ij} are dimensionless constants and $V(\phi)$ is the potential for ϕ. The upper minus sign in $\mp$ is for the case of quintessence while the lower plus sign for the phantom. This convention will be used throughout this paper. Now the Majorana mass matrix elements of the right-handed neutrinos can be written as

$$M_{ij}=g_{ij}\phi \tag{6}$$

and consequently via the seesaw mechanism we obtain the masses of the light neutrinos $\nu=\nu_{\rm L}+\nu^{\rm C}_{\rm L}$,

$$m_\nu\propto\frac{1}{\phi}\ . \tag{7}$$

Similar to the study on the mass varying neutrinos in Ref. [22], here we introduce also a coupling between ϕ and the baryon matter with the effective potential for ϕ at low energies given by[43, 44]

$$V^{\rm eff}(\phi)=V(\phi)+\sum_i\rho_i{\rm e}^{\beta_i\phi/m_{pl}}\ , \tag{8}$$

where β_i is a dimensionless constant[45, 46], ρ_i denotes the energy density of the i-th matter field, and $m_{\rm pl}$ is the reduced Planck mass. The dark energy scalar ϕ shall change its value in space[43, 44] according to the equation of motion

$$\nabla^2\phi=\pm\Big\{V_{,\phi}+\sum_i\frac{\beta_i}{m_{\rm pl}}\rho_i{\rm e}^{\beta_i\phi/m_{\rm pl}}\Big\}. \qquad (9)$$

In the following we will calculate the evolution of the dark energy field and the corresponding variation of neutrino masses in the Earth for both the quintessence and the phantom cases.

The density profile of baryon in the Earth is taken as the widely adopted PREM model[47], in which the Earth is taken to be spherically symmetric. The atmosphere is treated as a homogenous layer of 10 km in thickness with a constant density $\rho_{\rm atm}\approx10^{-3}$ g/cm^3. Defining $x=r/R_\oplus$ and $R_{\rm atm}=R_\oplus+10$ km with $R_\oplus=6371$ km the Earth's radius, the baryon density can be expressed as

$$\rho_i(r)=a_i+b_ix+c_ix^2+d_ix^3 \quad \text{for} \quad r_{i+1}<r\leqslant r_i \qquad (10)$$

with

$$\begin{aligned}(a_1,a_2,...,a_{11})=&(\rho_{\rm atm},1.02,2.6,2.9,2.691,\\&7.1089,11.2494,5.3197,7.9565,\\&12.5815,13.0885), \qquad (11)\\(b_1,b_2,...,b_{11})=&(0,0,0,0,0.6924,-3.8045,-8.0298,\\&-1.4836,-6.4761,-1.2638,0), \qquad (12)\\(c_1,c_2,...,c_{11})=&(0,0,0,0,0,0,0,0,5.5283,\\&-3.6426,-8.8381), \qquad (13)\\(d_1,d_2,...,d_{11})=&(0,0,0,0,0,0,0,0,\\&-3.0807,-5.5281,0) \qquad (14)\end{aligned}$$

in units of g/cm^3, and

$$\begin{aligned}(r_1,r_2,...,r_{12})=&(R_{\rm atm},R_\oplus,6368,6356,6346.6,\\&6151,5971,5771,5701,3480,1221.5,0) \qquad (15)\end{aligned}$$

in units of km. We also assume a homogeneous baryon background outside the atmosphere with the density

$$\rho_{\rm U}^{\rm B}\approx4\%\times\rho_{\rm c}\approx1.4\times10^{-29}\ {\rm g/cm^3}, \qquad (16)$$

where $\rho_{\rm c}\approx4.1\times10^{-47}$ GeV^4 is the critical energy density of the universe at the present epoch.

With these assumptions, Eq. (9) can be simplified as

$$\frac{{\rm d}^2\phi}{{\rm d}r}+\frac{2}{r}\frac{{\rm d}\phi}{{\rm d}r}=\pm\left\{\frac{{\rm d}V}{{\rm d}\phi}+\frac{\lambda_{\rm B}}{m_{\rm pl}}\rho_{\rm B}{\rm e}^{\lambda_{\rm B}\phi/m_{\rm pl}}\right\} \qquad (17)$$

with the boundary conditions

$$\phi=\phi_U \quad \text{for} \quad r=r_{\rm c}, \qquad (18)$$

$$\frac{{\rm d}\phi}{{\rm d}r}=0 \quad \text{for} \quad r=0\ . \qquad (19)$$

Here $r_{\rm c}$ denotes the interface between the static solution and the cosmological one. For $r>r_{\rm c}$, we expect ϕ to become a constant: $\phi\equiv\phi_{\rm U}$ and $\phi_{\rm U}$ is the value of the dark energy scalar field on cosmological scales at the present epoch. For simplicity we take $r_{\rm c}\sim R_{\rm atm}$ which is consistent with the assumption in Eq. (16) that the baryon background becomes very thin and homogeneous for $r>R_{\rm atm}$. It should be noted that we require $\lambda_{\rm B}<10^{-4}$ to satisfy the equivalence principle constraints[45, 46].

In addition, we take

$$V(\phi)=V_0{\rm e}^{-\beta\phi/m_{\rm pl}} \qquad (20)$$

as an example[48] and then write Eq. (17) as

$$\frac{{\rm d}^2\phi}{{\rm d}r^2}+\frac{2}{r}\frac{{\rm d}\phi}{{\rm d}r}=\pm\left\{-\frac{\beta}{m_{\rm pl}}V_0{\rm e}^{-\beta\phi/m_{\rm pl}}+\frac{\lambda_{\rm B}}{m_{\rm pl}}\rho_{\rm B}{\rm e}^{\lambda_{\rm B}\phi/m_{\rm pl}}\right\}. \qquad (21)$$

For this given potential, the value of $\phi_{\rm U}$ is

$$\phi_{\rm U}=\frac{m_{\rm pl}}{\beta}\ln\left[\frac{2V_0}{(1-w)\rho_\Phi}\right], \qquad (22)$$

with $w=\dfrac{\dot\phi^2/2-V}{\dot\phi^2/2+V}$ and $\rho_\phi=\dfrac{1}{2}\dot\phi^2+V$ for the quintessence case, while $w=\dfrac{-\dot\phi^2/2-V}{-\dot\phi^2/2+V}$ and $\rho_\phi=-\dfrac{1}{2}\dot\phi^2+V$ for the phantom. Here $w\approx-1$ is the equation of the state and $\rho_\phi\approx73\%\times\rho_{\rm c}\approx3.0\times10^{-47}$ GeV^4 is the energy density of the dark energy at the present time1).

Assuming $\phi/m_{\rm pl}\ll1$ for $0\leqslant r\leqslant R_{\rm atm}$, which we will show in the later numerical results is reasonable, we can simplify Eq. (21) as

$$\frac{{\rm d}^2\phi}{{\rm d}r}+\frac{2}{r}\frac{{\rm d}\phi}{{\rm d}r}=\pm\left\{-\frac{\beta}{m_{\rm pl}}\frac{1}{2}(1-w)\rho_\Phi+\frac{\lambda_{\rm B}}{m_{\rm pl}}\rho_{\rm B}\right\} \qquad (23)$$

and obtain the solution

$$\phi=\begin{cases}\phi_{\rm U} & \text{for} \quad r\geqslant R_{\rm atm}\\ g_i-\dfrac{f_i}{x}\pm\left\{-\dfrac{\beta}{m_{\rm pl}}\dfrac{1}{2}(1-w)\rho_\Phi R_\oplus^2\dfrac{x^2}{6}+\dfrac{\lambda_{\rm B}}{m_{\rm pl}}R_\oplus^2\left(\dfrac{a_i}{6}x^2+\dfrac{b_i}{12}x^3+\dfrac{c_i}{20}x^4+\dfrac{d_i}{30}x^5\right)\right\} & \text{for} \quad r_{i+1}\leqslant r\leqslant r_i\end{cases} \qquad (24)$$

1) Here we do not expect the dark energy model to preserve the tracking behavior[8, 9] and in this sense, the dark energy scalar field is essentially like the cosmological constant on the largest scales. This is also consistent with the static condition adopted in Eq. (9).

with

$$f_i = \begin{cases} 0 & \text{for } \ i=11 \\ f_{i+1} \pm \dfrac{\lambda_{\rm B}}{m_{\rm pl}} R_\oplus^2 \left(\dfrac{a_{i+1}-a_i}{3} x_{i+1}^3 + \dfrac{b_{i+1}-b_i}{4} x_{i+1}^4 + \dfrac{c_{i+1}-c_i}{5} x_{i+1}^5 + \dfrac{d_{i+1}-d_i}{6} x_{i+1}^6 \right) & \text{for } \ i \leqslant 10 \end{cases} \tag{25}$$

and

$$g_i = \begin{cases} \phi_{\rm U} + \dfrac{f_1}{x_1} \pm \left\{ \dfrac{\beta}{m_{\rm pl}} \dfrac{1}{2}(1-w)\rho_\phi R_\oplus^2 \dfrac{x_1^2}{6} - \dfrac{\lambda_{\rm B}}{m_{\rm pl}} R_\oplus^2 \left(\dfrac{a_1}{6} x_1^2 + \dfrac{b_1}{12} x_1^3 + \dfrac{c_1}{20} x_1^4 + \dfrac{d_1}{30} x_1^5 \right) \right\} & \text{for } \ i=1 \\ g_{i-1} \mp \dfrac{\lambda_{\rm B}}{m_{\rm pl}} R_\oplus^2 \left(\dfrac{a_{i+1}-a_i}{2} x_i^2 + \dfrac{b_{i+1}-b_i}{3} x_i^3 + \dfrac{c_{i+1}-c_i}{4} x_i^4 + \dfrac{d_{i+1}-d_i}{5} x_i^5 \right) & \text{for } \ i \geqslant 2. \end{cases} \tag{26}$$

Here we have adopted the definition of x_i: $x_i \equiv r_i/R_\oplus$.

In the numerical calculation, we take $\beta = 1$ and $\phi_{\rm U} \approx 10^{-15} m_{\rm pl}$ by choosing V_0 to satisfy the cosmological observations, $\rho_\phi \approx 3.0 \times 10^{-47}$ GeV^4 and $w \approx -1$. In Fig. 1, we plot ϕ as a function of r with $\lambda_{\rm B} = 10^{-5}$ and 10^{-6} for the quintessence and phantom cases, respectively. Our results show that in the two cases the variations of the dark energy field can be sizable inside the Earth. Accordingly, as shown in Fig. 2, the neutrino masses could have a significant variation inside the Earth. Meanwhile we notice that the consequences of the quintessence and the phantom are different due to the opposite behaviors of the dark energy fields.

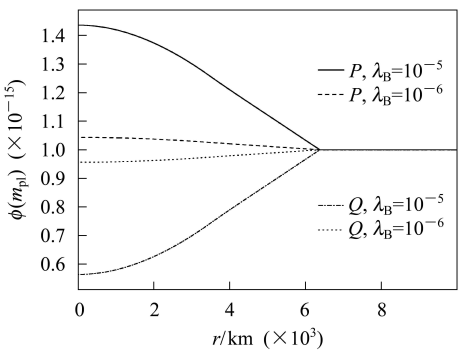

Fig. 1. The evolution of the dark energy field ϕ in the baryon matter background with $\lambda_{\rm B} = 10^{-5}$ and 10^{-6} for the quintessence and the phantom cases, respectively. It is shown that the assumption of $\phi/m_{\rm pl} \ll 1$ can be fulfilled in the whole space. P and Q are for the quintessence and phantom cases, respectively.

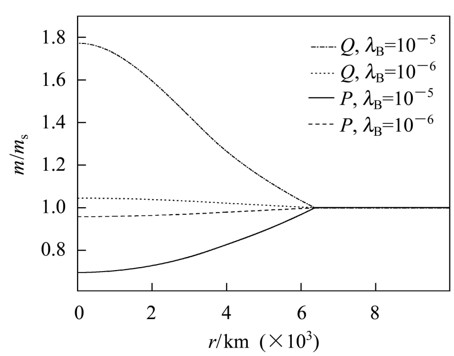

Fig. 2. The variation of the neutrino masses in the baryon background with $\lambda_{\rm B} = 10^{-5}$ and 10^{-6} for the quintessence and the phantom cases, respectively. Here m is the masses of the left-handed Majorana neutrinos and $m_{\rm s}$ denotes its value on the Earth surface. P and Q are for the quintessence and phantom cases, respectively.

3 Mass-varying effect in long baseline neutrino oscillations

Now we discuss the mass-varying effect induced by the evolution of the dark energy in neutrino oscillations. The neutrino propagation in matter is governed by the Shrödinger equation:

$$\mathrm{i}\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix} \nu_{\rm e} \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \left[\left[\frac{\phi_{\rm s}}{\phi(x)} \right]^2 \frac{1}{2E} U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{pmatrix} U^\dagger + \sqrt{2} G_{\rm F} \begin{pmatrix} N_{\rm e}(x) & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \right] \begin{pmatrix} \nu_{\rm e} \\ \nu_\mu \\ \nu_\tau \end{pmatrix}. \tag{27}$$

Here U is the usual 3-flavour vacuum mixing matrix and $\sqrt{2} G_{\rm F} N_{\rm e}(x)$ is the MSW term[49, 50]. We have also adopted the definition that $\phi_{\rm s}$, Δm_{ij}^2 are the values of the dark energy field and the neutrino mass squared differences on the Earth surface, respectively. In the following numerical estimate, we will take $\Delta m_{21}^2 \approx 7.9 \times 10^{-5}$ eV^2, $\tan^2\theta_{12} \approx 0.4$ from KamLAND[51], $\Delta m_{31}^2 \approx 2.8 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{23} \approx 1.0$ from K2K[52], $\sin^2 2\theta_{13} \leqslant 0.1$ from Chooz[53] which we will take to be zero for simplicity, and a zero Dirac CP phase in Eq. (27).

In Fig. 3, by taking the longest baseline $L = 2R_\oplus$ which appears in the atmospheric neutrino oscillations and $L = 732$ km which is Fermilab to Soudan or CERN to Gran Sasso (the right panel), we plot the survival probabilities of ν_μ with $\lambda_{\rm B} = 10^{-5}$, 10^{-6} and 0 for the case of the quintessence and the phantom, respectively. For $\lambda_{\rm B} = 0$, the spatial variation of the dark energy is negligible and the neutrino oscillation is identical to the case of decoupling between the neutrino mass and dark energy. For $\lambda_{\rm B} = 10^{-5}$, it is clear that the survival probabilities differ significantly for the cases of the quintessence, phantom, and decoupling of neutrino and dark energy for $L = 2R_\oplus$. But for $L = 732$ km the different cases can not be distinguished.

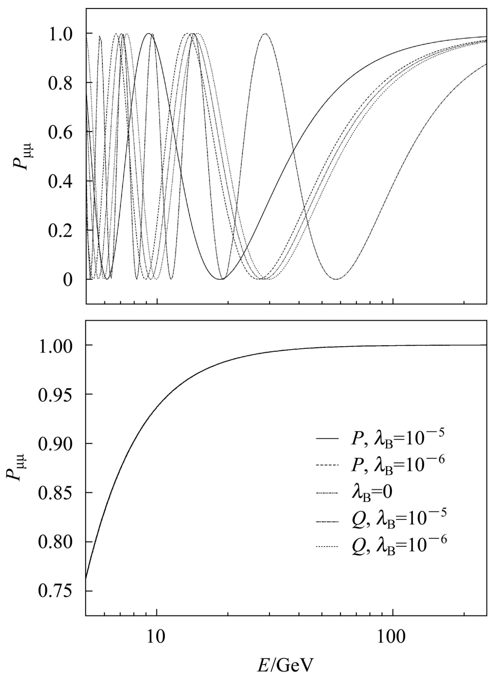

Fig. 3. The survival probabilities $P_{\mu\mu}$ of ν_μ in the long baseline $L = 2R_\oplus$ and $L = 732$ km with $\lambda_B = 10^{-5}$, 10^{-6} and 0. P and Q are for the quintessence and phantom cases, respectively. Note that $\lambda_\beta = 0$ is identical to the case of decoupling between the neutrino mass and dark energy. In the calculations, we have used $\Delta m_{21}^2 \approx 7.9{\times}10^{-5}$ eV^2, $\Delta m_{31}^2 \approx 2.8{\times}10^{-3}$ eV^2, $\tan^2\theta_{12} \approx 0.4$, $\sin^2 2\theta_{23} \approx 1.0$, $\sin^2 2\theta_{13} \approx 0$, and a zero CP phase. The left panel if for $L = 2R_\oplus$ and the right panel $L = 732$ km.

We also consider the very long baseline $L = 7332$ km which is the distance from Fermilab to Gran Sasso underground laboratory in Italy[54] and $L = 9400$ km which is the distance from Fermilab to Beijing. As shown in Fig. 4, the survival probabilities $P_{\mu\mu}$ with $\lambda_B = 10^{-5}$ sensitive enough to distinguish the cases of the quintessence, phantom, and decoupling. The most sensitive measurement is perhaps at the second zero of the survival probability. For $L = 9400$ km, the decoupling case has the zero at about muon neutrino energy of 20 GeV, the quintessence above 20 GeV, and the phatom below 20 GeV. The separation in energy is sufficiently large that it should make the distinction of the three case clean.

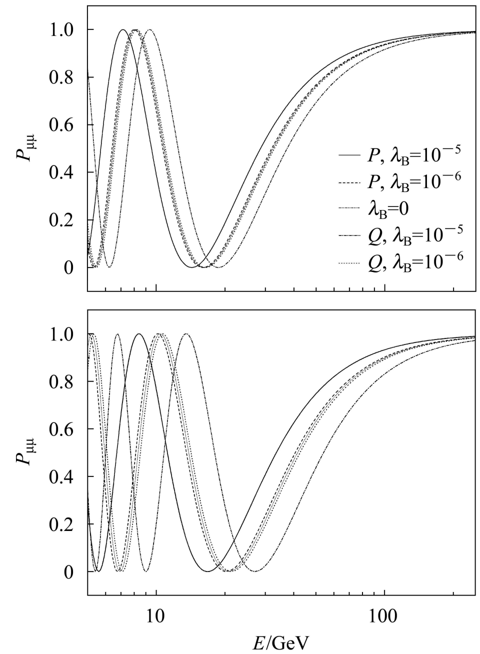

Fig. 4. The survival probabilities $P_{\mu\mu}$ of ν_μ in the very long baseline $L = 7332$ km and $L = 9400$ km with $\lambda_B = 10^{-5}$, 10^{-6}, and 0. P and Q are for the quintessence and phantom cases, respectively. Note that $\lambda_\beta = 0$ is identical to the case of decoupling between the neutrino mass and dark energy. In the calculations, we have used $\Delta m_{21}^2 \approx 7.9 \times 10^{-5}$ eV^2, $\Delta m_{31}^2 \approx 2.8 \times 10^{-3}$ eV^2, $\tan^2\theta_{12} \approx 0.4$, $\sin^2 2\theta_{23} \approx 1.0$, $\sin^2 2\theta_{13} \approx 0$, and a zero CP phase. The left panel is for $L = 7332$ km and the right panel for $L = 9400$ km.

4 Summary

In this paper, we discuss a possibility of studying the dark energy property with long baseline neutrino oscillation experiments. We consider two types of models of neutrino dark energy where for one model the scalar is taken to be quintessence-like and for another model phantom-like. These scalars couple to the neutrinos which give rise to a variation of the neutrino masses. We take a specific scalar dark energy potential with the Earth baryon background and then calculate the spatial variation of the dark energy field for the case of the quintessence and the phantom, respectively. We find the corresponding evolution behaviors of the neutrino masses inside the Earth could be significantly different in the two cases and hence the property of the dark energy may be probed in the long baseline neutrino oscillations.

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