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Model of mass varying neutrinos in SUSY

Ryo Takahashi [a,*], Morimitsu Tanimoto [b]

[a] *Graduate School of Science and Technology, Niigata University, 950-2181 Niigata, Japan*
[b] *Department of Physics, Niigata University, 950-2181 Niigata, Japan*

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Abstract

We discuss the mass varying neutrino scenario in the supersymmetric theory. In the case of the model with the single superfield, one needs the soft SUSY breaking terms or the μ term. However, fine-tunings of some parameters are required to be consistent with the cosmological data. In order to avoid the fine-tuning, we discuss the model with two superfields, which is consistent with the cosmological data. However, it is found that the left-handed neutrino mixes with the neutrino of the dark sector maximally. Adding a right-handed neutrino, which does not couple to the dark sector, we obtain a favorable model in the phenomenology of the neutrino experiments. In this model, the deceleration of the cosmological expansion converts to the acceleration near $z \simeq 0.5$. The speed of sound c_s becomes imaginary if we put $w_0 = -0.9$, which corresponds to $m_\nu^0 = 3.17$ eV. On the other hand, if we take $w_0 = -0.998$, which leads to $m_\nu^0 = 0.05$ eV, c_s^2 becomes positive since w evolves rapidly near the present epoch in our model.

1. Introduction

One of the most challenging questions in both cosmological and particle physics is the nature of the dark energy in the Universe. At the present epoch, the energy density of the Universe is dominated by a dark energy component, whose negative pressure causes the expansion of the Universe to accelerate. In order to clarify the origin of the dark energy, one has tried to understand the connection of the dark energy with particle physics.

Recently, Fardon, Nelson and Weiner [1] proposed an idea of the mass varying neutrinos (MaVaNs), in which the neutrino couples to the dark energy. The variable neutrino mass was considered at first in [2], and was discussed for neutrino clouds [3]. However, the renewed MaVaNs scenario [1] has tried to make a connection between neutrinos and the dark energy. In this scenario, an unknown scalar field which is called "acceleron" is introduced, and then, the neutrino mass becomes a dynamical field.

The acceleron field sits at the instantaneous minimum of its potential, and the cosmic expansion only modulates this minimum through changes in the neutrino density. Therefore, the neutrino mass is given by the acceleron field and changes with the evolution of the Universe. The cosmological parameter w and the dark energy also evolve with the neutrino mass. Those evolutions depend on a model of the scalar potential strongly. Typical examples of the potential have been discussed by Peccei [4].

The MaVaNs scenario leads to interesting phenomenological results. The neutrino oscillations may be a probe of the dark energy [5,6]. The baryogenesis [7–9], the cosmo MSW effect of neutrinos [10] and the solar neutrino [11,12] have been studied in the context of this scenario. Cosmological discussions of the scenario are also presented [13–17].

In this Letter, we study the MaVaNs scenario in the supersymmetric theory and construct models which are consistent with the current cosmological data [18]. We discuss the dark energy in the some cases of the superpotential. Then, we present the numerical results for the evolution of the neutrino mass and w. In Sections 2 and 3, we study the superpotential with the single superfield and the double superfields, respectively. The Section 4 devotes to the discussions and summary.

* Corresponding author.
E-mail addresses: takahasi@muse.sc.niigata-u.ac.jp (R. Takahashi), tanimoto@muse.sc.niigata-u.ac.jp (M. Tanimoto).

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2. The single superfield model

The simplest assumption of the MaVaNs with the supersymmetry is to introduce a single chiral superfield A, which is a singlet under the gauge group of the Standard Model. The superfield A couples to the left-handed lepton superfield L. In this framework, we discuss three cases of the superpotential.

2.1. The simplest model $W = \frac{\lambda}{3}A^3 + m_D LA$

We suppose the dark sector with the superpotential

$$W = \frac{\lambda}{3}A^3 + m_D LA, \tag{1}$$

where λ and m_D are a coupling constant and a mass parameter, respectively. The scalar and spinor components of A are (ϕ_a, ψ_a), and the scalar component ϕ_a is assumed to be the acceleron. The second term of the right-hand side $m_D LA$ in Eq. (1) is derived from the Yukawa coupling $yLAH$ with $y\langle H\rangle = m_D$, where H is the Higgs doublet. Assuming the vanishing vacuum expectation value of the left-handed slepton, the superpotential of Eq. (1) is enough to discuss the dark energy, because only the scalar potential of the acceleron and the neutrino energy density contribute to the dark energy in the MaVaNs scenario. We omit other terms, which does not couple to A, in our superpotential.

Then, the scalar potential for ϕ_a is given by

$$V(\phi_a) = \lambda^2|\phi_a|^4 + m_D^2|\phi_a|^2. \tag{2}$$

We can write down a Lagrangian density from Eq. (1),

$$\mathcal{L} = m_D \nu_L \psi_a + 2\lambda\phi_a\psi_a\psi_a. \tag{3}$$

This means that the dark sector interacts with the standard electroweak sector only through neutrinos. By solving the eigenvalue equation of the 2×2 mass matrix,

$$\begin{pmatrix} 0 & m_D \\ m_D & 2\lambda\phi_a \end{pmatrix}, \tag{4}$$

ϕ_a is given in terms of the neutrino mass,

$$\lambda\phi_a = \frac{m_\nu}{2} - \frac{m_D^2}{2m_\nu}. \tag{5}$$

Using this relation, the scalar potential of Eq. (2) is given in terms of the neutrino mass m_ν as follows:

$$V(m_\nu) = \frac{1}{16\lambda^2}\left(m_\nu - \frac{m_D^2}{m_\nu}\right)^4 + \frac{m_D^2}{4\lambda^2}\left(m_\nu - \frac{m_D^2}{m_\nu}\right)^2, \tag{6}$$

where, for simplicity, we take the scalar field real.

In the MaVaNs scenario, there are two constraints on the scalar potential. The first one comes from the observation of the Universe, which is that the present dark energy density is about $0.7\rho_c$, ρ_c being a critical density. Since the dark energy is assumed to be the sum of the energy densities of the neutrino and the scalar potential

$$\rho_{\text{dark}} = \rho_\nu + V\big(\phi_a(m_\nu)\big), \tag{7}$$

the first constraint turns to

$$\rho_\nu^0 + V\big(\phi_a^0\big(m_\nu^0\big)\big) = 0.7\rho_c, \tag{8}$$

where "0" represents a value at the present epoch and 70% is taken for the dark energy in the Universe.

The second one comes from the fundamental assumption in this scenario, which is that ρ_{dark} is stationary with respect to variations in the neutrino mass. This assumption is represented by

$$\frac{\partial\rho_\nu}{\partial m_\nu} + \frac{\partial V(\phi_a(m_\nu))}{\partial m_\nu} = 0. \tag{9}$$

For our purpose it suffices to consider the neutrino mass as a function of the cosmic temperature [4]. Then the stationary condition Eq. (9) turns to [4]

$$T^3\frac{\partial F}{\partial\xi} + \frac{\partial V(\phi_a(m_\nu))}{\partial m_\nu} = 0, \tag{10}$$

where $\xi = m_\nu(T)/T$, $\rho_\nu = T^4F(\xi)$ and

$$F(\xi) = \frac{1}{\pi^2}\int_0^\infty \frac{dy\, y^2\sqrt{y^2+\xi^2}}{e^y+1}. \tag{11}$$

We have the time evolution of the neutrino mass from the relation of Eq. (10). Since the stationary condition should be satisfied at the present epoch, the second constraint on the scalar potential is

$$\left[T^3\frac{\partial F}{\partial\xi} + \frac{\partial V(\phi_a(m_\nu))}{\partial m_\nu}\right]\Bigg|_{m_\nu=m_\nu^0,\,T=T_0} = 0. \tag{12}$$

This condition turns to

$$\frac{\partial V(\phi_a(m_\nu))}{\partial m_\nu}\Bigg|_{m_\nu=m_\nu^0,\,T=T_0} = -n_\nu^0, \tag{13}$$

where n_ν^0 is the neutrino number density at the present epoch.

Since neutrinos are supposed to be non-relativistic at the present epoch, $\rho_\nu^0 = m_\nu^0 n_\nu^0$ is given and the equation of state becomes

$$w^0 + 1 = \frac{m_\nu^0 n_\nu^0}{m_\nu^0 n_\nu^0 + V(\phi_a^0(m_\nu^0))}. \tag{14}$$

Taking the typical observed value $w_0 = -0.9$, we can fix ρ_ν^0. Then the neutrino mass m_ν^0 is obtained by putting the neutrino number density at the present epoch $n_\nu^0 = 8.82 \times 10^{-13}\ \text{eV}^3$ on $\rho_\nu^0 = m_\nu^0 n_\nu^0$. Finally, we get $m_\nu^0 = 3.17$ eV and $V(\phi_a^0(m_\nu^0)) = 2.52 \times 10^{-11}\ \text{eV}^4$, where we take $\rho_{\text{dark}} = 0.7\rho_c = 2.8 \times 10^{-11}\ \text{eV}^4$ at the present epoch. The neutrino mass 3.17 eV may be large compared with the terrestrial neutrino experimental data. The neutrino mass of the 1 eV scale is related with the LSND evidence [19] and will be tested at the MiniBooNE experiment [20]. On the other hand, putting $w_0 = -0.998$ we get $m_\nu^0 = 0.05$ eV, which is consistent with the atmospheric neutrino mass scale. Thus, the value of m_ν^0 depends on w_0. In our following analyses, the numerical value of m_ν^0 is not so important as far as the neutrino is non-relativistic at the present epoch. We take $m_\nu^0 = 3.17$ eV with $w_0 = -0.9$ as a reference value in the following numerical studies.

Now, we have two constraints on the potential and its derivative at the present epoch as follows:

$$V\big(\phi_a^0(m_\nu^0)\big) = 2.52\times 10^{-11}\ \text{eV}^4, \tag{15}$$

$$\left.\frac{\partial V(\phi_a(m_\nu))}{\partial m_\nu}\right|_{m_\nu=m_\nu^0} = -8.82\times 10^{-13}\ \text{eV}^3. \tag{16}$$

It is found that the gradient of the scalar potential should be negative and very small. These constraints on the scalar potential are very severe. By using the potential of Eq. (6) in the model, we have

$$\frac{\partial V(m_\nu)}{\partial m_\nu} = \frac{1}{4\lambda^2}\left(m_\nu - \frac{m_D^2}{m_\nu}\right)^3\left(1+\frac{m_D^2}{m_\nu^2}\right) + \frac{m_D^2}{2\lambda^2}\left(m_\nu - \frac{m_D^2}{m_\nu}\right)\left(1+\frac{m_D^2}{m_\nu^2}\right). \tag{17}$$

Therefore, the scalar potential satisfies the relation

$$\left.\frac{V(\phi_a(m_\nu))}{\frac{\partial V(\phi_a(m_\nu))}{\partial m_\nu}}\right|_{m_\nu=m_\nu^0,\ T=T_0} = \frac{m_\nu^0}{4}\frac{1-\frac{m_D^4}{(m_\nu^0)^4}}{1+\frac{m_D^4}{(m_\nu^0)^4}} > -\frac{m_\nu^0}{4}. \tag{18}$$

This ratio must be -28.6 from Eqs. (15) and (16), however, our input $m_\nu^0 = 3.17$ eV never reproduce this value. One cannot build any models with only one superfield A unless the SUSY breaking term or the μ term is added.

2.2. $W = \frac{\lambda}{3}A^3 + m_D LA$ with soft breaking terms

Let us take into account the soft-breaking effect of the supersymmetry. Then the scalar potential is given by

$$V(\phi_a) = \lambda^2|\phi_a|^4 + m_D^2|\phi_a|^2 + m^2|\phi_a|^2 + V_0, \tag{19}$$

where m is the soft-breaking mass and V_0 is a constant. The scale of the supersymmetry breaking in the standard sector $\tilde{m}$ is supposed to be of order the electroweak scale $\tilde{m} = v$. However, if the dark sector couples to this supersymmetry breaking only via the neutrino, radiative corrections give the supersymmetry breaking mass scale of order $(m_D/v)\tilde{m}$. Therefore, the soft-breaking mass m in the dark sector is expected to be comparable to m_D, which is taken to be $\mathcal{O}(1\ \text{eV})$. Such a small soft mass of the supersymmetry breaking corresponds to the small gravitino mass $m_{3/2} \simeq \mathcal{O}(1\ \text{eV})$, which has been given in the gauge-mediated model of Ref. [21].

The gradient of the potential are given as

$$\frac{\partial V(\phi_a(m_\nu))}{\partial m_\nu} = \frac{\phi_a}{\lambda}\left(2\lambda^2\phi_a^2 + m_D^2 + m^2\right)\left(1+\frac{m_D^2}{m_\nu^2}\right), \tag{20}$$

where ϕ_a is given in terms of m_ν as in Eq. (5). Since we have four free parameters, λ, m, V_0 and m_D, we can adjust parameters to constraints of the potential and its derivative. Putting the typical values for two parameters by hand as follows:

$$\lambda = 1, \qquad m_D = 10\ \text{eV}, \tag{21}$$

with $m_\nu^0 = 3.17$ eV, we have $\phi_a^0(m_\nu^0) = -14.2$ eV. Then, m^2 and V_0 are fixed by the data of Eqs. (15) and (16) as follows:

$$m^2 = -2\times 14.2^2 - 10^2 + \epsilon\ (\text{eV})^2, \tag{22}$$

$$V_0 = 14.2^4 - 14.2^2\epsilon + 0.7\rho_c - \rho_\nu^0\ (\text{eV})^4, \tag{23}$$

where $\epsilon = 2\lambda^2(\phi_a^0)^2 + m_D^2 + m^2 = -5.67\times 10^{-15}$ eV^2. It is remarked that the parameters m^2 and V_0 are fine-tuned on the order of 10^{-15} eV^2 to guarantee the tiny $V(m_\nu)$ and $\partial V(m_\nu)/\partial m_\nu$ at the present epoch, respectively. Using these parameters, we can get the evolution of the neutrino mass and w from the stationary condition and the equation of state, respectively. However, since such a case of fine-tunings is not interesting, we do not discuss the case furthermore.

2.3. $W = \frac{\lambda}{3}A^3 + m_D LA + \frac{\mu}{2}A^2$ model

We consider the model including μ term as follows:

$$W = \frac{\lambda}{3}A^3 + m_D LA + \frac{\mu}{2}A^2, \tag{24}$$

which leads to the scalar potential as

$$V(\phi_a) = \left|\lambda\phi_a^2 + \mu\phi_a\right|^2 + m_D^2|\phi_a|^2. \tag{25}$$

Taking a Lagrangian density of the form

$$\mathcal{L} = m_D\nu_L\psi_a + (2\lambda\phi_a + \mu)\psi_a\psi_a, \tag{26}$$

we get ϕ_a in terms of the neutrino mass instead of Eq. (5) as follows:

$$\lambda\phi_a = \frac{m_\nu - \mu}{2} - \frac{m_D^2}{2m_\nu}. \tag{27}$$

The derivative of the scalar potential is given as

$$\frac{\partial V(m_\nu)}{\partial m_\nu} = \left(1+\frac{m_D^2}{m_\nu^2}\right)\frac{\phi_a}{\lambda}\left[(\lambda\phi_a+\mu)(2\lambda\phi_a+\mu) + m_D^2\right]. \tag{28}$$

It is easily found that there is the parameter set, which satisfies the present data of Eqs. (15) and (16) as

$$\left[(\lambda\phi_a+\mu)(2\lambda\phi_a+\mu) + m_D^2\right] \sim 10^{-10}\ \text{eV}^2, \qquad m_D \ll \phi_a^0 \sim \mu \sim 10^{-3}\ \text{eV}. \tag{29}$$

This result indicates the fine-tuning among $\lambda\phi_a$, μ and m_D on the order of 10^{-7}. If the value of m_D is much smaller than values of $\lambda\phi_a$ and μ, numerical solutions are

$$\phi_a = \pm 2.24\times 10^{-3}\ \text{eV}, \qquad \mu = \mp 4.48\times 10^{-3}\ \text{eV}, \qquad |m_D| = 10^{-4}\ \text{eV}, \tag{30}$$

with $\lambda = 1$. Such a small value of $|\mu| \sim 10^{-3}$ eV may be explained by the suppression of $M_{\text{TeV}}^2/M_{\text{Planck}}$ [22].

Since two mass eigenvalues are almost degenerate due to $m_D \gg 2\lambda\phi_a + \mu$, the left-handed neutrino ν_L mixes maximally with ψ_a, which is a kind of sterile neutrinos. Thus, this model is unfavored in the phenomenology of neutrino experiments.

3. The double superfields model

It is very difficult to build a model with the single superfield without fine-tuning of parameters of the model. In this section, we introduce two superfields, A and N [23], which are singlets under the gauge group of the Standard Model.

3.1. The simple model $W = \lambda ANN + m_D LA + m'_D LN$

It is assumed that the dark sector consists of two chiral superfields A and N, whose scalar and spinor components are (ϕ_a, ψ_a) and (ϕ_n, ψ_n), respectively, with the superpotential

$$W = \lambda ANN + m_D LA + m'_D LN, \tag{31}$$

where the scalar component ϕ_a of A is assumed to be the acceleron. The scalar potential is given by

$$V(\phi_a, \phi_n) = \lambda^2|\phi_n|^4 + 4\lambda^2|\phi_a\phi_n|^2 + m_D^2|\phi_a|^2 + m_D'^2|\phi_n|^2. \tag{32}$$

The gradient of this potential is describing as follows:

$$\frac{\partial V(\phi_a)}{\partial \phi_a} = 8\lambda^2\phi_n^2\phi_a + 2m_D^2\phi_a, \tag{33}$$

where we assume the scalar component of two chiral superfields to be real. Then, we can write a Lagrangian density of the form

$$\mathcal{L} = m_D \nu_L \psi_a + m'_D \nu_L \psi_n + \lambda\phi_a\psi_n\psi_n + \lambda\phi_n\psi_a\psi_n. \tag{34}$$

Therefore the mass matrix in the coupled system of the left-handed neutrino and the dark sector is given by

$$\begin{pmatrix} 0 & m_D & m'_D \\ m_D & 0 & \lambda\phi_n \\ m'_D & \lambda\phi_n & \lambda\phi_a \end{pmatrix}, \tag{35}$$

in the (ν_L, ψ_a, ψ_n) basis. The eigenvalue equation gives

$$\phi_a = \frac{m_\nu^3 - (\lambda^2\phi_n^2 + m_D^2 + m_D'^2)m_\nu - 2\lambda m_D m'_D\phi_n}{m_\nu^2 - m_D^2}. \tag{36}$$

By using this relation, the potential of Eq. (32) is given in terms of the neutrino mass m_ν. Putting $\lambda = 1$ and $m'_D = 1$ eV by hand, other three parameters are fixed by three constraints of m_ν^0, $V(m_\nu^0)$ and $\partial V(m_\nu)/\partial m_\nu|_{m_\nu = m_\nu^0}$ as follows:

$$\phi_a^0 = -2.42\times 10^{-15}\ \text{eV}, \qquad |\phi_n| = 5.02\times 10^{-6}\ \text{eV},$$
$$|m_D| = 3.01\ \text{eV}, \tag{37}$$

where mass eigenvalues are obtained

$$m_\nu^0 = \pm 3.17\ \text{eV}, \qquad -3.01\times 10^{-6}\ \text{eV}. \tag{38}$$

We can see that two neutrinos are degenerate in the mass, in other words, ν_L and ν_a mix maximally. Therefore, this model is also unfabored in the phenomenology of the neutrino experiments.

3.2. Right-handed neutrino

Towards a realistic model, we introduce a right-handed heavy Majorana neutrino, which is assumed to decouple from ψ_a and ψ_n. Then, the effective mass matrix in Eq. (35) is modified in the (ν_L, ψ_a, ψ_n) basis as follows:

$$\begin{pmatrix} C_{LL} & m_D & m'_D \\ m_D & 0 & \lambda\phi_n \\ m'_D & \lambda\phi_n & \lambda\phi_a \end{pmatrix}, \tag{39}$$

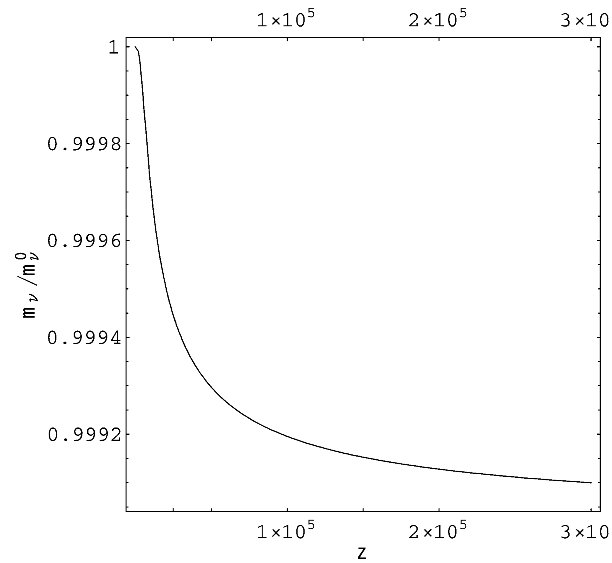

Fig. 1. Plot of the scaled neutrino mass versus the redshift z.

where C_{LL} is the effective mass given by the seesaw mechanism between the left-handed and right-handed neutrinos. The eigenvalue equation gives

$$\phi_a = \left(m_\nu^3 - C_{LL}m_\nu^2 - \left(\lambda^2\phi_n^2 + m_D^2 + m_D'^2\right)m_\nu - 2\lambda m_D m'_D\phi_n + C_{LL}\lambda^2\phi_n^2\right)\left(m_\nu^2 - m_D^2 - C_{LL}m_\nu\right)^{-1}. \tag{40}$$

Putting $\lambda = 1$, $m_D = 0.01$ eV and $m'_D = 0.1$ eV by hand, other three parameters are fixed by the three constraints of m_ν^0, $V(m_\nu^0)$ and $\partial V(m_\nu)/\partial m_\nu|_{m_\nu = m_\nu^0}$ as follows:

$$\phi_a^0 = -4.38\times 10^{-12}\ \text{eV}, \qquad \phi_n = \pm 5.02\times 10^{-5}\ \text{eV},$$
$$C_{LL} = 3.17\ \text{eV}, \tag{41}$$

where mass eigenvalues are obtained

$$m_\nu^0 = 3.17\ \text{eV},\ -3.17\times 10^{-3}\ \text{eV},\ -9.18\times 10^{-6}\ \text{eV}, \tag{42}$$

where 3.17 eV is the mass of the active neutrino, and other ones are for sterile neutrinos. Actually, the mixing between the active neutrino and sterile ones are tiny.

The evolution of the neutrino mass is given by using the stationary condition of Eq. (10). We show the scaled neutrino mass m_ν/m_ν^0 versus the redshift $z = T/T_0 - 1$ in Fig. 1, because the absolute neutrino mass is not important as far as the neutrino is non-relativistic at the present epoch. As seen in Fig. 1, the neutrino mass evolves only 0.1%. This weak ϕ_a dependence of the neutrino mass is understandable in the approximate mass formula:

$$m_\nu \simeq C_{LL} + \frac{m_D^2 + m_D'^2 + \lambda^2\phi_n^2}{C_{LL}}\left(1 + \frac{1}{C_{LL}}\lambda\phi_a\right), \tag{43}$$

where the constant term $C_{LL} = 3.17$ eV dominates the neutrino mass and the ϕ_a dependence is suppressed on the order of m_D^2/C_{LL}^2.

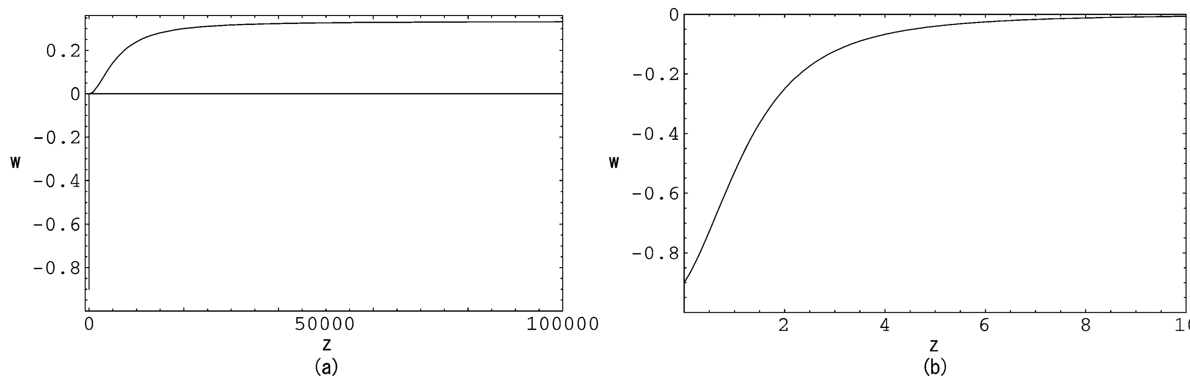

Fig. 2. Plot of the equation of state parameter w versus z in the region of (a) $z = 0 \sim 100\,000$ and (b) $z = 0 \sim 10$.

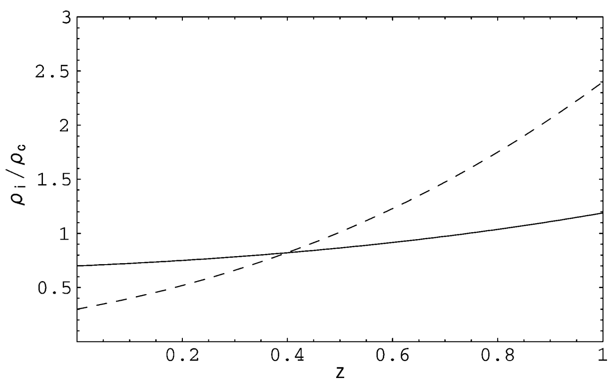

Fig. 3. Plot of the energy density of the dark energy and of the matter in the unit of ρ_c versus z, where the solid line and the dashed line correspond to the dark energy and the matter, respectively.

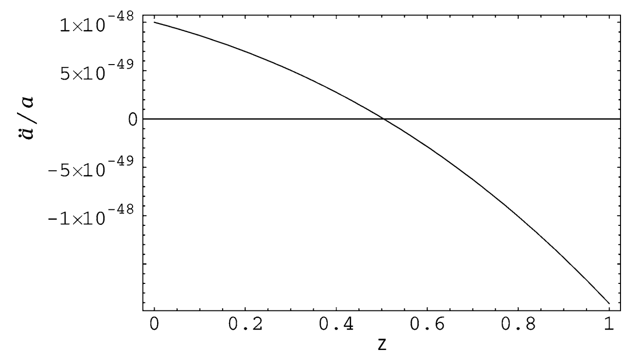

Fig. 4. Acceleration $\ddot{a}/a$ versus z.

Once the evolution of m_ν is given, one can calculate the equation of state parameter w as follows:

$$w + 1 = \frac{4 - h(\xi)}{3\left[1 + \frac{V(m_\nu)}{T^4 F(\xi)}\right]}, \tag{44}$$

where

$$h(\xi) = \frac{\xi}{F(\xi)} \frac{\partial F(\xi)}{\partial \xi}. \tag{45}$$

The evolution of w versus z is shown in Fig. 2. In order to see the behavior of w near the present epoch, we also plot w at $z = 0 \sim 10$. It is noticed that w evolves rapidly near the present epoch.

The evolution of the dark energy in the unit of ρ_c is shown in Fig. 3, in which the evolution of the matter is presented in comparison. It is found that the matter dominates the energy density of the Universe at $z \geqslant 1$.

In order to see when the acceleration of the cosmological expansion begun, we calculate the acceleration $\ddot{a}/a$ in the Friedmann equation;

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left[\rho_M + (3w+1)\rho_{\mathrm{dark}}\right], \tag{46}$$

where ρ_M is the matter density and the contribution of radiation is neglected since we consider the epoch of $z = 0 \sim 1$. As seen in Fig. 4, the deceleration of the cosmological expansion converts to the acceleration near $z = 0.5$ in this model. This result is different from the one in the power-law or exponential potential discussed by Peccei [4], in which the conversion from the deceleration to the acceleration is predicted near $z = 5 \sim 7$.

4. Discussions and summary

In our work, we have presented numerical results in the case of the non-relativistic neutrino at the present epoch. However, it was remarked that the speed of sound, c_s, which is given as [15]

$$c_s^2 = w + \frac{\dot{w}}{\dot{\rho}_{\mathrm{dark}}} \rho_{\mathrm{dark}}, \tag{47}$$

becomes imaginary in the non-relativistic limit at the present and then the Universe cease to accelerate. Actually, c_s^2 is negative in our potential if we put $w_0 = -0.9$, which corresponds to $m_\nu^0 = 3.17$ eV. On the other hand, if we take $w_0 = -0.998$, which leads to $m_\nu^0 = 0.05$ eV, we get positive c_s^2 since the time evolution of ρ_{dark} becomes slower in the case of smaller m_ν^0 near the present epoch. Therefore, the atmospheric mass scale of the neutrino mass $m_\nu^0 = 0.05$ eV may be favored.

We have not discussed the quantum corrections to the scalar potential. These corrections were discussed in Ref. [1], in which it was remarked that the neutrino mass should be lower than $O(1\ \mathrm{eV})$ although these are model dependent. The quantum corrections will be investigated carefully in the coupled system of the neutrino and the acceleron [24].

We have discussed the MaVaNs scenario in the supersymmetric theory and found a model which is consistent with the cosmological data. In the case of the model with the single superfield, one needs the soft SUSY breaking terms or the μ term. However, fine-tunings of some parameters are required to be consistent with the cosmological data.

In order to avoid these defects, we have discussed the model with two superfields, which is consistent with the cosmological data. However, the left-handed neutrino mixes with the neutrino of the dark sector maximally in this case.

Adding a right-handed neutrino, which does not couple to the dark sector, we obtain the model, in which the mixing between the left-handed neutrino and the neutrino of the dark sector is tiny. This model is the first example of the MaVaNs with the supersymmetry. In our model, the deceleration of the cosmological expansion converts to the acceleration near $z = 0.5$. The related phenomena of our scenario and the extension to the three families of the active neutrinos will be discussed elsewhere.

After this Letter was submitted to the journal, the paper in Ref. [25] appeared, which presents a different supersymmetric model of MaVaNs.

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