Model of Mass Varying Neutrinos in SUSY

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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 $\mu$ 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 $\omega_0 = -0.9$, which corresponds to $m_\nu^0 = 3.17$ eV. On the other hand, if we take $\omega_0 = -0.998$, which leads to $m_\nu^0 = 0.05$ eV, $c_s^2$ becomes positive since $\omega$ evolves rapidly near the present epoch in our model.

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1 Introduction

One of the most challenging questions in both cosmological and particle physics is the nature of the dark energy in the Universe. The energy density of the Universe is dominated by a dark energy component, whose negative pressure causes the expansion of the Universe to accelerate. What is the dark energy? In order to answer this question, one has tried to understand the connection of the dark energy with particle physics.

Recently, Fardon, Nelson and Weiner [1] proposed a idea of the mass varying neutrinos (MaVaNs), in which the neutrino couples to the dark energy. The variable mass neutrinos was considered at first in [2], and was discussed for neutrino clouds [3]. However, this renewed MaVaNs scenario [1] has tried to make a connection between neutrinos and the dark energy. The neutrino mass is a dynamical field, and an unknown scalar field which is called “acceleron” is introduced. 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 $\omega$ 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 in the model independent way by Peccei [4].

The MaVaNs scenario leads to interesting phenomenological results. The neutrino oscillations may be a probe of the dark energy [5]. The baryogenesis [6, 7, 8], the cosmo MSW effect of the neutrinos [9] and the solar neutrinos [10, 11] have been studied in the context of this scenario. Cosmological discussions of the scenario are also presented [12, 13, 14].

In this paper, we study the MaVaNs scenario in the supersymmetric theory and construct models which are consistent with the current cosmological data [15]. 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 $\omega$. In section 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.
2 The single superfield model

The simplest assumption of the MaV aNs with the supersymmetry is to introduce a single chiral superfield \( A \), which is a singlet under the gauge group of the standard model. In this framework, we discuss three cases of the superpotential.

2.1 The simplest model \( W = \frac{\lambda}{3} A^3 \)

We suppose that the dark sector consists of a single chiral superfield \( A \) with the superpotential

\[
W = \frac{\lambda}{3} A^3 ,
\]

where the coefficient \( \lambda \) is an arbitrary coupling constant. The scalar and spinor components of \( A \) are \( (\phi_a, \psi_a) \), and the scalar component \( \phi_a \) is assumed to be the acceleron.

Then, the scalar potential is given by

\[
V(\phi_a) = \lambda^2 |\phi_a|^4 .
\]

We take a Lagrangian density in which the left-handed neutrino \( \nu_L \) couples to \( \psi_a \) in the dark sector,

\[
L = m_D \nu_L \psi_a + 2 \lambda \phi_a \psi_a \psi_a .
\]

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

\[
\begin{pmatrix}
0 & m_D \\
m_D & 2 \lambda \phi_a
\end{pmatrix},
\]

\( \phi_a \) is given in terms of the neutrino mass,

\[
\lambda \phi_a = \frac{m_\nu}{2} - \frac{m_D^2}{2m_\nu} .
\]

Using this relation, the scalar potential of eq.(2) is given in terms of the neutrino mass \( m_\nu \) as follows:

\[
V(m_\nu) = \frac{1}{16\lambda^2} \left( m_\nu - \frac{m_D^2}{m_\nu} \right)^4 ,
\]

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 $0.7\rho_c$, $\rho_c$ 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

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

the first constraint turns to

$$\rho_\nu^0 + V(\phi_a^0(m_\nu^0)) = 0.7\rho_c,$$

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 $\rho_{\text{dark}}$ is stationary with respect to variations in the neutrino mass. This assumption is represented by

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

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

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

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

$$F(\xi) = \frac{1}{\pi^2} \int_0^\infty \frac{dyy^2\sqrt{y^2+\xi^2}}{ey^2+1}.$$

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

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

This condition turns to

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

where $n_\nu^0$ 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

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

(14)

Taking the typical observed value $\omega_0 = -0.9$, we can fix $\rho_\nu^0$. Then the neutrino mass $m_\nu^0$ is obtained by putting the neutrino number density at the present epoch $n_\nu^0 = 8.82 \times 10^{-13}$ eV$^3$ on $\rho_\nu^0 = m_\nu^0 n_\nu^0$. Finally, we get $m_\nu^0 = 3.17$ eV and $V(\phi_a^0(m_\nu^0)) = 2.52 \times 10^{-11}$ eV$^4$, where we take $\rho_{\text{dark}} = 0.7 \rho_c = 2.8 \times 10^{-11}$ 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 [16] and will be tested at the MiniBOON experiment [17]. On the other hand, putting $\omega_0 = -0.998$ we get $m_\nu^0 = 0.05$ eV, which is consistent with the atmospheric neutrino mass scale. Thus, the value of $m_\nu^0$ depends on $\omega_0$. In our following analyses, the numerical value of $m_\nu^0$ 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 $\omega_0 = -0.9$ 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:

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

(15)

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

(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

$$V(m_\nu) = \frac{1}{16\lambda^2} \left( m_\nu - \frac{m_D^2}{m_\nu} \right)^4, \quad \frac{\partial V(m_\nu)}{\partial m_\nu} = \frac{1}{4\lambda^2} \left( m_\nu - \frac{m_D^2}{m_\nu} \right)^3 \left( 1 + \frac{m_D^2}{m_\nu^2} \right).$$  

(17)

Therefore, the scalar potential satisfies the relation

$$\left. \frac{V(\phi_a(m_\nu))}{\partial V(\phi_a(m_\nu))} \right|_{m_\nu = m_\nu^0}, T = T_0 \geq -\frac{m_\nu^0}{4} \frac{1 - \frac{m_D^2}{m_\nu^2}}{1 + \frac{m_D^2}{m_\nu^2}}.$$  

(18)
This ratio must be $-28.6$ from eqs. (15) and (16), however, our input $m^0_\nu = 3.17$ eV never reproduce this value. One cannot build any models with only one superfield $A$ unless the SUSY breaking term or the $\mu$ term is added.

### 2.2 $W = \frac{\lambda}{3} A^3$ with soft breaking terms

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

$$V(\phi_a) = \lambda^2 |\phi_a|^4 + m^2 |\phi_a|^2 + V_0,$$

where $m$ is the soft-breaking mass and $V_0$ is a constant. The gradient of the potential are given as

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

where $\phi_a$ is given in terms of $m_\nu$ as in eq.(5). Since we have four free parameters, $\lambda$, $m$, $V_0$ 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:

$$\lambda = 1, \quad m_D = 10 \text{ eV},$$

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

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

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

where $\epsilon = 2 \lambda^2 (\phi^0_a)^2 + m^2 = -5.67 \times 10^{-15}$ eV$^2$. It is remarked that the parameters $m^2$ and $V_0$ are fine-tuned in 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 $\omega$ 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 $W = \frac{\lambda}{3} A^3 + \frac{\mu}{2} A^2$ model

We consider the model including $\mu$-term as follows:

$$W = \frac{\lambda}{3} A^3 + \frac{\mu}{2} A^2,$$ (24)
which leads to the scalar potential as

\[ V(\phi_a) = |\lambda \phi_a^2 + \mu \phi_a|^2 . \]  

Taking a Lagrangian density of the form

\[ \mathcal{L} = m_D \nu_L \psi_a + (2 \lambda \phi_a + \mu) \psi_a \psi_a , \]  

we get \( \phi_a \) in terms of the neutrino mass instead of eq.(5) as follows:

\[ \lambda \phi_a = \frac{m_\nu - \mu}{2} - \frac{m_D^2}{2 m_\nu} . \]  

The potential and its derivative are given as

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

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

\[ 2 \lambda \phi_a^0 + \mu \sim 10^{-8} \text{eV} , \quad \phi_a^0 \sim \mu \sim 10^{-3} \text{eV} , \quad m_D \sim m_\nu^0 . \]  

This result indicates the fine-tuning between \( \lambda \phi_a \) and \( \mu \) in order of \( 10^{-5} \). Actually, the numerical solution is

\[ \phi_a = 2.24 \times 10^{-3} \text{eV} , \quad \mu = -4.48 \times 10^{-3} \text{eV} , \quad m_D = \pm 3.17 \text{eV} , \]  

with \( \lambda = 1 \). Such a small value of \( |\mu| \sim 10^{-3} \text{eV} \) may be explained by the suppression of \( M_{\text{TeV}}^2 / M_{\text{planck}} \) [19].

Since two mass eigenvalues are almost degenerate due to \( m_D \gg 2 \lambda \phi_a + \mu \), the left-handed neutrino \( \nu_L \) mixes maximally with \( \psi_a \), 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 \( N \) [18], which are singlets under the gauge group of the standard model.
3.1 The simple model $W = \lambda A N N$

It is assumed that the dark sector consists of two chiral superfields $A$ and $N$, whose scalar and spinor components are $(\phi_a, \psi_a)$ and $(\phi_n, \psi_n)$, respectively, with the superpotential

$$W = \lambda A N N , \quad (31)$$

where the scalar component $\phi_a$ of $A$ is assumed to be the acceleron, on the other hand, $N$ is not dynamical field. In other words, $\phi_n$ is the constant. Then, we have the scalar potential

$$V(\phi_a, \phi_n) = \lambda^2 |\phi_n|^4 + 4\lambda^2 |\phi_a\phi_n|^2 . \quad (32)$$

The gradient of the scalar potential for $\phi_a$ is describing as follows:

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

where we assume the scalar component of two chiral superfields to be real. We take a Lagrangian density of the form

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

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

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

in the $(\nu_L, \psi_a, \psi_n)$ basis. The eigenvalue equation gives

$$\phi_a = \frac{m^3 - (\lambda^2 \phi_n^2 + m_D^2 + m'_D^2) \nu - 2\lambda m_D m'_D \bar{\phi}_n}{m^2_D - m^2} . \quad (36)$$

By using this relation, the potential of eq.(32) is given in terms of the neutrino mass $m_\nu$. Putting $\lambda = 1$ and $m_D = 0.1$ eV by hand, other three parameters are fixed by the three constraints of $m_\nu^0$, $V(m_\nu^0)$ and $\partial V(m_\nu)/\partial m_\nu |_{m_\nu = m_\nu^0}$ as follows:

$$\phi_a^0 = -1.10 \times 10^{-8} \text{eV} , \quad \phi_n = \pm 2.24 \times 10^{-3} \text{eV} , \quad m'_D = \mp 3.17 \text{eV} , \quad (37)$$

where mass eigenvalues are obtained

$$m_\nu^0 = 3.17101 \text{eV} , \quad -3.17115 \text{eV} , \quad 1.4 \times 10^{-5} \text{eV} , \quad (38)$$
where two neutrinos are quasi-degenerate in the mass. In other words, \( \nu_L \) and \( \nu_a \) mix maximally. Therefore, this model is also unfavored in the phenomenology of the neutrino experiments.

### 3.2 Right-handed neutrino

Towards the realistic model, we introduce a right-handed heavy Majorana neutrino, which is assumed to decouple from \( \psi_a \) and \( \psi_n \). Then, the effective mass matrix in eq.(35) is modified in the \( (\nu_L, \psi_a, \psi_n) \) basis as follows:

\[
\begin{pmatrix}
C_{LL} & m_D & m_D' \\
m_D & 0 & \lambda \phi_n \\
m_D' & \lambda \phi_n & \lambda \phi_a
\end{pmatrix},
\]

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

\[
\phi_a = \frac{m_\nu^3 - C_{LL}m_\nu^2 - (\lambda^2 \phi_n^2 + m_D^2 + m_D'^2)m_\nu - 2\lambda m_D m'_D \phi_n + C_{LL} \lambda^2 \phi_n^2}{m_\nu^2 - m_D^2 - C_{LL}m_\nu}.
\]

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

\[
\phi_a^0 = -2.18 \times 10^{-11} \, \text{eV}, \quad \phi_n = \pm 2.24 \times 10^{-3} \, \text{eV}, \quad C_{LL} = 3.16 \, \text{eV}, \quad (41)
\]
where mass eigenvalues are obtained
\[ m_0^\nu = 3.17 \text{ eV}, \quad -0.004 \text{ eV}, \quad -0.002 \text{ eV}, \] (42)
where 3.17 eV is the mass eigenvalue 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 \( m_\nu/m_0^\nu \) 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 \( \phi_a \) dependence of the neutrino mass is understandable in the approximate mass formula:
\[ m_\nu \simeq C_{LL} + \frac{m_D^2 + m_D^2}{C_{LL}} + \frac{\lambda^2 \phi_n^2}{C_{LL}} \left( 1 + \frac{1}{C_{LL}} \lambda \phi_a \right), \] (43)
where the constant term \( C_{LL} = 3.16 \text{ eV} \) dominates the neutrino mass and the \( \phi_a \) dependence is suppressed in order of \( m_D^2/C_{LL}^2 \).

Once the evolution of \( m_\nu \) is given, one can calculate the equation of state parameter \( \omega \) as follows:
\[ \omega + 1 = \frac{4 - h(\xi)}{3 \left[ 1 + \frac{V(m_\nu)}{T^2 F(\xi)} \right]}, \] (44)
where
\[ h(\xi) = \frac{\xi}{F(\xi)} \frac{\partial F(\xi)}{\partial \xi}. \] (45)

The evolution of \( \omega \) versus \( z \) is shown in Fig. 2. In order to see the behavior of \( \omega \) near the present epoch, we also plot \( \omega \) at \( z = 0 \sim 30 \). It is noticed that \( \omega \) evolves rapidly near the present epoch.

The evolution of the dark energy in the unit of \( \rho_c \) 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 \( z \geq 1 \).

In order to see when the acceleration of the cosmological expansion begun, we calculate the acceleration \( \ddot{a}/a \) in the Friedmann equation:
\[ \frac{\ddot{a}}{a} = -\frac{4\pi G}{3} \left[ \rho_M + (3\omega + 1)\rho_{\text{dark}} \right], \] (46)
Figure 2: Plot of the equation of state parameter $\omega$ versus $z$ in the region of (a) $z = 0 \sim 30000$ and (b) $z = 0 \sim 30$.

Figure 3: Plot of the energy density of the dark energy and of the matter in the unit of $\rho_c$ versus $z$, where the solid line and the dashed line correspond to the dark energy and the matter, respectively.
where $\rho_M$ 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 [14]

$$c_s^2 = \omega + \frac{\dot{\omega}}{\dot{\rho}_{\text{dark}}} \rho_{\text{dark}},$$

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 $\omega_0 = -0.9$, which corresponds to $m_{\nu}^0 = 3.17$ eV. On the other hand, if we take $\omega_0 = -0.998$, which leads to $m_{\nu}^0 = 0.05$ eV, $c_s^2$ becomes positive in our potential since $\omega$ evolves rapidly near the present epoch as seen in Fig. 2. 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. This corrections
were discussed in [1, 20], and it is found that the neutrino mass lower than $O(1\text{eV})$ is suitable.

We have discussed the MaVaNs scenario in the supersymmetric theory and found a model which are consistent with the cosmological data. In the case of the model with the single superfield, one needs the soft SUSY breaking terms or the $\mu$ term. However, fine-tunings of some parameters are required to be consistent with the cosmological data. Moreover, the left-handed neutrino mixes with the neutrino of the dark sector maximally in the model with $\mu$ term.

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.

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