Search for Radiative Decays of Cosmic Background Neutrino using Cosmic Infrared Background Energy Spectrum

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Abstract

We propose to search for the neutrino radiative decay by fitting a photon energy spectrum of the cosmic infrared background to a sum of the photon energy spectrum from the neutrino radiative decay and a continuum. By comparing the present cosmic infrared background energy spectrum observed by AKARI and Spitzer to the photon energy spectrum expected from neutrino radiative decay with a maximum likelihood method, we obtained a lifetime lower limit of $3.1 \times 10^{12}$ to $3.8 \times 10^{12}$ years at 95% confidence level for the third generation neutrino $\nu_3$ in the $\nu_3$ mass range between 50 meV/c$^2$ and 150 meV/c$^2$ under the present constraints by the neutrino oscillation measurements. In the left-right symmetric model, the minimum lifetime of $\nu_3$ is predicted to be $1.5 \times 10^{17}$ years for $m_3$ of 50 meV/c$^2$. We studied the feasibility of the observation of the neutrino radiative decay with a lifetime of $1.5 \times 10^{17}$ years, by measuring a continuous energy spectrum of the cosmic infrared background.
1 Introduction

The difference between the mass-squares of different-generation neutrinos has been measured by atmospheric neutrino oscillation experiments with Super-Kamiokande [1, 2], neutrino beam experiments with K2K [3] and MINOS [4, 5], solar neutrino oscillation experiments with Super-Kamiokande [6] and SNO [7, 8] and a nuclear reactor oscillation experiment with KamLAND [9, 10], but the neutrino mass itself has not been measured yet. Detection of neutrino radiative decay enables us to measure a quantity independent of the difference between the mass-squares of different-generation neutrinos. Thus we can determine the neutrino mass itself from these two independent measurements, the neutrino oscillation and the neutrino radiative decay.

As the neutrino lifetime is so long as to be much larger than the age of the universe, the most promising method is to observe the decay of the cosmic background neutrino. Detection of this radiative decay means a discovery of the cosmic background neutrino predicted by standard cosmology.

The cosmic background neutrino has a temperature of 1.9K and a particle density $\rho$ of 110 cm$^{-3}$ per generation.

Atmospheric neutrino data with Super-Kamiokande and neutrino beam data with K2K and MINOS gives the mass-square difference between $\nu_3$ and $\nu_2$, $\Delta m_{32}^2$ of $(2.43 \pm 0.13) \times 10^{-3} eV^2$ [11] and the mixing angle of $\sin^2 2\theta_{23} > 0.92$ at 90% confidence level [11].

Solar neutrino data with Super-Kamiokande, SNO and the reactor neutrino data with KamLAND give the mass-square difference between $\nu_2$ and $\nu_1$ of $\Delta m_{12}^2 = (7.59 + 0.19/-0.21) \times 10^{-5} eV^2$ [11] and the mixing angle of $\sin^2 2\theta_{12} = 0.87 \pm 0.03$ [11].

We search for the neutrino radiative decay under these constraints on the mass-square differences and the mixing angles between the neutrino generations. For this search, we make a fit of the photon energy spectrum of Cosmic Infrared Background (CIB) to a sum of a neutrino decay photon energy spectrum and a continuum spectrum.

In the left-right symmetric model, we make a feasibility study of the neutrino decay search in the CIB energy spectrum measurement.

2 Neutrino Radiative Decay

In this paper we report the analysis results on the normal hierarchy case where the $\nu_3$ is the heaviest neutrino and decay into $\nu_2$ or $\nu_1$ as $\nu_3 \rightarrow \nu_2$ (or $\nu_1$) $+ \gamma$.

In the $\nu_3$ rest frame, the decay photon energy $E_0$ is related to the neutrino masses by

$$E_0 = \frac{m_3^2 - m_2^2}{2m_3}.$$  

Since the term $m_3^2 - m_2^2$ was measured by the neutrino oscillation experiments, we can determine $m_3$ by measuring this $E_0$. The plot of $m_3$ versus $m_2$ is shown in Fig. [11]
The decay photon energy $E_0$ is given as a function of $m_3$ with the neutrino oscillation measurement constraint as shown in Fig. 2. When we consider the $m_3$ range between 50 meV/c$^2$ and 150 meV/c$^2$, $E_0$ ranges from 25 meV to 8 meV in the far-infrared region.

Taking into account the redshift of the decay photon energy, the observed photon energy $E_\gamma$ is given by

$$E_\gamma = \frac{E_0}{1+z},$$

where $z$ is a redshift. As the lifetime become longer because the neutrino is moving away, the decay rate of neutrino $R$ is given by $R = \frac{1}{\tau(1+z)}$, where $\tau$ is a neutrino lifetime at the rest frame. Thus the decay photon flux per unit solid angle is given by

$$\frac{dN_\gamma}{dSdt} = \frac{\rho c}{4\pi(1+z)} dr,$$

where $r$ is a distance between a neutrino decay point and a telescope with a detection area $dS$, and $\rho$ is a density of the cosmic background neutrino of 110 cm$^{-3}$. Assuming a flat universe, $dr$ is related with $dz$ by

$$dr = \frac{c}{H_0}[(1+z)^3 \Omega_M + \Omega_\Lambda]^{-0.5}dz,$$

where $H_0$ is a Hubble constant of $(74 \pm 4)$ km s$^{-1}$ Mpc$^{-1}$, and $\Omega_M$ and $\Omega_\Lambda$ are the matter density and the cosmological constant which were measured to be $\Omega_M = 0.26 \pm 0.02$,

$\Omega_\Lambda = 0.74 \pm 0.03$,

$\Omega_M + \Omega_\Lambda = 1.006 \pm 0.006$.

Thus under the assumption of a flat universe with $\Omega_M + \Omega_\Lambda = 1$, we obtain the following distribution of the decay photon flux $\frac{dN_\gamma}{dSdt}$ per unit solid angle and unit energy:

$$\frac{dN_\gamma}{dSdt} = \frac{\rho c}{4\pi H_0} E_\gamma^3 \Omega_M + \Omega_\Lambda]^{-0.5}.$$

If we use the energy flux per unit solid angle $I$ defined by

$$I \equiv \frac{d(N_\gamma \times E_\gamma)}{dSdt},$$

we obtain the energy flux per unit solid angle and unit energy given by

$$\frac{dI}{dE_\gamma} = \frac{\rho c}{4\pi H_0} E_\gamma^3 \Omega_M + \Omega_\Lambda]^{-0.5}.$$

Using $E_\gamma = h\nu$,

$$\nu \frac{dI}{d\nu} = \frac{\rho c}{4\pi H_0} h\nu[(\frac{E_0}{E_\gamma})^3 \Omega_M + \Omega_\Lambda]^{-0.5}.$$

This spectrum is smeared by the neutrino motion at 1.9K, but this effect is negligibly small. The photon energy spreads due to this neutrino motion are 0.6% and 1.5% in rms for the photon energies of 25 meV and 10 meV, respectively.

### 3 Neutrino Lifetime Limit

The Cosmic Infrared Background (CIB) continuum in photon energy spectrum is the most serious foreground against this neutrino radiative decay signal because the sharp
edge of the signal spectrum is located between 8 meV and 25 meV in our search region. There have been studies where the neutrino lifetime limit was obtained using the CIB data [12, 13]. However they did not use the photon energy spectrum expected from the neutrino radiative decay to estimate the neutrino lifetime limit but used only the total decay rate of neutrino. They did not use the AKARI CIB data which were not available at that time.

We perform a statistical test of the CIB data measured by COBE [14, 15] and AKARI [16] to estimate the neutrino lifetime limit. Since we do not have a sharp edge at high energy end of the CIB energy spectrum, we set a lower limit of the heaviest neutrino lifetime. The CIB data measured by COBE and AKARI were directly compared with the photon energy spectrum expected from the neutrino radiative decay neglecting the CIB continuum with a maximum likelihood method. In this comparison, we neglected the CIB continuum in order to estimate the neutrino lifetime limit in the worst case which gives the lowest lifetime limit. The curve with a maximum likelihood is shown together with the likelihood as a function of \( \nu_3 \) lifetime for \( m_3 = 50 \text{ meV}/c^2 \) and \( m_2 = 10 \text{ meV}/c^2 \) in Fig 3. The arrow point in this figure gives us a lower limit of \( \nu_3 \) lifetime at 95% confidence level. We performed this procedure for various \( \nu_3 \) masses to obtain a lower limit of the \( \nu_3 \) lifetime at 95% confidence level as a function of \( \nu_3 \) mass as shown in Fig. 4. They range from \( 1.7 \times 10^{12} \) to \( 2.4 \times 10^{12} \) years in the \( \nu_3 \) mass range between 50 meV/c\(^2\) and 150 meV/c\(^2\).

Recent deep galaxy surveys with infrared satellites, AKARI [16], Spitzer [17] and Hershel [18] have revealed that more than a half of the CIB energy originates from external galaxies. So we performed the analysis to obtain stronger constraint on the neutrino lifetime taking the integrated flux of galaxies into account. We subtracted the contribution of the distant galaxies as source points [17] from the CIB measured by AKARI as shown in Table 1. Since there were no measured values of the contributions at wavelengths of 60, 90 and 140 \( \mu \)m, we interpolated the measured values at wavelengths of 24, 70 and 160 \( \mu \)m. Thus we obtained the CIB after subtracting the contribution of distant galaxies. These corrected CIB data give a constraint on the neutrino lifetime as the most stringent lower limits.

With the AKARI CIB data after subtracting the contributions of distant galaxies as point sources, we performed a statistical test of the spectrum to obtain the neutrino lifetime limit, motivated by the fact that such corrected AKARI CIB data has much less contributions of distant galaxies than the COBE CIB data. The corrected AKARI CIB data were compared to the photon energy spectrum expected from the neutrino radiative decay with a maximum likelihood method. The curve with a maximum likelihood is shown together with the likelihood as a function of \( \nu_3 \) lifetime for \( m_3 = 50 \text{ meV}/c^2 \) and \( m_2 = 10 \text{ meV}/c^2 \) in Fig 5. An arrow point in this figure gives us a lower limit of \( \nu_3 \) lifetime at 95% confidence level. We performed this procedure for various \( \nu_3 \) masses to obtain a lower limit of the \( \nu_3 \) lifetime at 95% confidence level as a function of \( \nu_3 \) mass as shown in Fig. 6. They range from \( 3.1 \times 10^{12} \) to \( 3.8 \times 10^{12} \) years in the \( \nu_3 \) mass range between 50
meV/c^2 and 150 meV/c^2.

4 Neutrino Lifetime in the Left-Right Symmetric SU(2)_L × SU(2)_R × U(1) Model

In the standard model, the heaviest neutrino lifetime is predicted to be $10^{43}$ year for $\nu_3$ with a mass of 50 meV/c^2 [19] [20] [21] [22]. It is too long to be measured by the present method.

In the left-right symmetric model, the lifetime is predicted to be much shorter than in the standard model. The left-right symmetric SU(2)_L × SU(2)_R × U(1) model has two charged weak bosons, or the left-handed weak boson $W_L$ and the right-handed weak boson $W_R$ which are mixed with a mixing angle $\zeta$ into two mass eigenstates $W_1$ and $W_2$ as follows [21] [22]:

$$W_1 = W_L \cos \zeta - W_R \sin \zeta$$

$$W_2 = W_L \sin \zeta + W_R \cos \zeta$$

In this model, the lifetime of $\nu_3$ is given by

$$\tau^{-1} = \frac{\alpha G_F^2}{128 \pi^4} \left( \frac{m_3 - m_2}{m_3} \right)^3 |U_{32}|^2 |U_{33}|^2 \left[ \frac{9}{64} \left( \frac{m_3^2 + m_2^2}{M_{W_1}^2} \right) \left( 1 + \frac{M_{W_1}^2}{M_{W_2}^2} \right)^2 + 4 m_2^2 (1 - \frac{M_{W_1}^2}{M_{W_2}^2})^2 \sin^2 2\zeta \right].$$

where $\alpha$ is a fine structure constant, $G_F$ is a Fermi coupling constant, $m_\tau$, $M_{W_1}$ and $M_{W_2}$ are masses of $\tau$, $W_1$ and $W_2$, respectively [21] [22]. $U_{ij}$ is the (i, j)-th element of the Maki-Nakagawa-Sakata mixing matrix [23] and we took $|U_{32}| = 1/\sqrt{2}$ and $|U_{33}| = 1/\sqrt{2}$. The present mass limit of the right-handed weak boson $W_R$ is $M_R > 0.715$ TeV assuming $\zeta = 0$. The upper limit of the mixing angle between $W_L$ and $W_R$ is $\sin \zeta < 0.013$ [11]. The lifetime is shown as a function of $m_3$ with $M_{W_2}$ of 0.715 TeV, $\sin \zeta$ of 0.013 and $\Delta m_{32}^2$ of $(2.43 \pm 0.13) \times 10^{-3}$ eV^2 in Fig. 7.

For $m_3$ of 50 meV/c^2, the lifetime is calculated to be $1.5 \times 10^{17}$ years under the above conditions in left-right symmetric model. The present lifetime limit is shorter than this prediction by a factor of $2 \times 10^{-5}$.

We can improve the sensitivity of the search for neutrino radiative decay by measuring the continuous energy spectrum of the Cosmic Infrared Background (CIB). We fit the continuous spectrum with a sum of the CIB continuum and the neutrino decay photon spectrum to search for a sharp edge of the neutrino decay photon spectrum.

To estimate the energy resolution requirement, we performed the simulation study of the neutrino radiative decay assuming the following conditions:

- The present CIB continuum is dominated by other sources than the neutrino radiative decay. This CIB spectrum is represented by a Planck distribution plus a
quadratic function.

- $m_3 = 50 \text{ meV}/c^2$ and $m_2 = 10 \text{ meV}/c^2$.
- $\tau_3 = 1.5 \times 10^{17}$ years.

We simulated the CIB detection experiments with a 20cm-diameter telescope with a viewing angle of 0.1 degrees and energy resolutions of 0 to 5 % by 1 % step. With 100% detection efficiency and 10-hour data taking, we have the photon energy spectrum for the CIB and the neutrino radiative decay as shown in Fig. $\text{\ref{fig:8}}$. The CIB continuum was fitted to a function of the Planck distribution plus a quadratic function. Then we calculated the energy derivative of the photon energy spectrum for a sum of the CIB continuum and the neutrino radiative decay as shown in Fig. $\text{\ref{fig:8}}$. In this negative energy derivative plot, the sharp edge of the energy spectrum is identified as a clean peak. The excess is $6.7\sigma$ and we can see the clear signal peak in the distribution if the energy resolution is less than 2%.

We search for the neutrino radiative decay in the $m_3$ range between 50 meV/$c^2$ and 150 meV/$c^2$ which corresponds to the photon energy range between 25 meV and 8 meV with this experiment. Thus the photon energy range to be measured is between 5 meV ($\lambda = 250 \ \mu m$) and 35 meV ($\lambda = 35 \ \mu m$). In this photon energy range, the frequency of photon coming in this telescope is expected to be around 5 MHz. As we will use 400 pixels as a photon detector, the photon rate per pixel is around 12 kHz/pixel.

By this simulation study, we found that the required energy resolution is less than 2% at 25 meV. With this resolution, we estimated $5\sigma$ observation lifetime with 10-hour running of this telescope from the differential CIB energy spectrum including the radiative decay of the cosmic background neutrino for the $m_3$ range between 50 meV/$c^2$ and 150 meV/$c^2$ with $\Delta m_{32}^2$ of $2.43 \times 10^{-3} eV^2$. The $5\sigma$ observation lifetime ranges from $2.0 \times 10^{17}$ to $3.0 \times 10^{17}$ years as shown in Fig. $\text{\ref{fig:7}}$. Spectral emission features of the dusts in galaxies at redshifts of 1, when a large fraction of the CIB energy was generated [17], may produce a structure in the spectral energy distribution (SED) of CIB, similar to the neutrino decay photon SED. However, SEDs of such distant galaxies in the energy range where the neutrino decay photon is expected to be observed, have not been well explored. Further study of the SED of distant galaxies with future, large-aperture, infrared telescope such as JAXA’s SPICA (Space Infrared Telescope for Cosmology and Astrophysics) mission [24] is important to mitigate the spectral contamination of the neutrino decay photon.

The present measured CIB spectrum includes the point-sources of distant galaxies and the zodiacal light foreground ambiguity. By using small pixels with small viewing angle such as 0.005 degrees, we will be able to distinguish the distant galaxy point sources from the CIB spectrum. In the future project EXZIT (Exo-Zodiacal Infrared Telescope) [25] which will observe the CIB outside of Jupiter orbit, we will decrease the effect of the zodiacal emission significantly, and will have much less ambiguity of the zodiacal light foreground.
5 Conclusion

We propose to search for the neutrino radiative decay by fitting a photon energy spectrum of the cosmic infrared background to a sum of the photon energy spectrum from the neutrino radiative decay and a continuum. By comparing the present cosmic infrared background energy spectrum observed by AKARI and Spitzer to the photon energy spectrum expected from neutrino radiative decay with a maximum likelihood method, we obtained a lower limit of neutrino lifetime of $3.1 \times 10^{12}$ to $3.8 \times 10^{12}$ years at 95% confidence level for $\nu_3$ in the mass range between 50 meV/c$^2$ and 150 meV/c$^2$ under the present constraints by neutrino oscillation measurements.

In the left-right symmetric model, the lifetime is predicted to be much shorter than in the standard model. The present mass limit of the right-handed weak boson $W_R$ is $m_R > 0.715$ TeV and the mixing angle between $W_L$ and $W_R$ is $\sin \zeta < 0.013$. In this model, the minimum lifetime of $\nu_3$ is predicted to be $1.5 \times 10^{17}$ years for $m_3$ of 50 meV/c$^2$.

The present lifetime limit is shorter than this prediction by a factor of $2 \times 10^{-5}$. By measuring the continuous energy spectrum of the cosmic infrared background in the photon energy region between 5 meV ($\lambda = 250 \ \mu m$) and 35 meV ($\lambda = 35 \ \mu m$), we can expect 5$\sigma$ observation of the radiative decay of neutrino with a lifetime of $1.5 \times 10^{17}$ years.

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Figure 1: Relation between $m_3$ and $m_2$. The solid band shows the 1$\sigma$ constraint by the neutrino oscillation measurements ($\Delta m^2_{32}$ of $(2.43 \pm 0.13) \times 10^{-3} eV^2$). Three curves correspond to various neutrino decay photon energies of 25meV (dashed), 20meV (dotted) and 15meV(dot-dashed). (Color online)
Figure 2: Relation between $E_0$ and $m_3$. The solid band shows the 1σ constraint by the neutrino oscillation measurements ($\Delta m_{32}^2$ of $(2.43 \pm 0.13) \times 10^{-3}eV^2$).
Figure 3: Top plot shows the CIB data measured by COBE (dark square) and AKARI (dark circle) fitted to the photon energy spectrum expected from the neutrino radiative decay for $m_3 = 50\text{ meV}/c^2$ and $m_2 = 10\text{ meV}/c^2$ with a maximum likelihood method. The curve shows the best fit. Bottom plot shows the likelihood as a function of the $\nu_3$ lifetime. An arrow points to a lower limit of the neutrino lifetime at 95% confidence level.
Figure 4: Lower limits of the neutrino lifetime at 95% confidence level as a function of $m_3$ obtained with the CIB data measured by COBE and AKARI.
Figure 5: Top plot shows the AKARI CIB data after subtracting the contribution of distant galaxies as point sources (dark circle) fitted to the photon energy spectrum expected from the neutrino radiative decay for $m_3 = 50$ meV/c$^2$ and $m_2 = 10$ meV/c$^2$ with a maximum likelihood method. The curve shows the best fit. Bottom plot shows the likelihood as a function of $\nu_3$ lifetime. An arrow points to a lower limit of the neutrino lifetime at 95% confidence level.
Figure 6: Lower limits of the neutrino lifetime at 95% confidence level as a function of $m_3$ obtained with the CIB data measured by AKARI after subtracting the contribution of distant galaxies.
Figure 7: Expected lifetime minimum in the left-right symmetric model as a function of $m_3$. The solid band shows the $1\sigma$ constraint by the neutrino oscillation measurements ($\Delta m_{32}^2$ of $(2.43 \pm 0.13) \times 10^{-3} eV^2$). The sensitivity of $5\sigma$ observation with the proposed measurement is shown by dark circles.
Figure 8: The top plot shows the photon energy spectra of the CIB and the neutrino radiative decay with various energy resolutions from 0 % to 5 % by 1 % step. The CIB continuum is fitted to a sum of a function of the Planck distribution and a quadratic function. The bottom plot is the negative energy derivative of the photon energy spectrum for a sum of the CIB continuum and the neutrino radiative decay for energy resolutions of 0, 1, 2 and 3 %. (Color online)
Table 1: The AKARI CIB data before and after subtracting the contribution of distant galaxies.

| Wavelength (µm) | CIB$^a$ (MJy sr$^{-1}$) | contribution of distant galaxies$^b$ (MJy sr$^{-1}$) | CIB after subtraction$^c$ (MJy sr$^{-1}$) | CIB after subtraction$^d$ (nW m$^{-2}$ sr$^{-1}$) |
|-----------------|---------------------------|-----------------------------------------------|---------------------------------|---------------------------------|
| 24              | 0.017 ± 0.003             |                                               |                                 |                                 |
| 60              | 0.27 ± 0.20               | (0.112 ± 0.018)                               | 0.16 ± 0.20                     | 7.3 ± 9.2                       |
| 70              | 0.138 ± 0.023             |                                               |                                 |                                 |
| 90              | 0.67 ± 0.15               | (0.234 ± 0.042)                               | 0.44 ± 0.16                     | 14.4 ± 5.1                      |
| 140             | 0.94 ± 0.17               | (0.475 ± 0.095)                               | 0.47 ± 0.20                     | 9.8 ± 4.1                       |
| 160             | 0.73 ± 0.21               | 0.571 ± 0.120                                 | 0.16 ± 0.24                     | 3.0 ± 5.0                       |

$^a$ The CIB measured by AKARI in unit of MJy sr$^{-1}$.
$^b$ The contribution of distant galaxies to the CIB measured by Spitzer in unit of MJy sr$^{-1}$. The numbers in parentheses were obtained by a linear interpolation.
$^c$ The CIB measured by AKARI after subtracting the contribution of distant galaxies in unit of MJy sr$^{-1}$.
$^d$ The CIB measured by AKARI after subtracting the contribution of distant galaxies in unit of nW m$^{-2}$ sr$^{-1}$.