Search for Neutrino Decay

Shin-Hong Kim,

at US-Japan Joint Committee (April 18, 2012)

- Introduction
  - Motivation
    - Cosmic Infrared Background Measurement by COBE and AKARI
    - Past Results of Search for Neutrino Decay

- Neutrino Decay
  - Neutrino Lifetime
  - Energy Spectrum of Decay Photon and Background

- Proposal on Search for Neutrino Decay
  - Superconducting Tunnel Junction (STJ) Infrared Photon Detector
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Motivation of Search for Cosmic Background Neutrino Decay

- $\Delta m_{ij}^2$ have been measured accurately by neutrino oscillation experiments. But neutrino mass itself has not been measured. Can we measure it?
- Detection of neutrino decay enables us to measure an independent quantity. Thus we can obtain neutrino mass itself from these two independent measurements.

\[
E_\gamma = \frac{m_3^2 - m_2^2}{2m_3} = \frac{\Delta m_{23}^2}{2m_3}
\]

Using $\Delta m_{23}^2 = (2.43 \pm 0.13) \times 10^{-3}$ eV$^2$

$E_\gamma = 10 \sim 25$ meV at $\nu_3$ rest frame.

(Far-Infrared region: $\lambda = 50 \sim 125 \mu$)

- As the neutrino lifetime is very long, we need use cosmic background neutrino to observe the neutrino decay. To observe this decay of the cosmic background neutrino means a discovery of the cosmic background neutrino predicted by cosmology.
Cosmic Infrared Background (CIB) measured by COBE and Neutrino Lifetime Limit from CIB


CIB (Cosmic Infrared Background):
Calculate \( \tau_{\nu} \) by the following equation:

\[
\int_{E_{\text{min}}}^{E_H} \varphi_E dE < \Phi_{\text{CIB}},
\]

where \( \varphi_{\text{CIB}} = 24 \text{ nW m}^{-2} \text{ sr}^{-1} \) (COBE).
\( \rightarrow (0.5 \sim 1) \times 10^{20} \text{ sec} = (1.6 \sim 3.1) \times 10^{12} \text{ year} \)
Neutrino Decay Lifetime


Calculate the neutrino decay width in $\text{SU}(2)_L \times \text{SU}(2)_R \times \text{U}(1)$ model $M(W_R) = \infty$ and $\sin \zeta = 0$ corresponds to Standard Model.

$$W_1 = W_L \cos \zeta - W_R \sin \zeta$$
$$W_2 = W_L \sin \zeta + W_R \cos \zeta$$

$W_L$ and $W_R$ are fields with pure V-A and V+A couplings, respectively, and $\zeta$ is a mixing angle.

Using a lower mass limit $M(W_R) > 715\text{GeV}/c^2$, a mixing angle limit $\zeta < 0.013$, and $m_3 = 50\text{meV}$,

$$\tau(\nu_3 \rightarrow \nu_2 + \gamma) = 1.5 \times 10^{17} \text{ year} \quad (2.1 \times 10^{43} \text{ year in Standard Model})$$
Photon Energy Spectrum from Neutrino Decay

- 1.9K neutrino motion smears the sharp edge of high energy end.

- Measured photon energy $E_\gamma$ is shifted due to Doppler effect given by
  $$E_\gamma = \frac{E_0}{1+z},$$
  Where $z$ is a red shift and $E_0$ is the photon energy without Doppler shift and neutrino motion.

$$\frac{dN}{dE_\gamma dS d\Omega dt} = \frac{\rho c}{4\pi \tau H_0 E_\gamma} \left[ \left( \frac{E_0}{E_\gamma} \right)^3 \Omega_M + \Omega_\Lambda \right]^{-\frac{1}{2}}$$

$E_{\gamma \text{rest}}$: photon energy in $\nu_3$ rest frame, $\rho$: $\nu_3$ density, $\tau$: $\nu_3$ lifetime,
$H_0$: Hubble constant, $\Omega_M$: Matter density (0.76), $\Omega_\Lambda$: cosmological constant (0.24)$^6$
Our Estimate of Neutrino Lifetime Limit using the Cosmic Infrared Background measured by AKARI

SPITZER and AKARI measured the contribution of distant galaxies to the CIB. We obtained the neutrino lifetime limit from the AKARI CIB data (ApJ,737, 2, 2011) from which we subtracted the contribution of distant galaxies.

The lower limit of neutrino lifetime is $3.4 \times 10^{12}$ year at 95% C.L. for $m_3 = 0.05 \text{eV}$ and $m_2 = 0.01 \text{eV}$.

Lower limit of neutrino lifetime is $3.4 \times 10^{12}$ at 95% C.L. for $m_3 = 0.05 \text{eV}$ and $m_2 = 0.01 \text{eV}$.

For $m_3 = 0.05 \sim 0.15\text{eV}$, lower limit of $\nu_3$ lifetime at 95% C.L. ranges $(3.1 \sim 3.8) \times 10^{12}$ year.
Neutrino Decay Detection Sensitivity

Cosmic Infrared Background + Photon Energy Spectrum from Neutrino Decay \( (E_0 = 25\text{meV}, \tau = 1.5 \times 10^{17}\text{year}) \)

10-hour running with a telescope with 20cm diameter, a viewing angle of 0.1 degrees and 100% detection efficiency

- Need the energy resolution better than 2%. (plan to use STJ)
- Can observe the \( \nu_3 \) decay with a mass of 50meV, and a lifetime of \( 1.5 \times 10^{17}\text{year} \) at 6.7σ.
Search for Radiative Decays of Cosmic Background Neutrino using Cosmic Infrared Background Energy Spectrum

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(Received September 8, 2011; revised November 22, 2011; accepted December 1, 2011; published online January 18, 2012)

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 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.

KEYWORDS: neutrino radiative decay, neutrino mass, cosmic background neutrino, cosmic infrared background, COBE, AKARI, Spitzer
CIB Observation Plan (by JAXA Dr. Matsuura)

- Fluctuation (small) AKARI
- Fluctuation (large) CIBER
- Absolute value CIBER-2
- Foreground radiation MIRIS
- Search for new source COB-rocket
- Search for new source FIR-rocket

2010

2015

2020

SPICA

EXZIT

Background radiation

Foreground radiation

CMB

CIBR

AKARI

COBE

Wavelength [μm]

Surface brightness \( \lambda I_{\lambda} \) [nW/m²/sr]

放射強度

角度スケール: \( \log \theta \) [度]

DGL

初代天体によるCIBRスペクトラム

波長 [μm]

空間周波数 (多重極子): \( \log l \)

ゆらぎパワー: \( \log (l + 1)C_{l}/2\pi \) [nW/m²/sr]
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CIB Experiment for Neutrino Decay Search with JAXA Rocket

CIBER Rocket Experiment (Feb 25, 2009)

20 minutes DAQ at 200km height in 2015

Secondary mirror

Main Mirror 15cmΦ F=1m

Focal plane Instruments

IR Light

Superconducting Tunnel Junction (STJ) Detector Array (50 x 8 channels)

Tertiary mirror

Grating

Focal plane Instruments

LHe Cryostat 1.6K

Readout Electronics(4K)
Nb/Al - STJ Response to 5.9keV X rays

We have worked on STJ (Superconducting Tunnel Junction) detector R&D since 2007.

Up: 5.9keV X ray signal after preamplifier
Down: 5.9keV X ray signal after preamp + shaper
at T=0.4K

Double peak comes from that X rays are absorbed both in the upper layer and the lower layer.

ADC output distribution

Tunnel barrier
Hf-STJ I-V Curve
(Oxidation Condition: 10Torr 60min.)

V : 20μV/div
I : 20μA/div

T ~ 120 mK
pixel size 200μm × 200μm
I_C = 24μA, \quad R_d = 1Ω

With a magnetic field (2Gauss)

Josephson Current Disappeared.
Development of superconducting tunnel junction photon detector using Hafnium

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Abstract

We present the development of a Superconducting Tunnel Junction (STJ) detector using Hafnium (Hf) as a photon detector which was designed to search for radiative decay of cosmic background neutrinos. The photon energy spectrum from neutrino radiative decay has a sharp edge at high energy end. To detect this sharp edge, we need a micro-calorimeter of infrared photons with high energy resolution. We have optimized the condition of producing a Hf-STJ detector and observed that a Hf-STJ detector had Josephson currents which disappeared by applying a magnetic field.

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Plan

1. Design and detector R&D of CIB measurement with a FIR-rocket launched in 2015
   - Multi-cell Nb/Al-STJ (Tsukuba, Fukui, Okayama)
   - Low-temperature (4K) electronics (Fermilab, JAXA, Tsukuba)
   - Dispersive element such as grating (Tsukuba, JAXA)
   - Cryostat (~1K) (JAXA)

2. Superconducting detector R&D for satellite CIB measurement after 2018
   - Multi-cell Hf-STJ development (Tsukuba, Fukui)
BACKUP
US Collaborators’ Facility at Fermilab

March, 2011-
Started a collaboration with Fermilab Milli-Kelvin Facility group who will work on the readout electronics at low temperature around 4K.

Fermilab Milli-Kelvin Facility

Gustavo Cancelo, Herman Cease, Juan Estrada, Jonghee Yoo, Jiangnag Hao, Josh Frieman
Fermi National Accelerator Laboratory, Batavia, IL, 60510, USA

We propose to build a milli-Kelvin user facility at Fermilab. This facility would provide easy access to a sub-Kelvin cryogenic apparatus for the Fermilab Users. The facility will have immediate uses for SuperCDMS detector R&D, microwave kinetic inductance detector R&D (MKID), and crystal-phase low background detector R&D. Moreover, the facility would attract Users who wish to test devices such as ultra-sensitive superconducting sensors and low-noise quantum devices. An investment in a cryogen-free dilution refrigerator and related test equipment would be instrumental for future detectors and scientific experiments. In this proposal we request engineering/technical hours and support for the facility design and purchase of a cryogen-free dilution refrigerator which requires a year of lead time for delivery.

Calculate the neutrino decay width in SU(2)$_L \times$ SU(2)$_R \times$ U(1) model

$$\tau^{-1} = \frac{\alpha G_F^2}{128 \pi^4} \left( \frac{m_3^2 - m_2^2}{m_3} \right)^3 \times |U_{32}|^2 |U_{33}|^2 \left[ \frac{9}{64} (m_3^2 + m_2^2) \frac{m_4^4}{M_{W_1}^4} (1 + \frac{M_{W_1}^2}{M_{W_2}^2})^2 + 4m_\tau^2 \left( 1 - \frac{M_{W_1}^2}{M_{W_2}^2} \right)^2 \sin^2 2\zeta \right],$$

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 $|U_{33}| = 1/\sqrt{2}$.

$$\tau^{-1} \approx \frac{\alpha G_F^2}{64 \pi^4} \left( \frac{\Delta m_{32}^2}{m_3} \right)^3 m_\tau^2 \sin^2 2\zeta$$

$M_{W_2} = 0.715$ TeV, $\sin \zeta = 0.013$, $\Delta m_{32}^2 = 2.43 \times 10^{-3}$ eV$^2$, $m_\tau = 1.78$ GeV, $m_3 = 50$ meV, $\tau = 1.5 \times 10^{17}$ year

In the standard model,

$$\tau^{-1} \approx \frac{9\alpha G_F^2}{8192 \pi^4} \left( \frac{\Delta m_{32}^2}{m_3} \right)^3 \left( m_3^2 + m_2^2 \right) \left( \frac{m_\tau^2}{M_W^2} \right)^2$$

Thus $\tau = 2.1 \times 10^{43}$ year

Lower Limit of Neutrino Lifetime using Cosmic Infrared and Microwave Background measured by COBE


Neutrino Decay Photon Energy Spectrum $\phi_E$.

$$\phi_E = \frac{\Gamma_H}{4\pi} \frac{n_H}{H(z_H)} + \frac{\Gamma_L}{4\pi} \frac{n_L}{H(z_L)},$$

(assuming, for simplicity, a flat cosmology $H(z) = H_0 \sqrt{\Omega_M (1+z)^3 + \Omega_\Lambda}$, $H_0 \approx 73$ km s$^{-1}$ Mpc$^{-1}$, which is the present Hubble expansion rate, and $\Omega_M \approx 0.26$ and $\Omega_\Lambda \approx 0.74$ are, respectively, the matter and the cosmologi-

CMB (Cosmic Microwave Background):
CMB measured with COBE-FIRAS
CMB is fitted with a sum of 2.7K Plunck distribution and $\phi_E$.

CIB (Cosmic Infrared Background):
Calculate $\tau_H$ by the following equation:

$$\int_{E_{\text{min}}}^{E_H} \phi_E dE < \Phi_{\text{CIB}},$$

where $\phi_{\text{CIB}} = 24 \text{ nW m}^{-2} \text{ sr}^{-1}$ (COBE). $\rightarrow (0.5 \sim 1) \times 10^{20}$ sec $= (1.6 \sim 3.1) \times 10^{12}$ year
Neutrino Mass Relation

From neutrino oscillation measurement,

\[ \Delta m_{23}^2 = (2.43 \pm 0.13) \times 10^{-3} \text{eV}^2 \]
\[ \sin^2(2\theta_{23}) > 0.93 \]

\[ \Delta m_{12}^2 = (7.59 + 0.19/ -0.21) \times 10^{-5} \text{eV}^2 \]
\[ \theta_{12} = 34.4 \pm 1.3/ -1.2 \text{ degrees} \]

*From Tritium \( \beta \) decay measurement, \( m(\nu_e) < 2 \text{eV} \)
Our Estimate of Neutrino Lifetime Limit using the Cosmic Infrared Background measured by AKARI (2)

For $m_3 = 0.05 \sim 0.15\text{eV}$, lower limit of $\nu_3$ lifetime at 95% C.L ranges $(3.1 \sim 3.8) \times 10^{12}\text{ year or (1.0 \sim 1.2)} \times 10^{20}\text{ sec.}$

$\Delta m_{23}^2 = 0.00243\text{ eV}^2$
Neutrino Decay Detection Sensitivity (2)

- 5σ observation sensitivity by 10-hour measurement with a telescope with 20 cm diameter, a viewing angle of 0.1 degree and 100% detection efficiency.
Experiment Plan

Search for cosmic background neutrino decay with far-infrared observatory rocket launched in 2015

- Experiment Design
- Development of Multi-channel Nb/Al Superconducting Tunnel Junction (STJ) Infrared Photon Detector
- Development of Preamplifier and Shaper operating at 4K
- Design and Production of Dispersive Element and Optical System
- Design and Production of Cryostat

Search for cosmic background neutrino decay with far-infrared observatory satellite such as SPICA launched after 2018

- Experiment Design
- Development of Hf Superconducting Tunnel Junction (STJ) Infrared Photon Detector
Superconducting Tunnel Junction (STJ) Detector
STJ (Superconducting Tunnel Junction) Detector

- **Superconductor / Insulator / Superconductor** Josephson Junction

At the superconducting junction, excited electrons (quasi-particles) over their energy gap go through tunnel barrier by a tunnel effect.

By measuring the tunnel current of electrons excited by an incident particle, we measure the energy of the particle.

![Superconducting Tunnel Junction Diagram](image)
STJ Energy Resolution

\[ \sigma_E = \sqrt{1.7\Delta(FE)} \]

Using Hf as a superconductor,

\[ \frac{\sigma_E}{E} = 1.7\% \quad \text{at} \quad E = 25\text{meV} \]

<table>
<thead>
<tr>
<th>Material</th>
<th>( T_c (K) )</th>
<th>( \Delta (\text{meV}) )</th>
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<tr>
<td>Niobium</td>
<td>9.20</td>
<td>1.550</td>
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<tr>
<td>Aluminum</td>
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<td>0.172</td>
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<tr>
<td>Hafnium</td>
<td>0.13</td>
<td>0.021</td>
</tr>
</tbody>
</table>

\( \Delta \): Band gap energy
\( F \): Fano factor (= 0.2)
\( E \): Incident particle energy

\( T_c \): Critical Temperature

Operation is done at a temperature around 1/10 of \( T_c \)

No paper on Hf-STJ test in the world.
Basic Properties of STJ Detector

Nb-STJ current – voltage (I-V) curve

- Leakage current (Dynamic resistance $R_d$ in $|V| < 2\Delta/e$)
- Energy gap $\Delta$
- Critical current $I_c$

Josephson Current is suppressed by a magnetic field parallel to the insulator plane.
Hf-STJ Structure

Mask Design

Enlarging

Cross Section

50, 100, 200 μm

HfO$_2$(1-2nm)

5mm

Nb

Hf(250nm)

SiO$_2$

Si
R&D Status

(1) Search for the best condition for making a flat Hf layer: various pressures and voltages.
- 2.0 Pa, 70W (optimized)
R&D Status

(2) Search for the best condition for making the insulator layer (1 – 2 nm thick) as a tunnel barrier: various pressures and periods of oxidation.

- 5 Torr, 12 minutes Oxidation sample (TEM picture)
  - Confirmed 1.3nm-thick HfO$_2$ layer

TEM: Transmission Electron Microscope
EDX: Energy Dispersive X-ray Spectroscopy
R&D Status

(3) Operation of He$_3$/He$_4$ Dilution Refrigerator.

- We borrowed a He$_3$/He$_4$ Dilution Refrigerator from a group of Low Temperature Material Science at University of Tsukuba in 2008.
- Achieved 49mK in July 2009.
- Achieved 40mK in October 2011.

---

**Temperature stage**

![Graph showing temperature and time data for He$_3$/He$_4$ Dilution Refrigerator operation.](image)

Lowest: 49mK

I-V curve measured

---

**[K]**

0

0.05

0.1

0.15

0.2


time
Specification of 4K preamplifier

Mail from me to Erik on Dec. 18, 2011

Erik,

I am sending the specifications about 4K electronics. If you have a mK facility at Fermilab, we can test the 4K electronics together with a Hf Superconducting detector. However even if you do not have the mK facility, when you can develop and test 4K electronics, your contribution is very useful for this experiment. About the test of Nb/Al-STJ, 0.4K is enough for the test of preamplifier with the Nb/Al-STJ.

Our plan is to look at signals from visible photon (lambda=410nm) and near-infrared photon (lambda=1um) using a laser in 2012. For this purpose, we need a prototype preamplifier as specified below.

In 2013, we plan to look at signals from far-infrared photon (lambda=30um) and make a prototype of multi-channel preamplifiers for Nb/Al-STJ (400 channels).

Requirement for preamplifiers of Nb/Al-STJ and Hf-STJ is summarized below:

- Common specification: Operation temperature: ~4K Integration time: 10 usec

<For the Nb/Al-STJ and Hf-STJ prototype design>
Dynamic range < 20fC ( ~1.2 x 10**5 e) from the requirement of < 4.5eV gamma ( lambda=270 nm ) at HF-STJ
Noise < 0.34 fC ( ~2100 e) from the requirement of < 2.5% for 13.4 fC = 3 eV gamma ( lambda~410 nm ) at Hf-STJ
Gain: 400mV/fC

<For Nb/Al-STJ final design>
Dynamic range < 0.16fC ( ~1000 e) from the requirement of < 300 meV gamma at Nb/Al-STJ
Noise < 0.0045fC ( ~30e) from the requirement of <35% for 0.013 fC = 25meV gamma at Nb/Al-STJ
Gain: 10V/fC

<For Hf-STJ final design>
Dynamic range < 4.3fC ( ~27000 e) from the requirement of < 45meV gamma at HF/W-STJ
Noise < 0.012fC ( ~80e) from the requirement of <0.5% for 2.4 fC = 25meV gamma at Hf/W-STJ
Gain: 1V/fC

Best regards,
Shinhong
CIBER ロケット実験

CIBERロケット実験の第1回打上げの瞬間（2009年2月25日）

打上げ後に回収されたCIBERの観測装置。米国ホワイトサンズ（ニューメキシコ州）実験場
CIB Experiment for Neutrino Decay Search with JAXA Rocket

20 minutes DAQ at 200 km height in 2015

Grating

- d = 1 mm
- D = 10 cm
- m = 0
- m = 1
- 50 pixels
- 8 pixels
- Δx = 200 μ
- x = 10 mm

Focal plane Instruments

Superconducting Tunnel Junction (STJ) Detector Array (50 x 8 channels)

IR Light
- Secondary mirror
- Main Mirror
- 15 cm Φ
- F = 1 m

Focal plane Instruments

LHe Cryostat
- 1.6 K

Readout Electronics (4K)

m sin θ = λ
→ x = Dθ = Dλ/d = 100λ
If Δx = 200 μ, Δλ = 2 μ