Development of Superconducting Tunnel Junction Far-Infrared Photon Detectors for Cosmic Background Neutrino Decay Search - COBAND Experiment

Shin-Hong Kim (University of Tsukuba/TCHoU) for COBAND Collaboration

COBAND Collaboration

● Introduction

Motivation

COsmic BAckground Neutrino Decay search (COBAND) experiment

● R&D of Superconducting Tunnel Junction (STJ) Detector
Motivation of Search for Cosmic Background Neutrino Decay

- To determine the neutrino mass itself by neutrino decay observation.

\[ \nu_3 \rightarrow \nu_2 + \gamma \]

- As the neutrino lifetime is very long, we need use the cosmic background neutrino (CνB) as a huge neutrino source. Measured neutrino lifetime limit \( \tau > 3 \times 10^{12} \text{ year} \).

- To observe this decay means a discovery of the cosmic background neutrino predicted by cosmology.

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

Using \( \Delta m_{23}^2 = (2.43 \pm 0.09) \times 10^{-3} \text{ eV}^2 \)

\[ E_{\gamma} = 10 \sim 25 \text{ meV at } \nu_3 \text{ rest frame.} \]

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

\[ \lambda_{\gamma} \text{ distribution in } \nu_3 \rightarrow \nu_2 + \gamma \]

If assume \( m_1 \ll m_2 < m_3 \), \( m_3 \sim 50 \text{ meV} \) from neutrino oscillation measurements
Signal of Cosmic Background Neutrino Decay and its Backgrounds

By measuring the energy spectrum of the Zodiacal Emission with the CvB decay continuously, we can see the CvB decay signal as a high energy cutoff.

Requirements for the detector
- Continuous spectrum of photon energy around $E_\gamma \sim 25 \text{ meV}(\lambda = 50 \mu\text{m})$
- Energy measurement for single photon with better than 2% resolution for $E_\gamma = 25 \text{ meV}$ to identify the sharp edge in the spectrum
- Rocket and/or satellite experiment with this detector
**COBAND (COsmic BAckground Neutrino Decay Search) Experiment**

**Rocket Experiment**

Plan: 5 minutes data acquisition at 200 km height in 2020-21.

JAXA Sounding Rocket S520

Improve the current limit of lifetime $\tau(\nu_3)$ by two orders of magnitude (~$10^{14}$ years).

»Superconducting Tunneling Junction (STJ) detectors in development

- Array of 50 Nb/Al-STJ pixels with diffractive grating covering $\lambda = 40 - 80 \mu m$

**Satellite experiment after 2025 → sensitivity of $\tau(\nu_3)$ ~$10^{17}$ year** (L-R symmetric model prediction)

- STJ using Hafnium: Hf-STJ for satellite experiment (S. H. Kim et al. JPSJ 81,024101 (2012))

  - $\Delta = 20 \mu eV$: Superconducting gap energy for Hafnium

  Microcalorimeter $\Delta E/E < 2\%$ without diffractive grating.
STJ (Superconducting Tunnel Junction) Detector

- Superconductor / Insulator / Superconductor Josephson Junction

At the superconducting junction, quasi-particles over their energy gap go through tunnel barrier by a tunnel effect. By measuring the tunnel current of quasi-particles excited by an incident particle, we measure the energy of the particle.
**Nb/Al-STJ Photon Detector**

- Quasi-particles near the barrier can mediate Cooper pairs, resulting in true signal gain
  - Bi-layer fabricated with superconductors of different gaps $\Delta_{\text{Nb}} > \Delta_{\text{Al}}$ to enhance quasi-particle density near the barrier
  - Nb(200nm)/Al(70nm)/AlOx/Al(70nm)/Nb(100nm)
    \[ \Delta_{\text{Nb/Al}} = 0.57 \text{meV} \]
- Gain: $2 \sim 200$ (10 for Al)

### Number of Quasi-particles in Nb/Al-STJ

\[ N_q = G_{\text{Al}} \frac{E_0}{1.7\Delta} \]

- $G_{\text{Al}}$: Trapping Gain in Al ($\sim 10$)
- $E_0$: Photon Energy
- $\Delta$: E-Gap in superconductor

**For 25meV single photon**

\[ N_q = 250 \text{ e} \]

### Requirement for detector

- Leakage current $I_{\text{leak}} < 0.1 \text{nA}$: Done
- Noise integrated in 10μs < 30e: Cryogenic amplifier is needed
SOI Cryogenic Amplifier

FD-SOI (Fully Depleted Silicon-On-Insulator) device was proved to operate at 4K by a JAXA/KEK group (AIPC 1185,286-289(2009)).

SOI-STJ4 (the 4th prototype)

Amplification
Replace the resistance by a SOIFET as a current source (M2).

Feedback
Use the feedback between the drain and the gate of M1 to apply a stable bias voltage (M3).

Buffer
Add the follower to reduce the output impedance (M4 and M5).

This SOI amplifier board was made by LAPIS semiconductor company.
STJ signal amplified with the SOI cryogenic preamplifier

Nb/Al-STJ laser light response signal was amplified with this SOI cryogenic amplifier.

STJ signal to visible laser $\lambda=465\text{nm}$, 20kHz

Amplification Gain: 70

S/N improved by a factor of 2
Charge Amplifier Circuit for STJ (SOI-STJ5 design)

- Telescopic cascode differential amplifier
- Feedback $C(2\text{pF}) \times R (5\text{M}\Omega) = 10\mu\text{s}$
- Power consumption $\sim 150\mu\text{W}$

Test of this cryogenic charge amplifier is underway.

Working at 3K

Next cryogenic charge amplifier was designed with a higher gain to see a 25meV single photon.
R&D Status of Hf-STJ - Laser Light Response

We made a thin aluminum layer (9nm) on the HfO layer (1-2 nm) to improve the insulation of the HfO\textsubscript{X} layer. Hf/Al/HfO\textsubscript{X}/Hf-STJ

\[ \Delta = 20 \sim 30 \mu eV \]
Leakage current = 5\(\mu\)A@128mK for 200\(\mu\)m-square sample.

Visible light laser (\(\lambda=465\)nm) 10Hz duration

Response speed (120\(\mu\)s) is slower than Nb/Al-STJ response speed (around a few \(\mu\)s).
Hf/Al/HfO$_x$/Hf-STJ reduced the leakage current to one-tenth.

Hf-STJ with smoothed Hf layer reduced the leakage current to one-tenth.

Small size Hf-STJ (10μ-square) reduced the leakage current to 1/24.

We are working on the study on downsizing of Hf-STJ.

We plan to lower the operation temperature using another better dilution refrigerator.
R&D of STJ detectors and the design of the COBAND rocket experiment are underway.

- Nb/Al-STJ satisfied our requirement for leakage current less than 100pA.
- Cryogenic amplifier with the SOI technology worked at 300mK. We have succeeded in amplifying the STJ signal with the SOI cryogenic amplifier.
- Hf-STJ signal for visible laser light was observed.

Many applications of the STJ detector as a single photon detector in the far-infrared range, a very low energy particle detector, X-ray energy measurement with very higher energy resolution and so on.

COBAND WEB page       http://hep.px.tsukuba.ac.jp/coband/eng/
BACKUP
Big-Bang Cosmology and Cosmic Background Neutrino (CνB)

- A few seconds after Big Bang → Cosmic Background Neutrino (CνB) became free.
- 300,000 years after Big Bang → Cosmic Microwave Background (CMB) became free.
Search for Radiative Decays of Cosmic Background Neutrino using Cosmic Infrared Background Energy Spectrum

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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

Search Region: $\lambda = 35 - 250 \mu m$ (E$_\gamma = 35 - 5$ meV)
In Rocket experiment, $\lambda = 40 - 80 \mu m$ (E$_\gamma = 31 - 15$ meV)
**COBAND Rocket Experiment**

We measured CIB in the same points as S520-15 experiment measured the CIB in 1992. 方向からの宇宙赤外線

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**a. Pre-flight operation**

**X - 10h10m** start first liquid He transfer
- 4h10m start second liquid He transfer (fill up)
  - set the launcher angle to $Az=145^\circ$, $El=85^\circ$
- 1h43m power on (external supply)
- 40m start pumping the cryostat tank
- 5m close the pumping line valve
  - switch to the internal power supply
- 4m disconnect the pumping line
**X**
  - launch (1:00:00 JST, 1992 February 2)

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**b. In-flight operation**

**X + 55s**
  - open the nosecone covers,
  - open the pumping line valve
**+ 60s** separate the rocket motor
**+ 61s** open the gas shade
**+ 63s** start attitude control
**+ 90s**
  - point at “A”
**+ 130s**
  - open the cryostat lid
**+ 220s - 255s**
  - scan “A” → “B₁” (0.6 s⁻¹)
**+ 255s**
  - point to “B₂”
**+ 277s - 310s**
  - scan “B₂” → “A” (0.6 s⁻¹)
**+ 310s - 430s**
  - point at “A”
**+ 430s**
  - tip down to the earth limb
  - (recovery operation)
**+ 480s**
  - instrument jettison

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**Measured Points**
These are the same as S520-15.

A (Galactic Latitude 52°, Galactic Longitude 151°)
Parameters in the rocket experiment simulation

- telescope diameter: 15cm
- 50-column ($\lambda$: 40μm – 80 μm) × 8-row array
- Viewing angle per single pixel: 100μrad × 100μrad
- Measurement time: 200 sec.
- Photon detection efficiency: 100%

- If $\nu_3$ lifetime were $2 \times 10^{14}$ yrs, the signal significance is at $5\sigma$ level
COBAND Experiment Sensitivity to Neutrino Decay

L-R Sym. model $\zeta = 0.02$, $M(W_2) = 750$ GeV

$\Delta m_{31}^2 = 2.5 \times 10^{-3}$ eV$^2$

$\sum m_i < 0.23$ eV

MSSM extension model with vector-like lepton generation

S.H.Kim et. al (2012)

Mirizzi et. al (2007)

Present measured limit

COBAND Rocket Experiment

\text{x100 Improvement!}
**Nb/Al-STJ Photon Detector**

**Back tunneling Effect → Trapping Gain**

- Quasi-particles near the barrier can mediate Cooper pairs, resulting in true signal gain
  - Bi-layer fabricated with superconductors of different gaps $\Delta_{\text{Nb}} > \Delta_{\text{Al}}$ to enhance quasi-particle density near the barrier
  - Nb(200nm)/Al(70nm)/AlOx/Al(70nm)/Nb(100nm) $\Delta_{\text{Nb/Al}} = 0.57\text{meV}$
- Gain: $2 \sim 200$ (10 for Al)

**Number of Quasi-particles in Nb/Al-STJ**

$$N_q = G_{\text{Al}} \frac{E_0}{1.7\Delta}$$

$G_{\text{Al}}$: Trapping Gain in Al($\sim 10$)
$E_0$: Photon Energy
$\Delta$: E-Gap in superconductor

For 25meV single photon $N_q = 250$ e

**Response of Nb/Al-STJ to visible laser light pulse ($\lambda = 465\text{nm}$) at 350mK**

**Requirement for detector**

- Leakage current $I_{\text{leak}} < 0.1\text{nA}$: Done
- Noise integrated in 10$\mu$s < 30e: cryogenic amplifier is needed
Leakage Current of Nb/Al-STJ

- Leakage current $I_{\text{leak}}$ is required to be below 0.1nA to detect a single far-infrared photon ($\lambda = 40 - 80\mu m$).

Temperature Dependence of Leakage Current

$I_{\text{leak}} \propto \sqrt{T}e^{-\frac{\Delta}{k_bT}}$

$I_{\text{leak}} = 0.2\text{nA}$ at 300$\mu$V below 400mK

In 2014, AIST group joined us and produced Nb/Al-STJ with AIST CRAVITY processing system. Leakage current has satisfied our requirement of 0.1nA.

<table>
<thead>
<tr>
<th>STJ size</th>
<th># of samples</th>
<th>$I_{\text{leak}}$ at 0.3mV</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 x 50$\mu$m$^2$</td>
<td>18</td>
<td>224$\pm$29 pA</td>
</tr>
<tr>
<td>20 x 20 $\mu$m$^2$</td>
<td>7</td>
<td>39$\pm$13 pA</td>
</tr>
<tr>
<td>10 x 10 $\mu$m$^2$</td>
<td>20</td>
<td>14$\pm$7 pA</td>
</tr>
</tbody>
</table>

by T. Fujii (AIST)
Test Results of Nb/Al-STJ with Far-Infrared laser

Far-Infrared Laser at University of Fukui (λ=57.2μm)

- Nb/Al-STJ Response to Far-Infrared Laser

- 20μm-square Nb/Al-STJ made at AIST CRAVITY system
- Laser light was turned on and off with a chopper at a frequency of 200Hz. Measured the change of the I-V curve between the laser on and off to be 50~100nA in current.
New Charge Amplifier Circuit for STJ (SOI-STJ6 design)

- Feedback capacitance: $2\,\text{pF} \rightarrow 60\,\text{fF}$
- Power Consumption: $\sim 150\,\mu\text{W}$
- $24\,\text{meV}$ one photon $(0.03\,\text{fC})$ gives $\sim 40\,\text{mV}$ Output

Telescopic cascode

Amplifier (SOI-STJ4) Buffer stage

Simulation Result

Input ($\sim 0.036\,\text{fC}$)

$\sim 0.5\,\mu\text{V}$

Output

$\sim 40\,\text{mV}$

25 $\mu\text{s}$

This charge amplifier will arrive at our University soon.
Cosmic Background Neutrino

**Fermi and Bose Distribution Function**

\[ F(E) = \frac{1}{e^{(E-\mu)/kT} + 1} \]

*where* + for fermions and - for bosons, and E is energy and \( \mu \) is a chemical potential.

For \( \mu \ll T \) and \( m \ll T \),

**Energy density**

\[ \rho = g \int \frac{d^3p}{(2\pi)^3} EF(E) = g \left( \frac{7}{8} \right)^F \frac{\pi^2}{30} T^4 \]

**Number density**

\[ n = g \int \frac{d^3p}{(2\pi)^3} F(E) = g \left( \frac{3}{4} \right)^F \frac{\zeta(3)}{\pi^2} T^3 \]

**Entropy**

\[ s = \frac{4\rho}{3T} = g \left( \frac{7}{8} \right)^F \frac{2\pi^2}{45} T^3 \]

**Temperature:**

Below 3MeV, \( \nu \) is decoupled from other particles because the weak interaction cross section becomes too small.

Below 1MeV, \( e^+e^- \rightarrow \gamma\gamma \) is possible, but \( \gamma\gamma \rightarrow e^+e^- \) is impossible. so photons are reheated by this process. The entropies before and after this time are equal to each other:

**Entropy**

\[ s \propto g \left( \frac{7}{8} \right)^F T^3 \]

\( g \) = 2 (for \( \gamma \)), 2 (for \( e^- \) or \( e^+ \)), 1 (for \( \nu \) or anti-\( \nu \))

where \( g \) is the spin degree of freedom, and \( F = 1 \) (for fermions) and 0 (for bosons).

The present entropies of photons and neutrinos, \( s_{\gamma 0} \) and \( s_{\nu 0} \) are given by

\[ s_{\gamma 0} = a^3 \left( s_{\gamma} + s_{e^-+e^+} \right) , \quad s_{\nu 0} = a^3 s_{\nu} \quad \text{where} \quad a \text{ is a scale factor.} \]

\[ \frac{s_{\nu 0}}{s_{\gamma 0}} = \frac{s_{\nu}}{s_{\gamma} + s_{e^-+e^+}} = \frac{2 \times \frac{7}{8}}{2 + 4 \times \frac{7}{8}} = \frac{7}{22} \quad \therefore \quad s_{\nu 0} = \frac{7}{22} s_{\gamma 0} \]

\[ 2 \times \frac{7}{8} T_\nu^3 = \frac{7}{22} \times 2 T_\gamma^3 \quad \rightarrow \quad T_\nu = \left( \frac{4}{11} \right)^{\frac{1}{3}} T_\gamma^3 \quad \text{As} \quad T_\gamma = 2.73K, \quad \therefore \quad T_\nu = 1.95K \]
**Cosmic Background Neutrino**

Temperature:

\[ T_\nu = 1.95\text{K} \]

Number density:

As \( \mu / T \ll 1 \),

\[ n \propto g \left( \frac{3}{4} \right)^F T^3 \]

where \( g \) is the spin degree of freedom, and \( F = 1 \) (for fermions) and 0 (for bosons).

\[ \rightarrow n_\nu = \frac{3}{4} \left( \frac{T_\nu}{T_\gamma} \right)^3 \frac{n_\gamma}{2} \]

\[ : n_{\nu_\alpha} \approx n_{\bar{\nu}_\alpha} \approx 56 \text{cm}^{-3} \quad (\alpha = e, \mu, \tau) \]
Requirement for the photon detector in COBAND rocket experiment

- Sensitive area of 100μm×100μm for each pixel
- High detection efficiency for a far-infrared single-photon in λ = 40μm ~ 80μm
- Dark count rate less than 300Hz (expected real photon rate)

\[ \text{NEP} = \epsilon_\gamma \sqrt{2f_\gamma} \sim 1 \times 10^{-19} \text{ W/}\sqrt{\text{Hz}} \]

(Noise Equivalent Power), where \( \epsilon_\gamma \) is a photon energy and \( f_\gamma \) is a photon rate.

We are trying to achieve NEP \( \sim 10^{-19} \text{ W/}\sqrt{\text{Hz}} \) by using

- Superconducting Tunneling Junction detector
  (leakage current per pixel < 100pA)
- Cryogenic amplifier readout
FD-SOI (Fully Depleted Silicon-On-Insulator) device was proved to operate at 4K by a JAXA/KEK group (AIPC 1185,286-289(200 FD-SOI 9)). It has the following characteristics: low-power consumption, high speed, easy large scale integration and suppression of charge-up by high mobility carrier due to thin depletion layer (~50nm).

To improve the signal-to-noise ratio and to make multi-pixel device easily, we made a SOI-STJ detector where we processed Nb/Al-STJ on a SOI transistor board.
We observed the signal of Nb/Al-STJ processed on the SOI board to 465nm laser pulse at 700mK.

- We confirmed that the SOI-FET work as a preamplifier with a gain of 8.7 at 4K up to 100kHz.
Zodiacal Emission

Thermal emission from the interplanetary dust cloud

\[
I_v = \frac{2h\nu^3}{c^2} \frac{1}{\exp(h\nu/kT) - 1} \times A \left(\frac{\nu}{c} \times 10^{-5}\right)^B \text{Wm}^{-2}\text{sr}^{-1}
\]

- \( T = 270K \), \( A = 6 \times 10^{-8} \), \( B = 0.3 \)
- \( h \) [Js], \( c \) [m/s], \( \lambda \) [m]

Zodiacal Emission (ZE) is overwhelmingly dominating. Here we consider only ZE as the background.
Zodiacal Emission

Surface brightness $\nu I_\nu$ [W/m$^2$/sr]

- $\nu I_\nu$ (W/m$^2$/sr) vs. wavelength (m)
  - 1$\mu$m
  - 10$\mu$m
  - 100$\mu$m
  - 1mm

Total background data by COBE
Total background data by AKARI

$T=270$[K]
STJ Energy Resolution

$$\sigma_E = \sqrt{1.7\Delta(FE)}$$

Using Hf as a superconductor,

$$\sigma_E / E = 1.7\% \text{ at } E = 25\text{meV}$$

<table>
<thead>
<tr>
<th>Material</th>
<th>$T_c$ ($K$)</th>
<th>$\Delta$ (meV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Niobium</td>
<td>9.20</td>
<td>1.550</td>
</tr>
<tr>
<td>Aluminum</td>
<td>1.14</td>
<td>0.172</td>
</tr>
<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

Tc : Critical Temperature

Operation is done at a temperature around 1/10 of Tc

We reported that Hf–STJ worked as a STJ in TIPP2011.
STJ back tunneling effect

- Quasi-particles near the barrier can mediate Cooper pairs, resulting in true signal gain
  - Bi-layer fabricated with superconductors of different gaps $\Delta_{\text{Nb}} > \Delta_{\text{Al}}$ to enhance quasi-particle density near the barrier
  - Nb/Al-STJ  Nb(200nm)/Al(10nm)/AlOx/Al(10nm)/Nb(100nm)
- Gain: $2 \sim 200$

Diagram: 
- Photon
- Nb  Al  Al  Nb
- Nb  Al  Al  Nb
Goal: Measure energy of a single far-infrared photon for neutrino decay search experiment within 2% energy resolution.

Micro-calorimeter: Hf-STJ can generate enough quasi-particles from cooper pair breakings to achieve 2% energy resolution for photons with $E_\gamma = 25$ meV.

Earlier version of our Hf-STJ in 2011
- Structure: Hf/HfOx/Hf = 250nm/1.5nm/300nm
- Leakage current 20μA@50mK, 20μV for 100μm-square sample (our requirement: 10pA)

<table>
<thead>
<tr>
<th>STJ size</th>
<th># of samples</th>
<th>$R_d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 x 200μm²</td>
<td>3</td>
<td>0.22 ± 0.01 Ω</td>
</tr>
<tr>
<td>100 x 100 μm²</td>
<td>3</td>
<td>0.60 ± 0.10 Ω</td>
</tr>
</tbody>
</table>

I-V curve of Hf-STJ (100x100μm²)
- T~40mK, $I_c$=10μA, $R_d$=0.6Ω

B=0 Gauss       B=10 Gauss
Improvement of Hf Surface Smoothness

- We improved the Hf surface smoothness by optimizing the Hf sputtering parameters.
Hf-STJ with Improved Smoothness

200μ square Hf-STJ with improved smoothness. Wire bonding readout line.

- Josephson current is 2μA.
- Effective energy gap $\Delta = 25\mu$eV.
- Leakage current at 20μV is 7μA.
Small-size Hf-STJ with improved smoothness

10μ-square Hf-STJ. Signal line was made by sputtered Nb line not by wire bonding.

● Josephson current is 0.7μA.
● Effective energy gap $\Delta = 130\mu$eV.
● Leakage current at 20μV is 0.3μA (1/24 of 200μ-square Hf-STJ).
Neutrino Lifetime by Left-Right Symmetric Model

In the Left-Right Symmetric Model $SU(2)_L \otimes SU(2)_R \otimes U(1)$
there are two Weak Boson mass eigenstates:

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

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

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

$W^+_k \rightarrow \nu_i^{(i)} \ell^+ \rightarrow \nu_j^{(j)} \ell^+$
$W^+_k \rightarrow \nu_i^{(i)} \ell^+ \rightarrow \nu_j^{(j)} \ell^+$
$W^+_k \rightarrow \nu_i^{(i)} \ell^+ \rightarrow \nu_j^{(j)} \ell^+$
$W^+_k \rightarrow \nu_i^{(i)} \ell^+ \rightarrow \nu_j^{(j)} \ell^+$

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

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

$\tau^{-1} = \frac{\alpha G_F^2}{128 \pi^4} \left( \frac{\Delta m_{32}^2}{m_3} \right)^3 m_\tau^2 \sin^2 2\zeta$

Using a lower mass limit $M(W_R) > 715 GeV$, a mixing angle limit $\zeta < 0.02$, and $m_3 = 50 meV$,
$\tau = 1.5 \times 10^{17}$ year

Measured neutrino lifetime limit $\tau < 3 \times 10^{12}$ year from CIB results measured by COBE and AKARI
Other papers citing our JPSJ paper

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Radiative decays of cosmic background neutrinos in extensions of the MSSM with a vectorlike lepton generation

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An analysis of radiative decays of the neutrinos $\nu_j \rightarrow \nu, \gamma$ is discussed in minimal supersymmetric standard model extensions with a vectorlike lepton generation. Specifically we compute neutrino decays arising from the exchange of charginos and charged sleptons where the photon is emitted by the charged particle in the loop. It is shown that while the lifetime of the neutrino decay in the Standard Model is $\sim 10^{13}$ yrs for a neutrino mass of 50 meV, the current lower limit from experiment from the analysis of the Cosmic Infrared Background is $\sim 10^{12}$ yrs and thus beyond the reach of experiment in the foreseeable future. However, in the extensions with a vectorlike lepton generation the lifetime for the decays can be as low as $\sim 10^{12} - 10^{14}$ yrs and thus within reach of future improved experiments. The effect of CP phases on the neutrino lifetime is also analyzed. It is shown that while both the magnetic and the electric transition dipole moments contribute to the neutrino lifetime, often the electric dipole moment dominates even for moderate size CP phases.

MSSM extension with a vectorlike lepton generation

$\rightarrow \tau_v \sim 10^{12} \sim 10^{14}$ years
**MSSM extension model with a vectorlike lepton generation**

**Physical Review D 88, 013019 (2013)**

Radiative decays of cosmic background neutrinos in extensions of the MSSM with a vectorlike lepton generation

Amin Abou Ibrahim, Tarek Ibrahim, and Pran Nath

\[ S U(3)_C \times S U(2)_L \times U(1)_Y \]

\[ \psi_{IL} = \begin{pmatrix} \nu_{IL} \\ l_{IL} \end{pmatrix} \sim (1, 2, -\frac{1}{2}) \]

\[ \nu_{IL} \sim (1, 1, 0), \quad i = 1, 2, 3 \]

\[ Q = T_3 + Y \]

**Physical Review D 89, 055009 (2014)**

Large neutrino magnetic dipole moments in MSSM extensions

Amin Abou Ibrahim, Tarek Ibrahim, Ahmad Itani, and Pran Nath

\[ \chi^e = \begin{pmatrix} E_L^e \\ N^e_L \end{pmatrix} \sim (1, 2, \frac{1}{2}) \]

\[ E_L \sim (1, 1, -1) \]

Vectorlike lepton generation

**V+A interaction**

\[ \left( \begin{array}{c} \nu_{\tau R} \\ N^R_e \\ \nu_{\mu R} \\ \nu_{\tau R} \end{array} \right) = D_R^V \left( \begin{array}{c} \psi_{1R} \\ \psi_{2R} \\ \psi_{3R} \\ \psi_{4R} \end{array} \right), \quad \left( \begin{array}{c} \nu_{\tau L} \\ \nu_{\mu L} \\ \nu_{\tau L} \end{array} \right) = D_L^V \left( \begin{array}{c} \psi_{1L} \\ \psi_{2L} \\ \psi_{3L} \end{array} \right). \]

Neutrino mass eigenvalues (GeV)

\[
\begin{array}{cccc}
(i) & m_{\chi^e} = 256 \text{ GeV} & \mu_2 & 1.2 \times 10^{-10} \\
 & m_{\ell} = 162 \text{ GeV} & \mu_1 & 2.5 \times 10^{-13} \\
 & \nu_3 & \text{lifetime} & 3.9 \times 10^{14} \text{ yr} \\
(ii) & m_{\chi^e} = 267 \text{ GeV} & \mu_2 & 4.6 \times 10^{-10} \\
 & m_{\ell} = 202 \text{ GeV} & \mu_1 & 1.3 \times 10^{-12} \\
 & \nu_3 & \text{lifetime} & 2.5 \times 10^{14} \text{ yr} \\
(iii) & m_{\chi^e} = 268 \text{ GeV} & \mu_2 & 2.2 \times 10^{-10} \\
 & m_{\ell} = 158 \text{ GeV} & \mu_1 & 1.1 \times 10^{-13} \\
 & \nu_3 & \text{lifetime} & 1.8 \times 10^{14} \text{ yr} \\
(iv) & m_{\chi^e} = 272 \text{ GeV} & \mu_2 & -7.6 \times 10^{-10} \\
 & m_{\ell} = 195 \text{ GeV} & \mu_1 & -1.3 \times 10^{-13} \\
 & \nu_3 & \text{lifetime} & 8.8 \times 10^{13} \text{ yr} \\
\end{array}
\]

\[ -\mathcal{L}_{CC} = \frac{g}{2\sqrt{2}} W^\dagger_\rho \left[ \bar{\nu}_\tau \gamma^\rho (1 - \gamma_5) \tau + \bar{\nu}_\mu \gamma^\rho (1 - \gamma_5) \mu + \bar{\nu}_e \gamma^\rho (1 - \gamma_5) e + N \gamma^\rho (1 + \gamma_5) E \right] + H.c. \]
STJ Energy Resolution for Near-Infrared Photon

P. Verhoeve et. al 1997
- 30μm sq. Ta/Al-STJ
- ΔE~130meV @ E=620meV(λ=2μm)
- Charge sensitive amplifier at room temp.
  - Electronic noise ~ 100meV

In sub-eV ~ several-eV region, STJ gives the best energy resolution among superconductor based detectors, but limited by readout electronic noise.