

Progress Report on “Neutrino Decay Search” project in JFY 2012

1. Motivation of Experiment

The difference between the mass-squares of different-generation neutrinos has been measured by various neutrino oscillation experiments, 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. The heaviest neutrino ν_3 decays into a lighter neutrino ν_2 and a photon via a Feynman diagram as shown in Fig. 1. 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. The cosmic background neutrino has a temperature of 1.9K and a particle density of 110 cm^{-3} per generation. If a neutrino decays at rest, the decay photon energy E_γ is given by $E_\gamma = \Delta m_{32}^2 / 2m_3$ where Δm_{32}^2 is the mass-square difference between ν_3 mass m_3 and ν_2 mass m_2 . By measuring E_γ in neutrino decay, we can determine the neutrino mass itself. We search for the neutrino radiative decay under these constraints on the mass-square differences and the mixing angles between the neutrino generations. Assuming the m_3 is between 50meV and 150meV, the decay photon energy at ν_3 rest frame (E_γ) is between 10meV and 25meV which is far-infrared region. The photon energy spectrum from neutrino decay has a shape as shown in Fig.2 which has a sharp cutoff at the high energy end $E_\gamma = \Delta m_{32}^2 / 2m_3$ and a tail in the low energy side due to a red shift effect. 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

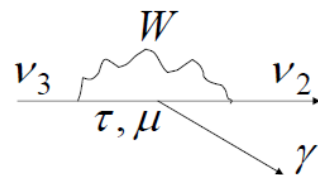


Fig1. $\nu_3 \rightarrow \nu_2 + \gamma$ Feynman Diagram

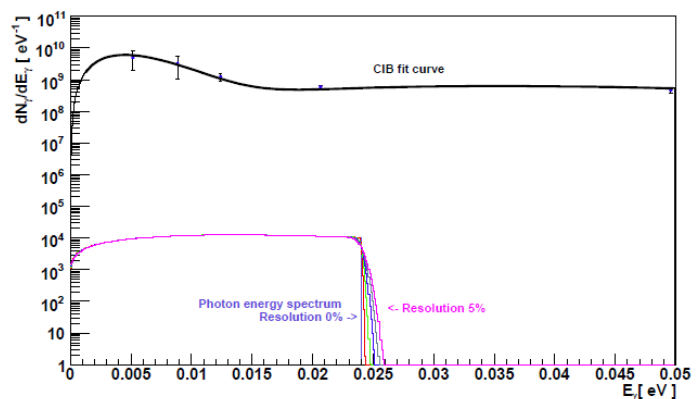


Fig.2. Energy spectrum of photons from neutrino decay with various energy resolutions from 0% to 5% (lower curves) and foreground from Cosmic Infrared Background (CIB) radiation (upper curve)

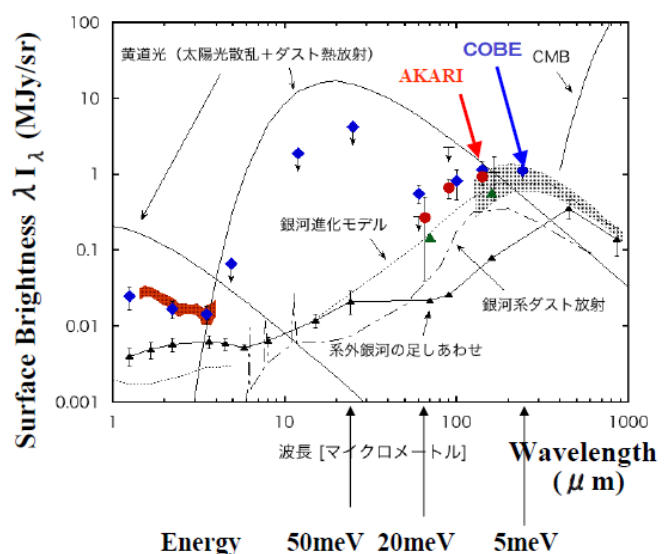


Fig.3. Cosmic Infrared Background measurement results by COBE (blue diamonds) and AKARI (red circles).

spectrum. The continuum of the CIB is the background against the neutrino decay signal. In the above far-infrared region between 10meV and 25meV, only two satellite observatories of COBE and AKARI have measured this CIB in 1998 and 2011, respectively, as shown in Fig. 3. Using AKARI CIB results, we determined the lower limit of neutrino lifetime to be $(3.1 \sim 3.8) \times 10^{12}$ years at 95% C.L. for m_3 between 50meV and 150meV [1].

In the left-right symmetric model, the neutrino lifetime is predicted to be 1.5×10^{17} years at minimum. We made a feasibility study of the neutrino decay search in the CIB energy spectrum measurement. Neutrino decay signal rate is expected to be 50 sec^{-1} with a telescope of 20 cm diameter and a viewing angle of 0.1 degrees for neutrino lifetime of 1.5×10^{17} years. The CIB values measured by COBE and AKARI give a signal-to-noise ratio of 2×10^{-5} , when the energy resolution of the detector is better than 2%. We can expect to observe the neutrino decay signal with 5σ significance by 6-hours measurement with this telescope. We published these results in JPSJ on January 2012 with a title of “Search for Radiative Decays of Cosmic Background Neutrino using Cosmic Infrared Background Energy Spectrum” [1].

2. Superconducting Tunnel Junction (STJ) Detector and Experimental Apparatus

We have worked on the experimental design and the research and development of the detector for the neutrino decay search experiment. In this experiment, 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. A heavier neutrino decays into a lighter neutrino with an infrared photon. To detect this signal, we need measure the energy spectrum of the cosmic infrared photon background with energy resolution better than 2%. We adopted a Superconducting Tunnel Junction (STJ) detector as such a detector.

The STJ has a sandwich structure of superconductor and insulator as shown in Fig.4. By measuring the tunnel current of electrons (quasi-particles) excited by an incident particle, we can measure the energy of the incident particle. The number of excited quasi-particles is inversely proportional to the energy gap Δ of the superconductor. The energy gap Δ of superconductors are shown in Table 1. As the energy gaps of the superconductors are much smaller than those of semiconductors, the detection of far-infrared photon with STJ has much better efficiency than the present far-infrared detector.

We have worked on the research and development of STJ photon detector to detect the far-infrared photon since 2006. We have studied the characteristics of Nb/Al-STJ detector as shown in Fig.5 and Hf-STJ detector.

Hf-STJ has better energy resolution than Nb/Al-STJ because it has 10 times more excited quasi-particles, but need much lower temperature to operate as a STJ than Nb/Al-STJ. We are developing both Nb/Al-STJ and Hf-STJ. We succeeded in measuring X-ray photon energy and

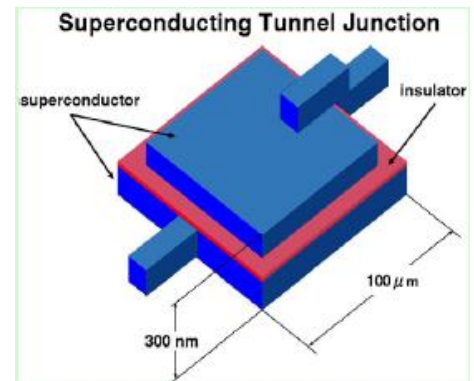


Fig.4. structure of Superconducting Tunnel Junction detector.

Material	$T_c(K)$	$\Delta(\text{meV})$
Niobium	9.20	1.550
Aluminum	1.14	0.172
Hafnium	0.13	0.021

Table 1. Critical temperature T_c and energy gap Δ of superconductor .

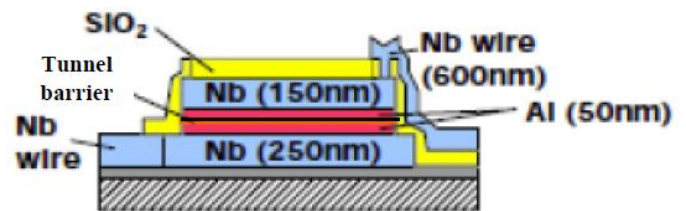


Fig.5. structure of Nb/Al-STJ detector.

detecting visible photons with our Nb/Al-STJ photon detector. We also succeeded in producing Hf-STJ photon detectors which work as STJ for the first time in the world. We reported these results titled with “Development of Superconducting Tunnel Junction Photon Detector using Hafnium” in the international conference on Technology and Instrumentation in Particle Physics 2011 (TIPP 2011), Chicago, in June 2011[2].

Our purpose is to measure CIB energy spectrum with a telescope of 20 cm diameter and a viewing angle of 0.1 degree installed on a satellite with more than 6-hour running time to observe the decay of cosmic background neutrino with lifetime of 1.5×10^{17} years at 5σ significance. For this purpose, we plan to do a preparatory rocket experiment in 2016. In this rocket experiment, we will use a multi-pixel Nb/Al-STJ detector with a grating and three mirrors installed in a 1.7K cryostat as shown in Fig.6. We will take data for 5 minutes at 200km height in this experiment and can improve the neutrino lifetime limit by one order. To do this rocket experiment in 2016, we have to complete the R&D of the Nb/Al-STJ photon detector, the readout electronics, the optical elements and the cryostat, and start production of whole detector in 2014. We are collaborating with a JAXA cosmic infrared background team headed by Dr. Shuji Matsuura and will propose this rocket experiment to JAXA as soon as completing the detector R&D.

Then in the next stage we will install this detector in a satellite, and perform a satellite experiment for the cosmic background neutrino decay search around 2020. As a detector installed in the satellite, we have two designs: the base design is Nb/Al-STJ with a grating and the alternative is a Hf-STJ micro-calorimeter.

The collaboration members of this project are from University of Tsukuba, Okayama University, RIKEN, Fukui University, Kinki University, JAXA/ISAS, KEK, SNU and Fermilab. The research and development of the following subjects are being and will be done by this collaboration: Nb/Al-STJ, Far-Infrared light source, 1.7K Cryostat installed in a rocket, Optical system such as a grating, Hf-STJ, and Electronics such as preamplifiers working at very low temperature around 1.7K

3. Progress in JFY2012

In JFY2012, we have worked on the development of Superconducting Tunnel Junction (STJ) detector for the neutrino decay search experiment and obtained the following results:

About Hf-STJ detector, we improved the dilution refrigerator and enabled it to operate at

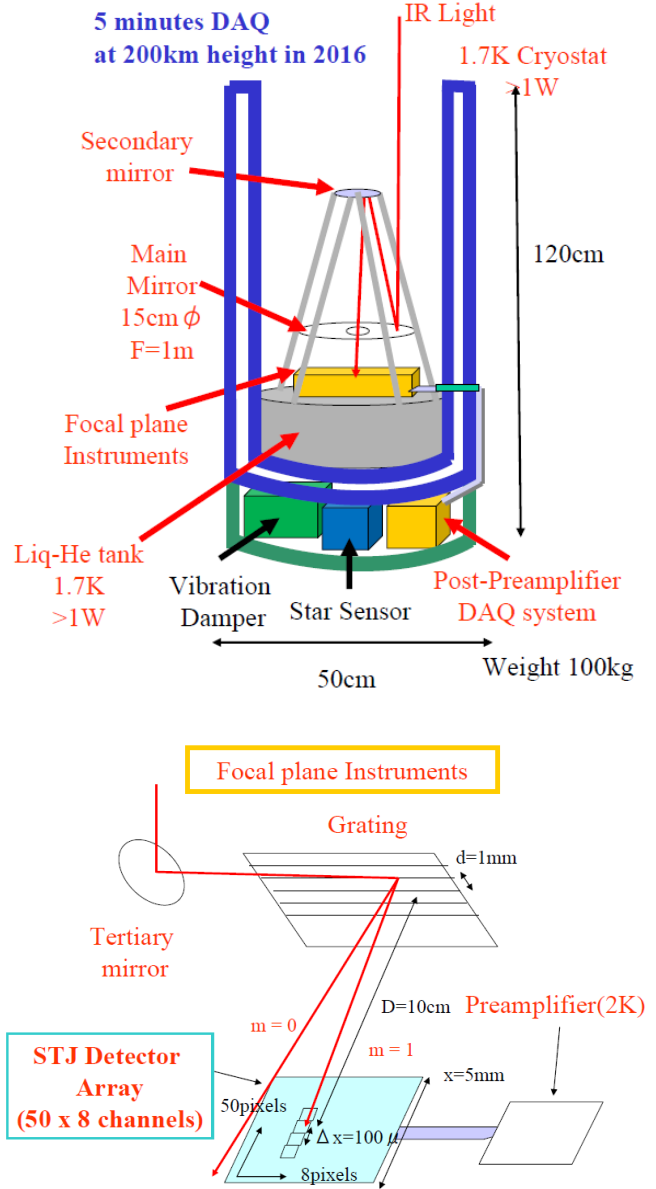


Fig.6. Apparatus of the rocket experiment for neutrino decay search

28mK. Using this dilution refrigerator, we confirmed that seven Hf-STJ chips showed I-V characteristics of SIS structure with operation around 80mK. We could also decrease the leakage current and the noise down to 30% by decreasing the Hf-STJ size from $200\mu\text{m} \times 200\mu\text{m}$ to $100\mu\text{m} \times 100\mu\text{m}$.

We observed that the leakage current of Nb/Al-STJ (chip size of $100\mu\text{m} \times 100\mu\text{m}$) decreases rapidly as the temperature decreases. The leakage current measured at $V = 0.5\text{mV}$ changed from $10\mu\text{A}$ to 10nA as the temperature decreased from 1.8 K to 0.9 K as shown in Fig.7.

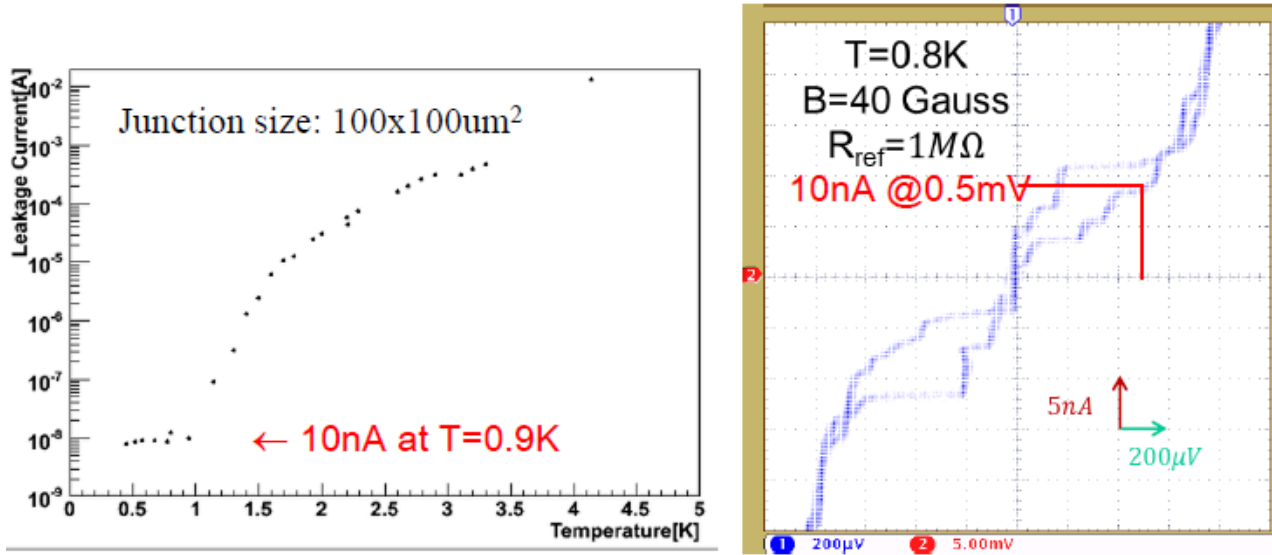


Fig.7. Leakage current of Nb/Al-STJ as a function of temperature and I-V curve at $T = 0.8\text{K}$

We observed the Nb/Al-STJ response to infrared laser lights of wavelength $1.31\mu\text{m}$. The Nb/Al-STJ was operated at $T = 1.8\text{ K}$ with a depressurized He refrigerator. When we injected infrared laser light in 10 pulses during 200 ns period, we observed the Nb/Al-STJ signal has a time spread of $1\mu\text{s}$ as expected as shown in Fig.8.

Far-infrared light source with a wavelength of $53\mu\text{m}$ and a pulse width of $30\mu\text{s}$ was successfully made using a CO_2 laser and CD_3OH gas at Fukui University. As a next target, $1\mu\text{s}$ width beam is being developed.

We developed preamplifiers which work at low temperature around 2K . We started making a test setup of HEMT preamplifier with Nb/Al-STJ at Fermilab. In December 2012 and March 2013, Japan-US collaboration team worked on the setup construction as shown in Fig.9 and measured I-V curve of Nb/Al-STJ at 1.5K with the setup at Fermilab.

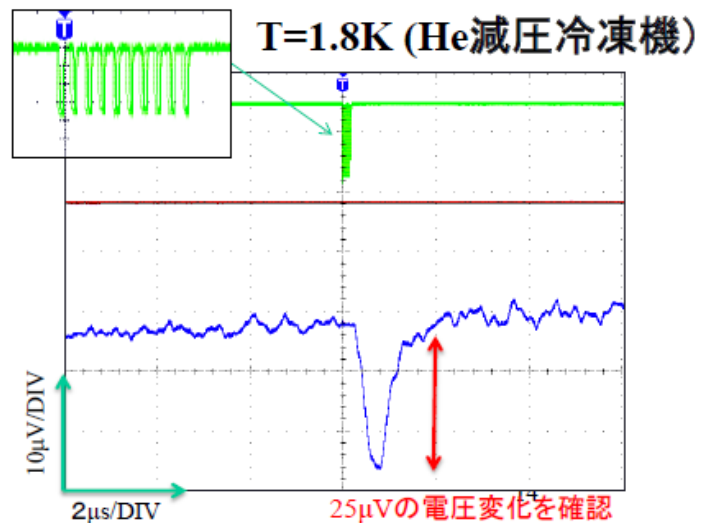


Fig.8. Response of Nb/Al-STJ to infrared laser light of wavelength $1.31\mu\text{m}$ at $T= 1.8\text{K}$.

We also made a STJ-SOI combined test sample where Nb/Al-STJ's were processed on the SOI board. PMOSFET's and NMOSFET's were made on this SOI board. We confirmed that the

SOI FET's in this sample worked normally at 1.8K.

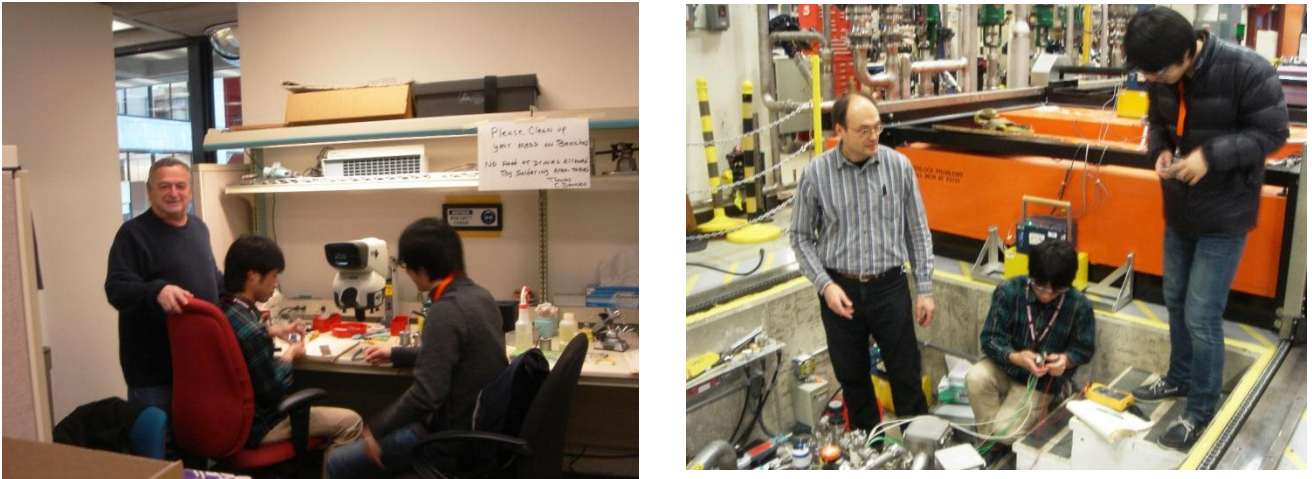


Fig.8. Two Japanese graduate students and Fermilab collaborators are working on the test setup of Nb/Al-STJ and preamplifier at very low temperature at Fermilab.

References

- [1] S. H. Kim, K. Takemasa, Y. Takeuchi and S. Matsuura “Search for radiative decays of cosmic background neutrino using cosmic infrared background energy spectrum.”, J. Phys. Soc. Jpn., 81 024101 (2012).
- [2] S.H. Kim et al. “Development of Superconducting Tunnel Junction Photon Detector using Hafnium” TIPP2011 Physics Procedia 37 (2012) 667-674.