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Development of Nb/Al superconducting tunnel junction detector of a single infrared photon to search for radiative decay of the cosmic background neutrinos

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Takuya Okudaira (University of Tsukuba)
For Neutrino Decay Collaboration*

Radiative Decay of Cosmic Background Neutrino

The difference between the mass-squares of different- generation neutrinos has been measured by various neutrino oscillation experiments, but the neutrino mass has not been measured yet. Detection of neutrino radiative decay enables us to determine the neutrino mass itself.

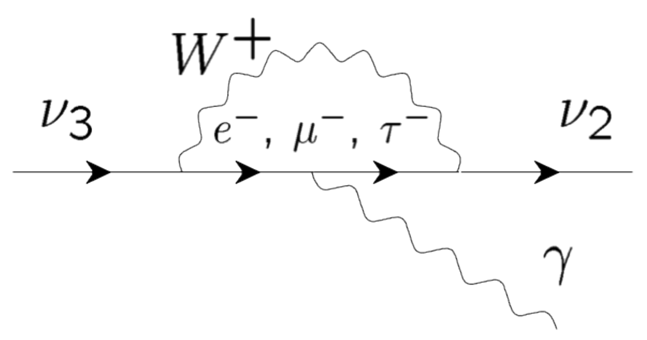

Fig1 $\nu_3 \to \nu_2 + \gamma$ Feynman diagram

We plan a rocket experiment to search for photons from the radiative decay of the cosmic background neutrinos. If we assume the mass of the heaviest neutrino to be about 50 meV, the expected photon energy would be 25 meV at the heaviest neutrino rest frame, which corresponds to 50 um in wavelength in far infrared region.

The requirement to detect the neutrino radaitive decay is detecting a single photon of 25meV. The candidate device to detect the far infrared photons is Nb/Al based superconducting tunnel junction(Nb/Al-STJ) detector.

If you wish to know more detail, please refer to P-46

Nb/Al Superconducting Tunnel Junction Detector (Nb/Al-STJ)

STJ(Superconducting Tunneling Junction) is a superconducting photoelectric detector which consists of two superconducting layer and an very thin insulating oxide layer as shown in Figs.2 and 3.

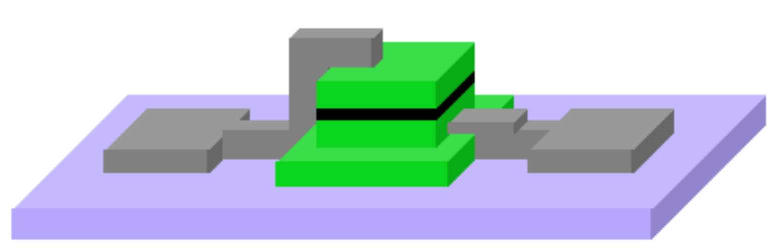

Fig.2 The schematics of STJ. The green, black and, gray area indicate superconducting film, oxide film and wire, respectively

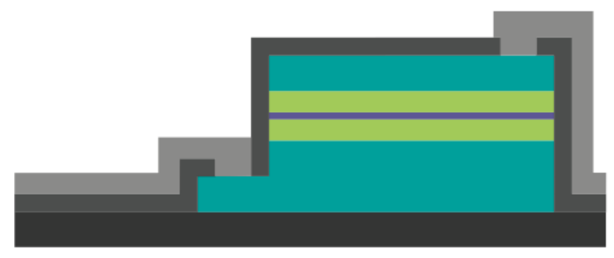

Fig.3 Cross-sectional view of Nb/Al-STJ. The green, yellow, black area indicate Nb, Al and Al_2O_3, respectively.

When photons break up cooper pairs in STJ. the electrons from the broken cooper pairs go across the insulating layer, and cause a current. As energy required to break up cooper pairs, called band gap, is as low as ~meV, the energy resolution of STJ can be much better than semiconductor detector.

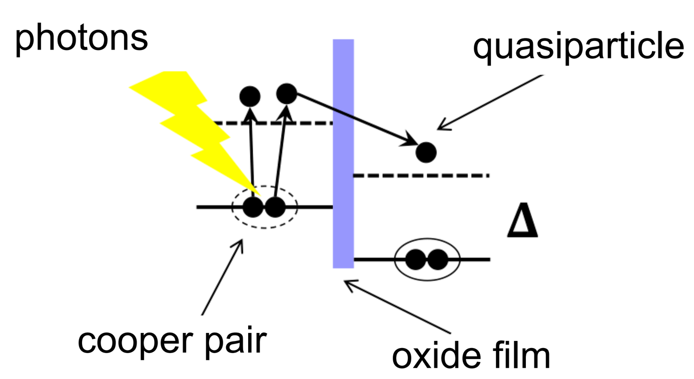

Fig.4 Operation principle of STJ. First, photons break up cooper pairs, then the quasiparticles across the oxide film and are collected as a current.

	Si	Nb	Al	Hf
Tc[K]		9.23	1.20	0.165
Δ[meV]	1100	1.550	0.172	0.020
$\hbar\omega_D$ (meV)	55	23.7	34	21.7
Hc[G]		1980	105	13

TABLE.1 A list of energy gap. Energy gap of Silicon is about 1eV, in contrast, Energy gap of superconductor is very small(~meV).

A charge caused by photon is proportional to the energy of photon, and the charge is given by equation (1).

$$q = G_{Al}\frac{\varepsilon_p}{1.7\Delta} \quad (1)$$

G_{Al} trapping gain of Al
ε_p Energy of photon
Δ Gap energy of superconducter

A Josephson current flows across the oxide film when STJ is in superconducting state, and that causes noise. Therefore the Josephson current is suppressed by applying a magnetic field in the STJ operation.
As a leak current causes noise, and so the leak current must be as low as possible.

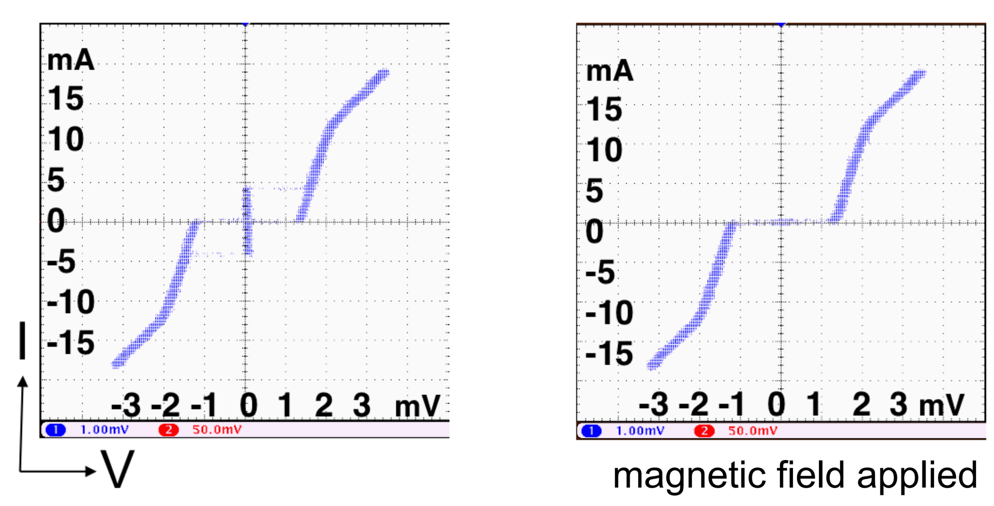

Fig.5 I-V curve of Nb/Al-STJ.The Josephson current is disappeared by magnetic field.

Experiment and Results

The Nb/Al-STJ was operated at 1.9K in a depressurized ^{4}He cryostat, and the response to visible and infrared light was measured.

We made the system for measuring the STJ characteristics with a superconducting coil and a fiber system for exactly irradiating light onto the STJ in the ^{4}He cryostat.
Size of STJ are 100um×100um and 4 um^2. We used a pulsed photon sources, which are blue(E=2.6eV, λ=465nm) and infrared (E=0.95eV, λ=1310nm) laser.
The frequency of the pulse is 50MHz and the duration of single pulse is 50ps.

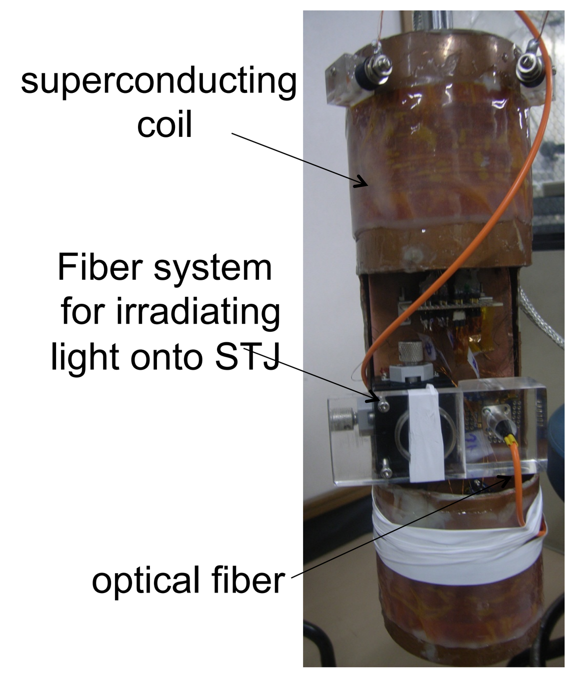

Fig6. A part of system of measuring STJ characteristics

Figure 7 shows the output signal of STJ when the infrared light is irradiated. According to this, STJ response time is about 0.2us,and width of signal is about 2us.

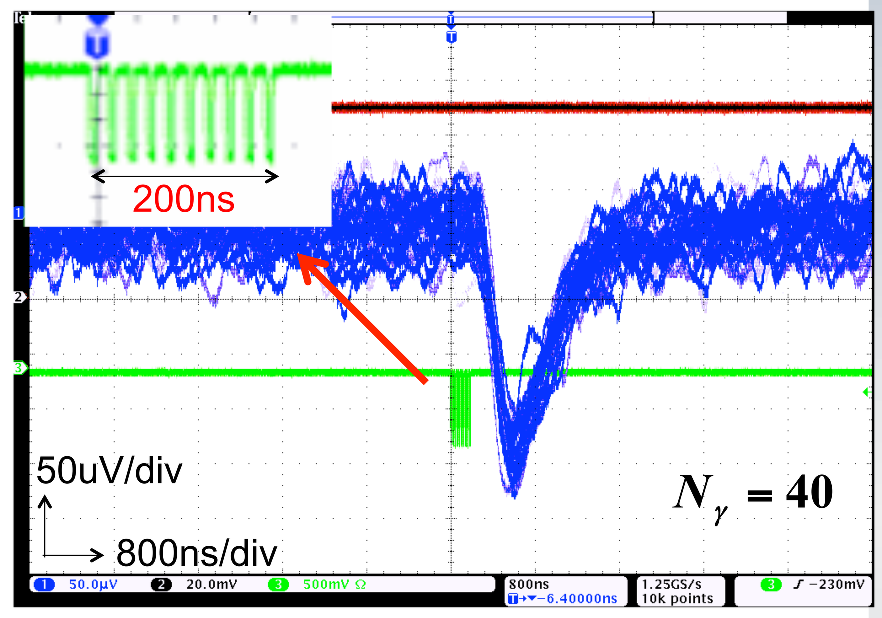

Fig.7 The output voltage of 100um×100um STJ with 10th infrared light pulse

We measured the pulse charge distribution and obtained the mean (M) and r.m.s (σ) for two kinds of blue light input onto 4 um^2 STJ as shown in Figs.8 and 9.
Taking into account the pedestal spread σ_p, we calculated the number of photons N_γ according to equation (2).
Figure 8 shows the distribution irradiated 5 pulses light, and a mean output charge is 1.16fC.We estimated that number of detected photon is 2.7±0.1. Similarly Figure 9 shows 15 pulses one, and the mean charge and the number of photons are 2.30fC and 5.1. respectively.

$$N_\gamma = \frac{M^2}{\sigma^2 - \sigma_p^2} \quad (2)$$

M mean
σ r.m.s
σ_p pedestal r.m.s

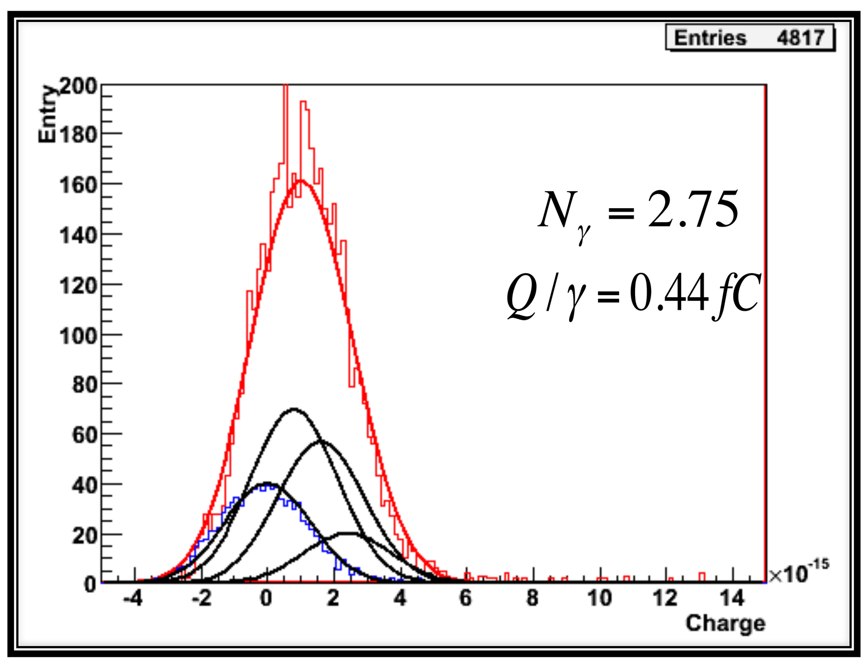

Fig.8 The pulse height distribution with 5 pulses light. Blue histogram indicates pedestal. Red histogram, that indicated signal, is fitted by 4 Gaussian of 0, 1, 2 and 3 photon peaks.

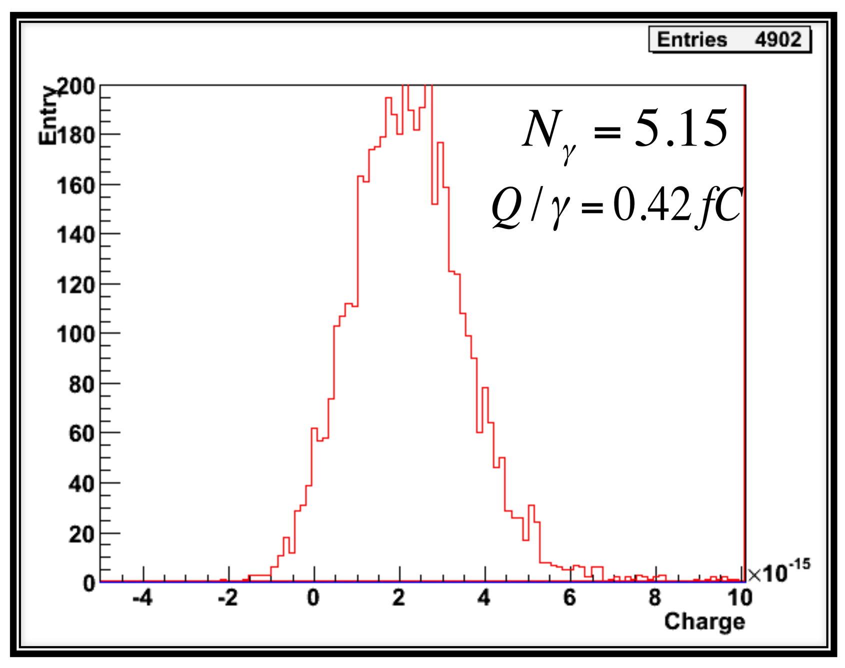

Fig.9 The pulse height distribution with 15 pulses light

The distributions should be Poisson distribution. In Fig.8, black curves are components of four Gaussians of 0, 1, 2 and 3 photon peaks. The sum of these 4 Gaussians (red curve) are fitted to the pulse charge distribution (red histogram) in Fig.8, and the peak heights of 0, 1 , 2 and 3 photons corresponds to the values expected from Poisson distribution of the mean value 1.6, The separation between single photon peak and the pedestal is about 1 σ. As we aim at 5 σ separation of single photon peak, we need to improve S/N further. The pulse charge per a single photon is estimated 0.44fC, and 0.42fC for 5 pulses input and 15 pulses input, respectively, and both are consistent with each other. According to this result and equation (1), the trapping gain G_{Al} is estimated 2.75.

Summary

- We detected a single photon peak (465nm) by a separation of 1σ now. Our development to decrease the noise is underway to detect infrared single photon.
- To detect a single photon from neutrino decay, we have to develop a low noise preamplifier which operates at 1K such as STJ−SOI.

If you wish to know detail about STJ-SOI, please refer to P-48

Neutrino Decay Collaboration
Shin-Hong Kim, Yuji Takeuchi, Kazuki Nagata, Kota Kasahara, Takuya Okudaira (University of Tsukuba) , Hirokazu Ikeda, Shuji Matsuura, Takehiko Wada (JAXA/ISAS) , Hirokazu Ishino, Atsuko Kibayashi (Okayama University) ,Satoshi Mima (RIKEN), Takuo Yoshida, Shota Kobayashi, Keisuke Origasa (Fukui University) ,Yukihiro Kato (Kinki University), Masashi Hazumi, Yasuo Arai (KEK), Erik Ramberg, Jonghee Yoo, Mark Kozlovsky, Paul Rubinov, Dmitri Sergatskov (Fermilab), Soo-Bong Kim (Seoul National University)