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

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Abstract: We present the status of development of the Superconducting Tunnel Junction (STJ) detector for the COsmic BAckground Neutrino Decay search (COBAND) experiment. The signal of the cosmic background neutrino decay is identified as a sharp cutoff at high energy end in a far-infrared region ranging from 15meV to 30meV in the energy spectrum of the photons from the space. The COBAND experiment will be done as rocket and satellite experiments in order to detect the far-infrared photons from the space. For the photon detector of the COBAND experiment, we are developing the STJ detectors. We will use a combination of the diffraction grating and the array of Nb/Al-STJ pixels with cryogenic amplifier for the rocket experiment, and use Hf-STJ without a grating for the future satellite experiment. The present status of the detector R&D and the experimental design for the COBAND experiment is reported.

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1. Introduction

We have developed the Superconducting Tunnel Junction (STJ) detector for the cosmic background neutrino (CνB) decay search experiment. The motivation of this experiment is to determine neutrino masses and to observe the cosmic background neutrino. We reported the proposal of rocket and satellite experiments of the cosmic background neutrino decay search which is called COBAND experiment [1]. We plan to perform a rocket experiment in 2020 in the earliest, aiming at improving the current experimental lower limit 3×10^{12} years of the neutrino lifetime up to 10^{14} years by a factor of 100 in a 5-minute measurement. In the normal hierarchy case where the ν_3 is the heaviest neutrino, ν_3 decays into ν_2 or ν_1 as $\nu_3 \rightarrow \nu_2$ (or ν_1) + γ. Neutrino lifetime is predicted to be 10^{17} years by left-right symmetric model [2], and 10^{12}-10^{14} years by a MSSM extension model with vector-like lepton generation [3]. 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. In the ν_3 rest frame, the decay photon energy E_0 is related to the neutrino masses by $E_0 = (m_3^2 - m_2^2)/2m_3 \equiv \Delta m_{32}^2/2m_3$, where m_3 and m_2 are the masses of ν_3 and ν_2, respectively. Since Δm_{32}^2 was measured to be $(2.45 \pm 0.05) \times 10^{-3}$ eV^2 by the oscillation experiments [4], we can determine m_3 by measuring this E_0. The upper limit of m_3 is given as $\Sigma m_i < 0.23$eV from recent measurements of cosmic microwave background (CMB) in combination with baryon acoustic oscillation (BAO) measurements, and consequently, m_3 is within the range of 50meV $< m_3 <$ 87meV on the assumption of the normal neutrino mass hierarchy. When we consider m_3 to be 50meV, E_0 is 25meV in the far-infrared region. The photon energy spectrum expected from the cosmic background neutrino (CνB) decay with the lifetime of 10^{14} years is shown in Fig.1. The energy cutoff at high energy end is the photon energy from the decay of a neutrino at rest. As the cosmic background neutrino is going far away from us by the universe expansion, it causes the low energy tail due to the red shift effect. The backgrounds against the

Fig.1. Photon energy spectra shown as surface brightness from the cosmic background neutrino (CνB) decay with a neutrino lifetime of 1014 years. Backgrounds of the zodiacal emission and CIB measured with COBE and AKARI are also shown.

CνB decay are overwhelming zodiacal emission and cosmic infrared background (CIB). By measuring the energy spectrum of the zodiacal emission with the CνB decay, we can see the CνB decay signal as a high energy cutoff. So we require the following characteristics for the detector: to measure continuously photon energy around 25meV with energy resolution better than 2% to identify the sharp energy cutoff, and to work at rocket or satellite experiment because a far-infrared photon from the space cannot reach us through air. As a detector of far-infrared photons with high energy resolution, we are developing the following Superconducting Tunnel Junction (STJ) photon detectors: Nb/Al-STJ with a diffraction grating and Hf-STJ without a grating. This paper reports on the development of Nb/Al-STJ and Hf-STJ. We plan to perform a rocket experiment with a STJ based detector in 2021 in the earliest [1] with 8
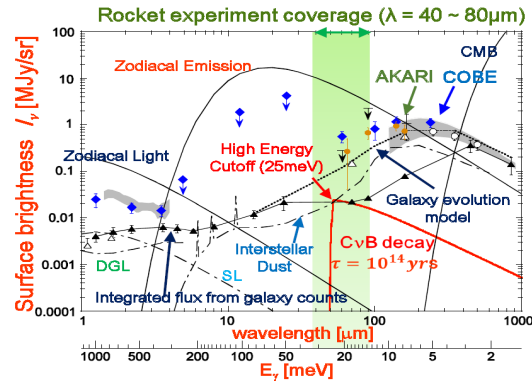
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spectrometers each of which consists of 50-pixels of Nb/Al-STJ and a diffraction grating, to measure the photon energy in the energy range between 15meV and 30meV (λ= 40~80μm), and to measure the direction dependence. The telescope diameter is 15 cm and the field of view is 0.006°×0.05°. The expected rate from zodiacal background is 15kHz per 50-pixel-spectrometer and 300Hz per pixel. We will also search for the neutrino decay for the neutrino lifetime of 2 ×10^{17}year which is predicted by left-right symmetric model in a 100-days satellite based measurement with Hf-STJ after 2025.

2 Development of Superconducting Tunnel Junction Detector

2.1 Development of Nb/Al-STJ with SOI cryogenic preamplifier

We are developing Nb/Al-STJ single photon detectors to cope with 2% energy resolution at E_γ =25meV with a diffraction grating for the rocket experiment. As a basic properties of STJ detector, we measure the current-voltage (I-V) curve . From this I-V curve, we know the leakage current in the flat region ($|V| < 2\Delta/e$) and the energy gap Δ from the width of the flat region. Critical current is obtained from the height of Josephson current. We operate the STJ detector in the flat region after suppressing the Josephson current by applying a magnetic field parallel to the insulator layer. The fluctuation of the leakage current in this region causes a noise against the signal. We have a requirement for the leakage current of Nb/Al-STJ to be less than 0.1nA to detect a single far-infrared photon for the COBAND experiment. Nb/Al-STJ made at AIST CRAVITY system satisfied this requirement [1]. For seven samples of 20mm-square STJ's, the leakage current was 39±13pA at 0.3mV and 400mK. The STJ has a sandwich structure of Nb(200nm)/Al(70nm)/AlOx/Al(70nm)/Nb(100nm), of which Δ was measured to be 0.57meV. Quasi-particles near the barrier can mediate Cooper pairs, resulting in true signal gain. This gain is called a trapping gain G_{Al} which is about 10 for Al. The number of quasi-particles N_{qp} made in Nb/Al-STJ is given by $N_{qp} = G_{Al} E_\gamma /(1.7\Delta)$. So for 25meV photon, we have 250 quasi-particles. The STJ response signal to visible laser light pulse showed the response speed of a few μsec which is fast enough for the COBAND experiment. The COABND experiment has a requirement for noise less than 30e after 50μsec integration. To reduce the electronics noise down to 30e level, we use a cryogenic amplifier which is placed close to Nb/Al-STJ. We have developed the cryogenic amplifier which works at 0.3K using SOI (Silicon-On-Insulator) technique [5]. SOI-MOSFET is created on an insulator and separated from each other by the insulator and has very thin depletion layer around 50nm. Then we did the amplification test of the STJ signal with this SOI cryogenic amplifier.   Both the 20μ-square Nb/Al-STJ and the SOI amplifier were placed on the stage of ^{3}He sorption refrigerator and operated at 350mK. We illuminated visible laser pulse light of 465nm wavelength on the STJ. The STJ signal was amplified by a gain factor of 70 with the SOI cryogenic amplifier at 350mK. We improved the signal-to-noise ratio significantly with this amplifier. Next we made the SOI cryogenic charge amplifiers with gains of 0.3mV/fC, 3mV/fC, 15mV/fC and 1.2V/fC. About the gain of 1.2V/fC,
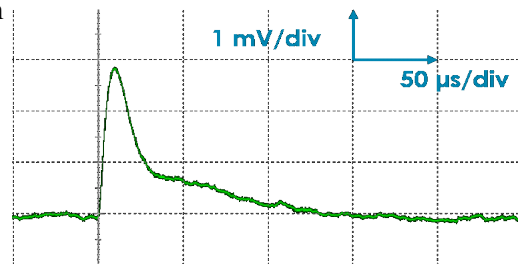

Fig.3. SOI cryogenic charge amplifier output. STJ signal for visible laser pulse light was amplified by the cryogenic charge amplifier with a gain of 0.3mV/fC.

we designed the charge amplifier with voltage amplification part after charge amplification part. This charge amplifier is expected to satisfy our requirement for noise less than 30e after 50μsec integration. We tested the charge amplifier with a gain of 0.3mV/fC to amplify the STJ signal and found it working as well as designed as shown in Fig.2. In this test, both the 20μ-square Nb/Al-STJ and the SOI charge amplifier were placed on the stage of ^{3}He sorption refrigerator and operated at 350mK.The test of the other charge amplifiers is undeway.

2.2 Development of Hf-STJ

As Hf has much smaller energy gap of 21μeV than Nb (Δ=1.55meV) and Al (Δ=0.172meV), Hf-STJ can work as a single far-infrared photon detector with 2% energy resolution. We have developed Hf-STJ and observed the STJ signal response for visible laser pulse light from Hf/Al-STJ with a structure of Hf(250nm)/Al(10nm)/HfOx(1.5nm)/Hf(400nm) for the first time as reported in [6]. Our present target is to decrease the leakage current of Hf-STJ. The COBAND satellite experiment require the Hf-STJ leakage current less than 10pA at 50mK. By decreasing the size of the STJ junction of Hf(250nm)/HfOx(1.5nm)/Hf(400nm) from 200μ-square to 10μ-square, we could reduce the leakage current to 200nA at 20μV and 150mK by a factor of 570. We plan to make small-size Hf/Al-STJ's to reduce the leakage current and to measure the leakage current of all types of Hf-STJ samples at lower temperature than 50mK.

3. Summary

We are developing STJ-based far-infrared photon detector to search for the cosmic background neutrino decay, COBAND experiment. Nb/Al-STJ was proved to satisfy the leakage current requirement for COBAND experiment. The visible light response signal of Nb/Al-STJ was amplified by a SOI-technology-based cryogenic amplifier placed at 350mK successfully for both types of voltage amplification and charge amplification. The leakage current of Hf-STJ was reduced by decreasing the junction size and now planned to be tested at lower temperature than 50mK.

Acknowledgement

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