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Solar axion search with TES microcalorimeters and an iron-57 absorber

Tomonori Ikeda,[a,*] **Yuta Yagi,**[b,c] **Tasuku Hayashi,**[d] **Keita Tanaka,**[b,c] **Ryo Ota,**[b,c] **Mikiko Saito,**[e] **Takayuki Homma,**[e,f] **Nao Yoshida,**[f] **Fuminori Hirayama,**[g] **Akira Sao,**[g] **Takahiro Kikuchi,**[g] **Satoshi Kohjiro,**[g] **Yuki Nakashima,**[g] **Noriko Y. Yamasaki**[b,c,] **and Kazuhisa Mitsuda**[a,c,i]

[a] *International Center for Quantum-field Measurement Systems for Studies of the Universe and Particles (QUP), KEK,*
1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan

[b] *Department of Physics, School of Science, The University of Tokyo,*
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan

[c] *Department of Space Astronomy and Astrophysics, Institute of Space and Astronautical Science (ISAS), Japan Aerospace Exploration Agency (JAXA),*
3-1-1 Yoshinodai, Chuo-ku, Sagamihara-shi, Kanagawa 252-5210, Japan

[d] *Department of Physics, School of Science, Rikkyo University, 3-3-4-1 Nishi-ikebukuro, Toyoshima, Tokyo, Japan, 171-8501*

[e] *Research Organization for Nano and Life Innovation, Waseda University,*
Shinjuku-ku, Tokyo 162-0041, Japan

[f] *Department of Applied Chemistry, School of Advanced Science and Engineering, Waseda University,*
Okubo 3-4-1, Shinjuku-ku, Tokyo 169-8555, Japan

[g] *National Institute of Advanced Industrial Science and Technology (AIST),*
1-1-1 Umezono, Tsukuba, Ibaraki 305-8568, Japan

[h] *Department of Physics, School of Science, Kitasato University,*
1-15-1 Kitasato, Minami-ku, Sagamihara-shi, Kanagawa 252-0373, Japan

[i] *Advanced Technology Center, National Astro- nomical Observatory of Japan,*
Mitaka-shi, Tokyo 181-8588, Japan,

E-mail: ikedat@post.kek.jp

The axion offers a compelling solution for the strong CP problem and stands as one of the promising candidates for dark matter. One of the primary methods for axion detection involves probing gamma-ray emissions resulting from nuclear transitions mediated by axion-nucleon couplings. Monochromatic 14.4 keV axions could be produced by de-excitation of the thermally excited ^{57}Fe isotopes in the Sun and detected as 14.4 keV gamma-rays via the inverted production process on Earth. We developed a Transition-Edge-Sensor (TES) microcalorimeter, featuring high energy resolution with an iron absorber. In this report, we present the scientific objectives, experimental setup, and recent progress, including the development of a microwave multiplexer based on microstrip SQUIDs for enhanced scalability.

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*Speaker

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1. Introduction

The discovery of the Higgs boson completed the Standard Model of particle physics. However, several unresolved issues remain. One such issue is the strong CP problem, wherein the theory of quantum chromodynamics requires an extremely fine-tuned parameter to account for the experimentally observed electric dipole moment of the neutron [1, 2]. To solve this issue, Peccei an Quinn proposed a global $U(1)$ symmetry (PQ symmetry), whose breaking consequently give rise to a new psudoscalar boson called axion [3–5]. Therefore, the discovery of axions is one of the most important topics in the field of astrophysics and particle physics.

Early axion searches ruled out "standard axions," where the PQ symmetry breaking scale was assumed to be related to the electroweak scale. In contrast, "invisible axions" arise from a higher PQ symmetry breaking scale, making them weakly interacting and therefore harder to detect. Such axions can be created through the axion-photon and axion-electron coupling by the Primakoff effect and Compton interaction in the Sun, and the solar axion flux on Earth is calculated in Ref. [6]. Moriyama also proposed the novel production mechanism relating to the axion-nucleon coupling of the hadronic axion [7]. In this mechanism, ^{57}Fe nuclei are thermally excited in the Sun and can decay by emitting monochromatic axions corresponding to 14.4 keV. As inverse reaction, such created axions can resonantly excite ^{57}Fe nuclei thanks to the doppler broadening of the axion energy due to the thermal motion of the ^{57}Fe nuclei in the Sun. Eventually, x-rays or Auger electrons are emitted, and the total energy corresponds to 14.4 keV. Several experiments based on this detection principle have been conducted using Si detectors and gas detectors [8, 9].

We have initiated a search for monochromatic 14.4 keV axions using a superconducting Transition-Edge Sensor (TES), a highly sensitive energy-resolving detector. In this paper, we detail the detector design and discuss the future experiment.

2. TES design for the solar axion search

The TES operates by measuring heat through the increase in resistance of a superconducting film. The superconducting phase transition is extremely sharp, and the heat sensitivity is logarithmic, characterized by $\alpha = d \log R / d \log T$, where R and T represent the resistance and temperature, respectively. As a result, the TES offers a sensitivity that is two orders of magnitude higher than that of semiconductor thermistor thermometers. This enhanced sensitivity provides exceptional energy resolution, expressed as $\Delta E \propto \sqrt{k_B T^2 C / \alpha}$, where C is the thermal capacitance. The energy resolution of 2.8 ± 0.3 eV at 5.9 keV was reported using a Ti/Au bilayer TES [10]. Furthermore, in axion search experiments, the TES microcalorimeter offers an additional advantage by improving detection efficiency, as it is sensitive to all forms of energy deposition, including Auger electrons and low-energy x-rays.

We developed a TES microcalorimeter array with ^{57}Fe absorbers functioning as axion converters. Since the energy resolution of the TES microcalorimeter can be degraded by the magnetization effect of iron [11], the iron absorber was placed adjacent to the TES with a 30 μm gap, connected by a gold thermal transfer strap. The gold thermal transfer strap and the ^{57}Fe absorber were produced using an electroplating method to enhance thermal conductivity and reduce material costs. Detailed descriptions of the fabrication process and simulations can be found in Refs. [12–14].

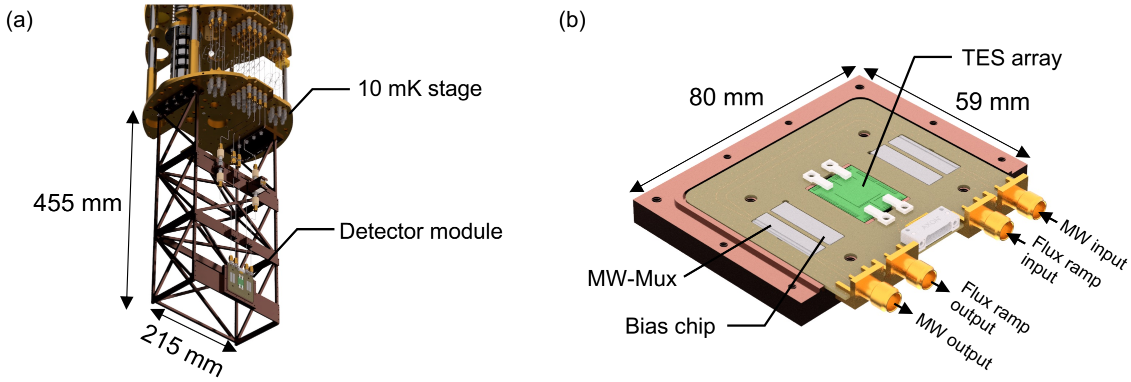

Figure 1: (a) The 3D model of the instrumentation within the dilution refrigerator. (b) The 3D model of the detector module. The 64-pixel TES chip and MW-Mux chips are mounted on a printed circuit board.

3. Future work

We are planning to install a 64-pixel TES chip into a dilution refrigerator in the Fuji laboratory of High Energy Accelerator Research Organization (KEK). The 3D model of the instrumentation is shown in Fig. 1(a) and (b). The detector module is mounted on the 10 mK stage. A microwave superconducting quantum interference device (SQUID) multiplexer, referred to as MW-Mux,is employed for TES readout[15, 16]. Since each MW-Mux chip can process 40 TES channels, we will use two MW-Mux chips to read out the 64-pixel TES array. We will initially operate with a single detector module, and in the future, we plan to scale up to 20 modules, enabling operation with world-leading sensitivity.

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