Snowmass2021 - Letter of Interest

Detection of Superlight Dark Matter Using Graphene-Based Josephson Junction Photon Counter

CF Topical Groups:

■ (CF1) Dark matter: particle-like

IF Topical Groups:

■ (IF2) Photon detectors

TF Topical Groups:

■ (TF09) Astro-particle physics & cosmology

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Abstract: This Letter of Interest discusses the graphene-based Josepthson junction (GJJ) microwave single photon detector whose energy resolution equivalent to $\sim$ 0.1 meV quanta was recently demonstrated in experiment. We discuss detection of superlight dark matter of $\sim$ 0.1 keV mass as an immediately feasible application, together with other potential applications.

Introduction: In this Letter of Interest, we discuss the graphene-based Josepthson junction (GJJ) microwave single photon detector [1] which can have energy resolution equivalent to ~ 0.1 meV quanta, which was recently demonstrated in the laboratory [2]. As a concrete example, we discuss the application of the GJJ device for detecting dark matter of ~ 0.1 keV mass (often called "superlight" dark matter), to which the dark matter direct detection experiments with the other existing technologies have never achieved sensitivity, whereas it is possible to immediately design and embark on "table-top" experiments for searching for such dark matter [3].

Superlight dark matter: As dark matter is now a compelling paradigm for new physics beyond the Standard Model, a host of theoretical/experimental effort has been devoted to understanding the weakly interacting massive particles (WIMPs), mainly motivated by the WIMP miracle. Nevertheless, no conclusive signal observations have been made thus far, directing the spotlight toward other dark matter mass scales.

Dark matter of keV-to-MeV mass draws growing attention as it is less constrained by the conventional dark matter direct detection experiments and can be thermally produced. Especially, keV-scale superlight dark matter is receiving particular attention, as its existence is a crucial criterion to determine the "coldness" of dark matter in the cosmological history. See also Refs. [4–14] for the theoretical/phenomenological motivations for such dark matter.

While MeV-range light dark matter direct searches are being actively performed, experimental detection of keV-range "superlight" dark matter is very challenging as the expected energy deposit is of order $\mathrm{meV}-\mathrm{eV}$, requiring a tiny energy threshold. A handful of detection schemes [15–26] have been proposed thus far, adopting one or two out of a transition-edge sensor (TES) [27], a microwave kinetic inductance device (MKID) [28], and a superconducting-nanowire single-photon detector (SNSPD) [29, 30]. However, their sensitivity has reached down to an energy deposit of $\mathcal{O}(10)$ meV or larger which would be sensitive to a few tens or hundreds of keV dark matter, and improving the sensitivity requires further R&D. In light of this situation, the GJJ device whose sensitivity to a ~ 0.1 meV energy deposit was demonstrated experimentally enables us to probe even sub-keV-scale (warm) dark matter rather soon.

Detection principle: A single unit of the device consists of a sheet of mono-layer graphene two sides of which are joined to superconducting material, forming a superconductor-normal metal-superconductor (SNS) Josephson junction (JJ) [1], as schematically shown in Figure 1(a). Basically, when injected energy raises the electron temperature in the graphene sheet, the calorimetric effect can switch the zero-voltage of JJ to resistive state with an appropriate level of bias current. Its electronic band structure shows linear energy-momentum dispersion relationship which resembles to that of massless Dirac fermions in two-dimension. Near the Dirac point where the density of state vanishes, electronic heat capacity also vanishes. Due to the extremely suppressed electronic heat capacity of mono-layer graphene and its constricted thermal conductance to its phonons, the device is highly sensitive to small energy deposition. Lee *et al*. [2] have demonstrated a microwave bolometer using GJJ with a noise equivalent power (NEP) corresponding to the thermodynamic limit. This NEP infers to the energy resolution of single 32-GHz (or equivalently, ~ 0.13 meV) microwave photon in a single-photon detection mode.

If dark matter of interest couples to electrons, it can scatter off π-bond free electrons in the graphene sheet, transferring some fraction of its incoming kinetic energy. The recoiling electron heats up and thermalizes with nearby electrons rapidly via electron-electron interactions within a few picoseconds [31, 32], and the JJ is triggered. The dark matter in the present universe floats around the earth with the typical velocity being $\sim 10^{-3}c$. Therefore, a dark-matter particle of order 1 keV carries a kinetic energy of order 1 meV [$\approx 1\ \mathrm{keV} \times (10^{-3})^2$] so that the GJJ device can possess the sensitivity to the signal induced even by sub-keV-range dark matter.

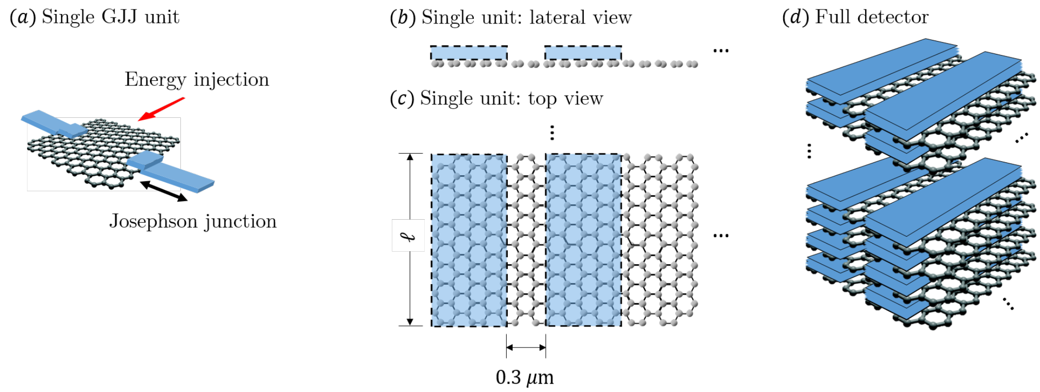

Figure 1: (*a*) A schematic description of detection principle. (*b*-*d*) A conceptual design for the proposed GJJ dark matter detector.

Detector proposal and an application to detection of superlight dark matter: We have performed a dark matter sensitivity study, using a detector whose conceptual design is displayed in Figure 1(b) through Figure 1(d). A single-detector unit is the assembly of a graphene sheet and a number of superconducting-material strips with a length of ℓ. The strips of $\ell = 3$ μm ($\ell = 30$ μm) corresponding to a threshold energy of 0.1 meV (1 meV) are laid on a graphene sheet by an interval of 0.3 μm, showing an array of superconducting-graphene-superconducting-graphene-superconducting-$\cdots$ (SGSGS$\cdots$). When the strip length increases, the area of graphene increases so the heat capacity also increases. Therefore, more energy is needed to trigger the GJJ device. Each sequence of SGS represents a single GJJ device. Figure 1(b) and Figure 1(c) display schematic layouts of the detector unit from one side and top, respectively. A full detector can be made of a stack of such detector units as schematically depicted in Figure 1(d). Since the GJJ bolometer is extremely sensitive to small changes in temperature, it is crucial to keep the system temperature low enough to suppress potential thermal backgrounds or noise. To this end, we place the detector in the cryogenic surroundings by cooling the detector system down to ~ 10 mK using dilution refrigerators.

Due to its outstanding sensitivity to energy changes as small as ~ 0.1 meV, we found that the proposed detector made of an array of GJJ devices is capable of probing dark matter candidates as light as ~ 0.1 keV via the scattering of dark matter off electrons [3]. We have shown that the sensitivity of detectors of 1 g graphene can reach $\sigma_{e\chi} \approx 10^{-37}\,\text{cm}^2$ and $\sigma_{e\chi} \approx 10^{-54}\,\text{cm}^2$ for the case where the interaction between dark matter and electrons is mediated respectively by the heavy and the light mediators, with one-year exposure.

Developing applications and outlook: We are now preparing for the first experiment using the sample GJJ devices which were fabricated for experimental demonstration of their performance, aiming to report the first result within one-year time scale. We also expect that the GJJ detector can be applied to various physics projects requiring sensitivity to sub-meV to eV scale energy deposits. Examples include detection of axion-like or dark gauge boson dark matter (denoted collectively by χ) by the absorption to detector material via a Compton-like process, $\chi + e^- \to \gamma + e^-$ and the observation of cosmic neutrino backgrounds.

Given great low-energy sensitivity of the GJJ device and its versatile application, we believe that it will be an important aspect of not only the cosmic-frontier program but the instrumentation-frontier program and the theory-frontier program in the next decade.

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