Graphene-Based Bolometer for Detecting keV-Range Superlight Dark Matter

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We propose a new dark matter detection strategy using the graphene-based Josephson junction microwave single photon detector, a “state-of-the-art” technology. It was recently demonstrated in the laboratory that the device is sensitive even to sub-meV energy deposited at π-bond electrons. Therefore, the associated detectors are, for the first time, capable of sensing (warm) dark matter of sub-keV mass scattering off electrons, more specifically of $m_\chi \gtrsim 0.1$ keV. We investigate detection prospects with a mg-scale prototypical detector and a g-scale detector, calculating the scattering event rate between dark matter and free electrons in the graphene with Pauli blocking factors included. We expect not only that the proposed detector serves as a complementary probe of superlight dark matter but that due to the extremely low energy threshold it can achieve higher experimental sensitivities than those of other proposed experiments featured by a low threshold, with the same target mass.

Introduction. - While dark matter is a crucial ingredient of the universe and its cosmological history (see also Ref. [1] for a recent review), the elusive nature of dark matter renders its detection via non-gravitational interactions rather challenging. A host of theoretical and experimental effort has been devoted to understanding the weakly interacting massive particles (WIMPs), mainly motivated by the so-called WIMP miracle. The null signal observations thus far sets stringent bounds on dark matter candidates of $m_\chi \sim 10$ GeV – 100 TeV [2]. On the other hand, the dark matter mass can range, in general, from $10^{-22}$ eV to $10^{98}$ eV [2], so the spotlight is gradually directed toward other mass scales.

Dark matter candidates lying in the keV-to-MeV mass range have received particular attention. Most of the conventional dark matter direct detection experiments are nearly insensitive to the associated signal due to the energy threshold to overcome, and thus relevant dark matter models are less constrained. Moreover, thermal production of such dark matter is still allowed. Many models containing dark matter candidates of this mass scale have been proposed and addressing various interesting phenomenology; for example, self-/strongly-interacting dark matter [3, 4], dark matter freeze-in production [5, 6], keV mirror-neutrino dark matter [7], MeV dark matter for $511$ keV $\gamma$-ray [8], MeV secluded dark matter [9, 10], and elastically decoupling dark matter [11].

MeV-range light dark matter searches are being actively performed by e.g., DAMIC [12], DarkSide [13], SENSEI [14], SuperCDMS [15], and XENON [16] Collaborations. However, experimental detection of keV-range “superlight” dark matter is very challenging as the expected energy deposit is of order meV – eV, requiring a tiny energy threshold. A handful of detection schemes have been proposed thus far [17–27], based on new technologies measuring small energy depositions in the detector. They assume that dark matter scatters off either electrons [17, 18, 20, 21, 23, 26, 27], nuclei [19, 21] or phonons [24, 25] in the detector material. Various detector materials were investigated, including superconducting devices [17, 18, 27], superfluid helium [19, 21], graphene [20, 26], carbon nanotube [22], three-dimensional Dirac materials [23] and polar materials [24, 25]. Although some of them may accommodate dark matter events invoking meV-range energy deposits, the actual detection is essentially limited by the bolometer technology. The aforementioned proposals adopt one or two out of a transition edge sensor (TES) [25], a microwave kinetic inductance device (MKID) [29], and a superconducting-nanowire single-photon detector (SNSPD) [30, 31]. The TES, MKID, and SNSPD technologies can be usually used for applications requiring sensitivities to frequencies ranging from X-ray to near-infrared [32], from X-ray to far-infrared [33], and from ultraviolet to mid-infrared [34], respectively, and they are well developed in the laboratory in their respective energy bands. To achieve the sensitivity to energy deposit as small as meV (i.e., below far-infrared), further R&D is therefore needed.

In light of this situation, we propose a new experimental strategy for detecting superlight dark matter, adopting newly proposed technology of using graphene-based Josephson junction (GJJ) microwave single photon detector [35]. It was recently demonstrated in the laboratory
that the GJJ device can have energy resolution equivalent to sub-meV energy quanta \( c_0 \). Therefore, it is possible to immediately design and embark on experiments aiming at detecting dark matter of \( m_\chi \gtrsim 0.1 \) keV. We provide a conceptual detector design proposal and study the detection prospects of superlight dark matter interacting with \( \pi \)-bond electrons not only at the proposed detector but at its smaller-version prototype.

**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) \( c_0 \). As schematically shown in Figure \( 1 \) and Figure \( 2 \). 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.

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. Graphene is a mono-atomic layer of carbon atoms in a hexagonal structure \( c_0 \). Its electronic band structure shows linear energy-momentum dispersion relationship which resembles 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. Very recently, Lee et al. \( c_0 \) have demonstrated microwave bolometer using GJJ with noise equivalent power (NEP) corresponding to the thermodynamic limit. This NEP corresponds to the energy resolution of single 32-GHz (or equivalently, \( \sim 0.13 \) meV) microwave photon in a single photon detection mode.

If dark matter of interest couples to electrons, it can scatters off (\( \pi \)-bond) 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 \( c_0 \), 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 \( \sim 1 \text{ keV} \times (10^{-3})^2 \) so that the GJJ device can possess the sensitivity to the signal induced even by sub-keV-range dark matter. To the best of our knowledge, no device ever known has exhibited the sensitivity of this level practically, so we expect that the microwave single photon detector technology using GJJ enables us to explore parameter regions for superlight particle dark matter in the near future.

**Conceptual design proposal.** Inspired by the GJJ device, we propose a dark matter detector which consists of a multitude of the GJJ devices. A single detector unit is the assembly of a graphene sheet and a number of superconducting material strips with a length of \( \ell \). The strips of \( \ell = 3 \text{ } \mu \text{m} \) \( (\ell = 30 \text{ } \mu \text{m}) \) correspond to a threshold energy of 0.1 meV (1 meV) are laid on a graphene sheet by an interval of 0.3 \( \mu \text{m} \), showing an array of superconducting-graphene-superconducting-graphene-superconducting-··· (SGSGS···). 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 \( 2(a) \) and Figure \( 2(b) \) 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 \( 2(c) \).

Our sensitivity study is based on a g-scale detector, while a mg-scale prototype detector can be prepared first to test the feasibility of larger-scale detectors. To prepare for the units forming a mg-scale graphene device, one needs a total of \( \sim 1 \text{ m} \times 1 \text{ m} \) sheet of graphene, which can be grown using current technology \( c_0 \). 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 \( \sim 10 \text{ mK} \) using dilution refrigerators. An irreducible background may arise from the solar neu-
trinos (mostly pp neutrinos) scattering off an electron and depositing a small amount of energy \[13\]. However, considering the volume of the detector at hand, the expected number of background events is negligible \((\lesssim O(10^{-3}) \text{ g}^{-1} \text{year}^{-1})\) \[18\] \[24\].

We remark that in our study here the proposed detector plays a role of not only the bolometer to measure the temperature change or the single photon detector to count the number of scattering events, but target material off which dark matter scatters. Depending on experimental purposes and designs, alternatively, this can be used only for a bolometer or a single photon detector. For example, a detector made of a few GJJ units can be attached to the target superconducting observer proposed in Ref. \[18\]. In this case, energetic quasiparticles generated in the superconducting observer by dark matter get absorbed into graphene, followed by increasing the electronic temperature of the graphene and triggering GJJ.

**Experimental sensitivities.** - We are now in the position to study dark matter signal sensitivities which would be achieved by the proposed GJJ detector. Our interest here is the interaction between dark matter and \(\pi\)-bond electrons in the graphene which can behave like free electrons. Indeed, dark matter may deposit energy via scattering off the \(\sigma\)-bond electrons, making an additional contribution to the signal sensitivity. However, we conservatively restrict our analysis to the former channel to demonstrate the usefulness of the GJJ-based detector as a superlight dark matter detector, while deferring a full analysis for a future publication.

While our sensitivity calculations closely follow the procedure formulated in Refs. \[17\] \[18\], we modify them wherever the two-dimensional nature of graphene is relevant. The total expected event count per unit mass per unit time, \(n_{\text{eve}}\), is given by

\[
n_{\text{eve}} = \int dE_r d\nu_i \frac{d\langle n_{\text{gr}}^e \sigma \nu_{\text{rel}} \rangle}{dE_r} \frac{1}{a_{\text{gr}}} \frac{\rho_{\chi}}{m_{\chi}} f_{\text{MB}}(v_{\chi}) ,
\]

where \(n_{\text{gr}}^e\) is the number density of target electrons per unit area and \(a_{\text{gr}} = 7.62 \times 10^{-8} \text{ g cm}^{-2}\) is the areal density of graphene. \(m_{\chi}\) is the mass of dark matter and \(\rho_{\chi}\) is the local dark matter energy density which is chosen to be 0.3 GeV cm\(^{-3}\) throughout our analysis. \(f_{\text{MB}}\) is the graphene-surface-parallel velocity profile of dark matter for which we take a plane-projection of a modified Maxwell-Boltzmann distribution \[45\] with root-mean-square velocity \(v_0 = 220 \text{ km s}^{-1}\) and escape velocity \(v_{\text{esc}} = 500 \text{ km s}^{-1}\) (see Appendix):

\[
f_{\text{MB}}(v_{\chi}) = \frac{2(\mathrm{erf}(v_{\chi}/v_0) - 2v_{\chi}e^{-v_{\chi}^2/v_0^2})}{\sqrt{\pi}v_0 \sqrt{\pi}v_0}.
\]

Finally, the velocity-averaged event rate on a (sufficiently thin) graphene sheet per unit time \(\langle n_{\text{gr}}^e \sigma \nu_{\text{rel}} \rangle\) is

\[
\langle n_{\text{gr}}^e \sigma \nu_{\text{rel}} \rangle = \int \frac{d^3p_{\chi,f}}{(2\pi)^3} \frac{|M|^2}{16m_{\chi}^2 m_{\phi}^2} S_{gr}(E_r, q) ,
\]

where \(p_{\chi,f}\) is the momentum of final-state dark matter and where all the total energy quantities are taken in the non-relativistic limit. The Pauli blocking effects are encoded in \(S_{\text{gr}}(E_r, q)\), a structure function over electron recoil kinetic energy \(E_r\) and the magnitude of momentum transfer along the graphene surface \(q = |\vec{p}_{\chi,f} - \vec{p}_{\chi,f}|\) with subscript \(i\) implying the initial state. It is then convenient to convert \(d^3p_{\chi,f}\) to \(dE_r\) and \(dq\):

\[
d^3p_{\chi,f} \rightarrow \frac{dE_r dq}{(2\pi)^3} \sqrt{E_r^2 - m_{\chi}^2} \frac{q(E_{\chi,i} - E_r)}{|\vec{p}_{\chi,f} - \vec{p}_{\chi,f}|^2 - m_{\chi}^2} ,
\]

where we integrate out \(p_{\chi,f}^i\) by pulling out the delta function factor in \(S_{\text{gr}} = (2\pi)^3 \delta(p_{\chi,f}^i - p_{\chi,f}^f) \cdot S\) (see Appendix). We next take the analytic expression for \(S\) derived in Ref. \[18\] based on Ref. \[16\]:

\[
S(E_r, q) = \frac{m_{\chi}^2 T}{\pi q} \left[ \frac{E_r/T}{1 - \exp(-E_r/T)} \right] \left( 1 + \frac{\xi}{E_r/T} \right) ,
\]

where \(T\) is the system temperature surrounding the detector which we take to be 10 mK as mentioned earlier. The \(\xi\) quantity is given by

\[
\xi = \log \left[ 1 + \frac{e^{(\epsilon_\mu \phi)}/T}{1 + e^{(\epsilon_\mu + \epsilon_\chi \phi)}/T} \right]
\]

with

\[
\epsilon_\mu = \frac{(E_r - q^2/(2m_e))^2}{q^2/(2m_e)}
\]

Here \(\mu\) is the chemical potential which is identified as the Fermi energy \(E_F\) at zero temperature. For a two-dimensional object like graphene, the linear energy-momentum dispersion suggests

\[
E_F = v_F \sqrt{\pi n_e}.
\]

Here the Fermi velocity of graphene \(v_F\) is 1.15 \times 10^6 \text{ cm s}^{-1} \[47\] and carrier density \(n_e\) is chosen to be 10^{12} \text{ cm}^{-2}.

We assume that dark matter interacts with electrons via an exchange of mediator \(\phi\) whose mass is \(m_\phi\), as in many of the preceding studies. In the non-relativistic limit, the scattering cross section between free electrons and say, fermionic dark matter \(\chi\) is given by

\[
\sigma_{\chi e} \approx \frac{g_e^2 g_\chi^2}{\pi} \frac{\mu_{\chi e}^2}{(m_\phi^2 + q^2)^2} ,
\]

where \(g_e\) and \(g_\chi\) parameterize couplings of \(\phi\) to electrons and \(\chi\) and where \(\mu_{\chi e}\) is the reduced mass of the electron-\(\chi\) system. If the mediator is heavy enough such that \(m_\phi^2 \gg q^2\), Eq. \[9\] is simplified to

\[
\sigma_{\chi e}^{\text{heavy}} \approx \frac{g_e^2 g_\chi^2}{\pi} \frac{\mu_{\chi e}^2}{m_\phi^4} .
\]
On the other hand, for the opposite limit or the light mediator case (i.e., $m_\sigma \ll q^2$), we get

\[
\sigma_{\text{light}} \approx \sqrt{\frac{q^2}{m_\chi \bar{\epsilon}_\chi^2}}.
\]  

(11)

The matrix element in Eq. (3) is related to the scattering cross section in Eq. (9) as

\[
\sigma_{\text{e}\chi} = \frac{1}{16\pi} \frac{|\mathcal{M}|^2}{m_{\ell}^2 m_\chi^2 \bar{\epsilon}_\chi^2}.
\]  

(12)

To estimate our sensitivity reach, we take Eqs. (10) and (11) as the reference cross sections. For the light mediator case, we replace the $q$-dependence by a reference value $q_{\text{ref}} = \alpha_e m_\chi$ with $\alpha_e$ being the usual electromagnetic fine structure constant, following the prescription in Refs. [27, 44].

Figure 3 displays the sensitivities of the proposed GJJ detector to 0.1 keV – 0.1 GeV dark matter in the plane of dark matter mass $m_\chi$ and scattering cross section $\sigma_{\text{e}\chi}$. For estimating the sensitivity reach, we require 3.6 signal events which correspond to the 95% C.L. upper limit under the assumption of a null event observation over negligible neutrino-induced background events with Poisson statistics [49]. As mentioned before, such dark matter is assumed to interact with the $\pi$-bond electrons in the graphene target through an exchange of $\phi$. The top and the bottom panels are for the heavy and the light mediator cases, respectively. In both panels, the blue (red) curves show the sensitivities with electron kinetic energy deposit being in-between 0.1 meV and 0.1 eV (1 meV and 1 eV), i.e., the superconducting strips of the GJJ detector have $\ell = 3 \mu m$ ($\ell = 30 \mu m$). The dashed curves are the expected results with a 1 g-scale detector exposed for a year, whereas the solid curves are the ones corresponding to a 1 mg-scale prototypical detector. For the heavy mediator case, we exhibit the existing bounds (gray region) together from DAMIC [12], DarkSide-50 [13], SENSEI [14], SuperCDMS [15], XENON10 [18], and XENON1T [10] by the orange, purple, cyan, pink, brown, and green lines, respectively. The current limits for the light mediator case are set by DAMIC [12], DarkSide-50 [13], SENSEI [14], SuperCDMS [15], and XENON10 [18], but they appear outside the displayed region.

**Discussions.** - While the aforementioned dark matter direct search experiments are exploring $m_\chi - \sigma_{\text{e}\chi}$ space, cosmological and astrophysical observations provide bounds on superlight dark matter. For example, the so-called Lyman-α forest is a powerful tool to constrain keV-range dark matter which was thermally produced in the early universe. Such “warm” dark matter behaves relativistically when freezes out, so it may affect the structure formation, leaving appreciable differences in the Lyman-α absorption features from what is observed today (see, for example, Ref. [50]). Currently, warm dark matter of $m_\chi \lesssim 0.1$ keV is disfavored by Lyman-α forests, while there still exist relatively large uncertainties even among very recent results: e.g., Ref. [51] claims that $m_\chi > 10$ keV is allowed at 95% C.L., whereas Ref. [52] claims $m_\chi > 1.9$ keV is allowed at 95% C.L.. In fact, the proposed GJJ detector enables to probe 1 – 10 keV dark matter very efficiently by lowering the threshold to 0.1 meV, as compared to dark matter detectors adopting other bolometer technologies. This is because a lower threshold allows to access the phase space associated with recoil electrons carrying smaller energy. This is also clearly demonstrated by the red (higher threshold) and the blue (lower threshold) curves in Figure 3.
By contrast, if dark matter is produced non-thermally, the bounds from the Lyman-$\alpha$ forest are generically not relevant. It is therefore important to explore the $O(\text{keV})$ mass region in a model-independent sense. There are many well-motivated physics models containing such non-thermal superlight dark matter candidates: for example, sterile neutrinos [53-54], superlight dark gauge bosons [55-57], axion-like dark matter particles [58-60], axino/gravitino dark matter [55-56]. We expect that such ejected electron signals [12, 14-16, 66-77], and is supported in part by the Department of Energy under Grant DE-FG02-13ER41976 (de-sc0009913) and is supported in part by the Department of Energy under Grant de-sc0010813. The work of JCP is supported by the National Research Foundation of Korea (NRF-2019R1C1C1005073 and NRF-2018R1A4A1025334). GHL acknowledges support from Samsung Science and Technology Foundation (Project No. SSTF-BA1702-05).

APPENDIX

Projected Maxwell-Boltzmann distribution. - When a dark matter particle of velocity $v_\chi$ is incident on a graphene sheet by angle $\theta$, the parallel component, i.e., $v_\parallel = v_\chi \cos \theta$, is involved in the momentum transfer. Utilizing the fact that $\cos \theta$ is a flat variable, we find that the dark matter number distribution in $v_\parallel$ for a given $v_\chi$ is

$$ \frac{dN_\chi}{dv_\parallel} \bigg|_{v_\chi} = \frac{dN_\chi}{d\cos \theta} \frac{d\cos \theta}{dv_\parallel} = \frac{1}{2v_\chi}, \quad (13) $$

The whole distribution $f_{MB}(v_\parallel)$ is obtained by convolving Eq. (13) with the probability density of $v_\chi$ given by a modified Maxwell-Boltzmann distribution [45]:

$$ f_{MB}(v_\parallel) \propto \int_{v_\chi}^{v_{\text{max}}} dv_\chi \frac{1}{v_\chi^2} e^{-v_\parallel^2/v_\chi^2}, \quad (14) $$

which results in the expression in Eq. (4).

Structure function. - The structure function for the graphene system of interest $S_{gr}$ is given by

$$ S_{gr}(E_r, q) = 2 \int \frac{d^3p_{e,i}}{(2\pi)^3} \int \frac{d^3p_{e,f}}{(2\pi)^3} (2\pi)^4 \delta(p_{e,i} - p_{e,f}) \times \delta(E_r + E_{e,i} - E_{e,f})(1 - f_{e,f}(E_{e,f})) f_{e,i}(E_{e,i}) \varepsilon_{e,i}, \quad (15) $$

where $p_{e,i}(f)$ denotes the momentum of the initial-state (final-state) electron. The delta function in the first line reflects the assumption that the free electrons are confined in the graphene surface, or equivalently, they do not get any significant momentum change along the surface-normal direction, as far as the electron recoil kinetic energy is sufficiently smaller than the work function of graphene. The Fermi-Dirac distribution functions for the initial-state (final-state) electrons $f_{e,i}(f)$ are

$$ f_{e,i}(f) = \left[ 1 + \exp \left( \frac{E_{e,i}(f) - \mu}{T} \right) \right]^{-1}, \quad (16) $$

where $\mu$ and $T$ are the chemical potential and the system temperature, respectively. Integrating over $d^3p_{e,f}$ in combination with the spatial components of the four-dimensional delta function yields

$$ S_{gr}(E_r, q) = (2\pi)^4 \delta(p_{e,i} - p_{e,f}) \cdot \frac{1}{2\pi^2} \int d^3p_{e,f} \times \delta(E_r + E_{e,i} - E_{e,f}) f_{e,i}(E_{e,i})(1 - f_{e,f}(E_{e,f})) \varepsilon_{e,i} \equiv (2\pi)^4 \delta(p_{e,i} - p_{e,f}) S(E_r, q), \quad (17) $$

where we factor out the delta function of $p_{e,f}$, which is used for the $d^3p_{e,f}$ integral, and separately define $S(E_r, q)$. The closed form for $S(E_r, q)$ is available in the non-relativistic limit [49], as shown in Eq. (5).

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