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Direct dark matter searches using ALPS II's TES detection system

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The elusive Dark Matter (DM), proposed due to its gravitational interaction with ordinary matter, supposedly makes up $\sim 25\,\%$ of our universe's energy content. Various models aim to explain the origin and properties of DM, many of these proposing beyond standard model particles. It is foreseen that the ALPS II (Any Light Particle Search II) light-shining-through-walls experiment will use NIST Transition Edge Sensors (TESs) to detect low-energy single-photons originating from axion(ALP)-photon conversion with rates as low as $10^{-5}\,\mathrm{s}^{-1}$. Even beyond ALPS II, these superconducting microcalorimeters, operated at cryogenic temperatures, offer an approach to search for another class of particle-DM candidate. Much of the work to ensure the viability of the TES detector for use in ALPS II, such as calibrating the detector and mitigating external sources of backgrounds, also leads to the ability to utilize the TES for an independent direct-DM search. For this purpose, the superconducting sensor, sensitive to sub-eV energy depositions, can be used as a simultaneous target and sensor for DM-electron scattering for sub-MeV DM.

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1. Motivation

In recent years, a majority of searches for particle Dark Matter (DM) has focused on Weakly Interacting Massive Particles (WIMPs) [1]. Many experiments search for these particles by exploiting the mechanism of DM-nucleon scattering using heavy nuclei as targets and measuring the recoil energy. However, in the most favored parameter space for WIMP masses and nucleon scattering cross sections, no WIMPs have been found so far. Furthermore, most WIMP direct detection experiments are going to be completed soon, or their upgrades will reach the neutrino fog, at which point it will be difficult to go further with these methods [2–4].

The majority of WIMP searches focus on masses above 1 GeV, but what happens below this mass? Usually, when trying to search for lower mass particles with nucleon scattering, the mass of the projectile particle is too low to produce a measurable recoil with nuclei [5]. Therefore, many nucleon scattering experiments lose sensitivity when the mass of the projectile particle drops below the GeV scale, even though well-motivated DM models exist in this regime [6].

A possible solution to this problem is to focus on electron scattering. With this technique, one can extend the search to sub-GeV and even sub-MeV light DM particle candidates. To explore this further, one can follow the rule of thumb outlined in Ref. [7], which suggests a six orders of magnitude difference between the DM particle mass and the maximum transferred energy. Therefore, superconductors are a viable option for sub-MeV masses since the binding energy of Cooper pairs is on the order of meV. Hence, superconductors might be feasible targets and sensors for measuring DM electron scattering signatures of sub-MeV DM particles.

This work proposes using a superconducting Transition Edge Sensor (TES) for direct DM searches in the sub-MeV mass range. We will explore the concept employing the NIST TES used in a setup for single-photon detection in the Any Light Particle Search II (ALPS II) experiment, which is a light-shining-through-a-wall experiment at DESY in Hamburg, Germany, currently operated in it's first detection scheme using heterodyne sensing [8–12]. With this we face two challenges: Measuring meV energies with low background and reaching the sensitivity to test models as in [6]. In this work, we outline how we plan to address the former challenge.

2. Dark Matter Searches with Superconductors

Similar direct DM searches exploiting DM-electron scattering have already been performed with so-called Superconducting Nanowire Single-Photon Detectors (SNSPDs) [7]. These low-noise counters with thresholds below 1 eV are able to set the most stringent terrestrial constraints on DM-electron scattering for sub-MeV masses with measurement times of less than eight days [13].

However, SNSPDs work like Geiger counters, which renders an estimate of the recoil energy and effective signal and background discrimination impossible (e.g. pulse shape analysis). When a particle hits one of the nanowires cooled down to superconducting temperatures below 1 K, the scattering or absorption process breaks Cooper pairs and creates a hot spot across the wires leading to the count of an event. The only parameter that can be derived from this interaction is that the energy transferred to the SNSPD was above the device's sensitivity threshold.

To better understand backgrounds or even mitigate them, techniques preserving e.g. the energy information of a signal, are preferable. This leads to the idea of using TESs for such direct DM searches. TESs, like SNSPDs, rely on superconducting technology. However, the resulting pulse shapes are determined not only by sensor characteristics, but also by the energy deposited in the sensor and its time profile. Furthermore, they might even be able to reach lower energy thresholds than the above-mentioned SNSPDs [14].

We are proposing to use the ALPS II TES detection system for a direct search as a proof-of-principle for TES-based dark matter searches. The ALPS II experiment will use a tungsten TES detector as a single-photon detector to measure reconverted photons from ALP-photon oscillations in the search for Axion-Like Particles (ALPs) at a rate of down to $10^{-5}\,\mathrm{s}^{-1}$ [8, 10]. An optical fiber will connect the ALPS II experiment directly to the TES detector inside a cryostat. In the interest of this measurement, the so-called intrinsic background was studied extensively, which are the dark counts of the sensor without the attached optical fiber [9, 15, 16]. Based on these studies, one can predict the performance of our TES detector for DM-scattering experiments (also with disconnected fiber) using the dielectric function of the target [17]. Figure 1 shows the covered parameter space following this prediction.

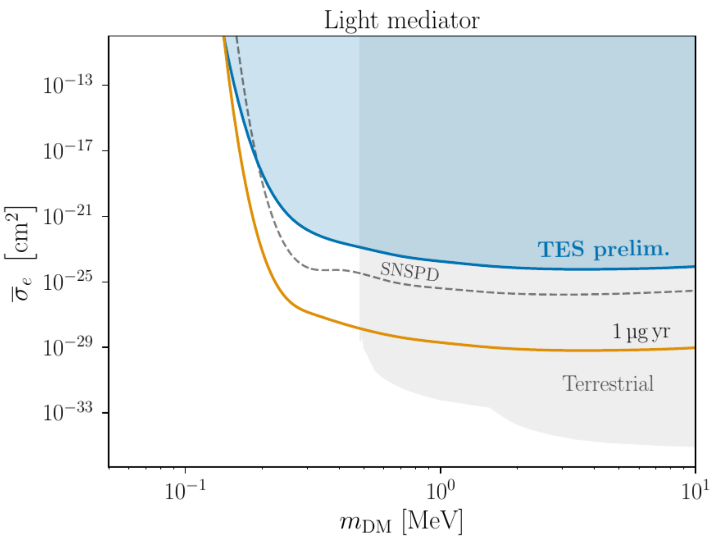

Figure 1: Terrestrial parameter space for DM-electron scattering with a light mediator in the ~MeV mass range dependent on the DM-electron scattering cross section $\bar{\sigma}_e$. The blue area shows the preliminary projection (20 ng hr) for our TES based only on intrisics measurements (for ALPS II). The dotted gray line describes the parameter space covered by SNSPD measurements (774 ng hr) with the projection for a larger exposure of SNSPDs in orange (from [13]). The shaded gray area represents other terrestrial constraints.

Our TES detector would be able to cover new parameter space below 0.2 MeV, exceeding the SNSPD performance, notably without any prior optimization for these DM searches.

3. TES Detection

TESs are commonly used as single-photon sensors, as in the ALPS II experiment, or e.g. in arrays in cameras of large telescopes [18, 19]. Their working principle (extensively described in Ref. [20]) is that of a cryogenic microcalorimeter. The TES detector is operated at a transition temperature (here ~ 140 mK) between the superconducting and normal conducting state, which can be influenced by a bias current applied to the circuit. When an incident photon hits the sensitive area of the TES, it leads to a minuscule temperature increase ΔT, which results in a considerable increase in resistance ΔR and therefore a change of the current. This variation in current is read out using Superconducting Quantum Interference Devices (SQUIDs). This allows for the measurement of exceedingly small incident photon energies. Figure 2 shows an example of a single-photon pulse measured by our TES.

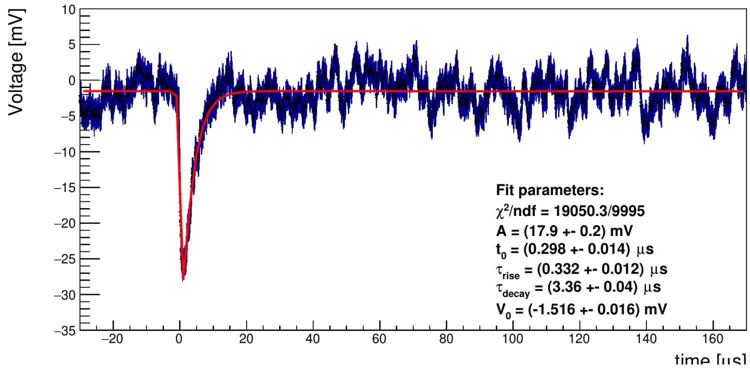

Figure 2: Example TES 1064nm pulse (blue) with fit (red) and fit parameters. From [21].

In addition to energy discrimination, our TES shows a good energy resolution (at 1.165 eV i.e. 1064 nm) of ~ 5 % [22]. When photons hit the active TES area, the pulse shape is mainly governed by the TES circuit itself. This includes characteristics such as the rise time of the pulse, indicating how quickly a signal pulse reaches its maximum height from the noise baseline, and the decay time, representing the duration to relax back to the noise baseline. DM scattering (and/or absorption) in our detector is expected to resemble single-photon pulses since both processes rely on the breaking of Cooper pairs, leading to similar TES responses [5]. Therefore, we expect pulse shapes like the one shown in Figure 2, but with a pulse height proportional to the energy transferred in a scattering event.

4. TES as Dark Matter Detector

Before using the ALPS II TES detector for direct DM searches, we have to consider some of the setup's peculiarities. For one, the whole infrastructure of the current system is optimized for signals at the ALPS II laser wavelength of 1064 nm (1.165 eV). Consequently, we have limited knowledge about the TES response to other energies. To perform direct DM searches similar to the SNSPD searches, we need to understand the TES response to lower energies, especially below 1 eV.

A setup is currently in development to determine the TES response at different energies and verify our assumptions: The TES response should be mainly governed by the TES circuit itself [20], therefore we assume that the pulse height changes linearly with energy, while the rise and decay time is constant for different energies. Moreover, the linearity between pulse height and energy has already been confirmed for light signals above 1 eV [23]. With the new setup, we will perform calibration measurements using laser diodes operating at different wavelengths (880 nm - 2000 nm or 1.4 eV - 0.6 eV).

Notably, our setup has already achieved very low intrinsic dark count rates (in an analysis optimized for 1.165 eV) as low as $(2.16 \pm 2.02) \cdot 10^{-6}$ Hz [16]. These dark counts include mainly electronic noise but also radioactivity or cosmic backgrounds. However, we need to explore the acceptance of lower energy photons and further investigate the intrinsic backgrounds at lower energies signal searches and lower trigger levels (see Section 5) as well.

5. Baseline noise simulations

For evaluating the TES performance as a DM detector, simulations have been performed to test the TES response to lower energies and the expected low signal-to-noise ratio and to determine the viability of our TES detector for DM searches.

For these tests, the (electronic) noise and the well-known 1.165 eV pulses were simulated. An example pulse is shown together with different trigger levels in Figure 3.

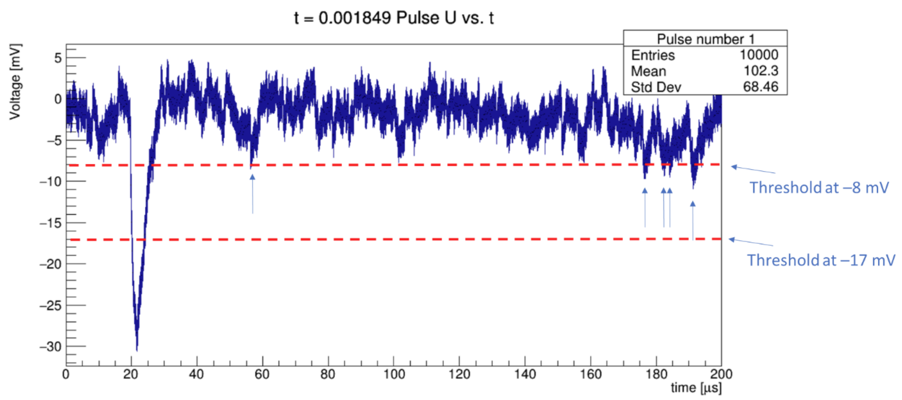

Figure 3: Simulated example TES pulse (1.165 eV) compared to different trigger levels. For standard measurements with 1.165 eV pulses, a trigger level around −17 mV is usually employed. At lower levels, the noise baseline repeatedly starts causing false triggers, as shown by the vertical blue arrows.

To assess the false trigger rate for low thresholds, which are suitable for DM searches, we simulate pure electronic noise (without any signal pulses) for different trigger levels. In actual measurements, we save the full trace (or time line) including 20 µs before and 180 µs after the trigger at a sampling rate of 50 MHz. Triggering at this sampling rate and the amount of recorded information currently limits the experimental setup to a trigger rate of around 1 Hz. With this limit, a simulated threshold of ≥ -12 mV still allows a non-zero acceptance for smaller pulses. We performed an intrinsic background test measurement to verify the simulated prediction and measured a rate of (0.5070 ± 0.0014) Hz for a trigger level of −12 mV after a measurement time of 72 hr.

In a next step, we simulated lower energy pulses (0.583 eV, half the energy the system is optimized for) based on our above mentioned assumptions together with the noise baseline, using this trigger threshold of −12 mV. Next, a known pulse shape (based on 1.165 eV pulses) for photon signals was adjusted to this lower energy and fitted to all triggered pulses (see Ref.[21]). By applying cuts based on fit parameters, we estimated the pulse acceptance in the 0.583 eV energy bin. A preliminary cut optimization was done using the same rise and decay time cuts as for 1.165 eV signals and by assuming proportionally smaller pulse heights. With these cuts, we currently achieve an acceptance of $\sim 56\,\%$ for 0.583 eV pulses.

Lastly, we can investigate how many background pulses would survive when applying this analysis to simulated noise-only background data: When simulating 70 min of noise background, a trigger rate of (0.422 ± 0.010) Hz is recorded. After applying the above analysis with both adjusted fits and cuts for 0.583 eV pulses, no signals survive this process with an upper uncertainty limit of 0.0007 Hz at 95 % C.L.. Therefore, the suppression of noise background after the analysis and its acceptance for this low energy bin show promising prospects for direct DM searches using our TES detector. This would be a lower energy threshold than the one of the SNSPD device considered in Figure 1 (0.73 eV). The future goal will be to confirm and expand this with dedicated measurements.

6. Conclusion and Outlook

The TES technology that will be used as one of the detection schemes in the ALPS II experiment at DESY in Hamburg offers an interesting avenue for direct DM searches in the sub-MeV DM mass range by exploiting the mechanism of DM-electron scattering. Similar measurements performed with SNSPDs have already been conducted and have been able to set the most stringent terrestrial constraints in the respective DM-electron scattering parameter space so far. Based on measurements to characterize our TES detector for the ALPS II experiment, projections expect the TES being able to reach and test new parameter space. The fact that new sensitivities might be within reach without dedicated hardware development could lead to a proof of principle for similar technologies for DM searches and might even pave the way for new types of DM detectors.

More research and characterization of the TES is already ongoing, and the TES response to different energies will be determined soon. This will improve our understanding of surviving background events we still observe in intrinsic measurements and of the TES response for lower trigger thresholds. As a next step, we will perform an intrinsic background measurement with a calibrated TES detector to compare the results with the previous SNSPD measurements. Simultaneously, we will further investigate the intrinsic background in all performed measurements and simulations. Once we can prove or even surpass the above predictions for the TES performance for these direct DM searches, we plan to investigate new TES modules optimized for direct DM searches.

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