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A WIMP Dark Matter Detector Using MKIDs

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Abstract We are pursuing the development of a phonon- and ionization-mediated WIMP dark matter detector employing microwave kinetic inductance detectors (MKIDs) in the phonon-sensing channel. Prospective advantages over existing detectors include: improved reconstruction of the phonon signal and event position; simplified readout wiring and cold electronics; and simplified and more reliable fabrication. We have modeled a simple design using available MKID sensitivity data and anticipate energy resolution as good as existing phonon-mediated detectors and improved position reconstruction. We are doing preparatory experimental work by fabricating strip absorber architectures. Measurements of diffusion length, trapping efficiency, and MKID sensitivity with these devices will enable us to design a 1 cm^2 × 2 mm prototype device to demonstrate phonon energy resolution and position reconstruction.

Keywords WIMP detectors · Dark matter detectors · Microwave kinetic inductance detectors · Phonon-mediated detectors · Strip detectors · Position-sensitive detectors · Nuclear-recoil discrimination

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1 Introduction

Weakly Interacting Massive Particles (WIMPs) are an excellent dark matter candidate, on both general grounds and as motivated by SUSY. Expected interaction rates

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are < 0.1/kg/day and energy depositions are $\mathcal{O}(10)$ keV. The CDMS experiment has made successful use of detectors that measure both phonon and ionization production by interacting particles to determine the deposited energy and discriminate nuclear from electron recoils. This has provided world-leading sensitivity to WIMP dark matter [1]. The athermal phonon measurement employed by the CDMS ZIP detectors [2] provides additional critical event position information that enables cutting-edge WIMP sensitivity:

- Surface vs. bulk Z-position separation is provided by the phonon timing, relying on the fact that phonons from surface events experience enhanced downconversion to ballistic phonons and thus reach the phonon sensors more quickly
- Relative phonon timing provides event XY position

Nevertheless, significant improvements can yet be made (and are being pursued [3]) to further increase WIMP sensitivity:

- Increased area coverage
- Improved energy collection
- More prompt energy collection (fewer bounces)
- Finer pixellization of sensors
- Two-sided coverage
- Reliability of fabrication (scaling to higher mass)

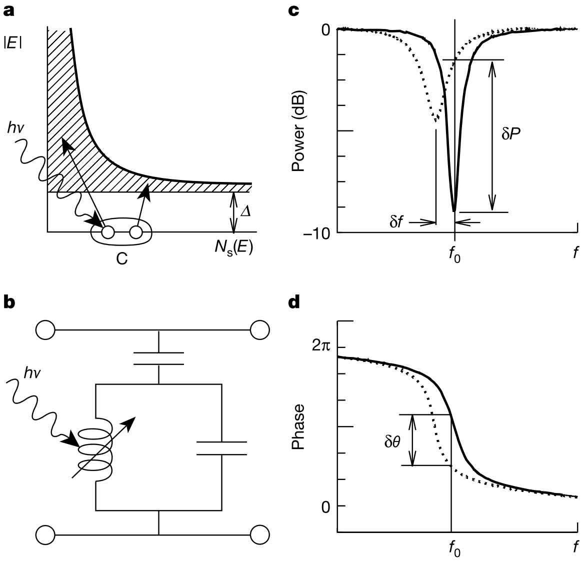
Microwave Kinetic Inductance Detectors [4, 5] may provide a convenient means to obtain these improvements because:

- Their demonstrated single-sensor sensitivity is comparable to TESs
- Multiplexability allows 2-sided surface coverage with sub-cm-scale pixels
- RF readout simplifies cold electronics
- Rapidly advancing digital signal processing technology allows warm electronics to be built using largely commercial hardware and ensures costs will decrease with time [6]
- Insensitivity of performance to T_c makes fabrication easier

2 MKID Fundamentals

See Fig. 1. The kinetic inductance of a superconductor is the inductive surface impedance of the superconducting Cooper pair condensate at microwave frequencies due to its inertia when an electric field is applied. There is also an ohmic surface resistance due to quasiparticles (broken Cooper pairs). Thus, L_{kin} and R_{kin} measure the quasiparticle density and change when Cooper pairs are broken by input energy (a). To monitor these quantities, the superconductor can be placed in a resonant circuit in which L_{kin} and R_{kin} make measurable contributions to f_0 and Q (b). The circuit transmission changes due to changes in f_0 and Q when energy is deposited (c), (d). By monitoring the amplitude and phase of a drive signal at the quiescent f_0, these changes can be measured. The sensitive bandwidth of the MKID is set by the resonator bandwidth and is $f_0/2Q$.

Fig. 1 Schematic of MKID operation. See text for explanation. Figure courtesy of P. Day [4]



The best achieved NEP is 4×10^{-18} W/$\sqrt{\text{Hz}}$ in a thin Al resonator on sapphire. It has been demonstrated that this noise is due to RF coupling to fluctuating, dissipative two-level defect systems in surrounding insulators. More recent work [7] has demonstrated that the TLSs are in surface oxides, not the substrate. The fundamental MKID noise limit is due to quasiparticle generation-recombination noise and can be exponentially suppressed via reduction of the operating temperature.

The resonant design of MKIDs immediately suggests frequency-domain multiplexing [6]. A set of resonators can be designed with different f_0 values, separated by a few resonator bandwidths $f_0/2Q$, and driven with a frequency comb. The MKID output signal is amplified near the device with a wide-bandwidth, cryogenic HEMT. The signals are demultiplexed and demodulated using 300 K electronics. No cold electronics are required except the HEMT and RF cabling.

3 Detector Architecture

See Fig. 3. Superconducting films absorb athermal phonons produced in a substrate particle interaction. The resulting quasiparticles diffuse to and are trapped in lower-superconducting-gap MKIDs at the phonon absorber edges.

Each phonon absorber is 1 mm wide × 5 mm long. The absorber width is set assuming a 500 μm diffusion length (see Sects. 5 and 6). The absorber length is determined by the MKID length, which is set for resonant frequencies in the few GHz. Each MKID is sensitive to the ∼1 mm × 5 mm region surrounding it.

The MKIDs are arranged as ∼ 5-mm-long, 1/4-wave, coplanar waveguide (CPW) resonators capacitively coupled to a single feedline. The ∼ 5-μm-wide CPW center conductors are shorted to the phonon absorbers at one end; the phonon absorbers are the RF ground plane. The CPW ground plane, rather than the center conductor, acts

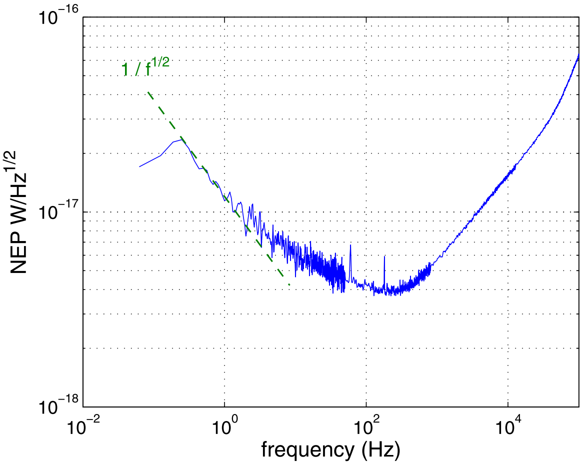


Fig. 2 (Color online) Best achieved noise spectrum, in NEP units, of a 20-nm thick Al MKID. The slope at low frequency is two-level-system $1/f$ noise (in NEP^2). The rise at high frequency is not inherent in the fundamental noise, but arises because we convert to NEP, which requires a $\sqrt{1+\omega^2\tau_{qp}^2}$ factor ($\tau_{qp} = 400$ µs). The slope change above 10 kHz is due to a similar factor from the resonance frequency width. Figure provided by P. Day

as the quasiparticle trapping region to avoid grounding the entire center conductor. The current distribution in the ground plane is only a factor of 2 smaller than in the center conductor, so this comes at a modest loss in sensitivity. The sinusoidal current distribution in each resonator renders its sensitivity dependent on position. By alternating adjacent resonator orientations, this fine-scale position dependence will be averaged over.

4 Readout Requirements

20 resonators are needed to cover 1 cm^2 of detector surface. A detector made from standard 75-mm-diameter substrates has 100 cm^2 surface area (top and bottom faces), requiring 2000 resonators. Resonator spacings of 3 MHz have been regularly achieved, which would require 6 GHz of bandwidth for readout of a single detector. A single 4–12 GHz HEMT is capable of covering the bandwidth.

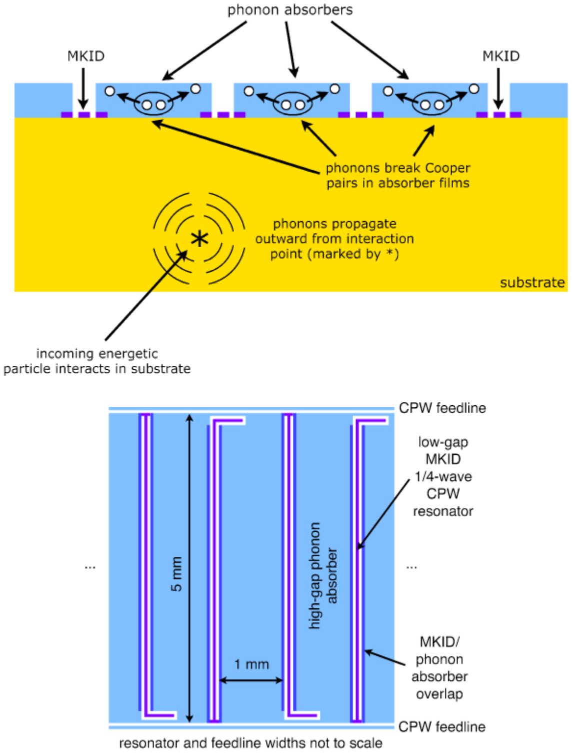
A 1 cm × 1 cm prototype requires only 120 MHz, to be provided by the system we are designing for the next prototype MKID Camera [8]. The bandwith necessary for a full-size detector will be covered by the full MKID Camera readout [8].

The resonator count may be reduced by increasing the resonator length to 15 mm and operating the resonators in their first overtone. Device noise and responsivity in this operating mode has, however, only undergone cursory investigation to date.

5 Expected Sensitivity

We performed a strawman sensitivity calculation as follows. We assume a Ta phonon absorber and Al MKID so we can make direct use of the existing noise spectrum shown in Fig. 2. (Since the noise appears to be related to surface oxides, we expect that semiconducting substrates can be passivated to yield sapphire-quality noise.) Given the low energy densities in a phonon-mediated detector ($\sim$ 100 eV/cm^2 for

Fig. 3 (Color online) *Top*: Full detector schematic. *Bottom*: Phonon sensor unit cell



a 10 keV event), such a thin device is practical. We reduce the assumed Al quasiparticle lifetime from the measured 400 μs to 100 μs, thereby degrading the NEP, to be conservative. We also assume conservative values for the diffusion constant ($D = 20$ cm^2/sec) and Ta quasiparticle lifetime ($\tau_{qp} = 100$ μs). The resulting diffusion length is $l_{qp} = \sqrt{D\,\tau_{qp}} = 450$ μm, only 2 times larger than we have achieved in early devices (see Sect. 6).

We assume the phonon energy incident on a single absorber is uniformly distributed, and similarly for the resulting quasiparticles. We assume perfect quasiparticle trapping at the MKIDs (confirmed for Ta/Al trapping by [9]). The diffusion problem is analytically solvable. MKID theory combined with measured Al parameters provides the conversion from trapped quasiparticles to signal size. (Trapping into the MKID ground plane rather than center conductor, as well as the MKID position sensitivity, is accounted for.) We combine the calculated signal with the measured NEP to calculate energy and timing resolution. We find:

- For a single 1 mm × 5 mm cell: 1.3 eV and 4 μs (the latter at 100 eV energy; scales as $1/E$)
- For a 20 keV event in a full-size detector (200 eV/cm^2, 10 eV/absorber): in each cm^2: S/N = 30 on energy, 4 μs timing resolution. 58 eV resolution for the energy summed over the entire detector.

These energy and timing resolutions are very competitive with existing detectors. Moreover, recent advances in our understanding of the dominant two-level-system noise noted above guide the way to improved noise by surface passivation. In the long term, we will use Al absorbers (because of its fast diffusion) and Ti MKIDs (appropriate and reliable Tc, high sensitivity due to large penetration depth).

6 Preparatory Experimental Work using Strip Detectors

Strip detectors consist of a long strip of superconducting material with MKIDs on two ends. The strip is illuminated directly (not via substrate phonons) with X-ray or optical photons. The distributions in relative signal size and timing in the two MKIDs provide the diffusion constant, D, and quasiparticle lifetime, τ_{qp}, and we derive from them the diffusion length l_{qp} [10, 11]. Ta absorber/Al MKID and Al absorber/Ti MKID devices have been fabricated to measure these parameters for Ta and Al absorber films. Detailed results are presented in [12, 13]. Briefly, our results are as follows:

- Ta diffusion: A Ta absorber/Al MKID strip detector was illuminated with 5.9 keV and 6.4 keV Mn K_α and K_β X-rays from a ^{55}Fe source. We measured $D = 14$ cm^2/sec, $\tau_{qp} = 35$ µs, and $l_{qp} = 216$ µm. l_{qp} is about two times lower than assumed for our sensitivity calculation. The diffusion constant is better than that achieved by other investigators [9, 14], but the lifetime is lower. Efforts to improve the Ta lifetime have not yet succeeded. We attribute the poor lifetime to damage to the Ta surface due to later MKID processing (the Ta film is deposited first) or to trapping at the long absorber edges due to a reduced Ta gap due to sloping of edges, which was done intentionally to provide good step coverage for the Ta/Al interface.
- Al diffusion: An Al absorber/Ti MKID strip detector was illuminated with a Si fluorescence source (^{55}Fe illuminating a Si wafer, yielding 1.74 keV and 1.83 keV Si lines). Due to the low gap energy of aluminum and the high kinetic inductance of Ti (due to its high penetration depth), these X-rays saturated the device—all coincident strip events show MKID phase shifts much greater than 45°—so a full analysis is not possible. However, the fact that the device shows coincident events suggests a diffusion length of at least 100 µm, comparable to that achieved by other groups [9, 15]. The high RRR of our Al (10 @ 200 nm, 18 @ 400 nm) suggests 500-µm diffusion lengths are achievable.

We are now attempting to fabricate "optical" Al/Ti devices—devices with Ti thin enough to have sufficient responsivity to see 5-eV UV photons [6]. These devices would more closely approximate phonon-sensing devices given the 5 eV expected per absorber. Once we have reliable diffusion parameters for Al and sufficient S/N in Al/Ti devices, we will proceed to designing and fabricating a 1 cm × 1 cm × 2 mm prototype phonon-mediated detector.

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