Snowmass2021 - Letter of Interest

Spin-triplet superconductivity - a new foundation for magnetically resistant resonators and devices for dark matter detection

Thematic Areas: (check all that apply □/■)

□ (CF1) Dark Matter: Particle Like
■ (CF2) Dark Matter: Wavelike
□ (CF7) Cosmic Probes of Fundamental Physics
■ (IF01) Quantum Sensors

□ (CF2) Dark Matter: Wavelike

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Abstract:

The axion haloscope technique is arguably the most sensitive search technique for dark matter axions in the few to tens of μeV mass range. Current operating experiments use copper and dielectric resonators but these typically have much lower quality factors than what can be achieved with superconducting resonators. However, current superconducting resonators cannot operate in the high static magnetic fields, a necessity for dark matter detection. The recently discovered spin-triplet superconductor is a fundamentally different form of superconductivity, where superconductivity not only coexists with magnetism but can be enhanced by it. The potential for magnetically-tolerant devices can revolutionize the field of quantum-based devices and computing. Therefore we propose to make a new superconducting resonator made of the ferromagnetic superconductor UCoGe.

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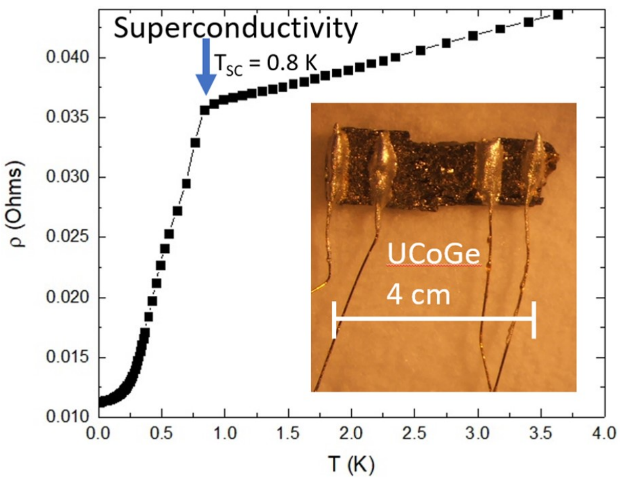

Figure 1: An electrical resistivity profile of UCoGe taken from K. Huang et al., [11]. The material becomes superconducting below T_{SC} = 0.8 K, well above the operating temperatures in dark matter detectors. Inset: A sample of UCoGe prepared for 4-wire DC electrical resistivity measurements.

1 Introduction

Superconducting resonators are increasingly employed in quantum information systems and devices such as quantum readout devices, memories [1], quantum limited signal amplifiers [2], or extremely sensitive dark matter detectors [3]. Haloscope-based detectors in particular will benefit from advancements in superconducting resonators as the two key components of the detector, the microwave cavity resonator and the signal amplifier, have quantum device analogues. However, these detectors operate in high magnetic fields that are detrimental to superconductivity. Current Al-based superconducting resonators have an upper field H_c = 0.5 T, significantly lower than the 8 T used in recent ADMX experiments [3]. The recently discovered spin-triplet superconductors (STS) are fundamentally different, where magnetism and superconductivity can not only coexist but even enhance each other.

The Cooper pair is the basic component of superconductor, made of a pair of electrons with anti-parallel spins. Magnetic fields are destructive to superconductivity as the electron spins will align parallel with the field, breaking the Cooper pair. However, in STS the Cooper pairs form with parallel spins which can can result in unusual and exotic forms of superconductivity. For example, UCoGe is a ferromagnetic superconductor (T_{SC} = 0.8 K, T_C = 3 K), a combination historically prohibitive [4]. Muon spin relaxation (μSR) measurements use spin-polarized muons as a sensitive probe of internal magnetic environments, contributing significantly to understanding high-Tc cuprate superconductors [5]. μSR measurements on UCoGe show that the superconductivity not only coexists with the magnetism but is induced by the magnetic fluctuations [6]. High magnetic field measurements show that the superconductivity persists up to 20 T [7], three orders of magnitude larger than current Al-based superconducting resonators and well in excess of the 8 T used for dark matter detection. Furthermore, in the range of 5 T up to 13 T, superconductivity (T_{SC}) is enhanced with increasing H [8].

A radioactive quantum device is an unusual choice, not least because of potentially heating the detector. UCoGe uses depleted uranium, which is one of the most stable radioactive isotopes with a half life of 4.5 billion years. Furthermore, the primary emission of depleted uranium is α particles with 5 MeV, correlating to 9.9 pW/kg, orders of magnitude lower than the 30 μW cooling power from typical dilution refrigerators.

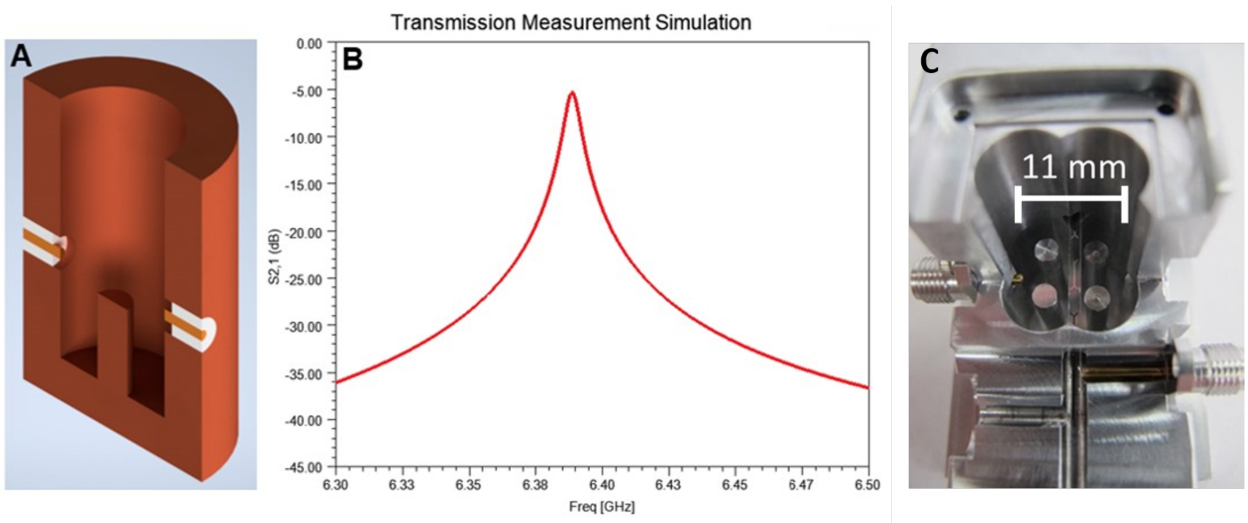

Figure 2: Ansys HFSS simulation of a transmission measurement between the two ports on a copper 1 cm long quantum wave resonator as seen in (A). The simulated data is displayed in (B) where the full width half maxima provides a measurement of the microwave losses within the resonator. A typical Al-based microwave resonator cavity (C). The UCoGe resonator will reside in the central pillar, on which the currents are applied.

We propose to build a superconducting resonator made of the STS UCoGe to determine its viability for applications such as axion dark matter detection. Fabrication and quality control characterization of UCoGe will be performed at LLNL. The quality factor will be measured in an Al-based microwave cavity similar to the one shown in Fig 2C. Both reflection and transmission measurements using a network analyzer will be performed, as shown in the simulated data in Fig 2 on a copper resonator 1 cm in length. The quality of the resonator will be determined by the sharpness of the dip. Of particular interest will be measuring quality factor in the H = 5 - 13 T region where superconductivity is enhanced with increasing field. Additionally a spin-triplet UCoGe resonator will be an ideal platform to investigate decoherence such as unpaired electron spins on the surface of the superconductor or substrate [9, 10], of vital interest to quantum computing and information systems.

2 Conclusion

Spin-triplet superconductivity represents a new foundation for superconducting resonators and devices that can not only operate in high magnetic fields but opens the possibility of non-mecahnical tuning through magnetism. Proving the viability of a STS resonator will have wide-arcing impacts from dark matter detectors that operate in high magnetic fields to isolating sources of decoherence with a new type of resonator.

Additional Authors:

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