Sapphire substrate qubit-based detector for light dark matter search

Kester Anyang
Rakshya Khatiwada, Israel Hernandez, Ryan Linehan
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Illinois Institute of Technology-Graduate Student

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Goal

We are hoping to build a prototype qubit-based dark matter detector.

Polar Materials Motivation

Phonons For Sub-eV Energy Detection

Direct dark matter searches use:

- Nuclear recoil.
- Electron transition(1eV-10eV Semiconductor band gap).
- Phonon excitation(Acoustic and Optical).

Optical phonons in crystals have energies in the range of 10meV-100meV. They are gapped and correspond to out-of-phase oscillations of the atoms in the unit cell.

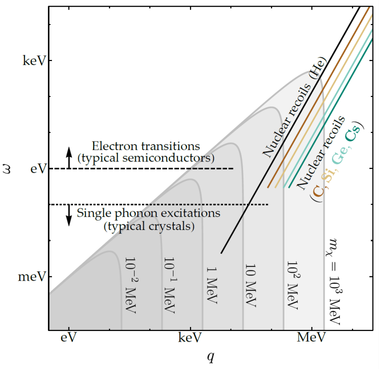


Figure 1: Bounded regions of energy deposition ω and momentum transfer q, for various dark matter masses m_χ. $\omega = qv - q^2/2m_\chi$: arXiv:1910.08092

Dark Matter Target Material: Polar Materials (Sapphire)

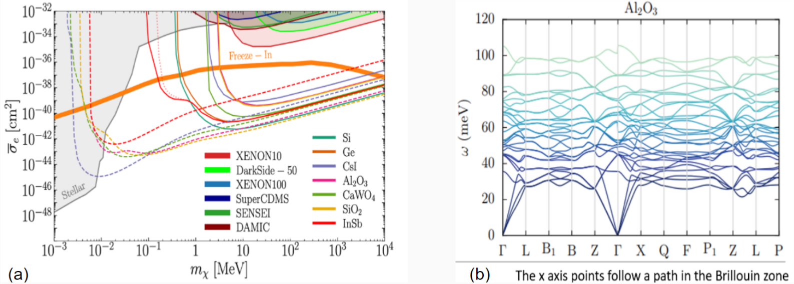


Figure 2: (a) Projected reach for single phonon excitation(dashed) and electron excitation(solid):arXiv:1910.10716v3 (b) Phonon Band Structure in Sapphire(Al_2O_3) : *arXiv* : 1807.10291

- **Sapphire** has differently charged ions in the unit cell
- **Optical phonons** (out of phase lattice vibrations) behave as oscillating dipoles
- Phonons could couple to the **light dark photon mediator** and the heavy **dark photon dark matter**. arXiv:1807.10291
- **Optical phonons** energy range **30meV - 100meV**.
- Sapphire is anisotropic and expected to display **daily modulation in dark matter scattering rate**.
- **Qubits on a sapphire substrate** will be used to investigate the dark matter-phonon interaction.

Qubit Detector Mechanism

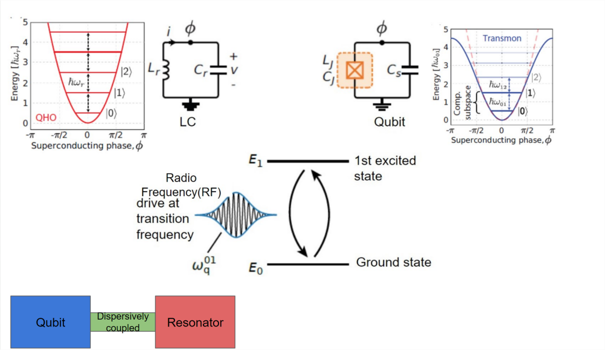


Figure 3: Superconducting qubit schematic: arXiv:1904.06560

- Superconducting qubits are anharmonic oscillators in the form of non-linear inductance-capacitance (LC) circuits. The nonlinearity is contributed by the Josephson junction, which is a non-dissipative and nonlinear inductor.
- These qubits are operated as two-level systems by driving the qubit with an electromagnetic pulse at the transition frequency ω_q^{01}.

Qubits As Dark Matter And Radiation Sensors

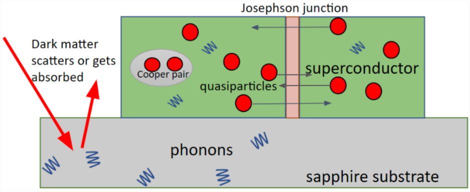


Figure 4: Energy deposition to quasiparticle tunneling. ("Early career effort of Khatiwada supported by QSC")

- Sub eV dark photon dark matter gets absorbed.
- Dark matter scatters via light photon mediator.
- Dark matter deposits energy, exciting optical phonons in the substrate.
- Phonons travel throughout the substrate, scattering and downconverting to lower energy phonons.
- Some phonons cross over into the superconductor and break Cooper pairs when E$>$2Δ. ($2\Delta_{Nb} = 4.6meV$ and Aluminum has $2\Delta_{Al} = 0.68meV$).
- Quasiparticles tunnel across the junction and may cause qubit decoherence.

Sapphire Transmon Qubit Device

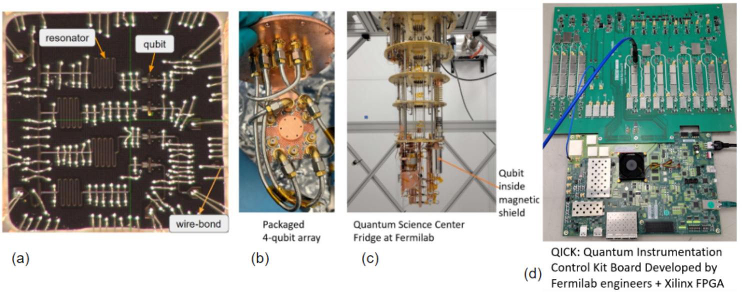


Figure 5: (a) 4-Qubit Array with Sapphire substrate (b) Qubit Chip Packaged (c) Qubits Installed In Dilution Fridge (d) QICK For Qubit Control And Readout.

- 4 qubit array from Purdue University.
- Qubit fabrication by: Alex Ruichao Ma and Botao Du
- QICK toolkit is used to generate pulses, readback and process readout pulses for qubit experiments. :[https://doi.org/10.1063/5.0076249]. QICK supports ZCU111, ZCU216, and RFSoC4x2 boards.

- Qubit device and accessories have been installed.
- Characterization of the qubit readout setup is ongoing to improve signal-to-noise ratio for the next experimental run.

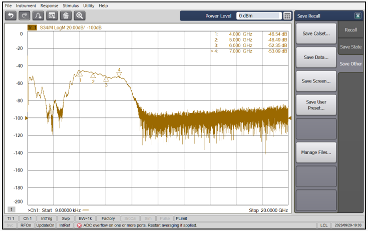


Figure 6: Transmission Measurement Through The Fridge Input and Output RF Lines

Device Characterization using Cryogenic Micro-Electromechanical System (MEMS)

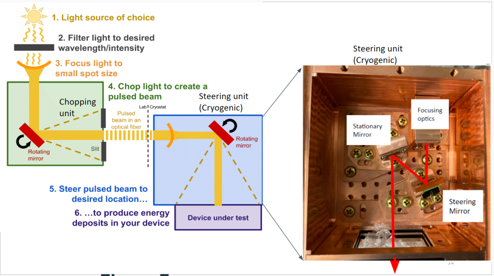


Figure 7: Cryogenic MEMS Calibration Device

- Development began at Fermilab and is ongoing at SLAC(Kelly Stifter's Team). The MEMS device has been deployed (E 1.9 ev) and is being used for qubit studies at Fermilab.
- **Noshin Tabassum: RDC7: Cryogenic optical beam steering for calibration of superconducting sensors 5:00PM - 5:15PM 48/1-112C/D - Redwood C/D (SLAC)**

Detector Characterization

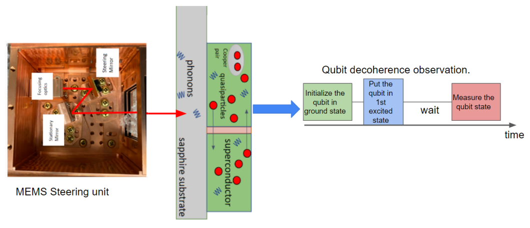


Figure 8: Detector Characterization

- Qubit to be integrated with the MEMS source that will enable phonon dynamics studies, quasiparticle production in and near the qubit and its decoherence.
- Simulation of sapphire phonon kinematics is ongoing, results will be compared with the detector calibration and measurement.
- Studies will be conducted to understand impact of variation of initial energy and source position in the device along with phonon absorption efficiency in the superconductor.
- **Ryan Linehan: RDC7: RD for Use of Superconducting Qubits as Dark Matter Detectors 2:00PM - 2:15PM 51/1-102 - Kavli Auditorium (SLAC)**

G4CMP simulation of sapphire is ongoing (led by **Israel Hernandez**). Already demonstrated and verified phonon caustic pattern for Sapphire. Energy deposition and phonon kinematics will be simulated for the sapphire substrate next.

Israel Hernandez: RDC7: Energy dissipation and phonon kinematics simulation in qubits with G4CMP 4:30PM - 4:45PM 51/1-102 - Kavli Auditorium (SLAC)

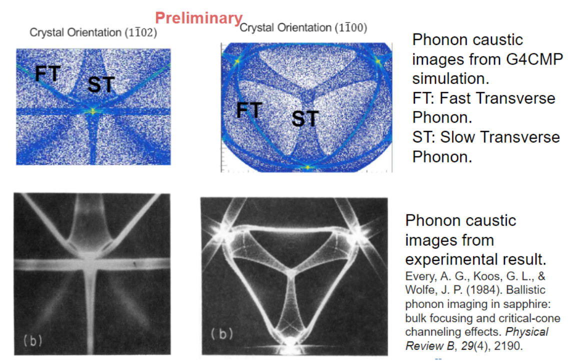


Figure 9: G4CMP Saphire Simulation

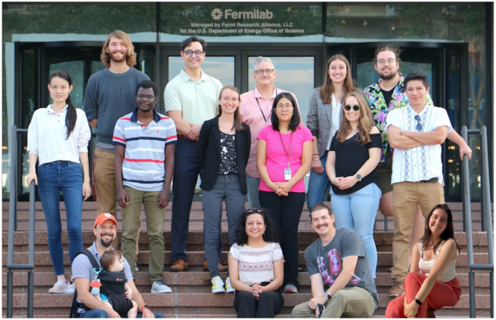
Summary and Conclusion

- Polar materials are good targets for dark matter.
- Radiation or dark matter excites phonons in qubit substrate, which break Cooper pairs and can expedite qubit decay rate.
- In the near future, we will characterize the qubits (Resonator, Qubit Spectroscopy, Pi pulse, T1, T2, ...) and calibrate the readout and control.
- Ongoing G4CMP simulation of the Sapphire-substrate qubit to study phonon dynamics and qubit decoherence.
- Characterize device with 1.9 eV source first then sub-eV source next.

This work will enable us to develop our understanding of energy dissipation in qubits and take a step closer to building a prototype dark matter detector.

Acknowledgements

Acknowledgements



Collaborators

QSC@FNAL:
Aaron Chou
Lauren Hsu
Daniel Baxter
Rakshya Khatiwada
Daniel Bowring
Gustavo Cancelo
Sho Uemura
Sami Lewis
Dylan Temples
Sara Sussman
Kester Anyang
Israel Hernandez
Jialin Yu
Stella Dang
Matthew Hollister
Chris James
Grace Wagner

Northwestern:
Enectali Figueroa
Grace Bartrud
Shilin Ray

SLAC:
Noah Kurinsky
Kelly Stifter
Hannah Magoon
Noshin Tabassum

QSC@Purdue
Alex Ma
Botao Du

UW Madison
Robert McDermott
Sohair Abdullah

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Fermilab

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