Qubit-based detector for light dark matter search

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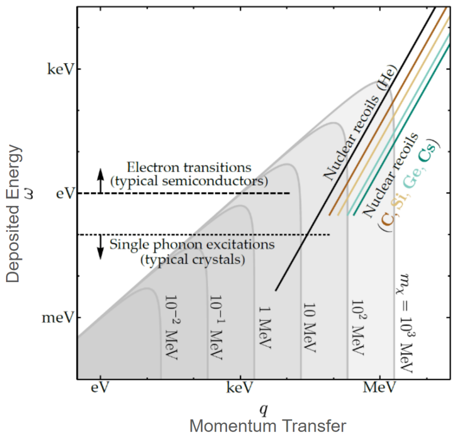


Figure 1: Bounded regions of energy deposition ω and momentum transfer q, for various dark matter masses m_χ. $\omega = qv - q^2/2m_\chi$: arXiv:1910.08092

Direct dark matter searches use:

- Nuclear recoil.
- Electron transition: 1eV-10eV Semiconductor band gap.
- Phonon excitation: Optical($E_{optical}$ =10meV-100meV) and Acoustic($E_{acoustic} < E_{optical}$).

Designing A Qubit-Based Detector

Superconducting Qubits As Dark Matter And Radiation Sensors

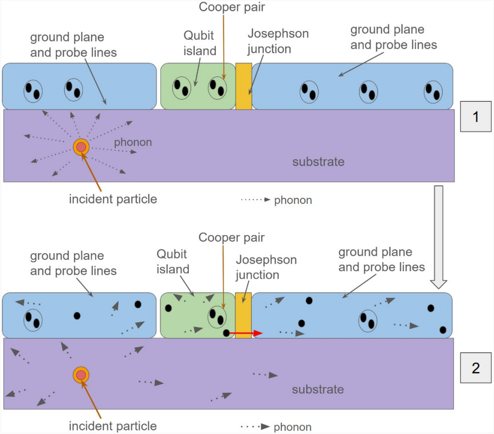


Figure 2: Energy deposition to quasiparticle tunneling.

- 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 $E > 2\Delta$. $2\Delta_{Al} = 0.34 meV$
- Quasiparticles tunneling across the junction change the qubit charge parity and may also cause qubit decoherence.

Phonon Sensing Via Quasiparticle Monitoring

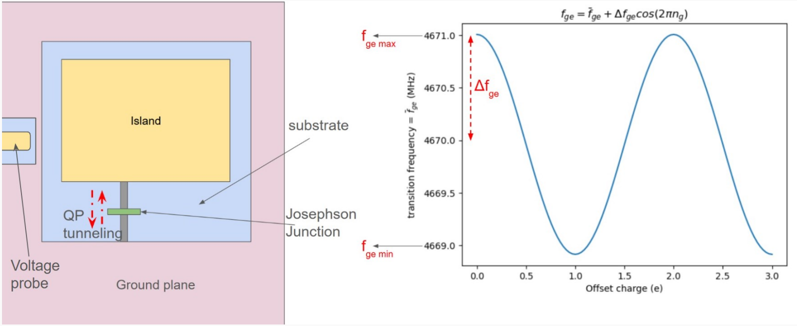


Figure 3: Left: Quasiparticle tunneling across the junction. Right: Each tunneling event changes the qubit parity (f_{ge-max} to f_{ge-min} or vice versa).

- A quasiparticle tunnels:
  - Parity changes but no change in qubit energy state. $|g\rangle \rightarrow |g\rangle$ Or $|e\rangle \rightarrow |e\rangle$
  - Parity and qubit energy state change. $|g\rangle \rightarrow |e\rangle$ Or $|e\rangle \rightarrow |g\rangle$
- The parity measured with a Ramsey measurement.
- The quasiparticle tunneling rate $\Gamma_{Tun} = \Gamma^{gg}_{Tun} + \Gamma^{ee}_{Tun} + \Gamma^{eg}_{Tun} + \Gamma^{ge}_{Tun} \propto x_{QP}$.
- Phonons of $E > 2\Delta$ reaching the island breaks Cooper pairs, generating quasiparticles.

Charge Parity Readout Methods for Detecting Energy Deposited In The Qubit Island

Assessing Parity Measurement

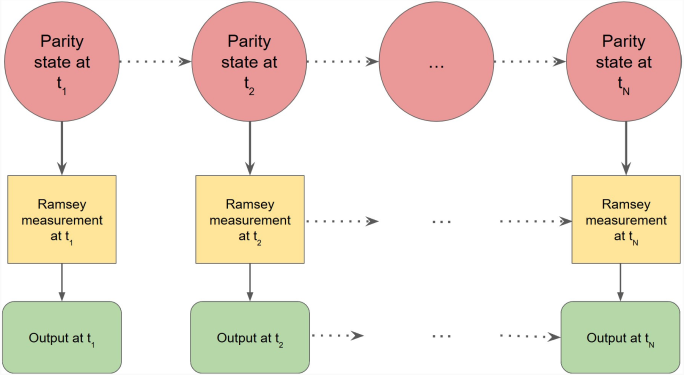


Figure 4: Structure of parity measurements

- Without errors, Ramsey measurement output corresponds to the qubit parity
- The measurement can result in errors from readout noise or decoherence.
- Statistical tools such as the Hidden Markov model could estimate the parity switching rate with reduced noise from errors to get a low threshold.

Assessing Readout Methods

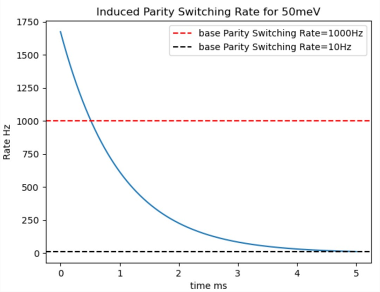


Figure 5: Comparing Base Parity Switching Rates

- Decreasing the base parity switching rate is a key metric for reducing the background.
- Energy resolution of parity measurement method to be measured with cryogenic photon source.

- Ongoing simulation study of Ramsey parity measurements as a readout method for probing the energy deposited into the qubit island.
- Simulation study of the T1 qubit readout method has been done (Led by Ryan Linehan). arXiv preprint arXiv:2404.04423 (2024). RDC8: Simulation Tools to Estimate Energy Thresholds of Superconducting Qubit-based Athermal Phonon Detectors.
  - Improving phonon collection efficiency of qubit island improves threshold.
  - Improving base qubit decay time (base T1) also improves threshold

Simulation Studies Of Energy Deposited Into Substrate

Phonon Simulation Efforts

Incorporation of phonon caustics into G4CMP for sapphire(Al_2O_3), LiF, GaAs, $CaWO_4$ and CaF_2 has been done by **Israel Hernandez**. Simulation of phonon kinematics in qubit with a sapphire substrate has been done.

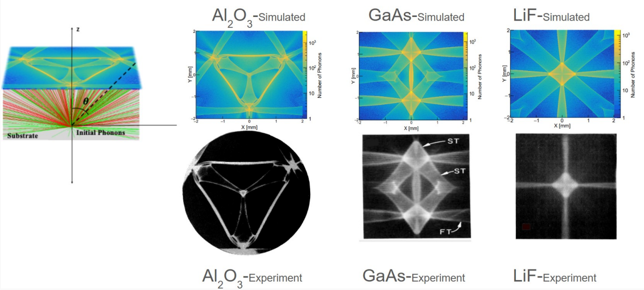


Figure 6: G4CMP Saphire Simulation.

- Hernandez, Israel, et al. "Modeling Athermal Phonons in Novel Materials using the G4CMP Simulation Toolkit." arXiv preprint arXiv:2408.04732 (2024).
- Understanding the Response of a Qubit Chip Using Novel Materials in the G4CMP Simulation Toolkit: Israel Hernandez 11/19/24, 4:45 PM

Phonon Collection Efficiency

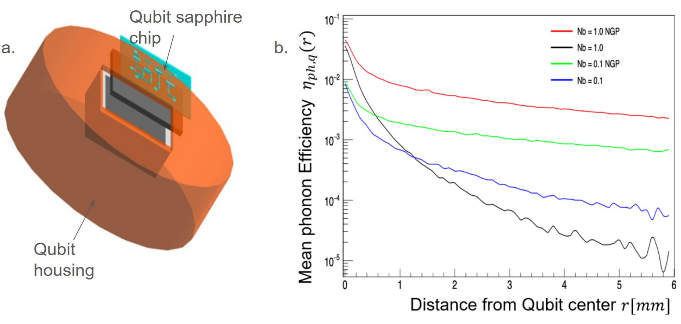


Figure 7: a. 3D rendering of qubit with Al_2O_3 substrate in a Cu housing. b. Single-qubit phonon collection efficiency ph,q versus radial distance from a given qubit island.

Single-qubit phonon collection efficiency ph,q versus radial distance from a given qubit island. Each curve is averaged over the 4 qubits simulated in our baseline geometry. This simulation is estimated for 2 different chip designs: full ground plane, limited ground plane.

Experimental Progress

Device Characterization using Cryogenic Micro-Electromechanical System (MEMS)

- To develop a prototype detector, we need to deposit energy into the substrate and superconductor film of the qubit and study its response and sensitivity.
- This requires a system to deliver energy to the detector in cryogenic environment.
- The quasiparticle tunneling rate will be measured for various energy depositions into the qubit chip.
- Studies will be conducted to understand the phonon absorption efficiency from the chip to the superconductor as a function of deposited energy and source position.

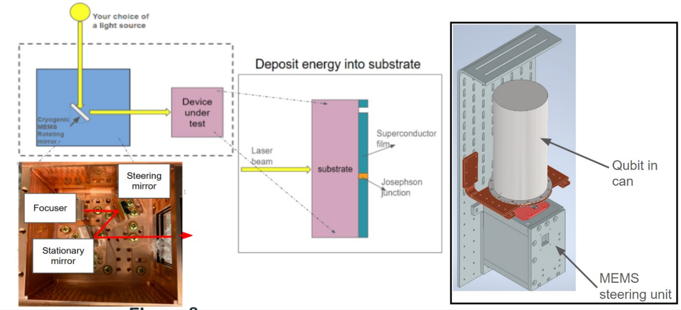


Figure 8: Qubit integration with cryogenic MEMS calibration device.

Experimental Progress: Detector Setup

- Characterization of the qubit readout setup is ongoing, and so is the installation of the MEMS and qubit integration setup.
- Modifying setup to obtain a low population of photons that can break Cooper pairs. (Coating qubit environment with IR absorbent, improving filtering)
- Getting charge-sensitive qubits from Alex Ma from Purdue University.
- Improving detector design with Qiskit metal and SQUADDS (Sara Sussman and Olivia Seidel: Fermilab)

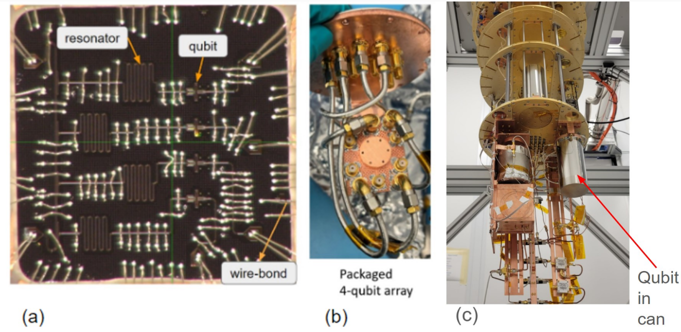


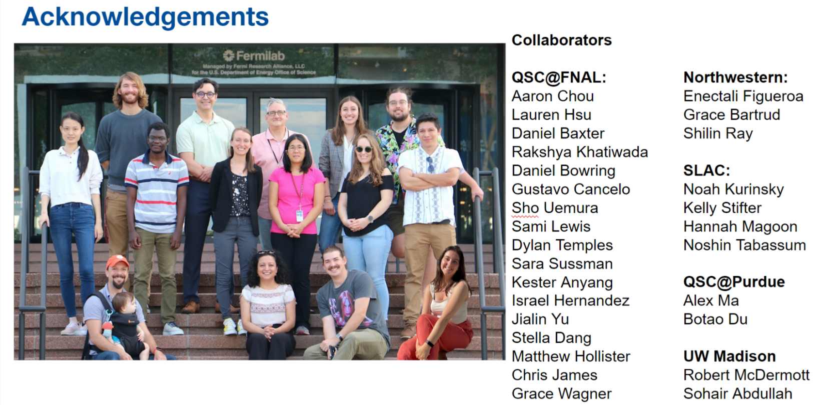
Figure 9: a. Qubit chip. b. Qubit housing. c. Dilution fridge. d. QICK

Summary and Future Plans

- Ramsey parity measurements can be used to monitor quasiparticle tunneling.
- Sapphire, a common superconducting qubit substrate, is a good target material for direct dark matter searches.
- Radiation or dark matter excites phonons in qubit substrate, which break Cooper pairs and can expedite qubit decay rate.
- Shortly, we will test integrated qubits + MEMS mirror/laser calibration system.

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

Acknowledgements



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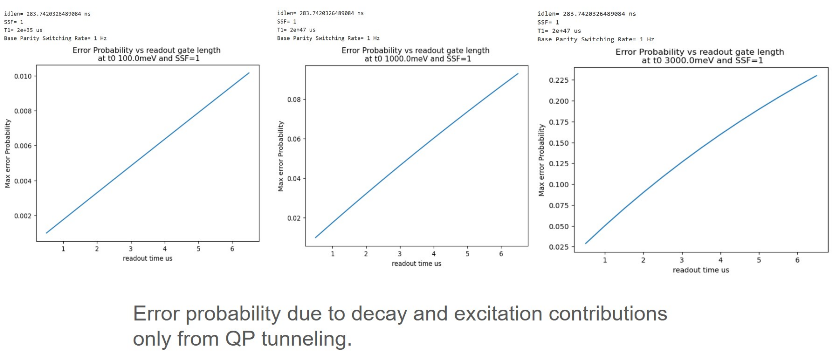
Thank you

Backup: Error probability=$P(1\|even) + P(0\|odd)$: Due to QP tunneling



```
idlen= 283.7420326489084 ns
SSF= 1
T1= 2e+35 us
Base Parity Switching Rate= 1 Hz
```

```
idlen= 283.7420326489084 ns
SSF= 1
T1= 2e+47 us
Base Parity Switching Rate= 1 Hz
```

```
idlen= 283.7420326489084 ns
SSF= 1
T1= 2e+47 us
Base Parity Switching Rate= 1 Hz
```

Error probability due to decay and excitation contributions only from QP tunneling.

Figure 10: T1 set to infinity, SSF=1.

Backup: Total error probability=$P(1 \| even) + P(0 \| odd)$

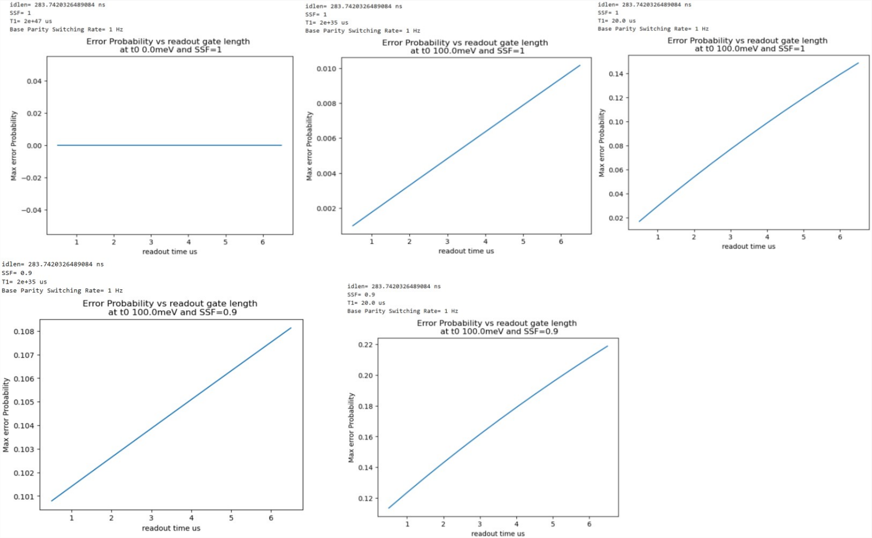


Figure 11: T1 and SSF On or Off.