Optical Strain Sensing for Particle Detection

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7 November 2023
CPAD Workshop -- RDC8
Primary Motivation: Phonon Bursts from Stress Release

Dark Matter Detectors
- Low energy excess < 50 eV
- Stress release produces $\sigma(10)$ eV phonon bursts

Superconducting Qubits
- Rate of phonon burst decays as device thermalizes
- Inconsistent with radioactive background

Common source: stress
- Mounting stress (glue)
- Surface stress (deposited materials)
**Embedded SiN Optical Strain Sensors**

**Stress-optical effect:** stress modulates the refractive index of the resonator.

→ Modulates transmission through waveguide for fixed $\lambda_{\text{optical}}$

Provides readout channel to directly probe crystal stress and substrate deformation.

**Embedded sensors:** surface free for deposition of primary sensors (qubit, MKID, TES, CCD).
Embedded SiN Optical Strain Sensors

Photonics: microwave-optical transduction via piezo actuation

Sensing: micro-mechanical accelerometers with integrated test mass (Windchime)

- Sub-ns optical response
- Optical Q > $10^6$
- Sensitivity: $10^{-7}$ g/$\sqrt{\text{Hz}}$ (accelerometer device)

Opportunities Enabled by Strain Sensing

Crystalline Dark Matter Detectors

- Anticoincidence to reject low energy stress events
- Possibility for ER/NR discrimination (background rejection & signal ID)

Direct Particle Detection

- Resonant scattering processes?
- Athermal phonon sensing?
- Acoustic phonon sensing?

Superconducting Qubits

- Evaluate stress in chip design
- Conclusively determine if stress is progenitor of phonon burst decoherence
Detection of Resonant Scattering Processes

Resonant scattering (e.g., Mössbauer): recoil energy imparted into entire crystal lattice

→ Zero-phonon final state (no detectable quanta in target)

→ Necessitates a backing detector to measure reduced flux when on-resonance

A fixed-in-place crystal target deforms from the microscopic recoil momentum of the lattice → generates stress

Can this be leveraged to develop an on-chip detector for resonant scattering?
Resonant Neutrino Scattering

Atomic neutrino capture (bound state e-): \( \bar{\nu}_e + A(Z) + e^- \rightarrow A(Z - 1) \).

A(Z-1) decays through inverse process, resonant enhancement of cross-section:

- \(10^{-17} \text{ cm}^2\) (Suzuki et al., 2010)
- \(10^{-22} \text{ cm}^2\) (Potzel, 2009),
- \(10^{-42} \text{ cm}^2\) (Raghavan, 2005)

for various targets, contexts.

Target reactor neutrinos using device substrate containing \(\nu\)-capture candidates

- Low energy (10s keV) -- small resonant spectral density
- Background (IBD > 1.8 MeV, CE\(\nu\)NS, \(\nu\)-e scattering) -- rate calculations ongoing
- Solid state considerations: Debye-Waller factor, line broadening factors

\[ \sigma_{\alpha\alpha'}(E) = \pi \cdot \lambda^2 \cdot \frac{\Gamma_{\alpha} \Gamma_{\alpha'}}{(E - E_{\text{res}})^2 + (\Gamma_T/2)^2}, \]

Cross-section scales as \(1/E_{\nu}^2\)
Objective: evaluate the feasibility of using these strain sensors for particle detection

- Do these sensors directly (or indirectly through phonons) respond to radiation?
- What is the spatial resolution of these devices?
- What is their energy resolution and threshold?

Use these results to inform design of resonant scattering detector
Conclusion

• Optical ring resonator strain sensors offer insight into stresses internal to device
• Dark matter searches: reject stress-induced phonon backgrounds
• Qubits: evaluate mask design to minimize phonon bursts
• Potential avenue for directly observing resonant scattering processes
• Preliminary evaluation of strain sensors as particle detectors underway at FNAL

Thank You!
Device Packaging

Manual alignment

Packaged device (cryo-compatible)

Photonic Wire Bonding (S. Preble, RIT)
Recoilless Neutrino Absorption Candidates

Table I. Candidates for recoilless neutrino absorption.

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>$Q$ (keV)</th>
<th>$\tau$ (yr)</th>
<th>$f_R$ a</th>
<th>$\alpha$ $(10^{-4})$</th>
<th>$\gamma$ $(10^{-16})$</th>
<th>$\sigma_{\text{eff}}$ $(10^{-36} \text{ cm}^2)$</th>
<th>$\sigma_{\text{eff}}/\tau$ b</th>
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</thead>
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<tr>
<td>$^3$H</td>
<td>18.6</td>
<td>12.3</td>
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<td>200 c</td>
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<td>0.1</td>
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<td>$^{63}$Ni</td>
<td>68</td>
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<td>$^{93}$Zr</td>
<td>60</td>
<td>$1.5 \times 10^6$</td>
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<tr>
<td>$^{107}$Pd</td>
<td>33</td>
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<td>$10^{-16}$</td>
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<td>$^{151}$Sm</td>
<td>76</td>
<td>90</td>
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<td>$^{171}$Tm</td>
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<td>$^{187}$Re</td>
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<td>$^{157}$Tb</td>
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<td>150</td>
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<td>$^{163}$Ho</td>
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<td>$^{205}$Pb</td>
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<td>$10^{-11}$</td>
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Table I from Kells & Schiffer, PRC (1983).
Abstract

Optomechanical strain sensing provides attractive opportunities for novel particle detection schemes, as well as studying stress-induced (i.e. non-radiogenic) phonon bursts, which have been demonstrated to limit the coherence times of superconducting qubits and are a suspected culprit in the low energy excesses observed by many dark matter direct detection experiments. We are investigating SiN microring optical resonator strain sensors, developed at Purdue University, for applications in fundamental particle sensing and QIS. These sensors can be embedded in the substrate upon which superconducting qubits are patterned, providing a handle to distinguish decoherence events of radiogenic origin from those due to crystal stress. In a similar way, these sensors can be operated in conjunction with superconducting detectors (e.g., MKIDs, TES) to enable multi-channel readout of particle interactions in the device substrate or serve as anticoincidence detectors, which may be required to identify low-energy interactions from dark matter particles down to the fermionic thermal relic mass limit of a few keV. Such sensors can potentially be used to directly observe resonant scattering processes of gamma rays (and perhaps neutrinos) where no detectable quanta are produced in the target, via the microscopic stress induced by the momentum transfer to the (fixed-in-place) crystal lattice as a whole. These strain sensors have so far found application in photonics and communications, but have yet to be adopted for HEP uses, where they can provide unique capabilities in the search for dark matter as well as understanding and improving the coherence times of superconducting qubits.

Talk format: 12+3
References