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Optical Strain Sensing for Particle Detection

Dylan J Temples

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10 November 2023

CPAD Workshop -- RDC8

QUANTUM SCIENCE CENTER

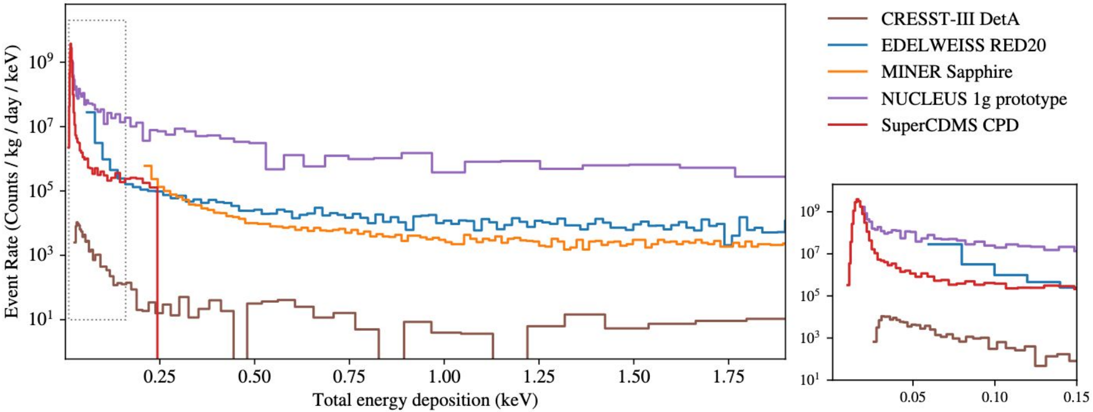
FERMILAB-SLIDES-23-347-ETD

Primary Motivation: Phonon Bursts from Stress Release

Dark Matter Detectors

- Low energy excess < 250 eV

SciPost Phys. Proc. **9**, 001 (2022) [EXCESS]



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- Stress release produces $\mathcal{O}(10)$ eV phonon bursts

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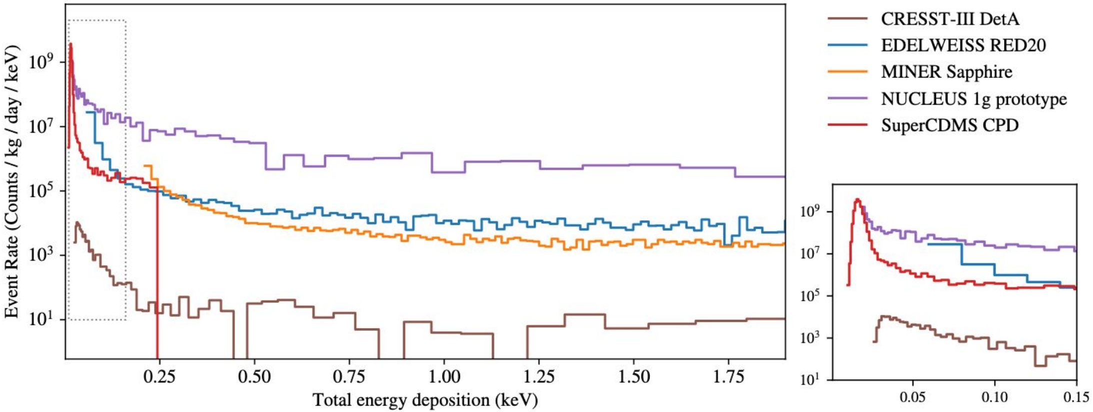

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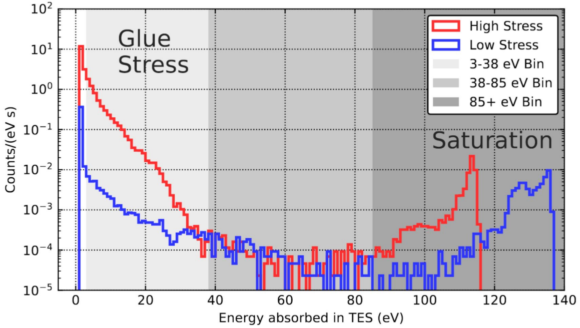

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Superconducting Qubits

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

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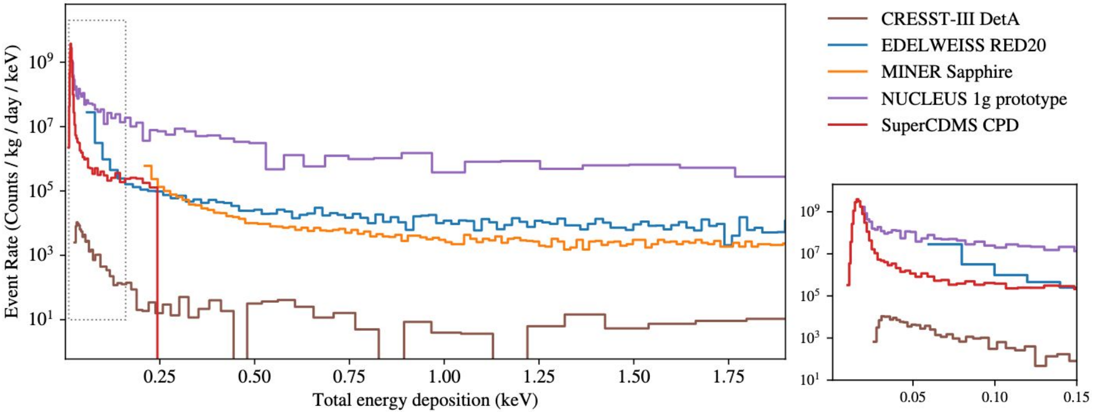

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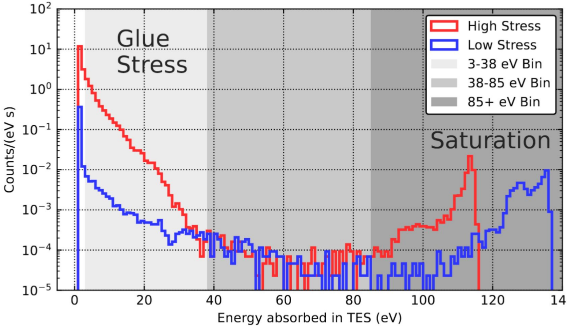

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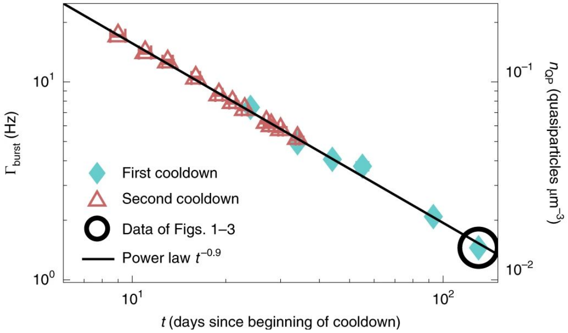

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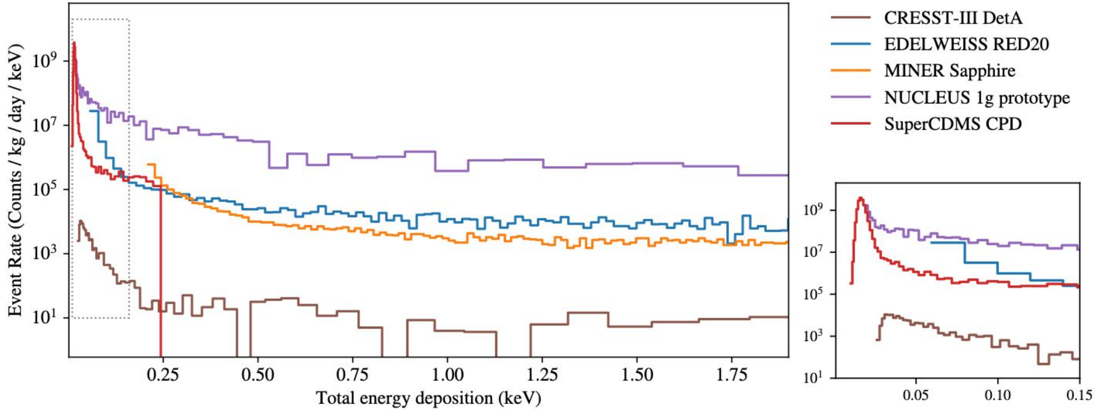
Common source: stress

- Mounting stress (glue)
- Surface stress (deposited materials)

SciPost Phys. Proc. **9**, 001 (2022) [EXCESS]



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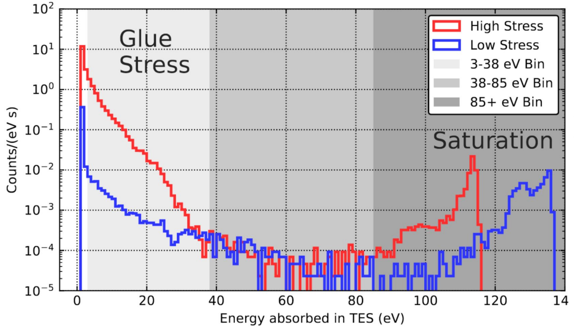

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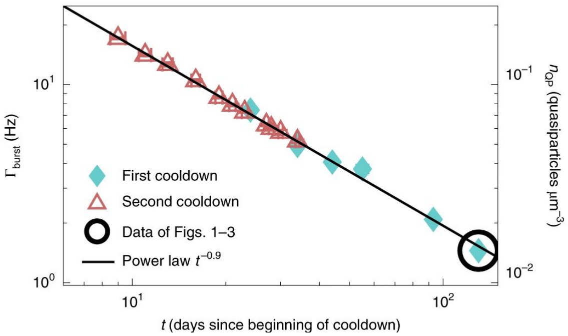
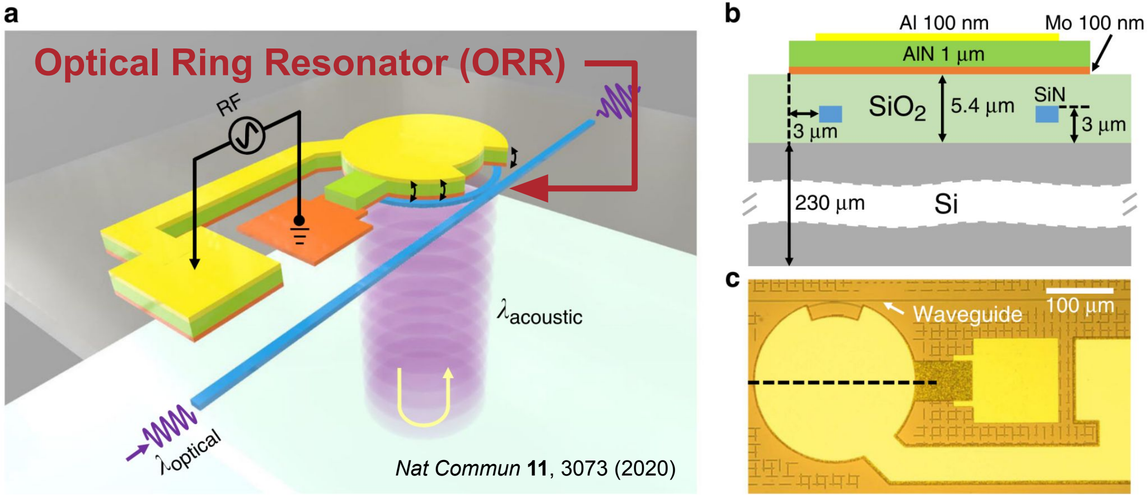


Embedded SiN Optical Strain Sensors



OxideMEMS Lab, Purdue

A. Attanasio

S. Bhave (PI)

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

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

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

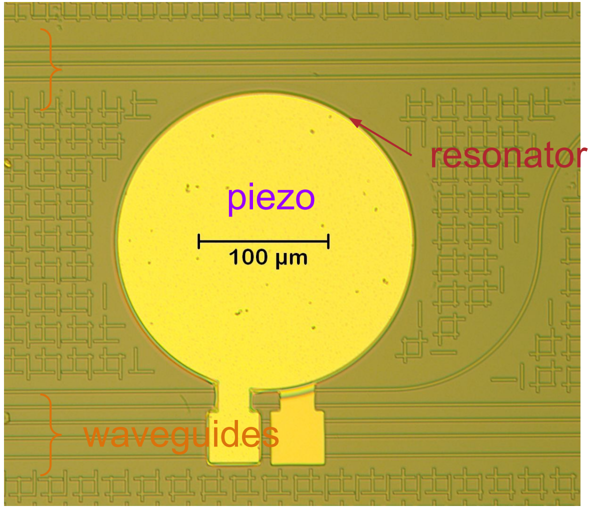
Embedded sensors: surface free for deposition of primary sensors (qubit, MKID, TES, CCD).

Embedded SiN Optical Strain Sensors

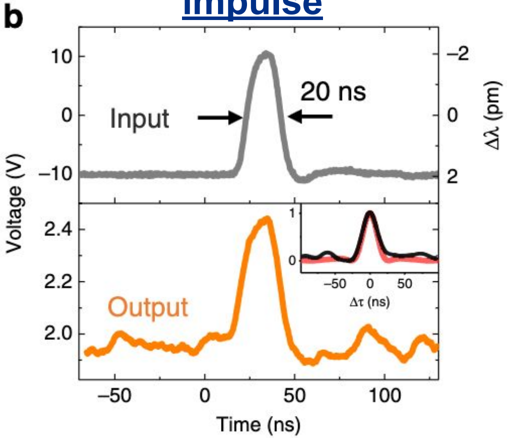
Photonics: microwave-optical transduction via piezo actuation   Tian et al. *Nat Commun* **11**, 3073 (2020)

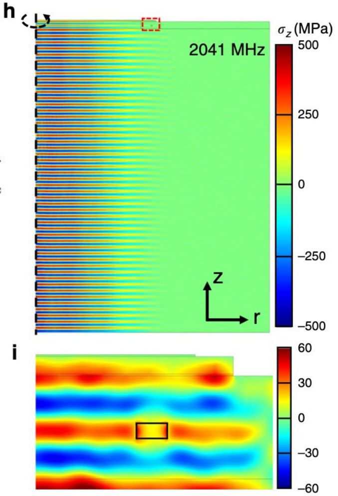
Sensing: micro-mechanical accelerometers with integrated test mass (Windchime)

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



Device response to piezo impulse





Windchime Accelerometer

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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)

Superconducting Qubits

- • Evaluate stress in chip design
- ➢ Conclusively determine if stress is progenitor of phonon burst decoherence

Direct Particle Detection

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

DM: Background Rejection and ER/NR Discrimination

Stress background rejection & ER/NR discrimination strongly dependent on ORR response to radiation.

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Scenario 1. ORR inert to athermal phonons

Stress background rejection:

- Phonon sensor (TES, MKID) sees event
- Coincident ORR response?
  - Yes: stress release event
  - No: potential DM event

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Scenario 2. ORR sensitive to athermal phonons

- Primary sensing channel: ionization
- ER/NR discrimination via applied E field

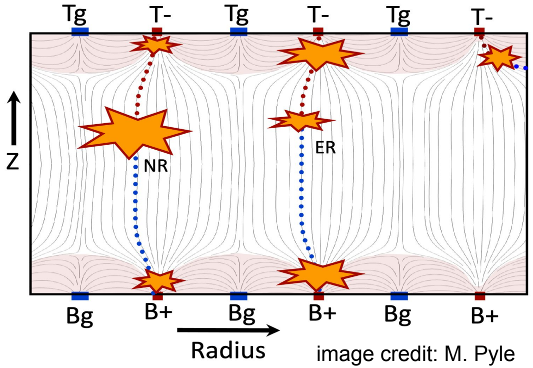

image credit: M. Pyle

SuperCDMS piZIP: ER/NR produce different ratio of prompt phonons to phonons from charge drift.

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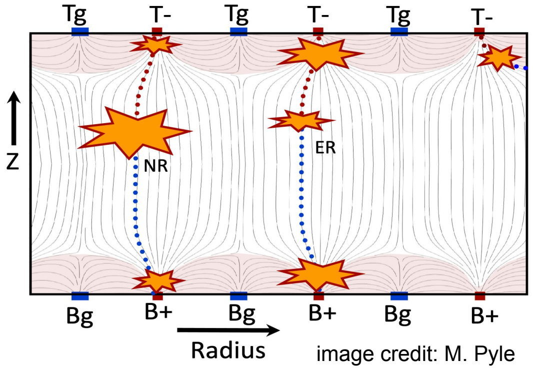
ER/NR discrimination(?):

- Hypothesis: NRs produce more stress than ER (disfavors ionization)
- Ratio of signal in primary sensor to ORR lower for NRs



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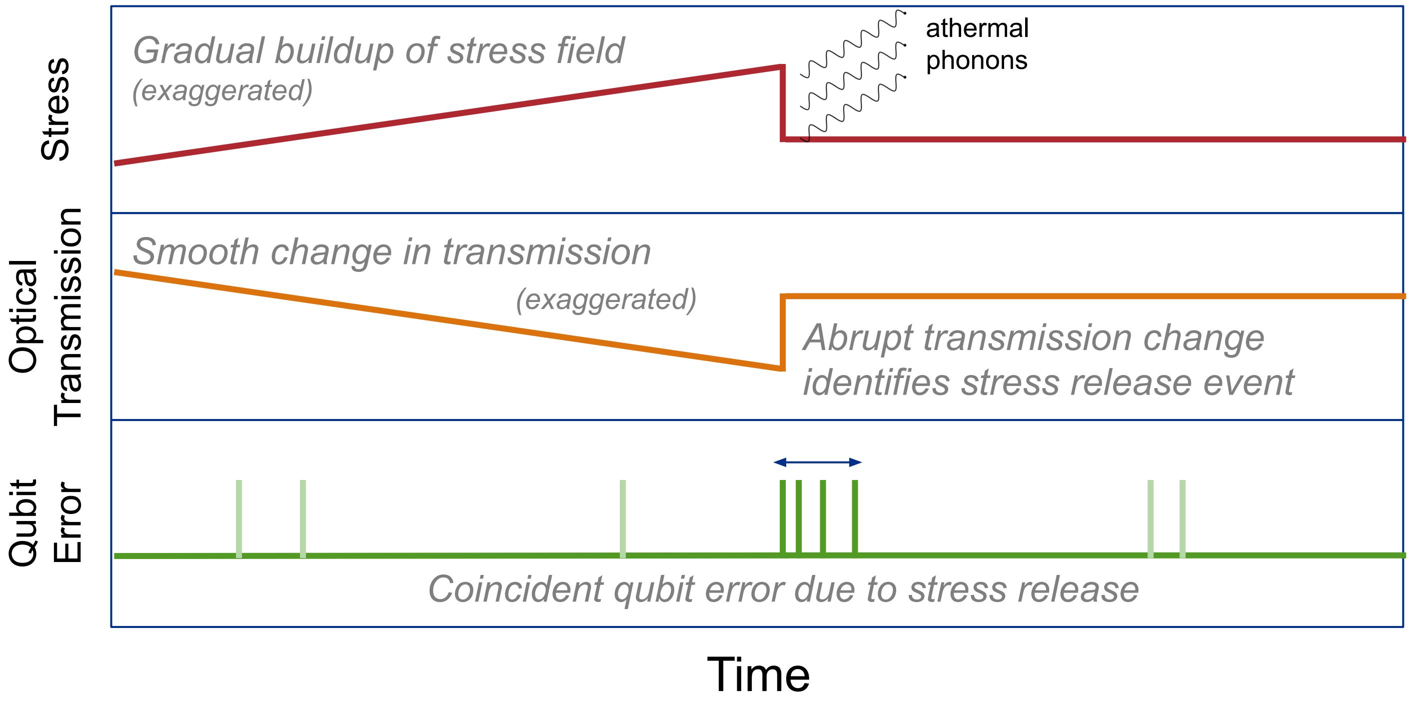
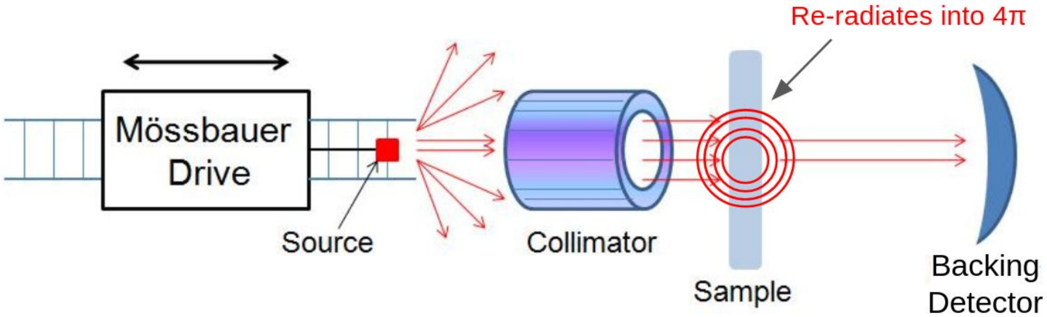
Identifying Stress as Source of Phonon-Induced Qubit Errors



Detection of Resonant Scattering Processes



Resonant scattering (Mössbauer)

- ➢ Recoil energy imparted into entire crystal lattice
- ➢ Zero-phonon final state (no detectable quanta in target)

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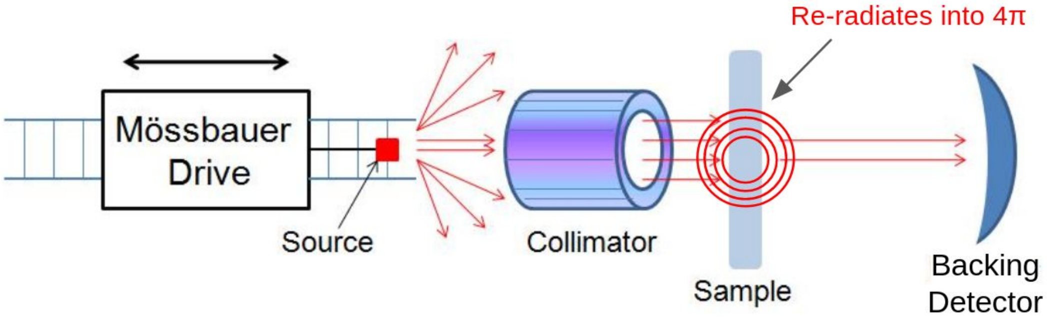

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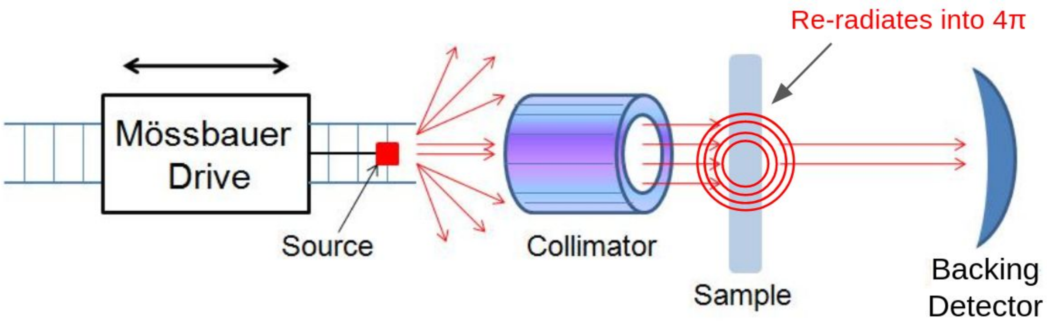

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Atomic neutrino capture (bound-state e-): $\bar{\nu}_e + A(Z) + e^- \longrightarrow A(Z-1).$

Resonant enhancement in cross-section

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

ν deBroglie wavelength

- As high as 10^{-17} cm^2 (Suzuki et al., 2010)
- **Cross-section scales as $1/E_\nu^2$**

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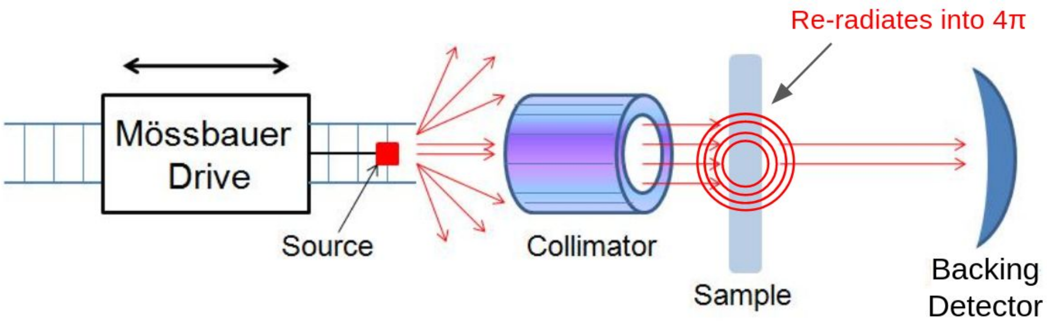

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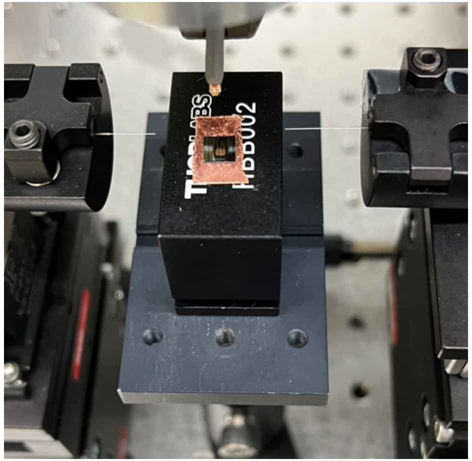
Sticking points: solid state factors, neutrino fluxes & spectral densities, backgrounds

Device Packaging

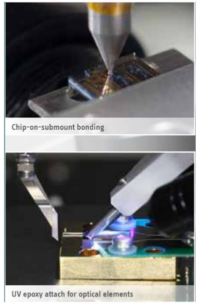
Manual alignment



Packaged device (cryo-compatible)

Fiber Attach at RIT

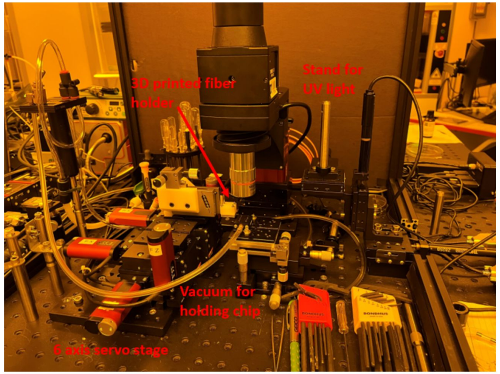
Ficontec 'align-&-attach' platform



Source: ficontec website

- ✓ Very similar to TAP's tool
- ✓ Highly customizable
- ➢ Long training time

RIT's optical packaging setup



Photonic Wire Bonding (S. Preble, RIT)

Improving light coupling into instruments with integrated photonic and low temperature sensors

Nov 9, 2023, 1:15 PM

15m

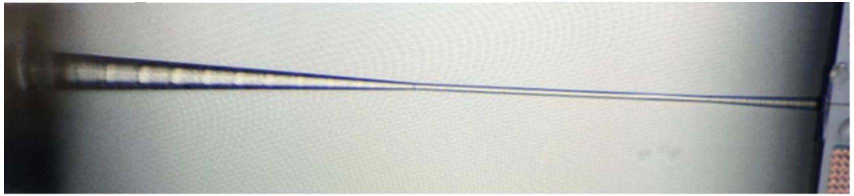
51/1-102 - Kavli Auditorium (SLAC)

RDC8

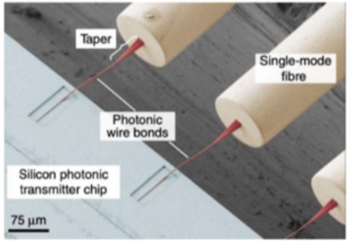
Speaker

Miguel Daal (Tel Aviv University)

M. Daal @ CPAD



Source: vanguard automation website

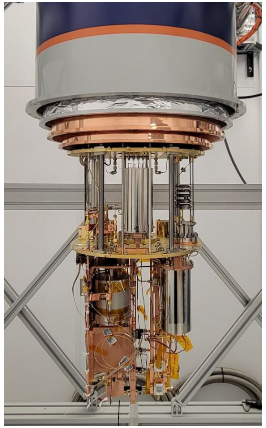


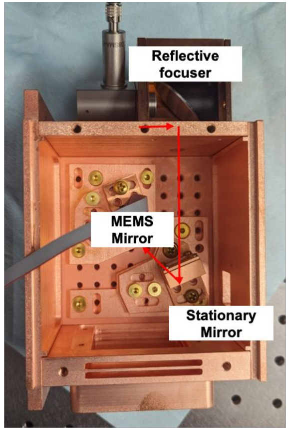
Preliminary R&D at Fermilab

Objective: evaluate the feasibility of using these strain sensors for particle detection

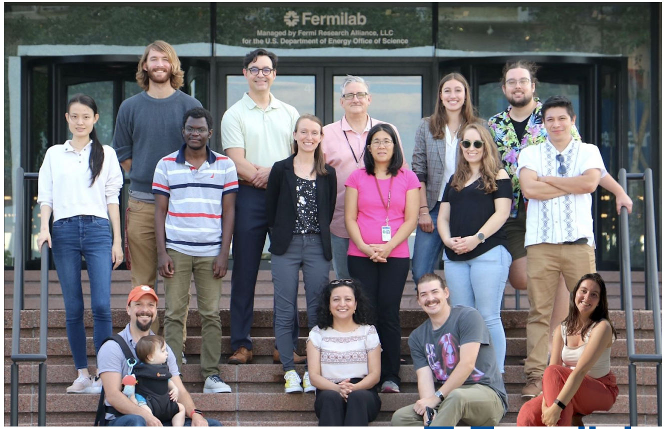
- Do these sensors directly (or indirectly through phonons) respond to radiation?
- What is the spatial resolution of these devices?
- What is their energy resolution and threshold?

Use these results to inform stress evaluation & design of resonant scattering detector





See **N. Tabassum**'s talk (RDC7 11/8) for MEMS mirror system info!



3 open postdoc positions at Northwestern in DM/QIS:
https://figueroa.physics.northwestern.edu/jobs/index.html

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
  - Currently purchasing optical source, readout electronics
  - Fridge space allocated in low-background facility (QUIET)

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Postdoctoral Research Award

Thank You!

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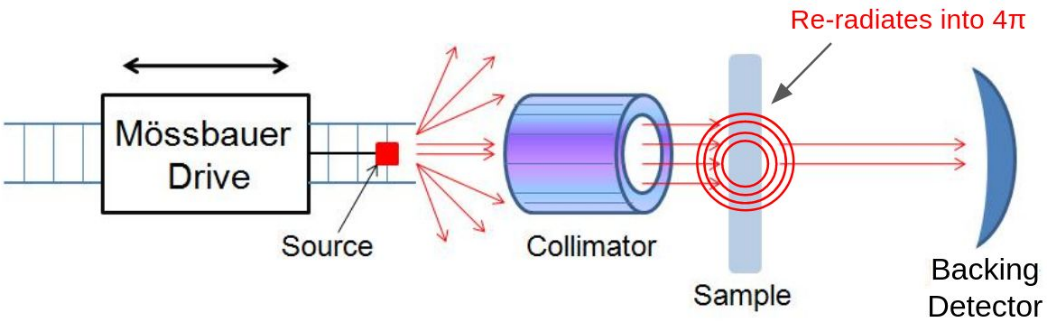
Recoilless Neutrino Absorption Candidates

TABLE I. Candidates for recoilless neutrino absorption.

Nuclide	Q (keV)	τ (yr)	f_R[a]	α (10^{-4})	γ (10^{-16})	σ_{eff} (10^{-36} cm^2)	σ_{eff}/τ[b]
^{3}H	18.6	12.3	0.40	200[c]	8	0.1	1.0
^{63}Ni	68	92	0.07	1	1	10^{-9}	10^{-9}
^{93}Zr	60	1.5×10^{6}	0.18	1	7×10^{-5}	10^{-12}	10^{-16}
^{107}Pd	33	6×10^{6}	0.62	1	2×10^{-5}	10^{-11}	10^{-16}
^{151}Sm	76	90	0.11	1	1	10^{-9}	2×10^{-9}
^{171}Tm	97	1.9	0.04	1	50	5×10^{-9}	3×10^{-7}
^{187}Re	2.6	4×10^{10}	1.0	1000[d]	10^{-9}	2×10^{-7}	10^{-15}
^{193}Pt	61	50	0.29	1	2	3×10^{-8}	8×10^{-8}
^{157}Tb	58	150	0.29	0.4[d]	0.7	2×10^{-9}	10^{-9}
^{163}Ho	2.6	7000	1	73[d]	0.01	7×10^{-3}	1×10^{-4}
^{179}Ta	115	1.7	10^{-2}	0.5[d]	60	10^{-10}	6×10^{-9}
^{205}Pb	60	1.4×10^{7}	0.3	8[d]	10^{-5}	10^{-11}	10^{-16}

- Table I from Kells & Schiffer, PRC (1983).

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-): $\bar{\nu}_e + A(Z) + e^- \longrightarrow A(Z-1).$

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

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

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

ν deBroglie wavelength

for various targets, contexts.

Cross-section scales as $1/E_\nu^2$

Target reactor neutrinos using device substrate containing ν-capture candidates

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

References

[1] Tian *et al*. Hybrid integrated photonics using bulk acoustic resonators. *Nat Commun* **11**, 3073 (2020).

[2] Adari *et al*. EXCESS workshop: Descriptions of rising low-energy spectra. *SciPost Phys. Proc.* **9**, 001 (2022).

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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.