Searching for Light Dark Matter with Narrow-Gap Semiconductors: The SPLENDOR Experiment

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Dark Matter Detection: Last 10 Years

- Lots of focus on DM-electron interactions
- Many experiments probing DM masses in the MeV-GeV range

Mass reach is limited by O(eV) band gaps of Si/Ge
Searching Below the MeV Scale

- Low kinetic energy of DM requires targets sensitive to very small energy depositions
- Existing detection technologies have O(eV) thresholds
- Probing fermionic DM with masses below O(MeV) requires new detection techniques

Adapted from arXiv:2203.08297
Next-Generation Experiments

Novel narrow bandgap semiconductors

Dirac materials and superconductors

Optical phonons in polar crystals
The SPLENDOR Experiment

• **Search for Particles of Light Dark Matter with Narrow-Gap Semiconductors**

• SPLENDOR is developing novel single crystal semiconductors with bandgaps of \(O(1-100 \text{ meV})\)

• Single crystal synthesis allows for scalable substrates with lower dark rates than existing heavily-doped IR-sensitive photodiodes

• Materials have highly-anisotropic band structures
  - Providing sensitivity to daily DM modulation effects
Dark Matter-Electron Scattering in Semiconductors

- Inelastic scattering process
- Can formulate in terms of the Loss Function
  - Experimentally measurable and theoretically calculable

\[
\Gamma(v_x) = \int \frac{d^3q}{(2\pi)^3} |V(q)|^2 \left[ 2\frac{q^2}{e^2} \text{Im} \left( -\frac{1}{\varepsilon(q, \omega_q)} \right) \right]
\]

\[
\mathcal{W}(q, \omega) \equiv \text{Im} \left( -\frac{1}{\varepsilon(q, \omega)} \right)
\]


- What materials can we use?
In-House Materials Discovery

- LANL has the in-house capability to synthesize new single-crystal materials
  - Using flux growth and chemical vapor transport techniques
- Many small bandgap candidate materials grown and characterized

**Flux Growth**

- Quartz tube
- Quartz wool
- Flux
- Single Crystals
- Temperature profile: 200°C/h from Room-T to T_f, T_f to T_cryo

**Chemical Vapor Transport**

- Temperature range: T_f to T_cryo

**Examples of Materials Synthesized**

- $\text{Eu}_5\text{In}_2\text{Sb}_6$
- $\text{EuZn}_2\text{P}_2$
Materials Characterization

- Initial resistivity measurements indicate activated behavior with band gaps of $O(1-100 \text{ meV})$
  - Indicates sub attoAmps dark rates at mK temperatures
- Materials have photoresponse to IR light
- Beginning to show signs of full charge collection
  - Ongoing studies at lower temperatures
Materials Theory

- Use many-body perturbation theory to calculate loss function from first principles

\[
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\]

Band structure of Eu$_5$In$_2$Sb$_6$  
Dielectric function via DFT at zero momentum
Detection Scheme

- Use well-known point-contact style detector design
- Design goal: minimize total capacitance

\[ \sigma_E \sim E_{gap} \times \sigma_V \times (C_{detector} + C_{input} + C_{parasitic}) \]

charge resolution (goal: \( \sigma_{e^-} \sim O(1) \text{ e}^- \))
Charge Amplifier Design

- Split-stage cryogenic HEMT-based amplifier
  - 4 K gain stage with 200 pF HEMT
  - 10 mK buffer stage with 1.6 pF HEMT (buffers the upstream capacitance)

- Detector housing
  - Minimize capacitance by placing detector material as close to 10 mK board as possible

- Currently testing in a BlueFors dilution refrigerator!
Preliminary Performance of Amplifier

- First input noise measurements in non-optimized setup
  - Indicates a charge resolution of $22e^-$!
Summary and Outlook

• Narrow bandgap materials can significantly expand our low-mass DM reach
  – Using tried-and-true detection techniques

• Near-term goals of SPLENDOR:
  – Optimization of HEMT operating conditions
  – Hunting noise sources
  – Surface DM search dataset expected later this year with prototype detector
Thank you!
Backup
HEMT IV Curves

200 pF HEMT B13 at 4K

1.6 pF HEMT B2A5 at 380mK