Low-Temperature Anomaly in Dielectric Behavior: Excited Dipole States and Neutrality Induction in Germanium Detectors for MeV-Scale Dark Matter Detection

Narayan Budhathoki
University of South Dakota

CONFERENCE ON SCIENCE AT THE SANFORD UNDERGROUND RESEARCH FACILITY

South Dakota Mines campus, May 14-16, 2024

Support by: **DE-SC0024519** and **OISE-1743790**

Motivation

- **Utilizing Germanium Detectors' Potential**
  - Energy resolution optimization
  - Ultra low energy threshold

- **Enhancing Sensitivity to Low-Energy Events**
  - Exploring novel materials
  - Innovative techniques
  - Sensitivity to detect 1 e-h pair

- **Understanding Freeze-Out Phenomenon**
  - Helium temperature studies
  - Dipole state characterization
  - Theoretical modeling

- **Proposing Innovative Detector Design**
  - Internal charge amplification

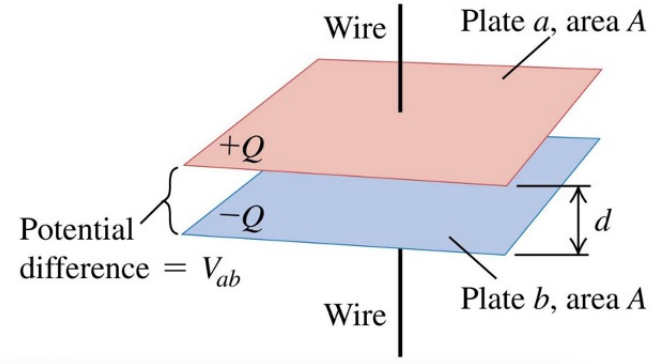
Background

Capacitor

Stores electrostatic energy in an electric field.
The space between filled by dielectric.
Factors:

- ✓ Effective area.
- ✓ distance
- ✓ Dielectric

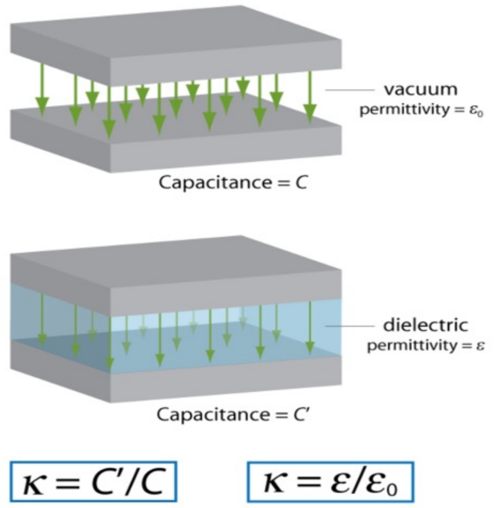
$$C = \frac{\varepsilon \times A}{d}$$



Dielectric constant

Permittivity is a quantity that describes the effect of an electric field: the higher the permittivity the more the materials tends to reduce any field set up in it.
Factors:

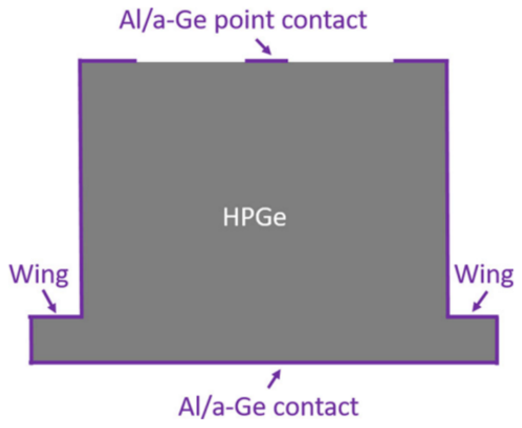
- ✓ Changing field
- ✓ Permanent Dipoles
- ✓ Temperature

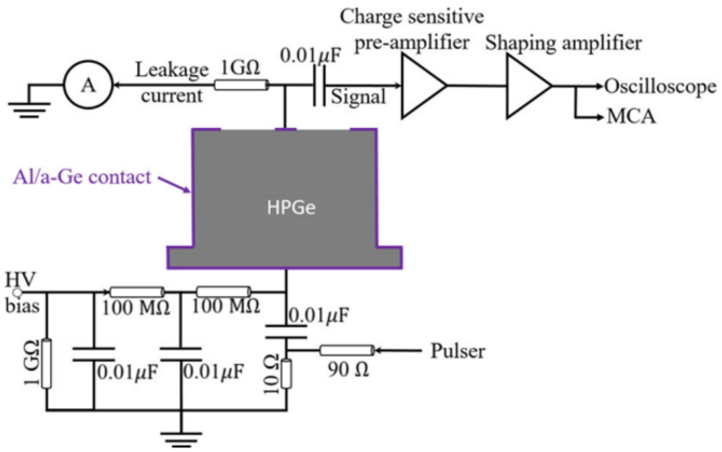


Research Methodology

Detector information: USD Grown, named ‘RL’

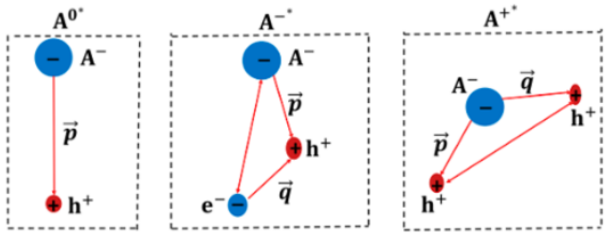
- Impurity: $6.2 \times 10^9/cm^3$
- Dimension: $18.8\ mm \times 17.9\ mm \times 10.7\ mm$
- Depletion Voltage: 400 V
- Capacitance (depleted around 80 K) = 4.51pF
- $E_a - E_V = 0.01\ eV$
- $\text{Capacitance}(C) = \frac{K\varepsilon_0 A}{d}$



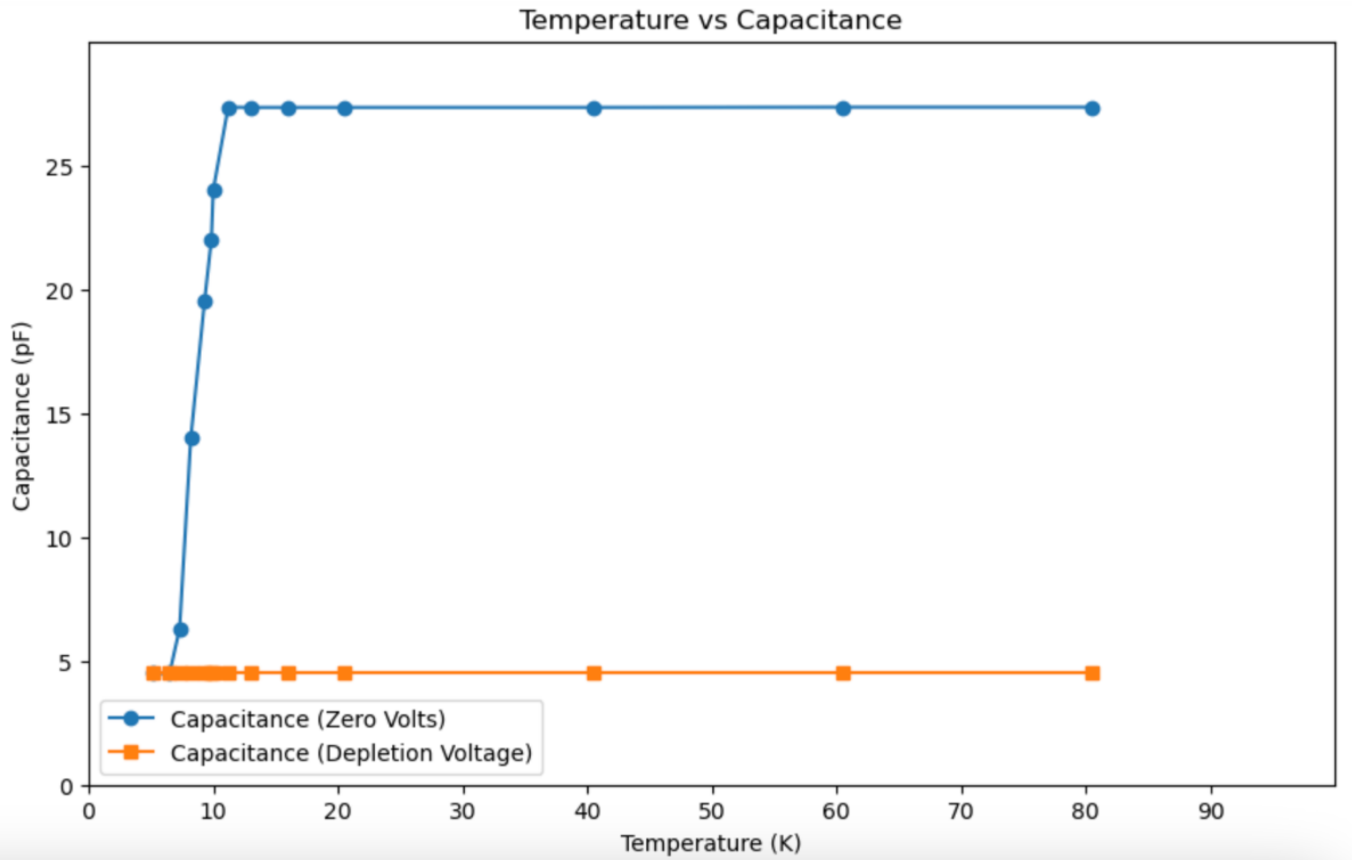


“W.-Z. Wei, H. Mei, K. Kooi, D.-M. Mei, J. Liu, J.-C. Li, R. Panth, G.-J. Wang, "Development of Planar P-Type Point Contact Germanium Detectors for Low-Mass Dark Matter Searches," arXiv: 2105.02109. Eur. Phys. J. C 82 (2022) 3, 203) “

Freeze out Phenomena



"Mei, D-M and Panth, R and Kooi, K and Mei, H and Bhattarai, S and Raut, M and Acharya, P and Wang, G-J, "Evidence of cluster dipole states in germanium detectors operating at temperatures below 10 K", AIP Advances 12, 065113 (2022) "



The range of confinement (Dipole)

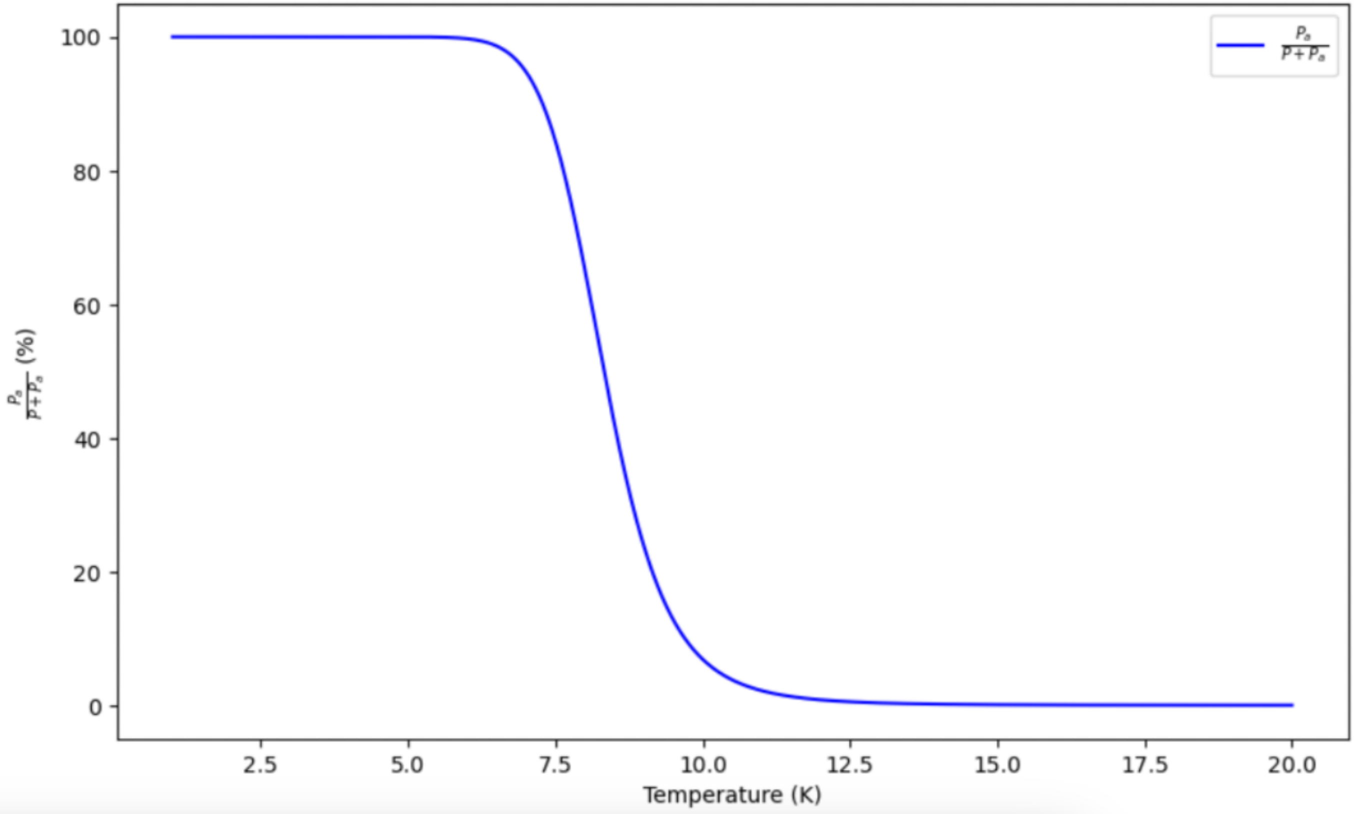
Onsager radius(R)= $\frac{1}{4\pi\epsilon K_B T}$

Mei, D-M and Panth, R and Kooi, K and Mei, H and Bhattarai, S and Raut, M and Acharya, P and Wang, G-J, "Evidence of cluster dipole states in germanium detectors operating at temperatures below 10 K", AIP Advances 12, 065113 (2022)

Behavior of Bound Charge with Temperature

$$\frac{P_a}{P_a + P} = \frac{1}{\frac{N_v}{4N_a} e^{\left[\frac{-(E_a - E_v)}{K_B T}\right]} + 1}$$

N_v=density of States in valence band
N_a= $6.2\times10^9/cm^3$
$E_a - E_v$= 0.01 eV
P_a= number of holes bound to acceptors
P= total free holes in the valence band



7

GeICA Process

Amplification Factor $(A) = e^{(N_d \times \sigma_0 \times \sqrt{E} \times d)}$

N_d= impurity density,

σ_0= $5\times10^{-13}\ cm^{-2}$(Cross section for impact ionization of impurities)

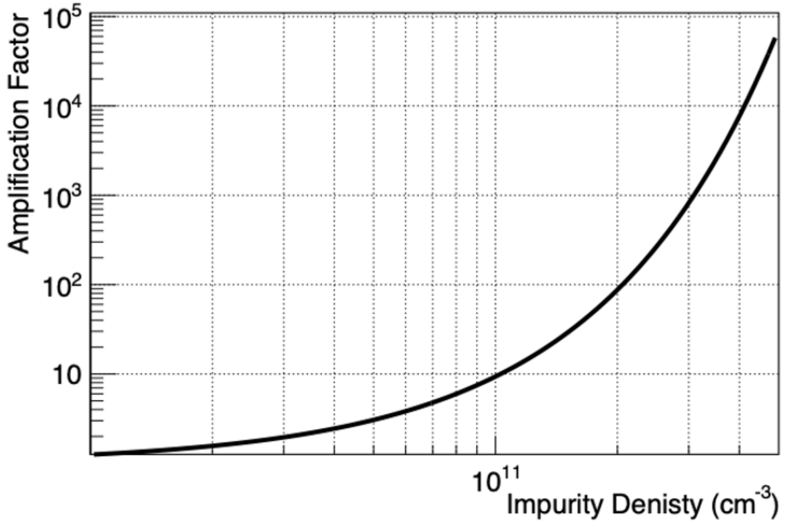
$$DM + Ge \rightarrow Phonon\ emission\ (\ 0.1eV)(100meV)$$

$$Phonon + excited\ dipole \rightarrow e - h\ Created$$

1phonon=26meV, 0.1 eV= 4 phonon, BE(dipole)=5-8meV

After applying electric field

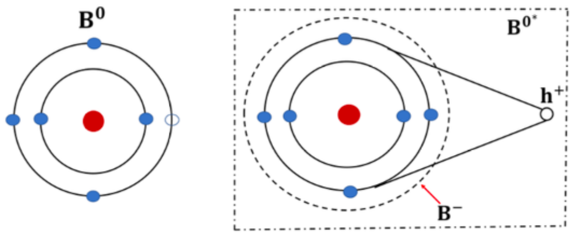
e-h drifted (K.E≈ $0.1eV$) $\xrightarrow{Impact\ Ionization(A)}$ $Additional\ e - h\ created$



"Mei, D. Exploring the Potential of Residual Impurities in Germanium Detectors for MeV-Scale Dark Matter Detection. *J Low Temp Phys* (2024)"

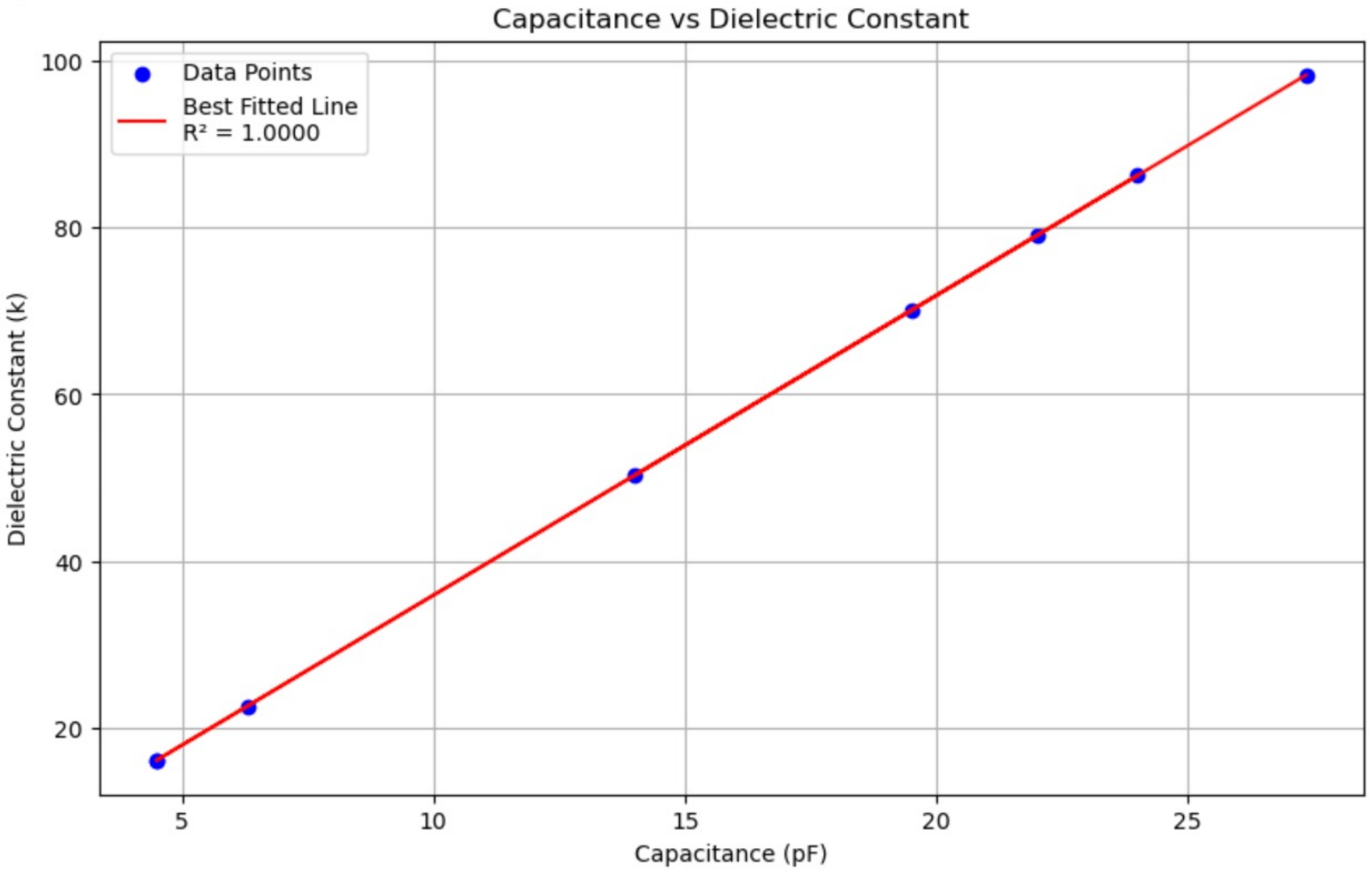
- $h^+ + A^- \rightarrow A^{0*}$
- $h^+ + A^{0*} \rightarrow A^- + 2h^+$

- $h^+ + A^{0*} \rightarrow A^{+*}$
- $h^+ + A^{+*} \rightarrow 2h^+ + A^{0*}$

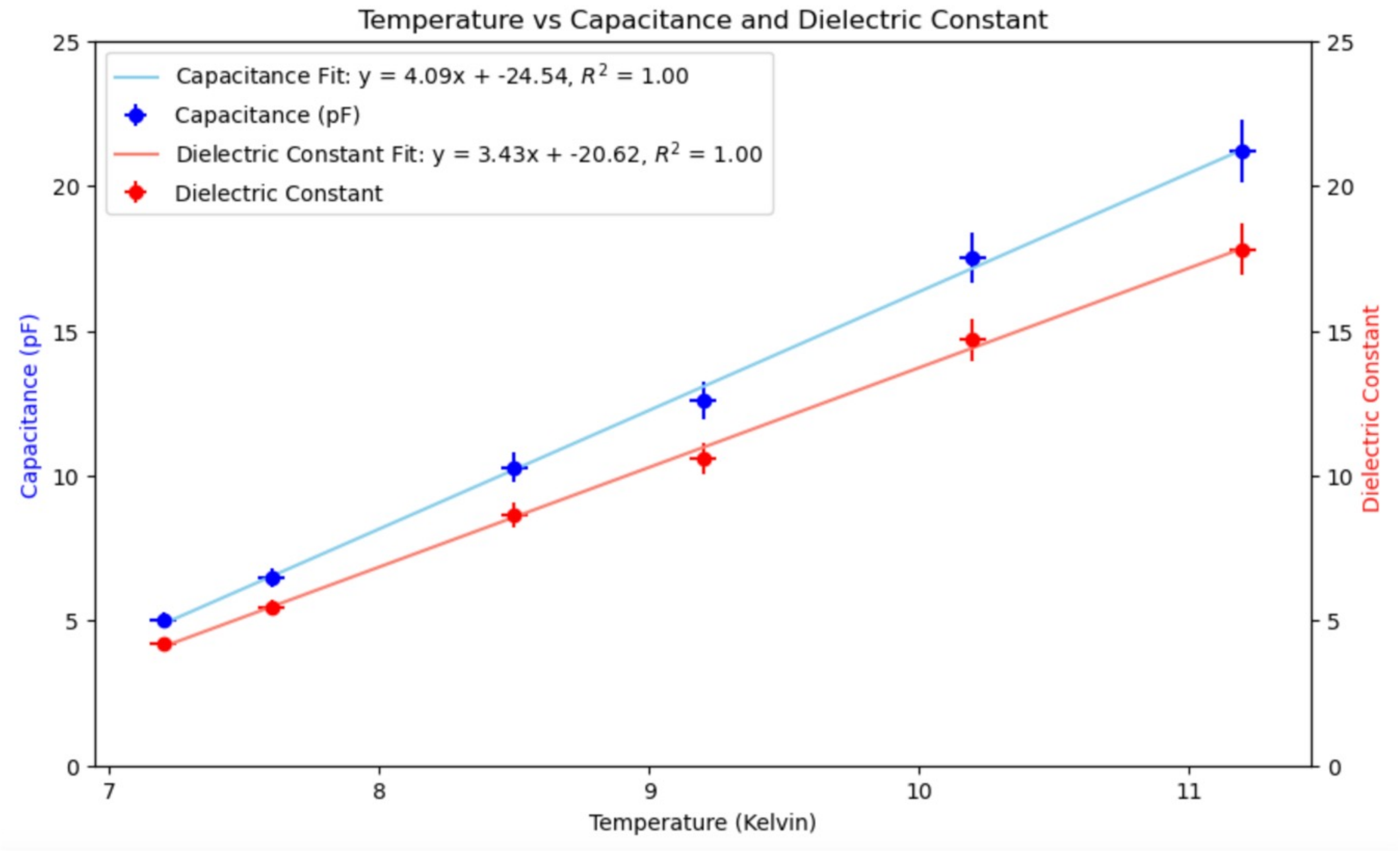


"Mei, D. Exploring the Potential of Residual Impurities in Germanium Detectors for MeV-Scale Dark Matter Detection. *J Low Temp Phys* (2024)"

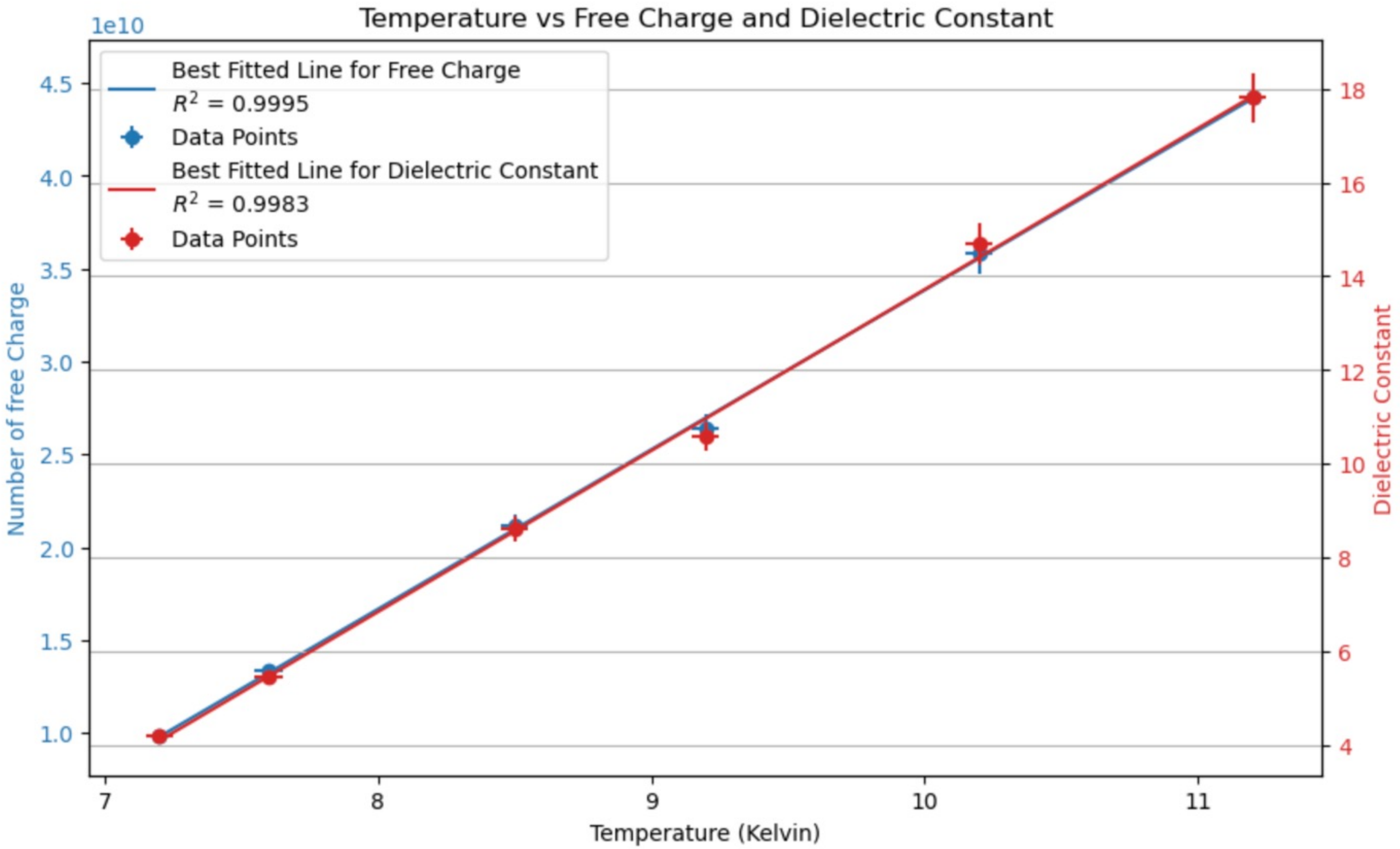
Results:


Capacitance vs Dielectric Constant
Data Points
Best Fitted Line
R² = 1.0000
100
80
60
40
20
Dielectric Constant (k)
5
10
15
20
25
Capacitance (pF)

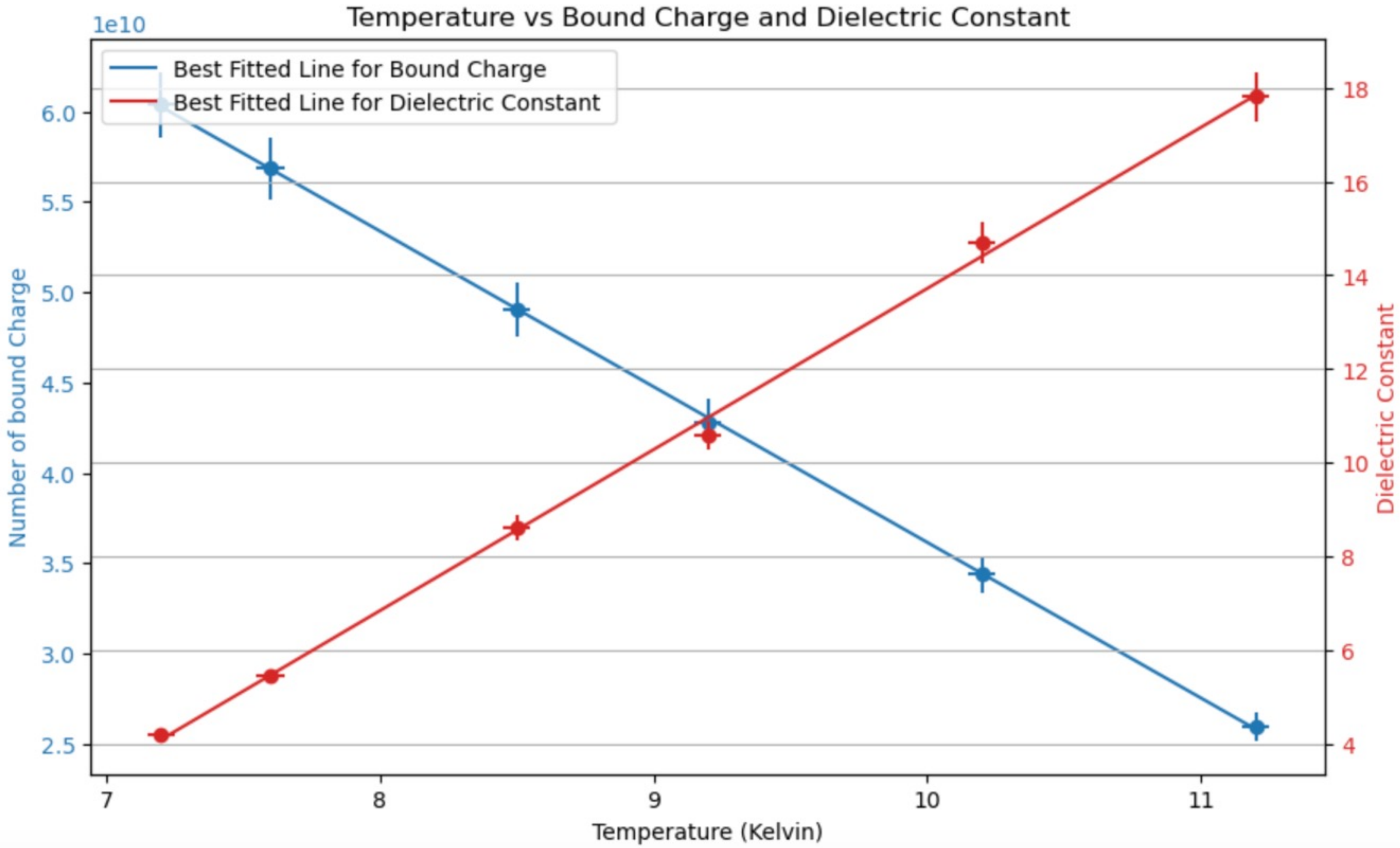
Results:


Temperature vs Capacitance and Dielectric Constant
Capacitance Fit: y = 4.09x + -24.54, R^2 = 1.00
Capacitance (pF)
Dielectric Constant Fit: y = 3.43x + -20.62, R^2 = 1.00
Dielectric Constant
Capacitance (pF)
Dielectric Constant
Temperature (Kelvin)
0
5
10
15
20
25
7
8
9
10
11

Results


Temperature vs Free Charge and Dielectric Constant
1e10
Best Fitted Line for Free Charge
R^2 = 0.9995
Data Points
Best Fitted Line for Dielectric Constant
R^2 = 0.9983
Data Points
Number of free Charge
Dielectric Constant
Temperature (Kelvin)
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
4
6
8
10
12
14
16
18
7
8
9
10
11

Results:


Temperature vs Bound Charge and Dielectric Constant
1e10
Best Fitted Line for Bound Charge
Best Fitted Line for Dielectric Constant
Number of bound Charge
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
Dielectric Constant
18
16
14
12
10
8
6
4
7
8
9
10
11
Temperature (Kelvin)

Conclusion

1. **Significant Decrease in Relative Capacitance: At** helium temperatures, particularly between 11 K and 6.5 K. It is due to the transition of free charges within the Ge detector into stable localized dipole states.

2. **Formation of Stable Localized Dipole States**: Impurity atoms undergoes transition from free charge states to stable localized dipole states, with B.E ranges from 5 to 8 meV. These dipole states exhibit thermal stability and play a crucial role in the detection process.

3. **Impact Ionization of Dipole States**: Dipole states undergo ionization upon phonon absorption, liberating free charges within the detector volume. This process, coupled with appropriate bias voltage application, amplifies charge signals and surpasses electronic noise levels encountered in traditional detectors.

4. **Implications for Dark Matter Detection**: The signal amplification achieved through the impact ionization of dipole states holds significant implications, particularly for detecting faint interactions between MeV-scale dark matter and ordinary matter, where phonon emission predominates.

Future Direction

1.Development of Ge Detector: with an estimated mass of approximately 1 kg, aiming for a detection threshold of less than 0.1 eV. This will require further optimization of impurity levels and operating parameters.

2. Mitigation of Technical Challenges: (Injection/Surface) leakage current, is crucial for achieving the desired low-energy detection threshold. Strategies like implementing guarding rings and collaborating with research institutions are being explored.

3. Validation and Testing: Collaborative efforts with PNNL aim to validate findings and test detector prototypes within low-noise systems. These tests will provide deeper insights into phenomena and potential advancements.

4. Advancement in Dark Matter Detection: Successful validation and implementation of proposed strategies will represent a significant advancement in direct dark matter detection capabilities, enabling exploration across a wide parameter space and unraveling mysteries of the universe.

Thank You

For Your Attention