Suppressing Low-Energy Excess in Graphene Josephson Junction Detectors

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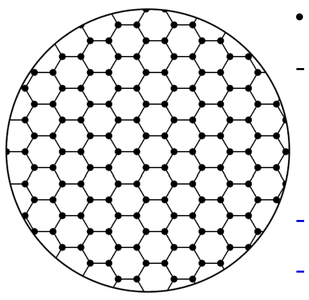
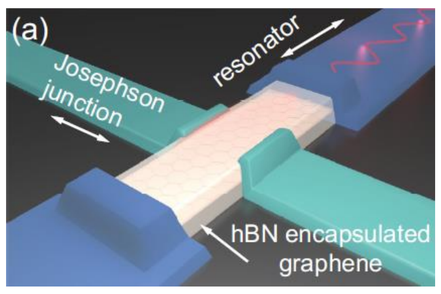
Low-energy excess (LEE) in low energy event detectors poses significant challenges for quantum device applications by generating unwanted conductance signals that deviate from theoretical predictions. Our measurements confirm that LEE also appears in graphene Josephson junction detectors and is correlated with the superconducting electrode area. This result suggests that the LEE in the graphene Josephson junction is likely attributed to the excess quasiparticle population.

Future work will focus on investigating two complementary strategies to suppress LEE : reducing superconducting electrode contact area and implementing normal metal electrodes. These approaches are expected to significantly reduce LEE, improve theoretical agreement, and enhance device reproducibility. This research will provide insights into the origins of LEE in solid-state detectors while offering practical solutions for superconducting quantum computing applications where LEE compromises qubit performance and coherence times.

Graphene Josephson Junction(GJJ) detectors

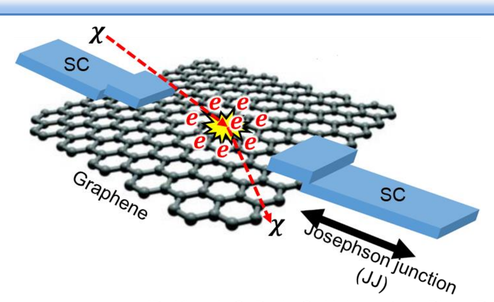


- **Graphene**
  - Low electronic heat capacity
  → **Large response** in electron temperature
  - **Fast thermalization** time
  - **Slow cooling** time



[G.-H.Lee, D.K.E., W.C.Jung *et al.*, Nature (2020)]

- **GJJ microwave bolometer**
  - Achieved fundamental limit of sensitivity : NEP = 0.7 aW/Hz
  - Corresponding Energy Threshold: ΔE = 0.1 meV



[D. Kim, J.-C. Park, G.-H. Lee *et al.*, Phys. Rev. D (2025)]

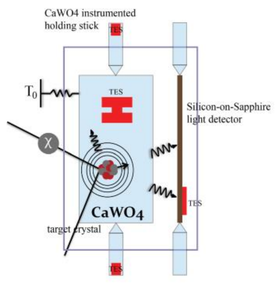
- **Super-light DM interacting with π–bond electrons**

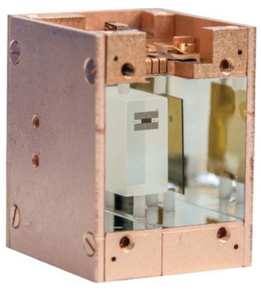
Low Energy Excess (LEE)

- **Attempts to detect dark matter (DM) & coherent elastic neutrino-nucleus scattering (CEνNS)**

[Q. Arnaud *et al.*, Phys. Rev. Lett. (2020)]

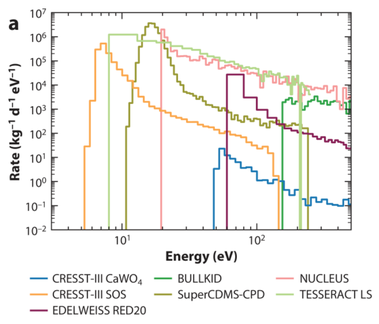
- EDELWEISS
  - Ge-NTD
  - CEνNS





[G. Angloher *et al.*, J. Low Temp. Phys. (2024)]

- CRESST-III
  - W-TES
  - DM

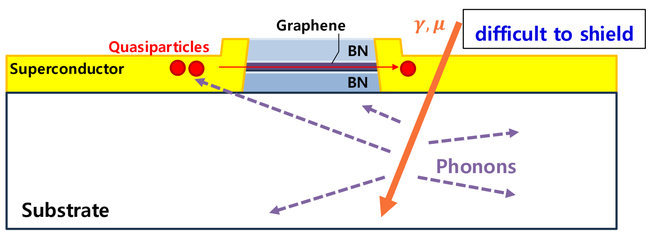


- Low-threshold detectors (~ 100 eV)
→ steeply-rising event rate w/ decreasing energy
  - common in various types of detectors
  - common origin is inconsistent
  (stress / defects / excess quasiparticle …)

➔ **LEE interrupts low-threshold DM & CEνNS detection**

Excess quasiparticle population

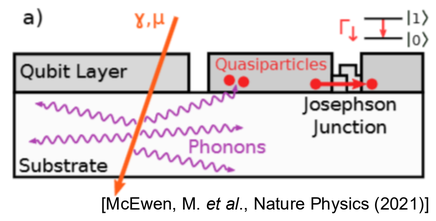
- Cosmic rays / Vibrations / Radioactivity / IR radiation



Cosmic rays & Chip interaction
↓
High energy phonon
↓
Excess Quasiparticles

- Similarly, quasiparticles can tunnel through Josephson junctions in **transmon qubits**

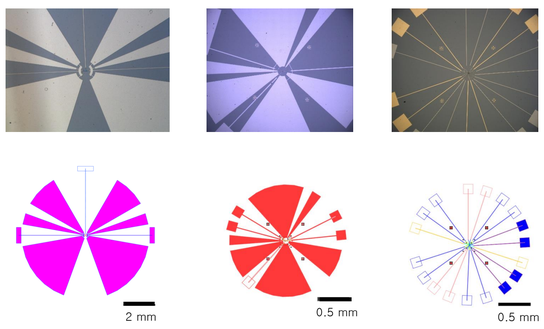
→ **Decoherence**

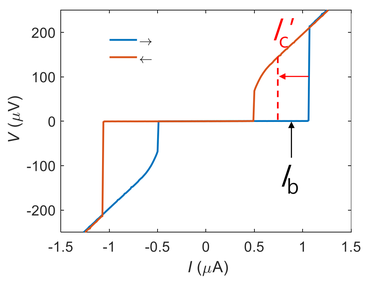


[McEwen, M. *et al.*, Nature Physics (2021)]

➔ Causing **LEE** & **Correlated errors in superconducting qubit**

Methods



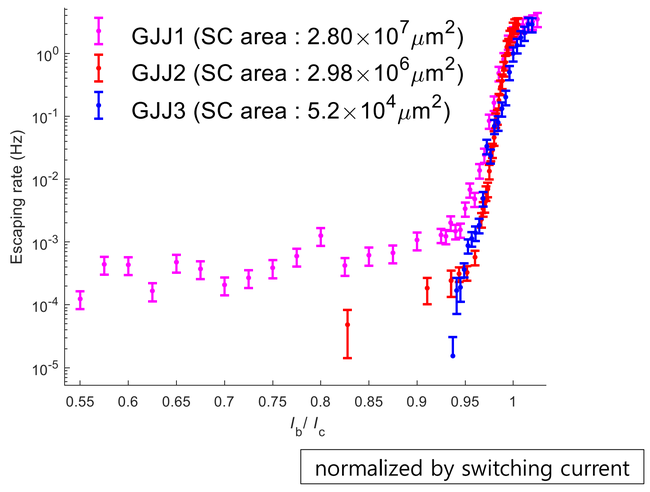


- 3 Josephson junctions with various superconducting electrode area (Electrodes : MoRe / Si wafer)
→ $2.80 \times 10^7\ \mu m^2 : 2.98 \times 10^6\ \mu m^2 : 5.2 \times 10^4\ \mu m^2$
(~ $\mathbf{5.38 \times 10^2 : 5.73 \times 10 : 1}$)

Detection Mechanism

- Excess quasiparticle
→ Critical current I_c decreases
→ Voltage jump

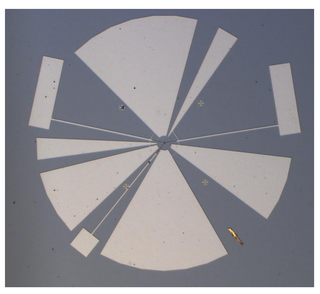
Results & Analysis



normalized by switching current

- **SC area ↓ → LEE** (escaping rate saturation) **↓**
- LEE of GJJ detector is due to **excess quasiparticle population**

Experimental Plan



- Measurements on different devices : Other factors (substrate volume, quality of the Josephson junction) could have influenced

➔ Make a Josephson junction with **adjustable** superconducting electrode area

- Investigate **methods to reduce LEE** : Normal electrode, substrate type

Summary

1. **LEE** is a commonly observed phenomenon in low-energy event detectors with no common origin, which interferes with **rare event detection** and degrades **quantum device performance**.
2. LEE was observed in **graphene Josephson junction detectors**, correlating with the **superconducting electrode area** and likely originating from **excess quasiparticle** population.
3. Future research will focus on **suppressing LEE** by reducing **superconducting electrode** area and implementing **normal-metal electrodes**.