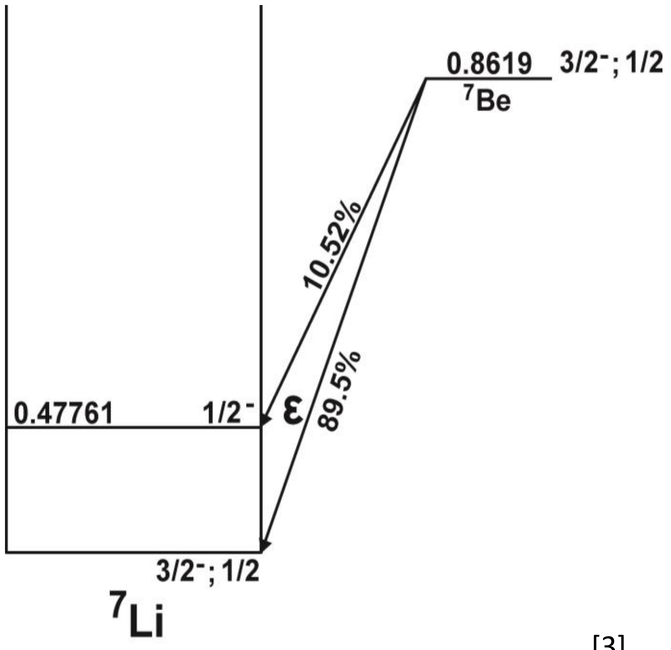
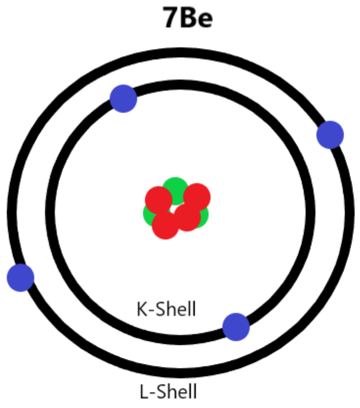
eV-scale Modelling of Low-Energy Backgrounds in Superconducting Tunnel Junctions utilizing GEANT4 and G4CMP

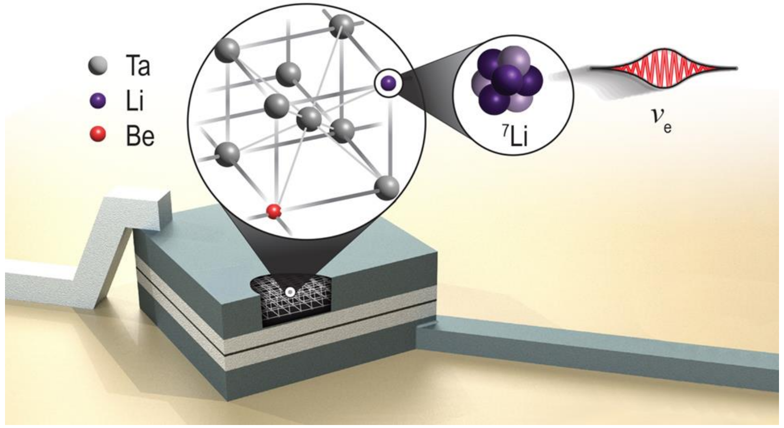
By: Caitlyn J Stone-Whitehead

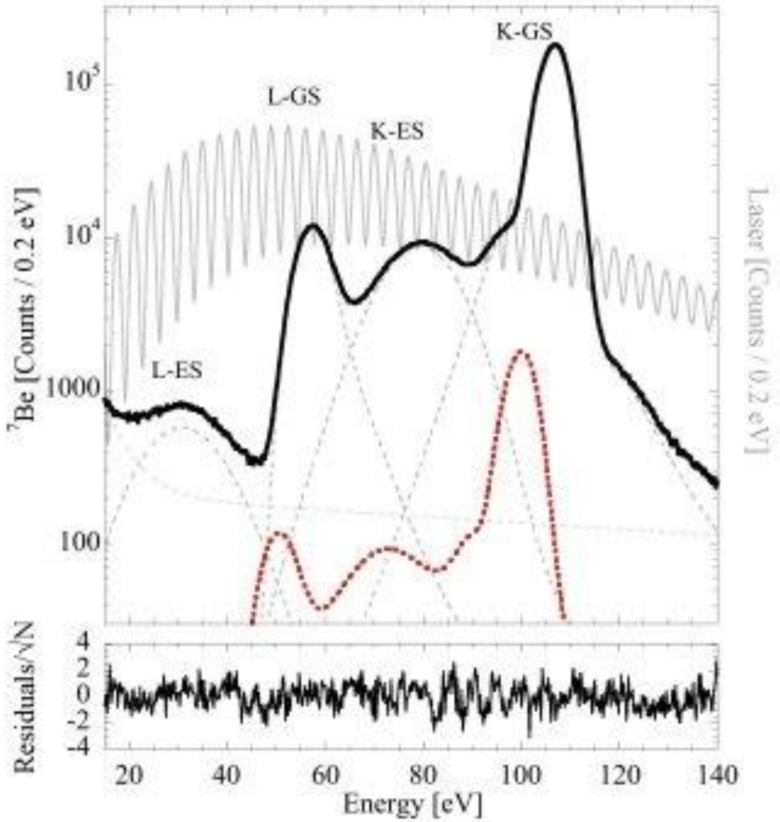
EC Decay overview





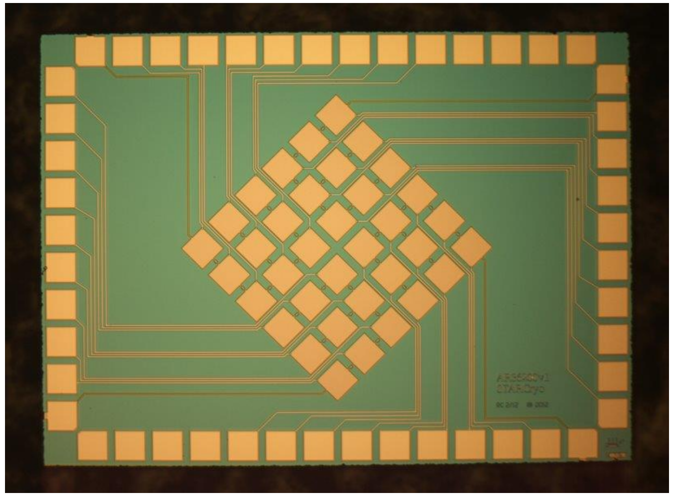
[3]

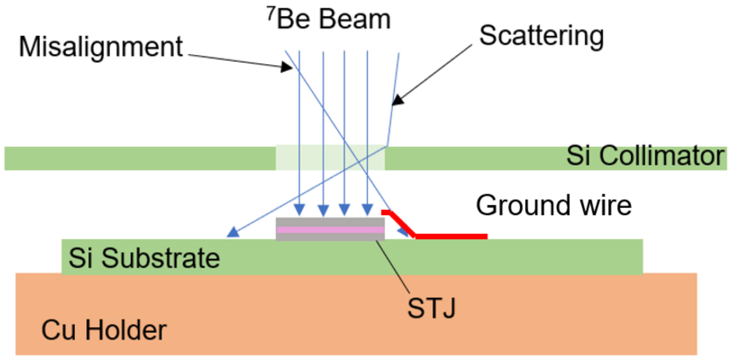




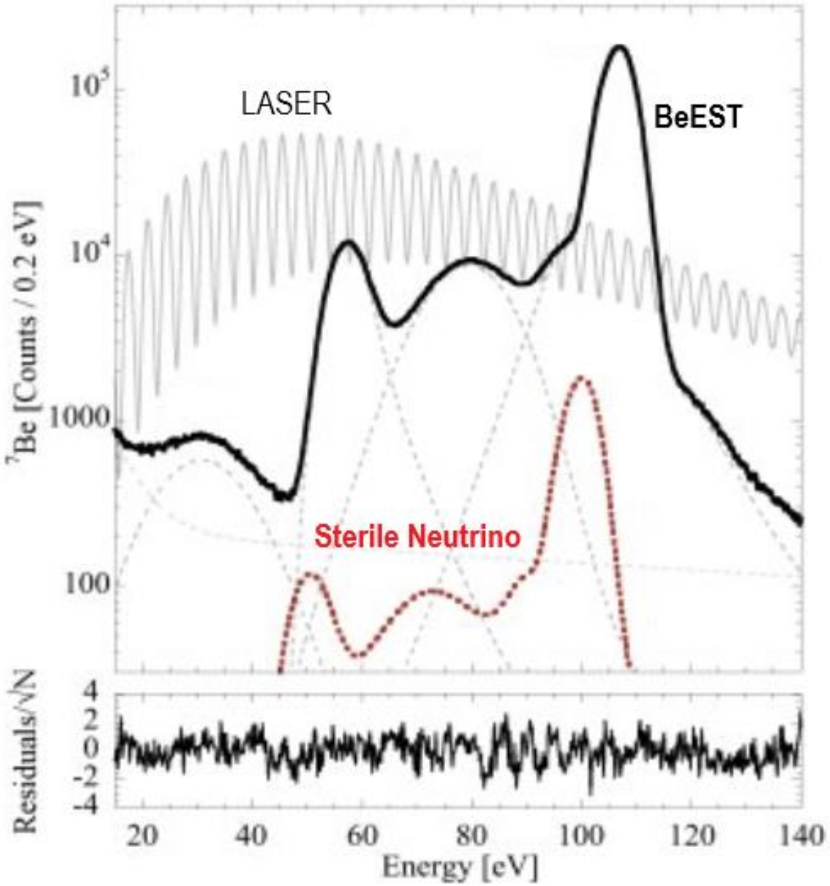
[3] “7Be,” Duke.edu, 2020. https://nucldata.tunl.duke.edu/nucldata/GroundStatedecays/07Be.shtml (accessed Feb. 21, 2024).

The BeEST Experiment





[1]

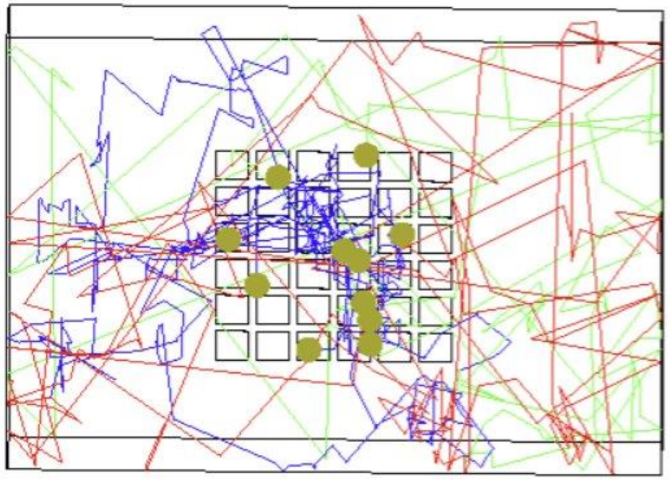


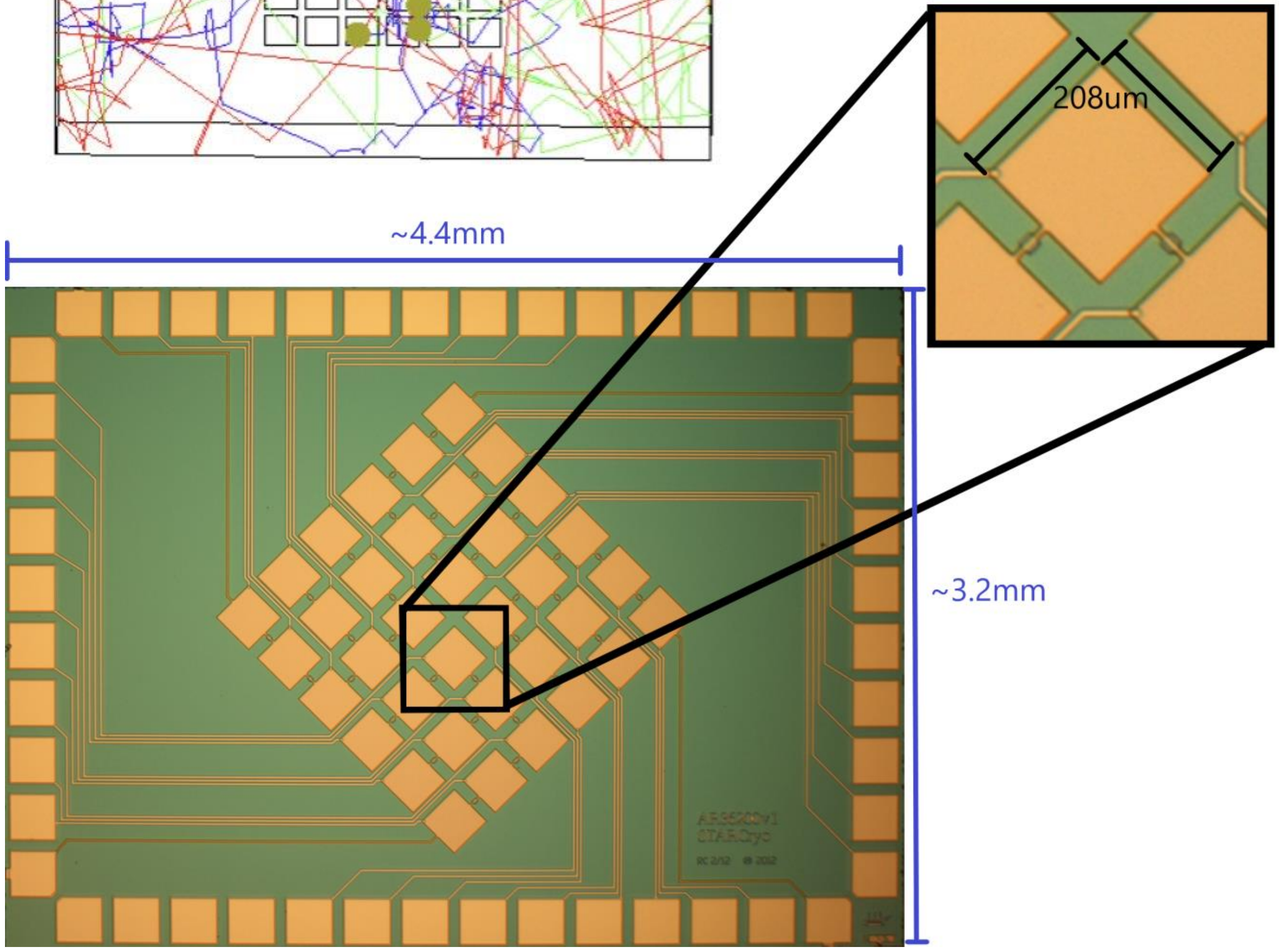
[2]

[1] A. Lamm, APS April Meeting, B19:4 (2024)
[2] S. Fretwell et al., Phys. Rev. Lett. **125**, 032701 (2020).

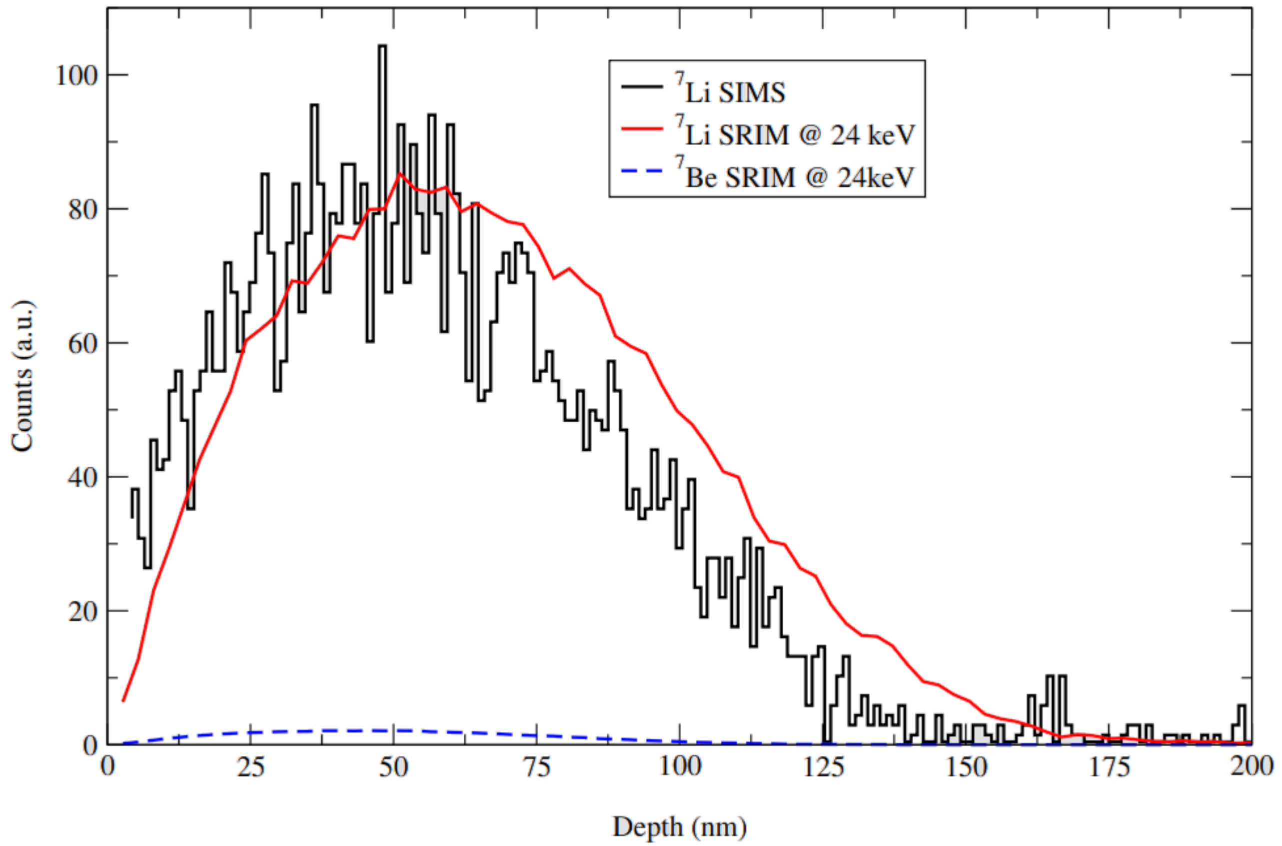
Geometry

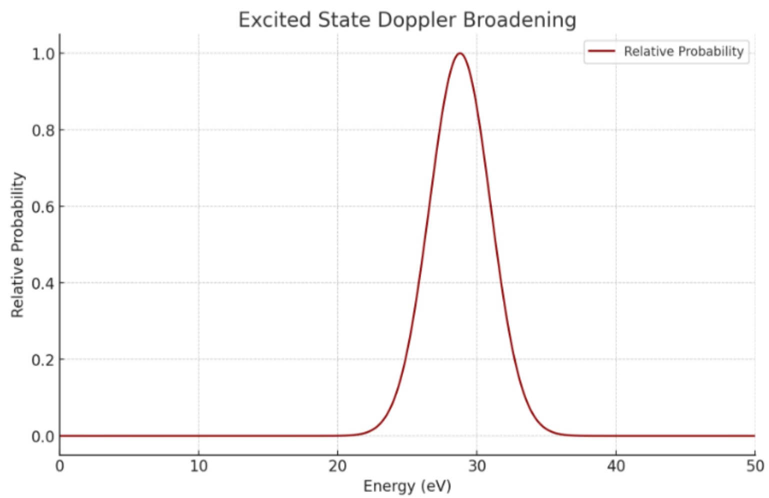
- Atmosphere: Vacuum
- Target: Silicon substrate
- Detector: 32pi Ta STJ array (each 200um x 200um)
- Particle Source:
  - Events confined to edges of pixels

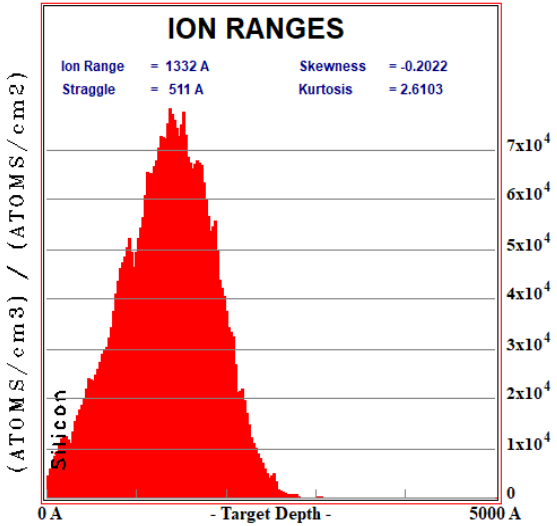




Physics Implemented







[4]

[4] Connor E. Bray et al., "Monte-Carlo Simulations of Superconducting Tunnel Junction Quantum Sensors for the BeEST Experiment," Journal of Low Temperature Physics 209, 857 (2022).

Physics Lists

Particle	Interaction	Process class	Model class	Min. energy	Max. energy	Kill
Electron	Elastic scattering	G4MicroElecElastic	G4MicroElecElasticModel	5 eV	100 MeV	16.7 eV (*)
Electron	Ionisation	G4MicroElecInelastic	G4MicroElecInelasticModel	16.7 eV	100 MeV	-
Proton and heavy ions	Ionisation	G4MicroElecInelastic	G4MicroElecInelasticModel	50 keV/u	10 GeV/u	-

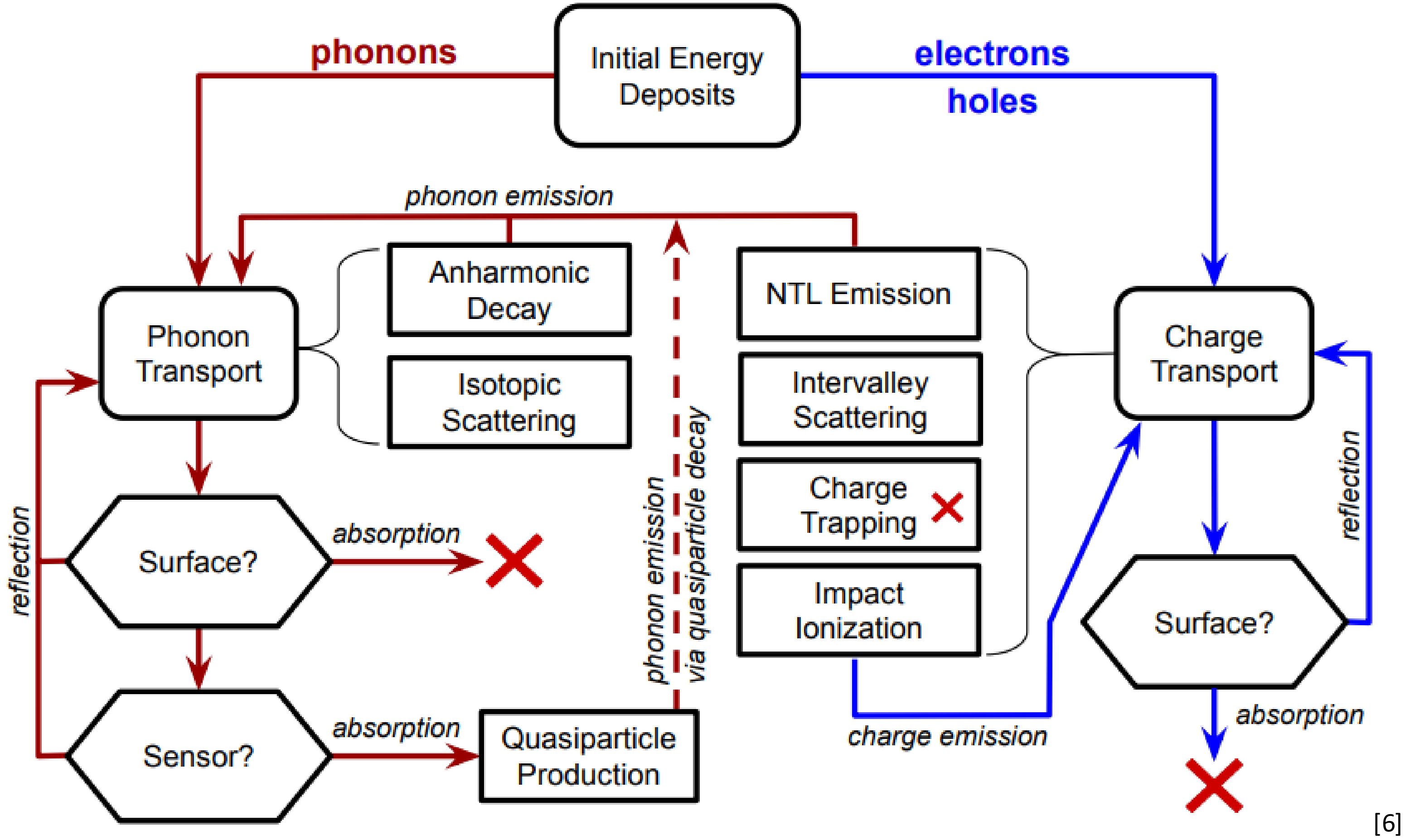
[5]

Other

- Compton Scattering and Photoelectric effect
  - G4EmLowEPPhysics()
- Hadronic Physics (nucleus-nucleus inelastic scattering)
  - G4IonPhysics()
- Urban Multiple Scattering (E<100MeV)

[5] S. Agostinelli et al., "Geant4—a simulation toolkit", Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 506, 250-303 (2003). DOI: 10.1016/S0168-9002(03)01368-8.

Physics Lists



[6] D. Brandt et al., "Semiconductor phonon and charge transport Monte Carlo simulation using Geant4," Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 1055, 16847 (2023).

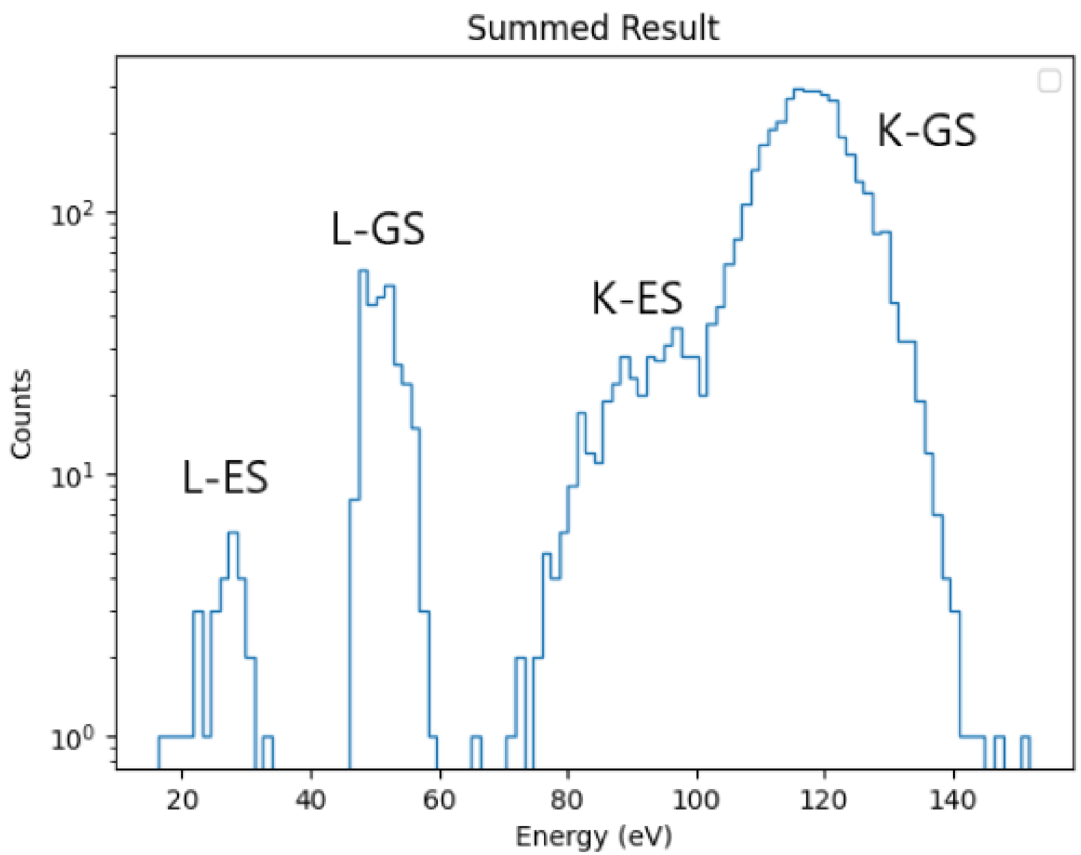
Physics Lists

Detector Properties	Description	Value
Film Absorption	Probability of incident phonon being absorbed	0.081
Film Thickness	Thickness of superconducting film	165 nm
Gap Energy (Δ)	Superconducting Energy Gap	667.300 ueV
Low Quasiparticle Limit	Minimum energy for a phonon to be radiated	3 (multiples of Δ)
Phonon Lifetime (τ)	Avg time for a phonon to lose energy to Anharmonic decay or Isotopic scattering	242 ps
Phonon Lifetime Slope (δτ)	Dimensionless slope δτ of the phonon lifetime vs. energy	0.29
Sound Velocity	Sound speed (longitudinal) in film material	5.84 km/s
Sub Gap Absorption	Probability of an incident phonon absorbed below Δ	0.1

Event overview

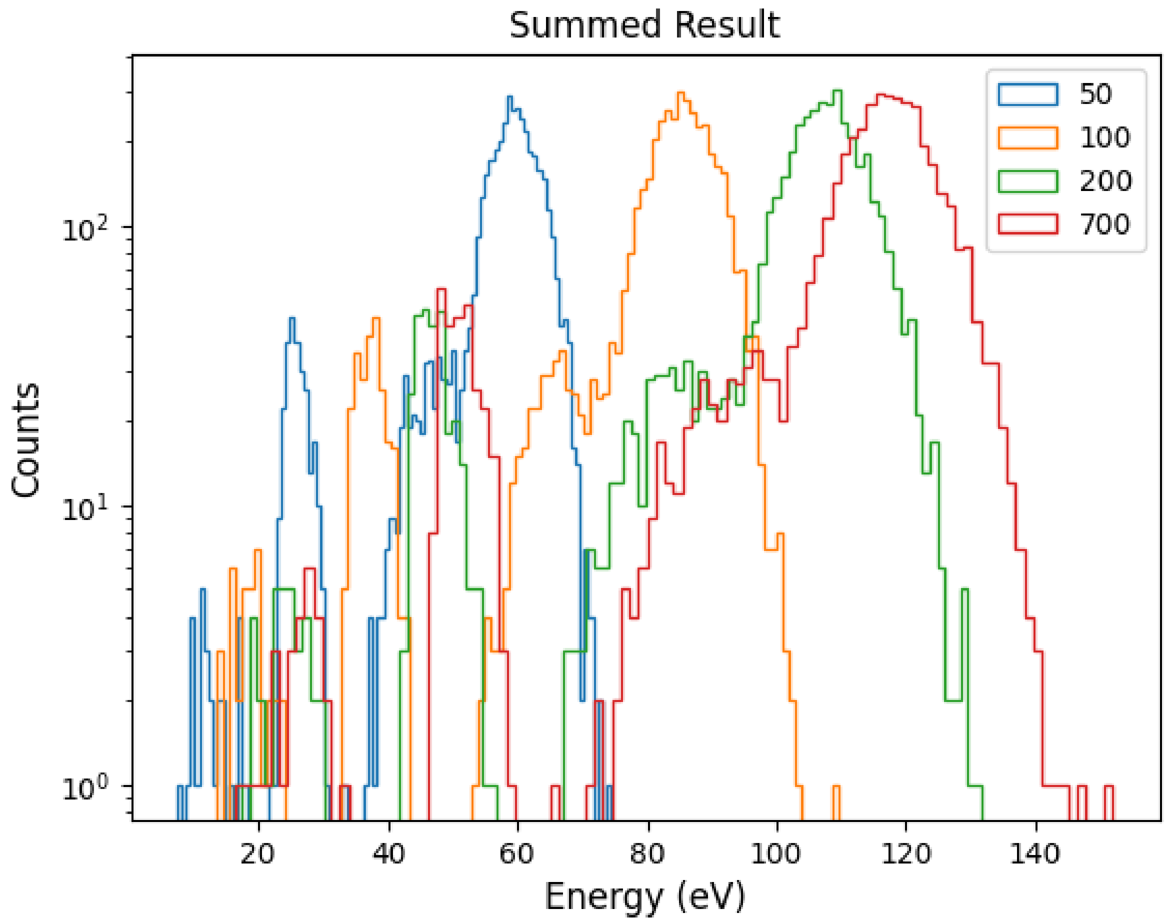
1. Primary Interaction
   1. Electron capture decay of 7Be
2. Secondary Interactions
   1. Single Scattering
   2. Multiple Scattering
   3. Ionization
3. Phonon and Charge Interactions
   1. Reflection, Scattering and Absorption
      - Phonons: Anharmonic decay
      - Charge Carriers: Trapping, phonon emission and ionization
4. Detector Interactions
   1. Quasiparticle production

Preliminary Results



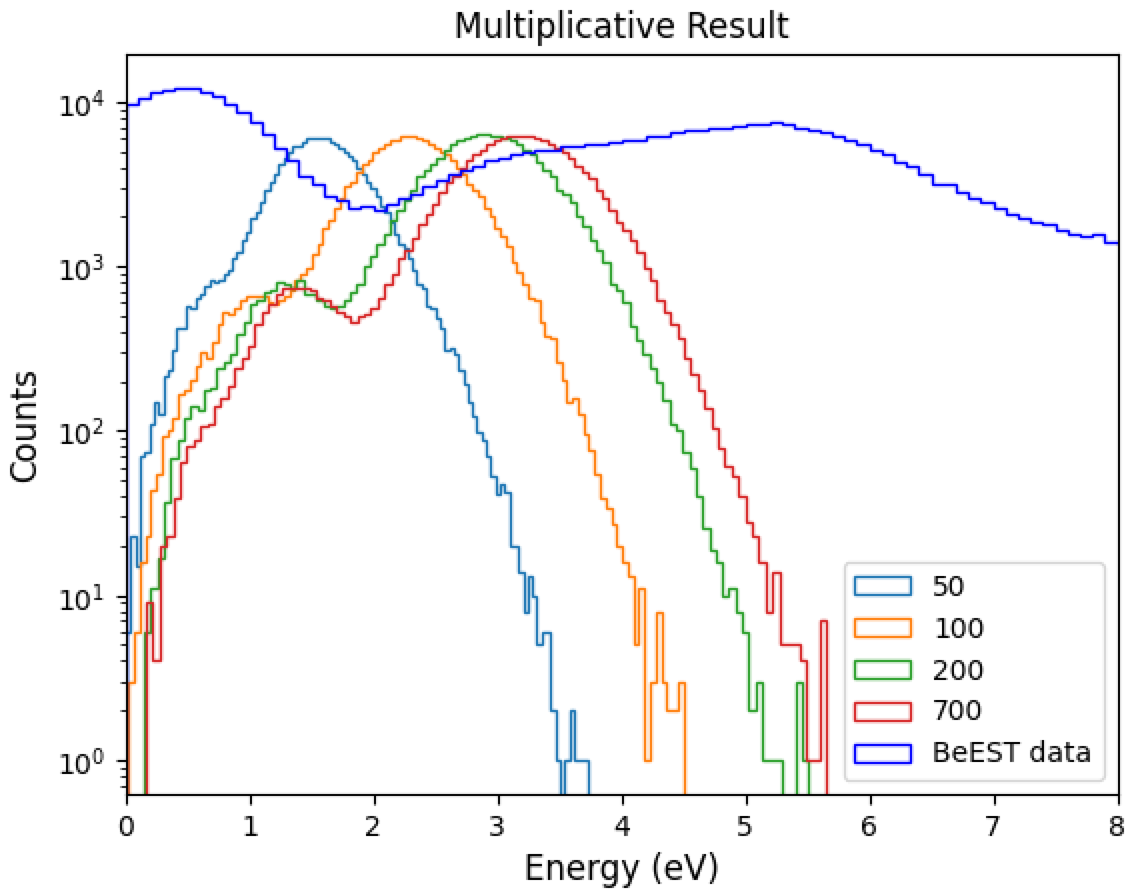
- EC decay verification
- Summed result

Phonon Bounces



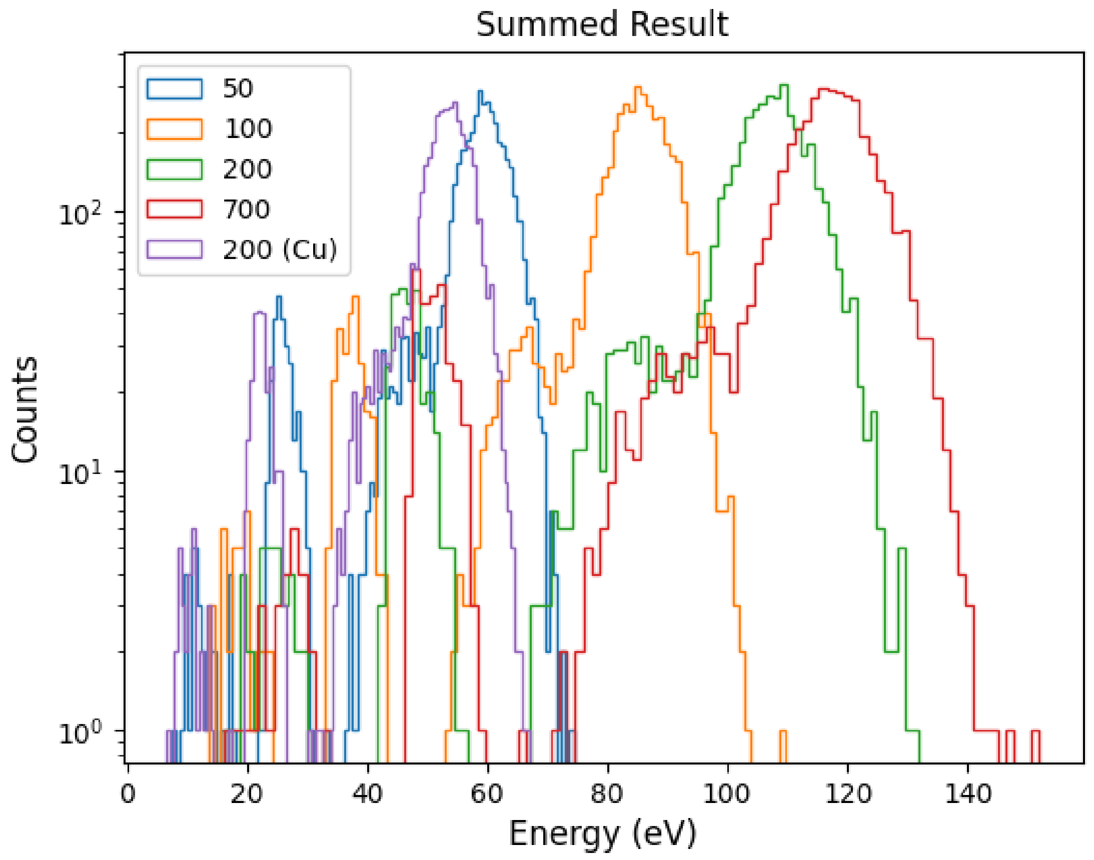
- Phonon bounces: How many boundaries can the phonon 'bounce' off until it is killed?
- Summed result
- Variable

Pixel Separation

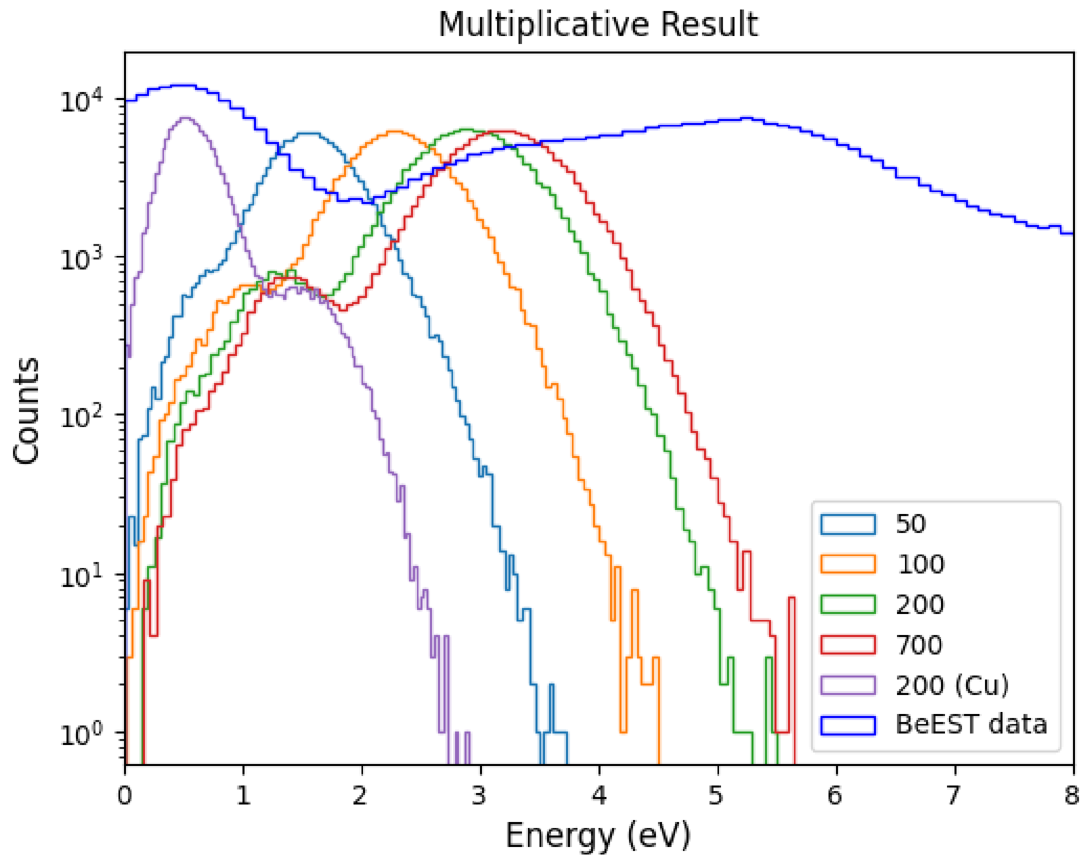


- Phonon bounces: How many boundaries can the phonon 'bounce' off until it is killed?
- Multiplicative result

Cu Holder

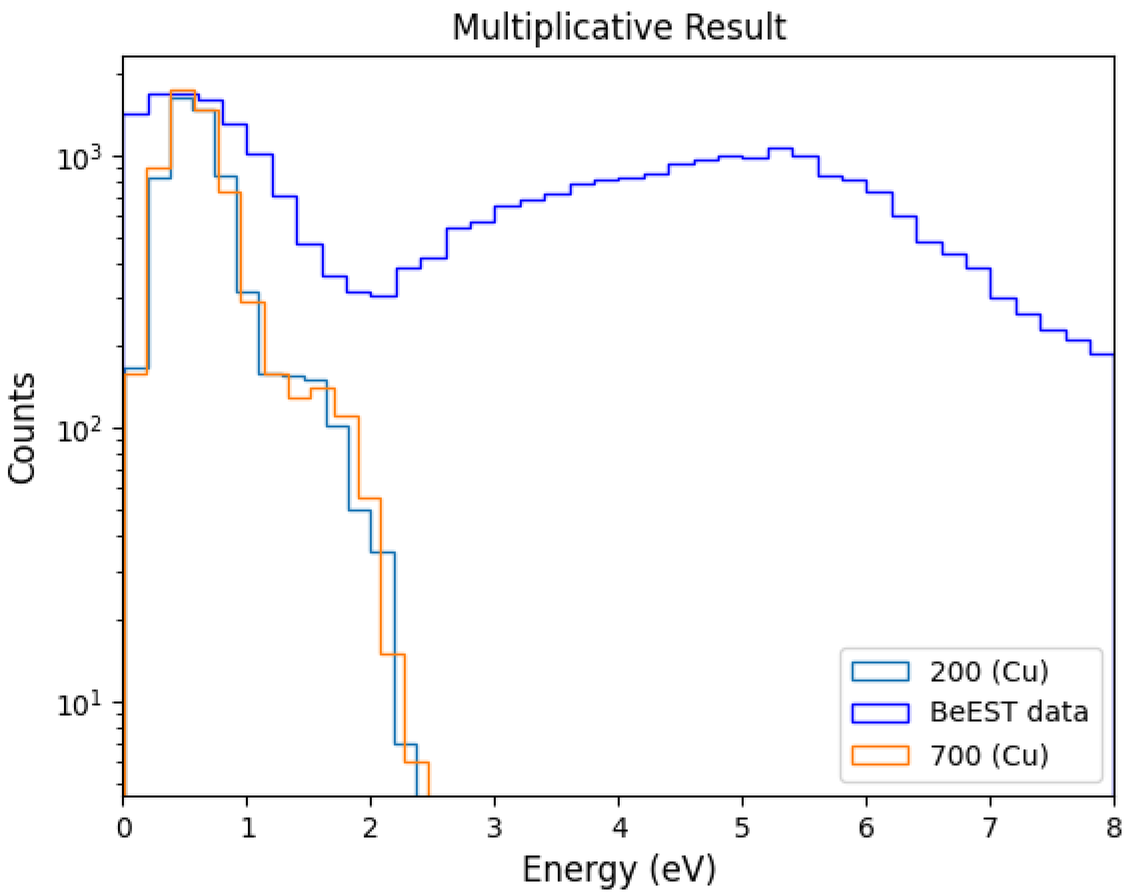


Summed Result
50
100
200
700
200 (Cu)
Counts
Energy (eV)



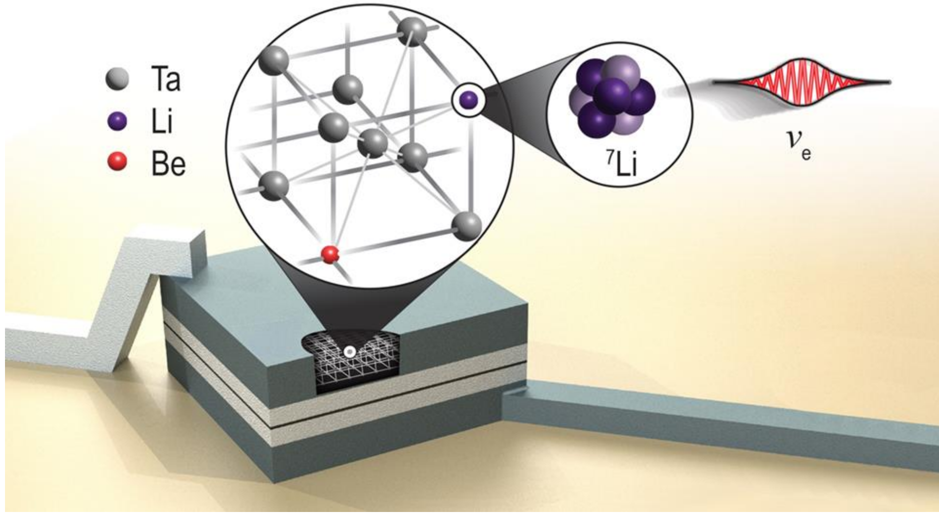
Multiplicative Result
50
100
200
700
200 (Cu)
BeEST data
Counts
Energy (eV)

Current Results



Summary & Outlook

- BeEST uses 7Be implanted in STJs to study neutrino physics
- G4CMP is used to model phonon generation, propagation and energy deposition at low energy in Si substrate
- Next major goal: Model quasiparticle and phonon generation within the superconductor with G4CMP
    - Requires a community effort (Maybe ongoing?)
    - Searching for overlap with other groups doing similar work
- Ultimate goal: Model weak nuclear decay processes within superconductors (BeEST & SALER)



The BeEST Collaboration

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THE BeEST

GORDON AND BETTY MOORE FOUNDATION

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EMPIR EURAMET
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NNSA National Nuclear Security Administration

2023 Collaboration Meeting
Livermore, California

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