The BeEST Experiment: A Search for sub-MeV Sterile Neutrinos with Superconducting Quantum Sensors

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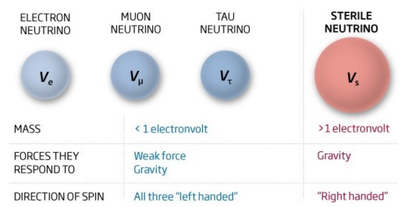
Introduction

The lepton sector of the Standard Model (SM) provides perhaps the best window into Beyond Standard Model (BSM) physics given the confirmed observation of non-zero neutrino masses. So-called "sterile neutrinos" are are present in almost all SM extensions that include neutrino mass, and have the characteristic property that they are non-interacting with respect to the SM forces. In particular, sterile neutrinos in the sub-MeV mass range are among the most highly motivated, since they have the right cosmological properties to explain the observed dark matter in our universe [1, 2, 3, 4]. The BeEST experiment is a *model independent* search for these heavy mass states (and other exotic scenarios) in the 10 - 862 keV mass range that uses decay momentum reconstruction of the electron capture (EC) nuclear decay of ^{7}Be.

Sterile Neutrinos

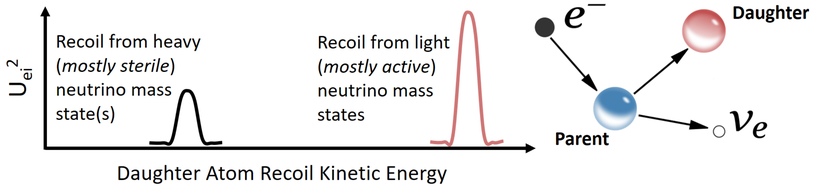
- Natural extensions to the SM that can reconcile the small "mostly active" neutrino masses by adding n RH neutrinos (νMSM and Type-I Seesaw) [2]
- Generalizes the PMNS matrix to a $(3+n)\times(3+n)$ transformation with $\nu_i \geq 4$ "mostly sterile" mass eigenstates



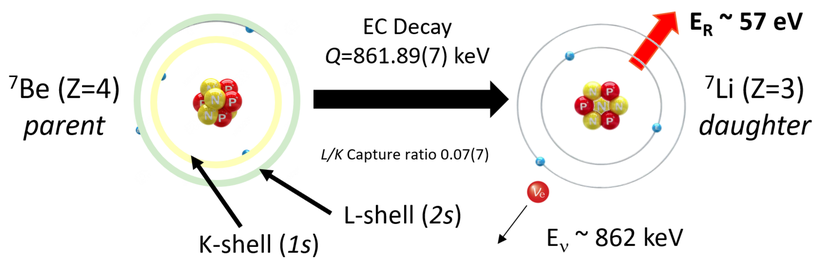
$$\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix} = \begin{bmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{bmatrix}\begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix} \implies |\nu_\alpha\rangle = \sum_{i=1}^{(3+n)} U_{\alpha i}|\nu_i\rangle.$$

Decay Momentum Reconstruction as a Neutrino-Mass Probe

- The weak interaction process of orbital EC produces a two–body final state
  - Discrete kinetic energies for the emitted ν_e and daughter recoil
- Heavy neutrino admixtures to ν_e generates less energetic atomic recoil peaks.

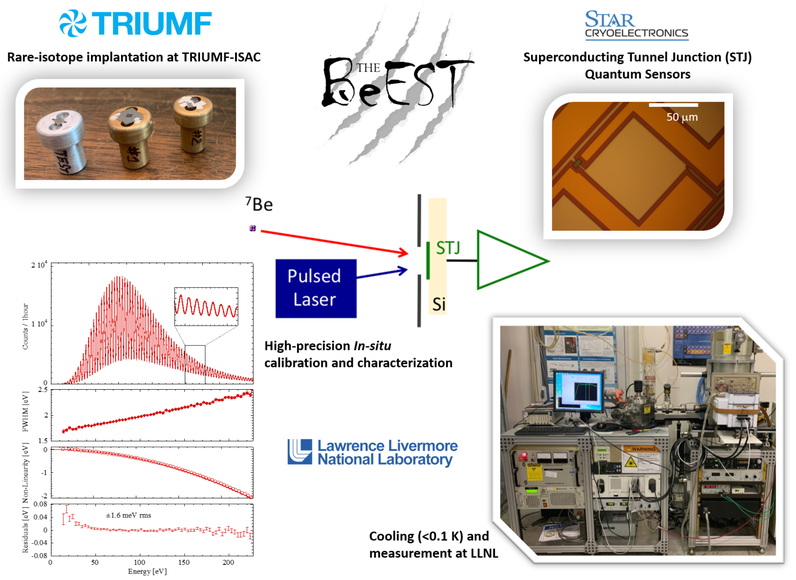


Orbital Electron Capture Decay of Beryllium-7



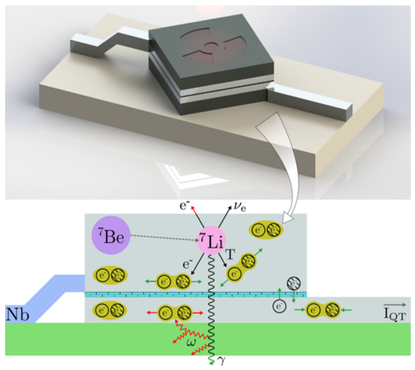
- ^{7}Be is the ideal system to perform these studies:
  - Pure EC decaying nucleus
  - Largest decay energy of all pure EC cases → probes $m_s \leq 862$ keV
  - Simple atomic ($Z = 4$) and nuclear ($A = 7$) structure

The BeEST Experimental Concept

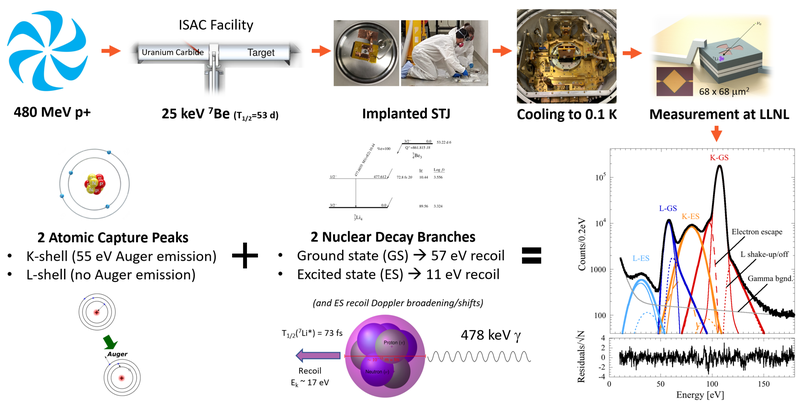


Superconducting Tunnel Junction (STJ) Quantum Sensors

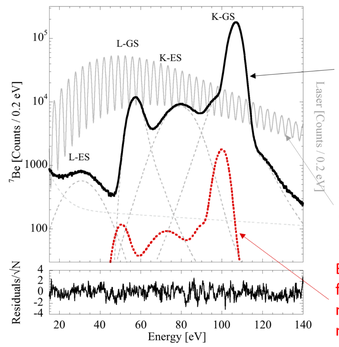
- Two superconducting electrodes separated by a thin (∼nm) insulating tunnel barrier
- Thin devices ($\sim 0.5\ \mu$m) optimized for low-energy radiation
- Superconducting energy gap $\Delta \approx$ meV
  - High Energy Resolution (~ 1 eV)
- Timing resolution on the order of ms
  - Operate at $> 10^3$ counts/s/pixel
- Well characterized response [5, 6, 7]

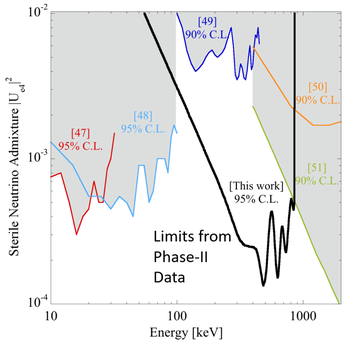


Phase-I: Proof-of-Concept – [PRL 125, 032701 (2020)]



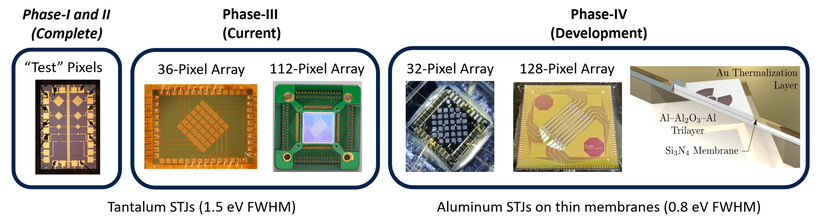
First Limits from "Low Rate" Phase-II Data – [PRL 126, 021803 (2021)]



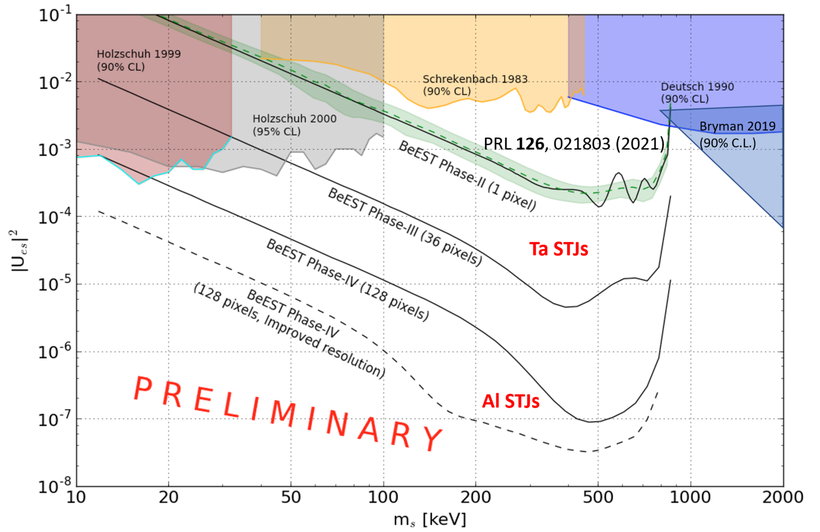


- Single sensor counting at low rate (≤ 10 counts/s) for 28 days
- Up to an order of magnitude improved limits for $m_s \approx 100 - 850$ keV

Scaling to Large STJ Arrays for Phases-III and -IV



Sensitivity Projections for the BeEST Experiment



References and Funding

[1] S. Dodelson and L. M. Widrow, Phys. Rev. Lett. **72**, 17-20 (1994)
[2] T. Asaka *et al.*, Phys. Lett. B **631**, 151-156 (2005)
[3] R. Adhikari *et al.*, J. Cosmol. Astropart. Phys. **25**, (2017)
[4] A. Boyarsky *et al.*, Prog. Part. and Nucl. Phys. **104**, 1-45 (2019)
[5] F. Ponce *et al.*, Phys. Rev. C **97**, 054310 (2018)
[6] S. Fretwell *et al.*, Phys. Rev. Lett. **125**, 032701 (2020)
[7] S. Friedrich *et al.*, Jour. Low Temp. Phys. **200**, 200 (2020)
[8] S. Friedrich *et al.*, Phys. Rev. Lett. **126**, 021803 (2021)

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Lawrence Livermore National Laboratory
NSERC CRSNG
APS physics
GORDON AND BETTY MOORE FOUNDATION
EMPIR EURAMET
The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States
NNSA National Nuclear Security Administration

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