Ion Implantations and βNMR Detector Material Effects Characterization for The BeEST Experiment

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BeEST Experimental Objective & Sterile Neutrinos

- Weak nuclear decay is among the most sensitive BSM physics probes.
- Unlike active neutrinos in the Standard Model (SM), **sterile neutrinos** do not couple to left-handed currents in the weak interaction.
- Best observed via their mass–generated effects that result from momentum conservation with SM particles.
- Model independent search method: high-precision measurements of electron capture (EC) nuclear decay.

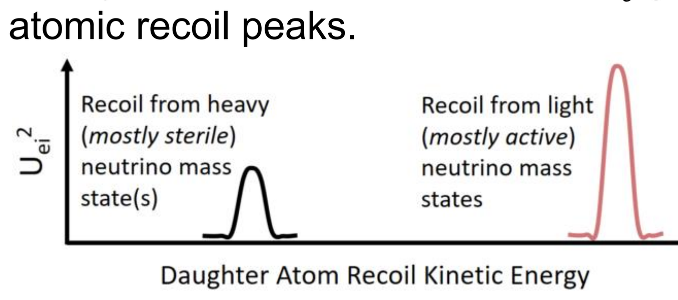
- BeEST aims to measure the $^7Be \rightarrow {}^7Li$ recoil energy spectrum in STJs.
- Natural extensions to the SM that can reconcile the small "mostly active" neutrino masses by adding n right-handed neutrinos.

$$\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix} = \begin{bmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3}\\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3}\end{bmatrix}\begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix} \Longrightarrow |\nu_\alpha\rangle = \sum_{i=1}^{(3+n)} U_{\alpha i}|\nu_i\rangle$$

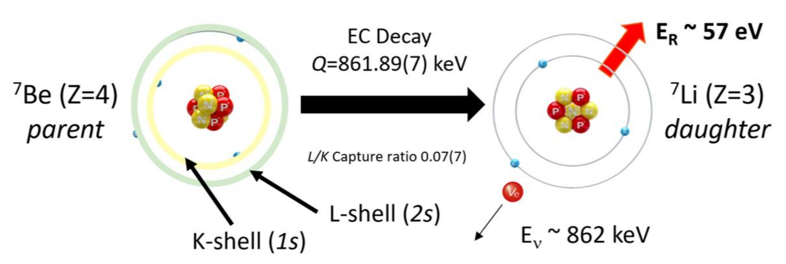
- Generalizes the PMNS matrix to a $(3+n) \times (3+n)$ transformation with $\nu_i \geq 4$ "mostly sterile" mass eigenstates

Decay Momentum Reconstruction and EC Decay of ^7Be

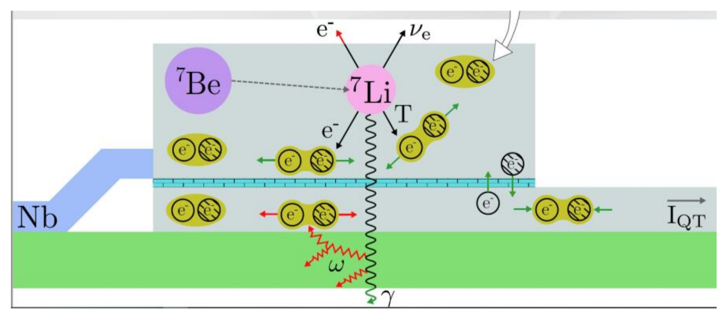
- The weak interaction process of orbital EC produces a two-body final state → discrete kinetic energies for the emitted ν_e and daughter recoil
- Heavy neutrino admixtures to the ν_e generates less energetic atomic recoil peaks.



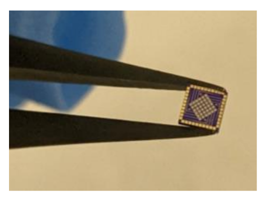
- ^7Be is the ideal isotope to perform these studies
  - ✓ Covers widest neutrino mass range ($m_s \leq 862$ keV)
  - ✓ Simple atomic (Z=4) and nuclear (A=7) structure



How do STJs work?

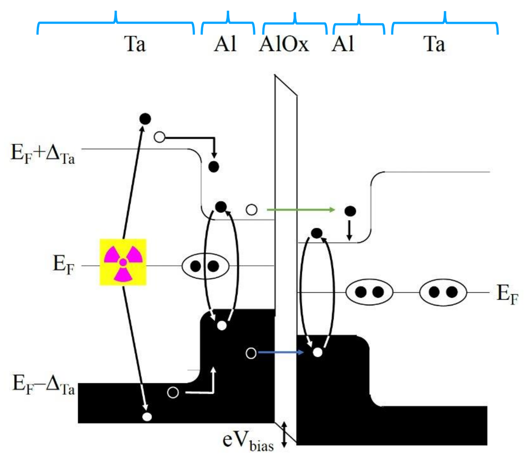


- Sub-keV measurements with resolution of ~2 eV



- "Superconducting tunnel junction"
- The layers of an STJ sensor:

Ta (165 nm) – Al (50 nm) – Al_2O_3 (1 nm) – Al (50 nm) – Ta (265 nm)

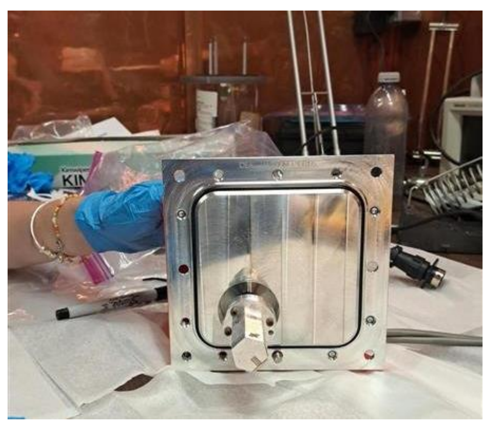


- Incoming radiation (^7Li recoils of ~57 eV) breaks Cooper pairs and creates excess charge-carriers
- These quasiparticles tunnel across the insulating barrier.
- This generates the electric signal current.

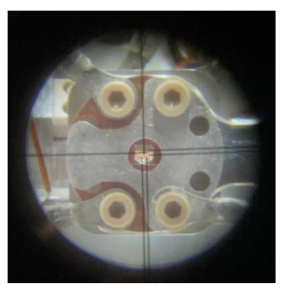
Implantation of ^7Be into Superconducting Tunnel Junctions (STJs) at TRIUMF

A Ta-STJ sensor (seen in gold) mounted to the sample holder during the recent June 2025 implantation. An Al-STJ sensor is also shown mounted on the left.

- The STJ sensors are irradiated with ^7Be at TRIUMF.
- Depending on the detector type, different beam energies are required: 25 keV for Ta-based and 10 keV for Al-based.
- The sensors are coated in a photoresist mask to prevent radioactive contamination between the pixels.
- The mounting piece and target mount are mounted onto stepper motor to control the target position.



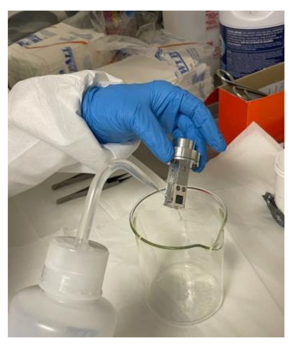
The sample holder mounted to the stepper motor.



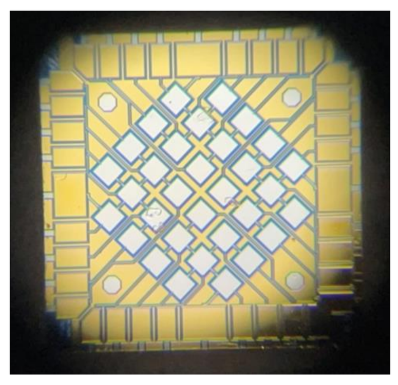
Alignment process: the optimal positions of the sensors are found and recorded.

Implant with ^7Be ($\tau_{1/2} = 53d$)

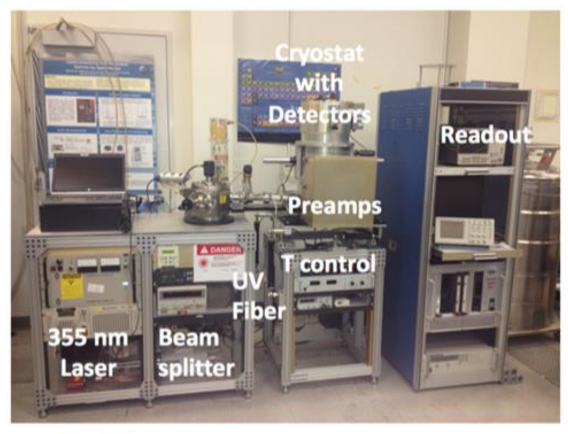
- Post-implantation rinse and removal procedure



The STJs undergo multiple rounds of ethanol and acetone baths to remove the photoresist mask and any residual radiation on the surface.



The Al-STJ after 10 rinses, image taken with microscope.

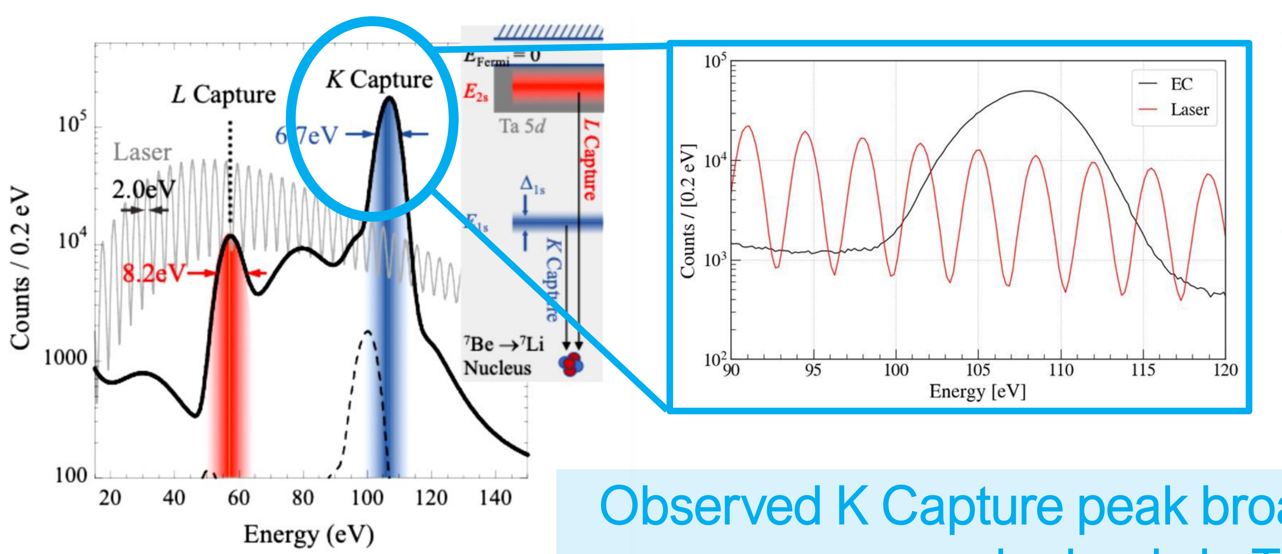


Lawrence Livermore National Laboratory

- The STJs are then sent to collaborators at Lawrence Livermore National Laboratory for signal readout at 100 mK in an adiabatic demagnetization refrigerator.
- Simultaneous laser calibration is performed.

How could material effects influence the recoil energy spectrum?

Recoil Energy Spectrum



Two atomic capture peaks

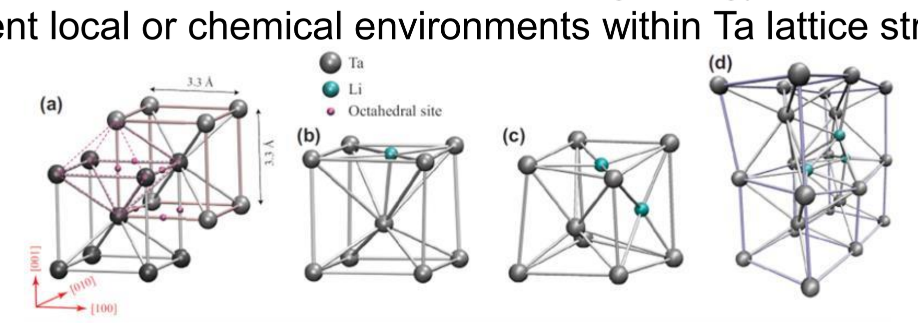
- K-shell (55 eV Auger emission)
- L-shell (no Auger emission)

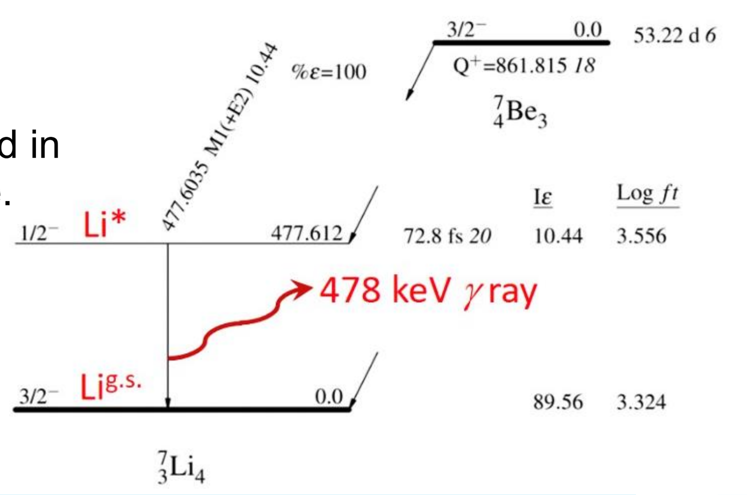
Two Nuclear decay branches

- Ground state
- Excited state (produces 478 keV gamma ray)

Observed K Capture peak broadening → resolve where Li probe lands in Ta with βNMR

- Energy spectra peaks are much broader than expected from the laser energy calibration (roughly 3 times as broad).
- Limits the sensitivity of the BeEST experiment.
- Could be due to variations of Li 1s binding energy when implanted in different local or chemical environments within Ta lattice structure.

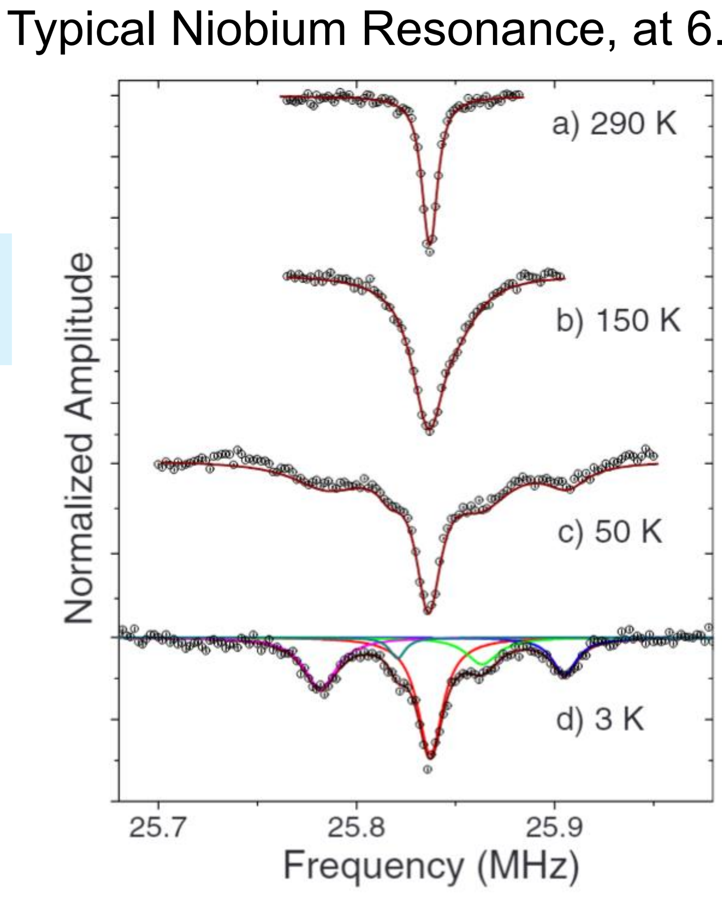




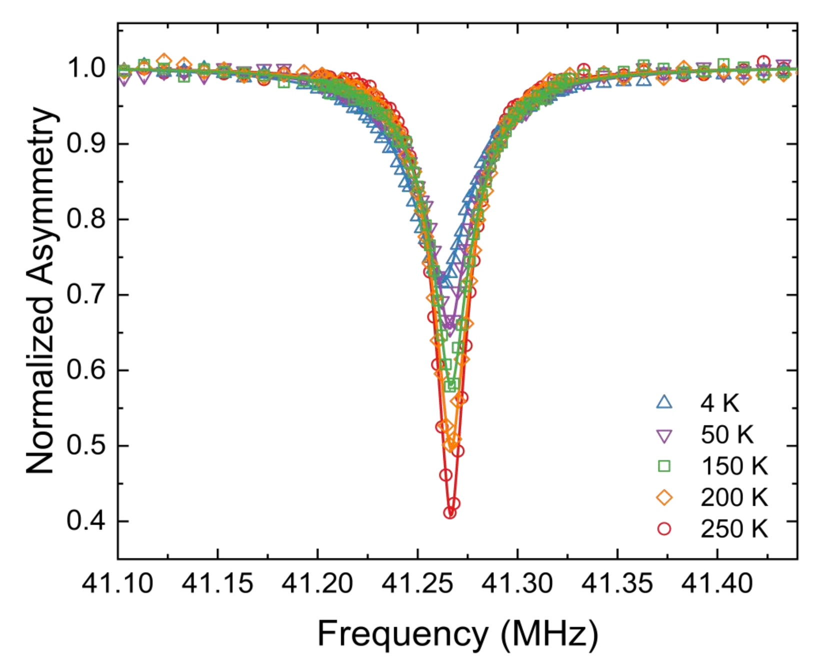
Performing Material Studies with Ta

Unexpected finding: Ta does not behave like Nb, but why?

Typical Niobium Resonance, at 6.55 T

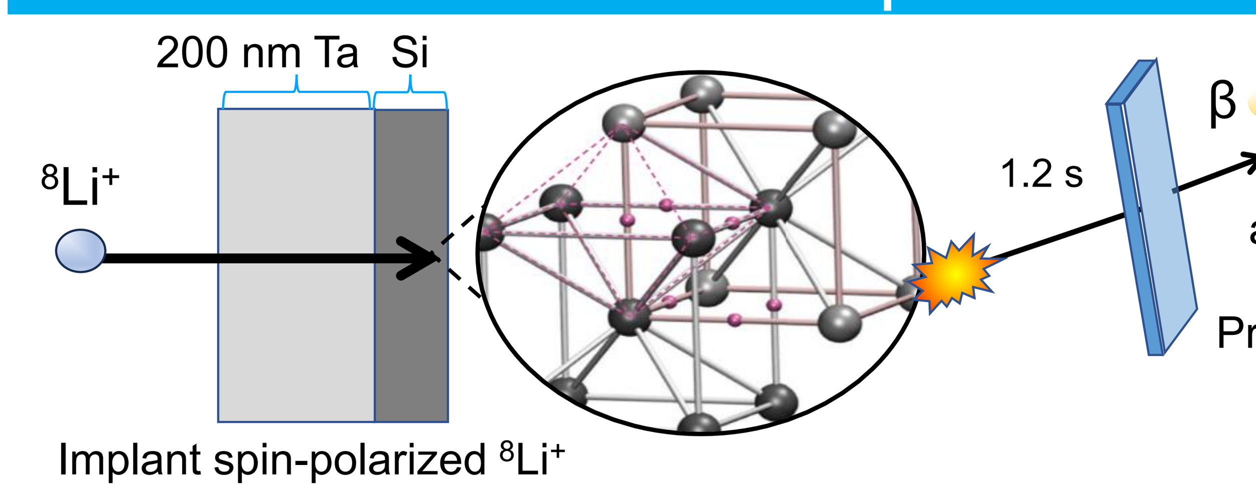


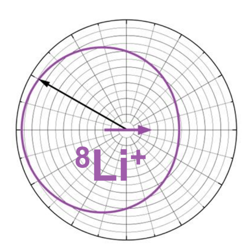
First Tantalum Resonance, at 6.55 T



- Nb demonstrates quadrupole splitting.
- Sputtered Ta does not.
- Preliminary results of epitaxial Ta run shows quadrupole splitting.
- This difference could be due to material impurities, but still under investigation.

How does βNMR work?

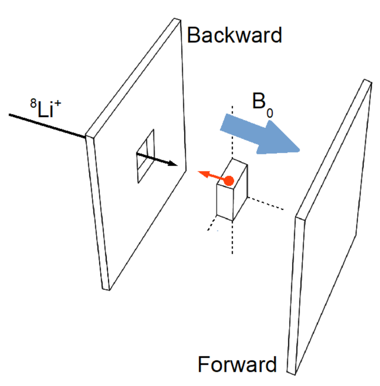




β Emission Probability Relative to Spin

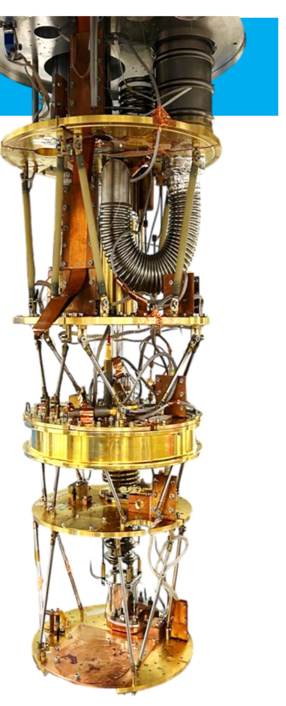
$$^8_3\mathrm{Li} \longrightarrow {}^8_4\mathrm{Be} + e^- + \overline{\nu}_e$$

$$P(t) \propto \frac{N_F(t) - N_B(t)}{N_F(t) + N_B(t)}$$



Outlook for BeEST at TRIUMF

- Upgrades are underway to equip a **dilution refrigerator** (DR) with the capability to perform STJ readout at TRIUMF.
- The DR is currently capable of reaching temperatures of approximately 20-30 mK.
- Additions to the DR to perform cosmic muon-tagging and gamma-tagging are in progress.
- Continue investigating Ta material effects to increase sensitivity to the recoil energy.



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