Snowmass2021 - Letter of Interest

Laboratory-Based keV-Scale Sterile Neutrino Searches and the BeEST Experiment

NF Topical Groups: (check all that apply ☐/■)

☐ (NF1) Neutrino oscillations
■ (NF2) Sterile neutrinos
■ (NF3) Beyond the Standard Model
☐ (NF4) Neutrinos from natural sources
■ (NF5) Neutrino properties
☐ (NF6) Neutrino cross sections
☐ (NF7) Applications

Secondary Topical Groups:

■ (RF3) Fundamental Physics in Small Experiments
■ (IF1) Quantum Sensors

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Abstract: The search for keV-scale neutrinos via precision nuclear decay measurements is among the most powerful methods for BSM neutrino mass searches since it relies only on the existence of a heavy neutrino admixture to the active neutrinos, and not on the model-dependent details of their interactions. Within this context, the BeEST (Beryllium Electron-capture with Superconducting Tunnel junctions, pronounced "beast") experiment uses the decay-momentum reconstruction technique to precisely measure the ^{7}Be→^{7}Li recoil spectrum via ^{7}Be ions implanted into high-rate superconducting quantum sensors. This Letter of Interest presents the experimental concept of the currently running experiment, sensitivity to additional BSM physics scenarios, and future plans for scaling to 10,000 STJ pixels using new materials for ultra-high energy resolution detectors to search for 5-862 keV neutrinos with couplings of $|U_{ei}|^2 \leq 10^{-10}$.

Laboratory-Based keV Sterile Neutrino Searches–Sterile neutrinos on the keV-scale are well motivated, natural extensions to the Standard Model (SM) that have been extensively studied over the past 25 years[1–3]. Originally suggested by Dodelson and Widrow in 1994[1], heavy sterile neutrinos in the keV mass range also have ideal characteristics to serve as a warm dark matter (DM) candidate since they are neutral, massive, and have lifetimes longer than the age of the Universe. Such sterile neutrinos are produced in the early Universe, but unlike other cosmic relics such as photons, the tiny interaction strength of sterile neutrinos requires that they were never in thermal equilibrium in the early Universe and that their exact production mechanism is model-dependent[3]. To date, the vast majority of laboratory-based experimental searches for keV-scale sterile neutrinos have been performed using momentum and energy conservation in nuclear β decay due to the high-level of statistical precision that is achievable from increasingly available samples of unstable atoms. In these experiments, the primary concept is momentum reconstruction of the emitted e^- and/or nuclear daughter recoil, while the neutrino is not detected and contributes to *missing momentum* in the observed spectrum. The experimental situation is simplified dramatically in neutron-deficient nuclei where the 3-body β-decay mode is energetically forbidden ($Q_{EC} < 1022$ keV), and thus the parent nucleus *only* undergoes nuclear electron capture (EC) decay. This provides a pure two-body final state that consists of the recoiling daughter atom and the emitted ν_e - both of which (in principle) are mono-energetic. Thus, by making a precision measurement of the low-energy recoiling atom, information on momentum conservation with the neutrino can be directly probed. This concept is ideal for heavy BSM neutrino searches since it relies only on the existence of a heavy neutrino admixture to the active neutrinos, which is a generic feature of neutrino mass mechanisms, and not on the model-dependent details of their interactions. Measurements of this type are currently being performed using superconducting quantum sensors embedded with ^{7}Be by the BeEST experiment (described here), and trapped atoms of ^{131}Cs by the HUNTER experiment[4]. These two experiments are highly complimentary, as they have very different systemics associated with them and thus provide an excellent avenue for potential discovery confirmation.

The Case of ^{7}Be and the BeEST Experimental Concept–The pure EC decaying nucleus of ^{7}Be is the ideal case for neutrino studies via momentum reconstruction due to its large Q_{EC}-value (862 keV), relatively high recoil energy ($\sim$ 50 eV), and simple atomic and nuclear structure. These features of the decay allow for probing neutrino masses up to 862 keV with minimal requirements for nuclear and atomic structure corrections, but require high-resolution, low-energy detection of the recoiling atom. ^{7}Be EC decay was first used in the early 1950's as a search for single neutrino emission[5], and has been suggested as an ideal case for keV-mass sterile neutrino searches[4;6] but has not been explored due to various technical challenges of previously considered techniques. The BeEST (Beryllium Electron-capture with Superconducting Tunnel junctions, pronounced "beast") experiment overcomes previous technical challenges by implanting intense beams of unstable ^{7}Be atoms created at the TRIUMF-ISAC rare-isotope beam facility[7] into high-rate quantum sensors to perform low-energy calorimetry of the decay products following ^{7}Be EC.

Superconducting Tunnel Junction (STJ) Quantum Sensors–STJs are high-speed quantum sensors that were originally developed for high-resolution X-ray spectroscopy in astronomy and material science[8;9]. STJs are a type of Josephson junction that consists of two superconducting electrodes separated by a thin insulating tunneling barrier. The absorption of radiation in one of the electrodes breaks the Cooper pairs of the superconducting ground state and excites free excess charge carriers above the superconducting energy gap Δ in proportion to the absorbed energy. The high energy resolution in STJs is due to the fact that the energy to create an excess charge $\epsilon = 1.7\Delta$ scales with the energy gap Δ[8]. For superconductors, Δ is of order 1 meV and thus roughly three orders of magnitude smaller than the band-gap in semiconductors, giving rise to ~ 1 eV resolution at the signal energies relevant to the BeEST[10;11]. The maximum STJ count rates are determined by the time that the excess charges remain excited above Δ before they recombine into the superconducting ground state and again form Cooper pairs, which is typically in the 10 μs range. This enables each STJ detector pixel to operate at rates up to 10^4 counts/s[12], which places them among the highest-rate high-resolution quantum sensors, and makes them ideal for the BeEST experiment.

Completed and Future Phases of the BeEST Experiment–The first demonstration of high-resolution nuclear recoil detection with STJs was recently performed, and serves as the proof-of concept for the technique employed by the BeEST[11]. From these test data with a single Ta-based STJ detector, preliminary limits on sterile neutrino coupling to ν_e of $|U_{ei}|^2 < 10^{-3}$ or better are possible in the mass range 100-800 keV - roughly an order of magnitude better than previous decay measurements. Briefly, the work and milestones planned for the four Phases of the BeEST experiment are:

1. Phase-I (completed): Proof-of-concept measurement with ^{7}Be test implantation into previously characterized Ta-based STJ detectors[11].
2. Phase-II *(in-progress)*: Precision energy calibration (completed). Optimization of implantation technique and full characterization of Ta-based STJs using γ-ray coincidence measurements.
3. Phase-III *(in-progress)*: Scaling of the BeEST to existing 36- and 112-pixel Ta-based STJ arrays and evaluation of scaling effects and possible limitations.
4. Phase-IV *(in progress)*: Design and fabrication of 128-pixel arrays of Al-based STJ detectors deposited on thin Si_3N_4 membranes, and running for 100 days at 1 kHz per STJ, enabling sensitivites of $|U_{ei}|^2 \approx 10^{-5} - 10^{-7}$ couplings for masses above 10 keV.

Sensitivity to Other BSM Physics in the Neutrino Sector–If light enough, new states that couple to neutrinos can be emitted during an electron capture event and thus the BeEST or HUNTER experiments may be sensitive to them. The kinematics of the decay in this case would be modified from the standard two-body final state and would include some three-body component that could be observed. Thus, a sensitive measurement of the recoil energy spectrum can reveal the emission of such new states through a distribution of observed recoil energies, rather than the discrete recoil peaks generated by the mostly active neutrino masses (or mostly sterile keV-scale neutrino masses, if they exist). Examples of light new states that couple to neutrinos are “majorons,” motivated by neutrino mass models[13–16], neutrino portal dark matter[17–23], and the mediators of “secret interactions” in the sterile neutrino sector[24–26]. The BeEST collaboration is currently in the process of estimating the experimental sensitivities to such scenarios for the various Phases outlined above.

Summary and Outlook Beyond Sterile Couplings of $|U_{ei}|^2 < 10^{-7}$–The BeEST experiment is a currently running high sensitivity search for keV-scale neutrinos in the EC decay of ^{7}Be using STJ radiation detectors. Within the next 5 years, limits approaching $|U_{ei}|^2 \approx 10^{-7}$ in the $\sim$ 100 keV mass range are projected based on the initial data runs over the past year. Following Phase-IV of the BeEST, a dramatic improvement in sensitivity is planned using large ($\sim 10^4$-pixel) arrays of Hf-based STJs which have energy resolutions on the order of 0.2 eV. This requires significant development work, but leverages the existing effort for the current BeEST experiment, and may be among the best laboratory-based experimental approaches to search for the possible 7 keV sterile neutrino DM candidate with a relative coupling to the electron neutrino flavor of $|U_{ei}|^2 \leq 10^{-10}$[27–30].

Acknowledgements–This work is supported by the U.S. Department of Energy, Lawrence Livermore National Laboratory, the Canadian Natural Sciences and Engineering Research Council, and the European EMPIR Project No. 17FUN02 MetroMMC. TRIUMF receives federal funding via a contribution agreement with the National Research Council of Canada. This work is performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

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