Sub-keV Decay-Recoil Spectroscopy with Superconducting Quantum Sensors

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Colorado School of Mines

Facility for Rare Isotope Beams
Michigan State University

TRIUMF Science Week 2022

Vancouver, BC, Canada – July 20, 2022

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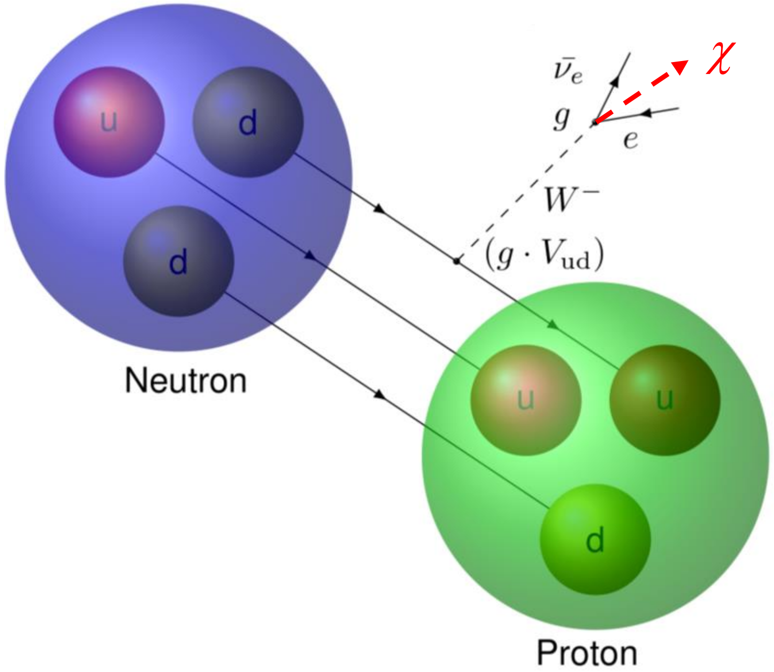
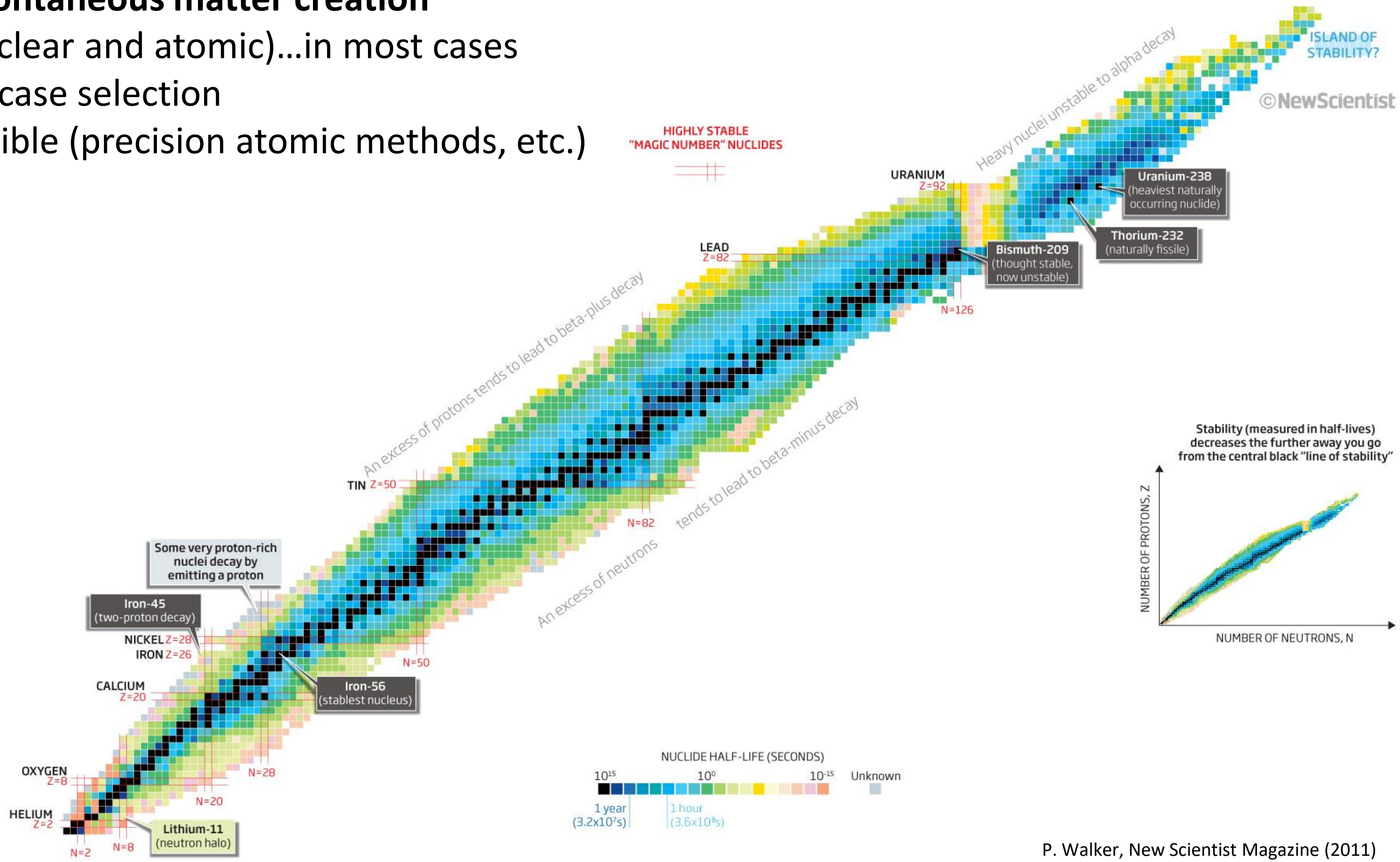
Creating New Physics in the Laboratory with Rare Isotopes

Weak Nuclear Decay is among the *MOST* sensitive BSM physics probes:

- Pure energy-to-matter conversion: **spontaneous matter creation**
- Complex, but understood systems (nuclear and atomic)…in most cases
- More than 3500 different systems for case selection
- Exceptional experimental control possible (precision atomic methods, etc.)





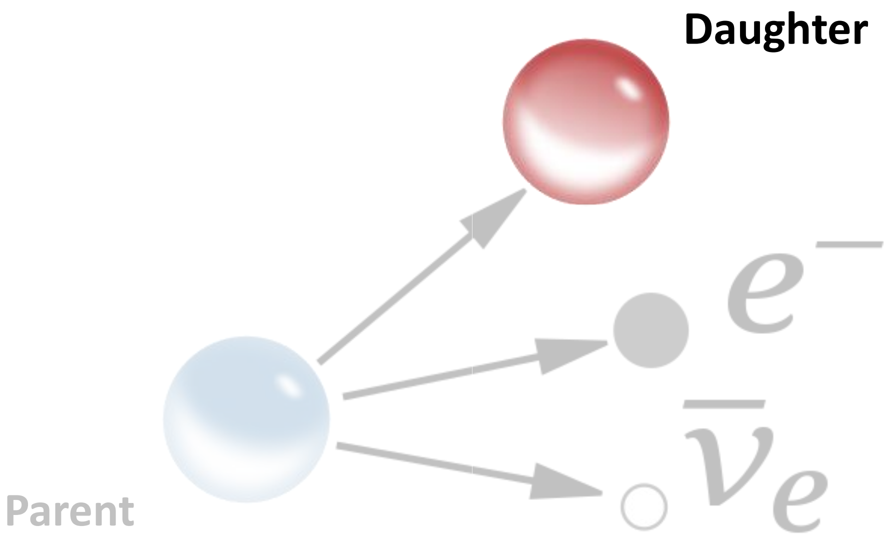
P. Walker, New Scientist Magazine (2011)

Atomic Recoils Following Nuclear β Decay

We typically characterize β decay via measurements of:

- Electrons (β^-, atomic Auger, CE, etc.)
- Positrons (β^+ and IPC)
- Photons (γ-ray, bremsstrahlung, and X-rays)

} keV/MeV Scale



The daughter atomic recoil is entangled with the other final state products, and contains some difficult to access information:

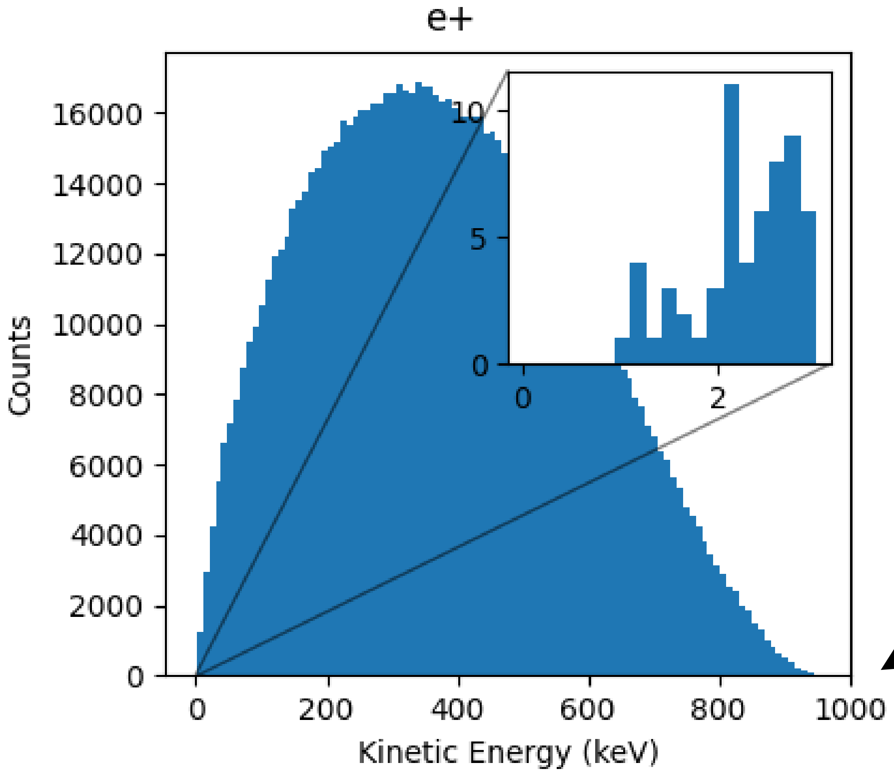
- Momentum conservation with neutrino and electron
  - β–ν angular correlation
  - ν mass
- Nuclear and atomic final-state information

In several cases, the recoil is a unique probe – particularly for tests of fundamental symmetries

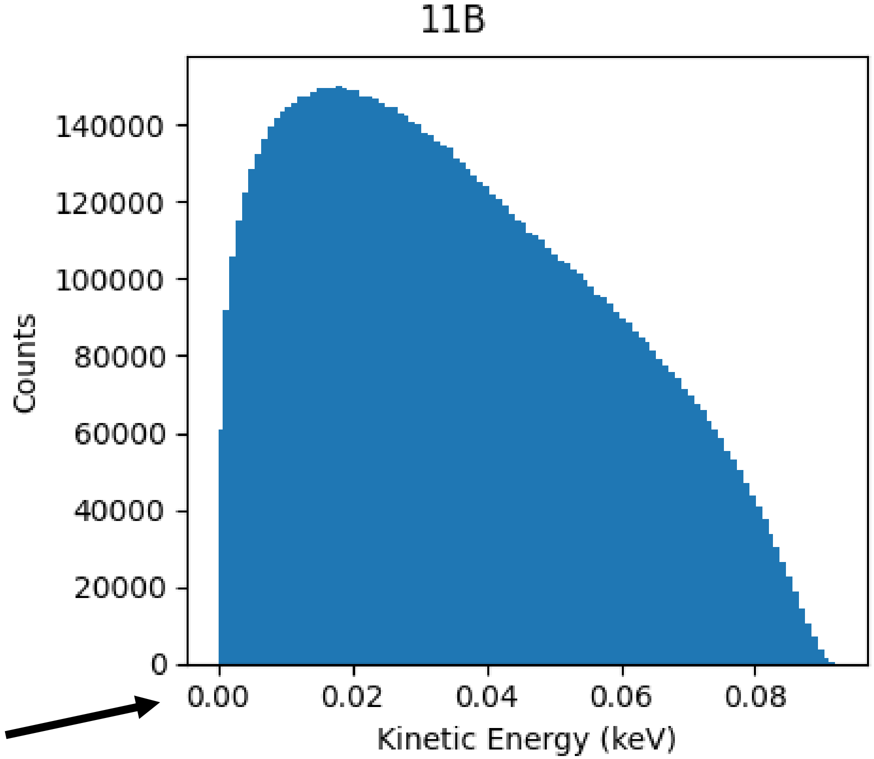
Atomic Recoil Spectroscopy

Typically, we measure energy not momentum, and thus the main experimental challenge is finding an experimental technique capable of handling the very small (eV-scale) recoils.

Example: ^{11}C β^+ decay



keV → MeV



< 0.1 keV

Plots courtesy of L.M. Hayen

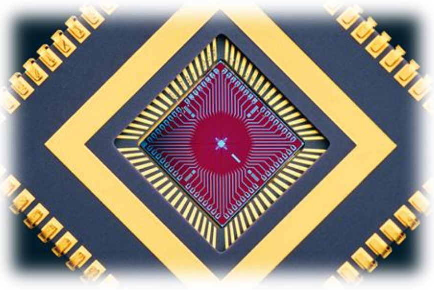
Quantum Sensing

"…the design and engineering of quantum sources and quantum measurements that are able to beat the performance of any classical strategy in a number of technological applications…"

The U.S. National Quantum Initiative

⟨quantum|gov⟩

$2.8 B (2017 – 2021)
FY22 > $800M
FY23 (est.) > $1B



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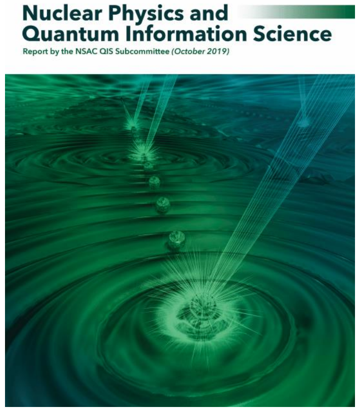
NSAC 2019 report on NP and QIS



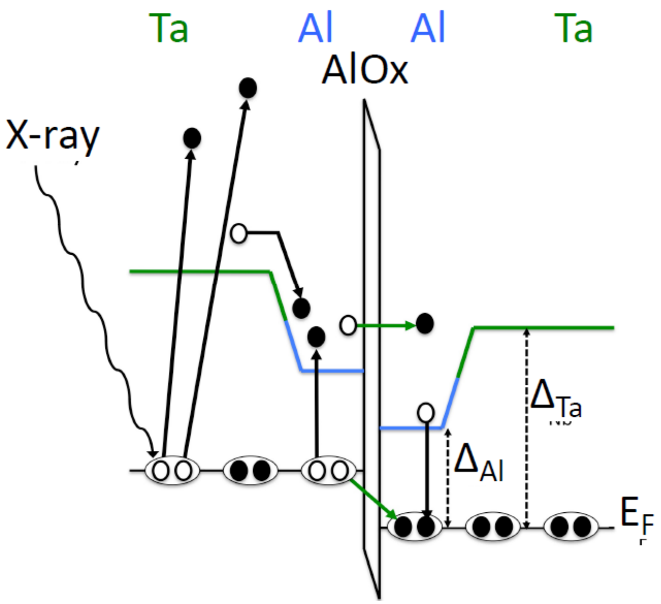
Superconducting sensors:

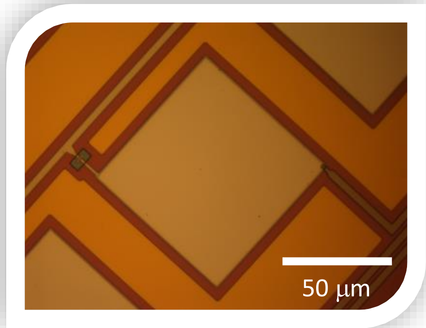
- They are small and thin devices
- Characterized by high energy resolution
- Multiple technologies for application specific uses
- Require operation temperatures <0.1 K

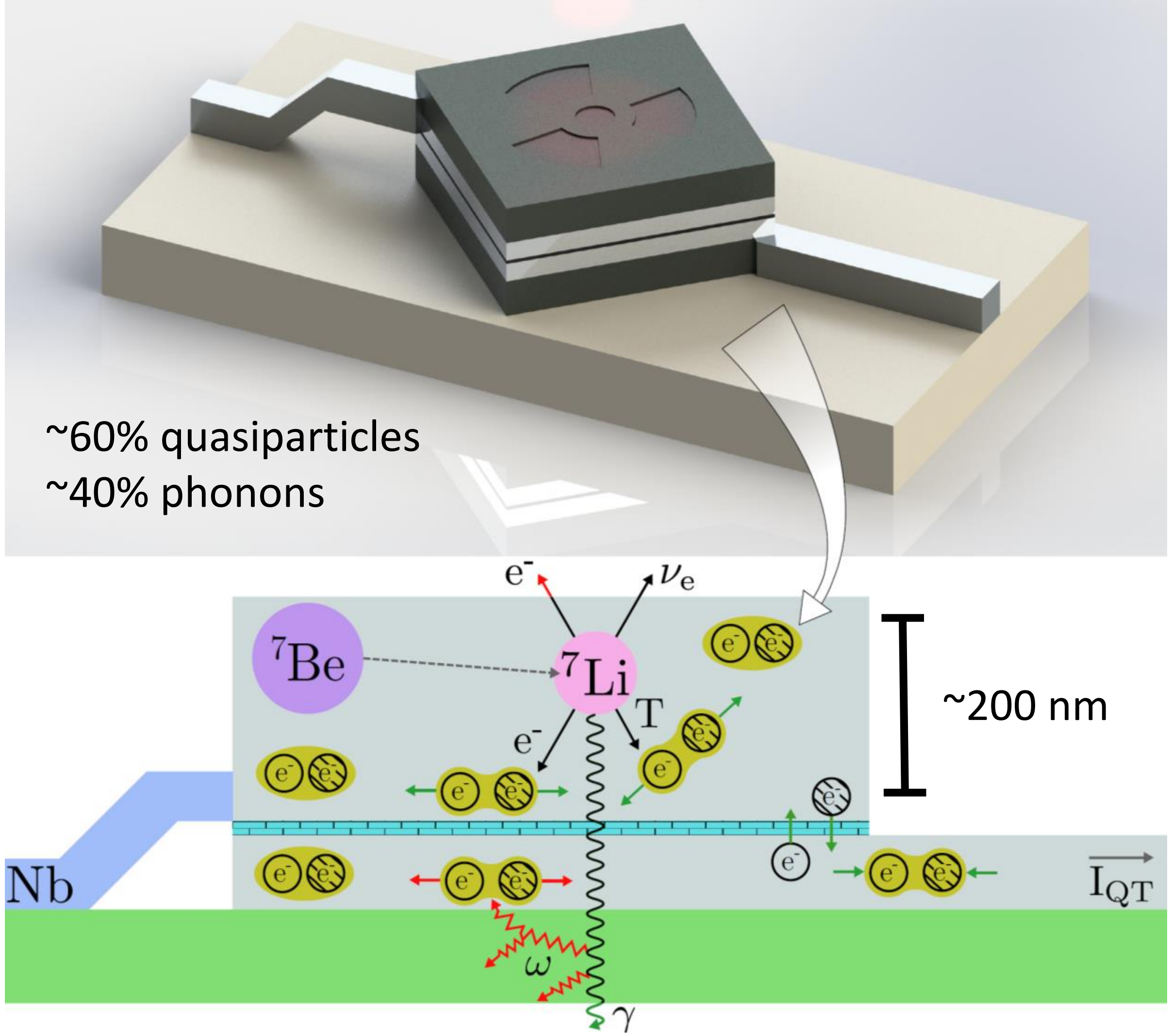
Superconducting Tunnel Junctions (STJs)

- *Cryogenic-charge* superconducting sensor
- Superconducting energy gap Δ is of order ~meV
  → High Energy Resolution (~1 eV)
- Timing resolution on the order of 10 μs, allowing for faster count rates than most superconducting sensors
  → "High" Rate (10^4 s^{-1} per pixel)

← *Allows us to probe weak couplings*



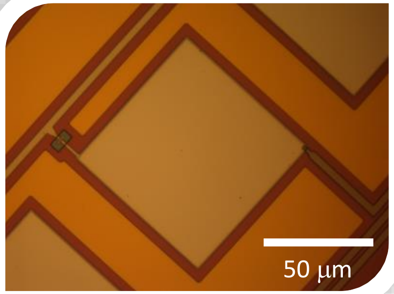




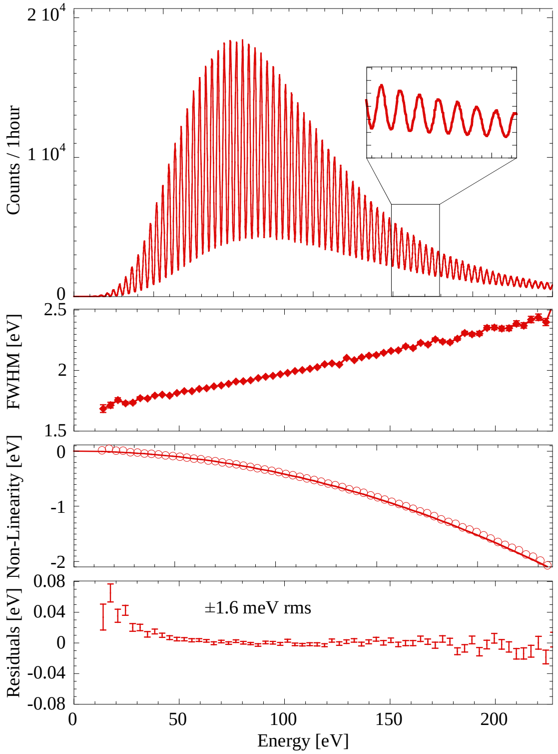
Direct Implantation of RIBs into Superconducting Sensors

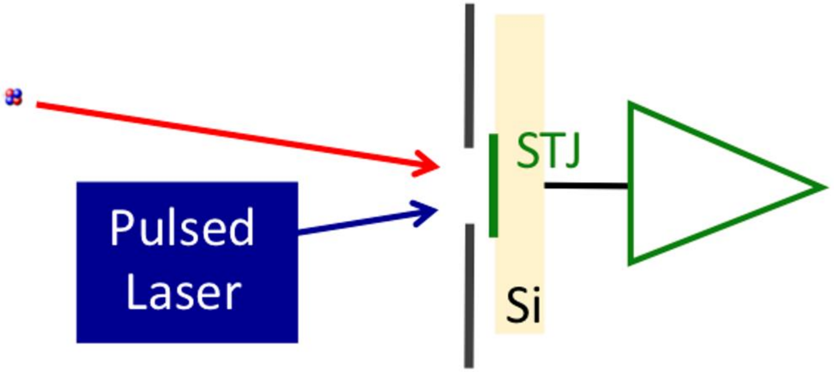
Rare-isotope implantation

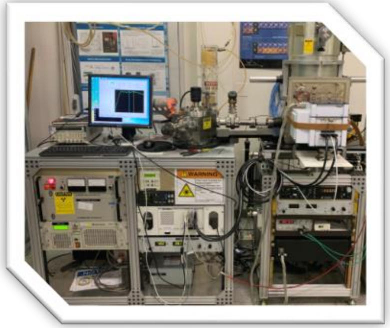
Ta, Al, and Nb-based STJ Sensors

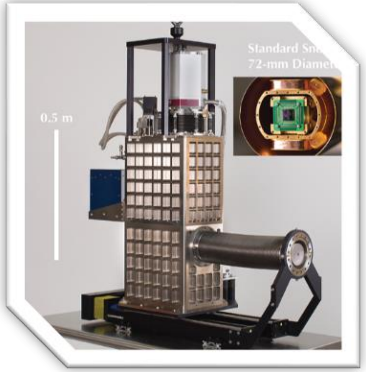


A. Samanta *et al*., Phys. Rev. Mat. (*submitted*) (2022)
S. Friedrich *et al.,* J. Low Temp. Phys. (in press) (2022)
C. Bray *et al*., J. Low Temp. Phys. (*in press*) (2022)
K.G. Leach and S. Friedrich, J. Low Temp. Phys. (*in press*) (2022)
S. Friedrich *et al*., Phys. Rev. Lett. **126**, 021803 (2021)
S. Fretwell *et al*., Phys. Rev. Lett. **125**, 032701 (2020)
S. Friedrich *et al*., J. Low Temp. Phys. **200**, 200 (2020)





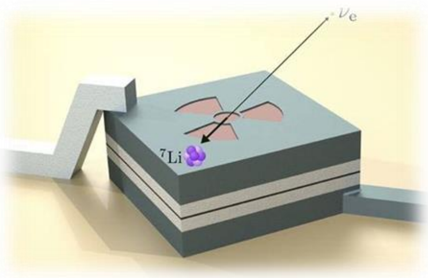




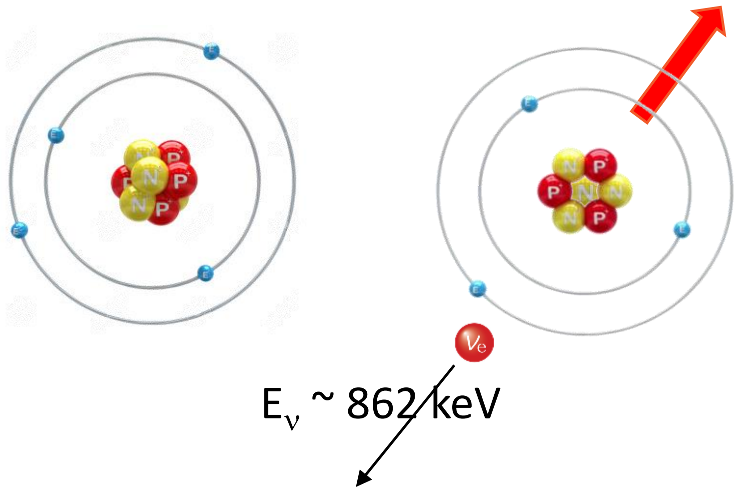
High-precision *In-situ* calibration and characterization

Cooling (<0.1 K) and measurement in ADR

First Nuclear Recoil Experiments with STJs – ^{7}Be Decay

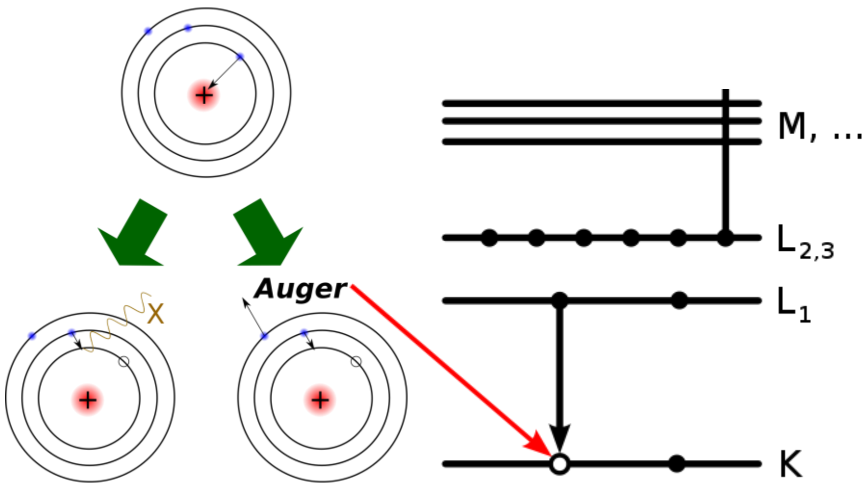


^{7}Be (Z=4)
parent

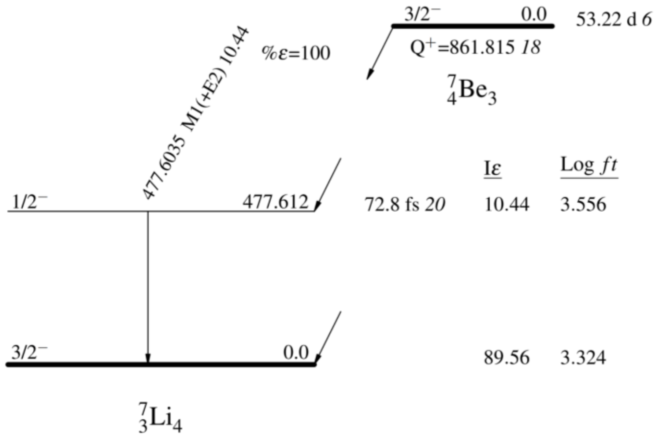


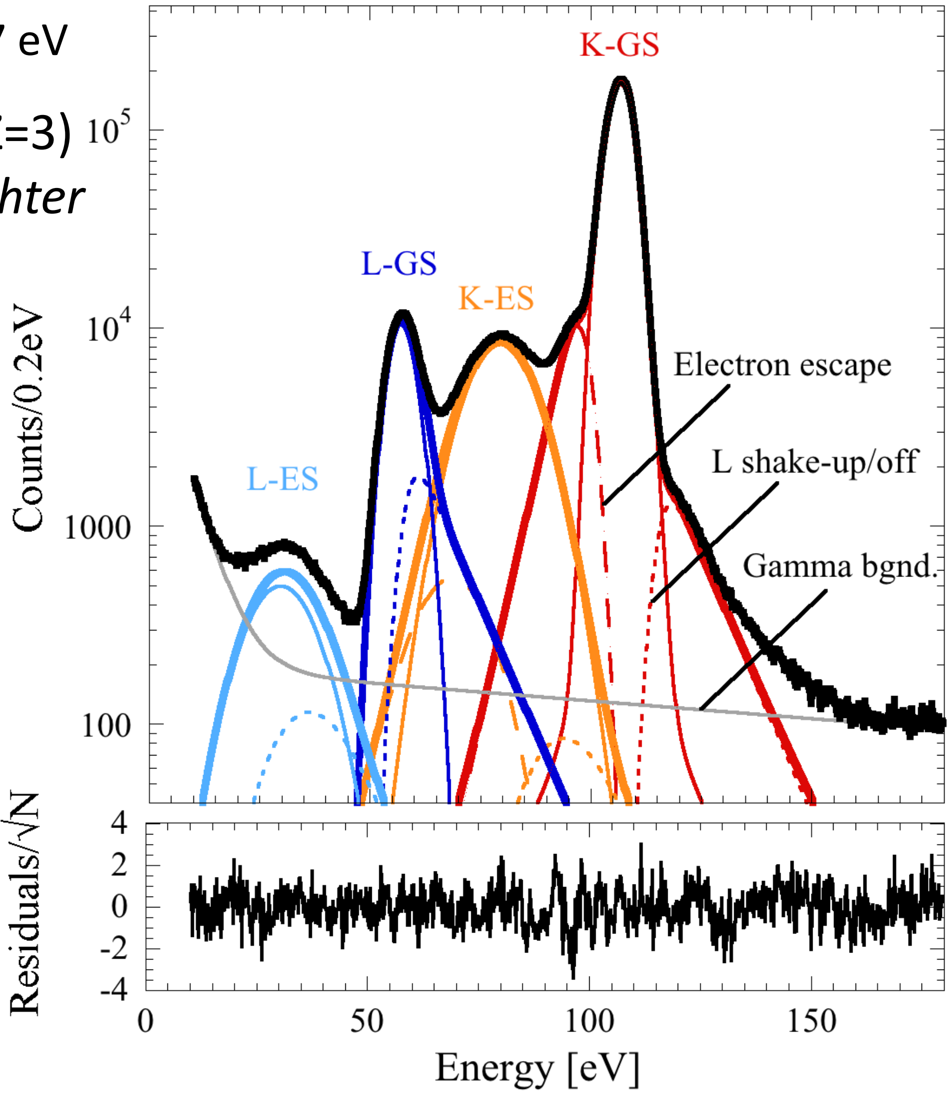
^{7}Li (Z=3)
daughter

Atomic Effects



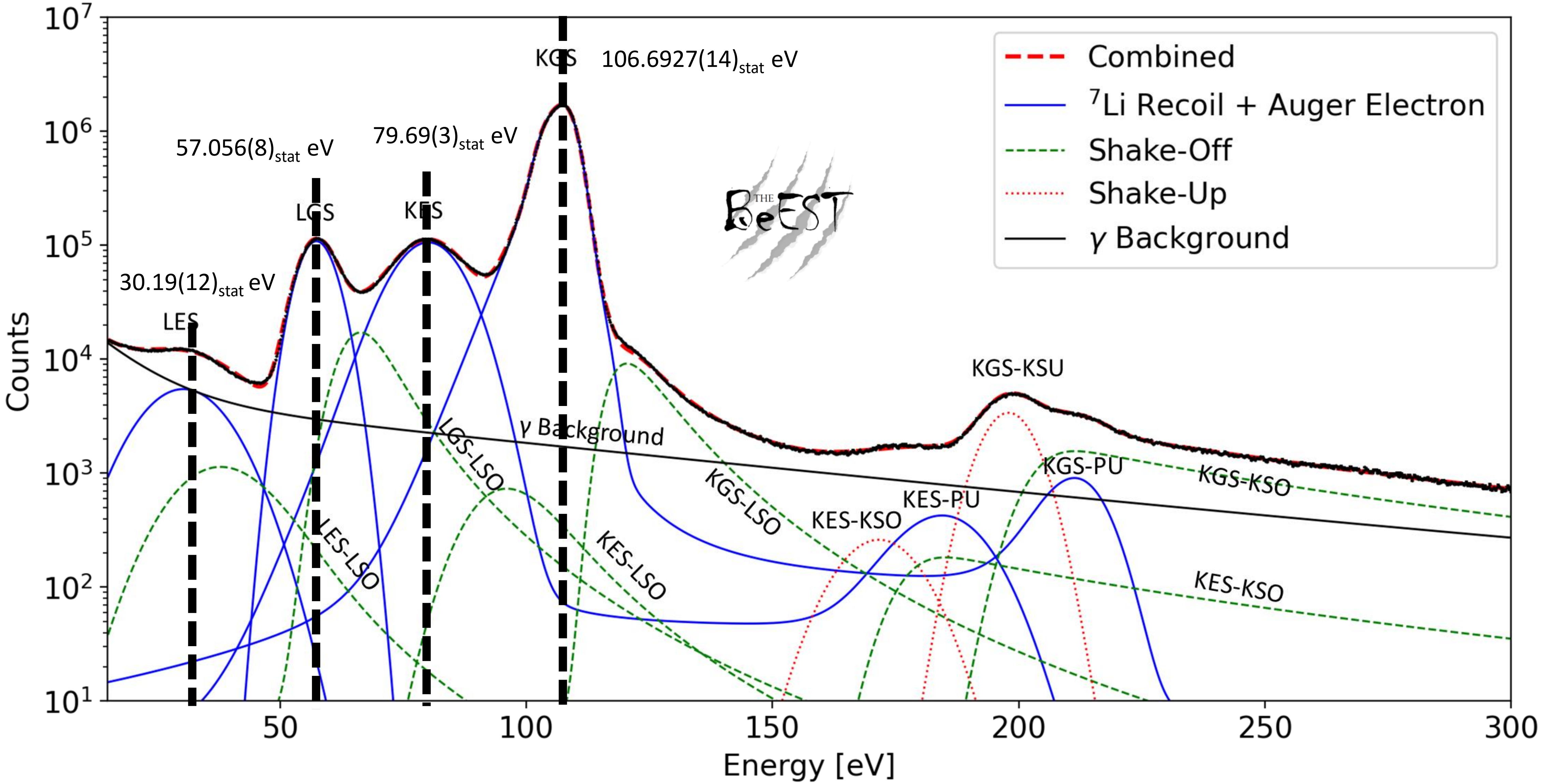
Nuclear Effects





S. Fretwell *et al.*, Phys. Rev. Lett. **125**, 032701 (2020)

Precision Low-Energy Nuclear Recoil Spectroscopy



Nuclear Astrophysics and BSM Neutrinos

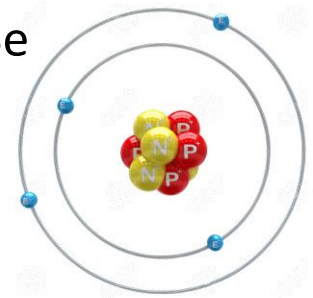
Data from 20 minutes of A=7 beam from TRIUMF-ISAC and 1 month of counting

PHYSICAL REVIEW LETTERS **125,** 032701 (2020)

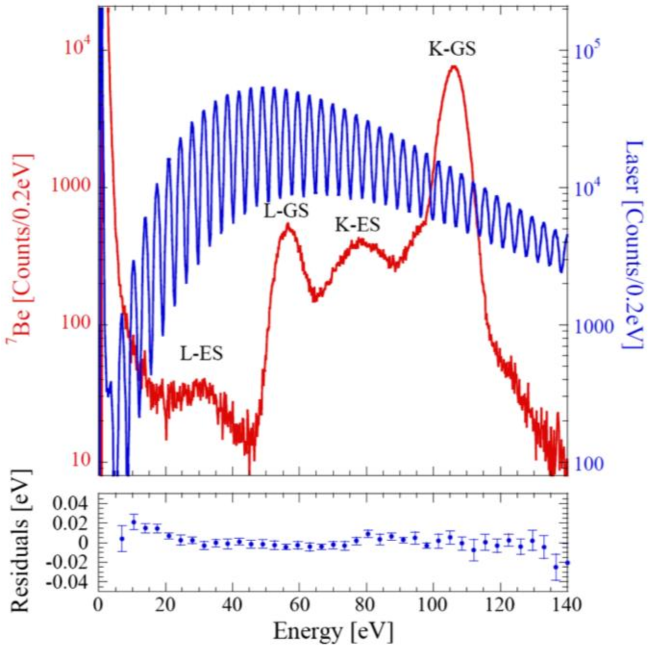
Direct Measurement of the ^{7}Be L/K Capture Ratio in Ta-Based Superconducting Tunnel Junctions

S. Fretwell,[1] K. G. Leach,[1,*] C. Bray,[1] G. B. Kim,[2] J. Dilling,[3] A. Lennarz,[3] X. Mougeot,[4] F. Ponce,[5,2] C. Ruiz,[3] J. Stackhouse,[1] and S. Friedrich[2]
[1]Department of Physics, Colorado School of Mines, Golden, Colorado 80401, USA
[2]Nuclear and Chemical Sciences Division, Lawrence Livermore National Laboratory, Livermore, California 94550, USA
[3]TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia V6T 2A3, Canada
[4]CEA, LIST, Laboratoire National Henri Becquerel, CEA-Saclay, 91191 Gif-sur-Yvette Cedex, France
[5]Department of Physics, Stanford University, Stanford, California 94305, USA

^{7}Be



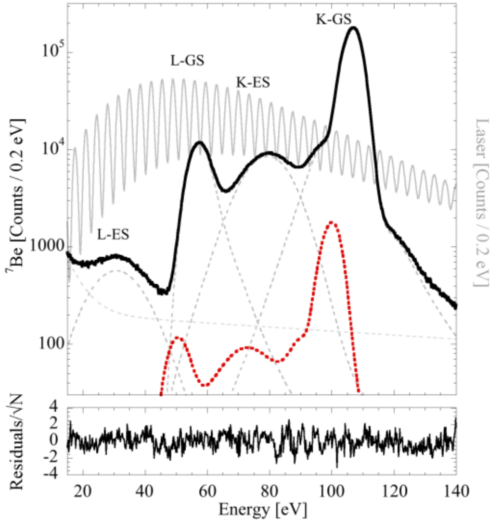
L/K = 0.070(7)

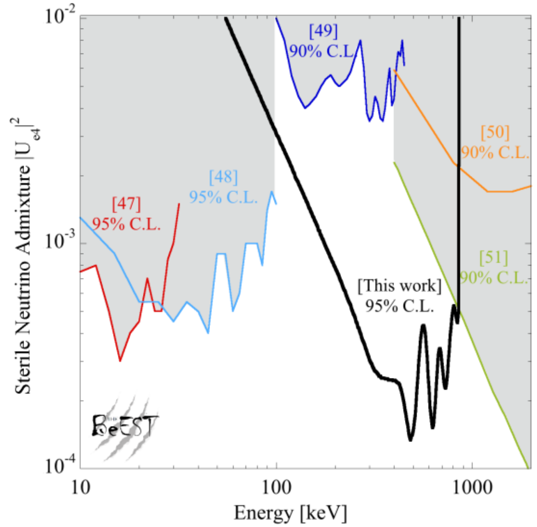


PHYSICAL REVIEW LETTERS **126,** 021803 (2021)

Limits on the Existence of sub-MeV Sterile Neutrinos from the Decay of ^{7}Be in Superconducting Quantum Sensors

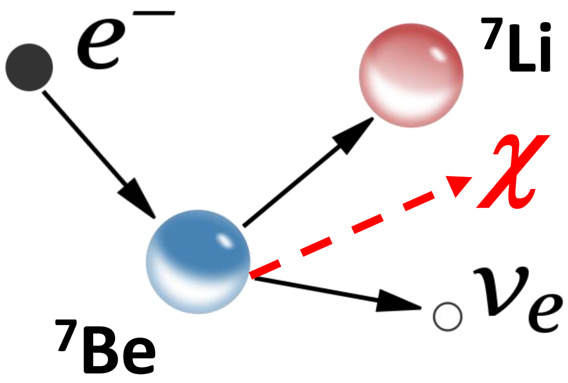
S. Friedrich,[1,*] G. B. Kim,[1] C. Bray,[2] R. Cantor,[3] J. Dilling,[4] S. Fretwell,[2] J. A. Hall,[3] A. Lennarz,[4,5] V. Lordi,[1] P. Machule,[4] D. McKeen,[4] X. Mougeot,[6] F. Ponce,[7,1] C. Ruiz,[4] A. Samanta,[1] W. K. Warburton,[8] and K. G. Leach[2,†]
[1]Lawrence Livermore National Laboratory, Livermore, California 94550, USA
[2]Department of Physics, Colorado School of Mines, Golden, Colorado 80401, USA
[3]STAR Cryoelectronics LLC, Santa Fe, New Mexico 87508, USA
[4]TRIUMF, Vancouver, British Columbia V6T 2A3, Canada
[5]Department of Physics and Astronomy, McMaster University, Hamilton, Ontario L8S 4M1, Canada
[6]Université Paris-Saclay, CEA, List, Laboratoire National Henri Becquerel (LNE-LNHB), F-91120 Palaiseau, France
[7]Department of Physics, Stanford University, Stanford, California 94305, USA
[8]XIA LLC, Hayward, California 94544, USA

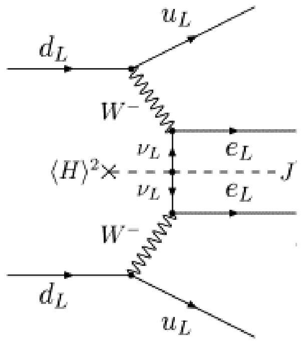


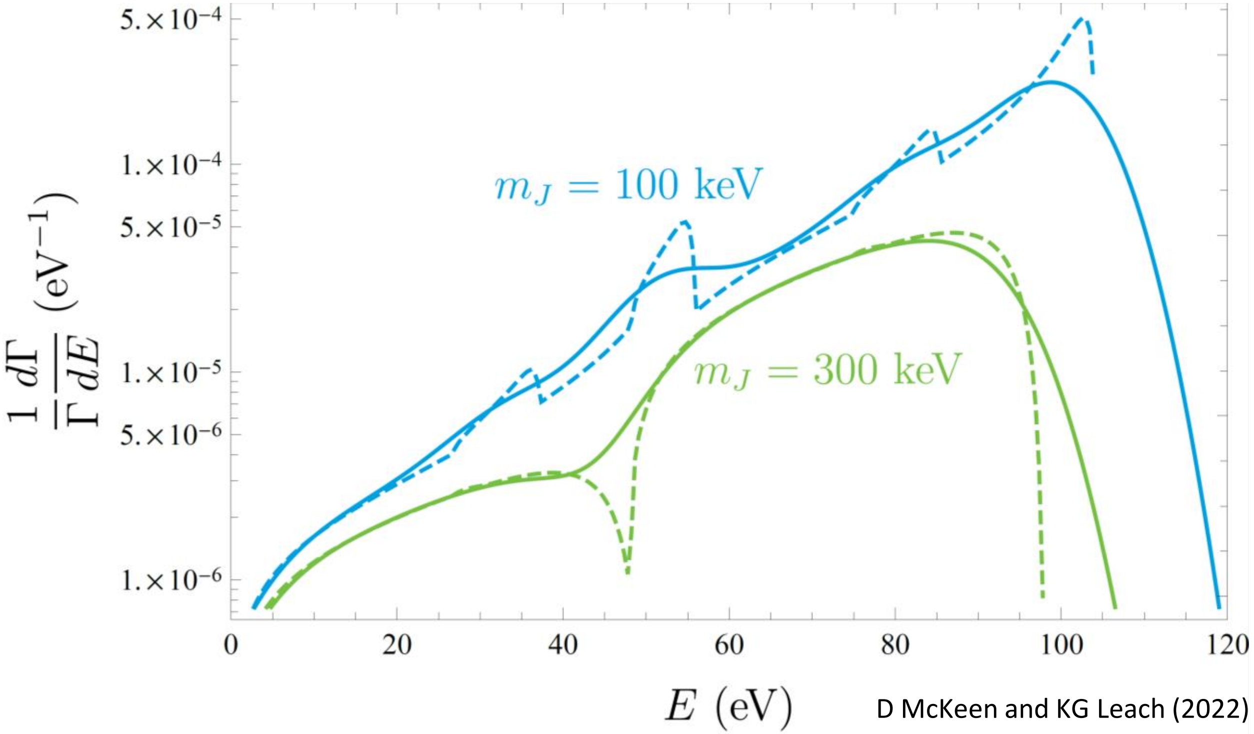


The TIP of the Iceberg……

- Is there more we can pull out of precision data like this?
- Momentum reconstruction in EC decay is sensitive to any deviation from the SM recoil signal (e.g. Majoron emission)
- This can be extended to search for physics in a number of models
- Can we extend this technique to isotopes other than ^{7}Be?

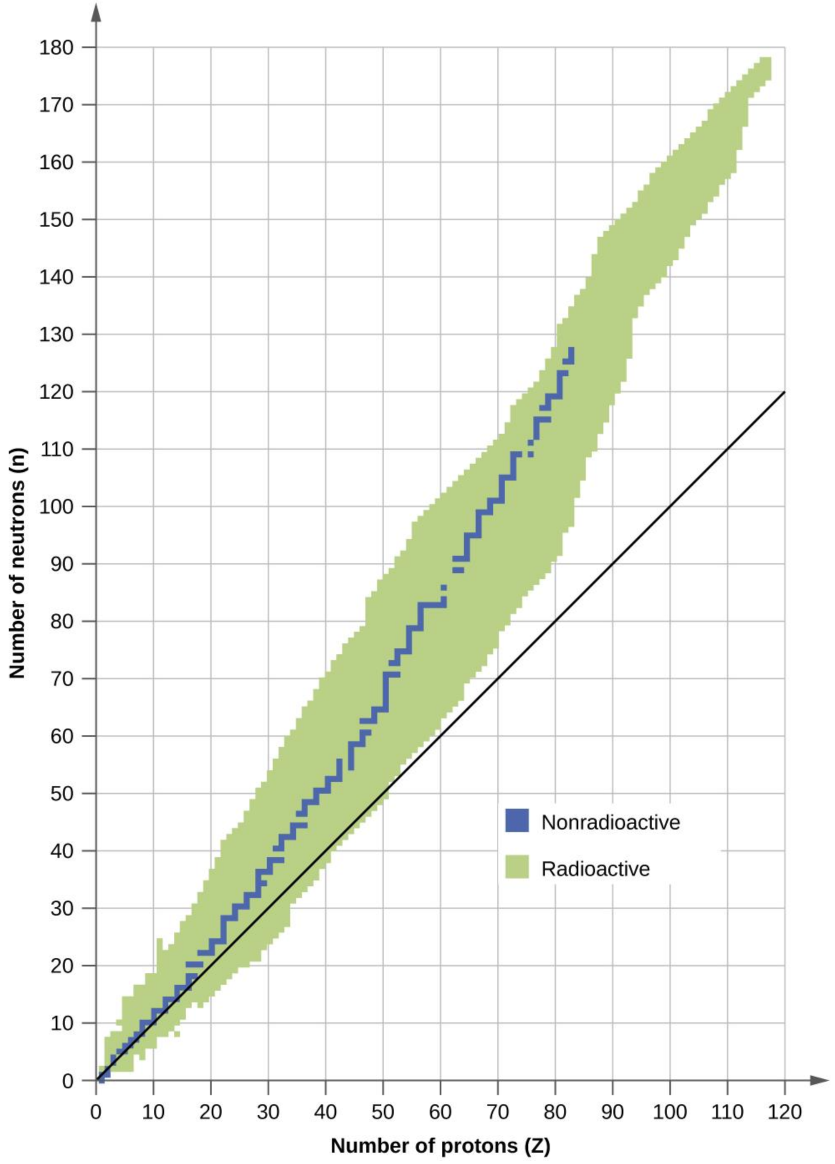






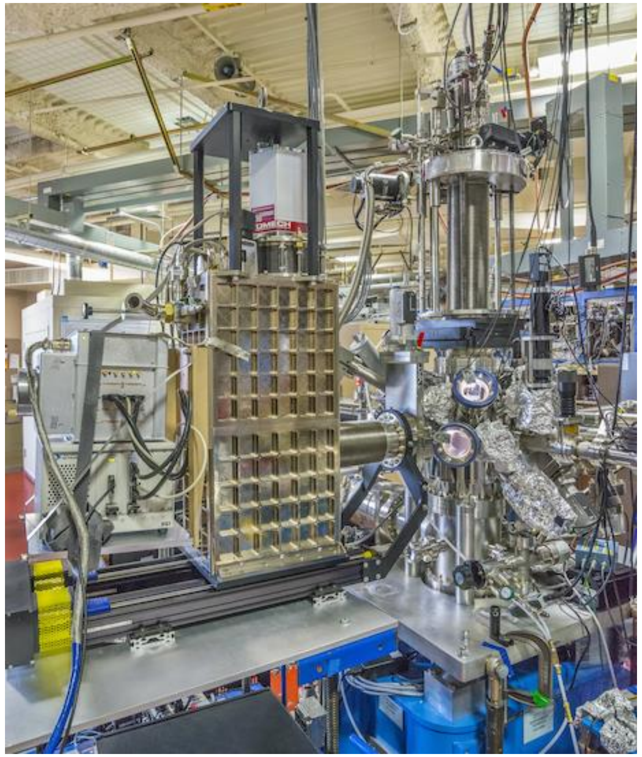
D McKeen and KG Leach (2022)

STJs as a Broad Tool for Precision sub-keV Decay Studies



The BeEST method requires isotopes with half-lives on the order of days or longer, significantly limiting the practicality of low-T quantum sensing for a wide range of experiments on short-lived isotopes.

Superconducting **A**rray for **L**ow **E**nergy **R**adiation



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Short-lived RIBs from on-line facilities (FRIB, TRIUMF-ISAC, CERN-ISOLDE)

COLORADO SCHOOL OF MINES
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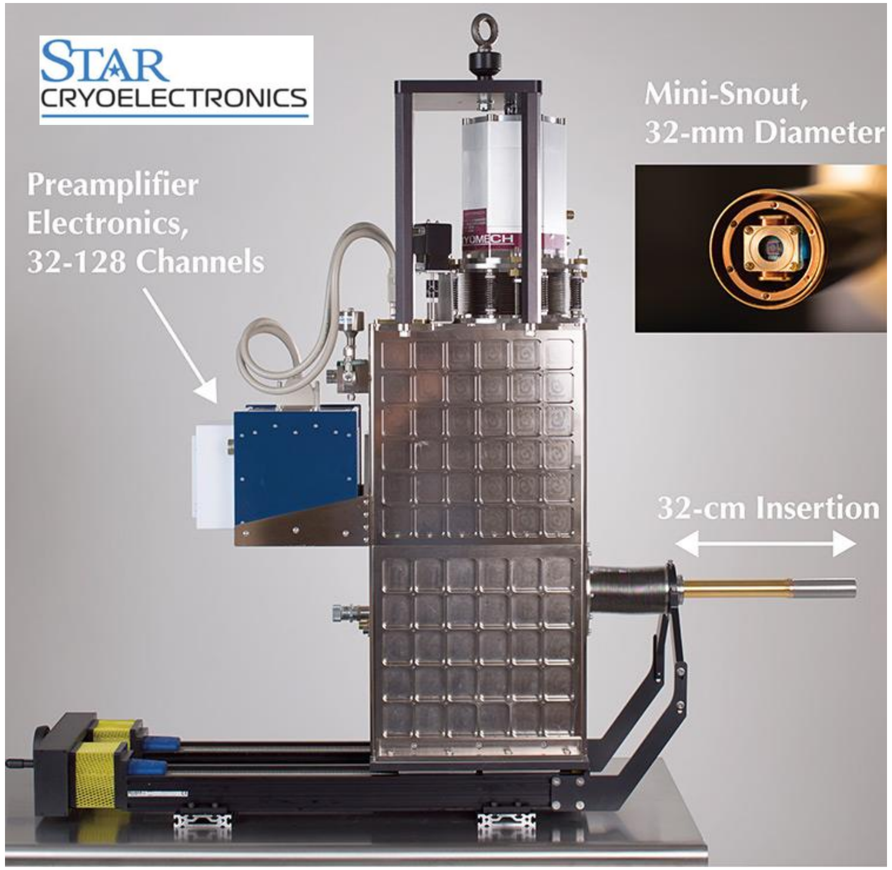
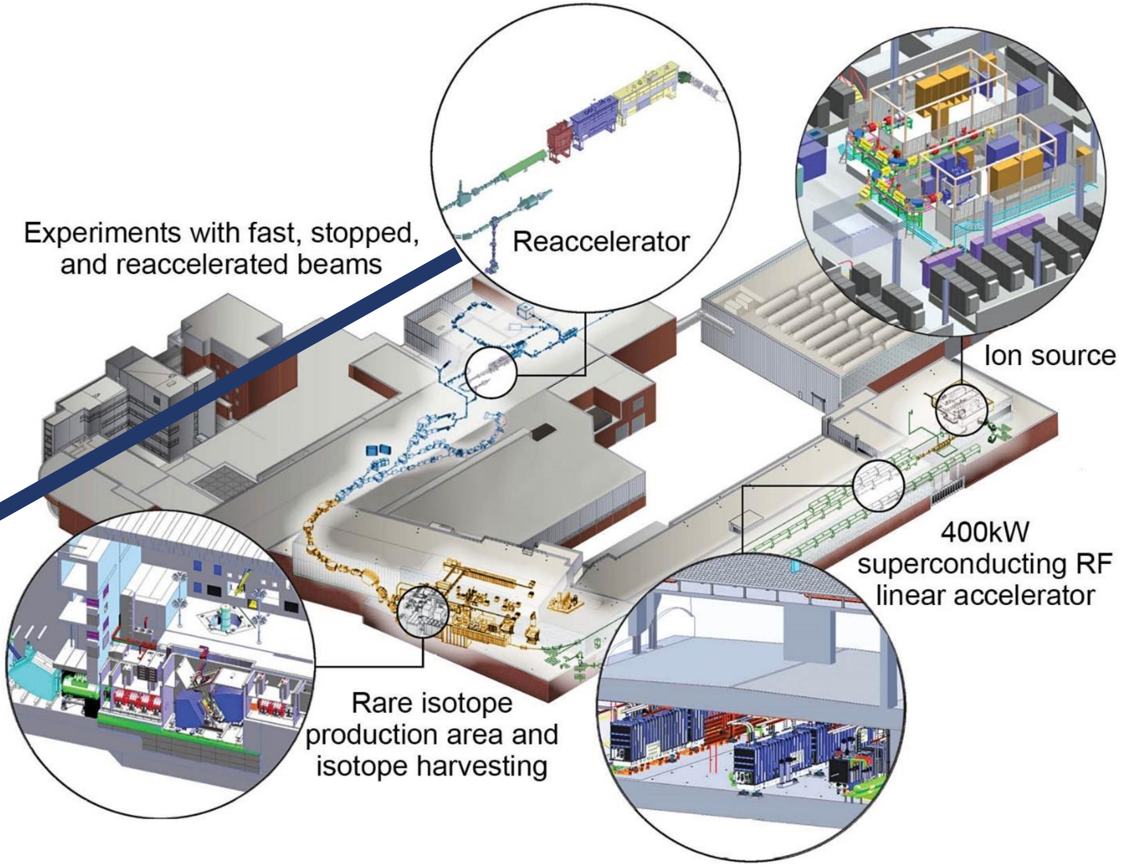
NC STATE UNIVERSITY

SALER @ FRIB

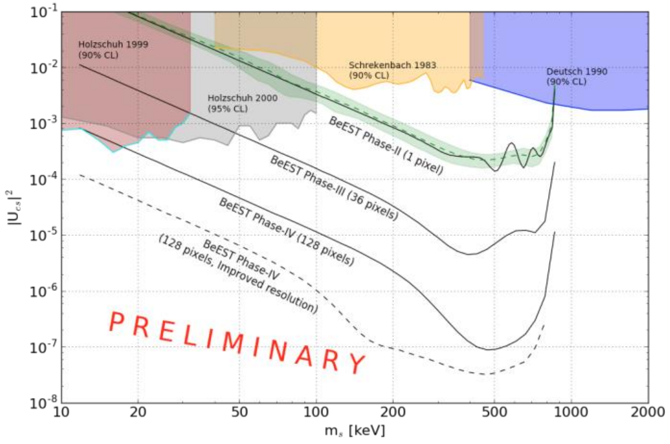
"Low" Energy ReA beam (~1 MeV/u)

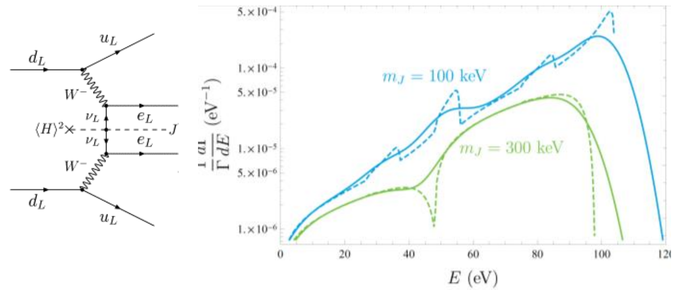


~ 8 μm Al degrading foil



Superconducting Sensors for Low-Energy Spectroscopy





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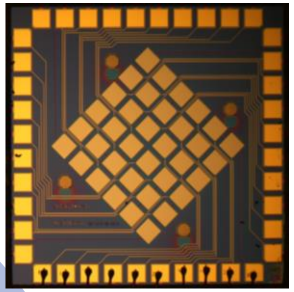
Lawrence Livermore National Laboratory

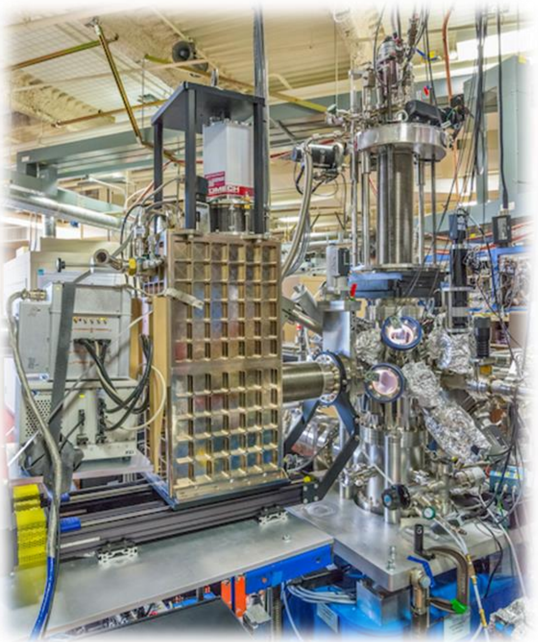
EMPIR EURAMET

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

THE BeEST

BSM Neutrino Mass Studies





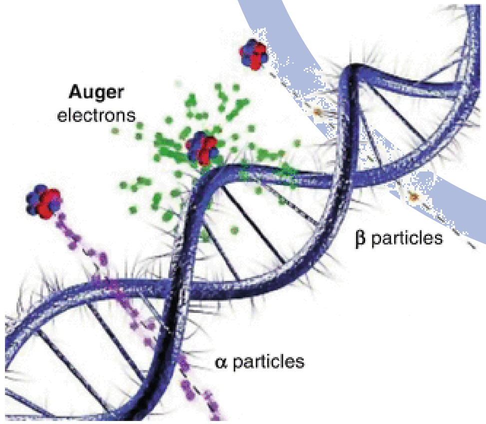
Exotic Dark Matter Searches

Superconducting Quantum Sensors

+

Rare Isotope Decay

New TeV Scale Physics Searches



Surrogates for Living Cells (Cancer Radiotherapy)

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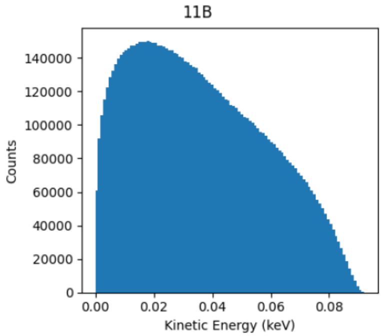

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Conclusions

- Implanted rare isotopes in STJs are a powerful tool for sub-keV nuclear decay spectroscopy
- Since 2018 we have done precision measurements in the EC decay of ^{7}Be – motivated primarily by heavy BSM neutrino searches (the BeEST experiment).
- Using STJs, we are able to measure radiation from ~2.5 eV to 1 keV with ~ meV precision at decay rates of up to 10 kBq
- We have extended the BeEST concept to develop the superconducting array for low-energy radiation (SALER) to perform nuclear recoil spectroscopy using short-lived RIBs on-line.
- The first step for SALER will be offline commissioning and first beam tests at FRIB in 2023