Experimental overview of precision beta-decay measurements (for BSM neutrino physics)

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A Snowmass view from the NP community
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.)

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P. Walker, New Scientist Magazine (2011)
The 3x3 Paradigm: A Tale of Two Symmetries

The Standard Model includes an inherent symmetry breaking mechanism that accounts for three generations of quarks and leptons – the weak interaction and mass eigenstates are not equal to each other.

CKM Matrix (Quark Mixing)

\[
\begin{pmatrix}
(d') \\
(s') \\
(b')
\end{pmatrix} = 
\begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix} 
\begin{pmatrix}
d \\
s \\
b
\end{pmatrix}
\]

If they are indeed complete, these are unitary transformations.

PMNS Matrix (Lepton Mixing)

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} = 
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix} 
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

Can be probed via semi-leptonic decay of hadrons.

*There is currently a 4σ tension with the SM unitarity condition for the top row sum.

Can be probed via oscillation and neutrino mass experiments.

*The elements of the PMNS matrix are very different from the CKM matrix → Flavour Puzzle.
Nuclear $\beta$ Decay as a Probe of BSM Hadronic Physics

Search for Additional Quarks – Superallowed Fermi $\beta$ Decay

Exotic Weak Currents – $\beta$-v Angular Correlations

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Model Independent Probes of BSM *Leptonic* Physics

- **Direct observation of “neutrinoless” mode**
- **Any observation of** $0
\nu\beta\beta$ **is a smoking gun signature of BSM physics (ie. Majorana)**

**$\beta/EC$ decay**
- $T_{1/2}$ from a few ms to $\geq 10^{15}$ y
- Observed in $> 1000$ different nuclei from $n$ to $A \geq 250$

**$\beta\beta$ decay**
- $T_{1/2} \sim 10^{19–24}$ y
- Observed in only 11 nuclei from $^{48}$Ca to $^{238}$U

- Energy and momentum conservation
- Model independent search for ANY new physics that couples to the neutrino mass
Momentum and Energy Conservation in Nuclear $\beta$ Decay

- Decay momentum reconstruction is a simple, model-independent approach to neutrino mass (heavy and light).

- If any new physics couples to the neutrino mass, energies of the other particles in the decay will be altered and can be observed.

$\beta$ decay provides a sensitive, model independent probe of any new physics in the neutrino sector that couples to their mass states.
Absolute Neutrino Mass Scale via $\beta$ Endpoint Measurements
Precision Tritium Endpoint Measurement: KATRIN and Project-8

- strong tritium source: $10^{11}$ decays/s
- < 0.1 cps background level
- $\sim 1$ eV energy resolution
- 0.1% level understanding of the spectrum shape
- 0.1% level hardware stability controlled over the years

Only $10^{-13}$ of all decays in last 1 eV

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Precision Tritium Endpoint Experiments - $m_{\bar{\nu}_e}$

Slide Courtesy Thierry Lasserre and Elise Novitski
Where do we stand on Neutrino Masses from Tritium Decay?

Goals:

- Sensitivity to 40 meV/c\(^2\) neutrino mass
- Measure neutrino mass or exclude inverted hierarchy
- Simultaneous sensitivity to active and sterile neutrinos
Precision Holmium EC Decay: ECHO and HOLMES

\[ ^{163}_{67}\text{Ho} \rightarrow ^{163}_{66}\text{Dy}^* + \nu_e \]

Atomic de-excitation:
- X-ray emission
- Auger electrons
- Coster-Kronig transitions

Calorimetric measurement

\[ ^{163}_{66}\text{Dy}^* \rightarrow ^{163}_{66}\text{Dy} + E_C \]

- \( \tau_{1/2} \approx 4570 \text{ years} \) (2*10^{11} atoms for 1 Bq)

- \( Q_{EC} = (2.833 \pm 0.030^{\text{stat}} \pm 0.015^{\text{syst}}) \text{ keV} \)


Ab-initio calculations foresee a smooth shape at the endpoint region

Slide Courtesy: Loredana Gastaldo

Precision Holmium EC Decay - $m_{\nu_e}$

60 MMC pixels with about 1 Bq $^{163}$Ho: Achievable sensitivity $m(\nu_e) < 20$ eV (95% C.L.)

4-day measurement with 4 pixels loaded with ~0.2 Bq $^{163}$Ho

Energy resolution $\Delta E_{\text{FWHM}} = 9.2$ eV

Background level $b < 1.6 \times 10^{-4}$ events/eV/pixel/day

- $Q_{EC} = (2838 \pm 14)$ eV
- $m(\nu_e) < 150$ eV (95% C.L.)

low $T$ microcalorimeters with implanted $^{163}$Ho

- 6.5 x $10^{13}$ atom/det $\rightarrow A_{EC} = 300$ Bq/det
- $\Delta E \approx 1$ eV and $\tau_R \approx 1$ µs

1000 channel array

- 6.5 x $10^{16}$ $^{163}$Ho nuclei $\rightarrow \approx 18$ µg
- 3 x $10^{13}$ events in 3 years

exposure $N_{\text{det}} \tau_M = 1000 \text{ det} \times 3 \text{ y}$

$A_{EC} = 10$ Bq/det  30 Bq/det  100 Bq/det  300 Bq/det

$\tau_R = 10$ µs  $\tau_R = 5$ µs  $\tau_R = 3$ µs  $\tau_R = 1$ µs

Energy resolution $N_{\text{det}} \tau_M = N_{ev}$

Slide Courtesy Loredana Gastaldo and Angelo Nucciotti
The Future of Neutrino Masses from Ho Decay?

Snowmass LOI: Measuring the electron neutrino mass using the electron capture decay of $^{163}$Ho

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Search for Heavy (Mostly Sterile) Neutrino Mass States
Mostly Sterile keV Neutrino Mass States

- Beta decay is particularly sensitive to keV-MeV mass states
- Mass states in this region have $\tau \approx \tau_{\text{universe}}$ and could thus serve as some fraction of the observed DM in our universe
  - Excellent candidates for warm dark matter

Dodelson and Widrow, PRL 72, 17 (1994)
Heavy Neutrino Mass Studies via Coupling to $\nu_e$

- In EC/$\beta^+$ and $\beta^-$ decay, we study the relative coupling of the mass states to $\nu_e$ ($\bar{\nu}_e$)
- Momentum is conserved with the mass states, not flavor states

In EC/$\beta^+$ and $\beta^-$ decay, we study the relative coupling of the mass states to $\nu_e$ ($\bar{\nu}_e$). Momentum is conserved with the mass states, not flavor states.
Tritium Endpoint Measurements – KATRIN/TRISTAN

Idea:
• Make use of the strong KATRIN tritium source and beamline
• Perform a differential measurement of the full tritium spectrum
• Requires new detector system → TRISTAN detector

S. Mertens et al. JCAP 1502 (2015)
S. Mertens et al, PRD 91 (2015)
First keV-Mass Neutrino Search with KATRIN Data

**Search for keV-scale Sterile Neutrinos with first KATRIN Data**


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Rare Isotopes in Superconducting Sensors for keV Searches

$^3$H in LiF Bolometer + MMC

YC Lee, LTD-19 2021

$^{241}$Pu in Au + MMC : Magneto-$\nu$ Experiment

Au foil
Au wire
(Thermal couple)
Magnetic sensor
Sample holder
Superconducting Pick-up coil

Phase-0 Data
24 hours, 4 Bq, 1 pixel

PRELIMINARY

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The BeEST Experiment

Rare-isotope implantation at TRIUMF-ISAC

First Limits from “Low-Rate” Phase-II Data

Limits on the Existence of sub-GeV Sterile Neutrinos from the Decay of $^7$Be in Superconducting Quantum Sensors


Phase-II data from a single 138x138 $\mu$m$^2$ STJ counting at low rate (~10 Bq) for 28 days

Recoil spectrum generated by pseudo-degenerate mass states from ~28 days of counting

Example of signal that would be generated by 300 keV neutrino with 1% mixing

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EC Decay of $^{131}$Cs - HUNTER

- Elementary EC decay is two-body but reality is not so kind.
- $^{131}$Cs $\rightarrow$ $^{131}$Xe$^{+2}$ + $\gamma$ + (2)$e^-$ + $\nu_e$
- Two high-resolution electrostatic spectrometers plus x-ray detectors needed to detect all final state particles

J. Martoff et al., Q. Sci. Tech. 6, 024008 (2021)
Future Projections for Sterile Searches

- Nuclear decay provides a powerful, model-independent probe in the keV – MeV mass range

- Significant progress in measurements over the past 3 years – enabled by quantum sensing

- Experiments poised to increase sensitivity by 5+ orders of magnitude in the next decade

Figure courtesy - W. Pettus for Snowmass Light Sterile Searches White Paper
How do we go Beyond the State-of-the-Art?
Direct Momentum Measurements of Decay Products

Searches for massive neutrinos with mechanical quantum sensors

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100 nm diameter nanosphere, 1% by mass $^{37}$Ar, 30 days counting, $m_4 = 750$ keV, 2e-4 mixing

Developments in this area may also allow for light neutrino mass state measurements if a suitably low Q-value decay is found (<0.1 keV)
Momentum reconstruction in EC decay is sensitive to any deviation from the SM recoil signal (e.g. Majoron emission).
Conclusions

• Nuclear $\beta$ decay is a powerful, model-independent probe of BSM physics

• In particular, any new physics that couples to the neutrino mass can be accessed via precision measurements of the energy or momentum of the other final-state particles

• A number of new technologies have driven this field forward and we are just at the very beginning of exploring this developing research space

• Planned future work with superconducting sensors can expand this work to a larger range of quantum systems for addition BSM physics and applications