Ultra-low Q values for neutrino mass measurements

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Outline

1. Introduction
2. Nuclear decays with ultra-low Q values
3. Feasibility of a neutrino mass measurement using low-Q decays
4. Summary & Conclusions

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Introduction

Problem of kinematic neutrino mass measurements:
Relative effect of neutrino mass (m_ν/Q) is small

Remedy:
Look for the smallest possible Q value (kinetic energy release)
→ for β^- decays of neutral atoms: Tritium (18.6 keV), ^{187}Re (2.657 keV)

Main ideas here

Reduce Q by

- Considering decays to excited daughter states
- Using partial ionization to tune the electronic contribution to Q.

Decays to excited nuclear daughter states

- Rich nuclear excitation spectrum
  → many possibilities, some happen to have very low Q
- Problem:
  - Decays to different daughter states must be distinguished reliably, e.g. by γ spectroscopy

Tuning Q values by ionization

- In a weak decay, spectator electrons lose or gain energy due to the change in the nuclear charge.
- Ionization increases Q for β^+ or EC decay, and decreases Q for β^- decay.
- In bound state β^- decay, ionization also opens up new decay modes. Example: ^{163}Dy is stable as neutral atom, but unstable when ionized.

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Survey of suitable isotopes

- Based on Firestone's Table of Isotopes
- Consider only decays with large signal and small background:
  - Low-Q decay should be allowed from spin-parity arguments
  - Other decay modes (with larger Q) should be at least first forbidden.
- Problem: Data on nuclear structure is often incomplete (unknown spin/parity, excitation energies inaccurate)
  → We may have missed some good candidates.

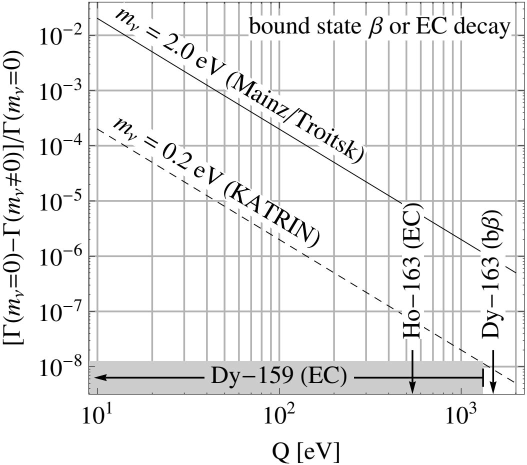
Survey of suitable isotopes (2)

- Continuum β decay
  - Measure for sensitivity to m_ν: Number of events expected in small intervall $[Q - \delta E, Q]$ near the endpoint.
    . . . is independent of Q!
  - At zeroth order, only statistics matters, so no advantage in using low-Q isotopes (which are harder to produce and store in large numbers).
  - Nevertheless, small Q makes experiment more robust against systematical errors, limited resolution, etc.
  - Tagging the decay by γ or x-ray detection allows operation of spectrometer in time-of-flight mode (MAC-E TOF).
- Bound state β decay
  - Only suitable isotope is ^{163}Dy, but $Q \sim 1.5$ KeV is still too large.
- Electron capture
  - ^{159}Dy ($Q = 130^{+1200}_{-130}$ eV) and ^{163}Ho ($Q \approx 540$ eV) look most promising.

Survey of suitable isotopes (3)

Decay	$t_{1/2}$	Q_0 [keV]	E^* [keV]	Q [eV]	Comment
Continuum β^- decay					
$^{188}\text{W} \to {}^{188}\text{Re}^*$	69.4 d	349 ± 3	346.58	80^{+150}_{-80}	decay to E^* not yet observed decay impossible for unfavorable Q_0 daughter spin uncertain
$^{193}\text{Os} \to {}^{193}\text{Ir}^*$	30.5 h	1140.6 ± 2.4	1,131.2	50^{+1150}_{-50}	decay to E^* not yet observed
$^{194}\text{Ir} \to {}^{194}\text{Pt}^*$	19.15 h	2246.9 ± 1.6	2,239.8	310^{+200}_{-310}	decay to E^* not yet observed
Bound state β^- decay					
$^{163}\text{Dy} \to {}^{163}\text{Ho}$	stable	-2.576 ± 0.016	0	$\approx 1,500$	
Continuum β^+ decay					
$^{189}\text{Pt} \to {}^{189}\text{Ir}^*$	10.87 h	1971 ± 14	958.6	1880^{+670}_{-1180}	allowed background modes with %-level branching ratio decay impossible for unfavorable Q_0
Electron capture decay					
$^{159}\text{Dy} \to {}^{159}\text{Tb}^*$	144.4 d	365.6 ± 1.2	363.51	130^{+1200}_{-130}	might not require ionization
$^{163}\text{Ho} \to {}^{163}\text{Dy}$	4570 y	-2.576 ± 0.016	0	≈ 540	might not require ionization

Relative effect of m_ν in bound state β and EC decay



Even for $Q \sim 100$ eV (possibly for ^{159}Dy), sensitivity to $m_\nu = 2$ eV (0.2 eV) requires 10^{16} (10^{20}) stored parent particles at any time.

(One problem are the small matrix elements in the decay $^{159}\text{Dy} \rightarrow {}^{159}\text{Tb}^*$).

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Feasibility issues I:
Producing a sufficient number of parent nuclei

- Proposed facilities like FAIR at GSI: $10^8 - 10^{10}$ ions/s
  for nuclei not too far from stability
- For isotopes with half-lives of $\mathcal{O}$(days), this is sufficient to sustain a sample of 10^{13}–10^{15} ions (in an ideal world)
- Still not quite sufficient for the isotopes we have found in our survey
- But remember: We might find more isotopes with more precise nuclear structure data.

Feasibility issues II: Storing a sufficient number of parent nuclei

- Neutral atoms: Relatively easy, use gaseous, liquid, or solid source
- Ions: Use trap or storage ring
  - Ion traps: max. $10^8 e$ (10^6 heavy ions) can be improved by one order of magnitude soon

    Traps at ISOLDE/Cern and MPI Heidelberg
  - Storage rings: max. $10^{11} e$ (10^9 heavy ions) can be improved by one order of magnitude

    storage rings at GSI Darmstadt

Feasibility issues III: Predicting the decay rate (bβ and EC decay)

Main unknowns:

- Nuclear matrix element
  - Can be measured in other decay modes (e.g. other ionization level) into the same nuclear final state
- Nuclear mass difference
  - Use e.g. ion trap mass spectroscopy
  - Relative accuracy to date: $\mathcal{O}(10^{-11})$, but would need to be improved by at least one order of magnitude.
- Electron wave functions, electronic energy levels
  - Have to be calculated numerically
  - Computations could be calibrated using measured x-ray spectra, ionization energies, etc.
  - Feasibility assessment by atomic structure expert desirable

Feasibility issues IV: Counting the number of decays

- Easy for continuum β decay (count electrons/positrons)
- For bound state β and EC decay: Count accompanying x-ray and/or gamma photons.

  Requirements:

  - Good solid angle coverage
  - Good (but not extreme) energy resolution
  - Efficient background suppression (shielding, radiopure material, if possible rock overburden)

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Summary & conclusions

- Two possibilities to obtain low Q value in nuclear decay
  - Consider decays to excited daughter states
  - Use ionization to tune the spectator electron contribution to Q
- We have identified some interesting isotopes
  - Most interesting: EC in ^{159}Dy, ^{163}Ho
    no ionization required → storage is easy
    measures $m(\nu_e)$ as opposed to $m(\bar{\nu}_e)$ → test CPT)
- More precise nuclear structure data needed
  - Required to better assess virtues of isotopes discussed here
  - Might reveal further candidate isotopes
- Feasibility issues:
  - Production of parent particles
  - Storage of large number of parent particles
  - Predicting the decay rate
  - Counting the number of decays using γ and/or x-ray spectroscopy
- Desirable next step:
  Precision measurement of Q_0 (atomic mass difference) for candidate isotopes

Thank you!