The QTNM collaboration: a project for neutrino mass measurement

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(on behalf of the QTNM collaboration)

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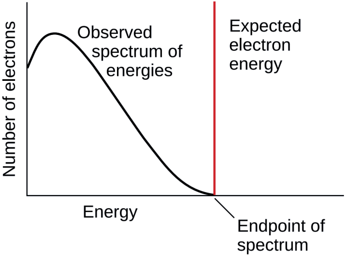
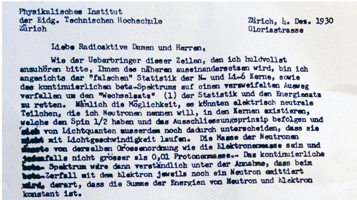
November 15, 2023

The neutrino

- Existence first postulated by Pauli in 1930 to explain shape of β decay spectrum
- Directly detected by Cowan & Reines in 1956
- Three flavours discovered: ν_e, ν_μ, ν_τ. All appeared to be massless.





Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

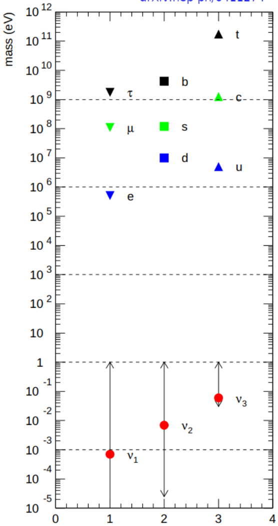
Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Neutrino oscillations

- Evidence from atmospheric, solar, reactor and accelerator neutrinos all confirms the existence of neutrino oscillations
- 2015 Nobel Prize awarded to Takaaki Kajita & Arthur B. Macdonald “*for the discovery of neutrino oscillations, which shows that neutrinos have mass”*
- Oscillations arise from mixing between flavour and mass eigenstates of neutrinos
- Neutrino mass scale very different from other fermions

arXiv:hep-ph/0411274



Neutrino oscillations and neutrino mixing

- Mixing between flavour and mass eigenstates given by

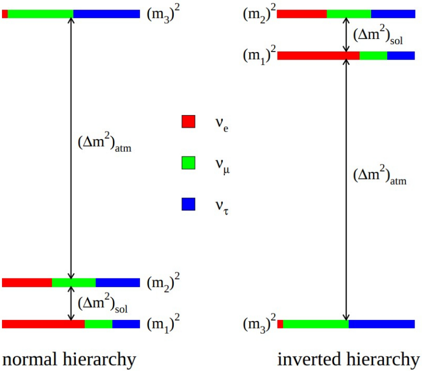
  $$|\nu_i\rangle = \sum_i U_{\alpha i}\,|\nu_\alpha\rangle$$

  where

  $$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

  is a unitary matrix
- Oscillations controlled by the matrix U and the squared differences between the mass eigenstates, $\Delta m^2_{ij} = m^2_i - m^2_j$
- These Δm^2_{ij} control the length/energy scale at which oscillations occur

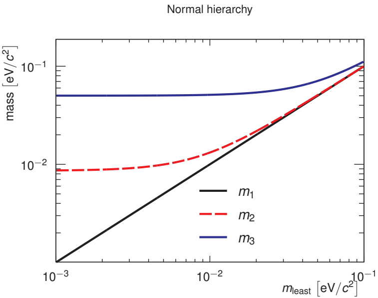
Neutrino mass hierarchy

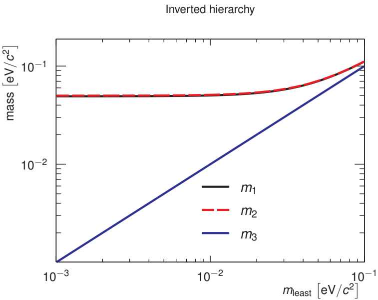


arXiv:1310.4340

- Differences between m_i^2 known from oscillations
- Ordering of mass eigenstates currently unknown
- Lightest mass eigenstate is either m_1 (normal hierarchy) or m_3 (inverted hierarchy)

Possible neutrino masses


Normal hierarchy


Inverted hierarchy

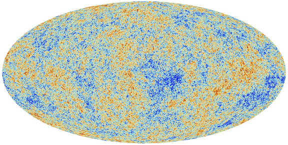
- It is possible the lightest mass eigenstate (either m_1 or m_3) may in fact be massless
- Masses of the other eigenstates are then constrained by the mass splittings

Why measure the neutrino mass?

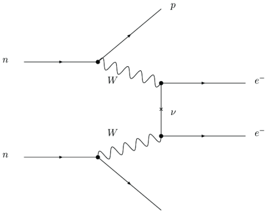
- One of the most abundant particles in the universe – and we don’t know its mass!
- Very different mass scale suggests different mass generation mechanism (compared to just Higgs)
- Connected to various other areas of physics:
  - Lepton number violation
  - Cosmology
  - Sterile neutrinos

Measuring the neutrino mass

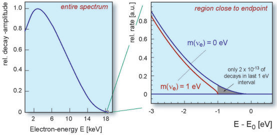
Cosmological measurements



Neutrinoless double β-decay

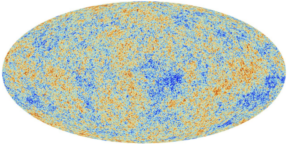


Direct measurement of β-decay



Measuring the neutrino mass

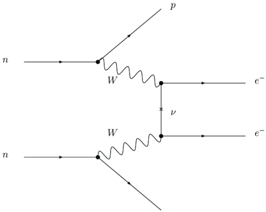
Cosmological measurements



$$\Sigma = \sum_i m_i$$

$\Sigma < 0.111$ eVc^{-2}
arXiv:2007.08991 [astro-ph.CO] (2021)

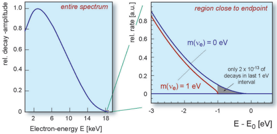
Neutrinoless double β-decay



$$m_{\beta\beta} = \sum_i (U_{ei})^2 m_i$$

$|m_{\beta\beta}| <$
$0.036 - 0.156$ eVc^{-2}
arXiv:2203.02139 [hep-ex] (2022)

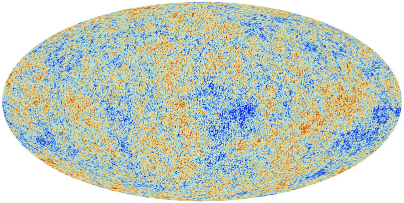
Direct measurement of β-decay



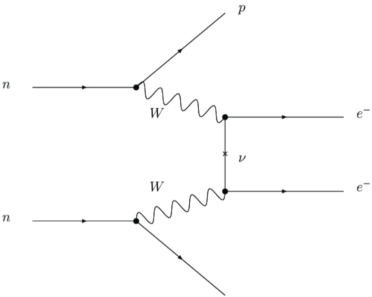
$$m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2}$$

$m_\beta < 0.8$ eVc^{-2}
Nat. Phys. **18**, 160-166 (2022)

The first two have their issues



Relies on cosmological models



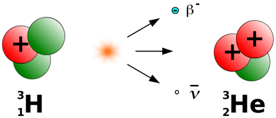
Only works if neutrinos are Majorana particles

- Neither of these are model-independent measurements in the same way that direct measurement is

Measurements of β-decay

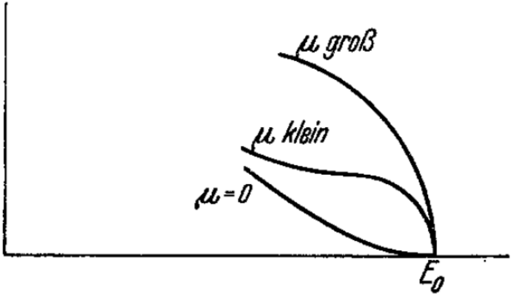
$$^{A}_{Z}X \rightarrow ^{A}_{Z+1}X' + e^{-} + \bar{\nu}_e$$

- For β-decay the total energy of the initial state is well known and the kinematics of the final state can be precisely measured
- Can use energy and momentum conservation to constrain the neutrino mass
- Processes such as this often referred to as 'direct measurement'
- Isotope commonly used is tritium



Direct measurement

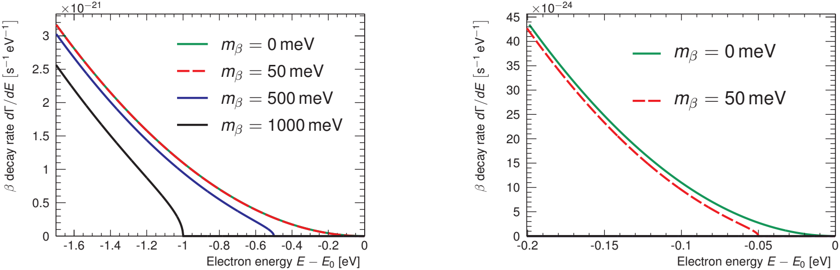
Z. Phys. **88**, 161 (1934)



- An old idea – Fermi suggested the shape of the β-ray spectrum could be used to determine the neutrino mass in 1934, as did Perrin separately in 1933

Tritium β-decay spectrum

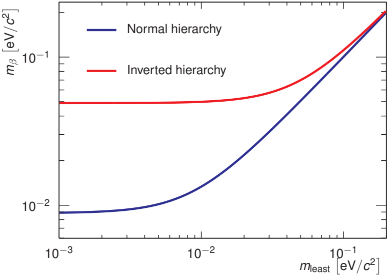
$$\frac{d\Gamma}{dE} \approx 3r_0\,(E_0 - E)\left[(E_0 - E)^2 - m_\beta^2\right]^{1/2}\Theta\,(E_0 - E - m_\beta)$$



- Information about m_β is encoded in last eV of energy spectrum (endpoint energy, $E_0 \approx 18.6$ keV)

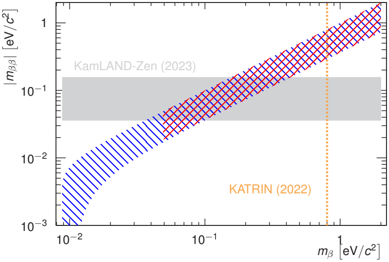
Limits on m_β

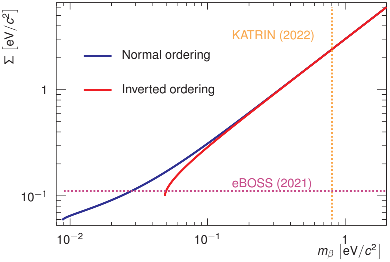
$$m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2}$$



- Mass splittings from oscillation experiments provide a lower limit on m_β
  - For normal hierarchy $m_\beta \gtrsim 9\,\mathrm{meV}$
  - For inverted hierarchy $m_\beta \gtrsim 50\,\mathrm{meV}$
- An experiment with a sensitivity below $m_\beta \approx 50\,\mathrm{meV}$ will determine the mass hierarchy (if still unknown)
- A sensitivity of 9 meV gives us a guaranteed discovery

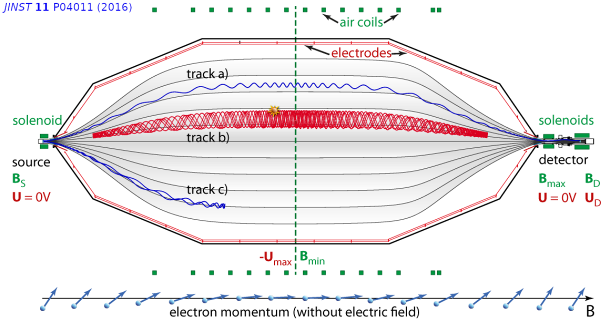
What can measuring m_β tell us?





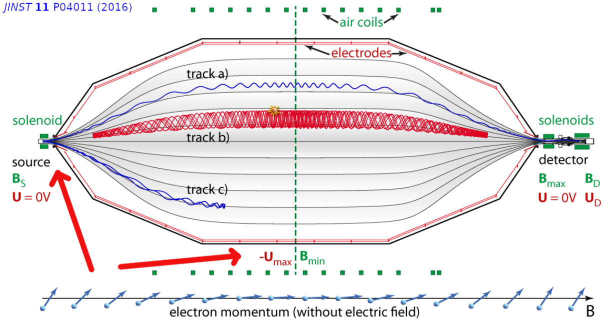
- Results can augment those from $0\nu\beta\beta$ experiments and cosmology
- Red here is IH, blue is NH

MAC-E filter – Current state of the art



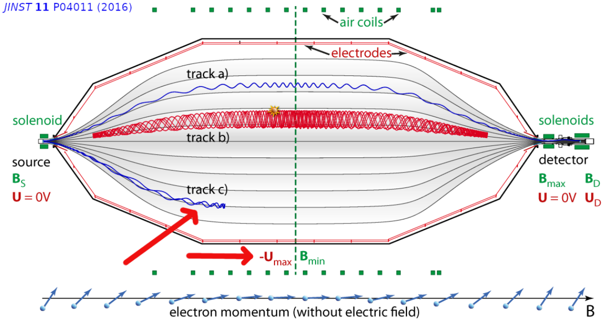
- **M**agnetic **A**diabatic **C**ollimation – **E**lectrostatic

MAC-E filter – Current state of the art


JINST **11** P04011 (2016)

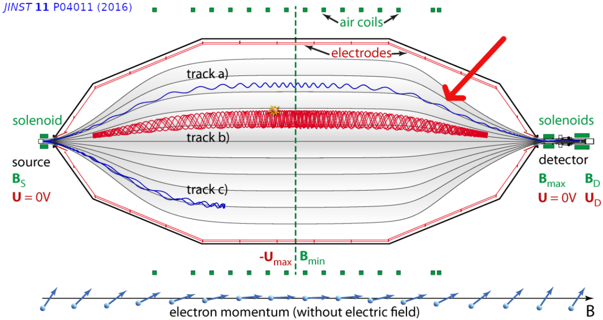
- **M**agnetic **A**diabatic **C**ollimation – **E**lectrostatic
- Electrons emitted in source region with high magnetic field, B_S, and travel adiabatically along field lines to analysing region with much lower field, B_{min}

MAC-E filter – Current state of the art



- **M**agnetic **A**diabatic **C**ollimation – **E**lectrostatic
- Retarding potential at central analysing plane prevents electrons without sufficient energy from passing

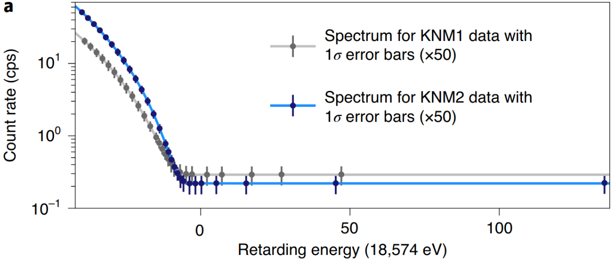
MAC-E filter – Current state of the art



- **M**agnetic **A**diabatic **C**ollimation – **E**lectrostatic
- Those electrons with sufficient energy to pass the potential barrier are re-accelerated and detected

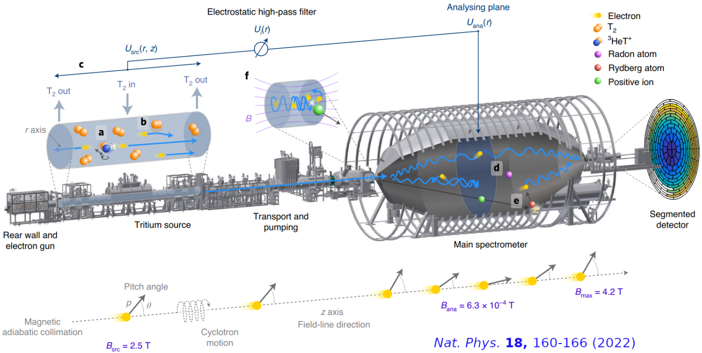
MAC-E filter – Current state of the art

Nat. Phys. **18**, 160-166 (2022)



- Repeat this for different retarding potentials in order to generate spectrum

KATRIN experiment



Nat. Phys. **18,** 160-166 (2022)

- Current best limits on m_β are produced by the KATRIN experiment – $m_\beta < 0.8\ \mathrm{eV}/c^2$
- Expected final sensitivity of $0.2\ \mathrm{eV}/c^2$
- 70 m long beamline, spectrometer is 9.8 m in diameter and 23.3 m in length held at pressure of 10^{-11} mbar

Limitations of MAC-E filters

- To increase statistical power, can increase source size
- However, source thickness is limited by $\sigma n \leq 1$ to avoid collisional losses
- For a MAC-E filter:

$$\frac{\Delta E}{E} = \frac{B_{\text{ana}}}{B_{\text{src}}} = \left(\frac{R_{\text{src}}}{R_{\text{ana}}}\right)^2$$

- Therefore, increasing R_{src} requires a corresponding increase in the spectrometer size

Limitations of MAC-E filters

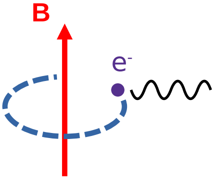
- Impractical to scale KATRIN up

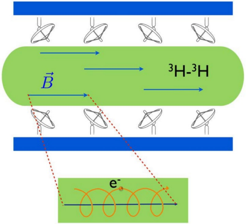
- We require a different technique for $m_\beta < 0.2$ eV$/c^2$

CRES overview

- **Cyclotron** **Radiation** **Emission** **Spectroscopy**
- Concept pioneered by Project 8 collaboration[a]
- β-decay electrons immersed in B-field emit EM radiation – frequency depends only on electron energy and B-field strength
- $E_{\text{kin}} = Q_{\beta} = 18.6\,\text{keV}$, $B = 1\,\text{T}$
- $f = 27\,\text{GHz}$, $\lambda \sim 1\,\text{cm}$, MW radiation
- Radiation collected with antenna, waveguide or resonant cavity

$$f = \frac{1}{2\pi}\frac{eB}{m_e + E_{\text{kin}}/c^2}$$





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[a] Monreal, B.; Formaggio, J. A. *Phys. Rev. D* **2009**, *80*.

CRES advantages

- Frequency measurements can reach precision of $\Delta f/f \sim 10^{-6}$

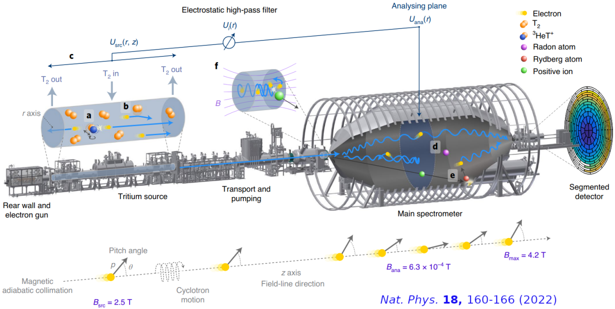
A. L. Schawlow

"Never measure anything but frequency"

CRES advantages

- Frequency measurements can reach precision of $\Delta f/f \sim 10^{-6}$
- No losses while transporting e^- from the source to the detector

Unlike MAC-E filters, no need to transport electrons from source to detector – fewer electrons lost to scattering



Nat. Phys. **18,** 160-166 (2022)

CRES advantages

- Frequency measurements can reach precision of $\Delta f/f \sim 10^{-6}$
- No losses while transporting e^- from the source to the detector
- The source (tritium gas) is transparent to MW radiation

CRES advantages

- Frequency measurements can reach precision of $\Delta f/f \sim 10^{-6}$
- No losses while transporting e^- from the source to the detector
- The source (tritium gas) is transparent to MW radiation
- Differential spectrum measurements

- MAC-E filters are ‘integral filters’ – intensity above a point in the spectrum is counted
- Extra time required for measuring background, spectrum intensity, endpoint energy
- Differential spectrometers do not have this issue

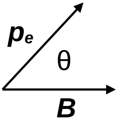
CRES challenges

- Radiated powers are very small

$$\text{Radiated power} \approx \frac{2\pi e^2 f_0^2}{3\epsilon_0 c} \frac{\beta^2 \sin^2\theta}{1-\beta^2}$$

$$\text{where } f_0 = \frac{1}{2\pi}\frac{eB}{m_e} = 27.9925\,\text{GHz for } B = 1\,\text{T}$$

$$P = 1.17\,\text{fW for } B = 1\,\text{T and } \theta = \frac{\pi}{2}$$

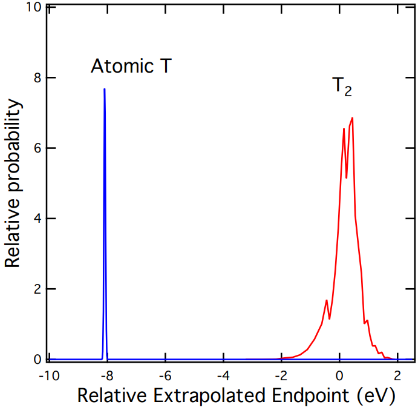


CRES challenges

- Radiated powers are very small
- Atomic tritium source required

- Molecular tritium has rotational and vibrational excitations that broaden the endpoint peak
- Production and preservation of atomic tritium is a key challenge for any future experiment

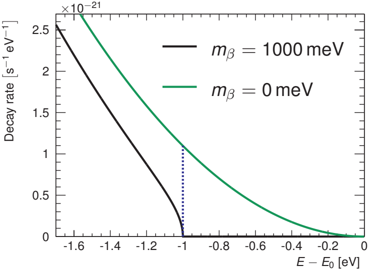
arXiv:2102.00594 [nucl-ex]



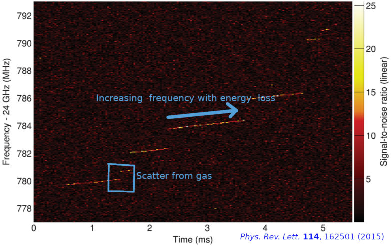
CRES challenges

- Radiated powers are very small
- Atomic tritium source required
- Need to trap and observe $\sim 10^{20}$ tritium atoms for $\sim$ year

- Last eV of the spectrum contains 2.9×10^{-13} of the events
- Necessitates an intense source



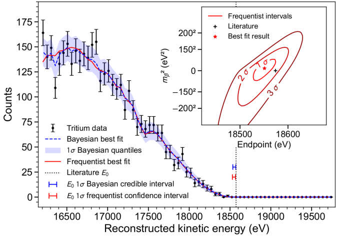
Project 8



Phys. Rev. Lett. **114**, 162501 (2015)

- Above: CRES signal from 30 keV ^{83m}Kr decay electrons in Phase I

- Phase II with molecular tritium in a ∼ 1 T field
- Detected 3742 events over 82 days



Ashtari Esfahani et al. arXiv:2303.12055 [nucl-ex]

QTNM collaboration

Quantum **T**echnologies for **N**eutrino **M**ass Collaboration

- **Proposal goal: build a demonstrator apparatus for determining neutrino mass via CRES from tritium β-decay – CRESDA**
- This entails:
  - Demonstration of confinement of atoms with densities of $10^{12} - 10^{13}\text{cm}^{-3}$, scalable to ultimate exposure of $\sim 10^{20}$ T atoms
  - Magnetic field mapping with $< 1\,\mu\text{T}$ absolute precision and ~ 1 mm spatial resolution
  - Observation of CRES electrons (non-tritium source), potentially with quantum noise limited MW detection systems
  - Experiment to be built at University College London

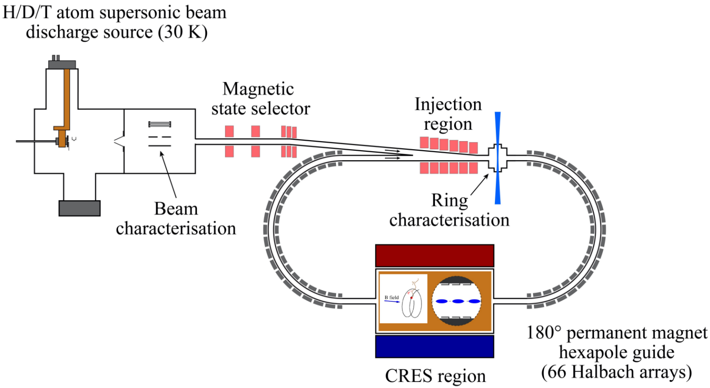
Potential project pathway

Quantum Technologies for Neutrino Mass Collaboration

- Basic technology demonstration at UCL (2021–2025)
- Tritium demonstrations at Culham (2025–2030+)
- Final neutrino mass experiment with $\sim 10 - 50$meV sensitivity at Culham or similar facility (2030–2040)

CCFE CULHAM CENTRE FOR FUSION ENERGY

CRESDA outline



H/D/T atom supersonic beam
discharge source (30 K)

Magnetic
state selector

Injection
region

Beam
characterisation

Ring
characterisation

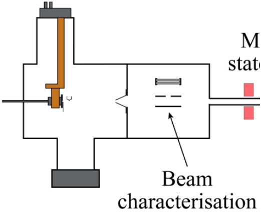
180° permanent magnet
hexapole guide
(66 Halbach arrays)

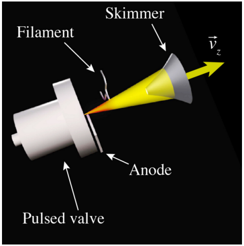
CRES region

- Consists of source, atomic trapping storage ring and instrumented CRES region

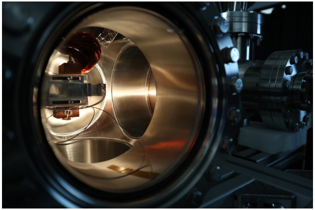
Atomic source

- When measuring the endpoint of atomic tritium any molecular tritium contamination acts as a background

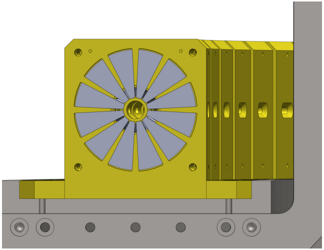




- Cryogenic (30 K) pulsed supersonic source
- $H_2/D_2/T_2$ dissociation using DC discharge seeded with electron from tungsten filament

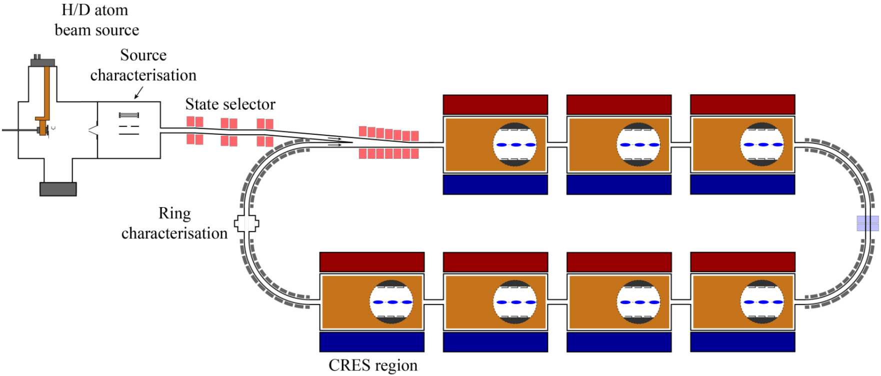


Storage ring



- Need to confine neutral atoms and prevent them forming molecules on surfaces
- Advantages of storage ring design include:
    - Lower atomic losses than occur when loading a trap (no deceleration and cooling required)
    - Separates magnetic field requirements for optimal high-frequency resolution CRES from magnetic trapping
    - Scalability (see next slide...)

Scalability of storage ring concept



- One option: multiple CRES modules connected by single storage ring

Electron trapping

$$f = \frac{1}{2\pi}\frac{eB}{m_e + E_k/c^2} = \frac{eB}{2\pi}\left(\frac{E_{\mathrm{tot}}}{c^2}\right)^{-1}$$

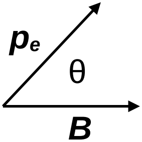
$$\frac{df}{dE_{\mathrm{tot}}} = -\frac{eBc^2}{2\pi}\left(E_{\mathrm{tot}}\right)^{-2} = 51\,\mathrm{kHz\,eV^{-1}}$$

for $B = 1\,\mathrm{T}$, $E_k = 18.6\,\mathrm{keV}$

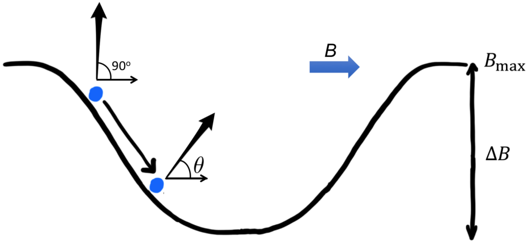
$\therefore$ for $\Delta E = 1\,\mathrm{eV}$, we require $\Delta f \approx 50\,\mathrm{kHz}$

$$t_{\mathrm{obs}} \sim \frac{1}{\Delta f} \qquad \therefore\ t_{\mathrm{obs}} \geq 20\,\mu\mathrm{s}$$

An endpoint electron travelling at 89° to B-field will travel 275 m parallel to B-field in this time



Electron trapping



$$\theta \geq \sin^{-1}\left(\sqrt{1-\frac{\Delta B}{B_{\max}}}\right)$$

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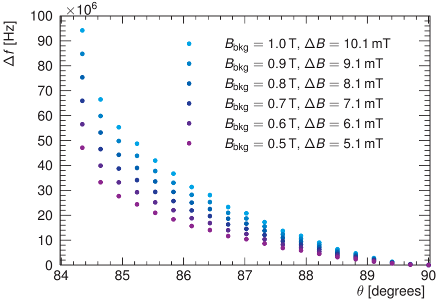
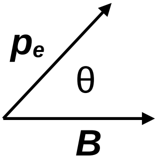
- Solution: Trap β-decay electrons in a 'no-work' trap where they can be continuously observed for 10s or 100s of μs
- Local minimum in magnitude of background *B*-field
- Require trapping field of order 1 mT against 1 T background
- Trap design has large effect on range of observed frequencies – key to understand this

Importance of electron trap design

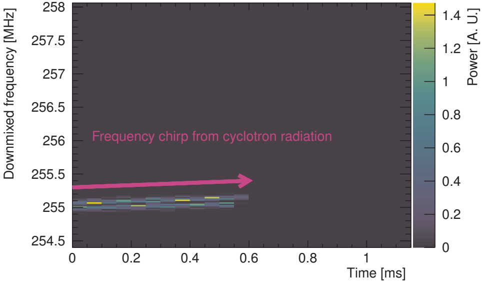




- Electrons with pitch angle, $\theta < 90^\circ$ experience different average *B*-field as a result of motion in trap
- Deeper magnetic traps contain more electrons but these will radiate at different frequencies (for the same energy)
- Other features of the signal must be used to get best energy resolution

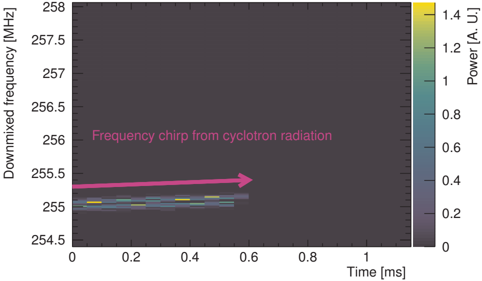
Simulation & analysis

- Work ongoing to optimise trap and RF collection design
- Can simulate an (idealised) decay electron signal in a variety of traps using custom software
- Simulation includes electron propagation, RF collection and basic model of signal processing



Simulation & analysis

- Many interesting CRES signal features that can be used to constrain electron energies
- Chirp rate of our signal tells us about the rate of energy loss



Simulation & analysis

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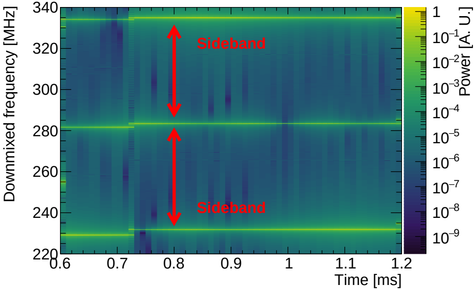
- Sidebands caused by AM and FM of signal – tell us about axial motion of electron



Simulation & analysis

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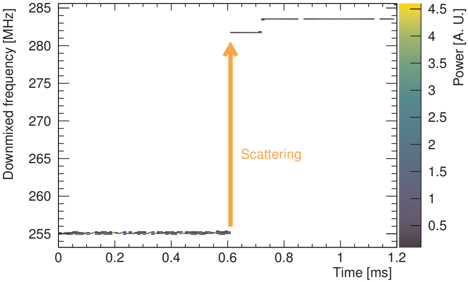
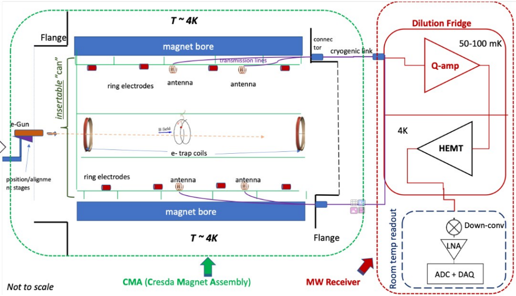


- Discrete jumps in frequency caused by scattering from residual gas – need to fully understand frequency of these scatters in order to reconstruct original frequency

CRES Magnet Assembly (CMA)



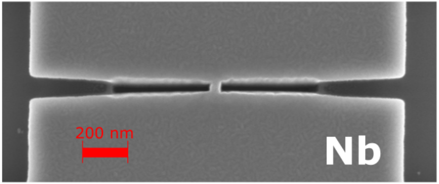
Source of (10-20 keV electrons to simulate Tritium β-decay

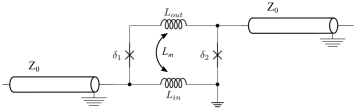
- Aim to detect CRES at cryogenic temperatures (minimise noise)
- Exploring use of quantum-limited amplifiers to overcome small signal power
- Possible electron source to calibrate energy

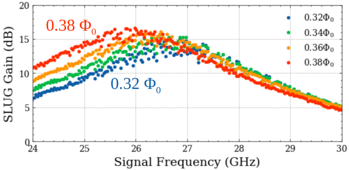
Quantum-limited microwave amplifiers

- CRES signal is very weak ($\sim$ 1 fW)
- State-of-the-art HEMT amplifiers have noise temperatures of about 7 K
- We require quantum-limited amplifiers:
  - **S**uperconducting **L**ow-Inductance **U**ndulatory **G**alvanometer (SLUG)
  - Superconducting parametric amplifiers

SLUG amplifiers

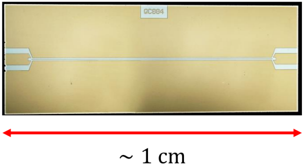


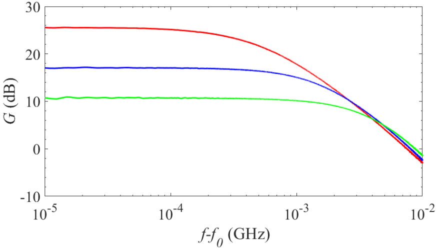




- **S**uperconducting **L**ow-inductance **U**ndulatory **G**alvanometer
- Non-parametric low-noise cryogenic amplifier under development at NPL
- Nb nanobridge junctions fabricated (above left) to allow operation at high frequencies
- Numerical simulations and experiments ongoing to characterise and tune SLUGs for our use

Superconducting parameteric amplifiers

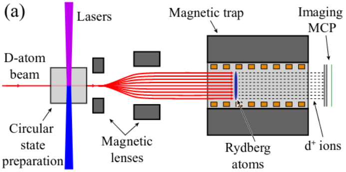


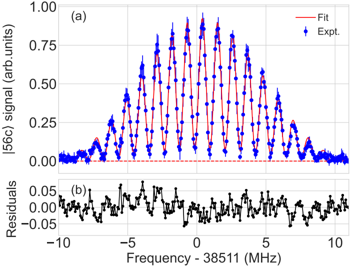


- Members at Cambridge Quantum Sensors group have designed, fabricated and tested high-gain parametric amplifiers based on superconducting resonators
- Superconducting NbN optimised as amplifier material
- Right: Power gain vs frequency – high gains with a bandwidth of several MHz. Distribution is two-sided about central RF frequency
- Noise measurement of amplifiers ongoing and making good progress

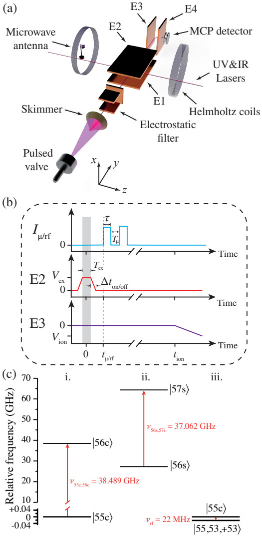
Magnetometry

- Measuring electron energy with resolution of 10^{-6} requires that *B*-field be known to similar level
- Deuterium or tritium atoms can be used as quantum sensors for *B*-field mapping to better than 1 µT
- Circular Rydberg states prepared in beam and passed through CRES volume
- Pulses of MW radiation drive Rydberg-Rydberg transitions – sensitive to *B*-field
- Potential spatial resolution of 1 mm





Magnetometry



- Current results:
  - Absolute field precision of ±2 µT, relative ±900 nT
  - Spatial resolution of ±0.87 mm
  - Electrometry precision of 85 µV cm^{-1}
- Paper detailing method and results published this year[a]

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[a] Zou, J.; Hogan, S. D. *Phys. Rev. A* **2023**, *107*.

Summary

- The neutrino mass scale remains unknown but the answer has the potential to provide key constraints in several areas
- Current measurement techniques (MAC-E filters) are at their limits and cannot take us to an experiment with guaranteed discovery potential
- CRES is a recent technique that allows the measurement of electron energy at unprecedented precision
- The QTNM collaboration is building on unique quantum techniques to demonstrate the viability of a CRES experiment
- Provides the exciting possibility of having the ultimate neutrino mass experiment in the UK

Thanks for listening!

Backup

Are calorimetric techniques the solution?

- Can embed isotopes in microcalorimeters – decay via electron capture
- Calorimeter measures the atomic de-excitation energy (minus the neutrino's energy)
- ^{163}Ho used by ECHo and HOLMES collabs.
  - In order to get required energy resolution for a high enough activity may require thousands or 100s of thousands of microcalorimeters operated at mK level