

The QTNM collaboration: a project for neutrino mass measurement

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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.





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



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Neutrino oscillations and neutrino mixing

Mixing between flavour and mass eigenstates given by

$$\left|\nu_{i}\right\rangle = \sum_{i} U_{\alpha i} \left|\nu_{\alpha}\right\rangle$$

where

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

is a unitary matrix

- Oscillations controlled by the matrix *U* and the squared differences between the mass eigenstates, $\Delta m_{ii}^2 = m_i^2 m_i^2$
- These △m²_{ij} control the length/energy scale at which oscillations occur



Neutrino mass hierarchy



- Differences between m²_i known from oscillations
- Ordering of mass eigenstates currently unknown
- Lightest mass eigenstate is either m₁ (normal hierarchy) or m₃ (inverted hierarchy)



Possible neutrino masses



- It is possible the lightest mass eigenstate (either m₁ or m₃) 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

Direct measurement of β-decay





Measuring the neutrino mass

Cosmological measurements





Neutrinoless double

Direct measurement of β -decay



$$\Sigma = \sum_{i} m_{i}$$

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

$$egin{aligned} m_{etaeta} &= \sum_i \, (U_{ei})^2 \, m_i \ &|m_{etaeta}| < 0.036 - 0.156 \, \mathrm{eV} c^{-2} \end{aligned}$$

arXiv:2203.02139 [nep-ex] (2022)

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

 $m_eta < 0.8 \ {
m eV} c^{-2}$ Nat. Phys. 18, 160-166 (2022)



The first two have their issues



Relies on cosmological models

 $n \longrightarrow \psi$ $W \longrightarrow \psi$ $n \longrightarrow \psi$ $W \longrightarrow \psi$ e^{-}

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

$$A_Z X
ightarrow^A_{Z+1} X' + e^- + ar{
u}_e$$

- 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



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

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



Information about m_{β} is encoded in last eV of energy spectrum (endpoint energy, $E_0 \approx 18.6 \,\text{keV}$)



Limits on m_{β}



- Mass splittings from oscillation experiments provide a lower limit on m_β
 - For normal hierarchy $m_{eta}\gtrsim$ 9 meV
 - For inverted hierarchy $m_{eta}\gtrsim$ 50 meV
- An experiment with a sensitivity below m_β ≈ 50 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 0νββ experiments and cosmology
 Red here is IH, blue is NH





Magnetic Adiabatic Collimation – Electrostatic





- Magnetic Adiabatic Collimation Electrostatic
- 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}





- Magnetic Adiabatic Collimation Electrostatic
- Retarding potential at central analysing plane prevents electrons without sufficient energy from passing





- Magnetic Adiabatic Collimation Electrostatic
- Those electrons with sufficient energy to pass the potential barrier are re-accelerated and detected





 Repeat this for different retarding potentials in order to generate spectrum



KATRIN experiment



- Current best limits on m_β are produced by the KATRIN experiment
 - $-m_{eta} < 0.8 \ {
 m eV}/c^2$
- Expected final sensitivity of 0.2 eV/c²
- 70 m long beamline, spectrometer is 9.8 m in diameter and 23.3 m in length held at pressure of 10⁻¹¹ mbar

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Limitations of MAC-E filters

- To increase statistical power, can increase source size
- However, source thickness is limited by *σn* ≤ 1 to avoid collisional losses
- For a MAC-E filter:

$$egin{aligned} &\Delta E \ \overline{E} &= rac{B_{ extsf{ana}}}{B_{ extsf{src}}} \ &= \left(rac{R_{ extsf{src}}}{R_{ extsf{ana}}}
ight)^2 \end{aligned}$$

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 $m_{\beta} < 0.2 \text{ eV}/c^2$



CRES overview

- Cyclotron Radiation Emission Spectroscopy
- Concept pioneered by Project 8 collaboration - *Monreal & Formaggio*, Phys. Rev. D (2009)
- β-decay electrons immersed in B-field emit EM radiation – frequency depends only on electron energy and B-field strength
- $E_{kin} = Q_{\beta} = 18.6 \, keV, \, B = 1 \, T$
- f = 27 GHz, $\lambda \sim$ 1 cm, MW radiation
- Radiation collected with antenna, waveguide or resonant cavity





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



A. L. Schawlow "Never measure anything but frequency"



- 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





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- 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

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

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





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



 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 Technologies for Neutrino Mass 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 10¹² - 10¹³ cm⁻³, scalable to ultimate exposure of ~ 10²⁰ T atoms
 - Magnetic field mapping with < 1 µT 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 ~ 10 - 50meV sensitivity at Culham or similar facility (2030–2040)





CRESDA outline



 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
- H₂/D₂/T₂ 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

$$f = \frac{1}{2\pi} \frac{eB}{m_e + E_k/c^2} = \frac{eB}{2\pi} \left(\frac{E_{\text{tot}}}{c^2}\right)^{-1} \qquad \frac{df}{dE_{\text{tot}}} = -\frac{eBc^2}{2\pi} (E_{\text{tot}})^{-2} = 51 \text{ kHz eV}^{-1}$$

for B = 1 T, $E_k = 18.6$ keV

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

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

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



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Phys. Rev. C 99, 055501 (2019)

- 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, θ < 90° 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



- 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





- 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





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



- 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:
 - Superconducting Low-Inductance Undulatory Galvanometer (SLUG)
 - Superconducting parametric amplifiers



SLUG amplifiers





- Superconducting Low-inductance Undulatory Galvanometer
- 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 accepted





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)
- ¹⁶³Ho 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