Quantum Sensors for Fundamental Physics

WP4. Absolute Neutrino Mass

1. Introduction

Quantum sensors can potentially offer a breakthrough in the laboratory measurement of the absolute neutrino mass. The current leading technique employed by the KATRIN experiment is based on magnetic adiabatic collimation and electrostatic (MAC-E) filtering, a technology that cannot be extended beyond the 0.2 eV sensitivity of KATRIN. Cosmology currently offers the most sensitive probe of the absolute neutrino mass but is heavily model dependent and is not a substitute for laboratory measurements.

Results from neutrino oscillations show that the electron neutrino mass, the sensitive parameter in beta decay experiments, has a strict lower bound; it cannot be smaller than 50 meV for an inverted and 9 meV for a normal ordered spectrum [1], as illustrated in Fig. 1. It is also independent of the Majorana or Dirac nature of neutrinos.

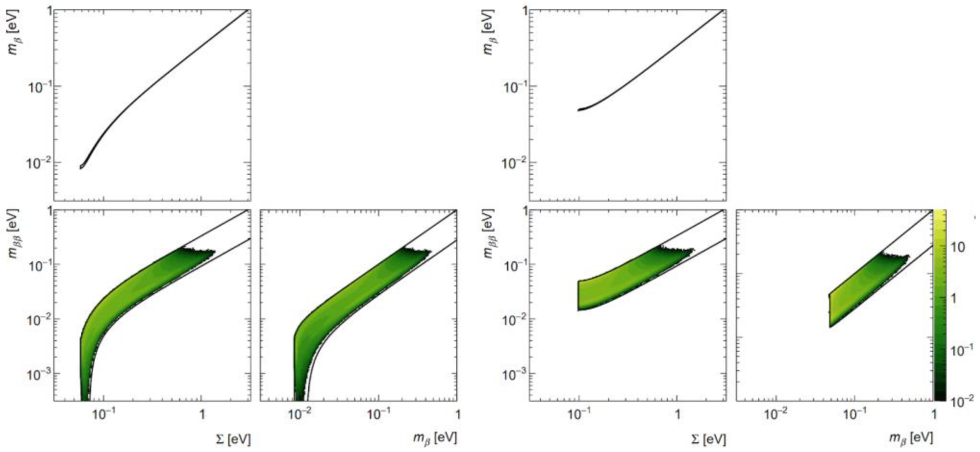

Figure 1. Relation between the electron neutrino mass m_β, the effective neutrinoless double beta decay mass $m_{\beta\beta}$ and the sum of neutrino masses Σ for a normally ordered (left panel) and inversely ordered (right panel) neutrino spectrum. The plot is taken from [1] based on a recent global fit of neutrino mass measurements.

The goal of WP4 is to leverage the UK expertise in quantum sensors, specifically in cryogenic superconductor calorimeters (SC) and atomic traps, to develop a technology which is capable of measuring a beta decay electron spectrum with a resolution of *O*(meV) near the end point. If such a resolution is reached then either a measurement of the absolute neutrino mass ***is guaranteed*** or, in its absence, new physics will be discovered. Such a "***no-lose theorem"*** situation is unique in modern particle physics and is akin to motivations for Higgs searches at the LHC, and has a comparable Nobel-prize winning potential.

A positive measurement of the absolute electron neutrino mass is highly complementary to cosmological probes and neutrinoless double beta decay, 0νββ. The relation between m_β and Σ shown in Fig. 1 is free from uncertainties in 3-neutrino oscillation parameters, and any deviation from expectation would indicate new physics. Moreover, if 0νββ is observed the absolute neutrino mass measurement can be combined with neutrino oscillation results to extract Majorana CP-violating phases which are directly related to the most fundamental questions of the matter-antimatter asymmetry in the universe.

The two main technologies that are suggested here to address the absolute neutrino mass problem are briefly described in section 2. below.

2. Cryogenic calorimeters

In recent years a range of cryogenic calorimeters have been developed which exhibit extremely high sensitivity for photon or other energetic particle detection and can achieve a superior energy resolution required for the m_β measurement.

Transition Edge Sensors (TES) is the most mature form of the SC technology having undergone some 20 years of development [2]. A SQUID (superconducting quantum interference device) is used to readout the change in resistance of the TES absorber, biased half way between normal and superconducting state. Multi detector arrays up to some 100 elements have been demonstrated in the lab, using either time division multiplexed readout or more recently frequency division multiplexing.

Another cryogenic calorimeter technology, which has also undergone significant development, is the Metallic Magnetic Calorimeters (MMC), where the temperature dependent element is the susceptibility of a paramagnetic material. A SQUID is used to measure the small magnetisation change arising from the temperature change.

Both TES and MMC have already been involved in early and current development of neutrino mass measurement experiments [3]. A ^{163}Ho electron capture source was embedded in the detector. Such a pure calorimetric measurement removes uncertainties in the final states distribution and energy losses in the source that are common for Tritium-based experiments such as KATRIN. TES and MMC calorimeters are currently shown to be capable to reach m_β sensitivity of the order of 1 eV.

Two novel approaches to cryogenic calorimeters, which could see further energy resolution improvements are pursued at NPL. In the first approach, an Inductive Superconducting Transition Edge detector (ISTED) uses a sharp variation of the London penetration depth of a superconducting absorber just below its transition temperature, with the change being read out by a SQUID. In the second, strong temperature dependence of the permittivity of some single crystal perovskites at low temperatures is used.

<u>Neutrinoless Double Beta Decay</u>

Existing experiments searching for 0νββ can also constrain the effective mass of the neutrino if it is a Majorana fermion. Here the energy of the electrons from the beta-decay of a suitable isotope is often measured through the detection of secondary, visible or UV photons produced by the electrons interaction in some absorber - often a scintillator of some sort. These photons are conventionally detected by classical (non-quantum) photon sensors such a PMTs, SIPMs, etc.

The intention of this section of WP4 is to derive large area detectors for visible and UV photons from superconductive quantum nano-wire or TES detectors. The larger photon energy should allow the use of larger SC-feature sizes that can be fabricated using conventional photolithography - as opposed to the currently used electron beam lithography - as well as SC materials with larger band-gaps and hence higher transition temperatures. If the extremely high quantum efficiencies and time resolution of the superconducting strip detectors can be translated into their large area counterparts then large volume cryogenic 0νββ-experiments could use them and dramatically improve their sensitivity for a given target mass.

Cryogenic calorimeters are directly used to search for 0νββ, for example in crystals of Zn^{82}Se. The detection of both heat and light signals enables the efficient discrimination of electron-induced signals from other (e.g. alpha-particle induced) signals. An element of the neutrinoless double-beta decay programme described here will be to investigate the potential increase in sensitivity of such experiments using the novel quantum sensors described above.

3. Cyclotron Radiation Emission Spectroscopy with Atomic Tritium

Currently the most sensitive laboratory probe of m_β is based on MAC-E filtering employed by the KATRIN experiment. KATRIN's sensitivity of 0.2 eV is limited by the available ratio of magnetic fields in the spectrometer, which scales with its diameter. With current spectrometer size of 10 m in diameter and 24 m in length this approach cannot be scaled up further.

An alternative suggestion to look for the tritium spectrum endpoint is by detecting the cyclotron radiation emitted by electrons moving in a magnetic field. CRES (Cyclotron Radiation Emission Spectroscopy) adopted by Project 8 exploits the fact that frequency can be measured with a better precision and resolution than a direct electron energy measurement [4]. First R&D results and simulations show that <0.1 eV sensitivity is possible.

Further sensitivity improvements however are limited by uncertainties in the final state energy distribution of molecular tritium relative to the electron spectrum endpoint. This limitation does not exist in case of atomic tritium which is required to reach the ultimate sensitivity of ~10 meV. It is this challenging task of trapping the atomic tritium in a large volume (~m^3) that we propose to address in this part of WP4 by leveraging the existing UK expertise in the area.

4. UK infrastructure and work plan

UK has considerable infrastructure and experience in cryogenic quantum sensors. The two groups involved in WP4 with most experience are the Quantum Sensors Group at Cambridge University and the Quantum Detection Group at National Physics Laboratory. In particular, the Cambridge group has substantial relevant expertise in developing multiplexed arrays of TES detectors, for a range of different applications. The NPL group has led developments of novel technologies involving ISTED and perovskites mentioned above which is a promising direction to improve the energy resolution of cryogenic SC devices to unprecedented levels. The Atomic and Molecular Physics group at UCL are world experts in atomic traps and uniquely placed to deliver the Tritium atom trapping requirements of this project. Prof. Stephen Hogan has developed magnetic deceleration methods, and performed the only experiments to date in which deuterium atoms have been magnetically trapped. Hogan has also applied this magnetic trapping methodology to trap hydrogen atoms, and it can be directly adapted to trap atomic tritium. The expertise in quantum sensors is combined with the team's internationally recognised leadership in neutrino physics (UCL, Oxford, Warwick) through pioneering involvement in $0\nu\beta\beta$ (SNO+, SuperNEMO) and neutrino oscillation experiments (NOvA, DUNE).

The key goals and deliverables of WP4 are summarised below:

Year 1 and 2:

- Evaluation of performance and scalability of cryogenic SC detectors for neutrino mass measurement applications: TES, nano-wires, MMC, ISTED, perovskite.
- Evaluation of β-source (^{163}Ho, Tritium trapped in graphene etc).
- Development and characterisation of a dense Deuterium (D) atom source.

Year 3

- Down-selection of SC detector options based on studies in Yr1-3.
- Demonstration of magnetic deceleration of D-source below 50 m/s.
- Preparation of bid for technology demonstration prototypes (Year 4-6)

Year 4-6

- SC calorimeter prototype construction, commissioning and operation.
- Finalising the selection of source and calorimeter technologies.
- Publication of prototype resolution results.
- Demonstration of efficient transfer of decelerated D atoms into magnetic trap.
- Optimisation of number of trapped atoms and maximisation of trapping time.
- Trapping demonstration with Tritium source.
- Evaluation of two techniques performances and ability to reach 10 meV sensitivity to m_β
- Technical proposal for a full-scale experiment.

5. Resources Estimates

The 5 institutions in the working group all intend to contribute to the work package at a significant level and the work package aims to produce internationally competitive physics results. The primary resource required is scientific and engineering staff (PDRAs and engineers) as well as equipment costs.

Broadly, the following resources are requested:

- £3,000k for the first 2+1 years to deliver tasks outlined in section 4. The breakdown of the budget is as follows: 2,000k for staff (80% FEC) £850k for equipment and £150k for travel.
- £3,500k for a further 3 years to build prototypes that will pave the way to a full-scale experiment to reach 9meV sensitivity. The breakdown is: £2,350k for staff, £1,000k for the prototype and £150k for travel.

References

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