Case For Support: Determination of Absolute Neutrino Mass Using Quantum Technologies

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1 Aims and Background

Research and scientific merit of the proposal. A laboratory measurement of the absolute neutrino mass is one of the most important experimental challenges that remains in particle physics. Cosmology currently provides the most sensitive constraints but cannot be a substitute for a laboratory measurement. The current leading technique is based on measuring the electron energy spectrum of tritium (T) near its end point using magnetic adiabatic collimation and electrostatic (MAC-E) filtering employed in the KATRIN experiment. Despite its success this technology cannot probe neutrino mass scales below 200 meV. Reaching better sensitivities is motivated by the two mass scales: one corresponding to the inverted ordering of neutrino masses in which case $m_\beta \geq 50$ meV, and the other to the normal ordering with $m_\beta \geq 9$ meV. The MAC-E technique limitation can be overcome by using a completely different concept of measuring electron energies. In this approach, pioneered by the Project-8 experiment, one can determine the energy of the electron by measuring the frequency of electromagnetic radiation generated as a result of the electron's cyclotron motion in a magnetic field [1]. This technology is known as Cyclotron Radiation Emission Spectroscopy (CRES). The overarching goal of this proposal is to use recent breakthroughs in quantum technologies to assess the feasibility of an experiment capable of a ***guaranteed*** measurement of neutrino mass, even in the worst case scenario of the mass being at a $O(10$ meV$)$ level.

Aims and Feasibility. To reach this ultimate sensitivity a CRES-based experiment has to overcome a number of formidable challenges: a) trapping large numbers, $O(10^{20})$, of T-atoms; b) measuring sub-fW level microwave signal at a frequency of ~25 GHz[1] with $\Delta f/f \leq 10^{-6}$; c) mapping the magnetic field with an accuracy of ≤ 1 ppm. We propose to build a CRES Demonstration Apparatus (CRESDA) to address the three key challenges above. CRESDA will be hosted at UCL and using deuterium (D) atoms rather than radioactive T. It will have a 1-litre magnetic trap with number densities of trapped atoms of 10^{14} cm^{-3} coupled to microwave detectors. The performance will be characterised using electrons from ionised D-atoms (eV-scale) and a gaseous radioactive source (keV-scale) in terms of energy resolution, and with microwave spectroscopy and ion imaging methods to measure the atom densities and temperatures in the trap. Early discussions are underway to move CRESDA to a tritium facility, e.g. to the Culham Centre for Fusion Energy (CCFE) if the performance is successfully demonstrated at the end of this 3 year period. This will require a follow-on proposal but it also requires that all CRESDA components are "tritium-ready". This proposal is therefore a critical milestone that will pave the way to the ultimate neutrino mass experiment. Given the technological challenges involved we believe that a phased approach suggested here is the only feasible way to proceed.

Contribution to the establishment of a new community. The proposal brings together particle, atomic and cold matter physicists, quantum electronics and superconductor detector experts as well as electronics engineers. Despite significant experience of participants in the forefront of physics research over many decades this is the first time the proponents have formed such a broad collaboration in terms of variety of expertise.

Strength and appropriateness of the proposed collaboration. This is a collaboration of physicists and engineers with specific expertise that is necessary to deliver the goals of the proposal mentioned above and, in more detail in Section 3. The solutions to the CRES challenges suggested here are innovative and complementary to those pursued elsewhere. They are built on quantum technologies developed by researchers in participating institutions over the past decades.

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[1] A 18.6 keV electron near the endpoint of T β-decay will produce a microwave signal from its cyclotron motion in a 1T magnetic field peaked at $f \sim 25$ GHz

The UCL group have unique expertise in trapping cold hydrogen isotopes (H and D) in their ground and excited states using magnetic and electric fields, and in high-resolution laser and microwave spectroscopy of hydrogenic atoms. They also have extensive experience in particle interaction modelling, off-line signal processing, data analysis and neutrino physics phenomenology. The Warwick group has extensive experimental neutrino physics experience in the areas of detector development, simulations and data analysis. The Cambridge group runs a unique facility developing science-grade superconducting sensors from microwave to x-ray wavelength. NPL and Swansea have been leading many developments involving superconducting quantum interference devices, microwave resonators and quantum electronics. The Sussex team leads a novel development of detectors based on a single trapped electron.

2 Research Programme and Work Plan

The research programme is subdivided into 5 work packages with the aim to build CRESDA and demonstrate performance that can be scaled up to an ultimate neutrino mass experiment. The schedule and milestones of the proposal can be found in the Management Plan document.

WP1: Simulations and Analysis A simulation campaign will be needed throughout the project, to support the instrument development and ultimately to construct a robust model that will enable us to extrapolate the performance to a much larger experiment capable of measuring the neutrino mass. This work package is broken down as follows:

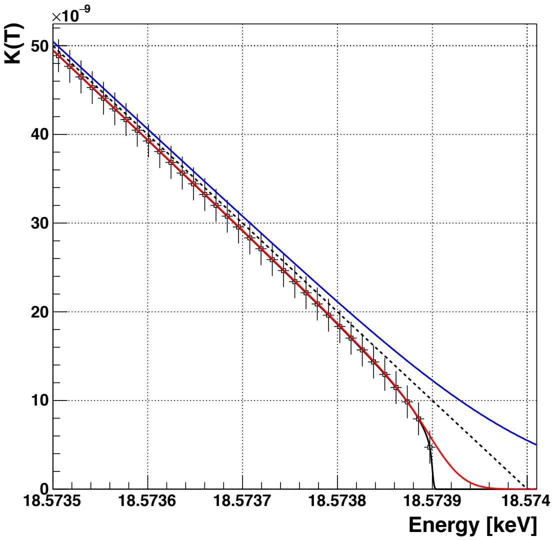

Figure 1: Kurie function for $m_\nu = 0$ (black dashed line) and a 100 meV neutrino (black curve). The red (blue) curves represent energy resolutions of 1 ppm (100 meV) respectively, showing the importance of having an energy resolution lower than the neutrino mass being probed. The black points give an indication of statistical precision for 3×10^{17} T decays.

Atomic Beamline Simulations 3D particle-trajectory simulations are used to interpret time-of-flight measurements from Zeeman decelerators [2]. Such simulations will be developed for the beam-line constructed as part of this project, in order to verify the D atom velocity distribution that is achieved, as well as other parameters such as the particle densities.

Cyclotron Emission & Detection Modelling A detailed model of the cyclotron emission mechanism will be implemented following [1]. It will be combined with a model of the RF propagation and detection in order to develop a CRES detection model which can be used to quantitatively assess the ultimate energy resolution that can be reached using this technique. A preliminary choice is to use the RF module of COMSOL to undertake this modelling.

Atomic Trap Simulations A CRES experiment would use a magnetic trap to contain a large ensemble of atomic T with long residence times required to reach the necessary exposure. The beamline and CRES simulations above will be combined with a simulation of such a trap so that the key experimental parameters such as detection efficiencies and the effect of electron-gas scattering can be evaluated. COMSOL may again be the simulation package of choice. Expertise from a world-leading research group at UCL in the area of electron-gas interactions will be leveraged.

CRES Analysis & Sensitivity A full CRES analysis framework will be developed. CRES spectrograms will constitute a very rich dataset, with the potential to deploy machine-learning techniques to extract the maximum possible electron-energy information, as well as other information (e.g. the spatial distribution of decays) required to minimise systematic uncertainties. All of these experimental elements will be combined with a tritium decay MC generator and spectrum fitter. Analysis of Kurie plots such as those in Fig 1 will be used to evaluate the ultimate reach of the CRES technique for determining the neutrino mass.

WP2. Atomic Beam Source and Magnetic Trapping. The goal of WP2 is to demonstrate magnetic trapping of cold D atoms at number densities of 10^{14} cm^{-3} using the methods of multistage Zeeman deceleration which can be directly extended at a later stage to work with T atoms (i.e., in a "tritium-ready" apparatus). This WP is composed of three main tasks.

D-atom source. To prepare large quantities of D atoms we will develop a cryogenically cooled pulsed supersonic source based on an electric discharge of D_2. We have extensive experience operating discharge sources of this kind in experiments at UCL with metastable He atoms [3]. The discharges will be seeded with electrons generated from a heated tungsten filament. The resulting pulsed supersonic beams of D will have mean longitudinal speeds of $\sim 650 \pm 50$ m/s for a source operated at 30 K [4] and be ideally suited for multistage Zeeman deceleration. The typical densities of these beams are expected to be 10^{14}–10^{15} cm^{-3}. Velocity distributions will be determined by time-of-flight and ion imaging methods [5]. Density measurements will be made by microwave spectroscopy of mean-field energy level shifts of transitions between Rydberg states arising from electrostatic dipole-dipole interactions [6].

Zeeman decelerator. Three methods have been demonstrated in the literature to prepare cold trapped samples of H atoms: (1) magnetic trapping after thermalisation of atoms on cryogenically cooled surfaces [7], (2) magnetic trapping after multistage Zeeman deceleration of pulsed supersonic beams [8], and (3) electrostatic trapping atoms in excited Rydberg states after Rydberg-Stark deceleration of pulsed supersonic beams [9]. Of these methods, only those involving multistage Zeeman deceleration and Rydberg-Stark deceleration have been successfully applied to trap D atoms [2, 10] with Zeeman deceleration being particular suitable for long trapping times and high particle number densities. These methods can also be extended directly to experiments with T atoms.

A new multistage Zeeman decelerator designed to match the phase space properties of the atomic source will be constructed at UCL. This instrument will be based upon an existing design [8], however, adaptations and refinements will be made to optimise its operation for the D, and later T, atom source. It is expected that this decelerator will be composed of 36 stages. Currents of up to 300 A will be pulsed thorough the solenoid comprising each stage to generate B-fields on the axis of the decelerator of > 2 T. The rise and fall times of these current, and hence B-field pulses will be ~ 5 μs [11]. Recent developments in multistage Zeeman decelerator methodologies will be incorporated in the design of this instrument (e.g., [12, 13]). At the end of the decelerator the D atoms will have mean speeds of $\sim$50 m/s and translational temperatures of ~ 0.1 K, ideally suited for confinement in a superconducting magnetic trap.

Magnetic Trap. The final task of WP2 will involve trapping high density samples of cold D atoms after multistage Zeeman deceleration in a prototype multipole superconducting magnetic trap with a volume of 1 L. Previously used methods for magnetic trapping H and D atoms after multistage Zeeman deceleration will act as the starting point for this work with adjustments and refinements implemented to maximising the trap loading efficiency. The identification of optimal trap loading methodologies will be achieved through the particle trajectory simulations of the Zeeman deceleration and magnetic trap loading process preformed as part of WP1 where we have extensive expertise. As part of this work we will test approaches to loading multiple bunches of atoms into the magnetic trap, and investigate the limits of the atom number densities that can be achieved in traps. Throughout the experimental work in this part of WP2 we will characterize the density of the trapped atoms by laser and microwave spectroscopy of electrostatic dipole-dipole interactions upon photoexcitation to low angular momentum Rydberg states. We will characterise the temperature of the trapped atoms in all three spatial dimensions by photoion imaging methods that were developed previously for this purpose [9]. Once the trap is operational it will be used to test the CRES detectors developed in WP4 and WP5 with electrons generated by photoionisation of confined D atoms, and the decay of $^{83\mathrm{m}}$Kr. In the ultimate neutrino mass measurement with magnetically trapped T atoms, monitoring the fraction of untrapped T_2 molecules in the trap volume will be essential. As part of WP2 we will aim to investigate the presence of D_2 molecules in volume that may enter as a residual component of the D atom beam by comparing resonance-enhanced multiphoton ionisation (REMPI) spectra of D atoms with those of D_2.

WP3. 3D Magnetic Field Mapping by Quantum Sensing.

To measure the electron energy from T β-decay with a resolution of 10^{-6} through CRES it is necessary to achieve a similar uniformity of the B-field in the T atom trap. To address this challenge in WP3 we will develop a new high-precision quantum sensing scheme for in situ B-field mapping directly using D atoms in the trap. The scheme, related to recent work in the literature [14], will incorporate time-resolved high-resolution microwave spectroscopic measurements of transitions between circular Rydberg states by Ramsey-spectroscopy (e.g., [15, 3]), with state-selective electric field ionisation and ion imaging [9]. The crossed fields method [17] will be used to prepare circular Rydberg states of D atoms. Circular Rydberg states are particularly suited to this B-field mapping scheme since they can act as almost ideal two-level quantum systems with long coherence times allowing high precision measurements of transition frequencies and hence Zeeman energy shifts. A magnetic lens system will be designed and implemented to expand the beam of circular Rydberg D atoms in the transverse direction and collimate it to the dimensions of the trap as shown schematically Figure 2(a).

The absolute precision of the 3D field maps will be set by the precision with which the microwave transition frequencies between the circular Rydberg states are determined. A precision of $\sim$ 1 kHz is expected from related measurements performed with He atoms at UCL [see Figure 2(b)]. In a magnetic field of 1 T, for which the Zeeman shift of the transitions between consecutive circular Rydberg states in D is 14 GHz, this will permit a precision in the measurement of the field strength of better than 0.1 ppm. The spatial resolution in the transverse direction will be set by the spatial resolution of the ion imaging apparatus, $\sim$ 100 μm based on previous experience. The spatial resolution in the longitudinal direction will be determined by the longitudinal spread of the excited atoms at the time the microwave pulses are applied. Since photoexcitation of the D atoms to the Rydberg states will be carried out using pulsed laser beams, the spatial spread of the atoms in this dimension can be adjusted by controlling the size of these beams that are expected to be between 100 μm and 1 mm in the longitudinal dimension, leading to a comparable spatial resolution.

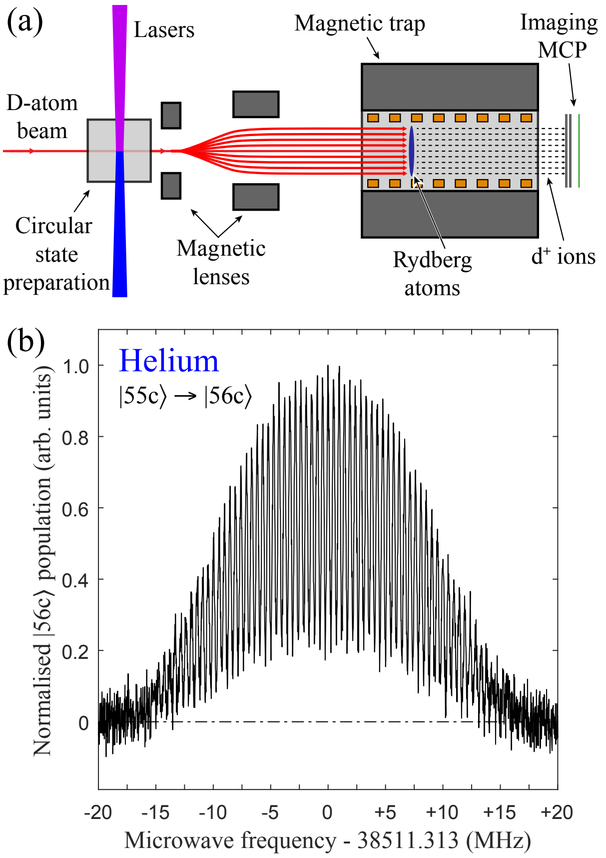

Figure 2: (a) Schematic diagram of 3D magnetic field mapping procedure. (b) Example high-resolution Ramsey spectrum of the transition between the $n = 55$ and $n = 56$ circular states in helium [16]

This quantum sensing scheme for magnetic field mapping involves high-precision spectroscopic measurements of frequency intervals between circular Rydberg states. The measurement of these frequency intervals are of relevance to the determination of the Rydberg constant and the resolution of the 'proton radius puzzle' [18]. We expect these measurements performed in WP3 will contribute to this area of precision measurement.

WP4:Cyclotron Radiation Detection In WP4 the overall aim is to develop practical amplifiers operating at and beyond the standard quantum limit of sensitivity at higher microwave frequency than has currently been developed. The main CRES detection electronics will be developed, comprising a low-noise front end at a centre frequency of 25 GHz and a bandwidth range up to 10 GHz. Demand for such amplifiers goes beyond the search for neutrino mass and includes rapidly developing areas of fundamental and applied physics and engineering, including quantum information processing, quantum computing, quantum metrology, radio-astronomy, communications, etc. This objective requires amplifiers working close to a region of high magnetic field (1T) and achieving a CRES resolution of $\leq$ 1ppm. There are 4 main tasks in WP4.

Baseline Detector. The detector will be built by NPL and will consist of a cryogenic HEMT amplifier and a heterodyne receiver. The input will be a waveguide section in the 1T B field, coupled to the electron cyclotron trap. Swansea University will design and build the antenna structures to match the trap and the receiver. We envisage to have 2 antennas and 2 receiver chains to carry out cross-correlation measurements. Apart from antenna structures, high frequency amplifier circuits will be investigated using air-suspended microwave transmission lines for the purpose of minimising the substrate loss of microwave signals. The suspended structures can be achieved using micromachining processes such as front-side or backside etching of the substrate. Full wave simulations of the suspended microwave structures will be conducted using the COMSOL RF module or ANSYS HFSS. Electron transport of the Josephson junction will be simulated with the density functional theory to investigate the impact due to material impurities and defects at the junction interface. To reach the performance with sub-K noise levels required for $\leq$ 1ppm resolution a *quantum-limited* pre-amplifier will be developed that will provide the first amplification stage followed by the Baseline Detector. Given the challenges involved we will develop two types of pre-amplifiers in the early stages of the project, evaluate their performance and down-select the best performing design.

Quantum-limited Microwave SLUG pre-Amplifier. High frequency SQUID amplifier is based on the SLUG (Superconducting Low-Inductance Undulatory Galvanometer) design. This would use microbridge Josephson junctions which have been developed at NPL and shown to be both low noise (for low frequency nanoSQUIDs) and exhibiting Josephson supercurrent performance to above 50GHz. Initial tests of the SLUG geometry will be carried out in a pulse tube cooler operating down to 2.5K. Further improvements will then be carried out in a 3He $-$ 4He dilution fridge closed cycle refrigerator, cooled to below 50mK. The SLUG devices will be modelled and designed at NPL but the mask design and fabrication carried out at Cambridge.

Quantum-limited Josephson Travelling Wave Parametric pre-Amplifier (JTWPA). In parallel, Cambridge will design, fabricate and test a Josephson Travelling Wave Parametric pre-Amplifier (JTWPA) with microwave pump electronics. Josephson junction technology will use tri-layer tunnel junction design, with in-house fabrication. This would operate in the Cambridge adiabatic demagnetisation refrigerator operating down to 50mK.

Down-Selection and Integration with Baseline Detector. After 2 years a down-selection will be carried out to choose between the SLUG or JTWPA options. The pre-amplifer of choice will be integrated with the Baseline Detector on CRESDA at UCL. CRES measurements with electron sources inside the trap will be carried out as described in WP2 with the final performance in terms of the signal-to-noise and electron energy resolution fully characterised.

WP5: Geonium Atom CRES Detector In the worst case scenario of the normal ordering of neutrino masses with the $m_1 = 0$ a ~ 1 meV resolution will be required to reach m_β sensitivities of $O(10\text{ meV})$. Such a detector should also have a near 100% efficiency for T β-decay electrons. WP5 will investigate the possibility to reach this ultimate sensitivity with a single electron captured in a planar Penning trap, a so called "geonium atom", as a quantum microwave sensor of the β's cyclotron radiation. The Sussex group will develop such a sensor based on their previous work in this area.

The geonium atom is a quantum cyclotron oscillator naturally lends itself for CRES. Its detection bandwidth is given by the quality factor of its quantum cyclotron oscillation $\sim 10^9$. Thus, at a cyclotron frequency of 25 GHz (1 T field), the geonium atom MW detection bandwidth is 25 Hz. This constrains the βs that it can "see" to only those with an extremely narrow energy spread of $T_\beta \pm 0.5$ meV. All other βs outside the relevant energy band, are transparent to the geonium sensor. The geonium atom is cooled down to 4K and its cyclotron oscillation is not relativistic. This allows for the particular value of energy being observed with T_β being resonantly tuned with great accuracy. As a first step of demonstrating this technology WP5 will aim at achieving an energy resolution of 20 meV within 3 years of the programme, which corresponds to 1ppm for 18.6 keV electrons. This will be done through addressing the following tasks.

Geonium chip in magnetic field. We will design, fabricate and test a "geonium chip" a planar trap capable of reaching $B \geq 1$ T, and hosting one electron MW sensor. The trap will be fabricated with PCB technology. The B-field source will consist of five pairs of coplanar superconducting rectangular coils machined from NbTi, magnetised by "flux pumping"and operated in persistent mode. A cryogenic vacuum chamber enclosing the trapping volume will be also fabricated. The trap will be loaded with photoelectric effect electrons, released with UV light. Cooling the system down to 4K reduces the pressure to $\leq 10^{-16}$ mbar, allowing for lifetimes of many months of the geonium atom.

Installation of the geonium atom sensor on CRESDA. After testing at Sussex, the geonium atom sensor will be moved to UCL and integrated with CRESDA. The equipment required at UCL for this is detailed in the justification of resources.

Demonstration of β particle detection with geonium atom. The geonium atom sensor will be coupled to the cyclotron antennas in CRESDA, where the detection of MW radiation will be investigated experimentally. The first tests will be done using a standard generator as a source of MW radiation with known properties. Once this calibration procedure is completed tests with βs will be performed as detailed in WP2. The goal of this proposal is to demonstrate that the geonium atom detector is sensitive to detection of $O(100)$ of MW-photons with a resolution of 20 meV, which is scalable and can be eventually extrapolated to $O(1\text{ meV})$ levels.

3 Project Deliverables

The key project deliverables by the end of the 3-year period are listed below:

- A software framework for detailed simulations of atomic beam, magnetic trap, T-decay and CRES as well as for signal processing and data analysis. The developed software will provide detailed sensitivity estimates and systematic error analysis.
- A cryogenic supersonic source of D atoms that can be used as T-atom source in the future.
- A multistage Zeeman decelerator optimised for the preparation of cold beams of D atoms designed for future implementation with tritium.
- A fully operational CRES Demonstrator Apparatus (CRESDA) based at UCL comprising a 1L trap of D atoms with number densities of 10^{14} cm^{-3}, and microwave detector operating at or below the quantum noise limit to detect electrons produced inside the trap with a resolution of $\leq$ 1ppm.
- The experimental implementation of a quantum measurement scheme for 3D B-field mapping with a sensitivity of $\leq$ 1ppm using D atoms as quantum sensors.
- A series of publications reporting on the results achieved during the 3-year project:
  1. On the design, construction and characterisation of D-atom source and Zeeman decelerator.
  2. On the design and characterisation of a 1L D-atom trap with number densities of 10^{14} cm^{-3}.
  3. On the performance of quantum-limited MW receivers and amplifiers in the 20-30 GHz range.
  4. On the performance of "geonium atom" as a MW detector in the 20-30 GHz frequency range.
  5. On the performance of CRESDA and its implications for the feasibility of a neutrino mass measurement at the $O(10\text{ meV})$ level.

4 Risk Analysis

A thorough risk analysis has identified several key risks and proposed mitigations for these risks.

In WP1, there is a risk due to a loss of key personnel which will be partially mitigated by cross-training postdoctoral researchers to minimise any potential knowledge or skill loss. If the simulation of the $^{83\text{m}}$Kr CRES does not adequately match the experimental data, further simulation studies will be required with more experimental detail in order to gain the required confidence for extrapolation to the tritium experiment.

If there are problems producing the high-density pulsed supersonic beam of D atoms by electric discharge of D_2, alternative methods for D atom production will be explored including dissociation by electron impact or photodissociation. If there are problems encountered completely matching the transverse spatial distribution of D atoms in circular Rydberg states to the trap using magnetic Rydberg atom optics elements, then alternative approaches to rastering the beam across the trap volume will need to be investigated.

Deviations in performance of the baseline detector due to manufacturing imperfections, will be mitigated by varying the device dimensions and taking parasitic parameters into consideration in the simulations. The nanobridge junctions of the SLUG microwave amplifier may not perform to the the required sensitivity at the resonant frequency, in this case we can either change the superconducting material (e.g. from Nb to NbN) or reduce the magnetic field to lower the cyclotron resonance frequency. Impedance (and other parameter) mismatches between different parts of the quantum sensors will be mitigated through design and simulation at the system level.

5 Track Record

Prof. F. Deppisch's is a world's expert on the theory of neutrino mass generation and the associated phenomena of lepton flavour and lepton number violation in rare low energy processes such as neutrinoless double beta ($0\nu\beta\beta$) decay. FD leads the BSM theory effort at UCL with continuous support from STFC Consolidated grants as PI. He has a particularly successful track record in collaborating with experimentalists; e.g. he performed simulations and analyzed exotic $0\nu\beta\beta$ decay modes with the SuperNEMO collaboration and has proposed novel modes which are being searched for by the KamLAND-Zen experiment.

Prof. J. Gallop is a Senior Research Scientist at NPL. He has over 50 years experience in superconducting electronics and reduced carbon materials. He is a Fellow of the Institute of Physics, Chartered Physicist and a visiting professor at Imperial College London with an extensive publication record of more than 300 research papers.

Prof. L. Hao is a Principal Research Scientist at NPL. She has over 30 years experience in superconductivity, quantum sensor technologies and microwave detection. She leads a team in the Quantum Materials and Sensors Group at NPL. She is a Fellow of the Institute of Physics, Chartered Physicist and a visiting professor at Imperial College London. She has published more than 180 research papers as well as six book chapters. Her work has been funded by NMS, EMPIR (EU), ESA and Industry. She has coordinated a major European EMRP project MetNEMS.

Prof. S. Hogan is Head of Atomic Molecular Optical and Positron Physics group at UCL. SH's work covers quantum information processing with Rydberg atoms and microwave circuits, matter-wave interferometry with Rydberg atom beams, collisions and decay processes of cold Rydberg atoms and molecules and tests of fundamental physics positronium atoms. SH developed the technique of multistage Zeeman deceleration of atoms and molecules and techniques for deceleration and electrostatic trapping of atoms and molecules in Rydberg states. This included the first demonstration of magnetic trapping of H atoms after multistage Zeeman deceleration, and the first experiments to demonstrate trapping cold ground-state D atoms using magnetic fields, and cold D atoms in highly-excited Rydberg states using electric fields. In the last 7 years SH's group have carried out the first experiments to demonstrate coupling of Rydberg atoms to microwave fields in superconducting coplanar microwave resonators for applications in quantum sensing and quantum information processing. In 2015 Hogan was awarded an ERC Consolidator grant.

Prof. L. Li is a Professor at College of Engineering, Swansea University, leading the Semiconductor Electronic Materials Institute (SEMI). He has over 20 years' experience in the design, modelling, fabrication and characterisation of micro and nanoelectromechanical devices. A Fellow of IET, and Senior Member of IEEE, he is the author/co-author of more than 160 journal and conference papers in the above research areas. His research has been supported by various funding bodies including EPSRC, Innovate UK, the Royal Society, the Leverhulme Trust, and the European Union. He serves as an editor of high impact journals, such as Scientific Reports and Nano-Micro Letters. He has developed a range of microwave sensors direclty relevent to this proposal.

Prof. R. Nichol is a Professor of Physics with the UCL High Energy Physics group. He has specialised in neutrino physics and astroparticle physics for almost 20 years. RN has a long standing involvement with experiments detecting particles through their emissions in the microwave frequency regime including ANITA and ARA where he has been responsible for data acquisition integration, calibration and the analysis software framework. In addition to his work on microwave detection, RN is also a leading member of the neutrino oscillation experiments MINOS, NOvA and DUNE.

Prof. Y. Ramachers is an experimental particle physicist at the University of Warwick. He has specialized in $0\nu\beta\beta$ physics and novel instrumentation for future neutrino physics projects since 2004. Before that he worked on germanium detectors and cryogenic bolometers for dark matter detection. His background in instrumentation also includes close collaboration with surface physics on an STFC impact project for a novel type of UV light sensor.

Prof. R. Saakyan is an experimental particle physicist and head of the UCL High Energy Physics group. He has over 25 years experience in experimental neutrino physics, ultra-low background processes, instrumentation development and particle interaction simulations. RS worked across several disciplines delivering advanced detection systems for particle physics , medical physics (proton therapy) and nuclear forensics. He has had leadership roles in a number of international collaborations delivering complex R&D and construction programs (MINOS,NEMO-3, SuperNEMO). Saakyan initiated $0\nu\beta\beta$ researh in the UK and was co-spokesperson of the SuperNEMO experiment. His current main involvement is in SuperNEMO and LEGEND $0\nu\beta\beta$ experiments. He has a number of coordination roles in several committees in the UK and Europe that are responsible for providing a road map for European astro-particle physics (APPEC).

Prof. J. Verdu-Galiana is a Reader in experimental atomic physics at the Sussex Centre for Quantum Technologies. He has long experience in Penning trap technology and the ultra-precise measurement of fundamental constants, such as the mass of the electron and the g-factor of highly charged ions. He and his team at Sussex have developed a novel planar Penning trap technology, the "geonium chip", from scratch. JV is the inventor of this novel quantum technology, for which he has been awarded two International Patents. He has attracted significant research income from EPSRC, Marie Curie, Innovate UK as well as investments from private companies, such as Leonardo MW Ltd. In June 2015, he was awarded an EPSRC Quantum Technology Fellowship for the development of the geonium atom quantum microwave sensor. He is the founder and director of the geonium chip research group (www.geoniumchip.org).

Prof. D. Waters is an experimental particle physicist at UCL. Having worked previously in collider and high-energy cosmic-ray physics, his main research focus currently is to uncover the fundamental properties of neutrinos. He is currently co-spokesperson of the SuperNEMO $0\nu\beta\beta$ experiment and also participates in the LEGEND project, both of which are searching for ultra-rare exotic nuclear decay processes. He is an expert in aspects of instrumentation, in particular for low-background detectors, as well as simulation & analysis and this will form the basis for his co-leadership of WP1 in the current proposal. He has a variety of other research responsibilities including membership of the LHC committee at CERN and serves as an editor of the journal Astroparticle Physics.

Prof. S. Withington is Head of the Quantum Sensors Group in the Cavendish Laboratory at the University of Cambridge. Withington has 35 years of experience developing instrumentation for millimetre-wave, submillimetre-wave, and far-infrared astronomy. The Quantum Sensors Group has active and internationally leading programmes in the areas of quantum device physics, ultra-low-noise device physics, plasmonic structures and radiation transfer, low dimensional heat flow, thermal fluctuation noise, and partially coherent long-wavelength optics. Withington has published over 380 conference and journal papers relating to ultra-low-noise devices and optics.

6 Justification of Resources

WP1 (Simulations & Analysis). We request 1 PDRA to work on the simulation of the Zeeman decelerator and the atomic trap, working in close cooperation with WP2; this post is essential to support the instrument development at UCL both in guiding the design and interpreting the experimental results which are obtained. We furthermore request 0.3 FTE of a Warwick Senior Research Fellow (John Back), who has more than 15 years of experience in modelling physical systems. His experience with finite element calculations will be vital to create a multi-physics model of the source and receiver of cyclotron RF radiation. His extensive data analysis expertise will also play a major role in this aspect of the project. The UCL WP1-RA and Warwick SRF will be jointly responsible for developing the CRES analysis framework and leading the subsequent sensitivity estimation. The tritium-decay simulation will be supervised by Deppisch, with the broader simulation effort and sensitivity studies supervised jointly by Ramachers and Waters. Nichol will bring CRES detection and spectrogram analysis experience and Saakyan overall oversight to this task.

A total of £26.6k (FEC) consumables are requested for WP1. This will provide 100 TB of RAID storage for the datasets that will be collected (dominated by the CRES receivers), COMSOL licenses for the simulation work, and a small number of high-performance computing nodes to test analysis code on heterogeneous (e.g. GPU) architectures.

WP2 (Atomic Beam Source and Magnetic Trapping) and WP3 (3D B-Field Map)
Personnel: WP2 and WP3 will be led by Hogan (UCL). Two PDRAs (PDRA-i and PDRA-ii) will work on these workpackages. PDRA-i will develop the D atom beam (WP2 Task 1), design the magnetic trap (WP2 Task 3) and then move to work on the magnetic field mapping experiments using quantum sensing techniques that form WP3. PDRA-ii will develop the multistage Zeeman decelerator (WP2 Task 2) which will then lead into the magnetic trapping studies (WP2 Task 3). The construction of all of the pieces of purpose built apparatus for WP2 and WP3 will be supported throughout the period of the project by a full time mechanical technician.

Large equipment (>£10k): The apparatus developed in WP2 requires the purchase of 7 pieces of large equipment. UCL will cover 50% of the cost of each of these items:
(1) The cryogenically cooled D atom source will be operated using a 30K pulse tube cryostat. £21,643
(2) The D atoms detection and laser photoexcitation will be carried out using two pulsed dye lasers, 2 x £77,520. These will be pumped by one seeded, pulsed Nd:YAG, £78,190.
(3) The wavelengths of these lasers will be calibrated using a fibre coupled wavelength meter, £38,568.
(4) High resolution MW spectroscopy of transitions between Rydberg states which will be used to determine atom number densities will be performed using a MW source that can operate in short pulsed mode, with precise frequency calibration and an operating range up to 40 GHz, £78,992.
(5) The superconducting multipole magnetic trap will be constructed around a 4K pulse tube cryostat, £65,586.
Small equipment (<£10k): All of the remaining component parts of the apparatus developed as part of WP2 have individual costs less than £10k. The total value of these items is £288k. The itemized breakdown is available in the JeS form, below we group them under broader categories:
(1) D atom source, £42,540.
(2) Zeeman decelerator, £74,892.
(3) Magnetic trap, £170,568
Computer related: Three PCs will be purchased for use in WP2 and WP3 (3 x £800). One of these will be used to operate the experiment, with the other two reserved for the two PDRAs working on these workpackages. *Consumables*: In addition to these items of equipment we request a total budget of £45,000 (£15,000) per year for addition consumables items. These will include, e.g., gas, cables, screws and small mechanical parts, cleaning materials, gloves, filaments for the discharge etc.

WP4 (Cyclotron Radiation Detection). At NPL: Hao (0.30 FTE) will lead WP4 with support from John Gallop (0.25 FTE). They will design and build the baseline detector while working on the SLUG amplifier design and testing at NPL supported by a Higher Research Scientist (Task 4.1,2,4: 1.10 FTE). Admin Support (0.10 FTE) will be required to manage finances, project progress and reporting. NPL will require £250K Capital Equipment (50% from UKRI) for a $<$ 50 mK cooler with 1T magnet for testing the baseline detector and measure the performance of the MW SLUG amplifier close to the quantum limit. Consumables of £74k are requested to allow for essential items such as cryogenic microwave low noise HEMT amplifiers, circulators & mixers, low noise current source, microwave source, magnetic shielding, temperature controller and sensors to build the baseline detector.
In Cambridge: Withington (0.2 FTE) will make a major contribution to developing, refining, and packaging superconducting quantum components and circuits for 25 GHz, and quantum system engineering and characterization for CRES including the construction of the quantum spectrometer at NPL. A PDRA (Task 4.3; 1.0 FTE) will provide the effort on designing and modelling 25 GHz thin-film superconducting paramps, detailed design and customization, establishing a suitable test system, detailed cryogenic measurement and characterisation of ultra-low coherent amplifier, working with NPL to establish amplifier and auxiliary room temperature electronics in their cryogenic receiver, and full characterization prior to delivery to UCL. Crane (Task 4.2-3; 0.4 FTE), Molloy (Task 4.1,3; 0.3 FTE) and Electronics technician (Task 4.3-4; 0.2 FTE) will

execute the fabrication, assembly, readout electronics, shielding, packaging and calibration of the quantum sensors in addition to running experiments and the clean-room fabrication facilities. Consumable costs will be £20k for the electronics clean room, 3 complete mask sets (£18k), Si/SiN wafers and DRIE (£2.8k), test assemblies and mechanical cryostat work including magnetic shielding (£3k), RF electronics for pump generation and low noise readout including high-frequency cables and connectors (£25.0k). Auxillary electronics, PSU's, computing & software add up to £27.2k.
In Swansea: Li (0.2 FTE) together with PDRA (Task 4.1-3; 1.0 FTE for 24 months), will contribute to WP4 and WP5 based on their experiences in MW sensors and quantum device simulations, focusing on MW antenna/receiver design and simulation of superconducting quantum devices. Various processing and characterisation equipment at Centre for NanoHealth (CNH) of Swansea will be used for microfabrication and measurements. The clean room general consumables during the project period and building of the microwave circuits will be ∼£5k. A high-performance workstation (£5k) will be requested dedicated for 3D full wave simulation of the devices. Access to facilities at Swansea will cost £10k.

WP5 (Geonium Atom Detector). will require a full time PDRA for three years who will work on the design and delivery of the geonium atom detector at Sussex. In addition, one 3.5 years PhD project studentship is requested, £66,065 including fees and stipend, who will work on geonium detector characterisation and data analysis from CRESDA. Both the PDRA and the PhD student will be supervised by J. Verdu-Galiana (0.25 FTE) who will lead WP5. For impact case management, 5% of the business development manager is requested. We also request laboratory consumables including: chip + magnetic field fabrication costs and materials, five voltage calibrators, two RF function generators , one 200-250 nm UV light source, two 4-channel precision current sources, one 4-channel power supply plus two laptops with a total required contribution of £ 64,000. Other costs include results dissemination and recruitment, £2,800.

The Lead PI will spend 0.2FTE on consortium management and coordination across different work packages and 0.1 FTE contributing to WP1 and CRESDA data taking (WP2).

Each participating institution has requested travel funds to facilitate collaboration travel within the UK and the presentation of results in selected international workshops and conferences.

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