7 Quantum Technologies for Neutrino Mass. Pathways to Impact.

Our aim is to deliver high quality science and to ensure that all our scientific results are published in journals and further disseminated through conference talks and reports. In the course of our research, whenever we find something which looks promising from the point of view of economic and/or wider societal impact, we will take every care to ensure that such potential impact pursues the numerous pathways available to the collaboration.

The project presents a unique opportunity to provide PhD students and early career physicists with truly interdisciplinary training that cuts across such diverse areas as particle, atomic and cold matter physics, quantum sensor technologies, electronics and data intensive science. The advanced novel technologies and results this project sets out to deliver contributes directly to the National Strategy for Quantum Technologies (https://epsrc.ukri.org/newsevents/pubs/quantumtechstrategy) and to growing a skilled UK workforce in this high priority area.

UCL's Department of Physics & Astronomy have a strong record in delivering impact from their research. Examples include using advanced assay techniques to address heavy-metal pollution in water in developing countries. UCL investigators on this proposal have a track record of cutting edge instrument development and translational work, for example adapting calorimeters originally developed for nuclear physics to perform fast and reliable QA for proton cancer therapy centres. Another notable strength is the quality and breadth of outreach activities undertaken by members of the UCL group. In the context of the current bid, UCL will take the lead in consulting and planning future activities with one of the key external partners, the Culham Centre for Fusion Energy.

The Department of Physics at Warwick hosts an STFC IPS fellow, Dr Theresa Harrison, an experienced professional in knowledge exchange and commercialisation (KEC). Dr. Harrison will work closely both with the group at Warwick and with the Warwick technology transfer office, Warwick Ventures, to initiate a concerted and sustained effort to maximise current and future impact outcomes for this project. The pathways to impact at Warwick have been well used over several years with two patents pending, a Spin-out company formed, and an actively pursued Impact case study on UV sensor technology.

Swansea University (SU) has a rich history and culture for collaborative and industrially driven research – specifically in semiconductor materials and devices. SU's multidisciplinary nanotechnology facility (1) the Centre for NanoHealth (CNH) – a 1600 m^2 purpose built open-access facility providing a technology and innovation base for industry and academia in Wales, UK and beyond will be used to develop the microwave antenna and other quantum microwave circuits prototypes. Swansea's other key research facilities, CISM (The Centre for Integrative Semiconductor Materials), planned for the Bay Campus is a £90M joint industry-university semiconductor foundry – which will be used to facilitate volume production and future commercialisation of devices.

The Swansea group will schedule a project kick-off meeting, and regular meetings with potential stakeholders for advice on IP and commercialisation – ensuring maximum impact. New theories and technologies generated from this project will lead to IP creation, which will be assisted by Swansea University's research and innovation department and the AgorIP project, a unique open innovation project (£13.5M from Welsh government) led by Swansea University, which can help researchers realise the potential of ideas, products, service or research. This will greatly help take our innovations to the marketplace and help make it a commercial success.

Superconducting electronics and especially devices based on the Josephson effects have been leading the way world-wide towards quantum technology applications in information processing and sensing. Surprisingly, the UK does not have a Quantum Hub dedicated to this topic, although there is plenty of existing UK activity in these areas, based in universities and research institutes. For this proposal an important component of future impact is the Advanced Quantum Metrology Laboratory (AQML) nearing completion at the National Physical Laboratory, funded by £25M from the National Quantum Technologies Fund. The AQML will provide a centre for industry engineers, academic researchers and NPL scientist. In addition a number of solid state superconducting electronics Ph.D studentships have been completed or are underway, sponsored by the Quantum CDTs at Imperial College, UCL and RHUL. NPL itself also has a number of on-going projects, funded by the National Measurement System, in the areas of quantum information processing using microwave manipulated superconducting qubits and sensors. All of these activities will benefit from, and feed into, the growing UK community of solid state quantum technologies which this QTFP project will also feature. Future direction for the UK effort in this area is influenced by a report produced in 2018 by NPL and other authors, titled 'Opportunities for superconducting quantum technology in the UK'.

The Quantum Sensors Group at the Cavendish Laboratory was established 15 years ago through a major donation of the Thin Film Division of Oxford Instrument to the University of Cambridge. It has expertise and IP in superconducting sensors and electronics going back 30 years, in areas such as TESs, SIS mixers, SQUIDs, optical photon counting STJs, KIDs, DROIDs, etc. Its repertoire includes complex multilayer microcircuits using materials such as Ti, Nb, Ta, Al, Mo, NbN, NbTiN, Hf, Ir as well as normal metals and oxides on SiN and SoI micromachined structures. In recent times, the Group has worked extensively in areas such as multi-layer superconducting science, superconducting resonator physics, the development of ultra-low-noise detectors for FIR space science, and chip spectrometers for Earth Observation. It has worked with Airbus on techniques for deploying sensitive superconducting electronics on space instruments, and has been selected as the European provider of superconducting focal-plane flight hardware for the space telescope SPICA. As part of the Government's recent investment in Quantum Technology Capital (EPSRC), the Quantum Sensors Group has installed a new dual-chamber UHV sputtering machine and 10 mK dilution refrigerator, with wide capabilities for fabricating and testing quantum devices. This has initiated a programme in superconducting parametric electronics. All of the Group's device processing expertise and facilities and cryogenic test equipment (several fridges covering the range 10 mK to 100 mK) will be available to the proposed programme.

The University of Sussex owns the intellectual property (IP) on the geonium atom quantum microwave sensor, through two granted international patents. This project will provide an excellent platform for probing the geonium atom sensor technology under realistic laboratory conditions and in a very challenging task, such as the measurement of the energy spectrum of an electron. Demonstrating experimentally the geonium atom sensor will increase its Technology Readiness Level (TRL) from its current level TRL = 1 to TRL = 4 (following the EU TRL definition given in HORIZON 2020). Beyond the expected academic impact of showing the feasibility of the geonium atom sensor for the neutrino mass measurement, this project will also establish this novel quantum technology for further, future potential applications. Among these are the possibility of developing a novel near-field scanning quantum microwave microscope and also a quantum radar, thereby using the geonium atom as the quantum microwave transducer. In particular, the current market for near-field scanning probe microscopes -of all types- is forecasted to US $ 1.3 billion in 2019. The geonium atom technology might gain a competitive position in the microwave sector and, more importantly, it might open new, unforeseen markets. The geonium research group is currently assisted by an external advisory board, with members of the private industry, such as Leonardo MW Ltd, represented by Mr Stephen Clark (Chief Technologist - Electronic Warfare, Airborne & Space Systems Division, 300 Capability Green, Luton LU1 3PG, UK) and the Defence Science and Technology Lab (DSTL), represented by Dr Stephen Till. The advisory board monitors the progress of the geonium atom quantum microwave sensor technology towards future concrete applications, particularly quantum radar. These companies have already provided contributions (in cash) of around £150,000 for its development and might invest further, bigger amounts in the future. Funding this project will definitely boost future investments. Besides the external advisory board, the group at Sussex will be assisted during this project by a team of experts in impact delivery, such as, a Knowledge Transfer/Exchange expert (Mr Ian Sillett) and an expert in IP management (Mr Keith O'Brien). Funds have been requested for the support of these applications and exploitation activities. Besides the usual communications and engagement through academic publications and outreach activities, the geonium group at Sussex will also disseminate its results though a dedicated webpage and LinkedIn profile. Funds have been also requested for this purpose.