WP2: Macroscopic quantum superpositions for physics beyond the standard model (MaQS)

1. Introduction and Science Goals: A key question in quantum mechanics is "Do quantum effects survive in the large scale limit?". Answering this question will shed new light on our understanding of fundamental physics. To attack this tantalising problem, we will create table-top experiments demonstrating the most macroscopic matter-wave interferometry. We will develop towards tests of proposed phenomenological models for the spontaneous collapse of the wave function [1]. Continuous spontaneous localisation (CSL) is one such model. If collapse is detected, our results would galvanise the need to identify as yet unknown mechanisms, phenomena or forces beyond the standard model of particle physics. On the other hand, if our macroscopic quantum superpositions do not collapse, we will have exquisitely sensitive quantum sensors for particle and astrophysics. These sensors could enable the direct detection of undiscovered short-range forces, or a new light field associated with hidden sector, dark matter, quantum gravity or neutrino physics. This dual purpose is a great strength of our approach. To achieve these ambitious goals, we seek to put 10-1000 nm nanoparticles into quantum superpositions of different positions in space.

The MaQS team includes 31 PIs and a key goal of this project is to facilitate the sharing of techniques between STFC and EPSRC groups, such as LIGO's vibration damping and NQIT's quantum control of nitrogen vacancy centres and trapped ions. The UK has a vibrant experimental and theoretical community working towards the creation of macroscopic quantum superpositions. MaQS will unite this with world-leading UK expertise in HEP to lead the world towards a new frontier. Our consortium has described ground-breaking proposals and experiments in this area [2-15]. Our core experiment will realise the specifications demanded in these proposals by rebuilding key aspects of our existing experiments in parallel. Quantum sensing, particle and astro-particle theory will meanwhile collaboratively refine the design and applications of such interferometers for the science phase, extending particle physics models in the process. After five years we would demonstrate the first experiments ever testing quantum interferometry with nanoparticles: a new window onto Nature.

2. Background: Optomechanical quantum sensors leverage the ability to control the quantum states of motion of nano- and micro-scale mechanical objects, using quantum properties of light combined with electric and magnetic fields. Suitable platforms include levitated or freely falling nanoparticles, clamped oscillators, and hybrid systems including coupling to nitrogen vacancy (NV^-) spins in diamond. Owing to the relatively high mass and ultrahigh precision of such systems, optomechanics offers a powerful toolbox to test the very fundamentals of physics on a table-top. Prominent research directions include: creating macroscopic superposition states [3, 5, 7, 15-18], testing objective collapse models [1, 3, 5-7, 15, 19-25], precision measurement of short-range forces such as non-Newtonian gravity [26-29], testing the generalised uncertainty principle [30], searching for new light fields such as keV-MeV dark-matter [31], precision measurement of the gravitational constant, testing the quantum nature of gravity [11], the detection of mid- and low-frequency gravitational waves from massive binaries [14], and the emergence of the arrow of time. This research strongly leverages previous and planned EPSRC investments (such as Phase 2 Hubs) in the development of quantum sensors and other quantum technologies, without any overlap.

3. Plan of work: This consortium has the ambitious goal of testing whether spatial superpositions can be created for particles that are 10 to 1000 nm in diameter. These particles comprise between 10^5 and 10^{11} atoms (10^{-21} to 10^{-15} kg). By contrast, the most macroscopic superposition created so far is interference of molecules comprising just 810 atoms (2×10^{-23} kg) going through gratings with period 266 nm [19, 22, 23].

In the initial two-year period (**Per 1**) and the middle one-year period (**Per 2**) we will rebuild our existing experiments to push beyond current limits so as to meet the required specifications, and in the following three year period (**Per 3**) we will put nanoparticles into a spatial superposition over a small distance for a short time. This would be a substantial step beyond the state-of-the-art, and would demonstrate all of the key experimental components for the more macroscopic superpositions we want to test next. These experiments could then be used for some of the additional science goals mentioned above. Beyond the first six years, a test of whether gravity permits quantum superpositions would be exciting [11].

We routinely levitate nanoparticles in vacuum [9, 10, 12] and will now extend this to allow these particles to be put into spatial superpositions on the basis of our theoretical proposals [3, 5, 7, 15] and others [16, 24, 32]. The key experimental requirements for this are reducing the internal temperature of levitated nanoparticles, reducing their centre-of-mass temperature, reducing decoherence rates, free-fall in ultra-high vacuum, creating the spatial superposition, high-precision timing, low translational and rotational vibrations including the stability to average multiple runs, and high-precision optical readout.

We aim to demonstrate spatial superpositions of 10-100 nm silica nanoparticles and 100 nm nanodiamonds with a small spatial superposition distance in an optical trap and an ion trap respectively. In parallel, we will work with 1 µm diamonds using a magnetogravitational trap. The diamonds contain single nitrogen vacancy centres with electron spins that will in time allow for more macroscopic superpositions than is possible for the silica. Building the full superposition experiment with the 1 µm particles will take longer but their mass is 10^6 larger leading to much more macroscopic superpositions. Clamped oscillator experiments will create superpositions of even greater (1 g) masses but with much smaller superposition distance. All of these experiments will heavily borrow instrumentation developments from each other. All experimentalists will work very actively together, and indeed all theorists will very actively work with all experimentalists in order to achieve the experimental goals.

Subpackage 1: Trapped silica spheres: The optical trapping and centre-of-mass cooling already demonstrated by us [8, 10] will be extended to test for small superpositions. An optical grating will be used to create the spatial superposition without the need for ground-state cooling [5]. Brief periods of free-flight will be achieved by turning off the trapping laser and then turning it on again before the particle is lost from the trap. Free flight permits greater spatial superposition distances by avoiding the trapping force which tends to hold the two spatial superposition components together [5, 7]. A 30 cm drop will be performed as a step towards the implementation of the full Talbot interferometer we proposed [5], which would come after six years. Wavefunction expansion experiments will be built using an ion trap because a signature of CSL manifests in excess heating of the particle without the need to create a spatial superposition state. The leader of SP1 is Hendrik Ulbricht (HU) at Southampton. The work will take place at Southampton led by HU with input from James Bateman and Alexander Belyaev, apart from deliverables D4 (Christopher Foot and Andrew Steane, Oxford) and D6 (Michael Vanner, Imperial).

Per 1: D1: Implement low-noise electronics with high-precision timing for switching the trap
D2: Reach the lowest ever centre-of-mass (CM) temperatures for nanoparticles [9, 10, 33]
D3: CM cooling followed by free-fall experiments and wavefunction expansion studies
D4: Build ion trap for non-interferometric tests of CSL heating with 1 µm silica [25]
Per 2: D5: CM cooling and free flight with an optical grating applied within the trap [5]
D6: Quantum non-demolition pulsed position measurements for levitated nanoparticles [2, 34]
Per 3: D7: Measure spatial superposition of 10-100 nm silica spheres with small superposition distance
D8: 30 cm free-fall with silica spheres and implementation of Talbot interferometer [5]

Subpackage 2: Diamonds containing NV$^-$ centres: We will build and demonstrate the key components of the experiment we have proposed for testing if a nanodiamond can be put into a spatial superposition [3, 7, 15]. The diamond contains a nitrogen vacancy (NV$^-$) centre which will be put into an electron spin superposition so that an inhomogeneous magnetic field creates a superposition of forces and hence a spatial superposition. The two components of this matter wave will then be interfered with each other to produce fringes. We will attempt this initially in an unusual linear Paul trap without turning off the trap, following our 2013 proposal which does not require ground-state cooling of the centre-of-mass motion [3].

We will also construct a magnetogravitational trap [15, 32] because these do not heat the diamond as much as an optical trap [12, 35], and they can trap uncharged particles to avoid noise from electrical charges in the environment. We will demonstrate helium buffer gas cooling to extend the expected spin coherence time of the NV$^-$ centre, allowing longer free-fall and hence larger spatial superposition distances following our new proposal [15]. The low temperature would also allow single-shot spin readout, reducing the number of nanodiamonds that need to be dropped by a factor of 10,000. Relatively macroscopic 1 µm diamonds (10^{-15} kg) will be used for which the magnetogravitational trap is well-suited [32]. The tilt control of this experiment is important [15], so we will test commercial electrolytic tilt sensors.

The leader of SP2 is Peter Barker (PB) at UCL. Deliverables D9, D11, D14 & D15 will take place at UCL led by PB with input from James Millen (KCL), while deliverables D10, D12, D13, D16 & D17 will take place at Warwick led by Gavin Morley with input from Yorck Ramachers and Gary Barker (Warwick). D13 will be led by Giles Hammond and Sheila Rowan (Glasgow).

Per 1: D9: Trapping and CM cooling in linear Paul trap of 100 nm diamonds containing NV^- centres
D10: Build and test magnetogravitational (MG) trap for 1 μm diamonds containing NV^- centres [32]
Per 2: D11: Install an inhomogeneous magnet into the Paul trap
D12: Implement helium buffer gas cooling within the MG trap for 1 μm diamonds [15]
D13: Implement active damping of vibrations and tilt following LIGO work
Per 3: D14: In-trap Ramsey interferometry of 100 nm diamonds using linear Paul trap [3]
D15: Charge neutralisation and free fall from the Paul trap
D16: Demonstrate dropping 1 μm diamonds out of the MG trap using electric fields [15]
D17: Install inhomogeneous magnet and reach ultra-high vacuum in chamber below MG trap [15]

Subpackage 3: Clamped oscillators: Building on our recent work demonstrating optomechanical strong coupling to the 11 GHz mechanical mode in silica microresonators [36], we will generate superposition states in these high-frequency oscillations of gram-scale objects. This will be achieved using a sequence of photon counting operations and using a quantum-state-synthesis technique that we have proposed [4, 37]. The leader of SP3 is Michael Vanner (MV) at Imperial. The work will take place initially at Cardiff (collaboration between Oliver Williams and Sean Giblin of Cardiff and MV), and subsequently in Imperial.

Per 1: D18: Reach ground state of silica microresonators at cryogenic temperatures
Per 2: D19: Generate superposition states in bulk clamped systems [4, 36, 37]

Subpackage 4: Theory: HEP and quantum sensing theorists will work closely with all of the experimentalists to guide and realise the deliverables in SP1-3. SP4 will focus on the theory of sensing relative phase in massive quantum superpositions as well as the noise processes leading to their collapse. Since the laws of quantum mechanics set the fundamental limit of precision sensing, we will use quantum metrology to identify and attain these limits, deploying ideas from quantum information science as well as classical and non-commutative probability theory. We will build on our recent results on sensing small displacements in multimode optomechanical systems [13], and further improve our theoretical proposals for creating macroscopic superpositions [3, 5, 7, 11, 15]. The leader of SP4 is Sougato Bose of UCL. Deliverables are led by Animesh Datta (D20), Paul Harrison (D21), Andrew Steane (D22), John March-Russell (D23), Myungshik Kim (D24), Mauro Paternostro (D25), Haixing Miao (D26), Sougato Bose (D27) and Xavier Calmet (D28).

Per 1: D20: Theory of quantum-limited and quantum-enhanced sensing in optomechanical interferometry
D21: Identify system specifications for the detection of dark matter and neutrinos
D22: Design hybrid system of atomic ion Coulomb-coupled to an ion-trapped nanoparticle
D23: Design optomechanical short-range force tests in unexplored regimes
D24: Design proposal to test relativistic effects in quantum mechanics
Per 2: D25: Self-consistent description of non-equilibrium mesoscopic quantum mechanics including CSL
D26: Extend our gravitational wave detector proposals [13, 14]
D27: Improve simulations and proposals for macroscopic superpositions based on experiments
Per 3: D28: Comprehensive study of models with very light scalar fields using QFT methods

4. Approximate budget: In the first two years (**Per 1**) the experimental work in subpackages 1, 2 and 3 will require eight PDRAs (£1.6M), plus equipment (£600k), consumables (£100k), travel (£40k) and technician time (£70k), totalling £2.4M. The theory efforts in **Per 1** will require four PDRAs (£800k) and travel (£40k), costing £840k. PI time (which could be used as travel money instead) for the 31 team members will cost £700k in **Per 1**. The total estimated budget is then £3.9M for the first two years (**Per 1**) and correspondingly £1.9M for the middle year (**Per 2**) when the last equipment will be bought. Period **Per 3** then costs £4.8M.

5. International Landscape: The leading researchers outside of the UK include people we collaborate fruitfully with. There are relevant experiments on levitated silica [26, 33, 38, 39] and diamond [32, 40, 41] nanoparticles as well as proposals for creating macroscopic superpositions of nanoparticles [16-18, 24]. Advanced experiments on the use of levitated nanoparticles for sensing short-range forces and related work exists in the USA [26-29]. Impressive demonstrations of clamped quantum oscillators come from the

EU [42] and the USA [43]. The MaQS project would bring together the critical mass of researchers within the UK on these topics in a coordinated national programme to share skills. This is an ideal time for the UK to realise the advantages it has from investing early in quantum technology (QT) through the Hubs.

6. Management structure: The project will be run by the management team made up of the four SP leaders plus Clare Burrage, Sheila Rowan and John March-Russell (to highlight particle physics and astrophysics context and opportunities), and the overall project coordinator, Gavin Morley. The management team will re-evaluate plans for **Per 2** and **Per 3** based on progress in the first two years (**Per 1**) but will not move **Per 1** resources without a good reason. The management team will meet monthly to check on progress.

7. Full team: Michael Vanner & Myungshik Kim (Imperial), Hendrik Ulbricht & Alexander Belyaev (Southampton) Mauro Paternostro (QUB), Peter Barker, Tania Monteiro, Chamkaur Ghag & Sougato Bose (UCL), Gary Barker, Yorck Ramachers, Paul Harrison, Animesh Datta & Gavin Morley (Warwick), Andrew Steane, Christopher Foot, Hans Kraus & John March-Russell (Oxford), James Bateman (Swansea), Xavier Calmet (Sussex), Haixing Miao (Birmingham), James Millen (KCL), Clare Burrage & Pierre Verlot (Nottingham), Oliver Williams & Sean Giblin (Cardiff), Sheila Rowan & Giles Hammond (Glasgow), Andreas Nunnenkamp (Cambridge), Kishan Dholakia (St Andrews) and Michael Hartmann (Heriot Watt).

8. Experience of the team: MaQS brings together 19 EPSRC and 12 STFC researchers to do fundamental physics using quantum sensor technology with insights from LIGO, the LHC, T2K, Hyper-K, DUNE and the UK QT Hubs. Our quantum sensors have been developed within the QT Hub for Sensors and Metrology, the QUANTIC (imaging) Hub and the Networked Quantum Information Technology (NQIT) Hub. Students from the Quantum Technology Centres for Doctoral Training (CDT) in Imperial and UCL have contributed. The strong publication record of the team in the area of macroscopic superpositions [1-15] shows the great excitement building around this topic in the UK and worldwide. Most of the equipment required is already in our labs, and the PDRAs hired will rebuild it according to our new proposals [5, 7, 15, 25] allowing us to generate results relatively quickly. No civil engineering is required as these are table-top experiments. Each university will provide one PhD studentship per 3-year PDRA, plus 50% of their equipment costs.

9. Project meetings: We will hold an informal project meeting in Oxford on 18th January 2019, and Myungshik Kim is organising our International Workshop on 1st April 2019 in Imperial. We will hold an annual international conference and an annual internal project meeting.

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