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ABSTRACT

The work proposed here will develop a unique new experimental platform capable of investigating fundamental scientific questions across a wide range of disciplines. This platform consists of a millimeter-scale drop of superfluid liquid helium that is magnetically levitated in vacuum. The unique properties of liquid helium (LHe), combined with the isolation provided by magnetic levitation in vacuum, will be used to address outstanding questions in quantum optomechanics, quantum sensing, the foundations of quantum physics, particle physics beyond the standard model, fluid mechanics, and physical chemistry.

The proposed experiments are designed around the LHe drop's ability to simultaneously serve as a high-finesse optical cavity, an ultrasensitive mechanical element, and as a refrigerant. Specifically, optical whispering gallery modes (WGMs) within the drop will serve as cavities, while the drop's shape oscillations and rotations will serve as the mechanical degrees of freedom. Unlike other levitated systems, the drop can cool itself efficiently via evaporation. The optical WGMs are expected to have world-record finesse, owing to the nearly vanishing optical loss in LHe. Likewise, the superfluidity of LHe suppresses the mechanical modes' damping, while these modes' exceptionally low stiffness results in large quantum fluctuations of the drop and correspondingly strong coupling between the drop's mechanical and optical degrees of freedom.

In addition, this system's unusual features extend beyond its optomechanical parameters. For example, the drop's near-perfect symmetry provides a large number of optical and mechanical modes that can be tuned into (or out of) degeneracy to optimize a given measurement. At the same time, the purity and isotropy of LHe can be exploited to realize new precision tests of fundamental symmetries.

The specific goals that will be enabled by support from the Vannevar Bush Faculty Fellowship are: (1) to increase the mass of objects that exhibit Gaussian quantum effects by a factor of one thousand; (2) to increase the mass of objects that exhibit non-Gaussian quantum effects by a factor of sixty million; (3) to make the first measurements of quantum effects in the rotational motion of a macroscopic object; (4) to improve tests of the electrical neutrality of atomic matter by a factor of one hundred; (5) to improve bounds on the presence of fractionally-charged fundamental particles by a factor of one thousand; (6) to search for spacetime discreteness on a length scale ten times smaller than the present limit; (7) to make the first test of spacetime classicality using macroscopic objects; (8) to study the fundamental components of superfluid turbulence; (9) to measure the equilibrium shapes of rotating liquids as they approach instability; and (10) to make precise and noninvasive measurements of deeply supercooled liquid water;

We emphasize that all of these goals will be pursued using magnetically levitated drops of LHe (or water in the case of item (10) in the list above) in the two experimental setups to be purchased with funds from the Vannevar Bush Faculty Fellowship, and by the postdoctoral and graduate students who would be supported by the Fellowship.

Approved for Public Release