Spin-Squeezed Large Momentum Transfer Dual-Species Atom Interferometric Accelerometer for Precision Test of the Equivalence Principle

J Li[1], G R M da Silva[1], S Kain[2], J Bonacum[3], D D Smith[4], T Kovachy[1], and S M Shahriar[5]

[1] *Physics and Astronomy, Northwestern University, Evanston IL, USA*
[2] *Physic and Astronomy, Northwestern University, Evanston IL, USA*
[3] *ECE, Northwestern University, Evanston IL, USA*
[4] *MSFC, NASA, Huntsville, AL, USA*
[5] *ECE and Physics, Northwestern University, Evanston IL, USA*
Contact Email: shahriar@northwestern.edu

General Relativity (GR) is a classical theory of gravity. As currently formulated, it cannot be reconciled with Quantum Mechanics (QM). On scales where both GR and QM are relevant, it is expected that violation of either theory or both of these theories would occur. Theories of Quantum Gravity (TQG), which are yet untested, prescribe modifications of both GR and QM in a manner that make them consistent with each other. Tests of predictions made by various forms of TQG represent arguably the greatest challenge facing our understanding of the nature of the universe, including its birth.

In this talk, I will describe a scheme which is expected to be sensitive enough for one such test, namely the violation the Equivalence Principle (EP), which is a fundamental tenet of GR. EP states that two objects with different inertial masses experience the same acceleration in a gravitational field. Violation of EP is characterized by a nonzero Eötvös parameter, eta, defined as the ratio of the differential acceleration and the mean acceleration experienced by two objects with different inertial masses in a gravitational field. EP violations at approximately the level of $\eta \sim 10^{-18}$ arise in many versions (*e.g.*, string theory) of TQG. Thus, tests of the EP at this level would either lead to the verification of a deeper underlying theory governing the universe, or in the case of a null result, force us to rethink entirely our theoretical framework for addressing the irreconcilability of GR and QM [1]. The most precise test of the EP has been carried out under the satellite-borne MICROSCOPE experiment employing classical accelerometers, constraining the value of η to $\sim 1.5 \times 10^{-15}$ [2]. Under the scheme we have developed [3], we will test the EP with dual species atom interferometry using Schroedinger Cat (SC) states. We are working on verifying the method in a laboratory-based testbed, paving the way for a follow-on space-borne mission capable of testing the EP at level of $\eta \sim 10^{-20}$. In this scheme, we use two simultaneous SC state atom interferometers employing two different isotopes of Rb, ^{85}Rb and ^{87}Rb. Consisting of N atoms, the SC state for each isotope (generated by non-linear interaction in an optical cavity) behaves as a single particle, in an equal superposition of two states with spatially separated centers of mass [4]. In comparison to typical atom interferometers that use uncorrelated atoms, the incorporation of SC states is predicted to improve the sensitivity by a factor of approximately $\sqrt{N}$, corresponding to a thousandfold improvement for $N = 10^6$. I will describe the theoretical work underlying this scheme, as well as the current status of the experimental effort.

Acknowledgements: This work has been supported in equal parts by NASA (80NSSC20C0161), the DOD Center of Excellence in Advanced Quantum Sensing under ARO (W911NF202076), ONR (N00014-19-1-2181), and the U.S. Department of Energy, Office of Science, National Quantum Information Science Research Centers, Superconducting Quantum Materials and Systems Center (SQMS) under contract number DE-AC02-07CH11359.

References

[1] J Overduin, F Everitt, P Worden and J Mester, Classical Quantum Gravity **29**, 184012 (2012)

[2] P Touboul *et al.* (MICROSCOPE Collaboration), Phys. Rev. Lett. 129, 121102 (2022)

[3] J Li, G R M da Silva, S Kain, J Bonacum, D D Smith, T Kovachy and S M Shahriar, arXiv:2209.06549 (2022); Phys. Rev. D (2023), accepted

[4] J Li, G R M da Silva, S Kain and S M Shahriar, Phys. Rev. A **107**, 032610 (2023)