Macroscopic quantum superpositions to test quantum gravity: References

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Lecture 1: Introduction

- Most macroscopic superposition: molecules with 2000 atoms [1]
- COW experiment: Neutron interferometer measures phase shift due to gravitational potential [2]
- Early quantum gravity work from Matvei Bronstein [3-5]
- Feynman thought experiment on page 250 [6]
- Double-interferometer experiment to test quantum gravity [7, 8]

[1] Y. Y. Fein, P. Geyer, P. Zwick, F. Kiałka, S. Pedalino, M. Mayor, S. Gerlich & M. Arndt, Quantum superposition of molecules beyond 25 kDa, Nature Phys. **15**, 1242 (2019).

[2] R. Colella, A. W. Overhauser & S. A. Werner, Observation of Gravitationally Induced Quantum Interference, PRL **34**, 1472 (1975).

[3] M. P. Bronstein, Translated republication of: Quantum theory of weak gravitational fields, Gen. Relativ. Gravit. **44**, 267 (2012).

[4] G. E. Gorelik, Matvei Bronstein and quantum gravity: 70th anniversary of the unsolved problem, Physics-Uspekhi **48**, 1039 (2005).

[5] M. P. Bronstein, Quantentheorie schwacher Gravitationsfelder, Phys Z Sowjetunion **9.2–3**, 140 (1936).

[6] D. Rickles & C. M. e. DeWitt, The Role of Gravitation in Physics: Report from the 1957 Chapel Hill Conference, https://edition-open-sources.org/sources/5/index.html (2011).

[7] S. Bose, A. Mazumdar, G. W. Morley, H. Ulbricht, M. Toroš, M. Paternostro, A. A. Geraci, P. F. Barker, M. S. Kim & G. Milburn, Spin Entanglement Witness for Quantum Gravity, PRL **119**, 240401 (2017).

[8] C. Marletto & V. Vedral, Gravitationally Induced Entanglement between Two Massive Particles is Sufficient Evidence of Quantum Effects in Gravity, PRL **119**, 240402 (2017).

Lecture 2: Decoherence and experimental progress

- Pioneering theory work on the idea of decoherence [9, 10]
- Modern textbooks on decoherence [11, 12]
- Decoherence theory of levitated nanoparticles (see section III) [13]
- Review papers on macroscopic superpositions [14, 15]
- Cooling a levitated nanoparticle to the ground state [16-18]
- Cooling a LIGO mirror close to ground state [19]
- Detecting gravitational interaction between 90 mg masses [20]

[9] E. Joos & H. D. Zeh, The emergence of classical properties through interaction with the environment, ZPhyB **59**, 223 (1985).

[10] H. D. Zeh, On the interpretation of measurement in quantum theory, Foundations of Physics **1**, 69 (1970).

[11] H.-P. Breuer & F. Petruccione, The Theory of Open Quantum Systems, OUP (2007).

[12] M. A. Schlosshauer, Decoherence and the Quantum-To-Classical Transition, Springer (2007).

[13] O. Romero-Isart, Quantum superposition of massive objects and collapse models, PRA **84**, 052121 (2011).

[14] A. Bassi, K. Lochan, S. Satin, T. P. Singh & H. Ulbricht, Models of wave-function collapse, underlying theories, and experimental tests, RMP **85**, 471 (2013).

[15] F. Fröwis, P. Sekatski, W. Dür, N. Gisin & N. Sangouard, Macroscopic quantum states: Measures, fragility, and implementations, RMP **90**, 025004 (2018).

[16] U. Delić, M. Reisenbauer, K. Dare, D. Grass, V. Vuletić, N. Kiesel & M. Aspelmeyer, Cooling of a levitated nanoparticle to the motional quantum ground state, Science **367**, 892 (2020).

[17] L. Magrini, P. Rosenzweig, C. Bach, A. Deutschmann-Olek, S. G. Hofer, S. Hong, N. Kiesel, A. Kugi & M. Aspelmeyer, Real-time optimal quantum control of mechanical motion at room temperature, Nature **595**, 373 (2021).

[18] F. Tebbenjohanns, M. L. Mattana, M. Rossi, M. Frimmer & L. Novotny, Quantum control of a nanoparticle optically levitated in cryogenic free space, Nature **595**, 378 (2021).

[19] C. Whittle, E. D. Hall, S. Dwyer, N. Mavalvala, V. Sudhir & R. Abbott, Approaching the motional ground state of a 10-kg object, Science **372**, 1333 (2021).

[20] T. Westphal, H. Hepach, J. Pfaff & M. Aspelmeyer, Measurement of gravitational coupling between millimetre-sized masses, Nature **591**, 225 (2021).

Lecture 3: Extensions of the proposal for a quantum-gravity test which aim to deal with decoherence

- Proposal to use LIGO to test quantum gravity [21] (compare with experiments in ref 19 above)
- Expand wavefunction without using a spin [22]
- Closed Stern-Gerlach experiment with atoms [23, 24]
- Extensions to the nanodiamond Stern-Gerlach proposal (ref 7 above): motional dynamic decoupling [25], spin coherence measurements in nanodiamonds plus magnetic teeth proposal [26] and Faraday screen [27]

[21] A. Datta & H. Miao, Signatures of the quantum nature of gravity in the differential motion of two masses, Quantum Science and Technology **6**, 045014 (2021).

[22] T. Weiss, M. Roda-Llordes, E. Torrontegui, M. Aspelmeyer & O. Romero-Isart, Large Quantum Delocalization of a Levitated Nanoparticle Using Optimal Control: Applications for Force Sensing and Entangling via Weak Forces, PRL **127**, 023601 (2021).

[23] Y. Margalit, O. Dobkowski, Z. Zhou, O. Amit, Y. Japha, S. Moukouri, D. Rohrlich, A. Mazumdar, S. Bose, C. Henkel & R. Folman, Realization of a complete Stern-Gerlach interferometer: Toward a test of quantum gravity, Sci. Adv. **7**, eabg2879 (2021).

[24] O. Amit, Y. Margalit, O. Dobkowski, Z. Zhou, Y. Japha, M. Zimmermann, M. A. Efremov, F. A. Narducci, E. M. Rasel, W. P. Schleich & R. Folman, T^3 Stern-Gerlach Matter-Wave Interferometer, PRL **123**, 083601 (2019).

[25] J. S. Pedernales, G. W. Morley & M. B. Plenio, Motional Dynamical Decoupling for Interferometry with Macroscopic Particles, PRL **125**, 023602 (2020).

[26] B. D. Wood, G. A. Stimpson, J. E. March, Y. N. D. Lekhai, C. J. Stephen, B. L. Green, A. C. Frangeskou, L. Ginés, S. Mandal, O. A. Williams, S. Bose & G. W. Morley, Matter and spin superposition in vacuum experiment (MASSIVE), arXiv:2105.02105 (2021).

[27] T. W. van de Kamp, R. J. Marshman, S. Bose & A. Mazumdar, Quantum gravity witness via entanglement of masses: Casimir screening, PRA **102**, 062807 (2020).

More videos:

- Seminar series: https://www.quantumgravityinlab.com
- Quantum Foundations, Gravity, and Causal Order 2021 (BIRS), https://www.birs.ca/events/2021/5-day-workshops/21w5104/videos
- Challenges for Witnessing Quantum Aspects of Gravity in a Lab 2021, ICTP: https://www.ictp-saifr.org/qgem2021