Quantum Information, Foundations and Gravity (L16)

Prof. Adrian Kent

The course gives an introduction to foundational questions in quantum theory and quantum information, with a focus on the relationship between quantum theory and gravity. We will examine arguments that the gravitational field must necessarily be quantized, together with counter-arguments, review old ideas of semi-classical theories of gravity and their problems, and discuss recently proposed experiments that aim to use the properties of quantum information to test whether gravity is indeed mediated by quantum particle exchange.

Topics covered in the course will include:

- Basic concepts in quantum theory and quantum information: pure and mixed states, density matrix, the Schmidt decomposition, entanglement, the no-cloning theorem.
- Relationship between quantum theory and relativity: the no-signalling principle; quantum state summoning and the no-summoning theorem; possible and impossible summoning tasks.
- Bell's theorem and Bell nonlocality.
- Entanglement measures and entanglement witnesses.
- Brief review of basic ideas of Everettian quantum theory and collapse-based versions of quantum theory.
- Basic notions of semi-classical gravity; the Page-Geilker experiment.
- Quantum theory and gravity: the Colella, Overhauser and Werner experiment; the Eppley-Hannah argument.
- Non-linear extensions of quantum theory; refutation of the Eppley-Hannah argument
- The proposed experiments of Bose et al. and Marletto-Vedral testing the generation of entanglement between separated mesoscopic quantum systems in superposition.
- Discussion of what positive or negative results in BMV experiments would imply.
- Thought experiments illuminating constraints on interference experiments for massive and charged particles.

If time permits we may also discuss other recent experimental proposals.

Prerequisites

Familiarity with undergraduate level quantum mechanics is essential. Familiarity with a first course in quantum information theory, such as the Cambridge Part II Quantum Information and Computation course, would be highly advantageous.

Literature

1. Kenneth Eppley and Eric Hannah. The necessity of quantizing the gravitational field. Foundations of Physics, 7(1-2): 51-68, 1977.

2. Don N Page and CD Geilker. Indirect evidence for quantum gravity. Physical Review Letters, 47(14):979, 1981.

3. James Mattingly. Why Eppley and Hannah's thought experiment fails. Physical Review D, 73(6):064025, 2006.

4. Adrian Kent, Simple Refutation of the Eppley-Hannah argument. Classical and Quantum Gravity 35 (24) 245008 (2018)

5. Sougato Bose, Anupam Mazumdar, Gavin W. Morley, Hendrik Ulbricht, Marko Toros, Mauro Paternostro, Andrew A Geraci, Peter F Barker, MS Kim, and Gerard Milburn. Spin entanglement witness for quantum gravity. Physical Review Letters, 119(24):240401, 2017.

6. Chiara Marletto and Vlatko Vedral. Gravitationally induced entanglement between two massive particles is sufficient evidence of quantum effects in gravity. Physical Review Letters, 119(24):240402, 2017.

7. Daniel Carney, Philip CE Stamp, and Jacob M Taylor. Tabletop experiments for quantum gravity: a user's manual. Classical and Quantum Gravity, 36(3):034001, 2019.

8. Mari, A., De Palma, G. and Giovannetti, V. Experiments testing macroscopic quantum superpositions must be slow. Sci Rep 6, 22777 (2016). https://doi.org/10.1038/srep22777

9. Huggett, N., Linnemann, N. and Schneider, M.D. (2023) Quantum Gravity in a Laboratory? Cambridge: Cambridge University Press (Elements in the Foundations of Contemporary Physics).

Additional support

Three examples sheets will be provided and three associated examples classes will be given. There will be a one-hour revision class in the Easter Term.