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IOP Publishing *New J. Phys.* **19** (2017) 050401 https://doi.org/10.1088/1367-2630/aa6fdc

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Deutsche Physikalische Gesellschaft DPG
IOP Institute of Physics
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PUBLISHED
26 May 2017

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EDITORIAL

Focus on gravitational quantum physics

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Abstract

The interplay between quantum theory and gravity remains one of the least explored fields of physics. The current ‘focus on’ collection summarises experimental and theoretical results from many of the leading groups around the world on the research of phenomena which cannot be explained without involving both quantum theory and gravitational physics.

Einstein’s theory of general relativity and quantum theory are two pillars of modern physics. The two theories differ significantly, not only in their mathematical formulations, but also in their foundational concepts. Even with either theory independently and indisputably tested to high precision, observed gravitational effects in current laboratory quantum experiments can be explained with the help of the non-metric, Newtonian limit of gravity [1–3], and the results of completed tests of general relativity are all consistent with classical mechanics [4–6]. There is therefore of fundamental interest to probe the intersection between quantum theory and gravity, as well as to develop a unified consistent framework in which the two theories appear as appropriate limits.

The focus on ‘gravitational quantum physics’ offers a glimpse of an emerging field of research in which phenomena are investigated that require both, quantum theory *and* gravity, for their explanation. It showcases both experimental and theoretical work from many of the leading groups in this area, who pull together concepts and ideas from special and general relativity, quantum optics, and quantum information science to achieve a deeper understanding of the phenomena at the interface between the two theories.

Whether gravitational field requires a quantum description or not is still subject of an ongoing debate and a question that is approached from various angles in the papers published in the current focus. Given that gravity is fundamentally classical, Kafri, Taylor and Milburn show that two gravitationally coupled resonators cannot create entanglement [7, 8]. In turn, observing gravity-mediated entanglement in an experiment would rule out any view of gravitational interactions as purely classical. The concept according to which the gravitational field remains classical at the fundamental level, but where matter is quantised, naturally leads to the nonlinear Schrödinger–Newton equation. Giulini and Grossard investigate the implication and possible observational consequences of the multi-particle Schrödinger–Newton equation for the motion of the mass-centre of an extended multi-particle system [9]. This should be contrasted with quantum-field theory combined with gravity by Anastopoulos and Hu, who show that the Schrödinger–Newton equation appears as a mean-field limit effective theory, but on the fundamental level the theory remains linear [10]. Another nonlinear extension of quantum theory designed to be compatible with the occurrence of closed time-like curves in space-times that may appear as solutions to the field equations of general relativity is discussed by Ralph and Pienaar [11].

Whether caused by gravity or other reasons, *any* nonlinear modification of quantum dynamics is prone to pathologies, above all faster-than-light signalling, at least if the usual reduction-postulate is taken over from the linear theory. Bahrami *et al* compare the nonlinearity of the Schrödinger–Newton equation with that of the collapse models, for which faster-than-light signalling can be avoided due to stochastic modification of the dynamics [12]. A gravity-induced collapse model is the subject of a publication by Diósi, who applies it to bulk matter and calculates the amount of the spontaneous heating as its side-effect [13]. Gravity is assumed to cause a breakdown of quantum theory also in the paper by Stamp, where gravitational correlations cause ‘bunching’ of

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quantum trajectories [14]. A different route is taken where gravity leads to decoherence without modifying quantum theory. Pikovski *et al* review their results on decoherence due to centre-of-mass coupling to internal degrees of freedom in the presence of time dilation [15]. Finally, Franson reports a result of speculative nature about an apparent correction to the speed of light when the gravitational potential energy of massive particles is included in the Hamiltonian of quantum electrodynamics [16].

It is fair to say that with the current state of physics the question concerning the quantum nature of gravity is entirely open. Ultimately, its answer is likely to be decided by experiment. It is therefore of much interest to test the foundational principles of general relativity, like the equivalence principle, on systems in non-classical states.

In that spirit, the bulk of papers by experimental groups are in-depth studies of novel ways to test Einstein's equivalence principle on quantum systems. Hartwig *et al* develop a proposal for testing the universality of free fall for two elements with high atomic numbers, rubidium and ytterbium, in a very large baseline atom interferometer [17]. Barrett *et al* describe and demonstrate two new methods for extracting the differential phase between dual-species atom interferometers for precise tests of the weak equivalence principle [18]. Williams *et al* describe a concept for an atom interferometry mission on the International Space Station, which promises testing the equivalence principle on quantum systems with unpreceded precision, sensitive also to time-dependent violations [19]. Expanding on their previous analysis, Marin *et al* consider the main vibration mode of gravitational wave bar detectors for setting an upper limit to possible modifications of the Heisenberg uncertainty principle that are expected as an effect of quantum gravity [20].

The field of analogue gravity tries to understand gravitational systems, or in general curved spacetimes, by means of analogue systems that simulate the relevant features in non-gravitational systems. This idea is represented by two papers. Westerberg *et al* show that time-dependent spacetimes can be simulated by using intense tailored laser pulses that modify the refractive index of an optical medium [21]. In a similar vein, Neuenhahn and Marquardt describe how expanding spacetimes can be simulated via time-dependent variation of the tunnel-coupling between two weakly interacting quasi-1D condensates of cold bosonic atoms [22].

Relativistic quantum information aims at investigating quantum information processing in relativistic regimes. A number of papers from the current focus illustrates this aim. Salton, Mann and Menicucci investigate entanglement extraction from the vacuum of relativistic quantum field theories through local interaction with Unruh–DeWitt detectors undergoing linear acceleration [23]. Applying developed relativistic quantum metrology techniques Brown *et al* propose a way to detect weak vibrational disturbances [24], Sabín *et al* suggest to use phonon creation in a Bose–Einstein condensate to detect gravitational waves [25] and Rudolph *et al* pave the way for transportable high-precision quantum sensors by developing a compact and robust design of a high-flux BEC source for atom interferometers [26].

We are just about to enter the phase when actual experiments at the intersection between quantum theory and gravity become feasible with current technology. A rapid development of atom interferometry, the emerging field of quantum optomechanics, together with highly controllable multi-photon experiments, will open an entirely new parameter regime for quantum experiments where gravity plays a role, as well as for gravitational experiments where quantum physics plays a role. Further theoretical investigations in this direction could reveal to which extent foundational principles of the two theories are compatible with each other. This may open new possibilities to reassess already known formal difficulties in the development of a complete theory unifying quantum theory and general relativity from a new perspective.

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