DELIVERABLE 1.2

List of fundamental tests

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INTRODUCTION

Space presents an ideal environment in which to conduct several kinds of tests of fundamental physics. It enables free-fall times many orders of magnitude beyond those which can be achieved in drop towers on Earth, during parabolic flights, or using sounding rockets. Beyond low Earth orbit and towards the Lagrange points of the Earth–Moon–Sun system, gravitational forces practically cancel out and are highly stable. Relativistic velocities are, in some contexts, not unrealistic. Delicate measurements can be performed free from the seismic, electrical, and other noise that is an inevitable consequence of operating on Earth.

The rest of this document is meant to give a comprehensive overview of the relevant published literature and pre-prints. We discuss proposed, proof-of-principle, or actual experiments to explore fundamental physics using quantum technologies in space, as well as theoretical works, to elucidate the different physical effects that can be tested, demonstrated, or exploited in space.

IMPLEMENTATION

We have identified a number of publications and pre-prints as a representative cross-section of the state of the art on the tests of fundamental physics in space. We have not distinguished between the physical mechanism exploited by each proposal, proof of concept, or experiment, and refer the reader to the list of experiments with different physical systems for more information. We have, however, limited the list to encompass only those tests described in the peer-reviewed literature or in pre-prints freely available online.

Quick-reference list

Relativity

- Einstein's equivalence principle and general relativity (Aguilera et al., 2014; Amelino-Camelia et al., 2008; Everitt et al., 2011; Muntinga et al., 2013; Sumner et al., 2007; Touboul et al., 2017; Williams et al., 2016; Zych and Brukner, 2018)
- Gravitational wave detection (Amaro-Seoane et al., 2012a,b; Anderson et al., 2018; Antonucci et al., 2011; Armano et al., 2015, 2017; Gibert et al., 2015; Hogan and Kasevich, 2016; Isleif et al., 2018; Loriani et al., 2019; Norcia et al., 2017; Yu and Tinto, 2011)
- Relativistic quantum information and curved space-time (Ahmadi et al., 2014a,b; Alsing and Fuentes, 2012; Bruschi et al., 2013a, 2010, 2013b, 2014a; Bruschi et al., 2016; Dimic et al., 2020; Downes et al., 2011; Dragan et al., 2011; Fink et al., 2017; Friis et al., 2012a; Friis and Fuentes, 2013; Friis et al., 2012b; Fuentes et al., 2010; Kohlrus et al., 2017; Kohlrus et al., 2018; Lee and Fuentes, 2014; Liu et al., 2016; Lock and Fuentes, 2017; Radchenko et al., 2014; Ratzel et al., 2018b; Regula et al., 2016; Toros et al., 2017; Safranek et al., 2015; Zych et al., 2011)

Tests of quantum mechanics

- Optomechanical tests (Hechenblaikner et al., 2014; Kaltenbaek, 2013, 2015; Kaltenbaek and Aspelmeyer, 2015; Kaltenbaek et al., 2012; Kaltenbaek et al., 2016; Zanoni et al., 2016)
- Gravity and gravitational decoherence (Bassi et al., 2017; Belenchia et al., 2018; Bonder et al., 2015; Bruschi et al., 2014b; Carlesso et al., 2017; Castro Ruiz et al., 2017; Koduru Joshi et al., 2018; Lindkvist et al., 2015; Pikovski et al., 2015a,b,c; Ratzel et al., 2018a; Roura, 2020; Zych et al., 2016)

Quantum information, excluding relativistic effects

- Long-distance entanglement (Carrasco-Casado et al., 2018; Chandrasekara et al., 2017; Grieve et al., 2018; Hos-seinidehaj and Malaney, 2016; Kerstel et al., 2018; Liao et al., 2017; Liao et al., 2017, 2018; Meyer-Scott et al., 2011; Oi et al., 2017; Pugh et al., 2017; Ren et al., 2017; Sharma and Banerjee, 2019; Takenaka et al., 2017; Ursin et al., 2009; Wang et al., 2013; Yin et al., 2013; Yin et al., 2017; Zhang et al., 2018)
- Non-locality (Handsteiner et al., 2017; Rauch et al., 2018; Steinbring, 2018; Wu et al., 2017)

General discussions

- General discussions (Becker et al., 2018; Kaltenbaek et al., 2004)

General relativity

The first set of space-borne fundamental tests of general relativity that we consider are concerned with Einstein's equivalence principle. The Satellite Test of the Equivalence Principle (STEP) (Sumner et al., 2007) proposes using pairs of concentric free-falling proof masses to test the equivalence principle, aiming to reach sensitivity levels of one part in 1018. The GrAnd Unification and Gravity Explorer (GAUGE) (Amelino-Camelia et al., 2008) mission proposes to use a drag-free spacecraft platform hosting a number of experiments that probe the unification of gravity with the other forces of nature. The planned tests include both macroscopic test masses and cold-atom interferometry experiments. The measured values are consistent with the predictions of general relativity. The MICROSCOPE mission, which was launched in 2016 and whose first results were published in 2017 (Touboul et al., 2017) also made use of test masses on a satellite. This mission used two different masses, one made of titanium and the other platinum; its results were consistent with the weak equivalence principle to a few parts in 10^{15}. A number of experiments made use of atom interferometry to test this same principle in microgravity environments. Initial proof-of-concept tests using Bose–Einstein condensates in drop-tower experiments (Muntinga¨ et al., 2013) led the way to proposals such as the Spacetime Explorer and Quantum Equivalence Principle Space Test (STE-QUEST) (Aguilera et al., 2014) mission proposal that proposes using dual-species atom interferometry to conduct tests of the weak equivalence principle to a precision of a few parts in 10^{15}. The Quantum Test of the Equivalence principle and Space Time (QTEST) (Williams et al., 2016) proposal suggested using the International Space Station to conduct space-borne experiments to test the equivalence principle to similar levels of precision without necessitating the creation of Bose–Einstein condensates. Recent theoretical work (Zych and Brukner, 2018) extended considerations of the equivalence principle into the quantum regime, claiming that confirmation of the classical equivalence principle does not imply confirmation of the quantum equivalent, which must therefore be verified independently. This may inspire a next generation of equivalence principle experiments to incorporate quantum considerations. Gravity Probe B, whose results were published in 2011 (Everitt et al., 2011) made use of cryogenic gyroscopes on a satellite to test two predictions of general relativity, i.e., the geodetic and frame-dragging effects.

General-relativistic tests also include the detection of gravitational waves, a topic which has seen significant interest in recent years. Broadly speaking two categories can be identified of gravitational-wave tests in space, atomic and photonic platforms. Photonic platforms are more advanced in this regard. The Laser Interferometer Space Antenna (LISA) has produced a number of studies. Proofs of concept of its forerunner mission, LISA Pathfinder, have been published that demonstrated the flight hardware necessary to guide its motion along a geodesic (Antonucci et al., 2011) and in-spec thermal performance (Gibert et al., 2015), proposals for drag-free flight around a test mass while measuring the acceleration of this test mass relative to a second (Armano et al., 2015). Results from the mission verified the possibility of maintaining charge-induced forces at an acceptably low level (Armano et al., 2017) and the viability of its colloidal micro-Newton trust system to control the attitude and position of the spacecraft and its two test masses (Anderson et al., 2018). The LISA proposal envisages three satellites, maintained at a constant distance from one another by means of an optical link and a phase reference distribution system, whose concept was verified in (Isleif et al., 2018). The LISA proposal was not selected for a mission; further instrument verification and proposals were published in the context of the subsequent “eLISA” (Amaro-Seoane et al., 2012a,b) mission proposal, also referred to as the European New Gravitational Wave Observatory mission. Atom interferometry has also been proposed as the basis for gravitational wave detection in space. The basic configuration consists of two atom interferometers separated by a distance (Yu and Tinto, 2011) and connected by means of a laser. Improvements on this scheme were proposed, weakening constraints on collimation by employing strong a local oscillator near each ensemble locked to a reference laser beam (Hogan and Kasevich, 2016). The mechanism underlying the sensitivity of atom-interferometric setups to gravitational waves was elucidated in (Norcia et al., 2017), opening the door to enhancing the sensitivity of such instruments. Further considerations are discussed in a recent review (Loriani et al., 2019) concerning the selection of atomic sources in space-based atomic gravitational wave detectors.

Relativistic quantum information, and specifically the effects of the curvature of space-time on the generation and distribution of entanglement, is a relatively young topic of study dominated by theoretical research work. Quantum-optical theoretical discussions include entanglement in expanding space-time (Fuentes et al., 2010). The deep link between motion and quantum information was explored by showing that one may entangle cavities through motion in relativistic scenarios (Downes et al., 2011) and that, more generally, motion generates entanglement (Friis et al., 2012a; Friis and Fuentes, 2013; Regula et al., 2016) as well as quantum gates (Bruschi et al., 2013a; Friis et al., 2012b), in the absence of particle creation (Bruschi et al., 2013b), and can be used for universal quantum computation (Bruschi et al., 2016). Particle creation has been investigated both in the context of the dynamical Casimir effect (Lock and Fuentes, 2017) and in a model of an expanding universe (Liu et al., 2016). The Unruh effect was recently explored in the context of quantum optics, clarifying the validity of the single-mode approximation (Bruschi et al., 2010). Motion necessitates revisiting several aspects of quantum optics; local measurements have been shown to be sufficient to determine absolute acceleration (Dragan et al., 2011), and observers in the vicinity of an event horizon of a black hole could be used to simulate indefinite causal order (Dimic et al., 2020). Relativistic effects necessitate deeper exploration of detector models (Lee and Fuentes, 2014); these considerations are crucial for analysing entanglement in non-inertial frames of reference, e.g., to show that quantum entanglement in curved space-time is observer-dependent (Alsing and Fuentes, 2012). The visibility of quantum interference has been proposed as a witness of general-relativistic proper time in (Zych et al., 2011), and triggered an investigation into quantum mechanics for non-inertial observers (Toros et al., 2017). Curved space-time also leads to modifications of the frequency spectrum of an optical resonator (Ratzel et al., 2018b), and affects the polarisation state of photons (Kohlrus et al., 2018). All these effects conspire to impose new bounds on quantum metrology, which must be taken into account when calculating ultimate bounds on precision (Ahmadi et al., 2014a,b; Safranek et al., 2015). One direct application of these studies is in quantum communication. It has been shown theoretically that gravity adds additional noise which affects the transmission of information (Bruschi et al., 2014a; Kohlrus et al., 2017). Relativistic effects may also be taken into account and new schemes for quantum key distribution proposed for operating in the relativistic regime (Radchenko et al., 2014). The first steps towards experimental demonstrations of these results were taken recently; a proof of concept experiment was reported in 2017 that tested the behaviour of photonic entanglement in accelerated reference frames up to 30 g (Fink et al., 2017).

Tests of quantum mechanics

Space provides an ideal environment for testing quantum mechanics, for a number of reasons. The field of optomechanics, which investigates the interaction between light and motion, has seen several proposals for testing the large-mass limit of quantum mechanics. Conducting experiments in space would allow for longer-lived and larger superposition states (Kaltenbaek and Aspelmeyer, 2015) to be produced, thus helping to falsify or constrain spontaneous collapse theories and similar models. The most prominent proposal for conducting optomechanical experiments in space is the MAcroscopic Quantum ResOnators (MAQRO) mission (Hechenblaikner et al., 2014; Kaltenbaek, 2013, 2015; Kaltenbaek et al., 2012; Kaltenbaek et al., 2016; Zanoni et al., 2016), which aims to use a satellite platform at one of the Lagrange points of the Earth–sun–moon system in order to place a nanosphere with a relatively large mass in a Schrodinger¨ cat state and observe the dynamics of this state on time-scales longer than those possible on Earth-bound experiments.

Gravitational decoherence (Bassi et al., 2017), whereby gravity is postulated as the mechanism through which superposition states of massive objects collapse to classical states, and the study of the effects gravity has quantum systems, have seen a flurry of interest in recent years. It has been explored how gravitational time dilation could give rise to decoherence (Pikovski et al., 2015c), which claim has led to some discussion in the literature and is not universally acknowledged (Bonder et al., 2015; Pikovski et al., 2015a,b). Gravitational fields can similarly affect the precision of clocks (Lindkvist et al., 2015), allow to entangle clocks through gravity (Castro Ruiz et al., 2017), and give rise to redshifts in clocks that may be revealed through appropriately designed experiments (Roura, 2020). Furthermore, the quantum interference of clocks (Zych et al., 2016) could allow to test for novel quantum effects that arise from time dilation. The gravitational field of a small oscillating mass has been shown theoretically to affect a Bose–Einstein condensate by creating phonons that heating and transitions between phonon modes (Ratzel¨ et al., 2018a), which may make accessible the probing of gravitational fields caused by small masses. Several space-based experimental proposals have been put forward to explore the effects of gravity on quantum systems. Cold atoms may be used to test the effects of gravity and motion on quantum entanglement (Bruschi et al., 2014b). Although entangled photons can be used to test gravitational decoherence (Koduru Joshi et al., 2018), massive objects are more commonly proposed as probes to explore the quantumness of gravity (Belenchia et al., 2018; Carlesso et al., 2017).

Quantum information, excluding relativistic effects

Space is seen as one means of facilitating the spread of quantum communication networks, which on Earth are currently hampered by distance limitations and to point-to-point connections. This inspired a number of proposals, ranging from satellite platforms for performing experiments with quantum entanglement in space (Ursin et al., 2009) to smaller cubesats for facilitating quantum communications and quantum key distribution (Grieve et al., 2018; Hosseinidehaj and Malaney, 2017; Kerstel et al., 2018; Oi et al., 2017). Several proofs of concept have been demonstrated, including the implementation of decoy-state quantum key distribution for a satellite uplink (Meyer-Scott et al., 2011), verification of ground-to-satellite quantum key dis-tribution (Wang et al., 2013), progress towards inter-satellite communication (Liao et al., 2017), an airborne demonstration of a quantum communication receiver system (Pugh et al., 2017), and miniaturised entangled photon-pair sources for use in nano-satellites (Chandrasekara et al., 2017). More recently several key advances have taken place; quasi-single-photon trans-mission was reported from a satellite to Earth in 2013 (Yin et al., 2013), eventually culminating in quantum key distribution from a satellite to ground (Ren et al., 2017), teleportation from ground to a satellite (Liao et al., 2017), entanglement distribution over a distance of 1; 200 km using a satellite (Yin et al., 2017), a satellite-based intercontinental quantum network (Liao et al., 2018), and quantum communication from satellite to ground using micro-satellites (Carrasco-Casado et al., 2018; Takenaka et al., 2017). These demonstrations have paved the way to large-scale quantum key distribution, although significant challenges remain (Sharma and Banerjee, 2019; Zhang et al., 2018).

Most of the discussion so far has focused on space as a platform for experimental investigations that cannot be performed, easily or at all, on Earth. A recent set of experiments (Handsteiner et al., 2017; Rauch et al., 2018; Wu et al., 2017) uses cosmological light sources as a source of randomness for Earth-based tests of Bell's inequality, eliminating some loopholes in traditional experiments. While photons from the kinds of cosmic sources used in these experiments are usually assumed to be uncorrelated, some recent work (Steinbring, 2018) has cast doubt on this assertion.

General discussions

Some other works appearing in the past 15 years do not directly deal with one specific fundamental test, but are rather presentations or demonstrations of generically-applicable platforms. In (Kaltenbaek et al., 2004), the authors propose a set of fundamental quantum physics experiments using entangled photons and satellites as a platform. Potential experiments discussed include tests of Bell-type inequalities, tests of special and general relativistic effects on quantum entanglement, Wheeler's Delayed choice experiment; an experimental platform and protocols are presented that would make possible these tests. More recently, (Becker et al., 2018) presented results from the launch of the MAIUS-1 sounding rocket, where a Bose–Einstein condensate was generated and probed in space during the six-minute space flight of this rocket. A total of 110 matter-wave interferometry experiments were conducted, taking advantage of the extended free-fall time made possible by working in space. The cited reference focuses on the phase transition and collective dynamics of the generated condensates.

CONCLUSIONS

Space provides a unique environment to arrive closer to the bounds of measurement allowed by quantum mechanics, to test the limits of quantum mechanics and its interaction with gravity, and to explore quantum information on scales not possible on Earth.

Within these three strands, a large body of work has appeared in the last fifteen of years, ranging from theoretical work identifying new effects in quantum systems and experimental proposals for observing such effects, through proof-of-principle experiments that demonstrate the viability of conducting full-scale missions, all the way to actual experiments conducted either flown on purpose-built satellites or as experiments at the International Space Station.

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