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List of experiments with different physical systems

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INTRODUCTION

Space presents an ideal environment where to conduct several kinds of tests of fundamental physics. It enables free-fall times 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 noises that are 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, focusing on the different physical systems and mechanisms exploited.

IMPLEMENTATION

Over the past decade a number of experiments have been conducted in space, including experiments performed in sounding rockets, purpose-built satellites, and the International Space Station. To this we must add a number of proof-of-principle experiments that have been performed, both on Earth and in the form of demonstration missions in space, whose aim is constrained to showing the flight-readiness of subsystems or to show that effects should be visible in technologically feasible scenarios.

This list of experiment and proofs of concept should be read in tandem with the list of fundamental tests which focuses on the different aspects of physics that may be explored in a space environment. This list only includes experiments whose descriptions or results were published in the peer-reviewed literature or as a freely available pre-print. Where useful, we have sub-divided the list by the kind of physical mechanism exploited.

Quick-reference list

Photons

- Interferometry or spectroscopy (Amaro-Seoane et al., 2012a,b; Anderson et al., 2018; Antonucci et al., 2011; Armano et al., 2015, 2017; Gibert et al., 2015; Isleif et al., 2018)
- Entanglement (Bruschi et al., 2014a; Carrasco-Casado et al., 2018; Chandrasekara et al., 2017; Fink et al., 2017; Grieve et al., 2018; Kaltenbaek et al., 2004; Kerstel et al., 2018; Koduru Joshi et al., 2018; Kohlrus et al., 2017; Liao et al., 2017; Liao et al., 2017, 2018; Meyer-Scott et al., 2011; Oi et al., 2017; Pugh et al., 2017; Radchenko et al., 2014; Ren et al., 2017; Takenaka et al., 2017; Ursin et al., 2009; Wang et al., 2013; Yin et al., 2013; Yin et al., 2017; Zhang et al., 2018)
- Correlation (Handsteiner et al., 2017; Rauch et al., 2018; Wu et al., 2017)

Cold atoms

- Interferometry (Aguilera et al., 2014; Amelino-Camelia et al., 2008; Becker et al., 2018; Hogan and Kasevich, 2016; Loriani et al., 2018; Muntinga¨ et al., 2013; Norcia et al., 2017; Williams et al., 2016; Yu and Tinto, 2011)
- Entanglement (Bruschi et al., 2014b)

Macroscopic matter-waves

- Matter-wave interferometry (Belenchia et al., 2018; Carlesso et al., 2017; Kaltenbaek, 2013, 2015; Kaltenbaek and Aspelmeyer, 2015; Kaltenbaek et al., 2012; Kaltenbaek et al., 2016; Zanoni et al., 2016)

Massive test masses

- Anomalous motion (Amelino-Camelia et al., 2008; Everitt et al., 2011; Sumner et al., 2007; Touboul et al., 2017)

Photons

Terrestrial interferometric experiments using light are ubiquitous. It has been suggested to use space-based interferometers to build gravitational-wave detectors of sizes and with sensitivities far surpassing those achievable on Earth. The most significant push in this direction took the form of the Laser Interferometer Space Antenna (LISA) mission proposal, which more recently became the “eLISA” (Amaro-Seoane et al., 2012a) mission proposal. Proofs of concept have been published showing the possibility of guiding the satellites along a geodesic with the required performance (Antonucci et al., 2011). One area where space-based interferometric gravitational wave detectors are far superior to their terrestrial counterparts is in detecting low-frequency gravitational waves (Amaro-Seoane et al., 2012b). The LISA Pathfinder mission was designed to test the components and subsystems for an eventual full-scale mission including their thermal performance (Gibert et al., 2015); and demonstrate mitigation of additional sources of noise (Armano et al., 2015), measurement and control of charge-induced acceleration noise on test masses (Armano et al., 2017), low phase noise optical phase reference distribution system (Isleif et al., 2018), and operation of colloidal micro-Newton thrusters to the required specifications (Anderson et al., 2018).

Aside from gravitational wave detection, photonic experiments in space have been proposed as a platform with which to perform fundamental quantum physics experiments (Kaltenbaek et al., 2004; Ursin et al., 2009). Uplinks to satellites have been proposed as a means to test gravitational decoherence mechanisms (Koduru Joshi et al., 2018). The effects of space-time on satellite-based quantum communications and metrology have been analysed (Bruschi et al., 2014a; Kohlrus et al., 2017), as has performing quantum cryptography in relativistic scenarios (Radchenko et al., 2014). A recent experiment (Fink et al., 2017) tested the behaviour of photonic entanglement in accelerated reference frames up to 30g in a terrestrial environment, laying the foundation for further tests of these proposals. Experimental satellite-based quantum communication has also taken off in very recent years. Proofs of concept have implemented quantum key distribution for a satellite uplink (Meyer-Scott et al., 2011) and full-scale experimental verification for ground to satellite quantum key distribution (Wang et al., 2013), shown progress towards inter-satellite quantum communication (Liao et al., 2017) and airborne quantum key distribution receivers (Pugh et al., 2017), and miniaturised entangled photon-pair sources for future quantum key distribution missions using nano satellites (Chandrasekara et al., 2017). Several groups (Grieve et al., 2018; Kerstel et al., 2018; Oi et al., 2017) have proposed the use of cubesats for quantum key distribution, illustrating a shift towards smaller and more affordable platforms. Recent important experimental results include quasi-single-photon transmission from a satellite to Earth (Yin et al., 2013), satellite-to-ground quantum key distribution (Liao et al., 2017), ground-to-satellite quantum teleportation (Ren et al., 2017), distribution of entanglement over a distance of 1; 200 km using a satellite (Yin et al., 2017), quantum communication using a micro-satellite (Carrasco-Casado et al., 2018; Takenaka et al., 2017), and a satellite-relayed intercontinental quantum network (Liao et al., 2018). Despite this remarkable progress, however, significant challenges remain in implementing truly global-scale quantum networks (Zhang et al., 2018).

An alternative point of view is to use distant natural photon sources as part of quantum optics experiments. Photons from causally-disconnected remote light sources were used in several recent experiments (Handsteiner et al., 2017; Rauch et al., 2018; Wu et al., 2017) to close loopholes in tests of the Bell inequality.

Cold atoms

The use of cold atoms for the detection of gravitational waves has attracted considerable interest. The topology proposed in many studies consists of two atom interferometers separated by some distance and connected by means of an optical link (Yu and Tinto, 2011). Distances between the interferometers in space are likely to present collimation problems for the reference laser that links them; a solution was proposed (Hogan and Kasevich, 2016) that uses a weak reference laser to lock a strong local oscillator at the site of each interferometer. Further investigation into the physics underlying the detection of gravitational waves by cold atoms (Norcia et al., 2017) led to proposals for further enhancements in sensitivity, analogous to the large-momentum-technique used in atom interferometry, and a method to increase the coherence time of the sensor beyond the excited state lifetime of the atom in question. The issue of selecting the appropriate atomic source in space-based gravitational wave detectors was considered in a recent review (Loriani et al., 2018).

Cold atoms in space-based platforms can also be used to measure a variety of other physical effects. The STE-QUEST (Aguilera et al., 2014) mission proposal was designed to test Einstein's equivalence principle at the level of a few parts in 10^{15} by means of Bose–Einstein condensates of two different isotopes of rubidium. The Quantum Test of the Equivalence principle and Space-Time (QTEST) (Williams et al., 2016) proposal is designed to use cold atoms aboard the International Space Station to achieve the same goal, again using two isotopes of rubidium. The GrAnd Unification and Gravity Explorer (GAUGE) (Amelino-Camelia et al., 2008) mission incorporates a number of components, including cold atom experiments to test for violations of the equivalence principle at the atomic level and decoherence of atomic matter waves caused by the quantum vacuum. It has also been proposed to use two Bose–Einstein condensates to test for the effects of gravity and motion on quantum entanglement (Bruschi et al., 2014b). Proofs of concept for the cold-atom and Bose– Einstein condensate technologies that are essential to conduct these experiments in microgravity were conducted in the drop tower of the Centre of Applied Space Technology and Microgravity (ZARM) in Bremen (Muntinga et al., 2013) and, more recently, on the MAIUS-1 sounding rocket (Becker et al., 2018).

Macroscopic matter-waves

Experiments making use of large-scale superpositions and interference of relatively large objects have attracted the attention of the community for several years. The MAcroscopic Quantum ResOnators (MAQRO) (Kaltenbaek, 2013, 2015; Kaltenbaek et al., 2012; Kaltenbaek et al., 2016; Zanoni et al., 2016) mission proposes to use macroscopic superpositions of nanospheres. The case for space, as made also in (Kaltenbaek and Aspelmeyer, 2015), stems from the expected ability of macroscopic superpositions to survive significantly longer in a microgravity environment than in an Earth-based laboratory. One goal of this mission is to understand the possible processes, not predicted in standard quantum mechanics, which could exist that cause massive superpositions to collapse spontaneously. Superpositions of massive objects may also allow to understand better the relationship between quantum mechanics and gravity, eventually revealing clues about the quantisation of gravity itself (Belenchia et al., 2018; Carlesso et al., 2017).

Massive test masses

Einstein's equivalence principle, in its weak form, postulates that the inertial and gravitational masses of an object are identical. Space-borne experiments are ideal to test this principle. The Satellite Test of the Equivalence Principle (STEP) (Sumner et al., 2007) mission proposal was designed to test this principle to one part in 10^{18} using two test masses of different composition, whose differential equations are measured by superconducting quantum interference device (SQUID) magnetometers. A second proposal, the GrAnd Unification and Gravity Explorer (GAUGE) (Amelino-Camelia et al., 2008) mission was designed to make a number of tests, including the Einstein equivalence principle, string-dilation theories, the $1/r^2$ variation of gravitational forces at intermediate ranges, mass–spin coupling, and quantum decoherence from space-time fluctuations at the Planck scale; it was designed to achieve this using a combination of test masses and atom interferometry. A further two missions making use of massive test masses are of note, both of which have flown and returned data. The first results from the MICROSCOPE mission (Touboul et al., 2017) are consistent with the equivalence principle to a few parts in 10^{15}. Tests of general relativity are also facilitated in space. Gravity Probe B, whose final results were published in 2011 (Everitt et al., 2011), returned data that are similarly consistent with the predictions of general relativity.

CONCLUSIONS

We have identified four broadly defined kinds of physical system that are used, or proposed to be used, to conduct fundamental physics experiments in space. These range from massless photons, whose use as information carriers is undisputed, through cold atoms, including very recent results that demonstrate the creation and operation of Bose–Einstein condensates in space, to macroscopic matter-wave systems, which are ideal for exploring the limits of quantum mechanics, and massive test mass systems, whose behaviour can be detected at the quantum limit to reveal more about gravitational and relativistic effects.

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