Research Campaign:
Quantum Optics in the Regime of General Relativity–
The Deep Space Quantum Link (DSQL)

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ABSTRACT

The DSQL mission will probe gravitational effects on quantum optical systems. Quantum theory and general relativity, the most successful theories describing the physical universe, have been tested in their own domains – macroscopic for relativity, and microscopic for quantum theory – but experiments conducted in a regime where both theories manifest measurable effects on photons are extremely limited. Satellite platforms enable the transmission of optical quantum states between different inertial frames and over distances impossible to emulate in the laboratory, allowing tests in new regimes.

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1. INTRODUCTION

Recently, satellite-based quantum experiments and applications have witnessed unprecedented growth spanning from fundamental physics to experimental demonstrations and technological development, including the launch and operation of the first quantum satellite, Micius,\(^1\) by the Chinese Academy of Science. These groundbreaking results have spurred an international space race\(^2\) involving university consortia, national agencies, and private companies, including QEYSat (Canada),\(^3\) SpooQy-1 (Singapore),\(^4\) and IOD-6/ROKS (UK).\(^5\) A comprehensive review on the latest status of the field can be found in Ref.\(^6\)

The maximum range over which QM was directly tested was an experiment carried out using the Micius spacecraft, which resulted in quantum optical teleportation and Bell tests across a 1200 km baseline.\(^1,7\) In particular, the experimental configuration of Micius was not designed to observe predicted relativistic impacts on quantum measurements. The orbital distance is insufficient to observe significant general relativistic effects\(^\ast\) under the Earth gravity conditions. Much larger distances, as well as stronger variation of the gravity potentials, are required to return insight on the unification of quantum mechanics and general relativity.

Quantum Field Theory in Curved Space-time (QFTCST) provides the theoretical framework to predict the interaction between gravitational and quantum mechanical systems.\(^8,9\) Some astrophysical and laboratory observations are compatible with QFTCST (e.g., the scale-invariant spectrum of cosmic microwave background radiation predicted by inflation model, the Casimir effect,\(^10\) and the circular Unruh effect\(^11\)) but they do not constitute a direct test. DSQL will provide the first direct test of QFTCST, using long-range quantum optical channels that are only possible using spacecraft.

The experiments proposed by DSQL will help bound alternative theories to QFTCST. Along these lines, the Micius spacecraft was also used to test coupling between quantum states and curved spacetime predicted by the “Event operator formalism”,\(^12\) obtaining a null-result.\(^13\) This and other alternative theories to QFTCST\(^1\), if true, would profoundly modify physics but have only been tested partially. Precise measurements of their predictions would be valuable even to provide upper bounds, or disprove, the proposed coupling mechanisms.

DSQL\(^17–20\) will explore QFTCST in the weak-field regime, using quantum optics in space. The regime where both quantum optics and general relativity manifest non-trivially is defined by the sensitivities of available instrumentation. Satellites allow access to long transmission baselines, large relative velocities, and large difference of gravitational potentials not achievable using laboratory experiments. Practically, given today’s state-of-the-art quantum optical light sources and detection systems, these effects are measurable directly across spacecraft-to-earth links.

2. PROPOSED EXPERIMENTS

DSQL experiments are built on three pillars: Tests of the Einstein equivalence principle, long-baseline Bell tests, and long-baseline teleportation. These experiments require the distribution of quantum states and their uniquely quantum correlations, i.e., entanglement, over extremely long distances. The technical tasks are challenging, but these same challenges need to be resolved to develop a global quantum network. Therefore, the technological developments required to perform the DSQL fundamental physics experiments will also pave the way for the implementation of the future quantum internet.\(^21\)

2.1 GR Effects on Light and Tests of the Equivalence Principle

The Einstein equivalence principle is at the heart of every metric theory of gravity, such as general relativity.\(^22\) One of its consequences is the Weak Equivalence Principle (WEP), according to which all test masses fall with the same acceleration in a gravitational field. A second consequence is Local Position Invariance (LPI), which requires that the outcome of any local non-gravitational experiment is independent of where and when in the universe it is performed.

\(^\ast\)Beside, of course, GPS corrections.

\(^1\)See, for example, references (14–16).
Figure 1. DSQL mission concept. a) A generic photonic-COW test. The proposed experiments will test the predicted gravitationally-induced interference effect on photonic quantum states input into an interferometer, of local arm length $\ell$ and height $h$ aligned with gravity vector $\vec{g}$, resulting in a relative phase shift (Equation 2). b) Proposed DSQL photonic COW implementation, allowing photons to travel along a single, upward trajectory; interference occurs between photons that travel the short path in the lower unbalanced interferometer and the long path in the upper interferometer and vice versa. Depending on the experiment, the transmitted quantum state can be a single photon, one member of an entangled or hyper-entangled pair of photons, or both members of a highly frequency entangled state. c) Mission configuration concept. Different regions of a highly elliptical orbit optimize sensitivity to different DSQL experiments, although each experiment will be performed across the entire orbit.

The LPI can be tested by using identical frequency standards subject to different values of the gravitational potential, where the LPI implies the redshift and the frequency variation are linked to the gravitational potential variation via the formula:

\[
\frac{\omega_2 - \omega_1}{\omega_1} = (1 + \alpha) \frac{U_2 - U_1}{c^2},
\]

where $\omega_{1(2)}$ and $U_{1(2)}$ are the frequency and gravitational potential at location 1 (2). The parameter $\alpha$ is equal to zero for general relativity. The goal of this experiment is to measure possible deviation of $\alpha$ from such a value and therefore possible violations of general relativity in the quantum optical regime.

To do so, DSQL will execute a set of experiments using the basic setup shown in Fig. 1a-b. Here, a quantum photonic state is injected into an interferometer whose upper and lower arms are subject to different gravitational potentials. As a consequence of the LPI there is a gravitationally induced relative phase shift $\phi$ between the two paths that will be imprinted on the quantum state:

\[
\phi \sim (1 + \alpha) \frac{2\pi}{\lambda} \frac{ghl}{c^2}.
\]

Here, $\lambda$ is the vacuum wavelength of the source (measured at $h = 0$), $l$ is the optical delay line (including any index of reflection), $g$ is the acceleration of gravity at altitude $h$, and $c$ is the speed of light.

Such a phase shift can be measured using the detection-event counting statistics between the two detectors. The first quantum interferometry measurement sensitive to the gravitational field was performed by Colella, Overhauser, and Werner (COW) employing neutrons. However, that experiment and more recent ones based on light-pulse atom interferometry test the WEP, but not LPI, which can be probed instead with recently proposed interferometry schemes involving atomic clock states.

Assuming a low Earth orbit platform and 1-km fiber, the magnitude of the effect is a few radians. The magnitude of the relative phase increases with the altitude, though so do the transmission losses. This trade leads to an optimization of the orbital parameters to achieve the best sensitivity to a quantum measurement given the available classical and quantum optical capabilities. We propose to conduct four versions of this experiment using DSQL: with classical light, single-photon temporal superposition states, entangled-photon pair states, and
hyper-entangled states\textsuperscript{19} (in the latter two, one member of each photon pair is transmitted to the satellite). One additional test is included, in which both photons of a highly frequency entangled state are transmitted, and detected in a generalized Hong-Ou-Mandel interferometer\textsuperscript{27} – the resulting purely quantum mechanical 2-photon interference has no classical analog and is robust to noise and asymmetric loss.\textsuperscript{19,20} Each experiment is optimized by a different spacecraft orbit. A unique feature of an elliptical satellite-orbit is the opportunity to optimize all sets of measurements across different regions of the orbital trajectory; furthermore, such orbits allow one to distinguish between general and special relativistic effects on the measured phase.\textsuperscript{19} This is a key reason elliptical orbits are proposed for a future DSQIL mission.

There are numerous challenges associated with these experiments, for example, the compensation of the first-order Doppler effect due to the relative motion of the satellite and the ground station. A technique to correct for this was recently proposed.\textsuperscript{28,29} These experiments also require stabilization of fiber coils: any mismatch in their length should be minimized in order to not compromise the phase measurement.

It is important to stress that the original COW experiment was conducted on massive particles in a regime where it can be described using Newtonian gravity. The use of photons requires the use of general relativity to describe the effects on the state of the quantum system, so this new experiment would be a genuinely simultaneous test of quantum theory and general relativity.\textsuperscript{30}

\subsection*{2.2 Long-Baseline Bell Test}

Entanglement is a uniquely quantum correlation by virtue of which joint quantum systems can be fully described only using a non-separable joint quantum state. Entangled states are at the heart of the violation of the Bell inequality implying that quantum mechanics is incompatible with all “local realistic” hidden-variable theories.\textsuperscript{31} Quantum mechanics and its most credited extension to the relativistic domain, QFTCST, predict that entanglement essentially persists at any length scale, provided the quantum system at hand is protected from its environment. Photons are excellent candidates for long-baseline tests because of their limited interaction with the environment compared to other particles.

The empirical violation of a Bell inequality is one of the biggest successes of quantum science and has been performed with increasing precision and scope, for example, by closing first the locality loophole,\textsuperscript{32} then the detection loophole,\textsuperscript{33} and finally both of these simultaneously.\textsuperscript{34–36} Currently, the longest-range Bell-inequality violation is over a distance of 1200 km, obtained by the quantum satellite Micius.\textsuperscript{33} It is fundamentally important to test the persistence of entanglement and therefore the validity of quantum mechanics and QFTCST over longer and longer baselines. Disentanglement due to some interaction with the space-time structure could in principle produce detectable traces in a Bell test. The aim of DSQIL is to conduct Bell tests over increasing distances in a series of experiments, culminating with one at the Earth-Moon distance. Besides the expected confirmation of the predictions of quantum mechanics and QFTCST, this will also allow us to assess a number of more exotic theories predicting detectable influences on entangled quantum states by the space-time features.\textsuperscript{12,14–16}

Finally, approaching the baseline length of the order of the Earth-Moon distance results in a propagation time long enough to allow for real-time human involvement in the Bell test; a similar test has been proposed recently.\textsuperscript{37} Such distances will allow for a latency of the order of a second, enabling each experimenter to make the basis decision outside of the light-cone of the created entangled photon and the other experimenter, thereby addressing the “freedom of choice” loophole.\textsuperscript{38,39} To achieve this, one could place the entangled state source in some convenient orbital mid-point between the Earth and the Moon, as proposed.\textsuperscript{19} The experimenters located near the Earth and on the Moon, possibly in the Lunar Gateway, would have sufficient time to perform the basis choice in the Bell test.

An Earth-Moon link is a good estimation of what state-of-art technology can currently achieve. This link will be subject to extreme link losses (as high as 90 dB for a one-way link). To compensate for this, an exceptionally bright, high-fidelity entangled photon source with a pair production rate of the order of $10^8$ pairs per second is required.\textsuperscript{15} This experiment could also benefit from further development in photonic quantum memories, as one photon could be stored locally and the other sent away.\textsuperscript{26} However, analysis shows that existing technological performance is sufficient to implement practical human-decision Bell tests involving astronauts on the moon.\textsuperscript{19}
2.3 Long-Baseline Teleportation

The third class of the proposed experiments are long-baseline teleportation\textsuperscript{40} and entanglement swapping.\textsuperscript{41} Teleportation is a quantum protocol with no classical analog, transmitting an unknown quantum state between two users using a maximally entangled state and classical communication channel as resources. Entanglement swapping is a modification (the particle to be teleported is itself already entangled with another particle) that can be used to distribute entanglement between distant parties with no direct quantum communication link. Here also, standard quantum theory does not predict any limitation in the range of validity of these protocols.

Teleportation was initially demonstrated about two decades ago first in the laboratory\textsuperscript{42} and soon after over long ranges outside the laboratory.\textsuperscript{43} Since then, experiments have been refined and the ranges have been pushed up to 1200 km using Micius.\textsuperscript{7} The Micius implementation was “passive”– the last operation of the protocol was performed post-selecting the data; also, the source to be teleported and the entanglement source were in fact collocated, so there was no actual benefit to communication applications using the Micius teleportation configuration. In contrast, the DSQL tests will enable active teleportation and entanglement swapping between platforms in different, moving inertial frames.

Testing these protocols at increasing distances and in the presence of general relativistic effects, like the gravitational redshift, will improve our understanding of the interplay between gravity and quantum mechanics. Besides this relevance for fundamental physics, the development of long-distance teleportation and entanglement swapping capabilities will serve as pathfinder for the deployment of a global space-based quantum network harnessing the promised power of quantum communication, distributed sensing, and computing. For example, entanglement swapping could also be used as a resource to enable multi-party quantum communication and to improve the sensitivity of networks of clocks.\textsuperscript{44}

It is important to note that efficient entanglement distribution over planetary scale cannot be achieved only by ground-based infrastructures. In fact, the unavoidable losses of fiber networks prevent the distribution of entanglement at a non-negligible rate at distances above a thousand kilometers, without incorporating a large number of currently unavailable high-efficiency, high-rate multiplexed quantum repeaters. A first remarkable milestone would thus be to achieve teleportation over a range of the order of the Earth’s diameter, followed by teleportation over a distance of the order of a geostationary orbit (because of its role in the classical telecommunication infrastructure). Finally, a teleportation experiment between the Earth and the Moon would allow a test of the scenario where the experiment events are space-like separated, i.e., their order depends on their reference frame.\textsuperscript{45} This experiment would be extremely difficult, not only due to the extreme losses, but also because of the requirement of quantum memory with a storage time of the order of the light propagation time between the Earth and the Moon ($\sim 1.3\) s), in order to complete the protocol without post-selection. Memories with such storage time are still in their infancy; however, shorter-lived memories could be used as a temporary storage to improve the entanglement distribution rate over a global quantum network.\textsuperscript{46}

3. RESEARCH CAMPAIGN CONCEPT

The experiments described in this white paper can be achieved by a staged deployment of spacecraft and ground infrastructure. Stage 1 represents an ambitious mission concept that can be executed in the next decade, while Stages 2 and 3 represent future missions to build on the success of the Stage 1 campaign.

1. **Stage 1**: Elliptical orbit with multiple ground stations
2. **Stage 2**: Spacecraft array with multiple ground stations
3. **Stage 3**: Lunar node with extremely large aperture ground station

Spacecraft occupying elliptical orbits are well suited for explorations of relativistic effects. Phase 1 of DSQL could involve a single spacecraft in such an orbit. The spacecraft would be outfitted with an optical payload consisting of: a pair of independent telescopes – one on a gimbal mount and the other fixed to the spacecraft frame – and a high-rate entangled photon pair source (for Bell tests, teleportation and entanglement-swapping experiments); a stabilized fiber optical delay line unbalanced interferometer (for COW-type tests); a high performance
single-photon detection system capable of performing quantum state measurements (for all experiments); and a reconfigurable optical switch array (to select the experiments). The flight terminal, which also includes hardware for the various experiments, requires exceptional pointing accuracy to leverage larger apertures for high efficiency links. Recent flight missions have demonstrated performance commensurate with the requirements.\textsuperscript{1, 47, 48}

The Stage 1 system would enable COW tests, tests of quantum teleportation, and a subset of the Bell tests between inertial frames. An array of ground stations, potentially located around the world, could establish quantum communication links with the spacecraft in support of the experiments described here, as well as supporting new experiments and technology demonstrations by a user community. Link analysis was used to determine optimum orbital configurations for the experiments described above.\textsuperscript{19} The COW tests involving single-photon transmission are optimized for orbital altitudes of $h = 5,000$ km, while the photon-pair experiments are optimized near $h = 600$ km. A spacecraft in a highly elliptical orbit provides line-of-sight for both cases.

JPL’s Advanced Projects Design Team (Team X) developed cost and schedule estimates for standard Phase A-D activities associated with this concept. Team X is a concurrent engineering design environment with representatives from all JPL technical disciplines. JPL line organizations create, maintain, and operate Institutional Cost Models (ICMs) within Team X, and Team X management ensures consistency between the use of ICMs and institutional guidelines. The Team X study determined that the Stage-1 system is executable with a total budget estimated at $200M. One proposed orbital profile is a highly elliptical orbit, with minimum (maximum) orbital altitudes of 600 km (6,000 km).

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Table 1. Yearly cost estimates and mission development phases (pre-ΦA-ΦD) for DSQL Stage-1.

The cost, broken down into development phases in Table 1, was estimated through analogy to the OPALS mission for the flight telescope system; a grassroots model for the ground systems; and analogy to the DSOC mission for flight operations, science and technology maturation. The assumed mission lifetime is 3 years, with no orbital maneuvers planned. The DSQL Stage-1 spacecraft, estimated at 320 kg, fits within a single ESPA volume and Falcon 9 launch vehicle. Launch costs are not included in the cost estimate in Figure 1.

Key technology development items are: 1) high clock-rate (hyper)entangled photon pair sources; 2) high clock-rate single-photon sources; 3) low dark-count rate, high timing resolution single-photon detection flight systems; 4) timing synchronization architectures for high-latency quantum networking; and 5) fiber delay line length synchronization schemes. There is considerable research already underway for all of these topics that will be leveraged in the first three years of the program. Based on the detailed mission description produced by the DSQL Science Definition Team\textsuperscript{19}, approximately 1 year of time is required to refine the mission architecture and complete the concept formulation for DSQL Stage 1.

Stage 2 adds additional spacecraft to the network, in complementary elliptical orbits with lower orbital period (greater orbital semimajor axis) than the Stage-1 spacecraft. The Stage-2 array will perform additional COW tests, Bell tests, and quantum teleportation, all across longer baselines and more varied inertial frames. One or more of the spacecraft would be located at a point suitable to support a future human-decision Bell test, either in a 9-day period orbit (roughly corresponding to a “midway between Earth and moon” configuration), or in orbit about the fourth/fifth Lagrange point of the Earth-Moon system. Stage 3 of DSQL provides the capability to perform quantum optical tests well into the regime of 2-body gravitational physics, with baselines long enough to finally perform human-decision Bell tests, requiring astronauts on or near the Moon. The simplified human-decision Bell test described in\textsuperscript{19} is the recommended approach.

The experiments supported by DSQL Stage 1 will shed new light on QFTCST, the best tool we have for describing quantum processes in the relativistic regime. The proposed experiments cannot be addressed by ground-based experiments and will require the deployment of space-based platforms. Beside the relevance for fundamental physics, these activities will spearhead the development of the first global quantum networking capabilities. DSQL Stage 1 represents a profound step forward both scientifically and technologically for NASA and the fundamental physics community.
REFERENCES


