Space-QUEST
Experiments with quantum entanglement in space

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The European Space Agency (ESA) has supported a range of studies in the field of quantum physics and quantum information science in space for several years, and consequently we have submitted the mission proposal Space-QUEST (Quantum Entanglement for Space Experiments) to the European Life and Physical Sciences in Space Program. We propose to perform space-to-ground quantum communication tests from the International Space Station (ISS). We present the proposed experiments in space as well as the design of a space based quantum communication payload.

SCIENTIFIC BACKGROUND

Quantum entanglement is, according to Erwin Schrödinger in 1935 [1], the essence of quantum physics and inspires fundamental questions about the principles of nature. By testing the entanglement of particles we are able to ask fundamental questions about realism and locality in nature [2, 3]. Local realism imposes certain constraints in statistical correlations of measurements on multi-particle systems. Quantum mechanics, however, predicts that entangled systems have much stronger than classical correlations that are independent of the distance between the particles and are not explicable with classical physics.

It is an open issue whether quantum laws, originally established to describe nature at the microscopic level of atoms, are also valid in the macroscopic domain such as long distances. Various proposals predict that quantum
entanglement is limited to certain mass and length scales [4, 5] or altered under specific gravitational circumstances [6]. Testing the quantum correlations over distances achievable with systems placed in the Earth orbit or even beyond [7] would allow to verify both the validity of quantum physics and the preservation of entanglement over distances impossible to achieve on ground.

Using the large relative velocity of two orbiting satellites, one can perform experiments on entanglement where—due to special relativity—both observers can claim that they have performed the measurement on their system prior to the measurement of the other observer. In such an experiment it is not possible anymore to think of any local realistic mechanisms that potentially influence one measurement outcome according to the other one.

Moreover, quantum mechanics is also the basis for emerging technologies of quantum information science, presently one of the most active research fields in physics. Today’s most prominent application is quantum key distribution (QKD) [8], i.e. the generation of a provably unconditionally secure key at distance, which is not possible with classical cryptography. The use of satellites allows for demonstrations of quantum communication on a global scale, a task impossible on ground with current optical fiber and photon-detector technology. Currently, quantum communication on ground is limited to the order of 100 of kilometers [9, 10]. Brining quantum communication into space is the only way to overcome this limit with state-of-the-art technology.

Another area of applications is in metrology, where quantum clock synchronization and quantum positioning [11] are studied. Furthermore, sources of quantum states in space may have applications in the new field of quantum astronomy [12].

**THE PROPOSAL**

We propose to perform these experiments in space by placing a quantum transceiver on the external pallet of the European Columbus module at the ISS. The entire terminal must not exceed the specifications given for pallet payloads as provided by ESA [13]. The requirements are: size $1.39 \times 1.17 \times 0.86$ m$^3$, mass $< 100$ kg, and a peak power consumption of $< 250$ W, respectively. A preliminary design of a satellite-based quantum transceiver (including an entangled photon source, a weak pulse laser sources, single photon detection modules together with two transceiver telescopes) based on state-of-the-art optical communication terminals and adapted to the needs of quantum communication is already published in [14].

The entangled photons are transmitted to two distant ground stations via simultaneous down-links [15], allowing a test on entanglement and the generation of an unconditional secure quantum cryptographic key between stations separated by more than 1000 km.

Additionally, such a quantum transceiver in space is capable of performing two consecutive single down-links—using the entangled or the weak pulse laser on-board the satellite—establishing two different secure keys between the satellite and each of the ground stations (say, Vienna and Tokyo). Then a logical combination of the two keys (e.g. bitwise XOR) is sent publicly to one of the two ground stations. Out of that only unconditionally secure key between the two ground stations can be computed. Using such a scheme would allow for the first demonstration of global quantum key distribution. Furthermore an uplink scenario is published in [16].

An important step towards the applicability of quantum communication on a global scale, is to extend single QKD links to a quantum network by key relaying along a chain of trusted nodes [17, 18] using satellites as well as fiber-based systems. Furthermore, the efficiency of quantum networks can be improved employing quantum percolation protocols [19].

It would be favorable to include in parallel to the QKD down-link from the ISS a high-speed communication link providing several Gigabit per second bandwidth [20, 21].

**PROOF-OF-PRINCIPLE EXPERIMENTS**

As an important step towards quantum communication protocols using satellites various proof-of-principle
demonstrations of quantum communication protocols have already been performed over terrestrial free-space links [22, 23, 24, 25]. One experiment was carried out on the Canary islands using a 144 km free-space link, between the neighboring islands La Palma and Tenerife (Spain), where ESA’s 1-meter-diameter receiver telescope, originally designed for classical laser communication with satellites, was used [26, 27] to receive single photons.

In a second experiment the Matera-Laser-Ranging-Observatory (Italy) was used to establish a single photon down-link from a low-earth orbit satellite [28]. A satellite-to-Earth quantum-channel down-link was simulated by reflecting attenuated laser pulses off the optical retroreflector on board of the satellite Ajisai, whose orbit has a perigee height of 1485 km.

An important component in space based quantum communication is a source for entangled photons, that is suitable for space applications in terms of efficiency, mass and power consumption. A source fulfilling the payload requirements based on highly efficient down-conversion crystals which deliver the necessary numbers of photon pairs is published in [29].

**TOPICAL TEAM**

In 2007 the formation of a Topical Team for supporting the Space-QUEST experiment comprised of researchers from academia actively involved in relevant scientific fields was initiated by ESA and currently consists of 27 members from 10 countries. This team will support the proposal with their individual scientific and technical expertise and also aims to increase the research community’s interaction with industry. The present programmatic roadmap of Space-QUEST is compatible with a launch date by end of 2014 [30].

**CONCLUSIONS**

We emphasize that the space environment will allow quantum physics experiments with photonic entanglement and single photon quantum states to be performed on a large, even global, scale. The Space-QUEST proposal aims to place a quantum communication transceiver containing the entangled photon source, a weak pulsed (decoy) laser source and single photon counting modules in space and will accomplish the first-ever demonstration in space of fundamental tests on quantum physics and quantum-based telecom applications. The unique features of space offer extremely long propagation paths to explore the limits of the validity of quantum physics’s principles. In particular, this system will allow for a test of quantum entanglement over a distance exceeding 1000 km, which is impossible on ground.

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