Entangled Photons in Larger Real and Hilbert Spaces

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Abstract: These experiments are reported: quantum teleportation with feed-forward between Canary Islands, loophole-free Schrödinger steering, entanglement of 300 units angular momentum, entanglement in a 100-dimensional Hilbert space, and closing the fair-sampling loophole for photons.
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Experiments with entangled photons have now reached a high level of maturity. Some recent experiments involved technologies in real-world scenarios. Also, novel experiments in higher dimensional Hilbert spaces became possible.

In a recent experiment, long-distance quantum teleportation between the Canary Islands of La Palma and Tenerife was realized over a distance of 143 km (Fig. 1) [1]. This experiment also implemented active feed-forward of two different Bell states. The fidelity of the teleported states was always above the classical limit of 2/3. The feasibility of future entanglement swapping experiments over such distances will also be discussed.

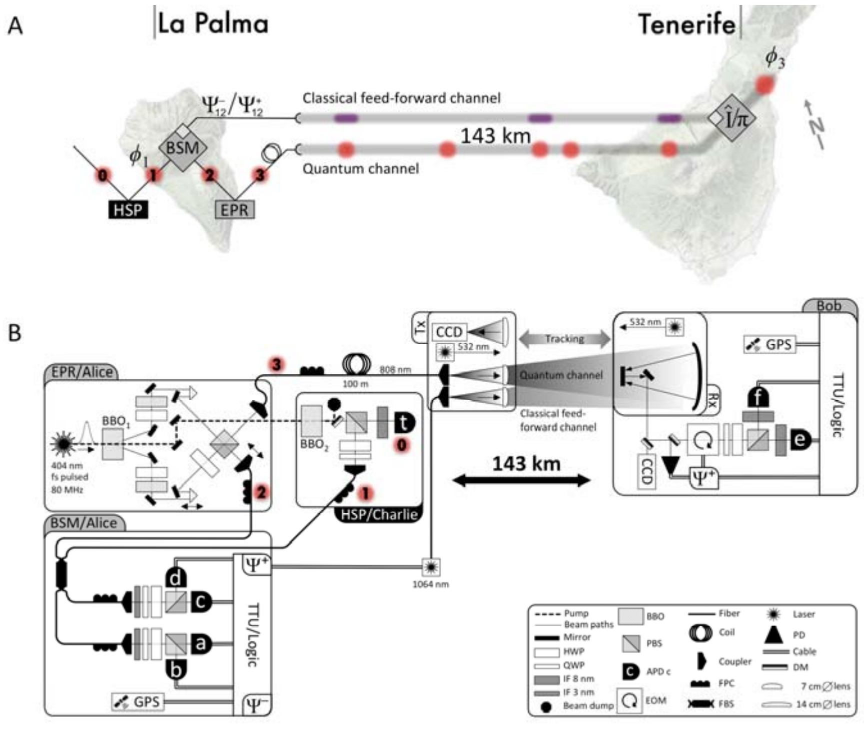

Figure 1. Quantum teleportation between the Canary Islands of La Palma and Tenerife. The two islands are linked both by the quantum channel and the classical feed-forward channel (A). The teleported state is φ_1. Both Ψ^+ state and Ψ^- state are identified at a Bell state analyzer. The result is fed forward over to Tenerife, where either the identity operation or the π phase shift is applied to the state of photon 3. Then, φ_3 represents the original state φ_1 within experimental inaccuracies. The details of the experiment are shown in B. Pairs of photons 0 and 1 are created in BBO_2. One of them is the trigger, the other one the teleported state. Of the pair created in BBO_1, photon 2 enters the Bell state measurement device of Alice and photon 3 propagates over to the island of Tenerife. In the parallel classical feed-forward channel, the result of the Bell state measurement is also signaled to Bob, who applies the appropriate unitary operation [1].

In experiments testing Bell's inequality, the issue of addressing loopholes is very important to finally close any possibility for local realism. While all major loopholes have been closed in individual experiments, a separate experiment which closes all loopholes at the same time is still an open challenge. Interestingly, quantum steering as proposed by Schrödinger implies the possibility of having a loophole-free experiment without the necessity of violating a Bell inequality. The basic idea is that, summing up the correlations in three mutually unbiased bases, entangled states violate a limit for product states. In a recent experiment [2], it was possible to violate the steering limit in a setting where all major loopholes, namely the locality loophole, the freedom of choice loophole and the fair sampling loophole, have been closed at the same time. While the experiment does not rule out all local hidden variable theories, it is a rather convincing confirmation of the nonlocal features of quantum entanglement without going outside standard theory.

An interesting challenge of current experiments is to extend the experiments to higher and higher quantum numbers and larger system etc., thus, as some would say, exploring the quantum-classical boundary or, perhaps better, demonstrating that there is no such boundary and that it is only a question of the skill of the experimentalist for how large the complex systems are where such phenomena can be shown. One of the possibilities is to go to very high quantum numbers. Recently, an experiment was realized that demonstrated the entanglement of very high angular momentum. Using orbital angular momentum states (OAM) of photons, an entangled state between two photons was produced where a state of +300 ħ angular momentum and one of -300 ħ angular momentum were entangled. Thus, the difference between quantum numbers was 600 in that experiment [3]. This was achieved by transforming polarization entanglement into OAM entanglement using spatial light modulators. The identification of the quantum states was done using slotted masks (Fig. 2). It is expected that there is no principal limit in angular momentum difference whatsoever. Evidently, the experiment becomes more and more challenging for larger OAMs, because of the necessary spatial resolution and size of the modes.

In a most recent experiment [Mario Krenn et al., unpublished], entanglement was introduced where each photon enjoys a 100-dimensional Hilbert space. Thus, the total space had 100x100 dimensions. Such an experiment might open up the possibility for more security in quantum communication.

Finally, in an experiment with entangled photon pairs [4], the fair sampling loophole for photons was finally closed. In the experiment, TES superconducting photon detectors were used with a total photon collection efficiency of well above 70%. This allowed a statistically significant violation of an Eberhard-type Bell inequality. Further possible extensions to close all loopholes in a single experiment will be discussed.

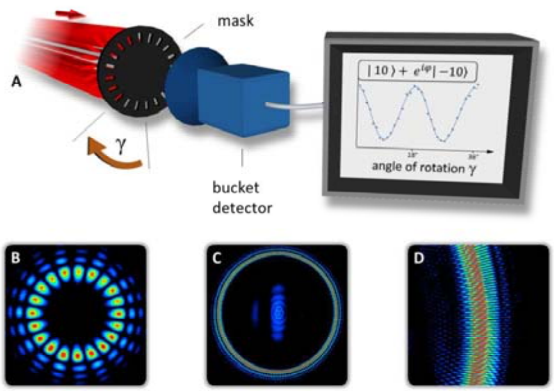

Figure 2. Measurement of the entanglement of high orbital angular momentum (A). The specific OAM state is identified using a rotated slit wheel which has 2n slits to identify a superposition of +n and –n angular momentum. A superposition is then seen as a sinusoidal variation (insert) of the transmitted intensity. B, C and D show the experimentally produced superpositions of that kind for n=±10, n=±100 and n=±300 respectively. To identify entanglement, correlations between two such setups, one for each photon, are employed [3].

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