FUNDAMENTAL QUANTUM OPTICS EXPERIMENTS IN SPACE AND LAB

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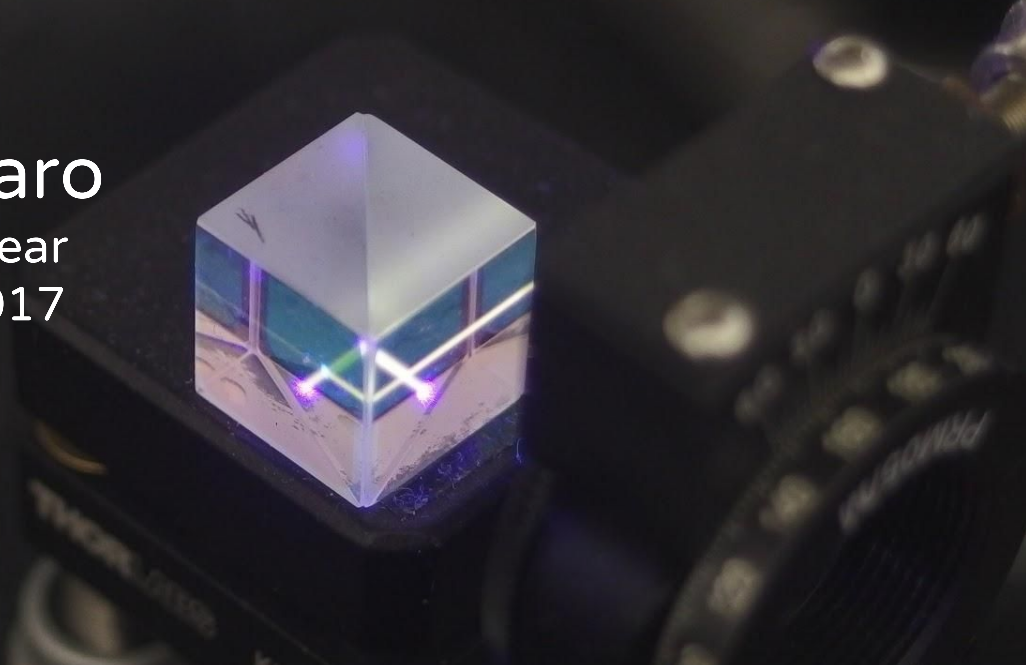
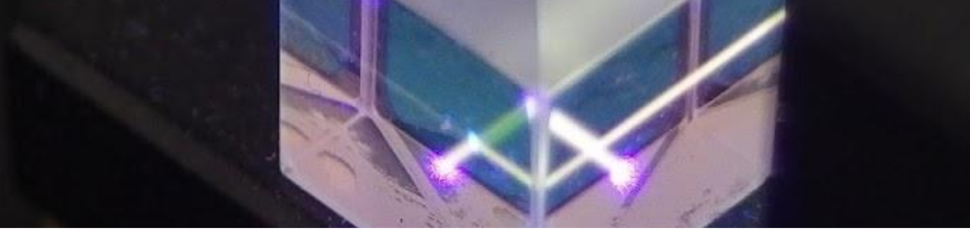
Admission to III year

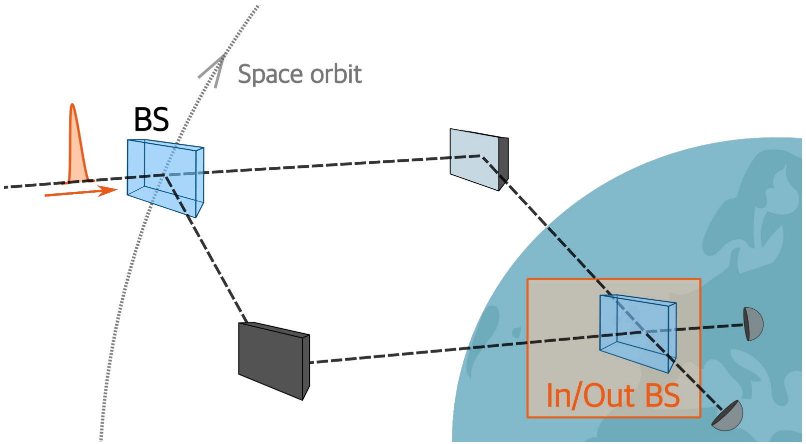
22 September 2017



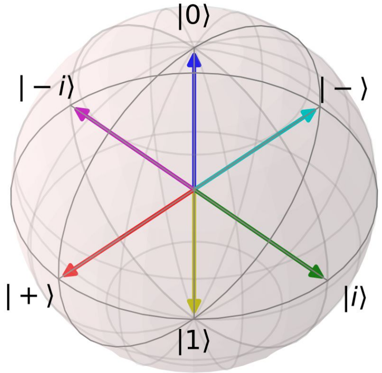
II year experiments



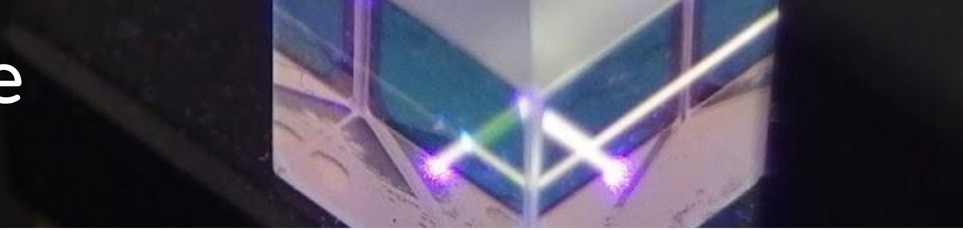
Extension of the Wheeler's delayed choice experiment in space



Direct Measurements of quantum states



Wheeler’s delayed choice experiment in space

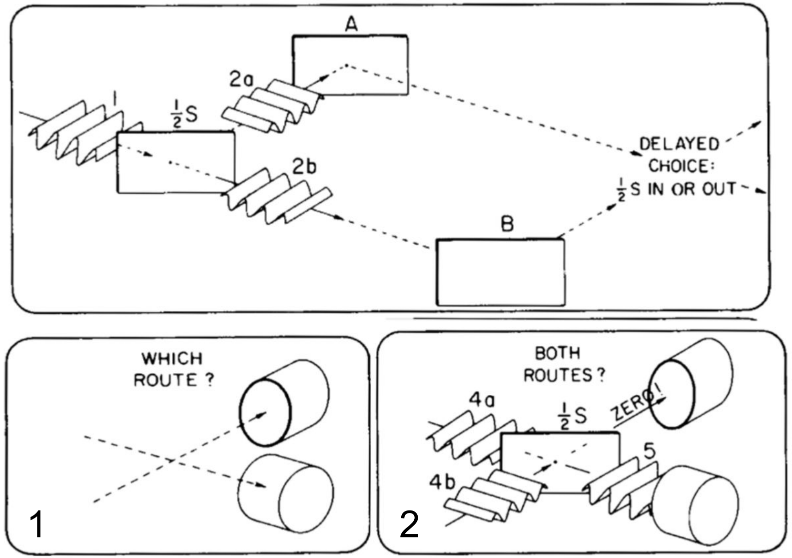


Goal
The goal is to test the wave-particle duality of the photons. There is no classical theory where a particle behaves like a wave and where a wave behaves like a particle. The property of being both a wave and a particle is explainable only in the framework of a quantum theory.

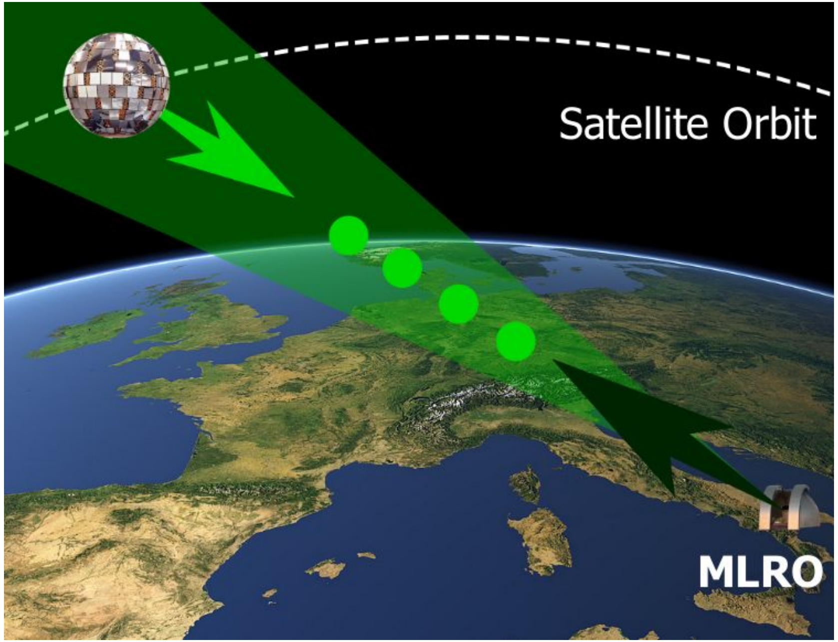
Test

- In setup 1, the photon behaves like particles: the two detectors can click with same probability.
- In setup 2, the photon behaves like wave: only one detector clicks (interference).

Once the photon has entered the interferometer, the experimenter decides randomly if using setup A or B.



Wheeler's delayed choice experiment in space



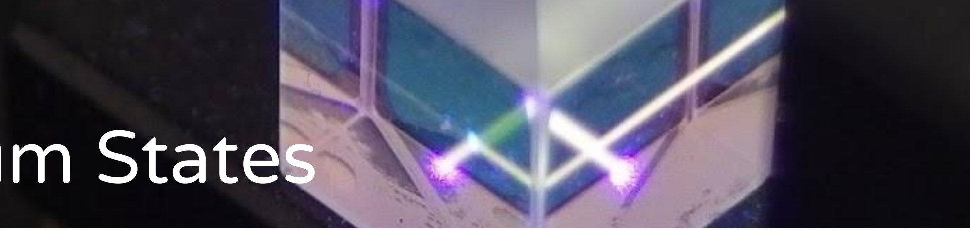
We extended this test on the space scale [F. Vedovato et al., arXiv:1704.01911v1].

Goals

- Test whether the wave-particle duality survive to large distance scales
- Pave the way for the realization of fundamental tests of quantum mechanics on the space scale.

See Francesco's slides for the experimental implementation and the results.

Measurement of Quantum States



A general quantum state is mathematically represented by a matrix (*density matrix*).

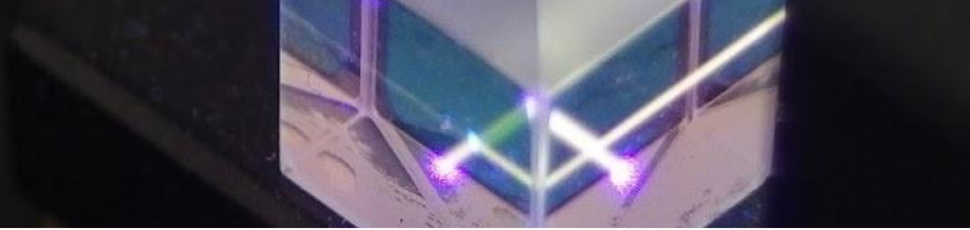
How do we measure the state of a quantum particle?
Since any interaction with a quantum particle changes or destroy its state and since a single measurement on the particle retrieves only partial information on its state, we need a set of different measurements performed on many identical copies of the particle. The state is then reconstructed from the outcomes of the measurements through an algebraic relationship. This technique is called *quantum state tomography* (QST).

For a two dimensional system: $\rho = \frac{1}{2}\left(1 + x\sigma_x + y\sigma_y + z\sigma_z\right),\ x^2 + y^2 + z^2 \leq 1$

The set of measurements is: $\sigma_x, \sigma_y, \sigma_z \qquad x = \mathrm{Tr}(\sigma_x \rho)$

Drawback of QST:
The set of measurements increase exponentially with the dimension of the quantum state. For large systems it becomes impractical.

Direct measurement of Quantum States



However one can be interested in only some elements of the density matrix. But QST does not provide access to single elements of the density matrix.

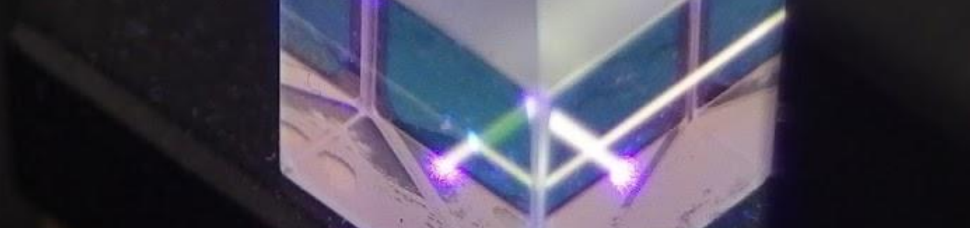
Recently, a new technique have been proposed to provide *direct* access to the quantum state of a particle: the outcome of the measurements is proportional to the element of the density matrix [G.S. Thekkadath, “Direct measurement of the density matrix of a quantum system”, PRL 117, 120401 (2016)].

Advantages of direct measurement over QST:

- Access to single elements of the density matrix
- No need of a global reconstruction

This technique promises to be useful for large dimensional states.

Direct measurement of Quantum States



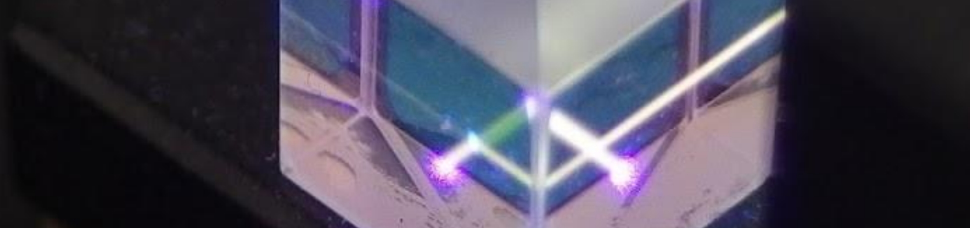
Lundeen's protocol

The element *(i,j)* of the density matrix is given by $\rho_{i,j} = d \cdot \mathrm{Tr}\left(\Pi_{i,j}\rho\right)$ where:

- $\Pi_{i,j} = \Pi_i \Pi_{b_0} \Pi_j$ is the product of three projectors
- $\Pi_i = |i\rangle \langle i|$
- $|b_0\rangle = \frac{1}{\sqrt{d}} \sum_{k=1}^{d} |k\rangle$

If $\Pi_{i,j}$ were an hermitian operator then there would be a measurement whose result is $\mathrm{Tr}\left(\Pi_{i,j}\rho\right)$. This would be a direct measurement of the element $\rho_{i,j}$. However this is not the case since the projectors do not commute with each other.

Publications



<u>Publications and pre-prints</u>:

- ➢ Matteo Schiavon, Luca Calderaro, Mirko Pittaluga, Giuseppe Vallone and Paolo Villoresi, "Three-observer Bell inequality violation on a two-qubit entangled state", Quantum Science and Technology (2017).
- ➢ Francesco Vedovato, Costantino Agnesi, Matteo Schiavon, Daniele Dequal, Luca Calderaro, Marco Tomasin, Davide Giacomo Marangon, Andrea Stanco, Vincenza Luceri, Giuseppe Bianco, Giuseppe Vallone, Paolo Villoresi, "Extending Wheeler's delayed-choice experiment to Space", (arXiv:1704.01911).

<u>Conferences</u>:

- **Contributed talk** “Three-observer Bell inequality violation on a two-qubit entangled state” at Scientific School Architectures for Quantum Photonics Circuits, February 2017, Nice, France.
- **Poster** “Three-observer Bell inequality violation on a two-qubit entangled state” Italian Quantum Information Science Conference, September 2017, Florence, Italy.