Satellite Realization of Wheeler's Delayed-Choice Thought Experiment

Costantino Agnesi,[1,*] Francesco Vedovato,[1,†] Matteo Schiavon,[1] Daniele Dequal,[1,2] Luca Calderaro,[1] Marco Tomasin,[1] Davide Marangon,[1] Andrea Stanco,[1] Vincenza Luceri,[3] Giuseppe Bianco,[2] Giuseppe Vallone,[1] and Paolo Villoresi[1]

[1] *Dipartimento di Ingegneria dell'Informazione, Università degli Studi di Padova, Padova, Italy*
[2] *Matera Laser Ranging Observatory, Agenzia Spaziale Italiana, Matera, Italy*
[3] *e-GEOS spa, Matera, Italy*

Since the dawn of quantum mechanics, Gedankenexperiment have been conceived to inspect its counterintuitive principles. One of the most "disturbing" of these principles is the *wave-particle duality* [1]. John Wheeler proposed his delayed-choice thought experiment to test the validity of the dual description of photons and to highlight the naive and contradictory interpretation given by classical physics which leads to a "strange inversion of the normal order of time" [2]. In his idea, by changing the configuration of a two-path interferometer after the photon has entered the setup, one can either investigate the particle-like nature of the photon by recovering which-path information, or its wave-like behavior by observing interference.

Motivated by the need of testing quantum mechanics in new scenarios, we implemented the delayed-choice experiment along a satellite-ground interferometer which extends for thousands of kilometers in Space [3] allowing us to probe the laws of nature at this unprecedented scale.

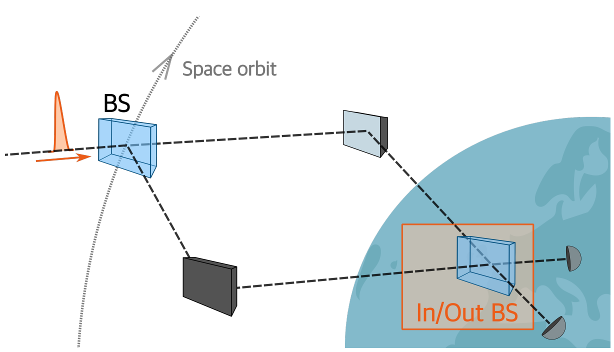

FIG. 1. *Pictorial representation of Wheeler's delayed choice experiment in Space.*

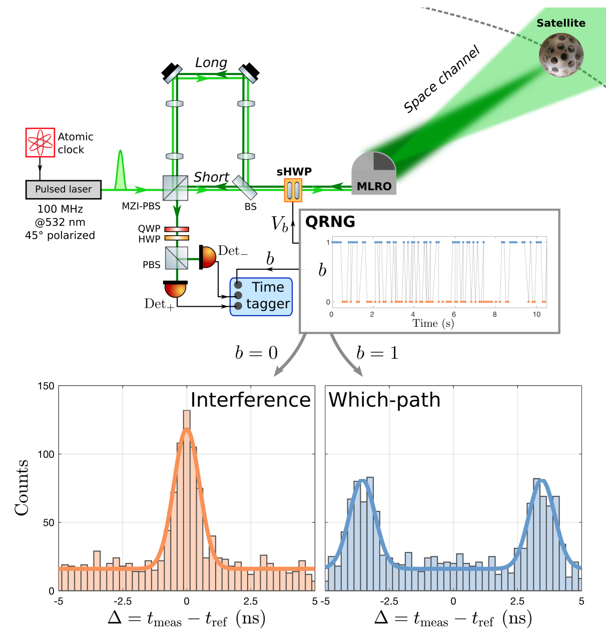

FIG. 2. *Scheme of the experimental setup and detection histograms.*

We exploit temporal and polarization degrees of freedom of photons reflected by a fast moving satellite equipped with retro-reflecting mirrors. By introducing a kinematic phase that modulates the interference pattern, the satellite has an active role in the experiment [4]. As required for a faithful realization of the delayed-choice experiment, our setup was designed to guarantee that the choice of the measurement apparatus, performed by a Quantum Random Number Generator, is space-like separated from the photon reflection at the satellite. By observing single-photon interference and recovering which-path information after the propagation along an up to 3500 km Space channel, we can confute the description of light quanta as classical particles with clear statistical evidence.

Our results extend the validity of the quantum complementarity to the scale of Low Earth Or-

* costantino.agnesi@phd.unipd.it
† francesco.vedovato@phd.unipd.it

bits, paving the way for novel applications of quantum information processing in Space links involving multiple photon degrees of freedom. Furthermore, they attest the feasibility of efficient encoding via both polarization and time-bin for high-dimensional free-space quantum key distribution over long distances. Finally, our experiment is a workbench for the development of new quantum technologies and techniques that enable the ability of propagating and controlling quantum phenomena over increasingly larger distances.

[1] N. Bohr, *The Quantum Postulate and the Recent Development of Atomic Theory*, Nature **121**, 580-590 (1928)

[2] J. A. Wheeler, *The "Past" and the "Delayed-Choice" Double-Slit Experiment*, in *Mathematical Foundations of Quantum Theory*, edited by A. R. Marlow (Academic Press, New York, 1978), pp. 9–48

[3] F. Vedovato et al., *Extending Wheeler's delayed-choice experiment to Space*, arXiv:1704.01911

[4] G. Vallone et al., *Interference at the Single Photon Level Along Satellite-Ground Channels*, Phys. Rev. Lett. **116**, 253601 (2016).