Indefinite Causal Order Advantage for Noisy Metrology

Melvee George[1,2], William Gunn[1,2], Jaden McKinlay[1,2], Aaron Z. Goldberg[3,4], Khabat Heshami[3,4], Laura Serino[1], Markus Rambach[1,2], Luis L. Sánchez-Soto[5,6], Andrew G. White[1,2]

[1] Centre for Engineered Quantum Systems & [2] University of Queensland, Brisbane, Australia

[3] National Research Council of Canada &[4] University of Ottawa, Ottawa, Canada

[5] Max-Planck-Institut für die Physik des Lichts, Erlangen, Germany

[6]Universidad Complutense, Madrid, Spain

Quantum physics allows for nonclassical causal structures where the order of events is indefinite. Events in such processes are said to have an indefinite causal order (ICO) [1]. ICO provide a significant advantage in quantum metrology by increasing the precision in parameter estimation protocol—even in the presence of noise [2,3]. Here we experimentally demonstrate that using indefinite causal order to probe noisy channels and a to-be-measured channel can withstand arbitrarily more noise than any quantum system with definite causal order, even if the probe is fully mixed and one of the noisy channels erases all information [3]. We investigate indefinite causal order advantages in quantum metrology by making use of polarisation and spatial degree of freedom of single photons. The experimental setup is shown in figure 1. A maximally mixed probe—the target, implemented with the transverse spatial mode of the beam—is sent through a quantum switch which is realised in a Sagnac configuration.

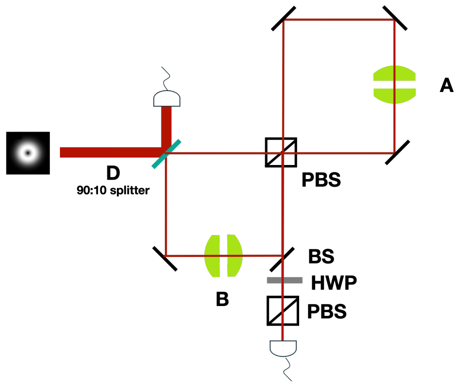

Fig. 1: ***Schematic of the experimental setup***. *The target and control state of the quantum switch is the transverse spatial mode and the polarisation of the photon respectively. A is the mixing channel implemented by continous rotation of a pair of cylindrical lenses and B is the unitary operation. HWP: Half wave plate, PBS: Polarising beam splitter, SPAD: Single photon avalanche diode.*

Funding acknowledgement

This research was partially funded by the Australian Government through the Australian Research Council Centre of Excellence for Engineered Quantum Systems (EQUS, CE170100009). Also, AGW is the recipient of an Australian Research Council Laureate Fellowship (FL210100045) funded by the Australian Government.

References

1. K. Goswami, C. Giarmatzi, M. Kewming, F. Costa, C. Branciard, J. Romero, and A. G. White, *Physical Review Letters* **121**, 090503 (2018).
2. K. Goswami, Y. Cao, G. A. Paz-Silva, J. Romero, and A. G. White, *Physical Review Research* **2**, 033292 (2020).
3. A. Z. Goldberg, K. Heshami, and L. Sánchez-Soto, *Physical Review Research* **5** 033198 (2023).