Quantum steering with vector vortex states with the detection loophole closed

Farzad Ghafari [a], Dominick Joch [a], Sergei Slussarenko [a], Nora Tischler [a], Lynden K. Shalm [b], Varun B. Verma [b], Sae Woo Nam [b], and Geoff J. Pryde [a]

[a] *Centre for Quantum Dynamics and Centre for Quantum Computation and Communication Technology, Griffith University, Brisbane, Queensland 4111, Australia.*

[b] *National Institute of Standards and Technology, 325 Broadway, Boulder, Colorado 80305, USA.*

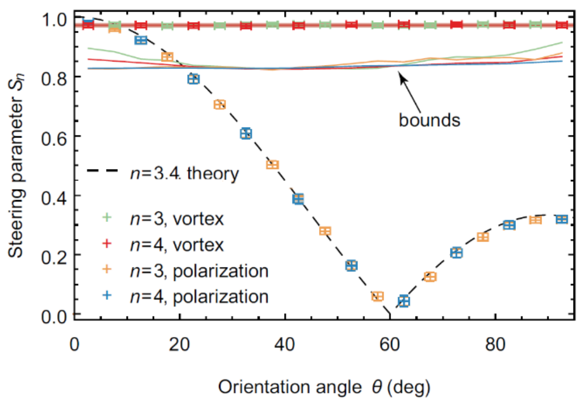
Quantum nonlocality is a resource that enables secure quantum information tasks, such as device-independent-type (DI-type) quantum communications and certified randomness. Steering (or Einstein-Podolsky-Rosen) nonlocality is a scenario where one party is in a secure location and another remote party is not [1], and is particularly useful for one-sided device-independent protocols. To minimize the reliance on assumptions that may not hold or may permit eavesdroppers to spoof nonlocality, rigorous nonlocality verification is required, which needs closing several loopholes. Strong loophole-free nonlocality has been demonstrated with photons entangled in polarization; however, it has not been shown using other photonic degrees of freedom. Physical encodings other than polarization can provide unique advantages such as better noise tolerance, access to qudits, or, as in our case, rotational invariance. Here [2], we show detection-loophole-free quantum steering, using a vector vortex state encoding for one qubit, formed by a combination of orbital angular momentum and polarization.

The detection loophole is the most challenging to close experimentally; it simultaneously requires high photon transmission and detection efficiencies to rule out the statistics being corrupted by cheating strategies concealed as loss [3]. Most methods to encode information in other degrees of freedom besides polarization are limited in state quality and efficiency, hence the loophole has not been closed with other photonic degrees of freedom. To overcome this challenge, we achieve a total throughput and detection efficiency of ~0.39-0.48 in conversion to vortex states, transmission, and analysis, allowing us to close the detection loophole in a steering test. Our measured steering parameter shows a violation of the inequality at the level of 15 standard deviations on average. Finally, we observe that encoding in a vortex state, which is predicted to be invariant to rotations of the observer around the transmission axis, allows for violations of a steering inequality over the whole rotation range (see figure), while a rotation-sensitive polarization encoding quickly fails, as expected. This represents a key step in the ability to apply physical encodings, beyond conventional polarization qubits, to demanding DI-type protocols.

[1] Branciard, C., et al., *Phys. Rev. A* **85**, 010301(2012).

[2] S. Slussarenko, et al., *npj Quantum Information* **8**, 1, p 1-6 (2022).

[3] Bennet, A. J. et al., *Phys. Rev. X* **2**, 031003 (2012)



Quantum steering versus the orientation angle. Dots are the experimental data, and the lines with corresponding colours represent steering bounds taking into account the number of measurement settings, *n*, and detection efficiency.