Hance, J. R., & Rarity, J. G. (2022). *Exchange-Free Polarimetry of a Polarising Object*. Abstract from Optica Optical Sensors and Sensing Congress, Vancouver, British Columbia, Canada.

Exchange-Free Polarimetry of a Polarising Object

Jonte R. Hance, John Rarity
Quantum Engineering Technology Laboratories, Department of Electrical and Electronic Engineering,
University of Bristol, Woodland Road, Bristol, BS8 1US, UK
jonte.hance@bristol.ac.uk

Abstract: We extend exchange-free imaging to polarimetry of a polarising object. This allows imaging of these samples with far less absorbed energy - a key concern when imaging with high-frequency radiation.

Interaction-free detection involves using single-particle interferometry to detect whether or not there is a block on the arm of an interferometer the particle didn't travel down. Elitzur and Vaidman initially described this phenomenon in their famous 'bomb detector thought experiment', where there is a chance to see whether a potentially faulty bomb works without detonating it [1]. Kwiat et al then refined this using the Quantum Zeno effect, to reduce the chance of the particle going down the arm with the blocker (or bomb) to effectively zero [2]. However, while this phenomena has been developed to great effect for both classical [3–6] and quantum [7–9] communication, so far interaction-free measurement has only been deployed to image the presence/absence (or opacity/transparency) of an object [10–18]. In this paper, we extend this powerful tool to the detection of polarising effects in a given sample. We do this while still maintaining the key benefits of the exchange-free/quantum Zeno coupled approach - low photon flux/energy absorption by the object being imaged.

To achieve exchange-free polarimetry, we start with an apparatus similar to that used to counterfactually ghost image objects in [14], but arranged both to allow the probing of an object with different polarisations of light, and for the intensified charge-coupled device (ICCD) cameras to receive the photon from the counterfactual protocol directly, with what was the ghost-path in [14] now being used for polarisation-based heralding. We give an apparatus for this in Fig.1.

In this protocol, we use a polarisation and position-momentum entangled pair of photons, sending one photon to our chained common-path Michelson interferometer array (the imaging photon), with the object to be imaged in one path, while sending the other photon goes to our variable polarising beamsplitter (PBS) (the heralding photon), where we can choose a polarisation basis to image the object in. On exiting the 1:1 beamsplitter, the imaging photon enters a common-path version of Salih et al's 2013 protocol [3], designed to maintain pixel coherence. The two outputs corresponding to the photon being blocked or not blocked by the object (D_0 and D_1, following the nomenclature in [4]), then have variable polarisers placed in front of them, to allow a detection polarisation to be chosen (H, V, D, A, R or L).

The variable-PBS (heralding) arm uses a quarter wave, then half-wave, then another quarter wave plate to rotate the photon from the imaging basis (either H/V, D/A or R/L) into the H/V basis, then using a normal PBS. We then record the correlations between either of the two ICCD and either of the two polarisation-basis detectors (DX and DY). By building up correlation-based images of the object in each of the three mutually unbiased bases (MUBs) which exist for polarisation (e.g. H/V, D/A, L/R), we can slowly build up polarisation statistics for the object - allowing us to derive the Mueller matrices for each of the pixel-regions of the object.

In this paper, we gave an extension of counterfactual imaging to imaging of polarising objects. This allows far better imaging of these samples than is currently available, with far less absorbed energy - a key concern for delicate samples being imaged with high-frequency radiation.

Acknowledgements This work was supported by the University of York's EPSRC DTP grant EP/R513386/1, the EPSRC Quantum Communications Hub (funded by the EPSRC grant EP/M013472/1), and QuantIC - The UK Quantum Technology Hub in Quantum Imaging (funded by the EPSRC grant EP/T00097X/1).

References

1. A. C. Elitzur and L. Vaidman, "Quantum mechanical interaction-free measurements," Found. Phys. **23**, 987–997 (1993).
2. P. Kwiat, H. Weinfurter, T. Herzog, A. Zeilinger, and M. A. Kasevich, "Interaction-free measurement," Phys. Rev. Lett. **74**, 4763–4766 (1995).
3. H. Salih, Z.-H. Li, M. Al-Amri, and M. S. Zubairy, "Protocol for direct counterfactual quantum communication," Phys. Rev. Lett. **110**, 170502 (2013).

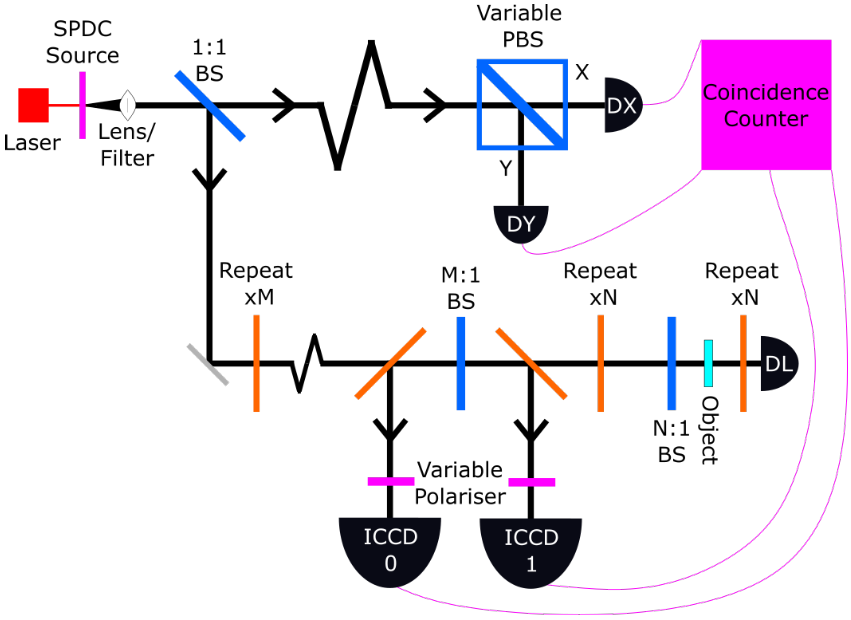

Fig. 1. Protocol for using an entangled photon pair to image a transparent, potentially polarised object, using interaction free measurement and the quantum Zeno effect to reduce photon flux on (and so energy absorbed by) the object. The variable polarising beamsplitter (PBS) allows us to pick a polarisation basis to image in (e.g. H/V, D/A, R/L), by using half-wave plates to rotate from that basis into the H/V basis, then applying a standard H/V polarising beamsplitter. As the number of interferometer runs N (inner) and M (outer) goes to infinity, the probability of the photon interacting with the transparent object goes to 0.

4. H. Salih, W. McCutcheon, J. R. Hance, and J. Rarity, “Do the laws of physics prohibit counterfactual communication?” arXiv preprint arXiv:1806.01257 (2018).
5. J. Hance, W. McCutcheon, P. Yard, and J. Rarity, “Modal, truly counterfactual communication with on-chip demonstration proposal,” in *Quantum Information and Measurement (QIM) V: Quantum Technologies,* (Optical Society of America, 2019), p. T5A.50.
6. J. R. Hance, J. Ladyman, and J. Rarity, “How quantum is quantum counterfactual communication?” Found. Phys. **51**, 12 (2021).
7. H. Salih, “Protocol for counterfactually transporting an unknown qubit,” Front. Phys. **3**, 94 (2016).
8. H. Salih, J. R. Hance, W. McCutcheon, T. Rudolph, and J. Rarity, “Exchange-free computation on an unknown qubit at a distance,” New J. Phys. **23**, 013004 (2021).
9. H. Salih, J. R. Hance, W. McCutcheon, T. Rudolph, and J. Rarity, “Deterministic teleportation and universal computation without particle exchange,” arXiv preprint arXiv:2009.05564 (2020).
10. A. G. White, J. R. Mitchell, O. Nairz, and P. G. Kwiat, ““interaction-free” imaging,” Phys. Rev. A **58**, 605–613 (1998).
11. J.-P. Wolf and Y. Silberberg, “Spooky spectroscopy,” Nat. Photonics **10**, 77–79 (2016).
12. Y. Zhang, A. Sit, F. Bouchard, H. Larocque, F. Grenapin, E. Cohen, A. C. Elitzur, J. L. Harden, R. W. Boyd, and E. Karimi, “Interaction-free ghost-imaging of structured objects,” Opt. Express **27**, 2212–2224 (2019).
13. Y. Chen, Y.-J. Cai, X.-T. Li, K. Huang, J.-M. Liu, and E. Wu, “Interaction-free quantum spectroscopy,” Adv. Photonics Res. p. 2000206 (2021).
14. J. R. Hance and J. Rarity, “Counterfactual ghost imaging,” npj Quantum Inf. **7**, 1–7 (2021).
15. J. R. Hance and J. Rarity, “Ghost imaging counterfactually,” in *Conference on Lasers and Electro-Optics,* (Optical Society of America, 2021), p. JTu3A.14.
16. J. R. Hance and J. Rarity, “Ghost imaging exchange-free,” in *2021 Conference on Lasers and Electro-Optics Europe European Quantum Electronics Conference (CLEO/Europe-EQEC),* (2021), pp. 1–1.
17. J. R. Hance and J. Rarity, “Ghost imaging counterfactually,” in *Frontiers in Optics + Laser Science 2021,* (Optical Society of America, 2021), p. FM5C.2.
18. J. R. Hance and J. Rarity, “Exchange-free ghost imaging,” in *OSA Optical Sensors and Sensing Congress 2021 (AIS, FTS, HISE, SENSORS, ES),* (Optical Society of America, 2021), p. SW5F.5.