Time-resolved double-slit interference pattern measurement with entangled photons

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The double-slit experiment strikingly demonstrates the wave-particle duality of quantum objects. In this famous experiment, particles pass one-by-one through a pair of slits and are detected on a distant screen. A distinct wave-like pattern emerges after many discrete particle impacts as if each particle is passing through both slits and interfering with itself. Here we present a temporally- and spatially-resolved measurement of the double-slit interference pattern using single photons. We send single photons through a birefringent double-slit apparatus and use a linear array of single-photon detectors to observe the developing interference pattern. The analysis of the buildup allows us to compare quantum mechanics and the corpuscular model, which aims to explain the mystery of single-particle interference. Finally, we send one photon from an entangled pair through our double-slit setup and show the dependence of the resulting interference pattern on the twin photon’s measured state. Our results provide new insight into the dynamics of the buildup process in the double-slit experiment, and can be used as a valuable resource in quantum information applications.

While the double-slit experiment can be used to demonstrate the wave-like nature of quantum particles with mass, it can also be used to show the particle-like nature of light. Double-slit experiments with photons have been carried out using relatively slow exposing charge-coupled device (CCD) cameras1–3 and by scanning a single-photon detector through a detection plane4, which cannot simultaneously record full spatial and temporal information. In our setup, we use an array of 32 single-photon avalanche diodes (SPAD)5,6 as a detection “screen” for our double-slit setup. Using this SPAD array in our interference setup, we are able to observe the buildup of the double-slit interference pattern with high resolution in both space and time.

Our experimental setup, shown in Fig. 1, uses photon pairs generated at 842 nm and 776 nm via the nonlinear process of spontaneous parametric downconversion (SPDC)7. The 776 nm photon acts as a trigger to herald the presence of the 842 nm photon8. The 842 nm photon is coupled into a single-mode fibre, and a polarization controller prepares the state in an equal superposition of horizontal (H) and vertical (V) polarizations. This is then outcoupled, resulting in a free-space Gaussian spatial mode with a waist of 1.3 mm. This beam is collimated and sent to a polarization-based double slit composed of a calcite beam displacer. The birefringence of this crystal results in the displacement of horizontally polarized photons by 3.68 mm with respect to the vertically polarized photons. The beam displacer maps the polarization state of a photon into a spatial state, which is encoded in its path. These two paths are analogous to a double-slit apparatus. They are orthogonally polarized and thus carry distinguishing information, which is erased by a polarizer set at 45 degrees. A compensating crystal (CC) is placed after the beam displacer to make the two path lengths equal, and a series of lenses maps the interference pattern onto the SPAD array.

Each of the 32 detectors in the SPAD array records the arrival time of single photons with a timing uncertainty of about 150 ps, which is the combined timing jitter of the detectors and time tagging logic. Fig. 2(a) shows the arrival times of the first 200 detection events passing through the slits. The accumulation of these events results in an interference pattern, as shown in Fig. 2(b–d). After the detection of 2000 photons, the interference pattern becomes very clear, with a visibility of 93(2)%. This visibility is not perfect as a result of inexact compensation of
obtain its detection probability distribution, which is dependent on the number of detected photons. In contrast, the quantum mechanical distribution has no such dependence. Next, we calculate how likely it is that our experimental data emerges from these probability distributions and compare them using the likelihood ratio, $\Lambda$. As long as $\log \Lambda > 0$, we can say that quantum mechanics is better than the corpuscular model. Since $\log \Lambda \approx 0.83$ for all points in Fig. 3(b), we conclude that quantum mechanics is a better indicator of the behaviour seen in nature.

In a second experiment, we use our setup with a Sagnac-type source to generate polarization-entangled photons in the state $|\psi\rangle = \frac{1}{\sqrt{2}} (|VH\rangle_{i\#} + |HV\rangle_{i\#})$ with fidelity 0.94. Here $s$, $i$ represent the signal and idler photons. The orthogonal polarization states of the 842 nm signal photon, $|H\rangle$ and $|V\rangle$, are transformed into the spatial states $|\uparrow\rangle$ and $|\downarrow\rangle$ by the calcite crystal. These refer to the two possible paths through the beam displacer. The resulting entangled state is $|\psi\rangle = \frac{1}{\sqrt{2}} (|V\rangle_{i\#} + |H\rangle_{i\#})$. The 776 nm idler photon is sent to a polarization analyzer, which consists of waveplates, a polarizing beamsplitter and two detectors (see Fig. 1). The orientation of the HWP is set such that detection by D1 and D2 correspond to projection on $(|H\rangle + |V\rangle)/\sqrt{2}$ and $(|H\rangle - |V\rangle)/\sqrt{2}$, respectively.

After taking data for 60 s, we filter the detection events by choosing detections at either D1 or D2 as the trigger. If we choose D1 as the trigger, we herald the state $(|\uparrow\rangle + |\downarrow\rangle)/\sqrt{2}$, which leads to the interference fringes shown in Fig. 4(a). Similarly, triggering by detection at D2 heralds $(|\uparrow\rangle - |\downarrow\rangle)/\sqrt{2}$, resulting in a complementary interference pattern. The fringes are complementary because of the phase difference between the states heralded by D1 and D2. If we instead choose to herald using D1 or D2 without distinguishing between the two, there is no interference pattern. This is because we effectively ignore the polarization state of the trigger photon, leaving the signal photon in a mixed state. This can be seen as a nonlocal manifestation of a quantum eraser.

Because the photons are entangled, the phase of the interference pattern is correlated with the polarization state of the signal photon. To show that we indeed have entanglement between spatial and polarization degrees of freedom, we rotate the QWP in the polarization analyser. The resulting effect on the fringes are shown in Fig. 4(b,c). The phase of the pattern is clearly dependent on the polarization state of the trigger photon. In contrast, the polarization state of the trigger photon would have no effect on the phase of the interference pattern if these were non-entangled pairs. This heralding can also work in reverse. By post-selecting on a particular point in the interference pattern, it is possible to prepare the idler photon in a specific polarization state. Such a flexible remote state preparation could be very helpful in photonic quantum information processing.

The double-slit experiment, which is at the “heart of quantum mechanics”, has played a central role in our understanding and interpretation of quantum theory. Now, over two hundred years after the first experiments by Thomas Young, our results provide the most complete picture of single-photon interference to date.

In the future, our measurement techniques will dramatically decrease the difficulty of directly measuring the wave-function of a system by performing weak measurements. Additionally, these will allow us to herald a variety of polarization states in a multiplexed fashion, as well as facilitate the encoding and transfer of information using the hyper-entanglement of the spatial, temporal and polarization degrees of freedom.

Methods

Experimental setup. The details of the Sagnac-type source of photon pairs are described in Ref. 12, with a few modifications. The pump is a 404 nm laser diode.
Figure 2 | Interference pattern buildup. Panel (a) shows first 200 heralded counts in time, and panels (b–d) depict the statistics of the first 2000, 200 and 20 heralded detections.

Figure 3 | Statistical tests. (a) Coefficient of determination. For a given photon number, the statistics of $R^2$ is generated after $10^5$ numerical Monte Carlo simulations for the corpuscular and quantum mechanical models. The red (blue) belt shows 50% of the most frequent values of $R^2$ for the case of the corpuscular (quantum mechanical) model. (b) Likelihood ratio test. The smallest likelihood ratio value is $\log \Lambda = 0.83$, which shows that quantum mechanics is a better indicator of the behaviour seen in nature.
second. All 32 channels of the SPAD array are recorded individually as time tags by the array detector dark count rate gives rise to approximately 5 accidental coincidences/second which resulted in around 36 SPCM-AQ4C single photon detectors. The photon source produced around 2

and lens L3 is a plano-convex cylindrical (f = 5 mm) lens. The calcite crystal is 41 mm long, and the compensation crystal is 150 mm, lens L2 is aspherical (f = 15 mm) and the compensation crystal is 5 mm long. Lens L1 is plano-convex (f = 150 mm), lens L2 is aspherical (f = 11 mm) and lens L3 is a plano-convex cylindrical (f = 25 mm). D1 and D2 are Perkin Elmer SPCM-AQ4C single photon detectors. The photon source produced around 2 × 10^10 photon pairs/second which resulted in around 36 × 10^10 fiber coupled pairs/second. Then the transmission of the calcite system decreased this number to approximately 72 × 10^10, which results in around 2000 detected coincidences/second. The SPAD array detector dark count rate gives rise to approximately 5 accidental coincidences/second. All 32 channels of the SPAD array are recorded individually as time tags by two logic units (UQDevices).

**SPAD array.** The SPAD array is a 32 × 1 array of single-photon avalanche diodes, with pixel pitch of 100 µm and photon detection efficiency 5% in the range 770–840 nm. It has active area diameter of 50 µm and a dark count rate of 100 counts/s per pixel. For technical reasons, we use 28 of the pixels.

1. Garcia, N., Saveliev, I. G. & Sharonov, M. Time-resolved diffraction and interference: Young’s interference with photons of different energy as revealed by time resolution. *Phil. Trans. R. Soc. A* 360, 1039 (2002).
2. Jacques, V. *et al.* Single-photon wavefront-splitting interference. An illustration of the light quantum in action. *Eur. Phys. J. D* 35, 561–565 (2005).
3. Fickler, R., Krenn, M., Lapkiewicz, R., Ramelow, S. & Zeilinger, A. Real-time imaging of quantum entanglement. *Sci. Rep.* 3, 1914 (2013).
4. Zeilinger, A., Weihs, G., Jennewein, T. & Aspelmeyer, M. Happy centenary, photon. *Nature* 433, 230–238 (2005).
5. Zappa, F., Tisa, S., Tosi, A. & Cova, S. Principles and features of single-photon avalanche diode arrays. *Sensors and Actuators A: Physical* 140, 103 (2007).
6. Scarcella, C., Tosi, A., Villa, F., Tisa, S. & Zappa, F. Low-noise low-jitter 32-pixels CMOS single-photon avalanche diode array for single photon counting from 300 nm to 900 nm. *Rev. Sci. Instrum.* 84, 123112 (2013).
7. Hubel, H. *et al.* Direct generation of photon triplets using cascaded photon-pair sources. *Nature* 466, 601 (2010).
8. Rarity, J., Tapster, P. & Jakeman, E. Observation of sub-poisonian light in parametric downconversion. *Opt. Comm.* 62, 201–206 (1987).
9. Jin, F., Yuan, S., Raedt, H. D., Michielsen, K. & Miyashita, S. Corpuscular model of two-beam interference and double-slit experiments with single photons. *J. Phys. Soc. Jpn.* 79, 074401 (2010).
10. Zwillinger, D. *CRC Standard Mathematical Tables and Formulas* (Chapman and Hall, 1995).
11. Casella, G. & Berger, R. L. *Statistical Inference* (Cengage Learning, 2001).
12. Hamel, D. R. Realization of novel entangled photon sources using periodically poled materials. Master’s thesis, University of Waterloo (2010).
13. Kwiat, P. G., Steinberg, A. M. & Chiao, R. Y. Observation of a “quantum eraser”: A revival of coherence in a two-photon interference experiment. *Phys. Rev. A* 45, 7729 (1992).
14. Wallborn, S. P., Terra Cunha, M. O., Pidua, S. & Monken, C. H. Double-slit quantum eraser. *Phys. Rev. A* 65, 033818 (2002).
15. Ma, X.-S. *et al.* Quantum erasure with causally disconnected choice. *Proc. Natl. Acad. Sci. U.S.A.* 110, 1221 (2013).
16. Feynman, R., Leighton, R. B. & Sands, M. L. *Quantum Mechanics*, vol. 3 (Addison Wesley, 1963).
17. Young, T. *The bakerian lecture: On the theory of light and colours.* *Philos. Trans. Roy. Soc. London* 92, 12–48 (1802).
18. Young, T. *The bakerian lecture: Experiments and calculations relative to physical optics.* *Philos. Trans. Roy. Soc. London* 94, 1–16 (1804).
19. Kocsis, S. *et al.* Observing the average trajectories of single photons in a two-slit interferometer. *Science* 332, 1170 (2011).
20. Lundeen, J. S., Sutherland, B., Patel, A., Stewart, C. & Ramerb, C. Direct measurement of the quantum wavefunction. *Nature* 474, 188 (2011).
21. Barreiro, J. T., Langford, N. K., Peters, N. A. & Kwiat, P. G. Generation of hyperentangled photon pairs. *Phys. Rev. Lett.* 95, 260501 (2005).
22. Kolenderski, P. *et al.* Playing the aharon-vidam quantum game with a young type photonic qutrit. *Phys. Rev. A* 86, 012321 (2012).

**Figure 4 | Interference.** (a) The round (square) points show the interference pattern of the first 2000 photons heralded by a |H⟩(|V⟩) polarized photon. The triangular points show the envelope that results from heralding by either polarization. Limitations of electronics resulted in fewer coincidences at detectors 7 and 10. (b,d) Interference pattern fringes move as the phase is changed remotely by the QWP. The measurements are taken every 10-degree rotation. See Supplementary Table I for the visibilities of each set of measurements. (c,e) The trajectory of the Bloch vector related to the remotely prepared states heralded by (c) D1 and (e) D2.

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**Author contributions**
P.K., L.K.S. and T.J. led the experimental design. P.K., C.S., K.D.J. and D.R.H. performed experiments. P.K., K.D.J. and C.H. analyzed data. C.S., S.T. and A.T. supplied detection equipment. D.R.H. and K.R. provided entangled photon source. All authors wrote and reviewed the manuscript.

**Additional information**

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