Testing foundations of quantum mechanics with photons

Peter Shadbolt, Jonathan C. F. Mathews*, Anthony Laing and Jeremy L. O'Brien

Quantum mechanics continues to predict effects at odds with a classical understanding of nature. Experiments with light at the single-photon level have historically been at the forefront of fundamental tests of quantum theory and the current developments in photonic technologies enable the exploration of new directions. Here we review recent photonic experiments to test two important themes in quantum mechanics: wave–particle duality, which is central to complementarity and delayed-choice experiments; and Bell nonlocality, where the latest theoretical and technological advances have allowed all controversial loopholes to be separately addressed in different experiments.

ight has featured in tests of fundamental physics during times that witnessed key advances in our understanding of nature. Newton's investigation of the nature of light, using prisms to reveal the visible spectrum, is iconic of the scientific revolution of the sixteenth and seventeenth centuries. Early tests of Einstein's general relativity involved observations of starlight passing close to the Sun during a solar eclipse. Scientific advances have led to more convincing (and striking) observations of relativistic effects, with images from the Hubble Space Telescope revealing the gravitational lensing of galactic light. And we now know how the electromagnetic spectrum extends beyond the visible range and is quantized into single photons.

Because the primary detection apparatus in early experimental physics consisted of the physicists themselves, light made a natural observable. As our understanding of quantum photonics deepened, the utility of photons in tests of foundational concepts in physics became more evident. Photons are robust to environmental noise, have low decoherence properties, and are easily manipulated and detected.

The first half of this Review discusses tests of wave–particle duality with one photon, and the second half looks at experimental tests of nonlocality with two or more photons.

Wave–particle duality

The double-slit experiment has famously been said to contain the entire mystery of quantum mechanics. It provides a concise demonstration of the fact that single quanta are neither waves nor particles, and that in general they are neither in one single place, nor in two places at once.

The experiment begins with a source of single quanta. Here we will consider only photons, but qualitatively identical results have been observed in a wide variety of quantum systems including electrons[1–3], atoms[4], and even large molecules such as C_{60} (ref. 5). Single photons are sent towards a mask into which two slits have been cut. On the far side of the mask, the spatial distribution of single-photon events is measured by a sensitive detector. For each photon, the detector registers a 'click' at position x. Simultaneous detection of two clicks never occurs, and the photon initially seems to travel and arrive as a discrete particle. But after many photons have been detected, the observed probability distribution $p(x)$ can only be explained by wave interference due to components of the photon that travel through both slits simultaneously. Confoundingly, when detectors are placed directly inside the two slits, the photon is only ever detected at one slit or the other — never at both.

Where was the photon when it travelled through the mask? If it passed through one slit and not the other, wave interference effects would not be observed. If it passed through both slits at once, it should be possible to detect it at both simultaneously — this never occurs. If it passed through neither slit, we should not detect it at all — but we do. In this way, the double-slit experiment reveals the inadequacy of classical language when describing quantum systems.

In 1909, Geoffrey Taylor used a sewing needle to split a beam of light into two paths, and observed interference fringes in the resulting pattern of light and shadow[6]. He used an incandescent source of "feeble light" with roughly the intensity of a candle held at a distance of one mile. Since then, single photons have played a pivotal role in tests of wave–particle duality. This is largely due to the ease with which quantum states of light can be generated, manipulated and measured under ambient laboratory conditions, that is, at room temperature and pressure. Many of these experiments are based on a very natural question: what do we know, and how much can we measure, of the state of the photon as it passes through the slits?

The light source used by Taylor was thermal — it did not generate photons one by one — and his experiment consequently admits a classical model. The fact that true single photons are not detected at both slits simultaneously (antibunching) was confirmed experimentally by Clauser[7], who used a more sophisticated light source, based on atomic cascades in mercury atoms. A similar source was used by Grangier et al.[8], who observed both antibunching and wave interference effects analogous to those of the double-slit experiment.

In the quantum-mechanical description, detection of the photon at one slit 'collapses' the single-photon wavefunction and precludes detection at the other. Collapse is instantaneous, even when the slits are very far apart, and it was emphasized by Einstein at the Solvay conference[9] that the effect is thus seemingly nonlocal. A recent experiment by Guerreiro et al.[10] tested Einstein's thought experiment for the first time, using space-like-separated (causally independent) detectors.

The notion of wavefunction collapse originates from the Copenhagen interpretation of quantum mechanics, and encompasses Niels Bohr's principle of complementarity. Bohr maintained that in order to observe complementary properties of a quantum system, an experimentalist must necessarily use mutually incompatible arrangements of the measurement apparatus. In the context of the double slit, this means that any experiment that fully reveals the wave-like properties of the photon must obscure its particle-like character, and *vice versa*.

Centre for Quantum Photonics, H. H. Wills Physics Laboratory and Department of Electrical and Electronic Engineering, University of Bristol, Merchant Venturers Building, Woodland Road, Bristol, BS8 1UB, UK. *e-mail: jonathan.matthews@bristol.ac.uk

Bohr's principle has only very recently been formalized in universal complementarity relations, such as those due to Ozawa and Hall[11–13]. These relations formalize the notion that although the inaccuracy in either of two complementary observables can individually be made arbitrarily small, one cannot measure both to an arbitrary degree of accuracy using a single configuration of the measuring device. This is distinguished from the Heisenberg uncertainty principle, which places more general limits on the precision of ensemble measurements, and does not demand any such limitation on the measuring device(s). Very recently, Weston et al.[14] used a spontaneous parametric down-conversion source together with a linear-optical circuit to test these new relations experimentally. Making use of entanglement generated by the photon source, the authors were able to test complementarity under conditions in which previously discovered, non-universal complementarity relations fail.

On first encountering the double-slit experiment, it is natural to wonder about the trajectory of the photon during its path from source to detector. Complementarity implies that a single experimental set-up cannot simultaneously obtain precise values of the position and momentum of the photon. Indeed, a naive experiment hoping to track the route of the photon by measurement of its position will destroy all wave-like effects. However, Kocsis et al. recently demonstrated[15,16] that quantum weak measurement[17] can be used to approximately reconstruct the average trajectory of ensembles of photons as they undergo double-slit interference. Weak measurement allows approximate information to be obtained on a particular observable without appreciably disturbing 'strong' measurement outcomes on a complementary variable. The authors sent single photons from a GaAs quantum dot through a double-slit interferometer, in which a piece of birefringent calcite imposes a weak polarization rotation depending on the angle of incidence — and thus the momentum — of the photon. Then, by simultaneous detection of the lateral position and polarization using a high-resolution CCD (charge-coupled device) camera, weak measurement of the photon's momentum was accomplished at the same time as strong measurement of position. The trajectories measured in this experiment hold particular significance in the de Broglie–Bohm interpretation of quantum mechanics, where they are literally interpreted as the path taken by a single particle-like photon.

John Wheeler's famous 'delayed-choice' thought experiment[18,19] also addresses the question of the position or trajectory of the photon in a two-path set-up. Considering the double-slit experiment, one might attempt to side-step the uncomfortable implications of wave–particle duality by means of a pseudoclassical explanation in which the photon decides in advance to behave as a particle or wave, depending on the choice of measurement set-up. If the photon notices that a particle-like measurement is planned, it dispenses with all wave-like properties and passes through one slit at random, and *vice versa*. Wheeler proposed an elegant test of this comforting (if pathological) model, in which the decision to measure wave-like or particle-like behaviour is delayed until after the photon has passed the slits, but before it reaches the measuring apparatus. Delayed-choice experiments have been performed in a variety of physical systems[20–23], all of which confirm the quantum predictions and refute the notion that the photon decides in advance to behave as a particle or a wave.

Of particular significance is a recent result[24] of Jacques et al., in which relativistic space-like separation between the random choice of measurement setting and slits was achieved for the first time. This ensures that there can be no causal link between the free choice of measurement setting and the behaviour of the photon at the slits. Here, a nitrogen-vacancy colour centre in diamond was used as the source of single photons, ensuring extremely close approximation to the single-photon Fock state $|1\rangle$. An electro-optic modulator, driven by a quantum random-number generator at 4.2 MHz, was
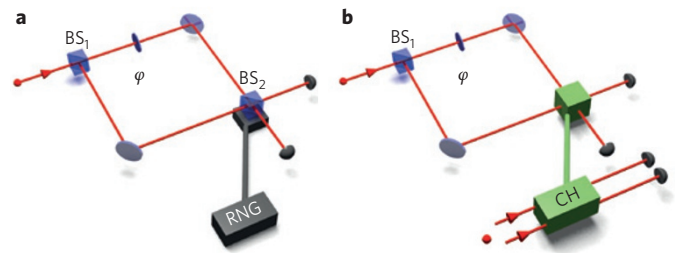

Figure 1 | Delayed-choice experimental set-ups. a, Wheeler's delayed-choice experiment. A photon is sent into a Mach–Zehnder interferometer. On arrival at the first beamsplitter BS_1, it is split into a superposition across both paths. A random-number generator (RNG) then toggles a fast optical switch, closing or opening the interferometer by insertion or removal of BS_2, leading to wave-like or particle-like measurement of the photon, respectively. Two detectors reveal wave-like behaviour in the event that the interferometer is closed; otherwise, particle-like statistics are seen. **b**, Quantum delayed choice. The optical switch is replaced by a quantum-controlled beamsplitter: a controlled-Hadamard gate (CH). An ancilla photon controls this gate: ancilla states $|0\rangle$ and $|1\rangle$ lead to presence and absence of BS_2, respectively. By preparing the ancilla in a superposition state, BS_2 can be placed into a superposition of present and absent, leading to a superposition of wave-like and particle-like measurement.

used to implement the choice of measurement setting. A similar experimental set-up was more recently used by the same group[25] to refute the controversial claims due to Afshar et al.[26,27] that Bohr's complementarity principle could be violated in a subtle variation on the double-slit experiment.

In delayed-choice experiments, the selection of measurement setting is generally implemented using a classical optical switch, driven by a random-number generator, which rapidly inserts or removes an optical beamsplitter in the path of the photon (Fig. 1a). If the beamsplitter is present, which-way information is erased and full-contrast wave-like interference is observed. If the beamsplitter is instead absent, each detection event yields full which-way information, but no interference is seen. A recent proposal by Ionicioiu and Terno[28] suggested that the classical random bit might be replaced by a quantum bit (a qubit), and the classically controlled beamsplitter by a quantum-controlled beamsplitter, or controlled-Hadamard (CH) gate (Fig. 1b). By preparing the ancilla qubit in the superposition state $\cos(\alpha)|0\rangle+\sin(\alpha)|1\rangle$, the beamsplitter is effectively placed into a coherent superposition of being present and being absent. One can then continuously tune between particle-like and wave-like measurement settings, in close analogy with the weak measurement technique of ref. 16. This idea was quickly implemented by a number of groups[29–31], two of which used photon pairs generated by spontaneous parametric down-conversion (SPDC). The result of Peruzzo et al.[30] exploits recent developments in integrated quantum photonics[32], with Wheeler's interferometer and the CH gate both implemented on-chip[33]. In the latter experiment, entanglement generated by the CH gate allows for device-independent refutation of hidden variable models in which the photon decides in advance to behave as a particle or a wave, by violation of the Bell–CHSH (Clauser–Horne–Shimony–Holt) inequality[34].

In the scheme of Ionicioiu and Terno, the which-way information is carried by the ancillary particle. This possibility was previously emphasized by Scully and Drühl[35], who pointed out that the choice of the measurement basis for the entangled ancilla determines the contrast of wave interference observed, and that this choice can be made even after the system photon has been detected. Only a subset of allowed measurement settings completely and irrevocably erase all which-way information, resulting in high-contrast interference fringes. In 2000, Kim et al.[23] implemented this so-called

delayed-choice quantum eraser using single photons generated by SPDC. More recently, Ma et al.[36] demonstrated a quantum eraser using entangled photon pairs. The team went to great lengths to rule out models in which the circumstances of the ancilla are communicated to the system photon through a local, causal mechanism. The system and ancilla photons were sent to separate islands, 144 km apart, so that the choice of measurement setting, system photon and interferometer, and measurement of the ancilla photon, were all mutually space-like separated — and therefore causally disconnected.

In all of these variants of the double-slit experiment, we see a fundamental trade-off between the information that can simultaneously be obtained on particular properties of quantum systems, as well as a behavioural dependence on the choice of measurement setting. These effects seem contrary to what is known as non-contextual realism, the (rather natural) assumption that the observable properties of objects are well defined independent of measurement. Kochen and Specker[37] proved that there exist sets of quantum-mechanical observables to which a unique set of values cannot be consistently and simultaneously assigned — rendering non-contextuality untenable. No direct experimental implementation has yet been reported, and indeed it is unlikely that a meaningful direct implementation of Kochen–Specker (KS) measurement is possible[38,39]. A number of theoretical works[40–43] have shown, however, that non-contextual realism can be revoked under much less demanding conditions, and many of these theories have since been tested using single photons. An early result by Michler et al.[44] mimicked three-particle Greenberger–Horne–Zeilinger (GHZ) correlations, using entangled photon pairs generated by SPDC. Huang et al.[45] tested the 'all-or-nothing' KS-like theory of Simon[41], encoding two qubits in the path and polarization degrees of freedom of a single photon. The authors used an SPDC photon pair source as a 'heralded' single-photon source. Here, the detection of one of a pair of photons collapses, or heralds, the other arm of the source into the single-photon Fock state $|1\rangle$. More recently, Lapkiewicz et al. reported[46] an experiment using a single photonic qutrit, encoded in path and polarization using calcite beam displacers, to implement the theoretical proposal of Klyachko and colleagues[47]. This result is notable as it reinforces the strong incompatibility between the quantum and classical pictures of physics with only a single quantum particle and in the absence of multiparticle entanglement.

A fundamental tenet of quantum mechanics is the Born rule, which states that given a system with wavefunction $\psi(\mathbf{r},t)$, the probability that it is detected in the volume element d^3r at time t is given by

$$p(\mathbf{r},t) = |\psi(\mathbf{r},t)|^2 d^3r \qquad (1)$$

It can easily be shown that because this expression depends only on the square of the wavefunction, probabilities generated by multiparticle wavefunctions can always be written in terms of interference between pairs; three-body interference terms never appear in the expansion of equation (1). Indeed, almost all nonlinear models of quantum mechanics that permit three-body interference have extreme and highly unlikely consequences. Such models allow quantum states to be cloned, and enable polynomial-time algorithms for computational tasks, which are believed to be exponentially hard for any physical machine[48]. A recent experiment by Sinha et al.[49] went in search of such effects using a triple-slit variation on the double-slit experiment. Using a lithographically fabricated triple slit, a coherent laser source and heralded single photons from SPDC, the team gathered strong evidence against the existence of higher-order corrections to the Born rule.

Nonlocality

'Locality' is the concept describing the behaviour of space-like-separated objects that depend only on events in their respective light-cones. Confoundingly, entangled particles exhibit correlations that defy this understanding. Many attempts have been made to explain these correlations in terms of local hidden variable models (LHVs), which try to capture our everyday experience of the Universe. LHVs associated with each particle can be imagined as having been determined from some earlier local interaction. This aligns with an intuitive local and realistic view of a Universe that is causally connected by locality. In 1964, John Bell described an experimentally tenable scenario in which quantum mechanics predicts outcomes that are incompatible with all possible LHVs[50], provided that the experiments are rigorously performed. The platform of entangled single photons is the only platform to have addressed all the known key requirements of a quantum theory of nonlocality, albeit in separate experiments. Here we review a selection of recent developments using entangled photons to test quantum nonlocality and explore its properties. For an exhaustive review of the subject's history we point the reader towards more in-depth reviews on multiphoton entanglement[51] and theoretical developments[52].

Since the seminal experiments of Freedman and Clauser[53] in 1972, and Aspect et al.[54] in 1982, nonlocality experiments have typically comprised a source of entangled photon pairs that are shared between observers Alice and Bob who independently perform measurements and subsequently compare their results (Fig. 2a). The measurements have two possible settings, 0 or 1, and have only two possible outcomes $a,b \in \{-1,+1\}$, often assigned to the polarization of the photons. The CHSH version[34] of Bell's inequality sets an upper bound on the strength of correlations allowed by LHVs using the sum of expected values for ab, for each possible combination of measurement outcome:

$$S = |\langle a_0 b_0 \rangle + \langle a_0 b_1 \rangle + \langle a_1 b_0 \rangle - \langle a_1 b_1 \rangle| \leq 2 \qquad (2)$$

Quantum mechanics predicts that this bound can be experimentally violated, demonstrating the inadequacy of LHV. If the two particles are entangled — for example in the singlet state
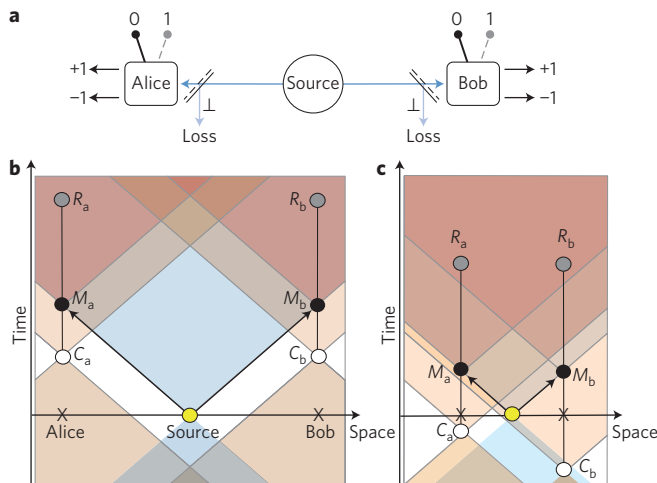

Figure 2 | A nonlocality experiment and associated loopholes. a, The detection loophole can be opened by optical loss if there is a sufficiently high proportion of inconclusive outcomes ⊥. **b,** A space-like separation prohibits signalling between the various events occurring for each observer and closes the locality loophole. For example, Alice's measurement M_a and results R_a are outside the light-cone of influence from Bob's measurement choice C_b. Furthermore, because C_a and C_b are causally disconnected from detection events and the source, Alice and Bob are free to choose their measurement settings without influence. **c,** If the observers are not space-like separated, it is possible for signalling to occur between events. In this example, M_a and M_b can respectively influence R_b and R_a, and C_b can influence both M_a and R_a.
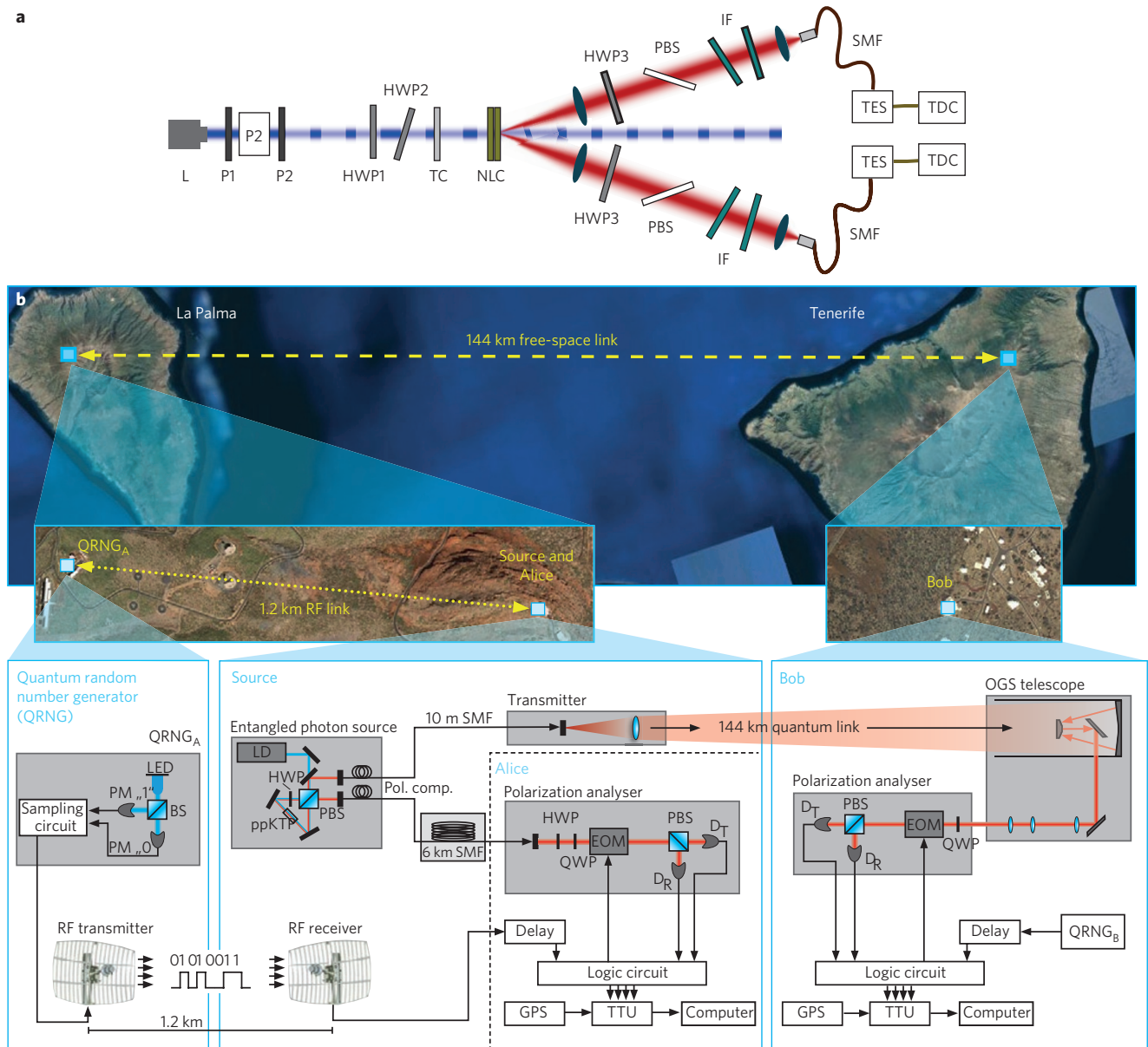
Figure 3 | Experiments for closing the Bell nonlocality loopholes. a, High detection efficiency can be achieved with TES to close the detection loophole. L, laser; PC, Pockels cell; P1 and P2, crossed polarizers; PBS, polarizing beamsplitter; NLC, paired nonlinear BiBO crystals; TC, BBO crystal; HWP, half-wave plate; IF, interference filters; TDC, time-to-digital converter; SMF, single-mode fibre. **b**, Space-like separation of the quantum random-number generators that choose the random measurement settings and the measurement apparatus. This enables the locality and freedom of choice loopholes in the experiment to be closed. LD, laser diode; ppKTP, periodically poled potassium titanyl phosphate crystal; QWP, quarter-wave plate; EOM, electro-optical modulator; D_T, D_R, photodetectors; QRNG, quantum random number generator; LED, light-emitting diode; PM, photomultiplier; TTU, time-tagging unit; GPS, global positioning system. Figure reproduced with permission from: **a**, ref. 60 © 2013 APS; **b**, ref. 68 © 2010 PNAS; Geographic pictures taken from Google Earth, © 2008 Google, Map Data © 2008 Tele Atlas.

$(|\psi^-\rangle = (1/\sqrt{2})(|0\,1\rangle - |1\,0\rangle))$ — then a choice of measurement settings σ_z and σ_x for Alice, and $\sigma_z + \sigma_x$ and $\sigma_z - \sigma_x$ for Bob, leads to a violation of equation (2), with $S = 2\sqrt{2}$.

The implications of rigorously violating this inequality have a profound effect on our intuition of how the Universe works, for it suggests that the two particles are instantaneously communicating with one another, even though they are far apart. Although the randomness of outcomes to measurements means that no communication can occur between Alice and Bob, these nonlocal effects seem to be in contradiction with the spirit, if not the letter, of special relativity. These far-reaching implications have motivated particular scrutiny of the possible ways in which nature might somehow fake nonlocality, with

focus mainly falling on experimental limitations. An apparent experimental violation $S > 2$ could be attributed to assumptions exploited by LHVs known as loopholes, the more famous of which are the 'locality', 'detection' and 'freedom of choice' loopholes (Fig. 2). A completely unambiguous experimental demonstration of Bell nonlocality requires the simultaneous obstruction of every possible loophole. Although this milestone is yet to be reached in experimental physics, photons have been used to address each of these loopholes individually.

The detection loophole. Optical tests of nonlocality have suffered from low detection efficiency. With an experimental efficiency of $\eta < 100\%$ there exist, in addition to '+1' and '−1', inconclusive

measurement outcomes '⊥' that represent the failure to detect an emitted photon (Fig. 2a). The outcome ⊥ can be ignored by including only measurements that register photon detection. But this relies on the assumption of a fair sampling, because otherwise, local models may skew the detection statistics of +1 and −1 to falsify violation of equation (2). This has been illustrated experimentally through the use of side channels to intentionally falsify signatures of nonlocality in experimental set-ups that are otherwise considered as standard Bell-inequality experiments[55–57].

When including ⊥ outcomes, violation of CHSH (equation (2)) only occurs when experimental efficiencies are beyond the threshold of $\eta > 82.8\%$. Remarkably, Eberhard discovered that lowering the amount of entanglement by controlling the r parameter in $(r|01\rangle - |10\rangle)/\sqrt{1+r^2}$ reduces the threshold efficiency to $\eta > 66.7\%$ in testing nonlocality[58]. Denoting as $n_{k,l}(a_i b_j)$ the number of photon pairs with outcome $k \in \{+1, -1, \perp\}$ and $l \in \{+1, -1, \perp\}$ when using measurement settings $i \in \{0,1\}$ on one particle and $j \in \{0,1\}$ on the other, Eberhard's inequality (which holds for LHVs) is written as

$$J = n_{+1,+1}(a_1, b_1) - n_{+1,+1}(a_0, b_0) + n_{+1,-1}(a_1, b_1)$$
$$n_{+1,\perp}(a_0, b_1) + n_{-1,+1}(a_1, b_0) + n_{\perp,+1}(a_1, b_0) \geq 0 \tag{3}$$

Notably, each observer needs only one detector, as the decrease in efficiency of detectors responsible for '−1' outcomes causes outcomes nominally '−1' to be included as ⊥, mapping $n_{+1,-1}(a_0, b_1)$ to $n_{+1,\perp}(a_0, b_1)$ and $n_{-1,+1}(a_1, b_0)$ to $n_{\perp,+1}(a_1, b_0)$ (ref. 59). Furthermore, testing nonlocality with equation (3) is robust to the Poissonian nature of photon-counting measurements on SPDC sources, and removal of the vacuum state through post-selection is not required.

Two recent experiments[59,60] report violation of Eberhard's inequality to close the detection loophole. Both experiments use transition-edge sensors[61] (TES), which are high-efficiency single-photon detectors, and high-collection-efficiency photon sources to surpass Eberhards efficiency threshold, and each obtain $\eta > 70\%$: ref. 59 uses a high-collection-efficiency photon source based on a Sagnac configuration[62,63]; ref. 60 uses a non-collinear SPDC photon source configuration (Fig. 3a). Although both demonstrations are of sufficient efficiency to close the detection loophole, the experiment in ref. 59 is still open to the 'coincidence-time' loophole[64]. This experiment relies (like numerous others) on using timing windows defined by single-photon detection events to perform coincident detection analysis: when one photon detector registers a single-photon event, a coincidence event is recorded if a second single-photon event is recorded within a prescribed window of time. The coincidence-time loophole allows the detection time to be shifted by the local measurement settings in or out of the coincidence window, so that a completely local process can match quantum mechanical expectation values. But this loophole can be avoided by using a coincidence window defined around a system clock: ref. 60 achieves this with a chopped laser pulse that drives the SPDC to create photon pairs in well-defined events.

The work in ref. 60 also highlights the 'production-rate loophole' where non-random drifting of the pump laser power or detection efficiency can be exploited by local realistic models. The experimental drifts in ref. 59 have, however, been shown[65] not to be sufficient for this loophole. Alternatively, a quantum random-number generator can be used to choose measurement settings randomly in order to close the production-rate loophole[60]. Furthermore, satisfying the more stringent requirement of randomly chosen measurement settings for every entangled particle pair in order to close the 'freedom of choice' loophole simultaneously addresses the production-rate loophole.

Freedom of choice and locality loophole. Two famous experiments attempted to close the locality loophole through space-like separation by fast measurement settings chosen during the time of

flight of the entangled photons[66,67]. But the settings of ref. 66 were chosen using periodic sinusoids and were therefore predictable and susceptible to influence by hidden variables created at the source, so failed to close the freedom of choice loophole — the possible influence of measurement settings either by other measurement apparatus or by hidden variables created at the source of photons. The random settings of ref. 67 were chosen within the forwards light-cone of the emission point of the entangled photons, so could also have been influenced by hidden variables created at the source. Improving on these experiments, the authors of ref. 68 separated their random-number generators in a space-like way, to remove the possibility of transmitting any physical signal between entangled particle emission and the random measurement settings. This Bell test was performed between two Canary Islands, La Palma and Tenerife, separated by 144 km, with the quantum random-number generator used to choose measurement bases space-like separated from the rest of the experiment (Fig. 3b).

EPR-steering. Almost 80 years after Schrödinger referred to the effects of entanglement as 'piloting' or 'steering' of one quantum state by the measurement of another, the concept of EPR-steering was formalized[69,70] and was swiftly followed by an EPR-steering inequality based on local models[71]. Steering sits strictly between entanglement witnesses[72] and Bell nonlocality. The idea of entanglement witnesses relies entirely on assumptions that quantum mechanics is correct, to test for the presence of non-separability, whereas in Bell nonlocality ideally no assumptions are made about the experimental set-up or the model of physics. The concept of steering (Fig. 4) assumes that one half of the system, an observer Bob, fully trusts his measurement apparatus and that any states in his possession adhere to the laws of quantum mechanics. A second party (Alice) is tasked with convincing Bob that she can steer a quantum state that she has already sent to him. Importantly, no assumptions are made about the physics to which Alice has access, so she is free to use any means to carry out her task. Assuming local models, this experiment is constrained by the inequality[71]

$$S_n \equiv \frac{1}{n}\sum_{k=1}^{n}\langle A_k \hat{\sigma}_k^B \rangle \leq C_n \tag{4}$$

in which Alice and Bob compare n measurement results; σ_k^B is the kth of n measurements performed by Bob in conjunction with Alice declaring a measurement result $A_k \in \{-1, +1\}$. C_n is the maximum value that can be obtained for the quantity S_n, provided Bob has pre-existing states known to Alice. This inequality is violated when Alice instead shares entanglement with Bob, and, through her own measurements, affects Bob's results.

Saunders et al.[73] performed the first experimental demonstrations of violating the steering inequalities with polarization-entangled photons, showing that increasing the number of measurements n (testing up to $n = 6$) increases the robustness of this nonlocality test to experimental noise. Just like Bell-like inequalities, however, local models can also exploit loopholes to explain steering. Steering has less stringent requirements than the aforementioned nonlocality tests, owing to the asymmetry of the experiment, and has an experiment efficiency threshold of $\eta > 1/3$ for closing the detection loophole when using $n = 3$ measurements. Three experiments published around the same time collectively address loophole-free steering[74–76]. All three experiments use Sagnac entanglement sources (see Box 1) to increase experiment efficiency and close the detection loophole; in addition, Smith et al.[75] use TES single-photon detectors. Bennet et al.[74] use up to $n = 16$ measurement settings, and they show that this allows them to measure violation of equation (4) without assuming fair sampling, despite high loss (87%) induced by 1 km of coiled optical fibre between the entanglement source and
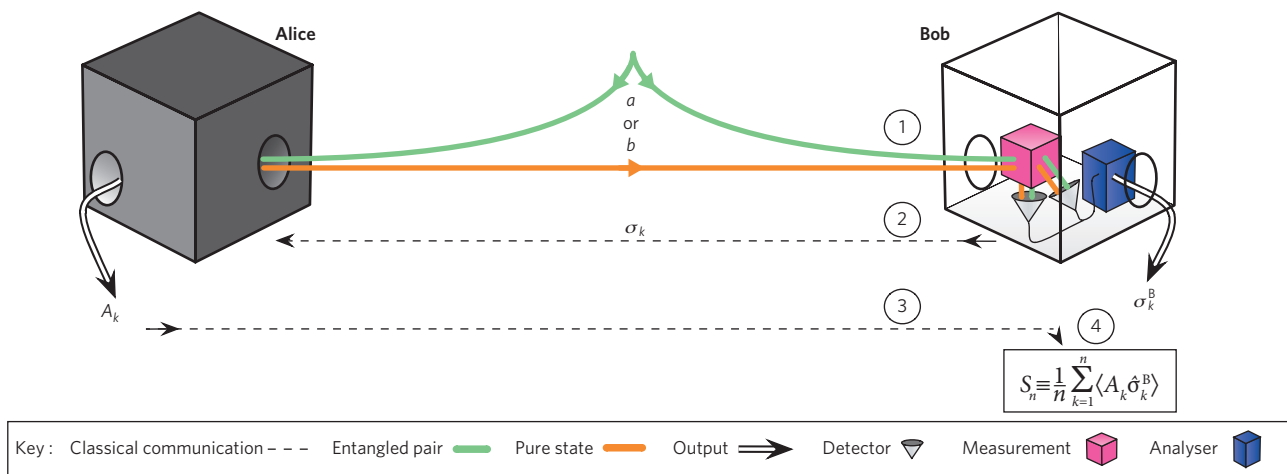
$$S_n \equiv \frac{1}{n} \sum_{k=1}^{n} \langle A_k \hat{\sigma}_k^{B} \rangle$$

Key : Classical communication – – –   Entangled pair ━━ Pure state ━━ Output ⟹   Detector ▽   Measurement ◼   Analyser ◼

Figure 4 | EPR steering. Here, one observer (Bob) trusts that his system works according to quantum mechanics (denoted by a clear box), while another party (Alice) is tasked with supplying Bob with a quantum state and demonstrating that she can affect his measurement results by any means (black box). Assuming local laws of physics, an inequality for this experiment is derived, which is violated when Alice chooses to share entanglement between herself and Bob. Figure reproduced with permission from ref. 73, 2010 NPG.

one of the measurement apparatus; this explores the conditions for closing the freedom of choice and locality loopholes over a lossy channel. In addition to closing the detection loophole, Wittmann[76] enforces strict Einstein locality conditions, with space-like separation over 48 m of optical fibre. This closes the locality loophole. In addition, they use a space-like-separated quantum random-number generator, closing the freedom of choice loophole that would otherwise allow the photon pair source to influence the choice of measurement setting. This is the first time a nonlocal quantum effect has been explored while simultaneously closing three important loopholes. Collectively, these experiments[74–76] mark important progress towards loophole-free, device-independent tests of Bell nonlocality.

Reference-frame-independent nonlocality tests. Traditionally, nonlocality tests take place within a shared reference frame. That is to say, Alice and Bob are able to align their measurement apparatus with respect to one another. This may be problematic for experiments using long optical fibre or free-space orbital communications. One solution is to harness decoherence-free subspaces[77], and this has been recently implemented using rotationally invariant entanglement in which photon pairs are entangled in their orbital angular momentum states and their polarization states, to violate a Bell inequality in alignment-free settings[78]. This requires an increase in dimension of the quantum system investigated. Remarkably, it has been shown that sharing a complete reference frame is not required for two remote parties to violate a Bell inequality: provided the parties share one measurement direction perfectly, they have high probability of violating a Bell inequality perfectly with a maximally entangled state by each choosing maximally complementary measurements in the plane orthogonal to the shared direction in the Bloch sphere[79]. By increasing the complexity of the measurements that each party makes, observers can always violate a Bell inequality without sharing any information about their reference frames[80,81]. This potentially removes the need for establishing reference frames for future nonlocality tests, in particular when taking nonlocality tests into orbit to help address the locality loophole.

Multipartite locality tests. Most nonlocality tests have been focused towards using bipartite entanglement. Greenberger, Horne and Zeilinger extended nonlocality tests to that of three-party entanglement[82]; this was formulated into an inequality to test for multipartite nonlocality by Mermin[83]. The first three-photon GHZ

entanglement was demonstrated 15 years ago using a pulsed SPDC source[84] and was then subsequently used to violate Mermin's inequality[85]; four-photon GHZ states[86,87] have also been used for local realism tests[88]. Until recently, however, no multiphoton experiment has succeeded in addressing loopholes that can be exploited by LHVs. The main contributing factor is the typically low brightness of multiphoton entangled sources. Recently, Erven et al.[89] reported the generation of heralded three-photon GHZ entanglement at sufficient rates (40 Hz) to distribute the three photons using optical fibre and free-space links to independent measurement stations to violate Mermin's inequality. With sufficiently separated measurement stations and entanglement source, the authors address the locality loophole, while the freedom of choice loophole is closed by spatially separating a random-number generator that defines the measurement basis settings. But experiment efficiencies below the threshold required to close the loophole of Mermin's inequality mean that the detection loophole is not closed, and fair sampling is assumed. This leaves open the possibility of using high-efficiency photon detectors and developing efficient collection in multiphoton entangled states for loophole-free multipartite nonlocality tests in the future.

Outlook

Photonic experiments over the past four decades have answered many important debates in the fundamental theory of quantum mechanics, and new photonic technologies continue to create opportunities to close loopholes, answer old questions and even inspire new theoretical research. Experimental confirmation of the predictions of quantum physics during the previous century forced a re-evaluation of the understanding of the operation of the Universe as a classical machine, at least at the microscopic scale. Over the coming decades, as we increase our capabilities to harness the effects of quantum mechanics to build quantum computers[90], we will test the extent to which quantum effects persist at a macroscopic scale, with further potential consequences for our understanding of the Universe. Famously, the extended Church–Turing thesis (ECT) says that all computational problems that are efficiently solvable with realistic physical systems can be efficiently solved with a classical machine — a statement clearly in conflict with our hopes for the capabilities of quantum computers[91]. Although we might have to wait some time for a universal quantum computer to operate at the scale that challenges the ECT, recent theoretical[92] and technological

Box 1 | Enabling technology for current and future nonlocality tests.

Sources of entangled photons

For nearly two decades, spontaneous parametric down-conversion (SPDC) based on nonlinear crystals has been the most widely applied source of entanglement in quantum optics[98]. A configuration that has recently advanced collection efficiency is that of collinear SPDC, coherently pumped in both directions with a laser split by a beamsplitter, in a polarization Sagnac interferometer[62,63] (Fig. B1a). This allows inherent stability without the need for active stabilization. By eliminating the transverse walk-off effect by periodically poling in the nonlinear crystal (that is, alternating the orientations of the birefringent material), high collection efficiency into single-mode fibre is obtained. This configuration has been demonstrated to operate with continuous-wave or pulsed regimes[99] with at least 80% coupling efficiency and for a number of nonlinear materials[100]. For future experiments, a more compact source of entangled photons would probably use an integrated architecture, where stabilized path-entangled photons[101] and polarization-entangled photons[102] can be generated (Fig. B1b).

Increasing detector efficiency

Single-photon detectors[103] underpin the measurements made by the observers in any photonic nonlocality experiment. Transition-edge sensors (TES) are fabricated using a thin tungsten film embedded in an optical stack of materials to enhance the absorption[61]. With the voltage biased at their superconducting transition, absorbed photons cause a measurable change in the current flowing through the tungsten film that is efficiently measured with a superconducting quantum interference device (SQUID) amplifier. TES require cooling to about 100 mK using adiabatic demagnetization refrigerators, and detection efficiencies of about 95% are now routinely reported. Nanowire superconducting single-photon detectors[104] have emerged as a promising alternative for both free-space and integrated applications: here a single photon absorbed by a superconductor biased just below its critical current I_c creates a local resistive 'hotspot', generating a voltage pulse. Superconducting detectors based on NbN nanowires operate at about 4 K temperatures and are capable of very fast counting rates (up to gigahertz) and low dark counts (<1 Hz)[104]. Such NbN nanowire detectors can operate in commercial cryocoolers[103]. Recent NbN nanowire detectors using a travelling-wave design[105] (Fig. B1c) have demonstrated on-chip detection efficiency above 90%. In addition, recent realization of NbTiN nanowire single-photon detectors on SiN (ref. 106) extends the operating wavelength from infrared to visible, and reduces the dark count rate to millihertz.
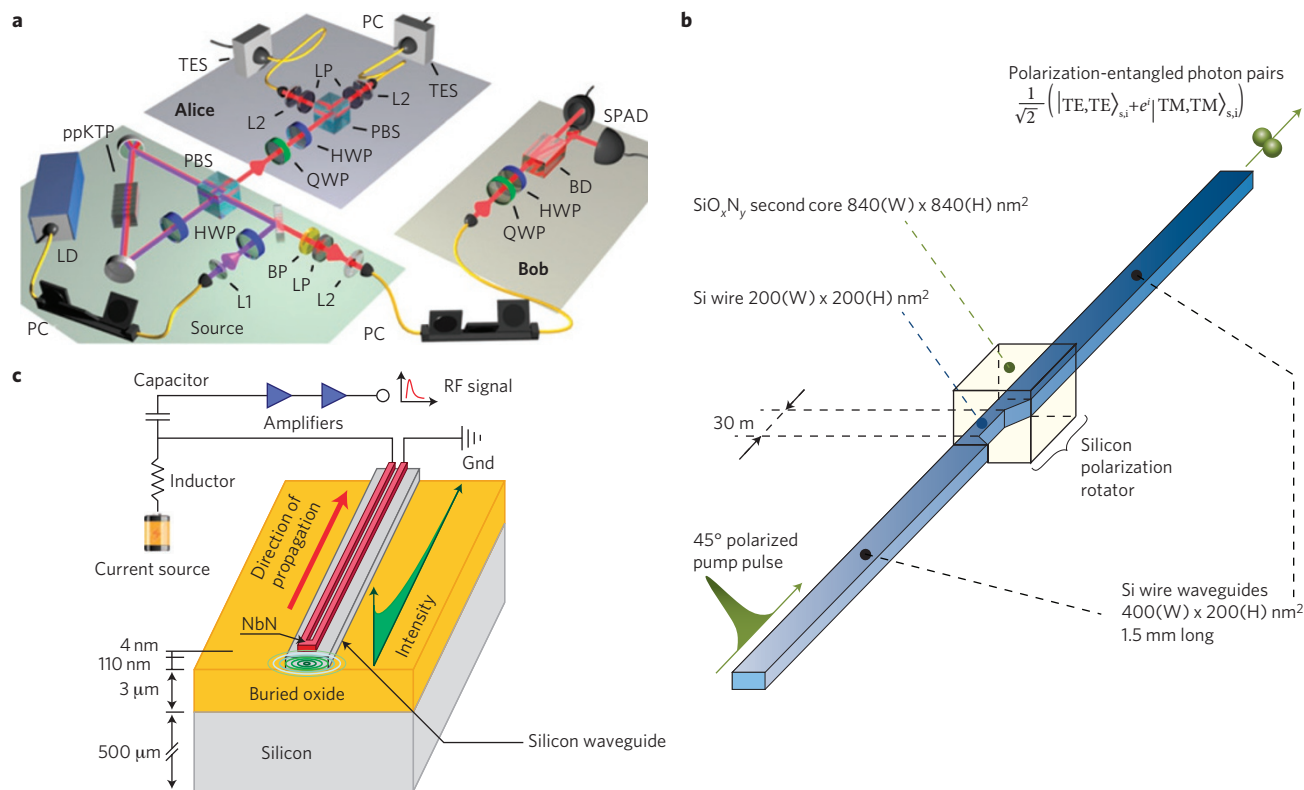

Figure B1 | Current and future photonics for nonlocality tests. a, A polarization Sagnac interferometer configuration can offer >80% collection efficiency of generated photon pairs into optical fibre. When used together with high-efficiency (>95%) TES single-photon detectors, this can be used to address the detection loophole in nonlocality tests. The example here depicts Alice using TES to address the detection loophole in EPR steering in the experiment reported in ref. 75. SPAD, single-photon avalanche diode; BD, polarization beam displacer. Other abbreviations as in Fig. 3. **b**, Waveguide entangled sources offer potentially repeatable, high brightness and high-efficiency sources of entanglement. s, single photon; i, idler photon; TE, horizontally polarized; TM, vertically polarized. **c**, Superconducting single-photon detectors offer a low-temperature (4 K) alternative in high-efficiency and fast single-photon detection that can be monolithically integrated into waveguide structures for potentially compact photonics measurement apparatus. Figures reproduced with permission from: **b**, ref. 102, 2012 NPG; **c**, ref. 105, 2012 NPG.

advances in quantum photonics[93] have developed a path to challenging the ECT on a near-term timescale, with a non-universal quantum photonic device that performs a task known as boson sampling[94–97]. If experiments confirm the prediction, as we believe they will, that our Universe cannot be efficiently simulated by a classical machine, then there may be other confounding features of quantum mechanics currently hidden from us and apparent only through simulations on a quantum computer. It is therefore possible that, rather than confirming existing theory, future photonic experiments might be the first to reveal new and complex quantum phenomena, requiring innovative theoretical explanations.

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