Happy centenary, photon

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One hundred years ago Albert Einstein introduced the concept of the photon. Although in the early years after 1905 the evidence for the quantum nature of light was not compelling, modern experiments — especially those using photon pairs — have beautifully confirmed its corpuscular character. Research on the quantum properties of light (quantum optics) triggered the evolution of the whole field of quantum information processing, which now promises new technology, such as quantum cryptography and even quantum computers.

Of the papers written by Einstein in his *annus mirabilis* (1905), it was not the one where he introduced the special theory of relativity[1], but the one where he proposed the idea of quanta of light[2], later called photons[3], that received the acclaim of the Nobel committee. This paper is often presented as if Einstein, having analysed the photoelectric effect, arrived at the idea of the photon. Yet, as is so often the case, the real story is much more interesting (see Box 1).

Since 1905, the photon has come a long way, considering that it was first regarded only to be a 'mathematical trick' or a concept without any deeper meaning (Box 1). But what exactly do we mean by a 'photon' today and what experimental evidence do we have to support the concept of the photon?

Single photons as particles and waves

A basic meaning of the term 'photon' is that radiation only exists in quantized energy packets. This contrasts with semi-classical radiation theories (see Box 2), which propose that matter is ruled by quantum physics, while the radiation field is classical.

One essential experiment that discriminates the quantum theory of light from a semiclassical one uses a stream of single photons incident on a beam splitter (Fig. 1). A semiclassical theory predicts that the two detectors in the output beams sometimes register in coincidence; according to this theory, the probability of registering a count is proportional to the square of the electric field. In contrast, full quantum theory predicts that the two detectors never register in coincidence. The quantum mechanically predicted statistics were experimentally confirmed by Clauser in 1974 (ref. 4), who used sources that emitted photons in pairs. Here, the registration of one of the two photons in a trigger detector indicates that a second, single photon is available for the experiment (Fig. 1). In Clauser's and in other early experiments the source was an atomic cascade where two photons are emitted, one after the other, within the lifetime of the intermediate state, which in general is very short.

Today, the source of choice for photon pair creation is the process of spontaneous parametric down-conversion (SPDC), the inverse process of frequency doubling. Both SPDC and frequency doubling are nonlinear optical processes. Whereas in frequency doubling two photons are converted into one photon of higher energy, in SPDC one photon from a pump laser beam is spontaneously converted into two photons, which emerge simultaneously[5]. Here also, registration of one of the two photons can serve as a trigger to indicate that the second photon has been generated. This results in single-photon states to a good approximation, because higher-order emission processes are negligible.

Very early on, Einstein criticized the new nature of randomness in quantum physics, most unforgettably by stating: "God does not play dice." In the light of this randomness, he also said that he would prefer to be an employee in a casino than a physicist. How would he comment on the later finding that one can construct random number generators on the basis of a single photon and a beam splitter[6], as just described? Such a quantum random number generator could well be used in a casino because of the high quality of its random sequences.

Clauser's experiment[4] contains the first demonstration of sub-poissonian photon counting statistics, which can only be understood within a quantum theory of light. Further experiments showed other purely quantum-based effects, such as the observation of photon antibunching in a resonance-fluorescence experiment[7]. These early experiments used beams of atoms as sources, where fluctuations in the atom number, and thus in the emission statistics, are unavoidable. Later, Walther's group in Munich realized such experiments using single atoms in traps[8].

Single-photon interference

One of the most fascinating phenomena is quantum interference with individual photons. The interference pattern is observed by sending particles, one by one, through, say, a double slit assembly; many particles are then collected at the observation plane. In the simplest of such experiments, the light intensity can be dimmed down far enough that only one photon at a time is inside the apparatus. This was first demonstrated by Taylor[9]. In his experiment Taylor simply had a very dim light source together with a double slit assembly and a photo plate inside a box. But the results of such experiments can easily be understood semiclassically without having to assume the existence of photons; that is, without having to quantize the electromagnetic field as discussed above.

A single-photon interference experiment was performed by Grangier *et al.*[10], who also used photon pairs emitted by atomic cascades. He and his colleagues employed a Mach–Zehnder interferometer to observe real single-photon interferences. Figure 2 shows the results of a single-photon double-slit experiment[11,12] where the photon source was parametric down-conversion. The intensities are extremely low; nevertheless, the interference pattern accumulated photon by photon shows perfect interference fringes. Experiments of this kind clearly confirm that the quantum state is not just a statistical property of an ensemble of particles; indeed, it makes very precise predictions even for individual particles. Following Feynman[13], the fact that the predictions of quantum mechanics hold for individual particles and not just for ensembles is best illustrated by the

Box 1

A heuristic concept

The way that Einstein arrives at the photon concept in his seminal paper "Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt" ("On a heuristic aspect concerning the production and transformation of light")[2] is, contrary to widespread belief, not through the photoelectric effect. Instead, Einstein compares the entropy of an ideal gas filling a given volume with the entropy of radiation filling a cavity. The logarithmic dependence on the volume of the entropy of the gas can easily be understood by referring to the connection between entropy and probability suggested by Boltzmann. Because it is less probable that the gas particles will occupy a smaller volume, such a state has a higher order, and hence lower entropy. Interestingly, for the case of radiation filling a cavity, Einstein merely uses the Wien black-body radiation density, which is known to be correct only for high radiation frequencies.

Einstein's crucial insight comes when he observes that the entropy of light in a cavity varies in exactly the same way with the volume of the cavity as the entropy of a gas. On the basis of this observation, he suggests that light also consists of particles which he calls light quanta. He clearly states that this is only a heuristic point of view and not a logically binding conclusion. Only in the last chapter (of eight) of the paper does Einstein finally get to the photoelectric effect by asking where quanta of light might have implications. He notes that it would naturally explain why the wavelength of light emitted in photoluminescence is always larger than that of the absorbed light. This is because a single particle of light is absorbed and unless additional energy is supplied, the energy of the emitted particles of light in general is lower.

When coming finally to the photoelectric effect Einstein observes that the energy of the emitted electrons, as measured by Lenard[84], can be understood quantitatively by means of his light quanta (see also Box 2). The only, but crucial, prediction he makes is that the maximum energy of the electrons must vary linearly with the frequency of the incident light. This prediction was confirmed experimentally to high precision ten years later by Millikan[85]. Millikan could extract from the slope of his measured curve a value for Planck's constant h that precisely agreed with the number found in earlier measurements of the black-body radiation. This is one of the most convincing confirmations of the idea of quanta. Millikan recalled: "I spent ten years of my life testing that 1905 equation of Einstein's and, contrary to my expectations, I was compelled in 1915 to assert its unambiguous experimental verification in spite of its unreasonableness since it seemed to violate everything that we knew about the interference of light"[86]. Indeed, while Millikan proved the validity of Einstein's equation beyond doubt, he categorically rejected Einstein's light-quantum hypothesis as an interpretation of it. Only after the discovery of the Compton effect in 1923 (ref. 87) and subsequent experiments[88] did Millikan, like many other physicists, accept Einstein's light-quantum hypothesis. These experiments established the conservation of energy and momentum of individual light quanta for the specific case of elastic scattering from electrons, and so finally made it clear that Einstein's 1905 conception was more than simply "heuristic"[89].

However, the apparent conflict between a corpuscular theory and interference could not be resolved before quantum mechanics itself was fully developed. Once Schrödinger's and Heisenberg's formulations of quantum mechanics were known, it was obvious that these should be applied to the electromagnetic cavity oscillators and eventually to the field itself[79]. QED accommodates both interference and quantization. Its fields are built on Maxwell's equations and populated with integral numbers of photons. QED gives us the fundamental properties of the photon: the photon has no rest mass, or, equivalently, moves at the vacuum speed of light. Any finite rest mass would make the vacuum dispersive and modify Coulomb's law. Experiments put an upper limit of about 10^{-50} kg on the photon mass[90]. The photon is also predicted to have zero electric charge. The experimental upper limit is approximately $10^{-17}e$ (ref. 91).

Einstein's observations about the entropy of radiation are intimately connected to the quantum statistics of photons, and from Bose's and Einstein's work we know that the photon is a boson. In accordance with the vector character of the electromagnetic field it must therefore have spin 1. Further, equivalent to the transversality of electromagnetic radiation and as a consequence of the the photon's zero rest mass, we know that only the spin eigenstates of $+1$ and -1 along its linear momentum are allowed. These give rise to the two orthogonal polarizations of light. Finally, in modern field theory the photon is the exchange particle of electromagnetic interaction and it was the first example of a gauge boson, eventually leading to the gauge theories that form today's standard model[92].

Box 2

Semiclassical radiation theories are a dead end

A fascinating irony is that the photoelectric effect, as it was known in Einstein's time, can be understood without having to assume that light, or, in modern terms, the radiation field, is quantized. It suffices to assume that the surface can only absorb or emit light in energy quanta. More generally speaking, many phenomena thought to be due to the quantum nature of light can actually be explained by using a classical electromagnetic field and by assuming that only the processes of absorption and emission are quantized. In the simplest way, this is done by assuming that the absorbers consist of oscillators which can absorb and emit radiation in quantized packets only. Among the initial advocates of this semiclassical theory, in which only the atoms are quantized while the electromagnetic field remains as classical waves, were Planck and Bohr themselves.

Bohr even pursued a wave-theoretic explanation of the Compton effect within the later refuted Bohr–Kramers–Slater (BKS) theory. It turns out, however, that semiclassical ideas cannot account for all experimental observations. Examples are experiments showing that there is no lower limit on the accumulation time of radiation energy in the photoelectric effect, which suggests an instantaneous energy transfer, such as would be expected from a particle-like interaction[93,94]. Other examples are correlation experiments related to quantum entanglement, which can in principle not be modelled by local classical theories.

Curiously, Einstein together with Podolsky and Rosen first discussed such correlations in 1935 (ref. 22) for completely different reasons and apparently without perceiving that this famous paper would eventually deliver another independent proof of the photon hypothesis. A detailed discussion of the quantum versus the semiclassical approach in the light of quantum non-locality has been given by Clauser[95]. The interested reader is referred to the accounts of Klein[96], Stachel[97], Pais[98] or Clauser[99].

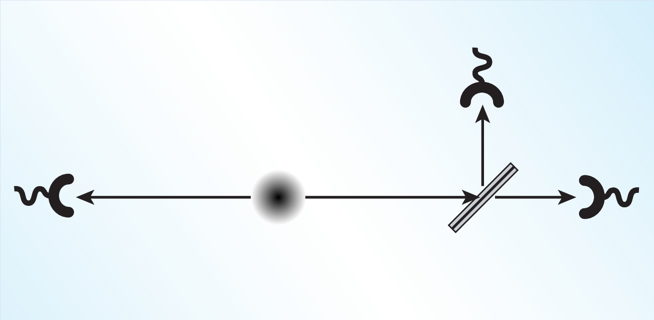

Figure 1 Principle of Clauser's experiment with correlated pairs of photons (simplified). The source emits two photons. Registration of a photon on the left detector provides the information that one and only one photon at the right side encounters a 50/50 beam splitter where it is either reflected or transmitted. The fact that only one of the two detectors behind the beam splitter registers and never both can easily be understood using the photon concept, and is in clear conflict with semiclassical theories of radiation[4].

finding that each individual photon 'knows' it should never end up in the minimum of an interference fringe.

We emphasize that the conceptual questions arising for photon interference are the same as those arising for interference of massive particles. In both cases we see particle-like and wave-like properties. An inequivalence arises for certain interference experiments[14] because the photon has no rest mass.

Two-photon interference

An interesting consequence of the bosonic character of photons is their bunching behaviour. This is seen most directly when two photons—one from each input port—are incident on a beam splitter (Fig. 3). If the two photons do not arrive simultaneously, each has a 50% chance of going either way after the beam splitter, independently of the other photon. This results in the coincidences shown. But if the photons arrive simultaneously, they become indistinguishable and end up together randomly in either beam. In the experiment the rate of coincident photon detections at the beam splitter outputs is monitored. The resulting dip in the coincidence rate is called the Hong–Ou–Mandel dip[15].

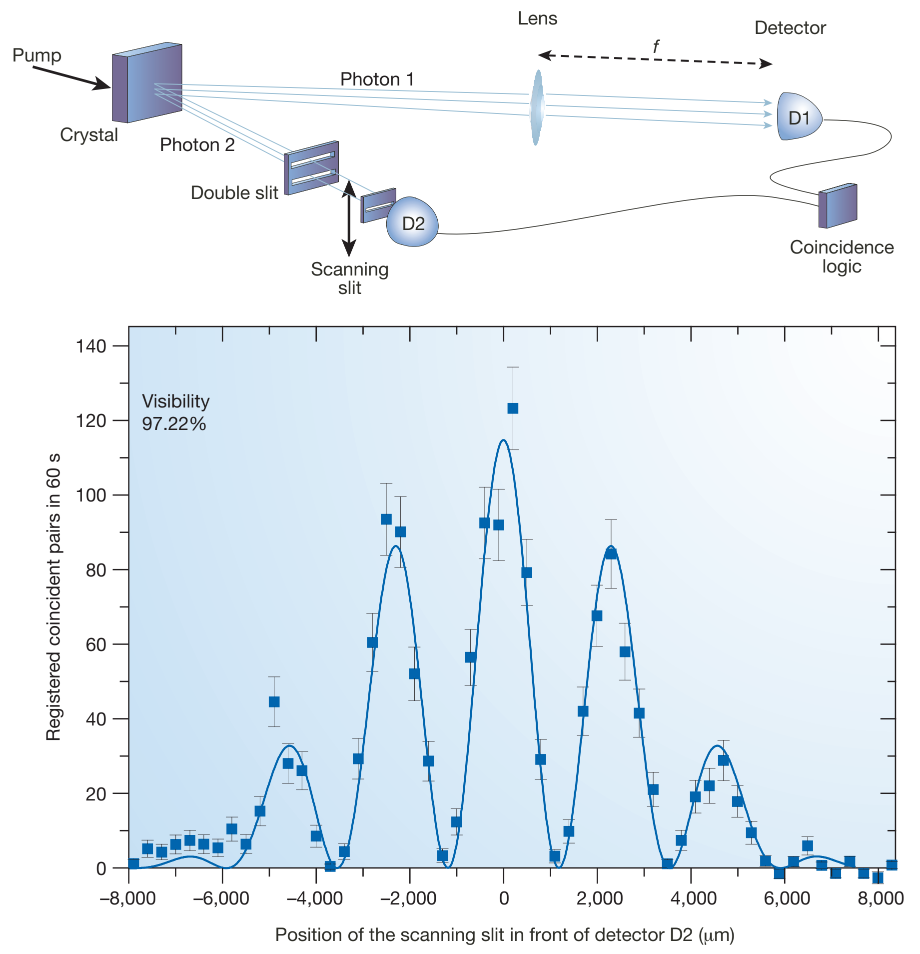

Figure 2 Single-photon double-slit interference. A pair of momentum-entangled photons is created by type-I parametric down-conversion. Photon 2 enters a double-slit assembly and photon 1 is registered by a detector D1 placed at distance *f* in the focal plane of the lens. This projects the state of photon 2 into a momentum eigenstate which cannot reveal any positional information and, hence supplies no information about slit passage. Therefore, in coincidence with a registration of photon 1 in the focal plane, photon 2 exhibits the interference pattern shown. On the other hand, when the detector is placed in the imaging plane, it does reveal the path photon 2 takes through the slit assembly, which therefore does not show the interference pattern. The observed count rate of at most two photons per second implies that the average spatial distance between photons registered would be of the order of 100,000 km or more. Therefore, most of the time the apparatus is empty (from refs 11 and 12). The error bars (s.d.) show the statistical errors of photon counting.

What happens is a quantum interference effect. The only way that one photon can arrive at each detector is if both photons are either reflected or transmitted. The detection probability in quantum physics is given by the square of the probability amplitude, which is different from squaring the actual electromagnetic field. Curiously, the probability amplitudes for these two possibilities destructively interfere with each other. This results from the well-known phase jump of 90 degrees that each photon experiences upon reflection. This implies a total phase of 180 degrees of the state |both photons reflected⟩ relative to the state |both photons transmitted⟩.

Fermions would behave differently because their quantum state is antisymmetric, as reflected by a negative sign in their initial state. In this case the two amplitudes introduced above interfere constructively and the two particles are always found in separate outputs. Interestingly, this 'fermionic' behaviour can also be observed for two photons if the photons are prepared in an antisymmetric state with respect to their spin (Fig. 3). This latter observation turned out to be crucial for many quantum information applications, specifically for quantum dense coding[16].

Complementarity, information and quantum physics

Complementarity, the mutually exclusive nature of the wave and particle concepts, has led to intense discussions. Of these, the early ones between Einstein and Bohr raised the key issues. Whereas Einstein thought that it should be possible to observe an interference pattern and at the same time know for each photon which slit it went through, Bohr was always able to show that an apparatus capable of determining the particle's path was by necessity constructed such

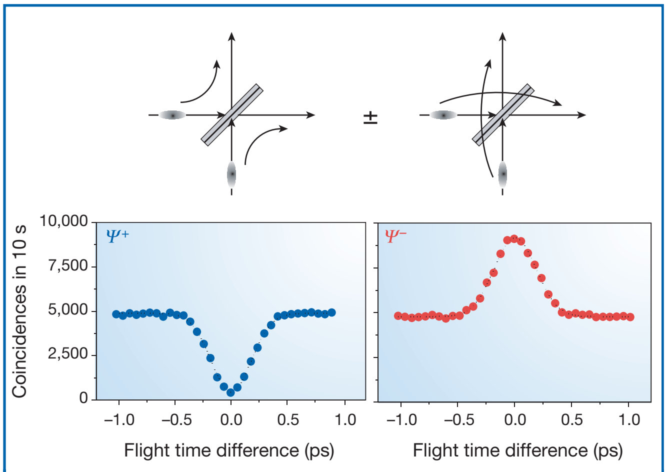

Figure 3 Bunching (left) or antibunching (right) behaviour of photon pairs. One photon each is incident from each input of a 50/50 beam splitter. Coincidences between detectors in the two output beams are registered as a function of the flight time difference of the incident photons. No coincidences are observed for zero flight time difference (left) for the usual symmetric spatial state of the two photons. This is because the probability amplitudes for the transmission of both photons and for the reflection of both photons destructively interfere: the latter one picks up a minus sign owing to the phase shift of the photons upon reflection. Interestingly, the two incident photons can also be in an antisymmetric spatial state (which occurs if the two-photon spin state is also antisymmetric). In this case, the two amplitudes interfere constructively. This results in the two photons always exiting in separate beams for zero flight time difference. The observed coincidence peak (right) confirms this expected antibunching.

that no interference pattern could arise and vice versa[17]. Today, it is thought that a perfect interference pattern arises only when there is no possible way of finding out which path the particle took. Evidently, intermediate cases are also possible, of partial path information together with non-perfect interference fringes[18]. In so-called delayed choice experiments[19,20] the decision of whether to observe path information can be delayed to when the particle is already inside the interferometer setup and even until after it has been registered. This again supports the view that the quantum state may be seen as a representation of the information about the probabilities of possible measurement results, which may include mutually exclusive, that is, complementary ones.

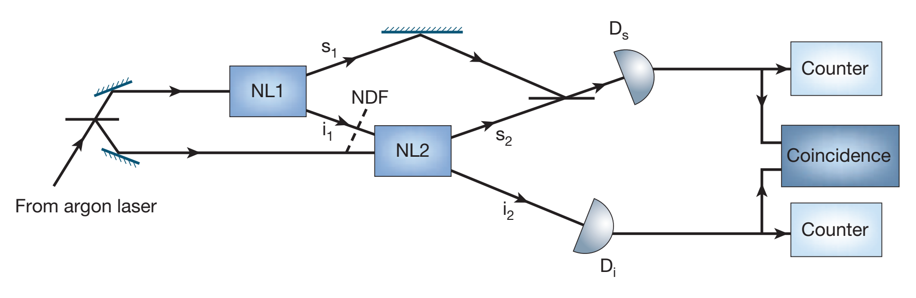

Figure 4 A mind-boggling interference experiment (from ref. 21). Two nonlinear crystals NL1 and NL2 are pumped by the same laser and produce one pair of photons in the superposition of being in beams s_1 and i_1, or in beams s_2 and i_2. After transmission through NL2, the photons from i_1 are indistinguishable from photons in i_2 and thus the original distinguishability of the path of s_1 and s_2 disappears, and quantum interference is observed for pairs of photons that are detected in coincidence between detectors D_i and D_s. Insertion of an absorber (neutral density filter, NDF) can be used gradually to introduce distinguishability and thus to make the interference disappear. Note that no disturbance whatsoever acts on the interfering photon in beams s_1 and s_2.

An experiment supporting the information aspect of quantum interference[21] has been performed by Mandel's group at Rochester as part of a series of ground-breaking experiments on the quantum nature of light. In their experiment (Fig. 4), they used the emission of one photon pair from two down-conversion crystals. One photon passed a modified Mach–Zehnder interferometer, and what happened to the other photon decided whether the first photon showed interference or not. Thus, the still widespread view that the act of determining the path taken by the particle disturbs its state enough to destroy the interference is untenable. The key factor is whether path information is available: it does not matter if someone takes care to read it out or not. Indeed, there have even been experiments where the path information carried by the second particle is destroyed after the particle passing through the double slit has already been registered. Here, the interference pattern is still observed. The double-slit diffraction pattern shown in Fig. 2 was obtained in this way.

When analysing quantum interference we can fall into all kinds of traps. The general conceptual problem is that we tend to reify — to take too realistically — concepts like wave and particle. Indeed if we consider the quantum state representing the wave simply as a calculational tool, problems do not arise. In this case, we should not talk about a wave propagating through the double-slit setup or through a Mach–Zehnder interferometer; the quantum state is simply a tool to calculate probabilities. Probabilities of the photon being somewhere? No, we should be even more cautious and only talk about probabilities of a photon detector firing if it is placed somewhere. One might be tempted, as was Einstein[2], to consider the photon as being localized at some place with us just not knowing that place. But, whenever we talk about a particle, or more specifically a photon, we should only mean that which a 'click in the detector' refers to.

Nonlocality, Bell and GHZ

Einstein did not only criticize quantum mechanics for the new role of randomness mentioned above. His criticism went much further in his insistence on the existence of a real factual world and on the role of physics to describe that reality. This criticism forms the basis of his famous article published in 1935, together with Podolsky and Rosen. The Einstein–Podolsky–Rosen (EPR) paper[22] makes use of correlations shown by entangled quantum states. Bell discovered in 1964 (ref. 23) that the predictions of quantum physics for these correlations are at variance with a local realistic world view. Such a classically intuitive view holds that the outcome of a measurement on a physical system is determined by physical properties of the system prior to and independent of the measurement (realism), and that the outcome cannot depend on any actions in space-like separated regions (Einstein locality). The quantum correlations are too strong to be reproduced by any such model. After the initial experiments by Freedman and Clauser[24], and the much refined experiments by Aspect[25] (Fig. 5) confirming the quantum predictions, two loopholes remained open. Thus, a local realistic viewpoint remained at least logically possible. The first loophole, the so-called communication loophole, used the fact that even before the two photons are registered, the apparatus settings could be communicated to detectors and/or to the source. A beautiful experiment to close this loophole using periodically switched time-dependent polarizer settings was performed by Aspect in 1982 (ref. 26). The loophole was more decisively ruled out by an experiment of Weihs *et al.*[27] where the measurement settings

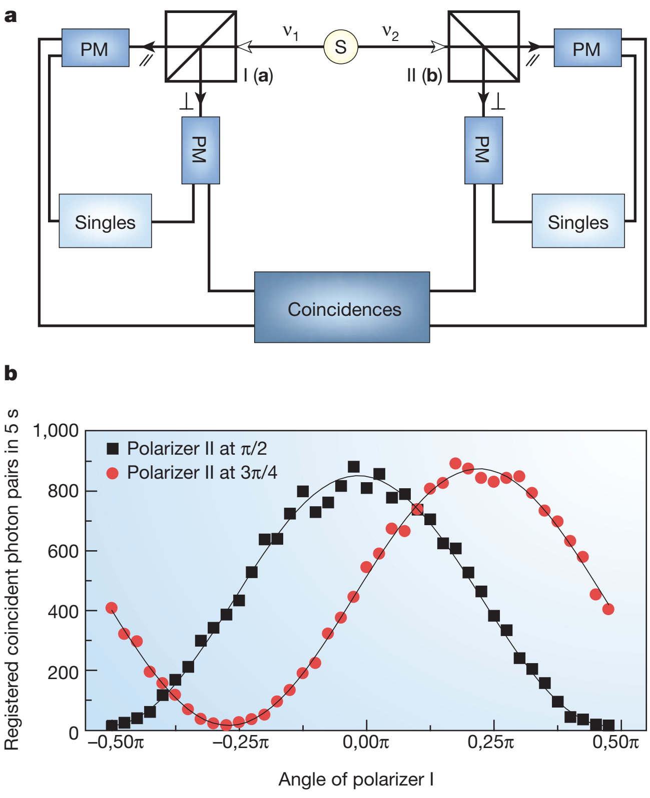

Figure 5 Bell tests violating local realistic predictions. **a**, Setup of the experimental test of Bell's inequality with correlated photon pairs produced by atomic cascade relaxation (from ref. 25). The two photons ν_1 and ν_2 are analysed in separate polarizers (I in direction **a** and II in direction **b**), and detected with photomultipliers (PM). A dedicated electronic circuit is used to determine the coincidences, which are included in evaluating the correlation terms in Bell's inequality. This and several other similar experiments proved with high significance that real particles follow the prediction of quantum mechanics, and violate the limits imposed by local realistic theories. **b**, Correlation curves (from ref. 27) in a Bell inequality experiment. A characteristic of such experiments is that the correlation depends on the difference angle of the analysers only and not on any of their absolute values.

were changed randomly and fast with respect to the distance between the stations. This left only the so-called detection loophole open, which implied that although all photon pairs would obey local realism and hence be at variance with quantum physics, the small detected subset confirmed quantum mechanics. Since the detection efficiencies were far from ideal, such reasoning could not be ruled out. This latter loophole was closed in an experiment on entanglement between two ions in a cavity[28], in which it was possible to detect nearly all entangled pairs. So, although both remaining loopholes have now been closed in separate experiments, the logical possibility exists that nature tricks us and makes use of different loopholes in different experiments. Although no one reasonably assumes nature to be so capricious, a future experiment that closes both loopholes together would still be interesting.

The conflict of local realism with quantum mechanics, first exposed by Bell for entangled pairs, is even more striking for three or more entangled particles. For the so-called GHZ (Greenberger–Horne–Zeilinger) states[29,30], situations exist for which a local realist and a quantum mechanic make completely opposite predictions, even for individual measurement results on one photon. Needless to say, experiments[31] have confirmed the quantum prediction (Fig. 6).

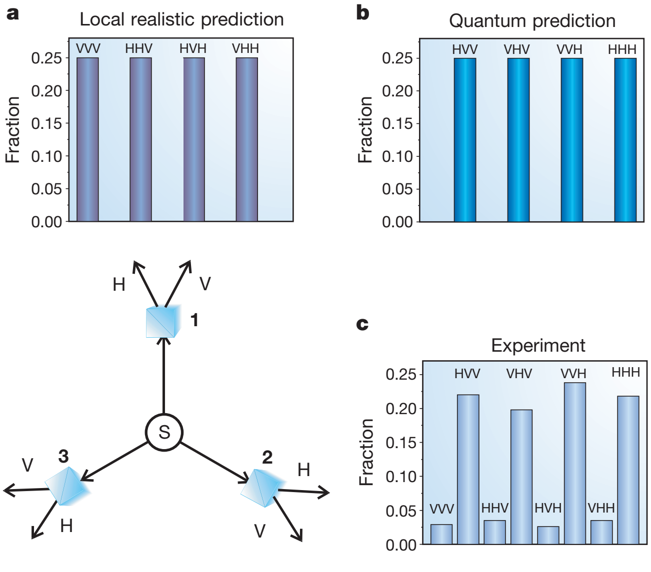

Figure 6 Sketch of an experimental test of the GHZ argument against local realistic theories (from ref. 31). A source (S) emits polarization entangled photon triplets in a GHZ state (bottom left). Measurements in three different combinations of circular and diagonal polarization (not shown) show perfect correlation. These correlations define local realistic elements of reality, which lead to definite predictions (**a**) for a measurement in all diagonal polarization bases. The quantum predictions (**b**) are exactly opposite. **c**, The experimental relative frequencies of triple coincidences behind polarizers 1, 2 and 3. For example, for photons 2 and 3, which are both horizontally (H) polarized, local realism (**a**) predicts the first photon to be vertically (V) polarized, quantum mechanics (**b**) predicts it to be H polarized, and experiment (**c**) confirms the predictions of quantum mechanics within experimental accuracy.

Photons, atoms and beyond

As mentioned above, the initial question of whether it is only matter or also radiation that is quantized has finally been settled in favour of the photon. It has now become possible to investigate the interaction between photons and atoms in great detail. For example, Kimble's group at Caltech[32] showed that it was possible to observe the phase shift experienced by an atom while it interacted with a field of, on average, less than one photon. Haroche and his group at the École Normale in Paris[33] were able to construct entangled states between single photons trapped in a high-finesse cavity and atoms passing through (Fig. 7). Such experiments have also been used to demonstrate several interesting aspects, such as time-resolved quantum interference phenomena[34], trapping of atoms with single photons[35,36] or quantum non-demolition measurements, in which the presence of single photons can be determined without destroying the photon[37].

Quantum information processing with photons

In the emerging field of quantum information technology the two basic subfields are quantum communication and quantum computation. The photon has been put to work in recent years, particularly in new concepts of communication. In quantum cryptography the complementarity of different measurements on a quantum system[38–40] is used to establish a secure key between two partners. In quantum teleportation[41,42] it is possible to transfer the quantum state of independent particles from one system to another by employing entangled states as a quantum information channel.

When turning to future challenges and developments, it is likely that the photon will have a significant role in quantum communication. The currently most advanced source for entanglement, an important resource for quantum information processing, is photon

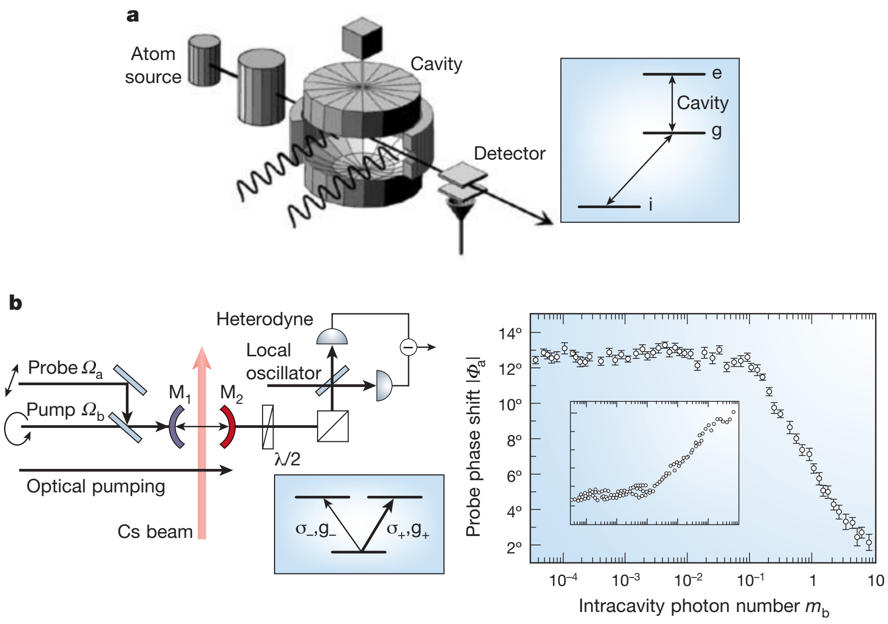

Figure 7 Photon–atom interaction. **a**, The strong coupling of light modes in a cavity, through which excited atoms pass, is used to perform a controlled quantum phase gate between the state of an atom and a photon (i, e and g are the internal states of the atom where e and g are coupled by means of the cavity photon). This operation is required to create entanglement between the atom and the photon (from ref. 82). **b**, Caesium (Cs) atoms passing through a high finesse optical cavity formed by two mirrors, M_1 and M_2, lead to a phase shift on a probe beam. The experimental data clearly show that even with a mean photon number below one, the probe beam will pick up a significant phase shift (from ref. 32).

pairs generated in SPDC (ref. 43). Moreover, only with photons is it possible to cover large distances outside the protected environment of the laboratory. There have been experiments transporting entangled states over more than 10 km using glass fibres[44] and across the river Danube in free space[45]. Quantum cryptography, with faint laser pulses containing less than one photon on average, has been tested in free space for distances of more than 20 km (ref. 46) — even in daylight[47] — and in optical fibres for a physical separation of 67 km (ref. 48). Furthermore, quantum communication through satellites is the only possible way to cover global distances. Satellite-based quantum communication may very well be realized within the next decade.

In terms of technical applications of the photon idea, the most advanced is quantum cryptography[49,50] (Fig. 8). Prototype devices are already on the market and the development of systems that are suitable for the security industry is well under way. Quantum teleportation might one day provide useful communication links between yet-to-be-developed quantum computers. Initial tests of long-distance quantum teleportation have recently been performed in Geneva[51] and in Vienna[52]. The latter was a real field test that even included active feed-forward of measurement results (Fig. 9). An important extension of teleportation in this sense will be quantum repeaters[53], a combination of entanglement swapping (that is, the teleportation of an entangled state)[54,55] and local atomic memories of quantum information, which also exploit the atom–photon interface[56,57]. The development of these applications is intimately connected to the development of the quantum computer itself.

Although for quantum communication the obvious choice is photons, for quantum computation, implementations in localized systems like atoms, ions or solid-state devices seem to be preferable. Yet, surprisingly, even for implementing quantum computation algorithms, photons offer interesting possibilities, despite the considerable difficulty of storing them for a long time. After the discovery that some gates could be realized through teleportation[58], an important breakthrough was the suggestion by Knill *et al.*[59] that even with linear optical elements, universal quantum computation could be realized. Following these suggestions, various quantum computation primitives have been demonstrated with photons alone — including conditional phase shift operations[60], and destructive[61,62] and even non-destructive controlled NOT (CNOT) gates[63]. All these schemes use unentangled states as inputs on which the quantum gates operate. A new and probably more practical approach is the concept of a 'one-way quantum computer'[64] that realizes universal quantum computation in a way that is totally different from that used by existing quantum computing schemes. Here, the idea is to start with a general, highly entangled multi-qubit state. The computation is then performed by applying a sequence of simple one-particle measurements, specific to the algorithm implemented. This new approach uses highly entangled cluster states, which recently have been realized with photons and applied to demonstrate elementary quantum gates[65]. Entangled multiparticle states also have a significant role in other new protocols of quantum information. For example, quantum error correction is based on such states[66,67].

Many laboratories all over the world are working towards developing many different physical implementations both of quantum communication devices and of quantum computers, and it will be interesting to see which technology will be the best. Yet, we are convinced that some day in the future, the present classical information technology will be replaced by a quantum one, even if this is only because of the continuing miniaturization of switching elements in computer chips.

For future technological developments, new sources for single-photon states will be needed. The most basic of such sources would be a single-photon source that, on demand, produces one, and only one, photon at a specific time and not at random. There has been important progress over the past few years in this field from various directions, including atoms in cavities[68,69] and solid-state devices such as cavity-coupled quantum dots[70]. An extensive account of such activities has recently been collected by Grangier *et al.*[71]. More generally, it would be good to have sources that produce any specific multiphoton state, even entangled ones, on demand. Promising experiments along this line have been performed in the context of cavity quantum electrodynamics (QED; ref. 72). Also, more efficient photon detectors are needed that operate over a broader wavelength range than those currently available. A particularly interesting development would be a detector that is able to discriminate clearly between 1, 2, 3 … *N* photons. Initial results discriminating between one and two photons have been reported, for example, by Yamamoto's group[73], by using a visible-light photon counter (VLPC). In the far future, a detector that identifies deterministically an arbitrary *N*-photon state would be useful.

We have been able to give only a glimpse of the vast expanse of implications and applications of the photon concept, and of quantum

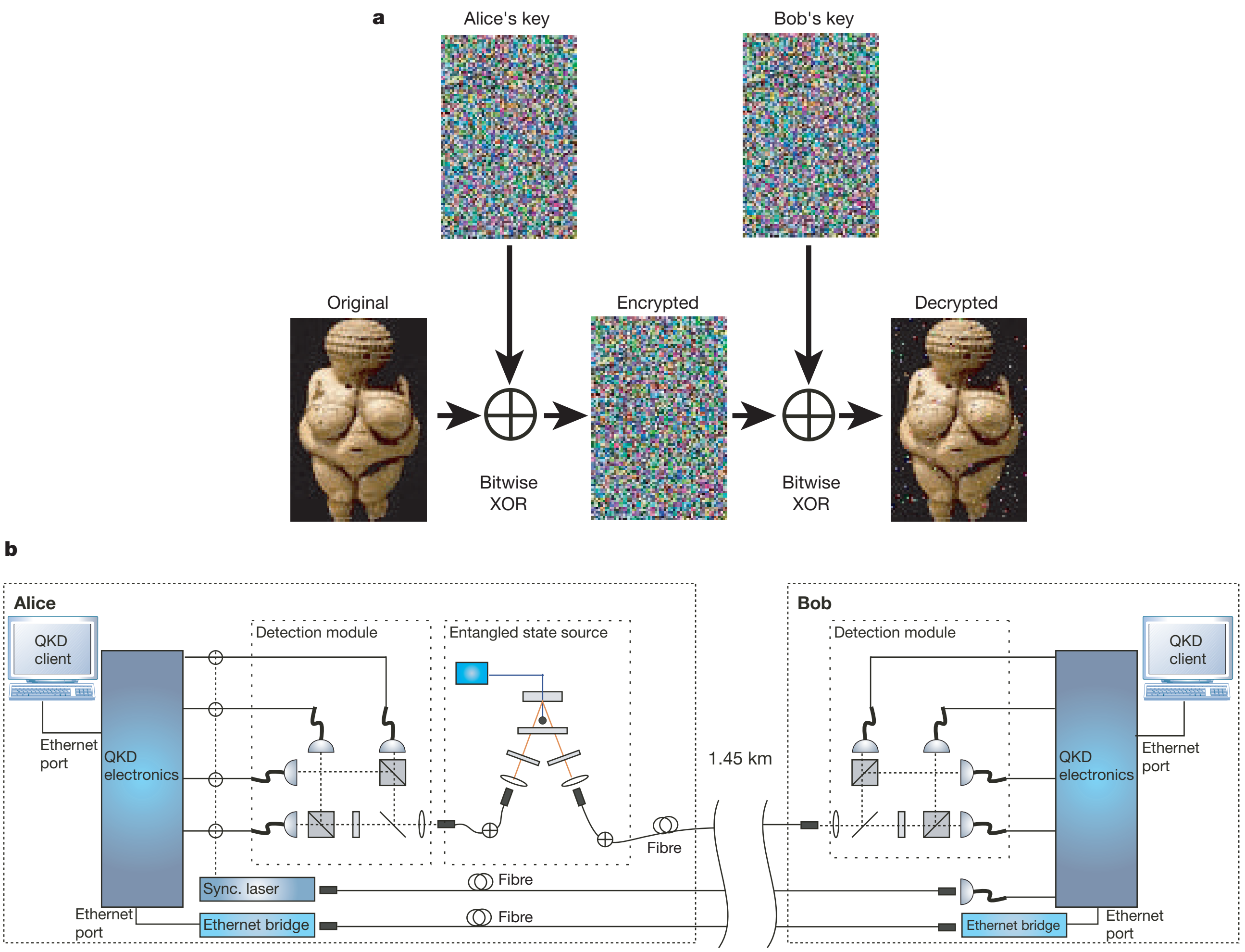

Figure 8 Quantum cryptography in practice. Entangled pairs of photons are used to generate secure keys at Alice's and Bob's distant stations. The local measurement outcomes at Alice are completely random but correlated to the results at Bob. Thus, a cryptographic key is created whose security rests only on the principles of quantum physics. **a**, The secure transmission of an image of the 'Venus of Willendorf' over 350 m (ref. 83). **b**, Experimental setup of a prototype system for entangled photon quantum key distribution (QKD), which has even been used in a real world demonstration — to securely transfer money into a bank account (from ref. 50).

optics in general. Also deserving a mention is the wide field of experiments on squeezed states initialized by Slusher *et al.*[74] and rapidly expanded by others. These include continuous-variable demonstrations of quantum teleportation[75], of quantum optics in phase space[76,77], and of quantum cryptography[78]. Here, phenomena are studied that are a consequence of the quantization of the electromagnetic field[79]. But in general, the concept of the photon as an individual particle is less important here.

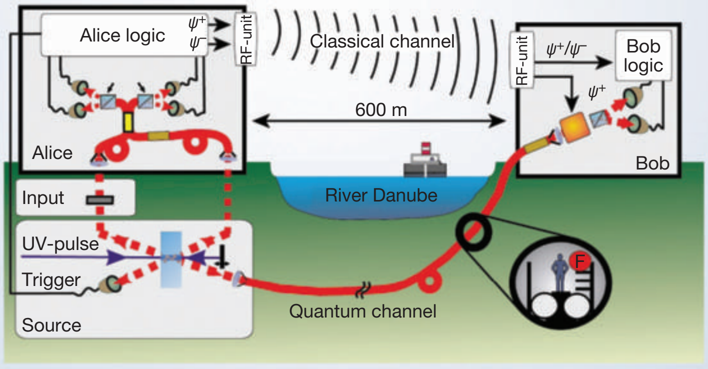

Figure 9 Schematic setup of quantum state teleportation across the river Danube (from ref. 52). The polarization state of a photon is transferred from Alice to Bob through the use of a quantum channel (entangled photons) and a classical channel (microwave pulses). Bob was able to regain the original photon state with a fidelity as high as 90%, which is clearly above the limits imposed by classical concepts.

Conclusion

Evidently, Einstein's 1905 proposal of the photon concept has had tremendous impact. But Einstein should also be highly credited for his various criticisms of quantum physics that were part of the early debate with his contemporaries (including Bohr). They triggered a body of both theory and experiments concerned with individual quantum systems. In this context, experiments with photons have had a pioneering role. Although such experiments now rule out Einstein's point of view, they gave rise to the new fields of quantum information processing. But the conceptual problems are not fully settled. This is signified by the wide spectrum of different interpretations of quantum physics that compete with each other. In our view, a common trait of many interpretations is that entities are taken to be 'real' beyond necessity. This is most obvious for the case of the 'many-worlds interpretation'[80] where the coexistence of parallel worlds is claimed without compelling evidence, but it also holds, for example, for the Bohm interpretation[81] where, again without compelling evidence, each particle is given a well-defined position and momentum at any time. We suggest that these are simply attempts to keep, in one way or other, a realistic view of the world. It may well be that in the future, quantum physics will be superseded by a new theory, but it is likely that this will be much more radical than anything we have today. ☐

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