Happy centenary, photon

Anton Zeilinger[1,2], Gregor Weihs[1], Thomas Jennewein[2] & Markus Aspelmeyer[1]

[1]*Institute for Experimental Physics, University of Vienna, Boltzmanngasse 5, A-1090 Vienna, Austria (e-mail: zeilinger-office@quantum.at)*
[2]*Institute for Quantum Optics and Quantum Information (IQOQI), Austrian Academy of Sciences, Boltzmanngasse 3, A-1090 Vienna, Austria*

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 semiclassical 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 photo-luminescence 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 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].

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.

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].

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
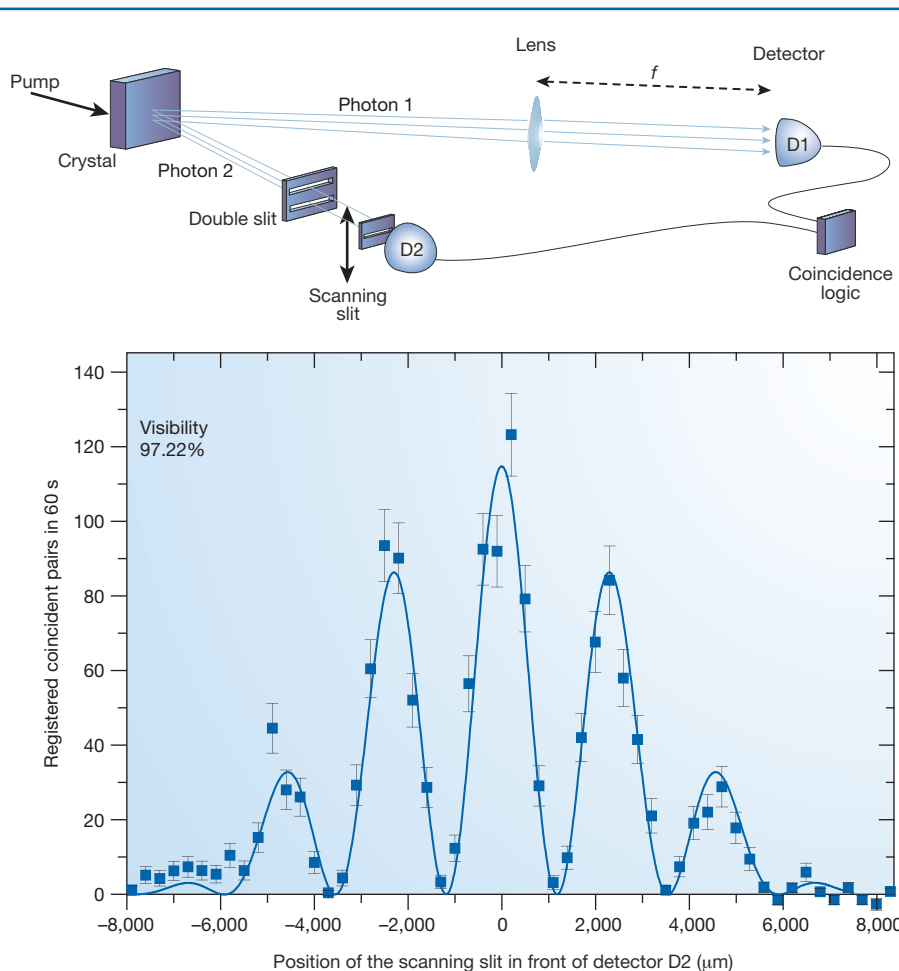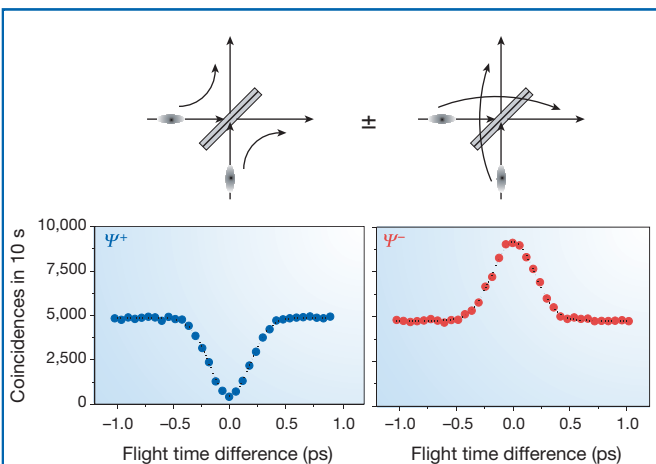
Figure 3 Bunching (left) or antibunching (right) behaviour of photon pairs. One photon each is incident from each input of a 50/50 beam splitter. Coincidences between detectors in the two output beams are registered as a function of the flight time difference of the incident photons. No coincidences 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.
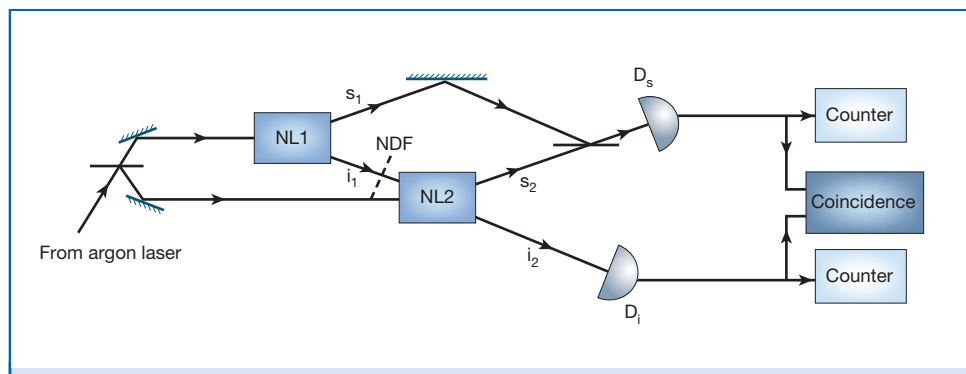
An experiment supporting the information aspect of quantum interference[21] has been performed by Mandel's group at Rochester as part of a series of ground-breaking experiments on the quantum nature of light. In their experiment (Fig. 4), they used the emission of one photon pair from two down-conversion 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 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.
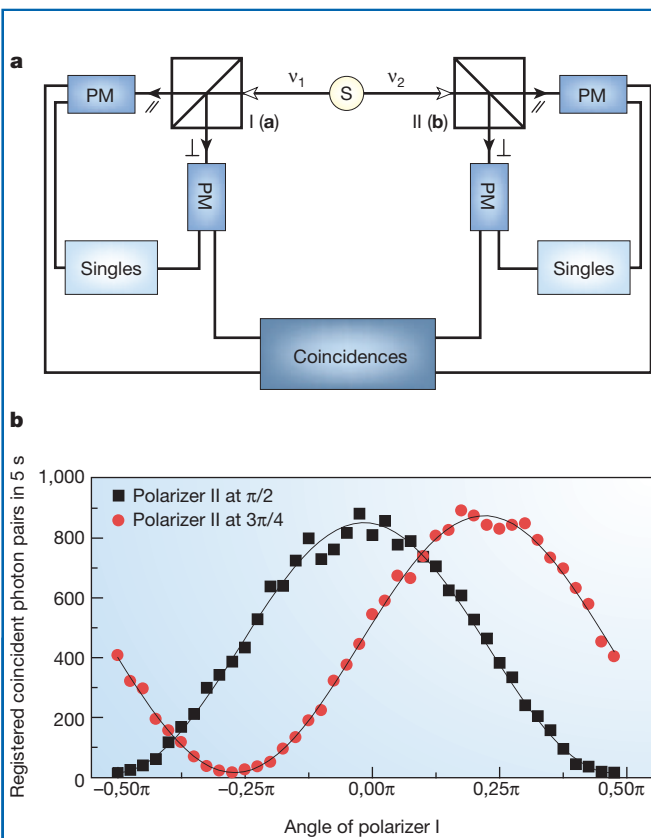
Figure 5 Bell tests violating local realistic predictions. **a**, Setup of the experimental test of Bell's inequality with correlated photon pairs produced by atomic cascade relaxation (from ref. 25). The two photons ν_1 and ν_2 are analysed in separate polarizers (I in direction **a** and II in direction **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.
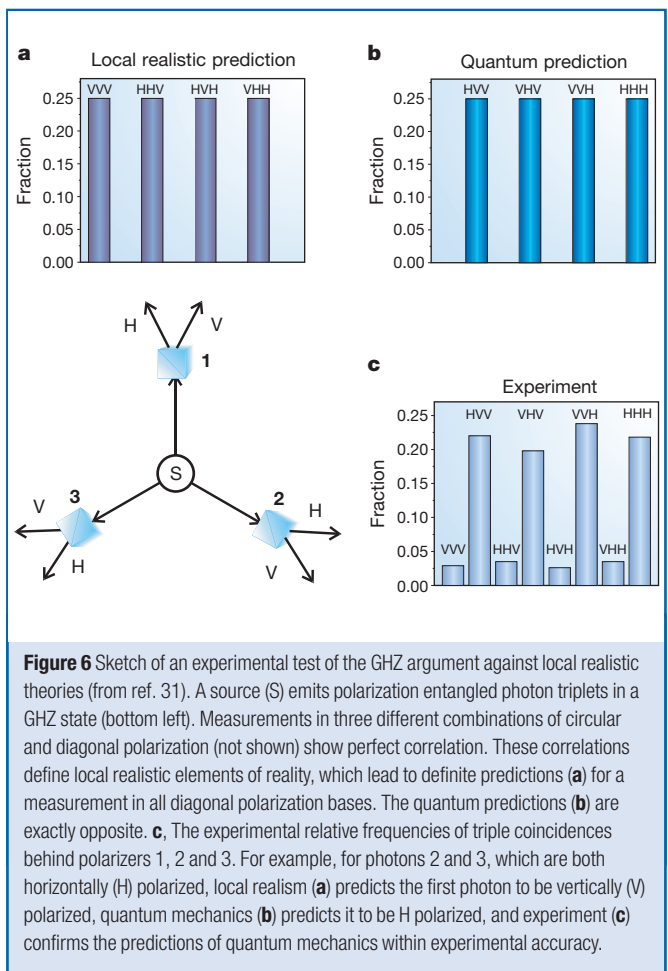

Figure 6 Sketch of an experimental test of the GHZ argument against local realistic theories (from ref. 31). A source (S) emits polarization entangled photon triplets in a GHZ state (bottom left). Measurements in three different combinations of circular and diagonal polarization (not shown) show perfect 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.

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).

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
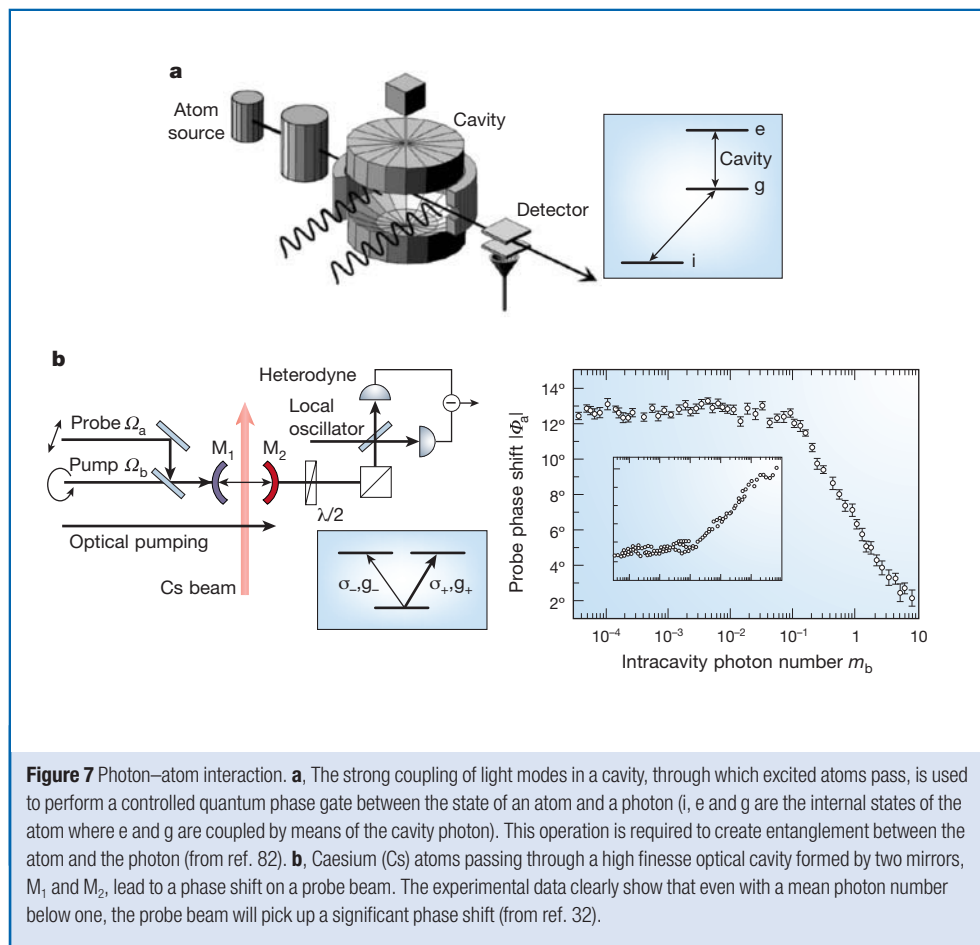
Figure 7 Photon–atom interaction. **a**, The strong coupling of light modes in a cavity, through which excited atoms pass, is used to perform a controlled quantum phase gate between the state of an atom and a photon (i, e and g are the internal states of the atom where e and g are coupled by means of 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).

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 multi-particle 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
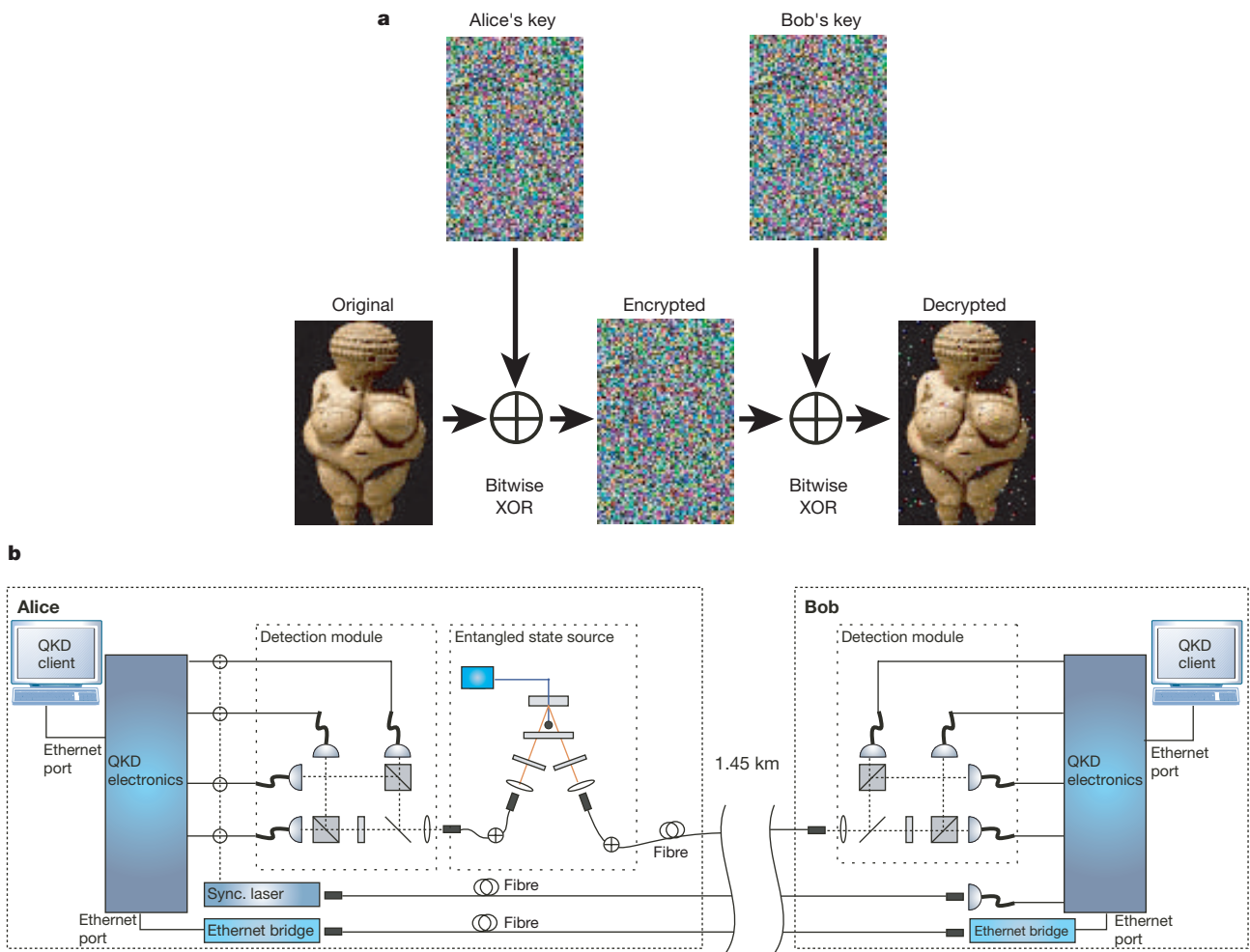
pairs generated in SPDC (ref. 43). Moreover, only with photons is it possible to cover large distances outside the protected environment of the laboratory. There have been experiments transporting entangled states over more than 10 km using glass fibres[44] and across the river Danube in free space[45]. 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

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.
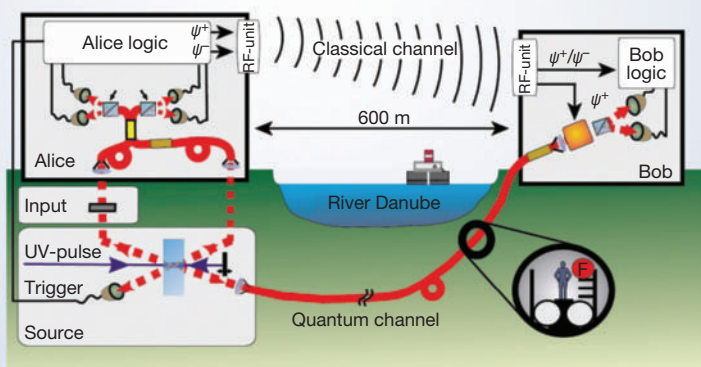

Figure 9 Schematic setup of quantum state teleportation across the river Danube (from ref. 52). The polarization state of a photon is transferred from Alice to Bob through the use of a quantum channel (entangled photons) and a classical channel (microwave pulses). Bob was able to regain the original 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. □

doi:10.1038/nature03280

1. Einstein, A. Zur Elektrodynamik bewegter Körper. *Ann. Phys.* **17**, 891–921 (1905).
2. Einstein, A. Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt. *Ann. Phys.* **17**, 132–148 (1905).
3. Lewis, G. N. The conservation of photons. *Nature* **118**, 874–875 (1926).
4. Clauser, J. F. Experimental distinction between the classical and quantum field-theoretic predictions for the photoelectric effect. *Phys. Rev. D* **9**, 853–860 (1974).
5. Burnham, D. C. & Weinberg, D. L. Observation of simultaneity in parametric production of optical photon pairs. *Phys. Rev. Lett.* **25**, 84–87 (1970).
6. Jennewein, T., Achleitner, U., Weihs, G., Weinfurter, H. & Zeilinger, A. A fast and compact quantum random number generator. *Rev. Sci. Instrum.* **71**, 1675–1680 (2000).
7. Kimble, H. J., Dagenais, M. & Mandel, L. Photon antibunching in resonance fluorescence. *Phys. Rev. Lett.* **39**, 691–695 (1976).
8. Diedrich, F. & Walther, H. Nonclassical radiation of a single stored ion. *Phys. Rev. Lett.* **58**, 203–206 (1987).
9. Taylor, G. I. Interference fringes with feeble light. *Proc. Camb. Phil. Soc. Math. Phys. Sci.* **15**, 114–115 (1909).
10. Grangier, P., Roger, G. & Aspect, A. Experimental evidence for a photon anticorrelation effect on a beam splitter: a new light on single-photon interference. *Europhys. Lett.* **1**, 173–179 (1986).
11. Dopfer, B. *Zwei Experimente zur Interferenz von Zwei-Photon Zuständen: Ein Heisenbergmikroskop und Pendellösung*. PhD thesis, Universtät Innsbruck (1998).
12. Zeilinger, A. Experiment and the foundations of quantum physics. *Rev. Mod. Phys.* **71**, S288–S297 (2000).
13. Feynman, R. P., Leighton, R. B. & Sands, M. L. *The Feynman Lectures on Physics* Vol. 3 (Addison-Wesley, Massachusetts, 1965).
14. Brukner, C. & Zeilinger, A. Nonequivalence between stationary matter wave optics and stationary light optics. *Phys. Rev. Lett.* **79**, 2599–2603 (1997).
15. Hong, C. K., Ou, Z. Y. & Mandel, L. Measurement of subpicosecond time intervals between two photons by interference. *Phys. Rev. Lett.* **59**, 2044–2046 (1987).
16. Mattle, K., Weinfurter, H., Kwiat, P. G. & Zeilinger, A. Dense coding in experimental quantum communication. *Phys. Rev. Lett.* **76**, 4656–4659 (1996).
17. Bohr, N. in *Albert Einstein: Philosopher-Scientist VII* (ed. Schilipp, P. A.) Vol. 7, 201–241 (Library of Living Philosophers, Evanston, 1949).
18. Englert, B.-G. Fringe visibility and which-way information: An inequality. *Phys. Rev. Lett.* **77**, 2154–2157 (1997).
19. Wheeler, J. A. in *Problems in the Foundations of Physics*. *Proc. Intl. School of Physics 'Enrico Fermi', Course LXXII.* (ed. di Francia, G. T.) 395–492 (North-Hollands, Amsterdam, 1979).
20. Scully, M. O. & Drühl, K. Quantum eraser: A proposed photon correlation experiment concerning observation and "delayed choice" in quantum mechanics. *Phys. Rev. A* **25**, 2208–2213 (1982).
21. Zou, X. Y., Wang, L. J. & Mandel, L. Induced coherence and indistinguishability in optical interference. *Phys. Rev. Lett.* **67**, 318–321 (1991).
22. Einstein, A., Podolsky, B. & Rosen, N. Can quantum mechanical description of physical reality be considered complete? *Phys. Rev.* **47**, 777–780 (1935).
23. Bell, J. S. On the Einstein Podolsky Rosen paradox. *Physics* **1**, 195–200 (1964).
24. Freedman, S. J. & Clauser, J. F. Experimental test of local hidden-variable theories. *Phys. Rev. Lett.* **28**, 938–941 (1972).
25. Aspect, A., Grangier, P. & Roger, G. Experimental realization of Einstein-Podolsky-Rosen-Bohm Gedankenexperiment: A new violation of Bell's inequalities. *Phys. Rev. Lett.* **49**, 91–94 (1982).
26. Aspect, A., Dalibard, J. & Roger, G. Experimental test of Bell's inequalities using time-varying analyzers. *Phys. Rev. Lett.* **49**, 1804–1807 (1982).
27. Weihs, G., Jennewein, T., Simon, C., Weinfurter, H. & Zeilinger, A. Violation of Bell's inequality under strict Einstein locality conditions. *Phys. Rev. Lett.* **81**, 5039–5043 (1998).
28. Rowe, M. A. et al. Experimental violation of a Bell's inequality with efficient detection. *Nature* **409**, 791–794 (2001).
29. Greenberger, D. M., Horne, M. A. & Zeilinger, A. in *Bell's Theorem, Quantum Theory, and Conceptions of the Universe* (ed. Kafatos, M.) 73–76 (Kluwer, Dordrecht, 1989).
30. Greenberger, D. M., Horne, M. A., Shimony, A. & Zeilinger, A. Bell's theorem without inequalities. *Am. J. Phys.* **58**, 1131–1143 (1990).
31. Pan, J.-W., Bouwmeester, D., Daniell, M., Weinfurter, H. & Zeilinger, A. Experimental test of quantum nonlocality in three-photon Greenberger–Horne–Zeilinger entanglement. *Nature* **403**, 515–518 (2000).
32. Turchette, Q. A., Hood, C. J., Lange, W., Mabuchi, H. & Kimble, H. J. Measurement of conditional phase shifts for quantum logic. *Phys. Rev. Lett.* **75**, 4710–4713 (1995).
33. Rauschenbeutel, A. et al. Step-by-step engineered multiparticle entanglement. *Science* **288**, 2024–2028 (2000).
34. Legero, T., Wilk, T., Kuhn, A. & Rempe, G. Time-resolved two-photon quantum interference. *Appl. Phys. B* **77**, 797–802 (2003).
35. Pinkse, P., Fischer, T., Maunz, P. & Rempe, G. Trapping an atom with single photons. *Nature* **404**, 365–368 (2000).
36. Hood, C. J., Lynn, T. W., Doherty, A. C., Parkins, A. S. & Kimble, H. J. The atom-cavity microscope: Single atoms bound in orbit by single photons. *Science* **287**, 1447–1453 (2000).
37. Nogues, G. et al. Seeing a single photon without destroying it. *Nature* **400**, 239–242 (1999).
38. Wiesner, S. Conjugate coding. *SIGACT News* **15**, 78–88 (1983).
39. Bennett, C. H. & Brassard, G. in *Proc. IEEE Intl.Conf. on Computers, Systems and Signal Processing* 175–179 (IEEE, Bangalore, 1984).
40. Ekert, A. K. Quantum cryptography based on Bell's theorem. *Phys. Rev. Lett.* **67**, 661–663 (1991).
41. Bennett, C. H. et al. Teleporting an unknown quantum state via dual classical and Einstein-Podolsky-Rosen channels. *Phys. Rev. Lett.* **70**, 1895–1899 (1993).
42. Bouwmeester, D. et al. Experimental quantum teleportation. *Nature* **390**, 575–579 (1997).
43. Kwiat, P. G. et al. New high-intensity source of polarization-entangled photon pairs. *Phys. Rev. Lett.* **75**, 4337–4341 (1995).
44. Tittel, W., Brendel, J., Zbinden, H. & Gisin, N. Violation of Bell inequalities by photons more than 10 km apart. *Phys. Rev. Lett.* **81**, 3563–3566 (1998).
45. Aspelmeyer, M. et al. Long-distance free-space distribution of quantum entanglement. *Science* **301**, 621–623 (2003).
46. Kurtsiefer, C. et al. A step towards global key distribution. *Nature* **419**, 450 (2002).
47. Hughes, R. J., Nordholt, J. E., Derkacs, D. & Peterson, C. G. Practical free-space quantum key distribution over 10 km in daylight and at night. *New J. Phys.* **4** 43, 1–43 (2002).
48. Stucki, D., Gisin, N., Guinnard, O., Ribordy, G. & Zbinden, H. Quantum key distribution over 67 km with a plug&play system. *New J. Phys.* **4** 41, 1–41 (2002).
49. Gisin, N., Ribordy, G., Tittel, W. & Zbinden, H. Quantum cryptography. *Rev. Mod. Phys.* **74**, 145–195 (2002).
50. Poppe, A. et al. Practical quantum key distribution with polarization entangled photons. *Opt. Express* **12**, 3865–3871 (2004).
51. Marcikic, I., de Riedmatten, H., Tittel, W., Zbinden, H. & Gisin, N. Long-distance teleportation of qubits at telecommunication wavelengths. *Nature* **421**, 509–513 (2003).
52. Ursin, R. et al. Quantum teleportation across the Danube. *Nature* **430**, 849 (2004).
53. Briegel, H.-J., Dür, W., Cirac, J. I. & Zoller, P. Quantum repeaters: The role of imperfect local operations in quantum communication. *Phys. Rev. Lett.* **81**, 5932–5935 (1998).
54. Żukowski, M., Zeilinger, A., Horne, M. A. & Ekert, A. K. "Event-ready-detectors" Bell experiment via entanglement swapping. *Phys. Rev. Lett.* **71**, 4287–4290 (1993).
55. Jennewein, T., Weihs, G., Pan, J.-W. & Zeilinger, A. Experimental nonlocality proof of quantum teleportation and entanglement swapping. *Phys. Rev. Lett.* **88**, 017903 (2002).
56. Blinov, B. B., Moehring, D. L., Duan, L.-M. & Monroe, C. Observation of entanglement between a single trapped atom and a single photon. *Nature* **428**, 153–157 (2004).
57. Julsgaard, B., Sherson, J., Cirac, J. I., Fiurasek, J. & Polzik, E. S. Experimental demonstration of quantum memory for light. *Nature* **432**, 482–486 (2004).
58. Gottesman, D. & Chuang, I. L. Demonstrating the viability of universal quantum computation using teleportation and single-qubit operations. *Nature* **402**, 390–393 (1999).
59. Knill, E., Laflamme, R. & Milburn, G. A scheme for efficient quantum computation with linear optics. *Nature* **409**, 46–52 (2001).
60. Sanaka, K., Jennewein, T., Pan, J.-W., Resch, K. & Zeilinger, A. Experimental nonlinear sign shift for linear optics quantum computation. *Phys. Rev. Lett.* **92**, 017902 (2004).
61. Pittman, T. B., Fitch, M. J., Jacobs, B. C. & Franson, J. D. Experimental controlled-NOT logic gate for single photons in the coincidence basis. *Phys. Rev. A* **68**, 032316 (2003).
62. O'Brien, J. L., Pryde, G. J., White, A. G., Ralph, T. C. & Branning, D. Demonstration of an all-optical quantum controlled-NOT gate. *Nature* **426**, 264–267 (2003).
63. Gasparoni, S., Pan, J.-W., Walther, P., Rudolph, T. & Zeilinger, A. Realization of a photonic controlled-NOT gate sufficient for quantum computation. *Phys. Rev. Lett.* **93**, 020504 (2004).
64. Raussendorf, R. & Briegel, H. J. A one-way quantum computer. *Phys. Rev. Lett.* **86**, 5188–5191 (2001).
65. Walther, P. et al. Experimental one-way quantum computing. *Nature* (in the press).
66. Steane, A. Multiple particle interference and quantum error correction. *Proc. R. Soc. Lond. A* **452**, 2551–2577 (1995).
67. Shor, P. in *Proc. 37th Symp. on Foundations of Computer Science* 15–65 (IEEE Computer Society Press, Los Alamitos, 1996).
68. Kuhn, A., Henrich, M. & Rempe, G. Deterministic single-photon source for distributed quantum networking. *Phys. Rev. Lett.* **89**, 679011–679014 (2002).
69. McKeever, J. et al. Deterministic generation of single photons from one atom trapped in a cavity. *Science* **303**, 1992–1994 (2002).
70. Santori, C., Fattal, D., Vučković, J., Solomon, G. S. & Yamamoto, Y. Indistinguishable photons from a single-photon device. *Nature* **419**, 594–597 (2002).
71. Grangier, P., Sanders, B. & Vuckovic, J. (eds) Focus on Single Photons on Demand *New J. Phys.* (Spec. Edn) **6**, 85–100 (2004).
72. Brattke, S., Varcoe, B. T. H. & Walther, H. Generation of photon number states on demand via cavity quantum electrodynamics. *Phys. Rev. Lett.* **86**, 3534–3537 (1999).
73. Kim, J., Takeuchi, S., Yamamoto, Y. & Hogue, H. H. Multiphoton detection using visible light photon counter. *Appl. Phys. Lett.* **74**, 902–904 (1999).
74. Slusher, R. E., Hollberg, L. W., Yurke, B., Mertz, J. C. & Valley, J. F. Observation of squeezed states generated by four-wave mixing in an optical cavity. *Phys. Rev. Lett.* **55**, 2409–2412 (1985).
75. Furusawa, A. et al. Unconditional quantum teleportation. *Science* **282**, 706–709 (1998).
76. Schleich, W. P. *Quantum Optics in Phase Space* (Wiley-VCH, Berlin, 2001).
77. Bachor, H.-A. & Ralph, T. C. *A Guide to Experiments in Quantum Optics* 2nd edn (Wiley-VCH, Weinheim, 2004).
78. Grosshans, F., Assche, G. V., Wenger, J., Cerf, R. B. J. & Grangier, P. Quantum key distribution using gaussian-modulated coherent states. *Nature* **421**, 238–241 (2003).
79. Dirac, P. A. M. Emission and absorption of radiation. *Proc. R. Soc. Lond. A* **114**, 243–265 (1927).
80. Everett, H. "Relative state" formulation of quantum mechanics. *Rev. Mod. Phys.* **24**, 454–462 (1957).
81. Bohm, D. A suggested interpretation of the quantum theory in terms of "hidden" variables. *Phys. Rev.* **85**, 166–179, 180–193 (1952).
82. Rauschenbeutel, A. et al. Coherent operation of a tunable quantum phase gate in cavity QED. *Phys. Rev. Lett.* **83**, 5166–5169 (1999).
83. Jennewein, T., Simon, C., Weihs, G., Weinfurter, H. & Zeilinger, A. Quantum cryptography with entangled photons. *Phys. Rev. Lett.* **84**, 4729–4732 (2000).
84. Lenard, P. Über die lichtelektrische Wirkung. *Ann. Phys.* **8**, 149–198 (1902).
85. Millikan, R. A. A direct photoelectric determination of Planck's h. *Phys. Rev.* **7**, 355–388 (1915).
86. Millikan, R. A. Albert Einstein on his seventieth birthday. *Rev. Mod. Phys.* **21**, 343–345 (1949).
87. Compton, A. H. The spectrum of scattered X-rays. *Phys. Rev.* **22**, 409–413 (1923).
88. Bothe, W. & Geiger, H. Über das Wesen des Comptoneffekts; ein experimenteller Beitrag zur Theorie

der Strahlung. *Z. Phys.* **32,** 639–663 (1925).

89. Stuewer, R. *The Compton Effect: Turning Point in Physics* (Science History, New York, 1975).
90. Tu, L.-C., Luo, J. & Gillies, G. T. The mass of the photon. *Rep. Prog. Phys.* **68,** 77–130 (2004).
91. Cocconi, G. Upper limits on the electric charge of the photon. *Am. J. Phys.* **60,** 750–751 (1992).
92. Weinberg, S. Light as a fundamental particle. *Phys. Today* **28,** 35–37 (1975).
93. Lawrence, E. O. & Beams, J. W. The element of time in the photoelectric effect. *Phys. Rev.* **32,** 478–485 (1928).
94. Forrester, A. T., Gudmundsen, R. A. & Johnson, P. Photoelectric mixing of incoherent light. *Phys. Rev.* **90,** 1691–1700 (1955).
95. Clauser, J. F. Experimental limitations to the validity of semiclassical radiation theories. *Phys. Rev. A* **6,** 49–54 (1972).
96. Klein, M. J. Einstein's first paper on quanta. *Nat. Phil.* **2,** 59–86 (1963).
97. Stachel, J. *et al.* in *The Collected Papers of Albert Einstein* (eds Stachel, J. *et al.*) Vol. 2, 134–148 (Princeton Univ. Press, Princeton, 1989).
98. Pais, A. Einstein and the quantum theory. *Rev. Mod. Phys.* **51,** 863–914 (1979).
99. Clauser, J. F. in *Quantum [Un]speakables: From Bell to Quantum Information* (eds Bertlmann, R. A. & Zeilinger, A.) 61–98 (Springer, Heidelberg, 2002).

CORRIGENDUM

Happy centenary, photon

Anton Zeilinger, Gregor Weihs, Thomas Jennewein
& Markus Aspelmeyer

Nature **433**, 230–238 (2005)

In the legend to Figure 1, the experiment shown was wrongly attributed to Clauser. The legend should have read 'Principle of Grangier, Roger and Aspect's experiment…(ref. 10)'. In contrast, the Clauser experiment (ref. 4) involved one beam splitter on each side with detectors in each of the resulting four output ports. Four characteristic correlations were measured. In both the Clauser (ref. 4) and the Grangier, Roger and Aspect (ref. 10) experiments the observed correlations cannot be explained via classical light fields, but can easily be understood by assuming single photons that can only be detected once behind a beam splitter.

CORRIGENDUM

The receptors and coding logic for bitter taste

K. L. Mueller, M. A. Hoon, I. Erlenbach, J. Chandrashekar, C. S. Zuker
& N. J. P. Ryba

Nature **434**, 225–229 (2005)

C.S.Z., N.J.P.R., K.L.M. and M.A.H. filed a patent application relevant to this work on 10 September 1999 (patent number US6558910), which should therefore have been declared as a competing financial interest.

CORRIGENDUM

Half-metallic graphene nanoribbons

Young-Woo Son, Marvin L. Cohen & Steven G. Louie

Nature **444**, 347–349 (2006)

In Fig. 2b of this Letter, the contour values were incorrectly normalized. The maximum and minimum values of ± 1.4 in the scale bar in Fig. 2b should read ± 36.6. This error does not affect any of our results. We thank E. Rudberg for pointing out this error.

CORRIGENDUM

The prolyl isomerase Pin1 regulates amyloid precursor protein processing and amyloid-β production

L. Pastorino, A. Sun, P.-J. Lu, X. Z. Zhou, M. Balastik, G. Finn, G. Wulf, J. Lim, S.-H. Li, X. Li, W. Xia, L. K. Nicholson & K. P. Lu

Nature **440**, 528–534 (2006)

During editing to meet *Nature*'s limits on length, we removed a reference to an earlier paper[1] reporting that the prolyl isomerase Pin1 promotes production of Alzheimer's amyloid-β (Aβ) from β-cleaved amyloid precursor protein (APP). That paper reported that Pin1 did not bind to full-length APP, but rather to the phosphorylated Thr 668–Pro motif of the carboxy-terminal C99 fragment of APP; Aβ production in Pin1-knockout mice was reduced only from this fragment.

1. Akiyama, H., Shin, R. W., Uchida, C., Kitamoto, T. & Uchida, T. Prolyl isomerase Pin1 facilitates production of Alzheimer's amyloid-β from β-cleaved amyloid precursor protein *Biochem. Biophys. Res. Commun.* **336**, 521–529 (2005).

CORRIGENDUM

Human embryonic stem cell lines derived from single blastomeres

Irina Klimanskaya, Young Chung, Sandy Becker, Shi-Jiang Lu
& Robert Lanza

Nature **444**, 481–485 (2006); doi:10.1038/nature05142 and
Nature **444**, 512 (2006); doi:10.1038/nature05366

The last sentence of the penultimate paragraph of this Letter should read ''Notably, individual morula (8–16 cell)-stage blastomeres have not been shown to have the intrinsic capacity to generate a complete organism in most mammalian species.'' (see refs 1 and 2).

1. Moore, N. W., Adams, C. E. & Rowson, L. E. A. Developmental potential of single blastomeres of the rabbit egg. *J. Reprod. Fertil.* **17**, 527–531 (1968).
2. Willadsen, S. M. The developmental capacity of blastomeres from four and eight-cell sheep embryos. *J. Embryol. Exp. Morph.* **65**, 165–172 (1981).

A quantum renaissance

ARKITEK
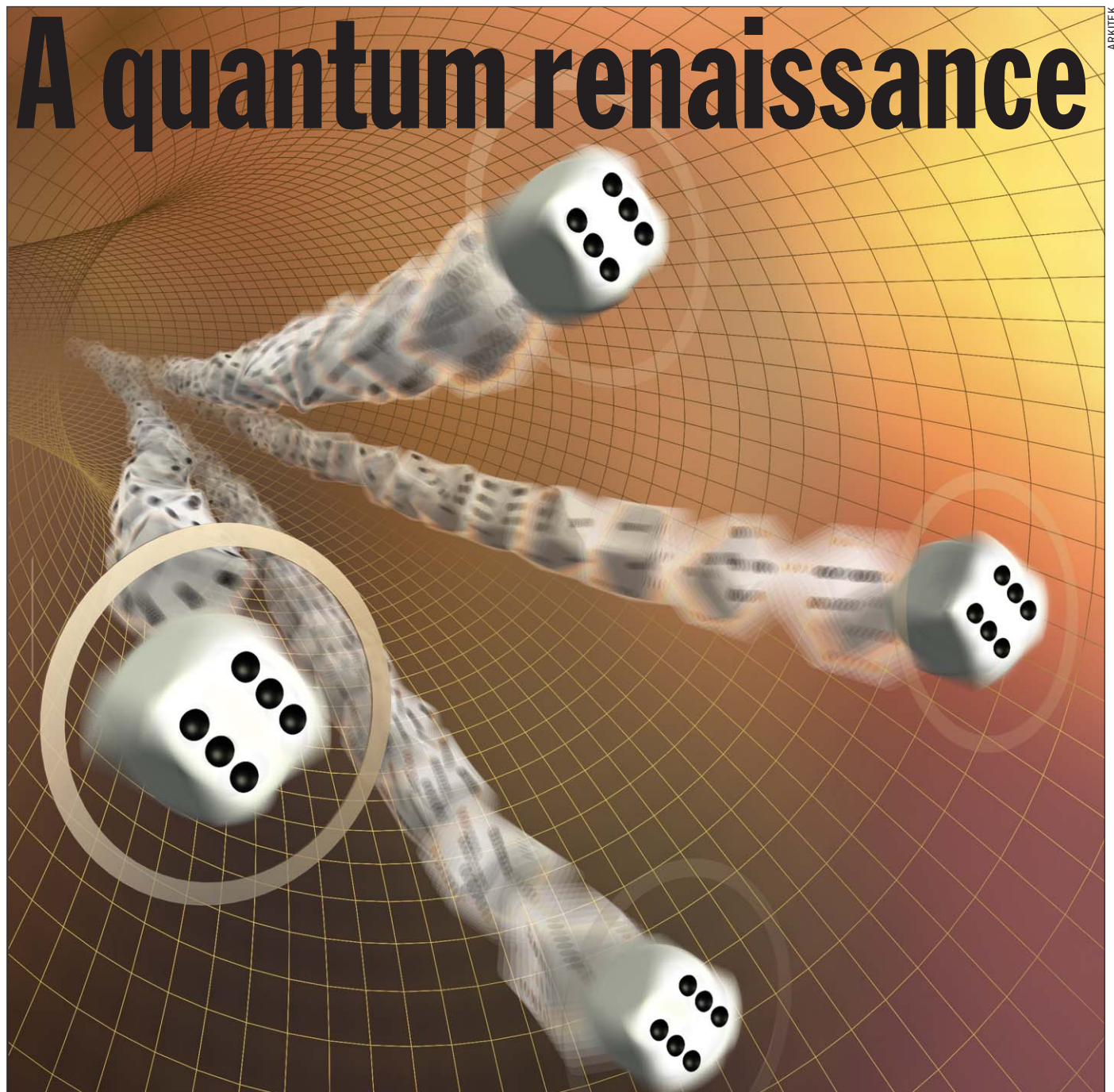
Physicists can now routinely exploit the counterintuitive properties of quantum mechanics to transmit, encrypt and even process information. But as **Markus Aspelmeyer** and **Anton Zeilinger** describe, the technological advances of quantum information science are now enabling researchers to readdress fundamental puzzles raised by quantum theory

Pure curiosity has been the driving force behind many groundbreaking experiments in physics. This is no better illustrated than in quantum mechanics, initially the physics of the extremely small. Since its beginnings in the 1920s and 1930s, researchers have wanted to observe the counterintuitive properties of quantum mechanics directly in the laboratory. However, because experimental technology was not sufficiently developed at the time, people like Niels Bohr, Albert Einstein, Werner Heisenberg and Erwin Schrödinger relied instead on "gedankenexperiments" (thought experiments) to investigate the quantum physics of individual particles, mainly electrons and photons.

By the 1970s technology had caught up, which produced a "gold rush" of fundamental experiments that continued into the 1990s. These experiments confirmed quantum theory with striking success, and challenged many common-sense assumptions about the physical world. Among these assumptions are "realism" (which, roughly speaking, states that results of measurements

reveal features of the world that exist independent of the measurement), "locality" (that the result of measurements here and now do not depend on some action that might be performed a large distance away at exactly the same time), and "non-contextuality" (asserting that results of measurements are independent of the context of the measurement apparatus).

But a big surprise awaited everyone working in this field. The fundamental quantum experiments triggered a completely new field whereby researchers apply phenomena such as superposition, entanglement and randomness to encode, transmit and process information in radically novel schemes. "Quantum information science" is now a booming interdisciplinary field that has brought futuristic-sounding applications such as quantum computers, quantum encryption and quantum teleportation within reach. Furthermore, the technological advances that underpin it have given researchers unprecedented control over individual quantum systems. That control is now fuelling a renaissance in our curiosity of the quantum world by allowing physicists to address new fundamental aspects of quantum mechanics. In turn, this may open up new avenues in quantum information science.

Against intuition
Both fundamental quantum experiments and quantum information science owe much to the arrival of the laser in the 1960s, which provided new and highly efficient ways to prepare individual quantum systems to test the predictions of quantum theory. Indeed, the early development of fundamental quantum-physics experiments went hand in hand with some of the first experimental investigations of quantum optics.

One of the major experimental leaps at that time was the ability to produce "entangled" pairs of photons. In 1935 Schrödinger coined the term "entanglement" to denote pairs of particles that are described only by their joint properties instead of their individual properties – which goes against our experience of the macroscopic world. Shortly beforehand, Einstein, Boris Podolsky and Nathan Rosen (collectively known as EPR) used a gedankenexperiment to argue that if entanglement exists, then the quantum-mechanical description of physical reality must be incomplete. Einstein did not like the idea that the quantum state of one entangled particle could change instantly when a measurement is made on the other particle. Calling it "spooky" action at a distance, he hoped for a more complete physical theory of the very small that did not exhibit such strange features (see "The power of entanglement" by Harald Weinfurter *Physics World* January 2005 pp47–51).

This lay at the heart of a famous debate between Einstein and Bohr about whether physics describes nature "as it really is", as was Einstein's view, or whether it describes "what we can say about nature", as Bohr believed. Until the 1960s these questions were merely philosophical in nature. But in 1964, the Northern Irish physicist John Bell realized that experiments on entangled particles could provide a test of whether there is a more complete description of the world beyond quantum theory. EPR believed that such a theory exists.

Bell based his argument on two assumptions made by EPR that are directly contradicted by the properties of entangled particles. The first is locality, which states that the results of measurements performed on one particle must be independent of whatever is done at the same time to its entangled partner located at an arbitrary distance away. The second is realism, which states that the outcome of a measurement on one of the particles reflects properties that the particle carried prior to and independent of the measurement. Bell showed that a particular combination of measurements performed on identically prepared pairs of particles would produce a numerical bound (today called a Bell's inequality) that is satisfied by all physical theories that obey these two assumptions. He also showed, however, that this bound is violated by the predictions of quantum physics for entangled particle pairs (*Physics* **1** 195).

Take, for example, the polarization of photons. An individual photon may be polarized along a specific direction, say the horizontal, and we can measure this polarization by passing the photon through a horizontally oriented polarizer. A click in a photon detector placed behind it indicates a successful measurement and shows that the photon is horizontally polarized; no click means that the photon is polarized along the vertical direction. In the case of an entangled pair of photons, however, the individual photons turn out not to carry any specific polarization before they are measured! Measuring the horizontal polarization of one of the photons will always give a random result, thus making it equally likely to find an individual photon horizontally or vertically polarized. Yet performing the same measurement on the other photon of the entangled pair (assuming a specific type of entangled state) will show both photons to be polarized along the same direction. This is true for all measurement directions and is independent of the spatial separation of the particles.
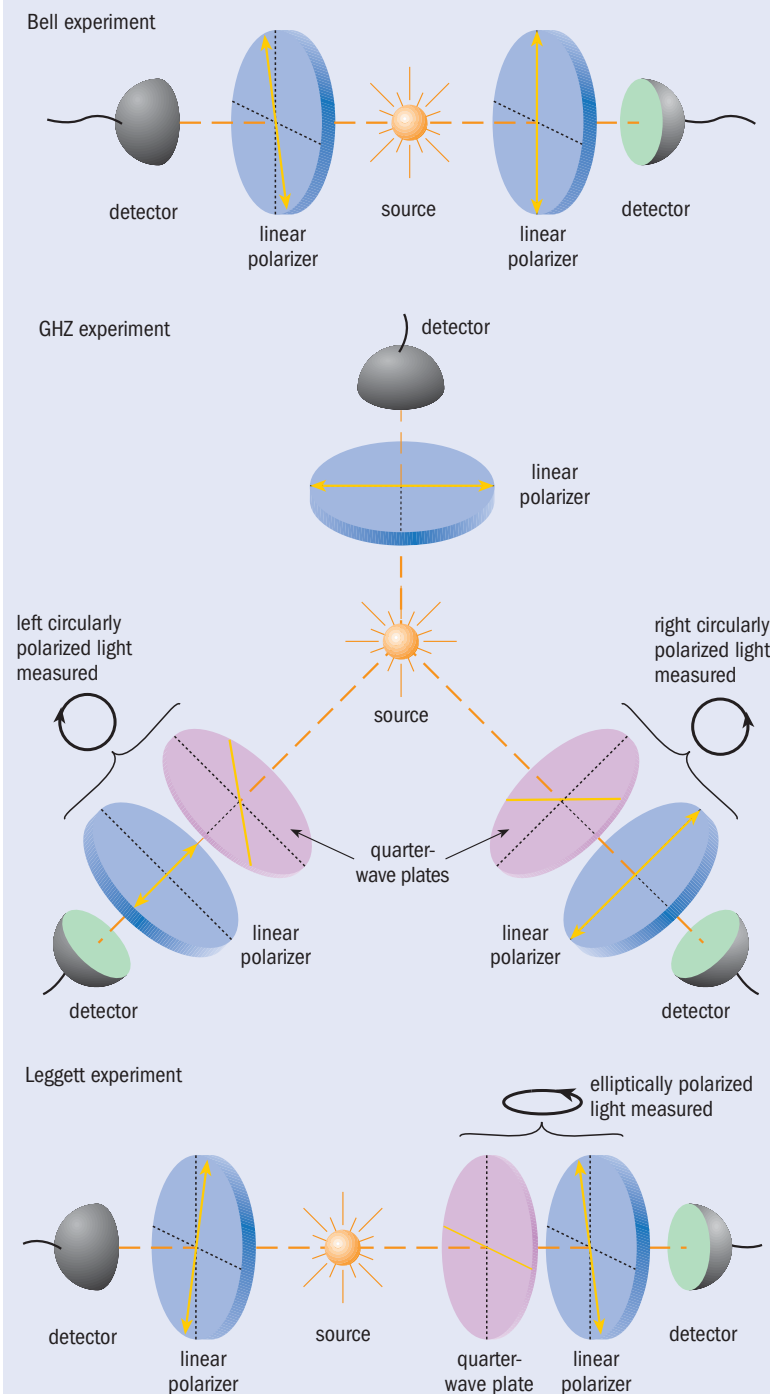
Bell's inequality opened up the possibility of testing specific underlying assumptions of physical theories – an effort rightfully referred to by Abner Shimony of Boston University as "experimental metaphysics". In such Bell experiments, two distant observers measure the polarization of entangled particles along different directions and calculate the correlations between them. Because the quantum correlations between independent polarization measurements on entangled particles can be much stronger than is allowed by any local realistic theory, Bell's inequality will be violated.

Markus Aspelmeyer is at the Institute for Quantum Optics and Quantum Information (IQOQI), Austrian Academy of Sciences, Vienna, and **Anton Zeilinger** is at the University of Vienna and also at the IQOQI, e-mail anton.zeilinger@ quantum.at

At a Glance: A quantum renaissance

- Quantum mechanics challenges intuitive notions about reality, such as whether the property of a particle exists before a measurement is performed on it
- Entanglement is one of the most perplexing aspects of quantum theory; it implies that measurement results on two particles are intimately connected to one another instantaneously no matter how far apart they are
- Since the 1970s, experiments have shown repeatedly that quantum theory is correct, but researchers are still devising measurements in order to find out what quantum mechanics tells us about physical reality
- These tests have sparked a new field called quantum information science, in which entanglement and other quantum phenomena are used in to encrypt, transmit and process information in radically new ways
- The increased level of control over individual quantum systems that has driven quantum information science is now enabling physicists to tackle once again the fundamental puzzles raised by quantum theory

1 Testing realism

Bell experiment

GHZ experiment

detector

linear
polarizer

left circularly
polarized light
measured

right circularly
polarized light
measured

source

quarter-
wave plates

linear
polarizer

linear
polarizer

detector

detector

Leggett experiment

elliptically polarized
light measured

detector

source

detector

linear
polarizer

quarter-
wave plate

linear
polarizer

detector

linear
polarizer

source

detector

linear
polarizer

Experiments on entangled pairs or triplets of photons can be used to test the notion of physical realism. In the original Bell-type experiments (top), both photons of an entangled pair have the same linear polarization for parallel polarizers. But for polarizers oriented at a small angle with respect to each other, as shown, the same result is more often obtained for both photons than would be permitted if polarization were a real local property of the photons. In the so-called GHZ experiments (middle) knowing, say, the circular polarizations of two photons of a three-photon entangled state allows quantum mechanics to predict with certainty the linear polarization of the third (top) photon, which in this case is horizontal. A local realist would predict orthogonal linear polarization – in this case vertical. In a Leggett-type experiment (bottom) the correlations between linear polarization for one photon and elliptic polarization of the other can be shown to violate a realistic world view even if instant non-local communication is allowed. As shown in the figure, circular and elliptical polarizations of single photons can be measured by using appropriate combinations of quarter-wave-plates and linear polarizers.

Quantum loopholes

The first such test was performed using entangled photons in 1972 by Stuart Freedman and John Clauser of the University of California at Berkeley; Bell's inequality was violated and the predictions of quantum theory were confirmed (*Phys. Rev. Lett.* **28** 938). But from early on there existed some loopholes that meant researchers could not exclude all possible "local realistic" models as explanations for the observed correlations. For example, it could be that the particles detected are not a fair sample of all particles emitted by the source (the so-called detection loophole) or that the various elements of the experiment may still be causally connected (the locality loophole). In order to close these loopholes, more stringent experimental conditions had to be fulfilled.

In 1982 Alain Aspect and colleagues at the Université Paris-Sud in Orsay, France, carried out a series of pioneering experiments that were very close to Bell's original proposal. The team implemented a two-channel detection scheme to avoid making assumptions about photons that did not pass through the polarizer (*Phys. Rev. Lett.* **49** 91), and the researchers also periodically – and thus deterministically – varied the orientation of the polarizers after the photons were emitted from the source (*Phys. Rev. Lett.* **49** 1804). Even under these more stringent conditions, Bell's inequality was violated in both cases, thus significantly narrowing the chances of local-realistic explanations of quantum entanglement.
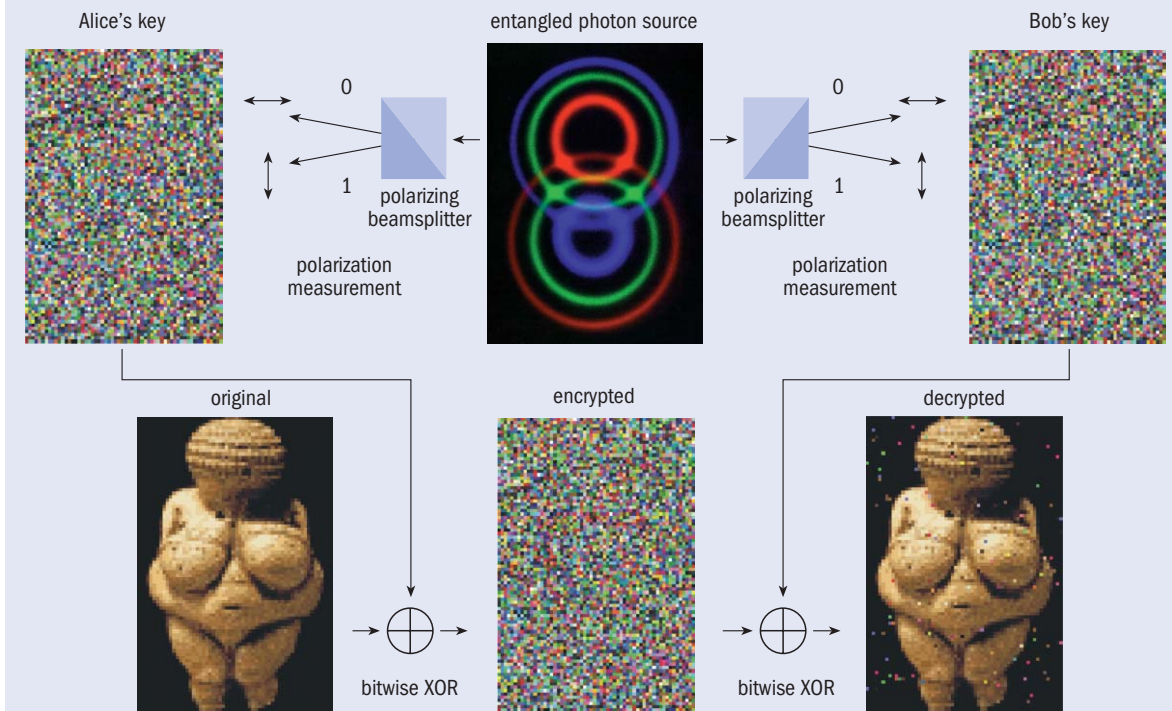
In 1998 one of the present authors (AZ) and colleagues, then at the University of Innsbruck, closed the locality loophole by using two fully independent quantum random-number generators to set the directions of the photon measurements. This meant that the direction along which the polarization of each photon was measured was decided at the last instant, such that no signal (which by necessity has to travel slower than the speed of light) would be able to transfer information to the other side before that photon was registered (*Phys. Rev. Lett.* **81** 5039). Bell's inequality was violated.

Then in 2004, David Wineland and co-workers at the National Institute of Standards and Technology (NIST) in Colorado, US, set out to close the detection loophole by using detectors with perfect efficiency in an experiment involving entangled beryllium ions (*Nature* **409** 791). Once again, Bell's inequality was violated. Indeed, all results to date suggest that no local-realistic theory can explain quantum entanglement.

But the ultimate test of Bell's theorem is still missing: a single experiment that closes all the loopholes at once. It is very unlikely that such an experiment will disagree with the prediction of quantum mechanics, since this would imply that nature makes use of both the detection loophole in the Innsbruck experiment and of the locality loophole in the NIST experiment. Nevertheless, nature could be vicious, and such an experiment is desirable if we are to finally close the book on local realism.

In 1987 Daniel Greenberger of the New York City College, Michael Horne of Stonehill College and AZ (collectively GHZ) realized that the entanglement of three or more particles would provide an even stronger constraint on local realism than two-particle entanglement (*Am. J. Phys.* **58** 1131). While two entangled particles are at variance with local realism only in their

2 Entanglement-based quantum cryptography

Alice's key   entangled photon source   Bob's key

0   1   polarizing beamsplitter   polarization measurement

original   encrypted   decrypted

bitwise XOR   bitwise XOR

Quantum cryptography, which allows information to be sent totally securely between two sites, relies on entanglement. Pairs of polarization-entangled photons are distributed between Alice and Bob, who want to share a secret message (in this case an image of the famous Venus of Willendorf effigy). Measuring the polarization of an individual entangled photon will give a totally random outcome. However, if Alice and Bob perform measurements along the same polarization direction, then their outcomes are always the same within each entangled pair. By measuring many pairs Alice and Bob obtain the same random sequence, which they then use as a secret key. Alice mixes her key (top left) with the picture of the original (lower left). The encrypted picture (lower middle) is secure against eavesdropping because of the randomness of the key. Bob, however, can easily decode the message using his key (lower right). A potential eavesdropper can be detected because tampering with the photons of the entangled pair destroys the entanglement. This is a consequence of the uncertainty principle, and thus the security of quantum cryptography is guaranteed. The original experiment demonstrating this effect was performed by a team at the University of Innsbruck in 1998 over a distance of more than 300 m (*Phys. Rev. Lett.* **84** 4729).

statistical properties, which is the essence of Bell's theorem, three entangled particles can produce an immediate conflict in a single measurement result because measurements on two of the particles allow us to predict with certainty the property of the third particle.

The first experiments on three entangled photons were performed in late 1999 by AZ and co-workers, and they revealed a striking accordance with quantum theory (*Nature* **403** 515). So far, all tests of both Bell's inequalities and on three entangled particles (known as GHZ experiments) (see figure 1) confirm the predictions of quantum theory, and hence are in conflict with the joint assumption of locality and realism as underlying working hypotheses for any physical theory that wants to explain the features of entangled particles.

Quantum information science

The many beautiful experiments performed during the early days of quantum optics prompted renewed interest in the basic concepts of quantum physics. Evidence for this can be seen, for example, in the number of citations received by the EPR paper, which argued that entanglement renders the quantum-mechanical description of physical reality incomplete. The paper was cited only about 40 times between its publication in 1935 and 1965, just after Bell developed his inequal-

ities. Yet today it has more than 4000 citations, with an average of 200 per year since 2002. Part of the reason for this rise is that researchers from many different fields have begun to realize the dramatic consequences of using entanglement and other quantum concepts to encode, transmit and process information.

Take quantum cryptography, which applies randomness, superposition and, in one scheme proposed by Artur Ekert of Oxford University in the UK, two-particle entanglement to transmit information such that its security against eavesdropping is guaranteed by physical law (see figure 2). This application of quantum information science has already left the laboratory environment. In 2004, for instance, AZ and co-workers at the University of Vienna transferred money securely between an Austrian bank and Vienna City Hall using pairs of entangled photons that were generated by a laser in a nonlinear optical process and distributed via optical fibres. More recently, two international collaborations were able to distribute entangled photons over a distance of 144 km between La Palma and Tenerife, including a demonstration of quantum cryptography, and earlier this year even showed that such links could be established in space by bouncing laser pulses attenuated to the single-photon level off a satellite back to a receiving station on Earth (*Physics World*

Researchers have begun to realize the dramatic consequences of using entanglement to encode, transmit and process information

3 One-way quantum computation
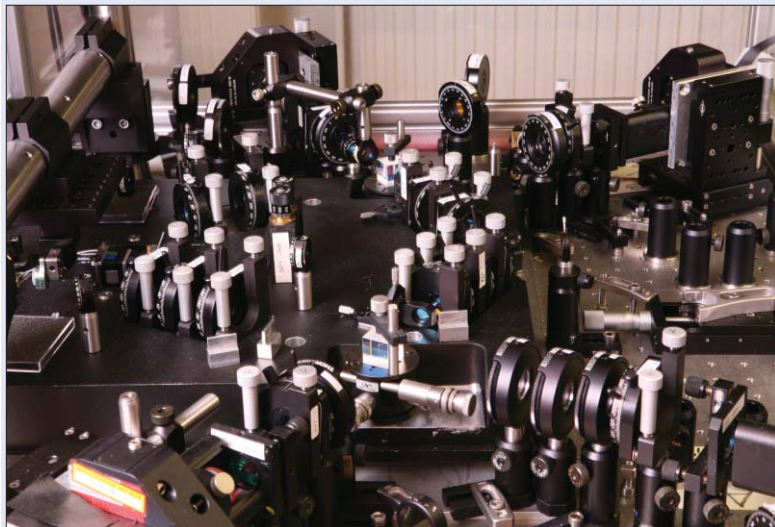
Quantum computers, by processing information via the states of quantum systems such as atoms and photons, promise to outperform classical computers for specific tasks. One approach to making a practical version of such a device is the so-called one-way quantum computer. Proposed in 2001, it relies on entanglement. In a photonic realization, the output from a pump laser passes through a nonlinear beta barium borate (BBO) crystal twice in order to generate two entangled pairs of photons, which means that the four spatial modes contain four photons altogether. Coherent superposition at the two polarizing beamsplitters ensures that the final four detected photons are in a "cluster state", given appropriate placing of half-wave plates and polarizers. Since 2005, proof-of-concept experiments (above) with this basic quantum-computer set-up allowed computations of Grover's search algorithm, a quantum prisoner's dilemma and the demonstration of decoherence-free subspaces (as required for fault-tolerant quantum computation) to be carried out.

May p4). Commercial quantum-encryption products based on attenuated laser pulses are already on the market (see *Physics World* March 2007 pp24–29), and the challenge now is to achieve higher bit rates and to bridge larger distances.

In a similar manner, the road leading to the GHZ experiments opened up the huge field of multiparticle entanglement, which has applications in, among other things, quantum metrology. For example, greater uncertainty in the number of entangled photons in an interferometer leads to less uncertainty in their phases, thereby resulting in better measurement accuracy compared with a similar experiment using the same number of non-entangled photons.

Multiparticle entanglement is also essential for quantum computing. Quantum computing exploits fundamental quantum phenomena to allow calculations to be performed with unprecedented speed – perhaps even solving problems that are too complex for conventional computers, such as factoring large prime numbers or enabling fast database searches. The key idea behind quantum computing is to encode and process information in physical systems following the rules of quantum mechanics. Much current research is therefore devoted to finding reliable quantum bits or "qubits" that can be linked together to form registers and logical gates analogous to those in conventional computers, which would then allow full quantum algorithms to be implemented.

In 2001, however, Robert Raussendorf and Hans Briegel, then at the University of Munich in Germany,

suggested an alternative route for quantum computation based on a highly entangled multiparticle "cluster state" (*Phys. Rev. Lett.* **86** 5188). In this scheme, called "one-way" quantum computing, a computation is performed by measuring the individual particles of the entangled cluster state in a specific sequence that is defined by the particular calculation to be performed. The individual particles that have been measured are no longer entangled with the other particles and are therefore not available for further computation. But those that remain within the cluster state after each measurement end up in a specific state depending on which measurement was performed. As the measurement outcome of any individual entangled particle is completely random, different states result for the remaining particles after each measurement. But only in one specific case is the remaining state the correct one. Raussendorf and Briegel's key idea was to eliminate that randomness by making the specific sequence of measurements depend on the earlier results. The whole scheme therefore represents a deterministic quantum computer, in which the remaining particles at the end of all measurements carry the result of the computation.

In 2005 the present authors and colleagues at Vienna demonstrated the principle of one-way quantum computing (see figure 3) and even a simple search algorithm using a four-photon entangled state (*Nature* **434** 169). Then in 2007, Jian-Wei Pan of the University of Science and Technology of China in Hefei and co-workers implemented a similar scheme involving six photons. A distinct advantage of a photonic one-way computer is its unprecedented speed, with the time from the measurement of one photon to the next, i.e. a computational cycle, taking no more than 100 ns.

Foundational questions

The technology developed in the last 20 years to make quantum information processing and communication a reality has given researchers unprecedented control over individual quantum systems. For example, it is now clear that all-photonic quantum computing is possible but that it requires efficient and highly pure single-photon and entangled-photon sources, plus the ability to reliably manipulate the quantum states of photons or other quantum systems in a matter of nanoseconds. The tools required for this and other developments are being constantly improved, which is itself opening up completely new ways to explore the profound questions raised by quantum theory.

One such question concerns once again the notions of locality and realism. The whole body of Bell and GHZ experiments performed over the years suggests that at least one of these two assumptions is inadequate to describe the physical world (at least as long as entangled states are involved). But Bell's theorem does not allow us to say which one of the two should be abandoned.

In 2003 Anthony Leggett of the University of Illinois at Urbana-Champaign in the US provided a partial answer by presenting a new incompatibility theorem very much in the spirit of Bell's theory but with a different set of assumptions (*Found. Phys.* **33** 1469). His idea was to drop the assumption of locality and to ask if, in such a situation, a plausible concept of realism – namely

to assign a fixed polarization as a "real" property of each particle in an entangled pair – is sufficient to fully reproduce quantum theory. Intuitively, one might expect that properly chosen non-local influences can produce arbitrary correlations. After all, if you allow your measurement outcome to depend on everything that goes on in the whole universe (including at the location of the second measurement apparatus), then why should you expect a restriction on such correlations?

For the specific case of a pair of polarization-entangled photons, the class of non-local realistic theories Leggett sets out to test fulfils the following assumptions: each particle of a pair is emitted from the source with a well-defined polarization; and non-local influences are present such that each individual measurement outcome may depend on any parameter at an arbitrary distance from the measurement. The predictions of such theories violate the original Bell inequalities due to the allowed non-local influence, so it is natural to ask whether they are able to reproduce all predictions of quantum theory.

Leggett showed that this is not the case. Analogous to Bell, he derived a set of inequalities for certain measurements on two entangled particles that are fulfilled by all theories based on these specific non-local realistic assumptions but which are violated by quantum-theoretical predictions. Testing Leggett's inequalities is more challenging than testing Bell's inequalities because they require measurements of both linear and elliptic polarization, and much higher-quality entanglement. But in 2007, thanks to the tremendous progress made with entangled-photon sources, the present authors and colleagues at Vienna were able to test a Leggett inequality experimentally by measuring correlations between linear and elliptical polarizations of entangled photons (*Nature* **446** 871).

The experiment confirmed the predictions of quantum theory and thereby ruled out a broad class of non-local realistic theories as a conceptual basis for quantum phenomena. Similar to the evolution of Bell experiments, more rigorous Leggett-type experiments quickly followed. For example, independent experiments performed in 2007 by the Vienna team (*Phys. Rev. Lett.* **99** 210406) and by researchers at the University of Geneva and the National University of Singapore (*Phys. Rev. Lett.* **99** 210407) confirmed a violation of a Leggett inequality under more relaxed assumptions, thereby expanding the class of forbidden non-local realistic models. Two things are clear from these experiments. First, it is insufficient to give up completely the notion of locality. Second, one has to abandon at least the notion of naïve realism that particles have certain properties (in our case polarization) that are independent of any observation.

Macroscopic limits

The close interplay between quantum information science and fundamental curiosity has also been demonstrated by some fascinating experiments that involve more massive particles. According to quantum theory, there is no intrinsic upper limit on size or complexity of a physical system above which quantum effects no longer occur. This is at the heart of Schrödinger's famous cat paradox, which ridicules the situation by

4 Macroscopic quantum experiments

20 μm

32 Å
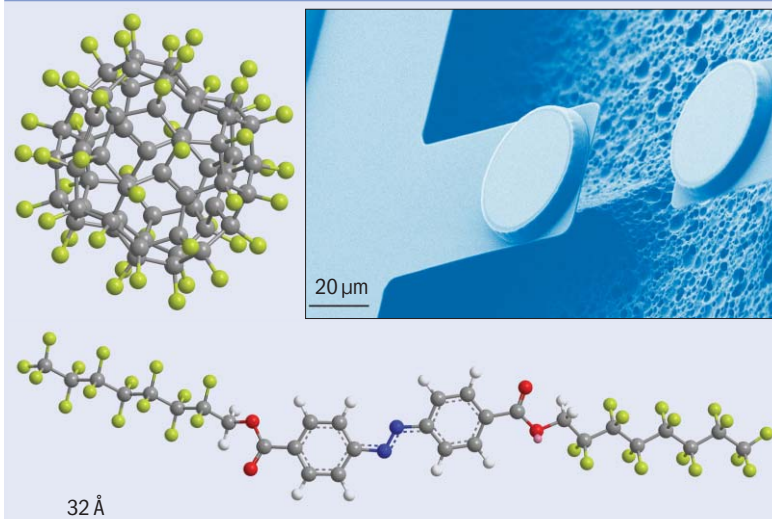
By studying the quantum-mechanical behaviour of ever larger and more massive objects, researchers stand a better chance of building reliable quantum computers or developing other applications of quantum information science. The current world record for the most massive objects to exhibit quantum interference in a two-slit type experiment, i.e. to demonstrate wave-like behaviour despite their corpuscular character, are fluorinated fullerene molecules $C_{60}F_{48}$ with a mass of 1632 atomic mass units (top left) (*Phys. Rev. Lett.* **91** 090408). The largest object showing interference is the molecule "azobenzene" (bottom) (*Nature Physics* **3** 711), as demonstrated by Markus Arndt's team at the University of Vienna. Mechanical resonators (top right) have not yet entered the quantum regime, but this could soon change with such objects being cooled to their quantum ground state. This particular resonator contains a highly reflecting mirror placed on top of a vibrating singly clamped cantilever, which can be actuated via radiation pressure in combination with a high-finesse optical cavity.

suggesting an experiment whereby someone could prepare a cat that is in a superposition of being alive and dead. One particularly interesting case is that of "matter–wave" interference.

Electrons, neutrons and atoms have been shown to exhibit interference effects when passing through a double-slit, thus proving that these massive systems neither passed through only one or the other slit. Similar behaviour was observed more recently in 1999 by AZ and colleagues at Vienna for relatively large carbon-60 and carbon-70 fullerene molecules (*Nature* **401** 680), and ongoing research has demonstrated interference with even heavier and larger systems (see figure 4). One of the main goals of this research is to realize quantum interference for small viruses or maybe even nanobacteria.

Very recently the ability to cool nanomechanical devices to very low temperatures has opened up a new avenue to test systems containing up to 10^{20} atoms. One fascinating goal of experiments that probe the quantum regime of mechanical cantilevers is to demonstrate entanglement between a microscopic system such as a photon and a mechanical system – or even between two mechanical systems.

While the underlying motivation for studying macroscopic quantum systems is pure curiosity, the research touches on important questions for quantum information science. This is because increasingly large or complex quantum systems suffer from interactions with their environment, which is as important for macromolecules and cantilevers as it is for the large registers

> Quantum physics and the information science that it has inspired are two sides of the same coin

of a quantum computer.

One consequence of this interaction with the outside world is "decoherence", whereby the system effectively becomes entangled with the environment and therefore loses its individual quantum state. As a result, measurements of that system are no longer able to reveal any quantum signature. Finding ways to avoid decoherence is thus a hot topic both in macroscopic quantum experiments and in quantum information science. With fullerene molecules, for instance, the effect of decoherence was studied in great detail in 2004 by coupling them to the outside environment in different, tuneable ways (*Nature* **427** 711). From an experimental point of view, we see no reason to expect that decoherence cannot be overcome for systems much more macroscopic than is presently feasible in the laboratory.

Quantum curiosity

Quantum physics and the information science that it has inspired emerge as two sides of the same coin: as inspiration for conceptually new approaches to applications on the one side; and as an enabling toolbox for new fundamental questions on the other. It has often happened that new technologies raise questions that have not been asked before, simply because people could not imagine what has become possible in the laboratory.

One such case may be our increasing ability to manipulate complex quantum systems that live in high-dimensional Hilbert space – the mathematical space in which quantum states are described. Most of the known foundational questions in quantum theory have hitherto made use only of relatively simple systems, but larger Hilbert-space dimensions may add qualitatively new features to the interpretation of quantum physics. We are convinced that many surprises await us there.

We expect that future theoretical and experimental developments will shine more light on which of the counterintuitive features of quantum theory are really indispensable in our description of the physical world. In doing so, we expect to gain greater insight into the underlying fundamental question of what reality is and how to describe it. The close connection between basic curiosity of the quantum world and its application in information science may even lead to ideas for physics beyond quantum mechanics. ■

More about: A quantum renaissance

M Arndt, K Hornberger and A Zeilinger 2005 Probing the limits of the quantum world *Physics World* March pp35–40
D Bouwmeester *et al.* (ed) 1999 *The Physics of Quantum Information* (Springer, Heidelberg)
A Steinberg *et al.* 1996 Quantum optical tests of the foundations of physics *The American Institute of Physics Atomic, Molecular, and Optical Physics Handbook* (ed) G W F Drake (AIP Press)
A Zeilinger *et al.* 2005 Happy centenary, photon *Nature* **433** 239