Chapter 30
New Dimensions for Entangled Photons: The Role of Information

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Introduction

This paper follows very closely the talk given at *Quantum (Un)Speakables II: 50 Years of Bell's Theorem*. It will be argued that information plays a central role in interpreting and understanding real experiments.

The relation of quantum theory to physical reality has been at the core of discussions since the very first beginnings of quantum mechanics. Just to emphasize the level of technical development achieved, Fig. 30.1 shows a telescope. It is the OGS (Optical Ground Station) operated by the European Space Agency on the Canary Island of Tenerife. This instrument was built for developing and testing optical communication with satellites. In our experiments, we utilize it for testing optical quantum communication over large earthbound distances, specifically ca. 150 km between the Canary Islands of La Palma and Tenerife. In that image, one can see a laser beam which serves as a guiding beacon for continuously adjusting the sending and the receiving telescopes onto each other in order to reduce the effect of atmospheric fluctuations.

This setup has served as a workhorse for many experiments on entanglement, some of which test the ideas of reality put forward by Einstein, Podolsky and Rosen in 1935 [1]. It is actually quite instructive to investigate the number of citations the Einstein-Podolsky-Rosen paper received (see Fig. 30.2). This paper came out in 1935. In the

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R. Bertlmann and A. Zeilinger (eds.), *Quantum [Un]Speakables II*, The Frontiers Collection, DOI 10.1007/978-3-319-38987-5_30

Fig. 30.1 Optical Ground Station OGS on the Canary Island of Tenerife. The laser beam shown is used as a guiding beacon for the quantum optical communication link to the island of La Palma. (*Photo* Daniel Padrón).

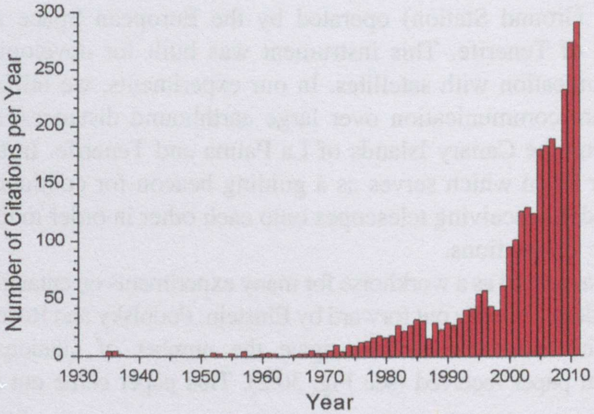

Fig. 30.2 Number of annual citations of the Einstein-Podolsky-Rosen paper.

beginning, it had very few citations. I would like to remark that these citations were not so bad. Two of them were by Schrödinger [2, 3] and one by Bohr [4]. So the paper immediately attracted attention by leading figures in quantum science. Yet, after that, there were no citations until the beginning of the 1950s. I would like to remark as a comment on today's situation regarding the ways in which careers are often decided that this paper would not have gotten Einstein a permanent position because of its low citation numbers. But then, citations took off for two reasons. Slowly, in the 1950s, the field of the foundations of quantum mechanics started again after it had lain dormant

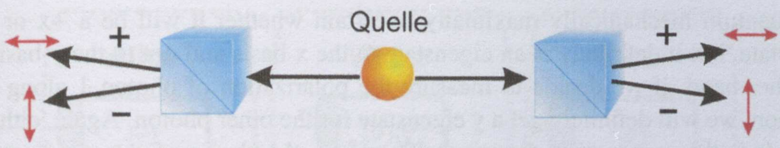

Fig. 30.3 Typical experimental set-up for measurements on polarization-entangled photon pairs. The source (Quelle) is assumed to emit an entangled pair, say, in the state of Eq. 1. Each photon path is a two-channel polarizer which may be rotated around the incident beam direction. Then, one always measures perfect correlations in either horizontal or vertical polarization when the polarizers are oriented along the same direction. A violation of Bell's Inequality arises for skewed angles between two-channel polarizers. (*Image* Thomas Jennewein)

for a significant time. And most importantly, in 1964, John Bell showed [5] that the fundamental concepts of reality and locality, as proposed by Einstein, Podolsky and Rosen, are in conflict with some predictions of quantum mechanics (for an explicit formulation of these conditions, see paper [6], which builds on [7]). The other significant increase in the number of citations occurred around 2000, when entanglement and Bell's theorem proved to be essential to basic concepts and new ideas in quantum information science. I should mention that, as was often the case in the history of physics, this development towards future applications was not foreseen by any of the early pioneers. Both theoretical and experimental work on the foundations of quantum mechanics was originally motivated by nothing but curiosity, and without even the slightest indication of applications on the horizon.

We will now discuss the specific situation of two entangled photons emitted by a source (Quelle) in the state Φ_+ (Fig. 30.3).

$$|\Phi_+\rangle = \frac{1}{\sqrt{2}}(|H\rangle|H\rangle + |V\rangle|V\rangle) \tag{1}$$

This is a maximally entangled state, where measurements on the two photons always show the same linear polarization, horizontal H or vertical V, independent of the measurement basis chosen, that is, along any direction as long as it is the same for both photons. Such states today are called "Bell states".

Albert Einstein most succinctly analyzed the situation in "Remarks to the Essays Appearing in this Collective Volume", his reply to the articles in the famous volume *Albert Einstein—Philosopher-Scientist* [8]. This volume, which has already been mentioned by Bertlmann in an earlier chapter of the current volume [9], contains a great collection of interesting papers relating to many aspects of Einstein's work. For example, it contains the famous Gödel paper, where he shows for the first time that there could be closed time-like curves in the Universe [10]. Many open questions that were raised in these papers, including some in mathematics, have not been resolved to date.

Einstein in his reply basically argues that when performing a measurement on photon 1, say the one on the left-hand side in Fig. 30.3, we can freely decide along which direction we measure, for example its linear polarization. If one decides to measure the polarization along x, then, Einstein argues, one definitely gets an x polarization eigenstate for photon 2 on the right-hand side. It is certainly unknown and quantum mechanically maximally uncertain whether it will be a +x or a −x eigenstate, but it definitely is an eigenstate to the x basis and not to the y-basis. On the other hand, if we decide to measure the polarization of photon 1 along the y direction, we will definitely get a y eigenstate for the other photon. Again, either +y or −y (z is the propagation direction). Therefore, the choice of measurement basis on one photon decides what kinds of eigenstates are permitted for the other photon, and this is a definite property of the system upon the first measurement. Therefore, as Einstein said, "the quantum state cannot describe the 'real factual situation'" [8]. In my opinion, this statement is absolutely correct. The question is, what is its significance? In my eyes, it can be interpreted that the quantum state is not about a reality existing prior to or independent of measurement, but it is the representation of information about possible future measurement results. It allows the maximal set of, in general probabilistic, predictions of future measurement results.

The essence of Bell's theorem is that for certain correlations between measurements on both photons, the predictions of quantum mechanics are in conflict with the philosophical position of local realism, as exposed by EPR. This is signified by Bell's inequality.

$$E_{11} + E_{12} + E_{21} - E_{22} \leq 2 \tag{2}$$

where E_{ab} describes the correlation between measurement results when photon 1 is measured along direction a and photon 2 is measured along direction b. Without going into detail, the implication is that the sum of correlations, as expressed in Eq. 2, between measurements on both sides is limited to 2 in a local realist point of view. But for quantum mechanics, the sum on the left-hand side can be as high as $2\sqrt{2}$ for two qubits, a qubit being any quantum mechanical two-state system.

Many contributions to the current conference refer to specific reformulations of this inequality and its variants, but the essential point is always the same, as outlined above.

The Role of Information as Underlined by Entanglement Swapping

The role of information in the understanding of quantum mechanics can most clearly be discussed for a variation of entanglement swapping [11] as proposed by Peres [12]. We have two EPR sources (Fig. 30.4), each one producing an entangled pair of photons. One of the photons of each source, photon 1 and photon 4, is measured locally. In some polarization bases, each basis is chosen arbitrarily and independently by Alice or Bob respectively. The results are recorded and printed out as shown. Photons 2 and 3, one from each source, are then directed to Victor, who can decide whether he wants to project these two photons onto an entangled state or whether he wants to measure their polarizations separately. These decisions can be made by Victor randomly and at any time before or after the outer two photons have been registered.

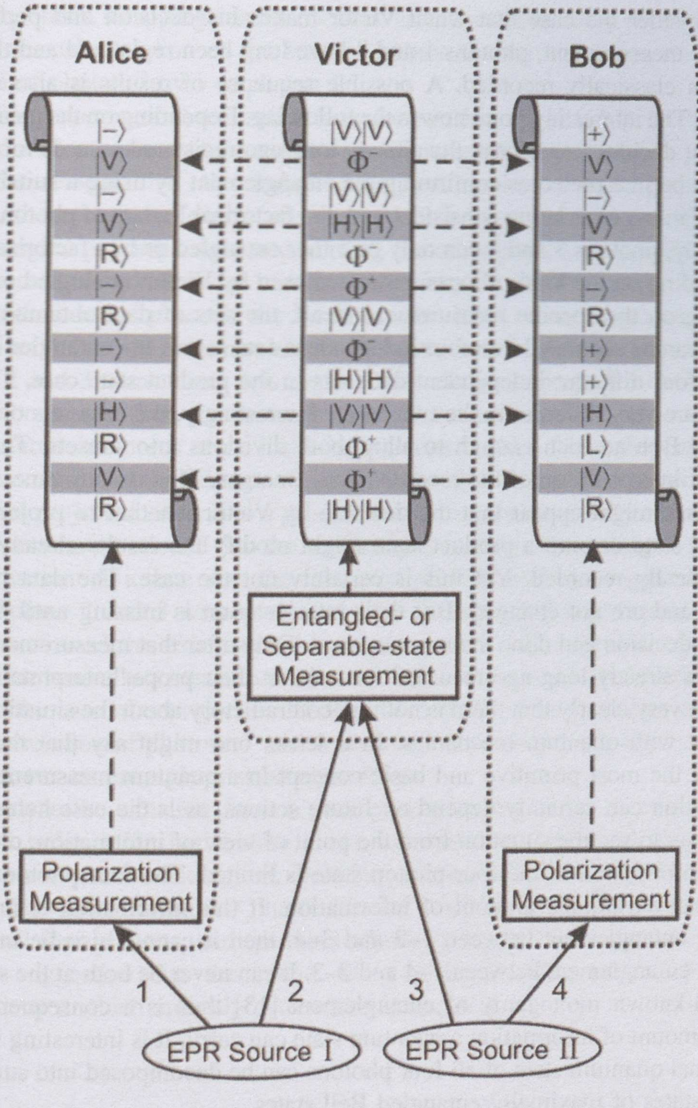

Fig. 30.4 The concept of delayed-choice entanglement swapping. Two entangled pairs—photons 1 and 2 and photons 3 and 4—are produced in the state $|\Psi^-\rangle_{12}\otimes|\Psi^-\rangle_{34}$ in the EPR sources I and II respectively. At first, Alice and Bob perform polarization measurements on photons 1 and 4, choosing freely the polarization analysis basis among three mutually unbiased bases (*horizontal/vertical* $|H\rangle/|V\rangle$, *right-circular/left-circular* $|R\rangle/|L\rangle$, *plus/minus* $|+\rangle/|-\rangle$, and record the outcomes. Photons 2 and 3 are sent to Victor, who then subjects them to either an entangled-state measurement or a separable-state measurement. He projects them randomly into one of two possible maximally entangled Bell states ($|\Phi^+\rangle_{23}$ or $|\Phi^-\rangle_{23}$) or one of two separable states ($|HH\rangle_{23}$ or $|VV\rangle_{23}$). Victor records the outcome and keeps it to himself. This procedure projects photons 1 and 4 onto a corresponding entangled ($|\Phi^+\rangle_{14}$ or $|\Phi^-\rangle_{14}$) or separable state ($|VV\rangle_{14}$ or $|HH\rangle_{14}$) respectively. According to Victor's choice and his results, he can sort Alice's and Bob's already recorded data into subsets and can verify that each subset behaves as if it consisted of either entangled or separable pairs of distant photons, which have neither communicated nor interacted in the past. From [16].

We consider the case that when Victor makes his decision and performs the respective measurement, photons 1 and 4 have long been registered and the results have been classically recorded. A possible sequence of results is also shown in Fig. 30.4. The interesting point now is the following. Depending on the measurement that Victor decides to perform, the already long ago registered records for photon 1 and 4 can be interpreted as confirming the entanglement by using a suitable entanglement witness or as being consistent with the factorizable state of photons 1 and 4. But, clearly, photons 1 and 4 can only be either entangled or in a factorizable state.

Depending on the kind of measurement chosen by Victor, entangled or not, and depending on the specific measurement result, the sets of data obtained by Alice and Bob can be separated into four independent data sets in the entangled state case and into four different independent data sets in the product state case. These four data sets are very different in the two cases. Interestingly, the data sets obtained by Alice and Bob are rich enough to allow both divisions into subsets. Therefore, a consistent interpretation of the recorded data emerges. This is sometimes seen as a puzzle, as it might appear that the decision by Victor whether to project onto an entangled state or onto a product state might modify the results already obtained and classically recorded. Yet this is certainly not the case. The data have been recorded and are not changed. But their interpretation is missing until Victor has made his decision and done the measurement. Only after that measurement, Alice's and Bob's already long ago recorded data obtain their proper interpretation. Peres points out very clearly that there is nothing contradictory about the situation. It is all consistent with quantum mechanics. In a sense, one might say that the data are somehow the most primitive and basic concept in a quantum measurement. Their interpretation can certainly depend on future actions, as is the case here.

In a way to see the situation from the point of view of information, one can say that the information in the four-photon state is limited. The four photons are only able to carry a limited amount of information. If this information is information implying entanglement between 1–2 and 3–4, then it cannot also be information implying entanglement between 1–4 and 2–3. It can never be both at the same time. The well-known monogamy of entanglement [13] thus is a consequence of the limited amount of information a quantum state can carry. It is interesting to see that the original quantum state of all four photons can be decomposed into sums of four product states of maximally entangled Bell states,

$$|\Psi\rangle_{1234}=|\Psi_-\rangle_{12}\otimes|\Psi_-\rangle_{34}=\frac{1}{2}(|\Psi_+\rangle_{14}\otimes|\Psi_+\rangle_{23}-|\Psi_-\rangle_{14}\otimes|\Psi_-\rangle_{23}-|\Phi_+\rangle_{14}\otimes|\Phi_+\rangle_{23}+|\Phi_-\rangle_{14}\otimes|\Phi_+\rangle_{23}), \tag{3}$$

where

$$\begin{aligned} |\Psi_{+,-}\rangle_{ab}&=\frac{1}{\sqrt{2}}|\mathrm{H}\rangle_a|\mathrm{V}\rangle_b\pm|\mathrm{V}\rangle_a|\mathrm{H}\rangle_b,\\ |\Phi_{+,-}\rangle_{ab}&=\frac{1}{\sqrt{2}}|\mathrm{H}\rangle_a|\mathrm{H}\rangle_b\pm|\mathrm{V}\rangle_a|\mathrm{V}\rangle_b. \end{aligned} \tag{4}$$

Entanglement swapping can also be seen as teleportation of an entangled state. It is either the teleportation of the state of photon 2 over to photon 4 or the teleportation of photon 3 over to photon 1.

The first experimental realization was done in Vienna [14, 15]. In these experiments, the situation was static, and no special precaution was taken to perform the Bell measurement after the independent photons had been registered. More recently, the proposal of Peres was realized [16] by measuring one photon from each entangled pair separately and sending the other photon from each pair into a rapidly tunable Mach-Zehnder interferometer (Fig. 30.5).

When the internal phase of the interferometer is set to an integer multiple of π, registration at the final detectors allows to conclude from which source each of the photons 2 and 3 came. And thus, in that case, they are projected onto a product state. In contrast, when the internal phase is set to, say, $\pi/2$, no conclusion is possible about the source of the incoming photons 2 and 3. Thus, they are projected onto a maximally entangled state. Consequently, also the earlier registered photons 1 and 4 are projected either into a product state or into a maximally entangled state. It should also be mentioned that the registration, and even the setting of the internal phase, was done at a time after the other two photons had been registered already. When photons 2 and 3 were projected onto an entangled state, an entanglement witness confirmed the existence of entanglement between photons 1 and 4. This witness was basically a measurement of the correlations in three mutually unbiased bases. In the case of a projection of photons 2 and 3 onto a product state, polarization correlation of photons 1 and 4 was only observed in one basis, confirming that there was no entanglement between them.

To analyze the situation from a conceptual point of view, we realize that the individual polarization registration events of photons 1 and 4 are classical long before the complete measurement, including photons 2 and 3, is finished. But only the complete measurement on photons 2 and 3 allows to determine the quantum state for all four photons, and therefore allows to fully interpret the situation. It is therefore suggestive that the events are a more fundamental reality than the quantum states which are only determined in the end.

The Quantum State as Representation of Information

Let us now come back to the famous double-slit experiment [17]. The message of that experiment is again related to the notion of information. Interference occurs if, and only if, no path information exists anywhere in the Universe about which of the two paths the particle took. It is irrelevant whether an observer takes note of that information. The quantum state then is just a representation of possible future measurement results or, following Schrödinger [2], an expectation catalogue (Fig. 30.6).

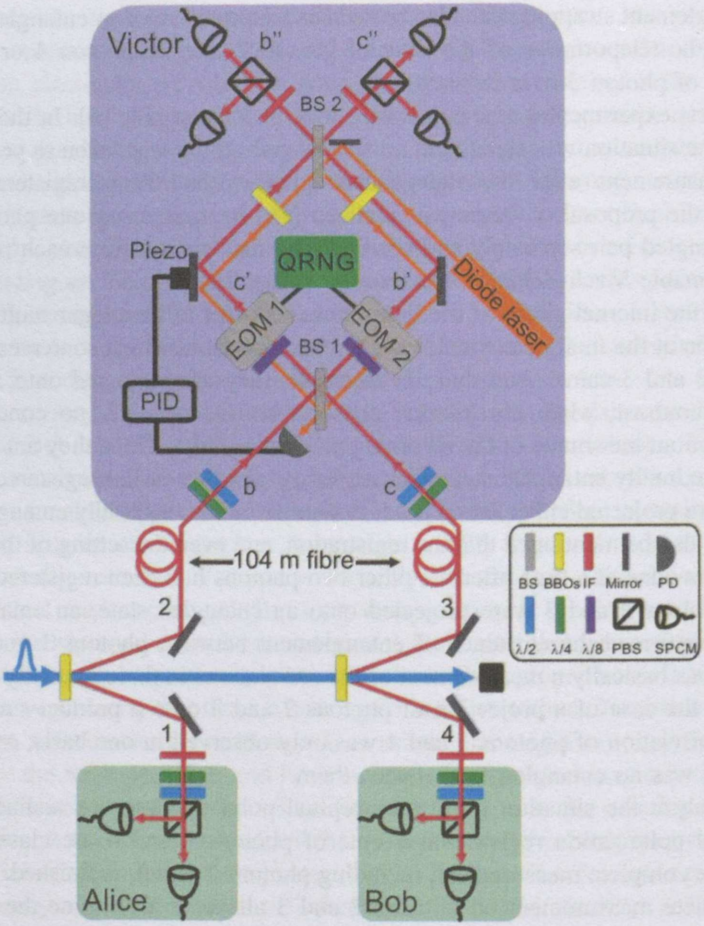

Fig. 30.5 Experimental set-up of delayed-choice entanglement swapping. A pulsed laser beam with a central wavelength of 404 nm, a pulse duration of 180 fs, and a repetition rate of 80 MHz successively passes through two BBO crystals to generate two polarization-entangled photon pairs (photons 1 and 2 and photons 3 and 4) through type-II spontaneous parametric down-conversion. Photons 1 and 4 are directly subjected to the polarization measurements performed by Alice and Bob (*green blocks*). Photons 2 and 3 are each delayed with a 104 m single-mode fiber and then coherently overlapped at the input beam splitter BS1 of a tunable Mach-Zehnder interferometer acting as a switchable interferometric Bell-state analyzer (*purple block*). Depending on the internal phase of the interferometer, it operates either as a Bell-state measurement device or it does not superpose the amplitudes of the two photons coming from the two down-conversion crystals. In the first case, photons 2 and 3 are projected onto an entangled state. In the second case, each photon's polarization is measured individually by Victor. The choice between the two measurements is made by a fast quantum random number generator at a time after the twin photons 1 and 4 have been measured. From [16].

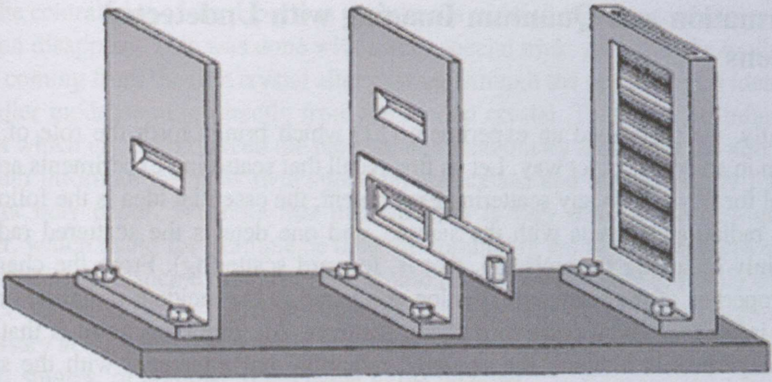

Fig. 30.6 Young's double-slit experiment as drawn by Niels Bohr in [17].

What is meant by information here is the possibility to obtain knowledge. Here, it is the possibility to obtain knowledge about the path taken. As long as that possibility exists, there cannot be any interference. All quantum eraser experiments [18] and their delayed-choice variants [19] indeed work by erasing just this possibility of obtaining knowledge about the path, i.e. the particle-like property. Finally, we remark that this knowledge could be obtained by any observer! It is irrelevant whether it is a conscious observer or not.

At about the same time when Bell discovered his theorem, Wigner expressed his position very clearly [20]:

> … it is impossible to give a satisfactory description of atomic phenomena (*i.e. by quantum mechanics*)[1] without reference to the consciousness. … the "reduction of the wave packet" … takes place when the result of an observation enters the consciousness of the observer … or, to be even more painfully precise, my own consciousness.

It is clear that this position differs significantly from Bell's view as expressed above. In contrast, Heisenberg wrote in a letter to Renninger on February 2 1960 [21]:

> The act of recording, on the other hand, which leads to the reduction of the state, is not a physical, but rather, so to say, a mathematical process. With the sudden change of our knowledge also the mathematical representation of our knowledge undergoes of course a sudden change.

I interpret Heisenberg's position—and in that respect, I share his point of view—in the way that there is no measurement problem. All that happens is a change of our representation of information, i.e. the quantum state. Concluding, I might suggest that it is most natural to change the representation of information, that is, the quantum state, when our knowledge changes because of new information obtained by measurement.

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[1]Cursive text in brackets inserted by the author of the current essay.

Information and Quantum Imaging with Undetected Photons

Recently, we performed an experiment [22] which brings forth the role of information in a very succinct way. Let us first recall that scattering experiments are very central for physics. In any scattering experiment, the essential idea is the following: Some radiation interacts with the sample, and one detects the scattered radiation (certainly including transmission, that is, forward scattering). From the change of the properties of the scattered radiation compared to the incident radiation one can make inferences about properties of the scatterer. An important point is that in all such experiments hitherto, the scattered radiation that interacted with the sample must be registered somehow, by a film, a detector or another suitable device. This is even true for holography, where the scattered radiation is superposed with coherent radiation. But it is not true in the experiment [22] which we will now discuss.

The experiment builds on a beautiful paper by Zou et al. [23]. The paper acknowledges Jeff Ou for the suggestion of aligning NL1 and NL2 as to make the idler trajectories coincide. In our review of multi-particle interference in Physics Today in 1993 [24], Greenberger, Horne and myself called it a 'mind-boggling' experiment.

The salient features of the experiment are (Fig. 30.7): Two nonlinear crystals are pumped by the same pump. In each of the two crystals, photon pairs can be produced. Let us assume that the pump intensity is such that the production of two photon pairs is negligible. Consider therefore the case that one pair is produced either in crystal NL1 or in crystal NL2. Quantum mechanically speaking, the photon pair is produced in a superposition of both possibilities. The outgoing modes in each crystal are called idler i and signal s. If now the two modes of the signal photon are brought back together, there should be no interference in general, because the idler could be used to find out by which of the two crystals the pair was produced, thereby revealing path information.

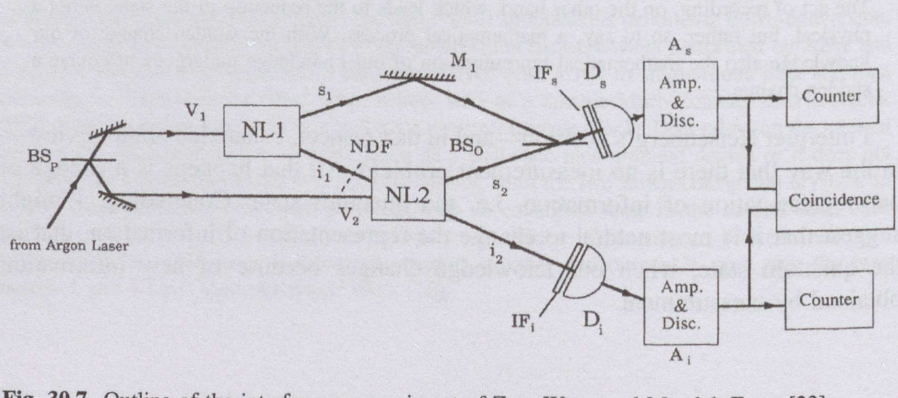

Fig. 30.7 Outline of the interference experiment of Zou, Wang and Mandel. From [23].

The central idea of the paper was to make the path information carried by the idler photon disappear. This was done with a very special trick, such that the mode of the idler coming from the first crystal after passage through the second one is identical to the idler mode coming directly from the second crystal. That way, no information about which crystal produced the pair can be found out by looking at the idler. Thus, no path information for its twin signal photon exists, and interference at the beam splitter may occur. We note that this situation is very different from a quantum eraser, which could for example be done by combining the two idler modes also at a beam splitter. In such a case, the idler would have to be detected to finally erase the source information. In the new situation, the detection of the idler photon is not necessary at all. Most importantly, the fringes for the signal occur not in coincidence, but as singles, in contrast to the usual ghost imaging.

I would suggest calling this phenomenon "coherence by identity". This is because the two signals for the idler are coherent for the very reason that the two modes of the idler are completely identical. Strictly speaking, it is actually wrong to talk about two modes for the idler. There is only one mode, which emerges from both crystals. Again, it is the absolute unavailability of information, and thus the impossibility to obtain path knowledge, which makes coherence and interference possible.

The experiment has various interesting, maybe even counter-intuitive properties. This can be seen, for example (Fig. 30.8), when inserting a phase-shifter into the idler mode between NL1 and NL2. The important point is that that phase shift cannot be attributed to the idler mode alone, even as it is introduced by the phase-shifter in the idler beam. Rather, it is a nonlocal phase shift experienced by the total two-photon state emerging from crystal NL1. It can therefore be revealed as the phase shift between the signal modes c and e meeting at the beam splitter BS2. Furthermore, if the object has some absorptive properties, full or partial, this provides path information between the signal modes *c* and *e*, which results in a reduction of the outgoing interference contrast in modes *g* and *h*.

We now discuss two imaging experiments which also underline salient features of the experimental set-up. Before discussing both experiments, we should realize once more that the idler in that experiment is not registered at all. It is just left to pass away freely. An experimental situation where the path information is directly relevant for obtaining the image occurs when an absorptive mass is placed into the idler beam. The object is a cardboard cut-out of the image of a cat. Light can freely pass through the cat opening, while outside, light is absorbed. This object is placed into the idler beam between the two crystals of Fig. 30.8. The image (Fig. 30.9) on the top left clearly shows that in both outgoing beams of the signal photon after the beam splitter, the cat image appears. We will now discuss briefly the image itself and how it relates to information. On the left-hand side, the cat is seen as bright, namely constructive, interference of the two signal beams. On the right-hand side, the cat is dark—destructive interference of the two signal beams. This is easily understood. The beam path was adjusted in such a way that for one of the two signal beams, constructive interference results, and for the other one, destructive interference arises. Outside of the cat images, we have a shadow region of the same brightness in both cases. This simply results from the fact that the idler mode

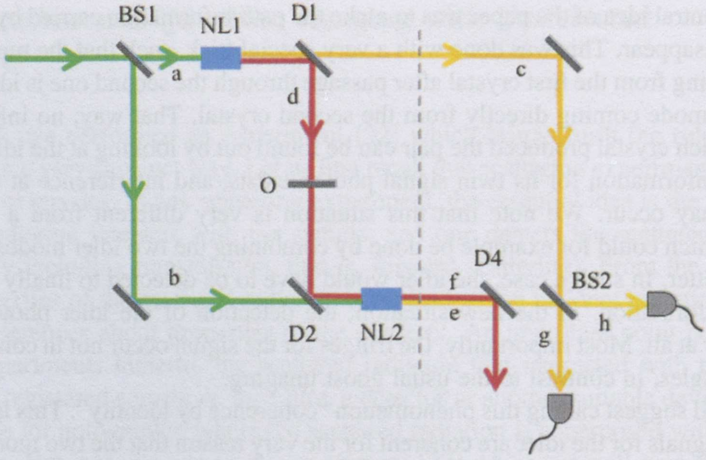

Fig. 30.8 Schematic of the experiment of quantum imaging with undetected photons. Laser light (*green*) splits at beam splitter *BS1* into modes *a* and *b*. Beam *a* pumps nonlinear crystal *NL1*, where collinear down-conversion may produce a pair of photons of different wavelengths called signal (*yellow*) and idler (*red*). After passing through the object *O*, the idler reflects at dichroic mirror *D2* to align with the idler produced in *NL2*, such that the final emerging idler *f* does not contain any information about which crystal produced the photon pair. As a consequence, signals *c* and *e* combined at beam splitter *BS2* interfere. Consequently, the superposition signal beams *g* and *h* reveal idler transmission properties of object *O*. From [22].

between crystal 1 and 2 is absorbed. Therefore, the idler emerging from the experiment could easily be used to find out that the pair was created in the second crystal. Likewise, we could consider the absorbing cardboard as a detector which, if it fires, tells us that the pair was created in the first crystal. Therefore, in that situation, one has path information outside the cat openings, and thus, no interference for the signal photon can arise. That is, the outside shady regions simply represent incoherent summations or incoherent mixtures of the two modes of the signal photon coming via the two paths. Thus, the existence or nonexistence of path information is clearly responsible for the production of the image. And, to stress that point again, that information is carried—or not—by the idler photon, which need not at all be deleted or erased.

A different physical argument leads to the imaging of phase objects (Fig. 30.10). There, an object introducing a phase shift of π was inserted into the idler mode between the two crystals. As discussed above, that phase cannot be considered to be carried by the idler beam alone. In fact, because the mode of the idler after emerging from the second crystal is the same whether the idler was created in either crystal, that phase cannot manifest itself in the emerging idler beam at all. Rather, it now manifests itself as a phase difference between the two signal modes superposed at the beam splitter. Again, the picture here is a consequence of firstly the fact that nowhere in the image, path information is available about where the pair was created, and secondly, it is a consequence of the fact that in a product state, the phase shift cannot be assigned to either member of the product.

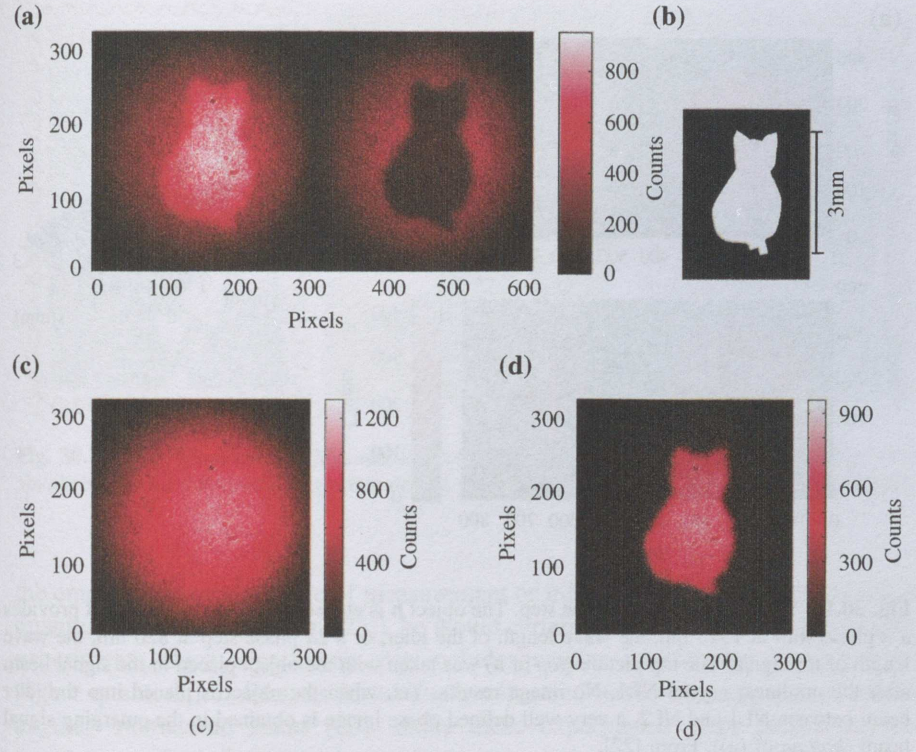

Fig. 30.9 Which-path imaging. **a** Inside the cat, constructive and destructive interference are observed at the two outputs of BS2 when we placed the cardboard cut-out shown in (**b**) into the idler path between NL1 and NL2. Outside the cat opening, the idler photon from NL1 is blocked and therefore the corresponding signal photon does not interfere, resulting in an unstructured background in both images in (**a**). **c** The sum of the outputs gives the intensity profile of the signal beam, not showing any effect of the absorption. **d** The subtraction of the outputs leads to an enhancement of the interference contrast, as outside of the cut-out, the two backgrounds completely subtract. The image arises because outside of the cut-out area, path information is available, while inside, this is not the case. From [22].

Finally, a small remark on entanglement might be in order. It is not irrelevant that the state used in the experiment is a high-dimensionally entangled state of superposed pairs created at different locations transversely to the pump beams.

Conclusion

I have given a number of examples which underline the role of information in quantum mechanics. This is part of an emerging view where it appears that information has a much more fundamental role in quantum physics than realized hitherto in general. I am very confident that while John Bell would not have liked

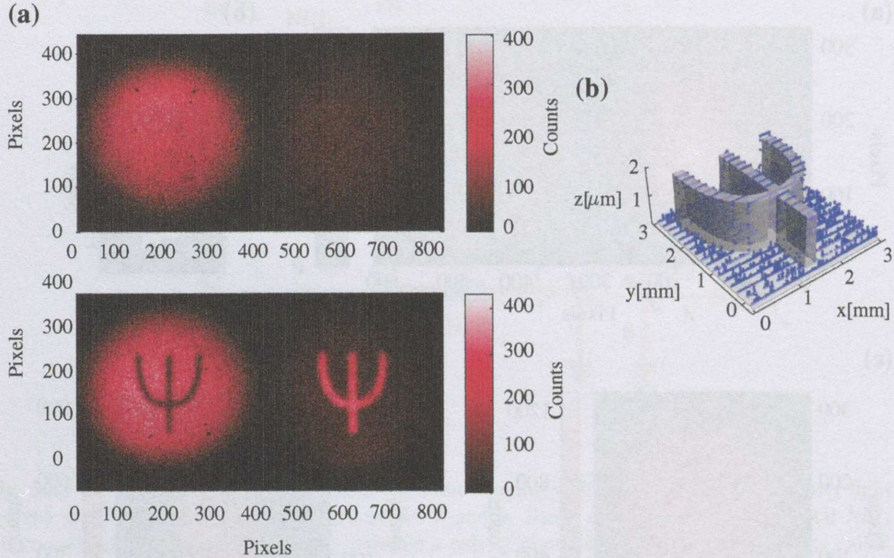

Fig. 30.10 Phase imaging of a phase step. The object **b** is etched into silicon such that it provides a π phase shift at 1515 nm, the wave length of the idler, or a 2π phase step at 820 nm, the wave length of the signal. The top picture (*top* of **a**) was taken with the object placed in the signal beam after the nonlinear crystal NL1. No image results. Yet, when the object is placed into the idler beam between NL1 and NL2, a very well defined phase image is obtained in the emerging signal beam (*bottom* of (**a**)). From [22].

Fig. 30.11 Photograph taken in Amherst, Massachusetts, in 1990. From *right to left*; John Bell, Mary Bell, AZ and Arthur Zajonc. In the *lower left corner*, you can see a beer, held by Mike Horne. (*Photo* Kurt Gottfried).

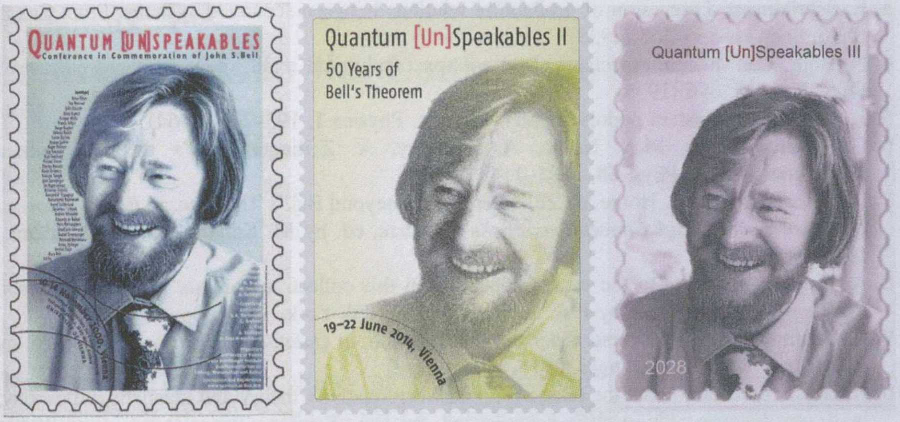

Fig. 30.12 The *Quantum [Un]Speakables* conference series. (Graphic design *Quantum [Un] Speakables* I: Julia Petschinka; graphic design *Quantum [Un]Speakables* II: Raoul Krischanitz).

the emerging increasing role of measurement or information in the interpretation of quantum mechanics (see e.g. [25]), he would certainly have loved to see the modern experiments. Such experiments also include quantum interference for higher and higher quantum numbers, as for example witnessed in the entanglement of orbital angular momentum states [26]. Since these experiments were performed, the quantum numbers for entanglement have been raised to beyond 10.000 ħ.

In the end, I would like to emphasize my deep appreciation and admiration of John Bell. I am very grateful for having met him personally, and having had the opportunity to discuss with him a couple of times our views of the foundations of quantum mechanics, even if they differed significantly (Fig. 30.11).

As you know, this is the second conference on *Quantum [Un]Speakables*. The first conference took place in 2000, to commemorate the tenth anniversary of John Bell's death. The present conference, in 2014, celebrates 50 years of Bell's theorem. It is therefore natural to see this as the start of a longer series. The next conference, again in 14 years' time, will therefore take place in 2028, and we will commemorate the 100^{th} birthday of John Stewart Bell (Fig. 30.12).

Acknowledgments This work was supported by the Austrian Science Fund (FWF) with SFB F40 (FoQuS).

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