Experimental delayed-choice entanglement swapping

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Motivated by the question of which kind of physical interactions and processes are needed for the production of quantum entanglement, Peres has put forward the radical idea of delayed-choice entanglement swapping. There, entanglement can be ‘produced a posteriori, after the entangled particles have been measured and may no longer exist’. Here, we report the realization of Peres’s gedanken experiment. Using four photons, we can actively delay the choice of measurement—implemented through a high-speed tunable bipartite state analyser and a quantum random-number generator—on two of the photons into the time-like future of the registration of the other two photons. This effectively projects the two already registered photons onto one of two mutually exclusive quantum states in which the photons are either entangled (quantum correlations) or separable (classical correlations). This can also be viewed as ‘quantum steering into the past’.

In the entanglement swapping1–3 procedure, two pairs of entangled photons are produced, and one photon from each pair is sent to Victor. The two other photons from each pair are sent to Alice and Bob, respectively. If Victor projects his two photons onto an entangled state, Alice’s and Bob’s photons are entangled although they have never interacted or shared any common past. What might be considered as even more puzzling is the idea of ‘delayed-choice for entanglement swapping’4,5. In this gedanken experiment, Victor is free to choose either to project his two photons onto an entangled state and thus project Alice’s and Bob’s photons onto an entangled state. If Alice and Bob measure their photons’ polarization states before Victor makes his choice and projects his two photons either onto an entangled state or onto a separable state, it implies that whether their two photons are entangled (showing quantum correlations) or separable (showing classical correlations) can be defined after they have been measured.

To experimentally realize Peres’s gedanken experiment, we place Victor’s choice and measurement in the time-like future of Alice’s and Bob’s measurements, providing a ‘delayed-choice’ configuration in any and all reference frames. This is accomplished by, first, proper optical delays for Victor’s photons and, second, a high-speed tunable bipartite state analyser (BiSA), which, third, is controlled in real time by a quantum random-number generator6 (QRNG). Both delay and randomness are needed to avoid the possibility that the photon pairs can ‘know’ in advance which setting will be implemented after they are registered and can behave accordingly by producing results of a definite entangled or a definite separable state. Whether Alice’s and Bob’s photons can be assigned an entangled state or a separable state depends on Victor’s later choice. In Peres’s words: “If we attempt to attribute an objective meaning to the quantum state of a single system, curious paradoxes appear: quantum effects mimic not only instantaneous action-at-a-distance but also, as seen here, influence of future actions on past events, even after these events have been irrevocably recorded.”

Historically, delayed-choice entanglement swapping4 can be seen as the fascinating consequence of quantum entanglement2–7 emerging from combining the gedanken experiments by Bohr7, illustrated by a double-slit set-up, and Wheeler8,9, illustrated by a Mach–Zehnder interferometer. In Bohr’s gedanken experiment, he demonstrated the complementarity principle, one of the most basic principles of quantum mechanics, with a double-slit apparatus. If both slits are open, the input quantum system exhibits ‘wave-like’ behaviour and shows interference on the detector screen. If only one slit is open, the system can propagate only through this slit. In this case, no interference will be observed and the system exhibits ‘particle-like’ behaviour with a well-defined path. In accordance with the complementarity principle, full interference and full path information will never be obtained simultaneously. As an explanation it is often said that any attempt to determine which path a particle takes inside a double-slit apparatus or an interferometer disturbs the particle and thus prevents the interference pattern from forming. From a modern point of view, however, interference patterns can arise if and only if no information about the path taken exists either on the particle itself or in the environment, regardless of whether or not an observer accesses this information.

If the choice between complementary experimental settings—on demonstrating interference, one revealing which-path information—is made in the past, an explanation of Bohr’s complementarity can be given in the following way: before the particle enters the interferometer, it ‘receives’ information as to which setting has been prepared and then behaves correspondingly. For example, the two complementary settings in a photonic Mach–Zehnder configuration can be implemented by inserting...
or removing the output beam splitter that recombines the two interfering paths. To avoid the possibility that the photon somehow ‘knows’ in advance whether the output beam splitter is chosen to be inserted or not, Wheeler suggested delaying this choice until after the photon has passed the input beam splitter\(^6\). Many so-called delayed-choice experiments have been performed\(^10-15\), including the scheme when the choice to insert or remove the output beam splitter is made at a spacetime location that is space-like separated from the entrance of the photon in the interferometer\(^14,15\). According to Wheeler, “We have a strange inversion of the normal order of time. We, now, by moving the mirror in or out have an unavoidable effect on what we have a right to say about the already past history of that photon.”\(^16\) Evidently, even in such a delayed-choice scenario, the choice has to be made in the past light cone of the final detection of the photon.

On the other hand, delayed-choice experiments with entangled photons pave the way for new possibilities, where the choice of measurement settings on the distant photon can be made even after the other photon has been registered. This has been shown in a delayed-choice-quantum eraser experiment\(^17\), where the which-path information of one photon was erased by a later suitable measurement on the other photon. This made it possible to decide \textit{a posteriori} a single-particle characteristic, namely whether the already measured photon behaved as a wave or as a particle. However, whereas all previous delayed-choice experiments\(^18-15\) focused on the characteristics of individual particles, delayed-choice entanglement swapping, using a four-partite entangled state, allows one to \textit{a posteriori} decide a two-particle characteristic and thus has qualitatively new features. Just as there is a wave–particle duality for single particles, there is an entanglement–separability duality for two particles. Entanglement and separability correspond to two mutually exclusive types of correlation between two particles.

Since Peres’s proposal, there have been pioneering delayed entanglement swapping experiments\(^18,17\). However, none of these demonstrations implemented an active, random, and delayed choice, which is required to guarantee that the photons cannot know in advance the setting of the future measurement. Thus, these experiments in principle allowed for a spatiotemporal description of which the past choice event influences later measurement events. Our experiment demonstrates entanglement–separability duality in a delayed-choice configuration through entanglement swapping. This means that it is possible to freely and \textit{a posteriori} decide which type of mutually exclusive correlations two already measured particles have. They can show either quantum correlations (due to entanglement) or purely classical correlations (stemming from a separable state). It can also be viewed as quantum steering\(^18\) of bipartite states into the past. Owing to the use of entanglement and active switching, it is also closely related to previous experimental tests of local realism\(^19-21\). Our experiment therefore implements the two important steps necessary on the way from Wheeler’s to Peres’s gedanken experiment: one needs to first extend Wheeler’s delayed-choice experiment to the delayed-choice quantum eraser to have the possibility that a choice (for one particle) can be made after the measurement (of another particle). In a second step, one has to go from the delayed-choice quantum eraser to delayed-choice entanglement swapping to be able to \textit{a posteriori} decide on a two-particle characteristic and show entanglement–separability duality.

In entanglement swapping\(^1\), two entangled pairs—photons 1 and 2 and photons 3 and 4—are each produced in the antisymmetric polarization-entangled Bell singlet state such that the total four-photon state has the form

\[
|\psi\rangle_{1234} = |\psi^\rightarrow\rangle_{12} \otimes |\psi^\rightarrow\rangle_{34}
\]

where \(|\psi^-\rangle_{12} = (|H\rangle_1|V\rangle_2 - |V\rangle_1|H\rangle_2)/\sqrt{2} \) and likewise for \(|\psi^-\rangle_{34}, |H\rangle_L (|V\rangle_R)\) denotes the horizontal (vertical) polarization state of the photon \( k = 1, 2, 3, 4 \). As schematically shown in Fig. 1, if Victor subjects his photons 2 and 3 to a Bell-state measurement (BSM), they become entangled. Consequently photons 1 (Alice) and 4 (Bob) also become entangled and entanglement swapping is achieved. This can be seen by rewriting equation (1) in the basis of Bell states of photons 2 and 3:

\[
|\psi\rangle_{1234} = \frac{1}{2} (|\psi^+\rangle_{14} \otimes |\psi^+\rangle_{23} - |\psi^-\rangle_{14} \otimes |\psi^-\rangle_{23} - |\phi^+\rangle_{14} \otimes |\phi^+\rangle_{23} + |\phi^-\rangle_{14} \otimes |\phi^-\rangle_{23})
\]

where the symmetric Bell triplet states are \(|\psi^\pm\rangle_{14} = (|H\rangle_1|V\rangle_2 \pm |V\rangle_1|H\rangle_2)/\sqrt{2}, |\phi^\pm\rangle_{14} = (|H\rangle_1|H\rangle_2 \pm |V\rangle_1|V\rangle_2)/\sqrt{2}\) (and likewise
It is realized with a Mach-Zehnder interferometer and consists of two 50/50 beam splitters, mirrors, and most importantly two for photons 2 and 3). Note that after the entanglement swapping, photons 1 and 2 (and 3 and 4) are not entangled with each other any more, which manifests the monogamy of entanglement\(^2\). The entanglement swapping protocol itself has been experimentally demonstrated with various physical systems\(^23\text{-}29\). It is at the heart of quantum information applications and the foundations of quantum physics, and is a crucial ingredient for quantum repeaters\(^30\text{-}31\), third-man quantum cryptography\(^32\), loophole-free Bell tests\(^33\) and other fundamental tests of quantum mechanics\(^34\text{-}35\).

In our experiment, the primary events are the polarization measurements of photons 1 and 4 by Alice and Bob. They keep their data sets for future evaluation. Each of these data sets by itself and their correlations are completely random and show no structure whatsoever. The other two photons (photons 2 and 3) are delayed until after Alice’s and Bob’s measurements, and sent to Victor for measurement. His measurement then decides the context and determines the interpretation of Alice’s and Bob’s data. In our set-up, using two-photon interference on a beam splitter combined with photon detections\(^36\text{-}37\), Victor may perform a BSM that projects photons 2 and 3 either onto \(|\psi^-\rangle\) or onto \(|\psi^+\rangle\). This would swap entanglement to photons 1 and 4. Instead of a BSM, Victor could also decide to measure the polarization of these photons individually and project photons 2 and 3 either onto \(|\psi^H\rangle\) or onto \(|\psi^V\rangle\), which would result in a well-defined polarization for photons 1 and 4, that is, a separable state. These two measurements are mutually exclusive (complementary in the sense meant by Bohr) in the same way as measuring particle or wave properties in an interference experiment. The choice between the two measurements is made by using a QRNG. The QRNG is based on the intrinsically random detection events of photons behind a balanced beam splitter\(^6\) (see Supplementary Information for details). According to Victor’s choice of measurement (that is, entangled or separable state) and his results (that is, \(|\psi^\pm\rangle\) or \(|\psi^H\rangle\) or \(|\psi^V\rangle\)), Alice and Bob can sort their already recorded data into 4 subsets. They can now verify that when Victor projected photons onto an entangled state \(|\psi^H\rangle\) or \(|\psi^V\rangle\), each of their joint subsets behaves as if it consisted of entangled pairs of distant photons. When Victor projected his photons onto a separable state \(|\psi^H\rangle\), Alice’s and Bob’s joint subsets behave as if they consisted of separable pairs of photons. In neither case Alice’s and Bob’s photons have communicated or interacted in the past. This indicates that quantum mechanical predictions are completely indifferent to the temporal order of Victor’s choice and measurement with respect to Alice’s and Bob’s measurements. Whether Alice’s and Bob’s earlier measurement outcomes indicate entanglement of photons 1 and 4 strictly depends on which measurements Victor performs at a later time on photons 2 and 3.

The scheme of the experimental set-up follows the proposals in refs 4, 38, and is shown in Fig. 2. Two polarization-entangled pairs of photons 1 and 2 and photons 3 and 4 are emitted by two β-barium borate (BBO) crystals through type-II spontaneous parametric down-conversion\(^39\) in the state shown in equation (1). All four photons are coupled into single-mode fibres. To fulfil the delayed-choice condition, the lengths of the fibres are chosen suitably. Photon 1 is sent to Alice and photon 4 to Bob with a 7 m fibre (35 ns), where their polarization states are measured. Photons 2 and 3 are each delayed with a 104 m single-mode fibre (520 ns) and sent to Victor, who projects photons 2 and 3 either onto an entangled state or a separable state\(^60\). See Supplementary Information for details on the experimental spacetime configuration.

One crucial component of our set-up is Victor’s high-speed tunable BiSA. This device is rapidly reconfigured such that it can project photons 2 and 3 either on a product or an entangled state. It is realized with a Mach–Zehnder interferometer and consists of two 50/50 beam splitters, mirrors, and most importantly two eighth-wave plates and electro-optic modulators (EOMs). The combination of eighth-wave plates and EOMs acts as a switchable quarter-wave plate, where the QRNG determines whether it acts as a quarter-wave plate oriented along 45° or whether it has no effect. The two complementary measurements are realized in the following ways: the BSM corresponds to turning on the switchable quarter-wave plates. In this case, the interferometer acts as a 50/50 beam...
splitter. Therefore, the two photons interfere and are projected onto a Bell state by polarization-resolving single-photon detections. The separable-state measurement (SSM) corresponds to turning off the switchable quarter-wave plates. Then the interferometer acts as a 0/100 beam splitter, that is, a fully reflective mirror. Therefore, the two photons do not interfere and are projected onto a separable state by polarization-resolving single-photon detections. For detailed information on the tunable BiSA, see the caption of Fig. 2, the Supplementary Information and ref. 41.

For each successful run (a fourfold coincidence count), not only does Victor’s measurement event happen 485 ns later than Alice’s and Bob’s measurement events, but Victor’s choice happens in an interval of 14 ns to 313 ns later than Alice’s and Bob’s measurement events. Therefore, independent of the reference frame, Victor’s choice and measurement are in the future light cones of Alice’s and Bob’s measurements. Given the causal structure of special relativity, that past events can influence (time-like) future events but not vice versa, we explicitly implemented the delayed-choice scenario as described by Peres. Only after Victor’s measurement, we can assert the quantum states shared by Alice and Bob. Our experiment relies on the assumption of the statistical independence of the QRNG from other events, in particular Alice’s and Bob’s measurement results. Note that in a conspiratorial fashion, Victor’s choice might not be free but always such that he chooses an SSM whenever Alice’s and Bob’s pair is in a separable state, and he chooses a BSM whenever their pair is in an entangled state. This would preserve the viewpoint that in every single run Alice and Bob receive a particle pair in a definite separable or a definite entangled state. A possible improvement of our set-up would be space-like separation of Victor’s choice event and the measurement events of Alice and Bob to further strengthen the assumption of the mutual independence of these events.

For each pair of photons 1 and 4, we record the chosen measurement configurations and the fourfold coincidence detection events. All raw data are sorted into four subensembles in real time according to Victor’s choice and measurement results. After all of the data had been taken, we calculated the polarization correlation function of photons 1 and 4. It is derived from their coincidence counts of photons 1 and 4 conditional on projecting photons 2 and 3 to \( |\phi^+\rangle_{23} = (|HH\rangle_{23} - |VV\rangle_{23})/\sqrt{2} \) when the BSM was performed, and to \( |HH\rangle_{23} \) or \( |VV\rangle_{23} \) when the SSM was performed. The normalized correlation function \( E(j) \) between two photons is defined as:

\[
E(j) = \frac{C(j,j) + C(j^+,j^+) - C(j^+,j) - C(j,j^+)}{C(j,j) + C(j^+,j^+) + C(j^+,j) + C(j,j^+)}
\]  

where \( j^\pm \) stands for horizontal/vertical (|H⟩/|V⟩) or plus/minus (|+⟩/|−⟩), with \( |\pm⟩ = (|H⟩ ± |V⟩)/\sqrt{2} \), or right/left (|R⟩/|L⟩), with \( |R⟩ = (|H⟩ + |V⟩)/\sqrt{2} \) and \( |L⟩ = (|H⟩ - |V⟩)/\sqrt{2} \) circular polarization. In equation (3), \( C(j,j^+) \) is the number of coincidences under the setting \( (j^+,j^-) \). In Fig. 3, we show the correlation functions of photons 1 and 4 in these three mutually unbiased bases derived from the measurement results. Note that the reason why we use one specific entangled state but both separable states to compute the correlation function is that the measurement solely depends on the settings of the EOMs in the BiSA. Then the same coincidence counts (HH and VV combinations of Victor’s detectors) are taken for the computation of the correlation function of photons 1 and 4. These counts can belong to Victor obtaining the entangled state \( |\phi^+\rangle_{23} \) in a BSM or the states \( |HH\rangle_{23} \) and \( |VV\rangle_{23} \) in an SSM.

We quantified the quality of the experimentally obtained states \( \hat{\rho}_{\text{exp}} \) using the fidelity defined as \( F(\hat{\rho}_{\text{exp}}, |\text{out}\rangle_\text{id} = \text{Tr}(\hat{\rho}_{\text{exp}}|\text{out}\rangle_\text{id}\langle\text{out}|) \), which is the overlap of \( \hat{\rho}_{\text{exp}} \) with the ideally expected output state \( |\text{out}\rangle_\text{id} \). The state fidelity of the Bell state can be decomposed into averages of local measurements in terms of Pauli σ matrices\(^{42,43}\), such as

\[
F(\hat{\rho}_{\text{exp}}, |\phi^+\rangle) = \frac{1}{4} Tr(\hat{\rho}_{\text{exp}}[I + \hat{\sigma}_x \hat{\sigma}_z + \hat{\sigma}_y - \hat{\sigma}_x \hat{\sigma}_y])
\]  

where I is the identity operator for both photons. An entanglement witness is also employed to characterize whether entanglement existed between the photons. It is defined as\(^{42,44}\) \( \hat{W}(|\text{out}\rangle_\text{id}) = I/2 - |\text{out}\rangle_\text{id}\langle\text{out}| \). A negative expectation value of this entanglement witness operator, \( \hat{W}(|\text{out}\rangle_\text{id}) = \text{Tr}(\hat{\rho}_{\text{exp}}\hat{W}|\text{out}\rangle_\text{id}\langle\text{out}|) = 1/2 - F(\hat{\rho}_{\text{exp}}, |\text{out}\rangle_\text{id}) \), is a sufficient condition for entanglement.

Figure 3a shows that when Victor performs the BSM and projects photons 2 and 3 onto \( |\phi^+\rangle_{23} \), this swaps the entanglement, which is
confirmed by significant correlations of photons 1 and 4 in all three bases. The state fidelity $F_{\text{BSM}}(\phi_{14}^\text{H})$, equation (4), is 0.681 ± 0.034 and the entanglement witness value $W_{\text{BSM}}(\phi_{14}^\text{H})$ is −0.181 ± 0.034, which demonstrates entanglement between photons 1 and 4 with more than 5 standard deviations. The imperfect results are mainly due to the higher-order emissions from spontaneous parametric down-conversion, as explained in the Supplementary Information. Note that although Victor, by means of the QRNG, can choose to make a BSM (with possible outcomes $|\phi_{23}^\text{H}|$ and $|\phi_{23}^\text{V}|$), he cannot choose the specific outcome. If photons 2 and 3 are projected onto the entangled state $|\phi_{23}^\text{H}⟩$, photons 1 and 4 are projected to $|\phi_{41}^\text{H}⟩$ according to equation (2). These results are summarized in the Supplementary Information.

On the other hand, when Victor performs the SSM on photons 2 and 3 and does not swap entanglement, the correlation exists only in the $|H⟩/|V⟩$ basis and vanishes in the $|R⟩/|L⟩$ and $|+⟩/|−⟩$ bases, as shown in Fig. 3b. This is a signature that photons 1 and 4 are not entangled but in a separable state. When Victor performed the SSM on photons 2 and 3, we found that entanglement between photons 1 and 2 and between photons 3 and 4 remained. These entanglements vanished when Victor performed the BSM on photons 2 and 3, which is consistent with the entanglement monogamy relation. All results are summarized in Table 1.

With our ideal realization of the delayed-choice entanglement swapping gedanken experiment, we have demonstrated a generalization of Wheeler’s ‘delayed-choice’ tests, going from the wave–particle duality of a single particle to the entanglement–separability duality of two particles. Whether these two particles are entangled or separable has been decided after they have been measured. If one viewed the quantum state as a real physical object, one could get the paradoxical situation that future actions seem to have an influence on past and already irrevocably recorded events. However, there is never a paradox if the quantum state is viewed as no more than a ‘catalogue of our knowledge’. Then the state is a probability list for all possible measurement outcomes, the relative temporal order of the three observers’ events is irrelevant and no physical interactions whatsoever between these events, especially into the past, are necessary to explain the delayed-choice entanglement swapping. What, however, is important is to relate the lists of Alice, Bob and Victor’s measurement results. On the basis of Victor’s measurement settings and results, Alice and Bob can group their earlier and locally totally random results into subsets that each have a different meaning and interpretation. This formation of subsets is independent of the temporal order of the measurements. According to Wheeler, Bohr said that no elementary phenomenon is a phenomenon until it is a registered phenomenon. We would like to extend this by saying that some registered phenomena do not have a meaning unless they are put in relationship with other registered phenomena.

Table 1 | Results of the state fidelities and the expectation values of the entanglement witness operator for different pairs of photons with delayed-choice condition.

| Photon pairs | BSM by Victor | SSM by Victor |
|--------------|---------------|---------------|
|              | State fidelity | Entanglement witness value | State fidelity | Entanglement witness value |
| Photons 2 and 3 in $|\phi^-⟩$ | 0.645 ± 0.031* | −0.145 ± 0.031* | 0.379 ± 0.026 | 0.120 ± 0.026 |
| Photons 1 and 4 in $|\phi^+⟩$ | 0.681 ± 0.034* | −0.181 ± 0.034* | 0.421 ± 0.029 | 0.078 ± 0.029 |
| Photons 1 and 2 in $|\psi^-⟩$ | 0.301 ± 0.039 | 0.199 ± 0.039 | 0.908 ± 0.016* | −0.408 ± 0.016* |
| Photons 3 and 4 in $|\psi^+⟩$ | 0.274 ± 0.039 | 0.226 ± 0.039 | 0.864 ± 0.019* | −0.364 ± 0.019* |

A negative witness value (or, equivalently, a state fidelity above 1/2) corresponds to an entangled state (marked by an asterisk). When Victor performs a BSM and photons 2 and 3 are found in the state $|\phi_{23}⟩$, then photons 1 and 4 were in the entangled state $|\phi_{41}⟩$, that is, the entanglement was swapped. When Victor performs an SSM, projecting photons 2 and 3 on the mixture of $|\psi_{23}⟩$ or $|\psi_{23}⟩$, correlations between measurement results on pair 1 and 2 and pair 3 and 4 show that these pairs were entangled in the states $|\phi_{41}⟩$ and $|\phi_{41}⟩$, that the entanglement was not swapped. This can be obtained by evaluations of the pair-wise correlations between different photons.

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Author contributions

X.-S.M. designed and carried out the experiment and analysed data. S.Z. provided experimental assistance. T.J. conceived the research, planned the experiment and performed the experiment and analysed data. J.K. provided the theoretical analysis and analysed data. R.U. provided experimental and conceptual assistance. T.J. conceived the research, planned the experiment, and M. Aspelmeyer and P. Walther for fruitful discussions. We acknowledge support from the European Commission, Q-ESSENCE (No. 248095), ERC Advanced Senior Grant (QIT4QAD) and the John Templeton Foundation, as well as SFB-FOQUS and the Doctoral Program CoQuS of the Austrian Science Fund (FWF).

Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/naturephysics. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to X.-S.M. or A.Z.
In the version of this Article originally published online, the definition of the witness operator given in the paragraph after equation (4) should have read $\hat{W}(\text{out}) = \hat{I}/2 - |\text{out}\rangle\langle\text{out}|$. This error has been corrected in all versions of the Article.