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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 swapping[1–3] 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, or to measure them individually and then project Alice's and Bob's photons onto a separable 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 generator[6] (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."[4].

Historically, delayed-choice entanglement swapping[4] can be seen as the fascinating consequence of quantum entanglement[1,2] emerging from combining the gedanken experiments by Bohr[7], illustrated by a double-slit set-up, and Wheeler[8,9], 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—one 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

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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[8,9]. 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."[9]. 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[13], 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 *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[8–15] focused on the characteristics of individual particles, delayed-choice entanglement swapping, using a four-partite entangled state, allows one to *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[16,17]. 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 in 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 *a posteriori* decide which type of mutually exclusive correlations two already earlier 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 *a posteriori* decide on a two-particle characteristic and show entanglement–separability duality.

In entanglement swapping[3], 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

$$|\psi\rangle_{1234} = |\psi^-\rangle_{12} \otimes |\psi^-\rangle_{34} \qquad (1)$$

where $|\psi^-\rangle_{12} = (|H\rangle_1|V\rangle_2 - |V\rangle_1|H\rangle_2)/\sqrt{2}$ and likewise for $|\psi^-\rangle_{34}$. $|H\rangle_k$ ($|V\rangle_k$) denotes the horizontal (vertical) polarization state of

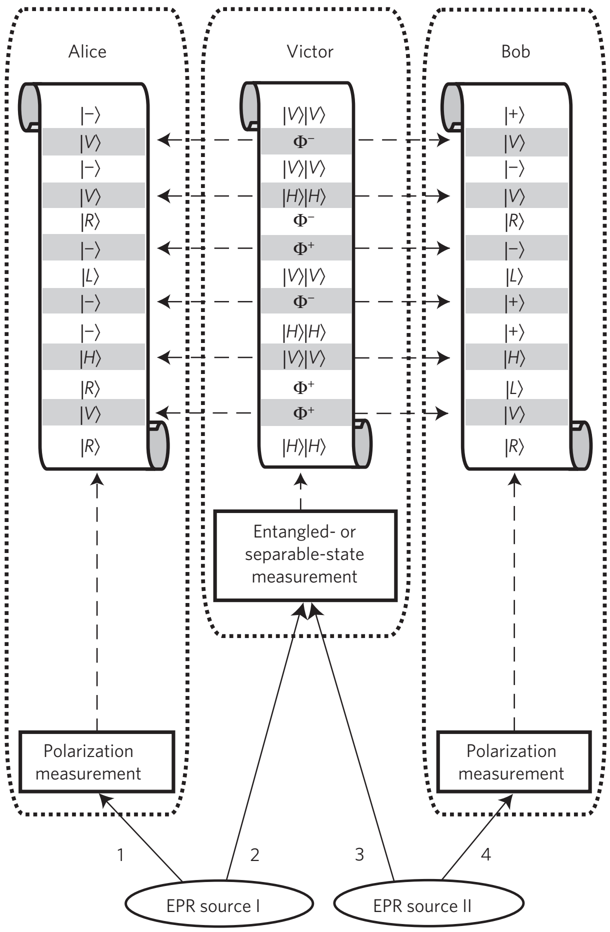

Figure 1 | The concept of delayed-choice entanglement swapping. Two entangled pairs—photons 1 and 2 and photons 3 and 4—are produced in the state $|\psi^-\rangle_{12} \otimes |\psi^-\rangle_{34}$ in the EPR sources I and II, respectively. At first, Alice and Bob perform polarization measurements on photons 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 (SSM), projecting them randomly onto one of two possible 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, Alice and Bob can sort their 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.

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:

$$\begin{aligned} |\psi\rangle_{1234} = \; & \frac{1}{2}(|\psi^+\rangle_{14} \otimes |\psi^+\rangle_{23} - |\psi^-\rangle_{14} \otimes |\psi^-\rangle_{23} \\ & - |\phi^+\rangle_{14} \otimes |\phi^+\rangle_{23} + |\phi^-\rangle_{14} \otimes |\phi^-\rangle_{23}) \qquad (2) \end{aligned}$$

where the symmetric Bell triplet states are $|\psi^+\rangle_{14} = (|H\rangle_1|V\rangle_2 + |V\rangle_1|H\rangle_2)/\sqrt{2}$, $|\phi^\pm\rangle_{14} = (|H\rangle_1|H\rangle_2 \pm |V\rangle_1|V\rangle_2)/\sqrt{2}$ (and likewise 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[22]. The entanglement swapping protocol itself has been experimentally demonstrated with various physical systems[23–29]. It is at the heart of quantum information applications and the foundations of quantum physics, and is a crucial ingredient for quantum repeaters[30,31], third-man quantum cryptography[32], loophole-free Bell tests[33] and other fundamental tests of quantum mechanics[34,35].

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[36,37], Victor may perform a BSM that projects photons 2 and 3 either onto $|\phi^+\rangle_{23}$ or onto $|\phi^-\rangle_{23}$. 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 $|HH\rangle_{23}$ or onto $|VV\rangle_{23}$, 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, $|\phi^+\rangle_{23}, |\phi^-\rangle_{23}$ or $|HH\rangle_{23}, |VV\rangle_{23}$), Alice and Bob can sort their already recorded data into 4 subsets. They can now verify that when Victor projected his photons onto an entangled state ($|\phi^+\rangle_{23}$ or $|\phi^-\rangle_{23}$), 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 ($|HH\rangle_{23}$ or $|VV\rangle_{23}$), 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 fibre (520 ns) and sent to Victor, who projects photons 2 and 3 either onto an entangled state or a separable state[40]. 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

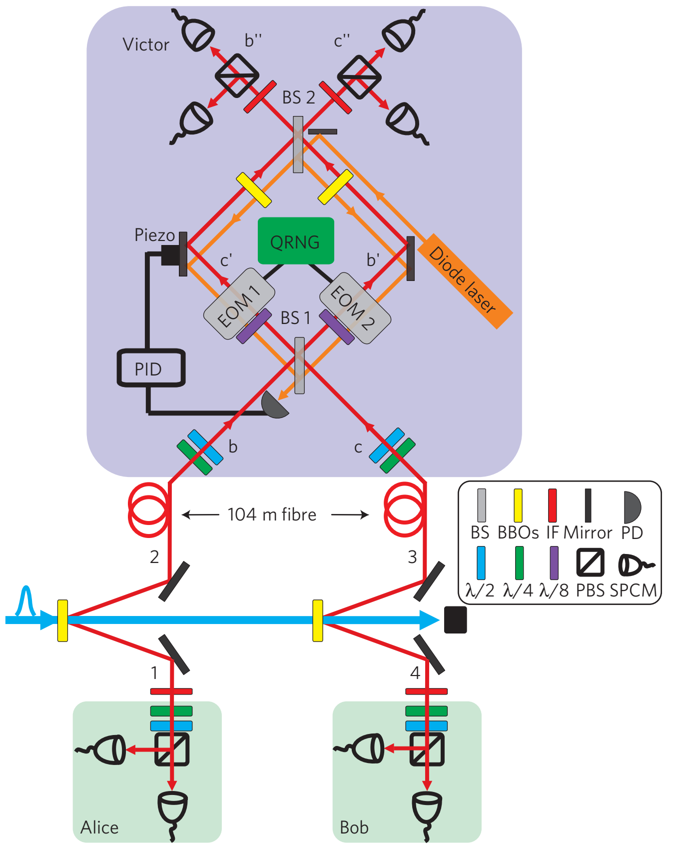

Figure 2 | Experimental set-up. A pulsed ultraviolet laser beam with a central wavelength of 404 nm, a pulse duration of 180 fs and a repetition rate of 80 MHz successively passes through two BBO crystals to generate two polarization-entangled photon pairs (photons 1 and 2 and photons 3 and 4) through type-II spontaneous parametric down-conversion[39,45]. Single-mode fibres and interference filters (IF) are used to clean their spatial and spectral modes. We use the interference filters with 1 nm (3 nm) bandwidth centred around 808 nm for photons 2 and 3 (photons 1 and 4). Photons 1 and 4 are directly subject to the polarization measurements performed by Alice and Bob (green blocks). Photons 2 and 3 are each delayed with a 104 m single-mode fibre and then coherently overlapped on the tunable BiSA (purple block). The single-mode fibre coupler of photon 2 is mounted on step motors and used to compensate the time delay for the interference at the tunable BiSA. An active phase-stabilization system is employed to compensate the phase noise in the tunable BiSA, which is composed of an auxiliary power-stabilized diode laser, a photon detector (PD) and a ring piezo-transducer controlled by an analogue proportional-integral-derivative (PID) regulator. Two pairs of cross-oriented BBO crystals (BBOs3 and BBOs4) are placed in each arm of the Mach–Zehnder interferometer (with input and output beam splitters BS 1 and BS 2) to compensate the unwanted birefringence. On each spatial mode, we employ the combination of a half-wave plate ($\lambda/2$), a quarter-wave plate ($\lambda/4$) and a polarizing beam splitter (PBS) for measuring the pair-wise correlations between different photons in different polarization bases. Photons are detected by using single-photon counting modules (SPCM). The fourfold coincidence count rate is about 0.016 Hz. See Supplementary Information for details.

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

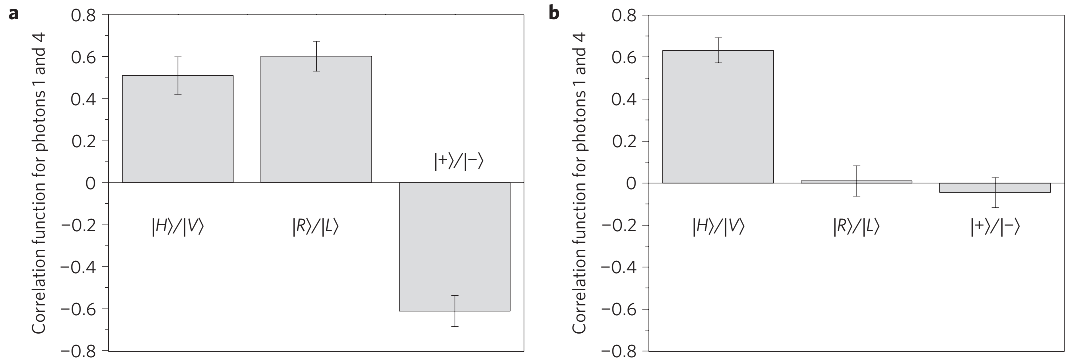

Figure 3 | Experimental results. Correlation function between photons 1 and 4 for the three mutually unbiased bases ($|H\rangle/|V\rangle$, $|R\rangle/|L\rangle$, $|+\rangle/|-\rangle$). **a**,**b**, Victor subjects photons 2 and 3 to either a BSM (**a**) or an SSM (**b**). These results are obtained from coincidence counts of photons 1 and 4, conditioned on the coincidence of same polarization and different spatial output modes of photons 2 and 3 (b″ and c″ in Fig. 2). **a**, When Victor performs a BSM and finds photons 2 and 3 in the state $|\phi^-\rangle_{23} = (|HH\rangle_{23} - |VV\rangle_{23})/\sqrt{2}$, entanglement is swapped to photons 1 and 4. This is confirmed by all three correlation functions being of equal magnitude (within statistical error) and their absolute sum exceeding 1. **b**, When Victor performs an SSM and finds photons 2 and 3 in either the state $|HH\rangle_{23}$ or $|VV\rangle_{23}$, entanglement is not swapped. This is confirmed by only the correlation function in the $|H\rangle/|V\rangle$ basis being significant whereas the others vanish. The experimentally obtained correlation functions of photons 1 and 4 in the ($|H\rangle/|V\rangle$, $|R\rangle/|L\rangle$, $|+\rangle/|-\rangle$) bases are 0.511 ± 0.089, 0.603 ± 0.071, -0.611 ± 0.074 respectively for case **a** and 0.632 ± 0.059, 0.01 ± 0.072, -0.045 ± 0.070 respectively for case **b**. Whereas entangled states can show maximal correlations in all three bases (the magnitude of all correlation functions equals 1 ideally), separable states can be maximally correlated (ideal correlation function 1) only in one basis, the others being 0. The uncertainties represent plus/minus one standard deviation deduced from propagated Poissonian statistics.

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 do 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:

$$E(j) = \frac{C(j,j) + C(j^\perp,j^\perp) - C(j^\perp,j) - C(j,j^\perp)}{C(j,j) + C(j^\perp,j^\perp) + C(j^\perp,j) + C(j,j^\perp)} \quad (3)$$

where $j/j^\perp$ stands for horizontal/vertical ($|H\rangle/|V\rangle$) or plus/minus ($|+\rangle/|-\rangle$, with $|\pm\rangle = (|H\rangle \pm |V\rangle)/\sqrt{2}$), or right/left ($|R\rangle/|L\rangle$, with $|R\rangle = (|H\rangle + i|V\rangle)/\sqrt{2}$ and $|L\rangle = (|H\rangle - i|V\rangle)/\sqrt{2}$) circular polarization. In equation (3), $C(j,j^\perp)$ is the number of coincidences under the setting $(j,j^\perp)$. 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 $\hat\rho_{\mathrm{exp}}$ using the fidelity defined as $F(\hat\rho_{\mathrm{exp}}, |\mathrm{out}\rangle_{\mathrm{id}}) = \mathrm{Tr}(\hat\rho_{\mathrm{exp}}|\mathrm{out}\rangle_{\mathrm{id}}\langle\mathrm{out}|)$, which is the overlap of $\hat\rho_{\mathrm{exp}}$ with the ideally expected output state $|\mathrm{out}\rangle_{\mathrm{id}}$. 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

$$\begin{aligned} F(\hat\rho_{\mathrm{exp}}, |\phi^-\rangle) &= \mathrm{Tr}(\hat\rho_{\mathrm{exp}}|\phi^-\rangle\langle\phi^-|) \\ &= \frac{1}{4}\mathrm{Tr}[\hat\rho_{\mathrm{exp}}(\hat I + \hat\sigma_z\hat\sigma_z + \hat\sigma_y\hat\sigma_y - \hat\sigma_x\hat\sigma_x)] \end{aligned} \quad (4)$$

where $\hat I$ 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] $\hat W(|\mathrm{out}\rangle_{\mathrm{id}}) = \hat I/2 - |\mathrm{out}\rangle_{\mathrm{id}}\langle\mathrm{out}|$. A negative expectation value of this entanglement witness operator, $W(\hat\rho_{\mathrm{exp}}, |\mathrm{out}\rangle_{\mathrm{id}}) = \mathrm{Tr}[\hat\rho_{\mathrm{exp}}\hat W(|\mathrm{out}\rangle_{\mathrm{id}})] = 1/2 - F(\hat\rho_{\mathrm{exp}}, |\mathrm{out}\rangle_{\mathrm{id}})$, 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

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 $\lvert\phi^-\rangle$	0.645 ± 0.031*	-0.145 ± 0.031*	0.379 ± 0.026	0.120 ± 0.026
Photons 1 and 4 in $\lvert\phi^-\rangle$	0.681 ± 0.034*	-0.181 ± 0.034*	0.421 ± 0.029	0.078 ± 0.029
Photons 1 and 2 in $\lvert\psi^-\rangle$	0.301 ± 0.039	0.199 ± 0.039	0.908 ± 0.016*	-0.408 ± 0.016*
Photons 3 and 4 in $\lvert\psi^-\rangle$	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 $\lvert\phi\rangle_{23}$, then photons 1 and 4 were in the entangled state $\lvert\phi\rangle_{14}$; that is, the entanglement was swapped. When Victor performs an SSM, projecting photons 2 and 3 on the mixture of $\lvert HH\rangle_{23}$ or $\lvert VV\rangle_{23}$, correlations between measurement results on pair 1 and 2 and pair 3 and 4 show that these pairs were entangled in the states $\lvert\phi\rangle_{12}$ and $\lvert\phi\rangle_{34}$; that is, the entanglement was not swapped. This can be obtained by evaluations of the pair-wise correlations between different photons. The uncertainties represent plus/minus one standard deviation deduced from propagated Poissonian statistics.

confirmed by significant correlations of photons 1 and 4 in all three bases. The state fidelity $F(\hat{\rho}_{\mathrm{exp}}, \lvert\phi^-\rangle_{14})_{\mathrm{BSM}}$, equation (4), is 0.681 ± 0.034 and the entanglement witness value $W(\hat{\rho}_{\mathrm{exp}}, \lvert\phi^-\rangle_{14})_{\mathrm{BSM}}$ 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 $\lvert\phi^-\rangle_{23}$ and $\lvert\phi^+\rangle_{23}$), he cannot choose the specific outcome. If photons 2 and 3 are projected onto the entangled state $\lvert\phi^+\rangle_{23}$, photons 1 and 4 are projected to $\lvert\phi^+\rangle_{14}$ 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 $\lvert H\rangle/\lvert V\rangle$ basis and vanishes in the $\lvert R\rangle/\lvert L\rangle$ and $\lvert+\rangle/\lvert-\rangle$ 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[40]. 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'[2]. 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[6,8]. 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.

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References

1. Einstein, A., Podolsky, B. & Rosen, N. Can quantum-mechanical description of physical reality be considered complete? *Phys. Rev.* **47,** 777–780 (1935).
2. Schrödinger, E. Die gegenwärtige Situation in der Quantenmechanik. *Naturwissenschaften* **23,** 807–812; 823–828; 844–849 (1935). English translation in *Proc. Am. Philos. Soc.* **124,** (1980), reprinted in Wheeler, J. A. & Zurek, W. H. (eds) *Quantum Theory and Measurement* 152–167 (Princeton Univ. Press,1984).
3. Žukowski, M., Zeilinger, A., Horne, M. A. & Ekert, A. K. 'Event-ready-detectors' Bell experiment via entanglement swapping. *Phys. Rev. Lett.* **71,** 4287–4290 (1993).
4. Peres, A. Delayed choice for entanglement swapping. *J. Mod. Opt.* **47,** 139–143 (2000).
5. Cohen, O. Counterfactual entanglement and nonlocal correlations in separable states. *Phys. Rev. A* **60,** 80–84 (1999).
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. Bohr, N. in *Quantum Theory and Measurement* (eds Wheeler, J. A. & Zurek, W. H.) 9–49 (Princeton Univ. Press, 1984).
8. Wheeler, J. A. *Mathematical Foundations of Quantum Theory* 9–48 (Academic, 1978).
9. Wheeler, J. A. in *Quantum Theory and Measurement* (eds Wheeler, J. A. & Zurek, W. H.) 182–213 (Princeton Univ. Press, 1984).
10. Alley, C. O., Jacubowicz, O. G. & Wickes, W. C. in *Proc. Second International Symposium on the Foundations of Quantum Mechanics* (ed. Narani, H.) 36–47 (Physics Society of Japan, 1987).
11. Hellmut, T., Walther, H., Zajonc, A. G. & Schleich, W. Delayed-choice experiments in quantum interference. *Phys. Rev. A* **35,** 2532–2541 (1987).
12. Baldzuhn, J., Mohler, E. & Martienssen, W. A wave-particle delayed-choice experiment with a single-photon state. *Z. Phys. B* **77,** 347–352 (1989).
13. Kim, Y-H., Yu, R., Kulik, S., Shih, Y. & Scully, M. O. Delayed 'choice' quantum eraser. *Phys. Rev. Lett.* **84,** 1–4 (2000).
14. Jacques, V. *et al.* Experimental realization of Wheeler's delayed-choice gedanken experiment. *Science* **315,** 966–968 (2007).
15. Jacques, V. *et al.* Delayed-choice test of quantum complementarity with interfering single photons. *Phys. Rev. Lett.* **100,** 220402 (2008).
16. Jennewein, T., Weihs, G., Pan, J-W. & Zeilinger, A. Experimental nonlocality proof of quantum teleportation and entanglement swapping. *Phys. Rev. Lett.* **88,** 017903 (2001).
17. Sciarrino, F., Lombardi, E., Milani, G. & De Martini, F. Delayed-choice entanglement swapping with vacuum–one-photon quantum states. *Phys. Rev. A* **66,** 024309 (2002).
18. Schrödinger, E. Discussion of probability relations between separated systems. *Proc. Camb. Phil. Soc.* **31,** 555–563 (1935).
19. Aspect, A., Dalibard, J. & Roger, G. Experimental test of Bell's inequalities using time-varying analyzers. *Phys. Rev. Lett.* **49,** 1804–1807 (1982).
20. Weihs, G. *et al.* Violation of Bell's inequality under strict Einstein locality conditions. *Phys. Rev. Lett.* **81,** 5039–5043 (1998).
21. Scheidl, T. *et al.* Violation of local realism with freedom of choice. *Proc. Natl Acad. Sci. USA* **107,** 19708–19713 (2010).
22. Coffman, V., Kundu, J. & Wootters, W. K. Distributed entanglement. *Phys. Rev. A* **61,** 052306 (1993).

23. Pan, J-W., Bouwmeester, D., Weinfurter, H. & Zeilinger, A. Experimental entanglement swapping: Entangling photons that never interacted. *Phys. Rev. Lett.* **80,** 3891–3894 (1998).
24. Riebe, M. *et al.* Deterministic quantum teleportation with atoms. *Nature* **429,** 734–737 (2004).
25. Barrett, M. D. *et al.* Deterministic quantum teleportation of atomic qubits. *Nature* **429,** 737 (2004).
26. Matsukevich, D. N., Maunz, P., Moehring, D. L., Olmschenk, S. & Monroe, C. Bell inequality violation with two remote atomic qubits. *Phys. Rev. Lett.* **100,** 150404 (2008).
27. Halder, M. *et al.* Entangling independent photons by time measurement. *Nature Phys.* **3,** 692–695 (2007).
28. Yuan, Z-S. *et al.* Experimental demonstration of a BDCZ quantum repeater node. *Nature* **454,** 1098–1101 (2008).
29. Kaltenbaek, R., Prevedel, R., Aspelmeyer, M. & Zeilinger, A. High-fidelity entanglement swapping with fully independent sources. *Phys. Rev. A.* **79,** 040302 (2009).
30. Briegel, H-J., Duer, W., Cirac, J. I. & Zoller, P. Quantum repeaters: The role of imperfect local operations in quantum communication. *Phys. Rev. Lett.* **81,** 5932–5935 (1998).
31. Duan, L-M., Lukin, M. D., Cirac, J. I. & Zoller, P. Long-distance quantum communication with atomic ensembles and linear optics. *Nature* **414,** 413–418 (2001).
32. Chen, Y-A. *et al.* Experimental quantum secret sharing and third-man quantum cryptography. *Phys. Rev. Lett.* **95,** 200502 (2005).
33. Simon, C. & Irvine, W. T. M. Robust long-distance entanglement and a loophole-free Bell test with ions and photons. *Phys. Rev. Lett.* **91,** 110405 (2003).
34. Greenberger, D. M., Horne, M. & Zeilinger, A. Bell theorem without inequalities for two particles. I. Efficient detectors. *Phys. Rev. A.* **78,** 022110 (2008).
35. Greenberger, D. M., Horne, M., Zeilinger, A. & Žukowski, M. Bell theorem without inequalities for two particles. II. Inefficient detectors. *Phys. Rev. A.* **78,** 022111 (2008).
36. 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).
37. Mattle, K., Weinfurter, H., Kwiat, P. G. & Zeilinger, A. Dense coding in experimental quantum communication. *Phys. Rev. Lett.* **76,** 4656–4659 (1996).
38. Jennewein, T., Aspelmeyer, M., Brukner, Č. & Zeilinger, A. Experimental proposal of switched delayed-choice for entanglement swapping. *Int. J. Quant. Info.* **3,** 73–79 (2005).
39. Kwiat, P. G. *et al.* New high-intensity source of polarization-entangled photon pairs. *Phys. Rev. Lett.* **75,** 4337–4341 (1995).
40. Brukner, Č., Aspelmeyer, M. & Zeilinger, A. Complementarity and information in delayed-choice for entanglement swapping. *Found. Phys.* **35,** 1909–1919 (2005).
41. Ma, X-S. *et al.* A high-speed tunable beam splitter for feed-forward photonic quantum information processing. *Opt. Express* **19,** 22723–22730 (2011).
42. Gühne, O. *et al.* Detection of entanglement with few local measurements. *Phys. Rev. A* **66,** 062305 (2002).
43. Zhang, Q. *et al.* Experimental quantum teleportation of a two-qubit composite system. *Nature Phys.* **2,** 678–682 (2006).
44. Gühne, O. & Toth, G. Entanglement detection. *Phys. Rep.* **474,** 1–75 (2009).
45. Žukowski, M., Zeilinger, A. & Weinfurter, H. Entangling photons radiated by independent pulsed sources. *Ann. N.Y. Acad. Sci.* **755,** 91–102 (1995).

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Author contributions

X-s.M. designed and carried out the experiment and analysed data. S.Z. provided experimental assistance. J.K. provided the theoretical analysis and analysed data. R.U. provided experimental and conceptual assistance. T.J. conceived the research, planned and performed the experiment and analysed data. Č.B. provided theoretical suggestions and analysis. A.Z. conceived the research, designed the experiment and supervised the project. All authors wrote the manuscript.

Additional information

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ERRATUM

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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 $\hat{W}(|\mathrm{out}\rangle_{\mathrm{id}}) = \hat{I}/2 - |\mathrm{out}\rangle_{\mathrm{id}}\langle\mathrm{out}|$. This error has been corrected in all versions of the Article.