High-fidelity entanglement swapping with fully independent sources

Rainer Kaltenbaek[*] and Robert Prevedel
Faculty of Physics, University of Vienna, Boltzmanngasse 5, A-1090 Vienna, Austria

Markus Aspelmeyer
Institute for Quantum Optics and Quantum Information (IQOQI),
Austrian Academy of Sciences, Boltzmanngasse 3, A-1090 Vienna, Austria

Anton Zeilinger[†]
Faculty of Physics, University of Vienna, Boltzmanngasse 5, A-1090 Vienna, Austria and
Institute for Quantum Optics and Quantum Information (IQOQI),
Austrian Academy of Sciences, Boltzmanngasse 3, A-1090 Vienna, Austria

Entanglement swapping allows to establish entanglement between independent particles that never interacted nor share any common past. This feature makes it an integral constituent of quantum repeaters. Here, we demonstrate entanglement swapping with time-synchronized independent sources with a fidelity high enough to violate a Clauser-Horne-Shimony-Holt inequality by more than four standard deviations. The fact that both entangled pairs are created by fully independent, only electronically connected sources ensures that this technique is suitable for future long-distance quantum communication experiments as well as for novel tests on the foundations of quantum physics.

To take full advantage of the powerful features of quantum information processing schemes [1], large scale quantum networks will have to be realized. These will inevitably involve the reliable distribution of entanglement [2] between distant, independent nodes. Photons are well suited to cover these distances as they do not tend to interact with the environment and can easily be transmitted via fibers or optical free-space links. Today, these methods are limited to distances on the order of a hundred kilometers [4, 5?] due to photon loss and detector noise [6]. Quantum repeaters [7, 8, 9, 10], which repeatedly swap and distill entanglement along a chain of distant sources, are expected to overcome this limitation.

The three principal ingredients of quantum repeaters are quantum memories [9, 10], entanglement distillation [11, 12], and entanglement swapping [13]. While a real-world implementation of a quantum repeater is still far down the road, gradual progress has been achieved in realizing its constituents [14, 16, 17, 18, 19, 20, 21, 22?]. In particular any future realization of a quantum repeater will involve entanglement swapping with pairs emitted from distant, independent sources.

Recently, the independence of the sources used for entanglement swapping was shown to be not only of practical interest. In [23] it is argued that independence in such an experiment allows to place even tighter restrictions on local hidden variable theories [24] than in experiments on pairs emitted directly by one source. This allows to circumvent the loophole of inefficient detectors. Therefore, the use of independent sources for entanglement swapping could help to close all loop holes, which up to now had to be closed in separate experiments [22, 25, 26, 27], in one ultimate Bell-type experiment.

Entanglement swapping has been demonstrated with photons [14, 18, 28?] and recently with atomic ensembles [20] and ions [22]. In all of these experiments a crucial requirement for use in quantum repeaters remains unfulfilled: the sources must be separable by large distances. In [14, 18, 20, 22?] the entangled pairs were created by interaction of one optical pump with one or two nonlinear media, while in [28] the two laser beams pumping two separate nonlinear media were not optically independent. To separate the sources in any of these implementations would require to distribute intense pump beams over large distances. That goal is practically unfeasible given dispersion, high loss at the pump wavelengths and path length fluctuations. Moreover, because of either the common origin or the optical interaction of the pump beams involved, in none of these experiments the sources meet the criteria for independence as needed for a real-life quantum repeater or for an experiment as presented in [23].

Previous experiments [29, 30] aimed to show that entanglement swapping with fully independent sources is in principle feasible. However, these experiments failed to show the genuine none-classical correlations of the swapped entangled states. In particular, while correlations were observed in [30], they where not strong enough to violate a Bell-type inequality [24], which would indicate that the swapped entanglement was sufficient for direct further use in, for example, quantum-state teleportation [31] or entanglement-based cryptography [32, 33] without the need for distillation.

Here, we fill this experimental gap and demonstrate high-fidelity entanglement swapping between entangled photon pairs emitted from time-synchronized independent sources. The resulting correlations between particles that do not share any common past are strong enough to violate a Clauser-Horne-Shimony-Holt (CHSH) inequality [34]. Our configuration is a prototype solution for use in future quantum repeaters. It is readily adaptable for use over large distances, and it implements a BSM with the maximum achievable efficiency for a linear-optics implementation.

Each source in our experiment emits pairs of polarization entangled photons along spatial directions 1 & 2 and 3 & 4, respectively (see fig. 1). We chose the singlet state ψ^-, which is one of the four maximally entangled Bell states:

$$\begin{aligned} |\psi^{\pm}\rangle &= \tfrac{1}{\sqrt{2}}|HV\rangle \pm |VH\rangle \\ |\phi^{\pm}\rangle &= \tfrac{1}{\sqrt{2}}|HH\rangle \pm |VV\rangle. \end{aligned} \qquad (1)$$

A successful entanglement swapping procedure will result in photons 1 and 4 being entangled, although they never interacted with each other [13**?**]. This is done by performing a Bell-state measurement on particles 2 and 3, i.e. by projecting them on one of the four Bell states. Consequently, photons 1 and 4 will be projected onto the Bell state corresponding to the BSM outcome. Because of the independence of the sources, either the emission or the detection of the individual photons has to be time-synchronized better than the coherence times of the photons [35]. One possible method to fulfill this requirement is to actively time-synchronize pulsed sources [29]. In contrast to techniques used in earlier experiments [14, 18, 20, 22, 28**?**] this allows to separate the sources, in principle, by arbitrary distances.

Each of the two separate spontaneous parametric down-conversion (SPDC) setups is pumped by a frequency-doubled beam ($\lambda = 394.25\,\mathrm{nm}$) generated by two separate, pulsed femtosecond lasers (Coherent MIRA, operating at 788.5 nm), each of which is in turn pumped by its own solid-state laser (Coherent Verdi V10). The timing of the pump pulses is synchronized purely electronically to an accuracy of $260 \pm 30\,\mathrm{fs}$ using the method described in [29]. No optical interaction between the two sources is necessary to sustain time-synchronization. The synchronization mechanism consists of two phase-locked loops (PLL), one for coarse and one for tight synchronization. The inputs of the PLLs are the signals of two fast photodiodes (2 GHz bandwidth), each monitoring the output of one of the lasers. For details see [29]. The feedback signals of the two PLLs that adjust the cavity length of the slave laser have a bandwidth $\Delta\nu \leq 10\,\mathrm{kHz}$. This restricts the maximum distance of the two sources to $c/\Delta\nu \approx 30\,\mathrm{km}$. Here, we assume that the PLLs are positioned at the slave laser, and that only the master laser's photodiode signal has to be transmitted over the separating distance, e.g. via a radio-frequency fiber-optic link. In practice, the maximum distance is additionally limited by path-length fluctuations and noise in the transmission of the diode signal.

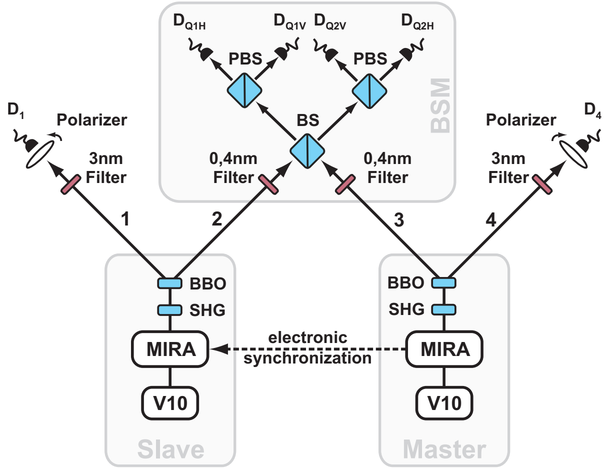

FIG. 1: Schematic of the setup for entanglement swapping. The two femtosecond lasers, which are separated by $\sim 4\,\mathrm{m}$, are time-synchronized by a Coherent Synchrolock (for details see ref. [29]). Each of the two infrared beams is frequency doubled to 394.25 nm by second-harmonic generation (SHG), the master's beam by a Lithium-Triborate crystal and the slave's beam by a β-Barium-Borate (BBO) crystal. The resulting beams each pump a BBO crystal to generate entangled photons via SPDC. Interference filters of 0.4 nm and 3 nm FWHM bandwidth guarantee high HOM interference visibility for the BSM, which is realized by a combination of two polarizing beam splitters (PBS) and a fiber beam splitter (BS).

We implement the Bell-state measurement by Hong-Ou-Mandel (HOM) interference at a 50:50 beam splitter [36] and subsequent polarizing beam splitters [18, 37] (see fig. 1). It allows to identify two out of four Bell states, as was first demonstrated in the experimental realization of dense coding [38]. This is the optimum efficiency possible with linear optics [39]. A two-fold coincidence detection event between either D_{Q1H} and D_{Q2V} or D_{Q1V} and D_{Q2H} indicates a projection on ψ^-. On the other hand, a coincidence detection event between either D_{Q1H} and D_{Q1V} or D_{Q2H} and D_{Q2V} indicates a projection on ψ^+. These events have to occur in coincidence with clicks in the detectors D_1 and D_4 in modes 1 and 4. All measurement results are, therefore, four-fold coincidence detection events, where the coincidence window has to be shorter than the delay between two successive pulses ($\sim 13\,\mathrm{ns}$).

Compared to [29] and [30] we observed a significantly higher HOM-interference visibility of $(I_{max} - I_{min})/I_{max} = 0.96 \pm 0.01$ (see fig. 2). This was achieved by using narrower bandwidth filters (0.4 nm FWHM). Using solid-state pump lasers in both of the sources, and stabilizing the laboratory temperature allowed us to dispense with the compensation for long-time drifts that was necessary in [29]. The considerably higher interference visibility observed was necessary in order to achieve the violation of a CHSH inequality [34] with the swapped entangled pairs.

We confirm successful entanglement swapping by testing the entanglement of the previously uncorrelated pho-

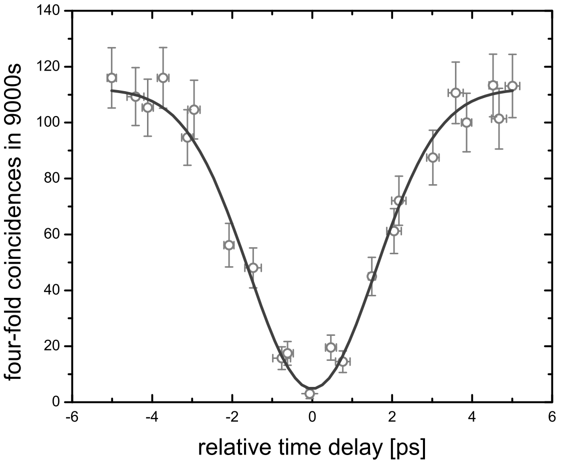

FIG. 2: Hong-Ou-Mandel (HOM) interference scan. The four-fold coincidences are measured between the detectors D_1, D_4 and two detectors placed directly behind the fiber beam splitter in the BSM (see Figure 1). These are plotted over the relative time delay of the interfering photons, which is determined via cross correlation of the laser pulses. Background has not been subtracted. Error bars indicate s.d. The solid line is a Gaussian fit to the data ($\chi^2 \sim 0.85$) with a visibility of $96 \pm 1\,\%$..

tons 1 and 4. Violation of a CHSH inequality is not only of fundamental interest because it rules out local-hidden variable theories. It also proves that the swapped states are strongly entangled and, as a result, distillable [40].

The specific state of photons 1 and 4 after entanglement swapping depends on the result of the BSM, which can either be ψ^+ or ψ^-. The relevant CHSH inequalities for these cases are

$$\begin{aligned} S_{\psi^\mp} \;=\; & |\pm E(\boldsymbol{a}_1, \boldsymbol{b}_1) \mp E(\boldsymbol{a}_1, \boldsymbol{b}_2) \\ & + E(\boldsymbol{a}_2, \boldsymbol{b}_1) + E(\boldsymbol{a}_2, \boldsymbol{b}_2)| \leq 2. \end{aligned} \qquad (2)$$

$E(\boldsymbol{a}_i, \boldsymbol{b}_i)$ denotes the expectation value of the product of the outcomes of coincidence measurements along $\boldsymbol{a}_i$ and $\boldsymbol{b}_i$ of the polarizations of the two photons. Each polarization measurement has two possible outcomes, which are assigned the values $+1$ and -1. In the experiment the vectors $\boldsymbol{a}_i$ and $\boldsymbol{b}_i$ correspond to the well known angles for the maximal violation of the CHSH inequality, 0° and 45° for photon 1 and 22.5° and 67.5° for photon 4, respectively.

The results for the expectation values for the various measurement settings are given in table I. Applying them to equation 2 yields

$$\begin{aligned} S_{\psi^-} &= 2.40 \pm 0.09 \\ S_{\psi^+} &= 2.38 \pm 0.09, \end{aligned} \qquad (3)$$

where we have normalized the four-fold coincidence rates on the product of two-fold coincidences to take into account degrading alignment over the long scan times. Even without normalizing the four-folds we achieve a clear violation of the CHSH inequality with $S_{\psi^-} = 2.37 \pm 0.09$ and $S_{\psi^+} = 2.38 \pm 0.09$.

	$E\,(0°, 22.5°)$	$E\,(0°, 67.5°)$	$E\,(45°, 22.5°)$	$E\,(45°, 67.5°)$
ψ^-	-0.53 ± 0.05	0.65 ± 0.04	-0.68 ± 0.04	-0.54 ± 0.05
ψ^+	-0.44 ± 0.05	0.69 ± 0.04	0.69 ± 0.04	0.56 ± 0.05

TABLE I: Expectation values for the CHSH inequality depending on the outcome, ψ^- or ψ^+, of the BSM. Each of these values is calculated from four measurements of four-photon coincidences integrated over $15000\,\mathrm{s} \sim 4\,\mathrm{h}$.

In all cases the CHSH inequality is violated by more than four standard deviations. This shows that the independent photons in modes 1 and 4 clearly are entangled and can asymptotically be distilled into the maximally entangled singlet state [40], satisfying the central requirement for quantum repeaters. Because every (two qubit) entangled state can be distilled but does not necessarily violate a Bell inequality [41], the violation of the CHSH inequality is a stronger criterion than required for distillability. It implies that, even without distillation, the entanglement of the states obtained in our experiment is high enough for immediate further use in quantum communication protocols like quantum teleportation [31] or quantum cryptography [32, 33].

We have demonstrated high-fidelity entanglement swapping with time-synchronized independent sources. The swapped entanglement clearly violates a Bell-type inequality. These strong non-classical correlations between particles that do not share any common past are not only crucial for future quantum repeaters. They might also enable novel tests of quantum mechanics [23, 42, 43]. Because the time-synchronization depends only on electronic signals, our sources can, in principle, be separated by very large distances. A practical way to do so would be to synchronize each laser locally to a reference oscillator, e.g. an atomic clock. These reference oscillators can be synchronized remotely to sub-picosecond accuracy [44, 45, 46], which would be sufficient for our purposes. Recent results [47] show that even better remote timing stability is achievable with state-of-the-art technology. Future efforts should be directed at increasing the spectral brightness of the SPDC sources used, e.g. by employing pump lasers with narrower bandwidths and by using state-of-the-art SPDC sources [48]. Only recently it was shown that SPDC bandwidths narrow enough for quantum memories are feasible [49]. As an added benefit, narrower bandwidths loosen the constraints on laser and path-length synchronization to observe high-visibility HOM interference. Finally, a very important step will be to efficiently produce and detect entangled photons at telecom wavelengths to cover even larger distances.

We are grateful to M. Arndt, B. Blauensteiner, H. R. Böhm, Th. Jennewein and M. Żukowski for discussion and experimental advice. We acknowledge support from the Austrian Science Fund FWF, the City of Vienna, IARPA (U.S. Army Research Office) and the European Commission under projects SECOQC, EMALI and QAP.

---

[*] Present address: Institute for Quantum Computing and Department of Physics and Astronomy, University of Waterloo, Waterloo, Canada, N2L 3G1
[†] Electronic address: anton.zeilinger@univie.ac.at

[1] D. Bouwmeester, A. Ekert, and A. Zeilinger, *The Physics of Quantum Information* (Springer, Berlin, 2000).
[2] E. Schrödinger, Die Naturwissenschaften **48**, 807 (1935).
[3] I. Marcikic, H. de Riedmatten, W. Tittel, H. Zbinden, M. Legré, and N. Gisin, Phys. Rev. Lett. **93**, 180502 (2004).
[4] H. Hübel, M. R. Vanner, T. Lederer, B. Blauensteiner, T. Lorünser, A. Poppe, and A. Zeilinger, Optics Express **15**, 7853 (2007).
[5] R. Ursin, F. Tiefenbacher, T. Schmitt-Manderbach, H. Weier, T. Scheidl, M. Lindenthal, B. Blauensteiner, T. Jennewein, J. Perdigues, P. Trojek, et al., Nature Physics **3**, 481 (2007).
[6] E. Waks, A. Zeevi, and Y. Yamamoto, Phys. Rev. A **65**, 052310 (2002).
[7] H.-J. Briegel, W. Dür, J. I. Cirac, and P. Zoller, Phys. Rev. Lett. **81**, 5932 (1998).
[8] W. Dür, H.-J. Briegel, J. I. Cirac, and P. Zoller, Phys. Rev. A **59**, 169 (1999).
[9] L.-M. Duan, M. D. Lukin, J. I. Cirac, and P. Zoller, Nature **414**, 413 (2001).
[10] N. Sangouard, C. Simon, B. Zhao, Y.-A. Chen, H. de Riedmatten, J.-W. Pan, and N. Gisin, Phys. Rev. A **77**, 062301 (2008).
[11] C. H. Bennett, G. Brassard, S. Popescu, B. Schumacher, J. A. Smolin, and W. K. Wootters, Phys. Rev. Lett. **76**, 722 (1996).
[12] D. Deutsch, A. Ekert, R. Jozsa, C. Macchiavello, S. Popescu, and A. Sanpera, Phys. Rev. Lett. **77**, 2818 (1996).
[13] M. Żukowski, A. Zeilinger, M. A. Horne, and A. K. Ekert, Phys. Rev. Lett. **71**, 4287 (1993).
[14] J.-W. Pan, D. Bouwmeester, H. Weinfurter, and A. Zeilinger, Phys. Rev. Lett. **80**, 3891 (1998).
[15] T. Jennewein, G. Weihs, J.-W. Pan, and A. Zeilinger, Phys. Rev. Lett. **88**, 017903 (2001).
[16] J.-W. Pan, S. Gasparoni, R. Ursin, G. Weihs, and A. Zeilinger, Nature **423**, 417 (2003).
[17] D. N. Matsukevich and A. Kuzmich, Science **306**, 663 (2004).
[18] T. Jennewein, R. Ursin, M. Aspelmeyer, and A. Zeilinger (2004), quant-ph/0409008.
[19] P. Walther, K. J. Resch, Č. Brukner, A. M. Steinberg, J.-W. Pan, and A. Zeilinger, Phys. Rev. Lett. **94**, 040504 (2005).
[20] Z.-S. Yuan, Y.-A. Chen, B. Zhao, S. Chen, J. Schmiedmayer, and J.-W. Pan, Nature **454**, 1098 (2008).
[21] K. S. Choi, H. Deng, J. Laurat, and H. J. Kimble, Nature **452**, 67 (2008).
[22] D. N. Matsukevich, P. Maunz, D. L. Moehring, S. Olmschenk, and C. Monroe, Phys. Rev. Lett. **100**, 150404 (2008).
[23] D. M. Greenberger, M. Horne, A. Zeilinger, and M. Żukowski, Phys. Rev. A **78**, 022111 (2008).
[24] J. S. Bell, Physics **1**, 195 (1964).
[25] A. Aspect, J. Dalibard, and G. Roger, Phys. Rev. Lett. **49**, 1804 (1982).
[26] G. Weihs, T. Jennewein, C. Simon, H. Weinfurter, and A. Zeilinger, Phys. Rev. Lett. **81**, 5039 (1998).
[27] M. A. Rowe, D. Kielpinski, V. Meyer, C. A. Sackett, W. M. Itano, C. Monroe, and D. J. Wineland, Nature **409**, 791 (2001).
[28] T. Yang, Q. Zhang, T.-Y. Chen, S. Lu, J. Yin, J.-W. Pan, Z.-Y. Wei, J.-R. Tian, and J. Zhang, Phys. Rev. Lett. **96**, 110501 (2006).
[29] R. Kaltenbaek, B. Blauensteiner, M. Żukowski, M. Aspelmeyer, and A. Zeilinger, Phys. Rev. Lett. **96**, 240502 (2006).
[30] M. Halder, A. Beveratos, N. Gisin, V. Scarani, C. Simon, and H. Zbinden, Nature Physics **3**, 692 (2007).
[31] C. H. Bennett, G. Brassard, C. Crépeau, R. Jozsa, A. Peres, and W. K. Wootters, Phys. Rev. Lett. **70**, 1895 (1993).
[32] A. K. Ekert, Phys. Rev. Lett. **67**, 661 (1991).
[33] C. H. Bennett, G. Brassard, and N. D. Mermin, Phys. Rev. Lett. **68**, 557 (1992).
[34] J. F. Clauser, M. A. Horne, A. Shimony, and R. A. Holt, Phys. Rev. Lett. **23**, 880 (1969).
[35] M. Żukowski, A. Zeilinger, and H. Weinfurter, Ann. N. Y. Acad. Sci. **755**, 91 (1995).
[36] C. K. Hong, Z. Y. Ou, and L. Mandel, Phys. Rev. Lett. **59**, 2044 (1987).
[37] S. L. Braunstein and A. Mann, Phys. Rev. A **51**, R1727 (1995).
[38] K. Mattle, H. Weinfurter, P. G. Kwiat, and A. Zeilinger, Phys. Rev. Lett. **76**, 4656 (1996).
[39] J. Calsamiglia and N. Lütkenhaus, Appl. Phys. B **72**, 67 (2001).
[40] M. Horodecki, P. Horodecki, and R. Horodecki, Phys. Rev. Lett. **78**, 574 (1997).
[41] R. F. Werner, Phys. Rev. A **40**, 4277 (1989).
[42] B. Yurke and D. Stoler, Phys. Rev. A **46**, 2229 (1992).
[43] D. M. Greenberger, M. Horne, and A. Zeilinger, Phys. Rev. A **78**, 022110 (2008).
[44] G. Lutes, in *Proceedings of the 41^{st} Annual Symposium on Frequency Control* (1987), pp. 161–166.
[45] T. P. Celano, S. R. Stein, G. A. Gifford, B. A. Mesander, and B. J. Ramsey, in *Frequency Control Symposium and PDA Exhibition* (IEEE International, 2002), pp. 510–516.
[46] D. D. Hudson, S. M. Foreman, S. T. Cundiff, and J. Ye, Opt. Lett. **31**, 1951 (2006).
[47] J. Kim, J. A. Cox, J. Chen, and F. X. Kärtner (2008), Nature Photonics, Advance Online Pubication, 2. November, 2008, doi: 10.1038/nphoton.2008.225.
[48] A. Fedrizzi, T. Herbst, A. Poppe, T. Jennewein, and A. Zeilinger, Opt. Exp. **15**, 15377 (2007).
[49] X.-H. Bao, Y. Qian, J. Yang, H. Zhang, Z.-B. Chen, T. Yang, and J.-W. Pan, Phys. Rev. Lett. **101**, 190501 (2008).