AIP Conference Proceedings

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Citation: AIP Conference Proceedings **1363**, 13 (2011); doi: 10.1063/1.3630138
View online: http://dx.doi.org/10.1063/1.3630138
View Table of Contents: http://scitation.aip.org/content/aip/proceeding/aipcp/1363?ver=pdfcov
Published by the AIP Publishing

Experimental photonic state engineering and quantum control of two optical qubits

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Abstract. Optical implementations of qubits play an important role for quantum information science. Photons are ideal carriers of quantum information due to low decoherence rates and are easily controllable by standard off-the-shelf components. Over the last decade the degree of control over photonic single- and two-qubit operations has improved substantially, which recently enables the complex state engineering of various multi-photon states. The control of current four- and six-photon entangled states provides access for the investigation of interesting properties of multi-particle entangled states and for overcoming the random nature of spontaneous emission sources.

The controlled generation of entangled states is at the heart of quantum information processing [1], in particular for entanglement distribution, entanglement swapping, quantum teleportation, quantum cryptography and scalable approaches towards photonics-based quantum computing schemes. In current single-photon experiments, the entangled photon pair has to be concluded from post-selection of randomly occurring coincidences due to the spontaneous generation process of parametric down-conversion [2]. Now we realized the first heralded generation of photon states that are maximally entangled in polarization with linear optics and standard photon detection using spontaneous parametric down-conversion. We utilized the down-conversion state corresponding to the generation of three pairs of photons, where the coincident detection of four auxiliary photons unambiguously heralds the successful preparation of the entangled state. The production of heralded entangled states is a significant step towards a scalable linear optics quantum network and quantum computation.

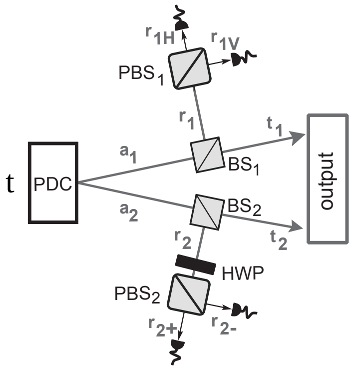
Another experiment utilizes the particular advantages of photons, the single-particle addressability and the tunable interactions among qubits, to achieve quantum control in an entangled four-photon state. A continuous change of the interaction between two entangled photon pairs enables us to simulate various configurations of so-called valence-bond states [3]. In particular the studies of delocalized or resonating valence-bond states that origin from anti-ferromagnetic Heisenberg-type interactions is of broad interest due to the interesting spin frustration which are conjectured to be the reason for the high-temperature superconductivity of anti-ferromagnetic insulators [4]. The fact that this quantum system provides direct access to all degrees of freedom for each particle enables the observation of all pair-wise quantum correlations.

Quantum Communication, Measurement and Computing (QCMC)
AIP Conf. Proc. 1363, 13-16 (2011); doi: 10.1063/1.3630138

Heralded generation of entangled photon pairs

It was shown that the production of one heralded polarization-entangled photon pair using only conventional down-conversion sources, linear optical elements, and projective measurements is not possible with less than three initial pairs [5]. Here we describe an experimental realization for producing heralded two-photon entanglement along these lines, suggested by Śliwa and Banaszek that relies on triple-pair emission from a single down-conversion source [6]. In our case the coincident detection of four photons is used to predict the presence of two polarization entangled photons in the output modes. Figure 1 gives a schematic diagram of our setup to generate the heralded state, $|\phi^+\rangle = \frac{1}{\sqrt{2}}\left(t^\dagger_{1H}t^\dagger_{2H} + t^\dagger_{1V}t^\dagger_{2V}\right)|vac\rangle$, where H and V denote horizontal and vertical polarization, respectively, whereas t_1 and t_2 correspond to the transmitted modes after the beam splitters. For generating the heralded state, $|\phi^+\rangle$, three photon pairs have to be emitted simultaneously into spatial modes a_1 and a_2. These photons are guided to non-polarizing beam splitters (BS1 and BS2) with various splitting ratios. Our scheme only succeeds when four photons are reflected and measured in a four-fold coincidence. The two reflected photons of BS1 are projected onto the $|H/V\rangle$ basis for mode r_1, while the two reflected photons of BS2 are measured in the $|\pm\rangle = \frac{1}{\sqrt{2}}(|H\rangle \pm |V\rangle)$ basis for mode r_2. We are interested in the case where one photon is present in each of the modes $r_{1H,1V}$ and $r_{2+,2-}$. Considering only these terms, the output state results in $|\Psi_3\rangle = C(\theta_1,\theta_2)\cdot\frac{1}{\sqrt{2}}\left(t^\dagger_{1H}t^\dagger_{2H} + t^\dagger_{1V}t^\dagger_{2V}\right)\cdot r^\dagger_{1H}r^\dagger_{1V}r^\dagger_{2+}r^\dagger_{2-}|vac\rangle$,where $C(\theta_1,\theta_2)$ is a constant depending on transmission coefficients of beam splitters. The coincident detection of one and only one photon in the modes r_{1H}, r_{1V}, r_{2+} and r_{2-} heralds the presence of an entangled photon pair in $|\phi^+\rangle$ state in the output modes t_1, t_2.

In the present scheme such a case can only be achieved by three (or more)-pair emission from SPDC. The contribution from two-pair emission is suppressed by destructive quantum interference in the half-wave plate (HWP) rotation used for $r_{2+,2-}$. In our case of using standard detectors (photo-avalanche diodes by PerkinElmer) the transmission of the non-polarizing beam splitters should ideally be as high as possible to obtain a high probability for heralding an entangled state (see Figure 1). In that case, a measured four-photon coincidence corresponds to precisely four photons and thus heralds our desired state in the output modes t_1 and t_2 . Obviously the trade-off for increasing this probability of heralding $|\phi^+\rangle$ is a reduction in the four-fold coincidence rate for triggering this state (see Figure 1). Therefore for demonstrating this dependency we choose beam splitters with different transmission rates T, of 17%, 50% and 70% and reconstructed the density matrix ρ of the heralded entangled pair [7]. The state fidelities, shown in Figure 1, to the real state $|\phi^+\rangle$ are influenced by result of the eight-photon emissions. At our given laser power of 1.2W the probability of obtaining a higher-order emission for a given six-fold coincidence is about 10%. To show the dependency of the state fidelity on the laser power, we did an additional experiment with a reduced laser power (LP) of 620 mW and a beam splitter transmission of 30%. Uncertainties in quantities were calculated assuming Poissonian errors.



	four-fold rate /minute	Probability of state preparation	Fidelity
17/83	83	$2.5 \pm 0.2\%$	$63.7 \pm 4.9\%$
$30/70^{LP}$	22	$6.5 \pm 0.4\%$	$84.2 \pm 8.5\%$
50/50	14	$29.4 \pm 1.0\%$	$57.5 \pm 3.4\%$
70/30	0.4	$77.2 \pm 6.6\%$	$61.9 \pm 7.7\%$

FIGURE 1. Left: Schematic drawing of the six-photon setup where the six-photon emission is split at the beam splitters BS1 and BS2. The successful detection event of four photons in the output modes r_{1H}, r_{1V}, r_{2+} and r_{2-} of the polarizing beam splitters (PBS) heralds the emission of an entangled photon pair in the output modes t_1 and t_2. A half-wave plate (HWP) is responsible for the quantum interference at PBS2. Right: Overview over the experimental results showing high- and low-power (LP) measurements.

Experimental photonic analog quantum simulation

The recent developments allow for bright four-photon quantum experiments, where the individual addressability and the implementation of tunable interactions among arbitrary qubits enable photonic quantum simulations of complex interactions (Figure 2A). Recently we realized the first analog quantum simulation of arbitrary Heisenberg-type interactions among four spin-1/2 particles. This spin-1/2 tetramer is the two-dimensional archetype system and its ground state belongs to the class of so-called valence-bond states. These states are of interest because it was conjectured that a transition from an localized valence-bond configuration to the superposition of different valence-bond states might explain high-temperature superconductivity in cuprates [3]. Here we model our spin tetramer with nearest-neighbor interactions of the strength J_1 and J_2 by the Hamiltonian $H = J_1\vec{S}_1\vec{S}_3 + J_1\vec{S}_2\vec{S}_4 + J_2\vec{S}_1\vec{S}_2 + J_2\vec{S}_3\vec{S}_4$, where $\vec{S}_i$ is the Pauli spin operator for spin i. All the properties of the system depend only on the coupling ratio $\kappa = J_2/J_1$ (Figure 2B). In our quantum simulation, we use the polarization states of four photons to simulate the spin of this tetramer, where the singlet state is analogous to the anti-ferromagnetic coupling of two spin-1/2 particles. The initial ground state, $|\Phi_=\rangle$, is prepared by generating the photon-pairs 1 & 2 and 3 & 4 in two singlet states (see Figure 2A). Then the analog quantum simulation is performed utilizing the measurement-induced interaction, consisting of quantum interference and the detection of a four-photon coincidence after superimposing photons 1 & 3 on a tunable directional coupler (TDC). We map the parameter κ to the splitting ratio of the tunable directional coupler: reflection rate (R) / transmission rate $(T) = \kappa + \sqrt{\kappa^2 - \kappa + 1}$. The particular advantages of the precise single-particle addressability and a tunable measurement-induced interaction allow us to obtain not only various valence-bond states, but also fundamental insights into entanglement dynamics among individual particles. Figure 2C shows various valence-blond states created in our experiment.

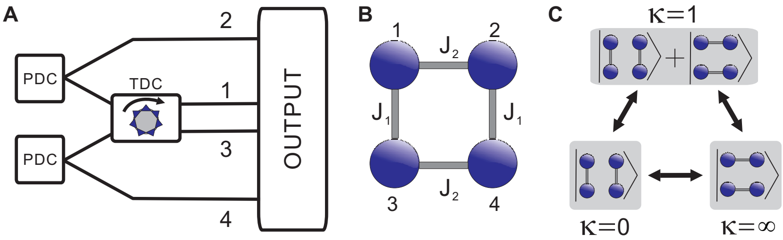


FIGURE 2. A schematic drawing of the experimental setup (A). Two parametric down-conversion crystals (PDC) are pumped to emit two pairs of photons that are superimposed at a tunable directional coupler (TDC). Dependent of the TDC's splitting ratio various spin-configurations can be simulated (B,C). For the case of $\kappa = 0$ ($R = 0.5, T = 0.5$) the ground state of this spin-1/2 tetramer is $|\Phi_{||}\rangle = |\psi^-\rangle_{13}|\psi^-\rangle_{24}$ and the amount of entanglement of the pair 1 & 3 and 2 & 4 reaches its maximum. Similarly, for the case of $\kappa = +\infty$ ($R = 1, T = 0$) the ground state is reduced to $|\Phi_{=}\rangle = |\psi^-\rangle_{12}|\psi^-\rangle_{34}$, where pair 1 & 2 and 3 & 4 are now maximally entangled. For $\kappa = 1$ ($R = 0.66, T = 0.33$) we obtain the interesting resonating valence-bond state, in which we have a superposition of two localized valence-bond states.

Conclusion

The latest development of bright pulsed laser sources, interferometric setups and tunable beam splitters opens up the path to a new level of quantum control and state engineering for photonic systems. The main challenge in realizing more complex quantum states by either increasing the number of qubits or extending the number of degrees of freedom that can be entangled is to overcome the inefficient emission characteristic of parametric down-conversion. However, the recent achievements in photon-number resolving detectors using superconductivity technology might provide the solution for scalable photonic quantum information processing.

ACKNOWLEDGMENTS

We acknowledge support from the European Commission, Project QAP (No. 015848), Q-ESSENCE (No. 248095), ERC Senior Grant (QIT4QAD), the Marie-Curie research training network EMALI, and SFB-FOQUS, and the Doctoral Program CoQuS of the Austrian Science Foundation (FWF).

REFERENCES

1. M. A. Nielsen & I. L. Chuang, *Quantum Computation and Quantum Information* (Cambridge University Press, Cambridge, 2000).
2. P. G. Kwiat *et al.*, *Phys. Rev. Lett.* **75**, 4337–4341 (1995).
3. P. W. Anderson, *Science* **235**, 1196–1198 (1987).
4. T. J. Osborne & F.Verstraete, *Phys. Rev. Lett.* **96**, 220503 (2006).
5. P. Kok & S. Braunstein, *Phys. Rev. A* **62**, 64301 (2000).
6. C. Śliwa & K. Banaszek, *Phys. Rev. A* **67**, 030101 (2003).
7. D. James, P. Kwiat, W. Munro & A. White, *Phys. Rev. A* **64**, 52312 (2001).