Experimental tests of coherence and entanglement conservation

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Motivation

- For every quantum multipartite system one can measure classical coherence of separate particles and joint quantum correlation (entanglement) of the system.
- These two quantities – **COHERENCE** and **ENTANGLEMENT** – can be transformed into each other by unitary transformations [1,2].
- One can show that the sum of suitable coherence and entanglement measures is conserved and equals to the overall purity of the system, $\mathcal{P} = \mathrm{Tr}[\hat{\rho}^2]$.
- We test this relationship for two different unitary operations acting on systems composed of two photons (A,B).

Theoretical background

We use polarization of single photons to encode quantum states.

$$|H\rangle \quad |V\rangle \quad |D\rangle = (|H\rangle + |V\rangle)/\sqrt{2} \quad |A\rangle = (|H\rangle - |V\rangle)/\sqrt{2} \quad |R\rangle = (|H\rangle + \imath|V\rangle)/\sqrt{2} \quad |L\rangle = (|H\rangle - \imath|V\rangle)/\sqrt{2}$$

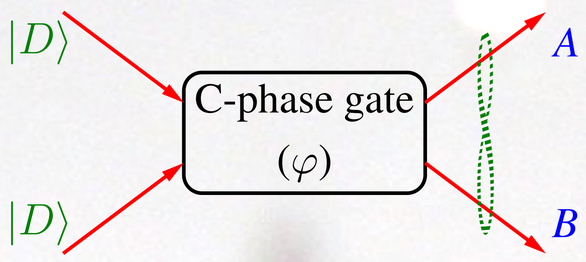
COHERENCE: first order coherence equals to degree of polarization: $D_{A,B} = p_{A,B} = \sqrt{2\,\mathrm{Tr}[\hat{\rho}^2_{A,B}] - 1}, \qquad D^2 = (D^2_A + D^2_B)/2$

ENTANGLEMENT: pure states – maximal violation of CHSH inequality $B_{\max}$
mixed states – $T = \left(1 + \sum t^2_{ij}\right)/4, t_{ij} = \mathrm{Tr}[\hat{\rho}\hat{\sigma}_i \otimes \hat{\sigma}_j]$

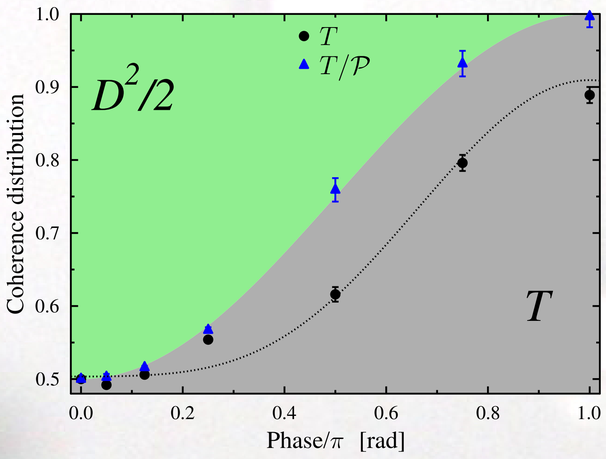
MAXIMAL ACHIEVABLE COHERENCE: $S = D^2/2 + T = \mathrm{Tr}[\hat{\rho}^2]$

Measurements

Two qubit interaction in a linear optical controlled phase gate



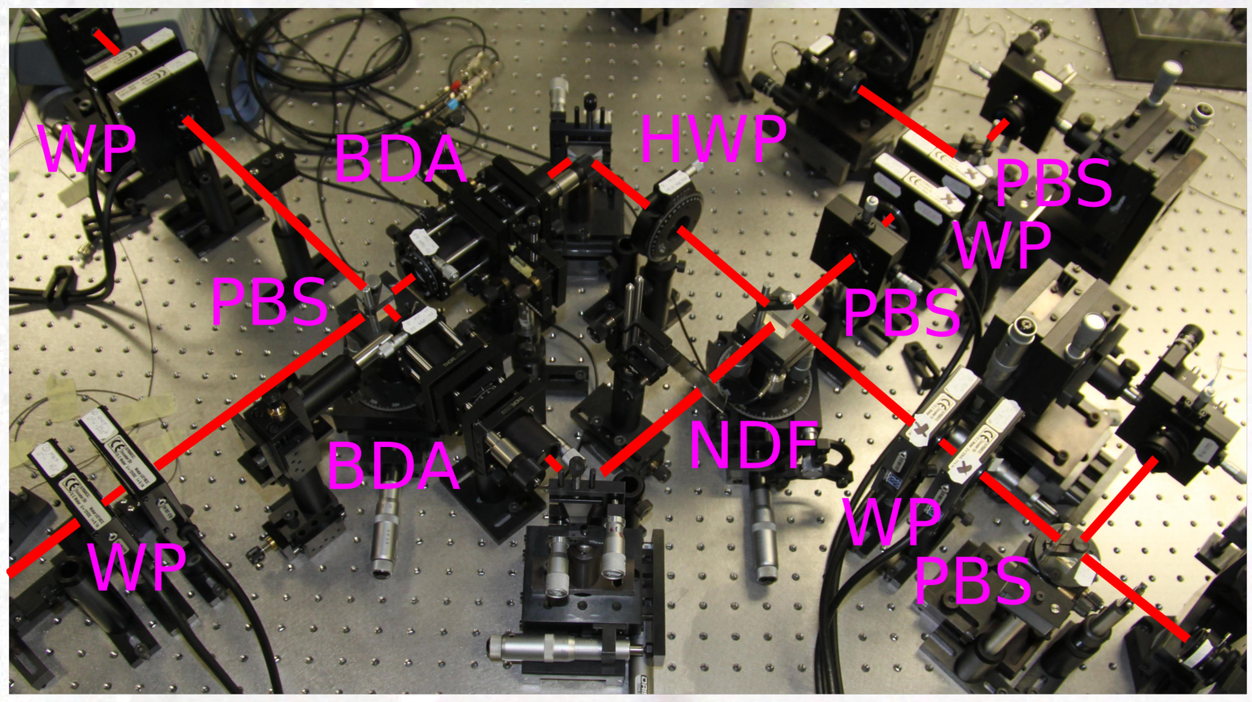
$$|HH\rangle \to |HH\rangle, \quad |HV\rangle \to |HV\rangle,$$
$$|VH\rangle \to |VH\rangle, \quad |VV\rangle \to \mathrm{e}^{\imath\varphi}|VV\rangle$$

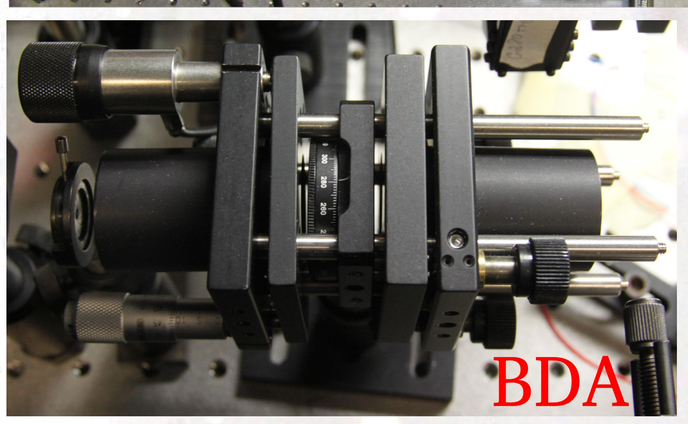


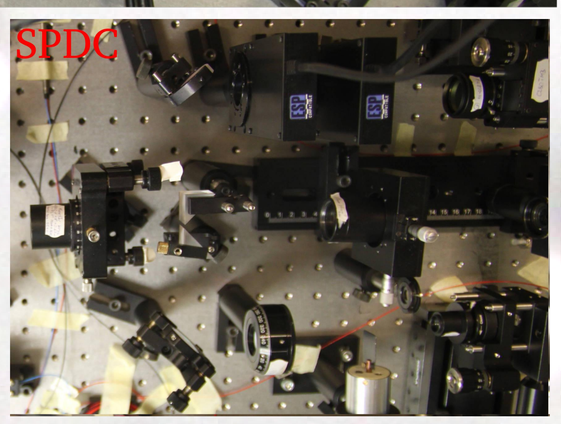
- This gate is able to continuously increase the degree of entanglement from separable input to maximally entangled output by changing phase φ from 0 to π. Vice versa, it can decrease degree of entanglement of entangled input.
- We use the data from our experiment published in PRL **106**, 013602 (2011) [3].
- We have separable state at the input, for several values of phase φ we calculate degree of entanglement T between outputs A and B and their degrees of polarization (local coherences $D_{A,B}$) from density matrices estimated using quantum state tomography.

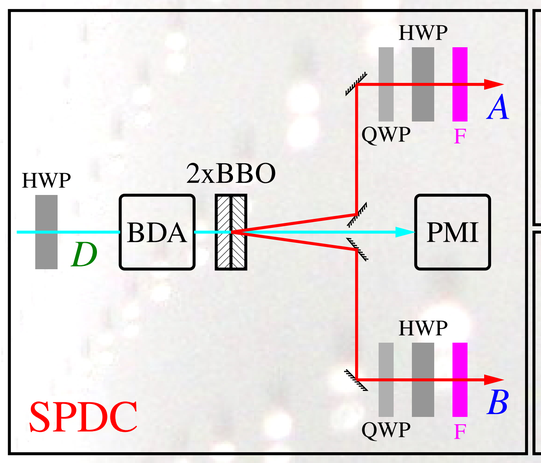
φ/π	D_A	δD_A	D_B	δD_B	T	δT	S	δS
0	1.000	0.000	1.000	0.000	0.500	0.000	1.000	0.000
0.05	0.978	0.006	0.995	0.002	0.492	0.003	0.979	0.006
0.125	0.981	0.001	0.968	0.003	0.506	0.002	0.981	0.003
0.25	0.916	0.004	0.923	0.004	0.554	0.004	0.976	0.004
0.5	0.636	0.011	0.613	0.012	0.616	0.010	0.809	0.012
0.75	0.322	0.011	0.358	0.010	0.796	0.011	0.854	0.010
1	0.091	0.010	0.058	0.012	0.889	0.011	0.892	0.011

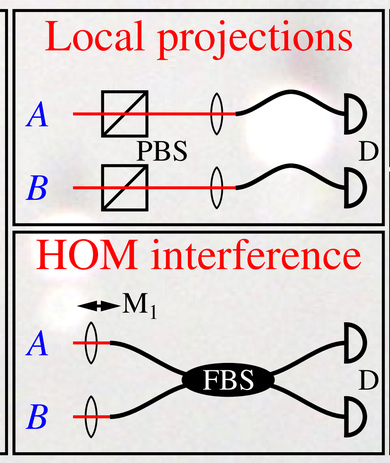
- Dotted line corresponds to setup imperfections – increased filtration in arms affects output purity [4] $\mathcal{P} = 0.909 - 0.047(\cos\varphi + \cos 2\varphi)$.

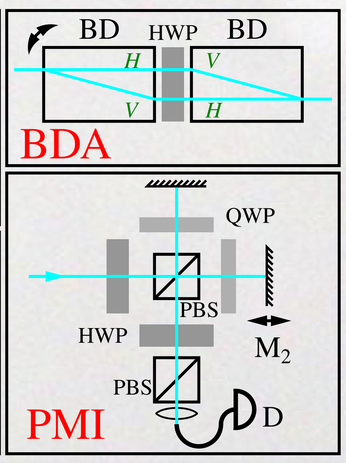










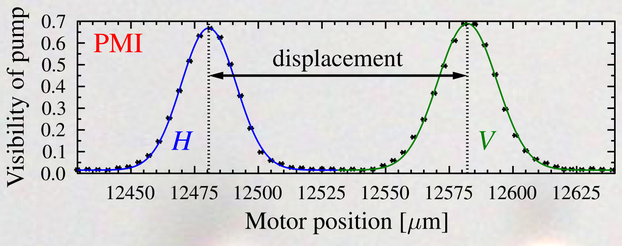


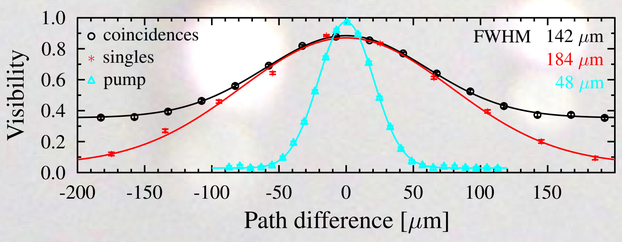
Nonlinear process of spontaneous parametric down-conversion

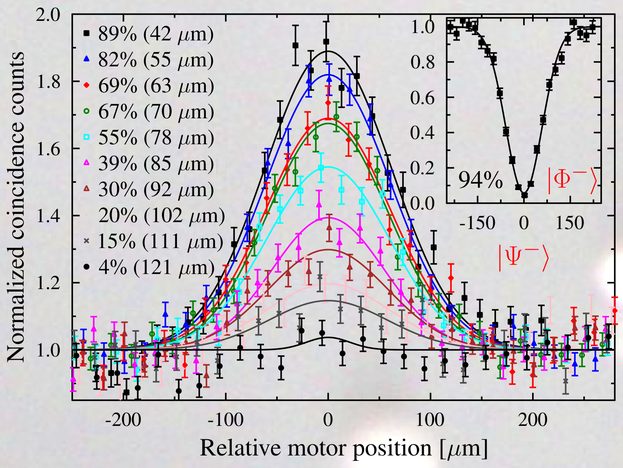
- Coherence of the pump beam is inscribed into entanglement of a photon pair produced by process of SPDC in a crystal cascade (Kwiat source).
- The H and V components of pump beam are displaced by Beam Displacer Assembly (BDA). Displacement is precisely measured by Polarizing Michelson Interferometer (PMI). Part of this delay compensates birefringence in the crystal cascade, $d = 2 \cdot \mathrm{displacement} - 84$ [μm].
- Due to band-pass interference filters F (3 nm FWHM) the autocorrelation functions of single photons and coincidences are broader then the autocorrelation of the pump beam. Input coherence is calculated from autocorrelation function visibility of the pump beam. The autocorrelation function is corrected because of spectral filtering:

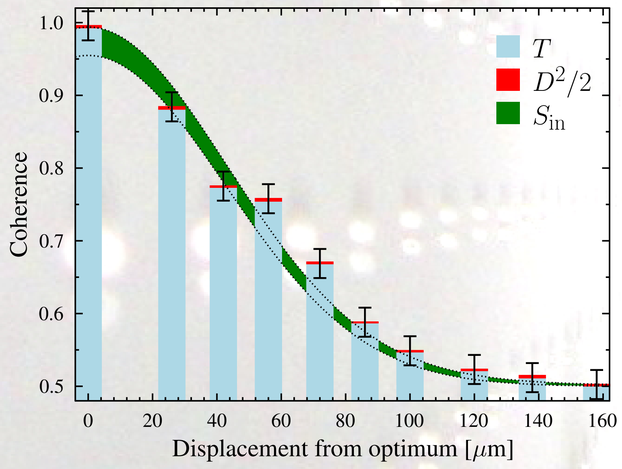
$$S_{\mathrm{in}} = \mathrm{Tr}[\hat{\rho}^2_{\mathrm{pump}}] = (1 - V^2)/2, \qquad V = 0.029 + 0.945\mathrm{e}^{-(d/\sigma)^2}, \qquad \sigma = 142/2\sqrt{\ln 2}\ [\mu m]$$

- The delay affects the degree of entanglement of singlet Bell state generated by Kwiat source. Entanglement T is estimated from contrast between two-photon HOM interference of singlet $|\Psi^-\rangle$ (antidip) and triplet $|\Phi^-\rangle$ (dip) state.
- The degree of polarization (p) of each photon remains almost zero which was tested by local projections, $D_{A,B} = p_{A,B}$.









d	D_A	D_B	T	S_{out}	S_{in}	$\lvert S_{\mathrm{out}} - S_{\mathrm{in}}\rvert$
0	0.091	0.033	0.993	0.996	0.974	0.021
26	0.097	0.046	0.881	0.884	0.896	0.012
42	0.043	0.058	0.774	0.775	0.796	0.021
56	0.105	0.061	0.755	0.758	0.706	0.052
72	0.062	0.056	0.669	0.671	0.620	0.050
86	0.021	0.045	0.588	0.588	0.568	0.020
100	0.052	0.048	0.548	0.549	0.535	0.014
120	0.014	0.070	0.522	0.523	0.512	0.011
138	0.058	0.086	0.512	0.515	0.505	0.010
158	0.068	0.042	0.501	0.502	0.502	0.001
$\langle\delta\rangle$	0.019	0.016	0.020	0.020	0.010	0.022

Conclusions

- DON'T DO THAT – IT HURTS
- We demonstrate for two different unitary operations (linear and non-linear) that overall coherence is a conserved quantity.

References:

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[3] K. Lemr, A. Černoch, J. Soubusta, K. Kieling, J. Eisert, and M. Dušek, "Experimental Implementation of the Optimal Linear-Optical Controlled Phase Gate", Phys. Rev. Lett. **106**, 013602 (2011).

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Acknowledgment:

This research was supported by the Czech Science Foundation project number 17-10003S.

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