Maximally Violation of Local Realism Using Optical Hybrid Entanglement

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Abstract

Optical hybrid entanglement can be created between two qubits, one encoded in a single photon and another one in coherent states with opposite phases:

$$|\psi\rangle = (|0\rangle|\mathrm{Cat}^{-}\rangle + |1\rangle|\mathrm{Cat}+\rangle)/\sqrt{2}$$

It opens the path to a variety of quantum technologies which often require testing for quantum nonlocality in underlying resources. These tests have been accomplished for two-mode CV states [1], this task becomes particularly challenging when dealing with optical hybrid entanglement which has a DV-CV nature [2].

Here we propose to employ the CHSH inequality and either on/off or parity measurements for testing the nonlocality in the optical hybrid entanglement state $|\psi\rangle$. In Fig.1(a), two modes of the shared state $|\psi\rangle$ are locally interfered with coherent fields, $|\alpha\rangle$ and $|\beta\rangle$ in the homodyne limit (HD), followed by measurements of efficiency $0<\eta\leq 1$. In this limit the beam splitter interference may be approximated with displacement operator $D(\delta)$ with $\delta_a = -i\,\alpha\sqrt{r_a}$ and $\delta_b = -i\,\beta\sqrt{r_b}$ where r_a, r_b are beam splitters' reflectivities and the δ_a and δ_b act as the Bell test settings. The readouts k and L are then coarse-grained into two sets, either zero/non-zero or even/odd numbers of photons.

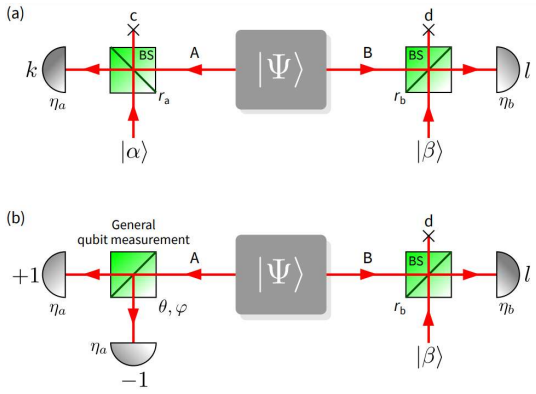

Figure 1: Bell tests setup for optical hybrid entanglement state $|\psi\rangle$.

We show that a practical violation of CHSH inequality is possible with simple photon number on/off measurements if detection efficiencies stay above 82%. We observe Bell violations, up to $S=2.71$, which are demonstrated for states with amplitudes $\gamma < 1.25$. Another test, based on parity measurements, requires 94% efficiency but works well in the limit of higher photon populations. In the ideal lossless conditions, this allows one to perform the even/odd Bell test for arbitrarily large amplitude γ, reaching the maximal value of $S=2.44$.

Another strategy linked to the specific nature of the considered state is to perform the hybrid Bell test, in which a general qubit measurement is performed on mode A while mode B is tested with on/off or parity measurements (Fig.1b). This strategy allowed us to maximally violate the CHSH inequality, up to $S = 2\sqrt{2}$.

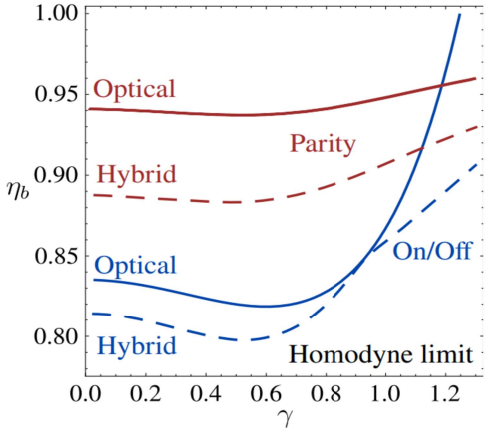

Figure 2: Comparison of CHSH violation for various detection strategies: on/off (blue lines) and parity (red line) with full optical (solid lines) and hybrid (dashed lines) measurements. The various lines correspond to the thresholds above which CHSH violation is observed.

All the tests use no postselection of the measurement outcomes and they are free of the fair-sampling hypothesis. In Fig.2, we compared CHSH violation for various detection strategies.

References

[1] Z.-B. Chen, J.-W. Pan, G. Hou, and Y.-D. Zhang, PRL, 88 (2002) 040406.
[2] H. Kwon and H. Jeong, PRA, 88 (2013) 052127.