Experimental testing of three-qubit nonlocality

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Introduction

- What is the best measure of entanglement? Entropy or Negativity?
- We vote for nonlocal volume [1] - probability of obtaining nonlocal correlations with random measurements.
- This measure corresponds well with the degree of entanglement, for maximally entangled state maximize the nonlocal volume.
- For maximally entangled 2 qubit system - value $4 \times 0.0708 \approx 28.32$ %.
- The nonlocal volume was studied in different systems [2–5].
- We want to experimentally measure nonlocal volume for 3 qubit generalized GHZ states:

$$gGHZ = \cos\theta|000\rangle + \sin\theta|111\rangle.$$

Witnesses of nonlocal correlations

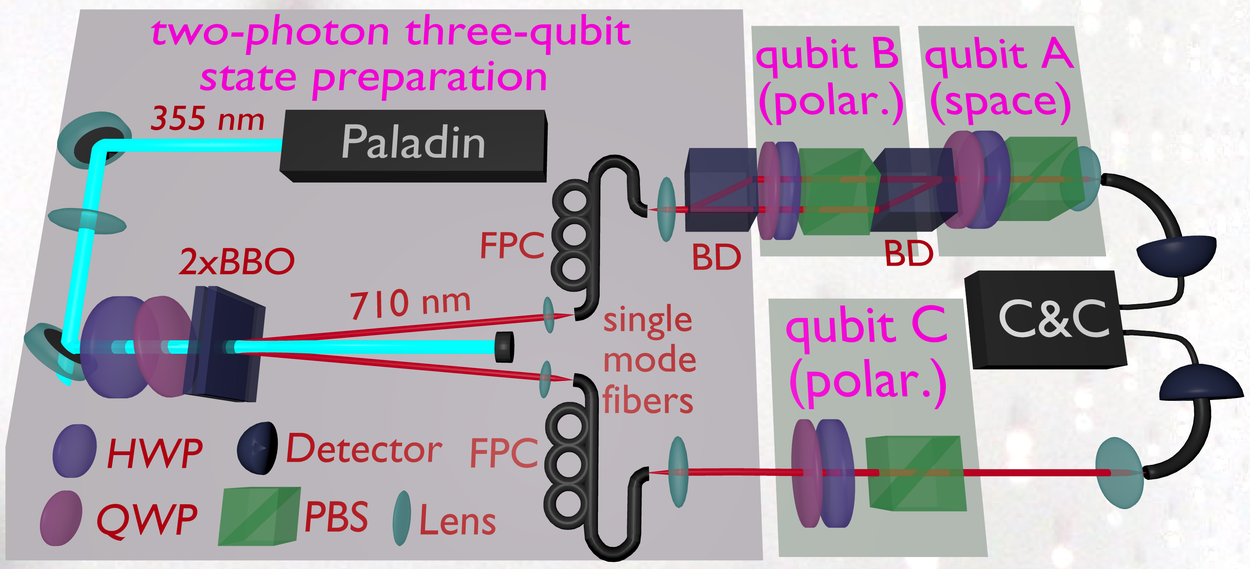
For generalized GHZ states one can apply Svetlicny type inequalities [6,7]. There are 185 of them, three are sufficient to cover maximal violation for angle $\theta \in [0°; 45°]$, I_{10}, I_{96} or I_{99} and I_{185}:

$$\begin{aligned}
I_{10} &= (-2\langle A_1\rangle - \langle B_0\rangle + \langle A_1B_0\rangle - \langle B_1\rangle + \langle A_1B_1\rangle - \langle C_0\rangle + \langle A_1C_0\rangle + \langle B_0C_0\rangle - \langle A_0B_0C_0\rangle + 2\langle A_1B_0C_0\rangle + \\
&+ \langle A_0B_1C_0\rangle + \langle A_1B_1C_0\rangle - \langle C_1\rangle + \langle A_1C_1\rangle + \langle A_0B_0C_1\rangle + \langle A_1B_0C_1\rangle + \langle B_1C_1\rangle - \langle A_0B_1C_1\rangle + 2\langle A_1B_1C_1\rangle)/6, \quad (1)\\
I_{96} &= (2\langle A_0B_0\rangle - \langle C_0\rangle - \langle A_0C_0\rangle - \langle B_0C_0\rangle + \langle A_0B_0C_0\rangle - 2\langle A_1B_1C_0\rangle - \langle C_1\rangle + \langle A_0C_1\rangle + \langle B_0C_1\rangle + \\
&+ \langle A_0B_0C_1\rangle - 2\langle A_1B_1C_1\rangle)/6, \quad (2)\\
I_{99} &= (\langle A_1B_1\rangle + \langle A_0B_0C_0\rangle + \langle B_1C_0\rangle + \langle A_1C_1\rangle - \langle A_0B_0C_1\rangle)/3, \quad (3)\\
I_{185} &= (-\langle A_0B_0C_0\rangle - \langle A_1B_0C_0\rangle + \langle A_0B_1C_0\rangle - \langle A_1B_1C_0\rangle - \langle A_0B_0C_1\rangle + \langle A_1B_0C_1\rangle - \langle A_0B_1C_1\rangle - \langle A_1B_1C_1\rangle)/4. \quad (4)
\end{aligned}$$

$A_{0,1}$, $B_{0,1}$ and $C_{0,1}$ means two different projective measurements for each of three qubits → six randomly selected basis. $\langle\cdot\rangle$ means correlation, one need 8 projective measurement for each.

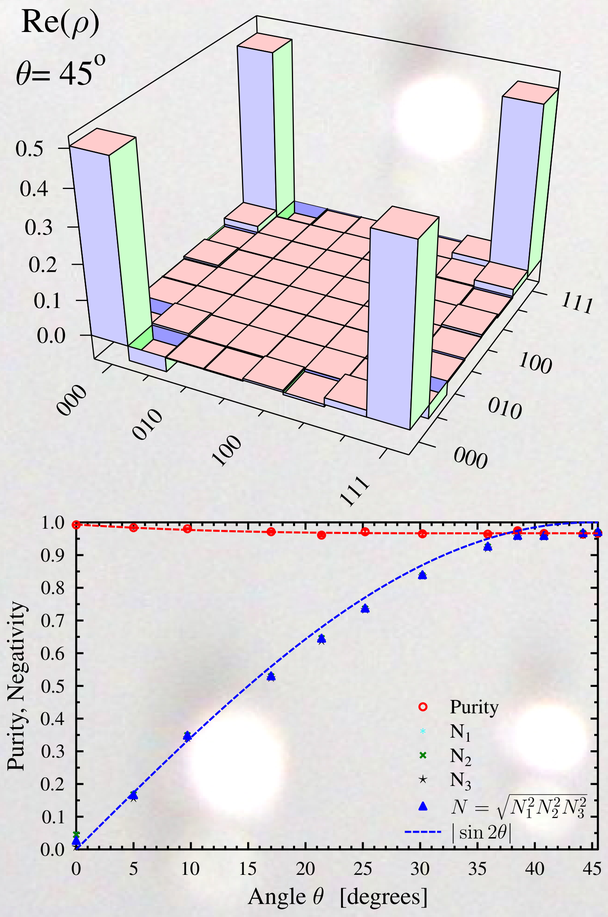
Nonlocal volume = cases when some $I > 1$ / all cases

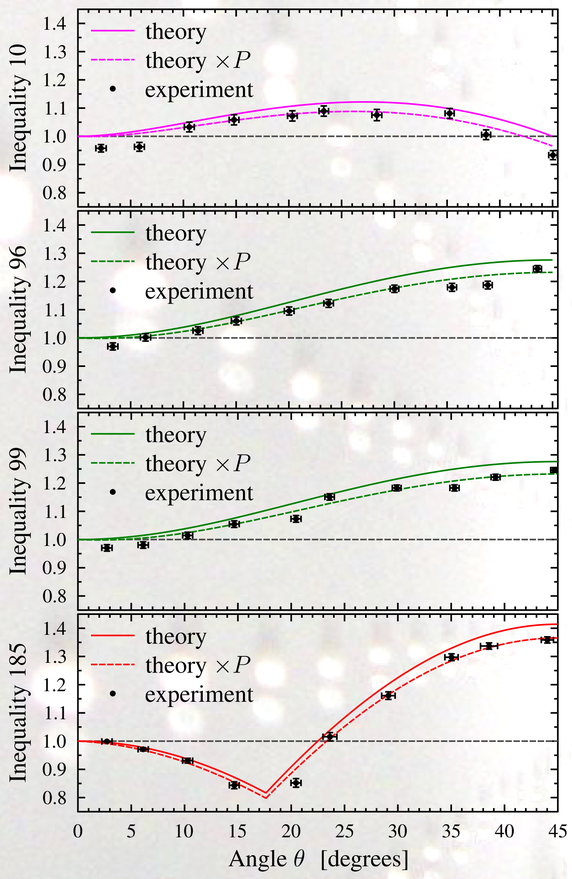
Experimental setup



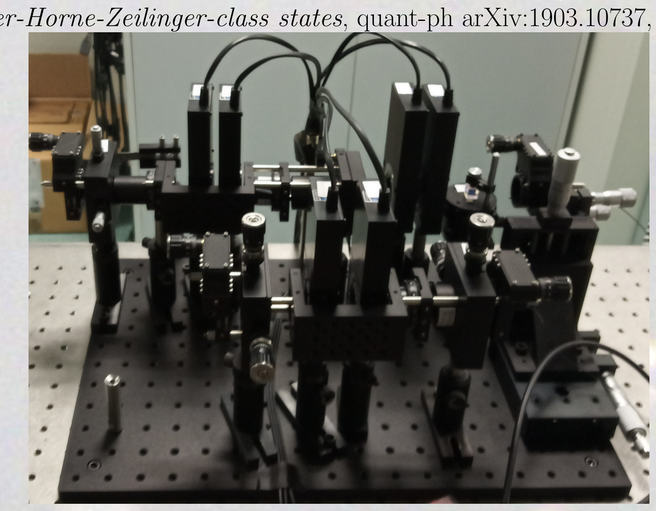
- polarization encoding → $\cos\theta|HHH\rangle + \sin\theta e^{i\varphi}|VVV\rangle$
- angle θ controlled by HWP in pump, phase φ set either by tilting QWP in soutce or by phase shift in MZ interferometer formed by BDs

States we are able to generate





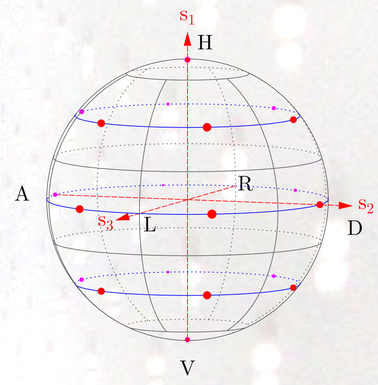
For more details see:
A. Barasiński, A. Černoch, K. Lemr, J. Soubusta, *Experimental verification of time-order-dependent correlations in three-qubit Greenberger-Horne-Zeilinger-class states*, quant-ph arXiv:1903.10737, accepted in PRA.



Three strategies to victory

1. Really measure it

- to calculate all 185 inequalities we need 64 different projective measurements
- this takes approximately 45 minutes - 10 s per projections + wave plate rotation
- because of small value of nonlocal volume we have to have at least 10 000 samples
- so for measuring one number we will pay by one year of laboratory time
- we abandon this strategy

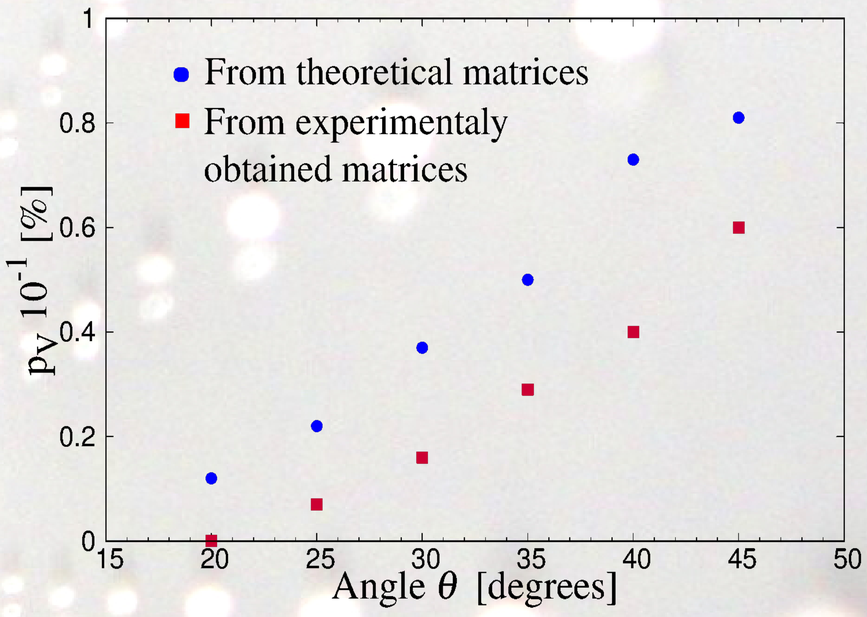


2. Fixed state combinations

- for each qubit 20 "equidistant" projections
- $20 \times 20 \times 20 = 8000$ projective measurements
- more than enough combinations for calculating inequality values
- but due to special angle between projection the value of nonlocal volume is artificially big (1.5× theoretical value)

3. Fake mode

- we have density matrices of generalized GHZ states for different angles $\theta \in [0^o, 45^0]$
- 10^9 randomly chosen projections acting on the density matrix simulate measurement on the state itself
- every time all 185 inequalities were tested



Conclusions

- Measuring nonlocal volume is impractical due to the huge number of measurement needed.
- For generalized GHZ states is better to perform 64 projective measurement to calculate Svetlicny inequalities.

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