Toward the Generation of Bell Certified Randomness Using Photons

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Random is hard

Randomness is hard to characterize

statistical test can never complete

Classical mechanics is deterministic

there is no true randomness, only lack of knowledge.

Quantum mechanics is based on randomness

in real experiments we need to separate the genuine randomness from apparent randomness (noise, lack of knowledge).

Outline

Certified randomness violating Bell inequality

Bell’s test with photons polarization

Closing the detection loophole

Locality loophole

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Certification of randomness

non local correlations of quantum states can be used to generate certified private randomness[*]

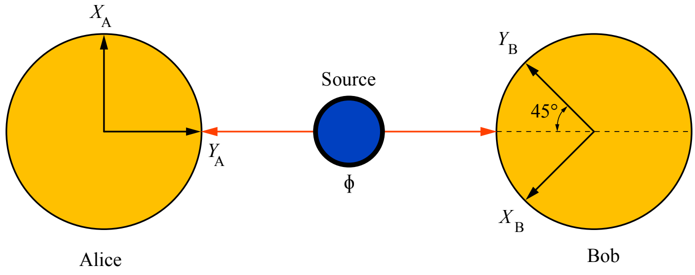
randomness

private

certified

[*] S. Pironio et al., Nature **464**, 1021 (2010)

Non local correlation: violation of Bell inequality



$$S = E(X_A, X_B) - E(X_A, Y_B) + E(Y_A, X_B) + E(Y_A, Y_B)$$

if $|S| > 2$ there is no local-realistic description for the observed correlation

Loopholes in the experimental violation

Detection

minimum necessary efficiency larger than $2/3$

Freedom of choice

random choice of the measurement basis

Locality

spatial separation sufficient to exclude direct communication in the choice of the basis

Loopholes in the experimental violation

1998	locality (SPDC, fibres)	Tittel et al.
	locality and freedom of choice (SPDC)	Weihs et al.
2001	detection ($^9Be^+$ ions)	Rowe et al.
2009	detection (Josephson phase qubits)	Ansmann et al.
2013	detection (SPDC)	Giustina et al.
	detection (SPDC)	Christensen et al.

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Optimal state for real detectors

With finite detection efficiency η the maximum violation* is observed for a non-totally entangled state of the form:

$$|\psi\rangle = \cos\theta\,|HV\rangle + \sin\theta\,|VH\rangle \quad \text{with } \theta = \theta(\eta)$$

and a set of measurement basis appropriately chosen:

$$X_a = \{\cos\alpha_1 H, \sin\alpha_1 V\}$$
$$Y_a = \{\cos\alpha_2 H, \sin\alpha_2 V\}$$
$$X_b = \{\cos\beta_1 H, \sin\beta_1 V\}$$
$$Y_b = \{\cos\beta_2 H, \sin\beta_2 V\}$$

with $\alpha_1, \alpha_2, \beta_1, \beta_2$ functions of η

[*] P. H. Eberhard, Phys. Rev. A 47, R747 (1993)

Bell's test with two detectors

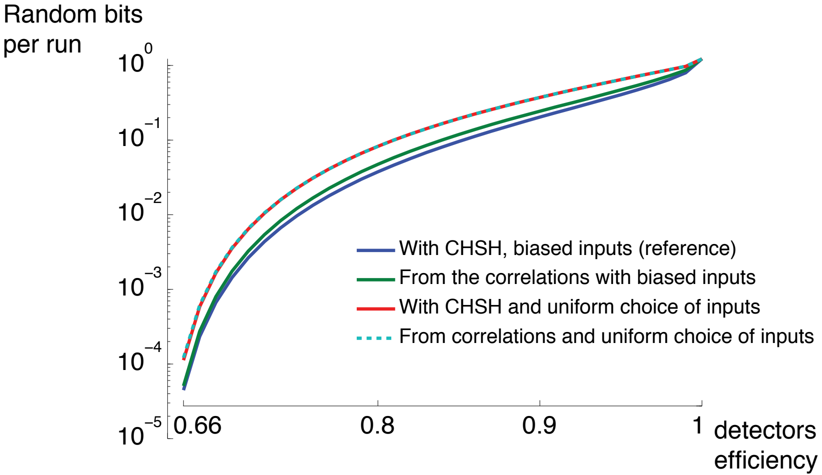
Using an appropriate time binning it is possible to use only two detectors instead of four.

For every time bin Alice and Bob assign a value to the measurement:

-1	single detection event
+1	no detection events
+1	multiple detection events

The optimal time bin duration μ depends on the detected count rate.

Quantify randomness from Bell's violation

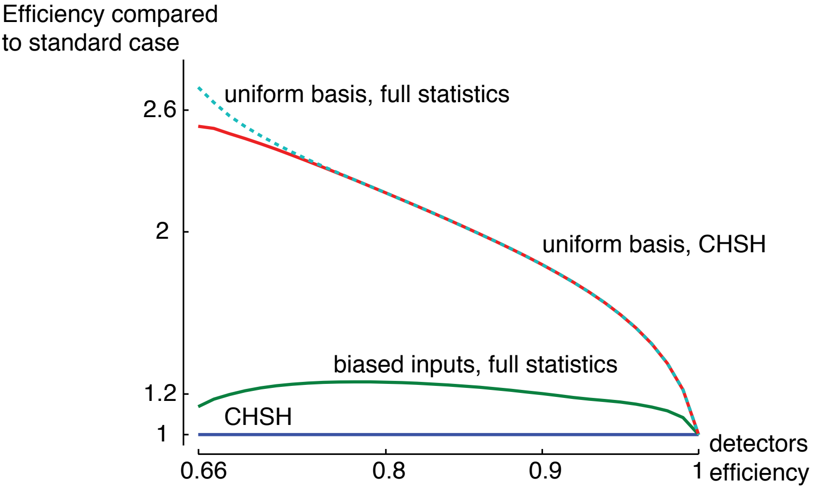


We can extract more random bit per run than before.

Advantage of the new lower bound

Unbiased choice of measurement basis

Use of the full statistics (i.e. E's), not only the correlation S



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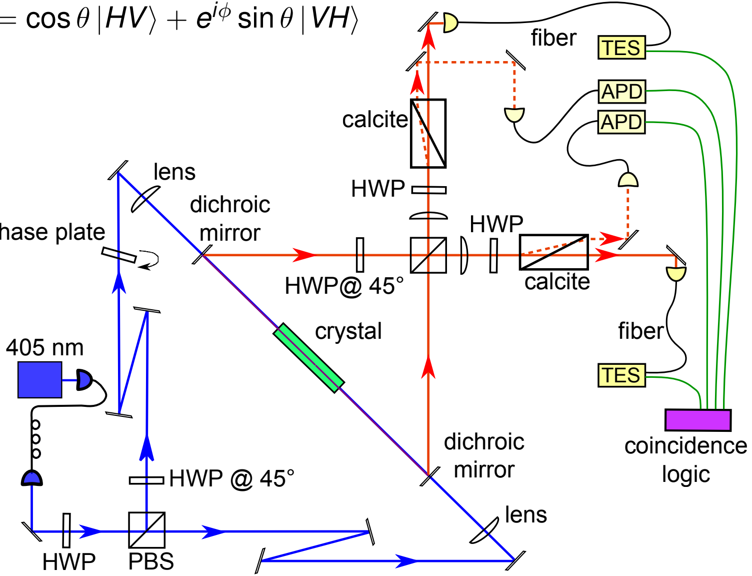
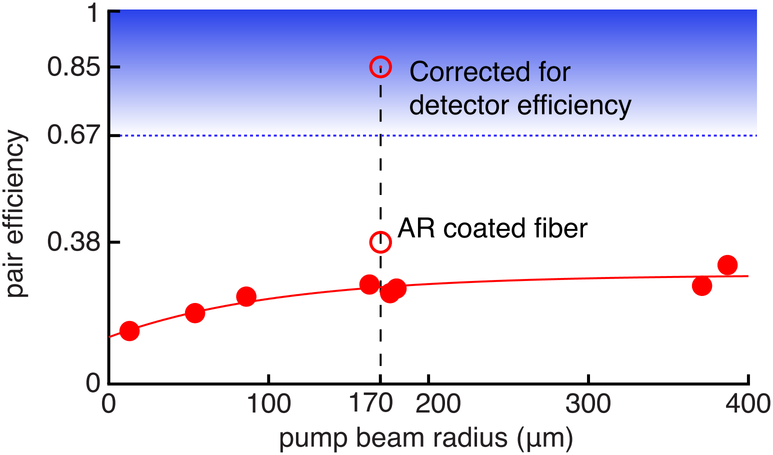
Experimental setup

$$|\psi\rangle = \cos\theta\,|HV\rangle + e^{i\phi}\sin\theta\,|VH\rangle$$

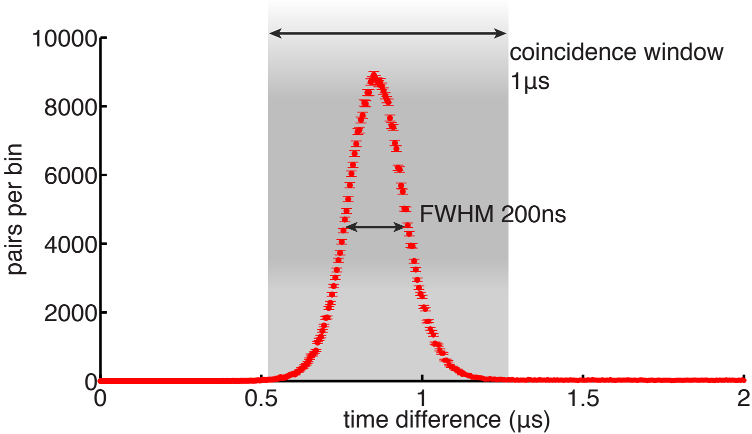


Optimal pump focus for collection efficiency



Measuring TES efficiency

Pairs efficiency $\eta = \frac{C}{\sqrt{S_1 S_2}} = 0.742 \pm 0.007$



Including an estimation of the losses $\Rightarrow$ TES efficiency > 0.93

Closing the detection loophole: table of efficiency

		η
pairs generation and collection		0.85
polarization projection		0.97
fiber transmission	intrinsic	0.99
	splices	0.94
detection		0.93
Total		$0.71 > 0.667$

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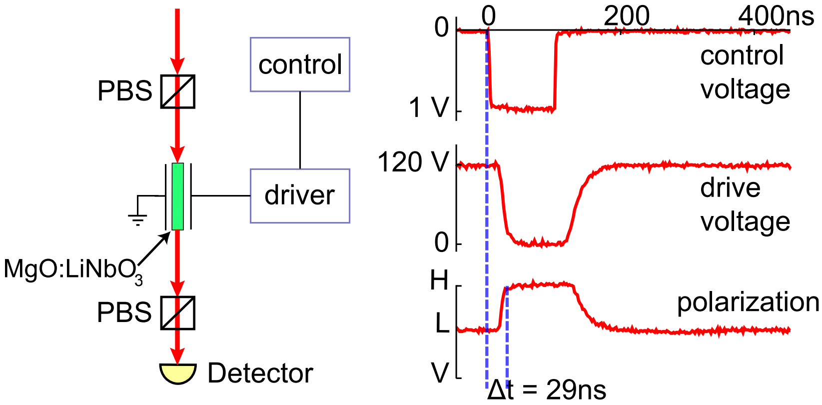
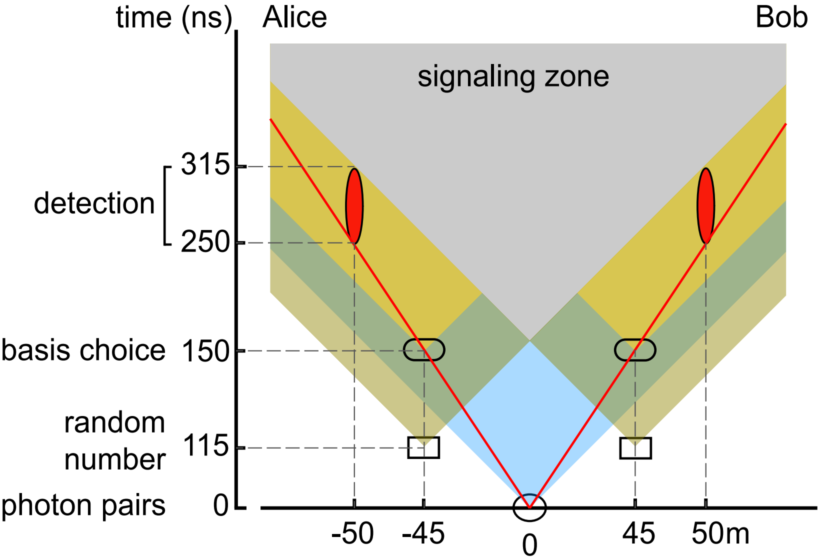
Fast polarization modulator



Timing considerations



Summary

- Using the full statistic we can extract more randomness
- Efficient source of polarization entangled photon pairs
- State of the art detection technologies allow us to overcome the detection loophole
- Fast polarization switch allows reasonable distances and rates

Outlook

- Improve the detection speed
- Include the fast polarization switch in the setup