Long-Distance Free-Space Distribution of Quantum Entanglement

M. Aspelmeyer, **et al.*, Science* 301, 621 (2003)[1]**

Talk held

by

Erich Schurtenberger and François Bianco

Introduction

Outline

1. Entanglement and Bell inequality
2. Experimental setup and methods
3. Result and Interest of this experiment
4. Summary and questions

Entanglement

Quantum Entanglement

Definition : An entangled state of a composite system is a state that cannot be written as a product state of the component systems.

- Only one quantum state for many objects (correlation)
- Possible to have spatially separated objects (non locality)

Bell inequality

John S. Bell showed in 1964 that

- in the *hidden variables theory* there is no possible perfect entangled state
- thus the maximal correlation is 2
- **but** QM allows perfect correlation in violation of the local realism (classical point of view)
- QM maximal correlation is $2\sqrt{2}$.

Bell states

There are four *maximal entangled two-qubit states* or *Bell states* written as :

- $|\Psi^{-}\rangle = \frac{1}{\sqrt{2}}(|H\rangle_A|V\rangle_B - |V\rangle_A|H\rangle_B)$ (the one used in the paper)
- $|\Psi^{+}\rangle = \frac{1}{\sqrt{2}}(|H\rangle_A|V\rangle_B + |V\rangle_A|H\rangle_B)$
- $|\Phi^{+}\rangle = \frac{1}{\sqrt{2}}(|H\rangle_A|H\rangle_B + |V\rangle_A|V\rangle_B)$
- $|\Phi^{-}\rangle = \frac{1}{\sqrt{2}}(|H\rangle_A|H\rangle_B - |V\rangle_A|V\rangle_B)$

With H for horizontal, V for vertical, A for the first qubit, and B for the second.

Correlation coefficient

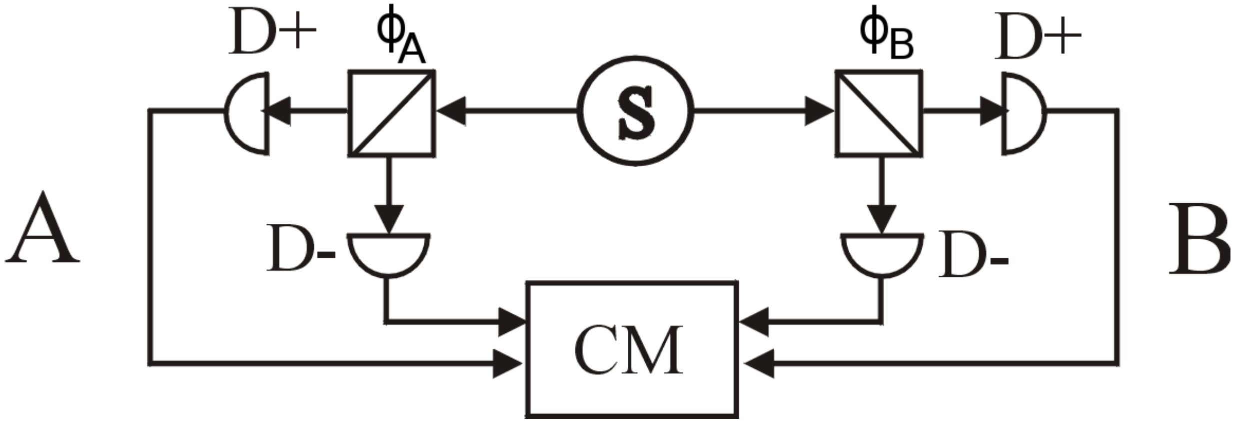

Figure 1: Coincidence measurement setup[4]

$$E(\phi_A, \phi_B) = \frac{N^{++} + N^{--} - N^{+-} - N^{-+}}{N^{++} + N^{--} + N^{+-} + N^{-+}} \quad (1)$$

N denotes the coincident detection event between the observers with respectively + or - orientation

CHSH inequality

Clauser-Horne-Shimony-Holt (CHSH) inequality

$$S = |E(\phi_A, \phi_B) - E(\phi_A, \widetilde{\phi}_B) + E(\widetilde{\phi}_A, \phi_B) + E(\widetilde{\phi}_A, \widetilde{\phi}_B)| \leq 2 \quad (2)$$

- Equivalent to Bell inequality
- If the photons are correlated the inequality is violated

Maximal violation

The maximal violation is found for the angles set $\{\phi_A, \widetilde{\phi}_A, \phi_B, \widetilde{\phi}_B\} = \{0^o, 45^o, 22.5^o, 67.5^o\}$

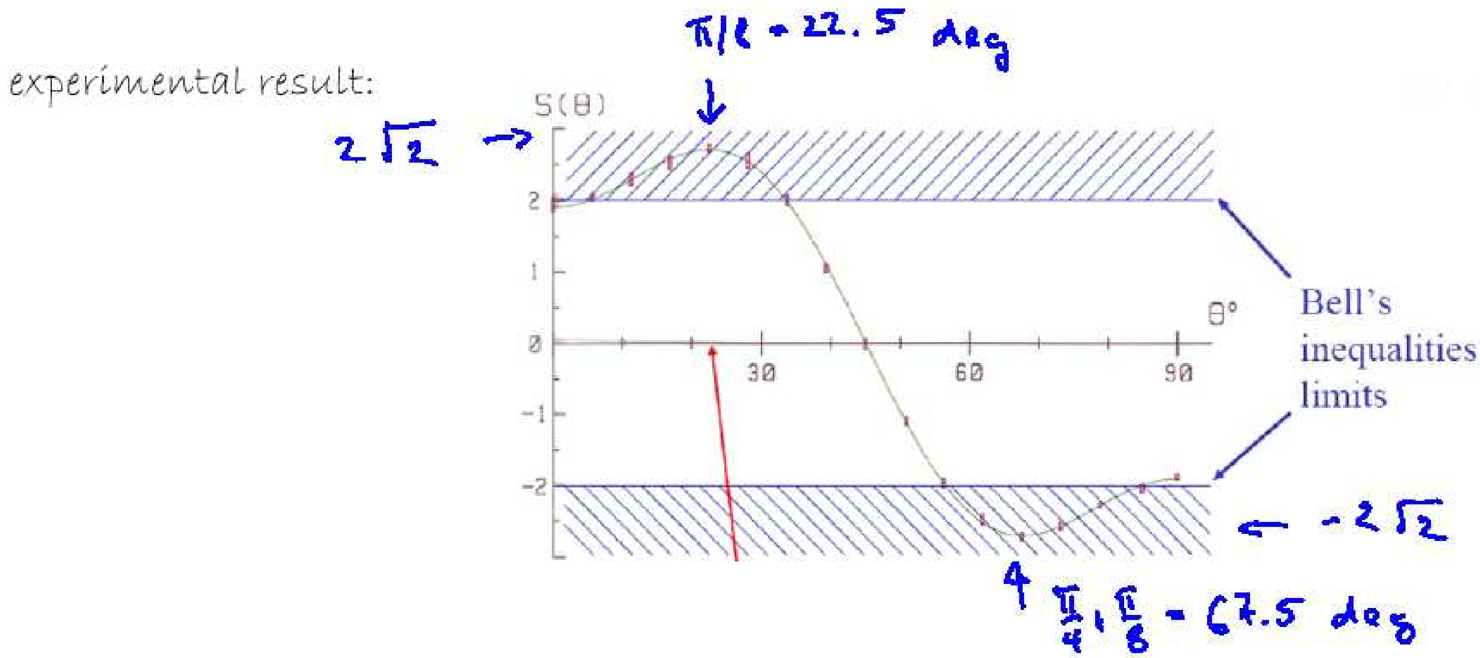

Figure 2: Bell inequality violation [3]

SPDC

Spontaneous parametric down-conversion, a source for polarization-entangled photons.

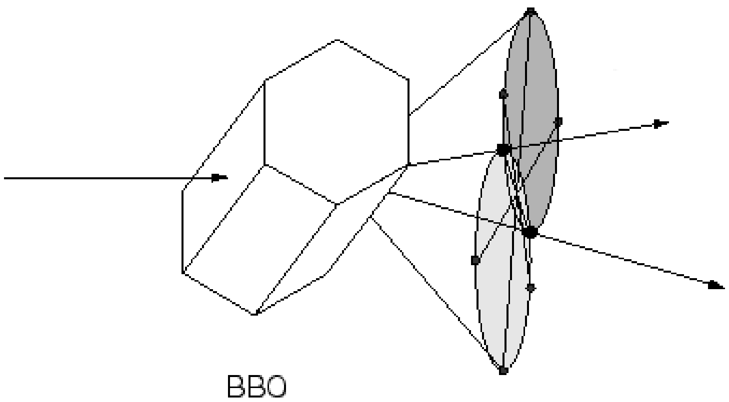

Figure 3: Parametric Down Conversion[5]

Principle

1. Produce an ultraviolet photon (laser diode)
2. Photon hits a non linear crystal
3. It produce two photons with doubled wavelength

Setup and methods

Free-space setup

Important points :

- no fibers between the source and receivers
- external conditions play a role
- no ideal laboratory environment

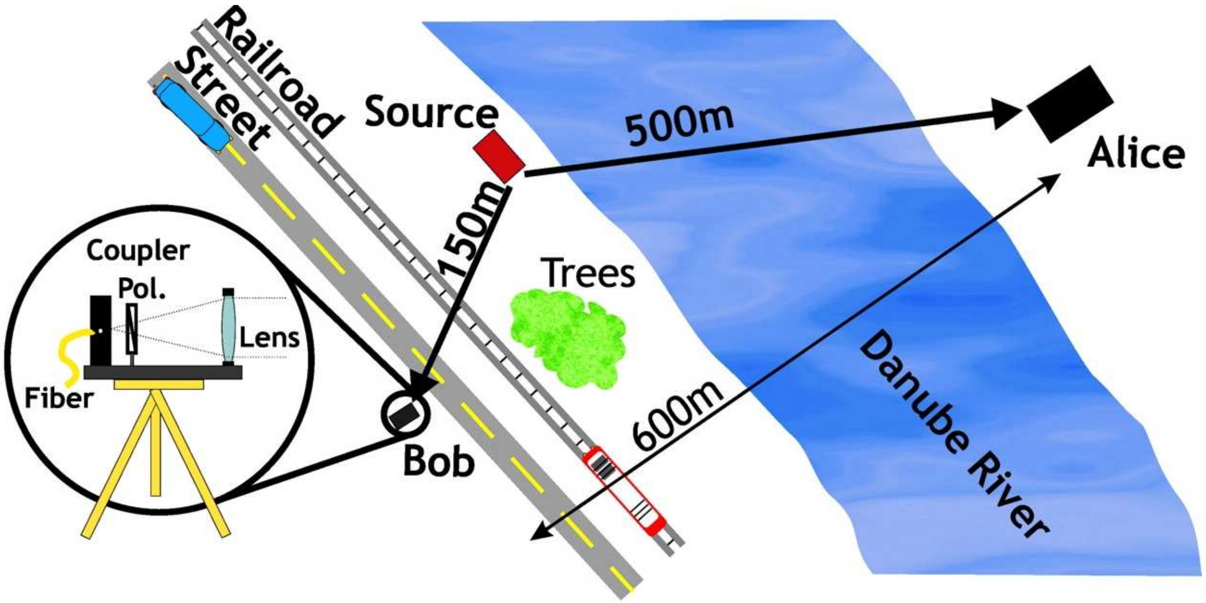

Figure 4: Experimental setup[1]

Experimental Setup

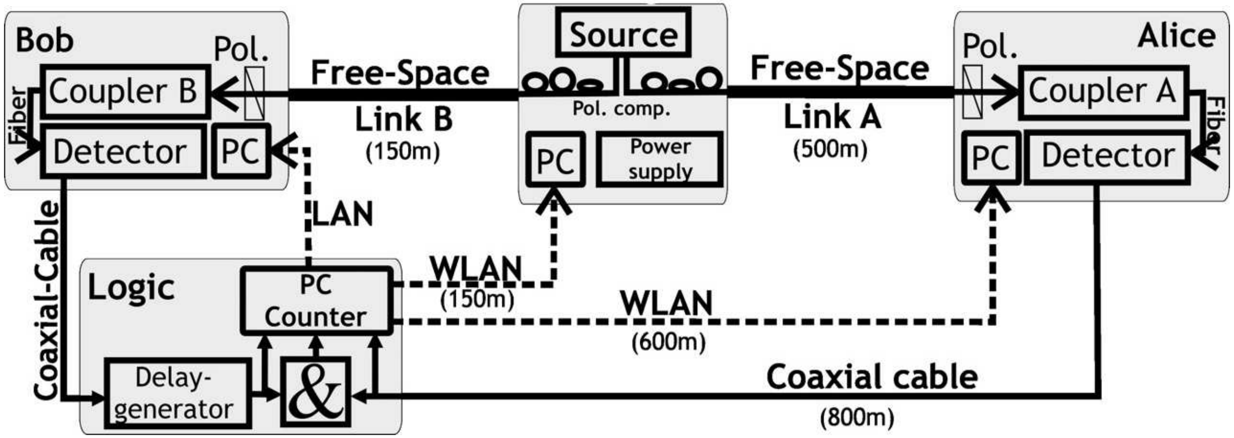

Figure 5: Experimental setup[1]

- Source produce with SPDC a given Bell state.
- Receivers are arranged for coincidence measurement.
- To show the quality of the entanglement, they measured polarization correlation.
- LAN and WLAN to monitor the detection events.

Experimental conditions

The outside environment is far away from an ideal laboratory

Conditions :

- Temperature 0^oC
- Wind (stability of detectors)
- Trees
- Trucks, boats, freight trains
- Environment lights

Setup :

- Wind protection
- Optical selectivity suppress the background lights
- Telescope (focus)
- Single mode fiber (filter)

Where are the photons ?

Many photons were lost :

- After the SPDC 120,000 photons s^{-1} in each arm of the source
- 20,000 photons s^{-1} are correlated
- Coincidence rate of 15 photons s^{-1} at the detectors

Possible reasons :

- Decoherence due to long-distance propagation
- Attenuation because of propagation and devices
- Detection of the avalanche photo diodes of about 40%

Requirement for CHSH

- Noise in an experiment produces a non-pure QM state.
- Thus the quantum optimum of $S_{qm} = 2\sqrt{2}$ cannot be obtained.
- Define a modified Bell-parameter

$$S_{exp} = VS \tag{3}$$

Where V is the Visibility $V = E(\phi, \phi)$ and is proportional to the fidelity.

The fidelity is the overlap of the state with the ideal pure state.

- To violate the Bell inequality $V > \frac{1}{\sqrt{2}} \approx 71\%$
- $\Rightarrow F \gtrsim 78\%$
- Measured value for $F = 87 \pm 3\%$

Results and Interest

Result

By measuring the correlation coefficients $E(\phi_A, \phi_B)$ they got

$$S = 2.41 \pm 0.10 \not< 2 \tag{4}$$

$\Rightarrow$ the two separated receiver stations shared an entangled quantum state.

Interest

This experiment could be used

- for satellites based communication with quantum cryptography.
- to study fundamental limits due to long-distance deterioration of quantum correlation because of decoherence.

Conclusion

To remember

- QM Entanglement can be showed by violation of Bell inequality.
- Experiment independent form an ideal laboratory environment, application for communications.
- It’s possible to distribute polarized-entangled photons without optical fibers.

References

1. M. Aspelmeyer, *et al.*, *Long-Distance Free-Space Distribution of Quantum Entanglement* *Science* **301, 621 (2003)**
2. Quantiki, http://www.quantiki.org
3. Andreas Wallraff, Lectures notes, Quantum System for Information Technology, ETHZ (WS 06/07)
4. Wikipedia, www.wikipedia.org
5. http://theory.gsi.de
6. M. Aspelmeyer, *et al.*, *Long-Distance Free-Space Distribution of Quantum Entanglement* *Science* Supporting Online Material - Material and Methods

Questions ?

La science ne sert guère qu'à nous donner une idée de l'étendue de notre ignorance. [Félicité de Lamennais]

The important thing is not to stop questioning. [Albert Einstein]