Experimental Violation of Bell Inequalities

QSIT, Paper presentation

EPR Paradox: Is the world quantum?

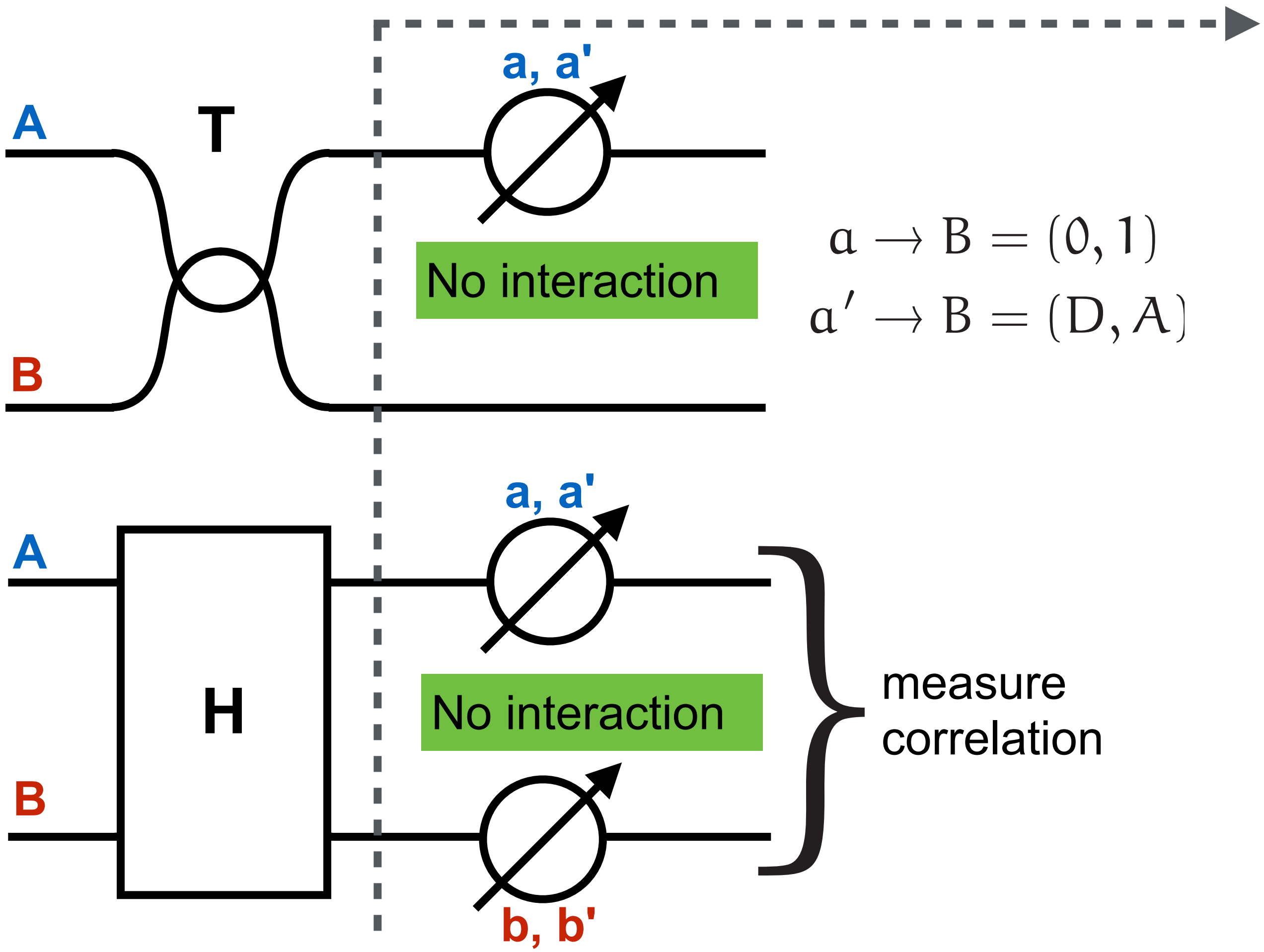
- **EPR 1935** Assumption:
  A measurement reveals a physical property
  “Local realism"
- EPR: Quantum mechanics not complete
- Later: Hidden local variables as alternative?
- **Bell 1965** provided idea for ultimate proof
- **Aspect 1982** performed the first measurement

Outline

- **Introduction, Theory**
  - EPR Paradox
  - Bell inequalities
- **Loopholes**
  - Angular correlation, Locality, Detection
  - Different setups
- **Implementation**
  - Experimental setup
  - Results
- **Conclusion**

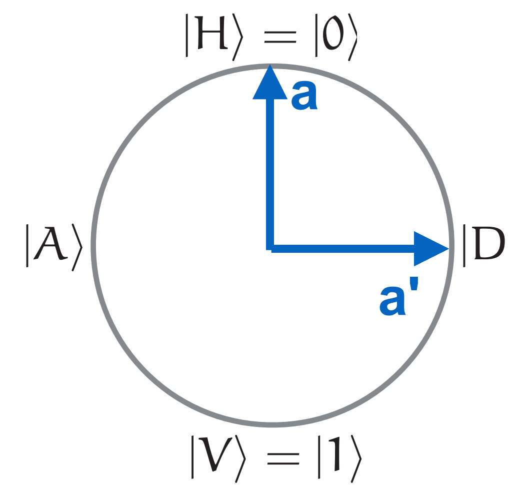
EPR vs Bell

$$|\Psi^-\rangle = \frac{1}{\sqrt{2}}\left(|01\rangle - |10\rangle\right) = \frac{1}{\sqrt{2}}\left(|DA\rangle - |AD\rangle\right)$$

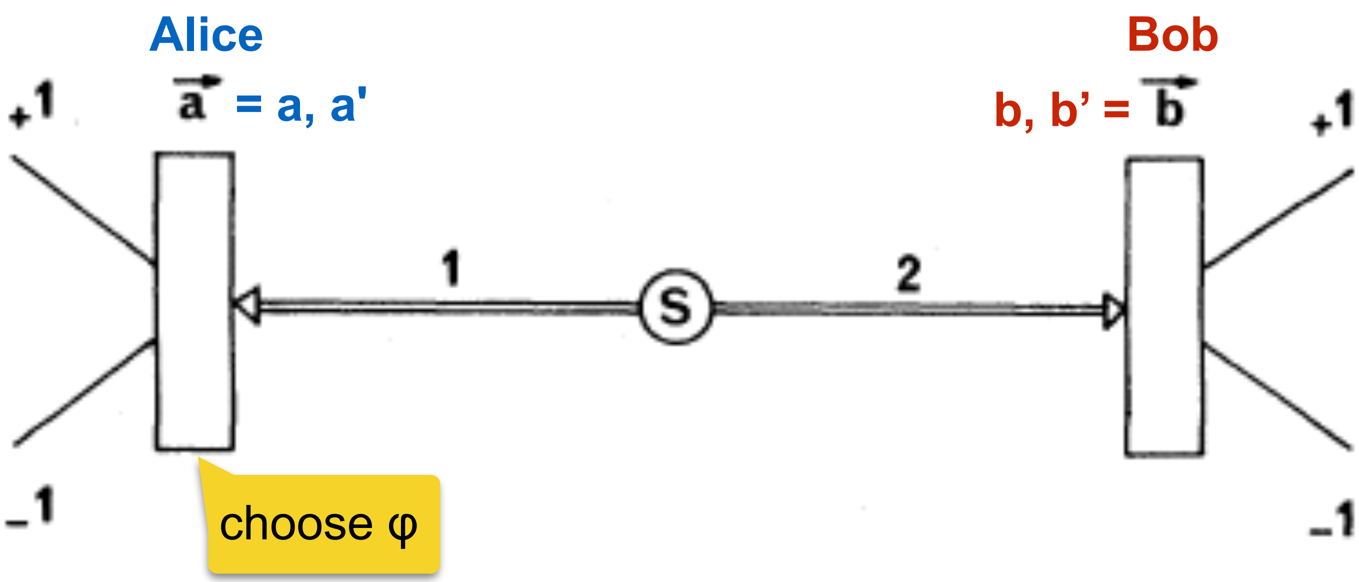


$$a \rightarrow B = (0, 1)$$

$$a' \rightarrow B = (D, A)$$



Bell Inequalities Contradiction Measurement



Bell Inequalities - CHSH version

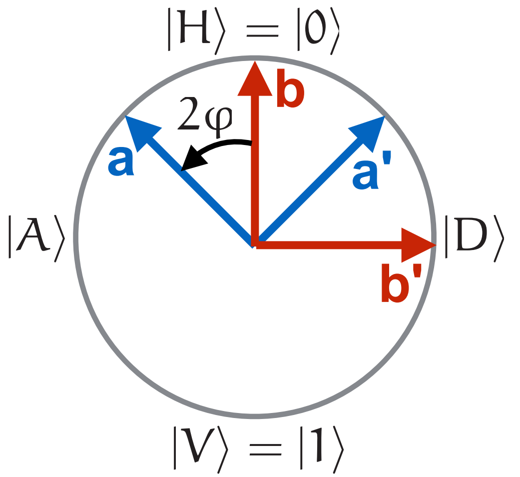
Correlation coefficient

$$E(\alpha,\beta) = P_{same}(\alpha,\beta) - P_{diff}(\alpha,\beta)$$
$$= P_{++} + P_{--} - P_{+-} - P_{-+}$$

$$|\Psi^-\rangle = \frac{1}{\sqrt{2}}(|01\rangle - |10\rangle)$$
$$= \frac{1}{\sqrt{2}}(|DA\rangle - |AD\rangle)$$

Bell signal

$$S = E(a,b) - E(a,b') + E(a',b) + E(a',b')$$
$$= A(a)B(b) - A(a)B(b') + A(a')B(b) + A(a')B(b)$$
$$= A(a)\left(B(b) - B(b')\right) \quad + A(a')\left(B(b) + B(b')\right)$$



Consider only extreme cases:

$$E(a,b) = \int A(a|\lambda)\cdot B(b|\lambda)\rho(\lambda)d\lambda$$
$$= A(a|\lambda)\cdot B(b|\lambda)$$
$$= \pm 1$$

hidden variable λ

CLASSICALLY

Bell Inequalities - CHSH version

Correlation coefficient

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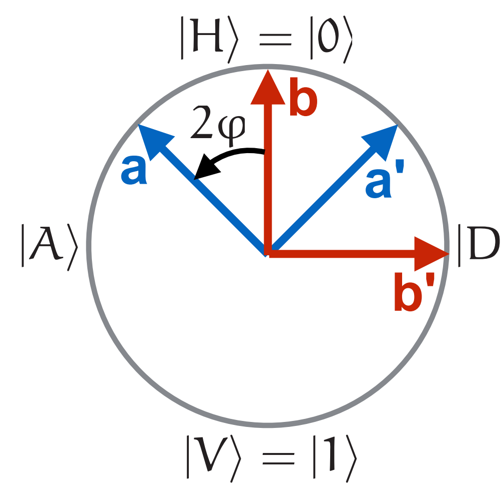


CLASSICALLY

One of the two has to be 0

$|S| \leq 2$

QUANTUM MECHANICS

It depends on A

$|S| \leq 2\sqrt{2}$

Bell Inequalities - CHSH version

Correlation coefficient

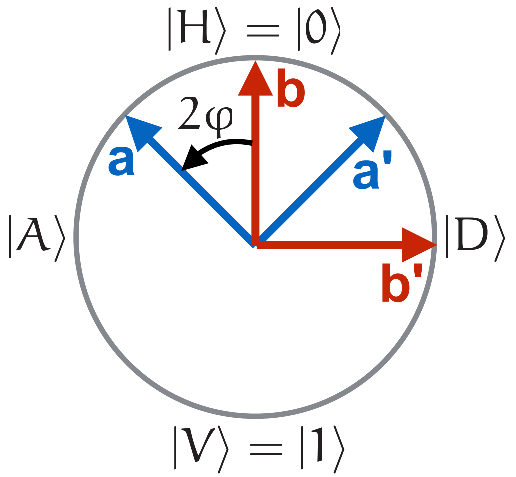
$$E(\alpha,\beta) = P_{same}(\alpha,\beta) - P_{diff}(\alpha,\beta)$$
$$= P_{++} + P_{--} - P_{+-} - P_{-+}$$

$$|\Psi^-\rangle = \frac{1}{\sqrt{2}}(|01\rangle - |10\rangle)$$
$$= \frac{1}{\sqrt{2}}(|DA\rangle - |AD\rangle)$$

Bell signal

$$S = E(a,b) - E(a,b') + E(a',b) + E(a',b')$$

$$E(\alpha,\beta) = \langle \alpha, \beta \rangle$$
$$= \langle \psi | \alpha\beta | \psi \rangle$$
$$= \dots$$
$$= -\cos(\alpha,\beta)$$



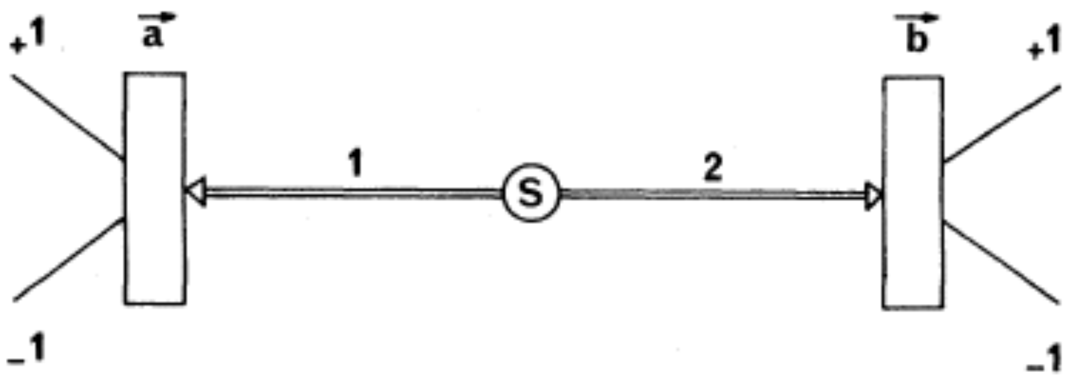
QUANTUM MECHANICS

It depends on A

$|S| \leq 2\sqrt{2}$

Bell Inequalities Violation Measurement

- Principle of measurement setup:



Loopholes

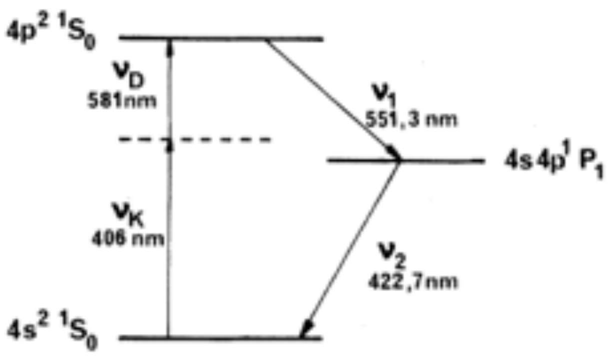
- *[...] (the derivation) is based on two assumptions, which, if not met, allow an experiment to return a Bell violation even for a classically predetermined process [...]*

- Those assumptions are called **Loopholes**.

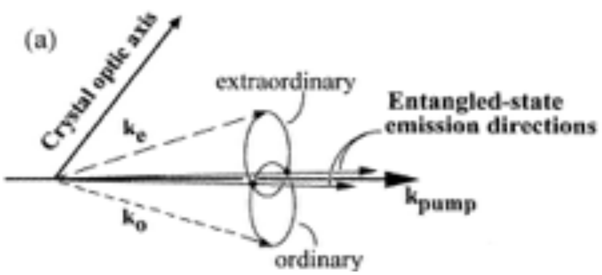
- For **photon** systems: 3 kinds of loopholes
  - Angular correlation loophole (generation)
  - Detection loophole
  - Locality loophole

Angular correlation loophole

- Generation of entangled photons
  - 2 laser excitation of calcium atoms
  - cascade emission of entangled photons
  - poor angular correlation



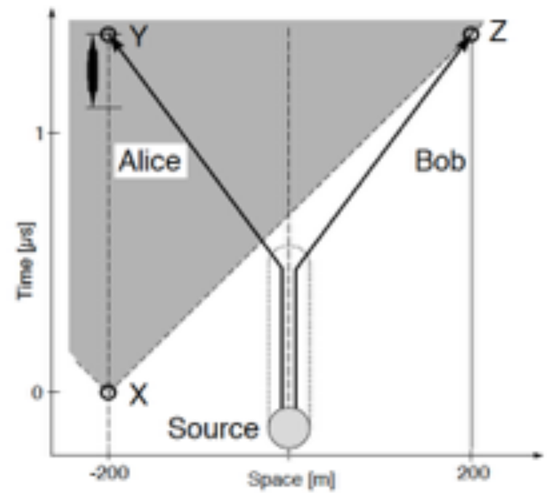
- Modern experiments
  - generation via parametric down-conversion in non-linear material such as BBO (barium beta bromate)
  - **loophole closed**



Locality loophole

- Measurement time greater than the time it would take the photons pair to communicate information about the state state

- Loophole closed by space-like separation
  - faster detection
  - greater distance between detection locations
  - $d > c * t_{meas}$



- Latest improvements: random polarization change during measurement

Detection loophole

- Arises due to low detection efficiency of single-photon detectors
  - for early experiments: between 5% and 20%
  - a lot of photons remain undetected

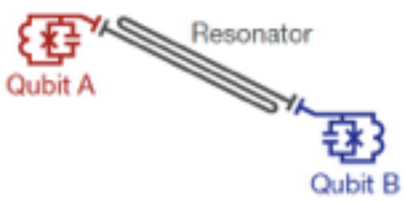
- **Fair-sampling assumption:**
  - fraction of detected pairs is representative for the whole ensemble of pairs

- Remains the most important loophole which has not been completely resolved for photonic systems

Various measurement setups

- **Photon** based systems
  - Pro: fast travel thus enabling the independent measurement of the 2 quantum systems => locality loophole closed
  - Contra: fast and accurate detection not reached yet
  - outlook: superconducting nanowire NbN detectors 67% efficiency

- **Other** systems
  - i.e.: ions, Josephson junction
  - Pro: nearly perfect detection
  - Contra: hard to separate the two Qubits
  - ongoing research, i.e. separate Josephson junction



Alternative measurement setups

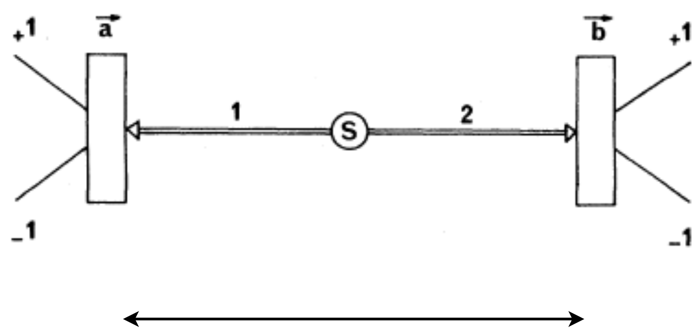
- Additional systems:
  - neutrons
  - K Mesons, B Mesons
  - atomic systems

- Loophole-free systems
  - those are often **mixed systems**
  - take advantage of different systems
  - only "**proposals**" so far

Violation of Bell's Inequality under Strict Einstein Locality Conditions

Gregor Weihs, Thomas Jennewein, Christoph Simon, Harald Weinfurter, and Anton Zeilinger
Institut für Experimentalphysik, Universität Innsbruck, Technikerstraße 25, A-6020 Innsbruck, Austria
(Received 6 August 1998)

- Bell Inequality Violation Measurement with photons
- Main aim: closing locality loophole

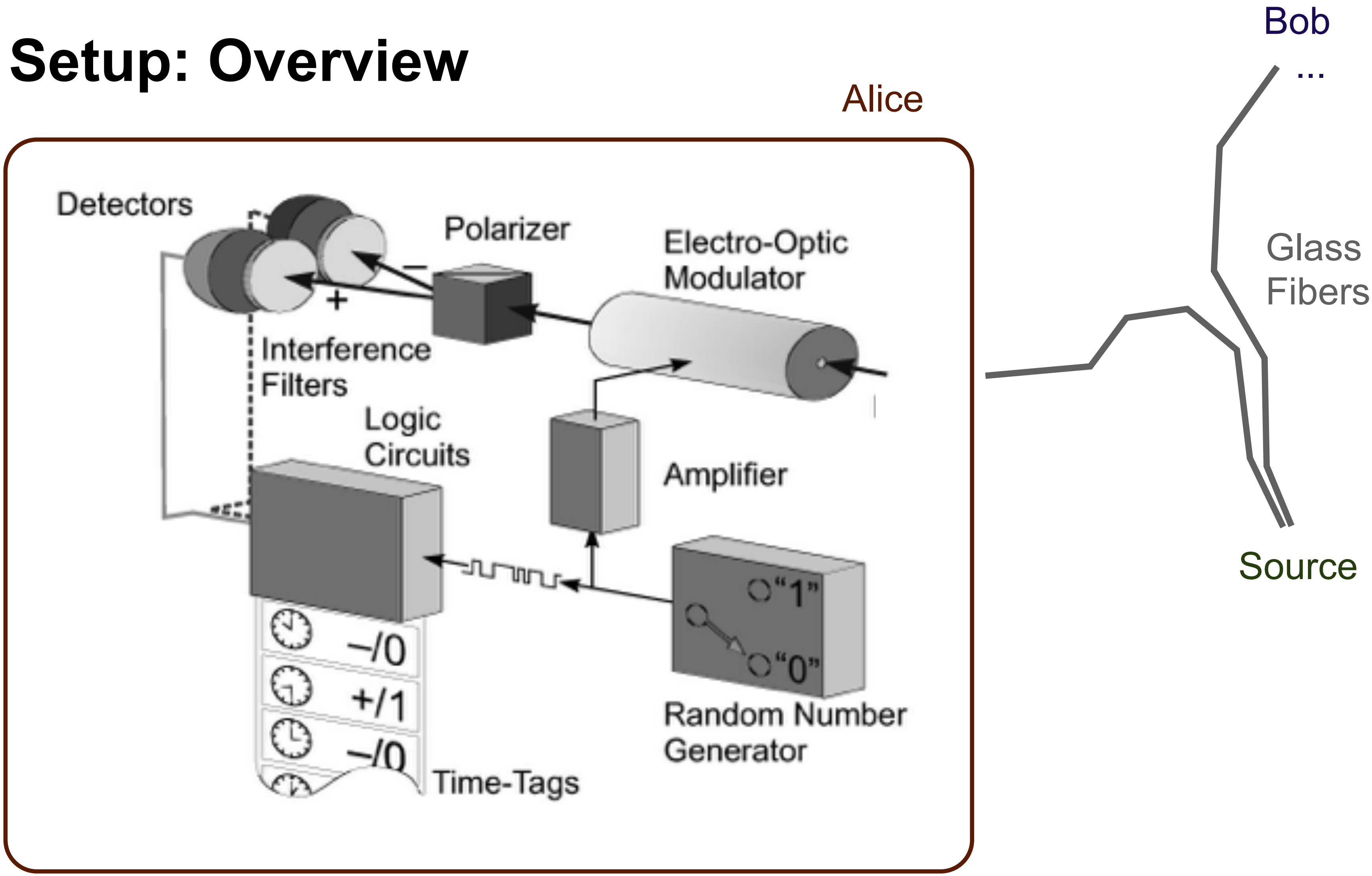


400 m
(1.3 µs)

Setup: Overview

- Sending entangled photon pairs through single-mode glass fibers to spatially separated regions (400 m)
- Choosing the measurement axes via physical random-number generators
- Changing the measurement axes via electro-optic modulators
- Storing the data locally together with the measurement time

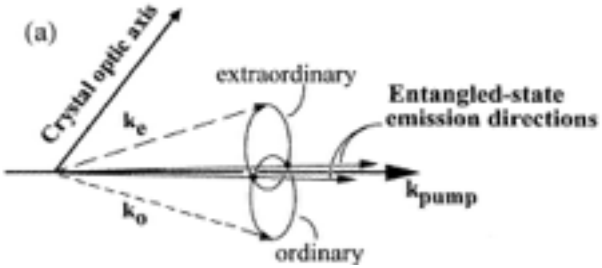
Setup: Overview

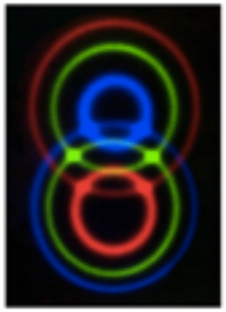


Setup: Details

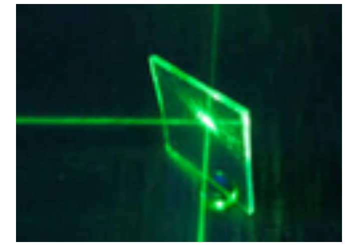
Creation of the photons:

- degenerate type II parametric down-conversion (emits entangled photons with perpendicular polarization)
- BBO crystal (Beta Barium Borate; non-linear crystal), shined at with 400 mW of 351 nm light from argon-ion laser



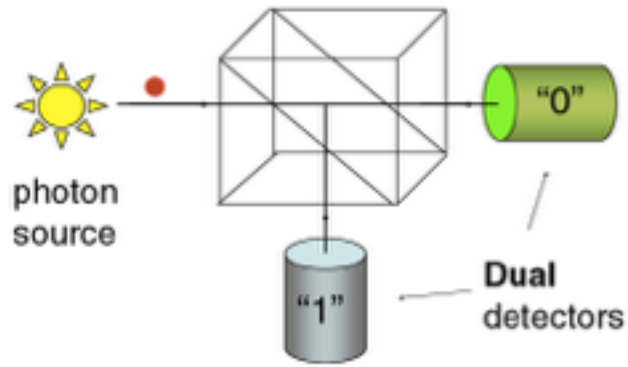


Setup: Details



Random Number Generation:

- light-emitting diode
- beam splitter
- photomultipliers & electric circuit
- detection window / max. frequency:
  2 ns / 500 MHz
- incl. modulation to uniform distribution:
  10 MHz



Setup: Details

Setting the measurement axes:

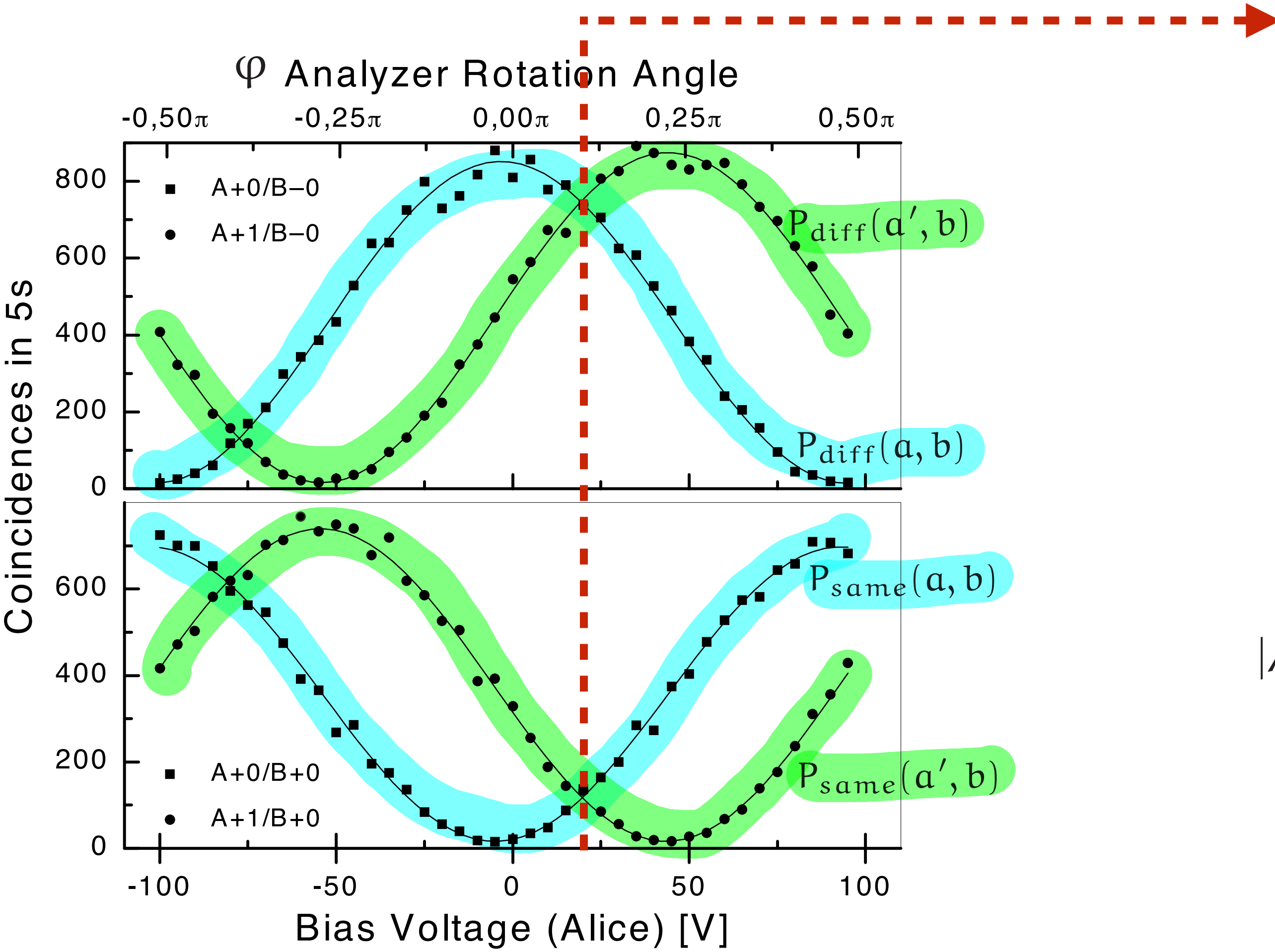
- electro-optic modulator: rotation of polarization proportional to the applied voltage
- Frequencies: DC to 30 MHz
- optic axis at 45 degrees to the polarizer ahead
- depending on the random number input:
  switch between 0 and 45 degrees rotation of polarization

Setup: Details

Detection:

- polarizer beam splitter
- silicon avalanche photodiodes: 10’000 - 15’000 counts / s, dark count of a few 100 / s
- selection of good inputs (right setup switching time)
- local time-tagged recording of output & switch positions: 75 ps resolution, 0.5 ns accuracy
- overall dead-time of detection channel: 1 μs

Measurement Results



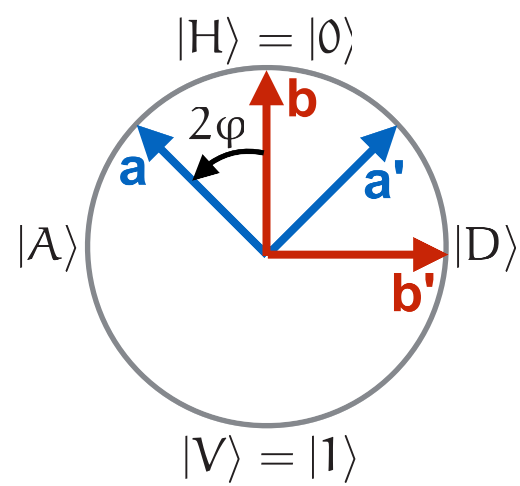
QM maximum

$$\varphi = \pi/8$$

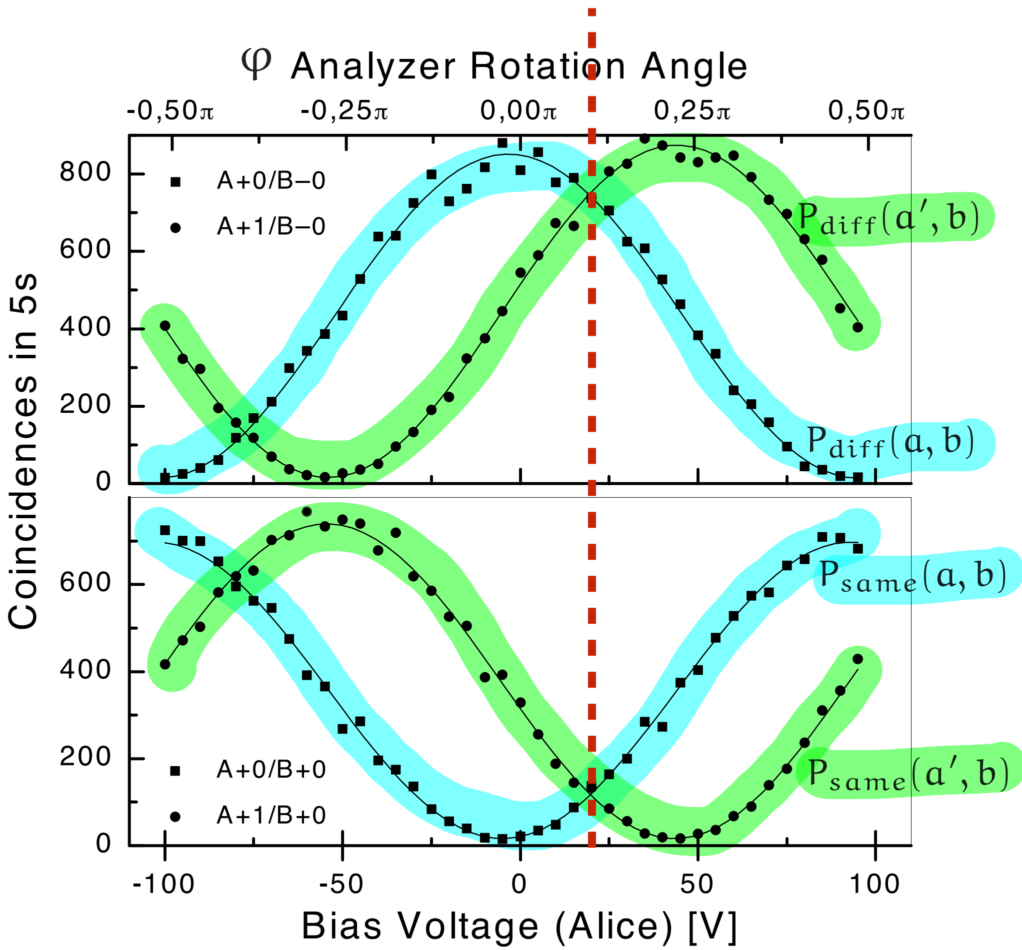
$$E(a, b) = -\frac{1}{\sqrt{2}}$$

$$E(a', b) = -\frac{1}{\sqrt{2}}$$

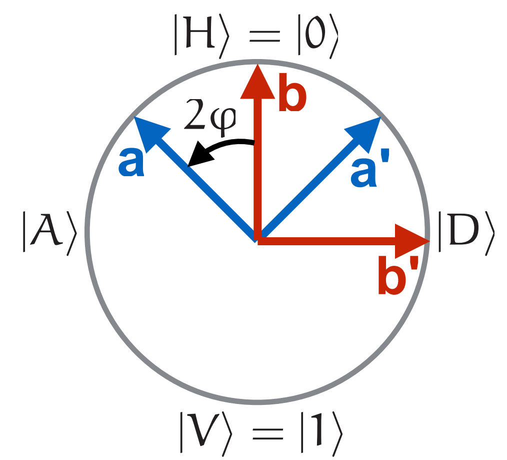
$$S = -2\sqrt{2}$$



Measurement Results



- SNR > 100
- coincidence window 6 ns
- visibility of correlations: ≈ 97 %
- 14’700 coincidence events in 10s
- Total detection / collection efficiency: 5 %



Results

- Bell inequality violation:
  2.73 ± 0.02
- Total detection / collection efficiency: 5 %
- Loopholes?
  - Detection Loophole: ✗ (5 %)
  - Locality Loophole: ✓ (1.3 μs vs. ≈ 100 ns)

Summary

- Theoretical Background:
  - EPR Paradox
  - Bell Inequalities
- Loopholes & Physical Systems
- Experimental Implementation:
  - Detailed Setup
  - Bell inequality violation: 2.73 ± 0.02
  - Detection Loophole: ✗ (5 %)
  - Locality Loophole: ✓ (1.3 μs vs. ≈ 100 ns)

Thank you for your attention.

References

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  Phys. Rev. A 52, 4381 – Published 1 December 1995

Setup: Details

Transmission:

- telescope to narrow the beam
- half-wave plate & compensator crystals to correct output to desired state:

  $$|\psi\rangle = \frac{1}{\sqrt{2}}(|H\rangle_1|V\rangle_2 + e^{i\phi}|V\rangle_1|H\rangle_2) \quad \text{with} \quad \phi = \pi$$

- manual fiber polarization controllers to correct unitary polarization transformations in fiber

Hg Atom Based Systems