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

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

\[ a \to B = (0,1) \]
\[ a' \to B = (D,A) \]

No interaction

measure correlation

\[ |H\rangle = |0\rangle \]
\[ |A\rangle \]
\[ |V\rangle = |1\rangle \]
\[ |D\rangle \]
Bell Inequalities Contradiction Measurement

Alice
= a, a'

Bob
b, b' =

choose φ
Bell Inequalities - CHSH version

Correlation coefficient

\[ E(\alpha, \beta) = P_{\text{same}}(\alpha, \beta) - P_{\text{diff}}(\alpha, \beta) \]
\[ = P_{++} + P_{--} - P_{+-} - P_{-+} \]

Bell signal

\[ S = E(a, b) - E(a, b') + E(a', b) + E(a', b') \]
\[ = A(a)B(b) - A(a)B(b') + A(a')B(b) + A(a')B(b') \]
\[ = A(a)(B(b) - B(b')) + A(a')(B(b) + B(b')) \]

Consider only extreme cases:

\[ E(a, b) = \int A(a|\lambda) \cdot B(b|\lambda) \rho(\lambda) d\lambda \]
\[ = A(a|\lambda) \cdot B(b|\lambda) \]
\[ = \pm 1 \text{ CLASSICALLY} \]

hidden variable \( \lambda \)

\[ |\Psi^-\rangle = \frac{1}{\sqrt{2}}(|01\rangle - |10\rangle) \]
\[ = \frac{1}{\sqrt{2}}(|DA\rangle - |AD\rangle) \]
Bell Inequalities - CHSH version

Correlation coefficient

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

$$= P_{++} + P_{--} - P_{+-} - P_{-+}$$

Bell signal

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

$$= A(a)B(b) - A(a)B(b') + A(a')B(b) + A(a')B(b')$$

$$= A(a)(B(b) - B(b')) + A(a')(B(b) + B(b'))$$

CLASSICALLY

One of the two has to be 0

$$|S| \leq 2$$

QUANTUM MECHANICS

It depends on A

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

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

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

$$|H\rangle = |0\rangle$$

$$|A\rangle$$

$$|b\rangle$$

$$|b'\rangle$$

$$|D\rangle$$

$$|V\rangle = |1\rangle$$
Bell Inequalities - CHSH version

Correlation coefficient

\[ E(\alpha, \beta) = P_{\text{same}}(\alpha, \beta) - P_{\text{diff}}(\alpha, \beta) \]

\[ = P_{++} + P_{--} - P_{+-} - P_{-+} \]

Bell signal

\[ S = E(a, b) - E(a, b') + E(a', b) + E(a', b') \]

\[ E(\alpha, \beta) = \langle \alpha, \beta \rangle \]

\[ = \langle \psi | \alpha \beta | \psi \rangle \]

\[ = \ldots \]

\[ = -\cos(\alpha, \beta) \]

\[ |\Psi^{-}\rangle = \frac{1}{\sqrt{2}}(|01\rangle - |10\rangle) \]

\[ = \frac{1}{\sqrt{2}}(|DA\rangle - |AD\rangle) \]

\[ |H\rangle = |0\rangle \]

\[ |A\rangle \]

\[ |V\rangle = |1\rangle \]

\[ |b\rangle \]

\[ \angle 2\varphi \]

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
  - \( d > c \cdot t_{\text{meas}} \)

- 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

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(Received 6 August 1998)

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

Bell Inequality Violation Measurement with photons

Main aim: closing locality loophole

\[ \text{400 m} \quad (1.3 \mu s) \]
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

- **Alice**
  - Source
  - Glass Fibers

- **Bob**
  - Interference Filters
  - Logic Circuits
  - Polarizer
  - Electro-Optic Modulator
  - Amplifier
  - Random Number Generator
  - Time-Tags
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

\[ \varphi = \pi/8 \]
\[ E(a, b) = -\frac{1}{\sqrt{2}} \]
\[ E(a', b) = -\frac{1}{\sqrt{2}} \]
\[ S = -2\sqrt{2} \]

\[ |H\rangle = |0\rangle \]
\[ |A\rangle \]
\[ |V\rangle = |1\rangle \]
Measurement Results

- SNR > 100
- coincidence window 6 ns
- visibility of correlations: $\approx 97\%$
- 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: $2.73 \pm 0.02$
  - Detection Loophole: $\times$ (5 %)
  - Locality Loophole: $\sqrt{1.3 \, \mu s \text{ vs. } \approx 100 \, \text{ns}}$
Thank you for your attention.
References


Setup: Details

Transmission:

- telescope to narrow the beam
- half-wave plate & compensator crystals to correct output to desired state:
  \[ |\psi\rangle = \frac{1}{\sqrt{2}} (|H\rangle_1 |V\rangle_2 + e^{i\phi} |V\rangle_1 |H\rangle_2) \]
  with \( \phi = \pi \)
- manual fiber polarization controllers to correct unitary polarization transformations in fiber
Hg Atom Based Systems