Loophole-free Bell inequality violation using electron spins separated by 1.3 kilometres

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EPR (Einstein-Podolsky-Rosen) Paradox

\[ |\psi\rangle = \frac{1}{\sqrt{2}} (|0\rangle_A |0\rangle_B + |1\rangle_A |1\rangle_B) \]

- Outcome of the measurement on qubit A could determine the outcome of the measurement on qubit B even if the two measurement events are space like
- Contradict with special relativity?

Physical review, 47(10), 777 (1935)
Two Explanations of the Paradox

- Non-locality:
  Influence could travel faster than c in Quantum Mechanics
  Does not allow for faster-than-light communication

- Hidden variables:
  Outcome of measurement is determined by some hidden variables
  Two qubits get same hidden variables when they are entangled
  Measurement of A provides information about which is local to B

Physical review, 47(10), 777 (1935)
Test the two explanations experimentally

For hidden variables case:
CHSH (Clauser-Horne-Shimony-Holt) Inequality

- Outcome of the measurement on qubit A, B along direction $\hat{a}$, $\hat{b}$ respectively with the same hidden variables $\lambda$: $A(\hat{a}, \lambda) \in \{-1, 1\}$, $B(\hat{b}, \lambda) \in \{-1, 1\}$

- Denote correlation between two measurements $\int d\lambda \rho(\lambda) A(\hat{a}, \lambda) B(\hat{b}, \lambda)$ as $P(\hat{a}, \hat{b})$, where $\rho(\lambda)$ is probability distribution with respect to $\lambda$

Correlation of measurements on four directions is constrained:

$$|P(\hat{a}, \hat{b}) - P(\hat{a}, \hat{c}) + P(\hat{d}, \hat{c}) + P(\hat{d}, \hat{b})| \leq 2$$

Physical review letters, 23(15), 880. (1969)
Violation of CHSH Inequality in Quantum Mechanics

In quantum mechanics:

- The correlation between measurement is not constrained as strong as in hidden variables theory

\[ P(\hat{a}, \hat{b}) = \langle \psi_{AB} | (\hat{\sigma}_A \cdot \hat{a})(\hat{\sigma}_B \cdot \hat{b}) | \psi_{AB} \rangle = -\cos \theta_{ab} \]

- Construct the measurement in four directions as shown in the figure

\[ \theta_{ab} = \pi/4, \theta_{ac} = 3\pi/4, \theta_{dc} = \pi/4, \theta_{db} = \pi/4 \]

\[ |P(\hat{a}, \hat{b}) - P(\hat{a}, \hat{c}) + P(\hat{d}, \hat{c}) + P(\hat{d}, \hat{b})| = 2\sqrt{2} > 2 \]

- CHSH inequality is violated!
- Quantum mechanics is non-local

Figure 1: Directions of measurement
Previous Bell Test Experiment Loopholes

- Previous tests of Bell’s inequality have loopholes
  - None have simultaneously closed detection and locality
  - Detection: detection efficiency is not 100%
    - Subsample may violate Bell inequality when the whole data set does not
  - Locality: timelike separation between measurement sites allows communication
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- Loophole-free Bell test would fundamentally test QM
- Test security of QM security protocols
  - Use Bell tests to detect interception
Closing Detection and Locality Loopholes

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- Additional signal to close detection loophole
  - Determines whether both photons arrived simultaneously
Creating and Entangling Electron Spins

- Unpaired Nitrogen electron and vacancy electron form a Spin-1 triplet.
- A magnetic field can mix the $m_S = -1$ and $m_S = 0$ states to create an effective 2 state system.

After 2 time intervals:
Sites are entangled or both bright.

Physical review A, 71(6), 060310 (2005)
Reading Out the Entangled Spins

- The group uses two binary RNGs to choose between two measurement bases to evaluate A and B on.
- After evaluation, but before entanglement is confirmed, the group rotates to the required basis and reads out the signal.
- Rotation and readout takes <4.27μs (the amount of time it would take for sites A and B to communicate).
Preliminary experiments predict strong entanglement

- Ignored site B, and generated spin-photon entanglement at A
- Measured spin at A and photon arrival time at C
- Spin is entangled with photon arrival time

From another preliminary experiment, the two-photon detection measurement at C is characterized by a visibility of (90±6)%

With these experiments as input, a model for the density matrix \( \rho \) (based on Barrett-Kok) gives

\[
\langle \Psi^- | \rho | \Psi^- \rangle = 0.92 \pm 0.03
\]

where

\[
| \Psi^- \rangle = \frac{1}{\sqrt{2}} (| \uparrow \downarrow \rangle + | \downarrow \uparrow \rangle)
\]
Generated spin states are highly entangled

- Ran experiment with fixed collinear measurement bases
- Data indicates entanglement
- Gives a lower bound $\langle \Psi^- | \rho | \Psi^- \rangle > 0.83 \pm 0.05$
- Numerically optimized angles of measurement bases for maximal correlations

Measurement outcomes for successful entanglement attempts (dotted: prediction based on model $\rho$)
CHSH-Bell inequality is violated with p-value 0.039

- Experiment was iterated 1 billion times per hour
  - Spin-photon entanglement at A and B
  - Two-photon measurement and event-ready signal at C
  - Measure spins along random bases

- 245 successful entanglements during 220 hours of data collection

- Iterations with successful entanglements were used to find $S$.

- Found $S = 2.42 \pm 0.20$, violating $S \leq 2$
Conclusions

- Reports the **first** Loophole-free Bell inequality violation detection using electrons. They found \( S = 2.42 \pm 0.20 \)

  as compared to \( S \leq 2 \)

- It successfully closes the **detection** loophole and the **locality** loophole.
- Uses an event-ready scheme to generate entanglement between electrons separated by 1.28 km.
- Statistically significant result with a P value of 0.039.
Critiques

- A concise and well-written abstract, which answers all the questions expected of it.
- For every ‘field-specific term’ that is used, a nice review paper/ publication (that first introduced the concept) has been cited. This makes the paper an ideal-read for a general Physics audience.
- Explains the footing of their experiment in the light of several past failures in the field.
- Covers all the bases- provides a detailed characterization of the experimental setup and explicitly shows how both the loopholes are taken care of.
- The paper is self-sufficient. But whatever little has been left out, is covered by the Supplementary Information.
Citation Report

- This paper was published on 29 October 2015
- It has been cited 314 times. (Scopus, 12 December 2017)
  - Facebook - Shares, likes and comments - 1379
  - Twitter - 200 Tweets
- A really important scientific paper in the field of quantum information.
- The follow up work, by a different group. Cited 149 times. It does a Loophole-free test of the Bell’s inequality with entangled photons.