Violation of Bell's Inequality under Strict Einstein Locality Conditions

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Violation of Bell's Inequality under Strict Einstein Locality Conditions

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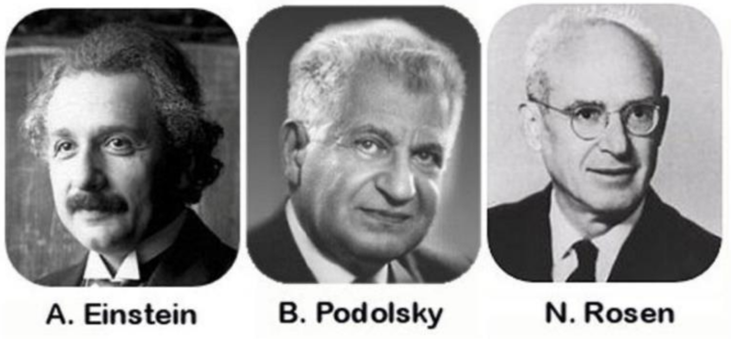
Overview

- EPR Paradox and Bell’s Theorem
- Local Realism and strict locality conditions
- Experiment methodology and CHSH Inequality
- Conclusions



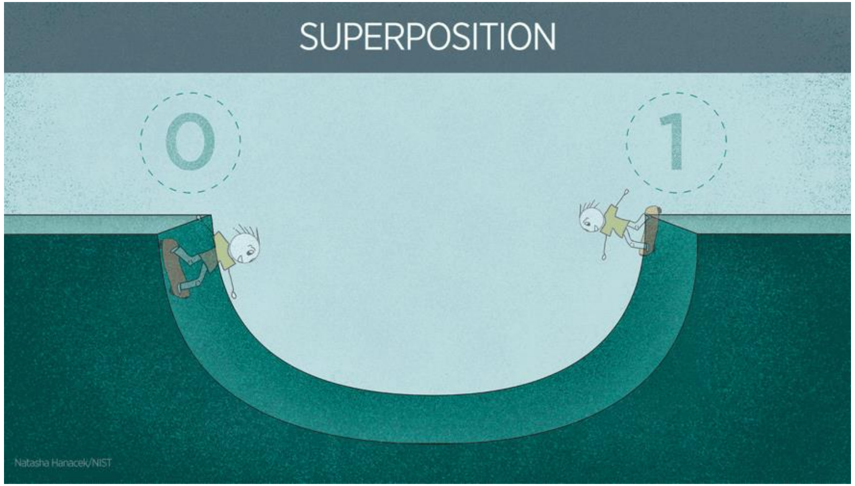


Image from “Local Realism, Bell’s Inequality, and T-Shirts: An Entangled Tale,” S. Glancy.

Definitions of Locality and Realism

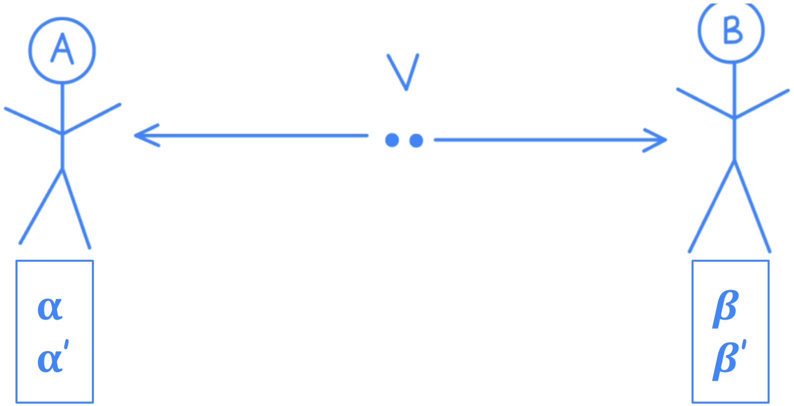
- Locality: a physical object is influenced only by its surroundings
- Realism: physical entities objectively exist and have definite values regardless of any observation or measurement

CHSH/Bell Theoretical Background

CHSH inequality

- Clauser, Horne, Shimony, Holt
- Assuming locality and realism

$$S(\alpha,\alpha',\beta,\beta') = |E(\alpha,\beta) - E(\alpha',\beta)| + |E(\alpha,\beta') + E(\alpha',\beta')| \leq 2$$



R. Cleve: Bell/CHSH Inequality (https://www.youtube.com/watch?v=EPG8ELV_9o)

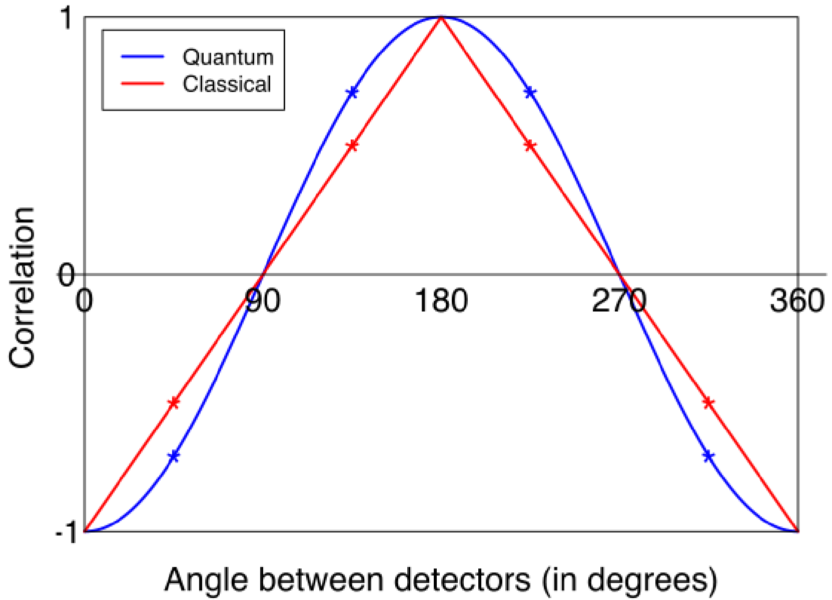
Quantum Entanglement

- Arises in correlated multiparticle states
- The state of any particle cannot be described independently of the state of the other particles

$$|\Psi\rangle = \frac{|\downarrow\uparrow\rangle - |\uparrow\downarrow\rangle}{\sqrt{2}}$$

Quantum Mechanical Violation of CHSH

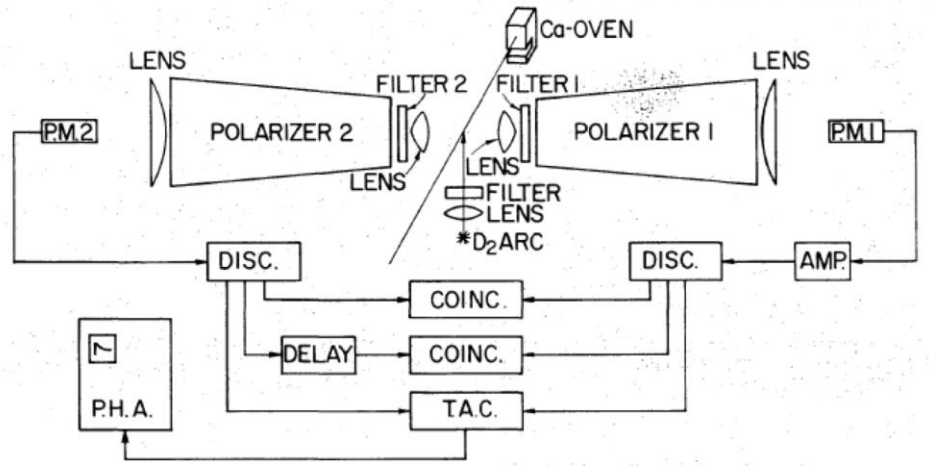
- Our favorite physicists Alice and Bob make spin measurements at two detectors
- Alice rotates her detectors 135 degrees with respect to Bob's
- Then the expectation value for the correlation ends up $2\sqrt{2}$



Measuring incompatible observables of entangled particles

Chien Shiung-Wu (1949): Orthogonal polarizations of photons from pair annihilations

Clauser, Freedman (1972): Polarization measurements along perpendicular axes violate CHSH



Clauser and Freedman's experiment

Image from "Scientific Background on the Nobel Prize in Physics 2022"

Delayed choice of measured observable

Alain Aspect (1982)

C_1, C_2 switched every 10 ns

Switches 12 m apart

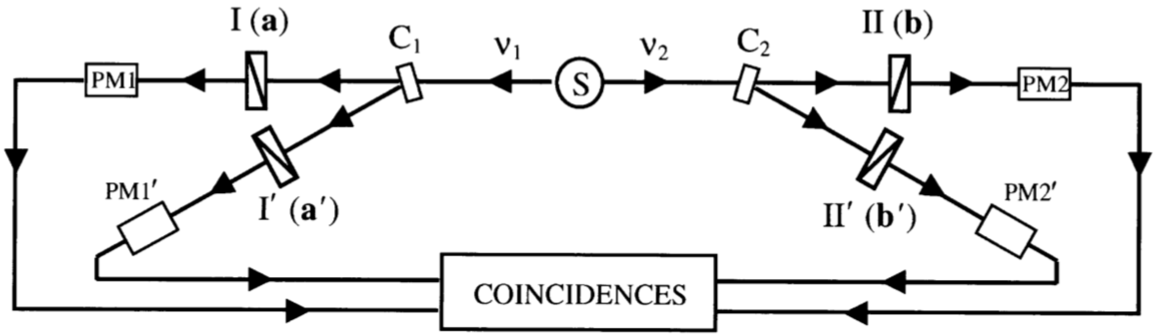


Image from "Bell's Theorem: The Naive View of an Experimentalist," A. Aspect (2002).

Randomizing measured observable

Anton Zeilinger (1998)

Separation of 400 m (1.3 us)

Randomized control of EOM

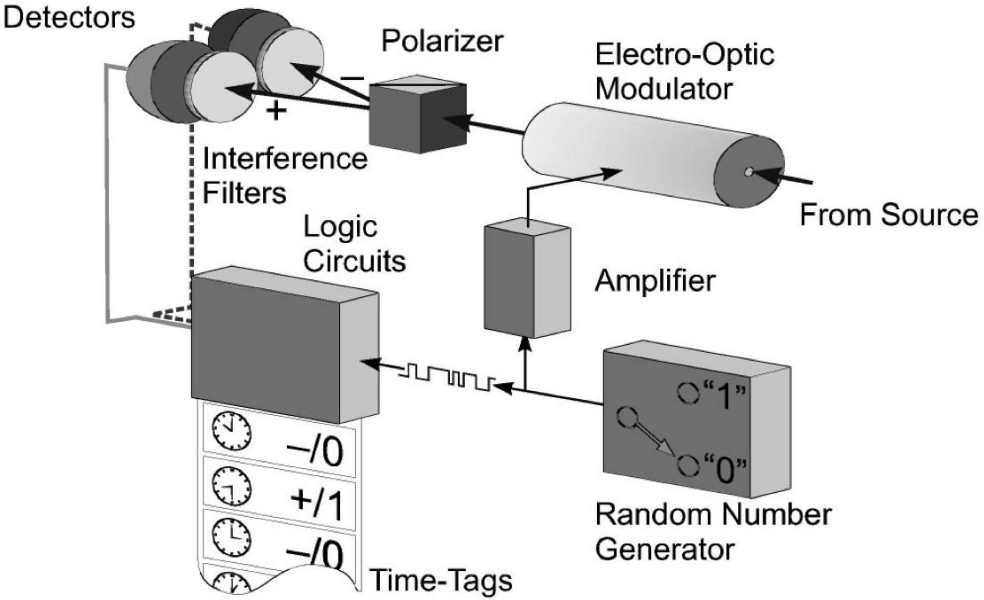
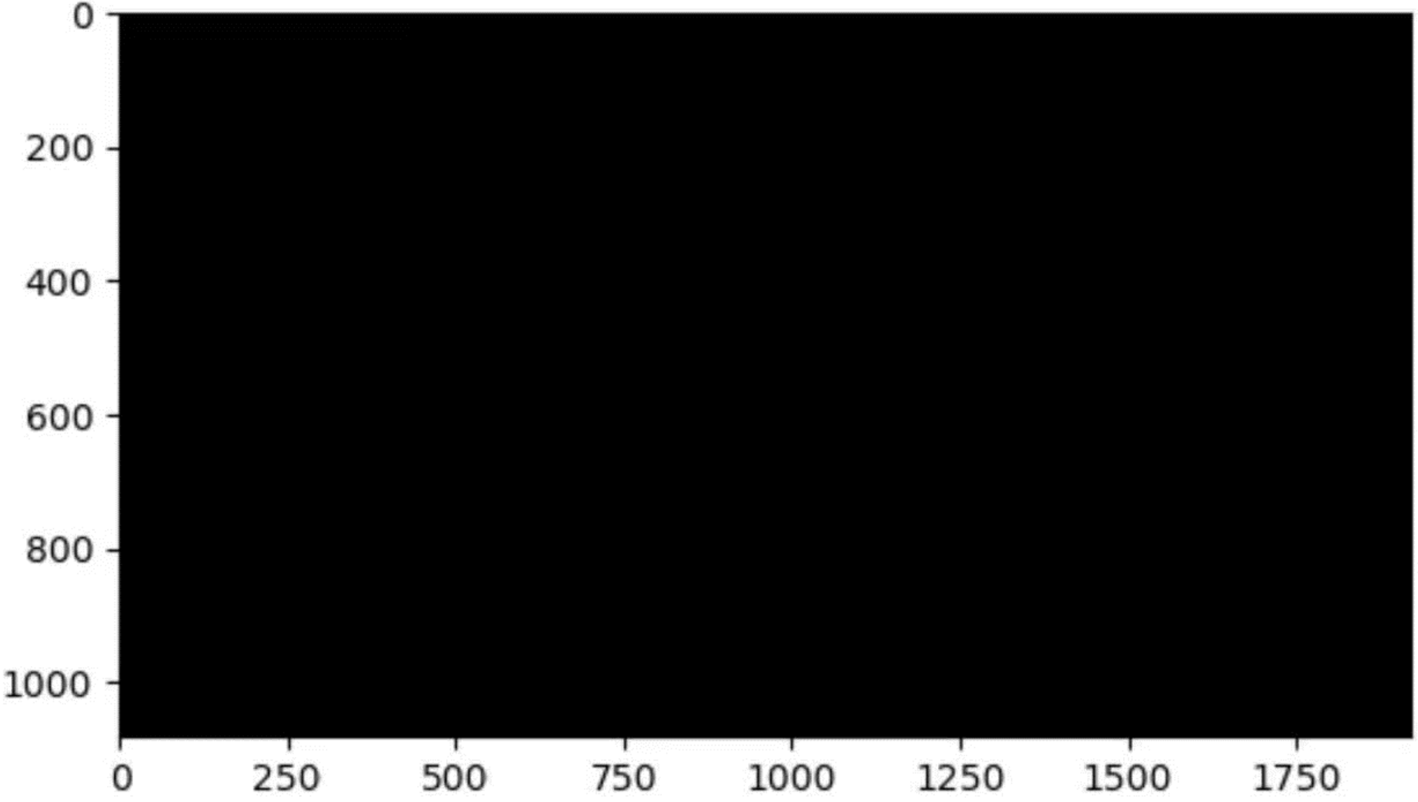
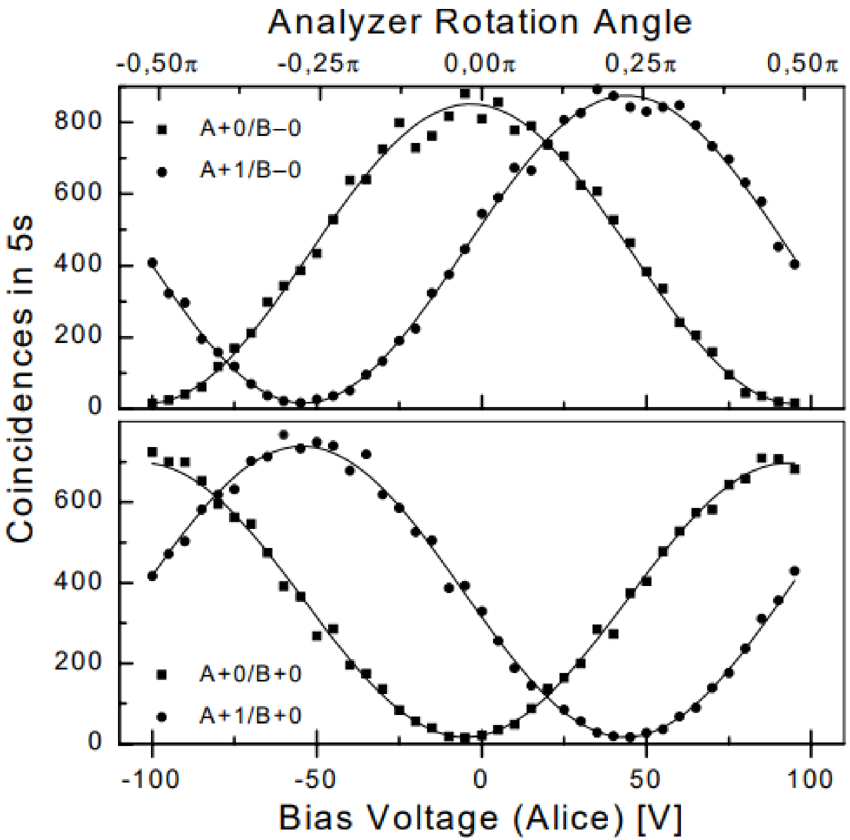


Image from Weihs (1998).


0
200
400
600
800
1000
0
250
500
750
1000
1250
1500
1750

Results



Analyzer Rotation Angle
-0,50π
-0,25π
0,00π
0,25π
0,50π
Coincidences in 5s
800
600
400
200
0
A+0/B−0
A+1/B−0
600
400
200
0
A+0/B+0
A+1/B+0
-100
-50
0
50
100
Bias Voltage (Alice) [V]

Conclusions

- Predicted quantum correlation S:

  $S = 2.74$
- $S(0°, 45°, 22.5°, 67.5°) = 2.73 \pm 0.02$
- $\approxeq$1 in 10^{202} probability of happening by chance
- Removes loophole of having predictable detector settings
- Second loophole remains: only 5% of photons were detected

Little doubt that inequality is violated, but what does this mean?

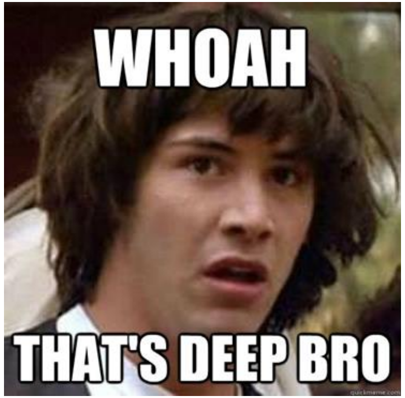
Conclusions

$$E(a,b) = \int \underline{A}(a,\lambda)\underline{B}(b,\lambda)\rho(\lambda)d\lambda$$

At least one of the assumptions must be wrong

- Inequality assumes that A and B don't depend on each other's settings (locality)
- Assumes A and B exist/are defined *before* measurement (realism)

- "A shift of our classical philosophical positions seems necessary"
  - Non-locality (info can travel faster than light)
  - Physical quantities not defined without measurement
  - Remaining loophole

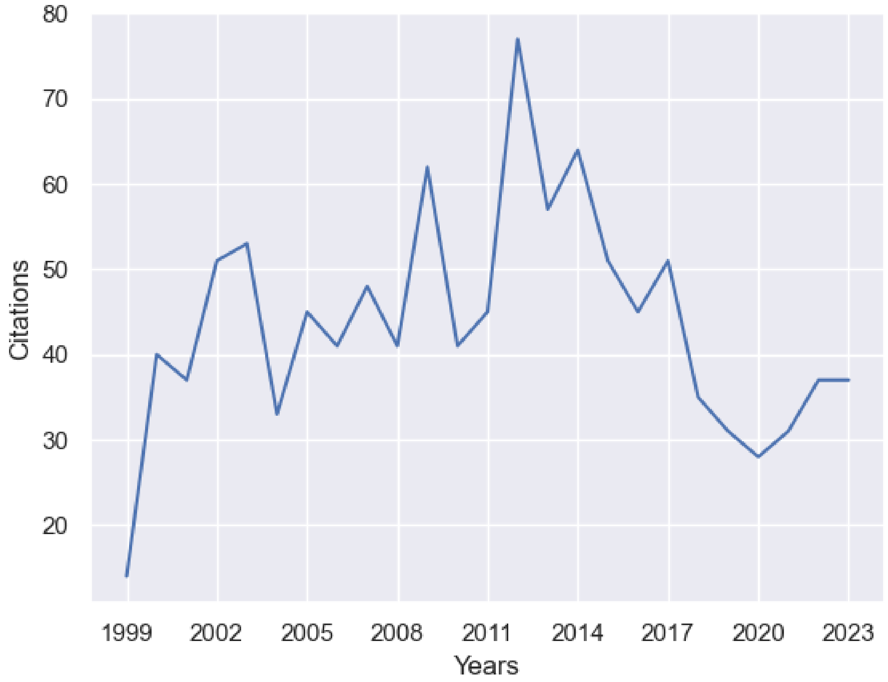


Critique

- Extremely dense
- Figure x-axis not explained
- Didn’t even close all the loopholes

Citation Summary

- Cited 1095 times according to Scopus
  - With FWCI of 12.95
- 2237 times according to Google Scholar



Evolution of Field

- Nobel Prize
- Detection efficiency of only 5% could be improved: these results could be an unrepresentative sample (detection loophole)
- Subsequent experiments closed this loophole.

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Loophole-free Bell inequality violation with superconducting circuits

References and further reading

Weihs, Gregor; Jennewein, Thomas; Simon, Christoph; Weinfurter, Harald; Zeilinger, Anton. *Violation of Bell's Inequality under Strict Einstein Locality Conditions*. Phys. Rev. Lett., vol. 81, no. 23, pp. 5039–5043, Dec 1998. DOI: 10.1103/PhysRevLett.81.5039

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