\[ |\Psi\rangle = \frac{1}{\sqrt{2}} (|TT\rangle - |TL\rangle) \]

**Entangled States: A Special Seminar on This Year’s Nobel Prize in Physics**

Profs. Chatzakis, DeGottardi, and Kim
Entangled States: A Special Seminar on This Year’s Nobel Prize in Physics

Friday, Nov. 4, 2022

Ioannis Chatzakis
Wade DeGottardi
Myoung-Hwan Kim
Bill Poirer
The Nobel Prize in Physics 2022

“for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science”
• In a famous paper, Einstein, Podolsky, and Rosen (EPR) asked whether quantum mechanics is complete.

• According to the Heisenberg uncertainty principle, the more precisely we know position, the more uncertain the momentum of the object becomes.

• EPR asked whether quantum mechanics is incomplete.

“God doesn’t play dice.”
Implications of Local Realism

\[ s_1^x s_2^y s_3^y = -1 \]
\[ s_1^y s_2^x s_3^y = -1 \]
\[ s_1^y s_2^y s_3^y = -1 \]

Implications of Local Realism

\[ s_x^x s_y^y s_z^y = -1 \]
\[ s_x^y s_x^x s_z^y = -1 \]
\[ s_x^y s_y^y s_z^y = -1 \]
\[ s_x^x s_y^x s_z^x = -1 \]

Local Realism Meets Quantum Mechanics

\[ |\Psi_{\text{GHZ}}\rangle = \frac{1}{\sqrt{2}} (|\uparrow\uparrow\uparrow\rangle + |\downarrow\downarrow\downarrow\rangle) \]

\[ \langle \sigma_1^x \sigma_2^y \sigma_3^y \rangle = -1 \]

\[ \langle \sigma_1^y \sigma_2^x \sigma_3^y \rangle = -1 \]

\[ \langle \sigma_1^y \sigma_2^y \sigma_3^x \rangle = -1 \]

Local Realism Meets Quantum Mechanics

\[ |\Psi_{\text{GHZ}}\rangle = \frac{1}{\sqrt{2}} (|\uparrow\uparrow\uparrow\rangle + |\downarrow\downarrow\downarrow\rangle) \]

\[ \langle \sigma_x^1 \sigma_x^2 \sigma_x^3 \rangle = 1 \]

\[ \langle \sigma_y^1 \sigma_x^2 \sigma_y^3 \rangle = -1 \]

\[ \langle \sigma_y^1 \sigma_y^2 \sigma_x^3 \rangle = -1 \]

Bell’s Inequality

- In a landmark paper, Bell showed that any theory that is both *local* and *real* must obey certain constraints.
- Bell’s original equality wasn’t testable and made some unrealistic assumptions. Clauser *et al.* corrected this to derive the CHSH inequality.

\[
\langle S \rangle = |E(A_1, B_1) + E(A_1, B_2) + E(A_2, B_1) - E(A_2, B_2)| < 2,
\]


**John Clauser** used calcium atoms that could emit entangled photons after he had illuminated them with a special light. He set up a filter on either side to measure the photons’ polarisation. After a series of measurements, he was able to show they violated a Bell inequality.

©Johan Jarnestad/The Royal Swedish Academy of Sciences
Decay transitions in Ca
First Experimental Test of Bell’s Inequality

from Freedman’s thesis, Berkeley (1972)
First Experimental Test of Bell’s Inequality

from Freedman’s thesis, Berkeley (1972)

\[ \left| \frac{R(22\frac{1}{2}^0)}{R_0} - \frac{R(67\frac{1}{2}^0)}{R_0} \right| - \frac{1}{4} \leq 0, \]
Closing Some Loopholes

Alain Aspect developed this experiment, using a new way of exciting the atoms so they emitted entangled photons at a higher rate. He could also switch between different settings, so the system would not contain any advance information that could affect the results.

©Johan Jarnestad/The Royal Swedish Academy of Sciences
Decisive Experiment

Anton Zeilinger later conducted more tests of Bell inequalities. He created entangled pairs of photons by shining a laser on a special crystal, and used random numbers to shift between measurement settings. One experiment used signals from distant galaxies to control the filters and ensure the signals could not affect each other.
The first classic example of a two-particle entangled state was suggested by Einstein, Podolsky, and Rosen.
A classic example of an entangled two-particle system, is a singlet state of two spin 1/2 particles

\[ |\Psi\rangle = \frac{1}{\sqrt{2}} [ |\uparrow\rangle_1 |\downarrow\rangle_2 - |\downarrow\rangle_1 |\uparrow\rangle_2 ] \]

where the kets represent states of:

spin “up”  \[ |\uparrow\rangle \]

spin “down,”  \[ |\downarrow\rangle \]

along an *arbitrary* direction.

For this state, the spin for neither particle is determined; however, if one particle is measured to be spin up along a certain direction, the other one must be spin down along that direction, despite the distance between the two spin 1/2 particles.
Entangled photon pairs generated via spontaneous parametric down conversion (SPDC)

The most widely used entangled two-particle states might have been the “Bell states” (or EPR–Bohm–Bell states).

\[ |\psi_{12}^\pm \rangle = \frac{1}{\sqrt{2}} \{ |H_1 H_2 \rangle \pm |V_1 V_2 \rangle \} \]

\[ |\psi_{12}^\pm \rangle = \frac{1}{\sqrt{2}} \{ |H_1 V_2 \rangle \pm |V_1 H_2 \rangle \} \]
An entangler EPR state is a signal-idler photon pair of spontaneous parametric down conversion (SPDC).

The nonlinear interaction of a laser beams with a crystal e.g. BBO leads to the annihilation of a high frequency pump photon and the simultaneous creation of two lower frequency photons which satisfy the energy and momentum conservation:

\[ \omega_p = \omega_s + \omega_i \]
\[ \mathbf{k}_p = \mathbf{k}_s + \mathbf{k}_i \]

Conservation of Energy

Conservation of Momentum

Incident photon

Daughter photons
Two-Photon State of Spontaneous Parametric Down Conversion (SPDC) Entangled Photons

Energy conservation

Momentum conservation

Energy conservation

Momentum conservation
The Three Types of SPDC Setups

(a) Type-I (The polarization of the Signal and Idler are the same and perpendicular to the pump polarization)
(b) Collinear degenerate type-II SPDC. The polarization of the Signal and Idler are the perpendicular to each other. Two rings overlap at one region
(c) Noncollinear degenerate type-II SPDC. Two degenerate rings overlap at two regions. For clarity, only two rings, one for e-polarization and the other for o-polarization, are shown.
The BBO crystal through SPDC generates the Entangled state

\[ |\psi_{12}^\pm\rangle = \frac{1}{\sqrt{2}} \{ |H_1 H_2\rangle \pm |V_1 V_2\rangle \} \]

\[ |\psi_{12}^\pm\rangle = \frac{1}{\sqrt{2}} \{ |H_1 V_2\rangle \pm |V_1 H_2\rangle \} \]
Photon-based quantum computer does a calculation that ordinary computers might never be able to do.

A section of the light-based quantum computer at the University of Science and Technology of China. [Photo/Xinhua] This photonic computer did a task that would take a classical computer 2.5 billion years. Pan and colleagues could find solutions to the boson-sampling problem in 200 seconds.
Cyber Security
For the rest of my life I want to reflect on what light is.
- Albert Einstein (1917)

Ref) NIST News 2022 “An Entangled Matter-Wave Interferometer: Now With Double the Spookiness!”
Quantum Teleportation

Ref) NPR All Tech Considered (July 29, 2015) “Beam Me Up? Teleporting Is Real, Even If Trekkie Transport Isn’t”
Quantum Teleportation Experiment

Ref) Scientific Background on the Nobel Prize in Physics 2022
Entanglement Swapping – a blockbuster application

Quantum Teleportation test over 143 km free-space channels

Island of Tenerife

La Palma
Entanglement Swapping with one source

Quantum Teleportation over 143 km free-space channels

Entanglement Swapping with two different sources

Incoherent holography with entanglement

Ref) OXFORD Instrument Andor news (May 2021)
“Modern physics is rife with provocative and fascinating ideas, from quantum mechanics to the multiverse…This book, written with deft hands by true experts in the field, helps to illuminate some of the most important and game-changing ideas in physics today.”
—Sean Carroll, Cal Tech Physics Professor, Preposterous Universe blog, NY Times Opinion Writer.

“This book stands above others in its genre of physics books for laypeople. The subtitle promises that commonly held fallacies about popular topics in physics will be clarified. … Topics covered include basic quantum mechanics, relativity theory, and particle physics. … Highly recommended. All levels/libraries.”

“This book explains and debunks misconceptions about quantum physics, particle physics, space-time, and Multiverse, separating science from pseudoscience.”

“I found Poirier to be a very lucid writer about difficult topics. He sticks to conceptual terms, and I think he succeeds pretty impressively.”

“Poirier nicely set up the punchline about the misconception that the quantum wave refers to individual particles.”

“Overall, I’m certainly glad I read the book, especially [Poirier’s] section, as it addressed the kind of misconceptions I was most concerned about.”
Classical EPRB Experiment

*Explained as a game of “Coin Toss”*

In the next run, the machine creates two American nickels, facing tails up. The lower two bulbs will now flash.

https://www.mvjs.org/
Thank you for Participating!

- Special Thanks:
  - Sabrina DeBreau
  - Lavonne Mack
  - Victor Bradley
  - Katrina Webb
  - Cristobal Moreno
  - Alex Droemer
  - Sung-Won Lee
  - Clive Binu

This Photo by Unknown Author is licensed under CC BY-SA