S3 Journal Club

Paper: Can Quantum-Mechanical Description of Physical Reality Be Consider Complete? (EPR Paradox)

Authors: A. Einstein, B. Podolsky, N Rosen (1935)

Link: https://cds.cern.ch/record/405662/files/PhysRev.47.777.pdf

Quantum Mechanics in One Slide

- How it works
  - At small scales, we only have probabilities.
  - States: A system in superposition
    - Described by a wave function $|\Psi\rangle$
  - Some quantities can’t be simultaneously be known
    - This is weird!

Copenhagen Interpretation

- Copenhagen Interpretation originated in ~1927
  - Complementarity: Your experiment decides what property you observe
  - Collapse: Observation yields a probabilistic outcome
  - After observation, the state is fixed

- EPR Motivation:
  - The Copenhagen Interpretation is unsettling

Historical Context

- 1935 – Quantum Mechanics is very successful
  - Blackbody Radiation Law (Planck)
  - Photoelectric Effect (Einstein)
  - Pauli Exclusion Principle → Periodic Table
  - Dirac Equation → Electron Spin

EPR Key Definitions

- Completeness
  - Every element of physical reality must have a counterpart in the physical theory
    - If something is there, a complete theory represents it
- Reality Criterion
  - If we can predict (before measuring/disturbing system) with certainty, the value of a physical quantity, there is something in physical reality that corresponds to this quantity.

Implicit Assumptions EPR needs

- Locality
  - Measurements cannot instantaneously influence physical reality
- Separability
  - A system can consist of parts with their own properties
- Freedom of choice
  - The choice to measure X isn’t influenced by some Y

What does EPR argue?

- Requirement for a “complete” physical theory:
  - *“… every element of the physical reality must have a counterpart in the physical theory.”*

- Central Thesis: Quantum mechanics is not “complete”

The EPR Paradox

- Entangle two photons
  - One is spin up → Other is spin down
- Separate these photons by a light year
  - Measure one (50% chance spin up/down)
  - Measure other 1s later (100% chance spin down/up)

- EPR: The states of the photons must have been pre-determined

Concrete Examples

- Introduce Alice and Bob
  - Get to the Bell State (EPR pair)

- $[x, p] = i\hbar$

Bell's Theorem

- 1964 – Bell proves local hidden-variable theories obey inequalities
  - Experiment rules out local hidden-variable explanations

- CHSH Value:
  - Assume Local Realism $S \leq 2$
  - Quantum Mechanics: $S \leq 2\sqrt{2}$
  - Experiment: $S \leq 2\sqrt{2}$

Modern Perspectives

- Entanglement (Weird, but useful!)
  - Quantum Teleportation
  - Entanglement Entropy

- No-Signaling Theorem: Information can’t travel faster than light
  - Relativity is safe

Discussion