Interpretation of Quantum Mechanics

Copenhagen, Dynamical Collapse and Many World Interpretation

December 5, 2024

Big Question

- What does quantum mechanics reveal about reality?
- Important Context
  - No consensus among physicists.
  - Understanding these interpretations has influenced breakthroughs (e.g., Bell inequality, quantum computing).

The Measurement Problem

- What’s the issue? Measurement in quantum mechanics introduces a fundamental weirdness:
- Unitary Evolution
  - Deterministic, reversible, continuous.
  - Describes quantum states when "no one is watching."
- Measurement
  - Probabilistic, irreversible, sudden.
  - Collapses a quantum state to a single outcome.
- The Core Question "How does the universe know when to switch between unitary evolution and measurement?”

Key Features of the Debate

- The Measurement Problem is central to understanding QM.
- Measurement treated as a primitive operation in physics texts, but deeper questions remain unanswered.
- Comparison to Philosophy
  - Like debates on consciousness:
    - Longstanding discussions.
    - Often circular arguments.
- Why Care?
  - Different interpretations shape our understanding of quantum mechanics and inspire scientific progress.

Preview of Interpretations

- Copenhagen Interpretation
  - Traditional and widely taught.
- Dynamical Collapse Theories
  - Introduce mechanisms for state collapse.
- Many-Worlds Interpretation (MWI)
  - Every possibility happens in a branching universe.
- Decoherence
  - Explains the transition from quantum to classical behavior.
- Next, we'll dive deeper into each school of thought!

The Copenhagen Interpretation

- Overview
  - Preferred by early quantum mechanics pioneers.
  - Closely associated with Niels Bohr (Copenhagen Institute) and Werner Heisenberg.
- Challenge
  - Difficult to define clearly due to varied, sometimes contradictory statements by its founders.

Two Worlds

- Quantum World
  - Objects follow non-intuitive, probabilistic rules.
  - Behaviors differ drastically from our everyday experience.
- Classical World
  - Where we live: objects have definite locations, measurements don’t disturb them.
- Measurement
  - Acts as a bridge between the quantum and classical worlds.
  - Enables us to glimpse the quantum world “beneath” the classical.

The Quantum-Classical Boundary

- A “boundary” or “cut” separates the quantum and classical realms.
- Location of this boundary:
  - Fuzzy and context-dependent.
  - Shaped by the nature of the measurement or question asked.
- Key Idea: Classical concepts may break down when applied to the quantum world.

Philosophical Takeaways

- Niels Bohr emphasized that even discussing the quantum world assumes the existence of the classical world.
- Advocates argue:
    - If the Copenhagen interpretation seems nonsensical, the issue lies with your classical intuition—not quantum mechanics.

S.U.A.C. - “Shut Up And Calculate!”

- What is S.U.A.C.?
  - The most practical "interpretation" of quantum mechanics.
  - Preferred by many physicists and chemists.
- Core Idea
  - Quantum mechanics works—it predicts experimental results accurately.
  - Asking for more might be unnecessary or unproductive.

S.U.A.C. vs. Copenhagen Interpretation

- S.U.A.C.:
  - Avoids philosophy, focusing purely on calculations and results.
- Copenhagen:
  - Shares the intuition that philosophizing is pointless.
  - Ironically, elevates this idea into a philosophical stance!

The Limits of S.U.A.C.

- Why It May Not Satisfy Forever
- Human Curiosity
  - Science seeks to understand what the world is really like.
  - Experiment and prediction are tools, not the ultimate goal.
- Quantum Superpositions
  - Experiments increasingly breach the boundary between quantum and classical worlds.
  - Quantum mechanics increasingly affects everyday experiences.
- Key Question: Can we continue treating quantum mechanics as "just a tool" as it encroaches on classical phenomena?

Thought Experiments

- To explore this boundary further, two famous thought experiments were developed:
  - Schrödinger’s Cat
  - Wigner’s Friend
- Purpose: These scenarios test the implications of quantum mechanics and its "breach" into the classical realm.

Dynamical Collapse: Revisiting Quantum Mechanics

- Why Consider Dynamical Collapse?
  - Quantum mechanics may be incomplete.
  - Suggests new physics:
    - Collapse occurs due to undiscovered rules.
    - Larger or more complex systems are more likely to collapse.
- Example: In Schrödinger's cat experiment, collapse could occur even in an isolated box due to these new rules.

Proposals for Collapse Criteria

- What Triggers Collapse?
  - Number of atoms involved.
  - Reaching a certain mass.
  - Achieving a specific level of complexity.
- Challenge
  - Contradicts reductionism: Each atom follows simple equations, regardless of the system's size.

Theories of Dynamical Collapse

- Ghirardi-Rimini-Weber (GRW) Theory
  - Each atom has a tiny probability of collapsing.
  - Collapse of one atom can propagate to collapse an entire system.
- Penrose Theory
  - Collapse occurs when mass in superposition creates vastly different spacetime curvatures.
  - Suggests a link between quantum mechanics and general relativity.

Testing Dynamical Collapse

- Larger systems are being tested in superposition:
  - Double-slit experiments with buckyballs (60 atoms).
  - Superconducting qubits involving billions of particles.
- Implications
  - GRW adjusts predictions to match experiments.
  - Penrose predicts collapse thresholds that could be testable soon.

Many Worlds Interpretation (MWI)

- Core Idea
  - The universe doesn’t collapse; it branches into multiple possibilities.
  - Measurement is entanglement:
    - Your brain, apparatus, and environment entangle with the quantum system.
- Implication
  - Both branches of reality (e.g., "alive cat" and "dead cat") are equally real.

MWI and Probability

- Born Rule Challenge
  - Why do probabilities match $|\alpha|$^2 and $|\beta|$^2?
  - Everett argues that branching aligns with the Born rule, but some call this circular reasoning.
- Modern View
  - Probability may be inherent in quantum mechanics' mathematical structure.

Copenhagen vs. MWI

- Criticism of Copenhagen
  - Struggles to explain observers in superposition (e.g., "observer through slits").
- MWI's Strength
  - Consistent with experiments showing superpositions in increasingly large systems.

Preferred Basis Problem

- What Basis Does Branching Occur In?
  - Why not decompose states in any basis?
- Decoherence Theory
  - Certain bases are robust to environmental interactions.
  - Events become “definite” when widely recorded and irreversibly distributed (like viral social media posts).

Final Thoughts on Collapse and Branching

- Dynamical Collapse introduces testable new physics.
- Many Worlds offers a deterministic view but raises foundational questions about probability and reality.
- Both interpretations push the boundaries of our understanding of quantum mechanics.
- Next Steps: Explore further thought experiments and technologies to probe these theories!