Interpretations of quantum mechanics—an overview

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Physics 43
Santa Rosa Junior College

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Many different interpretations

- The Copenhagen Interpretation
- Many Worlds
- Consistent Histories
- Von Neumann-Wigner
- Instrumentalism
- Ensemble, or statistical interpretation
- De Broglie-Bohm theory
- Relational quantum mechanics
- Transactional interpretation
- Stochastic mechanics
- Objective Collapse theories
- Many Minds
- Quantum Logic
- Modal interpretations of quantum theory
Schrödinger Equation

\[ i\hbar \frac{\partial}{\partial t} \Psi(r, t) = \left[ \frac{-\hbar^2}{2m} \nabla^2 + V(r, t) \right] \Psi(r, t) \]

- Linear partial differential equation
- Describes the quantum state of a particle and how it changes with time
- The equation is a quantum analog to Newton’s second law of motion
- Describes the wave state, or quantum state of the system
Wavefunction collapse

- Wavefunction describes only probabilities that certain things will be measured.
- When a measurement is made, however, one of the possibilities will become 100% probable, and at that moment the wavefunction seems to “collapse” instantly into this reduced state describing only the one 100% probable possibility.
- Is there really an instantaneous collapse?
- What exactly is a measurement? Does it need to involve someone to observe the results of the measurement?
- Is the wavefunction real, or does it just reflect our own incomplete knowledge of the world?
- If it is real, what does it mean that measurement causes a discontinuous change in reality?
• Wave function $\Psi$ describes a system of one or more of its particles, and contains all information about it.

• Wave function gave rise to wave-particle duality.
Hydrogen Wave Function

Probability density plots.

$$\psi_{nm}(r, \theta, \varphi) = \sqrt{\frac{2}{n \alpha_0}} \frac{(n - l - 1)!}{2n[(n + l)l]!} e^{-\rho/\rho} \rho^l L_{n-l-1}^l(\rho) \cdot Y_{nl}(\theta, \varphi)$$
Superposition: double-slit experiment

- If a double-slit experiment is set up such that one particle, say an electron, is fired at a time, and no attempt is made to determine which slit it passes through, an interference pattern will still emerge.

- This suggests that each electron passed through both slits to interfere with itself. This further suggests that before wavefunction collapse (or whatever actually happens), a system exists partly in all its possible states.
Quantum entanglement

- If two particles interact in such a way that they are in a singlet state—i.e., if you know the state of one, you know the state of the other—they are said to be entangled.

- When one is measured then, no matter how far apart they are, the state of each is instantaneously determined.

- Since, before the measurement, neither has a determined state but is in a superposition of possible states, and the two particles can be separated by an arbitrary distance, this suggests that some faster-than-light communication takes place between the two. In quantum jargon, this means nonlocality.

- Einstein didn't like this nonlocality. He called it “spooky action at a distance”, and in fact he and two others originally predicted this phenomenon—which has been observed many times experimentally—to try and point out how ridiculous the implications of quantum mechanics were.
The Copenhagen Interpretation

- Made by Bohr and Heisenberg in Copenhagen in the 1920s
- Mainstream interpretation
- Some might call it nonlocal
- Nondeterministic
- Wavefunction is not real
- Wavefunction collapse upon measurement
Many Worlds Interpretation

- Also known as
  - Relative state formulation
  - Everett Interpretation
  - Theory of the universal wave function
  - Many universes interpretation

- Considered a mainstream interpretation

- Unlike many interpretations, it denies the reality of wavefunction collapse.

- Problem with this interpretation: without the wave collapse postulate, the interpretation violates physical laws
Many Worlds: Main assertions

- Implies all alternate histories and futures are real
  - Each possible reality represents a different world, or universe
  - Implies there are an infinite number of concurrent universes
  - Everything that could have happened in history but did not happen in another universe, and everything that will not happen in the future of this universe will happen in another.
Superposition: Schrödinger's cat

- Schrödinger's cat: a thought experiment devised by Erwin Schrödinger in the 1930s in which a cat is in a box with a closed vial of poison. A random quantum event will trigger the release of the poison, killing the cat, such that it's a 50/50 chance that the cat is either alive or dead upon opening the box.

- Does this mean, by the same superposition evident in the double-slit experiment, that the cat is both alive and dead?
Superposition: seeing the cat dead and alive at the same time

- Experiments have been performed—and the 2012 Nobel Prize in Physics was awarded for them—in which the two superposed states of an atom were physically separated.
- In other words, the atom was in two places at once.
- (superposition—the ability to be in more than one state simultaneously—is the basis of quantum computing)
Schrödinger's Cat

Copenhagen vs Many Worlds

- **Copenhagen**
  - Until measured, there is a superposition of states where the cat is both dead and alive simultaneously.
  - Sometime before or when the box is opened, the wave function collapses into one of the two states.

- **Many Worlds**
  - The act of measurement does not collapse the wave function.
  - When the box is opened, the cat can be dead and alive simultaneously. These two states are decoherent, so there is no communication or interaction between these two quantum states.
Quantum Decoherence

- Mathematically, it is a loss of order between phase angles of two wave functions.
- This loss of order gives the false illusion of wave collapse.
- Events proceed in thermodynamically irreversible ways.
- Wave functions are prevented from interfering or interacting with each other.
Quantum decoherence: an attempt to explain why we don't see the cat dead and alive at the same time

- Not going to lie, don't understand it very well myself
- The basic idea seems to be this: real world quantum systems don't exist in isolation but interact with their environment. Each possible state interacts with the environment in a different way, and in this way they become too different to be superposed with each other. In other words, with the additional differences resulting from interacting with the environment in different ways, they become too different to both be at the same time and instead it becomes either one or the other. In still other words, in so interacting with the environment, the system expands outwards and perhaps in the bigger picture there is a superposition of larger states, but it's too big for us to notice.
- Or something like that.
Consistent Histories

- Similar but not identical to Many Worlds
- History is a method of measuring reality, not alternate realities produced by quantum decoherence
- Irreversible macroscopic events produced by quantum decoherence, those measured by classical physics, render histories automatically consistent.
- When a quantum event happens, one wavefunction becomes reality while the other becomes an alternate reality. The real state joins the history of our world’s real events.
- It is not possible to predict which paths will become reality
The Von Neumann-Wigner interpretation

- John Von Neumann in 1930s, Eugene Wigner in 1960s
- Like in the Copenhagen interpretation, measurement causes collapse
- Consciousness necessary for measurement process
- My own personal interpretation of the interpretations: The Copenhagen Interpretation reduces to the Von Neumann-Wigner interpretation when certain things are specified that are left vague in the general Copenhagen Interpretation. For example, the Copenhagen Interpretation generally does not seem to specify what is meant by “measurement”, while the Von Neumann-Wigner interpretation specifies measurement means conscious observation.
Wigner's friend thought experiment

- Wigner leaves his friend alone in a lab to perform the Schrödinger's cat experiment. His friend will be sad if the cat is found to be dead and happy if the cat is found to be alive. Wigner does not know if his friend is happy or sad until he returns to the lab. Is his friend therefore both sad *and* happy until observed?
Wigner believed his friend must be either sad or happy. If a physical measuring device had been left to see if the cat was dead or alive instead of a conscious observer, then indeed the cat/device system would have been a superposition of two states until Wigner returned. However since a conscious being cannot be in a superposition of two states, wavefunction collapse must have been triggered by Wigner's friend's seeing if the cat was alive or dead. From that point forward and until Wigner returned, that Wigner didn't know if his friend was happy or sad and the cat dead or alive represented not that there was no definite answer to that question yet, but that he simply didn't know what that definite answer was.
The Von Neumann-Wigner interpretation continued

- In positing that the measurement that collapses the wavefunction must include consciousness and that conscious beings cannot be in a superposition of states, this interpretation says that consciousness is unlike other physical processes.
Instrumentalism

- An approach to quantum mechanics in which one does not try to interpret what it all means, but uses it because it's useful.
- Treats concepts and theories as instruments and assigns value based on effectiveness to make predictions based on observational data
- Un-asks the question of how the concepts and theories relate to objective reality.
“The most embarrassing graph in modern Physics”?

And/or, exciting as to how much it implies there is to imagine and discover?

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<th>Question 12: What is your favorite interpretation of quantum mechanics?</th>
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<td>a. Consistent histories:</td>
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<td>b. Copenhagen:</td>
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<td>c. De Broglie–Bohm:</td>
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<td>d. Everett (many worlds and/or many minds):</td>
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<td>e. Information-based/information-theoretical:</td>
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<td>g. Objective collapse (e.g., GRW, Penrose):</td>
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<td>i. Relational quantum mechanics:</td>
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percent of votes

0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%
Depends on your interpretation!
References

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