Interpretations of Quantum Theory

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What needs to be interpreted?

- We don't need to "interpret" (for example) Newton's 2nd law

$$\textit{acceleration} = \textit{force}/\textit{mass}$$

- What's different about Schrödinger's equation, the equivalent in quantum mechanics?

$$i\hbar \frac{\partial}{\partial t}\psi(t) = \hat{H}\psi(t)$$

One difference is that we intuitively understand what *acceleration, force,* and *mass* are. These are things that we all agree actually exist in the real world. We can locate them, measure them and so on.

When it comes to the main player in Schrödinger's equation, ψ, there is no general agreement on what it really is. We can't measure it in any direct way. We can't even say that it's located in some specific place.

And, there are other issues ...

The main issues

- The ontological status of the wave function

  What is ψ?

- The locality debate

  Does quantum theory imply reality has some kind of non-local aspect.

- The measurement problem

  The measurement postulate appears to contradict the rest of the theory.

Some interpretations

- The Textbook Interpretation
- the “No Interpretation” Interpretation
- The Copenhagen Interpretation
- Everett
- The Pilot Wave Interpretation (de Broglie / Bohm)
- The Transactional Interpretation (Cramer / Kastner)
- Wave function collapse theories

The Textbook Interpretation

The wave function evolves according to Schrödinger's equation until a measurement happens. Then the wave function collapses into one of its basis states.

Q: What *exactly* distinguishes a measurement from other interactions?

A: You'll know one when you see it.

Q: So ψ real, or just a mathematical construction?

A: This is a physics textbook, not a philosophy book.

No Interpretation

We have a mathematical model, and we know how to use that model to predict the results of observations that we make in the real world. That's what a scientific theory consists of, and to ask for more is reaching beyond the realm of science.

You may think that quantum theory is "strange" or that it raises questions that don't come up in classical physics. But that's simply because your intuitions about how things "should" be is conditioned by the fact that you evolved as a macroscopic organism and not at the scale where quantum effects predominate.

Note: I believe that Sidney Coleman, in his famous "Quantum Mechanics in Your Face" lecture, may be taking this position. (See the references section.)

The Copenhagen Interpretation

Often, the way quantum mechanics is discussed in a typical textbook is called the "Copenhagen interpretation." I don't believe this is correct. First of all, Niels Bohr (the main guy in Copenhagen) appeared to take a more-or-less positivist approach. Perhaps not unlike what I'm calling the "no interpretation."

Secondly, there was no real consensus on the philosophy of quantum mechanics among the other physicists associated with the Copenhagen group, such as Werner Heisenberg, Wolfgang Pauli, and others. They all had their own points of view.

Just to be clear, the first three viewpoints we've considered (Textbook, No Interpretation, and Copenhagen) should not really be considered as "interpretations." They are, rather, heuristics for solving problems (in the textbook case) or philosophical positions which deny the *need for* an interpretation.

- The status of the wave function

  It seems to me that in Everett's approach ψ is a mathematical abstraction. But one which is fairly closely associated with the world, as it really exists. Perhaps making its interpretation more straightforward. Apparently some others disagree with this statement, saying that in Everett the world is "made out of" the wave function.

- Locality / Non-locality

  I don't believe Everett implies any sort of non-locality. I think it can be interpreted in a perfectly local way. Again, apparently not everyone agrees with this.

- The measurement problem

  This is the issue that Everett *clearly* addressed. A one line explanation of Everett's interpretation could simply be: **Delete the measurement postulate!**

  Everett has only unitary (linear) evolution ala Schrödinger's equation, and all the interactions implied by that. Nothing special happens when we do something that we call a measurement. We (and our instruments) simply interact with the systems we are observing, typically causing us to become entangled with them.

  Let's take a look at how this works ...

Mike flips a quantum coin: $|\text{Coin}\rangle \otimes |\text{Mike}\rangle$

- A textbook measurement

Before	After
$\frac{1}{\sqrt{2}}|\text{H}\rangle + \frac{1}{\sqrt{2}}|\text{T}\rangle \otimes |\text{What will it be?}\rangle$	Either: $|\text{H}\rangle \otimes |\text{I see Heads}\rangle$ Or: $|\text{T}\rangle \otimes |\text{I see Tails}\rangle$

- An Everett *interaction*

Before	After
$\frac{1}{\sqrt{2}}|\text{H}\rangle + \frac{1}{\sqrt{2}}|\text{T}\rangle \otimes |\text{What will it be?}\rangle$	$\frac{1}{\sqrt{2}}|\text{H}\rangle \otimes |\text{See heads}\rangle + \frac{1}{\sqrt{2}}|\text{T}\rangle \otimes |\text{See tails}\rangle$

Problems with Everett

- It's incoherent

  Some very smart people say this, or something close. I *think* what they are *really* saying is that they simply can't accept the physical reality of quantum superpositions. In order for Everett to make any sense, you need to believe that superpositions are not just mathematical tools for calculation, but that they reflect some aspect of reality.

- There's a problem with probabilities

  This comes in a number of different forms ...

- The basis ambiguity problem

  In my view, this is the *real* problem (or mystery :-) with Everett. Note that this is typically called the "preferred basis problem." I don't like that terminology because it pre-supposes that there *is* a preferred basis.

  (Try to verbalize a short description of this.)

The Pilot Wave Interpretation

- The status of the wave function

  The wave function (or at least a part of it) is a real, physical entity which exerts an influence on the paths of particles.

- Locality / Non-locality

  This interpretation has what some people have called "non-locality with a vengeance," with the pilot wave exhibiting explicit action at a distance.

- The measurement problem

  No problem here. In this interpretation we have real particles, with real positions and real trajectories. When we make an observation of the position of a particle, we simply see what that position actually is.

How the pilot wave works

Take the complex wave function $\psi(\vec{x}, t)$ from Schrödinger's equation. $\vec{x}$ is the position vector of a particle and t is time. Like any complex function ψ can be rewritten in exponential form as $\psi(\vec{x}, t) = Re^{iS}$, where R and S are both real functions, and S is the angle or phase in complex space.

Note: S is a function of position and time, $S = S(\vec{x}, t)$.

We then replace Newton's 2nd law $a = F/m$ with the formula $v = \nabla S/m$. So in other words the velocity of a particle is equal to the gradient of the phase of the wave function (divided by the particle's mass).

The fact that the velocity of the particle (rather than its acceleration) depends on the pilot wave is why we say the wave exerts an "influence" rather than a "force" on the particle. In fact, the trajectories of particles in the pilot wave interpretation look nothing like the way we picture the trajectories of particles in Newtonian dynamics.

Problems with the pilot wave

- Non-locality

  Some folks object to this interpretation simply because of the inherent non-locality, saying something along the lines of "it violates relativity." It's not clear how much force this objection has. Although pilot wave scenarios appear to go against the "spirit" of (say) special relativity, all the physically verifiable events are the same ones that you get with the standard theories and calculations.

- Special initial conditions

  In order to match the standard predictions of quantum theory, you need to assume special initial conditions for all the particles' positions and velocities (based on the Born rule).

- Extensibility to quantum field theory

  A more serious question arising out of the non-local nature of the pilot wave is the issue of whether it can be extended to work with quantum field theory. I'm really not sure what the status of this is.

The Transactional Interpretation

- Based on (or at least inspired by) the Wheeler and Feynman "time-symmetric" theory of emitters and absorbers (which I'm not really familiar with).
- There are forward-evolving waves ψ and backward-evolving waves ψ^*. These are real physical entities.
- A "handshake" needs to take place between the ψ and ψ^* in order for a "transaction" to complete.
- In Kastner's version of the theory, space-time is actually created out of these transactions.
- This is the only interpretation I'm aware of which starts from electrodynamics. It clearly doesn't fall into any of the other interpretational categories, and is particularly interesting in that (at least in Kastner) it claims to be at a more fundamental level than space-time.

Wave function collapse theories

- Collapse theories are actually alternate *theories* to standard quantum theory. They ultimately predict different results (although viable collapse theories must predict the same results for any experiments which have actually been done.)

- The collapse theories I've read about are all based on periodic, random collapses of the wave function. The parameters of these collapses have to be carefully constructed so as not to violate the results of previous experiments while leaving open the possibility of a future experiment which could decide between the new theory and the standard theory.

- Examples are the GRW Theory (GianCarlo Ghirardi, Alberto Rimini, Tulio Weber) which postulates that the wave function of a fundamental particle will experience a collapse on the average of once in 10^8 years, and "Relativistic Flashy GRW" which (I believe Tim Maudlin says) exhibits Lorentz invariance as well as passing John Bell's "local beable" test. (For more information, see Quantum Non-Locality and Relativity by Time Maudlin, Chapter 10 in the Third Edition only.)

References

- The Theory of the Universal Wave Function by Hugh Everett
  Everett's thesis actually starts on page 9 of the pdf you can download from this page.

- The Emergent Multiverse by David Wallace
  This is currently the best up-to-date reference for Everett's interpretation.

- Stanford - Everett's Relative-State Formulation of Quantum Mechanics
  Stanford - Many-Worlds Interpretation of Quantum Mechanics
  Two articles on Everett in Stanford's online Encyclopedia (better quality than Wikipedia).

- The Quantum Theory of Motion by Peter Holland
  This appears to me to be one pretty complete book on (Bohm's version of?) the pilot wave. But I've only looked it over a little bit, and there are a *lot* of much more recent works on this topic.

References

- Quantum Non-Locality and Relativity by Time Maudlin
  Philosophy of Physics: Quantum Theory by Tim Maudlin
  These two books by Tim Maudlin have *very* good discussions of the pilot wave, wave function collapse theories, and many other aspects of the philosophy of quantum theory. Not a good source on Everett, which Maudlin (mostly) dismisses as incoherent.

- The Quantum Handshake by John Cramer
- The Transactional Interpretation of Quantum Mechanics by Ruth Kastner
- Ruth Kastner's Blog

  John Cramer originated the transactional interpretation and Ruth Kastner is its current leading proponent.

- Sidney Coleman's "Quantum Mechanics in Your Face" video
  I highly recommend this lecture by the late Sidney Coleman, who has his own very interesting viewpoint on things. IMO it starts to get interesting about 20 or so minutes in.