Philosophy of Quantum Mechanics: Week 5

Another Angle on the Measurement Problem

Rather than seeing the measurement problem as a clash between two different kinds of dynamical process (i.e., dynamical evolution and collapse), Wallace says that we should see it as a clash between two different ways of thinking about the quantum state (e.g., $|\psi\rangle = \frac{1}{\sqrt{2}}(|\uparrow\rangle + |\downarrow\rangle)$). These are:

1. As a genuine, physical superposition state.
2. As a probabilisitic mixture—squaring the amplitudes to get the probabilities (in accordance with the Born rule), this tells us (e.g.) there is a 50/50 chance of measuring up/down.

In practice, we use the first whenever we're sticking to a microscopic/quantum description, and the second whenever we perform measurements. But this doesn't give us anything like a coherent interpretation, and has the pesky term 'measurement' cropping up as a primitive!

Two Strategies for a Solution

(A) *Solve* the measurement problem by substituting a new theory:

- Create a theory in which collapse on 'measurement' is implemented dynamically and unambiguously, in such a way that the superposition ceases to be physical. (Dynamical collapse theories, e.g. GRW.)
- Eliminate the genuinely probabilisitic element from the quantum state by keeping the linear dynamics but blocking the simple physical interpretation of the superposition. Probabilities arise as expressions of our ignorance. (Hidden variables.)

(B) *Dissolve* the measurement problem:

- Treat the quantum state as always physical.
- Treat the quantum state as always probabilistic.

Superpositions *vs.* Mixtures

Distinguish:

- *Real* superpositions, such as the ones we've been discussing in quantum mechanics.
- *Probabilisitic mixtures*. Classical-style combinations of definite states where our ignorance of the outcome reflects the fact that we don't know which state we'll pick.

Of course, if we could treat states like $|\psi\rangle = \frac{1}{\sqrt{2}}(|\uparrow\rangle + |\downarrow\rangle)$ as if they were probabilistic mixtures in the first place, then the dissolution would be completely obvious. But this won't work! It's useful to recap why not:

Interference

- Albert's beams (pg. 7).
- After combining the beams, we can perform more measurements:
  - Feed in hard electrons—measure colour—get 50/50 black/white.
  - Feed in soft electrons—measure colour—get 50/50 black/white.
- If the quantum state were to be understood probabilisitcally, would expect 50/50 black/white on feeding a white electron into the machine.
- However, when we feed in white electrons, and then measure colour afterwards, we get just white electrons!
  - The two branches of the wavefunction must be *interfering*.

Pure and Mixed States

Alice and Bob are going to do experiments involving measuring the spin of a single electron. Alice asks Bob to prepare an electron in an x-spin superposition state (specifically, the state

$|\psi\rangle = \frac{1}{\sqrt{2}}(|{\uparrow_x}\rangle + |{\downarrow_x}\rangle)$). Bob is lazy, and just prepared the electron in a probabilistic state (so it has x-spin or down definitely, but he makes sure there's a 50/50 chance of each).

Alice knows Bob well, and is suspicious. She doesn't have an interferometer to hand. What could she do to check up on Bob?

- Suppose Alice can perform linear transformations on the state that effectively rotate it: spin up states in the x direction become spin up states in the z direction (which are superpositions of x-spin states), etc.:

$$|{\uparrow_x}\rangle \rightarrow |{\uparrow_z}\rangle = \frac{1}{\sqrt{2}}(|{\uparrow_x}\rangle + |{\downarrow_x}\rangle)\,,$$
$$|{\downarrow_x}\rangle \rightarrow |{\downarrow_z}\rangle = \frac{1}{\sqrt{2}}(|{\uparrow_x}\rangle - |{\downarrow_x}\rangle)\,.$$

- What happens if Alice performs this transition on her desired superposition state? She gets a definite $|{\uparrow_x}\rangle$ state. (Do the calculation!)
- What happens when she performs this transformation on one of Bob's fake superpositions/really definite states? She gets a superposition state in the x basis.

So Alice can use the relationship between bases to uncover Bob's ploy! If she performs her transformation but continues to get a 50/50 mix of up and down results, she'll know they were never really superposition states!

How could Bob circumvent this problem?

- He could agree in advance with Alice to entangle the electrons with another electron in the singlet state:

$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|{\uparrow_x}\rangle_1|{\downarrow_x}\rangle_2 - |{\downarrow_x}\rangle_1|{\uparrow_x}\rangle_2)$$

- But recall that the singlet state is spherically symmetric:

$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|{\uparrow_z}\rangle_1|{\downarrow_z}\rangle_2 - |{\downarrow_z}\rangle_1|{\uparrow_z}\rangle_2)$$

- Now if Alice tries to perform her rotations, she won't get a definite spin state, so she won't expect to see a difference.

MORAL: ENTANGLEMENT CAN MAKE PROBABILISITIC MIXTURES INDISTINGUISHABLE FROM SUPERPOSITIONS (IF WE'RE NOT DOING INTERFERENCE EXPERIMENTS).

Decoherence

Decoherence is the study of interactions between a system and its environment as a result of which the system is in a *improper mixed state* (i.e. a superposition which is indistinguishable from a mixture—which we will call a *proper mixed state*). This occurs when quantum mechanical interference is suppressed.

- Suppose that the Hilbert space $\mathcal{H}$ of the (total) system we're interested in is factorised into 'system' and 'environment' subsystems, with respective Hilbert spaces $\mathcal{H}_S$ and $\mathcal{H}_E$, so that

$$\mathcal{H} = \mathcal{H}_S \otimes \mathcal{H}_E$$

- For decoherence to occur, there needs to be some basis $\{|\alpha\rangle\}$ of $\mathcal{H}_S$ such that the dynamics of the system-environment interaction give us ($|\psi\rangle \in \mathcal{H}_E$)

$$|\alpha\rangle \otimes |\psi\rangle \to |\alpha\rangle \otimes |\psi;\alpha\rangle \, ,$$
$$\langle\psi;\alpha|\psi;\beta\rangle \simeq \delta\left(\alpha-\beta\right) .$$

  - The environment effectively 'measures' the state of the system and records it.
  - Here, the second (orthogonality) requirement can be glossed as 'record states $|\psi;\alpha\rangle$ are distinguishable'. *It's this that ensures that branches of the quantum state (i.e. terms in the superposition) do not interfere with one another.*

- Typically, if a system is in a superposition, it gets entangled very quickly. For example, for a one-micron dust particle in a superposition of states 1mm apart, the time for decoherence is:
  * From the atmosphere: 10^{-30}s.
  * From sunlight: 10^{-15}s.
  * From the cosmic microwave background: 1s.

Decoherence and the Measurement Problem

What decoherence gives us:

- Systems that are big enough, and sufficiently entangled with their environments, will not exhibit quantum interference behaviour, as a result of decoherence.
- Such systems can be treated as probabilistic mixtures of *classical* states—so here we have the emergence of classical concepts to which Bohr gestured.

What decoherence doesn't do:

- Decoherence *does not* change superposition states into probabilistic mixtures.
  - Decoherence gets rid of macroscopic interference, but it doesn't get rid of macroscopic superpositions.
  - In other words, decoherence yields an *improper mixture*, not a *proper mixture*.
- It does not give us an exact divide between the micro-world and the macro-world: decoherence is inherently approximate.

Since it doesn't get rid of superpositions...

DECOHERENCE DOES NOT SOLVE THE MEASUREMENT PROBLEM!