Literature Review - 499Y

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What we observe is not nature itself,
but nature exposed to our method of questioning.
—Werner Heisenberg, *Physics and Philosophy*

1 Many Worlds, Collapse, and Incoherence

Quantum mechanics is, as far as experimental testing goes, among the most (if not the most) successful theories of the physical sciences. The wavefunction solutions that shake out from the Schrödinger Equation lend insight into the subatomic world and produce wonderfully precise experimental predictions. The profound results on which discussion of many-worlds quantum mechanics are built fall outside the scope of this paper,[1] but much attention will be paid to what the quantum formalism says about measurement, probability, and the evolution of the wavefunction. The importance here is seeing how these physical facts line up with our interpretation of quantum mechanics: the story one tells to make sense of our physical reality in light of the mathematics.

What sets the orthodox (Copenhagen) interpretation apart from boilerplate quantum mechanics? How have we made room for extra-physical features like indeterminism and anti-realism of pre-measurement physical values? These features follow from accepting the collapse postulate. Collapse is introduced as a practical way to make sense of our observations and measurements. Given a system in a known potential and well-defined wavefunction, we can calculate a distribution over the possible values that one might obtain (for example, a continuous distribution over position values in the position basis). The collapse postulate says that when we take a measurement of a particular system, its wavefunction localizes to a delta-spike rather than evolving in the fashion required by the Schrödinger Equation. Considering the example of position space, the wavefunction has very high amplitude at the position we obtain upon measurement and zero amplitude everywhere else (Griffiths and Schroeter 2018, p. 6). What troubles some physicists is that collapse does not follow from any

[1] I will point out relevant sections of David J. Griffith's *Introduction to Quantum Mechanics* and Sakurai's *Modern Quantum Mechanics* as necessary.

mathematical or physical facts. There is nothing which points to a discontinuity in the evolution of the wavefunction given a measurement, except that it seems to line up with our experience. This issue is largely ignored by physicists whose experimental verification goes through regardless of whether one accepts the collapse postulate or not.

Hugh Everett was bothered enough by this problem to reformulate quantum theory *sans* collapse. He found it problematic that the "probabilistic features are postulated in advance instead of being derived from the theory itself" (Everett 1957, p. 462). His relative state theory suggests instead that all components of a quantum superposition obtain:

> "Throughout all of a sequence of observation processes there is only one physical system representing the observer, yet there is no single unique state of the observer (which follows from the representations of interacting systems). Nevertheless, there is a representation in terms of a superposition, each element of which contains a definite observer state and a corresponding system state. Thus with each succeeding observation (or interaction), the observer state "branches" into a number of different states. Each branch represents a different outcome of the measurement and the corresponding eigenstate for the object-system state. All branches exist simultaneously in the superposition after any given sequence of observations" (Everett 1957, p. 459).

The relative state theory—along with the contemporary variations on the many-worlds quantum mechanics discussed herein—explain measurement phenomena without appeal to the collapse postulate. This feature is obviously an attractive one, but many-worlds brings with it a great deal of unanswered questions regarding probability.

Orthodoxy draws a wonderfully simple connection between the wavefunction and probability via the collapse postulate: the measured state has a likelihood of obtaining proportional to the squared amplitude such that[2]

$$P(\psi_i) = |\langle\psi_i|\Psi\rangle|^2 \text{ where } |\Psi\rangle = \sum_i c_i |\psi_i\rangle \tag{1}$$

Many-worlders cannot give such a simple answer, as it is not clear *prima facie* what probability even means under Everettian views. All states obtain, and so immediately we can say that all states are realized regardless of their squared amplitudes such that $P(\psi_i) = 1$.

We arrive at the conclusion that the many-worlds interpretation is a deterministic theory since this view says that, with certainty, a given history on a branch will occur (Albert 2010). The headache continues. In a laboratory where I measure the spin of an electron, should I then be certain that spin up will occur *and* that spin down will occur? This worry is two pronged:

[2]Full derivation for square amplitude from collapse postulate in Sakurai and Napolitano 2017.

1. The incoherence problem: many-worlds QM is deterministic, so there is something incoherent about assigning a probability less than one for a state which will surely obtain.

2. The quantitative problem: how can we recover the Born-rule probabilities (squared amplitude) on this view?

Responses vary widely, and this paper will focus on just two competing views. Namely, the fission program and the personal identity program.

2 Fission Program

Hillary Greaves is a vocal defender of the fission approach to understanding probability (Greaves 2004, 2007; Greaves and Myrvold 2010). Fissioners just accept that an agent should rationally expect to see, with certainty, that each state in a given superposition will obtain. Yet, an agent can only experience seeing one state obtain, and so expectation is seemingly at odds with experience.

The fission program pulls from decision theoretic axioms to construct an argument for rational constraints on a branching agent. The decision theoretic axioms are restated to capture the connection between an agent and their many branched successors as opposed to the possible outcomes of a single future agent (Wallace 2006, p. 18). A "caring measure" can then be constructed such that an agent places stock in each of their branched selves after a quantum event. Each branched self will then be cared about with weight equal to the Born-rule amplitudes (Greaves 2007, sec. 3.1.2).

What does this look like for an agent? Let's take a simple example of a spin 1/2 system prepared in the laboratory with non-equal squared amplitude for each state of a particle:

$$|\Psi\rangle = \frac{1}{\sqrt{5}} \left(2\,|\uparrow\rangle - |\downarrow\rangle\right) \tag{2}$$

A PI in the lab offers a wager to her research assistant. If the assistant observes the particle and finds spin up (down) then she will win (lose) \$20. Should the assistant take the bet? The assistant, having recently attended a lecture on many-worlds, knows that each state will necessarily obtain. At first, she is compelled to decline the bet because she knows she will lose \$20 no matter what (on one branch, at least). She then considers the set of branching futures which will occur if she takes the bet, and assigns a caring measure to each of her two branched selves (in this case, 2/5 for up and 1/5 for down). In this sense, she should care twice as much about the future on which she wins compared to the future in which she loses. With the odds in her favor, she takes the bet and branching occurs. The caring measure's constraint on her rational preferences allows her to act as if she never went to the lecture and just accepted the Born Rule probabilities as is.

This picture is no doubt a confusing one. A rejection of uncertainty and probability (she sees no odds associated with winning and losing), an acceptance that all possible states occur (she will both win and lose), but still a preference for taking the bet over not (preference via the caring measure). The way I have set up the fission schema for understanding probability, or lack thereof, is missing one key connection. If the caring measure assigns weights to branches, *why is it that those weights just are the squared amplitudes?*

2.1 Measurement Neutrality and Equivalence

The connection between square amplitudes and caring measures or weights is said to follow from twp assumptions (Greaves 2007, p. 10):

- "Measurement Neutrality: A rational agent is indifferent between any two quantum bets that agree on the state $|\psi\rangle$ on which the measurement is to be performed, the observable $\hat{X}$ to be measured, and the 'payoff function' P from the spectrum of $\hat{X}$ to the set of consequences."
- "Equivalence: A rational agent is indifferent between any two quantum bets that agree, for each possible reward, on the mod-squared measure of branches on which that reward is given."

[Introduce here the post-measurement uncertainty / ignorance probabilities introduced by (Vaidman 1998)]

3 Subjective Uncertainty Program

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