2. The mysteries of quantum mechanics. Interpretations.

Three mysteries of quantum mechanics.

The mathematics of quantum mechanics is given in terms of the wave function (Ch. 4; see also the state vector in A6.2). There are three interconnected mysteries associated with the properties of the wave function. First, as you can tell from its name, it acts like a wave. But matter has both wave-like properties *and* particle-like properties—mass, charge, localization and so on. So the first mystery that needs explaining is **wave-particle duality**; if matter is made up of wave functions alone, as the highly successful quantum mechanics mathematics seems to imply, why does it often act as if it is made up of particles?

The second mystery is worse. The mathematics of quantum mechanics says **several versions of reality** can simultaneously exist in the wave function. Schrodinger's cat (Ch. 7) can simultaneously be both dead and alive at the same time, for example. How are we to reconcile such a bizarre property with the obvious fact that we see only one version of reality and we all agree on it?

And the third mystery is **probability**. The mathematics does not predict which version of reality we perceive, but one can predict from the wave function the probability that we will perceive a live cat (or a dead cat). To make matters still more confusing, even though the probability can be predicted from the wave function, there is no probability whatsoever in the mathematics. Further, probability cannot be *deduced* from the basic theory (Ch. 18). It is something we know about strictly from experiment. So how does probability enter into physical reality if it is not in the basic theory? Does Nature make random choices? Does God really play dice with the universe? Is the highly successful basic mathematics inadequate? At this point, we simply do not know.

The fourth mystery.

This is not usually included in the list of quantum mysteries one needs to explain, but its solution is essential if we are to understand what matter 'really is.' The mystery is: What do the wave functions (or state vectors) refer to or represent? The conventional assumption is that the wave function represents the state of an associated particle. But we will find—surprisingly—that there is no evidence for particles, so this assumption doesn't work. For Parts I, II and III, we mostly ignore this problem because it can be considered separately from the other three mysteries, and also because it requires an additional degree of abstraction. Then we consider it in depth in Part IV.

Interpretations.

How do physicists deal with this lack of understanding of how the wave function relates to our perceptions? There are two ways: The first is the "shut up and calculate" approach in which physicists are only concerned with comparing experimentally observed results with the mathematical predictions of quantum mechanics. The second way is to superimpose an "interpretation" on the mathematics, with "interpretation" meaning either the mathematical theory or the conceptual picture of matter, or both, are modified.

The history of interpretations is interesting. Quantum mechanics was discovered more than 80 years ago when physicists were trying to explain the light spectrum of the hydrogen atom (Ch. 4). The problem was that even though the theory of the wave function gave the correct answer, it didn't come with an interpretive manual to explain what it "is" or how it relates to perception. Many of the best physicists who ever lived, including Schrödinger, Einstein, and Feynman have tried to interpret the mathematics but have gotten nowhere. And so there are now more than a dozen interpretations that have been seriously proposed, with each having its adherents.

The Everett strategy: Make maximum use of the mathematics.

How then are we to make our way through this morass? The strategy we use was suggested by Hugh Everett III over 60 years ago (although he only partially carried it out, and he gave a flawed treatment of probability). The problem with most interpretations is that they start from some pre-conceived notion (such as the existence of particles, or 'collapse') of what reality is like and try to fit quantum mechanics into that mold. Everett, in his many-worlds interpretation, suggested instead that we should proceed by considering what can be deduced about our perceptions of the physical world **from the mathematics alone**. That way we are on firmer ground because we know from the successes of the mathematics that it is "correct." (Of course, it is perilous to say quantum mechanics is the final theory of the physical universe. But one must admit that its myriad successes are impressive.)

Wave-particle duality. No interpretation needed.

What we are looking for in an interpretation is a conceptual model of reality that allows us to bridge the perceived gap between the highly successful mathematics and (1) wave-particle duality, (2) several versions of reality, and (3) probability. We start with wave-particle duality. The first step is to gather all the reputed evidence for the existence of particles. One might think there would be nearly an infinite number of observations and experiments which, it is claimed, show that particles exist. But actually, there are only five or six basic particle-like properties of matter. We then show that each of these can be explained by the mathematically deduced properties of the wave function alone. Thus, because the wave function, *by itself*, can explain all the particle-*like* properties of matter, there is **no evidence for particles**! Matter is, as far as we can currently determine constructed from wave functions alone. Wave-particle duality is just a duality in the properties—wave-like and particle-*like*—of the wave function. So the first mystery can be solved entirely within the mathematics of quantum mechanics; no additions to or interpretations of the wave-function-only mathematical-conceptual model of matter are needed.

Many versions of reality. Mostly no interpretation needed.

What about the second mystery, many versions of reality? We find that the mathematics alone can almost solve it. It can be shown that the mathematics implies more than one version of reality is never *perceived* and that all observers agree on the version perceived. But the mathematics does not tell us which version we will perceive.

Probability. An interpretation is definitely needed.

And the third mystery? The basic mathematics most definitely *cannot* account for probability (Ch. 18). Therefore the wave-function-only mathematical scheme of basic quantum mechanics, by itself, does not provide an entirely adequate description of the physical universe. Something must be added to that scheme to obtain the proper interpretation.

Evaluation:

There are two other phenomena that are considered by many physicists to be fundamental mysteries. First, there is the uncertainty principle which says that the position and velocity of a particle cannot both be measured to arbitrary accuracy. Second, there are Bell-like experiments in which a measurement on one particle seems to change the results of a measurement on a distant particle—spooky action at a distance. We consider both of these to be sub-mysteries of wave-particle duality, as is explained in Part II.