7.4: Sense and Nonsense in Quantum Mechanics

The essential mystery of quantum mechanics becomes clearer when discussed in the conceptually simpler context of two slit interference. If light and electrons can have both particle and wave properties, then one might ask through which of the two slits the particle passed. However, in physics a question simply doesn't make sense if it cannot be answered by experiment.

One can indeed perform an experiment to determine which slit the X-ray photon or electron passes through in the two slit experiment. However, by the very act of making this measurement, the form of the associated wave is altered. In particular, since the absolute square of the wave displacement represents the probability of finding the particle, once the particle has definitely been found passing through one or the other of the slits, the wave function collapses into a very small wave packet located at the observed position of the particle. Thus, the wave displacement becomes zero at the slit it didn't pass through. However, the interference pattern results from the superposition of waves emanating from two slits. If no wave comes from one of the slits (because the wave displacement is zero there), then there can be no interference pattern!

We can now make the inverse argument. If there is an interference pattern, then we know that the wave displacement is non-zero at both slits. From the probability interpretation of the wave displacement, we conclude that we cannot say, even in principle, through which slit the particle passed. It is not just that we don't know the answer to this question; there is simply no experiment which can give us an answer without destroying the interference pattern. In other words, the question "Which slit did the particle pass through?" is a nonsensical question in the case where an interference pattern is actually produced.

The American physicist Richard Feynman noticed that the above behavior can be interpreted as violating the normal laws of probability. These laws say that the probability of an event is the sum of the probabilities of alternate independent ways for that event to occur. For instance, the probability for a particle to reach point A on the detection screen of a two slit setup is just the probability P_1 for the particle to reach point A after going through slit 1, plus the probability P_2 for the particle to reach point A after going through slit 2. Thus, if $P_1 = P_2 = 0$, then the probability for the particle to reach point A irrespective of which slit it went through should be $P_{\text{total}} = P_1 + P_2 = 0.2$. However, if point A happens to be a point of destructive interference, then we know that $P_{\text{total}} = 0$

Feynman proposed that the above rule stating that alternate independent probabilities add, is simply incorrect. In its place Feynman asserted that probability amplitudes add instead, where the probability amplitude in this case is just the wave function associated with the particle. The total probability for a process is obtained by adding the alternate probability amplitudes together and taking the absolute square of the sum.

Feynman's view is a particularly compact expression of the so-called Copenhagen interpretation of quantum mechanics which evolved from the ideas of Niels Bohr, Werner Heisenberg, Max Born, and others in the 1920s. It dispenses with the wave-particle duality and other philosophical baggage by saying "Particles are real in that we can observe them, but the only theory we have is about probability amplitudes for particles." This interpretation of quantum mechanics may be weird, but it appears to be self-consistent and in agreement with experiment.