HPS/Pl 125: Problem 10

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Consider Maudlin's experiment 6, the Mach-Zender interferometer. In the many-worlds interpretation, should we say there is a world in which the electron travels along the upper path and another in which the electron travels along the lower path?

In the Mach-Zender interferometer experiment as Maudlin presented it on pages 23—24, we have the following setup: a beam of x-spin up electrons is sent through a z-oriented Stern-Gerlach. Since x-spin up is an equal superposition of z-spin up and z-spin down, the beam will be split into two beams. One beam will be z-spin up, sent up from the z-axis, and the other will be z-spin down, sent down from the z-axis. Each of these two beams has definite z-spin and therefore is an equal superposition of x-spin up and a-spin down. It seems we have destroyed the x-spin information contained in the original beam. However, if we then reflect each beam back towards each other and recombine them, then send the resulting single beam through an x-oriented Stern-Gerlach, we will see that the recombined beam is entirely x-spin up. This is a mystery; along each path, we can verify that there is an equal superposition of x-spin up and x-spin down (no x-spin information), yet somehow the information about the beam preparation is transmitted through the mechanism as a whole.

In most interpretations of quantum mechanics, this issue is resolved by adopting a ψ-ontic view of the wavefunction. In this view, the wavefunction is a real physical object that describes the state of the system. The wavefunction exists along each path of the Mach-Zender interferometer (regardless of whether the particle does or not) and thus the wavefunction is able to carry the information about the beam preparation through the mechanism as a whole. This approach holds true for the many-worlds interpretation as well, as the x-spin up information is carried by the wavefunction and the result predicted by ordinary time evolution, which functions as the full specification of the many-worlds interpretation. However, under the many-worlds interpretation, we end up with an entirely different mystery which arises from this experiment.

Under the many-worlds interpretation, we know that certain superpositions of states result in a branching of the universe. In the classic Schroedinger's cat experiment, the cat is in a superposition of alive and dead states, which manifests as a branching of the universe into two worlds: one in which the cat is alive and one in which the cat is dead. In the Mach-Zender interferometer experiment, we have a similar situation. The electron is in a superposition of travelling along the upper path and travelling along the lower path. At a first glance, it appears that this superposition should result in a branching of the into two worlds just as the cat experiment does. However, on this view, we encounter a significant problem. In the many-worlds interpretation, the different worlds that result from a branching are supposed to be orthogonal to each other. This means that the worlds are not able to interact with each other in any way. If this is not the case, then the many-worlds interpretation wouldn't solve the measurement problem — it is possible that I could still see macroscopic superpositions of states in my everyday life if my world interacted with other worlds that resulted from a branch. However, in the Mach-Zender interferometer experiment, the two worlds that would result from the branching of the electron travelling along the upper path and the electron travelling along the lower path are not orthogonal to each other. In fact, they are entangled with each other and the recombination of the two beams shows that they must interact. Therefore we *cannot* conclude that there is a branching of worlds at the beam-splitter if we want many-worlds to remain viable.

Then clearly, with this in mind, we must reconsider when branching happens in the many-worlds interpretation. What is it about Schroedinger's cat that causes branching while the Mach-Zender interferometer does not at the point of the beam splitter (Note that we still need branching to happen when we measure the final output of the interferometer)? The best answer available is that branching is not a result of simple superpositions of states in the wavefunction, but rather a result of the decoherence of the wavefunction. Decoherence is a process by which the wavefunction of a system becomes entangled with the wavefunction of its environment and separates into sufficiently separated components to be considered separate worlds. In the case of the Mach-Zender interferometer, the wavefunction of the electron becomes entangled with the wavefunction of the environment only after passing through the full apparatus and being measured by a measuring device at the end of the experiment. Thus the wavefunction only decoheres at the end of the experiment, when the electron is measured. This means that branching only occurs at the end of the experiment, and should not be considered to have happened at the beam-splitter. While not entirely unproblematic, this approach allows us to retain the usefulness of the many-worlds interpretation while still correctly generating the results of the Mach-Zender interferometer experiment.