Loss of Coherence

A property often associated with measurement is some or all loss of coherence of the particle due to the process of observation. For example, consider an experiment with an electron that is put through an interferometer based on its spin. Assume the electron is initially in an equal superposition of up and down spin, i.e. $|\psi\rangle = (|\uparrow\rangle + |\downarrow\rangle)/\sqrt{2}$, and the interferometer is set up so that spin-up takes the upper path of the interferometer, and spin-down takes the lower path. The upper and lower paths of the electron are recombined so that the electron exists in one of two Ports A and B. It is assumed, given the initial equal superposition state, that the interferometer is configured so that when the state $(|\uparrow\rangle + |\downarrow\rangle)/\sqrt{2}$ is input into the interferometer, the electron will always exit in Port *A* and when $(|\uparrow\rangle - |\downarrow\rangle)/\sqrt{2}$ is input, the electron will always exit in Port *B*. Now suppose that in the lower path there exists an interaction with a measurement device that can give information that the electron has passed through that path. If the device provides a readout that the electron has passed through the lower path, then the electron is projected into the state $|\downarrow\rangle$ and the electron experiences a total loss of coherence.

If the electron passes through the upper path then the device will not register the electron in the lower path. Hence, we know that when the device does not register the electron in the lower path, then the state of the electron via the measurement postulate is projected into the state $|\uparrow\rangle$, and again experiences a total loss of coherence. If a partial measurement were made by an imperfect device or via a weak measurement that does not reliably indicate the path, then one will generally find that the electron coherence is reduced but not eliminated entirely. Hence loss of particle coherence appears to be a property that is associated with measurement.

Discerning Loss of Coherence

Let us now ask whether or not the loss of particle coherence is either a necessary or sufficient condition for discerning measurement from unitary evolution. Consider that the device is composed of an atomic sample that is affected by the electron passing through either strongly (which will be assumed can be determined via a follow-up experiment on the atomic sample) or very little, depending on the device's setting. Furthermore, we assume that the electron interaction with the atomic sample is described via Schrödinger's equation. The initial state of the sample is assumed to be $|\psi_1\rangle$ which remains the same if the electron does not pass through the sample, and changes to $|\psi_2\rangle$ if the electron does pass through the sample. We assume that $\langle\psi_1|\psi_2\rangle = 1 - \beta$ where $0 \leq \beta \leq 1$ is the setting of the device. When $\beta = 0$ the sample is not affected at all by the electron passing through and when $\beta = 1$ the final state of the device is orthogonal to the initial state and hence which-way information of the electron can be perfectly obtained.

Suppose the atomic sample is set to $\beta = 1$ such that the electron strongly alters the quantum state of the sample upon passing through it. Then, after the electron passes through the interferometer, it is possible to probe the sample and determine which-way information. In such a case, the final state of electron-sample is

$$(|\uparrow\rangle \otimes |\psi_1\rangle + |\downarrow\rangle \otimes |\psi_2\rangle)/\sqrt{2}.$$

In this case the density matrix of the electron can be computed by tracing the atomic sample for which one finds that the state of the electron is a completely mixed state. Hence there has been a complete loss of coherence of the electron, and yet the entire treatment has been via Schrödinger unitary interaction. On the other hand, as the setting of the atomic sample is decreased $\beta < 1$, one finds that coherence is restored as a function of β. Hence both the loss of coherence and the restoration of coherence if there were partial measurement of the sample can be seen to be attributable to a unitary process. This indicates that measurement is not a necessary condition for loss of first-order coherence of the particle.

On the other hand, let us examine in the context of coherence, why the Chapter 3 experiment is successfully able to discriminate unitary evolution from measurement within the von Neumann formalism of quantum mechanics. It appears that when the entire device plus system is considered, the second-order coherence attributable to entanglement is predicted unitarily while under measurement the coherence is not predicted. Hence measurement is sufficient but not necessary for loss of coherence. As entanglement is a multi-degree of freedom effect, this indicates that, similar to the properties of wave function reduction and nondeterminism, entanglement does provide a means to discriminate unitary evolution from measurement when an improper mixture is predicted.

The breakdown of unitarily predicted entanglement is therefore a sufficient condition for measurement. This leads again to our dictum:

To the extent that there is entanglement, there is no measurement.