Quantum Jumps

Quantum jumps are a property that are often associated with measurement. Quantum jumps occur when a particle such as a photon is absorbed in a measurement. Quantum jumps are generally modeled by a physical discontinuity and within the von Neumann theory, such jumps are occurring nondeterministically or statistically. Planck's discovery in 1900 of the quantum of action was met with an interpretation by Bohr and others of the need for a non-causal or nondeterministic process to explain various phenomenon such as black-body radiation. Many researchers seem to be under the impression that quantum jumps were proposed only after Schrödinger's equation was put-forward. That is, quantum jumps were an outgrowth of the statistical Born rule and subsequent Copenhagen interpretation. This is historically inaccurate: the concept that there is a discontinuous action inherent in quantum theory was thought to be a property of the quantum of action and related to the problem of wave-particle duality well before the discovery of Schrödinger's equation. For example, Born refers to energy jumps in 1927 as always having been regarded as the basic pillar [181]

> *... the fact of "energy jumps," which has always been regarded as the basic pillar of quantum theory, as well as the most egregious contradiction to classical mechanics.*

As further discussed in Chapter 5, Bohr had also attributed such discontinuous actions to the existence of a noncausal or nondeterministic process, well before the discovery of Schrödinger's equation. When Schrödinger originally proposed his equation, he was invited by Bohr to his home for further discussions. According to the account by Heisenberg in [182, p. 75], Bohr made several points regarding the quantum of action in regards to Schrödinger's equation:

> *Bohr: But just take the case of thermodynamic equilibrium between the atom and the radiation field—remember, for instance, the Einsteinian derivation of Planck's radiation law. This derivation demands that the energy of the atom should assume discrete values and change discontinuously from time to time; discrete values for the frequencies cannot help us here. You can't seriously be trying to cast doubt on the whole basis of quantum theory!*
>
> *Schrödinger: There is no reason why the application of thermodynamics to the theory of material waves should not yield a satisfactory explanation of Planck's formula as well—an explanation that will admittedly look somewhat different from all previous ones.*
>
> *Bohr: No, there is no hope of that at all. We have known what Planck's formula means for the past twenty-five years. And, quite apart from that, we can see the inconstancies, the sudden jumps in*

atomic phenomena quite directly, for instance when we watch sudden flashes of light on a scintillation screen or the sudden rush of an electron through a cloud chamber. You cannot simply ignore these observations and behave as if they did not exist at all.

Schrödinger: If all this damn jumping were really here to stay, I should be sorry I ever got involved in quantum theory.

The dynamics of quantum jumps traces back to Bohr's (1913) transitions between stationary states in his model of the atom and Einstein's (1917) theory of stimulated and spontaneous emission between Bohr's stationary states. In a sense, Einstein's theory was an open quantum system that allowed stochastic jumps to lead to a thermal equilibrium state consistent with Planck's radiation law. After the development of quantum mechanics, quantum jumps were interpreted in terms of state reduction resulting from measurement. Quantum jumps were first directly observed in the 1980s in laser-cooled ions in radio-frequency traps [183]. Since the 1990s, quantum jumps have been described in terms of stochastic evolution equations [184] [185] in which the atom is weakly coupled to photodetectors, and the atom jumps due to entanglement between atom and detectors, which are represented by measurement operators. From this point of view, there would be no jump in the absence of the measurement. The detection scheme conditions the response of the atom so that direct detection results in quantum jumps similar to Einstein and Bohr (though not necessarily between eigenstates) whereas heterodyne detection gives rise to quantum state diffusion [186]. Although such models can be used to consistently analyze experiments, it is not known whether or not quantum jumps are actually detector-dependent. However, Wiseman and Gambetta have proposed an experimental test for whether quantum jumps are objective phenomena or else depend on the measurement device [187].

We have in Chapter 3 presented a technique that is used to show why the measurement problem is an actual problem versus only a problem that requires an interpretation to solve. The method presented in Chapter 3 requires one to test the existence of entanglement. As there are a number of properties of measurement, one might consider whether the detection of such a property might be used to confirm the existence of a measurement process versus unitary evolution. The ability of each of these properties of measurement is now examined with respect to a means to discern between measurement and unitary evolution.

Discerning Quantum Jumps

Suppose that quantum jumps do indeed occur within a measurement process. Are such jumps unique to measurement or are they also expected under unitary evolution? To simplify matters, let us consider a quantum jump that is deterministic. In the development of the quantum theory of radiation by Dirac [188], a photon undergoes annihilation and creation in the interaction of light and matter. Consider a two-level atom with states $|g\rangle$ and $|e\rangle$ interacting with a photon of energy E_P that is in the Fock state $|1\rangle$. If the initial state of the photon-atom is $|1\rangle|g\rangle$, then this will evolve under unitary evolution to a superposition of $|1\rangle|g\rangle$ and $|0\rangle|e\rangle$. In the Dirac model suppose that the state $|1\rangle|g\rangle$ evolves to $\sqrt{\alpha}|1\rangle|g\rangle + \sqrt{1-\alpha}|0\rangle|e\rangle$. Then the reduction of the amplitude of the state $|1\rangle|g\rangle$ from unity amplitude to $\sqrt{\alpha}$ coincides with the rise of the population of the state $|0\rangle|e\rangle$. Hence in some sense part of the amplitude of the state $|1\rangle|g\rangle$ is being converted to the state $|0\rangle|e\rangle$. But this Dirac process requires the annihilation of the photon state $|1\rangle$ and the excitation of the atom from the state $|g\rangle$ to state $|e\rangle$. One can see that even in the unitary process, there is a sense of a quantum jump occurring in that the photon energy is not being slowly and continuously reduced from energy E_P to energy 0, but rather the new term that emerges in the Dirac theory is $|1\rangle|g\rangle$ which represents a jump from $|0\rangle|e\rangle$. Hence jumps, of and by themselves, seem to be present in both unitary theory and measurement.

Let us suppose that an energy conserving Jaynes-Cummings Hamiltonian in quantum optics (or similarly in spin manipulation experiments such as NMR) is considered in which a π pulse is applied. This will entirely transfer the photon-atom state $|1\rangle|g\rangle$ to the state $|0\rangle|e\rangle$. Such a state transfer is indistinguishable from a quantum jump in which the state jumped from $|1\rangle|g\rangle$ to $|0\rangle|e\rangle$. If unitary evolution occurs the states at time zero and time π are given respectively by the two elements of the set $\{|1\rangle|g\rangle, |0\rangle|e\rangle\}$. Now suppose that measurements are made at time zero and time π of the EM-field and atom. Such measurements will also reveal $\{|1\rangle|g\rangle, |0\rangle|e\rangle\}$. Hence unless one can demonstrate that a deterministic quantum jump under measurement occurs faster or slower than a unitary π pulse or via some other distinguishing characteristic, then a quantum jump of and by itself does not appear to be unique to measurement. That is, something more is needed for a deterministic quantum jump to distinguish it from unitary evolution.

Distinguishing unitary evolution from measurement via a Chapter 3 UMDT may be possible if a quantum jump is represented as *steering*. In this way, the state of a distant entangled system exhibits a jump similar to that of an atom entangled with an electromagnetic field. As discussed in Chapter 5, Schrödinger introduced the phenomenon of steering in his 1936 paper in which he analyzed the Einstein-Podolsky-Rosen thought-experiment and demonstrated a nonlocal effect on a distant system so that by using entanglement, "a sophisticated experimenter can … produce a non-vanishing probability of steering the system into any state he chooses." The UMDT test of Chapter 3 used the Bell nonlocality or violation of the CHSH form of the Bell inequality. However, Bell nonlocality is a stronger concept than steering so that Bell-nonlocal states are a subset of steerable states. Similarly, steerability is a stronger concept than entanglement so that steerable states are a subset of entangled states [189]. Using steering, measurements by Alice could bring about a quantum jump in Bob's distant entangled system. However, Bell nonlocality and entanglement are both concepts that are symmetric between Alice and Bob, whereas steering is inherently asymmetric. There are situations where Alice can steer Bob's state but Bob cannot steer Alice's state, referred to as *one-way steering*, very much like the historical view of a quantum jump. Despite the differences between Bell nonlocality and steering, the phenomenon of steering can also be characterized by an inequality analogous to that of the CHSH inequality used in the Chapter 3 UMDT test. Cavalcanti et al. [190] have formulated an inequality that is necessary and sufficient for steering, which takes the form:

$$\sqrt{\langle (A+\acute{A})B\rangle^2 + \langle (A+\acute{A})\acute{B}\rangle^2} + \sqrt{\langle (A-\acute{A})B\rangle^2 + \langle (A-\acute{A})\acute{B}\rangle^2} \leq 2$$

where $\{A, \acute{A}\}$ and $\{B, \acute{B}\}$ represent the two dichotomic measurements of Alice and Bob. When the CHSH inequality is violated, the steering equality is also violated. When Alice and Bob share a maximally entangled state, the maximum violation of the inequality becomes $2\sqrt{2}$, just as for the CHSH inequality, although for steering this is independent of the relative angle between Alice's and Bob's measurements. The phenomenon of steering and the steering inequality have been experimentally demonstrated [191]. The steering inequality can then be used to devise a UMDT test for a steering model similar to that of the Bell-nonlocality test in Chapter 3. This would similarly distinguish unitary evolution from measurement for this situation of a steering model for a quantum jump.

Consider also the possibility the relationship between physical discontinuities and measurement. In the experiment of Steinberg, Kwiat, and Chiao [192], it was found that quantum wave functions can be reshaped so that the group velocity is higher than the speed of light *c*. However, information in the form a discontinuity or "front" must propagate at the front velocity which is limited by *c* [193]. An excellent discussion of the various velocities and their relationship to the work by Sommerfeld and Brillioun can be found in [194]. As it is widely accepted that information within a photon propagates unitarily, the discontinuity would be expected to propagate no faster than the speed of light and unitarily. The existence of a discontinuity within a wave function has not been proven to be a sufficient condition for a measurement.