Assumptions

There are several assumptions that are utilized in developing the theoretical basis to analyze the major issue of this chapter—whether the measurement problem has a solution with potentially new observational consequences or is a philosophical problem that only requires an interpretation, for which no new observational consequences are possible. In order to address this and related questions, it cannot be taken for granted that the detectors in Figure 3.2 or Figure 3.3 actually generate the statistics that are observed under Born's rule. In the consideration of the measurement problem (as opposed to the problem of nonlocality), the particles that compose a particular "detector" will be initially referred to as a device. Only after it is established via experimental test for which the operations will be specified in this chapter, will it be considered to be a bona fide detector.

One can separate the two devices in Figure 3.2 via an arbitrary large distance d, and one could in principle place a shutter in front of the photon emitter to limit the uncertainty of the time of emission to some Δt_e. As long as $d > 2c(\Delta t_e + \tau_l)$ where τ_l is the latency time of the devices, there can be no direct interaction between the devices such that the state of one device affects the individual statistics of the other device without violating relativistic constraints of no-signaling. Another distinct issue is whether there can be indirect interaction between separated systems and the correlation properties such as entanglement are affected. The potential existence of mechanisms that can affect the entanglement or correlation in separated systems in a manner that is faster-than-light is quite important for the issue of whether or not the measurement problem is an interpretational problem or whether the measurement problem is a real problem with observational consequences. It has been found under unitary evolution that interactions exist, such that the correlation properties between two separated systems can be affected faster than $d/\Delta t_e$ [97] [98] [99]. Although remarkable, such effects are predicted to be significantly reduced when the devices are sufficiently separated [98]. As the separation d between the devices can be made arbitrarily large so that the effects of such correlation can be made arbitrarily small, one can safely ignore such effects so long as any correlation that is under consideration also does not decrease toward zero with increasing separation; otherwise further analysis would be needed. The Hamiltonian is for now approximated in the form of Equation (3.1) but this issue will be revisited later to ensure that such an approximation is valid.

Moreover, the dimension of the detector Hilbert space could conceivably grow as a detection is made and the detector affects other particles in the local area. However, any growth in the dimension of the final detector state must be bounded because there is a well-defined distance that any time-like signals can propagate. Adler in [100] shows that only environmental particles that are within a distance $c\tau_l$, where c is the speed of light and τ_l is the measurement latency time, can causally affect the experimental outcome without violating no-signaling. Hence, to simplify matters, it will be assumed that the initial states of the detectors includes not only the initial particles that compose the detector but also the particles composing the environment surrounding the detector within a time-like effect between the time the photon wave function begins impinging upon the device and time τ_l, for which there can be potential direct interaction $\mathcal{D}(\mathcal{H}_i) = N$. Hence N remains the same throughout the interaction.

The initial ready state of Device i is initially assumed to be a pure state and is denoted by $|\psi_r^0\rangle_i \in \mathcal{H}_i$, *i=1,2*, $\mathcal{D}(\mathcal{H}_i) = N$. Later in this chapter, initial device states that are mixed will also be considered. The two devices are assumed to be capable of being initialized by an experimenter, and we assume that they are initialized in a product state given by $|\psi_r^0\rangle_1 \otimes |\psi_r^0\rangle_2$. The assumption that one can consider the device states to be initialized in this manner is important, and this assumption will be considered later in Chapter 4. The initial state of the photon sent into the polarizing beam splitter is assumed to be given by an arbitrary pure state $\sqrt{a}|1_V\rangle_A + \sqrt{1-a}|1_H\rangle_A$, where $a \in \mathbb{C}$, $|a| \leq 1$, $\mathbb{C}$ denotes the field of complex numbers and $|a|$ denotes the absolute value of a.

A single photon is assumed to obey quantum electrodynamics and to propagate unitarily. Given that the input to the polarizing beam splitter is $|1_V\rangle_A$, the output of the polarizing beam splitter is given by $|1_V\rangle_B|0\rangle_C$ and the photon will always be found in Port *B* when measured. Similarly, when the input is $|1_H\rangle_A$, the output of the polarizing beam splitter is given by $|0\rangle_B|1_H\rangle_C$, and the photon will always be found in Port *C* if measured. Assuming the time of photon emission is (approximately) known, it will be assumed that the start-time of the devices is synchronized to start in a short window just before the photons impinge on the devices. If the entire wave function of the photon interacts locally with the device at the start-time, it is assumed that the device will always evolve to its final state, whether the evolution is via a unitary or non-unitary process.

Suppose that in both paths there is only the vacuum state $|0\rangle$. After the interaction time, the initial ready device state $|\psi_r^0\rangle_i$ is assumed to change to a read-out state (or remains the same) that is indicative of no measurement and is denoted $|\psi^0\rangle_i, i = 1,2$. Consider the case that a photon with state $|1_V\rangle_B$ is inserted in Path B. Assuming the device always completely absorbs the photon, which will be referred to as 100% absorption, the state of Device 1 evolves to its readout state indicating that the Device has detected a photon, that will be denoted $|\psi^1\rangle_1 \in \mathcal{H}_1$. Similarly, if a photon with state $|1_H\rangle_C$ is inserted solely in Path C and Device 2 is 100% absorbing, the final state of Device 2 is denoted as $|\psi^1\rangle_2 \in \mathcal{H}_2$.

For macroscopic devices for which copies can be made, the states $|\psi^0\rangle_i$ and $|\psi^1\rangle_i$ $(i = 1,2)$ are fully distinguishable classically. Assuming that the two states are fully distinguishable and classical copies can be made, it follows by the no-cloning theorem [54] that such initial and final quantum device states must be orthogonal. However, such orthogonality is not guaranteed, and devices for which the device states $|\psi^0\rangle_i$ and $|\psi^1\rangle_i$ are not orthogonal, will be referred to as being less than 100% efficient. In order to consider such cases in more generality, we will include operations on the local electromagnetic field surrounding the devices as well as the devices themselves, denoted by System $1'$ and System $2'$.

An important assumption that is inherently made is that it is possible at least in principle to implement a unitary operation and perform a measurement on System $1'$ and System $2'$. However, a logical possibility is that it is impossible to implement one or more of the required operations because the conditions under which a measurement occurs prohibits such operations from being successfully implemented. This is an interesting possibility and is further examined in Chapter 4.

The method of state evolution of the devices is at this point unspecified as only an initial ready state and final detection state given a photon input are assumed; this is important as the device evolution can be specified either by unitary or non-unitary dynamics.