Introduction

In Chapter 1, the concept of wave-particle duality was explored. It was seen that light propagates as a wave and light can exhibit wave interference properties, but light also exists as individual quantized chunks of energy. The requirement that light is quantized in individual units originally came from Einstein's theoretical quantization predictions for light quanta. This led to the concept of wave-particle duality whereby light appears to propagate as a wave while at the same time existing in quantized individual energy units or photons. Wave-particle duality is an important concept, but by itself does not explain the measurement problem.

Einstein's 1905 proposal for the light quantum or photon was initially confirmed by experiments on the photoelectric effect by Millikan (1916) [69] and by electron-light scattering experiments by Compton (1923) [70], and Bothe and Geiger (1925) [71]. The postulate of the photon was made on the basis that the amount of energy flowing during a characteristic coherence time is small compared to $h\nu$ and that the detection process appears discrete [72]. However, the photoelectric effect could also be described semi-classically by assuming classical waves and quantized detector atoms [73] [74]. The photon concept was finally demonstrated definitively by photon-anti-correlation experiments in the 1970-80s [72] [75] [76]. In 1974, Clauser demonstrated the 'whole photon or nothing' property that photons do not split at a half-silvered mirror and that true single photons are not measured at both detectors simultaneously [75]. Thus, there exists the experimental results that once light of a single photon is detected, it is no longer found within the double slit experimental apparatus. Such experimental evidence indicates that although light may exist in quantized energies while at the same time exhibiting wave-like properties (wave-particle duality), the detection or *measurement* of the photon appears to be a process that results in some destruction of the wave-like properties of the photon within the double-slit apparatus.

In Chapter 2 characteristics of unitary evolution were explored in relation to the measurement problem. Light interferes as a wave if and only if which-way information about the path taken is not accessible. It was seen that unitary evolution generally produces entanglement and shows a difference in the state that is expected under unitary evolution when compared with the case of measurement. From experimental evidence, it is known for the case of measurement that a product state results. In the case of unitary evolution, we expect a superposition state. However, the arguments that were given in Chapter 2 did not rigorously establish that there was necessarily a real measurement problem in the aspects of wave-particle duality. That is, how do we know for general detector-photon interaction (other than a mirror) that the measurement problem doesn't go away in the sense that the expectation of a superposition under unitary evolution could be wrong and that the quantum state does become a product state. Or even if a superposition does exist, why are we assured that the particular superposition is not a sufficiently good approximation to a product state when the number of particles and interactions composing a detector becomes macroscopically large?

There have been a number of arguments in the literature indicating that there is a measurement problem (see for example Bassi et al. [77], Leggett [78], Gisin [79]), but the argument originated by the authors in this chapter is based on a constructive approach to show that there will generally be observable differences between the predictions of unitary evolution and measurement. We believe that for many, an explicit construction lends itself to a fuller understanding and appreciation of the measurement problem than an abstract argument. This construction will be utilized substantially in Chapter 4 in order to analyze various approaches that have previously been proposed to resolve the measurement problem.

In this chapter, the following will be shown:

- There is a “measurement problem” for any given configuration of particles that forms the detector
    - The argument often put forward that “somehow” the measurement problem goes away for macroscopically large detectors is conclusively invalidated.
    - Unitary evolution does not describe the quantum state evolution that occurs during measurement.