Chapter 2

Introduction to the quantum Zeno effect

The subject area of quantum measurement theory is immensely broad. To narrow the focus of this thesis we consider as a concrete example how continuous, inaccurate measurements generate the quantum Zeno effect. It is useful to first demonstrate this effect using the simplest possible measurement theory. To this end we introduce the quantum Zeno effect using the projection postulate. This demonstration serves to introduce the effect, and then to motivate first our developments of more refined measurement theories in the remainder of this thesis, and second our proposals of experimental tests for the quantum Zeno effect.

2.1 The quantum Zeno effect

In this section we introduce the quantum Zeno effect under the assumptions of instantaneous, perfectly accurate measurements modelled using the projection postulate. As we show below, the quantum Zeno effect is posed in terms of the repeated collapse of the system being measured, to its initial state, and this applies for an arbitary initial state. For this reason we only consider Type **I** measurements as any consideration of Type **II** measurements, featuring as they do, a collapse to some differing state, will not manifest the quantum Zeno effect as we define it.

We follow the simple derivation given by Peres in Ref. [53] where the passage to the continuous measurement regime is modelled by treating a sequence of n such measurements, each separated by time τ, over a total time period $t = n\tau$. The continuous limit is obtained by taking the limit $\tau \to 0$. See Fig. 2.1.

The measurement interaction (whether selective or non-selective) is modelled by the relevant projection

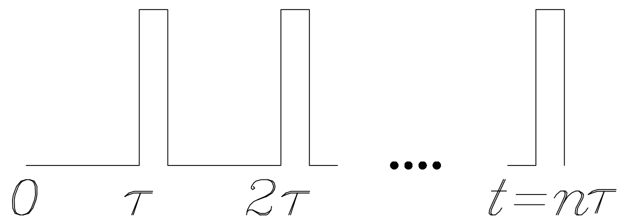

Figure 2.1: The sequence of projective measurement pulses designed to display the quantum Zeno effect in the limit $\tau \to 0,\ n \to \infty$.

operations given in Eqs. (1.5) and (1.7). In an experiment, the quantum Zeno effect is manifest in the enhancement of the survival probability of the initial state under the above measurement regime, and so we examine this probability now. We first consider a measurement interaction performing a selective operation on a system with time independent Hamiltonian possessing a discrete distribution of eigenvalues. As we consider measurements consisting of a projection onto the initial state this implies that our measurement operator also has a descrete set of eigenvalues. (This is relevant to the appearance of the quantum Zeno effect.) If the initial state at time $t = 0$ is $|\psi_0\rangle$ then the probability that the system is found in that state at time τ is obtained by applying the projector $|\psi_0\rangle\langle\psi_0|$ to the time evolved state $|\psi(\tau)\rangle$ given by Eq. (1.2).

$$\begin{aligned} P_0^{(S)}(\tau) &= \mathrm{tr}\left(|\psi_0\rangle\langle\psi_0|\psi(\tau)\rangle\langle\psi(\tau)|\right) = |\langle\psi(\tau)|\psi_0\rangle|^2 \\ &\approx 1 - (\Delta\hat{H})^2\tau^2, \end{aligned} \tag{2.1}$$

where we choose units so that $\hbar = 1$ and

$$(\Delta\hat{H})^2 = \langle\psi_0|\hat{H}^2|\psi_0\rangle - \langle\psi_0|\hat{H}|\psi_0\rangle^2, \tag{2.2}$$

and $\hat{H}$ is the Hamiltonian introduced in Eq. (1.1) which we here assume to be in the interaction picture so that $\langle\psi_0|\hat{H}|\psi_0\rangle = 0$. Here, we see that the probability that the initial state remains occupied decreases both with increasing strength of the free evolution $(\Delta\hat{H})$ and with increasing time for the free evolution to occur. We perform a selective operation on the system, and partition the ensemble based on the outcome of the measurement according to Eq. (1.5). We are interested in the proportion of systems in the ensemble that have collapsed back to the initial state. Therefore, the post-measurement state is given by $|\psi_0\rangle\langle\psi_0|$ demonstrating the "collapse" back to the initial state.

Once this is done, we have re-prepared the ensemble in the initial state $|\psi_0\rangle$, and it is then simple to repeat the above procedure. It is straightforward to show that the probability that the system is found in the initial state at every one of n independent measurements is

$$\begin{aligned} P_0^{(S)}(t = n\tau) &= |\langle\psi(\tau)|\psi_0\rangle|^{2n} \\ &\approx 1 - 2(\Delta\hat{H})^2\frac{t^2}{n}. \end{aligned} \tag{2.3}$$

Here, it is apparent that the initial state occupation probability tends to unity for $n \to \infty$. This is the quantum Zeno effect for systems with discrete eigenstates. In this case, continuous, perfectly accurate observation of the system prevents the system from coherently evolving. This is a result of the measurement feedback onto the system, and this effect must be taken into account in any experiment seeking to perform frequent observations of any sort of weak signal. If the measurement feedback is strong enough, then the continuous interaction between the system and detector overwhelms the internal system dynamics, and freezes the evolution of the system.

The measurement feedback has a similar effect when we perform a nonselective operation. In this case the matter is a little more complicated as the ensemble is not partitioned at each measurement. Consequently, we must take into account that those systems that have any occupancy outside the initial state at the completion of any measurement can unitarily evolve back to the initial state between subsequent measurements. For nonselective operations, the quantum Zeno effect is not displayed in the probability that the system is found in the initial state at every measurement, as this information is not available. Rather we complete the sequence of nonselective operations by performing a selective operation at time t. When this is done we have the probability that the system is (selectively) found to be in the initial state at time $t = n\tau$ as

$$P_0^{(NS)}(t = n\tau) = \sum_{a_1,\ldots,a_{n-1}} |\langle\psi_0|U|a_{n-1}\rangle|^2 \left(\prod_{k=2}^{n-1} |\langle a_k|U|a_{k-1}\rangle|^2\right) |\langle a_1|U|\psi_0\rangle|^2, \tag{2.4}$$

where we expand in an arbitrary basis $|a_k\rangle$ and use the evolution operator U of Eq. (1.2). The selection of the basis states is determined by the measurement apparatus being used. These basis states are referred to as the pointer basis [28]. As we are interested in measuring the occupancy of the initial state, we design our pointer basis to contain the initial state as one of its members, that is, we set $|a_i\rangle = |\psi_0\rangle$ for some i. The above is a complicated expression - and will be clarified by considering the case of a two level system in Sect. (2.1.1). We can reduce the nonselective probability to the selective probability [Eq. 2.3] by specifying all $|a_i\rangle = |\psi_0\rangle$, and eliminating the sum. This is equivalent to projecting the system back into the initial state at each (now selective) measurement. Of course, this necessitates that $|a_i\rangle = |\psi_0\rangle$ for some i. Once this is appreciated, it is seen that, in general, $P_0^{(NS)} \geq P_0^{(S)}$.

2.1.1 The quantum Zeno effect in two level systems

We narrow our focus to consider the appearance of the quantum Zeno effect in a two level system subject to continuous, projective measurements as described above. Again we note that the two level system (obviously) has a discrete set of eigenstates, and, as we wish to measure the population of the system, we choose to use these states as our measurement basis. That is we choose $|a_i\rangle$ to be equivalent to the two eigenstates of the two level system. The system will be initially prepared in one of these eigenstates, and to perform selective measurement interactions, we project onto the initial state. To perform nonselective measurement interactions, we measure the population, but take no account of the measurement outcomes. The examination of the quantum Zeno effect in a two level system is instructive as we later use this system to compare the above simple projective model of measurement interactions to the more refined theories presented later in the thesis. As well there has been one experimental test of the quantum Zeno effect [64] using two level atomic measurement, and in this thesis we will propose additional experiments for the two level systems.

We consider a two level system undergoing coherent Rabi oscillations under the Hamiltonian

$$\hat{H} = \kappa\sigma_x \tag{2.5}$$

where we make use of the Pauli spin matrices with $[\sigma_x, \sigma_y] = i\sigma_z$. The corresponding time evolution operator at time τ is

$$U(\tau) = \begin{pmatrix} \cos(\frac{\kappa\tau}{2}) & -i\sin(\frac{\kappa\tau}{2}) \\ -i\sin(\frac{\kappa\tau}{2}) & \cos(\frac{\kappa\tau}{2}) \end{pmatrix}, \tag{2.6}$$

It is relatively straightforward to determine the probability that the system is found in the initial state in each of n measurements separated by time τ in a total time t. From Eq. (2.3) this selective measurement probability is

$$\begin{aligned} P_0^{(S)}(t) &= \left(\cos(\frac{\kappa\tau}{2})\right)^{2n} \\ &\approx 1 - \frac{\kappa^2 t^2}{4n}. \end{aligned} \tag{2.7}$$

As before, it is apparent that $P_0^{(S)}(t) \to 1$ as $n \to \infty$ and thus, this equation displays the quantum Zeno effect.

We now consider the case of nonselective operations and using the same basis $|a_i\rangle$. Here, we perform n measurements, but take no account of the measurement results. The state of the system immediately after the n^{th} measurement is

$$\hat{\rho}^{NS}(t) = \frac{1}{2}\begin{pmatrix} 1 + \left(\cos(\frac{\kappa t}{n})\right)^n & 0 \\ 0 & 1 - \left(\cos(\frac{\kappa t}{n})\right)^n \end{pmatrix}. \tag{2.8}$$

It is then apparent that the survival probability of the initial state at time t (if tested by a selective operation) is

$$\begin{aligned} P_0^{(NS)}(t) &= \frac{1}{2}\left[1 + \left(\cos(\frac{\kappa t}{n})\right)^n\right] \\ &\approx 1 - \frac{\kappa^2 t^2}{4n}. \end{aligned} \tag{2.9}$$

This equation compares to Eq. (2.4). To first order these two probabilities are equal, but in general $P_0^{(NS)}(t) \geq P_0^{(S)}(t)$. The nonselective result was tested in the experiment by Itano *et.al.* [64] for increasing values of $n = 1, 2, 4, 8, 16, 32$ and 64.

In the case of either selective, or nonselective operations, the use of the simple projective theory to model continuous measurements on systems with discrete eigenstates, demonstrates that the very act of continuous observation on the system, destroys any chance of observing the system dynamics that we hoped to observe. This prediction is, of course, in contradiction to numerous experiments which routinely make use of continuous observations of quantum systems. It is this contradiction that makes the quantum Zeno effect a useful means of examining quantum measurement theory in this thesis.

2.2 Analogy to the Zeno paradoxes

The quantum Zeno effect (and a related quantum Zeno paradox) is named after the classical paradoxes of motion introduced by Zeno of Elea. These are extensively discussed in the epilogue: Chap. (9). The analogy between the quantum Zeno effect and the Arrow paradox of antiquity (Sect. 9.3.3) was first pointed out by Misra *et.al.* [52]. The classical paradox assumes discrete time instants, and considers an infinite sequence of instantaneous, arbitrarily accurate observations of the "moving" arrow. The paradox arises as the arrow is never observed to move under this measurement regime. The analogy to the quantum Zeno effect is clear, and hinges on the discreteness of the eigenstates of the measurement observable. (This has been emphasized in the examples given above.) For quantum systems with discrete eigenstates, and subject to measurements of discrete observables, there is finite separation between the initial state vector and other possible state vectors. When such a system is subject to frequent projective measurements, it is overwhelmingly likely that the wavefunction undergoes "collapse" back to the initial state at each projective measurement. This generates the quantum Zeno effect.

The related *quantum Zeno paradox* arises when we consider that a measurement interaction between a system and a detector is just a special case of a quantum system interacting with a macroscopic environment - albeit one which provides a channel for information flow from the microscopic realm to the macroscopic realm. The paradox lies in the question of why we do observe the evolution of quantum systems that are continuously interacting with either a measurement device, or an environment.

The resolution to this paradox follows similar lines to those resolving the classical paradox of motion. We do not generally observe the quantum Zeno effect in systems subject to measurement of observables with a continuous distribution of eigenstates, [though we present such an example in Chap. (4)]. A quantum system possessing a continuous set of eigenstates must always be represented by a collection of neighbouring states in the Hilbert space. When subject to a measurement, the system is not likely to preferentially collapse back precisely to its initial state. Just as in the classical paradox, the introduction of dense time and space continua permits the arrow to move, so does the conjunction between a dense time continuum and a continuous dense set of eigenstates (generally) allow the quantum system to evolve under continuous observation. This matter is not as simple as this though and will be considered in more detail in Chap. (4).

2.3 Literature survey and questions addressed by this thesis

In this section we canvass (briefly) some of the literature related to the quantum Zeno effect, with a view towards extracting the questions to be addressed in this thesis. As mentioned above, the term “quantum Zeno effect” was coined by Misra and Sudarshan in Ref. [52] and the related term “quantum watchdog effect” coined (I believe) by Kraus in Ref. [50]. Much of our work on the Zeno effect lies in using recently developed methods of quantum measurement theory, and because of this, we depart substantially from much of the previous literature in this field. In the sections above, we have followed the approach of Peres [53] and this brief paper serves as an introduction to two of the main themes of this thesis.

The first of these involves the quantum treatment of the system-detector interaction. In this early work [53], Peres demonstrated the detuning of the evolution of the system (here a two level atom) caused by the interaction with the detector (modelled via the introduction of a third atomic level). This work satisfactorily demonstrated that a quantum treatment of the combined system-detector is necessary in any analysis of the measurement interaction. Once embedded in the larger combined system-detector interaction, the evolution of the system of interest can be significantly detuned, and, this detuning hinders the evolution away from the initial state. This is a purely unitary effect. In this case measurements on such a detuned system will *not* be effecting a measurement of the system evolution of interest, but rather of the detuned system dynamics. In his work, Peres introduced the detuning, and noted its importance, but then did not treat the next stage of the measurement interaction, that is he did not provide a channel for information flow from the system-detector to the macroscopic world. We devote a large part of this thesis to providing just such a channel, and demonstrating the nonunitary measurement interaction can retune the evolution of the system of interest, and thus, we can assert that an effective measurement of the system dynamics of interest is occurring in certain circumstances.

The second issue introduced by Peres in this early paper is the appearance of the Zeno effect in various macroscopic systems. This question is also addressed in this thesis. In his paper [53], Peres considered (among other examples) the passage of a continuously monitored light beam through an active optical media. It is easy to show that, if we continuously monitor the polarization of the beam by introducing more and more polarizing elements into the media, then the polarization of the beam does not rotate. This result is not being questioned, but we assert that the similarity of the mathematical results do not make this situation analogous to the quantum Zeno effect. This effect hinges on the collapse of the wavefunction back to an initial starting state due to a measurement interaction. This formulation serves to clarify a number of questions. The first of these is whether a measurement has indeed been effected. A single polarizing element does not measure the polarization of a single photon incident on it, as further measurements are requirred to establish whether the photon transited the element or was absorbed. The assumption that such an element measures the polarization of a beam amounts to assuming that the beam is well described classically, with very large numbers of photons. This assumption of classicality suffices to prevent the use of this example as a classical instance of the quantum Zeno effect. A second question arises as to the form of the measurement interaction. The monitoring of the polarization of the light beam, does indeed return the light beam back to its starting state (with decreased amplitude), but not by any collapse mechanism. Rather this is effected by a nonunitary absorption of all photons with the "wrong" polarization. Because of these two points, we would assert that such an example does not constitute an example of a macroscopic quantum Zeno effect. In this thesis, we endeavour to examine systems with sufficiently large numbers of levels so that they well approximate semi-classical systems, and examine the conditions under which a quantum Zeno effect can be manifest. An early canvassing of the issue of macroscopic decoherence appeared in work by Simonius [58] and later by Joos and Zeh [10].

These two issues serve to categorize the field for the purposes of this thesis. We seek to address these issues by an explicit model of the measurement interaction, and, as such, our work is an extension of Milburn's in Ref. [51]. Because of this, our approach differs significantly from much of the earlier work in this area which is reviewed by Fonda, Ghirardi and Rimini in Ref. [46]. The early literature treated the unitary decay of an unstable system interacting with a continuum of states representing either an environment or a macroscopic detector. Early papers canvassed include Refs. [43, 45, 42] wherein the system-environment interaction was modelled by the Schrödinger equation. We do not take this direction in this thesis, as we feel this approach leads to considerable confusion over separating the effects of environment-caused system detuning and the measurement-induced quantum Zeno effect. Similar, but later papers include [47, 54, 50]. A paper that bridged both this unitary continuum approach, and the explicit modelling of pulsed measurements via the projection operator (as detailed in the sections above) is by Sudbery in Ref. [59].

A different approach was adopted by Joos in Ref. [49] and later by Milburn in Ref. [51] which modelled the system-detector interaction explicitly by employing the von Neumann measurement interaction model (detailed later). Joos [49] dealt with an exactly soluble model, but still suffered from some confusion over the detuning of the system evolution caused by the interaction with the measurement device. In Ref. [51], Milburn combined the von Neumann approach with recent developments in quantum measurement theory, namely, the methodology of effects and operations and techniques in describing continuous, inaccurate measurement interactions. This combination allowed the quantum Zeno effect caused by continuous, inaccurate measurement processes to be modelled using master equation techniques.

The use of master equation techniques clarifies investigations into systems interacting either with environments or macroscopic detectors. Throughout the entire history of the literature on the quantum Zeno effect there has always been an extensive interest in the issue of how the interaction with an environment effects system decay processes. Issues such as environmental influences on proton decay are canvassed in Ref. [48] and similarly in Ref. [57] but are peripheral to this thesis. Such topics are not covered in this thesis, as we focus more on the fundamentals of the measurement interaction in the quantum optical regime, and hope to propose experimental investigations into the quantum Zeno effect in this optical regime.

There have been numerous later works on the Zeno effect that cover a range of issues. For instance Peres in Ref. [56] deals with the need to use inaccurate measurements in order to monitor weak classical signals using a quantum detector. This paper was motivated by the stringent requirements imposed by tests for gravitational radiation. Complementing such experiments are simpler experiments designed to test the quantum Zeno effect in more accessible regimes. There has been one recent attempt to experimentally test the quantum Zeno effect (as discussed above). This experiment by Itano *et.al.* [64] in turn, stimulated responses in Refs. [60, 61, 63, 66]. There have been several further proposals for such experimental tests in Refs. [62, 65, 63].

The above is a brief survey of the publications relating to the quantum Zeno effect. There are further publications listed in the relevant section in the bibliography. We do not give a more extensive survey as, in this thesis, we approach this topic using new techniques from quantum measurement theory allowing the modelling of continuous, inaccurate measurement interactions. As mentioned above, these approaches start with the master equation derived under the Markoff approximation and of necessity employ the Heisenberg "cut" (detailed earlier) to separate the microscopic quantum realm from the macroscopic classical realm. This approach allows the modelling of environmental decay of quantum coherences and also permits us to introduce the technique of Quantum Trajectories. This recently developed technique permits us to model the dynamics of a single, decaying quantum system, and permits greater insight than those approaches used in the above papers. We use these techniques to model the measurement interaction and, in turn, to explicitly model the decay of single quantum systems.

2.4 The structure of this thesis

In view of the above comments, it is evident that the quantum Zeno effect has raised questions in many areas, and because of this, it provides a useful theme for this thesis. Our approach is motivated by the lessons of the epilogue [Chap. (9)] in that, we apply ourselves to the development of better tools to describe measurements, rather than seek to resolve the paradoxes surrounding the quantum Zeno effect as described by the elementary postulates of quantum measurement theory as detailed above. A further benefit of our approach is that our models will encompass the simple projective model as a special case. This, and our emphasis on proposing experimental tests of these theories, permits us to address questions such as what is the regime of applicability of the simple projective measurement model, and when can we expect a quantum Zeno effect to apply in a particular continuous measurement interaction.

We now discuss how we achieve these aims in this thesis.

- **A new model of the system-detector interaction:** The simple projective measurement model employed a projection postulate to model the outcome of a measurement interaction performed on a quantum system. This approach is improved by modelling the interaction between a system and a detector explicitly. The projection postulate must still be employed but is applied to the semi-classical meter rather than the system. This allows us to obtain better information about the measurement effected dynamics of the system. In Chap. (3) we refine previous models of the system-detector interaction by carefully selecting the parameters which define both the meter and the system-meter coupling. This coupling includes a feedback term that effects a relaxation of the meter pointer towards an appropriate read out. From this, we obtain a meter pointer with well defined position, and demonstrate that the system wavefunction undergoes a stochastic dynamical collapse.

We consider measurements of a continuous operator ($\hat{x}$) and a discrete operator ($\hat{J}_z$) on either, first, a particle moving in a potential or, second, on an angular momentum system. When we generalize to the continuous measurement limit, we introduce system master equations that well model many of the experimental systems that we propose later in the thesis. Such an approach allows us to determine the regime of validity of the continuous, projective measurement model by examining the limit of arbitrarily accurate, continuous measurements.

- **The quantum Zeno effect in tunnelling in a quartic potential:** In Chap. (4) we apply our new model of the system-meter interaction to the measurement of the position of a particle in a double well (quartic) potential. We perform both selective and nonselective operations. This serves to demonstrate the new features of our model. This specific application of our new model allows us to examine the effect of varying the accuracy of the measurement and the corresponding effect on the observability of quantum Zeno effect. Further, we use this model to gain insight into the appearance of the quantum Zeno effect in systems subject to measurement of observables which possess differing regimes that are respectively well described by either a continuous or a discrete set of eigenstates.

In the remainder of the thesis, we seek to apply the insights gained to propose possible experiments to test the quantum Zeno effect. Before we do this, however, it behoves us to examine previous experiments testing for the quantum Zeno effect.

- **Atomic tests of the quantum Zeno effect:** There has been one such previous test of the quantum Zeno effect in a quantum system with discrete eigenstates and subject to increasingly frequent pulsed measurements [64]. We consider this experiment in Chap. (5). The experiment was an explicit test of the simple projective measurement theory, and, in view of the aims of our thesis, we propose to modify the experiment so that it is more suited to a test of the continuous, inaccurate measurement theories. We demonstrate that this experiment was indeed a test of the quantum Zeno effect.

  In this chapter, we also address one of the questions raised in the previous section about when a particular interaction constitutes a measurement interaction. This question is best addressed through the elimination of the detector from the system-detector interaction, and an examination of the resulting measurement effected system dynamics. This allows us to make explicit the detuning effects of the system, and the regimes in which a measurement can be effected by allowing for the detuning.

- **Quantum Trajectories:** We model this same experiment using two measurement approaches. These are first, the ensemble approach where we consider nonselective measurement operations, and second, the selective measurement approach where full account is taken of the results of the measurements performed on individual quantum systems. In the latter case, we employ the quantum trajectories approach mentioned above. This methodology gains us insight into the measurement effected dynamics of a single decaying system. In turn, these insights complement the nonselective interpretations mentioned above.

We are now in a position to be able to propose further possible experimental tests of the quantum Zeno effect. The analysis of these proposed experiments must proceed in two stages. First, we examine a proposed measurement interaction, and second, we apply the measurement interaction to some quantum system to create the conditions for the quantum Zeno effect. This second stage includes a thorough investigation of detuning effects via a full model of the measurement interaction. In what follows we sometimes employ pre-existing well known measurement interactions such as photon counting, but in other cases, we become more speculative and propose new mechanisms for effecting quantum optical measurements.

- **Rydberg atoms and Zeno effect in a cavity:** In Chap. (6) we employ a recently proposed measurement scheme to monitor the exchange of a single photon between a cavity and a single Rydberg-atom. The measurement scheme we employ involves Rydberg-atom phase-sensitive detection [82, 83]. The cavity mode is then monitored using a beam of Rydberg atoms configured in such a way as to constitute a measurement of the cavity photon number. A beam of atoms necessarily constitutes a sequence of pulsed measurements. In the limit of very high measurement rates, we approach the continuous monitoring limit, and derive a measurement master equation for the system of interest. It turns out that the master equation is equivalent to the angular momentum model introduced in an earlier chapter.

- **Nondemolition measurement of photon number:** In Chap. (7) we utilize quantum nondemolition photon counting techniques to realize the quantum Zeno effect on the evolution of either a two level Jaynes-Cumming atom interacting with a resonant cavity mode, or on two electromagnetic modes configured as a multi-level parametric frequency converter. These systems interact with another electromagnetic cavity mode via a quadratic coupling system based on four wave mixing and constructed so as to be a nondemolition measurement of the photon number. This mode is then coupled to the environment, through the cavity mirrors, thus providing a channel for information to flow to the macroscopic realm. Again, we analyse the effects of the measurement on the dynamics of the system by eliminating the detector to obtain the measurement effected dynamics of the system of interest. By doing this the measurement is shown to be a measurement of system populations, which generates the desired Zeno effect. Further, we show that the system dynamics are again subject to the angular momentum master equation.

- **The quantum Zeno effect in the classical limit:** The above experimental proposal, which involves systems equivalent to angular momentum systems, enables us to examine what happens to the quantum Zeno effect as the number of levels of the system of interest goes to infinity. This approximates a sort of semi-classical limit. In this case, the angular momentum system approximates a semi-classical rotation system with an almost continuous distribution of eigenvalues of the angular momentum operators. Because we considered an explicit model of the measurement interaction, we are able to model the time over which the measurement interaction is completed. The explicit modelling of this detector resolution time then provides a testable limit to the regime of applicability of the quantum Zeno effect. This enables us to address the question of why the quantum Zeno effect is not applicable in the classical limit.

In the remaining chapter of this thesis we examine a proposed measurement technique that allows us to measure the square of the quadrature phase of a cavity mode, and thus of higher order squeezing effects. This measurement analysis is related to the continuous measurement model proposed in Chap. (3).

- **Measurements of the square of the quadrature phase:** In Chap (8) we frame a new measurement proposal to monitor the square of the quadrature phase of a cavity mode. We discuss a quantum nondemolition measurement based on a three mode interaction mediated by a second order nonlinear susceptibility. All three modes are treated quantum mechanically. The signal field is taken as one of the three modes and the probe field is the combined field in the other two modes. If the two modes of the probe system are initially in number states, the interaction between the signal and probe is equivalent to that between a harmonic oscillator and an angular momentum system. Photon counting on the probe field realises a quantum nondemolition measurement of the square of a quadrature phase amplitude of the signal and thus provides a direct measurement of second order squeezing.

- **Epilogue - Zeno and the art of measurement metaphysics:** Finally, we close this thesis with a frankly speculative look at the relationship between quantum measurement theory, and its associated metaphysics. However, rather than state our own, personal view on this subject, we seek to break new ground by examining the merits of the process by which a quantum metaphysics is articulated. To do this we carefully distinguish between a a fully articulated metaphysics and the process by which that metaphysics was articulated. As an example, we all generally (depending on our personal preferences) take different account of a metaphysics depending on wheterh its formulation was based on extending the axioms of a science or on extending the assumptions of an established religion.

With this in mind, we turn to examine the processes by which quantum metaphysical theories have been established. This speculative examination is based on a history of preceding metaphysical formulations. Specifically, we examine the history of the metaphysics associated with the classical paradoxes of Zeno of Elea. We establish in this epilogue, that first, there are strong similarities between the metaphysics of millenia ago and the quantum metaphysics propounded today, and second, that the conduct of metaphysics is often a flawed enterprise as it is so often based on the incorrect extension of poorly understood mathematical tools.

We apply these two conclusions to the process by which quantum metaphysical formulations are proposed to conclude that it is not yet the right time to successfully articulate a satisfactory theory of quantum metaphysics. Not only do we not yet possess the requisite tools of quantum measurement theory, such tools as we do possess are poorly understood.

The conclusions established in this epilogue are used to justify the glaring lack in this thesis on quantum measurement theory, of any strongly proposed "meaning" of the loosely used terms like "collapse of the wavefunction", the "Heisenberg cut" and such like. While we use these terms, and build an intuitive understanding of their use by comparison of theory to experiment, in this thesis we do not constrain our intuition by attempting to strongly assert a universal "meaning" to these common terms in the theory.