

## Chapter 1

### Introduction

Quantum theory [1, 2] has been with us now for sixty-five years. It is, most physicists believe, the underlying description of all physical phenomena, and it certainly is unparalleled in the accuracy of its quantitative predictions [3] and in the breadth of its applicability. However, certain aspects of quantum theory are, as yet, poorly understood. For instance, the transition between quantum and classical mechanics is still elusive: in particular, the conflict between the classical phenomenon of chaos [4] and Heisenberg's Uncertainty Principle [2] is only beginning to be understood and resolved [5, 6]. And, in general, a better understanding of how the transition from a microscopic to a macroscopic description of matter and how "emergent properties" [7] arise, would be desirable.

Even the formulation of quantum mechanics seems paradoxical in certain respects. In general, quantum mechanics allows for the possibility of *superposition states*. A classic (though not classical!) example is the two-slit experiment [8], in which we consider light which passes through a solid screen with two slits cut in it and then is detected on a piece of photographic film (or some other such photo-detector). At high light intensities, the film shows the alternating bright and dark bands due to constructive and destructive interference from the two possible paths from the source to the film. However, if we turn down the intensity to low levels, then we detect single photons on the film. This implies that the photons must pass through the slits one at a time. The distribution

of these photons, however, still follows the pattern of bright and dark bands, indicating interference. This implies that a single photon must, in some sense, “pass” through *both* slits on its way to the film or, at least, that the probability of detecting the photon at a given location must depend on information from both paths. We say that the photon’s path from source to film is a superposition of both possible paths, even though, if we place a photo-detector at the location of the slits, we will only ever detect a photon at one slit *or* the other. Although any particular measurement of the photon’s location will find it at one and only one place, we see the “shadows” of superpositions reflected in the *probabilities* of detecting photons at a particular location.

Even these “shadows” of superposition properties disappear when we reach the realm of the macroscopic. And yet, if quantum mechanics is a complete theory of our universe, it ought to describe both microscopic and macroscopic objects. To highlight this paradox, Schrödinger proposed the *gedankenexperiment* involving his now-famous cat [9]. This *gedankenexperiment* involves a box containing a single radioactive nucleus, a bottle of cyanide with a trigger mechanism to release this material, and a hapless feline. If the nucleus decays, then the trigger is activated, and the cat is killed. However, quantum mechanically, after some period of time on the order of the half-life of the nucleus, the nucleus must be described as being in a *superposition* of undecayed and decayed. Since the state of the cat is correlated with the state of the nucleus, the *cat* must be described as being in a superposition of alive and dead. We have absolutely no evidence that cats are ever found in such a state!

Two of the main impediments to really understanding what quantum mechanics is trying to tell us about the universe, then, are understanding the apparent disappearance of superposition properties in the course of a single measurement and the apparently complete lack of superposition behaviour in macroscopic objects. In some sense, these issues may be the same: since we, who ultimately register the outcome of measurements in our state of being, are macroscopic objects, it may be this fact which

destroys superposition in measurement. But it is not entirely clear if, and how, this might happen.

Part of the conflict on the first point seems to arise from the fact that standard formulations of quantum mechanics interpret it as an inherently probabilistic theory, which makes only statistical predictions: on the other hand, we appear to only experience a *single* reality. Particularly when dealing with separate objects whose properties are correlated but which properties are prepared in a superposition state (so-called “entangled”) systems, this interpretation can seem paradoxical. This conflict has led some physicists (e.g. Einstein, Podolsky, and Rosen [10]) to propose that quantum mechanics is an incomplete theory. Others of the “founding fathers” [11] disputed this contention.

According to the standard, Copenhagen interpretation, time evolution in quantum mechanics falls into two categories. The first is unitary time evolution, described by the Schrodinger equation. The second, which describes the outcome of measurements (by classical-like apparatus), is the explicitly non-unitary “collapse of the wave function” to one and only one of the measurement eigenvalues [2] and the subsequent renormalization of the wave function.

However, the “classic” Copenhagen interpretation requires the existence of classical measuring devices, which are not described by quantum theory. Any attempt to dispense with these necessitates positing the physical reality of the collapse of the wave function. Quantum theory provides no explanation of how this occurs. It certainly seems difficult to explain this through the Schrodinger equation, which is unitary. Indeed, the “measurement paradox,” as it is called, has provoked much discussion (for a good, “plain English” review of what the problem is, and a description of several physicists’ approaches to resolving it, see Ref. [12]).

Physicists have proposed various ways to resolve the “measurement paradox.” Some proposals attempt to do so with only the mathematical apparatus prescribed by quantum theory: examples are the “many-worlds” interpretation [13, 14], the “de-

coherence approach” [15], and the “consistent histories” or “decoherent histories” approach [16, 17]. Others [18] posit the existence of new fundamental physical processes or even [19] [20](Ch. 22) a different, entirely non-quantum description of the universe. Many of these theories tie in the resolution of this paradox with the disappearance of superposition properties in “large” objects. The detailed mechanism by which the superposition properties disappear of course differs from theory to theory. For example, in some approaches [18] “large” refers to systems with large numbers of particles. In others [15], “large” refers to distinguishable quantum states of a system coupled to a larger system with many degrees of freedom.

It would be desirable, therefore, to be able to study quantum mechanics in a well-controlled environment. Perhaps, if we can simplify experiment down to the essentials, we can obtain a more precise understanding of what quantum mechanics means. Or, if we can control the quantum behaviour of a very simple quantum system, perhaps we can begin to build up “quantum complexity” in a controlled manner and see how emergent behaviours come about. In addition, experiment often demands description in very precise terms and this can sometimes lend clarity to the essentials of a theory.

This thesis will describe experiments involving a single  ${}^9\text{Be}^+$  ion confined in an rf (Paul) trap. These experiments realize two of the simplest quantum systems: the two-level system and the harmonic oscillator. The two-level system is comprised of two, ground-state hyperfine electronic levels. The trapping potential is harmonic, to a high degree of approximation, and so the ion’s motion is that of a three-dimensional harmonic oscillator. When we laser cool [21, 22, 23, 24] this motion to near its ground state [25], the quantum properties of the motion become significant.

By coupling the ion’s motional and electronic degrees of freedom with lasers, we can engineer entanglement between these quantum systems. Although these dynamics can be well-described theoretically [26, 27, 28, 29, 30], they still offer many surprises. Furthermore, if several ions are held in the trap, their Coulomb interaction causes

their motion to become a joint property of all the ions. Thus, we can create quantum entanglement between the ions' electronic and motional degrees of freedom, and between the electronic degrees of freedom of different, spatially separated ions. This allows us to begin building up “large” quantum systems (in either of the above senses) in a well-controlled way. We refer to this as “quantum state engineering.”

Being able to controllably engineer quantum states, and to isolate them from outside influences, allows us to investigate the new ideas of “quantum computation” [31, 32, 33, 34, 35, 36]. This field has grown out of the realization that “information is physical” [37], but really took off with the discovery in the early 1990's [38, 39] that a computer which utilizes quantum superposition can be exponentially more efficient at solving certain problems than any classical computer. The component parts of a quantum computer, called “qubits,” must be well- insulated from outside influences (which cause decoherence — the destruction of superposition) while interacting with each other strongly enough to allow conditional logic. Trapped ions addressed by laser beams [40] offer such a system. We are attempting to construct simple quantum information processors [41] with our system, and to study the scalability of trapped ions for quantum computing. Furthermore, since many aspects of wave function collapse seem to deal with the transfer of information between quantum systems, it may well be that the language of quantum information theory (quantum computation) will shed light on the issues discussed above [42, 43].

In this thesis, I will describe some of the experiments which we have performed in the NIST Time and Frequency Division Ion Storage Group. I will begin by describing in general how we confine charged atoms using time-varying electric fields (Ch. 2), and how the trapping potential modifies the atoms' interactions with laser radiation (Ch. 3). I will go on to describe the particular arrangement of apparatus actually used in our experiments (Ch. 4). From that point, I will describe laser cooling one [44] or more [45]

trapped ions to their ground state of motion. This puts the ion's motion into the quantum regime of behaviour, and is the starting point for quantum state engineering.

In the rest of the thesis (Chapters 6 through 9), I will describe creation of various non-classical states of motion [46, 47, 48] and entangled states [49] and the application of quantum state engineering to quantum logic [41]. The same techniques may be used to allow the ion's motion to interact with the "outside world." I will discuss experiments along these lines [50], and their implications for decoherence studies and quantum measurement theory in Ch. 8, and conclude by discussing a proposal for an experiment to measure a "surprising" quantum phase factor: Berry's phase.