CHAPTER 1

INTRODUCTION

The emergence of quantum mechanics as a fundamental theory of nature symbolizes one of the greatest revolutions in physics. Since its inception eighty years ago, the theory has introduced stunning new ideas and made precise predictions about a wide range of physical phenomena. Quantum mechanics has the unique distinction of being the most successful 'working theory' of nature and there is no known example of any conflict between its predictions and experimentally observed results. The theory offers convincing explanations for the structure of the atom and the nucleus, the conduction of electricity, and the properties of solids among many other important phenomena. However, in spite of this tremendous success, physicists cannot stop debating the real meaning of the quantum theory. The concepts of quantum mechanics seem almost absurd when related to the world of our experience - the familiar physical world, and the philosophical implications of the theory remain highly controversial. Quantum mechanics, it seems, fails to provide a natural framework to accommodate our 'classical' perceptions of the physical world. Our perceptions of the world around us are classical in the sense that they are based on classical ideas like Newton's laws and well-understood concepts like precise positions, momenta and trajectories. A central concept of classical dynamics is predictability. Classical systems evolve deterministically and are expected to possess definite properties or 'elements of reality'. Quantum mechanics, however, calls for a radically different vision of the world. The quantum view is abstract and
counterintuitive.

At the heart of quantum mechanics is the wave function $|\psi\rangle$, a mathematical entity which contains all possible information about the system to which it is attributed. The wave function evolves in time according to the Schrödinger equation, which is linear and deterministic. The wave function (state vector), however, does not have a physical counterpart since it itself is not 'observable'. Inspite of the apparent determinism manifested in the Schrödinger equation, a knowledge of $|\psi\rangle$ does not ensure a precise knowledge of the observable properties of the system - the kind we are familiar with in the 'classical' world, e.g., position, momentum etc. The dynamical variables or observables are represented in quantum mechanics by linear hermitian operators, which act on the state vector. An operator $\hat{A}$ corresponding to a dynamical quantity $A$ is associated with eigenvalues $a_i$s and the corresponding eigenvectors $|\alpha_i\rangle$, the latter forming a complete orthonormal set, so that any arbitrary state vector $|\psi\rangle$ can be expanded as a linear superposition of these eigenvectors, i.e., $|\psi\rangle = \sum_i \alpha_i |\alpha_i\rangle$. The basic postulate of quantum mechanics is that a measurement of $A$ can yield only one of the eigenvalues $a_i$, but the result is not definite in the sense that different measurements for the quantum state $|\psi\rangle$ yield different eigenvalues. Quantum mechanics predicts the probability of obtaining the eigenvalue $a_i$ to be $|\alpha_i|^2$. This also implies that if the state $|\psi\rangle$ is one of the eigenstates $|\alpha_i\rangle$, then the result of the measurement is definitely $a_i$. The general state $|\psi\rangle$ can well be expanded in any basis which forms the complete eigenfunction set of any other observable whose observed values and their probabilities can be calculated.
similarly. Thus we see that the state vector contains familiar classical properties only as potentialities which emerge only when a measurement is performed. *Familiar classical perceptions are only potential outcomes of a measurement on a quantum system, they are not part of the quantum mechanical framework*. Consider the actual measurement process in which a system is brought in contact with an apparatus. This process can be visualized in the following way. The interaction with an apparatus purporting to measure $\lambda$ forces the state $|\psi\rangle$, which in general is a linear superposition of the eigenstates $|\alpha_{i}\rangle$, to go into one of the states $|\alpha_{k}\rangle$, and yield $a_{k}$ as the measured quantity. Clearly such a collapse cannot occur if the apparatus is also another quantum system, since under those conditions one would have the unitary evolution (Zurek 1981) of the combined quantum state of the system and the apparatus. This should again result in a quantum state which can be regarded as a superposition of states in any number of ways. This means that the act of measurement, which inevitably requires a sudden collapse of the state vector into one of the eigenstates of the dynamical operator, falls outside the realm of quantum mechanics. This leads to a serious difficulty in interpreting the connection between the 'classical' and the 'quantum'. Is there a definite relationship? Are classical mechanics and quantum mechanics two mutually exclusive incompatible theories or are they two aspects of the same underlying philosophy? We are confronted with the paradoxical situation where the state of a quantum system is meaningfully defined only with respect to the classical world. It is necessary that there already exist macroscopic concepts, such as a measuring apparatus, before microscopic properties, such as the position of an electron, have any meaning. On the other hand, classical objects are eventually comprised of elements of the microworld.
which can be described quantum mechanically. The quantum and the classical undoubtedly share an intimate bond.

Quantum mechanics is characterized by distinct nonclassical features which stem from its basic formalism that involves concepts like wave function or probability amplitudes, rather than probabilities. Heisenberg's uncertainty principle, the legitimate existence of states which are superpositions of macroscopically distinct states (popularly known as 'Schrödinger's cat paradox') (Schrödinger 1935), and the celebrated E-P-R paradox which demonstrates 'nonlocal' correlations (Einstein et al 1935) are some of these unique quantum features. These together with the 'measurement problem' represent quantum theory's strongest contradictions with classical physics. Several people have raised serious doubts about the validity of quantum mechanics as a theory of nature. How does quantum mechanics with these strange ideas unfold to give us the 'reality' of the familiar physical world? Can quantum mechanics actually be the fundamental theory of nature even though the world around us is far from being bizarre and spooky?

Experiments are the final test of any theory. That quantum mechanics is indeed the fundamental theory of nature is a fact firmly established and proven through a series of highly sophisticated experiments. The real impetus to experimentally test quantum mechanics came from John Bell's historic derivation of an inequality in 1965 (Bell 1965). According to Bell's theorem, the degree of cooperation between separated systems cannot exceed a certain definite maximum if one assumes the condition of locality. Quantum mechanics predicts that this limit can be exceeded and hence it is nonlocal. Advances
in technology enabled experimental tests to be conducted on Bell's inequality. In 1982 Alain Aspect and his colleagues at the University of Paris conducted an experiment with correlated photons which demonstrated the violation of Bell's inequality (Aspect et al. 1981, 1982). This experiment left little room for doubt that quantum theory is, indeed, nonlocal, and its bizarre ideas are true. With this overwhelming result, quantum theory reasserted its position as the fundamental theory of nature, and in one stroke demolished cherished common sense concepts about the nature of reality.

Quantum theory's unusual concepts, however, continue to puzzle and many questions about its connection with perceived classical dynamics remain unanswered. If quantum theory is, indeed, the fundamental theory of nature, then how does it explain classicality? How does familiar classical dynamics emerge from a quantum substrate? How do nonclassical features like nonlocality and superposition states disappear to give us the classical world which is more meaningful to us? How can the 'collapse' of the wave function be explained within the framework of quantum theory? What is the resolution to the measurement problem?

The main emphasis in this thesis is to probe the 'quantum-classical' connection keeping in view the following two perspectives: (i) the observation of various nonclassical and nonlocal features of light necessarily leads to a quantum mechanical treatment of such problems, and (ii) quantum mechanics should explain the measurement process and the observed classicality should emerge from quantum dynamics. The first half of
the thesis deals with (ii), i.e., the general problem of resolution of the measurement paradox. In Chapter 2, the 'environment-induced decoherence' approach is employed to study the measurement of a quantum spin by two different models of the measuring apparatus. The role of the environment is central to the entire treatment. It is based on the realization that an apparatus, being macroscopic, is never isolated from its environment. The interaction with the environment is dissipative and leads to a decoherence in the superposition states of the apparatus making its behaviour classical. We analyse two models of the apparatus. First we take the apparatus to be a quantum two-level system in a manner similar to that considered by Zurek (1981). Our analysis (Venugopalan et al 1993, 1995) reveals certain difficulties with Zurek's treatment and we show that the model does not really accomplish a measurement of the spin state of the system. We then analyse a Stern-Gerlach type apparatus in which a spin measurement is achieved by letting the position variables of the particle interact with an environment. This allows for a spin measurement via a momentum measurement on the particle with associated probabilities in accordance with quantum principles. We then look at the implication of environmental influence in a spin recombination setup. The role of the environment on the quantum correlations as seen in Bell inequalities (Bell 1965, Clauser and Shimony 1978) is studied by examining an E-P-R singlet state in an environment modelled by a fluctuating magnetic field. The analysis shows that environmental influence destroys these correlations over a time scale which depends on the parameters of the fluctuating field. The role of the 'preferred basis' (Zurek 1991, Zurek et al 1993) in the emergence of classicality from quantum dynamics is also examined in detail (Venugopalan
The second half of the thesis deals with (i) and the problem related to quantum fields of light. The birth of quantum mechanics was intimately linked with the theory of light. It was Planck's revolutionary idea to quantize the energy of an oscillator to explain the spectrum of black body radiation that led to the emergence of quantum theory in 1900. Prior to this, Maxwell had firmly established that light is an electromagnetic wave. Planck's theory along with Einstein's explanations of photoelectric effect in 1905 led to a new understanding of the nature of light. According to these new ideas, light is comprised of "particles"—quanta of energy called photons. The theoretical methods of quantum mechanics led to the formulation of the quantum theory of radiation. Although most phenomena in the field of optics are adequately described by the classical wave theory, there are some instances in which one has to invoke the quantum theory of light. Experimentally observed characteristics of antibunching (Teich and Saleh 1988, Walls 1979), sub-Poissonian statistics (Mandel 1979), squeezing (Walls 1983), quantum interference (Ghosh and Mandel 1987, Ghosh et al 1986, Mandel 1983) require the quantized field description. These effects survive the essentially classical act of measurement. There is also the case of quantum mechanical nonlocality which has prompted several optical correlation experiments (Kocher and Commins 1967, Aspect et al 1981, 1982) to probe the E-P-R paradox (Einstein et al 1935). The E-P-R experiments generally involve the measurement of the probability $P(\theta_1, \theta_2)$ that two photons are detected behind two linear polarizers oriented at angles $\theta_1$ and $\theta_2$. When the two photons are in a singlet state with respect to polarization, the probability $P(\theta_1, \theta_2)$ is
proportional to $[1 + \cos(\theta_1 - \theta_2)]$, which means that certain combinations of $\theta_1, \theta_2$ lead to a joint detection probability of zero, even when the individual probabilities $P(\theta_1)$ and $P(\theta_2)$ are nonzero—a very nonclassical state of affairs! Each of these quantum phenomena is normally expressed by the violation of a particular inequality associated with the quantum state under consideration. Methods of nonlinear optics are frequently used to generate nonclassical light. It is known that the strong correlations between the output modes generated in nonlinear processes, such as multimode parametric amplifiers and four-wave mixing, may lead to a violation of classical inequalities. Thus fields generated in such processes provide an excellent means of studying the ‘quantum-classical’ connection in depth. In Chapter 3 we propose a scheme for quantifying these nonclassical features via the parameters of phase-space distribution functions which can be associated with the fields. We consider an optical correlation experiment where two coupled modes are generated in a nonlinear optical process. The fields generated here can be described by a Wigner distribution function which is a Gaussian centered around the mean value of the field. We show (Venugopalan and Ghosh 1991, 1993) that the Bell inequality for these modes can be expressed as an inequality relating to the parameters of the underlying Wigner distribution function. Thus, the ‘quantum-classical’ connection is brought out via the quantum conditions on the distribution function parameters.

In Chapter 4 we examine this connection through the interesting class of two-level systems. We study (Venugopalan et al 1993) a model of a classical optical experiment which displays features that are associated with a discrete two-level quantum system. A simple model of scattering of two
optical propagation modes (clockwise and counterclockwise) by a partial reflector in a passive ring cavity is studied. Such systems have been extensively studied in the context of using optical cavities to create two-level systems (Spreeuw et al 1990). In our study we start from the actual dynamical equations for the electromagnetic field and give explicit forms for the frequencies of the split modes in terms of the parameters of the reflector. Our results differ from the conventional 'coupled oscillator model' for such systems (Spreeuw et al 1990). Finally, in Chapter 5 we summarize the main results in this thesis with a brief 'outlook'.
References


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