Preface

Over the course of the past decade, decoherence has become a ubiquitous scientific term popular in all kinds of research, from fundamental theories of quantum physics to applications in nanoengineering. Decoherence has been hailed as the solution to long-standing foundational problems dating back to the beginnings of quantum mechanics. It has been cursed as the key obstacle to next-generation technologies, such as quantum computers (another seemingly omnipresent field of research). And while decoherence has been directly observed in various experiments, its scope and meaning have often been misunderstood and misrepresented. Decoherence makes a fantastic subject of research, as it touches upon many different facets of physics, from philosophically inclined questions of interpretation all the way to down-to-earth problems in experimental settings and engineering applications.

This book will introduce the reader, in an accessible and self-contained manner, to these various fascinating aspects of decoherence. It will focus in particular on the relation of decoherence to the so-called quantum-to-classical transition, i.e., the question of how decoherence may explain the emergence of the classical appearance of the macroscopic world around us from the underlying quantum substrate.

The scope of this book is relatively broad in order to familiarize the reader with the many facets of decoherence, in both the theoretical and experimental domains. Throughout the book, I have sought to maintain a healthy balance between the conceptual ideas associated with the decoherence program on the one hand and the formal and mathematical details on the other hand. This book will establish a proper understanding of decoherence as a pure quantum phenomenon and will emphasize the importance of the correct interpretation of the consequences and achievements of decoherence.

One beautiful thing about learning about decoherence is that, as vast as its implications and applications are, the basic ideas and formal structures are actually quite clear and simple. As a general rule, I will wherever possible avoid muddling important general insights with complicated mathematical exercises. A basic knowledge of the formalism of quantum mechanics should suffice to follow most, if not all, explanations and derivations in this book. While certain sections inevitably contain somewhat lengthy mathematical considerations (the derivation of master equations in Chaps. 4 and 5 is

probably the most striking example), readers less interested in these formal structures underlying the decoherence program should be able to just glance over these sections—or even skip them altogether—without significantly compromising their understanding of other parts of the book. At the same time, the more advanced material included in this book will be useful to the working physicist who may already have some knowledge of decoherence and is looking for a self-contained and detailed reference. Philosophers of physics interested in the foundations of quantum mechanics should also find plenty of interesting material throughout this book (especially in Chaps. 1, 2, 8, and 9).

The book is organized as follows. In Chap. 1, we will take a first "bird's-eye look" at decoherence by introducing some of the basic ideas and concepts. We will emphasize the importance of considering "open" quantum systems in addressing some of the long-standing issues of quantum theory, and contemplate why it may have taken over half a century for this realization and the ideas of the decoherence program to take hold.

The core chapter of the book is Chapter 2, in which we will introduce and discuss in detail the key conceptual ideas and formal descriptions of decoherence. First, we will analyze fundamental concepts of quantum mechanics, such as quantum states (and their differences to classical states), the superposition principle, quantum entanglement, and density matrices. A proper grasp of these topics will turn out to be very important for the development of a solid understanding of decoherence. We will then illustrate and discuss different components of what has become known as the "quantum measurement problem." This problem encapsulates many of the fundamental conceptual difficulties that have to this date prevented us from arriving at a commonly agreed-upon understanding of the physical *meaning* of the formalism of quantum mechanics and of how this formalism relates to the perceived world around us. The measurement problem is also intimately related to decoherence, since decoherence has direct implications for the different components of the problem.

We will then illustrate basic concepts of decoherence in the context of the well-known double-slit experiment. This approach will allow the reader to develop a rather natural understanding of decoherence as a consequence of environmental "monitoring" and quantum entanglement. It will also establish a modern view of Bohr's famous "complementarity principle." We will formalize decoherence in terms of system–environment entanglement and reduced density matrices and discuss the two main consequences of decoherence, the environment-induced suppression of quantum interference and the selection of preferred "pointer" states through the interaction with the environment.

After the reader has thus become familiar with the ideas and formalism of decoherence, the subsequent chapters can either be read in order, or the reader may focus on particular chapters of interest. Each chapter is designed

to present a fairly self-contained discussion of a particular aspect of decoherence.

In Chap. 3, we will consider a very important model that describes decoherence of quantum objects due to collisions with environmental particles such as photons and air molecules. This scattering-induced decoherence is ubiquitous in nature and of paramount importance in describing the quantum-to-classical transition on macroscopic everyday-world scales.

Next, in Chap. 4, we will introduce the master-equation formalism that provides us with a general method for determining the dynamics of decoherence models in many cases of physical interest. We will spend some time deriving the important Born–Markov master equation that will allow us to treat many decoherence problems in a fairly straightforward and intuitive fashion.

In Chap. 5, we will then show how a large class of system–environment models can be reduced to a few "canonical" decoherence models. We will then analyze these models in detail. In particular, we will discuss so-called quantum Brownian motion, which can be viewed as the quantum approximation to the familiar classical Newtonian trajectories in phase space. We will also introduce the famous spin–boson model which has recently received additional attention in the context of quantum computing.

After so much theoretical material, the reader will certainly be longing for a break. Thus, in Chap. 6, we will describe some fascinating experiments that have made it possible to directly observe in the laboratory the gradual action of decoherence and therefore the transition from the quantum world to the classical domain.

In Chap. 7, we will shift gears somewhat and enter the field of quantum computing that has attracted so much interest over the past decade. We will explain the crucial role that decoherence plays in this field. We will then describe how the effects of decoherence can be mitigated through sophisticated (but ultimately easy to understand) methods such as quantum error correction, decoherence-free subspaces, and environment engineering.

Chapter 8 will discuss the implications of decoherence for several of the main interpretations of quantum mechanics. We will describe how decoherence may enhance, redefine, or challenge the most common interpretations, such as the orthodox and Copenhagen interpretations, relative-state interpretations, physical collapse models, modal interpretations, and Bohmian mechanics.

Finally, in Chap. 9, we will discuss the role of the observer in quantum theory and the question of decoherence processes in the brain. We will explain why this question is of interest in the first place and then review some explicit model calculations that demonstrate the efficiency of decoherence in the brain. The implications of these results will be discussed, in particular with respect to a "subjective" observer-based resolution of the measurement problem.

A brief remark on notation. I have set $\hbar \equiv 1$ throughout most of the book except in situations where explicit numerical estimates play a role. In this way, I hope to have kept the notation as clear as possible without compromising the reader's ability to derive and reproduce numerical values where needed.

There are many people who have contributed to making this book possible. First and foremost, I would like to thank my Ph.D. advisor, Arthur Fine, for giving me both the freedom and guidance to study the field of decoherence. He suggested to me that I write up some "personal notes" on decoherence so that he and I would better understand this area of research (which was, at the time, new to both of us). These notes evolved into a review article on decoherence [1], which in turn motivated this book. In this context, I am deeply indebted to H. Dieter Zeh for many helpful discussions and for bringing the idea for this book to the attention of Angela Lahee, editor at Springer, who has since lent her patient, encouraging, and helpful support to every aspect in the production of this book.

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