QUANTUM EFFECTS IN BIOLOGY

Quantum mechanics provides the most accurate microscopic description of the world around us, yet the interface between quantum mechanics and biology is only now being explored. This book uses a combination of experiment and theory to examine areas of biology believed to be strongly influenced by manifestly quantum phenomena.

Covering subjects ranging from coherent energy transfer in photosynthetic light-harvesting, to spin coherence in the avian compass and the problem of molecular recognition in olfaction, the book is ideal for advanced undergraduate and graduate students in physics, biology, and chemistry seeking to understand the applications of quantum mechanics to biology.

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Frontmatter
More information

Contents

Foreword

When the revolutionary conceptual structure for the description of the physical world which we know as quantum mechanics was first formulated nearly 90 years ago, and its predictions tested in the laboratory, most of the experiments in question were on systems which were both very well characterized and reasonably well isolated from their environments, such as single electrons and atoms, small molecules and near-perfect crystalline solids.

While from the very start most physicists have taken it for granted that the formalism of quantum mechanics, when combined with appropriate system-specific information, can "in principle" account for all phenomena occurring in the physical world, including those usually regarded as the subject-matter of biology, until quite recently the overwhelmingly majority opinion has been that in a biological context the role of quantum theory is confined to elucidating the equilibrium structures of the relevant molecules and their reaction processes, and that subtle phenomena such as superposition and entanglement, of which we can now routinely exhibit spectacular effects at the level of a few well-isolated photons or atoms, play at most a very indirect role in any phenomena of biological interest. A major reason conventionally given for this view has been that biological systems, at least working ones, are by their very nature "warm and wet" – a phrase which in the physicist's lexicon translates to "prone to massive decoherence"; it looks as though any interesting superposition, say of different energy eigenstates of one's system, would be rapidly decohered by the ever-present, and usually microscopically very complex, environment.

Over the last decade or so, however, it has become clear that this conclusion may be (from the point of view of the quantum theorist!) unduly pessimistic. There is by now rather convincing evidence that non-trivial quantum superpositions occur in the first stages of photosynthesis, and a plausible argument that they play a role also in the intriguing phenomenon of bird navigation; as argued in some of the chapters of this book, there are other biological contexts in which a significant role for superposition and possibly even entanglement are not excluded by the traditional arguments.

This situation poses a major challenge to our understanding of the more general and long-studied subject of "open quantum systems," that is, systems which may show subtle quantum effects even while in intimate contact with a complex and noisy environment, which may not even be reproducible from shot to shot of the experiment. Over the last few years many have risen to this challenge on the experimental, theoretical and computational fronts, with intriguing results; one particularly striking observation has been that under certain circumstances a noisy environment may actually enhance the characteristically quantum-mechanical features of the behavior of the system. This book should provide the reader with a broad-based introduction to this fascinating and rapidly developing field of research.

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Preface

Recent progress in science and technology has led to the revival of an old question concerning the relevance of quantum effects in biological systems. Indeed Pascual Jordan's 1943 book, *Die Physik und das Geheimnis des Lebens* had already posed the question "Sind die Gesetze der Atomphysik und Quantenphysik für die Lebensvorgänge von wesentlicher Bedeutung?" (Are the laws of atomic and quantum physics of essential importance for life?) and coined the term Quanten-Biologie (quantum biology). At the time this question was essentially of a theoretical nature as the technology did not yet exist to pursue it in experiment.

Indeed quantum biology has been benefiting considerably from the refinement in experimental tools which is beginning to provide direct access to the observation of quantum dynamics in biological systems. Indeed, we are increasingly gaining sensitivity towards quantum phenomena at short lengths and timescales. In recent years, these newly found technological capabilities have helped to elevate the study of quantum biology from a mainly theoretical endeavour to a field in which theoretical questions, concepts and hypotheses may be tested experimentally and thus verified or disproved. We should stress here that experiments are essential to verify theoretical models because biological systems already have a complexity and structural variety that prevents us from knowing and controlling all of the aspects. Results obtained using these refined experimental techniques lead to new theoretical challenges and thus stimulate the development of novel theoretical approaches. It is this mutually beneficial interplay between experiment and theory that promises accelerated developments within the field.

Biological systems tend to be warm, wet and noisy (the latter because they are exposed to environmental fluctuations), conditions which are normally expected to result in rapid decoherence and thus suppression of quantum features. Therefore quantum phenomena may at first sight seem to be unlikely to play a significant role in biology. Note, however, that at the level of molecular complexes and proteins, important biological processes can be very fast (taking place within picoseconds) and well localised (extending across a few nanometres, the size of proteins) and may thus exhibit quantum phenomena before the environment has had an opportunity to destroy them. Hence the possible existence of significant quantum dynamics is a question of length and timescale; indeed quantum phenomena such as electron tunneling have been observed in biological systems and there is some evidence for proton tunneling in enzymes. As such, tunneling phenomena are not intimately related to biology and the question therefore remains whether on the one hand biological systems will exhibit more complex quantum-dynamical phenomena that may either involve several interacting particles or multiple interacting components of a network, or on the other hand whether the specifics of the biological systems and their environments will play a crucial role in allowing or supporting certain quantum-dynamical phenomena in biology. Only then could we call these 'non-trivial' quantum effects in biological systems. Indeed, it appears that there are biological processes such as energy and electron transfer in photosynthesis, magneto-reception in birds or the olfactory sense that rely at a fundamental level on such 'non-trivial' quantum-dynamical processes. Thus quantum effects in biology may well be possible and more importantly relevant towards function.

This book reports on quantum biology, its theoretical foundations, experimental findings and future possibilities as they have emerged over the past few years. Needless to say not all subjects can be covered and we have had to make a subselection that has been driven by several objectives. Firstly, given that the basis of the field is the fruitful interplay between experiment and theory, we have endeavoured to choose subjects that are either already under experimental investigation or for which it could be expected that technology will give access to these theoretical predictions in the foreseeable future. This has led us to exclude subjects such as quantum conciousness or the speculations concerning the origin of life. Secondly, it is our aim to provide a reasonably coherent set of chapters, starting from experimental and theoretical foundations and leading on to specific topics of interest. Finally, of course, personal preferences and tastes do also play a role.

The original plan for this book was hatched during the first conference on Quantum Effects in Biological Systems (QuEBS 2009), held from 7–10 July, 2009 in Lisbon, Portugal, which has become the first of the annual QuEBS conferences. Subsequent QuEBS meetings were held at Harvard University in 2010, Ulm University in 2011, Berkeley in 2012 and Vienna in 2013, and their ever growing attendance attests to a growing interest in the field.

This steady development has convinced us that the time is right for an introductory book on quantum effects in biology and we do hope that the present text will help scientists, especially young and adventurous scientists, during or shortly after their PhD, to gain a first insight into the field of quantum biology. It is our hope that in this way we can assist the further development of the field by converting an increasing number of scientists into becoming quantum biologists.

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