The Strange World of Quantum Mechanics

This is an exceptionally accessible, accurate, and non-technical introduction to quantum mechanics.

After briefly summarizing the differences between classical and quantum behavior, this engaging account considers the Stern–Gerlach experiment and its implications, treats the concepts of probability, and then discusses the Einstein–Podolsky–Rosen Paradox and Bell's theorem. Quantal interference and the concept of amplitudes are introduced and the link revealed between probabilities and the interference of amplitudes. Quantal amplitude is employed to describe interference effects. Final chapters explore exciting new developments in quantum computation and cryptography, discover the unexpected behavior of a quantal bouncing ball, and tackle the challenge of describing a particle with no position. Thought-provoking problems and suggestions for further reading are included.

Suitable for use as a course text, *The Strange World of Quantum Mechanics* enables students to develop a genuine understanding of the domain of the very small. It will also appeal to general readers seeking intellectual adventure.

Dan Styer is Professor of Physics at Oberlin College. A graduate of Swarthmore College and Cornell University, he has published technical research papers in *Physical Review, Journal of Statistical Physics* and the *Proceedings of the Royal Society*. Styer is an associate editor of the *American Journal of Physics*, and his quantum mechanics software won the 1994 Computers in Physics Educational Software Contest. A man of lively intellect, Styer's goal in life is to keep learning new things, and to that end he invests energy into presenting science to a general audience. 'I learn a lot through research and by teaching technical courses to physics majors,' says Styer, 'but I learn even more by distilling the essence of physics ideas into a rigorously honest yet non-technical presentation for a general audience. To reach this group, I cannot hide my ignorance behind a screen of mathematical formulas or technical jargon.' Professor Styer enjoys running, backpacking, and rearing his two children as well as doing science.

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Dedicated to two extraordinary teachers of quantum mechanics:

John R. Boccio and N. David Mermin

There are more things in heaven and earth, Horatio,
Than are dreamt of in your philosophy.

Hamlet I.v.166

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Preface

This book presents the two central concepts of quantum mechanics in such a way that non-technical readers will learn how to work simple yet meaningful problems, as well as grasp the conceptual bizarreness of the quantal world. Those two central concepts are: (1) The outcome of an experiment cannot, in general, be predicted exactly; only the probabilities of the various outcomes can be found. (2) These probabilities arise through the interference of amplitudes.

The book is based on a short course (only fourteen lectures) that I have presented to general-audience students at Oberlin College since 1989, and thus it is suitable for use as a course textbook. But it is also suitable for individual readers looking for intellectual adventure. The technical background needed to understand the book is limited to high school algebra and geometry. More important prerequisites are an open mind, a willingness to question your ingrained notions, and a spirit of exploration. Like any adventure, reading this book is not easy. But you will find it rewarding as well as challenging, and at the end you will possess a genuine understanding of the subject rather than a superficial gloss.

How can one present a technical subject like quantum mechanics to a non-technical audience? There are several possibilities. One is to emphasize the history of the subject and anecdotes about the founders of the field. Another is to describe the cultural climate, social pressures, and typical working conditions of a quantum physicist today. A third is to describe useful inventions, such as the laser and the transistor, that work through the action of quantum mechanics. A fourth is to outline in general terms the mathematical machinery used by physicists in solving quantum mechanical problems.

I find all four of these approaches unsatisfactory because they emphasize quantum *physicists* rather than quantum *physics*. This book uses instead a fifth approach, which emphasizes how nature behaves rather than how humans behave. Humans have certainly been very clever in discovering and using quantum mechanics, and I am proud of our species for its activities in this regard. But in this book (except for the appendices) the focus rests squarely on nature and not on how we study nature.

In order to solve problems in quantum mechanics, the professional physicist has erected a gigantic and undoubtedly elegant mathematical edifice. This edifice is necessary for finding the answers to specific problems (which is, after all, what physicists are paid to do), but it often conceals rather than reveals the underlying physical principles of quantum mechanics. Physicists, in fact, are often clumsy in their use and understanding of quantum mechanics's central concepts; they are protected from them by a screen of mathematics. (The very name "*quantum* mechanics" memorializes an aspect of atomic physics that is not central to quantum mechanics and that appears in the classical world as well.) This book aims to strip away the machinery of the edifice and bare the raw ideas in their naked form.

An analogy helps to explain this aim. The professional automobile mechanic must be familiar with crankshafts and camshafts, pistons and plugs, transmissions and timing. His familiarity enables him to repair cars and earn his salary. Yet these practical and interesting devices are irrelevant to the central concept of how a car works — which is simply that hot air expands, whence heat from burning gasoline can be converted into motion. Many excellent mechanics are in fact unfamiliar with this central concept. A book on the fundamental workings of automobiles would discuss heat and motion, but would not tell you how to give your car a tune-up. You should expect analogous discussions here: no more and no less.

Above I have described the direct goals of this book. Two other goals are indirect yet just as important. First, I aim to describe scientific thought — its character, its strengths, its limitations — and to inspire an appreciation for the elegance, economy, and beauty of scientific explanations. Second, I hope to demonstrate the importance and power of reason as a tool for solving problems and probing the unknown. The popular press is fond of misstatements like "the belief in an objective reality, accessible to reason, … suffered a death blow with the advent of modern physics".* The truth is that quantum mechanics is unfamiliar, non-common-sensical, and weird, but it is perfectly logical and rational. Indeed, in the bizarre world of quantum mechanics, it is logic, and not common sense, that is the only sure guiding light. In today's cultural atmosphere — where in-your-face power play has largely displaced rational debate in the arena of public discourse — this point cannot be overemphasized.

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* Sources for direct quotations are gathered in appendix C on page 138.

This book describes quantum mechanics as most physicists understand it today. All scientific knowledge is tentative and the pillars of quantum mechanics are no exception. In addition, the experiments and principles described here are all subject to interpretation. I present the standard interpretation, which is not the only one. (I give only fleeting mention to alternative interpretations and formulations not because they are incorrect or unimportant, but because one must have a firm grasp on the standard interpretation before moving on to the alternatives.)

> *Technical aside:* Sometimes it is useful to make a point that is rather technical and that is not essential for developing the book's argument. Such technical asides are labelled and indented, like this sample.

Producing a completely honest yet non-technical account of quantum mechanics is an audacious enterprise, and while developing this treatment I have reached out for help from many people. I need to thank first the 985 Oberlin College students who have, since 1989, taken the course which led to this book. Their questions, objections, doubts, excitement, enthusiasm, and triumphs have inspired many changes — improvements, I hope — in the content and presentation given here, as well as in my own understanding of quantum mechanics. In the spring of 1996 I served as associate instructor for the computer conference course "Demystifying Quantum Mechanics", developed and taught by Edwin F. Taylor. Working with Professor Taylor and the fifteen intrepid students in that class (mostly high school teachers scattered across the nation) was a pleasure that further refined my understanding and this book's presentation.

I received helpful direct comments on this treatment from many of the students mentioned above, and from Gary E. Bowman, Amy Bug, Peter Collings, Rufus Neal, Joe Palmieri, Robert Romer, Dan Sulke, Edwin F. Taylor, and four anonymous reviewers. This is not to say that all of these readers approve of everything I say here — indeed, I know that some of them disagree with me on important points — but I appreciate the contribution that each one of them has made to this work. The illustrations were skillfully drawn by Byron Fouts.

The development of the course which led to this book was supported by a grant from the Sloan Foundation. This acknowledgement may sound like the bland gratitude of someone merely content to receive Sloan's money, but it is not. The encouragement of the foundation, and in particular of program officer Samuel Goldberg, led me to delve deeply into quantum mechanics as a set of physical ideas rather than as an elaborate and somewhat mystical algorithm for solving problems in atomic physics. I have learned much in preparing this account, and

I thank the Sloan Foundation for suggesting that someone other than myself would be interested in what I learned.

I invite you to join the community that has developed this approach and this book. If you have access to the Internet you can send me computer mail at address

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and you will find a World Wide Web page devoted to this book at

http://www.oberlin.edu/physics/dstyer/StrangeQM/

Comments on paper are just as welcome, and should be addressed to

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I offer you my welcome and my best wishes. Enjoy!