Bohmian Mechanics

The Physics and Mathematics of Quantum Theory

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Preface

This book is about Bohmian mechanics, a non-relativistic quantum theory based on a particle ontology. As such it is a consistent theory of quantum phenomena, i.e., none of the mysteries and paradoxes which plague the usual descriptions of quantum mechanics arise. The most important message of this book is that quantum mechanics, as defined by its most general mathematical formalism, finds its explication in the statistical analysis of Bohmian mechanics following Boltzmann's ideas.

The book connects the physics with the abstract mathematical formalism and prepares all that is needed to achieve a commonsense understanding of the non-relativistic quantum world. Therefore this book may be of interest to both physicists and mathematicians. The latter, who usually aim at unerring precision, are often put off by the mystical-sounding phrases surrounding the abstract mathematics of quantum mechanics. In this book we aim at a precision which will also be acceptable to mathematicians.

Bohmian mechanics, named after its inventor David Bohm,[1] is about the motion of particles. The positions of particles constitute the primitive variables, the primary ontology. For a quantum physicist the easiest way to grasp Bohmian mechanics and to write down its defining equations is to apply the dictum: Whenever you say particle, mean it!

The key insight for analyzing Bohmian mechanics lies within the foundations of statistical physics. The reader will find it worth the trouble to work through Chap. 2 on classical physics and Chap. 4 on chance, which are aimed at the understanding of the statistical analysis of a physical theory as it was developed by the great physicist Ludwig Boltzmann. Typicality is the ticket to get to the statistical import of Bohmian mechanics, which is succinctly captured by $\rho = |\psi|^2$. The justification for

[1] The equations were in fact already written down by the mathematical physicist Erwin Madelung, even before the famous physicist Louis de Broglie suggested the equations at the famous 1927 Solvay conference. But these are unimportant historical details, which have *no significance* for the understanding of the theory. David Bohm was not aware of these early attempts, and moreover he presented the full implications of the theory for the quantum formalism. The theory is also called the pilot wave theory or the de Broglie–Bohm theory, but Bohm himself called it the causal interpretation of quantum mechanics.

this and the analysis of its consequences are two central points in the book. One major consequence is the emergence of the abstract mathematical structure of quantum mechanics, observables as operators on Hilbert space, POVMS, and Heisenberg's uncertainty relation. All this and more follows from the theory of particles in motion.

But this is not the only reason for the inclusion of some purely mathematical chapters. Schrödinger's cat story is world famous. A common argument to diminish the measurement problem is that the quantum mechanical description of a cat in a box is so complicated, the mathematics so extraordinarily involved, that nobody has done that yet. But, so the argument continues, it could in principle be done, and if all the mathematics is done properly and if one introduces all the observables with their domains of definitions in a proper manner, in short, if one does everything in a mathematically correct way, then there is no measurement problem. This answer also appears in disguise as the claim that decoherence solves the measurement problem. But this is false! It is precisely because one can in principle describe a cat in a box quantum mechanically that the problem is there and embarrassingly plain to see. We have included all the mathematics required to ensure that no student of the subject can be tricked into believing that everything in quantum physics would be alright if only the mathematics were done properly.

Bohmian mechanics has been around since 1952. It was promoted by John Bell in the second half of the last century. In particular, it was the manifestly nonlocal structure of Bohmian mechanics that led Bell to his celebrated inequalities, which allow us to check experimentally whether nature is local. Experiments have proved that nature is nonlocal, just as Bohmian mechanics predicted. Nevertheless there was once a time when physicists said that Bell's inequalities proved that Bohmian mechanics was impossible. In fact, all kinds of criticisms have been raised against Bohmian mechanics. Since Bohmian mechanics is so simple and straightforward, only one criticism remains: there must be something wrong with Bohmian mechanics, otherwise it would be taught. And as a consequence, Bohmian mechanics is not taught because there must be something wrong with it, otherwise it would be taught. We try in this book to show how Bohmian mechanics could be taught.

Any physicist who is ready to quantize everything under his pen should know what quantization means in the simplest and established frame of non-relativistic physics, and learn what conclusions should be drawn from that. The one conclusion which cannot be drawn is that nothing exists, or more precisely, that what exists cannot be named within a mathematically consistent theory! For indeed it can! The lesson here is that one should never give up ontology! If someone says: "I do not know what it means to exist," then that is fine. That person can view the theory of Bohmian mechanics as a precise and coherent mathematical theory, in which all that needs to be said is written in the equations, ready for analysis.

Our guideline for writing the book was the focus on the *genesis* of the ideas and concepts, to be clear about *what it is* that we are talking about, and hence to pave the way for the hard technical work of learning *how it is done*. In short, we have tried not to leave out the letter 'h' (see the Melville quote on p. 4).

References

The references we give are neither complete nor balanced. Naturally the references reflect our point of view. They are nevertheless chosen in view of their basic character, sometimes containing many further references which the reader may follow up to achieve a more complete picture.

Acknowledgements

The present book is a translation and revision of the book *Bohmsche Mechanik als Grundlage der Quantenmechanik* by one of the present authors (D.D.), published by Springer in 2001. The preface for this book read as follows: "In this book I wrote down what I learned from my friends and colleagues Sheldon Goldstein and Nino Zanghì. With their cooperation everything in this book would have been said correctly – but only after an unforeseeably long time (extrapolating the times it takes us to write a normal article). For that, I lack the patience (see the Epilogue) and I wanted to say things in my own style. Because of that, and only because of that, things may be said wrongly." This paragraph is still relevant, of course, but we feel the need to express our thanks to these truly great physicists and friends even more emphatically. Without them this book would never have been written (but unfortunately with them perhaps also not). We have achieved our goal if they would think of this as a good book. With them the (unwritten) book would have been excellent. Today we should like to add one more name: Roderich Tumulka, a former student, now a distinguished researcher in the field of foundations who has since helped us to gain further deep insights.

The long chapter on chance resulted from many discussions with Reinhard Lang which clarified many issues. It was read and corrected several times by our student Christian Beck. Selected chapters were read, reread, and greatly improved by our students and coworkers Dirk Deckert, Robert Grummt, Florian Hoffmann, Tilo Moser, Peter Pickl, Sarah Römer, and Georg Volkert. The whole text was carefully read and critically discussed by the students of the reading class on Bohmian mechanics, and they are all thanked for their commitment. In particular, we wish to thank Dustin Lazarovici, Niklas Boers, and Florian Rieger for extensive and thoughtful corrections. We are especially grateful to Sören Petrat, who did a very detailed and expert correction of the whole text.

The foundations of quantum mechanics are built on slippery grounds, and one depends on friends and colleagues who encourage and support (with good criticism) this research, which is clearly not mainstream physics. Two important friends in this undertaking are Giancarlo Ghirardi and Herbert Spohn. But there are more friends we wish to acknowledge, who have, perhaps unknowingly, had a strong impact on the writing of the book: Angelo Bassi, Gernot Bauer, Jürg Fröhlich, Rodolfo Figari, Martin Kolb, Tim Maudlin, Sandro Teta, and Tim Storck.

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Landsberg and Tübingen, *Detlef Dürr*
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