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BOOK REVIEW

Detlef Dürr, Dustin Lazarovici: Verständliche Quantenmechanik. Drei mögliche Weltbilder der Quantenphysik

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My undergraduate physics professor used to say: "One cannot understand quantum mechanics, one can only get used to it." This sounds a bit more humane than the frequently heard slogan "Shut up and calculate!", but it is ultimately just as unsatisfactory. After all, isn't one of the main reasons for engaging with physics the desire for a better *understanding* of what happens in the material world? Detlef Dürr and Dustin Lazarovici, the authors of the book to be discussed here, firmly adhere to this view and oppose the quoted slogans by presenting quantum mechanics as intelligible (*verständlich*).

Now there are two kinds of difficulties that stand in the way of understanding quantum mechanics, and it is a great merit of this book to approach both of them together. On the one hand, there is the sophisticated mathematics required to formulate the theory. Providing students with orientation in this respect is part of the main business of conventional textbooks on quantum mechanics. Although the present book is not intended as a textbook of that sort, the central results are nevertheless derived in a mathematically clean way that can easily be followed by someone who has attended introductory lectures in mathematics and physics.

These mathematical challenges, however, are not what one usually has in mind when doubting the intelligibility of quantum mechanics. Rather, the second type of difficulty comes into play here, which is often discussed under the heading of the *interpretation(s)* of the theory. Dürr and Lazarovici prefer to speak of *ontology* here, by which they mean "that which the physical theory is about" (p. 2). Well, don't the textbooks on quantum mechanics tell us what the theory is about? In an important sense they do not, insofar as they predominantly talk about probabilities for measurement results, but do not give a clear answer to the question of what happens in the world when nobody is making a measurement. This is the well-known *measurement problem* of quantum mechanics, whose possible solutions lead to the "three possible world views of quantum physics" mentioned in the subtitle of the book. These are (1) *Bohmian mechanics*, which supplements the ordinary quantum

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formalism with position variables for all particles at all times, (2) the *collapse theory*, which changes the dynamics of quantum systems by introducing spontaneous localization processes, and (3) the *many-worlds theory*, which postulates a progressive splitting of the universe into branches developing independently of each other. One chapter of the book is dedicated to each of these world views (Chapters 4, 5 and 6), whereby the authors do not conceal their preference for option (1). (Anything else would be surprising, given that Detlef Dürr has been one of the formative figures in the development of Bohmian mechanics for decades.) Nevertheless, the presentation of the three world views is balanced in the sense that both the respective strengths and the most important objections to each of the three options are discussed.

Although in some respects one might wish for a more comprehensive description of the ontological debate (see below), it is very enjoyable to find such a description in a book explicitly addressed to physics students. In particular, it provides valuable insights into the relationship between the two types of difficulties just mentioned, the mathematical and the ontological ones. First, the authors rightly warn against expecting mathematics to solve ontological problems: "The famous debate about quantum mechanics has nothing to do with unclean mathematics" (p. 30). This does not mean, however, that the two areas should be treated separately (the physicists presumably being responsible for one area and the philosophers for the other). In fact, the strongest passages of the book are those in which the mathematical and ontological clarification of a matter go hand in hand, for example when Born's probability interpretation of the wave function (and from it Heisenberg's uncertainty principle) is derived in the context of Bohmian mechanics (Chapter 4), whereby the previously explained significance of *typicality* for statistical analyses (Chapter 3) comes into play. The matter becomes even more fascinating in the context of relativistic quantum theories, where the still remaining need for both mathematical and ontological clarification is discussed on the basis of Paul Dirac's (1963) distinction between "class one difficulties" and "class two difficulties" (Chapter 11).

Furthermore, the book contains thorough discussions of topics that are central to the understanding of quantum mechanics but are not treated with the necessary care in many textbooks. Thus one learns about the physical meaning of "observables" (self-adjoint operators) and their generalization in the form of positive operator-valued measures (Chapter 7), about the concept of "weak measurement" (Chapter 8), about theorems on the alleged impossibility of hidden variables (Chapter 9) and about the non-locality of the world implied by Bell's theorem (Chapter 10).

It is probably due to this broad range of topics that the description of the ontology (more precisely: the possible ontologies) of quantum mechanics is somewhat incomplete. Insofar as the book does not claim to provide a comprehensive introduction to the philosophy of quantum physics (for that purpose, one might want to start with, e.g., Friebe et al. 2015 or Myrvold 2018), such a shortening has its didactic justification. The following hints are therefore not so much to be understood as a criticism of the book, but as a supplement to the approach chosen by the authors, with the aim of situating the book within the current philosophical debate.

Thus, for example, the "orthodox answer" to the measurement problem may have more philosophical value than the somewhat caricatural description by Dürr and Lazarovici (p. 34/35) would suggest. This is not only a historical subtlety about the actual views of physicists like Bohr or Heisenberg, but also has systematic import, concerning (among other things) the highly non-trivial question why "orthodox quantum mechanics" works so well although it does not solve the measurement problem (see Wallace 2016). Similarly, what the book says about "further alternatives" (p. 37/38) is so brief

that it could easily create the impression that outside of the three world views discussed here, there is only the resigned attitude of "shut up and calculate". One can, of course, defend the position that we understand a theory only if we can formulate its ontology (in the sense of one of the three world views), but this attitude is by no means universally accepted, and a considerable part of the current debate (for example about information-theoretic or pragmatic approaches) revolves around the question of whether quantum mechanics should not encourage us to question this conception of "understanding".

Finally, even within the three world views discussed in the book, there is a complexity that is only marginally discussed in the presentation of the authors. The recent debate on the ontology of quantum mechanics has shown that the essential ontological question ("what is the theory about") is not answered by a solution of the measurement problem alone. Again, there are good didactic reasons to approach the ontological question from this side, but there are also the questions (hotly discussed in the current debate) about the ontological status of the wave function and the necessity of a so-called "primitive" ontology, and these questions lead to a completely different classification of possible world views than the three answers to the measurement problem discussed in the book (cf. Allori et al. 2008). Although the authors briefly refer to these additional ontological questions in connection with the collapse theory (p. 104/105) and the many-worlds theory (footnote 8 on p. 112), they do not seem to appreciate the true radicality of the situation (namely that each of the three solutions to the measurement problem is compatible with several ontologies). In this context, I think that one could expect an average reader to handle the fact that even Bohmian mechanics does not already answer all ontological questions by itself, but that within this theory there are different views on the status of the wave function and even on the existence of particles in three-dimensional space (see, e.g., Albert 2015, Chapters 6 and 7).

These would be weighty objections if the goal were to provide an up-to-date introduction to the philosophy of quantum mechanics, but, as already mentioned, this is not the book's ambition. Instead, *Verständliche Quantenmechanik* should be seen as a supplement to the existing physics textbook literature. This is urgently needed, since ordinary textbooks leave the crucial questions of quantum mechanics open, presumably because these are perceived as "too philosophical". Conversely, the book is also interesting for philosophers precisely because it makes contact (to a greater extent than most of the philosophical literature) with the mathematical formulation of quantum mechanics as taught in the physics curriculum. In this sense, *Verständliche Quantenmechanik* actually fills a gap, and I hope that it will be widely read.

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