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Book Review

The Meaning of the Wave Function – In Search of the Ontology of Quantum Mechanics, Shan Gao. Cambridge University Press (2017).

1. Introduction

The meaning of the wave function is an ongoing prominent topic in the foundations of quantum mechanics. The recent formal results on the onticity of the quantum state[1] have given a lot of food for thought and the time seems ripe for a deeper philosophical analysis.

Gao takes his cue from these results, adds to them, and then quickly moves on in search of the ontology of quantum mechanics. Indeed, only the first third of the book focuses on *possible* meanings of the wave function, while the remainder is based on what Gao takes to be *the* meaning of the wave function. He is a man with a plan, and that plan really starts to take shape in chapter 6 with the introduction of random discontinuous motion (RDM) of particles. The remaining two thirds are devoted to spelling out Gao's proposal for the ontology of quantum mechanics based on RDM which is spread out over four chapters. Indeed, the partitioning of the book could have been better considering that, for example, section 8.4 is about as long as chapters 2 and 3 together. That being said, the structure of the book is clear and the line of reasoning is often easy to follow, although at points somewhat reckless.

2. Short summary

The book is divided in three parts. The first part (chapters 1–5) focuses on the ontological status of the wave function. Chapter 1 provides a short introduction to the formalism of quantum mechanics and protective measurements and argues that “protective measurements provide a definite, direct connection between the wave function assigned to a physical system and the results of measurements on the system”. Chapter 2 rehearses the ψ-ontic/epistemic distinction and argues against an anti-realist stance (section 2.1) and in favor of the ψ-ontic view (section 2.2). The PBR theorem and Hardy's theorem are summarized in section 2.3. Chapter 3 is devoted to arguing against the nomological view: the view that the quantum state should be given a law-like status (a view that goes beyond the ψ-ontic/epistemic dichotomy). In chapter 4 new arguments for the reality of the wave function are presented based on an analysis of protective measurements. Finally, in chapter 5, a derivation of the Schrödinger equation is given based on an analysis of spacetime translation invariance and relativistic invariance.

From the second part onward (chapters 6 and 7), the ψ-ontic view is fully accepted and the focus is on what the accompanying ontology should be. Chapter 6 delves into Schrödinger's idea of the quantum state as a charge density distribution. Section 6.1 discusses two problems for this idea: explaining the electric quadrupole moment for two particles and the lack of electrostatic self-interaction for a single particle. On the other hand, Gao argues, with the use of protective measurements, that charge density distributions must be real. The apparent inconsistency is solved for single particles by the introduction of random discontinuous motion of particles. Instead of being spread out over space, particles are always at a well-defined location and follow a random discontinuous path in such a way that on average (over time) the density distribution arises. The multiple particle case is discussed in chapter 7. Here Gao argues against wave function realism and in favor of the 3N-dimensional quantum state describing N systems in 3-dimensional space. Section 7.3 further explicates how the RDM of multiple particles works mathematically.

The third part (chapters 8 and 9) further investigates and develops the ontology introduced in the second part. Chapter 8 starts with presenting a version of the measurement problem that focuses on the way mental states of observers relate to the ontology. Specifically, the incompatibility between (1) the mental state of an observer supervenes on her wave function and (2) the wave function always evolves linearly. Gao argues that neither Everettian quantum mechanics nor Bohmian mechanics solves this problem, but that collapse theories might. Section 8.3 argues that the RDM of particles may be able to explain the Born rule in a collapse theory, but not in Everettian quantum mechanics or Bohmian mechanics. Section 8.4 introduces a model of spontaneous collapse where collapse occurs to an energy eigenstate with a collapse time that is proportional to the inverse square of the energy uncertainty of the initial state. In section 8.4.4 it is argued, among other things, that the proposed collapse model can provide a solution to the measurement problem. The chapter ends with a discussion of some other spontaneous collapse models. Chapter 9 discusses the incompatibility of RDM of particles with special relativity. Section 9.2 argues in favor of a return to absolute simultaneity by the introduction of a preferred Lorentz frame. In section 9.3 a proposal for how the preferred frame may be detectable in Gao's collapse model is presented. The chapter ends with some considerations on how the RDM of particles may play a role in quantum field theory.

3. Highlights and criticisms

Highlights and criticisms go hand in hand in when it comes to this book. The ideas laid out in Gao's book deserve to be praised for their originality. But precisely the novel and provocative ideas explained are the ones whose tenability can be questioned.

At some points Gao is relying too much on the willingness of the reader to accept his conclusions. Consequently, some of his arguments are weak or even faulty. One such point is chapter 4 where

[1] See (Leifer, 2014) for an overview.

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a new argument for ψ-ontology in terms of protective measurements is given that allegedly improves on the PBR-theorem. A claimed problem for the PBR theorem is that, because it relies on the ontic models framework, it suffers from two shortcomings of this framework. These shortcomings are that (1) the framework “does not apply to deterministic theories” and (2) “considers only conventional projective measurements” and therefore isn't able to deal with protective measurements. But the first is solved by just restricting attention to those ontic states in the model that only give rise to $\{0,1\}$-valued probabilities[2] and the second is just plain false since the ontic models framework was specifically designed to apply to arbitrary operationally defined theories (Spekkens, 2005). Even if one restricts attention to ontic models for (fragments of) quantum mechanics, these fragments may include POVMs, which can be used to represent protective measurements (Combes, Ferrie, Leifer, & Pusey, 2017).

This latter paper in turn thoroughly criticizes an earlier version of Gao's argument for the ψ-ontic view presented in sections 4.2 and 4.3 of the book. Gao takes the opportunity to reply to an earlier version of that paper at the end of section 4.3. I found the reply underwhelming, and so vested my hope in section 4.4 which presents another argument for ψ-onticity based on protective measurements that makes no use of the ontic models framework at all. Since the definition of ψ-onticity relies on this framework, Gao has to introduce a new definition. He does so by introducing a modified version of EPR's sufficient condition for elements of physical reality, and showing that the quantum state satisfies this condition. The condition is that “if a measurement of a physical quantity on a system obtains a definite result, which is denoted by the value of a pointer variable after the measurement, and during the measurement the pointer shift rate is also determined by the value, then the measurement result reflects a physical property of the measured system.” I cannot see another reading of the first part of the antecedent other than “if a measurement of a physical quantity is successful”. So the content of the condition should be in the second part: “during the measurement the pointer shift rate is also determined by the value”. It is explained a few pages back in the book what this condition means and that it is satisfied for protective measurements, but I fail to see the significance of the condition. Now everybody has blind spots, and I figured this must be one of mine. A Google search of “pointer shift rate”, however, yielding 5 results, brought me right back to this book, leaving the impression that Gao's definition is just tailor-made for his ψ-ontology argument. On a relating note, it also isn't clear why Gao moved to this new criterion for reality and moved away from his earlier proposal: “if a certain observation of a physical system obtains a definite outcome, which is represented by a mathematical quantity assigned to the system by a theory, and the quantity does not change during the observation, then the system has a realistic property represented by that quantity according to the theory” (Gao, 2015).

But fair is fair, how many arguments for ψ-ontology do we really need? And regardless the alleged necessity of the ψ-ontic view, it is very much worth asking how the quantum state fits in the furniture of the world if it is real. Gao's proposal for answering this question is, I think, the most interesting part of the book. The journey starts in chapter 6 where he solves the problem of how the charge distribution of a particle can be real without introducing electrostatic self-interaction. The solution is that particles exhibit random discontinuous motion in such a way that at each instant t the probability for the particle being in a region Δ is given by $\int_\Delta |\psi(x,t)|^2 dx$. Since at each instant the particle is in a well-defined location, there is no self-interaction. The discontinuity ensures that the motion is ergodic in the sense that for arbitrary finite time intervals the particle covers all of space giving rise to the charge distribution $q|\psi(x)|^2$ as an average over time (assuming ψ to be constant in the time interval).

The radical discontinuities may be difficult to take in for many readers. But there is also a certain elegance and simplicity to the idea. The simplest explanation of why $|\psi(x)|^2$ gives the probability of a particle being found in a certain region, is that it is simply the probability for a particle being there. If one then also holds on to the idea that the wave function is complete, and thus refrains from adding Bohmian trajectories, one has to conclude that the motion of the particle is random and discontinuous. But regardless of how one feels about RDM, it is very interesting to see how far this idea can be pushed to provide an ontology for quantum mechanics. And Gao makes a tremendous effort to push it quite far.

However, the simplicity of Gao's idea also makes one wonder if there are obvious problems for it. The ontology suggests that almost trivially the Born rule is satisfied for position measurements. But this only holds if the position measurement occurs instantaneously over all of space, which is not typically the case in real measurements. To give an explicit example of the problem that may arise, consider a Stern-Gerlach measurement with two detectors: one to register spin up, and the other to register spin down. According to the RDM of particles, after passing through the magnetic field, a particle advances towards both detectors, randomly jumping back and forth between the two paths towards the detectors. This suggests that the particle is detected with probability one by the detector that is closest to the magnetic field. That obviously contradicts experience, so there should be a probability of 50% that the particle misses the first detector. To then ensure that the particle is detected by the other detector with certainty, we need some mechanism such that missing the detector causes a collapse to the single path towards the other detector.

This is just some thought experiment I concocted, so it is unfair to demand an answer in the book. But Gao does provide the seeds for an answer in chapter 8 where he proposes a mechanism for dynamical wave function collapse. There is still a long way to go towards an explanation though, with one of the problems being that the proposed collapse mechanism causes systems to collapse to energy eigenstates rather than position eigenstates.

I could fill several more pages with critical remarks on passages in the book. But it is perhaps better to leave them be until they are more matured. The take home message is that I found the book very thought provoking, which is what I think a philosophy book should be.

4. Conclusion

Gao mainly follows his own agenda and is regularly quick in dismissing other options when it comes to the meaning of the wave function and the ontology of quantum mechanics. If one is hoping to find a balanced discussion of the metaphysical options for the meaning of the wave function one would be better off reading, for example, the recent paper by Chen (2017). But I don't think that is necessarily a bad thing, because it results in a book that quickly gets where it wants to go: to explain a new ontology for quantum mechanics in terms of the RDM of particles and to investigate how this ontology can help solve big problems in the foundations of quantum mechanics. Consequently, though, the book is for a specialized audience: people who find the idea of RDM of particles intriguing enough to learn more about it. But for that audience, this is the book to buy.

[2] It is my understanding that at this point in the book determinism is meant as value definiteness and is thus unrelated to the evolution of ontic states, which may be stochastic.

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