Peter J. Lewis. (2016). ***Quantum Ontology: A Guide to the Metaphysics of Quantum Mechanics*****. Oxford University Press. 232 pp.**

Quantum mechanics (QM) has been a fascinating and challenging theory since its origins. This is because it casts doubt on many of our common sense intuitions, as well as for its astonishing successful predictions. However, if there is no agreement about the correct interpretation of QM, as indeed occurs, in what sense are our intuitions challenged? That is, is there any fundamental lesson to be learned about central issues such as indeterminacy, indeterminism and locality related to QM? Or, are these issues tied to a particular way of construing it? *Quantum Ontology: A Guide to the Metaphysics of Quantum Mechanics* by P. Lewis is an excellent book to delve into these questions.

Intended for an audience interested in the metaphysical debates of one of our most successful theories so far, P. Lewis has succeeded to convey the basics of QM without the mathematical apparatus frequently used by trained physicists. It also presents a thorough analysis of some of the main interpretations of QM: The Copenhagen (or orthodox) interpretation; the Broglie-Bohm theory and the relative-state theory originally proposed by H. Everett (and which has motivated interpretations such as 'many worlds' and the 'bare theory').

A central idea in P. Lewis' book is that general lessons about QM are probably false, so he refuses to support assertions like 'QM entails indeterminism', 'QM is non-local' or 'QM implies many worlds', etc. Although, one exception to this attitude is associated with the indeterminacy in QM, since P. Lewis argues that it is a feature existing, in various degrees, in all its main interpretations; accordingly, he maintains that most of the metaphysical consequences of QM are dependent on the prior acceptance of a particular interpretation. In the following section I critically summarize the central theses in Lewis' approach.

The book is divided in 8 central chapters. The first of them explains the counter-intuitive notions of interference and entanglement throughout the well-known double-slit experiment. This chapter is intended to show how "particles" that compose matter exhibit a wave-particle duality, and how this prompts questions about the very nature of these fundamental components. Entanglement, on the other hand, reveals a further phenomenon in the quantum realm, namely, the mysterious non-local correlation of observable properties between particles, for example, a system of two electrons with anti-correlated spins can instantaneously affect each other even if they are separated by a space-like distance.

On P. Lewis' view, both interference and entanglement represent revolutionary aspects of QM, and not so much the idea that some properties are quantized (e.g. that certain properties such as spin, energy and momentum are discrete rather than continuous). Besides, the reader will find, within the first chapter, a brief presentation of the key concepts from two of the main mathematical formalisms of QM, that is, matrix mechanics and wave mechanics; this section is rather introductory and does not intend to motivate queries about the existence of different mathematical formalisms.

The second chapter takes on the project of realism in the light of QM. A crucial question is the following: if scientific realism is defined as the search of true descriptive theories, how should we understand QM in order to explain phenomena like interference and entanglement? Traditionally, realism is a thesis about the existence of unobservable entities and properties, however, a problem in QM is that we cannot talk of 'definite' properties and entities independently of the experiments or measurements we chose to perform in a physical system.

For example, a beam of light might exhibit a particle or wave behavior depending on the experiment we chose to perform (if a photoemission or double slit experiment respectively), but what is its *real nature* when no measurement is being performed? As it is well noted by P. Lewis, it is not enough to point out the existence of hidden variables that, if known, would allow us to recover a full realist account of the definite nature of the fundamental components of matter. Here P. Lewis considers the argument defended by Einstein-Podolsky-Rosen (1935), as the first serious effort to demonstrate that QM is incomplete, followed by the counter-response offered by Bohr (1935), and a helpful discussion of Bell's theorem and Kochen and Specker's paper (1967).

One central argument is that the existence of no-go theorems imposes important constraints on any hidden variable project used to complement QM, namely, once it is granted that the universe is local and that properties do not depend on the measurements we perform on a physical system, a pre-measurement attribution of definite observable properties to physical systems will invariably lead to inconsistent predictions. Thus, a crucial problem emerges: should we abandon our aspiration to fully describe reality in the context of QM, or rather the presupposition of locality and/or independence?

The lesson to be learned is less obvious than it seems. Certainly, a satisfactory response to the latter question depends on what interpretation we are prone to accept, (un)fortunately, P. Lewis' book does not intend to offer a direct response to this question. Instead, he believes that realism might acquire different nuances according to the interpretation we decide to embrace.

In this context, chapter 3 is devoted to develop the core ideas underlying each of the interpretations of QM in the context of the measurement problem: Bohm's hidden-variable program; GRW theories and the many worlds interpretation. For example, Orthodox QM, taken literally, might entail indeterminacy and non-locality if we consider phenomena like superposition, interference and entanglement, albeit alternative interpretations may entail different commitments while preserving the same empirical adequacy of QM.

Bohm's approach, for instance, is a deterministic and a non-local theory, since there are particles that possess definite positions in every instant of time; indeterminacy is restricted just to certain properties though, and due to its non-locality, it directly conflicts with Einstein's theory of relativity. On the other hand, GRW theory is indeterministic, non-local and introduces a stochastic law that generates the collapse of the wave function without recurring to any observer.

The many worlds, or pure wave mechanics (Barret, 2011), is deterministic since each possible measurement outcome is instantiated in some world due to a branching process. Many worlds is also a local theory, what it is good news for those trying to reconcile the theory of relativity with QM. Still, many worlds needs to account for the probabilistic results obtained in each branch (a difficulty that will be addressed in chapter 6). At the end of chapter 3, it is far from clear which is the best interpretation to adopt, so in the next chapters Lewis proceeds to evaluate some of the well-known objections against each position in order to offer a general landscape.

It is worth to mention that P. Lewis assumes that QM probably exemplifies an exceptional case of underdetermination, since we face rival metaphysical pictures which cannot be reconciled. Now, in the literature over underdetermination there is a clear-cut distinction between a transient underdetermination (Stanford, 2001; Laudan, 1990) and a global (or permanent) underdetermination (Quine, 1975); by the same token, between a metaphysical and a structural sort (Lyre, 2011; French, 2014). However, since P. Lewis barely mentions which formulation he has in mind, it is difficult to agree with him about the consequences of underdetermination in QM.

One might argue that QM is underdetermined only transiently due to our lack of further evidence, but this difficulty does not represent a permanent challenge against the realist attempt to construe QM. On the other hand, if underdetermination were global, additional evidence would be helpless to single out *the* correct way to understand QM. Additionally, the challenge would aggravate if alternative interpretations postulated incompatible physical mechanisms (e.g. stochastic processes in the case of GRW, or Bohm's "hidden variables", etc.). I think P. Lewis must have addressed these difficulties instead of simply assuming that QM offers an incomparable case of underdetermination.

Chapter 4 deals with indeterminacy, that is, with the fact that some properties of physical systems possess a determinable property (for instance, spin) but an indeterminate value of that property (e.g. spin-up or spin-down). Though this kind of indeterminacy does not permeate all the interpretations in exactly the same degree (recall Bohm's hidden variables), it is argued that QM sheds light on a new form of indeterminacy that is different from compositional indeterminacy and vagueness.

In addition, within this chapter the reader will confront a view called 'the bare theory' –originally defended by Albert (1992)–, which supports a radical form of indeterminacy in all levels of reality, namely, microscopic and macroscopic, followed by a rich discussion of how this indeterminacy could originate the illusion of determinate experiences in human perception. Besides, issues related to simplicity and reducibility (GRW theory and Bohm's hidden variable project to many worlds) are explored and critically evaluated.

We have said that Bohm's theory rescues determinism, but not locality. Chapter 5 shows that even this is contestable. We could recover locality for hidden-variable theories if we were prepared to adopt retrocausality, namely, the counter-intuitive idea that future events (e.g. measurements) could have causal influence on the past. This violates the second presupposition of Bell's theorem, that is, independence (that collapse processes do not depend on the measurements that will be performed on a physical system), nonetheless, is it worth to pay such a high price and embrace retro-causality? P. Lewis maintains that the tenability of such a program is still an open question.

Chapter 6 focuses on how to recover probability for the many worlds interpretation: if every possible measurement outcome really occurs according to it (in different branches or worlds), an observer would still be uncertain about which particular result would obtain relative to its own branch, therefore, a couple of questions arise: does this uncertainty fit the probability axioms and the Born rule for the measurement outcomes? Should the frequency of an event be calculated relative to the outcomes in every branch, or just relative to one branch? P. Lewis is optimistic on being able to satisfactorily answer these questions and surveys some promissory responses.

Along this chapter, P. Lewis also examines how the various interpretations of QM can lead to interesting reflections on topics such as free will; personal identity; retrocausality; the very nature of individual particles and, even, how one could infer one's immortality according to many worlds interpretation. Again, there is no definitive lesson to be taken from these issues unless one is already committed with a particular interpretation of QM.

In chapter 7 and 8, P. Lewis approaches both the dimensionality of the universe and emergent properties (or holism). The former issue copes with the wave function and the configuration space which it inhabits. One central idea is that if one is a realist about the wave function, it follows that the 4-dimensional space we seem to inhabit is illusory since the configuration space is 3N-dimensional (where N is the number of particles in space), and it would represent a multidimensional space. Is this conclusion tenable? If so, how can we make sense of our three-dimensional perception? Chapter 7 is devoted to discuss these topics.

Finally, holism in QM refers to the relational properties that exist between particles but which do not depend on their intrinsic properties. For instance, two electrons which exhibit anti-correlated spins give rise to a relational property that does not supervene on the spin properties of the individual particles that compose the physical system (at least, if indeterminacy of properties is right). Chapter 8 deals with the relevance of holism and its metaphysical consequences against humean supervenience, which is a philosophical thesis that has been defended by D. Lewis (1986).

Within this chapter it is discussed the relevance of a naturalistic metaphysics: must science occupy a privileged position as a fundamental source of metaphysical knowledge? And, should the scientific research advice to disbelieve any metaphysical proposition which attempts to describe the reality independently of the results of our best science? P. Lewis is inclined to think that a naturalized metaphysics seems to have good arguments in its favor, though he recognizes that there are differences on how to characterize such a project. For instance, Maudlin (2007); Ladyman y Ross (2007); Morganti (2013) support incompatible naturalistic projects. As in previous chapters, P. Lewis provides an insightful analysis of holism under each of the main interpretations of QM.

For several reasons, *Quantum Ontology: A Guide to the Metaphysics of Quantum Mechanics* is a recommended introductory reading for those interested in contemporary philosophy of physics. Among its most compelling features are the following: 1) it is a broad and detailed study devoted to discuss topics related to the metaphysics of QM; 2) it provides a case by case analysis in a comprehensive and rigorous way according the various interpretations at stake, and 3) it presents an analysis of QM in relation to realism and anti-realism.

On the other hand, this book lacks a section of commented bibliography with various degrees of difficulty, so that the reader who is concerned with a particular topic could look into it. This feature might be especially important for those readers who have a first approximation to QM, as well as for an audience who wish to delve into the philosophical, or formal, debates within philosophy of physics.

Besides, P. Lewis scarcely mentions the relevance of Quantum Field Theory and String Theory with respect to QM. Since they are more fundamental theories than QM, he should have discussed how these theories might solve, or even complicate, the difficulties which arise in relation to the various interpretations of QM. Indeed, there are crucial questions unanswered, for example, do the underdetermination, indeterminacy and non-locality receive a different treatment in those research fields? And, should we be optimistic about realism in QM as science advances?

In the introduction the author outlines two reasons why the metaphysics of QM must be of special interest even if more fundamental theories are not examined. The first motivation is that QM would still be a formal device to describe the relevant level of reality (atoms, electrons, protons, etc.) and its strange behavior, no matter what the ultimate entities are postulated; the second motivation is that QM is revisionary in all its interpretations and a retreat to a classical view is not an available alternative, hence, it is important to study the metaphysical consequences of such a radical change in our conception of the reality.

Firstly, I would like to mention that even if QM can be treated as an approximate true theory, though not the ultimate one, it is essential to elucidate what components of its mathematical formalism (and its metaphysical interpretation) can be recovered by a succeeding theory, if this is not clear, and the underdetermination is not diluted, the metaphysical relevance of QM seems to be merely pragmatic, since we could not justify what to be realist about in QM. Then, we face a dilemma: we *choose* an interpretation over another one (by evaluating its merits and virtues), or we appeal to a more fundamental theory to break up underdetermination; however, P. Lewis has refused to go one way or another.

Secondly, if QM could not be construed in a realist fashion, in what sense should we be worried about its revisionary features? Certainly, one could formulate conditional assertions like 'if we believe many worlds theory, then a bunch of real worlds or universes really exist', or 'if the orthodox interpretation is right, then there is indeterminacy in the world', etc. However, if underdetermination is a substantial challenge for QM, then, it might provoke an instrumentalist position which would greatly diminish the impact of having found a revolutionary theory in QM.

In this vein, Okon and Sudarsky (2014) have defended that just certain interpretations of QM (e.g. GRW theories) could be explanatorily fruitful in domains such as cosmology and quantum gravity. Interestingly, their arguments pave the way to dismantle the challenge of underdetermination at stake. Arguments of this kind strongly advocate the importance of evaluating the various interpretations of QM in the light of other contexts of scientific research, a point that is not well developed by P. Lewis.

Notwithstanding, I am convinced that this book is an excellent reading in the metaphysics of QM. Yet, its objective is not to persuade the reader to adopt a particular interpretation and, to that extent, debates over realism and anti-realism constitute an open discussion. If realism is the right way to understand QM, then, we could certainly conclude that any alternative we finally opt for, it will inevitably be a revolutionary shift from our classical world view.

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