Review for *Metascience*

Interpreting Quantum Mechanics Modally

Dennis Dieks and Pieter Vermaas, editors, *The Modal Interpretation of Quantum Mechanics*. Dordrecht: Kluwer Academic Publishers, 1998. Pp. vii + 377. US$135.

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This is an excellent book about one of the most important developments in the philosophy of quantum theory in the last twenty years. The modal interpretation was initiated by Bas van Fraassen twenty years ago, and proposals related to his were made in the 1980s by such authors as Simon Kochen, Richard Healey and Dennis Dieks. In the 1990s, a 'second generation'—principally Guido Bacciagaluppi, Jeff Bub, Rob Clifton, Michael Dickson and Pieter Vermaas—developed the ideas much further. In view of this activity, Dieks and Vermaas organized a conference in 1996, the papers from which comprise this book. Dieks and the members of the second generation just listed all have papers; the other authors are Frank Arntzenius, Jeffrey Barrett, Harvey Brown, Paul Busch, Matthew Donald, Meir Hemmo, Bradley Monton, Nick Reeder, Mauricio Suarez, and Jason Zimba—all but one of whom writes about the modal interpretation. There are 15 papers in all; (rather less than this list of names suggests—three papers are co-authored). Thus the book gives an up-to-date overview of the modal interpretation; and at a vastly higher level of quality than most conference proceedings—thanks not least to the editors' very careful work, duly acknowledged in almost every paper. So, despite the outrageous (though typical) Kluwer price, the book is an ideal place to start studying the modal interpretation: though it is not the only such place—two monographs, by Guido Bacciagaluppi and by Pieter Vermaas, are forthcoming with C.U.P..

As readers of *Metascience* will be well aware, the founding fathers of quantum theory, such as Einstein, Bohr and Heisenberg, struggled heroically with questions about its interpretation. The main issue, at least from our present perspective, is the measurement problem: the threat that quantum theory's characteristic lack of values for quantities on microsystems could spread to the macroscopic realm ('Schrödinger's cat'), contrary to our experience. If one proposes to solve this problem by supplementing orthodox quantum theory's meagre ascription of values to quantities, how exactly should the extra values be assigned? And if instead one addresses this problem by proposing that on measurement there is a 'collapse of the wave-packet', there are other hard problems: in particular, if the collapse is a physical process, exactly when and how does it occur—and can it be reconciled with the frame-dependence of simultaneity, taught us by special relativity? After 1935, these problems were largely ignored for various reasons, among which one must no doubt include: the establishment of an orthodox 'Copenhagen' interpretation in the aftermath of Bohr's 'victory' over Einstein in the Einstein-Bohr debate; the physics community's excitement at being able to develop quantum theory, and successfully apply it to an ever-wider class of phenomena, without regard to foundational issues; and the impact of the Second World War.

But in the last thirty years, there has been a renaissance in the study of the interpretation of quantum theory. Again, the reasons are diverse, relating both to physics and philosophy. There are intellectual reasons such as the striking results of supreme talents like David Bohm and John Bell; and analytic philosophy's freeing itself from a preoccupation with language and becoming willing to engage in ontological speculation. There are also empirical reasons such as experimental physicists' ever-greater skill at realizing in the laboratory what had been for decades only gedanken experiments. There are also of course institutional reasons, such as universities' founding History and Philosophy of Science departments in the 1960s, and (more negatively) physicists coming to foundational studies as a result of the recent dearth of jobs in theoretical physics, in contrast to the Cold War expansion of the 1950s and 1960s.

In this renaissance, the modal interpretation is one of some half-dozen main research programmes. It is a so-called no-collapse interpretation: the quantum state of an isolated system always evolves by the deterministic Schrödinger equation. It proposes to solve the measurement problem by judiciously assigning extra values to certain quantities so as to secure definite results for quantum measurements; and more generally, so as to secure a macroscopic realm that has definite values, at least for most, or familiar, quantities, at all or almost all times. So far, this is like the pilot-wave interpretation first developed by deBroglie and Bohm; and indeed, the interpretations are similar, and the comparison between them is worth pursuing.

The main differences lie in the choice of the preferred quantity (i.e. the quantity that gets the extra values), and in the rules for the evolution over time of these values. The pilot-wave interpretation proposes once and for all a preferred quantity; in most versions, it is a configurational quantity, such as a point-particles' position or the configuration of a classical field. And in most versions, the extra values evolve over time by a deterministic equation (the so-called guidance equation) that describes how the values are to change at time t in terms of the quantum state (wave-function) at t: hence the name 'pilot-wave'.

But for the modal interpretation, which quantity is preferred depends on the quantum state: the interpretation includes a rule specifying for each quantum state, which quantities on which systems have definite values. (More precisely, this is so for most versions—the main exception is Bub, whose framework also encompasses the pilot-wave and even the Copenhagen interpretations). Since the quantum state always evolves by the Schrödinger equation, there will therefore be a deterministic evolution of *which* quantity is preferred. But on the other hand, this allows the evolution of the possessed values to be indeterministic; and in most versions, it is.

Of the rules specifying which quantity is preferred, the one most discussed uses the spectral decomposition of the quantum state. At its simplest, this 'spectral rule' says that for a composite system $S_1 + S_2$, in a state $\Sigma_i \ c_i \mid \phi_i\rangle \mid \psi_i\rangle$, S_1 has the property corresponding to one of its states $\mid \phi_i\rangle$, and S_2 the property corresponding to one of its states $\mid \psi_i\rangle$; and that these properties are exactly correlated and are possessed with the usual quantum probability $\mid c_i \mid^2$.

This example also shows how the measurement problem motivates the spectral rule. For if S_1 is a microsystem and S_2 an apparatus, and the pointer-position states $\mid \psi_i\rangle$ of

S_2 measure a quantity on S_1 with eigenstates $\mid \phi_i \rangle$, then $\Sigma_i \ c_i \mid \phi_i \rangle \mid \psi_i \rangle$ is an entangled post-measurement state of the composite system comprising microsystem and apparatus. Since it is not an eigenstate of S_2's pointer-position, orthodox quantum theory says that in this state, the pointer is in no definite position—a version of Schrödinger's cat (no less worrying for being inanimate!). But on th eother hand, the spectral rule says that the pointer is in one of its positions; more specifically, it is in the ith position with the usual (and empirically correct) quantum probability $\mid c_i \mid^2$.

This motivation has been criticized on the grounds that it only fits the special case where the post-measurement state has the special form $\Sigma_i \ c_i \mid \phi_i \rangle \mid \psi_i \rangle$, rather than the more general $\Sigma_i \ c_i j \mid \phi_i \rangle \mid \psi_j \rangle$; and that for the latter state, the spectral rule will assign a definite value, not to pointer-position, but to some arcane quantity. The main line of reply, much discussed in this book (especially in the papers by Bub and Ruetsche), has been to invoke an ubiquitous and very efficient process, called decoherence, that arises from the interaction of the apparatus with its environment. It turns out that in some well worked-out models, decoherence alters the apparatus state in such a way that the spectral rule gives definite values to a quantity that is very similar (in a precise sense) to pointer-position. (And no apparatus can be sufficiently isolated from its environment to avoid the decoherence process; even the microwave background radiation will serve as a decohering environment.) This reply leaves two worries: (i) that in *other* models, the spectral rule will still give the wrong verdict, i.e. make definite some arcane quantity; and (ii) that it is pointer-position itself, not some other quantity (no matter how similar), that needs to be definite. Both these worries are discussed in the book; (especially (ii), by Ruetsche).

Motivations aside, the properties of the spectral rule (and its close cousins) have been much studied; and many papers in this book pursue the theme. There are two broad aspects to consider, which we might call "algebraic" and "non-local". For both aspects, the main effort has been to consider the bearing on the modal interpretation's rules, of traditional 'no-go' theorems showing that certain ways of supplementing orthodox quantum theory's value-assignments cannot work.

The algebraic theorems, which go back to von Neumann, Gleason and Kochen and Specker, show that subject to some mathematically natural constraints, sufficiently large sets of quantities cannot have value assignments, on pain of contradiction. So for the modal interpretation, the obvious question is whether the spectral rule or its cousins assign values to sufficiently large sets of quantities, so as to face a 'Kochen-Specker contradiction'. All five authors in the 'second generation' have studied this question; and in this book, it is the main topic of the papers by Zimba and Clifton, by Vermaas and (in a more philosophical vein) by Reeder. (Yet more recent results, and a survey, is in: P. Vermaas, Two No-Go Theorems for Modal Interpretations of Quantum Mechanics, *Studies in History and Philosophy of Modern Physics*, vol. 30B, 1999, pp. 403-432.) Two other papers study broadly algebraic aspects of the spectral rule, without regard to non-locality. Donald studies the behaviour of the rule in the case where some of the eigenvalues (c_i above) are degenerate; and Brown et al. study the relation between the rule's verdicts in different inertial frames.

On the other hand, the non-locality theorems, which go back to Bell, show that certain models, that aim to assign extra values in a local way (i.e. the result of a measurement here and now should not depend on spatiotemporally distant matters of fact), are committed to inequalities (the Bell inequalities), that have been violated by many experiments. So although denying that the collapse of the wave packet is a physical process avoids one potential source of conflict with special relativity, the modal interpretation and other no-collapse interpretations must be wary of other conflicts: do they assign values either in some local way that makes them subject to a Bell theorem, or in some non-local way that makes them confict with relativity?

Here again, the comparison with the pilot-wave interpretation is enlightening. As is well-known, the pilot-wave interpretation vividly exhibits quantum non-locality (it was this that inspired Bell to prove his theorem); and does so in such a way that it is very hard to see how to reformulate it in a fundamentally relativistic way (as against securing Lorentz-invariance of predictions, by averaging over non-Lorentz-invariant individual processes). In this book, the paper by Dickson and Clifton argues that the modal interpretation has a similar feature: but the topic is subtle—Dieks' paper suggests a line of reply (which today, he continues to develop).

Finally, I should briefly take up the topic of the modal interpretation's proposed rules for the evolution of the extra values it assigns: i.e. its indeterministic analogue of the pilot-wave interpretation's guidance equation. (Indeed, since in relativity there is time-evolution between mutually tilted hyperplanes, a full resolution of the debate over Lorentz-invariance requires agreement on such rules.) In this book, this topic is the focus of Bacciagaluppi's paper. This is an excellent paper, which builds on his joint work with Dickson, and on earlier work by Bell and Vink about an indeterministic dynamics for extra values, within a generalised pilot-wave setting.

So much by way of stating the basic ideas of the modal interpretation, and where it lies in the landscape of interpretations of quantum theory. Outsiders to the field will want to know if my proclaimed renaissance of activity has yet answered the questions about the interpretation of quantum theory; and in particular, whether the modal interpretation is established, or is close to being so. I admit that the short answer, to both questions, is No. But the situation is much less depressing than this short verdict suggests; even for the modal interpretation. For we are getting substantially closer to answers to the questions, both through theoretical work of the sort filling this book, and through experimental work. (For example, there are good prospects in the next decade or two for testing the models of wave-packet collapse, proposed from the 1980s onwards by Gisin, Ghirardi, Pearle and others. Hitherto decoherence has made the differences in the predictions of orthodox quantum theory and of these models empirically inaccessible.) So to sum up: the whole field is active, but still open—and as this book splendidly testifies, the same goes for the modal interpretation.