ESSAY REVIEW

Interpreting the Quantum World

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Jeffrey Bub, *Interpreting the Quantum World* (Cambridge: Cambridge University Press, 1997), xiv + 298 pp. ISBN 0-521-56082-9 hardback £35.00 (US$49.95)

The object of this book is the physical interpretation of the abstract formalism of quantum theory. This issue has been controversial from the early days of quantum mechanics, more than 70 years ago. Many of the best minds struggled with this problem, only to reach conflicting conclusions. Obviously, there is no similar interpretation problem for classical mechanics, because the mathematical symbols that appear in the latter simply coincide with experimentally observable quantities. On the other hand, the quantum formalism is based on a complex vector space in which the dynamical evolution is generated by unitary operators. Everyone agrees on how to manipulate the mathematical symbols; the thorny problem is to relate them to the observable physical reality.

The traditional answer is to introduce ‘observers’ who sense the quantum world by interacting with it. While they are engaged in that interaction, the observers must obey quantum dynamics—this is needed for consistency of the formalism. Yet, after completion of the measuring process, the same observers must be given a mundane, classical, objective description, so that the ‘quantum measurement’ ends with a definite result, as we experience in everyday’s life. Quantum mechanics itself does not predict, in general, that result. It predicts only probabilities for the various possible outcomes of a measurement, once we specify the procedure used for the preparation of the physical system. This ad hoc approach is sufficient for the purposes of experimental physics, and it can even be rationalized by some theoretical physicists (including the author of this review). However, it is considered as unacceptable by philosophers of science. Bub’s book gave me an opportunity to understand why.

Bub’s goal is to liberate the quantum world from its dependence on observers. Various possibilities are carefully examined. The book contains an amazing wealth of information, including numerous excerpts of correspondence between Einstein, Schrödinger, Pauli, Born, and others. I have particularly been impressed by the two long chapters (75 pages) which analyze in exhaustive detail the celebrated ‘no go’ theorems of Bell and of Kochen and Specker, namely the contradictions that would arise in any attempt to supplement the

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quantum wave function by additional ‘hidden’ variables, whose objective values would un-
ambiguously determine the result of any quantum measurement (the wave function itself
supplies only statistical information on the possible outcomes of physical experiments).
These two chapters are a welcome update to Redhead’s (1987) treatise on this subject.
The other chapters of the book analyze various interpretations of quantum theory, on
which I shall say more later.

On the negative side, I must confess that I have often been irritated by what may be,
after all, only a matter of terminology. Bub repeatedly uses the expression ‘the value of
a dynamical variable.’ While reading the first pages of the book, I tried to count how
many times this expression appears, but I quickly lost the count. In classical mechanics,
a dynamical variable indeed has a definite value at each point of phase space. Specifying
a point in phase space is the standard way of indicating the state of a physical system.
However, in quantum mechanics, a dynamical variable is represented by a Hermitian ma-
trix (or, more generally, by a self-adjoint operator). It is manifestly pointless to attribute
to it a numerical value. The founding fathers (Einstein, Schrödinger, and others), who
had been bred in classical concepts, could be excused for trying to force the classical
language on quantum theory. There is no excuse for that today.

The real issue that I can see at this point is whether Bub’s interpretation problem
is artificial (namely, it results from imposing a classical language for the description of
quantum phenomena), or whether there is a genuine fundamental difficulty rooted in
inadequate physical concepts. At the very beginning of his book (page 2), Bub defines
the result of the measuring process as follows:

In the orthodox interpretation, neither the measured observable nor the pointer
reading have determinate values, after a suitable interaction that correlates pointer
readings with values of the measured observable. This is the measurement problem
of quantum mechanics.

In other words, quantum mechanics does not provide a satisfactory description of the
measuring process.

The entire book is devoted to a discussion of various attempts to solve the measurement
problem. The tacit assumption made by Bub (as well as by many other authors who tried
to come to grips with that problem) is that the wave function is a genuine physical entity,
not just an intellectual tool invented for the purpose of computing probabilities. Even if
the wave function is not an ordinary physical object, it still has ontological meaning: it
represents the factual physical situation, not only our subjective knowledge of nature.

Basically, the problem is whether quantum mechanics is a theory of physical reality, or
one of our perception of the physical world. For the advocates of the realistic alternative,
who wish to give a consistent dynamical description to the measuring process, the source of the difficulty is clear: the evolution that we know to write for the quantum mechanical wave function during a measurement does not correspond with what is actually seen happening in the real world.

In the theoretical laboratory, wave functions are routinely employed by physicists as mathematical tools, which are useful for predicting probabilities for the various possible outcomes of a measuring process. The natural question is: can a more detailed description of that process be given? In order to investigate this problem, the nature of a quantum measurement must be clearly understood. The outcome of a measurement is more than the mere occurrence of an unpredictable event, such as the blackening of a grain in a photographic plate, or an electric discharge in a particle detector. To be meaningful, these macroscopic events must be accompanied by a theoretical interpretation, and the latter is always at least partly formulated in a classical language. For example, the Stern-Gerlach experiment is interpreted as the measurement of a magnetic moment, because it could indeed be such a measurement if we sent little compass needles through the Stern-Gerlach inhomogeneous magnet, instead of sending silver atoms. When nuclear physicists measure cross sections, they assume that the nuclear fragment trajectories are classical straight lines between the target and the various detectors. Without this assumption, the macroscopic positions of the detectors could not be converted into angles for the differential nuclear cross sections. Quantum theory appears only at the next stage, to explain, or predict, the possible values of the magnetic moment, the cross sections, the wavelengths, etc.

The measuring process is concluded by establishing an objective indelible record. The record must be objective (i.e., all observers shall agree about its contents), even if the ‘physical quantity’ to which that record claims to refer is not. Moreover, to have a meaningful result, we must interpret the experimental outcomes produced by our equipment. As I just mentioned, this is done by constructing a theoretical model whereby the behavior of the macroscopic equipment is described by a few degrees of freedom, interacting with those of the microscopic system under observation. This is the procedure that is called a ‘measurement’ of the microscopic system. The logical conclusion was drawn long ago by Kemble (1937):

We have no satisfactory reason for ascribing objective existence to physical quantities as distinguished from the numbers obtained when we make the measurements which we correlate with them. There is no real reason for supposing that a particle has at every moment a definite, but unknown, position which may be revealed by a measurement of the right kind, or a definite momentum which can be revealed by a different measurement. On the contrary, we get into a maze of contradictions
as soon as we inject into quantum mechanics such concepts carried over from the
language and philosophy of our ancestors . . . It would be more exact if we spoke
of ‘making measurements’ of this, that, or the other type instead of saying that we
measure this, that, or the other ‘physical quantity.’

However, the above statements are not the interpretation that Bub takes as the basis
for his book. Rather, he considers the orthodox interpretation of quantum mechanics as
the one formulated by Dirac and von Neumann, with ‘quantum jumps’ (a.k.a. collapses
of the wave function). According to that interpretative principle, observables come to
have determinate values when they are actually measured. Bub thoroughly criticizes that
orthodoxy, and rightfully so. He writes (page 34):

The upshot of this analysis is that ‘measurement,’ in the sense required by the
orthodox interpretation of the dynamical state as yielding probabilities of measure-
ment outcomes, can’t be understood dynamically. It follows that an observable that
has no determinate value cannot come to have a determinate value as the result of
a measurement understood as a dynamical interaction between a measured system
and a measuring instrument, and so the requirement of the orthodox interpretation
that observables come to have determinate values when measured has no dynamical
justification.

As an example,

[Schrödinger’s] cat will be neither alive nor dead after the measurement interaction,
according to the orthodox interpretation.

Since the ‘orthodox’ interpretation is so badly flawed, what can be acceptable alternatives?
The introduction of additional, hidden variables has been proposed, but the latter lead
to new problems that are the subject of the next chapters.

Chapter 2 (Bell’s ‘no go’ theorem) starts with a lengthy discussion of the Einstein-
Podolsky-Rosen (1935) incompleteness argument. Bub then gives not one, but several
proofs of Bell’s theorem, under slightly different physical assumptions. All these proofs are
thoroughly analyzed from the logical point of view. Unfortunately, there is no mention of
possible loopholes in the corresponding experimental tests (these tests are an unalienable
part of the Quantum World). Loopholes in the tests were pointed out by Santos (1991,
1992) and by many others, and they also lead to exquisite logical problems.

Moreover, Bohr’s (1935) rebuttal of the article of Einstein, Podolsky, and Rosen is
almost completely ignored. It is not mentioned at all in Chapter 2, nor in Chapter 3
(which is about Bell’s other theorem, a.k.a. the Kochen-Specker theorem). Bub finally
acknowledges Bohr’s analysis of the Einstein-Podolsky-Rosen article only near the end of his book (pp. 198–200), and there he writes:

The heart of Bohr’s response to the EPR argument is in a footnote . . . [and] in a further footnote that comments on the original footnote. No part of the paper other than the two footnotes and the brief remarks preceding the second footnote specifically addresses the EPR argument.

I find it rather disappointing that the discussion of Bohr’s article is restricted to these two strictly technical footnotes. I have always considered that article as one of the landmarks of quantum theory!

Chapter 3 (The Kochen and Specker ‘no go’ theorem) contains the most comprehensive anthology I have seen on this subject. In its original form, the Kochen-Specker theorem asserts that, in a Hilbert space with a finite number of dimensions, \(d \geq 3\), it is possible to construct a set of \(n\) projection operators, which represent yes-no questions about a quantum system of dimensionality \(d\), such that none of the \(2^n\) possible yes or no answers is compatible with the sum rules of quantum mechanics. Namely, if a subset of mutually orthogonal projection operators sums up to the unit matrix, one and only one of the corresponding answers ought to be yes. The physical meaning of this theorem is that there is no way of introducing noncontextual ‘hidden’ variables which would ascribe definite outcomes to these \(n\) yes-no tests. This conclusion holds irrespective of the preparation (i.e., the quantum state) of the system being tested.

Bub provides numerous examples, starting with a hitherto unpublished letter written in 1965 by the logician Kurt Schütte to Ernst Specker. The latest and most economical proofs are due to Kernaghan (1994) and to Cabello et al. (1996).

It is flattering that several illustrations from my book (Peres, 1993) are reproduced here. Yet, I am again disappointed that Bub chose to refer only to these technical points in my book, and totally ignored the rest of my views on the physical interpretation of quantum theory. (O well, I have no right to complain. I wrote in the preface: ‘This is not a book on the philosophy of science.’)

The problem of interpretation is the subject of Chapter 4, which is the heart of the book. Bub points out (page 116), and I wholeheartedly agree, that von Neumann was a learned mathematician \textit{par excellence}, but he largely abdicates this rôle in his discussion of measurement in quantum mechanics in favour of that of a (rather uncritical) metaphysician.

Indeed, the ‘orthodox’ interpretation that was set up by Dirac and von Neumann states that (pp. 117, 118)
an observable has a determinate (definite, sharp) value for a system in a given quantum state if and only if the state is an eigenstate of the observable ... The orthodox interpretation leads to the measurement problem, which Dirac and von Neumann resolve formally by invoking quantum jumps or a projection postulate that characterizes the ‘collapse’ or projection of the quantum state of the system onto an eigenstate of the measured observable. Dynamical ‘collapse’ interpretations of quantum mechanics keep the orthodox interpretation of the quantum state and modify the unitary Schrödinger dynamics of the theory to achieve the required state evolution for both measurement and nonmeasurement interactions.

Chapter 4 is relatively short and is mostly devoted to a rigorous proof of a uniqueness theorem for the ‘no collapse’ interpretations of quantum mechanics. The theorem states that, subject to certain natural constraints, all these interpretations can be uniquely characterized and reduced to the choice of a particular preferred observable as determinate. The preferred observable and the quantum state of the system define a non-Boolean ‘determinate’ sublattice in the lattice of all subspaces of Hilbert space—namely, the sublattice of propositions that can be true or false. The actual properties of the system are selected by a two-valued homomorphism (a yes-no map) on the determinate sublattice, so that the range of possibilities for the system is defined by the set of two-valued homomorphisms on that sublattice. From this ‘modal’ perspective, the quantum dynamical state is distinct from the ‘property state’ defined by the two-valued homomorphism. Different choices for the preferred determinate observable correspond to different ‘no collapse’ interpretations of quantum mechanics.

All this is necessary preparatory work for Chapters 5 and 6, both entitled ‘Quantum mechanics without observers.’ Bub wants to get rid of these fictitious observers, in spite of the fact that they appear to be quite harmless. (They are like the ubiquitous observers who send and receive light signals in textbooks on the theory of relativity.) On the other hand Bub still endeavours to assign numerical values to observables, or truth values to lattices of propositions. These are notions that have been borrowed from the classical world, and I don’t see why quantum reality, whatever it is, has to be described in terms of observables or lattices of propositions. The fundamental conundrum in the quantum formalism is not there. It is that quantum mechanics permits the occurrence of all possible events (with definite probabilities), but in our consciousness there is only one world.

Among attempts to solve the measurement problem, Bub examines Bohmian mechanics, non-ideal measurements, and the environmental ‘monitoring’ that leads to decoherence. He gives a concise proof of the tridecompositional theorem (a generalization of the Schmidt decomposition), which is essential for the various modal interpretations (page 178):
All these modal interpretations share . . . the feature that an observable can have a
determinate value even if the quantum state is not an eigenstate of the observable, so
that they preserve the linear, unitary dynamics for quantum states without requiring
the projection postulate to validate the determinateness of pointer readings and
measured observable values in quantum measurement processes.

On the other hand, Bohmian mechanics, as defined by Bohm and and Hiley (1993) is a
reformulation of quantum mechanics in terms of ‘beables’:

This theory is formulated basically in terms of what Bell has called ‘beables’ rather
than of ‘observables.’ These beables are assumed to have a reality that is indepen-
dent of being observed or known in any other way. The observables therefore do not
have a fundamental significance in the theory but rather are treated as statistical
functions of the beables that are involved in what is currently called a measurement.

Likewise for Bell (1987), the ‘beables’ of a physical theory are equivalent to its ‘elements
of reality’ as defined by Einstein, Podolsky, and Rosen (1935). Bell writes:

In particular we will exclude the notion of ‘observable’ in favour of that of ‘beable.’
The beables of the theory are those elements which might correspond to elements
of reality, to things which exist. Their existence does not depend on ‘observation.’
Indeed observation and observers must be made out of beables.

Yet, as Bell himself had strikingly shown many years earlier, these elements of reality
engender serious difficulties when we want to retain the commonly accepted assumptions
on the locality of physical phenomena (see the ‘no go’ theorem in Chapter 2).

Chapter 7 is entitled ‘Orthodoxy,’ but it is not about the ‘orthodox’ interpretation of
Dirac and von Neumann, that was discussed above. The chapter starts with a section on
the so-called Copenhagen interpretation. [I always refrain from using that terminology,
because the ‘Copenhagen interpretation’ comes in many variants, which may be in com-
plete opposition to each other. Compare for example the reviews by Ballentine (1970)
and Stapp (1972).]

In the quantum folklore, the Copenhagen interpretation is linked to the uncertainty
relations, which are a special case of the complementarity principle. Bub points out minor
differences between the points of view of Bohr and Heisenberg. He mentions Wigner’s
dualism and Wheeler’s observer-participancy, and then he asserts (page 191):

It is generally recognized—at least, by all but the most recalcitrant positivists—
that the mere fact that measurements disturb what we measure does not preclude
the possibility that observables have determinate values, or even that measurements might be exploited to reveal these values in suitably designed measurement contexts. The ‘disturbance’ terminology itself suggests the existence of determinate values for observables, prior to measurement, that are ‘disturbed’ or undergo dynamical change in physical interactions.

For the opinion of some recalcitrant positivists on how to actually define ‘disturbance’ in quantum mechanics, see Fuchs and Peres (1996).

Bub does not do justice to Bohr’s point of view. He barely mentions Bohr’s insistence that measuring instruments must always be described on classical lines. This classical-quantum duality, not the particle-wave duality, is the most significant feature of Bohr’s interpretation (Bohr, 1949):

In a lecture on that occasion [Como, 1927], I advocated a point of view conveniently termed ‘complementarity,’ suited to embrace the characteristic features of individuality of quantum phenomena, and at the same time to clarify the peculiar aspects of the observational problem in this field of experience. For this purpose, it is decisive to recognize that, [author’s italics] however far the phenomena transcend the scope of classical physical explanation, the account of all evidence must be expressed in classical terms. The argument is simply that by the word ‘experiment’ we refer to a situation where we can tell others what we have done and what we have learned and that, therefore, the account of the experimental arrangement and the results of the observations must be expressed in unambiguous language with suitable application of the terminology of classical physics.

Bohr was very careful and never claimed that there were in nature two different types of physical systems. All he said was that we had to use two different (classical or quantum) languages in order to describe different parts of the world. The peculiar property of the quantum measuring process is that we have to use both descriptions for the same object: namely, the measuring apparatus obeys quantum dynamics while it interacts with the quantum system under study, and at a later stage the same apparatus is considered as a classical object, when it becomes the permanent depository of information. This dichotomy is the root of the quantum measurement dilemma: there can be no unambiguous classical-quantum dictionary. There can only be an approximate correspondence between the two languages. That mismatch is the source of the so-called ‘quantum uncertainties.’

Bohr also was sometimes quite elusive. He never explicitly treated a measurement as an interaction between two quantum systems followed by a collapse of their wave function, and he could thereby completely elude the measurement problem. Indeed Bub acknowledges (page 195) that
Complementarity, too, can be understood as a type of ‘no collapse’ interpretation. From the perspective of the uniqueness theorem, Bohr’s complementarity and Einstein’s realism (in the ‘beable’ sense, stripped of Einstein stringent separability and locality requirements) appear as two quite different proposals for selecting the preferred determinate observable: either fixed, once and for all, as the realist would require, or settled pragmatically by what we choose to observe. (So complementarity is not an observer-free ‘no collapse’ interpretation.)

Chapter 8 (The new orthodoxy) discusses various mutations of quantum mechanics that are currently popular: environment-induced decoherence (which cannot solve the measurement problem), the many-worlds interpretation, and the method of ‘consistent histories’ which is related to both of them. If taken seriously, the many-worlds interpretation leads to bizarre declarations, such as (page 227):

Suppose that Eve is competent to report her mental state when it is not an eigenstate of some definite belief about $S$-spin . . . Eve will respond that she has a definite belief about the spin of the electron even when she in fact has no definite belief . . . Eve is apparently going to be radically deceived even about what her own occurrent mental state is.

The subject is no longer physics. It is psychology, or perhaps psychiatry, well beyond my limited area of competence.

The theory of consistent histories is more technical, which makes it vulnerable to various technical claims of inconsistency. Its aim is to encompass the entire universe, including some ‘quasi-classical domains’ that play a role analogous to that of the Copenhagen observers. Here is the right place to ask whether there can be a meaningful non-Copenhagen variant of quantum theory that applies to everything in the universe, in particular to the atoms in my brain. It seems to me that such a quest makes no sense and can only lead to self-referential delusions, as in the above quote. The very idea of a wave function of the universe is beyond my comprehension.

Returning to physics, a completely different problem is whether we can consider just a few collective degrees of freedom of the universe, such as its radius, mean density, total baryon number, etc., and apply quantum theory to these degrees of freedom, which do not include the observer and other insignificant details. This seems legitimate: this is not essentially different from quantizing the magnetic flux and the electric current in a SQUID, and ignoring the atomic details. You may object that there is only one universe, but likewise there is only one SQUID in my laboratory. For sure, I can manipulate that SQUID more easily than I would manipulate the radius of the universe. Still, that SQUID is unique. There is no difference in principle.
The last chapter (Coda) summarizes the arguments of the book, and a long appendix (Some mathematical machinery) comes to help non-initiated readers. In conclusion, there is much to learn from Bub’s book, and I recommend it without hesitation to all those who are interested in the foundations of quantum theory.

However, I must add that the contents of this book did not fulfill some of my expectations. It has an attractive title, *Interpreting the Quantum World*, but is this a genuine interpretation? My dictionary (Webster, 1974) defines ‘interpret’: 1. to explain the meaning of, make understandable ... 2. to translate ... (there also are other definitions, not relevant here). To interpret quantum theory, to explain its meaning, to make it understandable, the way has been shown to us: we have to *translate* the abstract mathematical formalism in such a way that ‘we can tell others what we have done and what we have learned and [this] must be expressed in unambiguous language with the terminology of classical physics.’

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