Review of *Making Sense of Quantum Mechanics* by Jean Bricmont

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Is this just another addition to the exhausting literature on quantum theory and its much touted mysteries? Not exactly. Rather, it's a book to get into the hands of all young physics students as early on as possible, precisely so that they won't need to plough through any more literature than is absolutely necessary. And a handful of sources should be enough to state the remaining difficulties raised by this theory. Then at least we could focus on the real problems.

Oddly, some people seem to obstinately prefer mystery. This is clear from the views of the numerous expert practitioners of quantum theory, both past and present. Bricmont quotes a selection of these in Chap. 1 of the book, which carries the slightly mocking title *Physicists in Wonderland*. Such views are sometimes driven by overriding principles that one would like to expunge from the consideration of 'ordinary' matter, like the power of the mind over that same matter [1, 2]. And they are sometimes intent on the defence of an inescapable and intrinsic role for indeterminism in the world by people who assume this to be a *sine qua non* for them to be able to make free choices [3].

But many are just resigned to the idea that we could never really understand 'what is going on' in a theory whose ontology contains only a function defined on configuration space, whence any underlying happenings or mechanisms in the familiar 3D space of the laboratory must remain undisclosed by the theory. Naturally, there do remain unsolved problems with quantum theory on the most fundamental level, and Bricmont deals with these as succinctly as anyone could. Here is the voice of rationalism.

However, he first disposes of the 'problem of measurement' which, despite its endless ramifications, is a pseudoproblem that young people should no longer be made to worry about. Many accounts of quantum theory insist that it is only a theory about measurements of physical quantities, and that there must always be mention of an observer. But then we are left to wonder where the observer begins and ends, as John Bell put it [4, p. 48]. What is allowed to constitute an observer, and when can an interaction be counted as a measurement? Surely a theory as fundamental as this should apply to any physical configuration, whether it involves one of our experiments or not?

Certainly, quantum theory turns out to be about the results of measurements, in the sense that it predicts the frequencies with which different results will come up when certain measurements are made. And if the only object in the ontology of the theory is a wave function, then that leaves a lot to be explained. For one thing, the wave function is defined on a configuration space, and whenever more than one 'particle' is involved, this is not the 3D space we live in, so it is hard to see in those cases how to deduce anything from the theory about what is actually happening in our 3D space, and in particular, what it is happening to. Indeed, it is difficult even to explain the problem without the help of scare quotes on the word 'particle'.

Bricmont considers the main attempts to get round this obstacle and highlights their many and often disastrous weak points, apart from the generally expensive hypotheses they involve (Chap. 6). But a large part of the book (especially Chap. 5) is about a simple and natural way to extend the ontology of quantum theory and in so doing provide a straightforward account of what is actually happening in setups like the two-slit experiment, by straightforwardly introducing something that it can actually happen to, viz., particles. The result is known as the de Broglie–Bohm theory, or Bohmian mechanics.

Behind the screen with the two slits, points appear on the detection screen. There is no way to even approach an explanation of this simple fact if the ontology of one's theory contains only waves defined on configuration space. And what could be more natural than to assume that these detection points are made by pointlike or very small particles? A lot of the book is then, either directly or indirectly, about the resistance to this idea (see in particular Sects. 5.2–5.4, and 7.6), a resistance which is often simply misinformed. Indeed, Bricmont shows how many of the criticisms of the particle ontology are merely due to a misunderstanding of the de Broglie–Bohm theory. There is a moral here: to criticise a theory in any useful way, we must first make sure we understand what it says.

Of course there is a reason why uncautious criticism comes about in science, apart from the straight application of prejudice. It is just that science is demanding and time-consuming to understand, so when there are many theories around, we have to filter. Here we can often only apply our intuition, although inevitably this will itself be imbued with prejudice. On the other hand, such filtering may explain a choice but not justify it. And in the case of the de Broglie–Bohm theory, it is hardly an excuse, since the basics of the theory are very easy to grasp, as Bricmont shows here, and there are by now many good sources of information [5–8]. Even today, some of the errors by expert practitioners are surprising, to say the least.

An example can be taken from a recent book by the remarkable experimentalist Nicolas Gisin. He makes a misleading claim that is dispelled immediately just by the existence of Bohmian mechanics [3, p. 46]:

> If there are hidden positions, there must therefore also be hidden velocities. But that contradicts Heisenberg's uncertainty principle which is a key part of the quantum formalism.

The problem here is that there are simultaneously both hidden velocities and hidden positions in Bohmian mechanics, and since Bohmian mechanics makes the same predictions as quantum mechanics, we can only conclude that this version of Heisenberg's principle must be mistaken. But the uncertainty principle is concerned with the results of measurements rather than unobservable velocities. The very existence of Bohm's theory shows that Heisenberg's principle can in fact live alongside actual particle velocities and positions.

The second chapter of Bricmont's book discusses one of the characterising features of quantum theory: the way quantum waves can combine to produce interference effects. But it also discusses another key point about quantum systems which is crucial to this book and which is clearly revealed and explained only if one extends the ontology of quantum theory by including particles: the values of many physical quantities produced by measurements cannot be intrinsic properties of the system that are independent of the measurement process (Sect. 2.5.2). Only in certain very specific cases do measurements simply reveal pre-existing intrinsic values.

This is illustrated with the case of spin. The claim here does not mean that intrinsic spins cannot be attributed to the particles in the ontology. Indeed, as Bohm has shown, and as discussed in considerable detail by Holland and others (see [9] and references therein), a spin three-vector can always be associated with each particle whether it is being measured or not, and in such a way that, when a measurement of the spin is actually being carried out, the result will in fact be the value of this spin at the end of the measurement. The great advantage of the de Broglie–Bohm theory is that it provides a crystal clear picture of 'what is going on'.

There is absolutely no room for mystery here. But here is the rub: since measurements cannot reveal the pre-existing value postulated here, there is no way of knowing or establishing what that value was. In fact, there is a double-edged temptation to use an Ockham razor on these intrinsic spins, and even extend it to the particle positions and hence to the particles themselves. In a first swipe, one may declare Bohm's intrinsic pre-existing spin variables to be unnecessary because it turns out that the spins attributed to the particles in the system will always simply be position dependent, whence one might as well only attribute positions to the particles, a stance adopted by many Bohmians [5, 6].

But in a second swipe, since it turns out that even the particle positions remain 'hidden' in the sense that they may be vastly different in many different setups that would be described by the same wave function, the vast majority of physicists who actually think about this issue (and that is probably a vast minority of physicists) prefer to declare the particle positions, and with them the particles themselves, as unnecessary, unjustifiable, unphysical, or unreal. This leaves them with an ontology that contains only wave functions. Worse, we inherit the disastrously inappropriate appellation 'hidden variable' to describe physical quantities like particle positions.

Actually, it should be mentioned that, according to the assumptions of the de Broglie–Bohm theory, position measurements do in fact reveal where the particles are, i.e., values for positions are not affected by the measurement process. The postulated intrinsic spins, on the other hand, are in general very much affected by that process and in that sense are unattainable by direct measurement.

So spin and position measurements are not on the same footing. And the de Broglie–Bohm theory can perfectly well explain, without mention of any intrinsic spin, why particles with spin end up where they do in a spin measurement involving a Stern–Gerlach magnet. But the de Broglie–Bohm particle positions are still generally taken to be 'hidden' variables by those whose ontology contains only wave functions, since for any given wave function, there are many possible configurations of particle positions.

In Chap. 2, by considering the Mach–Zehnder interferometer, Bricmont shows how hard it is to make sense of a 'particle' interpretation until one gets the idea that the wave function, which depends on the whole configuration of the interferometer, might actually be guiding real particles. Then blocking one arm of the interferometer with a wall can be precisely and quantitatively understood as affecting particles going through the other arm. Without this, and imagining a situation in which the choice of whether to block the first arm is delayed in a certain way, one soon ends up with wild claims such as those made by Wheeler, according to which the past is not really the past until it has been registered, whatever 'registered' may mean [4, pp. 67–68]. Here we may say that it is probably better to understand the world in the de Broglie–Bohm way, even if there is no way of knowing or establishing what intrinsic values of physical quantities can be associated with particles when we are not looking at them.

In fact, despite the usual claim that there are only wave functions, it is still standard practice to pay lip service to the existence of particles in contexts where quantum theory is applied. How else could we talk about anything in our 3D world? But even today, people like Elitzur are still thinking up 'paradoxes', such as his bomb-testing paradox devised with Aharonov in [10], also discussed by Bricmont, while these conundrums can only remain paradoxical if we reject the startlingly clear picture of particle trajectories provided by the de Broglie–Bohm theory.

In his crucial Sect. 2.5, Bricmont discusses four possible reactions to the interference effects predicted by quantum theory:

- One can say that the ontology of the theory contains only the wave function and that the microscopic world is incomprehensible, allowing one merely to predict the results of measurements.
- One can say that the ontology of the theory contains only the wave function and try to analyse the measurement process as a purely physical process without mentioning any outside observer.
- One can say that the ontology of the theory contains only the wave function and that the wave function does not represent an individual system, but an ensemble of systems.
- One can say that there has to be more in the ontology of the theory.

He shows why the middle two options fail: the first predicts a superposition of macroscopic systems, something never yet observed, while the second collides with some well established mathematical theorems that can be derived from the quantum formalism.

These theorems have the unfortunate name of ‘no hidden variables theorems’. Bricmont describes and proves several in his Chap. 2. The name has led to much confusion. For example, Bell himself proved some of these, and yet always remained an ardent advocate of the de Broglie–Bohm theory, which is generally considered to be a theory that introduces hidden variables. But disregarding the name, and it is better to do so, these theorems all say the same kind of thing: when we consider spins or momenta, the statistical predictions of quantum theory are not about pre-existing values of the physical quantities that are merely revealed by the measurement process. We may say that ‘pre-existing value’ is a better appellation than ‘hidden variable’. At least, it is a better appellation in the de Broglie–Bohm theory, where it is actually possible to attribute pre-existing values and they are perfectly consistent with the statistical predictions of quantum theory. Then it has to be remembered that the latter concern the *results* of measurements, *not* pre-existing values, except in the case of position measurements.

Chapter 3 is a brief excursion into philosophy. It is brief because one of the messages of this book is that philosophy will not help solve any conceptual problems with quantum theory. The author discusses realism and the idealist challenge to it. The problem here is certainly that most quantum theorists refuse to augment the ontology of the theory beyond the wave function. What these physicists then discover is that such an ontology is highly problematic, often in more ways than they might imagine. It leads to claims that no distinction can be made between reality and our knowledge of reality, between reality and one of today’s great bandwagons, viz., information. If you have already been caused to fret over this pseudoproblem, then Chap. 3 will be useful reading.

As the author points out, however, idealism is related to one serious question: how does the cognitive interaction between ourselves and the world work? How do we form representations? Where do concepts come from? And, ultimately, how do conscious sensations arise? Let us just agree here with Bricmont that these difficult questions can themselves be the subject of scientific investigation, coming under the sway of cognitive science or neurophysiology. In the author’s own words, knowing how our minds work, what categories they use, and what limits those categories may impose on our ability to know the world are surely empirical questions. One might add that the answers are likely to be Darwinian, i.e., to be best expressed by applying the Darwinian algorithm [12].

So what about scientific realism: should our theories be understood realistically? Should we consider them to be approximately true in a Tarskian sense, as corresponding somehow to what we, as philosophical realists, would take to be ‘out there’? Bricmont succinctly considers the key issues:

- Underdetermination of theory by evidence (Sect. 3.2.1). The point that our imaginations can easily conjure up an unlimited number of theories that would be compatible with the data available at any given time. Here the fact that radical skepticism may always come up with some wild scheme to 'explain' what we observe is countered with the realist's no miracle argument: it would be a miracle if theories that have many empirical successes, like the best scientific theories, did not correspond in some way, or approximately, to what is actually going on in the world.

- Incommensurability of Kuhnian paradigms. Are atoms, for example, only the result of a certain way of looking at the world, as laid out by some theory or other? In this sense, it may be that evidence never decisively shows us anything about the way the world really is. See Sect. 3.2.2 for a rebuttal.
- What to think about unobservable entities (Sect. 3.2.3). The argument in favour of the existence of such entities is straightforward: we cannot effectively formulate our theories without postulating those entities and the evidence for the truth of the theory then counts as evidence for the existence of those unobservable entities.

What is at stake in the present context is the reality or otherwise of the de Broglie–Bohm particles with their trajectories. The author then discusses claims that quantum theory forces us to abandon realism, a position that has filtered through to an uninformed public and very likely led to much misunderstanding about the value of scientific endeavour.

The last subject of discussion in Bricmont's philosophical interlude concerns the usual understanding that quantum theory introduces an irreducible indeterminism into the nature of the world, that is to say, pure randomness or events without cause. The hope often seems to be that this will rescue our feeling that we have free will, i.e., that we are somehow free to choose between what we conceive of as a range of possible options (see in particular [3] for an outspoken defence of this aspiration). At least on the face of things, in a deterministic world, the prospects for such a freedom do not look encouraging. But then a little thought shows that the prospects would not be better in an indeterministic world: are our free choices supposed to occur at random? And it may be that we are compelled to rethink the nature of free will (see [11], for example).

The de Broglie–Bohm theory is an entirely deterministic theory of the microscopic world. The Schrödinger equation which describes the evolution of the wave function was always accepted as deterministic, but the equations showing how it guides the de Broglie–Bohm particles are also entirely deterministic. And there is no other evolution of the wave function here, because there is no mysterious 'wave collapse'. Probabilities enter only because the particles may have a whole range of different initial positions in any given situation described by some given wave function. They thus enter precisely as they do in statistical thermodynamics, where a whole range of particle configurations and velocities is compatible with a given macroscopic description in terms of a given temperature, pressure, and so on.

Bricmont takes some trouble to clarify the notions of determinism and indeterminism, with a discussion of chaos theory, probabilities in classical physics, and the law of large numbers, so crucial to understanding statistical physics in general and the de Broglie–Bohm theory in the present case. But in standard quantum theory we are brought face to face with one of the key issues raised by keeping an ontology that contains only the wave function: how can such a quantum state, whose meaning is purely probabilistic, nevertheless evolve according to a physical law (at least between measurements when it is not required to 'collapse')?

As the author points out, no clear answer is possible here because of the lack of clarity over the status of the quantum state. Is it ontic, i.e., a physical object, or is it purely epistemic, i.e., a mere reflection of our knowledge? If it is ontic, then we have a problem with the superpositions of states corresponding to macroscopic objects that evolve for example when we carry out experiments. If it is epistemic, then we at least have to accept the conclusion of the no hidden variables theorems, which tell us that it cannot generally be giving us the probabilities of pre-existing values of the relevant physical quantities.

Chapter 4 is about the only remaining mystery in quantum theory, the only one that young students need to focus on, namely, the way particles can interact instantaneously even when they are arbitrarily far apart. This so-called nonlocality, which has been demonstrated experimentally (or almost) by people like Aspect, Gisin, and Zeilinger (see [3] for an elementary account and references), seems to raise a problem when the nonrelativistic theory is transposed to the underlying structure of Minkowski spacetime, where relativity theory would constrain physical accounts to be Lorentz symmetric. And it is the de Broglie–Bohm theory that generates the starkest picture of this problem, for one can read off the instantaneousness of the interaction between entangled Bohmian particles, even when they are widely separated in space, directly from the dynamical equations in that theory.

But the problem is just as pressing in a quantum theory whose ontology includes only wave functions. It arises for the same reason, namely that the wave function is a function on configuration space, the $3N$-dimensional space of all ordinary space coordinates of N particles, in the case of an N-particle system. The problem is that any configuration space for a set of particles depends on a choice of spacelike hyperplane, thereby raising a problem for Lorentz symmetry, which requires that physical effects should not depend on any such choice.

Although he was not the first to spot the problem, it was Bell who first clearly spelt out why quantum theory, either in the standard version or in the de Broglie–Bohm theory, always entails nonlocal effects. Bricmont explains the historical context of this argument, which is not glorious for the physics community. The argument begins with the conclusion of the celebrated EPR paper [13], which came much earlier and was much misunderstood: if there are no nonlocal effects, by which was meant instantaneous action at a distance, then quantum mechanics implies that certain physical quantities, for whose values the theory only predicts relative frequencies of measurement results, must actually have one of the possible values prior to their measurement. This would mean that a quantum theory containing only the wave function in its ontology cannot be a complete description of the physical situation, because it would not actually say which of the possible values pre-existed the measurement.

Actually, EPR considered it obvious that there would be no nonlocal effects, because it went against the ethos of the already established relativity theories. So they felt they had proved that quantum mechanics could not be a complete theory in the above sense, i.e., that there had to be some kind of *hidden* variables. Bell's aim, however, was to show that there had to be nonlocal effects. What Bell added was a proof that, in the case of entangled states, the very fact that the results of certain measurements as predicted by quantum mechanics have to pre-exist their measurement would imply a certain inequality involving the relative frequencies of joint measurement results for the component subsystems of those states. But his inequality was contradicted by the quantum theoretical predictions for those relative frequencies.

This meant that quantum mechanics itself showed that the pre-existing values for the relevant physical quantities, if they existed at all, could not be the values that the theory predicted would result from measurements. It also showed, with the help of the EPR argument, that quantum mechanics does involve nonlocal effects in the case of these entangled quantum states. Note this, however: the de Broglie–Bohm theory shows that we *can* attribute pre-existing values to all physical quantities, and not just particle positions, but also momenta or spins. The point is that they cannot all be the results of measurements of those quantities. Moreover, it makes the nonlocality absolutely explicit.

Experiment has also shown (almost) that there are nonlocal effects in entangled systems because it has shown (almost) that various Bell-type inequalities are violated. By the same argument as above, this means that the results of certain measurements, e.g., spin or polarisation measurements, as predicted by quantum mechanics cannot pre-exist their measurement, so by the converse of EPR-type arguments, there must be nonlocal effects. Better still, the experimental results in these cases agree well with the predictions of quantum mechanics and therefore corroborate it, just as they corroborate the de Broglie–Bohm theory, which makes the same experimental predictions as standard quantum mechanics.

The conclusion from the EPR argument combined with the Bell inequality is a little delicate if we wish to say that recent experimental results demonstrate nonlocality, because these arguments involve reference to quantum mechanics and on the face of things it could be that quantum mechanics goes wrong somewhere and that locality might be saved. The whole reasoning has thus undergone careful scrutiny and refinement so that we now show a Bell-type inequality for much more general situations, viz., expectations of joint measurements of some quite general physical quantity associated with each component of a two-component system where the two components have a common source and the measurements are made at spacelike separation. Here we basically assume only that the world is locally causal in order to get the inequality (see [14, pp. 80–85] for in-depth discussion of what is assumed and why).

Bricmont provides a simple example of such a very general Bell inequality in his Sect. 4.4.1, and he shows how certain statistics for the results cannot be achieved without contravening the inequality, i.e., they cannot be achieved in a locally causal world. Applying this kind of inequality to a system comprising a pair of entangled photons and taking the physical quantity to be the photon polarisations, we then note that quantum mechanics would predict a violation of the given inequality, implying nonlocal effects, but also that experimental results violate the inequality, likewise implying nonlocal effects whether quantum mechanics is the right theory or not. Apart from certain tiny loopholes that remain to be closed off, experiment has thus demonstrated that nonlocal effects do occur in our world. The most thorough account of the ramifications of this discovery yet available can be found in [14].

Nonlocal effects in entangled quantum states are perhaps the greatest scientific discovery of the twentieth century, but they also raise the greatest challenge for fundamental physics. Bricmont lists the main features of these effects: they are restricted to specific systems whose 'components' are entangled in the quantum sense, their action extends arbitrarily far without diminution, and they are instantaneous. Although the second feature looks decidedly counterintuitive, it is the last feature that raises the problem, because relativity theory tells us that instantaneity can only be specified relative to a choice of reference frame. But relativity theory would have it that no real physical effect should depend on a choice of reference frame. The take-home message for the youthful reader of this book is that, having understood why there is no measurement problem in the de Broglie–Bohm theory, she may focus entirely on this issue. The book by Maudlin [14] is then essential further reading.

As Bricmont copiously explains, standard quantum theory does not escape this problem, despite the existence of quantum field theories that appear on the face of things to have Lorentz symmetric formulations. When one component of an entangled pair system is subjected to a measurement, the wave function is supposed to instantaneously collapse *everywhere*, whence measurements on the other component must be instantaneously affected. We thus encounter the same problem. And quantum field theories never treat the question of wave collapse.

One reaction is to say that the wave function must be epistemic, i.e., only providing information and not at all corresponding to a physical occurrence. But we know that the answers to questions posed by these experiments on the spins or polarisations in microscopic systems cannot just be pre-existing values of the relevant physical quantities, thanks to Bell's discovery of the inequalities discussed above. So the wave function is really only telling us about the values of physical quantities at the *outcome* of the measurement process, and we then have no idea why that should work. We have to say that the microscopic world necessarily remains a complete mystery to us and our theory is merely a tool for making predictions. We are thus reduced to instrumentalism.

It is to Bricmont's credit, although natural for a rationalist, to discuss all the issues raised here, including those that spell peril for the de Broglie–Bohm theory. But the point of the book is for a large part to show that many of the problems discussed at such enormous length over the last hundred years, those turning around the measurement problem, just need not concern us. Then it should be possible to focus on the issue of nonlocality, and in particular the revolutionary nature of these phenomena and their potential conflict with relativity theory.

He also reviews the main ideas put forward to save quantum theory from the measurement problem, viz., many-worlds theories, spontaneous collapse theories, decoherent histories, and QBism, then revisits the history of quantum theory and the way the de Broglie–Bohm theory was received, a sorry story for the history of science, from which we ought to draw lessons. Here is another area that young scientists might usefully focus on. After all, science sprang from, or created, the Age of Reason and the Enlightenment. Here we see how easy it is to slip back into irrationality, and how destructive it can be for progress in science, and hence progress in enlightenment, an ongoing problem for humanity. Social scientists will enjoy Bricmont's objective discussion of the way even politics and religion got themselves into the picture (Sect. 7.7).

The last chapter of the book discusses the effects of the quantum quandary on the way science is sometimes misrepresented and exploited. As Bricmont puts it, the problem here is not just that this area of science has been abused by people who are largely ignorant of it. The point is that scientists themselves have very largely contributed to that abuse, and in several different ways. One was to make the human observer a central element of fundamental physics, a fatal move for objective science, as Bell was so keen to point out. Another was to declare the microscopic world forever incomprehensible. The alternative would have been to admit that quantum theory is not after all the ultimate physical theory, as certain less-than-humble theoreticians would have had the world believe, but only a step in what is likely to be a neverending series of ever more comprehensive and refined hypotheses about the physical universe.

The paradox is that, through this lack of humility, physics has ended up by stimulating mysticism and a host of anti-scientific attitudes. But from another point of view, the arrogance of certain founding fathers of quantum theory in asserting one way or another that there was no need to worry about the philosophical issues, either because they had got everything worked out or because it would forever be impossible for any human being to understand the microscopic world any better than they could, meant that everyone else could get on with simply applying the theory, with the spectacular results that we see around us today.

Notwithstanding, the aim of science is presumably the pursuit of objective truth as some kind of ideal, and it would be a pity to halt the process here. As Bricmont puts it in his closing lines, quantum physics has changed the world in so many ways, and now the time has perhaps come to try to understand it. We could begin this task by changing the way we teach quantum physics, so that young physicists can tackle the fundamental difficulties without having to wade through endless philosophical literature, or simply being put off by it. They need at least to know that there is debate and that many claims about the status of quantum mechanics are simply wrong. For example, they need to be warned about the naive statistical interpretation which is ruled out by the no hidden variables theorems, and they could easily be introduced to the main features of the de Broglie–Bohm theory in which so many of the much advertised mysteries of quantum theory simply don't arise at all. But above all, they should be encouraged to focus on the feature of all these theories that distinguishes them as revolutionary: nonlocality.

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