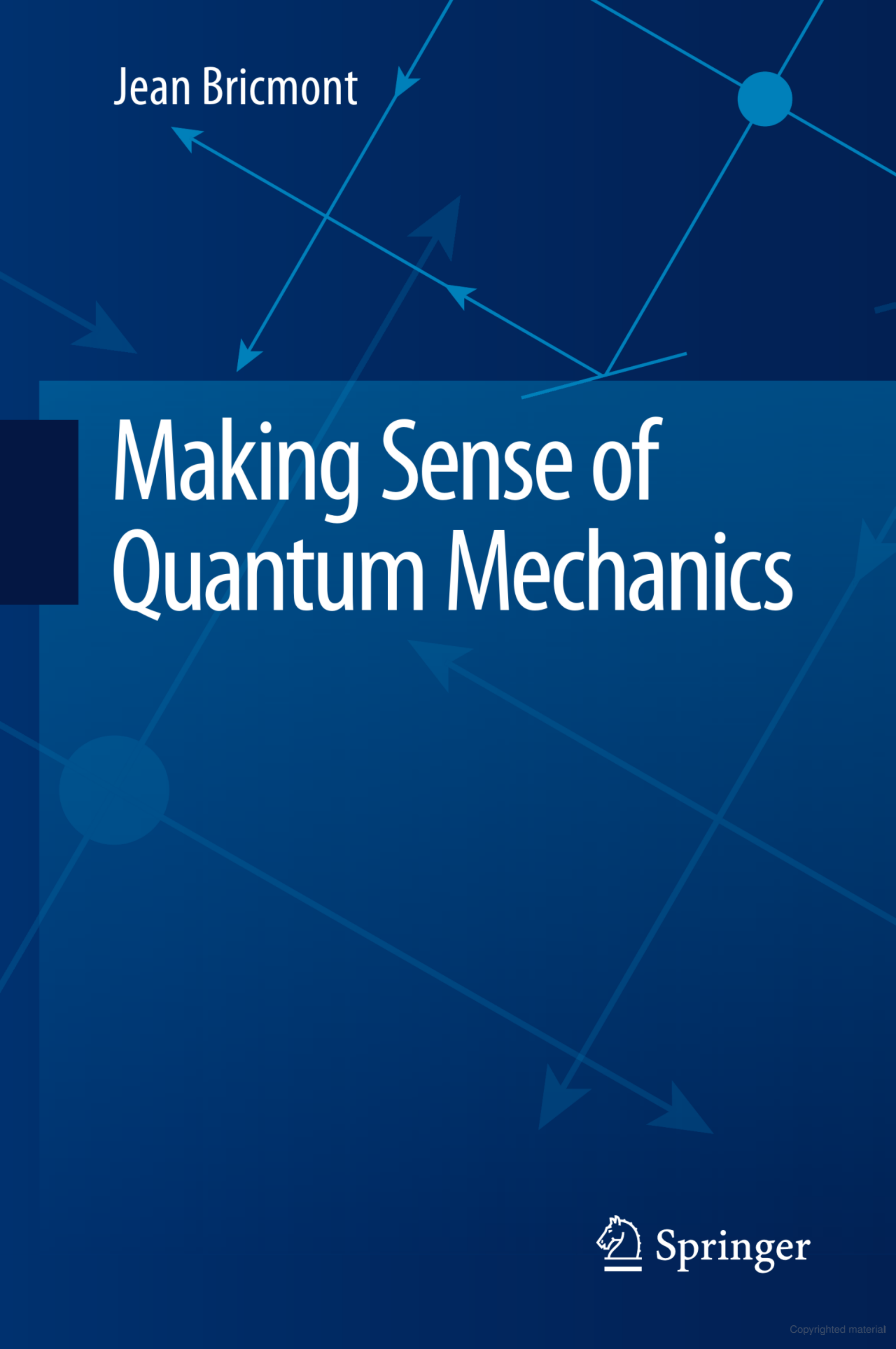

Jean Bricmont

Making Sense of Quantum Mechanics

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Physicists in Wonderland

1.1 What This Book Is About

According to the French newspaper *Le Monde*, a famous English rugby player, Jonny Wilkinson, claims to have been “saved from depression” by studying quantum physics [308]. The player even held a public conference with two well known French physicists, Jean Iliopoulos and Étienne Klein, attended by 500 people, and the conference was published (in French) under the title “Quantum Rugby” [519]. Interviewed by *Le Monde*, Étienne Klein says that the player did not really know quantum physics, and mostly relied on metaphors, linked to his interest in Buddhism.

If what Wilkinson understood of quantum mechanics is uncertain, one can be reasonably sure that nobody would claim to have been saved from a depression by studying any physical theory other than quantum theory.

Since its beginnings in 1900, the quantum theory[1] has led to the most spectacularly well confirmed predictions ever made in science (some experimental results agree with the theoretical predictions up to one part in a billion), and it underpins all modern electronics and telecommunications. It explains the stability of atoms and of stars, and lies at the foundation of the whole of particle physics, but also solid state physics, chemistry, and thus, in principle, biology. It is truly our most fundamental theory of the world. Yet, to quote the famous American physicist Richard Feynman,[2] “nobody understands quantum mechanics” [185].

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[1] Since this book deals mostly with non-relativistic quantum physics, we will use the expressions “quantum mechanics”, “quantum physics”, or “quantum theory” interchangeably.

[2] Feynman was comparing the situation in quantum mechanics with the one in the theory of relativity [185]: “There was a time when the newspapers said that only twelve men understood the theory of relativity. I do not believe there ever was such a time. There might have been a time when only one man did, because he was the only guy who caught on, before he wrote his paper. But after people read the paper a lot of people understood the theory of relativity in some way or other, certainly more than twelve. On the other hand, I think I can safely say that nobody understands

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In a nutshell, the goal of this book is to explain, in the simplest possible terms, what is so bizarre about quantum mechanics and, nevertheless, to try to show that one can to some extent understand its mysteries in rational terms.[3] This is not a book that will teach quantum mechanics in its technical aspects (there are plenty of good books doing that[4]). It will deal only with the conceptual problems associated with quantum mechanics.

"In the simplest possible terms" means with a minimum of mathematics, but a minimum that is not zero: this is not a "popular" book. However, the level of mathematics required is only what is typically taught in first or second year courses of mathematics for scientists and engineers: elementary linear algebra, including vector spaces and matrices, complex numbers, Fourier transforms, basic differential equations and some classical mechanics; but even that will be largely discussed in the appendices. Some technical aspects will be put in the footnotes (hoping that the experts will not be too irritated by the simplifications introduced in the text), where one will also find references to the more advanced literature.

In this introduction, we will discuss the mysteries of quantum mechanics, or at least the way they are often presented to the public, in non-technical terms. It will give a feel for what is so strange in quantum mechanics.

Let us start with excerpts from an article on the "queerness of quanta" in *The Economist* [157] (quoted by Jeremy Bernstein in [56, p. 6]):

> 1. There are no such things as 'things.' Objects are ghostly, with no definite properties (such as position or mass) until they are measured. The properties exist in a twilight state of 'superposition' until then.
> 2. All particles are waves, and waves are particles, appearing as one sort or another depending on what sort of measurement is being performed.
> 3. A particle moving between two points travels all possible paths between them simultaneously.
> 4. Particles that are millions of miles apart can affect each other instantaneously.
>
> The queerness of quanta [157]

These sentences express the two main "mysteries" of quantum mechanics, as they are usually presented, and which can be formulated as follows:

(Footnote 2 continued)
quantum mechanics." Many people, including some famous physicists, claim that the difficulty in understanding quantum mechanics is similar to that in understanding relativity, but this is just not so.

[3] There is an enormous amount of pseudo-scientific literature claiming to base itself on quantum mechanics. But we will not be concerned with that; given the way respectable scientists talk about quantum mechanics, as we will see in this book, its exploitation by the pseudo-sciences, while perfectly unfounded, may not be so surprising.

[4] In his critique of the standard discussions of the conceptual problems of quantum mechanics [46], Bell mentions three good books: those by Dirac [137], Landau and Lifshitz [302], and Gottfried [236], as well as an article by van Kampen [494]. These are classics and so is the one by Bohm [61]. One might add to that list the more recent one by Shankar [447]. However, Bell shows in [46] that even the good books do not deal in a satisfactory way with the conceptual problems.

a. Quantum objects can possess mutually exclusive properties, like traveling along different paths simultaneously. Further, quantum objects obtain definite properties when they are "measured", and *only* then. Moreover, those properties depend on which measurements we choose to make.
b. Particles can interact instantaneously even when they are arbitrarily far apart.

The last statement may sound violently counterintuitive, but it is not in principle impossible, and in fact it is the only one of the two that is essentially true. However, people who have "learned" from the special theory of relativity that "nothing goes faster than light" may wonder how interactions can be both instantaneous and take place between objects that are arbitrarily far apart. "Learned" here is put in scare quotes, because, although the statement "nothing goes faster than light" is frequently repeated, the actual implications of the theory of relativity are quite subtle, as we will discuss later.[5]

The statement about particles "traveling along different paths simultaneously", on the other hand, is obviously self-contradictory: by definition, a "particle" is something localized in space (as opposed to a wave, for example); to say that it follows two (or more) different paths at the same time makes no sense. How are we supposed to understand that? As a metaphor? But a metaphor of what? Is the particle divided into tiny parts, each of which follows a different path? Are we merely saying that we have no way of knowing which path is being taken (which is a meaning sometimes given to that statement)? In that case, the situation would be understandable, and not terribly surprising (why would gross creatures such as ourselves be able to follow the trajectories of tiny particles?), but admitting one's ignorance through a self-contradictory statement about the world is surely a rather strange way to express oneself.

The statement that "quantum objects obtain definite properties only when they are measured" may be the most fundamental and the most problematic. In almost all the talk about quantum mechanics, we find words such as "observer", "observation", and "measurement" playing a central role.[6] It is not just because observations are needed to verify or confirm the theory—that is true of all scientific theories. One would never hear a biologist speak of "observations" the way quantum physicists do, although biology is also an empirical science and thus is also "based on observations". For example, if biologists speak of dinosaurs, they speak of animals that lived in the past, not just of bones of dinosaurs, even though the bones are the only thing that we directly observe. Biology claims to study the properties of living beings, even when they are not observed, but the usual formulation of quantum mechanics speaks of systems having definite properties *only* when they are observed.

One of the main critics of the dominant discourse about quantum mechanics, the Irish physicist John Bell, raised the following objection:

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[5] In Chap. 4 and in Sect. 5.2.2.

[6] The physical reasons for this emphasis on measurements or observations will be explained in Chap. 2.

> The problem of measurement and the observer is the problem of where the measurement begins and ends, and where the observer begins and ends. Consider my spectacles, for example: if I take them off now, how far away must I put them before they are part of the object rather than part of the observer? There are problems like this all the way from the retina through the optic nerve to the brain and so on. I think, that—when you analyze this language that the physicists have fallen into, that physics is about the results of observations—you find that on analysis it evaporates, and nothing very clear is being said.
>
> John S. Bell [107, p. 48].

There is another obvious objection, also raised by Bell [46, p. 34]: “What exactly qualifies some physical systems to play this role of ‘measurer’?” And what happened before humans were around? Or maybe before modern laboratories were created? And what about the vast parts of the universe where there are no observers? Do the laws of physics cease to apply there or in the past? How can a physical theory, which is the most fundamental of all, which deals with atoms and elementary particles, and applies in principle to the entire universe, require for its very formulation something so contingent as certain manipulations (“measurements”) done during the last 100 years by a few members of a particular species, *Homo sapiens*, living on a particular planet somewhere in the cosmos?

Since the seventeenth century, science has decentered human beings; for instance, by realizing that the Earth is not at the center of the universe and also by showing that humans are not the object of a special act of creation, but rather the result of a long and contingent evolution. Quantum mechanics seems to have put humans back at the center of the picture: it is sometimes claimed that it abolishes the distinction between subject and object or that it gives a special role, in the formulation of our most fundamental physical theory, to human consciousness. If that were so, one might wonder how humans got to be there in the first place: if it is through evolution, then how is that supposed to work? Biology is based on chemistry, whose mechanisms are explained through quantum mechanics. But what role did the human subject have during this whole process, before the appearance of *Homo sapiens*?

To understand where all these strange-looking ideas came from, we must go back to the beginning of quantum mechanics.

1.2 Back to Copenhagen

One may object that *The Economist* is not a scientific journal and that what is quoted here is just due to the desire of popularizers to make spectacular statements. But one finds similar statements coming from the founding fathers of quantum mechanics, especially those associated with the “Copenhagen interpretation” of quantum mechanics, including Niels Bohr, Max Born, Werner Heisenberg, Pascual Jordan, Wolfgang Pauli, and later John von Neumann.[7] The name “Copenhagen” comes from

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[7] One should add to this list of founding fathers precursors like Max Planck and Albert Einstein, but also Louis de Broglie, Paul Dirac, and Erwin Schrödinger. However, Dirac was rather neutral on

the city where the Danish physicist Bohr lived and worked. However, it is far from clear that there is a unified doctrine, or even a well defined one, that can be systematically associated with the expression “Copenhagen interpretation” of quantum mechanics, since, for example, Heisenberg and Bohr had divergent views on many topics (see, e.g., [52, 275]). But there is a sort of vulgate in the popular literature, in philosophical reflections on quantum mechanics, and also in the teaching of quantum mechanics, whenever reference is made to “Copenhagen”, that stresses the central role of observations in the very formulation of the theory.

Let us consider some of those associated with “Copenhagen”, whether rightly or wrongly, and see what they said. Heisenberg,[8] for instance, wrote:

> […] the idea of an objective real world whose smallest parts exist objectively in the same sense as stones or trees exist, independently of whether or not we observe them […] is impossible […]
>
> Werner Heisenberg [259, p. 129]

And again:

> We can no longer speak of the behavior of the particle independently of the process of observation. As a final consequence, the natural laws formulated mathematically in quantum theory no longer deal with the elementary particles themselves but with our knowledge of them. Nor is it any longer possible to ask whether or not these particles exist in space and time objectively […].
>
> […] Science no longer confronts nature as an objective observer, but sees itself as an actor in this interplay between man and nature. The scientific method of analysing, explaining, and classifying has become conscious of its limitations […] method and object can no longer be separated.
>
> Werner Heisenberg [260, pp. 15, 29]

Here we encounter words such as “impossible”, “no longer”, etc., which are rather common in the “Copenhagen” rhetoric and which the historian of quantum mechanics Mara Beller calls the “rhetoric of inevitability” [52, Chap. 9], or what one might call the quantum mechanical version of Margaret Thatcher’s TINA (“there is no alternative”).

But how do they know that something is impossible? The fact that a theory is successful and that it does not permit us to answer certain questions or to think in certain ways does not, by any means, prove that one can never answer such questions or think otherwise in the future. To prove that something is impossible, one has to give arguments beyond the mere limitations of present-day science. Such arguments are sometimes given but, as we will see, they do not even begin to prove what is claimed.

(Footnote 7 continued)
these conceptual issues, de Broglie changed his views more than once, and Einstein and Schrödinger were strongly opposed to the Copenhagen interpretation.

[8] This is quoted and discussed by Sheldon Goldstein in [221].

Turning to Niels Bohr, Aage Petersen, who was his assistant for many years, characterized his views as follows[9]:

> When asked whether the algorithm of quantum mechanics[10] could be considered as somehow mirroring an underlying quantum world, Bohr would answer: "There is no quantum world. There is only an abstract physical description. It is wrong to think that the task of physics is to find out how nature is. Physics concerns what we can say about nature."
>
> Aage Petersen [395, p. 12]

Claims that "quantum theory no longer deals with the elementary particles themselves but with our knowledge of them" or that "physics concerns what we can say about Nature" were often heard in physics courses when I was a student, but it didn't make any sense to me then (or now). Indeed, if we say something about Nature or if we have knowledge of elementary particles, then we know something about the world, not just about our knowledge.

Besides, nothing in physics discusses the biological, psychological, or sociological factors that are usually associated with the acquisition of knowledge. So why this emphasis on knowledge? Only because quantum mechanics refers to some abstract "observer" which is a *deus ex machina* that gives definite properties to objects, but without explaining how this happens.

Going even further, Pascual Jordan, who was a very important contributor in the early days of quantum mechanics,[11] wrote:

> In a measurement of position, "the electron is forced to a decision. We compel it *to assume a definite position*; previously, it was, in general, neither here nor there; it had not yet made its decision for a definite position [...] If, in another experiment, the *velocity* of the electron is measured, this means: the electron is compelled to decide itself for some exactly defined value of the velocity; and we observe *which* value it has chosen. In such a decision, the decision made in the preceding experiment is completely obliterated."
>
> Pascual Jordan [285], quoted and translated by M. Jammer [281, p. 161] (original italics)

The defenders of the Copenhagen school sometimes present themselves as "hard-nosed scientists", whose views were driven by facts, while their opponents such as Einstein and Schrödinger were unable to accept the deep lessons of quantum mechanics because of their ideological and philosophical prejudices. For example, Max Born wrote that Einstein "could no longer take in certain new ideas in physics which contradicted his own firmly held philosophical convictions" [79, p. 72]. And Werner Heisenberg wrote:

---

[9] See [396] for a detailed presentation of Bohr's philosophy.

[10] This algorithm will be explained in Chap. 2. (Note by J.B.).

[11] As Norton Wise has shown [520], Jordan had rather strange views on biology (vitalism), parapsychology, and psychoanalysis and he was a committed member of the National Socialist party, mixing up his views on quantum mechanics with his politics. The subject-centered aspect of quantum mechanics was good news for him, since it put one more nail in the coffin of the Enlightenment. After the war, Jordan reincarnated himself as a democratic cold warrior, arguing for the nuclear armament of Germany, and denouncing the "naïve illusions" of pacifist-minded people such as Max Born. Concerning Jordan and his relationship with Bohr, see Heilbron [255].

> Most scientists are willing to accept new empirical data and to recognize new results, provided they fit into their philosophical framework. But in the course of scientific progress it can happen that a new range of empirical data can be completely understood only when the enormous effort is made to enlarge this framework and to change the very structure of the thought process. In the case of quantum mechanics, Einstein was apparently no longer willing to take this step, or perhaps no longer able to do so.
>
> Werner Heisenberg [79, p. X]

But the following quotes from Bohr, Pauli, and Born show that some of the founding fathers were not hostile to linking quantum mechanics and non-scientific speculations (to put it mildly)[12]:

> [...] this domain [psychology] [...] is distinguished by reciprocal relationships which depend on the unity of our consciousness and which exhibit a striking similarity with the physical consequences of the quantum of action. We are thinking here of well-known characteristics of emotion and volition which are quite incapable of being represented by visualizable pictures. In particular, the apparent contrast between the conscious onward flow of associative thinking and the preservation of the unity of the personality exhibit a suggestive analogy with the relation between the wave description of the motions of material particles, governed by the superposition principle,[13] and their indestructible individuality.
>
> Niels Bohr [71, p. 99]

> [...] science and religion *must* have something to do with each other. (I do *not* mean "religion within physics", nor do I mean "physics inside religion", since either one would certainly be "one-sided", but rather I mean the placing of both of them within a whole.) I would like to make an attempt to give a name to that which the new idea of reality brings to my mind: the idea of reality of the symbol. [...] It contains something of the old concept of God as well as the old concept of matter (an example from physics: the atom. The primary qualities of filling space have been lost. If it were not a symbol how could it be "both wave and particle"?). The symbol is symmetrical with respect to "this side' and 'beyond" [...]. The symbol is like a god that exerts an influence on man but which also demands from man that he have a back effect on him (the God symbol).
>
> Wolfgang Pauli [375, pp. 193–194] (italics in the original)

This comes from a private letter, but the reader can find several favorable references to Jungian psychoanalysis in Chaps. 17 and 21 of Pauli's *Writings on Physics and Philosophy* [382].[14]

> The thesis 'light consists of particles' and the antithesis 'light consists of waves' fought with one another until they were united in the synthesis of quantum mechanics. [...] Only why not apply it to the thesis Liberalism (or Capitalism), the antithesis Communism, and expect a synthesis, instead of a complete and permanent victory for the antithesis? There

---

[12] The three quotes here come from Mara Beller's article [51], which we will discuss in Chap. 8. The quote from Pauli comes from a *private* letter.

[13] This principle will be explained in Chap. 2. (Note by J.B.).

[14] See also [306, 16] for Pauli's views on religion and "deep psychology".

> seems to be some inconsistency. But the idea of complementarity[15] goes deeper. In fact, this thesis and antithesis represent two psychological motives and economic forces, both justified in themselves, but, in their extremes, mutually exclusive. […] there must exist a relation between the latitudes of freedom Δf and of regulation Δr, of the type $\Delta f \Delta r \sim p$ which allows a reasonable compromise. But what is the 'political constant' p? I must leave this to a future quantum theory of human affairs.
>
> Max Born [78, pp. 107–108]

Finally, according to the Belgian physicist Léon Rosenfeld, a close friend of Bohr's and one of the most vehement defenders of the Copenhagen interpretation,[16] Bohr seems sometimes to have suffered from delusions of grandeur:

> On one of those unforgettable strolls during which Bohr would so openly disclose his innermost thoughts, we came to consider that what many people nowadays sought in religion was a guidance and consolation that science could not offer. Thereupon Bohr declared, with intense conviction, that he saw the day when complementarity would be taught in the schools and become part of general education; and better than any religion, he added, a sense of complementarity would afford people the guidance they needed.
>
> Léon Rosenfeld [422]. Reprinted in [424, p. 535]

1.3 What Do Physicists Say Now?

The reader might think that these quotes are old, going back to the very beginning of quantum mechanics, and that the situation has been clarified since then. As we will see in Chaps. 4 and 5, the situation was actually clarified, first in 1952 through the work of David Bohm, and then in 1964 through that of John Bell, but few physicists have paid much attention to those contributions. So what did the generations following the founding fathers say, even long after 1964?

John Archibald Wheeler, who studied with Bohr and is well known for his contributions both to nuclear physics and to cosmology, is famous for saying [509, p. 192]: "No elementary phenomenon is a phenomenon until it is a registered (observed) phenomenon." Wheeler linked that idea to what he called "the participatory principle":

> According to it we could not even imagine a universe that did not somewhere and for some stretch of time contain observers because the very building materials of the universe are these acts of observer-participancy. You wouldn't have the stuff out of which to build the universe otherwise.
>
> John Archibald Wheeler [508]

Wheeler emphasized that this means that *past* events did not really occur until they are recorded *now*:

---

[15] A basic concept of Bohr, which will be discussed in Chap. 2, particularly in Appendix 2.C. (Note by J.B.).

[16] As we will see in Chap. 7.

> […] we have to say that we ourselves have an undeniable part in shaping what we have always called the past. The past is not really the past until it has been registered. Or put another way, the past has no meaning or existence unless it exists as a record in the present.
>
> John Archibald Wheeler [107, pp. 67–68]

Wheeler even wondered: “Are billions upon billions of acts of observer-participancy the foundation of everything?” Without answering this question affirmatively, he observed [509, p. 199]: “The very fact that we can ask such a strange question shows how uncertain we are about the deeper foundations of the quantum and its ultimate foundation.”

Eugene Wigner, co-recipient of the 1963 Nobel Prize in physics for his contributions to quantum and nuclear physics was quite explicit about the role of consciousness in physics, supposedly revealed by the quantum revolution:

> […] It will remain remarkable, in whatever way our future concepts may develop, that the very study of the external world led to the scientific conclusion that the content of the consciousness is an ultimate reality.
>
> […] The preceding argument[17] for the difference in the roles of inanimate observation tools and observers with a consciousness—hence for a violation of physical laws where consciousness plays a role—is entirely cogent so long as one accepts the tenets of orthodox quantum mechanics in all their consequences.
>
> Eugene Wigner [514]; reprinted in [510, pp. 169,178]

Wigner added that the “weakness” of this argument came from the “ephemeral nature of physical theories” and because it relied on “the tenets of orthodox quantum mechanics in all their consequences”. But he was absolutely convinced[18] that it was [510, p. 169] “not possible to formulate the laws of quantum mechanics in a fully consistent way without reference to the consciousness.”

Rudolf Peierls, who studied with Heisenberg and Pauli, and was a major theoretical physicist, both in quantum and statistical physics, wrote in 1979:

> In recent years the debate on these ideas has reopened, and there are some who question what they call “the Copenhagen interpretation of quantum mechanics—as if there existed more than one possible interpretation of the theory.
>
> Rudolf Peierls [388, p. 26]

Rudolf Peierls also declared in an interview published in 1993:

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[17] The argument is based on the reduction or collapse of the quantum state, which will be defined in Sect. 2.3. (Note by J.B.).

[18] Here, Wigner refers in a footnote to some of the statements by Heisenberg quoted in Sect. 1.2. According to Wigner, Heisenberg had “expressed this [idea] most poignantly”. He also refers to London and Bauer [312] who wrote in 1939 a detailed theory of measurement in quantum mechanics, which stressed “the essential role played by the consciousness of the observer” [510, p. 251]. To be fair to Wigner, one must add that his ideas on the role of consciousness in quantum mechanics changed over time (see Esfeld [177]).

> You see, the quantum mechanical description is in terms of knowledge. And knowledge requires *somebody* who knows.
>
> Rudolf Peierls [107, p. 74] (italics in the original)

Not surprisingly, when asked about the role of consciousness "in the nature of reality", Peierls answered [107, p. 74]: "I don't know what reality is."

In 1979, a well-known French theoretical physicist and philosopher of science, Bernard d'Espagnat, wrote an article in *Scientific American* with the following title[19]:

> The doctrine that the world is made up of objects whose existence is independent of human consciousness turns out to be in conflict with quantum mechanics and with facts established by experiment.
>
> Bernard d'Espagnat [124, p. 158]

D'Espagnat published another article, in the *Guardian* on 20 March 2009, with the title [125]: "Quantum weirdness: What we call 'reality' is just a state of mind."

The Cornell university physicist David Mermin, well known for his work in statistical and condensed matter physics and who also worked a lot on foundations of quantum mechanics, wrote in 1981:

> We now know that the moon is demonstrably not there when nobody looks.[20]
>
> David Mermin [331, p. 397]

In 2005, Anton Zeilinger, who has performed in Vienna some of the most remarkable quantum experiments, wrote in *Nature*:

> So, what is the message of the quantum? […] I suggest that […] the distinction between reality and our knowledge of reality, between reality and information, cannot be made.
>
> Anton Zeilinger [526, p. 743]

Finally, in the age of Twitter, Sean Carroll, theoretical physicist at Caltech, cosmologist and author of several popular books, considers that the best answer to "how to

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[19] In 2009, D'Espagnat won the Templeton Prize, which rewards a person who "has made an exceptional contribution to affirming life's spiritual dimension, whether through insight, discovery, or practical works".

[20] This refers to the following remark by Abraham Pais about his conversations with Einstein who, as we will see in the following section, was irritated by all the talk about "observations" [369, p. 907]: "We often discussed his notions on objective reality. I recall that during one walk Einstein suddenly stopped, turned to me and asked whether I really believed that the moon exists only when I look at it." Pais adds: "The rest of the walk was devoted to a discussion of what a physicist should mean by the term 'to exist'." Of course, Mermin may not have meant literally what he said about the *moon*. But what he really meant is not obvious. We will come back to that quote in Sect. 3.3. (Note by J.B.).

summarize quantum mechanics in five words?" comes from the physicist and science writer Aatish Bhatia (@aatishb):

> Quantum mechanics in 5 words. Don't look: wave. Look: particle.
>
> Sean Carroll [92, p. 35]

Of course, the statements quoted here do not reflect the views of most physicists (indifference to such questions or some form of "pragmatism" being the view of the majority), but their authors are certainly not marginal either and the statements should be sufficiently surprising to make the reader wonder what is going on.

However, there have also been views explicitly opposed to those mentioned here.

1.4 But There has Never Been a Consensus

From the early days of quantum mechanics, people like de Broglie, Schrödinger, and especially Einstein objected to the Copenhagen doctrine, but the dominant discourse misunderstood or ignored those objections. We will see that in detail in Chap. 7, but it is interesting to note the strength with which the opposition was expressed, at least in private letters. For example, in 1928, Einstein wrote to Schrödinger:

> The Heisenberg–Bohr tranquilizing philosophy—or religion?—is so delicately contrived that, for the time being, it provides a gentle pillow for the true believer from which he cannot very easily be aroused.
>
> Albert Einstein [163]

In another letter to Schrödinger, Einstein referred to Bohr as the "Talmudic philosopher" for whom "reality is a frightening creature of the naive mind" [165]. Einstein also referred to Bohr as [167] "the mystic, who forbids, as being unscientific, an enquiry about something that exists independently of whether or not it is observed, i.e., the question as to whether the cat is alive[21] at a particular instant before an observation is made (Bohr)." Schrödinger was equally critical[22]:

> Bohr's […] approach to atomic problems […] is really remarkable. He is completely convinced that any understanding in the usual sense of the word is impossible. Therefore the conversation is almost immediately driven into philosophical questions, and soon you no longer know whether you really take the position he is attacking, or whether you really must attack the position he is defending.
>
> Erwin Schrödinger [438]

---

[21] Here Einstein is referring to a famous thought experiment due to Schrödinger in which, if one follows the standard rules of quantum mechanics, a cat could be both alive and dead at the same time, before one looks at it. See Sects. 2.5 and 7.3 for further discussion of this argument. (Note by J.B.).

[22] Some of the quotes below come from Goldstein [221] and are discussed there.

And again:

> With very few exceptions (such as Einstein and Laue), all the rest of the theoretical physicists were unadulterated asses and I was the only sane person left.
>
> [...]
>
> If I were not thoroughly convinced that the man [Bohr] is honest and really believes in the relevance of his—I do not say theory but—sounding word,[23] I would call it intellectually wicked.
>
> Erwin Schrödinger [444]

Schrödinger put his finger on one of the main problems of the "Copenhagen" view, namely, the attempt to find an idealistic philosophical solution to the conceptual problems of quantum mechanics, when he wrote[24]:

> [...] the reigning doctrine rescues itself or us by having recourse to epistemology. We are told that no distinction is to be made between the state of a natural object and what I know about it, or perhaps better, what I can know about it if I go to some trouble. Actually—so they say—there is intrinsically only awareness, observation, measurement.
>
> Erwin Schrödinger [441], reprinted in [510, p. 157]

Schrödinger did not even try to hide his feelings when he wrote to "the other side", for example, to Max Born:

> Maxel, you know I love you and nothing can change that. But I do need to give you once a thorough head washing. So stand still. The impudence with which you assert time and again that the Copenhagen interpretation is practically universally accepted, assert it without reservation, even before an audience of the laity—who are completely at your mercy—it's at the limit of the estimable [...]. Have you no anxiety about the verdict of history? Are you so convinced that the human race will succumb before long to your folly?
>
> Erwin Schrödinger [445]

In a more constructive mode, Einstein nicely summarized his position in 1949:

> I am, in fact, firmly convinced that the essentially statistical character of contemporary quantum theory is solely to be ascribed to the fact that this (theory) operates with an incomplete description of physical systems [...].[25]
>
> Albert Einstein [170, p. 666]

---

[23] Schrödinger was referring to the word "complementarity", which was the foundation of Bohr's approach and will be discussed in Appendix 2.C. (Note by J.B.).

[24] This was written after he introduced his famous "cat" in [441], which is supposed to be "both alive and dead". The idealism, implicit in the view that Schrödinger rejects, will be criticized in Chap. 3.

[25] He added [170, p. 672]: "In a complete physical description, the statistical quantum theory would [...] take an approximately analogous position to the statistical mechanics within the framework of classical mechanics." This refers to an idea, developed at the end of the nineteenth century, according to which the laws of thermodynamics could be derived from an application of statistical reasoning to the motion of atoms, the latter giving a more complete description of matter than the one given by thermodynamics or fluid mechanics.

The root of the difference between Einstein and the Copenhagen school of thought was exactly about this issue of completeness: Einstein thought that the existing quantum mechanics was incomplete, i.e., that a more detailed description of the microscopic world was possible and that such a description would eliminate the need to refer to an observer.[26] We will see in Chap. 5 that Einstein's hope was not only reasonable but was even realized during his lifetime, although in ways that he did not like (for other reasons, that we will discuss in Sect. 7.6.2).

But even putting that aside, which position is the more radical? Einstein's hope expressed here or Heisenberg's view (shared by many physicists) that "we can no longer speak of the behavior of the particle independently of the process of observation", where "no longer" means that we will never be able to do so? Yet, most contemporaries of Einstein thought that he was the unreasonable fellow, who had become too old to appreciate the depth of the quantum revolution.

After World War II, the critique of the mainstream view was taken up for the main part by David Bohm and John Bell. We will discuss their objections in detail later (in Chaps. 4 and 5), but one can get their flavor by reading the following answer given by Bell in an interview with the BBC:

> One wants to be able to take a realistic view of the world, to talk about the world as if it is really there, even when it is not being observed. I certainly believe in a world that was here before me, and will be here after me, and I believe that you are part of it! And I believe that most physicists take this point of view when they are being pushed into a corner by philosophers.
>
> John Bell [107, p. 50]

Bell even met Bohr once. As he recalled later, in an interview, with the magazine *Omni*:

> I went up in a hotel lift with him. I didn't have the nerve to say. 'I think your Copenhagen interpretation is lousy'. Besides the lift ride wasn't very long. Now, if the lift had gotten stuck between floors, that would have made my day! In which way, I don't know.
>
> John Bell [45, p. 85]

Note that the interviewers wrote [45, p. 86]: "We first asked Bell over the telephone whether he himself felt he had demonstrated that 'reality doesn't exist'. He responded by warning us that he is an impatient, irascible sort who tolerates no nonsense."

Murray Gell-Mann, Nobel prizewinner and discoverer of quarks, said about finding "an adequate philosophical presentation" of quantum mechanics:

> Bohr brainwashed a whole generation of physicists into thinking that the job was done 50 years ago.
>
> Murray Gell-Mann [200, p. 29]

---

[26] He probably also thought that this description would render the theory deterministic, but it is doubtful that he was mainly concerned with determinism. We will discuss that in Sect. 7.1.

But the most emphatic reaction to the alleged need to put ourselves, the "observers", at the center of things is probably due to Bertrand Russell, who disliked nothing more than anthropocentrism and subjectivism, and who wrote the following "pessimistic meditation" about "Modern Physics":

> […] Formerly, the cruelty, the meanness, the dusty fretful passion of human life seemed to me a little thing, set, like some resolved discord in music, amid the splendour of the stars and the stately procession of geological ages. What if the universe was to end in universal death? It was none the less unruffled and magnificent. But now all this has shrunk to be no more than my own reflection in the windows of the soul through which I look out upon the night of nothingness. The revolutions of nebulae, the birth and death of stars, are no more than convenient fictions in the trivial work of linking together my own sensations, and perhaps those of other men not much better than myself. No dungeon was ever constructed so dark and narrow as that in which the shadow physics of our time imprisons us, for every prisoner has believed that outside his walls a free world existed; but now the prison has become the whole universe. There is darkness without, and when I die there will be darkness within. There is no splendour, no vastness, anywhere; only triviality for a moment, and then nothing. Why live in such a world? Why even die?
>
> Bertrand Russell [430, p. 374]

All this may look strange, but there is still a natural question to discuss.

1.5 Why Bother?

Most physicists are rather indifferent to the sort of issues discussed in this book, regarding them as "metaphysical". A good example of such a reaction is due to Pauli:

> As O. Stern said recently, one should no more rack one's brain about the problem of whether something one cannot know anything about exists all the same, than about the ancient question of how many angels are able to sit on the point of a needle. But it seems to me that Einstein's questions are ultimately always of this kind.
>
> Wolfang Pauli [79, p. 223]

Similarly, another founding father of quantum mechanics, the great British physicist Paul Dirac distinguished between two kinds of difficulties with quantum theory[27]:

> The difficulties in quantum theory are of two kinds. I might call them Class One difficulties and Class Two difficulties. Class One difficulties are the difficulties I have already mentioned: How can one form a consistent picture behind the rules for the present quantum theory? These Class One difficulties do not really worry the physicist. If the physicist knows how to calculate results and compare them with experiment, he is quite happy if the results agree

---

[27] The Class Two difficulties, which he discusses in the rest of this article, are those related to the mathematical formulation of quantum field theories.

> with his experiments, and that is all he needs. It is only the philosopher, wanting to have a satisfying description of nature, who is bothered by Class One difficulties.
>
> Paul Dirac [138]

Those physicists are both right and wrong. They are right in the sense that ordinary quantum mechanics works perfectly FAPP, to use an acronym introduced by John Bell, meaning “for all practical purposes” [46]. The theory, specially in quantum electrodynamics, makes spectacularly precise predictions confirmed by experiment, and nobody needs to understand quantum mechanics beyond what is in textbooks in order to make computers and telecommunications work. Nothing that is written in this book puts into question those facts. As an algorithm (described in Chap. 2) allowing us to predict results of experiments, and to use various powerful technologies, quantum mechanics is perfect.

But it is precisely *because* it works so well that trying to understand why it works makes sense. Obviously if quantum mechanics worked half of the time, so to speak, there would be no reason to try to understand it in depth. Many models in physics are known to be applicable within certain limits and, once we know that, there are no further questions to be raised about those models. But quantum mechanics works on all known scales and is not contradicted by any experiment whatsoever.[28] Isn’t it worthwhile to ask *why* it works so well?

To that question, there are typically two different types of answers, one “official” and one “implicit”. The official reply is that the goal of physics is to predict results of experiments, or to account for what we see, or perceive, and nothing else (as proposed by Dirac in the above quote). But this is inverting the means and the goal. Experiments are needed to test our theories in order to avoid falling into idle speculation or “metaphysics”, but our theories are about the world, not about the experiments themselves. As Bell said:

> But experiment is a tool. The aim remains: to understand the world. To restrict quantum mechanics to be exclusively about piddling laboratory operations is to betray the great enterprise. A serious formulation [of quantum mechanics] will not exclude the big world outside the laboratory.
>
> John Bell [46, p. 34]

Of course, it may be that it is simply impossible to understand the quantum world and that we have to content ourselves with predicting results of experiments. After all, who are we but somewhat evolved creatures and why should we expect to be able to understand how the world is? Isn’t the fact that quantum mechanics looks weird to us simply a consequence of the limitations of our minds? That may be the case, but one needs some argument to show that and not simply rely on the “rhetoric of inevitability”.

Besides, there is a serious issue of consistency raised by the notion that the only goal of physics is to predict results of experiments. If indeed that was all there is to

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[28] Putting aside the problem of quantum gravity, which is indeed a difficult and unsolved problem, but it cannot be considered as a refutation of quantum mechanics.

physics, why do experiments in the first place? The need to finance costly experiments is "sold" to politicians and the public by saying that we are discovering the fundamental laws of Nature. But, if "it is wrong to think that the task of physics is to find out how Nature is" (Bohr according to Petersen), or if, in quantum mechanics, we "no longer deal with the elementary particles themselves but with our knowledge of them" (Heisenberg), then how can we claim that we are trying to find the fundamental laws of Nature? What would the funders say if they read those statements? Wouldn't they at least be puzzled and ask for some clarification? Isn't it therefore simply a matter of intellectual honesty to ask ourselves how we would clarify those statements?

On the other hand, most physicists probably do not really believe the official answer. They do give some meaning to quantum mechanics beyond our "observations". Physicists do speak of particles going this way or that way, having a certain polarization or a "spin" or speed, or some other properties, even when those particles are not observed. From that point of view, which I call the "implicit" one, there is no problem about quantum mechanics and the centrality of "observations". However, the main defect of that "solution" is that it is never spelled out clearly: what exactly can we say about the world out there?

Moreover, and that will be one of the main points emphasized in this book, the sort of thing that people have in the back of their minds when they give a meaning to quantum mechanics outside of "measurements" is sometimes inconsistent and sometimes even in contradiction with the consequences of quantum mechanics.[29] This lack of clarity leads to a general uncertainty about what one is "allowed" to say about the world (or about what is "speakable and unspeakable" to use John Bell's expression [49]) and that in turn induces many physicists to fall back on the standard talk about measurements being all there is to physics, which they feel is safe, even if it "betrays the great enterprise".

What we need is a theory which tells a story about what is going on in the world, even when we do not "observe" it, and which makes the same predictions as ordinary quantum mechanics whenever we do make "observations" or experiments. If such a theory existed, then all the confusing talk about the centrality of observations would disappear and we could analyze that theory in order to see how it helps us to understand the quantum world.

Amazingly, such a theory actually does exist, and has even existed, in some preliminary form, since the beginning of quantum mechanics, i.e., since 1927; it was proposed by Louis de Broglie at that time and developed by David Bohm in 1952. One of the main goals of this book is to make this theory better known.

Since this theory implies no practical change to what we do as physicists in our daily lives when we use quantum mechanics, it should be good news to all those who do not want to be bothered with "foundational" issues. It "simply" clarifies what quantum mechanics is all about and allows us to get rid of entire libraries of confused talk about the centrality of human observations in science. Of course, whether that "simply" is important or not is a matter of taste.

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[29] See Sect. 2.5, and especially the theorem at the end of that section.

1.6 Outline of the Book

In this book, we will defend several theses. The first one is that there are genuine conceptual problems within the usual quantum formalism: the latter does not allow us to speak of the world beyond what happens in our laboratories and that is obviously unsatisfactory. Next, we will argue that there is no philosophical solution to this problem, contrary to the impression that one sometimes gets when one reads the proponents of the Copenhagen school.

Moreover, we will explain that there exists a way to complete the quantum formalism so that this problem is eliminated, and the completion is, in some sense, simpler to understand than the usual formalism. Finally, the refusal by a large part of the physics community to face the difficulties intrinsic to the quantum formalism has led it to ignore or misunderstand what is probably the main novel feature of quantum mechanics, namely the existence of nonlocal actions, or “particles interacting instantaneously even when they are arbitrarily far apart.”

Now, in more detail. The second chapter is devoted to the first mystery of quantum mechanics: interference phenomena and the superposition principle, which lead to statements such as “quantum objects can possess mutually exclusive properties, like traveling along different paths simultaneously” and “quantum objects obtain definite properties when they are ‘measured’, but only then, and those properties depend on which measurements we choose to make”. We will have to distinguish carefully between the phenomena to be explained, the quantum formalism that allows us to predict them, and the commentaries or mental pictures which accompany the formalism and which lead to the statements just mentioned.

This will do justice to the way physicists often speak about quantum phenomena. The phenomena are strange and all the talk about observations affecting reality is not based on pure prejudice, although it is not inevitable either.

In Sect. 2.5, we will define four possible reactions or attitudes with respect to that “first mystery” and to how one thinks of the quantum formalism. In the rest of the book, we will try to connect the various questions that we deal with to those four basic positions.

The third chapter can be skipped by those who are not interested in “philosophy”. But for those with a philosophical background, the statements associated with “Copenhagen” should remind them of the writings of Bishop Berkeley, Immanuel Kant, Ernst Mach,[30] or sometimes the logical positivists, even if the connection is

---

[30] Ernst Mach was an Austrian physicist and philosopher, active at the end of the 19th century and the beginning of the 20th, whose views were somewhat similar to those of the Copenhagen school, long before the advent of quantum mechanics. For example, in 1897, he wrote:

> Bodies do not produce sensations, but complexes of elements (complexes of sensations) make up bodies. If, to the physicist, bodies appear the real, abiding existences, whilst the “elements” are regarded merely as their evanescent, transitory appearance, the physicist forgets, in the assumption of such a view, that all bodies are but thought-symbols for complexes of elements (complexes of sensations).
>
> Ernst Mach [314, p. 29]

not straightforward. In this chapter, we will try to clarify notions such as "realism" or "determinism" which have the disadvantage of often being ill-defined and used in ways that confuse rather than clarify the discussion.

For example, when the people who interviewed Bell for the magazine *Omni* [45] asked him whether he felt that he had shown that "reality does not exist", what could they possibly have meant? After all, the telephone they used, Bell himself, and his answers were all part of reality. And if Bell had thought that reality did not exist, he would presumably have been a solipsist (meaning someone who thinks that only his own mind exists and that everything else is some sort of dream going on in his mind) and he would therefore have thought that the interviewers themselves did not exist (outside of Bell's mind). No wonder Bell replied that he "tolerates no nonsense".

The fourth chapter deals with Bell's result and the problem of nonlocal action, which is the second mystery of quantum mechanics. There, we will explain the meaning of the statement that "particles can interact instantaneously even when they are arbitrarily far apart" and discuss the extent to which it is true.

The fifth chapter, which is the heart of this book, is about the de Broglie–Bohm theory (nowadays also called Bohmian mechanics), first introduced by Louis de Broglie before 1927, and then quickly abandoned by him; it was rediscovered and developed by David Bohm in 1952, popularized by John Bell, and further developed and defended by, among other people, David Albert, Chris Dewdney, Detlef Dürr, Sheldon Goldstein, Basil Hiley, Peter Holland, Anastasios Kyprianidis, Tim Maudlin, Nelson Pinto-Neto, Ward Struyve, Stefan Teufel, Roderich Tumulka, Antony Valentini, Jean-Pierre Vigier, Nino Zanghì and their collaborators. In a nutshell, the de Broglie–Bohm theory is a theory of matter in motion, just like any other physical theory; but the motion is quite strange, as one would expect, given all the strange phenomena that led to the discovery of quantum mechanics in the first place. However, the strangeness does not come from putting the observer at the center of everything.

Indeed, the main virtue of the de Broglie–Bohm theory is that it is a clear theory about what is going on in the world, whether we look at it or not. So the vagueness and subjectivity of the notion of "observer" or of "measurement" simply disappear in this theory. Of course, the theory does make empirical predictions, and the latter are the same as those of ordinary quantum mechanics, but the de Broglie–Bohm theory and ordinary quantum mechanics are *not* the same theory, because the de Broglie–Bohm theory is a theory about microscopic reality, while ordinary quantum mechanics is not: it is an algorithm for very accurately predicting results of experiments, an algorithm that is, in fact, a consequence of the de Broglie–Bohm theory, as we will see in Chap. 5.

Using the de Broglie–Bohm theory, one can easily explain why all the arguments that are supposed to prove that such a theory is impossible are false. While deterministic, the de Broglie–Bohm theory also accounts naturally for the apparent indeter-

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(Footnote 30 continued)
Mach always rejected the existence of atoms. His philosophy influenced the school of logical positivism, which itself had an influence on the orthodox view of quantum mechanics. We will discuss logical positivism and its influence in physics in Sect. 7.7 and in Chap. 8.

minism of quantum phenomena. Finally, it explains the "active role" of measuring devices (the apparent effects of observations on reality), so strongly emphasized by the Copenhagen school, but by making it a consequence of the theory and not of some a priori philosophical doctrine. It also explains the nonlocal actions inherent in quantum phenomena.

What more could we ask for? As John Bell explained, after recalling the arguments claiming to show that a theory such as de Broglie–Bohm theory is impossible:

> But in 1952 I saw the impossible done. It was in papers by David Bohm. Bohm showed explicitly how parameters could indeed be introduced, into nonrelativistic wave mechanics, with the help of which the indeterministic description could be transformed into a deterministic one. More importantly, in my opinion, the subjectivity of the orthodox version, the necessary reference to the 'observer', could be eliminated. […] Should it not be taught, not as the only way, but as an antidote to the prevailing complacency? To show us that vagueness, subjectivity, and indeterminism, are not forced on us by experimental facts, but by deliberate theoretical choice?
>
> John Bell [49, p. 160]

In the sixth chapter, we will consider the main theories, other than the de Broglie–Bohm theory, that have been proposed in order to solve the conceptual problems of quantum mechanics. Their clarity and consistency will be compared with those of the de Broglie–Bohm theory.

In the seventh chapter, we will address various historical misunderstandings regarding Einstein, de Broglie, Schrödinger, Bohm, and Bell. All these authors, whether in their critique of the usual interpretation of quantum mechanics or in their attempt to complete it, have been ignored or misunderstood by the majority of physicists of their time and often also of today.

The eighth chapter will outline some conjectural thoughts about the general cultural impact of the various interpretations and misinterpretations of quantum mechanics.

Many of the ideas defended here are heterodox and may even seem shocking. However, the intention of this book is not to give final answers to the conceptual problems of quantum mechanics, but rather to open the reader's mind to the possibility that answers can be given beyond what is taught in standard quantum mechanics courses. The student I once was, who could not understand sentences such as "physics does not deal with Nature, but with our knowledge of it", would have been delighted to read such a book.

It should nevertheless be emphasized that this book is written in the same spirit as the following statement, where one could replace "philosophy" by "the conceptual problems of quantum mechanics":

> Philosophy is to be studied, not for the sake of any definite answers to its questions since no definite answers can, as a rule, be known to be true, but rather for the sake of the questions themselves; because these questions enlarge our conception of what is possible, enrich our intellectual imagination and diminish the dogmatic assurance which closes the mind against speculation […]
>
> Bertrand Russell [425, pp. 249–250]

Chapter 2
The First Mystery: Interference and Superpositions

2.1 The Spin

We will start with the simplest quantum mechanical situation, the one concerning the "spin" of a particle.[1] Despite its simplicity, it will allow us to explain one of the basic "mysteries" of quantum mechanics. Some particles, electrons for example, possess a property called "spin", which is a quantity that can be measured in different directions and takes, in each direction, only two values, denoted up ↑ and down ↓. We will consider here only two directions in which the spin can be measured, denoted 1 and 2, so that we can have four possibilities: spins that are up 1 ↑ or down 1 ↓ in direction 1 and up 2 ↑ or down 2 ↓ in direction 2. One should not confuse the directions 1 or 2 in which the spin is measured and the values up or down that can be the result of those measurements in each direction.

There is no need for the moment to try to understand what the property of "spin" means. We will start from a completely "phenomenological" attitude about the spin, namely, we will simply describe what happens in experiments that are "measuring" the spin, without at first trying to explain how these experiments work.

We put scare quotes here around the word "measuring" because, as we will see in Sect. 2.5 (and this will be one of the most important themes of this book), the notion that there is an intrinsic property of a particle corresponding to its spin in a given direction and that is being measured when one "measures its spin" is untenable. We will not put quotation marks everywhere, but it should be remembered that when we use the word "measurement" we do not want to suggest that some intrinsic property of a particle is being discovered.

The whole discussion using the spin may seem rather abstract, but it is easy to analyze mathematically, as we will see in Sect. 2.3. There is another, similar example,

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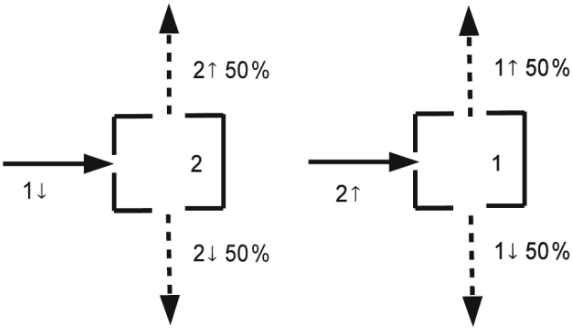
[1] The first four sections of this chapter draw heavily on David Albert's book *Quantum Mechanics and Experience*. We emphasize that the "experiments" here are meant to illustrate the theory rather than real experiments. The latter are generally carried out with photons, whose polarization plays a role similar to the spin here. But all the experiments described below correspond to what quantum mechanics predicts.

J. Bricmont, *Making Sense of Quantum Mechanics*,
DOI 10.1007/978-3-319-25889-8_2

Fig. 2.1 Measuring the spin



the double-slit experiment, which may seem more familiar, but is less easy to analyze and which will be discussed in Appendix 2.E.

Let us see what happens in the experiments described in Fig. 2.1, where many particles are sent, so that we get statistical results. Note also that here, as in every experiment described in this book, particles are sent (in principle at least) one at a time, so that there are no possible interactions between different particles that could account for their strange behavior. So in Fig. 2.1, we have two devices that "measure the spin" of the particle in two different directions (they are unrelated to each other). The reader who wants a more realistic view of these experiments can look at Fig. 5.4.

If we send a particle through one such device, the particle comes out through one of two holes, depending on the value of its spin, as shown in Fig. 2.1. We also suppose that we can select particles having a given spin value, up or down, in either of the two directions 1 or 2 (we will explain below how to do that). By "having a given spin value", we mean that if one measures, say, in direction 1 the spin of a particle that is up in that direction 1, we will always get up.

First, we send particles that are down in direction 1 into a device that measures the spin in direction 2 (Fig. 2.1 left); if we repeat that operation many times, we will get 50 % 2 ↑, 50 % 2 ↓. If we had started with particles that were up in direction 1, we would have gotten the same result. Likewise, if we send particles that are up in direction 2 into a device that measures the spin in direction 1 (Fig. 2.1 right), we get 50 % 1 ↑, 50 % 1 ↓ and we would get the same results starting with particles that are down in direction 2. So far, so good: there is no particular mystery here!

This explains also how one can select particles having a given spin value, up or down, in either of the two directions 1 or 2: just take the particle exiting, say, the device that measures the spin in direction 2 through the 2 ↑ hole and we will have selected particles that have spin up in direction 2 (i.e. if we then send those particles through a device that measures the spin in direction 2, they will always exit through the 2 ↑ hole). And likewise for the other possibilities.

Now, we may ask: can we select particles that are, say, down in direction 1 and up in direction 2? We might think that one way to do this, at least naively, is to send particles that are up in direction 2 in a device that measures the spin in direction

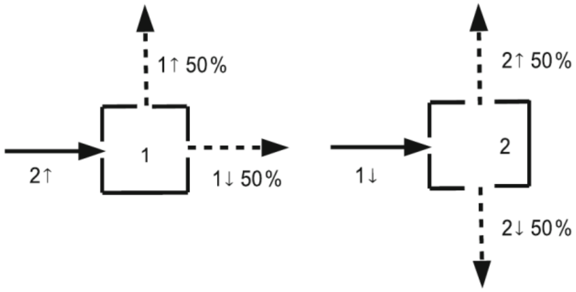


Fig. 2.2 Trying to measure the spin in both directions simultaneously

1 and select those that are down in that direction. That way, the particle should be down in direction 1 and up in direction 2 (see Fig. 2.2 left).

But if we want to check that we really have particles that are down in direction 1 and up in direction 2, we might measure the spin in direction 2 of those selected particles (see Fig. 2.2 right).[2] However, we find that the result is again 50 % 2 ↑, 50 % 2 ↓. This is our first surprise.

The same result would occur if we tried to have particles that are, say, down in direction 2 and up in direction 1, or with any of the four possible combinations. It seems that, by measuring in direction 1, the spin of a particle that is up in direction 2, we "erase" the fact that it is up in direction 2. Indeed, the results of a later measurement of the spin in direction 2 of the particles which are up or down in direction 1 are just what they would be for such particles, independently of the fact that they had a spin up in direction 2, before the measurement in direction 1.

This is a simple example of the Heisenberg uncertainty relations or of what Bohr called "complementarity"[3]: we cannot measure simultaneously the spin in two different directions, because they require different devices and, applying one device in one spin direction and then a second one in another direction, destroys the result of the first device. So, one could consider two different "complementary" pictures of the particle: one describing the spin in direction 1, the other the spin in direction 2. However, one should not try to combine the two pictures (spin in directions 1 and 2)

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[2] In Fig. 2.2 left, we put one hole to the right instead of downwards, because the particles exiting through that hole go into the box on the right of the figure.

[3] This is discussed mathematically in more detail in Appendix 2.C. Bohr explained the "complementary, or reciprocal, mode of description" by emphasizing [71] "the relative meaning of every concept, or rather of every word, the meaning depending upon our arbitrary choice of view point, but also that we must, in general, be prepared to accept the fact that a complete elucidation of one and the same object may require diverse points of view which defy a unique description. Indeed, strictly speaking, the conscious analysis of any concept stands in a relation of exclusion to its immediate application." The reader may be forgiven for not understanding exactly what this means. We try here to give a plausible interpretation of that idea. See [181] for a discussion of different interpretations of Bohr's thinking. We will return to a discussion of Bohr's views, in relation to his debate with Einstein in Sect. 7.1.

1. 50 % fewer particles (which is to be expected since half of the particles follow the path 2 ↓ and are now blocked).
2. Without the wall, 100 % of those that take the path 2 ↑ are found to be 1 ↓ after the black arrow. The same is true for those that followed the path 2 ↓. If one blocks the path 2 ↓, one would think that it should not affect the particles that take the path 2 ↑. Thus, one should get 100 % 1 ↓ (of the remaining 50 % of particles that reach the black arrow).

And here is the big surprise: one gets 25 % 1 ↓ and 25 % 1 ↑ (that is, half of the remaining 50 % for each possibility). Therefore, one acts in a certain way on the particles that take the path 2 ↑ by blocking the path 2 ↓ *that they do not take!*

This leads to an apparent *dead end*. Let us go back to the experiment without the wall, sending particles that are 1 ↓. What does each particle do?

- Does it take path 2 ↑ ? No because if it did, one would have 25 % 1 ↑, 25 % 1 ↓ at the black arrow, as one sees when one puts a wall blocking the path 2 ↓.
- The path 2 ↓ ? No, for the same reason.
- Both paths? No, one always finds the particle along one of the paths if one tries to measure it.
- Neither of the paths? No, if both paths are blocked, nothing happens at the black arrow.

This phenomenon and other related phenomena are called *interference*, because whether one path is open or not seems to influence the behavior of the particles following the other path. This is the essence of the first quantum mystery!

It should be remembered that, in principle, the experiment is done by sending one particle at a time, so that no explanation can possibly be based on interactions between particles.

The way this experiment is usually described is by saying that the particle "follows both paths if they are both open" and only one path if one of them is blocked. But how does the particle know ahead of time, whether both paths are open or not?

Indeed, one might do a "delayed choice" experiment,[6] that is, introducing the wall *after* the passage of the particle through the first box measuring the spin in direction 2 (we can imagine both paths to be very long or put the wall just before the black arrow).

Alternatively, one could remove the black arrow while the particle is in flight and then, there would be no recombination of the paths and the particles would continue their trajectory and pass each other (see Fig. 2.5). Those following the path 2 ↑ continue downwards and those following the path 2 ↓ continue upwards. If we then measure the spin in direction 1, along any of these paths, we get 25 % 1 ↑, 25 % 1 ↓ in each case. Indeed, we have, along each path, particles that are only 2 ↑ or 2 ↓, and are measured in direction 1; the result is then as in Fig. 2.1 (right) and also for 2 ↓ instead of 2 ↑.

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[6] See [507, 509] for the theoretical proposal of such experiments by Wheeler, and [280] for experimental realizations.

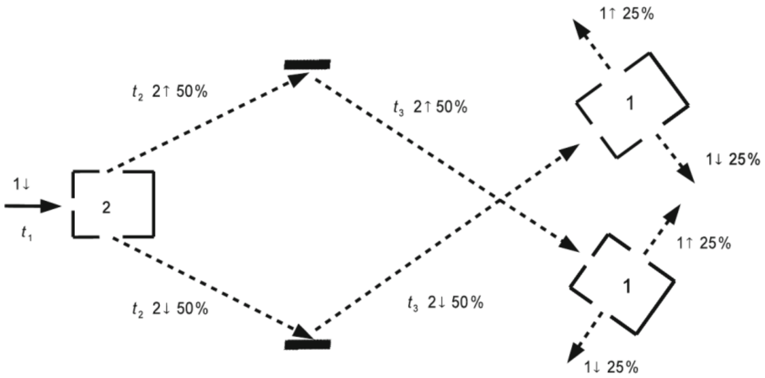

Fig. 2.5 No interference without the *black arrow*

This only deepens the mystery and is the basis of the claim by Wheeler, that "the past [meaning here whether the particle "has chosen" to follow both paths or only one] is not really the past until it has been registered" [107, p. 68]. Moreover, Wheeler invented an ingenious scheme where such "experiments" would not take place in the laboratory, but on a cosmic scale. If we accept his reasoning, this implies that we could decide *now*, by choosing which experiment to perform on the light coming from distant quasars, what happened billions of years ago[7] [507].

Another paradoxical consequence of the experiment described here is the Elitzur–Vaidman bomb-testing mechanism.[8] Suppose that we have a stock of bombs, some of which are active and some of which are duds. We want to find out which is which, but an active bomb will explode if it is hit by only one particle. On the other hand, by definition, a dud is totally insensitive to being hit by one or more particles, so that it does not affect those particles in any way. How could we tell, by classical means, which bombs are active without exploding them? There seems to be no way to do that.

But there is a trick, based on the Mach–Zehnder interferometer, that allows to identify at least a fraction of the active bombs as being active without exploding them. Let us replace the wall in Fig. 2.4 by a bomb. First, suppose that the bomb is a dud. Then, since it is insensitive to the particles, it is as if we had done nothing, i.e., as if we had not put a wall. The particle will behave as if there was no wall and therefore its spin at the black arrow will always be 1 ↓ if we measure the spin in direction 1.

On the other hand, if the bomb is active and detects the particle, it explodes and that's it—it is lost. That happens half of the time if the bomb is active. But suppose that the bomb is active and does not explode. This means that the particle took the path 2 ↑; if we then measure the spin at the black arrow in direction 1, we will get

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[7] This will be clarified in Sect. 5.1.2. See also [38], where Bell discusses the delayed-choice experiment from the viewpoint of the de Broglie–Bohm theory.

[8] See [173] for the theory and [300] for experiments.

$1 \downarrow$ for half of those particles and $1 \uparrow$ for the other half. If we get $1 \downarrow$, we cannot conclude anything since that would also happen if the bomb were a dud. *But*, if we get $1 \uparrow$, then we can be certain that the bomb was *not* a dud since that would *never* happen if the active bomb is replaced by a dud. Since each result $1 \downarrow$, $1 \uparrow$ happens half of the time (among the 50 % that have not exploded), we can identify 25 % of our initial stock of active bombs as being active without exploding them.

Altogether, half of the active bombs explode and are lost, but a quarter are "saved" (not exploded and known to be active). For the remaining quarter, we don't know. We can then repeat the operation (together with the duds, since we don't know which is which) and identify as active one quarter of that remaining quarter. Repeating the operation many times, we can get as close as we like to a total of one third of the initial stock of active bombs as being known to be active and not exploded,[9] since $1/3 = \sum_{n=1}^{\infty}(1/4)^n$.

2.3 The Quantum Formalism

We now describe a mathematical algorithm that allows us to predict these surprising results, without worrying yet about what it "means" physically.[10]

We associate with each particle a "state", which is simply a two-dimensional vector. In principle, the vector is complex, i.e., the vector space is $\mathbb{C}^2$ rather than $\mathbb{R}^2$, but this will not matter here. The association is as follows (there is of course some arbitrariness in the way this association is made, but let us put that aside):

$$|1 \uparrow\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix} , \tag{2.3.1}$$

$$|1 \downarrow\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix} , \tag{2.3.2}$$

$$|2 \uparrow\rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 1 \end{pmatrix} , \tag{2.3.3}$$

$$|2 \downarrow\rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ -1 \end{pmatrix} . \tag{2.3.4}$$

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[9] If one can modify the experiment so that a fraction p of particles follow the path $2 \downarrow$ and a fraction $1 - p$ follow the path $2 \uparrow$, then one can "save" a fraction $(1 - p)/2$ of the bombs in one operation and, repeating this many times, one can eventually identify a fraction $(1 - p)/(1 + p) = \sum_{n=1}^{\infty}[(1 - p)/2]^n$ of the active bombs, which is as close to 1 as one wants, for p small.

[10] For an elementary introduction to the quantum formalism, see also Susskind and Friedman [467].

We have the obvious relations

$$|2\uparrow\rangle = \frac{1}{\sqrt{2}}\big(|1\uparrow\rangle + |1\downarrow\rangle\big)\,, \tag{2.3.5}$$

$$|2\downarrow\rangle = \frac{1}{\sqrt{2}}\big(|1\uparrow\rangle - |1\downarrow\rangle\big)\,, \tag{2.3.6}$$

$$|1\uparrow\rangle = \frac{1}{\sqrt{2}}\big(|2\uparrow\rangle + |2\downarrow\rangle\big)\,, \tag{2.3.7}$$

$$|1\downarrow\rangle = \frac{1}{\sqrt{2}}\big(|2\uparrow\rangle - |2\downarrow\rangle\big)\,. \tag{2.3.8}$$

The states of the particles, i.e., the vectors, change according to the following rules:

1. When no measurements are made:

   $$|\text{state}(t)\rangle = c_1(t)\,|1\uparrow\rangle + c_2(t)\,|1\downarrow\rangle = d_1(t)\,|2\uparrow\rangle + d_2(t)\,|2\downarrow\rangle\,, \tag{2.3.9}$$

   where $c_1(t), c_2(t), d_1(t), d_2(t)$ are related by (2.3.7) and (2.3.8), and change *continuously* in time in such a way that, at all times, we have $|c_1(t)|^2 + |c_2(t)|^2 = 1$ and $|d_1(t)|^2 + |d_2(t)|^2 = 1$.

   This evolution is *deterministic*, i.e., if, at some time, say 0, we give ourselves a state $|\text{state}(0)\rangle$, then this determines a unique state $|\text{state}(t)\rangle$ for all times.

   To say more precisely what this evolution is, one would have to write down a differential equation for $c_i(t)$, $d_i(t)$, $i = 1, 2$, which in more general situations is called the Schrödinger equation.[11] But we will not need to go into that for the moment (the Schrödinger equation is discussed in Appendix 2.A).

   This evolution is *linear*, i.e., if, at some time, say 0, we have

   $$|\text{state}(0)\rangle = c_1|\text{state}_1(0)\rangle + c_2|\text{state}_2(0)\rangle\,, \tag{2.3.10}$$

   for two states $|\text{state}_1\rangle$ and $|\text{state}_2\rangle$ and numbers c_1, c_2, then, at all times, we have

   $$|\text{state}(t)\rangle = c_1|\text{state}_1(t)\rangle + c_2|\text{state}_2(t)\rangle\,. \tag{2.3.11}$$

2. But if a measurement is performed, the rule of evolution changes. Suppose the state is (2.3.9):

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[11] Or, to be precise, the Dirac or the Pauli equations in order to deal with spin.

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