# Chapter 4
# Quantum Matter

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**Abstract** Quantum mechanics is a fundamental theory that represents physical processes at atomic and sub-atomic level. It is an extraordinarily successful theory, but its interpretation has been the subject of endless controversies. Quantum mechanics and its further developments such as quantum field theory have been invoked to justify beliefs in idealism, the independent existence of the mind, infinite worlds, and almost anything imaginable. In this chapter I review the basic assumptions of both quantum mechanics and quantum field theory and present an analysis of their ontological implications. I evaluate the concept of matter in the light of both theories and conclude that, far from being idealistic theories, they agree with a fully materialistic view of the world.

## 4.1 Introduction

Quantum mechanics is a fundamental theory of physics developed in the first decades of the twentieth century. Based upon insights on micro-physical processes obtained by such figures as Max Planck, Albert Einstein, Louis de Broglie, and Niels Bohr, the theory achieved its mature form in the 1920s–1930s thanks to the work of Werner Heisenberg, Max Born, Pascual Jordan, Erwin Schrödinger, Paul Dirac, and Wolfgang Pauli, among others. Although the original goal of quantum mechanics was to correctly represent the physical processes involving elementary particles and atoms, the theory was later applied, also with great success, to explain macroscopic phenomena such as superconductivity and superfluidity. The final formalism is already exposed in early textbooks as the famous treatises by Dirac (1930) and von Neumann (1955, originally 1932). The interpretation of this formalism, however,

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has resulted in endless controversies. Early surveys of the interpretations of quantum mechanics by Margenau (1954) and Bunge (1956) already reflect the wide range and variety of views on the foundations of the theory. A detailed discussion of the different interpretations in a historical perspective is offered by Jammer (1974). More recent discussions can be found, for instance, in Lewis (2016) and Norsen (2017). Almost anything speakable and even many unspeakable things have been said about quantum mechanics, to use a famous figure of speech by Bell (2004).

Aversely to classical theories of mechanics and electrodynamics, whose referents are well-known from human experience, quantum mechanics deals with phenomena that are quite apart from common sense. One consequence of this was that the semantical interpretation of the mathematical formalism of the theory was not even clear to those who developed this very formalism. This incompleteness was aggravated by the unusual character of many quantum phenomena revealed by the experiments and correctly predicted by the theory. Philosophers and physicists alike started soon to associate quantum mechanics with all kind of propositions, from the non-existence of reality to the existence of infinite worlds. Bohr, the main advocate of the standard interpretation (known as the Copenhague interpretation), for instance, claimed that reality was not a property of the referents of quantum theory (neither of the physicists that formulated the theory, including himself):

> An independent reality, in the ordinary physical sense, can neither be ascribed to the phenomena nor to the agencies of observation.[1]

Heisenberg, among other things, held that materialism is untenable because quantum mechanics shows that it lacks of object:

> The ontology of materialism rested upon the illusion that the kind of existence, the direct "actuality" of the world around us, can be extrapolated into the atomic range. This extrapolation is impossible, however.[2]

Another well-known quantum physicist, Eugene Wigner, maintained that consciousness is a necessary ingredient of the theory:

> It is not possible to formulate the laws of quantum mechanics in a fully consistent way without reference to the consciousness.[3]

Wigner went as far as to vindicate a kind of "quantum solipsism" (see Wigner 1995). Examples as these can be multiplied endlessly with the result that many physicists despair when the discussion swifts to the deep meaning of quantum mechanics. Most of them simply prefer just to use the mathematical apparatus of the theory to make quantitative predictions without further questioning. Richard Feynman put it clearly in this way:

> On the other hand, I think I can safely say that nobody understands quantum mechanics. So do not take the lecture too seriously, feeling that you really have to understand in terms of

[1] Bohr (1987), p. 54.

[2] Heisenberg (1962), p. 145.

[3] Wigner (1995), p. 248.

> some model what I am going to describe, but just relax and enjoy it. I am going to tell you what nature behaves like. If you will simply admit that maybe she does behave like this, you will find her a delightful, entrancing thing. Do not keep saying to yourself, if you can possibly avoid it, 'But how can it be like that?' because you will get 'down the drain', into a blind alley from which nobody has yet escaped. Nobody knows how it can be like that.[4]

And yet we ultimately do science not because we want to calculate, but because we want to understand. And in the case of quantum mechanics we want to understand what this strange theory is about and what it does mean. Should we really reject materialism if we accept quantum mechanics? Minds can act upon microphysical systems? Is realism affected in any sensible way in the quantum picture of the world? Can truly quantum objects be both particles and waves? What is, after all, the ontology of the world according to quantum mechanics?

In this chapter I want to answer these questions. I am well aware that many people has done this before, in disparate ways and with disparate results. I do not want to add confusion to a confuse subject. My approach will be to stay close to the formalism, and to apply the tools of modern semantics to the analysis of this formalism. I will pay attention not to what scientists say, but to what they do when they research. The view that will emerge will be one that is in full agreement with a materialist conception of the world. Quantum mechanics is strange, surely, but it is so because reality is strange to us, not because it doesn't exist or because it is immaterial.

## 4.2 The Peculiarities of Quantum Systems

Perhaps the best way to get a first glimpse of the strangeness of the quantum phenomena is through the double slit experiment. Let us consider a screen with two slits. Thomas Young used a screen like this and a background screen to demonstrate the wave character of light in 1801. If we send a beam of monochromatic light to the first screen, each slit becomes a coherent light source that then interferes constructively or destructively with the other. The result in the background screen is the formation of an interference pattern that reveals the wave nature of light (see the left side of Fig. 4.1). If we send, instead, particles against the screen with the slits, some of them will bounce off the screen, but some will travel through the slits. These latter particles will travel to the second screen where they will impact producing two strips of marks with roughly the same shape as the slits (Fig. 4.1, middle image). This effect shows that what we throw through the slits were particles. All this sounds familiar to our experience. Let us know repeat the experiment using very narrow slits and throwing electrons. If we block one of the slits off for the moment, we will find that some of the electrons will pass through the open slit and strike the second screen just as particles would: the image on the screen will form a strip roughly of the same shape as the slit.

[4] Feynman (1965), p. 129.

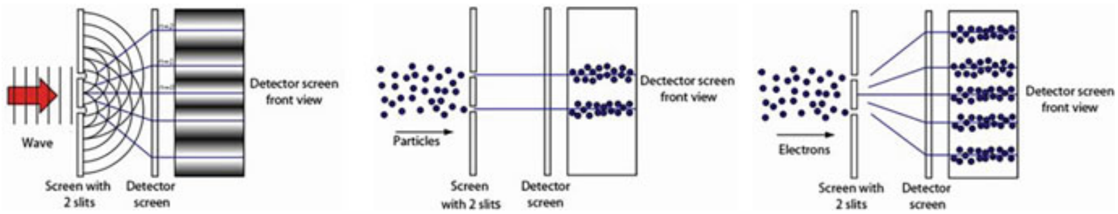


**Fig. 4.1** Double slit experiment. On the left a wave goes through a screen with two slits and produce an interference pattern on the detector. In the middle, classical particles are shot through the slits making impact on two points on the background screen. Finally, on the right, electrons are thrown to the two-slit screen. The result is an interference pattern as in the first case. But if a detector is located in one of the slits, a discrete event is register. The electron seems to behave both as a wave or as a particle according to the experimental array

Let us now open the second slit. If you expect two rectangular strips on the second screen, you are wrong. What you will actually see is that the spots where the electrons hit build up to replicate the interference pattern from a wave. Exactly as it was the case with light. How can this be? Perhaps, you might think, the electrons somehow interfere with each other, so they do not arrive in the same places they would if they were alone. Experiments show, however, that the interference pattern remains even when the electrons are fired one by one, so that they have no chance of interfering. Each individual electron contributes one dot to an overall pattern that looks like the interference pattern of a wave. Quite strange. Is the electron a wave or a particle? Maybe each electron somehow splits, passes through both slits at once, interferes with itself, and then recombines to meet the second screen as a single, localized particle?

One way to find out, is to place a detector in the slits, to report which slit an electron passes through. If you do that, then the pattern on the detector screen turns into the particle pattern of two strips, as seen in the middle image of Fig. 4.1. The interference pattern disappears! Somehow, the conditions in the slit make the electrons to travel like classical particles. Some people interpretes this as an effect of our act of 'seeing' the electron. Other people say that it is the act of measuring what creates the result of the experiment.

What seems to be for sure is that what we call 'particles', objects such as electrons and photons, somehow combine characteristics of classical particles and characteristics classical of waves. This is the famous wave particle duality of quantum mechanics. It also suggests that the conditions of the experiment have a deep effect on the quantum system. The question of exactly how that happens constitutes the core of the so-called measurement problem of quantum mechanics.[5]

Let us now consider another weirdness proper of the quantum world: entanglement. In 1935, Einstein noticed that since the dynamical equations of quantum

[5] The problem of measurement might be enunciated more precisely saying that quantum systems evolve in a superposition of states before a measurement. The measurement, however, always reveals a definite particular state. See the end of Sect. 4.3.

mechanics are linear, the so-called principle of superposition holds: the linear combination of solutions is also a solution. Einstein, and two of his assistants, Boris Podolsky and Nathan Rosen, showed in a famous paper (Einstein et al. 1935) that when those equations are applied to a system of two interacting particles that are then set apart, some strange effects appear. Let us imagine, for simplicity, a source of unpolarized photons. Photons admit two different states of polarization. If a pair of photons are emitted from the source their common state will be one of zero polarization. However, individual photons must have some state of polarization. Let assume that some detector measures the polarization of one of the photons and it results in a given value. Then the other photon, it doesn't matter how distant it is, even if it is beyond causal reach, shows exactly the opposite polarization in such a way that the total polarization of the pair remains zero. They are somehow linked, despite the distance. The situation is illustrated in Fig. 4.2.

This strange correlation, not observed in the macroscopic world, is called *entanglement*. Einstein thought that such a "spooky action at distance" was actually showing that quantum mechanics was an incomplete theory. In other words, that the theory must have hidden variables. However, a theorem due to Bell (1964, 1966) rules out local theories that have hidden variables. A class of experiments was devised to test Bell's theorem. Experiments of this type were first implemented

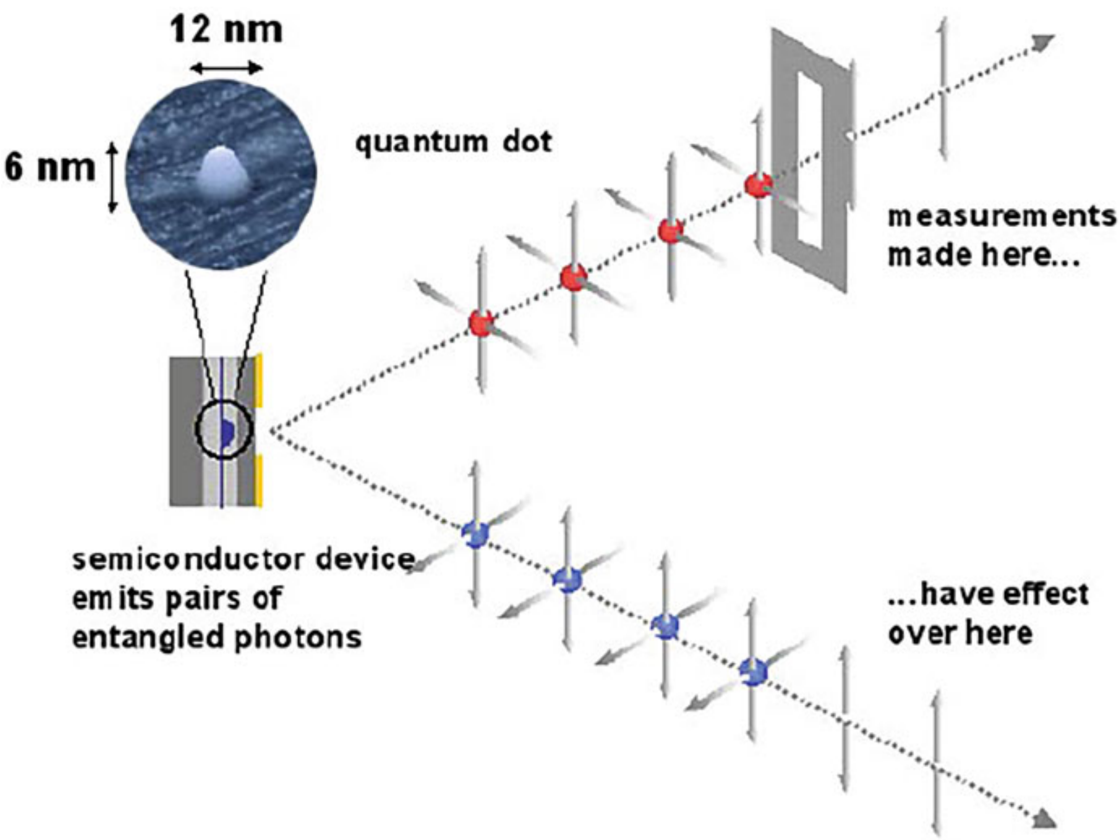


**Fig. 4.2** Entanglement. Two photons are prepared in such a way that their individual states remain correlated even on space-like separations. These correlations are non-local and apparently instantaneous

by Freedman and Clauser (1972) and Aspect et al. (1981, 1982). Since then, many of such experiments have been performed. In all cases their results are in complete agreement with quantum mechanics. There are not hidden variables in the theory. Quantum objects seem to have non-local properties, in the sense that they are correlated independently of the distance. Quantum physics cannot be represented by any version of the classical picture of the world.

## 4.3 The Formalism of Quantum Mechanics

If we want to get some insight into the meaning of quantum mechanics, first we need to have a look at its formalism. Theories are hypothetical–deductive systems of statements closed under the operation of entailment (e.g. Bunge 1967). But only mature theories are cast into axiomatic format. Most of them are presented as collections of statements, dynamic equations, assumptions, and collateral observations. All this tends to create an opacity of meaning, especially when the formalism is complex and the referents elusive, as in the case of quantum mechanics. Rigorous axiomatizations of the theory exist (e.g. Bunge 1967; Perez Bergliaffa et al. 1993, 1996; Romero 2018). Here I shall just show the basic elements of the theory in order to guide the reader through the interpretation. Details can be found in the mentioned papers and books.

The referents of quantum mechanics are physical systems called *quantum systems*. The states of a quantum system are represented by a non-unique, normalized, mathematical function $\psi(\overline{x}) \in \mathcal{H}$ called *wave function*, where $\overline{x}$ denotes the position of a point in Euclidean 3-dimensional space, and $\mathcal{H}$ stands for a Hilbert space.[6] The wave function is a fundamental mathematical tool for calculating the values of the different properties of the quantum system, but it should not be confused with the quantum system itself.

Unlike classical theories, quantum states are represented by complex functions in Hilbert space, where a summation operation is defined. This fact, and the already mentioned linearity of the dynamic equations of quantum mechanics, imply that the Principle of Superposition holds at the level of states. Many other theories have dynamical equations that are linear; for instance, Maxwell's equations for electrodynamics are linear. However, quantum mechanics is unique in the feature that the dynamical equations refer to *states* of systems, and not merely to properties such as the intensities or densities of fields. Although the wave function refers to the quantum system, it does not directly represent it. Being a complex function, it cannot represent real entities.

[6] A Hilbert space is an abstract vector space possessing the structure of an inner product that allows lengths and angles to be measured. Hilbert spaces are complete in the sense that there are enough limits in the space to allow the techniques of calculus to be used.

The *inner product*[7] of two states is defined by:

$$\langle \psi | \phi \rangle = \int \mathrm{d}\overline{x}\, \psi^*(\overline{x}) \cdot \phi(\overline{x}). \tag{4.1}$$

The values of the *properties* of a quantum system can be calculated with self-adjoint operators $\hat{A}(t) : \mathcal{H} \longrightarrow \mathcal{H}$, acting upon the corresponding wave functions. Unlike classical systems, quantum systems may not have precise or sharp values for their properties. Instead, we can calculate the average $\left\langle \hat{A} \right\rangle$ of a certain property of a system in a given state $\psi$ by:

$$\left\langle \hat{A} \right\rangle = \left\langle \psi | \hat{A} | \psi \right\rangle. \tag{4.2}$$

The spread $\Delta_\psi \hat{A}$ of the average is

$$\Delta_\psi \hat{A}^2 = \left\langle \hat{A} \right\rangle^2 - \left\langle \hat{A}^2 \right\rangle. \tag{4.3}$$

If the spread $\Delta_\psi \hat{A}$ of a certain property of a quantum state $\psi_k(\overline{x})$ is null, then the property takes a sharp value $\lambda_k$. The corresponding state $\psi_k(\overline{x})$ is called an eigenstate of the operator $\hat{A}$, $\lambda_k$ is its eigenvalue, and they satisfy:

$$\hat{A}\psi_k(\overline{x}) = \lambda_k \psi_k(\overline{x}). \tag{4.4}$$

Under certain conditions, the values $\lambda_k$ may constitute a countable set, i.e. the values of the property may be quantized. This is another specific feature of quantum systems. Actually, the term ‘quantum’ is derived from this feature of having discrete values of some properties.

Because of the Superposition Principle, quantum states are not exclusive. Given an eigenstate $\psi_k(\overline{x})$ of certain self-adjoint operator $\hat{A}(t)$, the propensity of any quantum system in a state $\psi(\overline{x})$ to take the value $\lambda_k$ is quantified by a probability $p_k$ given by:

$$p_k = | \langle \psi | \psi_k \rangle |^2, \tag{4.5}$$

where $0 < p_k < 1$.

Quantum mechanics has an evolution equation that describes how properties change with time. The equation reads:

$$\frac{d\hat{A}}{dt} = \frac{i}{\hbar}(\hat{H}\hat{A} - \hat{A}\hat{H}) + \frac{\partial \hat{A}}{\partial t}, \tag{4.6}$$

[7] In this definition the symbol $*$ designates the conjugate-complex of the wave function.

where $\hat{H}$ denotes a particular operator called Hamiltonian of the system and $\hbar$ is the Planck constant over $2\pi$. The Hamiltonian represents the energy of the system. This dynamical equation is called Heisenberg's equation. Notice that if the system is not interacting $\hat{H} \neq \hat{H}(t)$ and the evolution of any property is given by:

$$\hat{U}(t,\ t_0) = \exp -\frac{i}{\hbar}\hat{H}(t - t_0), \tag{4.7}$$

where the evolution operator is clearly unitary:

$$\hat{U}(t,\ t_0)\hat{U}(t,\ t_0)^{\dagger} = \hat{I}. \tag{4.8}$$

An alternative, equivalent, formulation of the theory can be obtained adopting time-independent operators to represent the properties and a time-dependent wave function $\psi(x) = \psi(\overline{x},\ t)$ that obeys the Schrödinger's equation:

$$\hat{H}\psi(x) = \frac{i}{\hbar}\frac{\partial\psi(x)}{\partial t}. \tag{4.9}$$

The two pictures only differ by a basis change with respect to time-dependency, which corresponds to the difference between active and passive transformations. The equivalence was proved by Schrödinger (1926) and Eckart (1926).

One immediate consequence of the dynamical equations (4.6) and (4.9) is that the evolution of the system is fully deterministic (see Earman 1986 for a full discussion of determinism in quantum mechanics): if we know the state of the system at the instant $t_0$ then we know the state of the system at any instant $t$. Every property evolves as:

$$\hat{A}(t) = \hat{U}(t,\ t_0)^{\dagger}\hat{A}(t_0)\hat{U}(t,\ t_0), \tag{4.10}$$

and the state evolves as:

$$\psi(x) = \hat{U}(t,\ t_0)\psi(x_0). \tag{4.11}$$

This fact is cause of much confusion. If the state $\psi(x)$, according to the Principle of Superposition, is a combination of states, then $\psi(x) = \Sigma_k \lambda_k \psi_k(x)$, where $\lambda_k$ is a set of eigenvalues of some operator $\hat{A}$ and the $\psi_k$ are the corresponding eigenstates that form a complete basis of the Hilbert space. As far as the system evolves unitarily, it is in a mixture of states. The prediction of quantum mechanics is that the probability of the system of being in a particular state $\psi_n$ with a value $\lambda_n$ under some specific boundary conditions is given by Eq. (4.5). When an effective measurement is done, the system is found in some definite or pure state with some actual value for the property represented by $\hat{A}$. It seems that the system is now in a state $\psi_h$, and remains there unless it is acted upon. How is possible for the quantum system to break unitary evolution and change its state? This is, again, the problem of measurement, now expressed in technical terms. And here is, perhaps, where most interpretational misunderstandings of the theory begin.

## 4.4 Interpretation

Quantum mechanics is a deterministic theory that makes probabilistic predictions. Such probabilities quantify the propensity of the quantum systems to go from a state described by $\psi(x)$ to an eigenstate $\psi_k(x)$. Before implementing a measurement (or more generally, before undergoing an interaction with the environment), the system has a propensity with a probability $|\langle\psi|\psi_k\rangle|^2$ to be found in a state $\psi_k(x)$ where a given property $\mathcal{A}$, represented by the operator $\hat{A}$, has a definite value $\lambda_k$. Unless the original state is already $\psi_k(x)$, this probability is smaller than 1. If, after the measurement or the interaction, the system is found to have a value for $\mathcal{A}$ of $\lambda_k$, the probability of a subsequent measurement of finding such a value is now 1. So it seems that there was a sudden change in the state of the system from $\psi(x)$ to $\psi_k(x)$. The system apparently experienced an irreversible transition from a mixed to a pure state, violating unitary evolution. Heisenberg expresses the situation in this way:

> Since through the observation our knowledge of the system has changed discontinuously, its mathematical representation also has undergone the discontinuous change and we speak of a 'quantum jump'.[8]

This statement seems to attribute the transition to the observation. To solve this problem, von Neumann introduced the famous postulate of the collapse of the wave function:

> If the measurement of a physical observable $A$ (with associated operator $\hat{A}$) on a quantum system in the state $\psi$ gives a real value $a_n$, then, immediately after the measurement, the system evolves from the state $\psi_n$, where $\hat{A}\ \psi_n = a_n\ \psi_n$.[9]

This postulate interprets the collapse of the wave function as a consequence of the act of measuring the property $\mathcal{A}$. To fix the state of the system in a sharp value for the property in question requires, accordingly, the intervention of 'an observer', or at least of a measurement device. This seems to suggest that the exact form of reality is dependent on our observations of it. From here to idealism there is just a small step:

> It is not a mysterious interaction between the apparatus and the object that produces a new $\psi$ for the system during the measurement. It is only the consciousness of an 'I' who can separate himself from the former function $\psi(x, y, z)$ and, by virtue of his observation, *set up a new objectivity* in attributing to the object henceforward a new function $\psi(x) = \psi_k(x)$.[10]

[8] Heisenberg (1958), p. 28.

[9] von Neumann (1955) (original 1932).

[10] London and Bauer (1939), p. 252.

The intrusion of ‘the observer’ is also frequently invoked as the origin of the so-called ‘Heisenberg’s uncertainty relations’:

$$\Delta\hat{x}_i\ \Delta\hat{p}_i \geq \hbar/2, \tag{4.12}$$

$$\Delta E\ \Delta t \geq \hbar/2, \tag{4.13}$$

where the operators represent components on the same direction of the position and linear momentum of the system, $E$ is the energy, and $t$ is the time.

The situation can be clarified through the investigation of the semantical assumptions of the theory. A way to approach this problem is casting the theory into an axiomatic format. In such a format not only the formal and nomological assumptions are made explicit, but also those that link formal constructs with extra-linguistic objects (see Bunge 1967, 1973, 1974; Perez Bergliaffa et al. 1993, 1996; Romero 2018). When this is done, several issues become evident. First, the direct referents of the theory are quantum systems and their environments, not observers or instruments, much less minds or conscious states. Second, the theory can be used (by imposing boundary conditions, which represent specific situations, to the dynamic equations) to predict the probability of some event to occur. This probability is the quantitative estimate of the propensity of the system to have a given value of a certain property under those conditions; it is calculated through the rule expressed by Eq. (4.5). If the system is effectively found through an experiment to have such a property, it means that its state evolved from a state described by $\psi$ to a state that corresponds to the measured value, say, $\psi_k$. A new determination of the same or of another property of the same system will correspond to one obtained from the new state $\psi_k$. The probability has not “collapsed” after the measurement from the initially predicted value to a value $p_k = 1$. The a priori probability remains the same, exactly as the a priori probability before a roll of dice does not change or collapse when the dice finds a final state. This interpretation of the theory remains silent about how the evolution of the state occurs. From the reference class, it is clear that the only thing that can affect the state is the interaction with the environment. It is this environment which is responsible for the evolution. Such evolution does not obey the linear equations (4.6) and (4.9). The full description of the process depends on the details of the interaction and is not a part of the original quantum theory but the core of the quantum theory of measurement, which rests on the concept of decoherence (see Schlosshauer 2007). A general theory of quantum measurement does not exist, and it is dubious whether it can be consistently formulated in all generality since it should depend on the specific experimental device.

A third important point that becomes clear from an axiomatization of the quantum theory is that the Heisenberg inequalities are theorems and have nothing to do with the effect of any observer. They can be derived from the non-commutation of the corresponding operators and the so-called Schwartz inequality, that is purely mathematical (Bunge 1967; Perez Bergliaffa et al. 1993). Since there is no time operator in quantum mechanics, the forth inequality (4.13) does not strictly hold. Instead, the correct expression is:

$$\Delta \hat{H}\, \tau_A \geq \frac{\hbar}{2}$$

with $\tau_A = \Delta\hat{A}/|d < \hat{A} > /dt|$. Here $\hat{A}$ is any time-dependent operator (see Bunge 1977 and Messiah 2014). All these inequalities represent actual relations among the properties of quantum systems. They have nothing to do with our knowledge, uncertainty, or our observations. They just say that some quantum properties are not defined simultaneously in a sharp way. Such properties are not classical properties, but *sui generis* properties of quantum systems.

Another issue that is illuminated by an analysis of the semantic structure of the theory when it is exposed through an axiomatization is the fact that neither realism nor materialism are ruled out by quantum entanglement. The experimental refutation of Bell's inequalities that demonstrate the reality of entanglement just expresses that (1) theories with hidden variables are false (i.e. quantum mechanics is complete) or (2) the theory is non-local or (3) both (1) and (2) are true. Non-locality is a feature of reality according to quantum mechanics if the theory is complete. This is far cry from stating that there is no reality. Reality might be strange to our common sense, but this does not mean lack of reality or idealism. Entanglement neither seems to violate causality. Causality is relation among events, not among things. A causal action of a thing A upon a thing X is just a way to say that an event in thing A triggers an event in thing B. Causality implies a change of the state of a particular entity. This seems not to be the case with quantum entanglement: when we determined the state of one of the components of the entangled system, there is no change in the state of the other component. The state of this component does not go, say, from state $s_1$ to state $s_2$. There is simply a *specification* of the state of the system: of the different states in which the system might be, it always occurs that the state is that corresponding to the initial preparation of the system. Since there is no work exerted on the second component, no energy transfer occurs (the energy of the component is exactly the same before and after the specification of its state). There is no causal connection between components at all; there are just non-local correlations: once an entangled state has been formed, the system remains intertwined regardless of the spatial separation of the components. When we specify the state of the first component of an entangled pair, the state of the second component is specified as well according to the initial preparation of system. Once an interaction has destroyed the interlacing, the components are separated and there are no more correlations. In this view, there is no action of one component of the system upon the other; there are just non-local correlations. Once the system is formed, some properties remain until some interaction destroys the entanglement (López and Romero 2017). It is because of no actual work is done that information cannot be transmitted faster than light through entanglement. Any transmission of information requires a signal that should move, at most, at the speed of light (see Romero 2018 for a discussion of the concept of semantic information).

Summing up, we can say that quantum mechanics admits a perfectly consistent interpretation that is realist because quantum systems are considered real entities endowed with properties existing in spacetime.[11] This interpretation is also objective, since there is no inclusion of observers or subjects in the formalism. The kind of reality revealed by quantum mechanics is non-local and certainly very removed from the usual intuitions based on the common sense, but the kind of entities that populate the quantum world seem to be entirely material. . . or do not?

## 4.5 Quantum Field Theory

The interpretation of quantum mechanics offered in the previous section implies that quantum systems are objective real entities with specific properties that manifest as propensities. They are neither particles nor waves, but *sui generis* objects that under some conditions behave like classical particles and under other conditions are similar to waves. Classical analogies of some of their properties cannot even be sharply defined simultaneously. Other properties, such as entanglement or spin, are exclusive of the quantum realm and do not have classical analogues.

This ontology is better understood if we conceive quantum systems as fields. The idea of fields was introduced by Faraday in the nineteenth century and was successfully applied to the electromagnetic field by Lorentz and others. Quantum field theory was the natural result of trying to accommodate the concept of electromagnetic field to the demands of quantum mechanics. The result, quantum electrodynamics, is a robust theory of extraordinary predictive power. Based on the success of this theory, the field approach was applied to weak and strong interactions, eventually leading to the standard model of current physics. This model presents a unified field view of all interactions (except gravity). Each field is an extended entity existing on spacetime. Particles are not anymore autonomous things but features of the field. Although they are countable, they are not distinguishable. Particles are just discrete excitations of the fundamental state of the field. All fields exist independently of whether they are excited or not. The fundamental level, when no excitation is present, is called the 'vacuum state'. This sate should not be

[11] This is not the only realist and objective interpretation that can be proposed for quantum mechanics. The Many-Worlds interpretation, for instance, adopts the collapse postulate and interprets it at face value accepting an ontological inflation. The overabundant ontology that results is perfectly compatible with materialistic views. This article is not the place to discuss the different arguments for and against these and other interpretations. Rather, the point to be emphasized here is the fact that quantum mechanics can be consistently understood in a way such that the theory does not imply a challenge for materialism. For discussions about interpretations of quantum mechanics see Ruetche (2011) and Acuña (2019).

confused with actual vacuum or absence of field. It has properties, such as energy fluctuations and is susceptible of polarization.

The vacuum state $|0\rangle$ can be excited to form a so-called Fock basis of the quantized field:

$$|1_k\rangle = \hat{a}_k^{\dagger}|0\rangle. \tag{4.14}$$

Each application of the operator $\hat{a}_k^{\dagger}$ adds one quantum excitation to the state $k$. It represents any physical process that produce such excitations. Successive applications of the operator $\hat{a}_k^{\dagger}$ yield:

$$\hat{a}_k^{\dagger}|n_k\rangle = (n+1)^{1/2}|(n+1)_k\rangle. \tag{4.15}$$

Similarly, the operator $\hat{a}_k$ removes quanta:

$$\hat{a}_k|n_k\rangle = n^{1/2}|(n-1)_k\rangle. \tag{4.16}$$

The operator $\hat{a}_k$ can be used to define the vacuum state as the state for which

$$\hat{a}_k|0\rangle = |0_k\rangle, \quad \forall k. \tag{4.17}$$

In this way, any system of $n$ particles is understood as a fundamental quantum field with $n$ excitations of the vacuum. The vectors $|n_1, n_2, \ldots, n_k\rangle$, where $n_i$ is the number of quanta in the state $i$, belong to the separable Hilbert space which is the tensor sum of a countable number of Hilbert spaces $\mathcal{H}_j$, where the subscript $j$ also corresponds to the number of (non-interacting[12]) particles present, namely, $\mathcal{H}_1 \bigoplus \mathcal{H}_2 \bigoplus \ldots \bigoplus \mathcal{H}_n$. Here $\bigoplus$ indicates the direct sum. The operators $\hat{a}_i^{\dagger}$ and $\hat{a}_j$ obey the operator algebra given by:

$$[\hat{a}_i,\ \hat{a}_j^{\dagger}] = \delta_{ij}, \tag{4.18}$$

$$[\hat{a}_i^{\dagger},\ \hat{a}_j^{\dagger}] = 0, \tag{4.19}$$

$$[\hat{a}_i,\ \hat{a}_j] = 0. \tag{4.20}$$

[12] For interacting particles the tensor product should be considered.

In the case of fermions, where only one excitation is possible in each state, the operator algebra becomes:

$$[\hat{a}_i,\ \hat{a}_j^\dagger]_+ = \delta_{ij}, \tag{4.21}$$

$$[\hat{a}_i^\dagger,\ \hat{a}_j^\dagger]_+ = 0, \tag{4.22}$$

$$[\hat{a}_i,\ \hat{a}_j]_+ = 0, \tag{4.23}$$

where the subscript $+$ stands for anti-commutation: $[A,\ B]_+ = AB + BA$.

In Minkowski space, a preferred basis can be constructed using the specific symmetries of this space (the Poincaré group). Then, if $\hat{N}_k = \hat{a}_k^\dagger \hat{a}_k$ is the operator number of particles, we get

$$\langle 0|\hat{N}_k|0\rangle = 0, \qquad \text{for all } k. \tag{4.24}$$

This means that the expectation value for all quantum modes of the vacuum is zero: if there are no particles associated with the vacuum state in one (non-accelerated) reference system, then the same is valid in all of them. In curve spacetime this is not valid any longer: general spaces do not share the Minkowski symmetries, and hence the number of particles is not a relativistic invariant. This reflects the fact that particles are features of the field and not independent entities. What exists cannot depend on the description offered in a particular frame, as it happens with the number of quanta.

Since in general spacetimes there are different complete sets of modes for the decomposition of the field, a new vacuum state can be defined:

$$\hat{\bar{a}}_j|\bar{0}\rangle = |0\rangle, \quad \forall j, \tag{4.25}$$

and from here a new Fock space can be constructed. The field $\phi(x)$ can be expanded in any of the two basis:[13]

$$\phi(x) = \sum_i [\hat{a}_i u_i(x) + \hat{a}_i^\dagger u_i^*(x)], \tag{4.26}$$

and

$$\phi(x) = \sum_j [\hat{\bar{a}}_j \bar{u}_j(x) + \hat{\bar{a}}_j^\dagger \bar{u}_j^*(x)]. \tag{4.27}$$

[13] For simplicity I consider here a scalar field.

Since both expansions are complete, we can express the modes $\bar{u}_j$ in terms of the modes $u_i$:

$$\bar{u}_j = \sum_i (\alpha_{ji} u_i + \beta_{ji} u_i^*), \tag{4.28}$$

and conversely,

$$u_i = \sum_j (\alpha_{ji}^{+} \bar{u}_j - \beta_{ji} \bar{u}_i^*). \tag{4.29}$$

The coefficients $\alpha_{ij}$ and $\beta_{ij}$ satisfy the relations

$$\sum_k (\alpha_{ik} \alpha_{jk}^* - \beta_{ik} \beta_{jk}^*) = \delta_{ij}, \tag{4.30}$$

$$\sum_k (\alpha_{ik} \beta_{jk} - \beta_{ik} \alpha_{jk}) = 0. \tag{4.31}$$

The operators on the Fock space then can be represented by:

$$\hat{a}_i = \sum_j (\alpha_{ji} \hat{\bar{a}}_j + \beta_{ji}^* \hat{\bar{a}}_j^{\dagger}), \tag{4.32}$$

and

$$\hat{\bar{a}}_i = \sum_i (\alpha_{ji}^* \hat{a}_i - \beta_{ji}^* \hat{\bar{a}}_i^{\dagger}). \tag{4.33}$$

An immediate consequence is that

$$\hat{a}_i |\bar{0}\rangle = \sum_j \beta_{ji}^* |\bar{1}_j\rangle. \tag{4.34}$$

Since in general $\beta_{ij} \neq 0$, the expectation value of the operator $\hat{N}_i$ is:

$$\langle \bar{0} | \hat{N}_i | \bar{0} \rangle = \sum_j |\beta_{ij}|^2 \neq 0. \tag{4.35}$$

This surprising result means that the number of quanta of the field (particles) is different for different decompositions. Since different decompositions correspond to different choices of reference frames, we must conclude that different observers detect a different number of quanta (particles). These particles activate detectors in some reference systems, but not in others. They are essentially a frame-dependent feature of the field. If we accept that whatever exists objectively cannot depend on our choice of a particular reference system, then the assumption that particles are self-subsistent individuals falls apart.

In quantum field theory particles are not dealt with as individuals but as features of the quantum fields and relative to some specific choice of mode decomposition of the field that is frame-dependent. Matters of existence should not be solved just counting or individuating with respect to some reference system, but considering true invariant properties and their referents. In this sense it is the energy-momentum complex and its mathematical representation through a second-rank tensor field $T_{\mu\nu}$ that provides an objective indicator of independent existence. Contrary to the excitations of the field, that depend on global modes defined over the whole spacetime, the energy-momentum of the field is defined locally through a tensor quantity. For a fixed state $|\psi\rangle$ the results of different detectors when measuring the expectation value $\langle\psi|\hat{T}_{\mu\nu}|\psi\rangle$ can be related by the usual transformation laws of tensors. In particular, if $\langle\psi|\hat{T}_{\mu\nu}|\psi\rangle = 0$ in one reference system, the energy density of the quantum field will be zero for any reference frame. This situation is quite different for particles, that might be detectable or not in the same region of space by different observers in different states. This clearly points out that the ontological import is in the quantum field, not in the particles. And it is not neither in the structure, since the structure emerges from the relations of the fields.

It might be objected that in the case of Minkowski spacetime all fields are in the vacuum state and then $\langle 0_{\mathrm{M}}|\hat{T}_{\mu\nu}|0_{\mathrm{M}}\rangle = 0$. But an accelerated observer in this spacetime actually should detect thermal radiation (Davies 1975; Unruh 1976). In the accelerated frame it is also valid $\langle 0_{\mathrm{M}}|\hat{T}^{\mathrm{acc}}_{\mu\nu}|0_{\mathrm{M}}\rangle = 0$, so the thermal radiation seems to violate energy conservation. But this is a wrong conclusion originated by considering only a part of the system. The whole system is the accelerated detector plus the field in the vacuum state. The field couples with the accelerated system producing a resistance against the accelerating force. It is the work of the external force that produces the thermal bath measured by the detector in the co-moving system. The same radiation is not measured by a detector at rest, since it is not coupled with the field. I remind here that a vacuum state of the field does not correspond to the absence of field, but to the absence of discrete excitations of the field. The example just shows the reality of the field, even when there are no excitations. The excitations themselves, the quanta, can be present in one system and not in other, according to the state of the system with respect to the field.

When curvature is present in spacetime, inertial frames are associated with free-falling systems and in general not unique choice of the vacuum state can be made to express the field, as we have seen above. So, different detectors located in different reference systems will detect different numbers of particles. Polarization of the vacuum by event horizons results in Hawking radiation that is detectable in the asymptotically flat region of spacetime, but such radiation is not seen by an observer falling freely into the black hole. In general, there is not simple relation between $\langle\hat{N}_i\rangle$ and the particle number measured by different detectors (Birrell and Davies 1982). The ontological status of particles in quantum field theory in curve spacetime is that of a complex relational property between fields and detectors (reference frames). The ontological substratum, however, is provided by the fields. Remove them, and nothing is left: no energy-momentum, no excitations, no expectations, no structure. I conclude that quantum objects are quantum fields over spacetime.

## 4.6 Quantum Ontology

If we accept the ontological principle that what there is cannot depend on our way to describe it, we are led to reject particles (quantum excitations of the field) as basic ontological entities. This point has been emphasized by Davies (1984) and Hobson (2013). The absence of particles that corresponds to a vacuum state defined by Eq. (4.17) is not universal. Even in Minkowski (flat) spacetime, this relation does not define a global vacuum since excitations are seen by accelerated observers (Unruh 1976). The vacuum in Minkowski spacetime is shared by all observers in *inertial frames* because of this spacetime is symmetric under the group of Poincaré transformations. But detectors in accelerated frames, as we already saw, will measure a flux of particles and for them the vacuum will be a different state. Particles, being excitations of the field, are frame-dependent.

If we want to probe the ontological substratum of the excitation, i.e. the field itself, we need to turn to *locally well-defined* properties, such as the energy and momentum that are represented by the expectation value of the energy-momentum tensor: $\langle 0|\hat{T}_{\mu\nu}|0\rangle$. If $\langle 0|\hat{T}_{\mu\nu}|0\rangle = 0$ in one reference system, then it will remain zero in the entire spacetime. Energy is relativistically invariant because what exists, exists in all reference frames. The group of symmetries of general relativity is the set of *all* frame transformations.

The energy-density of any field in any point of spacetime is well-defined through $\langle|\hat{T}_{\mu\nu}|\rangle$.[14] If we understand as material entities those capable of changing, this implies that the quantum fields are the true material constituents of the world because energy is just the capability of changing. Any field can change and do work, i.e. induce changes, in some potential detector.

I conclude that quantum ontology is an ontology of fields, not of particles or waves. Much less of minds, worlds, or observers. We live in a world of fields and we are nothing but a complex system of excitations of such fields. How many fields are there, exactly? So far we only know the fields of the standard model of quantum field theory. These are 12 fundamental fields for fermions (6 quarks and 6 leptons) and 13 fundamental fields for bosons (8 gluons; 3 for $W_+$, $W_-$ and $Z_0$ bosons; 1 for the photon and 1 for the recently discovered Higgs boson). All these fields exist on a background spacetime.

[14] All theories discussed here are renormalizable.

## 4.7 Quantum Matter and the Stuff of the World

Let us assume that the line interval of spacetime is given by a pseudo-Riemannian metric $g_{\mu\nu}(x)$:

$$ds^2 = g_{\mu\nu}(x)dx^\mu dx^\nu. \tag{4.36}$$

Einstein's field equations relate the metric structure of spacetime with the energy content of the fields defined on it:

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = \frac{8\pi G}{c^4}\langle\hat{T}_{\mu\nu}\rangle. \tag{4.37}$$

As we have seen, the fields represented on the right side of these equations are material, since $\langle\hat{T}_{\mu\nu}\rangle$ is well-defined, or can be renormalized to a well-defined quantity. But what about the left side of the equations? Is spacetime material? The answer seems to be 'yes, it is' (see the chapter by L. Combi in this volume). First, any perturbation of the fields produces a perturbation in spacetime. Such perturbations can travel even in the absence of any other field at the speed of light. They are changes in the curvature of spacetime. Such curvature should be interpreted as a physical property, not a purely geometrical one. This becomes clear when we realize that curvature changes produce changing tidal forces that can exert work and transfer energy to other material things. Second, global dynamical solutions of the equations exist. In models of universes represented by such solutions, spacetime can do work upon material systems through cosmological forces, clearly showing that spacetime is material as well (see Romero 2017 for further arguments).

If spacetime is material we can ask whether it is another quantum field. Certainly it is not the same kind of field as the quantum fields we have been discussing so far. All known fields are defined *on* spacetime, and cannot exist without it. Without spacetime, the energy-momentum of any field cannot be formulated because the metric is essential to it:

$$T_{\mu\nu} = \frac{2}{\sqrt{-g}}\frac{\delta\mathcal{L}_{\rm M}}{\delta g^{\mu\nu}}, \tag{4.38}$$

where $g = ||g^{\mu\nu}||$ is the determinant of the metric tensor, and $\mathcal{L}_{\rm M}$ is the effective Lagrangian density of the material fields other than gravitation. Clearly, without $g_{\mu\nu}$ there is not $T_{\mu\nu}$. The converse is not true: we can have spacetime without any quantum field, as indicated by vacuum solutions of Eqs. (4.37). We express this fact saying that spacetime is background independent.

At this point, if we are asked what is the stuff of the world, we might answer with the title of a famous book by Hermann Weyl: space, time, matter. Or better, material spacetime and material quantum fields. Matter, then, seems to come in two flavors: spacetime and quantum fields. Each of them is material because each of them has energy and can act upon the other. But they appear to be different in the sense that spacetime looks more independent and fundamental than quantum fields. The latter, we might say, are parasitic of the former. In addition, energy is not a well-localized property in spacetime. Any region of spacetime is locally flat, and energy is associated with curvature. Hence, it can be only attributed in a covariant sense to a region of spacetime, never to a point.

The description of spacetime given by general relativity, however, is far from satisfactory: many physically realistic models are singular, i.e. they give an incomplete description of spacetime (see Romero 2013). Simple examples are the hot big-bang model and black hole models. This fact has led to many different approaches of formulating a quantum theory of spacetime (and hence of gravity, which is a consequence of spacetime curvature). The direct attempt of considering the metric field as a classical field and to apply the standard quantification methods leads to non-renormalizable theories. A wide variety of different ways to circumvent this have been attempted (see, e.g. Oriti 2009). The crucial questions are about the nature of spacetime itself: has spacetime quantum properties? How such properties should be understood if they are not expressed in terms of spacetime itself? Attempts to answer such questions can be seen as the search for a conceptual unification of all forms of matter. A different path, followed by Einstein and Wheeler, was to consider spacetime as the basic entity, and then proceed to derive all other physical entities from it. Again, this is an attempt to unify the different types of matter. Both ways have problems and it is not even clear whether they can be formulated consistently. An intermediate approach is to look for a prior substratum, from where *both* spacetime and fields would emerge in the appropriate limits. What is such a material substratum is open to discussion (see Romero 2017 for some possibilities discussed from a philosophical point of view).

## 4.8 Summary and Conclusions

Quantum mechanics is a remarkable theory. It is remarkable for its accomplishments and triumphs, and it is remarkable for its opacity of meaning and the distance from its insights to the dictates of common sense. The strangeness of the theory manifests mainly in the form of entanglement, wave-particle duality, and the lack of sharpness of some quantum properties. All these features can be accommodated within a realistic and objective interpretation of the theory. In such interpretation the referents of quantum mechanics are quantum systems and their environments. The states of these systems are represented by complex functions that belong to a functional space called Hilbert space. The specific properties of a particular system are given by self-adjoint operators that act upon the corresponding Hilbert space. The eigenvalues of the operators are identified with the values of the properties. Since the values are discrete, the system is said to be quantized. If two operators do not commute, the corresponding eigenvalues are not simultaneously sharp. Such indeterminacy of properties, called Heisenberg's inequalities or dispersion relations, have nothing to do with observations. They just reflect the way of being of quantum objects.

The evolution of quantum systems obeys a linear equation. This equation can be formulated either for states or properties. The application of the Principle of Superposition to states leads naturally to entanglement. Once a system is prepared in a particular fashion, it evolves in such a way that its global properties are preserved. A result of this is the existence of non-local correlations among quantum states of the components of the system. This entanglement, very well verified from an experimental point of view, is no menace to the realist interpretation, conversely to what once Einstein thought. It only implies that quantum correlations in entangled systems are non-local.

The linearity of the dynamical equations of quantum mechanics also implies that the theory is fully deterministic. At each point of spacetime the state of a non-interacting quantum system is completely determined from the initial conditions. The theory is, nevertheless, probabilisitic in the sense that from a given state just propensities can be evaluated for different possible outcomes. Such propensities are mathematically represented by probabilities that are determined from the rule given by Eq. (4.5). In the evolution of the propensities observers are not involved, but just interactions with the environment, that can be artificial, as in an experiment, or natural, as in most cases.

The so-called wave-particle duality actually does not exist. Quantum systems are neither waves nor particles. They can display under some conditions a behavior that might resemble that of a wave and under other circumstances that of a classical particle, but they are neither of them: they are *sui generies* entities. What kind of entities? In this chapter I have argued that quantum systems are fields extended over spacetime. What we call individual particles are just excitations of this field. The fact that they are actually properties of the field and not entities reveals itself when we realize that they are not relativistically invariant. Different vacuum states can be found for the same field. This results in particles being detected in one reference frame and not in another.

The property that characterizes ontological existence is energy: the capability of changing and producing changes. The energy density of the field is always well-defined in all reference frames and cannot be leveled by a change of frame. This shows that the underlying entities in the theory are the quantum fields. Since these fields interact among them, we say that they are material.

Finally, the spacetime over which these fields exist is material as well because it also has energy, albeit with non-local distribution.

So far, we can say that according to our current views of the physical world whatever exists is material. There seems to be two kinds of matter: fields and spacetime. Whether these two kinds of matter can be reduced one into the other, is something to be found.

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