What if We Lived in the Best of All Possible (Quantum) Worlds?

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Abstract

For scientific realists, quantum mechanics is unsatisfactory because it suffers from the measurement problem. However, there are at least three promising solutions: the pilot-wave theory, the many-worlds theory, and the theory of spontaneous collapse. In this paper I argue that the measurement problem is a false problem for the realist: it was proposed as the last resort to convince the positivists that the theory is not empirically adequate. Instead realists should focus on preserving the reductive explanatory schema that had worked so well in physics before, which requires a theory to have a three-dimensional ontology. Incompleteness argument to this effect have been proposed in the 1920s, but effectively ignored due to the positivistic climate, other unscientific reasons, and theorems which claimed that this project was impossible. When realists re-examined quantum mechanics in the 1950s and later, they happened to focus on the measurement problem. In this paper I speculate on what would have happened if realists instead focused on finding a three-dimensional ontology to complete quantum theory. I show that most paradoxes, puzzles and mysteries connected with quantum mechanics would have never emerge, and that many of what are now considered possible ontological interpretations of the theory would have hardly been taken as viable options.

Keywords: quantum mechanics; measurement problem; completeness problem; scientific realism; Copenhagen Dogma.

1. Introduction

Quantum theory is one of the greatest accomplishments of scientific inquiry as it has an outstanding predictive power, both in depth and in breath: allegedly, with a single mathematical object, the wavefunction, and a simple equation, the Schrödinger equation, the theory delivers predictions which are incredibly accurate, and accounts for a vast variety of physical phenomena. However, its explanatory power is left to be desired: it is not clear how the phenomena the theory predicts are explained in terms of a microscopic description. In other words, scientific realists, who think that our best theories inform us about the nature of reality, consider quantum theory incompatible with realism, because the theory does not tell us a coherent microscopic story beyond the phenomena. Nonetheless, realists also think that one can provide such a picture by solving the measurement problem. This is the problem of dealing with the unobserved macroscopic superpositions (such as an instrument displaying all possible measurement outcomes at the same time) which are predicted by quantum mechanics, when assuming that the description of a physical system is entirely provided by a Schrödinger evolving wavefunction. Solutions of the measurement problem are found by denying each assumption, or by embracing the conclusion. One could for instance deny that the wavefunction always evolves according to the Schrödinger equation. The simplest way to do this is by postulating the collapse rule introduced by von Neumann: the wavefunction evolves according to the Schrödinger equation until a measurement is performed, and then it collapses into one of the terms of the superposition. Another way of doing the same thing is provided by the spontaneous localization theory of Ghirardi, Rimini and Weber which makes precise 'when' and 'where' the wavefunction collapses without referring to measurement processes. Alternatively, one could reject the claim that the wavefunction provides a complete description, which is the route taken by the pilot-wave theory: one also needs to specify the particles'

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position. The last option is to accept that macroscopic superpositions exist but are not observed, as defended by the many-worlds theory: ‘whatever can possibly happen, will indeed happen,’ not here but in another ‘world,’ which is suitably ‘transparent’ to us. These theories are commonly understood as theories about the wavefunction, namely a field in a high dimensional space. In other words, even if the world appears to us as being three-dimensional and populated with three-dimensional objects, it is rather high dimensional, and objects are fundamentally ‘made of’ a high dimensional field.

In this paper I argue that, contrary to the common opinion, it is misleading for the scientific realist to consider the measurement problem. In other words, there are no compelling reasons for realists to consider the measurement problem. Rather, it is a matter of historical contingency that people considered it as the problem to solve to make quantum theory and realism compatible. This attitude came as the conclusion of a series of ‘accidents:’ misunderstandings implications of experimental and theoretical results, the peculiar philosophical climate, the charisma of certain people and the lack of thereof of others, as well as additional other-than scientific factors. Classical physics provided a reductive understanding of the macroscopic phenomena in terms of the motion of their microscopic constituents (section 2). However, this was not the case in quantum mechanics. Therefore, some people looked for a completion of the theory, for a deeper explanation, as in similar situations it had usually been done before. In section 3, I pretend that everybody agreed that this was the thing to be done, and I show how, outside of that scientific and philosophical context, things could have evolved. Realists would have naturally understood quantum theory as they understood thermodynamics: as a theory in need of a deeper explanation. And as thermodynamics had statistical mechanics to provide a reductive explanation of the thermodynamic principles, the natural attitude would have been to think that quantum mechanics needed to be suitably completed to similarly provide a reductive explanation of the so-called quantum rules. Had realists focused on the project of explaining the phenomena microscopically, they would never have encountered the measurement problem. Consequently, there would have been no mention of consciousness, high dimensional wavefunction ontology, undetectable many-worlds, stochastic nonlinear modifications of the Schrödinger equation. Without being distracted from the measurement problem, realists would have naturally considered a theory in which particle deterministically evolve according to highly nonclassical laws and interact nonlocally. In section 4 I come back to what has actually happened, and I show how the measurement problem was put forward as the last of a series of arguments to convince instrumentalists. They do not care about realism or unobservable entities, they had nonetheless something to worry about: with only the Schrödinger evolving wavefunction, the theory is not empirically adequate. I conclude in section 5, arguing that solving the measurement problem is not a sufficient condition for finding a satisfactory realist theory: it merely points at a problem (empirical adequacy), and it should not be thought as a way of finding a satisfactory realist quantum theory able to explain the phenomena reductively.

2. The Reductive Explanatory Schema

According to classical mechanics the world is made of microscopic, massive three-dimensional point-particles which evolve according to Newton’s law. After Maxwell, electricity was taken to consist of charged particles, namely electrons, and electromagnetic phenomena were explained by introducing a new property, charge, and a new type of force. Newton believed that light, just as matter, was made of particles. However, in the early 1800s, experiments revealed interference and diffraction patterns for light, and Maxwell’s electrodynamics described light as the propagation of electromagnetic waves, supporting the theory that light is a wave. Therefore, the consensus settled that there are fundamentally two things in the world: matter, made of three-dimensional particles with mass and charge; and light, which instead is a wave oscillating in three-dimensional space. The macroscopic behavior of matter is accounted for in terms of the reductive schema, with the specification of the ways in which matter and light interact.

Classical physics explains the behavior of both earthly and celestial objects using a reductive explanatory schema in which the properties and behavior of macroscopic objects are accounted for in terms of the dynamics of their microscopic constituents, namely point-particles. Let's call this the 'reductive explanatory schema.' The story classical physics tells us about the macroscopic world is a 'geometrical' story: a table is just a table-shaped cluster of microscopic particles. Once the particles positions and the way in which they evolve are specified, everything else follows: the solidity of a table, the localization of a comet, the transparency of a pair of glasses, the liquidity of the water in this bottle, the compressibility of the air in this room, and so on. This project culminated in the work of Boltzmann, who developed statistical mechanics, which suitably reproduces the laws of thermodynamics in terms of the motion of microscopic point-particles. Similarly, the laws of geometrical optics, in terms of light rays, can be accounted for in terms of the vibrations of the electromagnetic waves.

To use a locution introduced by Einstein (1919), classical physics is a constructive theory. This is defined as a theory which involves the dynamical reduction of macroscopic objects in terms of the motion and interactions of their microscopic constituents. Thus, we can call this type of theories reductive theories. This is opposed to a principle theory, which is formulated in terms principles used as constraints on physically possible processes. Thermodynamics is an example of a principle theory (e.g. 'energy is conserved'), while statistical mechanics is the corresponding constructive theory, which explains why such principles hold. Before the end of the 19th century, the goal of physics was taken to propose constructive theories, because of the reductive explanatory schema that you have explained a phenomenon when you have understood how it can be derived dynamically by the motion of its microscopic constituents.

Often quantum theory is advertised as forcing us to abandon the idea that phenomena can be reductively explained in the sense I specified. We are told that we need to recognize that our language is hopelessly incomplete, that we will never be able to understand what lies beyond the phenomena, if there is such a thing. Bohr taught us that there is a classical world and a quantum world, which are complementary with one another: we need them both to get a complete picture of reality. The quantum world cannot be described in classical terms: when the wave description is adequate, the particle one is not and the other way around. The quantum world is inevitably hidden beyond our abilities. Experiments we perform on the quantum world are bound to change (or even create!) the reality beyond the phenomena. This distinctively nonclassical behavior needs to be reckoned and dealt with by recognizing that there is a paradigm shift. The reductive understanding used within classical physics was one in which we imagined the world as composed of microscopic entities moving around like little balls or sticking together to form macroscopic bodies. The quantum revolution is the acknowledgement that this type of understanding was impossible. Scientists need to swipe away the old picture and paint the canvas with new colors. We need to realize that we can only understand what is directly observable and we should give up all the desires to explain the quantum world like we did before, according to the reductive schema summarized above, because we simply cannot do it.

This is what everyone has been told, this is how students have been indoctrinated for years. However, this is what Beller (1999) calls the Copenhagen Dogma: the 'rhetoric of inevitability' championed by Bohr. It turns out that there is nothing inevitable about it: most of it was just very effective propaganda. In this paper I wish to go further than telling the story about the Copenhagen propaganda, and flip the inevitability claim on its head: what should have been inevitable is to notice that there is one natural extension of the reductive schema, namely the pilot-wave theory, and that, had this been recognized, all the other realist solutions of the measurement problem, as well as the idea that the wavefunction represents the ontology of the world, have received an attention that they would hardly have actually received.

3. In the Best of All Possible Worlds

Let us imagine, starting from the experiments that prompted the development of the first quantum rules, how one could have expanded the reductive explanatory schema to the quantum domain, had not the Copenhagen hegemony won without deserving it. I will simply list the arguments that were proposed, and not the ways in which they have been misunderstood, misconstrued, or ignored, and I will follow where this naturally leads. This 'what if?' exercise is obviously fiction, but it is useful to see how a rational development of quantum theory could have been.

3.1. Quantum Theory as a Principle Theory

Quantum theory first begun, at the beginning of the 20th century, as a slight modification of the classical picture to accommodate experimental outcomes (including the blackbody radiation problem, the various atomic spectra, the stability of the atom, and so on) that suggested that certain quantities are not continuous but rather are discrete or 'quantized.' The project at the time was to provide a principle theory to determine the right quantization rules for the various quantities, using the so-called Bohr–Sommerfeld quantization conditions, within the classical understating of matter as particles and light as a wave. In fact, it was difficult to come up with a constructive understanding because of several experiments which challenged the wave nature of light (Compton and photoelectric effects) and others which challenged the particle nature of matter (particle interference). Nonetheless, some suggested that one needs both particles and waves. For instance, to explain the photoelectric effect Einstein in 1905 proposed that light waves were associated with a particle, the photon, and this could also account for the Compton effect. De Broglie in 1924 interpreted this as the light wave 'guiding' the motion of the photons through space. Similarly, he proposed the existence of 'matter waves' associated with particles. De Broglie's project, dubbed the double solution theory, was to have particle behavior emerging as a singularity of a u wave, guided by another ψ wave, without physical significance except for its phase, which it shared with the u wave. This constructive theory would reductively explain the perceived particle-behavior in terms of the u wave's dynamics, coupled with the ψ wave. However, de Broglie could not find the right equation, which would have to be non-linear.[2] So, he started studying a simplified model in which the particles are postulated in place of the u wave, and they are guided by the ψ wave. While in the double solution theory this dynamical law would be a consequence of the coupling between ψ and u, in this simplified version the new particle dynamics is

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[2] Indeed, such a wave equation has never been found. See Colin, Durt, Willox (2017) for a discussion of de Broglie's double solution program and its latest developments.

postulated. However, de Broglie did not at the time have a successful proposal for the dynamical equation for the wave, and this is where Schrödinger came in.

3.2. Wave Mechanics as a First Attempt to Maintain the Reductive Schema

In a series of papers written in 1926-27, Schrödinger started to develop a wave-only constructive theory, called wave mechanics, to reductively explain where the quantization rules came from. Unlike de Broglie, however, he had no particles, and only one wave, ψ, evolving according to the equation which now carries his name. Schrödinger's wave is now called the wavefunction. Wave mechanics wished to provide a clear picture of what was going on inside an atom, along the lines of the reductive schema which has been used so far. In particular, Schrödinger could show that the hydrogen spectrum can be reproduced in terms of nodes of this wave. Particles are emergent: they are narrow wave packets, composed of wave with different wavelengths, which if they remain isolated in a small region of space (that is, if they do not spread), from a distance they give the impression of being particles.

De Broglie, Lorentz and Einstein were excited by the new proposal but at the same time they also quickly realized that the theory, as is, was not yet completely satisfactory. First, wave packets quickly spread out, and thus the observed stable 'particle' trajectories cannot be accounted for. Moreover, the wavefunction of a system with two or more 'particles' is not vibrating in three-dimensional space, but rather it is an object in configuration space. This is the space of the (three-dimensional) configurations of all 'particles,' which is therefore high dimensional. This does not make sense in the perspective of the reductive schema: how can you explain the phenomena by introducing an object living in an abstract, high-dimensional space? If the ontology of the theory is not something in three-dimensional space, then reductionism fails. In fact, one cannot derive the macroscopic phenomena in terms of the microscopic ones, because strictly speaking there's no microscopic reality in three dimensions. Since the wavefunction lives in a high-dimensional space, we need to find a new three-dimensional ontology to save the reductive explanatory schema. [3]

Schrödinger was aware of the wave packet spreading but could not find a solution. Moreover, he granted that a field in a high dimensional space could not be interpreted physically.[4] To address this

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[3] At the 1927 Sovlay conference de Broglie justified his introduction of particles because "it seems a little paradoxical to construct a configuration space with the coordinates of points that do not exist." (Bacciagaluppi and Valentini, 2009, p. 346). Lorentz writes to Schrödinger: "If I had to choose now between your wave mechanics and the matrix mechanics [referring to the quantum formalism proposed by Heinberg earlier that year], I would give the preference to the former, because of its greater intuitive clarity, so long as one only has to deal with the three coordinates x, y, z. If, however, there are more degrees of freedom, then I cannot interpret the waves and vibrations physically, and I must therefore decide in favor of matrix mechanics." Here are similar concerns expressed by Einstein in a letter to Lorentz dated May 1st, 1926: "Schrödinger's conception of the quantum rules makes a great impression on me; it seems to me to be a bit of reality, however unclear the sense of waves in n-dimensional q-space remains." (Lorentz in Przibram, 1967). Similarly, here is an excerpt from a June 18th, 1926 letter that Einstein sent to Paul Ehrenfest: "Schrödinger's works are wonderful – but even so one nevertheless hardly comes closer to a real understanding. The field in a many-dimensional coordinate space does not smell like something real." Both these quotes from Einstein are taken from Howard (1990).

[4] In fact, in 1926 he wrote: "The direct interpretation of this wave function of six variables in three-dimensional space meets, at any rate initially, with difficulties of an abstract nature." Also: "Of course this use of the q-space is to be seen only as a mathematical tool, as it is often applied also in the old mechanics; ultimately [...] the process to be described is one in space and time." (Bacciagaluppi and Valentini, 2009, p. 447).

problem he proposed that the square module of the wave function (a three-dimensional field) represents a charge density.[5] However, like all waves, Schrödinger's charged density waves superimpose, and their superpositions propagate to the macroscopic domain where are not observed. So, the theory is not empirically adequate when completed this way.

3.3. The de Broglie-Bohm Theory as a Reductive Quantum Theory

In 1952 Bohm came to the rescue and showed how, by using instead a particle ontology, and relegating the wavefunction to describe the motion of particles, one could avoid these problems: particles are particles (so they don't' spread); and superpositions of the wavefunction have no physical meaning.

Bohm wrote a second order equation for the motion of the particles similar to the one of Newton if one also adds a distinctively quantum term, which contains a Schrödinger evolving wavefunction. The wavefunction in terms into the definition of a quantum potential, similar to the gravitational or electromagnetic potential, as it affects the trajectories of the particles.

Nonetheless, starting from a particle theory whose motion is guided by a wave, symmetry constraints (such as rotation, time reversal and Galilei invariance) respectively select for the wave the Schrödinger evolution, and for the particles a first order guidance equation (constraining their velocities in terms of the wavefunction) as the simplest possibilities.[6] This formulation, which came to be known as de Broglie-Bohm theory or Bohmian mechanics, explicitly shows the nonlocality of the theory, as discussed in section 3.9.

3.4. Consequences: The Collapse of the Wavefunction

In this theory the wavefunction which evolves according to the Schrodinger equation is the wavefunction of the universe, while in general the wavefunction of systems smaller than the universe does not evolve according to this equation. In suitable situations one can however talk about the Schrodinger evolving 'effective' wavefunction of a (sub-)system and discuss the interaction among different systems as if they were isolated. Thus, the system's wavefunction may evolve into a superposition, given the linearity of the Schrödinger equation. However, when the system interacts with another system, say an apparatus, their interaction may be strong enough that the wavefunction ceases to evolve according to the Schrödinger evolution. That is, their wavefunction effectively evolve as if it 'collapsed' into one of the terms of the superposition. From that moment on, the motion of the particles in that system is governed by the 'collapsed' wave function, for all practical purposes. While it is determined in which term of the superposition the wavefunction will collapse, we cannot predict it, because it depends on the initial position of the particles, to which we have no access.[7] Why is that?

3.5. Consequences: The Uncertainty Principle

What we can know (or: the information we can have access to) has to do with how the system we are investigating correlates with another system (the measurement apparatus) that we can access directly (because macroscopic). For instance, if we put an object on a (properly calibrated) scale, it interacts with the scale and as result the pointer moves to indicate a location labelled '1 Kg.' Because of this we

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[5] He chose charge rather than mass, for instance, because he wanted to connect his theory with electromagnetism Schrödinger (1926).

[6] Dürr, Goldstein and Zanghí (1992).

[7] Dürr, Goldstein and Zanghí (1992).

acquire the information that the object on the scale weights 1 Kg. If instead a system is independent of the apparatus, then they do not interact, so there can be no correlation, and thus no knowledge of the system can be acquired by investigating the apparatus. We have independent systems when we have equilibrium, understood as in statistical mechanics, where nothing changes. So, to have information about a system we need non-equilibrium.

However, if the world is governed by the de Broglie-Bohm theory, the configurations of the particles are in 'quantum' equilibrium with respect to the wavefunction, which instead is not in equilibrium. So, as in statistical mechanics one cannot extract anything from a system in thermodynamic equilibrium, in a system in quantum equilibrium all one can know about it is given by the system's wavefunction (because that is the one which is not in equilibrium). That is, the maximal information one can have of where the particles are is given by their wavefunction, which is the reason why it can be called the state of the system. This limitation of what one can know about a system was first discovered by Heisenberg in 1927, who called it the 'uncertainty principle:' if we happen to know the particle position with high precision, we will be more uncertain about the particle momentum. [8]

3.6. Consequences: The Born Rule

The de Broglie-Bohm theory can correctly account for all the experimental result. They are statistical in character, as the theory provides only the probability distribution of the results rather than a unique result like a deterministic theory would. This is because we cannot know where the particles were, as just discussed.

It turns out that, assuming a given initial wavefunction of the universe, if the particles are initially randomly arranged according to a distribution given by the square module of the initial universal wavefunction $|\psi_{t=0}(x)|^2$, then they will continue to be distributed that way: $|\psi_t(x)|^2$ (this property is called 'equivariance').[9] That means that, when performing an experiment to determine where a particle is, the probability P of finding it in a given place x is provided the square module of the wavefunction evaluated at that point: $P(x) = |\psi(x)|^2$. This is the so-called Born rule, who discovered it in 1926. To make an analogy: while in statistical mechanics the system likely evolves towards the greater entropy, here the system likely evolves towards the greater value of the squared module of the wavefunction.

The theory received its first empirical confirmation in 2011, when the highly nonclassical character of the trajectories of the particles was experimentally observed.[10]

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[8] He took his principle in a much stronger sense, as discussed in section 4.1.

[9] Dürr, Goldstein and Zanghí (1992).

[10] The theoretical trajectories have been computed in Philippidis, Dewdney and Hiley (1979), while the experimental results are presented in Kocsis *et al.* (2011). One will wonder how it is possible to have a measurement for the trajectories, given the uncertainty principle. This relies on the notion of weak measurement (Aharonov, Albert and Vaidman 1988), and an ingenious experimental procedure. A weak measurement is an experiment to measure a quantity which does not disturb the system too much but, due to the uncertainty principle, gives the result with very high imprecision. Assume one weakly measures the position x_1 of a particle at time t_1. This gives an imprecise value for x_1. Repeating this many times for the same position, one obtains a statistical distribution of x_1. Taking the average, one gets a good estimate of x_1 at t_1. At a later time t_2, perform a strong (i.e. precise) measurement of x_2, the position of the particle later on. One then can compute the velocity of the particle at x_1 by dividing the two positions x_1 and x_2 (one measurement weakly, the other strongly) at the two times t_1 and t_2, by the time interval. Repeating this procedure for different positions, one obtains a velocity field, and the trajectories are calculated as the tangents to the field.

3.7. Consequences: Matrix Mechanics

As Bell (1982) have noticed, all experiments give results that ultimately describe where something is located: for instance, an experiment to determine the velocity of a particle, is a measurement of how far the particle has travelled in a given time. Also, a measurement of a body's weight is given by the scale pointer pointing at a given label, and so on. In general, thus, all measurements are position measurements. Nonetheless, it is possible to effectively summarize experimental results in terms of matrices or linear operators, as discovered by Heisenberg, Born and Jordan in 1926. To each experiment one can associate a suitable operator, A, and the possible experimental results are given by their eigenvalues a_i: $A\,\psi_i = a_i\,\psi_i$. If one writes the wavefunction as a linear combination of the corresponding eigenstates ψ_i, $\psi = c_1\,\psi_1 + \cdots + c_i\psi_i + \cdots$, the probability P of obtaining one of the possible results, call it a_i, is given by the square root of the coefficient c_i with which the eigenstate corresponding to c_i is weighted in the linear combination of the eigenstates of A: $P(a_i) = |c_i|^2$. This is the generalized Born rule that gives the probability of finding a given experimental result.

3.8. Consequences: Experiments Often are not Measurements

However, as first proven by von Neumann in 1932,[11] in general experiments do not reveal about the system, because they may end up perturbing the system too much.[12] Experiments which do not change the system excessively can be called 'genuine measurements' because they can be thought as revealing us a property of the system as it was before the experiment. Instead, experiments which disturb the system so as to change it significantly, cannot be properly called measurements. In classical physics it is safe to assume that the system-apparatus interaction can be neglected.[13] However, as also emphasized by Bohr (1928), this is no longer the case if the instrument is about the same size of the system under investigation. In fact, for instance, to determine the position of an unmoving particle one has to see it first. That is, one perturbs the particle with photons, which however also scatter the particle. And the more precisely one wishes to know the particle position, the more one will have to perturb its velocity, so the less one can get a precise estimate of it, as the uncertainty principle states.

These 'no genuine measurement' proofs (or impossibility proofs against genuine measurements) sometimes are also called 'contextuality' proofs because they show that, in general, whether an experiment is destructive or not depend on the context. When they are destructive, they (obviously) reveal noting about the system. For instance, assume one wants to make an experiment to determine the velocity of a particle inside of a box which, unknown to us, is not moving. To do so, one needs to remove the box to see where the particle goes. But at that point the particle will begin to move (because opening the box changes its wavefunction, so its velocity), so what one records at the end of the experiment is not the particle's initial velocity.[14] As anticipated, in the classical domain it is easy to perform non-

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[11] Von Neumann (1932), pp. 305-324 of the 1955 English translation. See also Jauch and Piron (1963), Gleason (1957), Kochen and Specker (1967) for similar proofs. See also Pusey, Barrett, Rudolph (2012).

[12] This is not what von Neumann and the others took to have proven. For that, see section 4.4.

[13] For instance, when you are measuring the temperature of an object using a thermometer, the temperature you are actually measuring is the equilibrium temperature between the object and the thermometer. However, given the physical features of the thermometer, this equilibrium temperature is sufficiently closer to the initial temperature that we can think of the temperature one reads on the thermometer as the temperature of the object before it touched the instrument.

[14] Notice that Einstein (1953) objected that the de Broglie-Bohm theory seems contradictory because he did not take seriously enough the fact that experiments are interactions. If one takes the wavefunction of the particle in the box and solves the guid-

destructive experiments whose results we can be safely interpret as revealing the properties of the system before the experiment.[15] Instead, in the quantum domain many experiments are destructive: their results should be taken as telling us about the interaction, rather than the system itself.

As we saw, the statistics of an experiment is suitably captured by an operator, and a series of destructive experiments (which therefore cannot be thought as measuring anything) is associated to operators which do not commute: that is, the value of their product depends on their order, so that $AB \neq BA$. This makes a lot of sense: given that the experiments are destructive, the order in which they are preformed matter. For instance, if someone reads a message and then they burn it, it is different than if someone burns it and then they read it.

3.9. Consequences: Quantum Nonlocality

As anticipated above, the most troubling aspect of the de Broglie-Bohm theory is that it is explicitly nonlocal. That is, since the wavefunction is defined on configuration space, by acting on a particle here, one affects a particle over there instantaneous, regardless of how far away the two particles are. This seems in contrast with relativity, where there is an upper limit to the velocity of propagation of interactions.

So, in 1964 Bell tried to see whether one could provide a different type of reductive understanding of the quantum phenomena, assuming locality to be true. He proposed a theory in which there is some generic 'hidden' ontology, whose dynamics is governed by a Schrödinger evolving wavefunction, and calculated its empirical predictions. These are different from the predictions of the de Broglie-Bohm theory, and so one could perform a crucial test. Freedman and Clauser (1972) carried out the first actual test, using an inequality, called CHSH (Clauser, Holt, Shimony, Horn), derived from the original one. When the results were later confirmed in 1982 to be in favor of the de Broglie-Bohm theory,[16] it had to be accepted that locality is no longer an option, and that the de Broglie-Bohm theory is the best constructive theory which explains the quantum phenomena according to the reductive schema. Then people started to think about what this means for relativity.

This is where we are right now. Or better, this is where we would be, if things had gone differently.

So far, we have seen no high dimensional field ontology, no macroscopic superpositions, no stochastic modifications of the Schrödinger equation, no undetectable worlds, no contextual properties, no consciousness. Everything got shut down right in the moment people understood that one has to have a three-dimensional ontology to continue to understand things along the lines of the reductive explanatory schema. There was no reason they did not try to find a theory like that, and when they found it, this led them to a clear and simple picture of the world, according to which particles move around in

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ance equation, one will predict that the particle does not move. Instead, if one calculates the probability distribution of observing the particle with a given velocity as given by the Born rule, one gets a non-zero distribution. Nonetheless, the contradiction disappears if one remembers that to determine the particle's velocity, one has to open the box, and thereby change the wavefunction so that the particle now moves, as discussed in the main text.

[15] Even if one can construct destructive experiments which may look like true measurements, but they really are not. Think about taking a picture of an object with an old-fashioned film. A non-destructive experiment on the film, or a true measurement of the objects depicted in the film, would be to develop the film in a darkroom: this will tell us where the object is. Instead, a destructive experiment is looking at the film in daylight. While the former 'fixes' the objects' position on the film, the latter makes it disappear.

[16] Aspect *et al.* (1982a, b).

three dimensions following highly nonclassical laws, and in which the main discovery of modern science, namely nonlocality, is explicit.

But this is not what had happened. The actual history of quantum theory is very different from the one we just discussed.

4. Resistance is Futile

Let us briefly summarize what had actually happened, which is not as linear as the story we just presented. It is filled with people misunderstanding one another, talking past each other, ignoring or misconstruing arguments, and silencing unwanted objections. Here is a short overview. [17]

4.1. Matrix and Wave Mechanics

As we saw, quantum theory begun with the quantization rules, and with people's struggles trying to figure out where they came from. In 1925 Heisenberg, with the help of Born and Jordan, developed the so-called 'matrix mechanics,' a unified model to systematize experimental results using matrices. This was a formal result, in which there was no dynamics, no spacetime, no objects, but it could nonetheless reproduce the quantization rules in terms of suitable matrices, rather than reductively in terms of a microscopic dynamics. Initially, the proponents of matrix mechanics were influenced by the emerging positivistic philosophy, according to which unobservable entities should be eliminated because meaningless. Many, including Heisenberg, got convinced that the reason it was difficult to reductively explain the experimental results was that they were trying to fit the data in the wrong explanatory schema. The right way of explaining things is not in terms of the motion of unobservable entities but rather to account for them in terms of a mathematically elegant unified formal picture referring only to what can be observed.

To Heisenberg's dismay, in 1926 Schrödinger proved them wrong by proposing wave mechanics, which aimed at providing a reductive explanation of the quantum rules with a wave ontology. He also proved that his theory and matrix mechanics are mathematically equivalent, and he also argued that wave mechanics was more explanatory because it is more visualizable. Heisenberg defended matrix mechanics from the lack of visualizability charge by dropping the positivist attitude and by endorsing a particle ontology. In 1927 he discovered the uncertainty principle, and claimed that there are particles, however without determinate trajectories because they cannot have positions and velocity at the same time.[18] In any case, Bohr violently quarreled with Heisenberg about the choice of a particle ontology because he wanted to keep both particles and waves (waves were also more compatible with his atomic model). In 1927 in the Como lectures Bohr anticipated his wave-particle complementarity view as a sort of compromise.[19] Born initially endorsed Schrödinger's picture to arrive to his statistical interpretation of the wavefunction, according to which the wavefunction tells us the probability of finding a particle in a measurement, but later he embraced Heisenberg's attitude. Be that as it may, the members of the Copenhagen school, guided by Bohr, hid their internal disagreements and formed a

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[17] In this review I have followed the work of van der Waerden (1968), Jammer (1974), Fine (1986), Cushing, (1994), Howard (1990, 2004, 2007, 2013), Bricmont (2016), Norsen (2017), Becker (2018).

[18] This is what he claimed his uncertainty principle forced him to accept, but this is not true, as one could have said that they have both, but we cannot know what they are with arbitrary precision.

[19] Bohr (1928).

compact front against Schrödinger's wave model. He was accused of not being able to explain quantum jumps, even if he did: he wrote papers accounting for the Compton and photoelectric effects in terms of wave vibrations. In addition, in 1927 at the Solvay conference, de Broglie's preliminary proposal for a complete quantum theory in terms of particles and waves was effectively shut down by a harsh criticism by Pauli, so that de Broglie abandoned his project for a long time.[20]

4.2. Unphysical Field Arguments against Quantum Theory

While everyone ended using Schrödinger's methods, undeniably easier than matrix mechanics, he effectively was left alone in thinking about the meaning of his theory until he finally gave up (like de Broglie before him, and Bohm afterwards). This happened in great part because of Bohr's power, influence, and charisma (as well as some others' lack of these features), and the rampant positivistic philosophical climate. Some, most notably Einstein and Schrödinger, resisted to the Copenhagen idea that we should learn to live with the fact that the quantum world is hopelessly incomprehensible. However, they have been either ignored or misunderstood. As anticipated, they proposed arguments ultimately for the conclusion that as thermodynamics can be more profoundly understood in terms of statistical mechanics, so quantum theory can be better understood in terms of a deeper, microscopic theory still to be found. The first argument of this type can be summarized as follows: quantum mechanics is incomplete otherwise reductionism is false (as there is nothing moving in three-dimensional space). We already mentioned in the previous section that this argument was proposed by de Broglie, Lorentz and Einstein against Schrödinger's picture. Interestingly, this problem can be tracked down historically also to Heisenberg, who did not think it made sense to have a theory with no fundamental three-dimensional fields and with no fundamental three-dimensional physical space.[21]

As we have also seen, Schrödinger proposed his three-dimensional charge density field ontology in response. Even if the theory was still inadequate (due to the macroscopic superpositions and the spreading of the wave packet) Schrödinger never endorsed de Broglie's particles, which would have solved at least the first of these problems.

4.3. Nonlocality Arguments against Quantum Theory

Heisenberg took the argument above to be a reinforcement of his instrumentalism. Instead Einstein looked for something in three dimensions which could represent physical entities, over and above the wavefunction. In 1927 he proposed a deterministic particle theory, which however, he later retracted, arguably because it was nonlocal.[22] Accordingly, he did not take it as a serious option, as he wanted to keep both reductionism and locality.

Instead of actively working on building a microscopic theory which would reductively account for the quantum rules, he started proposing arguments that quantum theory had to be incomplete, otherwise it would be nonlocal. There are several variations of this argument, proposed between 1927 and 1935. In 1927 at the Solvay conference, Einstein considered a particle traveling towards a narrow slit, behind which there is a curved detection screen. After the slit, because of diffraction, the wavefunction of the

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[20] See Bacciagaluppi and Valentini (2009).

[21] He has been reported to have said, very vividly, referring to Schrödinger's work: "Nonsense, […] space is blue and birds fly through it" (Bloch 1976).

[22] For a system with two independent components the theory would not provide independent velocities. See Belousek (1996), Holland (2005).

particle would propagate as a spherical wave, and thus hit the screen everywhere. Since instead experimentally one observes only one spot on the screen, there has to be some nonlocal interaction. Given that is unacceptable, Einstein concluded, quantum theory cannot be complete.[23] This argument was misunderstood by Bohr, who thought it had to do with the uncertainty principle,[24] but not by Heisenberg. In fact, in his 1929 Chicago lectures he conceded to Einstein that quantum theory is nonlocal.[25] However, he also claimed that it does not violate relativity when understood instrumentally as a theory of signals (in fact, such nonlocality cannot be used to send information).

In the 1930, at another Solvay conference, Einstein proposed a variation of the previous thought experiment to Bohr. Take a photon in a box, then open it and let the photon travel far away. The photon is in a superposition of energy states. However, by measuring the box's weight, one collapses the photon's energy state into one of them thereby violating locality, given that the photon is far away from the box. Bohr however again misunderstood the argument as having to do with the uncertainty relation,[26] and the legend says that the day after he triumphantly provided a reply to Einstein in which he used Einstein's own theory of relativity against him, inflicting him with a burning and embarrassing defeat. In reality, however, they were talking past one another, as Einstein's point had not much to do with the uncertainty relations but was about the nonlocality of the theory.[27]

In a 1935 letter to Schrödinger before the cat paper, Einstein considers another experiment in which there is a box filled with a wavefunction. By inserting a partition, the box is divided into two halves, thereby splitting also the wavefunction inside. These boxes are separated in opposite directions and one of them is opened when they are far away from one another. By opening one, the content of the other object is instantly affected, again violating locality.[28]

Furthermore, the 1935 Einstein, Podolsky and Rosen (EPR) paper was designed as an incompleteness argument. EPR argued that if quantum theory were complete, then an experiment on one component of a pair of entangled particles travelling in opposite directions would instantaneously determine the state of the other component of the pair, regardless of their mutual distance. This is because, according to quantum theory, before the experiment each system has no property. Each acquire one only after an experiment is performed in the other system. However, this again violates locality. So, EPR argue, the

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[23] See Bacciagaluppi and Valentini (2009), p. 440. Einstein anticipated this argument already in 1909 at a meeting in Salzburg (Bacciagaluppi and Valentini 2009, p. 198). Moreover, Schrödinger begins his 1935 cat paper presenting an example very similar to this one. Take a radioactive source which could emit particles, one at a time, in all directions. If the description provided by the wavefunction is complete, and the wavefunction evolves according to the Schrödinger equation, then the particle will be detected in all the directions at the same time, which is not what happens. So, again, either the theory is incomplete, or it is nonlocal.

[24] See Bohr (1949) for a recollection of Einstein's argument. Bohr's misunderstanding could come from the way the argument was phrased by Einstein, as he emphasized that when the particle passes through the slit its position is determined but its momentum is completely spread out. Perhaps, the argument could have been less prone to misunderstanding had Einstein not mentioned the momentum at all, as I did in my reconstruction.

[25] He considered an experiment in which a wave packet is split by a half-silvered mirror into a reflected and transmitted packet which travel to far-separated regions. If the reflected packet is detected then the other has to immediately disappear, violating locality (Heisenberg 1949, p.39).

[26] Again, this has to do to the fact that Einstein worded his thought experiment in term of the time-energy uncertainty relation: you could either measure the energy or the time with arbitrary precision.

[27] This is how this argument has been reconstructed by Howard (2007). See also Nikolić (2012).

[28] Einstein to Schrödinger, June 19, 1935, in Fine (1986), p. 35.

only option is to admit that the theory is incomplete: there have to be 'hidden' variable, unspecified by quantum theory, which represent the pre-existing (i.e. existing before the experiment) properties that the particles possess at all times and which are revealed, rather than created, by the experiment. Nonetheless, as in the case of the previous attempts, the point of the argument was completely misunderstood by Bohr,[29] and Einstein kept being painted by the growing Copenhagen school as the stubborn, old scientist who could not accept the revolutionary character of the quantum. He was uncharitably and unfairly considered as part of the old guard who could not let go of his ancient ways of thinking.

4.4. Proofs against the Possibility of a Quantum Reductive Schema

There were also more legitimate reasons to discard the project of completing quantum theory in terms of hidden variables. Theorems were proposed to prove that this program cannot be carried out. Most notably in 1932 von Neumann claimed to have shown that these hidden variables are impossible. He started by assuming that the preexisting properties mentioned by EPR exist, and that they are revealed by experiments in terms of eigenvalues of operators. Then he showed that, under what he thought to be reasonable assumptions, these properties have to stand into mathematically contradictory relations. Therefore, he concluded that we cannot think of quantum theory as providing the type of reductive understanding we had in classical physics.

It turned out that von Neuman's proof was not sound, because some of the assumptions were not physical. In addition, the theorems that came later on which did not use that assumption were instead relying on the idea that making an experiment on a system does not significantly change it. Instead, in general the interaction will be sufficient to disrupt the system so much that the experimental results are not the values of the properties before the experiment. In other words, these theories do not prove that hidden variables are impossible, but rather that experiments may often measure nothing of the system. However, Grete Hermann, who in 1933 quickly pointed out the problems in von Neumann's proof, at the time was ignored.[30] Also Einstein in 1938 dismissed the proof as unphysical but never wrote anything about it.[31] Only later more people became aware fo the problem, when Bell exposed the mistake in 1964 (see section 4.8).

Since everyone at the time accepted this proof, especially coming from a living legend like him, von Neumann effectively gave the final blow to the proposals to complete quantum theory. The logic of inevitability seemed to have finally found a conclusion: we cannot do better than what the Copenhagen school is offering us. Von Neumann's proof forces us to give up our dream of reductive quantum explanation.

4.5. The Measurement Problem against Quantum Theory

The arguments against the completeness of quantum theory became weaker and weaker. First, the argument for a three-dimensional ontology to preserve the reductive schema was ineffective, due to the positivist commitments of the Copenhagen school that led them to consider this type of explanation misguided because based on unobservable entities. Then, nonlocality arguments were put forward to show that at least the theory needs something more, otherwise locality is lost. But again, these arguments were impotent, even when understood, because a nonlocal quantum theory does not violate

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[29] The EPR argument was formulated in terms of measurements of position and momentum.

[30] Hermann (1933, 1935). See also Bacciagaluppi and Crull (2016).

[31] Shimony (1993).

relativity when understood according to the Copenhagen instrumentalism as a theory of signals. So, the last resort was to focus on what the instrumentalists seemed to care about, namely experimental results, to show that quantum theory is not empirically adequate. This is what the 1935 Schrödinger cat paper is about. Schrödinger imagined a cat in a box, where a vial of poison is connected with a radioactive nucleus. If the nucleus decays, the vial is broken and the cat dies, otherwise nothing happens. If the nucleus is in a superposition state of 'decayed' and 'not decayed,' then, due to the linear evolution of the wavefunction describing every physical system, the superposition propagates macroscopically into a 'living' and 'dead' cat superposition. However, when we open the box, the cat is either alive or dead. We never observe such macroscopic superpositions.[32] This argument therefore pointed out that the theory is not empirically adequate. This problem is also called the measurement problem: a Schrödinger evolving wavefunction which completely describe physical systems will predict all experimental outcomes to suitably realize at the same time, which is not what is observed.

However, this argument failed too, as von Neumann in 1932 provided an answer to it: he postulated that the wavefunction evolves according to the Schrödinger equation unless a measurement is performed. When that happens, the wavefunction spontaneously and randomly collapses into one of the terms of the superpositions.[33] This collapse is nonlocal, but so be it: as Heisenberg pointed out, this nonlocality cannot be used to send signals. So, Copenhagen won once again, and these problems were substantially ignored until the 1950s, when people started to question that the theory did not have a unified dynamics (see section 4.9).

In any case, the war came along, and it helped in forgetting these problems: the war put on hold many collaborations, conferences, and discussions, and pushed for technological results over conceptual ones. So, everyone ended up following along the mainstream Copenhagen vision without too many questions.

4.6. Bohm's Rediscovery of de Broglie's Beginning of a Reductive Theory

Slowly, things got back to normal in the 1950s. After having written a textbook in quantum theory, Bohm (1952) started to think harder about the theory and rediscovered de Broglie's work, expanding it: while he was at Princeton he proposed a theory in which particles evolve according to an equation defined in terms of a Schrödinger evolving wavefunction. He developed his theory as a microscopic and reductive understanding of quantum mechanics, not as a solution of the measurement problem. He wrote Newton's equation of motion and showed that one can reproduce the quantum predictions if one adds a quantum potential, which is written in terms of a Schrödinger evolving wavefunction.

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[32] In the weeks that preceded the publication of the cat paper, in a letter to Schrödinger, Einstein discusses an example in which there is a substance which may spontaneously combust. If it does combust, it makes some gunpowder explode, otherwise nothing happens. The substance microscopic superposition 'combust' and 'not combust' is amplified macroscopically into a superposition of 'explosion' and 'not explosion,' which is not observed. He wrote: "The system is a substance in chemically unstable equilibrium, perhaps a charge of gunpowder that, by means of intrinsic forces, can spontaneously combust, and where the average life span of the whole setup is a year. In principle this can quite easily be represented quantum-mechanically. In the beginning the ψ-function characterizes a reasonably well-defined macroscopic state. But, according to your equation, after the course of a year this is no longer the case at all. Rather, the ψ-function then describes a sort of blend of not-yet and of already-exploded systems." In A. Fine (1986). This is remarkably similar to the argument proposed by Schrödinger few months later.

[33] Von Neumann (1932), chapters V ad VI, pp. 184-237 of the 1932 German version and pp. 347-445 of the 1955 English translation. Reprinted in Wheeler and Zurek (2003): 549-647.

In this theory the wavefunction never collapses but there are no macroscopic superpositions. In fact, matter is made of particles, and the only term of the wavefunction that effectively guides their motion is the one under which the particles are, so that we can forget, for all practical purposes, the other terms.

Bohm was encouraged by Einstein to pursue this theory, but effectively ostracized by everybody else because he dared to put the Copenhagen dogma into doubt. Moreover, his sympathies towards communism got him exiled in Brazil, without a passport, so he could not even travel to defend his theory from the Copenhagen attacks. After few years mostly spent in exile, he effectively stopped defending his theory.

Einstein, while initially supportive of Bohm, did not like the explicit nonlocality of the theory. Also, he did not like the fact that later on Bohm proposed it as a theory of a field in configuration space,[34] which Einstein thought did not make any physical sense. So he got convinced that quantum theory had to be completely changed rather than supplemented: he wanted to keep both locality (because of relativity) and three-dimensionality of the ontology (because of reductionism), and there was no proposal for a constructive theory which was also local.

4.7. Contextuality of the de Broglie-Bohm Theory

Most people dismissed the theory: there had to be something wrong with it, because von Neumann proved that what he did was impossible. Even those who accepted that the theory could get around the impossibility proofs, thought that it could do it at great cost, namely postulating contextual properties. That is, when we think of a property of a system we think of it as some sort of timeless characterization: the spin along direction x is 'up,' and that is what it is. If we set up an experiment to measure such a property, the experiment is supposed to give us its value. If we repeat it after we have measured another property, say its spin under another direction, it should give us the same value as before. Instead, people thought, in the de Broglie-Bohm theory the properties depend of the context: if we measure spin along x, then its value changes depending on whether we measure it after we have measured the spin along another direction. But what kind of properties are these? This contextuality of the de Broglie-Bohm theory was taken as a disadvantage of the theory, as an indication that if we want to think in terms of some microscopic picture, then we end up with weird properties.

However, as Bohm himself explained in his 1952 paper but it is still today not enough appreciated, his theory does not fall prey of the impossibility proof not because it has contextual properties but because experiments change the system in accordance with Heisenberg's uncertainty principle (when properly understood): when an experiment is performed on a system, it may end up changing the system, so that if another experiment is performed, one should not necessarily expect to find as a result the value of the property it had at the very beginning.

4.8. Bell on the Impossibility Proofs and Bell's Theorem

After having seen Bohm 'doing the impossible' (namely avoiding the impossibility poofs) Bell proved the impossibility proofs assumed mistakenly that one can measure properties without modifying the system.[35] The de Broglie-Bohm theory assumes that experimental apparatuses may change the system,

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[34] See Bohm (1980).

[35] Bell (1966). This paper was written however in 1964.

so it can complete quantum theory bypassing these proofs. However, as anticipated, the theory is nonlocal. So, Bell started to wonder whether one could otherwise complete quantum theory while also preserving locality, like Einstein would have wanted. Thus, in 1964 Bell picked up where the EPR argument has stopped: the perfect correlations observed in entangled systems can only be locally explained by the existence of preexisting values. By assuming that these values exist, Bell derived an inequality which holds for his theory but not for quantum mechanics, and that can therefore be used as a crucial test. As we have seen, this test was later performed confirming the quantum mechanical predictions.

From this Bell wanted to argue that any theory which matches the quantum predictions had to be nonlocal. However, most people thought he proved that hidden variables as predicted by Einstein (local or not) are impossible, and took Bell to have provided another impossibility proof, similar to the one of von Neumann. This was true, in the sense that experiments do no reveal preexisting properties, but this is not what Bell wanted to prove, for one thing because he already knew that. Rather, he wanted to prove that you have to have nonlocality to reproduce the quantum predictions. However, it surely did not help to get the point across that he started from EPR, which included the assumption that experiments can reveal (preexisting) properties of the system. In fact, he knew was this assumption was false (indeed, this is what he himself said von Neumann got wrong in his impossibility proof), while others still took it seriously. Nevertheless, to remedy to this confusion, later Bell reformulated his inequality without passing from EPR, therefore without assuming that there are any preexisting properties, and only assuming the locality condition.[36] This shows that any theory that matches the quantum mechanical predictions has to be nonlocal. Nonetheless, for a variety of reasons, controversies are still open about what Bell did or did not prove.[37]

4.9. The Other Solutions of the Measurement Problem

The research on the meaning of quantum theory barely continued in an organized way after Bohm was ostracized. While Bohm wished to provide a reductive understanding of the quantum phenomena, but was shut down by the impossibility proofs, starting from the late 1950s, the attention of those isolated people still interested in understating the theory slowly started to shift from the problem of suitably completing quantum theory to get a microscopic description, to solving the measurement problem. Some researchers started to question the orthodoxy, which now included von Neumann's collapse postulate, not in virtue of its non-three-dimensional ontology or its nonlocality, but from within the dogma. For instance, Everett, a student at Princeton, started from the measurement problem and argued that the von Neumann collapse was unsatisfactory: what is a measurement, after all? In contrast with Schrödinger, Einstein, de Broglie and Bohm, he was not motivated by realism. Rather he was bothered by the imprecision of the von Neuman formulation and the inconsistency of applicability of the theory. He thus proposed, in his 1957 dissertation, an original way to make sense of macroscopic superpositions: he postulated that the various terms of the superposition express relative states of affair of an observer. One could think of the wavefunction as splitting into different worlds, one for each term of the superpositions. Naively Wheeler, his advisor, enthusiastically discussed this idea with Bohr, who instead did not react well, and ultimately helped destroying Everett's career, who abandoned academia for military research. Feynman, who heard about this theory from Wheeler,

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[36] Bell (1975).

[37] For discussion, see Gao and Bell (2016).

found the many-worlds idea preposterous.[38] The whole idea was forgotten for years by everyone except DeWitt, a cosmologist friend of Wheeler, who in 1970 published a paper on quantum theory and reality. This soon followed by the DeWitt and Graham book on many-worlds (1973), in which they address the problem of cosmology: where is the observer if the system is the universe? In 1985 Deutsch, who had attended an Everett lecture in 1977, published a paper on quantum computing, arguing that one could make sense of the reason why quantum computers are faster than classical ones, only assuming that there is a world for each branch of the wavefunction where the calculations happen. The many-world theory, not adding anything to the standard theory, unlike Bohm's, and not modifying the Schrödinger equation (like collapse theories, see below), seemed to many as the best compromise among the solutions of the measurement problem (if one forgets about the inflated metaphysics, that is). Because of this, it slowly grew in the sympathies of physicists. In particular it became popular among cosmologists, who already realized that the Copenhagen view was inadequate (who's the observer collapsing the universe as a whole?), and for people working on computation, after Deutsch's results on quantum computers. The many-worlds theory had the problem to show that the different worlds do not interact with one another, otherwise we would observe interference between them. Decoherence theory, which started being developed by Zeh (1970), provided an answer: physical systems, by interacting with their environment, lose coherence, and therefore their ability to interfere with themselves.

The measurement problem was also mentioned by Wigner (1961, 1963), who thought that the von Neumann collapse was real, and that it was triggered by consciousness, and Rosenfeld, Bohr's faithful soldier, immediately attacked.

In the 1970s, the first tests of Bell's inequality started to be performed, with confirmation of the violation of Bell's inequality in 1982. Moreover, the first conferences on quantum foundations were being held, all focusing on the measurement problems (1970 in Varenna, 1973 in Erice).

In the same period, people started criticizing the von Neumann collapse postulate because of the introduction of two fundamental evolutionary laws. Accordingly, new projects begun to incorporate the collapse process into the dynamical equation of the wavefunction, to provide a unified dynamics of the macroscopic and the microscopic. The spirit of this work was more similar to Everett's approach rather than the one of Einstein, Schrödinger, de Broglie, and Bohm, in the sense that this project did not focus on the ontology (so the problem was not the high dimensional wavefunction) or on the nonlocality of the collapse. Rather, these people wanted to make the Copenhagen recipe precise. Unlike Everett, however, they did not want to introduce many-worlds in the process. This project culminated in the 1980s in the dynamical collapse models of Ghirardi, Rimini and Weber (1986). In this theory, the wavefunction evolves according to a stochastic nonlinear equation so that it collapses at random times, into random places with a frequency that depends on how big the system is, so that macroscopic objects collapse almost instantly.

After their proposal, Bell started to advertise the idea that there are three ways of making realist sense of quantum theory, legitimizing the many-worlds theory and the dynamical collapse models: assuming measurements have results, "either the wavefunction, as given by the Schrödinger equation, is not everything, or it is not right" (Bell 1987).

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[38] See Becker (2018).

This is the story as we know it. Most researchers who found themselves wondering about the meaning of quantum theory ended up looking at the measurement problem, and took the de Broglie-Bohm theory, the Everettian many-worlds theory and the theory of dynamical collapse as equally plausible ways of making sense of quantum theory, each with their own pros and cons. For instance, the de Broglie-Bohm theory is often said to have the problem of being nonlocal, the many-worlds theory has the problem of probabilities, and the spontaneous collapse theory seems *ad hoc.*

In any case, given that all these theories have the wavefunction in it, it became natural to think of it as the fundamental ontology of the theory, embracing what was initially thought to be impossible: a high-dimensional ontology. One could argue that this is the straightforward way of interpreting these theories: they all have an equation for the temporal evolution of the wavefunction, so the wavefunction is the fundamental ontology, just like when we look at Newton's second law and we infer that this is a theory of particles.[39] Otherwise, one could argue that this is the only way to make the theory local again, even if in configuration space: Bell showed that the reality is nonlocal, but if we have an ontology in configuration space, we can still have that type of locality.[40] At any rate, this view has grown in popularity and now goes under the name of wavefunction realism. This growing field contributed to put even more bad light on the de Broglie-Bohm theory, because it does not fit the schema: if one sees the theory as having a wavefunction ontology living in a high dimensional space, one has to either postulate that there is also a three-dimensional space in which particles live, or that there is only one particle living in the same space of the wavefunction. In both cases, the picture of the theory provides of the world is extremely revisionary and it makes it seems like the presence of the particles is unnecessary: why postulate the particles, if you can do without, like in the many-worlds theory?[41] The point, however, is that you cannot do without particles, if you care about having a reductive explanation of the phenomena. But it is easy to miss this point if one focuses on solving the measurement problem.

5. The Measurement Problem is a Red Herring

Which argument should the realist have looked at instead? I have argued that the natural thing to look at would have been the unphysical field problem: if the ontology is not in three-dimensional space, then one cannot preserve the reductive schema. In this section, let's see how the various arguments for incompleteness discussed above are distinct in what they are asking. As we have seen, three of such arguments were proposed:

1) Unphysical field arguments (section 4.2): Quantum mechanics is incomplete otherwise reductionism is false (because there's nothing moving in three-dimensional space);
2) Nonlocality arguments (section 4.3): Quantum mechanics is incomplete otherwise relativity is false (because quantum theory is nonlocal);
3) Macroscopic superpositions arguments (that is, the measurement problem, section 4.5): Quantum mechanics is incomplete otherwise it is empirically inadequate (because it predicts unobserved macroscopic superpositions).

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[39] Albert (1996).

[40] Ney (2021).

[41] Brown and Wallace (2005).

As discussed, these arguments against the Copenhagen dogma were systematically ignored (like the physical field problem), or misunderstood (like the nonlocality problems). Ironically, as I have argued, the only argument that received attention later, namely the measurement problem, was only proposed as a last resort to convince the positivists that their theory was empirically inadequate.

The unphysical field problem is the strongest of these arguments. It was proposed to show that one needs to complete the theory with a three-dimensional ontology if we wish to preserve the reductive schema of explanation. And why should we abandon such schema, if we do not need to? So, this argument states that the wavefunction should not be interpreted as a physical field vibrating in space. The nonlocality arguments focus on the fact that if one does not complete quantum theory one way or the other then locality is lost. While the first argument tells us what to do (add a three-dimensional ontology), the locality argument does not tell how to complete the theory: it merely tells us that it needs to be done. Presumably, this drift is due to the fact that the members of Copenhagen school cared less about the microscopic description and more about the results. However, as mentioned already, Heisenberg did not worry about nonlocality conflicting with relativity. So, the last attempt was in 1935, when the incompleteness argument was formulated in macroscopic terms, the only terms positivists would care about: if quantum mechanics were complete, then there would be unobserved macroscopic superpositions. The measurement problem is the problem of empirical adequacy of the theory: one needs to suppress these superpositions, regardless of whether the theory is local or not, regardless whether one completes it with a three-dimensional ontology or not.

So, among all three, the measurement problem is the weakest of the problems a realist needs to solve. Indeed, it allows for *ad hoc*, nonlocal, imprecise solutions like the von Neumann collapse rule. Why should realists be bothered by such a problem? Rather, realists should care about having a three-dimensional ontology from which they can build a reductive schema, and then the problem becomes to find the correct ontology. The natural choice would be between particles and fields, like people had done since then. Take a field ontology, like Schrödinger's charge density proposal. Even assuming one can control the field packet's spreading through decoherence, the theory shows unobserved macroscopic (three-dimensional) superpositions. It is as if one postulates that matter is a wave, but then the expected interference is not observed. What should one conclude? One option is admitting of being wrong, and concede that matter is not a field. So, the best way to solve this problem is by adding particles, which is exactly what the de Broglie Bohm pilot-wave theory does. The second option is being stubborn: insist that matter is a field and adopt a many-worlds picture to account for the fact that macroscopic superpositions are not observed, even if they exist. That is, each term of the superpositions exists but they are in different worlds which do not interact. However, this second option seems completely *ad hoc* and unnecessary: the first option (particles) is much simpler, more sensible, and less revisionary. Before the advent of the quantum weirdness, no one would have dared to propose anything like that. Moreover, in contrast with the second option, the first option allows for the reductive schema. The goal of Schrödinger and Einstein was to find the corresponding constructive theory to explain quantum theory, seen as a principle theory. They were looking for the corresponding 'statistical mechanics' for quantum theory. This is what the first option provides. Instead, the many-worlds theory provides a principle theory like the standard theory, but perhaps even more complex, as the principles apply to unobserved and unobservable worlds. What is the advantage of doing that?

Are there other alternatives? Not really, if we care about the reductive schema. The other option proposed to solve the measurement problem is to modify the Schrödinger equation (stochastically and nonlinearly). This provides a more elegant, and unified principle theory, but not a constructive theory. If one looks for one in this context, one would have to add a three-dimensional ontology to the spontaneous localization dynamics. But what would be the point of complicating the wavefunction evolution, if one can obtain the same result with the Schrödinger evolution?

Needless to say, if someone thinks the collapse of the wavefunction is not a physical process (like in Bohm and Everett) or it is dynamical (like in collapse models), there is no reason to think physics needs consciousness to provide a complete description of reality.

So, I argue, by focusing on the measurement problem, namely the problem of suppressing unobserved macroscopic superpositions, one is giving too much credit to ideas that would have never been considered, had history been different. Realists should have focused on preserving the reductive schema, to the extent that it was possible. Thus, for this reason in the 1920s people argued that quantum theory needed a three-dimensional ontology. In this framework, the idea of a wavefunction ontology would have been dead since then, and together with it the many-worlds theory and the spontaneous collapse model, with the pilot-wave theory as the only surviving proposal. Perhaps further natural developments would have been to try to eliminate the wavefunction from a particle theory, as Norsen is proposing (2010), or to make progress in de Broglie's double solution program for a wave ontology.[42]

6. Nonlocality and , Reductive Explanation and Relativity

To conclude, let me notice that the locality argument discussed above asks us to complete the theory in a local way. However, Bell showed that we cannot have that: nature is nonlocal, and the pilot-wave theory embraces this nonlocality in the most straightforward way. So, we can keep reductionism and the classical explanatory schema in terms of three-dimensional entities moving around and composing macroscopic bodies. However, there are nonlocal correlations between these entities. As we have briefly mentioned, this creates a true conflict with the theory of relativity, understood as a theory about reality rather than signals.

However, one should not think that we can do better: nonlocality is a fact of nature, and all quantum theories are nonlocal. At least, this is the case unless one assumption in Bell's proof is incorrect. What I have in mind is the so-called hypothesis of statistical independence, according to which, roughly, one does not influence the properties of a system by choosing what one decides to measure. Intuitively this assumption seems necessary to do science: scientists want to check some correlations, like eating chocolate makes you gain weight, and thus they randomly select who eats chocolate and who doesn't, and then they observe what happens. They assume that the result of someone gaining weight is due to the correlation between eating chocolate and gaining weight. Assuming statistical independence means this: the choice of the sample has no influence on the result. In fact, assume it did. Then it would mean that not only all those who ate chocolate would gain weight but also that they were predetermined to be in the sample of people eating chocolate. Eating chocolate people had to be selected into the chocolate eating set, and it could not have been otherwise. However, that means that one learns nothing from experiments. One never has confirmation that it is a law that 'everyone eating chocolate gains weight.' Every time one thinks of having an instance of this law this is actually a conspiracy of the initial conditions that were so disposed as to give the result one would expect if the law

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[42] For a summary of the status of the double solution program, see Colin, Durt, Willox (2017).

was true. Instead, these results are not really evidence for it. Allowing for such superdeterministic correlation has been taken as a viable way out from the nonlocality conclusion by some.[43] Others have instead explored the possibility of retro-causality, where what happens later influence what happens earlier on.[44] Whether these options are really to be preferred to nonlocality is controversial and I will not attempt to discuss them here. However, if we look at these possibilities from the perspective of the realist which I have described in this paper, namely someone who would look for the simplest explanation in terms of a three-dimensional ontology which would reserve reductive explanation, they hardly seem more acceptable than nonlocality.

In any case, I think that the result of Bell's theorem is the true quantum revolution: not the paradigm shift in terms of the type of understating one can achieve, but a new feature of the world. The natural question then is how to combine quantum nonlocality with relativity.

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[43] See. e.g., Hossenfelder and Palmer (2019). For a discussion, see Chen (2022).

[44] For a discussion, see Norsen and Price (2021).

References

- Aharonov, Yakir, David Z. Albert, Lev Vaidman (1988): "How the Result of a Measurement of a Component of the Spin of a Spin-1/2 Particle Can Turn Out to be 100," *Physical Review Letters* 60: 1351.
- Albert, David Z. (1996): “Elementary Quantum Metaphysics,” In: J. Cushing, A. Fine, and S. Goldstein (eds.), *Bohmian Mechanics and Quantum Theory: An Appraisal*: 277-284. Kluwer.
- Aspect, Alain, Jean Dalibard, & Gérard Roger (1982): “Experimental Test of Bell’s Inequalities Using Time-Varying Analyzers.” *Physical Review Letters* 49: 1804-1807.
- Aspect, Alain, Philippe Grangier, & Gérard Roger (1982): “Experimental Realization of Einstein-Podolsky-Rosen-Bohm Gedankenexperiment: A New Violation of Bell's Inequalities,” *Physical Review Letters* 49 (2): 91–4.
- Bacciagaluppi, Guido, and Elise Crull (2016): *Grete Hermann - Between Physics and Philosophy*. Springer.
- Bacciagaluppi, Guido, and Antony Valentini (2009): *Quantum Theory at the Crossroads: Reconsidering the 1927 Solvay Conference*. Cambridge: Cambridge University Press.
- Becker, Adam (2018): *What Is Real? The Unfinished Quest for the Meaning of Quantum Physics*. New York: Basic Books.
- Bell, John S. (1964): “On the Einstein Podolsky Rosen Paradox.” *Physics* 1: 195–200. Reprinted as Ch. 2 in *Speakable and Unspeakable in Quantum Mechanics*. Cambridge: Cambridge University Press (1987).
  (written in 64 published in 66, reprinted as ch 1 “On the problem of HV in QM” in the Speakable Unspeakable book
- Bell, John S. (1966): “On the Problem of Hidden Variables in Quantum Theory.” Review of Modern Physics 38: 447-52. Reprinted as Ch. 1 in *Speakable and Unspeakable in Quantum Mechanics*. Cambridge: Cambridge University Press (1987).
- Bell, John S. (1975): “The Theory of Local Beables,” TH-2053-CERN, 1975 July 28. Reprinted in *Epistemological Letters* 9 (17): 11-24 (1976), in *Dialectica* 39: 86 (1980) and as Ch. 7 in *Speakable and Unspeakable in Quantum Mechanics*. Cambridge: Cambridge University Press (1987).
- Bell, John S. (1982): “On the Impossible Pilot Wave,” *Foundations of Physics* 12: 98-99. Reprinted as Ch. 17 of *Speakable and Unspeakable in Quantum Mechanics*. Cambridge: Cambridge University Press (1987).
- Bell, John S. (1987): “Are There Quantum Jumps?” In: C.W. Kilmister (ed.) *Schrödinger. Centenary Celebration of a Polymath*: 41–52. Cambridge: Cambridge University Press. Reprinted as Ch. 22 in *Speakable and Unspeakable in Quantum Mechanics*. Cambridge: Cambridge University Press (1987).
- Beller, Mara (1999): *Quantum Dialogue: The Making of a Revolution*. Chicago: University of Chicago Press.
- Belousek, Daniel (1996): “Einstein's 1927 Unpublished Hidden-variable Theory: Its Background, Context and Significance” Studies in History and Philosophy of Modern Physics 27(4): 437-461.
- Bloch, Felix (1976): “Heisenberg and the Early Days of Quantum Mechanics,” *Physics Today* 29 (12): 23-27.
- Bohm, David (1952): “A Suggested Interpretation of the Quantum Theory in Terms of “Hidden” Variables” I and II, *Physical Review* 85: 166-193. Reprinted in: J.A. Wheeler and W.H. Zurek (eds) (1983): *Quantum Theory and Measurement*: 356-396. Princeton: Princeton University Press.
- Bohm, David (1980): *Wholeness and the Implicate Order*. Routledge.

- Bohr, Niels (1928): “The Quantum Postulate and the Recent Development of Atomic Theory,” *Nature* 121 (suppl.): 580 -90. Reprinted in: J.A. Wheeler and W.H. Zurek (eds) (1983) *Quantum Theory and Measurement*: 87-126. Princeton: Princeton University Press.
- Bohr, Niels (1949): “Discussion with Einstein on Epistemological Problems in Atomic Physics.” In: P.A. Schilpp (ed.) *Albert Einstein: Philosopher-Scientist, vol. 1.*
- Born, Max (1926): “Zur Quantenmechanik der Stoßvorgänge,” *Zeitschrift für Physik* 37 (12): 863–867. English translation, “On the Quantum Mechanics of Collision Processes.” In J.A. Wheeler and W.H. Zurek (eds) (1983): *Quantum Theory and Measurement*: 52–61. Princeton: Princeton University Press.
- Born, Max, Werner Heisenberg, and Pascual Jordan (1926): “Zur Quantenmechanik, II” *Zeitschrift für Physik* 35: 557–615. English translation, “On Quantum Mechanics II,” In: B. L. van der Waerden (ed.) *Sources of Quantum Mechanics*: 321-386. Amsterdam: North-Holland Publishing (1968).
- Bricmont, Jean (2016): *Making Sense of Quantum Mechanics*. Springer.
- Brown, Harvey R., and David M. Wallace (2005): “Solving the Measurement Problem: de Broglie–Bohm Loses Out to Everett,” *Foundations of Physics* 35: 517–540.
- Chen, Eddy K. (2021): “Bell’s Theorem, Quantum Probabilities, and Superdeterminism.” In: E. Knox and A. Wilson (eds.), *The Routledge Companion to Philosophy of Physics*, Routledge.
- Clauser, John F., Michael A. Horne, Abner Shimony, and Richard Holt (1969): “Proposed Experiment to Test Local Hidden-Variable Theories.” *Physical Review Letters* 23 (15): 880–884.
- Colin, Samuel, Thomas Durt, Ralph Willox (2017): “De Broglie's Double Solution Program: 90 Years Later.” *Annales de la Fondation Louis de Broglie* 42(1): 19-27.
- Cushing, James T. (1994): *Quantum Mechanics: Historical Contingency and the Copenhagen Hegemony*. Chicago: University of Chicago Press.
- de Broglie, Louis (1924): *Recherches sur la théorie des quanta*. Ph.D. Thesis, Université de Paris. *Annals de Physique* (10) 3: 22-128 (1925). English translation, L. de Broglie (2004): “On the Theory of Quanta,” *Foundation of Louis de Broglie* ed.
- Deutsch, David (1985): “Quantum Theory, the Church-Turing Principle, and the Universal Quantum Computer.” *Proceedings of the Royal Society of London* A 400: 97–117.
- DeWitt, Bryce S. (1970): “Quantum Mechanics and Reality.” *Physics Today* 23 (9): 30–35.
- DeWitt, Bryce S., and Neil Graham (1973): The Many-Worlds Interpretation of Quantum Mechanics. Princeton: Princeton University press.
- Dürr, Detlef, Sheldon Goldstein, and Nino Zanghí (1992): “Quantum Equilibrium and the Origin of Absolute Uncertainty,” *Journal of Statistical Physics* 67: 843–907.
- Einstein, Albert (1905)” “Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt” (On a Heuristic Point of View about the Creation and Conversion of Light). *Annalen der Physik* 17 (6): 132–148. English translation, in: D. Ter Haas (ed.) *The Old Quantum Theory*: 91-107. Pergamon Press (1967).
- Einstein, Albert (1919): *What is the Theory of Relativity?* The London Times. Reprinted in A. Einstein (1982): *Ideas and Opinions*: 227-232. New York: Crown Publishers, Inc..
- Einstein, Albert (1953): ““Elementare überlegungen zur Interpretation der Grundlagen der Quanten-Mechanik.” In: *Scientific Papers Presented to Max Born on his retirement from the Tait Chair on Natural Philosophy in the University of Edinburgh*: 33–40. Edinburgh: Oliver and Boyd. English translation, “Elementary Considerations on the Interpretation of the Foundations of Quantum Mechanics,” https://arxiv.org/abs/1107.3701

- Einstein, Albert, Boris Podolsky, and Nathan Rosen (1935): "Can Quantum-mechanical Description of Physical Reality be Considered Complete?" *Physical Review* 47: 777–780. Reprinted in: J.A. Wheeler and W.H. Zurek (eds) (1983) *Quantum Theory and Measurement*: 138-143. Princeton: Princeton University Press.
- Everett, Hugh III (1957): "Relative State Formulation of Quantum Mechanics," *Review of Modern Physics* 29, 454-462. Reprinted in: J.A. Wheeler and W.H. Zurek (eds) (1983) *Quantum Theory and Measurement*: 315-323. Princeton: Princeton University Press.
- Fine, Arthur (1986): *The Shaky Game: Einstein, Realism and the Quantum Theory.* Chicago: University of Chicago Press.
- Freedman, Stuart J. and John F. Clauser (1972). "Experimental Test of Local Hidden-Variable Theories" Physical *Review Letters* 28 (938): 938–941.
- Gao, Shan, and Mary Bell (eds.). 2016. *Quantum Nonlocality and Reality**:** 50 Years of Bell's Theorem*. Cambridge University Press.
- Ghirardi, GianCarlo, Alberto Rimini, and Tullio Weber (1986): "Unified Dynamics for Microscopic and Macroscopic Systems," *Physical Review* D: 34: 470.
- Gleason, Andrew M. (1957): "Measures on the Closed Subspaces of a Hilbert Space," *Indiana University Mathematics Journal* 6 (4): 885–893.
- Heisenberg, Werner (1927): "Ueber den anschaulichen Inhalt der quantentheoretischen Kinematik and Mechanik," *Zeitschrift für Physik* 43: 172–198. English translation, "The Physical Content of Quantum Kinematics and Mechanics." In J.A. Wheeler and W.H. Zurek (eds) (1983): *Quantum Theory and Measurement*: 62–84. Princeton: Princeton University Press.
- Heisenberg, Werner (1949): *The Physical Principles of the Quantum Theory*. New York: Dover.
- Hermann, Grete (1933): "Determinismus und Quantenmechanik," manuscript. Dirac Archives DRAC 3/11.
- Hermann, Grete (1935): "Die naturphilosophischen Grundlagen der Quantenmechanik." *Abhandlugen der Fries'schen Schule* 6(2):75–152.
- Holland, Peter (2005): "What's Wrong with Einstein's 1927 Hid-den-Variable Interpretation of Quantum Mechanics?" *Foundations of Physics* 35 (2): 177–196.
- Hossenfelder, Sabine, and Tim Palmer (2019). "Rethinking Superdeterminism." arXiv preprint-arXiv:1912.06462.
- Howard, Don (1990): "'Nicht sein kann was nicht sein darf,' Or the prehistory of EPR, 1909–1935." In: A.I. Miller (ed.) *Sixty-Two Years of Uncertainty*: 61–111. New York: Plenum.
- Howard, Don (2004): "Who Invented the 'Copenhagen Interpretation'? A Study in Mythology." *Philosophy of Science* 71: 669–682.
- Howard, Don (2007): "Revisiting the Einstein-Bohr Dialogue." *Iyyun: The Jerusalem Philosophical Quaterly 56. Special Issue Dedicated to the Memory of Mara Beller*: 57–90.
- Howard, Don (2013): "Quantum Mechanics in Context: Pascual Jordan's 1936 Anschauliche Quantentheorie." In: M. Badino, J. Navarro (eds.) *Research and Pedagogy: A History of Quantum Physics through Its Textbooks*, Ch. 11. Berlin: Edition Open Access.
- Jammer, Max (1974): *The Philosophy of Quantum Mechanics*. New York: Wiley.
- Jauch, Josef M., and Constantin Piron (1963): "Can Hidden Variables be Excluded in Quantum Mechanics?" *Helvetica Physica Acta* 36: 827
- Kochen, Simon, and Ernst Specker (1967): "The Problem of Hidden Variables in Quantum Mechanics." *Journal of Mathematics and Mechanics* 17: 59–87.

- Kocsis, Sacha, Boris Braverman, Sylvain Ravets, Martin J. Stevens, Richard P. Mirin, L Krister Shalm, and Aephraim M. Steinberg (2011): “Observing the Average Trajectories of Single Photons in a Two-Slit Interferometer,” *Science* 332: 1170–1173.
- Ney, Alyssa (2021): *Finding the World in the Wave Function*. New York: Oxford University Press.
- Nikolić, Hrvoje (2012): “EPR before EPR: a 1930 Einstein-Bohr Thought Experiment Revisited.” *European Journal of Physics* 33: 1089–1097.
- Norsen, Travis (2010): “The Theory of (Exclusively) Local Beables.” *Foundations of Physics* 40: 1858–1884.
- Norsen, Travis (2017): *Foundations of Quantum Mechanics: An Exploration of the Physical Meaning of Quantum Theory*, Springer.
- Norsen, Travis, and Huw Price (2021): “Lapsing Quickly into Fatalism: Bell on Backward Causation.” Entropy 23(2): 251.
- Philippidis, Chris, Christopher Dewdney, and Basil J. Hiley (1979): “Quantum Interference and the Quantum Potential II,” *Nuovo Cimento* B 52, 15–28.
- Pusey, Matthew F., Jonathan Barrett, and Terry Rudolph (2012: “On the Reality of the Quantum State.” *Nature Physics* 8: 475-478.
- Przibram, Karl (1967): *Letters on Wave Mechanics*: *Schrödinger, Planck, Einstein, Lorentz*. New York: Philosophical Library.
- Schrödinger, Erwin (1926): “Quantisierung as Eigenwertproblem” (Quantization as an Eigenvalue Problem) *Annalen der Physik* 4 (79): 361–76; 489–527; 80, S.: 437–90; 81, S: 109–40. Reprinted in E. Schrödinger (1927): *Abhandlungen zur Wellenmechanik,* Johann Ambrosius Barth. English translation, E. Schrödinger (1928): *Collected Papers on Wave Mechanics*, Glasgow.
- Schrödinger, Erwin (1935): “Die gegenwärtige situation in der Quantenmechanik,” *Naturwissenschaften* 23 (48): 807–812. English translation, “The Present Situation in Quantum Mechanics," reprinted in: J.A. Wheeler and W.H. Zurek (eds) (1983) *Quantum Theory and Measurement*: 152-167. Princeton: Princeton University Press.
- Shimony, Abner (1993): *The Search for a Naturalistic World View, vol. 1. Scientific Method and Epistemology, vol. 2, Natural Science and Metaphysics*. Cambridge: Cambridge University Press.
- van der Waerden, Bartel L. (ed.) (1968): *Sources of Quantum Mechanics,* North-Holland Publishing, Amsterdam.
- von Neumann, John (1932): *Mathematische Grundlagen der Quantenmechanik*. Berlin: Springer. English translation, *Mathematical Foundations of Quantum Mechanics*. Princeton: Princeton University Press (1955).
- Wigner, Eugene (1961): “Remark on the Mind-Body Question.” In: I. J. Good (ed.), *The Scientist Speculates*: 248-302. Heineman. Reprinted in: Wigner, Eugene (1967): *Symmetries and Reflections*: 171-184. Bloomington: Indiana University Press. Reprinted in: J. A. Wheeler and W.H. Zurek (eds) (1983) *Quantum Theory and Measurement*: 168-181. Princeton: Princeton University Press.
- Wigner, Eugene (1963): “The Problem of Measurement.” American Journal of Physics 31:6-15. Reprinted in: Wigner, Eugene (1967): *Symmetries and Reflections*: 153-170. Bloomington: Indiana University Press. Reprinted in: J.A. Wheeler and W.H. Zurek (eds) (1983) *Quantum Theory and Measurement*: 234-341. Princeton: Princeton University Press.
- Zeh, H. Dieter (1970): “On the Interpretation of Measurement in Quantum Theory.” *Foundations of Physics* 1: 69-76. Reprinted in: J.A. Wheeler and W.H. Zurek (eds) (1983) *Quantum Theory and Measurement*: 342-352. Princeton: Princeton University Press.