

# Beyond the Quantum

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At the 1927 Solvay conference, three different theories of quantum mechanics were presented; however, the physicists present failed to reach a consensus. Today, many fundamental questions about quantum physics remain unanswered. One of the theories presented at the conference was Louis de Broglie's pilot-wave dynamics. This work was subsequently neglected in historical accounts; however, recent studies of de Broglie's original idea have rediscovered a powerful and original theory. In de Broglie's theory, quantum theory emerges as a special subset of a wider physics, which allows non-local signals and violation of the uncertainty principle. Experimental evidence for this new physics might be found in the cosmological-microwave-background anisotropies and with the detection of relic particles with exotic new properties predicted by the theory.

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# 1 Introduction

After some 80 years, the meaning of quantum theory remains as controversial as ever. The theory, as presented in textbooks, involves a human observer performing experiments with microscopic quantum systems using macroscopic classical apparatus. The quantum system is described by a wavefunction – a mathematical object that is used to calculate probabilities but which gives no clear description of the state of reality of a single system. In contrast, the observer and apparatus are described classically and are assumed to have definite states of reality. For example, a pointer on a measuring device will show a particular reading, or a particle detector will ‘fire’ a definite number of times. Quantum systems seem to inhabit a fuzzy, indefinite realm, while our everyday macroscopic world does not, even though the latter is ultimately built from the former.

Quantum theory is formulated as though there is a sharply defined boundary between the quantum and classical domains. But classical physics is only an approximation. Strictly speaking, the classical domain does not even exist. How does everyday reality emerge from the ‘unreal’ quantum domain? What happens to real macroscopic states as we move to smaller scales? In particular, at what point does macroscopic reality give way to microscopic fuzziness? What is really happening inside an atom? Despite the astonishing progress made in high-energy physics and in cosmology since the Second World War, today there is no definite answer to these simple questions. Standard quantum mechanics is successful for practical purposes, but it remains fundamentally ill-defined.

The quantum theory described in textbooks – with an ambiguous boundary between the quantum and classical domains – is known as the ‘Copenhagen interpretation’, named after Niels Bohr’s influential institute in the Danish capital. For much of the 20th century there was a broad consensus that matters of interpretation had been clarified by Bohr and Werner Heisenberg in 1927, and that, despite its apparent peculiarities, the Copenhagen interpretation should simply be accepted. But in the face of the above ambiguities, over the last 30 years or so, that consensus has evaporated and physicists find themselves faced with a plethora of alternative – and radically divergent – interpretations of their most fundamental theory.

Today, some physicists (following in the footsteps of Louis de Broglie in the 1920s and of David Bohm in the 1950s) claim that the wavefunction must be supplemented by ‘hidden variables’ – variables that would completely specify the real state of a quantum system. Others claim that the wavefunction alone should be regarded as a real object, and that when the wavefunction spreads out (as waves tend to do) this means that the system evolves into distinct, parallel copies. The latter view – proposed by Hugh Everett at Princeton University in 1957 – is particularly popular in quantum cosmology: the wavefunction of the universe describes an ever-expanding collection of ‘many worlds’. Other theorists, starting with Philip Pearle from Hamilton College in the US in the 1970s, posit a ‘collapse’ mechanism (perhaps induced by gravity) that makes all but one part of the wavefunction disappear. And some continue to maintain



Figure 1: Louis de Broglie presented his pilot-wave theory at the 1927 Solvay conference in Brussels. Among those present were Einstein, Dirac, Schrödinger, Bohr and Pauli.

that Bohr and Heisenberg were somehow right after all.

Remarkably, today's multiplicity of viewpoints is more or less comparable to how things were at the theory's inception in 1927 ('many worlds' being the main new interpretation since then). In retrospect, the attention given to the 'Copenhagen camp' obscured other points of view, which never went away entirely and which were eventually revived and have become widely known. In particular, at the crucial 1927 Solvay conference in Brussels, no less than three quite distinct theories of quantum physics were presented and discussed on an equal footing: de Broglie's pilot-wave theory, Schrödinger's wave mechanics, and Born and Heisenberg's quantum mechanics.

According to de Broglie's theory, particles (such as electrons) are point-like objects with continuous trajectories 'guided' or choreographed by the wavefunction. From a modern point of view, we would say that the trajectories are 'hidden variables' (because their precise details cannot be seen at the present time). Schrödinger, in sharp contrast, presented a theory in which particles are localized wave packets moving in space that are built entirely out of the wavefunction – a view that is reminiscent of modern theories of wave packet 'collapse' (though Schrödinger did not propose a collapse mechanism). According to Born and Heisenberg, neither picture is correct, and the idea of definite states of reality at the quantum level cannot be maintained in a way that is independent of human observation.

Standard historical accounts are, however, misleading. They say little about de Broglie's theory or about the extensive discussions of it that took place at the 1927 Solvay conference; and the little that is said is mostly mistaken. In effect, de Broglie's theory was essentially written out of the standard history of quantum physics.

It has taken some 80 years for de Broglie's theory to be rediscovered, extended and fully understood. Today we realize that de Broglie's original theory contains within it a new and much wider physics, of which ordinary quantum theory is merely a special case – a radically new physics that might perhaps be within our grasp.

## 2 A tower of Babel

The 'great quantum muddle' can be traced back to 1927 when, contrary to folklore, the participants at the fifth Solvay conference distinctly failed to arrive at a consensus (this is clear from the actual proceedings of the conference). The sheer extent of the disagreement among the participants was captured in a perceptive gesture by Paul Ehrenfest, who, during one of the discussions, wrote the following quotation from the book of Genesis on the blackboard: 'And they said one to another: Go to, let us build us a tower, whose top may reach unto heaven; and let us make us a name. And the Lord said: Go to, let us go down, and there confound their language, that they may not understand one another's speech.'

Like the builders of the Tower of Babel, it was as if the distinguished physicists gathered in Brussels could no longer understand one another's speech.

However, until recently our knowledge of what happened at the conference and in its aftermath came entirely from accounts given by Bohr, Heisenberg and Ehrenfest – accounts that essentially ignore the extensive formal discussions in the published proceedings. Particularly influential was Bohr's famous 1949 essay 'Discussion with Einstein on epistemological problems in atomic physics', published in a *Festschrift* for Einstein's 70th birthday and containing Bohr's account of his discussions with Einstein at the fifth and sixth Solvay conferences – discussions that, according to Bohr, centred on the validity of Heisenberg's uncertainty principle (which prevents simultaneous measurements of position and momentum). However, not a word of such discussions appears in the published proceedings, in which Bohr and Einstein are in fact relatively silent. The famous exchanges between Bohr and Einstein were informal discussions, mainly over breakfast and dinner, and were overheard by only a few of the other participants.

De Broglie's pilot-wave theory has been particularly neglected, and its high profile at the conference severely downplayed. According to Max Jammer's classic historical study *The Philosophy of Quantum Mechanics*, at the conference, de Broglie's theory 'was hardly discussed at all' and 'the only serious reaction came from Pauli', a view that is typical of standard historical accounts throughout the 20th century. And yet, the published proceedings show that de Broglie's

theory was in fact discussed extensively: at the end of de Broglie's talk, there are nine pages of discussion about his theory; while of the 42 pages of general discussion (which took place at the end of the conference), 15 pages include discussion of de Broglie's theory. And there were serious reactions and comments from Born, Brillouin, Einstein, Kramers, Lorentz, Schrödinger and others, as well as from Pauli. What exactly was the theory that de Broglie presented?

### 3 Pilot-wave dynamics

In his report – entitled ‘The new dynamics of quanta’ – de Broglie presented a new form of dynamics for a many-body system. In his theory, particle motions are determined by the wavefunction, which de Broglie called a ‘pilot wave’. This function obeys the usual quantum wave equation (the Schrödinger equation). For a many-body system, the pilot wave propagates in a multidimensional ‘configuration space’, which is constructed from the co-ordinates of all the particles involved. While it was not fully appreciated at the time, de Broglie's pilot wave is a radically new kind of causal agent that is more abstract than conventional forces or fields in 3D space.

De Broglie's law of motion for particles is very simple. At any time, the momentum is perpendicular to the wave crests (or lines of constant phase), and is proportionally larger if the wave crests are closer together. Mathematically, the momentum of a particle is given by the gradient (with respect to that particle's co-ordinates) of the phase of the total wavefunction. This is a law of motion for *velocity*, quite unlike Newton's law of motion for acceleration.

De Broglie had in fact first proposed this law in 1923, for the case of one particle. His motivation had been to arrive at a unified dynamics of particles and waves. Experiments had demonstrated the diffraction of X-rays, from which de Broglie deduced that photons do not always move in a straight line in empty space. He saw this as a failure of Newton's first law, and concluded that a new form of dynamics had to be constructed.

On the basis of his new law of motion, which he applied to material particles as well as to photons, it was de Broglie who first predicted that electrons would undergo diffraction. This remarkable prediction was spectacularly confirmed four years later by Clinton Davisson and Lester Germer of Bell Labs in their experiments on the scattering of electrons by crystals. Indeed, de Broglie won the 1929 Nobel Prize for Physics ‘for his discovery of the wave nature of electrons’.

De Broglie's earlier work – as presented in his doctoral thesis of 1924 – had in fact been the starting point for Schrödinger, who in 1926 found the correct wave equation for de Broglie's waves. In the meantime, de Broglie had sought to derive his law of motion from a deeper theory. But by 1927 he contented himself with proposing his pilot-wave dynamics as a provisional measure (much as Newton had regarded his theory of gravitational action-at-a-distance as provisional).

De Broglie showed how to apply his dynamics to explain simple quantum phenomena. But many details and applications were missing. In particular, de

Broglie seems not to have recognized that his dynamics was irreducibly non-local. Nor was this recognized by anyone else at the conference. The action of the wave in multidimensional configuration space is such that a local operation on one particle can have an instantaneous effect on the motions of other (distant) particles.

While de Broglie had (with some help from Léon Brillouin) replied to almost all of the many queries raised in Brussels about his theory, around 1928 he became dissatisfied. In particular, he did not understand how to give a general account of a measurement in quantum theory. To do so requires that the dynamics be applied to the measurement process, by treating the system and apparatus together as one larger system. This point was not fully appreciated until the work of Bohm in 1952. Furthermore, de Broglie was uneasy with having a wave in configuration space that affected the motion of an individual system. Even so, he remained sceptical of the Copenhagen interpretation.

## 4 The renaissance of de Broglie's theory

De Broglie's pilot-wave theory was resurrected in 1952 when Bohm used it to describe a general quantum measurement (for example of the energy of an atom). Bohm showed that the statistical results obtained would be the same as in conventional quantum theory – *if* we assume that the initial positions of all the particles involved (making up both 'system' and 'apparatus') have a Born-rule distribution, that is, a distribution proportional to the squared-amplitude of the wavefunction (as appears in conventional quantum theory).

In pilot-wave theory, the outcome of a single quantum experiment is in principle determined by the precise ('hidden variable') positions of all the particles involved. If the experiment is repeated many times, then the outcomes have a statistical spread caused by the spread in the initial distribution of particle positions.

Furthermore, Bohm noticed that the theory is non-local: the outcome of a quantum measurement on one particle can depend instantaneously on macroscopic operations performed on a distant particle – the so-called 'spooky' action-at-a-distance.

This feature caught the attention of the Northern Irish theoretical physicist John Bell, who devoted several chapters to pilot-wave theory in his remarkably clear and perceptive 1987 book *Speakable and Unsayable in Quantum Mechanics*. Here was a formulation of quantum mechanics that gave a precise, unified description of the microscopic and macroscopic worlds, in which systems, apparatus and observers were treated (in principle) on an equal footing.

But the theory was blatantly non-local. As is well known, in 1964 Bell showed that certain quantum correlations required any hidden-variables theory to be non-local (on some reasonable assumptions). For several decades this was widely seen as a blow to the hidden-variables approach, as many physicists thought that non-locality was unacceptable. Today, however, it is increasingly recognized that (leaving aside the many-worlds interpretation) quantum theory

itself is non-local – as Bell had taken pains to emphasize. Non-locality seems to be a feature of the world, and it is a virtue of pilot-wave theory to provide a clear account of it.

Bell made it clear that the pilot wave is a ‘real objective field’ in configuration space, and not merely a mathematical object or probability wave. Recent work at the University of Florence by Alberto Montina (now at Canada’s Perimeter Institute for Theoretical Physics) suggests that any reasonable (deterministic) hidden-variables theory must contain at least as many continuous degrees of freedom as are contained in the wavefunction – and therefore in this sense cannot be ‘simpler’ than pilot-wave theory.

## 5 What if pilot-wave theory is right?

Today, we still do not know what the correct interpretation of quantum theory is. It is therefore important to keep an open mind, and to explore the various alternatives. What if de Broglie’s pilot-wave dynamics is a correct (or at least approximately correct) description of nature? Here, too, there have been misunderstandings. It is usually thought that we would have to accept that the details of the particle trajectories can never be measured, and that non-local actions can never be controlled. This belief is based on the fact that, with an initial Born-rule distribution of particle positions, measurements are in practice limited by the uncertainty principle. Many scientists rightly feel unable to accept a theory the details of which can never be checked experimentally.

However, the correct conclusion to draw is that quantum theory is merely a special case of a much wider physics – a physics in which non-local (superluminal) signalling is possible, and in which the uncertainty principle can be violated. And furthermore, the theory itself points naturally to where this new physics might be found. Recall that pilot-wave theory gives the same observable results as conventional quantum theory *if* the initial particle positions have a standard Born-rule distribution. But there is nothing in de Broglie’s dynamics that requires this assumption to be made. A postulate about initial conditions can have no axiomatic status in a theory of dynamics.

An analogy with classical physics is helpful here. For a box of gas, there is no reason to think that the molecules *must* be distributed uniformly within the box with a thermal spread in their speeds. That would amount to restricting classical physics to thermal equilibrium, when in fact classical physics is a much wider theory. Similarly, in pilot-wave theory, the ‘quantum equilibrium’ distribution – with particle positions distributed according to the Born rule – is only a special case. In principle, the theory allows other ‘quantum non-equilibrium’ distributions, for which the statistical predictions of quantum theory are violated – just as, for a classical box of gas out of thermal equilibrium, predictions for pressure fluctuations will differ from the thermal case. Quantum equilibrium has the same status in pilot-wave dynamics as thermal equilibrium has in classical dynamics. Equilibrium is a mere contingency, not a law.

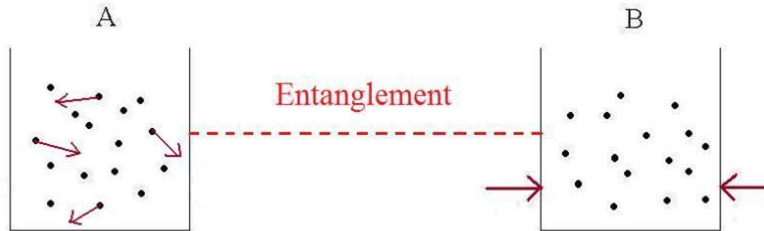


Figure 2: Two entangled boxes of particles. A local action at B – such as moving the walls of the box – induces an instantaneous change in the particle motions at A, thereby generally changing the distribution at A. For the special case of an equilibrium distribution, the effects at A average to zero.

## 6 The new physics of quantum non-equilibrium

We have said that pilot-wave theory contains action-at-a-distance. In particular, the outcome of a quantum measurement on one particle can depend on macroscopic operations performed on a distant particle. This occurs, specifically, when the wavefunction of the particles is ‘entangled’. In equilibrium, this non-local effect averages to zero and no signal can be sent in practice. But this ‘cancellation’ is merely a feature of the equilibrium state. It is *not* a fundamental feature of the world.

An analogy with coins is helpful here. Consider a box containing a large number of coins, each one showing either heads or tails. Imagine that someone far away claps their hands, and that through some ‘spooky action-at-a-distance’ each coin is instantly flipped over. If the coins initially had an even ratio of heads to tails, then after the flip the ratio of heads to tails would still be even. At the statistical level, the spooky flip would not be noticeable. But if instead the coins started with a ‘non-equilibrium’ distribution – say 10% heads and 90% tails – then the effect of the flip would be statistically noticeable, because afterwards there would be 90% heads and 10% tails.

Something similar happens in pilot-wave theory for pairs of entangled particles, as illustrated in figure 2. A local action at B causes an instantaneous response in the motion of each individual particle at A. As a result, the distribution of particle positions at A generally changes – except in the special case of equilibrium, for which there is no net change (at the statistical level).

Thus, if we had a large collection of non-equilibrium particles, then we could use them for practical signalling at speeds faster than the speed of light. Such signals could be used to synchronize clocks – there would be an absolute simultaneity. In the pilot-wave theory of high-energy physics, relativity theory emerges only in the equilibrium state where such signals vanish.

It may also be shown that non-equilibrium particles could be used to per-



form ‘subquantum’ measurements on ordinary (equilibrium) particles – measurements that would violate the uncertainty principle and allow us to measure a trajectory without disturbing the wavefunction. Essentially, the absence of quantum noise in our ‘probe particles’ would enable the experimentalist to circumvent quantum noise in the particles being probed. Such measurements would result in violations of standard quantum constraints, such as those on which the security of quantum cryptography rests.

But to perform these remarkable new operations requires in the first place that we find non-equilibrium systems. Where could these be found?

An atom in the laboratory, for example, has a past that stretches back to the formation of stars or even earlier, during which time the atom interacted extensively with other systems. This basic cosmological fact offers a natural explanation for the statistical noise found in quantum systems. Indeed, there has been ample opportunity for microscopic systems to relax to the quantum equilibrium state, as illustrated in figure 3. In other words, given the basic facts of astrophysics and cosmology, on the basis of de Broglie’s pilot-wave theory one would expect to find the quantum noise that we do indeed see all around us.

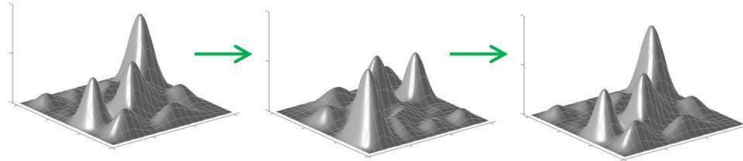
Returning to the analogy with the box of coins, it is as if the box has been violently shaken for a long time, so that the coins have long ago reached the ‘equilibrium’ state of an even ratio of heads to tails. And furthermore, all the boxes of coins we have access to have undergone such long and violent shaking.

It seems natural to assume that the universe began in a non-equilibrium state, with relaxation to quantum equilibrium taking place during the violence of the Big Bang. On this view, quantum noise is a remnant of the Big Bang – that is, part of the cosmological ‘fossil record’, rather like the cosmic microwave background (CMB) that also pervades our universe today.

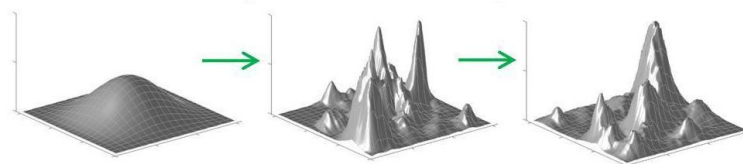
The crucial question is whether the early non-equilibrium state could have left traces or remnants that are observable today. Given the efficient relaxation seen in figure 3, it might be thought that any initial non-equilibrium would quickly relax and disappear without trace. However, the simulation shown in the figure is for a static space–time background. In the early universe, in contrast, we must take into account the fact that space expanded rapidly. In 2008 I showed that this can cause the initial quantum non-equilibrium to be ‘frozen’ at very large wavelengths (where, roughly speaking, the de Broglie velocities are too small for relaxation to occur). This result makes it possible to derive quantitative predictions for deviations from quantum theory, in the context of a given cosmological model.

Detailed predictions remain to be worked out, but there are two obvious avenues to explore. First, in the context of inflationary cosmology, quantum non-equilibrium at the onset of inflation would modify the spectrum for the CMB sky – the hot and cold spots shown in figure 4. In other words, measurements of the CMB can test for the presence of quantum non-equilibrium during the inflationary phase. A second, more exciting possibility is that some exotic particles in the very early universe stopped interacting with other particles before they had enough time to reach equilibrium. Such ‘relic’ particles

### Time evolution of quantum equilibrium



### Non-equilibrium relaxes to equilibrium



Quantum equilibrium may be understood as arising from a dynamical process of relaxation (broadly similar to thermal relaxation in classical physics). This is confirmed by numerical simulations, see the figure above, for a simple case of particles in a 2D box. For an initial wavefunction that is a superposition of 16 modes (or standing waves), the trajectories are very erratic, and an initial non-equilibrium distribution of particles (taken here to be a simple sine-squared) rapidly approaches equilibrium – much as, under appropriate conditions, a non-equilibrium distribution of classical particles in a box tends to thermalize rapidly.

Pilot-wave theory, as formulated by Louis de Broglie, is then *not* merely an alternative formulation of quantum theory. Instead, the theory itself tells us that quantum physics is a special 'equilibrium' case of a much wider 'non-equilibrium' physics.

But what would this new physics be like? And where might it be found? Again, the theory itself can tell us the answers.

Figure 3: Relaxation and quantum equilibrium.

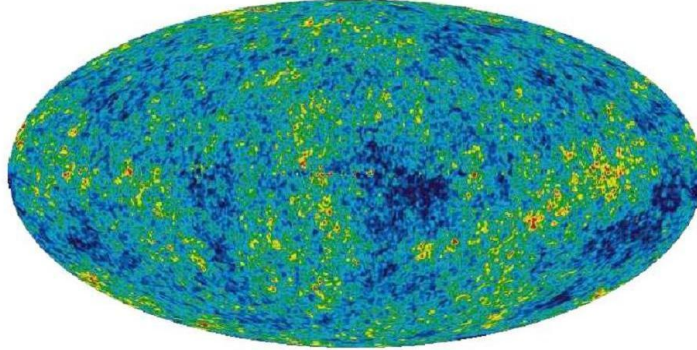


Figure 4: An all-sky map of cosmic-microwave-background (CMB) temperature anisotropies, as measured by the Wilkinson Microwave Anisotropy Probe (WMAP) satellite. Measurements of the CMB can be used to set limits on violations of quantum theory in the very early universe.

might still exist today. If we could find them, they would violate the usual rules of quantum mechanics. (On the analogy with the boxes of coins, some special boxes might have been shaken for a time so short that the even ratio of heads to tails was not reached.)

## 7 The quantum conspiracy

Our view of de Broglie's theory provides a very novel perspective, according to which our local and indeterministic quantum physics emerged via relaxation processes out of a fundamentally non-local and deterministic physics – a physics the details of which are now screened off by the all-pervading statistical noise. As equilibrium was approached, the possibility of superluminal signalling faded away and statistical uncertainty took over. Key features of what we regard as the laws of physics – locality, uncertainty and the principles of relativity theory – are merely features of our current state and not fundamental features of the world.

But is there any independent evidence that we are confined to a special statistical state? Arguably there is. Modern physics seems to contain a 'conspiracy' that prevents non-local quantum effects from being used to send a signal. Why should non-locality be hidden in this way? The conspiracy may be explained as a peculiarity of equilibrium, in which non-local effects are washed out – or aver-

aged to zero – by statistical noise. Out of equilibrium, the non-locality becomes controllable and the ‘conspiracy’ disappears.

To put this in perspective, recall that in the late 19th century some theorists were concerned about the universal ‘thermodynamic heat death’. In the far future, the stars would eventually burn out and all systems would reach thermal equilibrium with each other, after which all significant activity would cease. In such a world, in the absence of temperature differences it would be impossible to convert heat into work – a limitation that would be a contingency of the state and not a law of physics. If de Broglie’s dynamics is correct, then a subquantum analogue of the classical heat death has in fact *already occurred* in our universe, presumably some time in the remote past. In this special state, it is impossible to convert entanglement into a non-local signal – a limitation that is again a contingency of the state and not a law of physics.

The slow and intermittent development of pilot-wave theory is reminiscent of the development of the kinetic theory of gases. The work of Daniel Bernoulli in the 18th century, and of John Waterston and others in the early 19th century, was mostly ignored until the ideas were taken up by Rudolf Clausius in 1857. It took decades of further work, by Maxwell, Boltzmann, Gibbs and Einstein, among others, for the theory to yield the observable prediction of Brownian motion. The extent to which history will repeat itself remains to be seen.

### Further Reading

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