CHAPTER VII   DETAILS ON QUANTUM THEORY
AND ELECTROMAGNETISM

22.   Superpositions and probabilities – quantum theory without ideology

> Niels Bohr brainwashed a whole generation of physicists into believing that the problem
> [of the interpretation of quantum mechanics] had been solved fifty years ago.
> Murray Gell-Mann, Nobel price acceptance speech.

Why is this famous physical issue arousing such strong emotions? In particular, who is brainwashed, Gell-Mann, the discoverer of the quarks, or most of the other physicists working on quantum theory who follow Niels Bohr's* opinion?

In the twentieth century, quantum mechanics has thrown many in disarray. Indeed, it radically changed the two most basic concepts of classical physics: state and system. The *state* is not described any more by the specific values taken by position and momentum, but by the specific wavefunction 'taken' by the position and momentum operators.** In addition, in classical physics a *system* was described as a set of permanent aspects of nature; permanence was defined as negligible interaction with the environment. Quantum mechanics shows that this definition has to be modified as well.

In order to clarify the issues, we take a short walk around the strangest aspects of quantum theory. The section is essential if we want to avoid getting lost on our way to the top of Motion Mountain, as happened to quite a number of people since quantum theory appeared.

Why are people either dead or alive?

The evolution equation of quantum mechanics is linear in the wavefunction; thus we can imagine and try to construct systems where the state ψ is a superposition of two very distinct situations, such as those of a dead and of a living cat. This famous fictional animal is called *Schrödinger's cat* after the originator of the example. Is it possible to produce it? How

---

* Niels Bohr (1885, Copenhagen–1962) made his university, Copenhagen, into one of the centres of quantum theory, overshadowing Göttingen. He developed the description of the atom with quantum theory, for which he received the 1922 Nobel prize in physics. He had to flee Denmark in 1943 after the German invasion, because of his Jewish background, but returned there after the war.

** It is equivalent, but maybe conceptually clearer, to say that the state is described by a complete set of commuting operators. In fact, the discussion is somewhat simplified in the Heisenberg picture. However, here we study the issue in the Schrödinger picture, using wavefunctions.

would it evolve in time? Similarly, we can ask for the evolution of the superposition of a state where a car is inside a closed garage with a state where it is outside the closed garage.

All these situations are not usually observed in everyday life. What can be said about them? The answer to these questions is an important aspect of what is often called the 'interpretation' of quantum mechanics. In principle, such strange situations are possible, and the superposition of macroscopically distinct states has actually been observed in a few cases, though not for cats, people or cars. To get an idea of the constraints, let us specify the situation in more detail.* The object of discussion are linear superpositions of the type $\psi = a\psi_a + b\psi_b$, where ψ_a and ψ_b are macroscopically distinct states of the system under discussion, and where a and b are some complex coefficients. States are called *macroscopically distinct* when each state corresponds to a different macroscopic situation, i.e. when the two states can be distinguished using the concepts or measurement methods of classical physics. In particular, this means that the physical action necessary to transform one state into the other must be much larger than $\hbar$. For example, two different positions of any body composed of a large number of molecules are macroscopically distinct.
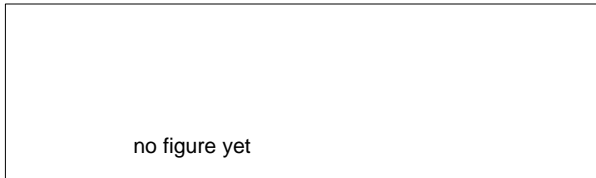

Figure 215 Artist's impression of a macroscopic superposition

Let us work out the essence of macroscopic superpositions more clearly. Given two macroscopically distinct states ψ_a and ψ_b, a superposition of the type $\psi = a\psi_a + b\psi_b$ is called a *pure state*. Since the states ψ_a and ψ_b can interfere, one also talks about a *(phase) coherent superposition*. In the case of a superposition of macroscopically distinct states, the scalar product $\psi_a^\dagger \psi_b$ is obviously vanishing. In case of a coherent superposition, the coefficient product a^*b is different from zero. This fact can also be expressed with help of the *density matrix* ρ of the system, defined as $\rho = \psi \otimes \psi^\dagger$. In the present case it is given by

$$\rho_{\text{pure}} = \psi \otimes \psi^\dagger = |a|^2 \psi_a \otimes \psi_a^\dagger + |b|^2 \psi_b \otimes \psi_b^\dagger + ab^* \psi_a \otimes \psi_b^\dagger + a^*b \psi_b \otimes \psi_a^\dagger$$
$$= (\psi_a, \psi_b) \begin{pmatrix} |a|^2 & ab^* \\ a^*b & |b|^2 \end{pmatrix} \begin{pmatrix} \psi_a^\dagger \\ \psi_b^\dagger \end{pmatrix} \quad . \tag{427}$$

We can then say that whenever the system is in a pure state, its density matrix, or *density functional*, contains off-diagonal terms of the same order of magnitude as the diagonal ones.** Such a density matrix corresponds to the above-mentioned situations so contrasting with daily life experience.

---

* Most what can be said about this topic has been said by two people: John von Neumann, who in the nine-
Ref. 583 teen thirties stressed the differences between evolution and decoherence, and by Hans Dieter Zeh, who in the
Ref. 584 nineteen seventies stressed the importance of baths in this process.

** Using the density matrix, we can rewrite the evolution equation of a quantum system:

$$\dot{\psi} = -iH\psi \quad \text{becomes} \quad \frac{d\rho}{dt} = -\frac{i}{\hbar}[H, \rho] \quad . \tag{428}$$

We now have a look at the opposite situation. In contrast to the case just mentioned, a density matrix for macroscopic distinct states with *vanishing* off-diagonal elements, such as the two state example

$$\rho = |a|^2 \psi_a \otimes \psi_a^\dagger + |b|^2 \psi_b \otimes \psi_b^\dagger$$
$$= (\psi_a, \psi_b) \begin{pmatrix} |a|^2 & 0 \\ 0 & |b|^2 \end{pmatrix} \begin{pmatrix} \psi_a^\dagger \\ \psi_b^\dagger \end{pmatrix} \tag{429}$$

describes a system which possesses *no* phase coherence at all. Such a diagonal density matrix cannot be that of a pure state; it describes a system which is in the state ψ_a with probability $|a|^2$ and which is in the state ψ_b with probability $|b|^2$. Such a system is said to be in a *mixed state*, because its state is *not known*, or equivalently, to be in a *(phase) incoherent superposition*, because interference effects cannot be observed in such a situation. A system described by a mixed state is always *either* in the state ψ_a *or* in the state ψ_b. In other words, a diagonal density matrix for macroscopically distinct states is not in contrast, but in agreement with everyday experience. In the picture of density matrices, the non-diagonal elements contain the difference between normal, i.e. incoherent, and unusual, i.e. coherent, superpositions.

The experimental situation is clear: for macroscopically distinct states, only diagonal density matrices are observed. Any system in a coherent macroscopic superposition somehow loses its off-diagonal matrix elements. How does this process of *decoherence* take place? The density matrix itself shows the way.

Indeed, the density matrix for a large system is used, in thermodynamics, for the definition of its entropy and of all its other thermodynamic quantities. These studies show that

Ref. 585
Challenge 981

$$S = -k \operatorname{tr}(\rho \ln \rho) \tag{430}$$

where tr denotes the *trace*, i.e. the sum of all diagonal elements. We also remind ourselves that a system with a large and constant entropy is called a *bath*. In simple physical terms, a bath is thus a system to which we can ascribe a temperature. More precisely, a *(physical) bath*, or *reservoir*, is any large system for which the concept of *equilibrium* can be defined. Experiments show that in practice, this is equivalent to the condition that a bath consists of many interacting subsystems. For this reason, all macroscopic quantities describing the state of a bath show small, irregular *fluctuations*, a fact that will be of central importance shortly.

It is easy to see from the definition (430) of entropy that the loss of off-diagonal elements corresponds to an increase in entropy. And it is known that increases in entropy of a reversible system, such as the quantum mechanical system in question, are due to interactions with a bath.

Challenge 982

Where is the bath interacting with the system? It obviously must be outside the system one is talking about, i.e. in its *environment*. Indeed, we know experimentally that any environment is large and is characterized by a temperature; examples are listed in Table 46.

Both are completely equivalent. (The new expression is sometimes also called the *von Neumann equation*.) We won't actually do any calculations here. The expressions are given so that you recognize them when you encounter them elsewhere.

Any environment therefore contains a bath. We can even go further: for every experimental situation, there is a bath *interacting* with the system. Indeed, every system which can be observed is not isolated, as it obviously interacts at least with the observer; and every observer contains a bath, as we will show in more detail shortly. Usually however, the most important baths we have to take into consideration are the atmosphere around a system, the radiation attaining the system or, if the system itself is large enough to have a temperature, those degrees of freedom of the system which are not involved in the superposition under investigation.

At first sight, this direction of thought is not convincing. The interactions of a system with its environment can be made very small by using clever experimental set-ups. That would imply that the time for decoherence can be made arbitrary large. Let us check how much time a superposition of states needs to decohere. It turns out that there are two standard ways to estimate the *decoherence time*: either modelling the bath as large number of colliding particles, or by modelling it as a continuous field.

Table 46 Some common and less common baths with their main properties

Bath type	temperature T	wavelength λ_{eff}	particle flux φ	hit time $t_{\text{hit}} = 1/\sigma\varphi$ for	
				atom[a]	object[a]
matter baths					
solid, liquid	300 K	10 pm	10^{31} /m²s	10^{-12} s	10^{-25} s
air	300 K	10 pm	10^{28} /m²s	10^{-9} s	10^{-22} s
laboratory vacuum	50 mK	10 μm	10^{18} /m²s	10 s	10^{-12} s
photon baths					
sunlight	5800 K	900 nm	10^{23} /m²s	10^{-4} s	10^{-17} s
'darkness'	300 K	20 μm	10^{21} /m²s	10^{-2} s	10^{-15} s
cosmic microwaves	2.7 K	2 mm	10^{17} /m²s	10^{2} s	10^{-11} s
terrestrial radio waves	300 K				
Casimir effect	.. K				
Unruh radiation of earth	.. K				
nuclear radiation baths					
radioactivity		10 pm		$10^{..}$ s	$10^{..}$ s
cosmic radiation	>1000 K	10 pm		$10^{..}$ s	$10^{..}$ s
solar neutrinos	$\approx$ 10 MK	10 pm	10^{15} /m²s	$10^{..}$ s	$10^{..}$ s
cosmic neutrinos	2.0 K	3 mm	10^{17} /m²s	$10^{..}$ s	$10^{..}$ s
gravitational baths					
gravitational radiation	10^{32} K	10^{-35} m		$>10^{..}$ s	$>10^{..}$ s

a. The cross section σ in the case of matter and photon baths was assumed to be 10^{-19} m² for atoms; for the macroscopic object a size of 1 mm was used as example. For neutrino baths, ...

If the bath is described as a set of particles randomly hitting the microscopic system, it is characterized by a characteristic wavelength λ_{eff} of the particles, and by the average interval t_{hit} between two hits. A straightforward calculationshows that the decoherence time t_d is in   Challenge 983

any case smaller than this time interval, so that

$$t_d \leqslant t_{\text{hit}} = \frac{1}{\varphi \sigma} \quad , \tag{431}$$

where φ is the flux of particles and σ is the cross section for the hit.[*] Typical values are given in Table 46. We easily note that for macroscopic objects, decoherence times are extremely short. Scattering leads to fast decoherence. However, for atoms or smaller systems, the situation is different, as expected.

A second method to estimate the decoherence time is also common. Any interaction of a system with a bath is described by a relaxation time t_r. The term *relaxation* designates any process which leads to the return to the equilibrium state. The terms *damping* and *friction* are also used. In the present case, the relaxation time describes the return to equilibrium of the combination bath and system. Relaxation is an example of an irreversible evolution. A process is called *irreversible* if the reversed process, in which every component moves in opposite direction, is of very low probability.[**] For example, it is usual that a glass of wine poured into a bowl of water colours the whole water; it is very rarely observed that the wine and the water separate again, since the probability of all water and wine molecules to change directions together at the same time is rather low, a state of affairs making the happiness of wine producers and the despair of wine consumers.

Now let us simplify the description of the bath. We approximate it by a single, unspecified, scalar field which interacts with the quantum system. Due to the continuity of space, such a field has an infinity of degrees of freedom. They are taken to model the many degrees of freedom of the bath. The field is assumed to be in an initial state where its degrees of freedom are excited in a way described by a temperature T. The interaction of the system with the bath, which is at the origin of the relaxation process, can be described by the repeated transfer of small amounts of energy E_{hit} until the relaxation process is completed.

The objects of interest in this discussion, like the mentioned cat, person or car, are described by a mass m. Their main characteristic is the maximum energy E_r which can be transferred from the system to the environment. This energy describes the interactions between system and environment. The superpositions of macroscopic states we are interested in are solutions of the Hamiltonian evolution of these systems.

---

[*] The decoherence time is derived by studying the evolution of the density matrix $\rho(x, x')$ of objects localized at two points x and x'. One finds that the off-diagonal elements follow $\rho(x, x', t) = \rho(x, x', 0) e^{-\Lambda t (x - x')^2}$, where the localization rate Λ is given by

$$\Lambda = k^2 \varphi \sigma_{\text{eff}} \tag{432}$$

where k is the wave number, φ the flux, and σ_{eff} the cross section of the collisions, i.e. usually the size of the macroscopic object.

One also finds the surprising result that a system hit by a particle of energy E_{hit} collapses the density matrix roughly down to the de Broglie (or thermal de Broglie) wavelength of the hitting particle. Both results together give the formula above.

[**] Beware of other definitions which try to make something deeper out of the concept of irreversibility, such as claims that 'irreversible' means that the reversed process is *not at all* possible. Many so-called 'contradictions' between the irreversibility of processes and the reversibility of evolution equations are due to this mistaken interpretation of the term 'irreversible'.

This is a section of the freely downloadable e-textbook
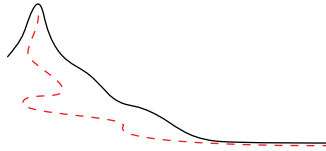
MOTION MOUNTAIN

Hiking beyond space and time
along the concepts of modern physics

available at www.motionmountain.net

Copyright © 1997 – 2002 by Christoph Schiller

To the kind reader

In exchange for getting this section for free, I ask you
for a short email on the following:

- What was hard to understand?
- Did you find any mistakes?
- What figure or explanation were you expecting?
- Which page was boring?

Of course, any other suggestion is welcome. This sec-
tion is part of a physics text written over many years.
The text lives and grows through the feedback from its
readers, who help to improve and to complete it. For a
particularly useful contribution (send it in english, ital-
ian, dutch, german, spanish, portuguese, or french) you
will be mentioned in the foreword of the text, or receive
a small reward, or both.

Enjoy!

Christoph Schiller
mm@motionmountain.net

The initial coherence of the superposition, so disturbingly in contrast with our everyday experience, disappears exponentially within a *decoherence time t_d* given by[*]

Ref. 588

$$t_d = t_r \frac{E_{\text{hit}}}{E_r} \frac{e^{E_{\text{hit}}/kT} - 1}{e^{E_{\text{hit}}/kT} + 1} \tag{435}$$

where k is the *Boltzmann constant* and like above, E_r is the maximum energy which can be transferred from the system to the environment. Note that one always has $t_d \leqslant t_r$. After a time interval of length t_d is elapsed, the system has evolved from the coherent to the incoherent superposition of states, or, in other words, the density matrix has lost its off-diagonal terms. One also says that the phase coherence of this system has been destroyed. Thus, after a time t_d, the system is found either in the state ψ_a or in the state ψ_b, respectively with the probability $|a|^2$ or $|b|^2$, and not anymore in a coherent superposition which is so much in contradiction with our daily experience. Which final state is selected depends on the precise state of the bath, whose details were eliminated from the calculation by taking an *average* over the states of its microscopic constituents.

The important result is that for all macroscopic objects, the decoherence time t_d is very small. In order to see this more clearly, we can study a special simplified case. A macroscopic object of mass m, like the mentioned cat or car, is assumed to be at the same time in two locations separated by a distance l, i.e. in a superposition of the two corresponding states. We further assume that the superposition is due to the object moving as a quantum mechanical oscillator with frequency ω between the two locations; this is the simplest possible system that shows superpositions of an object located in two different positions. The energy of the object is then given by $E_r = m\omega^2 l^2$, and the smallest transfer energy $E_{\text{hit}} = \hbar\omega$ is the difference between the oscillator levels. In a macroscopic situation, this last energy is much smaller than kT, so that from the preceding expression we get

Ref. 590

$$t_d = t_r \frac{E_{\text{hit}}^2}{2E_r kT} = t_r \frac{\hbar^2}{2mkTl^2} = t_r \frac{\lambda_T^2}{l^2} \tag{436}$$

in which the frequency ω has disappeared. The quantity $\lambda_T = \hbar/\sqrt{2mkT}$ is called the *thermal de Broglie wavelength* of a particle.

It is straightforward to see that for practically all macroscopic objects the typical decoherence time t_d is very short. For example, setting $m = 1$ g, $l = 1$ mm and $T = 300$ K we get $t_d/t_r = 1.3 \cdot 10^{-39}$. Even if the interaction between the system and the environment would

---

Ref. 589

[*] This result is derived as in the above case. A system interacting with a bath always has an evolution given by the general form

$$\frac{d\rho}{dt} = -\frac{i}{\hbar}[H, \rho] - \frac{1}{2t_o} \sum_j [V_j\rho, V_j^\dagger] + [V_j, \rho V_j^\dagger] \quad . \tag{433}$$

Challenge 985

Are you able to see why? Solving this equation, one finds for the elements far from the diagonal $\rho(t) = \rho_o e^{-t/t_o}$. In other words, they disappear with a characteristic time t_o. In most situations one has a relation of the form

$$t_o = t_r \frac{E_{\text{hit}}}{E_r} = t_{\text{hit}} \tag{434}$$

or some variations of it, as in the example above.

be so weak that the system would have as relaxation time the age of the universe, which is about $4 \cdot 10^{17}$ s, the time t_d would still be shorter than $5 \cdot 10^{-22}$ s, which is over a million times faster than the oscillation time of a beam of light (about 2 fs for green light). For Schrödinger's cat, the decoherence time would be even shorter. These times are so short that we cannot even hope to *prepare* the initial coherent superposition, let alone to observe its decay or to measure its lifetime.

For microscopic systems however, the situation is different. For example, for an electron in a solid cooled to liquid helium temperature we have $m = 9.1 \cdot 10^{-31}$ kg, and typically $l = 1$ nm and $T = 4$ K; we then get $t_d \approx t_r$ and therefore the system can stay in a coherent superposition until it is relaxed, which confirms that for this case coherent effects can indeed be observed if the system is kept isolated. A typical example is the behaviour of electrons in superconducting materials. We will mention a few more below.   Ref. 591

In 1996 the first actual measurement of decoherence times was published by the Paris team around Serge Haroche.   Ref. 592

Conclusions on decoherence, life, and death

In summary, both estimates of decoherence times tell us that for most macroscopic objects, in contrast to microscopic ones, both the preparation and the survival of superpositions of macroscopically different states is made practically impossible by the interaction with any bath found in their environment, even if the usual measure of this interaction, given by the friction of the motion of the system, is very small. Even if a macroscopic system is subject to an extremely low friction, leading to a very long relaxation time, its decoherence time is still vanishingly short.

Our everyday environment if full of baths. Therefore, *coherent superpositions of macroscopically distinct states never appear in nature.* In short, we cannot be dead and alive at the same time.

We also take a second conclusion: *decoherence results from coupling to a bath in the environment.* Decoherence is a thermodynamic, statistical effect. We will return to this issue below.

What is a system? What is an object?

In classical physics, a system is a part of nature which can be isolated from its environment. However, quantum mechanics tells us that isolated systems do not exist, since interactions cannot be made vanishingly small. The results above allow us to define the concept of system with more accuracy. A *system* is any part of nature which interacts *incoherently* with its environment. In other words, an *object* is a part of nature interacting with its environment only through baths.

In particular, a system is called *microscopic* or *quantum mechanical* and can described by a wavefunction ψ whenever
- it is almost isolated, with $t_{evol} = \hbar/\Delta E < t_r$, and
- it is in *incoherent* interaction with its environment.   Ref. 593

In short, a microscopic system interacts incoherently and weakly with its environment.

In contrast, a bath is never isolated in the sense just given, because its evolution time is always much larger than its relaxation time. Since all macroscopic bodies are in contact with baths – or even contain one – they cannot be described by a wavefunction. In particular, one cannot describe any measuring apparatus with help of a wavefunction.

We thus conclude that a *macroscopic system* is a system with a decoherence time much shorter than any other evolution time of its constituents. Obviously, macroscopic systems also interact incoherently with their environment. Thus cats, cars, and television news speakers are all macroscopic systems.

A third possibility is left over by the two definitions: what happens in the situation in which the interactions with the environment are *coherent*? We will encounter some examples shortly. Following this definition, such situations are *not* systems, and cannot be described by a wavefunction. For example, it can happen that a particle forms neither a macroscopic nor a microscopic system!

Nature is composed of many parts. Matter is composed of particles. Can parts be defined precisely? Can they be isolated from each other and pinned down unambiguously? In quantum theory, nature is not found to be made of isolated entities, but is still made of *separable* entities. The criterion of separability is the incoherence of interaction. Any system whose parts interact coherently is not separable. So the discovery of coherent superpositions includes the surprising consequence that there are systems which, even though they look separable, are not. In nature, some systems are *not* divisible. Quantum mechanics thus also stresses the *interdependence* of the parts of nature. By the way, in the third part of the walk we will encounter much stronger types of interdependence.

All surprising properties of quantum mechanics, such as Schrödinger's cat, are consequences of the classical prejudice that a system made of two or more parts must necessarily be divisible into two subsystems. Whenever one tries to divide indivisible systems, one gets strange or incorrect conclusions, such as apparent faster-than-light propagation, or, as one says today, non-local behaviour. Let us have a look at a few typical examples.

Is quantum theory non-local? – A bit about EPR

> [Mr. Duffy] lived a little distance away from his body ...
> James Joyce, *A Painful Case*

We asked about non-locality also in general relativity. Let us study the situation in quantum mechanics. We first look at the wavefunction collapse for an electron hitting a screen after passing a slit. Following the description just deduced, the process looks roughly as depicted in Figure 216. A movie of the same process can be seen in the lower right corners on the pages of the present, second part of our mountain ascent. The situation is surprising: a wavefunction collapse gives the impression to involve faster than light propagation, because the maximum of the function changes position at extremely high speed, due to the short decoherence time. Does this happen faster than light? Yes, it does. But is it a problem?

A situation is called *acausal* or *nonlocal* if energy is transported faster than light. Us-
ing Figure 216 youcan determine the energy velocity involved, using the results on signal
propagation. The result is a value smaller than c. A wavefunction maximum moving faster

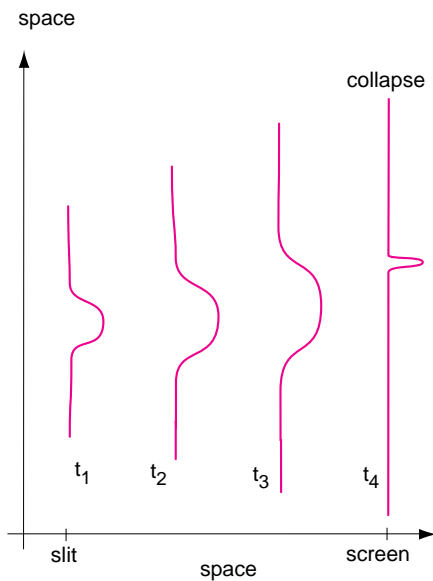than light does *not* imply energy motion faster than light. [*]

Figure 216 Quantum mechanical motion: an electron wave function (actually its module squared) from the moment it passes a slit until it hits a screen

Another often cited Gedankenexperiment was proposed by Bohm [**] in the discussion around the so-called Einstein-Podolsky-Rosen paradox. In the famous EPR paper the three authors try to find a contradiction between quantum mechanics and common sense. Bohm translated their rather confused paper into a clear thought experiment. When two particles in a spin 0 state move apart, measuring one particle's spin orientation implies an *immediate* collapse also of the other particle's spin, namely in the exactly opposite direction. This happens instantaneously over the whole separation distance; no speed limit is obeyed.

We note again that no energy is transported faster than light. No non-locality is present, against numerous claims of the contrary in older literature. The two electrons belong to one system: assuming that they are separate only because the wavefunction has two distant maxima is a conceptual mistake. In fact, no signal can be transmitted with this method; it is a case of prediction which looks like a signal, as we already discussed in the section on special relativity.

Such experiments have actually been performed. The first and most famous was the one performed in 1982, with photons instead of electrons by Alain Aspect. Like all latter ones, it has fully confirmed quantum mechanics.

In fact, such experiments just confirm that it is not possible to treat either of the two particles as a system, and to ascribe them any property by themselves, such as spin. The Heisenberg picture would express this even more clearly.

These first two examples of apparent non-locality can be dismissed with the remark that since obviously no energy flux faster than light is involved, no problems with causality appear. Therefore the following example is more interesting. Take two identical atoms, one in an excited state, one in the ground state, and call l the distance that separates them. Common sense tells that if the first atom returns to its ground state emitting a photon, the second atom can be excited only after a time $t = l/c$ has been elapsed, i.e. after the photon has travelled to the second atom.

---

[*] In classical electrodynamics, the same happens with the scalar and the vector potential, if the Coulomb gauge is used.
[**] David Joseph Bohm (1917–1992) American-British physicist, codiscovered the Aharonov-Bohm effect; he spent a large part of his life investigating the connections between quantum physics and philosophy.

Surprisingly, this conclusion is wrong. The atom in its ground state has a non-zero probability to be excited directly at the same moment in which the first is deexcited. This has been shown most simply by Hegerfeldt. The result has even been confirmed experimentally.

Ref. 597

More careful studies show that the result depends on the type of superposition of the two atoms at the beginning: coherent or incoherent. For incoherent superpositions, the intuitive result is correct; the surprising result appears only for coherent superpositions. This pretty conclusion again avoids non-locality.

Curiosities

▪ In a few rare cases, the superposition of different macroscopic states can actually be observed by lowering the temperature to sufficiently small values and by carefully choosing suitably small masses or distances. Two well-known examples of coherent superpositions are those observed in gravitational wave detectors and in Josephson junctions. In the first case, one observes a mass as heavy as 1000 kg in a superposition of states located at dif-

Ref. 590

Figure 217 Bohm's Gedankenexperiment

ferent points in space: the distance between them is of the order of 10^{-17} m. In the second case, in superconducting rings, superpositions of a state in which a macroscopic current of the order of 1 pA flows in clockwise direction with one where it flows in counterclockwise direction have been produced.

Ref. 604

▪ Obviously, superpositions of magnetization in up and down direction for several materials have also be observed.

Ref. 598

▪ Since the 1990s, the sport of finding and playing with new systems in coherent superpositions has taken off world-wide. Its challenges lie in the clean experiments necessary. Experiments with single atoms in superpositions of states are among the most popular ones.

Ref. 600
Ref. 601

▪ In 1997, coherent atom waves were extracted from a cloud of sodium atoms.

Ref. 602

▪ Macroscopic objects thus usually are in incoherent states. This is the same situation as for light. The world is full of 'macroscopic', i.e. incoherent light: daylight, and all light from lamps, from fire, and from glow-worms is incoherent. Only very special and carefully constructed sources, such as lasers or small point sources, emit coherent light. Only these allow to study interference effects. In fact, the terms 'coherent' and 'incoherent' originated in optics, since for light the difference between the two, namely the capacity to interfere, had been observed centuries before the case of matter.
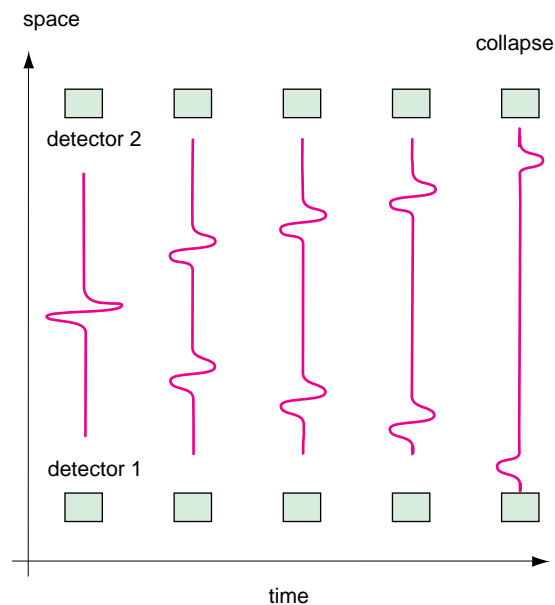
Coherence and incoherence of light and of matter manifest themselves differently, since matter can stay at rest but light cannot, and because light is made of bosons, but matter is made of fermions. Coherence can be observed easily in systems composed of bosons, such as light, sound in solids, or electron pairs in superconductors. Coherence is less easily observed in systems of fermions, such a s systems of atoms. However, in both cases a decoherence time can be defined. In both cases coherence in many particle systems is best observed if all particles are in the same state (superconductivity, laser light), and in both cases the transition from coherent to incoherent is due to the interaction with a bath. A beam is thus incoherent if its particles arrive randomly in time and in frequency. In everyday life, the rarity of observation of coherent matter superpositions has the same origin as the rarity of observation of coherent light.

▪ We will discuss the relation between the environment and the *decay* of unstable systems later on. The phenomenon is completely described by the concepts given here.

▪ Another conclusion deserves to be mentioned: *teleportation contradicts correlations*. Can you confirm it?

What is all the fuzz about measurements in quantum theory?

Measurements in quantum mechanics are disturbing. They lead to statements in which *probabilities* appear. That is puzzling. For example, we speak about the probability of finding an electron at a certain distance from the nucleus of an atom. Statements like this belong to the general type 'when the observable A is measured, the probability to find the outcome a is p.' In the following we will show that the probabilities in such statements are inevitable for any measurement, because, as we will show, any measurement and any observation is a special case of decoherence process. (Historically however, the process of measurement was studied before the more general process of decoherence. That explains in part why the topic is so confused in many peoples' minds.)

What is a measurement? As already mentioned in the intermezzo a measurement is any interaction which produces a record or a memory. Measurements can be performed by machines; when they are performed by people, they are called observations. In quantum theory, the action of measurement is not as straightforward as in classical physics. This is seen most strikingly when a quantum system, such as a single electron, is first made to pass a diffraction slit, or better – in order to make its wave aspect become apparent – a double slit, and then is made to hit a photographic plate, in order to make also its particle aspect appear. Experiment shows that the blackened dot, the spot where the electron has hit the screen, cannot be determined in advance. (The same is true for photons or any other particle.) However, for large numbers of electrons, the spatial distribution of the black dots, the so-called *diffraction pattern*, can be calculated in advance with high precision.

The outcome of experiments on microscopic systems thus forces us to use probabilities for the description of microsystems. We find that the probability distribution $p(\mathbf{x})$ of the spots on the photographic plate can be calculated from the wavefunction ψ of the electron at the screen surface and is given by $p(\mathbf{x}) = |\psi^{\dagger}(\mathbf{x})\psi(\mathbf{x})|^2$. This is in fact a special case of the general *first property of quantum measurements*: the measurement of an observable A for a system in a state ψ gives as result one of the eigenvalues a_n, and the probability P_n to

get the result a_n is given by

$$P_n = |\varphi_n^\dagger \psi|^2 \quad , \tag{437}$$

where φ_n is the eigenfunction of the operator A corresponding to the eigenvalue a_n.

Experiments also show a *second property of quantum measurements:* after the measurement, the observed quantum system is in the state φ_n corresponding to the measured eigenvalue a_n. One also says that during the measurement, the wavefunction has *collapsed* from
ψ to φ_n. By the way, both properties can also be generalized to the more general cases with degenerate and continuous eigenvalues.

At first sight, the sort of probabilities encountered in quantum theory are different from the probabilities we encounter in everyday life. Roulette, dice, pachinko machines, the direction in which a pencil on its tip falls, have been measured experimentally to be random (assuming no cheating) to a high degree of accuracy. These systems do not puzzle us. We unconsciously assume that the random outcome is due to the small, but uncontrollable variations of the starting conditions every time the experiment is repeated. *

gravity

Figure 218 A system showing probabilistic behaviour

But microscopic systems seem to be different. The two measurement properties just mentioned express what physicists observe in every experiment, even if the initial conditions are taken to be *exactly* the same every time. But why then is the position for a single electron, or most other observables of quantum systems, not predictable? In other words, what happens during the collapse of the wavefunction? How long does it take? In the beginning of quantum theory, there was the perception that the observed unpredictability is due to the lack of information about the state of the particle. This lead many to search for so-called 'hidden variables'; all these attempts were doomed to fail, however. It took some time for the scientific community to realize that the unpredictability is *not* due to the lack of information about the state of the particle, which is indeed described *completely* by the state vector ψ.

In order to uncover the origin of probabilities, let us recall the nature of a measurement, or better, of a general observation. *Any observation is the production of a record.* The record can be a visual or auditive memory in our brain, or a written record on paper, or a tape
recording, or any such type of object. As explained in the intermezzo, an object is a record if it cannot have arisen or disappeared by chance. To avoid the influence of chance, all records have to be protected as much as possible from the outer world; e.g. one typically puts archives in earthquake safe buildings with fire protection, keeps documents in a safe, avoids brain injury as much as possible, etc.

On top of this, records have to be protected from their internal fluctuations. These internal fluctuations are due to the many components any recording device is made of. But if the fluctuations were too large, they would make it impossible to distinguish between the
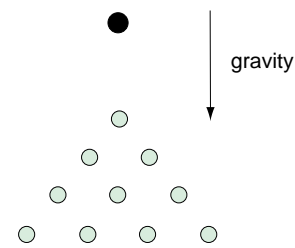

∗ To get a feeling for the limitations of these unconscious assumptions, you may want to read the story of those physicists who build a machine who could predict the outcome of a roulette ball from the initial velocity imparted by the croupier. The story is told by … …,

possible contents of a memory. Now, fluctuations decrease with increasing size of a system, typically with the square root of the size. For example, if a hand writing is too small, it is difficult to read if the paper gets brittle; if the magnetic tracks on tapes are too small, they demagnetize and loose the stored information. In other words, a record is rendered stable against internal fluctuations by making it of sufficient size. Every record thus consists of many components and shows small fluctuations.

Therefore, every system with memory, i.e. every system capable of producing a record, contains a *bath*. In summary, the statement that any observation is the production of a record can be expressed more precisely as: *Any observation of a system is the result of an interaction between that system and a bath in the recording apparatus.*[*]

But we can say more. Obviously, any observation measuring a physical quantity uses an interaction *depending* on that same quantity. With these seemingly trivial remarks, one can describe in more detail the process of observation, or as it is usually called in the quantum theory, the measurement process.

Any measurement apparatus, or *detector*, is characterized by two main aspects: the interaction it has with the microscopic system, and the bath it contains to produce the record. Any description of the measurement process thus is the description of the evolution of the microscopic system *and* the detector; therefore one needs the Hamiltonian for the particle, the interaction Hamiltonian, and the bath properties, such as the relaxation time. The interaction specifies what is measured, and the bath realizes the memory.

the quantum
mechanical
system

apparatus, e.g. eye, ear,
or machine, with memory,
i.e. coupled to a bath

H H_{int} t_r

description   determined   friction,
of its possible   by the type   e.g. due
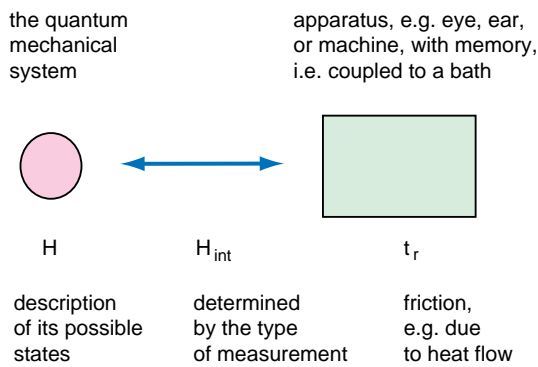states   of measurement   to heat flow

Figure 219 The concepts used in the description of measurements

We know that only classical thermodynamic systems can be irreversible; quantum systems are not. We therefore conclude: a measurement system *must* be described classically: otherwise it has no memory and is not a measurement system: it produces no record! Nevertheless, let us see what happens if one describes the measurement system quantum mechanically. Let us call *A* the observable which is measured in the experiment and its eigenfunctions φ_n. We describe the quantum mechanical system under observation – often a particle – by a state ψ. This state can always be written as $\psi = \psi_p \psi_{other} = \sum_n c_n \varphi_n \psi_{other}$, where ψ_{other} represents the other degrees of freedom of the particle, i.e. those not described – *spanned*, in mathematical language – by the operator *A* corresponding to the observable we want to measure. The numbers $c_n = |\varphi_n^\dagger \psi_p|$ give the expansion of the state ψ_p, which is taken to be normalized, in terms of the basis φ_n. For example, in a typical position measurement, the functions φ_n would be the position eigenfunctions and ψ_{other}

---

[*] Since baths imply friction, we can also say: memory needs friction.

would contain the information about the momentum, the spin, and all other properties of the particle.

How does the system-detector interaction look like? Let us call the state of the apparatus before the measurement χ_{start}; the measurement apparatus itself, by definition, is a device which, when it is hit by a particle in the state $\varphi_n\psi_{other}$, changes from the state χ_{start} to the state χ_n. One then says that the apparatus has *measured* the eigenvalue a_n corresponding to the eigenfunction φ_n of the operator A. The index n is thus the record of the measurement; it is called the *pointer* index or variable. This index tells us in which state the microscopic system was before the interaction. The important point, taken from our previous discussion, is that the states χ_n, being records, are macroscopically distinct, precisely in the sense of the previous section. Otherwise they would not be records, and the interaction with the detector would not be a measurement.

Of course, during measurement, the apparatus sensitive to φ_n changes the part ψ_{other} of the particle state to some other situation $\psi_{other,n}$, which depends on the measurement and on the apparatus; we do not need to specify it in the following discussion.[*] Let us have an intermediate check of our reasoning. Do apparatuses as described here exist? Yes, they do. For example, any photographic plate is a detector for the position of ionizing particles. A plate, and in general any apparatus measuring position, does this by changing its momentum in a way depending on the measured position: the electron on a photographic plate is stopped. In this case, χ_{start} is a white plate, φ_n would be a particle localized at spot n, χ_n is the function describing a plate blackened at spot n and $\psi_{other,n}$ describes the momentum and spin of the particle after it has hit the photographic plate at the spot n.

Now we are ready to look at the measurement process itself. For the moment, let us disregard the bath in the detector. In the time before the interaction between the particle and the detector, the combined system was in the initial state ψ_i given simply by

$$\psi_i = \psi_p\chi_{start} = \sum_n c_n\varphi_n\psi_{other}\chi_{start} \quad . \tag{440}$$

After the interaction, using the just mentioned characteristics of the apparatus, the combined state ψ_a is

$$\psi_a = \sum_n c_n\varphi_n\psi_{other,n}\chi_n \quad . \tag{441}$$

This evolution from ψ_i to ψ_a follows from the evolution equation applied to the particle detector combination. Now the state ψ_a is a superposition of macroscopically distinct states,

---

[*] How does the interaction look like mathematically? From the description we just gave, we specified the final state for every initial state. Since the two density matrices are related by

$$\rho_f = T\rho_i T^\dagger \tag{438}$$

Challenge 988 we can deduce the Hamiltonian from the matrix T. Are you able to see how?

By the way, one can say in general that an apparatus measuring an observable A has a system interaction Hamiltonian depending on the pointer variable A, and for which one has

$$[H + H_{int}, A] = 0 \quad . \tag{439}$$

as it is a superposition of distinct macroscopic states of the detector. In our example ψ_a could correspond to a superposition of a state where a spot on the left upper corner is blackened on an otherwise white plate with one where a spot on the right lower corner of the otherwise white plate is blackened. Such a situation is never observed. Let us see why. The density matrix ρ_a of this situation, given by

$$\rho_a = \psi_a \otimes \psi_a^\dagger = \sum_{n,m} c_n c_m^* (\varphi_n \psi_{\text{other},n} \chi_n) \otimes (\varphi_m \psi_{\text{other},m} \chi_m)^\dagger \quad , \tag{442}$$

contains non-diagonal terms, i.e. terms for $n \neq m$, whose numerical coefficients are different from zero. Now let's take the bath back in.

From the previous section we know the effect of a bath on such a macroscopic superposition. We found that a density matrix such as ρ_a decoheres extremely rapidly. We assume here that the decoherence time is negligibly small, in practice thus instantaneous,[*] so that the off-diagonal terms vanish, and only the the final, diagonal density matrix ρ_f, given by

$$\rho_f = \sum_n |c_n|^2 (\varphi_n \psi_{\text{other},n} \chi_n) \otimes (\varphi_n \psi_{\text{other},n} \chi_n)^\dagger \tag{443}$$

has experimental relevance. As explained above, such a density matrix describes a mixed state, and the numbers $P_n = |c_n|^2 = |\varphi_n^\dagger \psi_p|^2$ give the probability of measuring the value a_n and of finding the particle in the state $\varphi_n \psi_{\text{other},n}$ as well as the detector in the state χ_n. But this is precisely what the two properties of quantum measurements state.

We therefore find that describing a measurement as an evolution of a quantum system interacting with a macroscopic detector, itself containing a bath, we can *deduce* the two properties of quantum measurements, and thus the collapse of the wave function, from the quantum mechanical evolution equation. The decoherence time of the previous section becomes the time of collapse in the case of a measurement:

$$t_{\text{collapse}} = t_{\text{d}} < t_r \tag{444}$$

We thus have a formula for the time the wavefunction takes to collapse. The first experimental measurements of the time of collapse are appearing, and confirm these results.   Ref. 605

Hidden variables

Obviously a large number of people are not satisfied with the arguments just presented. They long for more mystery in quantum theory. The most famous approach is the idea that the probabilities are due to some hidden aspect of nature which is still unknown to humans. But the beautiful thing about quantum mechanics is that it allows both conceptual and experimental tests on whether such *hidden variables* exist without the need of knowing them.

---

[*] Note however, that an *exactly* vanishing decoherence time, which would mean a *strictly* infinite number of degrees of freedom of the environment, is in contradiction with the evolution equation, and in particular with unitarity, locality and causality. It is essential in the whole argument not to confuse the logical consequences of a very small decoherence time with those of an exactly vanishing decoherence time.

▪ Clearly, hidden variables controlling the evolution of microscopic system would contradict the result that action values below $\hbar/2$ cannot be detected. This minimum observable action is the reason for the random behaviour of microscopic systems.

▪ Historically, the first argument against hidden variables was given by John von Neumann.[*]

– CS – to be written – CS –

▪ An additional no-go theorem for hidden variables was published by Kochen and Specker in 1967, (and independently by Bell in 1969). It states that noncontextual hidden variables are impossible, if the Hilbert space has a dimension equal or larger than three. The theorem is about noncontextual variables, i.e. about hidden variables *inside* the quantum mechanical system. The Kochen-Specker theorem thus states that there is no noncontextual hidden variables model, because mathematics forbids it. This result essentially eliminates all possibilities, because usual quantum mechanical systems have dimensions much larger than three.

But also common sense eliminates hidden variables, without any recourse to mathematics, with an argument often overlooked. If a quantum mechanical system had internal hidden variables, the measurement apparatus would have zillions of them.[**] And that would mean that it could not work as a measurement system.

Of course, one cannot avoid noting that about *contextual* hidden variables, i.e. variables in the environment, there are no restricting theorems; indeed, their necessity was shown earlier in this section.

▪ Obviously, despite these results, people have also looked for experimental tests on hidden variables. Most tests are based on the famed *Bell's equation*, a beautifully simple relation published by John Bell[***] in the 1960s.

The starting idea is to distinguish quantum theory and locally realistic theories using hidden variables by measuring the polarizations of two correlated photons. Quantum theory says that the polarization of the photons is fixed only at the time it is measured, whereas local realistic theories say that it is fixed already in advance.

Imagine the polarization is measured at two distant points A and B, each observer can measure 1 or -1 in each of his favourite direction. Let each observer choose two directions, 1 and 2, and call their results a_1, a_2, b_1, and b_2. Since they all are either 1 or -1, the value of the specific expression $(a_1 + a_2)b_1 + (a_2 - a_1)b_2$ has always the value ± 2.

Imagine you repeat the experiment many times, assuming that the hidden variables appear statistically. You then can deduce (a special case of) Bell's equation

$$|(a_1b_1) + (a_2b_1) + (a_2b_2) - (a_1b_2)| \leqslant 2 \qquad (445)$$

[*] John von Neumann (1903, Budapest–1957, Washington DC) mathematician, one of the fathers of the modern computer.
[**] Which leads to the definition: one zillion is 10^{23}.
[***] John Stewart Bell (1928–1990), theoretical physicist who worked mainly on the foundations of quantum theory.

where the expressions in brackets are the averages of the measurement products over a large number of samples. This result holds independently of the directions of the involved polarizers.

On the other hand, if the polarizers 1 and 2 at position *A* and the corresponding ones at position *B* are chosen with angles of $\pi/4$, quantum theory predicts that the result is

$$|(a_1 b_1) + (a_2 b_1) + (a_2 b_2) - (a_1 b_2)| = 2\sqrt{2} > 2 \tag{446}$$

which is in complete contradiction with the hidden variable result.

So far, all experimental checks of Bell's equation have confirmed standard quantum mechanics. No evidence for hidden variables has been found. This is not really surprising, since the search for such variables is based on a misunderstanding of quantum mechanics or on personal desires on how the world should be, instead of relying on experimental evidence.

Another measurable contradiction between quantum theory and locally realistic theories has been predicted by Greenberger, Horn and Zeilinger. Experiments trying to check the result are being planned. No deviation from quantum theory is expected.

Conclusions on probabilities and determinism

> Geometric demonstramus quia facimus;
> si physics demonstrare possemus, faceremus.
> Giambattista Vico[*]

From the argument presented here, we draw a number of conclusions which we need for the rest of our mountain ascent. Note that these conclusions are not shared by all physicists! The whole topic is still touchy.

▪ Probabilities appear in measurements because the details of the state of the bath are unknown, not because the state of the quantum system is unknown. *Quantum mechanical probabilities are of statistical origin and are due to baths*. The probabilities are due to the large number of degrees of freedom contained in baths. These degrees of freedom make the outcome of experiments unpredictable. If the state of the bath were known, the outcome of an experiment could be predicted. The probabilities of quantum theory are 'thermodynamic' in origin.

In other words, there are *no* fundamental probabilities in nature. All probabilities in nature are due to statistics of many particles. Modifying well-known words by Albert Einstein, 'nature really does not play dice.' We therefore called ψ the *wave function* instead of 'probability amplitude', as is often done. 'State function' would be an even better name.

▪ Any observation in everyday life is a special case of decoherence. What is usually called the collapse of the wavefunction is a process due to the interaction with the bath present in any measuring apparatus. Because humans are warm-blooded and have memory, humans

---

[*] 'We are able to demonstrate geometrical matters because we make them; if we could prove physical matters we would be able to make them.' Giovanni Battista Vico (1668, Napoli– 1744, Napoli) important Italian philosopher and thinker. In this famous statement he points out a fundamental distinction between mathematics and physics.

themselves are thus measurement apparatuses. The fact that our body temperature is 37 °C is thus the reason that we see only a single world, and no superpositions. [*]

■ A measurement is complete when the microscopic system has interacted with the bath in the measuring apparatus. Quantum theory as a description of nature does not require detectors; the evolution equation describes all examples of motion. However, *measurements* do require the existence of detectors; and detectors have to include a bath, i.e. have to be classical, macroscopic objects. In this context one speaks also of a *classical apparatus*. This necessity of the measurement apparatus to be classical had been already stressed in the very early stages of quantum theory.

■ All measurements, being decoherence processes, are irreversible processes and increase entropy.

■ A measurement is a special case of quantum mechanical evolution, namely the evolution for the combination of a quantum system, a macroscopic detector and the environment. Since the evolution equation is relativistically invariant, no causality problems appear in measurements, no locality problems and no logical problems.

■ Since the evolution equation does not involve quantities other than space-time, Hamiltonians and wave-functions, no other quantity plays a role in measurement. In particular, no observer nor any consciousness are involved or necessary. Every measurement is complete when the microscopic system has interacted with the bath in the apparatus. The decoherence inherent in every measurement takes place even if 'nobody is looking.' This trivial consequence is in agreement with the observations of everyday life, for example with the fact that the moon is orbiting the earth even if nobody looks at it. [**] Similarly, a tree falling in the middle of a forest makes noise even if nobody listens. Decoherence is independent of human observation, of the human mind, and of human existence.

■ In every measurement the quantum system interacts with the detector. Since there is a minimum value for the magnitude of action, we cannot avoid the fact that *observation influences objects.* Therefore every measurement *disturbs* the quantum system. Any precise description of observations must also include the the description of this disturbance. In this section the disturbance was modelled by the change of the state of the system from ψ_{other} to $\psi_{other,n}$. Without such a change of state, without a disturbance of the quantum system, a measurement is impossible.

■ Since the complete measurement is described by quantum mechanics, unitarity is and remains the basic property of evolution. There are no non-unitary processes in quantum mechanics.

■ The argument in this section for the description of the collapse of the wavefunction is an explanation exactly in the sense in which the term 'explanation' was defined in the intermezzo; it describes the relation between an observation and all the other aspects of reality, in this case the bath in the detector. The collapse of the wavefunction has been

* Actually, there are more reasons; can youname a few?
   ** The opposite view is sometimes falsely attributed to Niels Bohr; the moon is obviously in contact with many
radiation baths. Can you list a few?

explained, it is not a question of 'interpretation', i.e. of opinion, as unfortunately often is suggested.*

▪ It is not useful to speculate whether the evolution for a *single* quantum measurement could be determined, if the state of the environment around the system were known. Measurements need baths. But baths cannot be described by wavefunctions.** Quantum mechanics is deterministic. Baths are probabilistic.

▪ In summary, there is *no* irrationality in quantum theory. Whoever uses quantum theory as argument for irrational behaviour, for ideologies, or for superstitions is guilty of disinformation. A famous example is the following quote.

> Nobody understands quantum mechanics.
> Richard Feynman

What is the difference between space and time?

More specifically, why are objects localized in space but not in time? Most bath-system interactions are mediated by a potential. All potentials are by definition position dependent. Therefore, every potential, being a function of the position **x**, commutes with the position observable (and thus with the interaction Hamiltonian). The decoherence induced by baths – except if special care is taken – thus first of all destroys the non-diagonal elements for every superposition of states centred at different locations. In short, *objects are localized because they interact with baths via potentials.*

For the same reason, objects also have only one spatial orientation at a time. If the system-bath interaction is spin-dependent, the bath leads to 'localization' in the spin variable. This happens for all microscopic systems interacting with magnets. For this reason, one practically never observes macroscopic superpositions of magnetization. Since electrons, protons and neutrons have a magnetic moment and a spin, this conclusion can even be extended: everyday objects are never seen in superpositions of different rotation states, because of spin-dependent interactions with baths.

As a counterexample, most systems are not localized in time, but on the contrary exist for very long times, because practically all system-bath interaction do *not* commute with time. This is in fact the way a bath is defined to begin with. In short, *objects are permanent because they interact with baths.*

Are you able to find an interaction which is momentum dependent? What is the consequence for macroscopic systems?

In other words, in contrast to general relativity, quantum theory produces a distinction between space and time. In fact, we can *define* position as what commutes with interaction Hamiltonians. This distinction between space and time is due to the properties of matter and its interactions; we could not have found this result in general relativity.

Ref. 608
∗ This implies that the so-called 'many worlds' interpretation is wishful thinking. One also reaches this conclusion when studying the details of this religious approach.
∗∗ This very strong type of determinism will be very much softened in the last part of this text, in which it will be shown that time is not a fundamental concept, and therefore that the debate around determinism looses most of its interest.

Are we good observers?

Are humans classical apparatuses? Yes, they are. Even though several prominent physicists claim that free will and probabilities are related, a detailed investigation shows that this in not the case. Our senses are classical machines, in the sense described above. Our brain is also a classical apparatus, but the fact is secondary; our sensors are the key.

In addition, we have stressed several times that any observing entity needs memory, which means it needs to incorporate a bath. That means that observers have to be made of matter; an observer cannot be made of radiation. Our description of nature is thus severely biased: we describe it from the standpoint of matter. That is a little like describing the stars by putting the earth at the centre of the universe. Can we eliminate this basic anthropomorphism? We will discover this question in the third part of our mountain ascent.

Does the 'wavefunction of the universe' exist?

This expression is frequently heard in discussions about quantum mechanics. Numerous conclusions are drawn from it, e.g. about the irreversibility of time, the importance of initial conditions, the decoherence of the universe, about changes required to quantum theory, changes necessary to thermodynamics or the importance of the mind. Are these arguments correct?

The first thing to clarify is the meaning of 'universe'. As already explained the term can have two meanings: either the collection of all matter and radiation, or this collection *plus* all of space-time. Secondly, we have to recall the meaning of 'wavefunction': it describes the *state* of a system. The state distinguishes two otherwise identical systems; for example, position and velocity distinguish two otherwise identical ivory balls on a billiard table. Alternatively and equivalently, the state describes changes in time.

Does the universe have a state? If we take the wider meaning of universe, obviously it does not. Talking about the state of the universe is a contradiction: by definition, the concept of state, defined as the non-permanent aspects of an object, is applicable only to *parts* of the universe.

We can take the narrower sense of 'universe', as sum of all matter and radiation only, without space and time, and ask the question again. To determine its state, we need a possibility to measure it: we need an environment. But the environment of the smaller universe is space-time only; initial conditions cannot be determined since we need measurements to do this, and thus an apparatus, i.e. a material system with a bath attached to it.

In short, standard quantum theory does not allow for measurements of the universe; therefore it has no state. Summing up, beware of anybody who claims to know something about the wavefunction of the universe. Just ask him: If you know the wavefunction of the universe, why aren't you rich?

Several famous physicists have proposed evolution equations for the wavefunction of the universe! It seems a silly point, but the predictions of these equations cannot be compared to experiments; the arguments just given even make this impossible in principle. The pursuits in this directions, so interesting they are, must therefore be avoided if we want to reach the top of Motion Mountain.

There are many more twists to this story. One possibility is that space-time itself, even without matter, is a bath. This speculation will be shown to be correct later on and seems to allow speaking of the wavefunction of all matter. But then again, it turns out that time is *undefined* at the scales where space-time would be an effective bath; this means that the concept of state is not applicable there.

We can retain as result, valid even in the light of the latest results of physics: there is *no* wavefunction of the universe, independently of what is meant by 'universe'. Before we go on studying the more complicated consequences of quantum theory for the whole universe, we first continue a bit with the consequences of quantum theory for our everyday observations.