2

The First Mystery: Interference

In *Alice Through the Looking-Glass*, the Queen says to Alice that she used to believe six impossible things before breakfast. In this book, we'll ask you to believe only two "impossible things" (before or after breakfast, as you wish): the *superposition of states* or the idea that particles can be in two different mutually incompatible states at once and *nonlocality*, which means that, in some circumstances, one can act at a distance, arbitrarily far, and instantaneously.

But, unlike what the Queen was speaking about, these "impossible things" are well-established facts. The first "impossible thing" will be explained in this chapter and in Chap. 4. We shall see in Chap. 8 that this "impossibility" is not only possible, but is not really that surprising. The second "impossible thing" will be explained in Chap. 7 and will be partly clarified in Chap. 8, but will nevertheless remain baffling.

We invite the reader to put herself or himself mentally in the shoes of a Sherlock Holmes or a Hercule Poirot and pay attention to what is really proven in the experiments below as opposed to what is often asserted in loose talk about them, and that we shall also explain.

As in every good detective novel, the reader has to be patient before learning about the denouement of the plot, which will come only in Chap. 8. Until then, we shall not try to demystify quantum mechanics too much, but rather explain the language physicists use and why they use it.

Indeed, before being demystified, the reader has to understand what is strange in quantum mechanics and, in some sense, "mystifying".

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2.1 The Double-Slit Experiment

To discuss the double-slit experiment, we shall follow the presentation by Feynman [78], and consider the behavior of three types of objects, bullets, waves and electrons, in a situation where they move towards a wall with two slits or holes in it, and where there is a second wall, behind the first one, on which the arrival of those objects is recorded.

Let us start with bullets. This is illustrated in Fig. 2.1: the little box on the left of each part (a, b, c) of the figure emits the bullets. They are sent one by one towards a wall with two slits in it, each of which can be open or not. If they miss the slits, they are absorbed by the first wall. If they pass one of the slits, they arrive somewhere on a second wall, behind the first one and that arrival is recorded. There is no aiming of the bullets towards one of the slits.

Since the bullets cannot always be sent with exactly the same initial position or the same initial velocity, there is some "random" distribution of the bullets on the second wall. In Fig. 2.1 one sees what happens when a set of bullets are sent when only the upper slit is open (part a), when only the lower slit is open (part b), and when both slits are open (part c). Each blue dot on the second wall represents the detection of one bullet, and the blue curves indicate the density of impacts of the bullets.

In part (c) of Fig. 2.1, when both slits are open, the density of impacts of bullets is simply the sum of the densities when each slit is open (see part (a) and (b) of Fig. 2.1).

There is no particular mystery here.

Consider now a wave, say a water wave, sent through the slits. Then, we get interference effects, shown in Figs. 2.2, 2.3 and 2.4. To understand that, think of throwing two pebbles in a pond, at some distance from each other. One

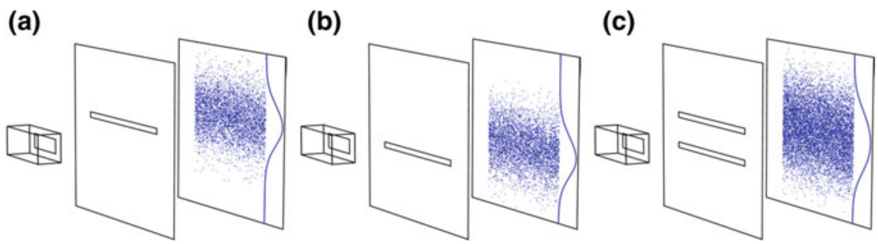

Fig. 2.1 The double-slit experiment with bullets. The little box on the left of each part **a**–**c** of the figure emits the bullets. Part **a** shows what happens when only the upper slit is open, part **b** when only the lower slit is open, and part **c** when both slits are open. Each *blue dot* on the second wall represents the detection of one bullet, and the *blue curves* indicate the density of impacts of the bullets (A. Gondran cc by-sa 4.0)

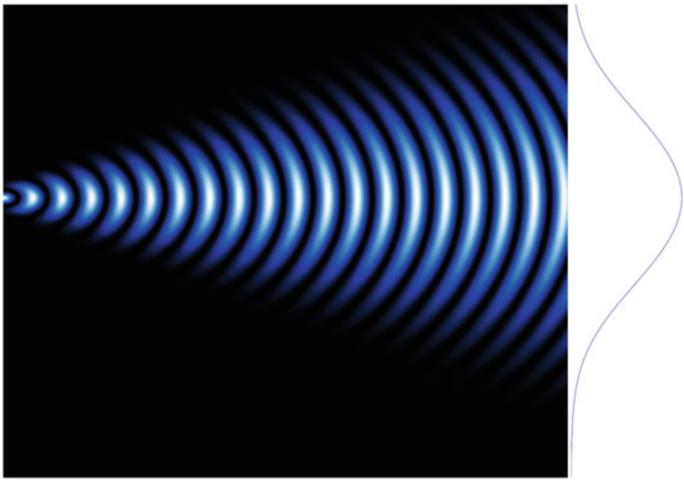

Fig. 2.2 The double-slit experiment with waves when only the upper slit is open. The intensity of the wave is shown in *white* (more intense) and *blue* (less intense). The *blue curve* on the right of the figure indicates the intensity of the wave on the second wall (A. Gondran cc by-sa 4.0)

Fig. 2.3 The double-slit experiment with waves when only the lower slit is open. The intensity of the wave is shown in *white* (more intense) and *blue* (less intense). The *blue curve* on the right of the figure indicates the intensity of the wave on the second wall (A. Gondran cc by-sa 4.0)

can see that the waves generated by the pebbles interfere: at some places the interference is constructive and the waves add to each other, at other places it is destructive and the waves subtract each other.

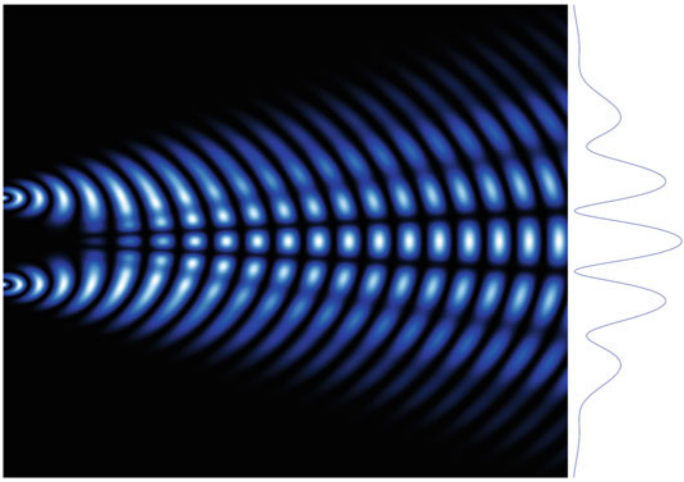

Fig. 2.4 The double-slit experiment with waves when both slits are open. The intensity of the wave is shown in *white* (more intense) and *blue* (less intense). The *blue curve* on the right of the figure indicates the intensity of the wave on the second wall. This exhibits an interference effect (A. Gondran cc by-sa 4.0)

In the two slits experiment with waves, if only one slit is open, we get the results of Figs. 2.2 and 2.3, which are not very different from what one gets with bullets, see parts (a) and (b) of Fig. 2.1.

But, when both slits are open, the wave goes through both slits and each slit acts as a source of a wave propagating towards the second wall (like the two waves produced by the two pebbles). The intensity of the wave indicated by the blue curve on the right of Fig. 2.4 is *not* the sum of the intensities of the waves indicated by the blue curves on the right of Figs. 2.2 and 2.3. Note that at some places the intensity of the wave on the second wall is less than what it is when only one slit is open, but that is exactly what one would expect for waves, because of interference.

In order to make the comparison with what happens with bullets easier, we have included in Fig. 2.5 a three dimensional picture with all three situations arising with waves (only the upper slit open, only the lower slit is open, and both slits open).

So far, so good; there is nothing surprising here and these two behaviors are called "classical": one for particles (bullets), one for waves.

The surprises come when one does the experiment with electrons. Electrons are little particles with a negative electric charge, and they surround the nucleus in atoms. When moving freely, they carry electricity.

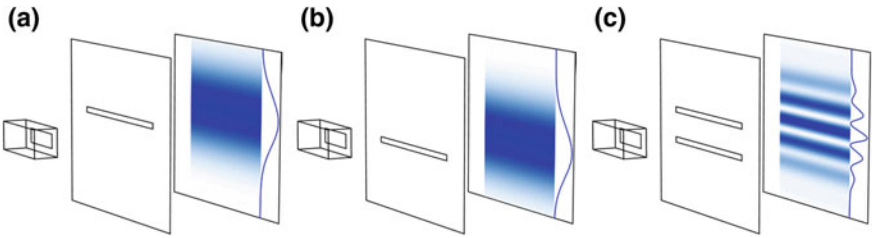

Fig. 2.5 The double-slit experiment with waves in three dimensions. Part **a** shows what happens when only the upper slit is open, part **b** when only the lower slit is open, and part **c** when both slits are open. The *blue areas* on the second wall in each part correspond to the detection of the intensity of the wave. The *blue curves* indicate the intensity of the wave on the second wall. This exhibits an interference effect (A. Gondran cc by-sa 4.0)

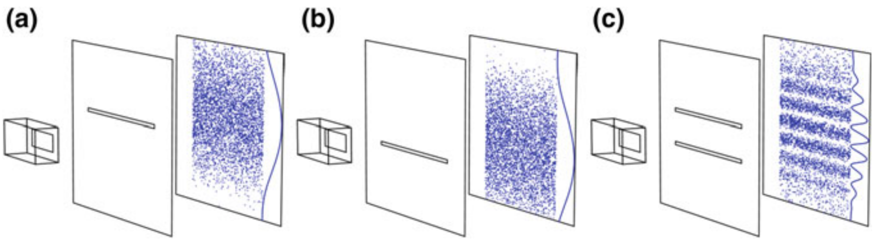

Fig. 2.6 The double-slit experiment with electrons, shown in three dimensions. Part **a** shows the detections of electrons on the second wall when only the upper slit is open. Each *dot* on the second wall corresponds to the detection of one electron. Part **b** shows the detections of electrons on the second wall when only the lower slit is open, and part **c** shows the detections of electrons on the second wall when both slits are open. In all three parts, the *blue curves* indicate the density of impacts of the electrons on the second wall (A. Gondran cc by-sa 4.0)

For the double-slit experiment with electrons, we show the situation in three dimensions, see Fig. 2.6, when only the upper slit is open, when only the lower one is open and when both slits are open.

When only one slit is open, one obtains the results of parts (a) and (b) of Fig. 2.6, where the blue curves describe the densities of the impact of the electrons on the second wall. The results are similar to what one obtains with bullets, see parts (a) and (b) of Fig. 2.1.

Now, *when both slits are open*, one obtains the results of part (c) of Fig. 2.6, which is similar to what one obtains with waves, see Fig. 2.4 and part (c) of Fig. 2.5. Note that there are places where the density of particle impacts is *less* when both slits are open than when only one of them is.

This phenomenon and many other related phenomena are called *interference phenomena*, because whether one slit is open or not seems to interfere with the behavior of the particles going through the other slit. This is the essence of the first quantum mystery!

Note that electrons are sent (in principle) one by one, so that no explanation of their behavior can be based on a possible interaction between the electrons. Note also that one detects always the electrons in one piece and at a precise location, no matter where the second wall is placed.

The mystery thickens if one puts a detector behind one of the slits, say the lower one, that would allow us to determine whether the particle goes through that slit.

Then, the interference pattern disappears (see Fig. 2.7)! And that is true even if one considers only the events where the detector *does not* detect a particle; which means that, in order for the interference pattern to disappear, it is enough that *we are able to know* through which slit the particle went (here, through the upper one), simply by checking that it does not go through the other slit.

Another way to remove the interference pattern is to put the second wall sufficiently close to the first one. Then, the interference pattern observed in part (c) of Fig. 2.6 essentially disappears, see Fig. 2.8.

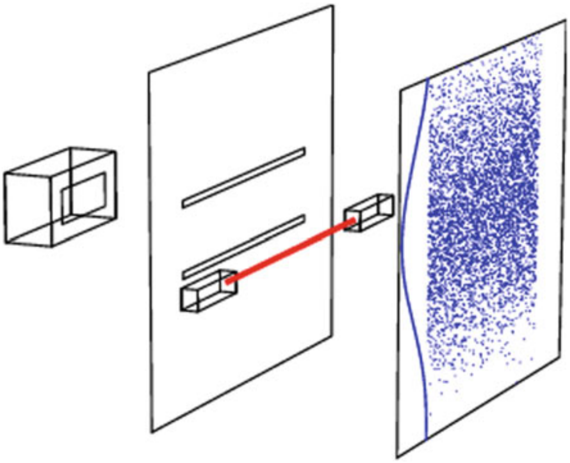

Fig. 2.7 The double-slit experiment with electrons when both slits are open, but where one puts a detector that detects particles going through the lower slit. The detector is indicated by the *red line* behind the first wall. Each *blue dot* on the second wall corresponds to the detection of one electron, which means that it was not detected after the first wall, and thus that it went through the upper slit. The *blue curve* indicates the density of impacts of the electrons on the second wall. We see that the interference pattern observed in part **c** of Fig. 2.6 disappears and that one gets results similar to what happens when only the upper slit is open (part **a**) of Fig. 2.6) (A. Gondran cc by-sa 4.0)

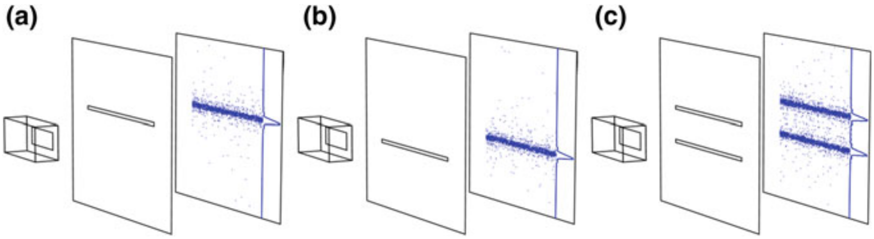

Fig. 2.8 The double-slit experiment with electrons, similar to Fig. 2.6, but where one puts the second wall sufficiently close to the first one (the distance between the walls is less by a factor of ten than in Fig. 2.6, although we have rescaled the figure so that this distance looks the same as in Fig. 2.6). We see that the interference pattern observed in part **c** of Fig. 2.6 essentially disappears (A. Gondran cc by-sa 4.0)

This is sometimes expressed by saying that, if we *look* or if we *know* through which slit the particle went, then it behaves like a particle, but if we do not know through which slit it went, it behaves like a wave.

And this leads to the famous expression: *the wave-particle duality*. Electrons are supposed to have a dual nature: sometimes they are particles, sometimes waves. Moreover, which "nature" they have seems to depend on whether we "look" at them or not!

In the age of Twitter, Sean Carroll, a theoretical physicist at the California Institute of Technology, who is also a cosmologist and author of several popular books, considers that the best answer to "how to summarize quantum mechanics in five words?" comes from the physicist and science writer Aatish Bhatia whom Carroll quotes:

> Quantum mechanics in 5 words. Don't look: wave. Look: particle.
>
> Sean Carroll [40, p. 35]

This is the first time that we refer to *our knowledge* of something as having apparently an impact on a physical situation. What this really means is of course one of the main subjects of this book!

To summarize, the double-slit experiment with electrons leads to an apparent *dead end* : indeed, what does each particle do?

1. Does it go through one slit? But then, why does the opening of the other slit affect the density of particles detected at a given point on the second wall? How come that this density is lower at some places when both slits are open than when only one slit is open?

2. Does it go through both slits? No, because one always detects the particle in one piece at a given place (there is no half-electron), and, by placing the second wall right next to the first one, one can determine through which slit the particle went, see Fig. 2.8.

These phenomena are sometimes described by saying that the particle goes through both slits when they are both open and through one slit otherwise. But what does it mean for a particle to go through two slits whose separation is far greater than the size of that particle? And how does the electron, while moving towards the wall with the slits, "know" whether one or both slits will be open, so as to know whether it should behave as a wave or as a particle?

This double-slit experiment is an example of what Niels Bohr called "complementarity": we can either check through which slit the particle went, when both slits are open, and then the particle behaves as a particle, or we can ignore which slit the particle went through, and then the particle behaves as a wave. But we cannot combine both pictures into a single coherent whole.

Note that "complementary" is used here in a non-habitual fashion: the word usually means that two pictures, say of a person viewed from the front and from the back, may "complement" each other in the sense that they yield a more precise image of that person. But one must stress that, for Bohr, the wave description and the particle one are "complementary" in the sense that they *exclude* each other.

In any case, these "ways of speaking" do not cast much light on what is really going on.

That the double-slit experiment is mysterious is acknowledged by most physicists. For example, in a standard textbook of quantum mechanics, written by two famous Soviet physicists, Lev Landau and Evgeny Lifshitz, one reads:

> It is clear that [the results of the double-slit experiment] can in no way be reconciled with the idea that electrons move in paths. [. . .] In quantum mechanics there is no such concept as the path of a particle.
>
> Lev Landau and Evgeny Lifshitz [114, p. 2]

And, after describing the double-slit phenomenon, Richard Feynman wrote:

> Nobody knows any machinery. Nobody can give you a deeper explanation of this phenomenon than I have given; that is, a description of it.
>
> Richard Feynman, [79, p. 145]

Coming back to the three fundamental questions raised in Chap. 1, what does the double-slit experiment suggest?

1. It suggests some sort of "reality created by the observer", since knowing through which slit the particle goes (by putting a detector behind one of the slits) seems to affect its behavior. But nothing can be concluded so far, as to what sort of "observer" we are talking about. Does it have to be a human subject or merely some purely physical interaction with the detector behind the slit in the first wall?
2. As for determinism, it seems that one cannot predict or control where the particle will be detected on the second wall. But that in itself may not be terribly surprising, since it is also true for the bullets, unless one is able to control very precisely their initial position and initial velocity. But one could expect that, the smaller the particle, the more difficult it is to control those values and that our incapability to predict where the electrons will be detected is thus not that strange and, by itself, does not prove indeterminism.
3. There seems also to be something nonlocal going on, since opening one slit affects the behavior of the particle going through the other slit (when only that slit is open), even if both slits are quite distant from each other. But there is no proof that the effect is instantaneous. Moreover, one can check that the size of the effect (the interference pattern) depends on how far apart the slits are and where the second wall is placed. For example, if the slits are far apart, or if the second wall is close to the first one, the interference effects will be small (see Fig. 2.8). So, we cannot conclude from this that any genuine nonlocality, namely any instantaneous action at a distance, exists.

2.2 Delayed Choices

John Wheeler invented a clever experiment, called the "delayed-choice" experiment, that makes the mystery of interferences even more troubling.

One can modify the double-slit experiment as follows (see Figs. 2.9 and 2.10): insert lenses behind the slits that will focus the incoming particles toward two counters C_1 and C_2 that may detect them. If one detects the particle on one of those counters, one will be tempted to conclude that the particle went through the upper slit if counter C_1 detects it, and that it went through the lower slit if counter C_2 detects it.[1]

[1] As we will see in Chap. 4, quantum mechanics does not assign paths to particles so that saying that the particle went through one slit or the other is not really allowed by the usual formalism. Besides, we will see in Sect. 8.2 that, in a theory that does assigns paths to particles, one can determine through which slit the particle went, but the result is not the one stated here.

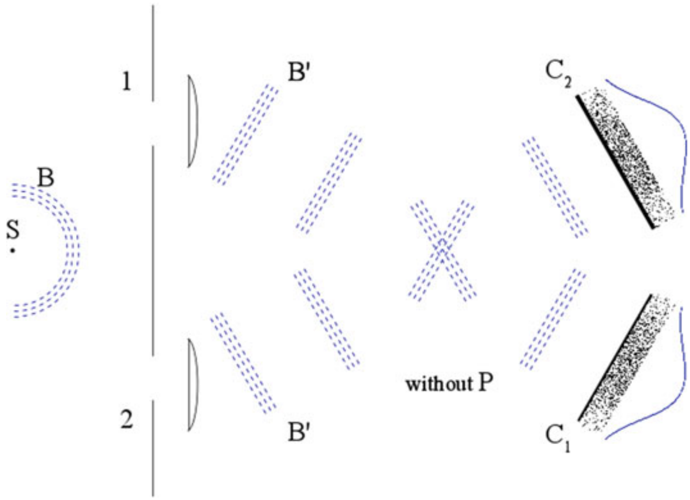

Fig. 2.9 The delayed double-slit experiment with electrons when both slits are open. The source indicated S sends a beam of particles denoted B towards both slits. One inserts lenses, behind the slits, that will focus the incoming beams of particles, denoted B', toward two counters C_1 and C_2 that may detect them. The resulting density of detections of particles on each counter is similar to what one obtains when only one slit is open, namely there are no interference effects. If one detects the particle on one of those counters, one will be tempted to conclude that the particle went through the upper slit if counter C_1 detects it, and that it went through the lower slit if counter C_2 detects it (A. Gondran cc by-sa 4.0)

But one can also insert a detection plate in the region where what appears to be the particles trajectories cross each other, as in Fig. 2.10 (the plate is denoted by P in that figure). Then, one will see an interference pattern as in part (c) of Fig. 2.6, and according to the standard way of speaking, one will say that the particle went through both slits.

But one can choose to insert the detection plate *after* the passage of the particles through the slits. So, it looks like we can decide whether the particle went through both slits or through only one of them by inserting or not the detection plate after the particle had supposedly decided to go through one slit or both!

This is the basis of the claim by Wheeler, that "the past is not really the past until it has been registered" [47, p. 68].

Moreover, Wheeler invented an ingenious scheme where such "experiments" would not take place in the laboratory, but on a cosmic scale: light sent by distant quasars can pass on either side of a galaxy [198]. The experiment here concerns photons instead of electrons, since light is composed of the former, but the phenomena are similar in both cases. The two sides of the galaxy are

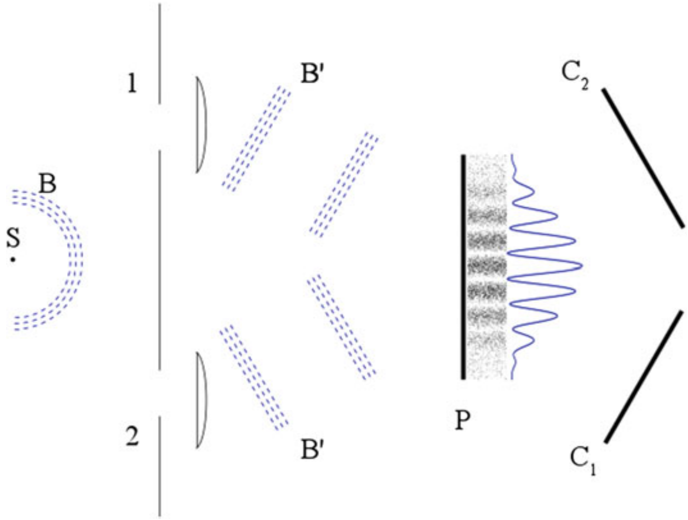

Fig. 2.10 The delayed double-slit experiment with electrons when both slits are open. As in Fig. 2.9, the source indicated S sends a beam of particles denoted B towards both slits. One inserts lenses, behind the slits, that will focus the incoming beams of particles, denoted B', toward two counters C_1 and C_2 that may detect them. But, contrary to what happens in Fig. 2.9, here one also inserts a detection plate (denoted by P in the figure) in the region where what appears to be the particles trajectories cross each other. Then, one sees an interference pattern as in part c of Fig. 2.6, and, according to the standard way of speaking, one will say that the particle went through both slits. Since one can choose to insert the detection plate P *after* the passage of the particle through the slits, it looks like we can decide whether the particle went through both slits or through only one of them (as in Fig. 2.9) by inserting or not the detection plate after the particle had supposedly decided to go through one slit or both (A. Gondran cc by-sa 4.0)

like the two slits here. Then, when the photon reaches the Earth, one can choose to either put some equivalent of the detection plate or not to put it: if we do not put it, we can detect on which side of the galaxy the light went, and, if we do put it, we can "observe" that it went on both sides at once.

If we accept Wheeler's reasoning, this implies that we could decide *now*, by choosing which kind of experiment to perform on the light coming from distant quasars, what happened billions of years ago! In other words, the choices we are making now do not only "create reality", but they also "create" the past. If this were true, it would give us, humans, a more fantastic role in Nature than what most of science fiction can imagine.

2.3 Summary

The phenomenon of interference can be intuitively grasped by thinking of two waves generated by two pebbles thrown in a pond at some distance of each other. At any given place away from the pebbles, the waves will add or subtract each other, which is also expressed by saying that they interfere constructively or destructively.

The first mystery of quantum mechanics is that particles seem to interfere with themselves, although, when one detects them, one always find them localized at some precise place and not spread out as waves are.

We illustrated that with the double-slit experiment: when quantum particles such as electrons are sent towards a wall with two slits in it, and their arrival is recorded on a second wall, beyond the first one, one gets the statistical results illustrated in parts (a) and (b) of Fig. 2.6, when only one slit is open (the blue curves represent the densities of the impacts of the detected particles). This is not mysterious: one should expect a certain "randomness" in the distribution of the initial positions and velocities of the electrons going towards the first wall and thus a certain random distribution of the impacts of the particles on the second wall.

What is mysterious is that, when both slits are open, the density of the impacts of the detected particles is described in part (c) of Fig. 2.6. This looks like Figs. 2.2, 2.3 and 2.4, which shows what happens with waves, and not at all like Fig. 2.1, which shows what happens with classical particles such as bullets.

Since the particles are sent in this experiment one by one and are detected in one piece and at precise locations on the second wall, one would naturally assume that they pass through one slit or the other. But, if they do, one would expect the density of the impacts of the particles on the second wall to be the sum of the corresponding densities when each slit is open, as in part (c) of Fig. 2.1. But that is not at all what part (c) of Fig. 2.6 shows.

This is the first example of interference: opening one slit seems to affect the behavior of particles that pass through the other slit. Besides, if we add a detector behind one of the slits to see whether the particle goes through it or not, then the interference pattern disappears. This happens when one considers the events where the detector does not detect the particle, namely when one considers only the particles that are known to go through the other slit (see Fig. 2.7). This is sometimes expressed by saying that, if we know through which slit the particle goes, then it behaves like a particle, but if we do not know through which slit it goes, then it behaves like a wave. But unless the word "know" here is better explained and clarified, this sort of summary only adds to the mystery of the situation.

This easily leads to the idea of "delayed-choices": one can insert a detection plate in the modified double-slit experiment of Figs. 2.9 and 2.10 and detect an interference pattern, or not insert it and then "see" through which slit the particle went by placing some detectors further away. In that way, we decide whether the particle "goes through both slits at once" or "goes through only one slit" *after* the particle has apparently "decided" to do one or the other.

This looks truly fantastic: we, humans, "create reality", not only in the present but also in the past!