Chapter 1
Three Simple Experiments

In this chapter, we consider a series of simple experiments. By contemplating the meaning of the outcomes of these experiments we are forced to adopt some very counterintuitive conclusions about the behaviour of quantum particles.

1.1 The Purpose of Physical Theories

Since antiquity, people have tried to understand the world around them in terms of simple principles and mechanisms. The Greek philosopher Aristotle (who lived in the 4th century BCE in Athens, Greece) believed that all heavenly bodies moved in perfect circles around the Earth. The discrepancy of this basic principle with the observed movement of the planets led to increasingly complicated models, until Copernicus introduced a great simplification by assuming that the planets orbit the Sun instead. Galileo, Kepler, and Newton refined this theory further in the sixteenth and seventeenth century, with only Mercury's orbit resisting accurate description. Solving this last puzzle ultimately culminated in Einstein's theory of general relativity in the early twentieth century.

What makes science different from other human endeavours is that our theories about the world we live in must conform to the outcomes of our observations in well-designed and well-executed experiments. Particularly in physics, our experiments form the ultimate arbiter whether we are on the right track with our theories or not. A theory that can predict the outcomes of our experiments is considered successful.

However, it is not enough to just predict the motion of the planets, the behaviour of magnets, or how electrical components should be wired to build a radio. We want to know why planets, magnets, resistors, and capacitors behave the way they do. We

Electronic supplementary material The online version of this chapter (https://doi.org/10.1007/978-3-319-92207-2_1) contains supplementary material, which is available to authorized users.

© Springer International Publishing AG, part of Springer Nature 2018

P. Kok, *A First Introduction to Quantum Physics*,
Undergraduate Lecture Notes in Physics,
https://doi.org/10.1007/978-3-319-92207-2_1

naturally assume that there is an underlying microscopic world that determines the way resistors and capacitors respond to currents, and how magnets interact. Indeed, this has been an extraordinarily successful programme. Electricity and magnetism are explained by only four basic equations, called Maxwell's equations, and gravity is understood by a single equation, called Einstein's equation.

These equations tell us not only how to describe the behaviour of planets and magnets, but they give an explanation of that behaviour in terms of underlying physical "stuff". In the case of electricity and magnetism the underlying stuff is charges, currents, and electric and magnetic fields. In the case of gravity, the underlying stuff is space-time, which has properties like curvature. These fields and curved space are assumed to really exist, independent of whether we look at it or not. Similarly, we all believe that atoms exist, and that their collective motion causes directly observable phenomena such as air pressure and temperature. In other words, atoms are real. And so are curved space and electromagnetic fields.

In physics, we want to construct theories that explain a wide variety of phenomena based on a few types of physical objects, plus the rules that govern these objects. The objects are taken as really "there". This is called scientific realism, and it is what most scientists believe at heart.

In the beginning of the twentieth century, physicists came up with a new theory to describe the behaviour of atoms that was extraordinarily successful. It predicted new phenomena that were subsequently discovered, and there has not been a single credible experiment that contradicts it. I am talking, of course, about quantum physics.

But quantum physics is not like electrodynamics or general relativity. Simple scientific realism is difficult to maintain, and this has led to all sorts of seemingly fantastical claims about the nature of underlying reality. We will explore these difficulties, and in the process develop the basic structure of the theory. You will be able to perform calculations in quantum physics, and develop a clear picture of what we can and cannot say about the underlying reality of nature according to quantum physics.

Fig. 1.1 A laser and a detector. The interactive figure is available online (see supplementary material 1)

Fig. 1.2 The idea of photons. The interactive figure is available online (see supplementary material 2)

1.2 Experiment 1: A Laser and a Detector

We start with a simple thought experiment. Consider the situation shown in Fig. 1.1, in which a laser is pointed at a photodetector. The laser has two settings, “HI” and “LO”, corresponding to high and low output power, respectively. There is an interactive version of the figure available online—like most figures in this book—and it lets you change the laser power to see the effect on the detector. Let us say that the high output is about 1.0 mW, which is the intensity of a typical laser pointer. The photodetector converts light into a current, which is read out by the current meter. When the laser is set to the high power output, we see a steady current on the meter. The strength of the current is directly proportional to the intensity of the light.

Next, we reduce the power of the laser by switching to the setting “LO”. We expect that continuously lowering the power output of the laser will continuously decrease the current in the detector. At first, this is indeed how the system behaves. However, it is an experimental fact that for very low intensities the current is no longer a continuous steady current, but rather comes in pronounced pulses. This is the first counterintuitive quantum mechanical result. In what follows we will explore the consequences of this fact.

You may imagine a constant beam of light from the laser to the detector, but there is a reason we have drawn no line in Fig. 1.1. At this stage we do not know what is happening between the laser and the detector, and we need to be very careful not to make any assumptions that do not have a so-called *operational* meaning in terms of light sources and detectors, that is, a meaning that relates directly to how things operate on a directly observable scale. You may say: “but I can see the light between the laser and the detector if I blow chalk dust in the beam”, and you would be right. However, the chalk dust and your eye would then become a second detection system that we do not yet wish to consider. Having said this, it is customary to interpret the current pulses as small “light packets” traveling from the laser to the detector, shown in Fig. 1.2. These chunks of electromagnetic energy are commonly called photons.

At this stage it is important to remember that we don’t really know anything about these photons, other than that they are defined as the cause of the pulses on the current meter. In particular, you should not assume that they behave like normal objects such as marbles or snooker balls. We need to perform more experiments to establish how they behave, and we will explore this in the coming sections.

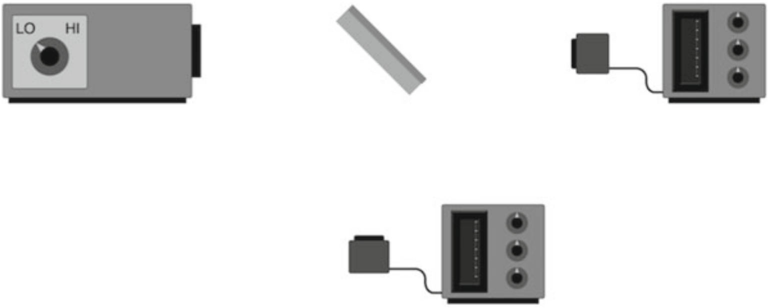

Fig. 1.3 A laser and a beam splitter. The interactive figure is available online (see supplementary material 3)

1.3 Experiment 2: A Laser and a Beam Splitter

For our next experiment, we set the laser output again to "HI". We place a beam splitter between the laser and the detector, which consists of a piece of glass with a semi-reflective coating that lets half of the light through to the original detector. The other half is reflected by the beam splitter. We set up a second detector and current meter to monitor the light that is reflected by the beam splitter (shown in Fig. 1.3). The current created by each detector is half the current created by the detector in experiment 1 (Fig. 1.1). You may know already that the intensity of light is related to its energy, so this experiment demonstrates energy conservation of the beam splitter. It divides the intensity of the laser evenly over the two detectors.

Incidentally, you may have noticed that this situation is somewhat similar to the chalk dust in the laser beam: the chalk acts a little bit like a beam splitter, and your eye is the detector. However, using a beam splitter is much more accurate, since we can in principle precisely tune the reflectivity.

Next, we switch the laser setting from "HI" to "LO", and observe that we again observe current pulses. The pulses look exactly the same as in experiment 1, and the total number of pulses that we detect per second is also unchanged (reflecting the fact that the power output of the laser is the same as in 1). This is shown in Fig. 1.3. The pulses appear randomly in the two detectors. We cannot predict which detector will trigger a current pulse in advance. In other words, the probability that detector D_1 is triggered is $p_1 = \frac{1}{2}$, and the probability that detector D_2 is triggered is $p_2 = \frac{1}{2}$. The sum of the probabilities is $p_1 + p_2 = 1$, as it should be.

Moreover, at low enough intensity we never find a pulse in both detectors simultaneously. If we return to the mental picture of chunks of energy, we can now say that the photon triggers detector D_1 or detector D_2, but never both simultaneously. In other words, the photon is *indivisible*. We have experimentally established this as a physical property.

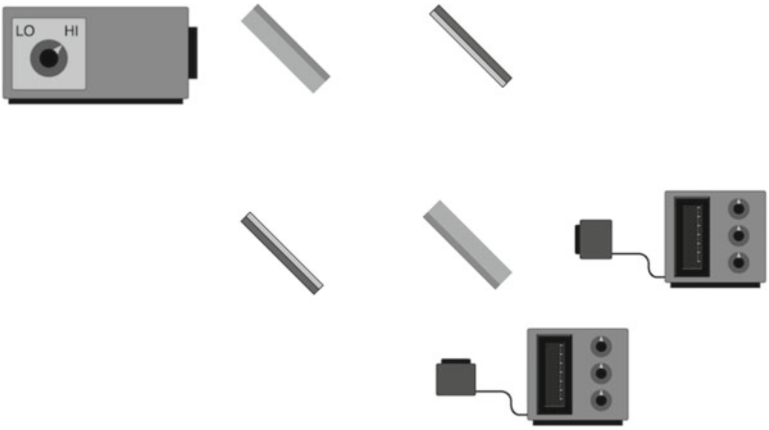

Fig. 1.4 A Mach–Zehnder interferometer. The interactive figure is available online (see supplementary material 4)

It looks like the photon really is behaving as a particle. What is a bit strange is that a static element such as a beam splitter (which is, after all, just a piece of glass) should introduce a probabilistic aspect to the experiment. On the other hand, how else could it be? Each photon is created independently, so there should not be any conspiracy between the photons to create a regular pattern of pulses in the detectors. Therefore, if the intensity of the light is to be divided evenly over the two detectors, each photon must make a random decision at the beam splitter. Or so it seems…

1.4 Experiment 3: The Mach–Zehnder Interferometer

For our final experiment we replace the detectors by mirrors, and recombine the two beams using a second beam splitter (see Fig. 1.4). The outgoing beams of this second beam splitter are then again monitored by detectors. The setup is shown above. When we set the laser to high intensity ("HI"), we can arrange the beam splitters and mirrors such that there is no signal in detector D_1, and all the light is detected by detector D_2. This is a well-known wave effect, called interference. According to the theory of optics, light is a wave, and the lengths of the two paths between the beam splitters are such that the wave transmitted from the top of BS2 has a phase that is exactly opposite to the phase of the reflected wave coming from the left of BS2 (see Fig. 1.5). The device is called a Mach–Zehnder interferometer.

When we reduce the power of the laser again all the way down to the single photon level (setting "LO"), the current in detector D_2 reduces until only single current pulses appear. Detector D_1 stays silent. This is consistent with experiment 2, where the signal also reduces to pulses in the current. However, this does not sit well with the mental image we developed earlier, in which photons are particles that

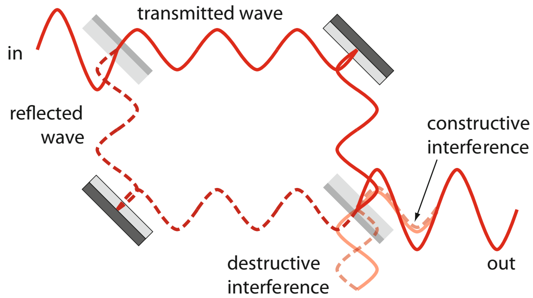

Fig. 1.5 Classical waves in a Mach–Zehnder interferometer. Waves appearing from the second beam splitter with opposite phase cause destructive interference, resulting in a complete absence of light in that output beam. All the light appears in the output with the constructive interference. The amplitude of the wave is the square root of the intensity

choose randomly whether they will be reflected or transmitted at the beam splitter. How can a single particle cause interference such that detector D_1 remains dark?

We have established that photons are indivisible, so it can not be true that the photon splits up into two smaller parts at the first beam splitter and recombines at the second beam splitter to always trigger detector D_2. A natural question to ask is then: which of the two paths between the two beam splitters does the photon take, the top or the bottom? To answer this we modify our experiment.

The photodetectors we considered thus far are not the only way to measure light. In recent years people have spent a lot of effort to create so-called quantum non-demolition (QND) detectors. These have the benefit that they do not destroy the photon. A detailed description of these detectors is beyond the scope of this book, and we do not really need to know how they work. It is sufficient to note that they detect the presence of a photon without destroying it. In Fig. 1.6, we draw them as loops connected to current meters. A blip on the meter indicates that a photon passed through the loop. We can use QND detectors to find out whether the photon took the upper path or the lower path of the Mach–Zehnder interferometer by placing a loop in each path. This is shown in Fig. 1.5.

As you may have expected, we find that our photon passes either through loop A or through loop B, but never through both. In addition, after finding a photon in one of our QND detectors, we always find a single current pulse in one of our regular photodetectors. However, it is no longer exclusively detector D_2 that creates the current pulses. After many trials in this experiment, it becomes clear that each QND detector is triggered with equal probability, and so are the normal photodetectors. In other words, the interference pattern, where detector D_1 always remained dark, has disappeared!

So the observation which path the photon takes, A or B, will destroy the interference effect. This is one of the most fundamental aspects of quantum physics: *looking at a physical system changes its behaviour*. This conclusion is entirely determined by experimental findings, making it inescapable. Note that in order to look at which

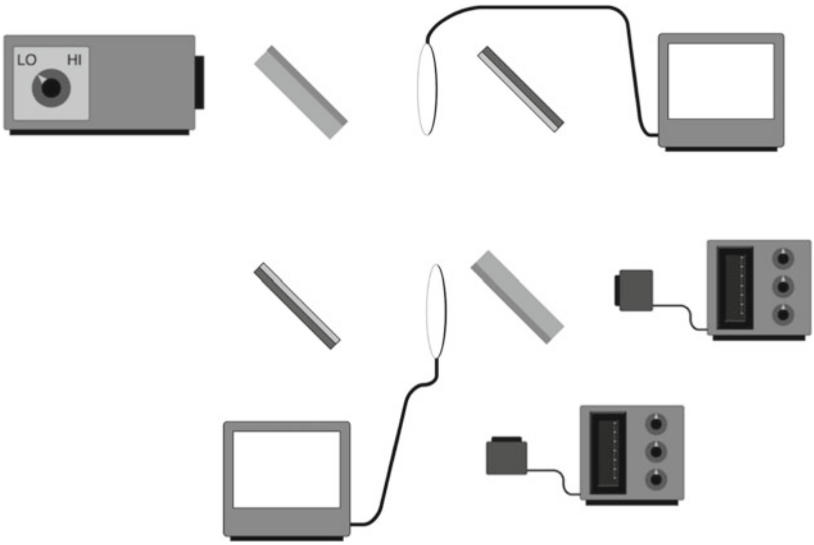

Fig. 1.6 A Mach–Zehnder interferometer with QND measurements of the photon path. The interactive figure is available online (see supplementary material 5)

path the photon took, we had to interact with the photon via the loops of the QND detectors. So it is not our "consciousness" that made that photon behave differently, but the physical interaction that is necessary to "look" at the system, just like the chalk dust revealing a laser beam interacts with the light by reflecting parts of the beam towards your eye.

The big difference between classical systems and quantum systems is that in classical systems we can often "peel off" a small part from a bigger system (for example, reflect a little bit of light out of a beam using chalk) to detect how the large system is behaving. We typically assume that this does not disturb the large system very much. In contrast, a quantum system tends to be small—like a single photon—and we fundamentally cannot peel off part of it and leave the remainder undisturbed. As the experiments in this chapter have shown, we cannot assume that *unobserved* quantum systems behave just like classical systems.

1.5 The Breakdown of Classical Concepts

The three simple experiments described above show us that photons behave in a rather strange way. This forces us to abandon some classical notions that are deeply ingrained in our thinking about nature. Here, by classical we mean those natural phenomena that are well described by the great "classical" theories of physics, including Newton's mechanics, Maxwell's electromagnetism, Kelvin's thermodynamics, and even Einstein's special and general theory of relativity. We start with a summary of what we have learned about photons in our experiments:

- Photons are defined as the cause of current pulses in our photodetectors.
- Photons are indivisible.
- Single photons can exhibit interference when there is more than one path a photon can take.
- Interference disappears when we measure which path the photon takes in the interferometer.

The first two properties lead us to believe that photons are indeed particles, but the last two properties complicate our mental picture considerably.

If the photon is actually going via either path A or path B, then extracting this information reveals something about reality, which is by definition independent of our knowledge about it. Therefore, if the path of the photon was a real property of the photon, the QND measurement should have no effect on its behaviour on the second beam splitter. Yet it does have an effect: the interference disappears when we know its path. We are therefore forced to conclude that our photon does not take a definite path that we just do not know about, but that somehow the path of the photon is not determined before we make the measurement! The act of the QND measurement brings into reality the physical property of the photon path. Before the measurement it is meaningless to talk about the path of the photon. This is very different from classical particles, which always have a well-defined path, whether we know about it or not.

To avoid confusion, it is helpful to introduce a new name for objects like the photon. Instead of calling the photon a particle or a wave, we say that it is a quantum of light. The term "quantum" means "little amount". You see that quanta are neither particles nor waves, but share some characteristics of both. In the next chapter we will attempt to describe these objects more accurately using maths.

Our discussion demonstrates that classical concepts such as intrinsic properties of a system are no longer valid in quantum physics. This was summed up by Wheeler (1979) as follows:

> *No phenomenon is a physical phenomenon until it is an* observed *phenomenon.*

It is very difficult to describe what happens to the photon, and ordinary language is almost inadequate. We will return to this in Chap. 10. Often people write that the photon takes both paths at the same time, but you can see from the experiments and their interpretation that this is not quite accurate. In the next chapter, we will make our discussion more precise and quantitative.

Exercises

1. What is the purpose of physical theories? Should they say something about the world beyond the correct prediction of measurement outcomes? Keep a record of your answer, so you can compare it to your answer to Exercise 1 of Chap. 10.
2. If the beam splitter in Fig. 1.3 is 70% reflective, instead of 50%, what would be the probabilities of finding the photon in detectors D_1 and D_2?
3. If both beam splitters in Fig. 1.4 are 70% reflective, instead of 50%, show that we can still have perfect destructive interference.
4. Imagine we send a high-intensity laser beam into the Mach–Zehnder interferometer with the QND detectors in Fig. 1.6. What do you expect will happen to the classical interference pattern in the output detectors? You may assume that the QND detectors are perfectly responsive.
5. What will happen to the interference pattern in the output detectors of Fig. 1.4 if the photon has a weak interaction with the medium it travels through, such that the medium has a (partial) memory of the photon's trajectory?
6. What are the probabilities of detectors D_1 and D_2 firing in the Mach–Zehnder interferometer of Fig. 1.4 if there is a 50:50 chance that the first beam splitter is not there?

Reference

J.A. Wheeler, interview in cosmic search, **1** (4), Fall (1979)