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Excerpt
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'God', said Albert Einstein, 'does not play dice'. This famous remark by the author of the theory of relativity was not intended as an analysis of the recreational habits of a supreme being but expressed his reaction to the new scientific ideas, developed in the first quarter of the twentieth century, which are now known as quantum physics. Before we can fully appreciate why one of the greatest scientists of modern times should have been led to make such a comment, we must first try to understand the context of scientific and philosophical thought that had become established by the end of the nineteenth century and what it was about the 'new physics' that presented such a radical challenge to this consensus.

What is often thought of as the modern scientific age began in the sixteenth century, when Nicholas Copernicus proposed that the motion of the stars and planets should be described on the assumption that it is the sun, rather than the earth, which is the centre of the solar system. The opposition, not to say persecution, that this idea encountered from much of the establishment of that time is well known, but this was unable to prevent a revolution in thinking whose influence has continued to the present day. From that time on, the accepted test of scientific truth has increasingly been observation and experiment rather than religious or philosophical dogma.

The ideas of Copernicus were developed by Kepler and Galileo and notably, in the late seventeenth century, by Isaac Newton. Newton showed that the motion of the planets resulted directly from two sets of laws: first, the laws of motion, which amount to the statement that the acceleration of a moving body is equal to the force acting on it divided by the body's mass; and, second, the law of gravitation, which asserts that each member of a pair of physical bodies attracts the other by a gravitational force proportional to the product of their masses and inversely proportional to the square of their separation. Moreover, he realised that the same laws applied to the motion of ordinary objects on earth: the apple falling from the tree accelerates because of the force of gravity acting between it and the earth. Newton's work also consolidated the importance of mathematics in understanding physics. The 'laws of nature' were expressed in quantitative form and mathematics was used to deduce the details of the motion of physical systems from these laws. In this way Newton was able not only to show that the motions of the moon and the planets were consequences of his laws but also to explain the pattern of tides and the behaviour of comets.

This objective mathematical approach to natural phenomena was continued in a number of scientific fields. In particular, James Clerk Maxwell in the nineteenth century showed that all that was then known about electricity and magnetism could be deduced from a small number of equations (soon to be known as Maxwell's equations) and that these equations also had solutions in which waves of coupled electric and magnetic fields could propagate through space at the speed of light. This led to the realisation that light itself is just an electromagnetic wave, which differs from other such waves (e.g. radio waves, infrared heat waves, x-rays etc.) only in the magnitudes of its wavelength and frequency. It now seemed that the basic fundamental principles governing the behaviour of the physical universe were known: everything appeared to be subject to Newton's mechanics and Maxwell's electromagnetism.

The philosophical implications of these developments in scientific thought were also becoming understood. It was realised that if everything in the universe was determined by strict physical laws then the future behaviour of any physical system – even in principle the whole universe – could be determined from a knowledge of these laws and of the present state of the system. Of course, exact or even approximate calculations of the future behaviour of complex physical systems were, and still are, quite impossible in practice (consider, for example, the difficulty of forecasting the British weather more than a few days ahead!). But the principle of determinism, in which the future behaviour of the universe is strictly governed by physical laws, certainly seems to be a direct consequence of the way of thinking developed by Newton and his predecessors. It can be summed up in the words of the nineteenth-century French scientist and philosopher Pierre Simon de Laplace: 'We may regard the present state of the universe as the effect of its past and the cause of its future'.

By the end of the nineteenth century, then, although many natural phenomena were not understood in detail, most scientists thought that there were no further fundamental laws of nature to be discovered and that the physical universe was governed by deterministic laws. However, within thirty years a major revolution had occurred that destroyed the basis of both these opinions. These new ideas, which are now known as the quantum theory, originated in the study of electromagnetic radiation, and it is the fundamental changes this theory requires in our conceptual and philosophical thinking which triggered Albert Einstein's comment and which will be the subject of this book. As we shall see, quantum physics leads to the rejection of determinism – certainly of the simple type envisaged by Laplace – so that we have to come to terms with a universe whose present state is not simply 'the effect of its past' and 'the cause of its future'.

Some of the implications of quantum physics, however, are even more radical than this. Traditionally, one of the aims of physics has been to provide an *ontology*, by which is meant a description of physical reality – things as they 'really are'. A classical ontology is based on the concepts of particles, forces and fields interacting under known laws. In contrast, in the standard interpretation of quantum physics it is often impossible to provide such a consistent ontology. For example, quantum theory tells us that the act of measuring or observing an object often profoundly alters its state and that the possible properties of the object may depend on what is actually being measured. As a result, the parameters describing a physical system (e.g. the position, speed etc. of a moving particle) are often described as 'observables', to emphasise the importance of the fact that they gain reality from being measured or 'observed'. So crucial is this that some people have been led to believe that it is the actual human observer's mind that is the only reality – that everything else, including the whole physical universe, is illusion. To avoid this, some have attempted to develop alternative theories with realistic ontologies but which reproduce the results of quantum physics wherever these have been experimentally tested. Others have suggested that quantum physics implies that ours is not the only physical universe and that if we postulate the existence of a myriad of universes with which we have only fleeting interactions, then a form of realism and determinism can be recovered. Others again think that, despite its manifest successes, quantum physics is not the final complete theory of the physical universe and that a further revolution in thought is needed. It is the aim of this book to describe these and other ideas and to explore their implications. Before we can do this, however, we must first find out what quantum physics is, so in this chapter we outline some of the reasons why the quantum theory is needed, describe the main ideas behind it, survey some of its successes and introduce the conceptual problems.

Light waves

Some of the evidence leading to the need for a new way of looking at things came out of a study of the properties of light. However, before we can discuss the new ideas, we must first acquire a more detailed understanding of Maxwell's electromagnetic wave theory of light, to which we referred earlier. Maxwell was able to show that at any point on a light beam there is an electric field and a magnetic field,[1] which are perpendicular both to each other and

[1] An electric field exerts a force on a charge that is proportional to the size of the charge. A magnetic field also exerts a force on a charge, but only when it is moving; this force is proportional to both the size of the charge and its speed.

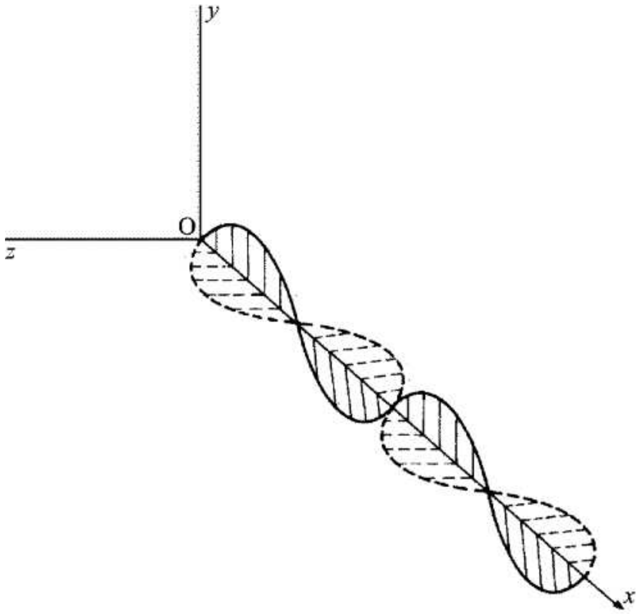

Fig. 1.1 An electromagnetic wave travelling along Ox consists of rapidly oscillating electric and magnetic fields which point parallel to the directions Oy and Oz respectively.

to the direction of the light beam, as illustrated in Figure 1.1. These oscillate many millions of times per second and vary periodically along the beam. The number of oscillations per second in an electromagnetic wave is known as its *frequency* (often denoted by f), while at any point in time the distance between neighbouring peaks is known as the *wavelength* (λ). It follows that the speed of the wave is $c = \lambda f$. The presence of the electric field in an electromagnetic wave could in principle be detected by measuring the electric voltage between two points across the beam. In the case of light such a direct measurement is quite impractical because the oscillation frequency is too large, typically 10^{14} oscillations per second; however, a similar measurement is actually made on radio waves (electromagnetic waves with frequency around 10^6 oscillations per second) every time they are received by an aerial on a radio or TV set.

Direct evidence for the wave nature of light is obtained from the phenomenon known as *interference*. An experiment to demonstrate interference is illustrated in Figure 1.2(a). Light passes through a narrow slit O, after which it encounters a screen containing two slits A and B, and finally reaches a third screen where it is observed. The light reaching a point C on this screen can

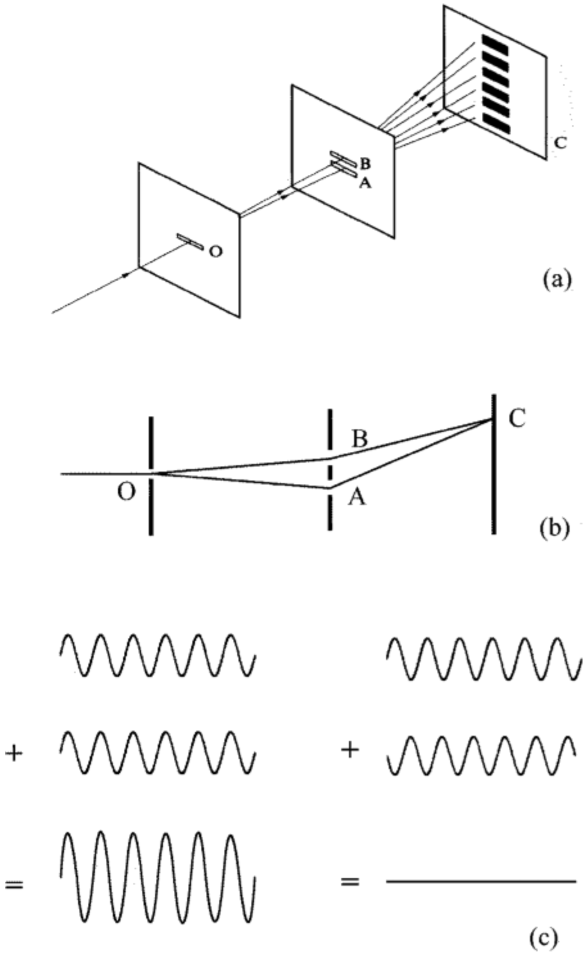

Fig. 1.2 (a) The two-slit interference pattern. (b) Light waves reaching a point C on the screen can have travelled via either of the two slits A and B. The difference in the distances travelled along the two paths is AC − BC. In (c) it is seen that if this path difference equals a whole number of wavelengths then the waves add and reinforce, but if the path difference is an odd number of half wavelengths then the waves cancel. As a result, a series of light and dark bands are observed on the screen, as shown in (a).

have travelled by one of two routes – either by A or by B (Figure 1.2(b)). However, the distances travelled by the light waves following these two paths are not equal, so they do not generally arrive at the point C 'in step' with each other. The difference between the two path distances varies across the pattern on the screen, being zero in the middle. This is illustrated in Figure 1.2(c), from which we see that if the paths differ by a whole number of light wavelengths then the waves reinforce each other, but if the difference is an odd number of half wavelengths then they cancel each other out. Between these extremes the waves partially cancel, so a series of light and dark bands is observed across the screen, as shown in Fig 1.2(a).

The observation of effects such as these 'interference fringes' establishes the wave nature of light. Moreover, measurements on the fringes can be used in a fairly straightforward manner to establish the wavelength of the light used. In this way it has been found that the wavelength of visible light varies as we go through the colours of the rainbow, violet light having the shortest wavelength (about 0.4 millionths of a metre) and red light the longest (about 0.7 millionths of a metre).

Another property of light that will be important shortly is its *intensity*, which, in simple terms, is what we call its brightness. More technically, it is the amount of energy per second carried in the wave. It can also be shown that the intensity is proportional to the square of the amplitude of the wave's electric field, and we will be using this result below.

Photons

One of the first experiments to show that all was not well with 'classical' nineteenth-century physics was the *photoelectric effect*. In this, light is directed on to a piece of metal in a vacuum and as a result subatomic charged particles known as electrons are knocked out of the metal and can be detected by applying a voltage between it and a collector plate. The surprising result of such investigations is that the energy of the individual emitted electrons does not depend on the brightness of the light, but only on its frequency or wavelength. We mentioned above that the intensity or brightness of light is related to the amount of energy it carries. This energy is transferred to the electrons, so the brighter the light, the more energy the body of escaping electrons acquires. We can imagine three ways in which this might happen: each electron must acquire more energy, or there must be more electrons emitted or both things happen. In fact, the second possibility is the one that occurs: for light of a given wavelength, the *number* of electrons emitted per second increases with the light intensity, but the amount of energy acquired by each individual electron is unchanged. However strong or weak the light, the energy given to each escaping electron equals hf, where f is the frequency of the light wave and h is a universal constant of quantum physics known as Planck's constant.

The fact that the electrons seem to be acquiring energy in discrete bits and that this can only be coming from the light beam led Albert Einstein (the same scientist who developed the theory of relativity) to conclude that the energy in a light beam is carried in packets, sometimes known as 'quanta' or 'photons'. The value of hf is very small and so, for light of normal intensity, the number of packets arriving per second is so large that the properties of such a light beam are indistinguishable from those expected from a continuous wave. For example, about 10^{12} (a million million) photons per second pass through an area the size of a full stop on this page in a typically lit room. It is only the very particular circumstances of experiments such as the photoelectric effect that allow the photon nature of light to be observed.

We can get further insight into the properties of photons by considering experiments where the incident light is very weak. If the light were simply a wave, we would not expect any electrons to be emitted until wave energy amounting to at least hf had arrived at one of the atoms. However, we actually find that some electrons are detected immediately after the light is switched on, and well before enough energy could have been supplied by the light wave. The conclusion to be drawn from this is that the photon energy must be carried in a small volume so that, even if the average rate of arrival of photons is low, there will be a reasonable chance that one of them will release its energy to an electron early in the process. In this sense at least, the photon behaves like a small *particle*. Further work confirmed this: for example, photons were seen to bounce off electrons and other objects, conserving energy and momentum and generally behaving just like particles rather than waves.

We therefore have two models to describe the nature of light, depending on the way we observe it: if we perform an interference experiment then light behaves as a wave, but if we examine the photoelectric effect then light behaves like a stream of particles. Is it possible to reconcile these two models?

One suggestion for a possible reconciliation is that we were mistaken ever to think of light as a wave. Perhaps we should always have thought of it as a stream of particles with rather unusual properties that give rise to interference patterns, so that we were simply wrong ever to describe it using a continuous-wave model. This would mean that the photons passing through the apparatus shown in Figure 1.2 would somehow bump into each other, or interact in some way, so as to guide most of the photons into the light bands of the pattern and very few into the dark areas. This suggestion, although elaborate, is not ruled out by most interference experiments because there is usually a large number of photons passing through the apparatus at any one

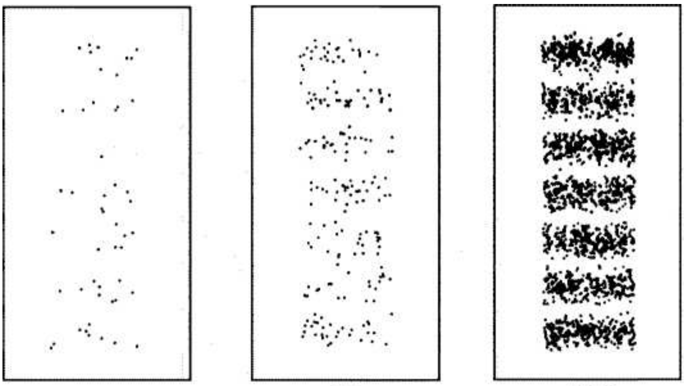

Fig. 1.3 The three panels show a computer reconstruction of the appearance of a two-slit interference pattern after 50, 200 and 2000 photons respectively have arrived at the screen. The pattern appears clear only after a large number of photons have been recorded even though these have passed through the apparatus one at a time.

time and interactions are always conceivable. If however we were to perform the experiment with very weak light, so that at any time there is only one photon in the region between the first slit and the screen, interactions between photons would be impossible and we might then expect the interference pattern to disappear. Such an experiment is a little difficult, but perfectly possible. The final screen must be replaced by a photographic plate or film and the apparatus must be carefully shielded from stray light; but if we do this and wait until a large number of photons has passed through one at a time, the interference pattern recorded on the photographic plate is just the same as it was on the screen in the earlier experiment!

We could go a little further and repeat the experiment several times using different lengths of exposure. We would then get results like those illustrated in Figure 1.3, from which we see that the photon nature of light is confirmed by the appearance of individual spots on the photographic film. At very short exposures these seem to be scattered more or less at random, but the interference pattern becomes clearer as more and more arrive. We are therefore forced to the conclusion that interference does not result from interactions between photons; rather, *each photon* must undergo interference at the slits A and B. Indeed, the fact that the interference pattern created after a long exposure to weak light is identical to one produced by the same number of photons arriving more or less together in a strong light beam implies that photons may not interact with each other at all.

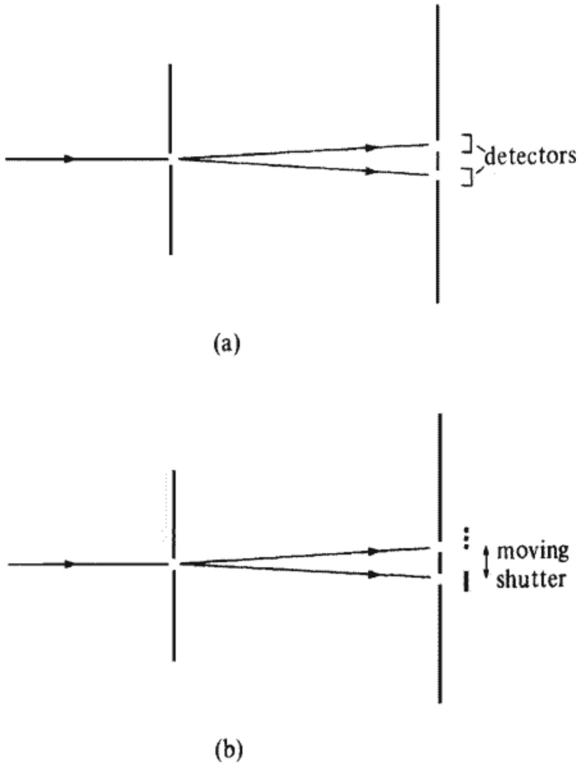

Fig. 1.4 If we place photon detectors behind the two slits of an interference apparatus, as in (a), each photon is always recorded as passing through one slit or the other and never through both simultaneously. If, as in (b), a shutter is placed behind the slits and oscillated up and down in such a way that both slits are never open simultaneously, the two-slit interference pattern is destroyed.

If interference does not result from interaction between photons, could it be that each individual photon somehow splits in two as it passes through the double slit? We could test for this if we put a photographic film or some kind of photon detector immediately behind the two slits instead of some distance away. In this way we could tell through which slit the photon passes, or whether it splits in two on its way through (see Figure 1.4). If we do this, however, we always find that the photon has passed through one slit or the other and we never find any evidence that the photon splits. Another test of this point is illustrated in Figure 1.4(b): if a shutter is placed behind the two slits and oscillated up and down so that only one of the two slits is open at any one time, the interference pattern is destroyed. The same thing happens when any experiment is performed that detects, however subtly, through which slit the photon passes. It seems that light passes through one slit or the other in the form of photons if we set up an experiment to detect through which slit the photon passes, but passes through both slits in the form of a wave if we perform an interference experiment.

The fact that processes like two-slit interference require light to exhibit both particle and wave properties is known as *wave–particle duality*. It illustrates a general property of quantum physics, which is that the nature of the model required to describe a system depends on the nature of the apparatus with which it is interacting. Light has the property of a wave when passing through a pair of slits but has to be considered as a stream of photons when it strikes a detector or a photographic film. This dependence of the properties of a quantum system on the nature of the observation being made on it underlies the conceptual and philosophical problems that it is the purpose of this book to discuss. We shall begin this discussion in a more serious way in the next chapter, but we devote the rest of this chapter to a discussion of some further implications of the quantum theory and to an outline of some of its outstanding successes in explaining the behaviour of physical systems.

The Heisenberg uncertainty principle

One of the consequences of wave–particle duality is that it sets limits on the amount of information that can be obtained about a quantum system at any one time. Thus we can *either* choose to measure the wave properties of light by allowing it to pass through a double slit without detecting through which slit the photon passes *or* we can observe the photons as they pass through the slits. We can never do both these things at once. Werner Heisenberg, one of the physicists who were instrumental in the early development of quantum physics, realised that this type of measurement and its limitations could be described in a rather different way. We can think of identifying which slit a photon went through as essentially a measurement of the position of the photon as it passes through the slits, while the observation of interference is akin to a measurement of its momentum. It follows from wave–particle duality that it is impossible to make simultaneous precise measurements of the position and momentum of a quantum object such as a photon.

The application of Heisenberg's ideas to the two-slit experiment is actually rather subtle, and a more straightforward example is the behaviour of light passing through a single slit of finite width. If this is analysed using the wave model of light, then we find, as shown in Figure 1.5, that the slit spreads the light out into a 'diffraction pattern'. We also find that if we make the slit in the screen narrower, the diffraction pattern on the screen becomes