4 Wave-Particle Duality

4.1 Both a wave and a particle

The upshot of all this is very simply that all entities that can transport energy are both particles as waves. Note that I say "both" and not "either". It is a misconception to argue that X-rays or electrons are "sometimes" waves and "sometimes" particles. They are always both. However, whether their wave nature or their particle nature dominates depends on the manner that they are being observed, and hence can be different in different experiments. A football in play during a match has a matter wave with a wavelength. This wavelength is approximately 0.0000000000000000000000000001 microns, and so that to all intents and purposes the wave nature of the football may be neglected and the football may be treated using Newtonian mechanics (e.g. in order to calculate how hard it must be kicked and in which direction to score a goal).

A less facetious example is the Geiger-Marsden experiment, described earlier, on the scattering of α-particles off a thin sheet of gold, that led to Rutherford's discovery of the nucleus. The experiment was analysed by Rutherford using classical physics to determine how the α-particles were scattered by the nuclei of the gold atoms. However, the gold sheet is a regular lattice of gold atoms and therefore it is reasonable to ask why the wave nature of the incident α-particles did not lead to a diffraction pattern similar to that observed in the Davisson-Germer experiment. The answer is very simply that if we use the de Broglie wave relation to determine the wavelength of the α-particles we find that their wavelength is many thousands times smaller than the spacing between gold atoms in the sheet. This means that although there is indeed a diffraction pattern, the fringes are so closely packed together that we can ignore them. Had the experiment been conducted using electrons rather than α-particles (electrons have a much smaller mass, hence a much smaller momentum, hence a much larger wavelength than α-particles.) then there would have been substantial diffraction and Rutherford's purely particle-like analysis would have been inadequate.

In general, the wave nature becomes important in situations where the wavelength is comparable in size with the dimensions probed by a particular experiment, e.g. the spacing of ions in a lattice. The wavelength of an electron inside an atom is approximately the same size as the atom itself. For this reason, it is the wave nature of the electron that is important when considering the structure of atoms. The particle picture of a nucleus at the centre with electrons moving around it in fixed orbits (which unfortunately is the one we find easiest to visualize) is wholly inadequate for the description of atoms. Remember that whereas we can just about construct an instrument (electron microscope) to locate individual atoms, we cannot, even in principle, construct a microscope which would enable us to track an electron inside an atom. We therefore have to live with the uncomfortable truth that our experience of the macroscopic world is inadequate for us to "visualize" the motion of electrons inside an atom.

The proposition that electrons and X-rays (and protons, neutrons, footballs etc.) are simultaneously both particles and waves already stretches our imagination and poses an

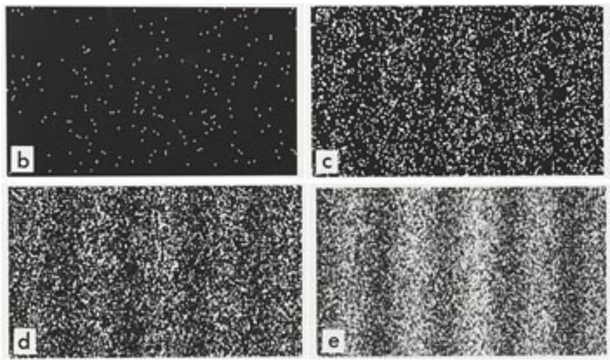

Figure 29: The distribution of the detector-screen of electrons passing individually through a double-slit as time advances. At later times well-defined maxima and minima can be identified.

impediment to our ability to visualize the sub-microscopic world.

4.2 Which Slit did the particle go through?

We have no conceptual difficulty in understanding what is happening in the double slit experiment performed with light (photons) by Young in 1801, when we consider the light to be a wave. The part of the **wavefront** that passes through one slit interferes with the part of the wavefront passing through the other slit in such a way that at certain angles the wave disturbances add, and we get maxima, whereas at other angles they cancel, and we get minima. But how do we explain this in terms of photons, which are treated as particles? The double-slit experiment was performed by Giulio Pozzi [22] and collaborators in 2007, using electrons instead of a monochromatic light source. The electrons were all accelerated through the same voltage, so that they had the same momentum and therefore the same wavelength. When they passed through a double-slit system and then continued to a detector screen similar fringes of maxima and minima were observed as in Young's original experiment with light. Once again, we can understand this in terms of the wave-nature of electrons, but not their particle nature.

It is tempting to argue that what is actually happening is that the electrons that pass through one slit interfere with the electrons that pass through the other. Unfortunately this has been shown not to be the case. In 2012, Pozzi and his colleagues reduced the flux of electrons in the experiment to such a low level that only one electron passed through the double-slit system at a time. The results are shown in Fig. 29, which demonstrates the density of electrons on the detector screen as a function of time. At first the electrons appeared to be landing at random positions on the screen with uniform probability to go in any particular direction, but as time passed it became clear that there were directions which were favoured and directions which were disfavoured. The favoured directions developed into maxima and the disfavoured into minima. Since only one electron was passing through the slit system at any one time, this interference behaviour was a property of each individual electron and *not* an interference between different electrons. Each electron has a probability of going in a particular direction and this probability has maxima and minima because of the interference of the electron wave. The strange (but nevertheless correct) feature of this probability is that even if the electron passes through one slit, the probability of it landing at a particular point on the screen is influenced by the existence of the other slit. If we close one of the slits the interference pattern is lost - even if that was not the slit that the electron passed through.

In our "understanding" each individual electron has to pass through either one slit or the other. Unfortunately, this "understanding", whether correct or incorrect, is irrelevant to the result of the experiment. Even if an individual electron passed through one slit or the other, the electron wave passes through both slits (just like the light wave in Young's experiment) and the emerging wave from the two slits produces an interference pattern.

The postulate that the electron passes through one slit or the other is experimentally untestable (and therefore outside the domain of physics) because it is impossible to ascertain through which slit the electron passed, without destroying the interference pattern. Suppose we placed a microscope at the rear side of the slits in order to observe through which slit the electron passes. If the separation of the slits is d, then we would need a resolution of less than d in order to distinguish between the two slits. This would mean that we would need to use light (or any other wave) whose wavelength is smaller than d. The minimum quantity of light that would enable us to observe the electron is a single photon. But a single photon whose wavelength is less than d, has a momentum of greater than h/d and when it scatters off the electron, it will impart some of this momentum to the electron. This "jogging" of the electron is sufficient to destroy the interference pattern.

Unfortunately, the real situation is even worse. We have assumed, in keeping with our "understanding", that an electron passing through the double-slit system has a well-defined position which can be used to determine through which slit it passed, as well as a well-defined momentum which can be used to predict where it will land on the detector-screen. As we shall see later when considering Heisenberg's uncertainty principle, such assumptions are false and we have to live with the fact that, in general, a particle does not actually possess well-defined position and momentum and that our inability to determine these quantities is not simply a limitation in our ability to make measurements. This means that the electron did not pass through one slit or the other, but in some sense (at least in the sense of a wave) it passed through both slits.