Wave Properties of Light

The measurement problem began to be formulated early in the history of quantum mechanics. One can argue that the measurement problem is deeply rooted in the issue of wave-particle duality. Here we give a brief historical review needed for this chapter; a more in-depth historical presentation is given in Chapter 5. The issue of wave-particle duality arose with Einstein's discovery of the photoelectric effect. It had already been known by Planck's discovery in 1900 that energy was quantized. However, the mechanism of how this quantization occurred was not known at that time, and in fact it was not generally accepted that individual particles existed. At the beginning of the 20th century, many believed that there was simply a continuum and not discrete atoms.

Long before 1900, it was known that light exhibited interference. Huygens proposed early in 1678 that light behaves as a wave. Newton believed that light was corpuscular, and this was accepted by many scientists. Interestingly the concept that light is corpuscular was also put forward by Gassendi and Hobbes before Newton. However, Young in 1803 demonstrated conclusively that light exhibits interference through his double slit experiment, and many scientists abandoned the corpuscular theory as it did not adequately appear to explain the interference phenomenon. Maxwell in the 1860s developed equations that describe classical light, which can take the form of a wave equation.

Before the measurement problem was clearly formulated, the issue of wave-particle duality existed. In order to understand the issue of wave-particle duality, we consider the double slit experiment as shown in Figure 1.1 in which a light source shines toward a surface containing two narrow slits. In terms of wave propagation, one can consider a similar experiment in which the double slit is placed on the surface of a

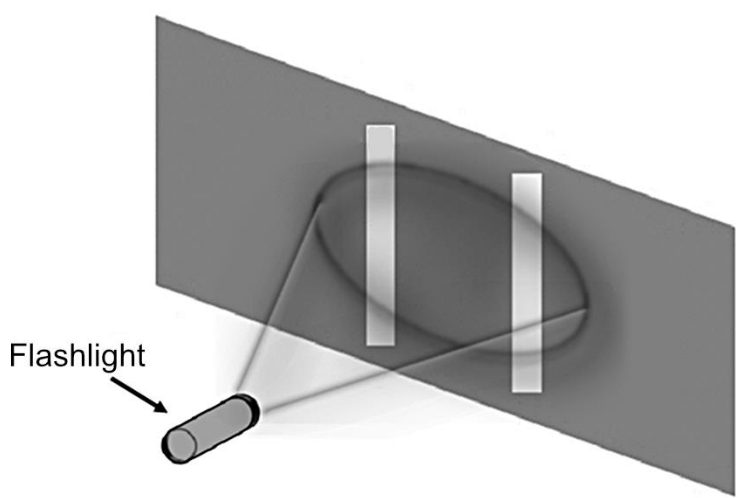

Figure 1.1: A light source shines on Young's double slit.

water tank, and the source consists of an oscillating plunger that creates waves.

Young, having studied the theory of sound propagation, argued that light should also behave as a wave phenomenon. His ideas were initially rejected by most. Later, an experiment was formulated by Augustin-Jean Fresnel, in which a circular body placed in front of the source would block the light if it consisted of particles and gave specific predictions if light were a wave. An experiment was conducted by François Arago in which a circular object was placed in the path of a light source. A particle theory predicts that there should only be a circular shadow due to the object blocking the light, whereas a wave theory predicts that light can further recombine from the edges of the object and at the center of the shadow there should be an additional bright spot due to constructive interference. Arago observed this additional spot in the center of the shadow which confirmed Fresnel's predictions for wave propagation. After this striking experimental confirmation, the theory that light propagates as a wave gained acceptance among the scientific community, and Newton's corpuscular theory was largely abandoned.

Young contemplated that each color of light corresponds to a particular frequency of the wave undulation or oscillation. The wave emitted from the flashlight then heads toward the two slits as shown in Figure 1.2. Once a wave enters a slit, there is an interaction between the wave and the slit. This interaction is similar to a scattering of a water wave that is initially moving in a particular direction which then enters a narrow slit. When the water wave exits the slit, it will be found to disperse in a wide range of

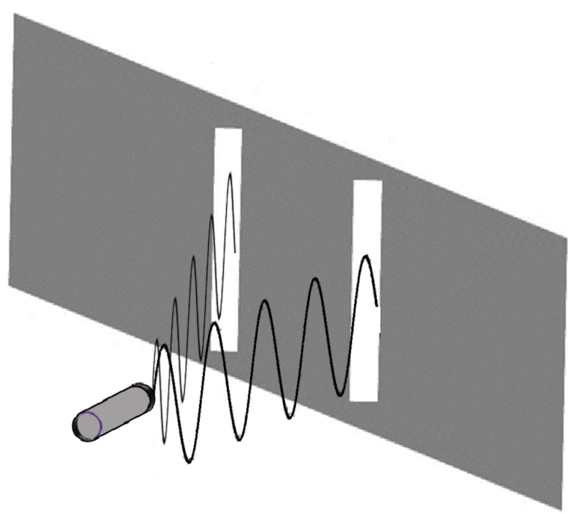

Figure 1.2: Young's double slit with light represented as a wave rather than a particle.

directions. Hence a wave that enters a single slit can exit in many directions. If one considers the Point x_1 after the double slit apparatus as shown in Figure 1.3, one sees that a wave that exits the left slit can continue directly to Point x_1 but also a wave that exits the right slit could scatter and change its direction and also have an effect at Point x_1. Any other Point x_2 could likewise be considered. Any given point after the double slit apparatus will be affected by a wave that went through the left slit and a wave that went through the right slit.

Note that one might instead believe that the wave representation of two waves going toward the two slits from the flashlight is simply an incomplete model, and that in reality there is but a single localized wave-particle that is simply oscillating toward only one of the two slits. As we will see, this explanation is inadequate and this is the importance of the double slit experiment. Suppose that one considers the light wave as localized but oscillating particle moving toward only one of the two slits in Figure 1.2. Such an explanation is incorrect; one must consider at any given point the contributions that could have occurred by the wave going through *both* slits. Again, let us consider Figure 1.3 where the wave at point x_1 is composed of the summation or *superposition* of waves that pass through *both* slits. Assuming $\psi`_L(x_1, t_0)$ is the value of the wave at the point x_1 (x_2 can likewise be considered) at time t_0 that emerges

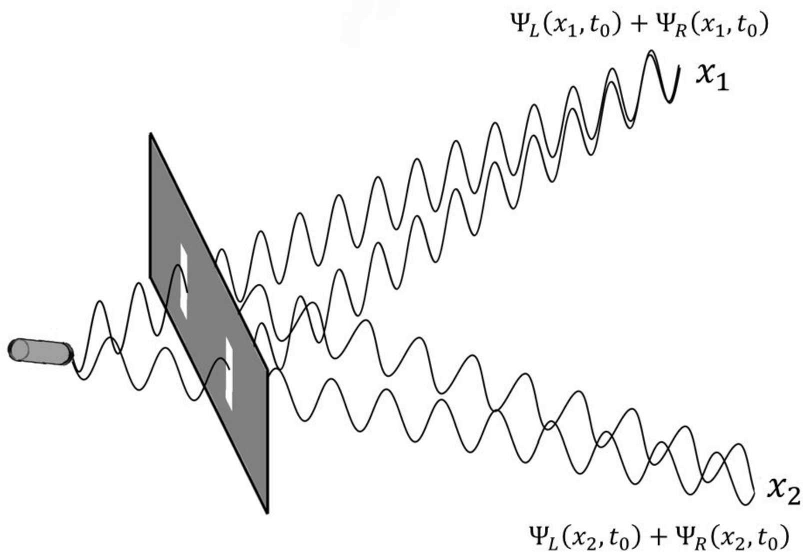

Figure 1.3: Young's double slit with output waves that are a superposition of the input wave passing through both slits.

from the left slit, and $\psi_R(x_1, t_0)$ is the value of the wave at the same point and time that emerges from the right slit, the overall wave is computed as the sum of the two waves, i.e. $\psi`_L(x_1, t_0) + \psi`_R(x_1, t_0)$. As the overall wave function is $\psi`_L(x_1, t_0) + \psi`_R(x_1, t_0)$, rather than either $\psi`_L(x_1, t_0)$ or $\psi`_R(x_1, t_0)$, interference is exhibited between $\psi`_L(x_1, t_0)$ and $\psi`_R(x_1, t_0)$ in the formation of the overall wave function. This is due to the detection probability being given by the absolute square of the overall wave function, $|\psi`_L(x_1, t_0) + \psi`_R(x_1, t_0)|^2 = |\psi`_L(x_1, t_0)|^2 + |\psi`_R(x_1, t_0)|^2 + \psi_L^*(x_1, t_0)\psi`_R(x_1, t_0) + \psi`_L(x_1, t_0)\psi_R^*(x_1, t_0)$, which came to be known as *Born's Rule*. Interference arises from the cross-terms and therefore it is not correct to consider the wave as a single localized particle (although as we will see in Chapter 4, Bohm's theory attempts to do just that, although by adding an additional quantum potential to the theory). Often one sees the double-slit pattern explained in terms of the placement of a screen that the light hits after it passes through the double-slit apparatus. More generally however a detector could be placed anywhere after the double slit, which is the case considered hereafter, and so a screen is not shown. Experimental results confirm that Figure 1.3 is correct, with the added interpretation that when a detector is placed at any position x_1 at time t_0 after the double slit apparatus, the detection probability is given by the square of the wave function, which is given by $|\psi_L(x_1, t_0) + \psi_R(x_1, t_0)|^2$. Interestingly an experiment reported as early as 1909 by G.I. Taylor used an attenuated light source from a gas flame to show wave interference from the shadow of a needle on photographs exposed for a period of three months. This provides evidence against the concept that light can be considered to be composed of propagating *localized* particles and in favor of the concept that light propagates as a wave that exhibits interference.

The wave in Figure 1.3 at (x_1, t_0) can be seen to be a superposition of the wave passing through both slits of the double slit apparatus. In general, for different experiments, there are many paths to any given point and infinitely many points may need to be considered.

In Figure 1.4, the full pattern (via computer simulation of the wave equation) can be seen. This pattern is similar to what would be seen if the flashlight was continually paddling water to create a water wave for a long time and a picture of the steady state amplitude of the existing wave was taken. Between the flashlight and double slit, only the direct paths to the slits are shown; the paths to the solid part of the apparatus are left out for simplicity. At any point past the double slit apparatus, a continuum is seen due to the possibility of the wave changing direction upon exiting either slit. Note the appearance of distinct peaks and nulls. These peaks and nulls are a direct consequence of the constructive and destructive interference due to summing the paths through both slits. A wave picture for describing light at least so far, provides an ample understanding to describe the phenomenon of light.