5. Light as a Wave.

We found in Ch. 4 that the spectrum of the hydrogen atom could be accounted for by the Schrödinger equation for the wave function of 'the electron,' with no mention made of the electron as a particle. So if we are to go on the Schrödinger treatment of the H atom *alone*, then we would think of 'the electron' simply as a wave function (not as a particle and not as a wave function plus a particle). This line of reasoning will be continued at length in Part II.

Light as a wave. Interference.

This brings up the question of how we are to think about light. The answer comes from interference experiments. Suppose we do a double slit experiment in which light of a single color (wavelength) goes through two very closely spaced slits, as in Fig. 5-1.

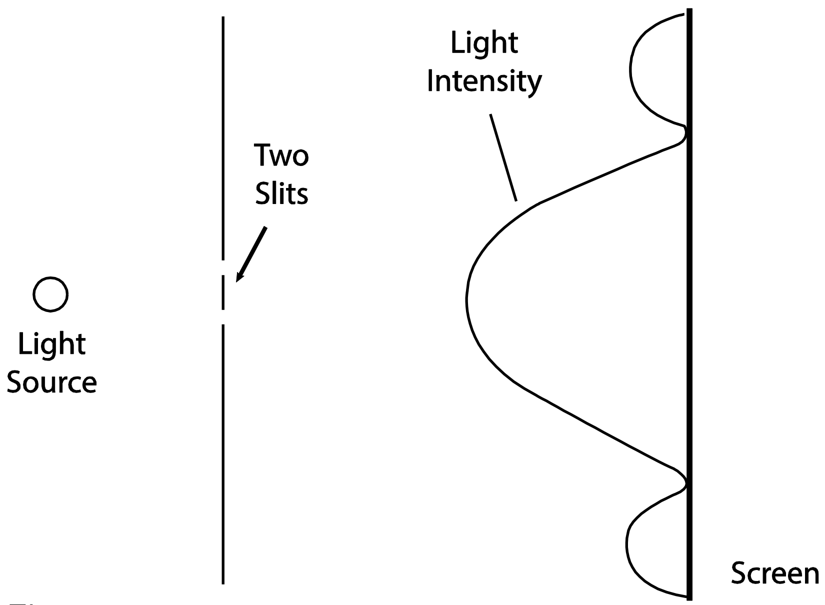

Fig. 5-1

Figure 5-1. Setup for the two slit interference experiment. The curve gives the light intensity at different points along the screen.

The resulting light that hits the screen will be the sum at each point of the light from the two slits. The light from the upper slit at the point shown travels farther than the light from the lower slit which results in a phase difference between the two beams of light and the consequent interference. If the two beams are in phase, (phase difference of a multiple of 2π) one gets constructive interference and a light band. If on the other hand, the two beams are out of phase by odd multiples of π, then one gets destructive interference and a dark band. (See A5.1 for more on interference and A5.2 on the Mach-Zender interferometer as another example of interference.) This pattern can be explained perfectly if one assumes light is a wave, and the two parts of the wave, one from each slit, **interfere.** Thus because the assumption that light is a wave gives a correct—that is, agrees with experiment—explanation of the double slit and other interference problems, we must assume **light is a wave**.

How do we know the light wave does not have a particle associated with it? At this point, we don't know that. This possibility will be discussed in detail in Part II.

Light wave packets. Photons

There is one more point about the waves—wave functions—which make up light. To use an analogy, if we have a number of hydrogen atoms, the electron in each atom has its own separate wave function. The same holds for light. It is not just one continuous wave; instead it comes in "packets" with each packet corresponding to the wave function of one **photon**—one minimal 'piece' of light. Each packet moves at the speed of light, carries a very small amount of energy, and can have almost any shape. Using interferometry techniques, one can show that a typical packet is about a meter long.

Like many of the phenomena at the quantum level, it is not obvious from naked eye observations that light comes in packets. If we look at the light from a flashlight, for example, it certainly looks like a continuous beam. This illusion, however has to do with the number of light packets per second and the timing of visual perceptual processes. Typical neural processes in the eye and brain occur on a time scale of a millisecond. To get some idea of the number of photons (packets) that enter the eye in that time, we note that in direct sunlight approximately 10^{17} (a hundred million billion) photons hit each cm^2 per second.

> The solar constant is about 1000 watts/m^2 and the energy per photon is hc/λ with the wavelength λ about 600nm.

Thus in one millisecond, some significant fraction of a hundred million million photons hit the retina. The brain, which functions entirely on millisecond neurochemical processes, interprets this as a continuous beam of light.

Polarization of light waves.

Each photon has two possible states of *polarization*, which is analogous to spin or angular momentum. This can be visualized in the following way: A photon can be thought of (at least classically) as consisting of oscillating electric and magnetic fields. If a photon is traveling in the vertical direction, its electric field can either oscillate in the east-west direction, with this polarization represented by $|x\rangle$, or it can oscillate in the north-south direction, with its polarization state represented by $|y\rangle$. These are the two states of polarization. See A5.3 for more on polarization.

Evaluation.

Many physicists would object to claiming that light consists of wave functions alone. We are not claiming that the arguments given in this chapter show light is only a wave (wave function). Instead we are saying that, if one just looks at interference experiments, it is plausible to suppose for the time being that light is a wave. The idea that light consists *only* of wave functions—with no *particulate* photon—will be explored in more detail in Part II. We show there that if one fully examines the mathematics of quantum mechanics and its implications for our perceptions, one finds there is no evidence for a particle associated with light. All the particle-*like* properties can be accounted for by the properties of the wave function.