Light in Modern Physics

CHAPTER 15

15.1 INTRODUCTION

Most of the basic properties of light that we've discussed so far were well understood by the turn of this century; it seemed that only details needed to be filled in and technological applications worked out. But in the first few decades of this century, a whole series of discoveries forced physicists to recognize a new reality; the old description of nature **(classical physics)** is only an idealization—rather like geometrical optics is only an idealized, special case of wave optics. Although many of the new principles that developed from this realization now date back over three score and ten years, they are commonly known as **modern physics.**

Light played a paramount role in the discoveries of modern physics. One reason was simply that our curiosity was reaching ever farther beyond the earth and the solar system, and light is the only reliable and available messenger from these distant places. Another reason is that light is the most easily observable *elementary* phenomenon; that is, it does not reveal layers upon layers of structure as it is examined in more and more detail. By way of contrast, sound waves consist of motion of a medium—usually air. The air, however, consists of molecules, which are made of atoms, which in turn have constituents such as electrons, and so forth—each layer of structure opens a new field of physics. Not so with light; there need be no medium, nor is light made of any other constituents.

A sound wave in air doesn't make sense at wavelengths that are smaller than the distance between air molecules. Light, being elementary, encounters no such limitations. Thus some unexpected features of wave behavior itself that become increasingly important at short wavelengths were first encountered with light waves, as we'll see.

Although there is no medium for light in vacuum, it nevertheless travels at a single, constant speed, as experiments from the turn of the century showed. In contrast, everything else that was known had a speed that depended on the speed of its source, its detector, or the medium in which it traveled. The notions of space and time, as then understood, did not allow for anything else. Ultimately it was space, time, and the laws of mechanics that had to be modified and made consistent with the properties of light.

Because light needs no medium, it comes to us through the vast interstellar space and thus provides a sensitive probe of space and time on a grand scale. This leads us to a discussion of galaxies and the universe—so that this book can end with a bang.

15.2 PARTICLES AND WAVES

Some of the basic discoveries of modern physics resulted from the study of the interaction of light with matter. We've talked before about the various ways of interacting, such as reflection, refraction, diffraction, scattering, etc.; here we are interested in *absorption* and *emission.* We already know that absorption can occur when light shakes the charges in matter, transferring energy to them by increasing their motion—heating them. However, sometimes we'd rather convert the light's energy into something else, say an electric current to run a camera's exposure meter, or a nerve impulse from eye to brain. One way such a conversion may happen occurs when light knocks an electron loose from matter.

A. The photoelectric effect

Electrons, as we know, are found in all matter and are particularly available in metals (conductors), where they can travel around freely. However, it is not easy for them to *escape* from the metal. If an electron with its negative charge leaves the (originally uncharged) metal, the metal becomes charged positively and hence tends to pull the electron back. So we can think of the metal as a zone of free travel surrounded by a barrier for electrons. To liberate an electron we must give it enough energy to carry it over this barrier. One way to do this is to heat the metal, literally boiling the electrons off, as is done in the electron gun in your TV. Another method is to hit the electron with light—the ***photoelectric effect*** (Fig. 15.1).

When we shine light on the metal, we expect that the light wave will rock the electrons back and forth, increasing their energy until some can make it over the top of the barrier. (These liberated electrons are

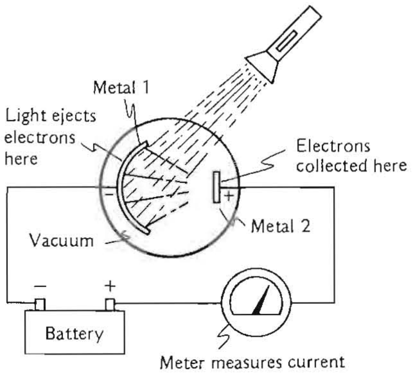

FIGURE 15.1

An evacuated glass tube containing two pieces of metal, which are connected to a battery and a meter that measures the electric current. In the dark no current flows in the circuit because the barrier of metal *1* prevents electrons from leaving it to get to metal *2*. However, when light strikes metal *1*, it knocks electrons out of the metal. These electrons flow to metal *2*, completing the circuit. A current then flows, as shown by the meter. The more light falls on metal *1*, the more photoelectrons are produced, so the meter reading is proportional to the light's intensity.

called ***photoelectrons.***) We shall then have converted light into an electric current. Generally this is indeed what happens, but the details don't make sense in terms of classical physics.

One puzzle is the role of the light's wavelength. Long-wavelength (low-frequency) light does not release any photoelectrons at all, no matter how intense the light. Photoelectrons are given off only for light frequencies higher than a certain cut-off frequency, which depends on the metal and on how great its electron barrier is. (For most metals the cut-off frequency is in the UV.) At those higher frequencies, the energy of each photoelectron is independent of the light's intensity (energy). Greater light intensity only gives more (not more energetic) photoelectrons, and even at low intensities some photoelectrons are emitted immediately after the light is turned on. On the basis of classical wave theory we would expect that the light's intensity should influence the photoelectron energy, and for sufficiently low intensity we would expect a considerable delay before any electron has collected enough energy from the light to get across the barrier.

By way of analogy, imagine your car is stuck in a snowbank, and you try to get it out by rocking it back and forth. If your car behaved as electrons do, you'd find you could always get it going by pushing at a high enough frequency. If you pushed rapidly but not very hard, sometimes you'd find that the car would jump the snowbank right away, after you barely touched it. But if you rocked the car too slowly, it would never move, no matter how hard you pushed. Clearly, then, the photoelectric effect doesn't behave the way classical physics would lead us to expect.

The part of modern physics that explains this odd behavior is called ***quantum theory,****[*] and the person who first explained the photoelectric effect was called Albert Einstein. He had a remarkable knack for taking some apparently paradoxical result and making it the basis of a new, successful theory. In the case of the photoelectric effect the relevant principle of quantum theory is:

> **Every monochromatic electromagnetic wave can transfer energy only in discrete units *(quanta)*. The size of the energy quantum is proportional to the wave's frequency.**

So, different electrons don't each get the same amount of energy as they dance in the wave's field—some get it all (a whole quantum) and others get nothing. If the quantum is too small (frequency too low), even the lucky electrons that get a quantum are not carried across the barrier; but if the quantum exceeds the barrier energy (frequency sufficiently high), they will become photoelectrons (Fig. 15.2).

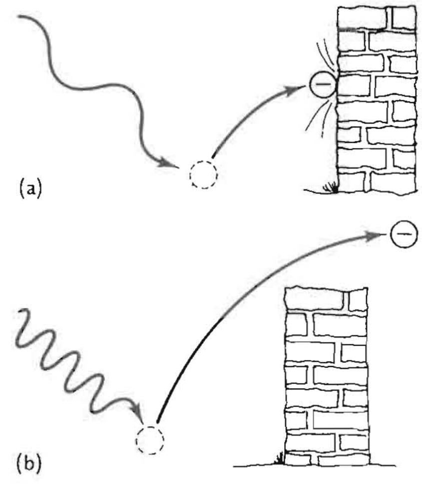

FIGURE 15.2

(a) An electron struck by a low-frequency photon gets insufficient energy to surmount the barrier. **(b)** An electron struck by a high-frequency photon receives enough energy to leave the metal.

In the high-frequency case, the more intense the light, the more quanta it can transfer, hence the more photoelectrons and the larger the resulting electric current. Of course, to compute this current we don't need to know which particular electrons are "lucky." In fact, quantum theory discourages attempts to make pictures in ordinary language (i.e., in terms of classical physics) of the intermediate steps in any physical process. But we like to have some mental picture anyway, and here is how it is usually described. The energy in a light beam is not only transferred in quanta, it is already present in the beam as discrete quanta, called ***photons,*** each carrying a quantum of energy. The more intense the beam (of a given frequency), the more photons it has. Common light beams, of the kind we've been discussing throughout this book, carry so many photons that we don't generally notice the quantum nature of the light. It required special circumstances, such as the photoelectric effect, before that became apparent.

Photons act in some ways like particles—they are discrete concen-

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[*] Latin *quantum* (plural *quanta*), literally "how much."

trations of energy, you can never absorb a fraction of a photon, you can count how many you have, and so on. However, unlike ordinary particles they have no definite position, but are spread out—just as a wave is spread out. Suppose now that a photon interacts with a material photon detector, for example a photographic film or a TV camera tube. The photon then concentrates and delivers all its energy to an electron at *one* place. Those places where the wave has high intensity are more likely to receive the energy, but wherever the photon goes, *all of it* goes.

Situations where light acts as photons include wave effects, such as the interference pattern of Young's fringes. For the whole interference pattern to be visible many photons must contribute to it, with most of the photons landing on the bright places and none at the dark places (Fig. 15.3). However, the same interference pattern results if the light is so faint that photons travel through an interferometer *one at a time* (and their effects are then added, say by exposing a photographic film for a long time). Each photon may therefore be said to interfere with itself, just as a wave does.

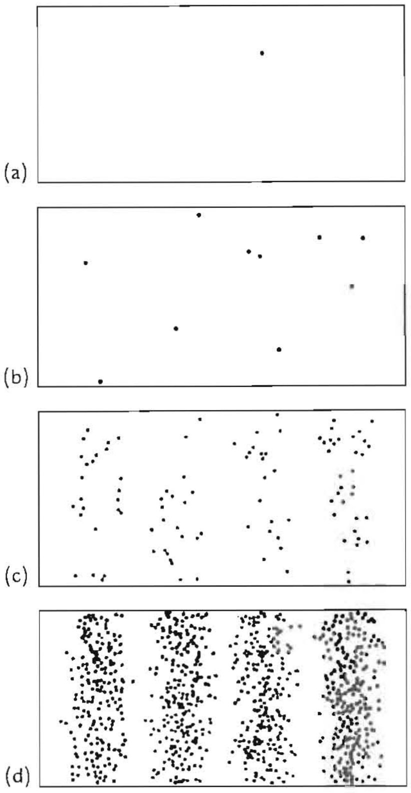

FIGURE 15.3

Simulated picture of interference fringes exposed with **(a)** one photon, **(b)** 10 photons, **(c)** 100 photons, and **(d)** 1000 photons.

The amount of energy absorbed by any photon detector equals the entire energy of the photon. By the quantum principle this energy, in turn, is proportional to the photon's frequency. Therefore, high-frequency photons carry more energy than low-frequency ones. That's why, for instance, blue light would expose all photographic emulsions (Sec. 4.7C) and why the yellow filter is needed in color film (Sec. 11.2). In Table 1.1, showing the electromagnetic spectrum, you find the high frequencies near the top. Thus gamma rays and x-rays carry a relatively large amount of energy per quantum. On an everyday scale this amount still seems tiny—it would take 10^7 gamma ray photons to equal the energy of a pin dropped from a height of 1 cm. Yet on the scale of energies that are typically exchanged within cells of our body, the gamma ray energy is very high. Therefore, gamma rays and x-rays (and even UV light, to some extent) can do damage to living cells. The high quantum energy also means that it is relatively easy to observe *single* photons at these high frequencies. Nearer the bottom of the table are radiations with very much smaller photon energies. A microwave photon, for example, carries a billion times less energy than an x-ray photon.

Our understanding of light as photons helps us, at last, clear up the mystery of Section 1.4B: why the black-body spectrum of Figure 1.19 has the shape it does. That figure shows the intensity of light at each wavelength coming from a cavity whose walls have a given temperature. The curve has a peak and falls off for both large and small wavelengths. The fall-off at large wavelengths is a wave phenomenon, which we could have understood much earlier: The larger the wavelength, the harder it is to fit a wave into a given volume. Hence, we expect the longer wavelengths to be relatively rare inside the cavity. This much was understood classically, before the advent of quantum theory.

But the classical theory gave no hint of why the curve should fall off at shorter wavelengths. Shorter wavelengths mean higher frequencies, and the quantum theory now tells us that the higher the frequency of light, the more energy it takes to make a photon. Since the walls of the cavity are at a definite temperature, they only have a certain amount of thermal energy to emit as light—they cannot radiate very energetic, short-wavelength photons. That's why the spectrum falls off at *short* wavelengths. Of course, the hotter the walls, the more thermal energy is available, and therefore the more short-wavelength photons can be radiated. Thus as we heat the walls, the peak of the spectrum moves towards the short-wavelength end, as the figure shows.

*B. Applications of the photoelectric effect

An electric current is produced by the set-up of Figure 15.1 whenever light strikes the metal surface. Such a device is called a ***phototube***, and it is useful for all sorts of gadgets, for example to make a simple electric eye (see Sec. 7.10).

Phototubes (or their solid-state equivalents, photocells) are also used to decode the sound track of movie films. The sound oscillations are recorded as alternate bright and dark bands on the edge of the film (see Fig. 4.16). After a given picture on the film has been jerked through the projection beam, its jerky motion is smoothed out by a flywheel, and it then moves past a light source that focuses a slit of light on the sound track. The transmitted light intensity varies in accordance with the sound oscillations. A pho-