CHAPTER 4

Einstein's Photons

The development of the quantum ideas themselves occurred in discrete jumps, quantum leaps of the creative insights of a few people. The next significant progress came in 1905, five years after Planck had proposed the energy quanta, from a young man named Albert Einstein, who at the time worked in a patent office in Switzerland.

If one shines monochromatic light on a metal, electrons come out of it, but in a very odd way. The energy of the outcoming electron has nothing to do with the intensity of the wave train of radiation incident on the metal. Now this is not the way waves behave. You can imagine ocean waves imparting energy to a piece of driftwood on a beach. The more energy the waves have, the more energy they will impart to the wood; it is the total energy of the waves that counts. In contrast, if you fire a bunch of bullets at a piece of wood, one of which hits the wood, the energy all the bullets impart to the wood depends entirely on the energy of the bullet that hits it. The other bullets don't matter. If you shoot a large number of bullets, you increase your chance of hitting the wood, but the energy change of the wood upon being hit still depends on just the individual energy of the bullet that hits it. Thus, in the case of the interaction of a beam of light with a metal, the imparting of energy to the metallic electrons takes place as with bullets, not as with ocean waves. Indeed, having a more intense light beam just enhances the chance of the light "bullet" to hit an electron. More electrons are found to come out, but all with the same energy so long as you keep the frequency of the light fixed (Figure 4.1).

Einstein identified the individual bullets of light as energy quanta and eventually the name of ***photon*** was given to them; the phenomenon of ejection of electrons from a metal

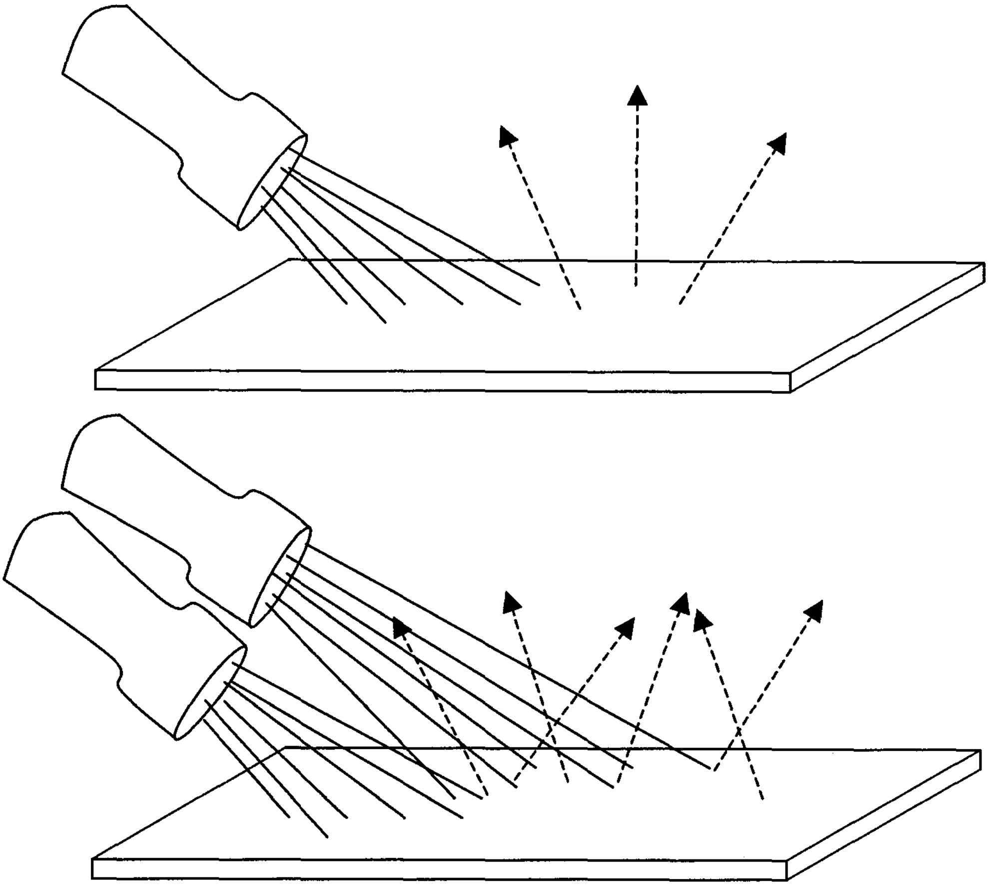

Figure 4.1
The number of photoelectrons emitted from a metal plate depends on the intensity of the light shone on the plate.

is called the ***photoelectric effect***. For each photon, the energy is connected with the frequency through Planck's relation:

$$E = h\nu.$$

A high-frequency photon has more energy than a low-frequency one.

Figure 4.2 shows an experimental arrangement for observing the photoelectric effect. We let light shine on a negatively charged metal surface that then ejects electrons that are attracted to the positively charged plate, producing a current, as shown, which is measured by the current meter (called an ammeter).

Two interesting aspects of Einstein's photon theory of photoelectric effect are borne out by more elaborate experiments. First, for a higher frequency of the light beam, more energetic photons, we do get more energetic electrons. Second, and even more telling is

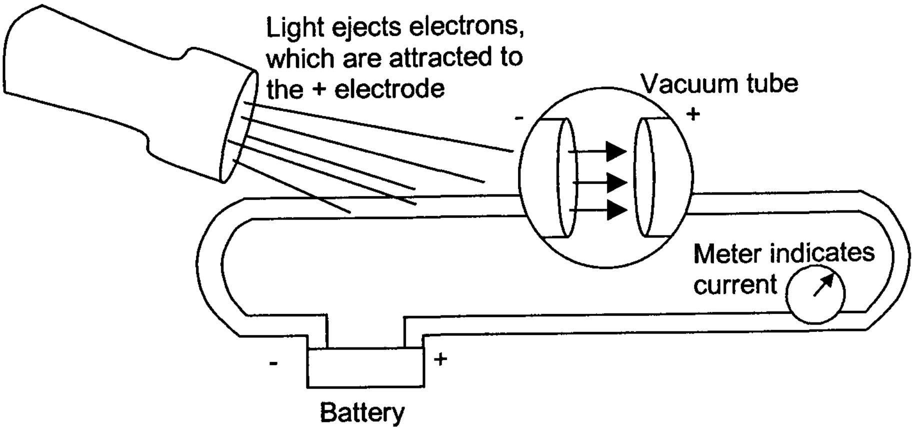

Figure 4.2
Schematic of an apparatus for measuring the photoelectric effect.

that often even an intense red beam is unable to eject photoelectrons from a metal, but even a weak blue beam carrying adequate individual photon energy does the job (Figure 4.3). You can relate to this. In a darkroom for developing film (which contains metallic compounds), red light is quite safe to use, but anything higher in frequency, even a little bit of white light, will ruin the film.

Thus, Einstein's work established the quantum nature of light. Let's consider an application of the quantum idea that you will like, it is within your everyday experience. There is something about vision in dim light that can be explained very simply by using the photon picture, but it is very difficult to understand if we insist that light is continuous energy. When we look at objects in dim light, we don't see sharp outlines; the shapes of the objects seem to merge into each other instead of being distinct. If the light energy coming to the receptors of our eyes were continuous, there would always be some light, albeit of low intensity, coming from all parts of an object and falling on all the receptors. Granted, the contrast between light and dark would not be very great in dim light, but this would not affect the sharpness of the outline.

Instead, what happens is that the receptors of our eyes work on the principle of photoelectricity–they respond to the graininess of light, to the individual photons. Since dim light gives fewer photons, this means that too few receptors will be stimulated at one time to define an outline or shape of the object; the picture is too fragmentary. If the receptors stored the information, of course, there would be enough fragmentary pictures for the brain to put together to make the whole. Unfortunately, the receptor information is retained for only a tiny interval of time, so the result is that in dim light not enough receptors will fire at any one time to give a sharp picture of the shape of an object. Next time you say goodbye to your loved one in twilight, watch how, as he or she moves away, his or her silhouette becomes more and more obscure, and then you can think of photons; surely that will lessen the pain of separation. The opposite effect of this happens when we develop a photographic film. Initially we cannot see a distinct shape; the image is too fragmented. Only when there are a lot of grains of the film developed is there a shape.

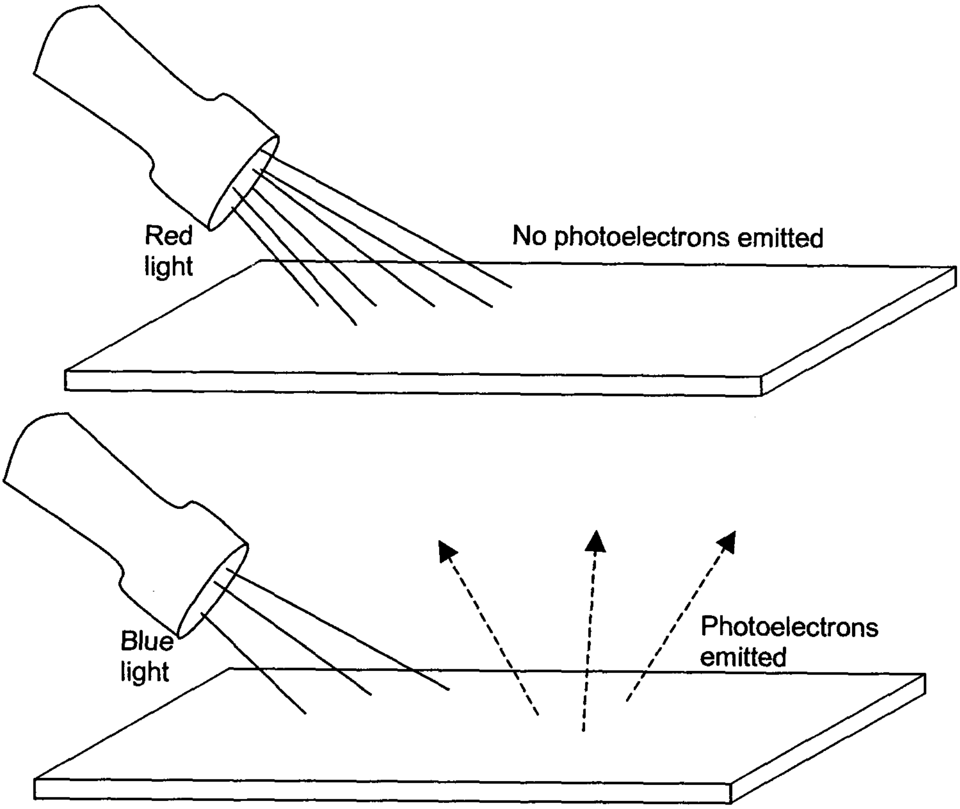

Figure 4.3
Even intense red light does not cause photoelectrons to be emitted from the metal plate; even weak blue light does cause photoelectrons to be emitted.

Question: If a beam of blue photons has the same total energy as a beam of red photons, which beam has more photons?

Answer: The red beam, of course. Because the energy per photon is lot less for red than for blue, the red beam has to make up by number.

Wave-Particle Duality of Light

If light consists of quanta, bundles of concentrated energy, then is light better conceived as particles than waves? The problem is that light also behaves like waves, and it is quite easy to verify that this is so. Just go out on a dark night with an umbrella and look at a distant street light through the fabric of the umbrella. If light were particles, the pattern you should expect is the same as when sugar falls through a sieve, making a lump below. But when light falls through an umbrella into your eyes, there is not one lump, but an entire pattern of fringes greets your eyes. This is to be understood as diffraction of light—light waves bending around the fabric. (You must be familiar with the phenomenon of diffraction of sound—bending of sound waves around a corner—as when you can hear your friend speaking from behind a wall. Diffraction of light is the same phenomenon, unmistakably telling us of light's wave nature.)

So how can light be both wave and particle? When you think about it, this should be very surprising. Particles are localized entities, always following definite trajectories of movement. In contrast, waves spread out, they have the ability of being in two or more places at the same time. Verify this. Throw a ball and see that it describes a trajectory, always being at one place at a time. Now speak and see that more than one person can simultaneously hear your every word, giving away the secret that waves can reach more than one place at the same time.

So Einstein's discovery of the particle nature of light in addition to the earlier-known wave nature makes one thing very clear. The quantum dimension of reality is weird, very contrary to our common-sense expectation. Of course, there is a little consolation in the wave-particle paradox—light shows up as particle in some experiments (e.g., the photoelectric effect), and as waves in some other experiments (for example, diffraction experiments), but never as both wave and particle in the same experiment. Later, we will see that this was the Danish physicist Niels Bohr's basis for understanding the wave-particle duality as complementarity—the wave nature and the particle nature of a quantum object are complementary aspects.

Actually, Niels Bohr is famous not so much for his attempt to understand the wave-particle duality, but for a model of the atom he built, a model that paved the way for quantum physics, a full-fledged replacement of Newtonian physics. We now turn to a discussion of the Bohr atom.

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