QUANTUM OPTICS

PHOTONS

In the 18th century, Newton advanced a sort of quantum theory of light, the energy coming in tiny corpuscular projectiles. Maxwell's theory and the observation of interference phenomena set the corpuscular theory to rest until early in this century. Then theoretical explanations of several phenomena revived it. The most important two were black body radiation and the photoelectric effect.

BLACK BODY RADIATION

An object that absorbs all incident radiation is a black body. For concreteness, one can think of something like an anodized ball bearing or a light bulb filament, or a cube of lampblack (figure 1). If a black body is heated it will emit light over a range of wavelengths, the energy distribution depending on the temperature.

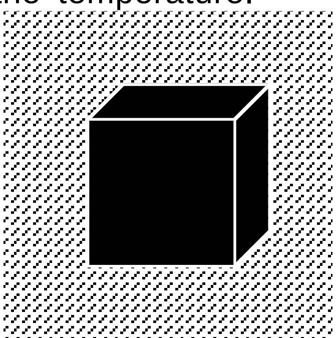

Figure 1. A cubic black body.

In the last decades of the 19th century there was a great deal of interest in black body radiation. Measurements of the amount of radiation emitted at a particular wavelength produced spectra like those shown in figure 2. As the figure shows, the higher the temperature of the black body, the greater the fraction of energy is radiated at short wavelengths. The wavelength of the maximum radiation, λ_{max} can be calculated from Wien's Displacement Law,

$$\lambda_{max}=(2.898\text{x}10^6 \text{ nm-deg})/T,$$

where T is the temperature in °K. The total energy radiated by the black body is the area under the radiation curve and increases as T^4, according to the Stefan-boltzmann law. Thus as a cold black body is heated it becomes brighter and brighter, at first radiating reddish, then yellow, and finally blue-white light.

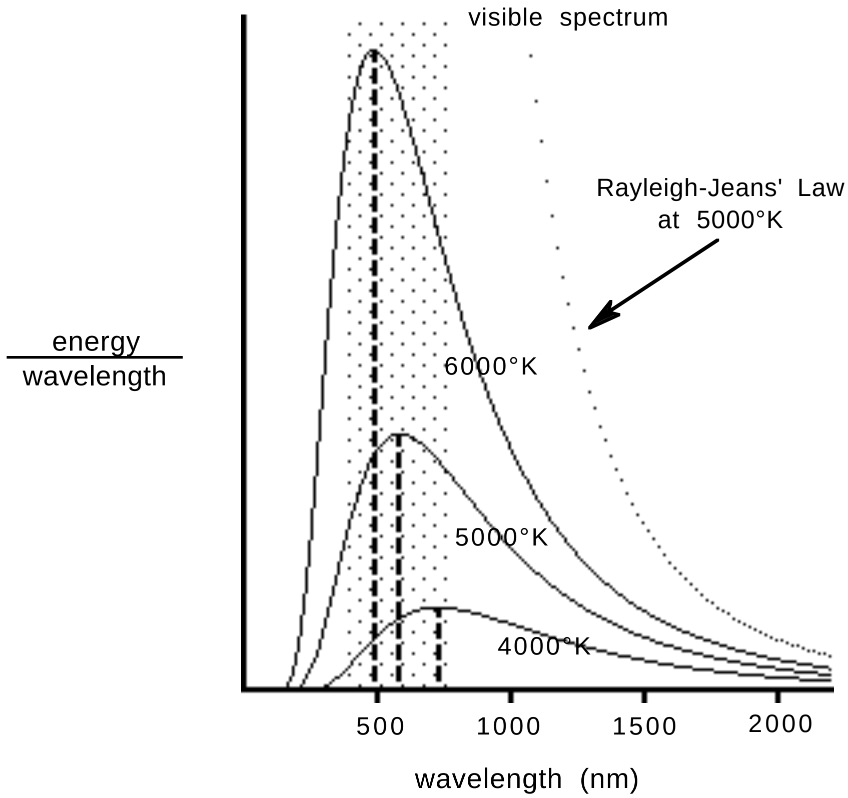

Figure 2. The black body radiation curve. Curves corresponding to 4000°K, 5000°K, and 6000°K are shown, the vertical dotted lines indicating the position of λ_{max}. The dotted curve at the right shows Rayleigh-Jeans' law. The shaded region is the visible spectrum.

The classical explanation of black body radiation produced Rayleigh-Jeans' law. This worked well for long wavelengths but failed miserably for short wavelengths. As wavelength became shorter the Rayleigh-Jeans' law predicted more and more radiation, an infinite amount at zero wavelength! This failure became known as the ultraviolet catastrophe.

In order to explain the shape of the black body radiation curve, Max Planck assumed that the radiation emitted by the body came in clumps. These clumps carried energy

$$E=h\nu=hc/\lambda$$

where h=6.626x10^{-34} Joule seconds is Planck's constant. Planck thought of his result as a cheap mathematical trick, but it actually was describing physical reality, as math so often does. The little clumps of electromagnetic energy were particles called photons.

PHOTOELECTRIC EFFECT

When short wavelength visible or ultraviolet light falls on a metal plate in a set-up like that shown in figure 3, electrons are emitted from the plate. This is the photoelectric effect.

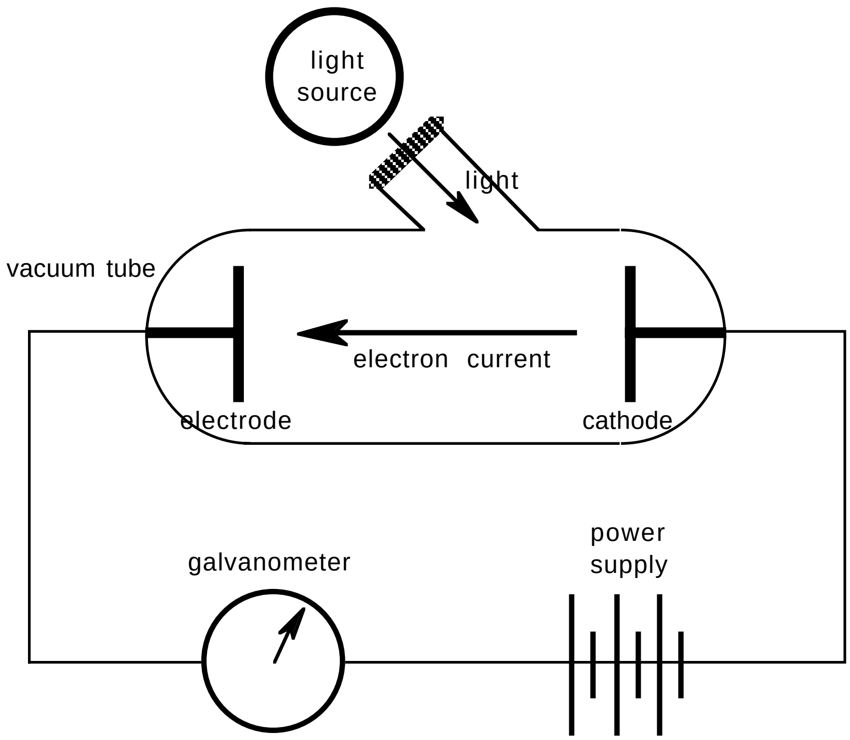

Figure 3. In the photoelectric effect, light incident on the cathode of a vacuum tube liberates electrons which produce a current.

Einstein gave an elegant explanation of the way the current generated depended on the number of photons and on their frequency. He assumed that an electron was released as a consequence of its interaction with a single photon, and the energy of the released electron would be

$$mv^2/2=h\nu-W.$$

The term W is called the work function, a measure of how tightly bound the electron is by the metal. The higher the frequency (and the lower the wavelength) of the light, the more energy the photon would have. But clearly, the existence of the work function and the fact that kinetic energy=$mv^2/2>0$ means that for frequencies below a certain limit (and wavelengths above a certain limit) *no* electrons would be emitted. That critical frequency is given by $h\nu_o=W$. Once above the critical frequency, the number of electrons released would depend on the number of photons incident.

Einstein won the Nobel prize for his work on photoelectric effect.

THE ELECTRON VOLT

The usual MKS unit for energy, the joule, is much too coarse to use in quantifying the energy of a photon. A more appropriate and commonly used unit is the electron volt, the energy given an electron when it accelerates through a one volt potential difference. The electron volt is abbreviated "ev" and 1 ev=1.60×10^{-19} joules.

In electron volts $hc=1.2396\times10^3$ ev-nm, so that Planck's quantum equation becomes

$$E=(1.2396\times10^3 \text{ ev-nm})/\lambda,$$

where energy E is in electron volts and wavelength λ is in nanometers.

SPECTRA

Whenever an electron is accelerated, electromagnetic theory predicts that electromagnetic energy will be liberated. Free electrons bouncing around in the spaces between atoms and molecules can have energies ranging within a continuum and can produce continuous spectra such as the bremstrahlung spectrum.

Within an atom, however, quantum theory requires that there be discrete energy levels. Electrons within an atom can only hop between these energy levels and so can only release certain discrete quantities of energy (figure 4). This energy is emitted in the form of the light corpuscles called photons. When an electron falls from a higher energy level E_2 to a lower level E_1, the frequency of the photon emitted satisfies E_2-E_1=ΔE=hν=hc/λ.

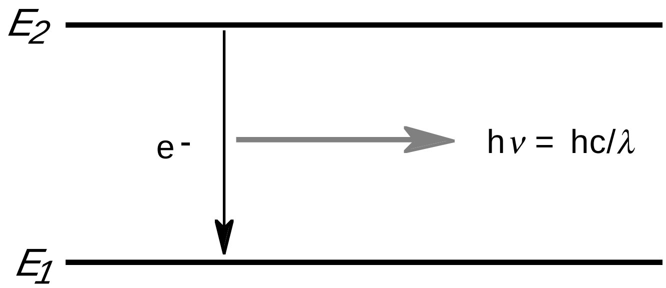

Figure 4. When an electron falls from a higher to lower energy level, a photon is emitted.

A familiar example of energy levels is the Bohr model of the hydrogen atom in which electrons are constrained to move around the atomic nucleus in discretely spaced orbits. Each orbit is characterized by a quantum number n, where n=1 for the innermost orbit, n=2 for the next orbit out and so forth. The energy associated with a particular orbit is E(ev)=(-13.6 eV)/(n^2).

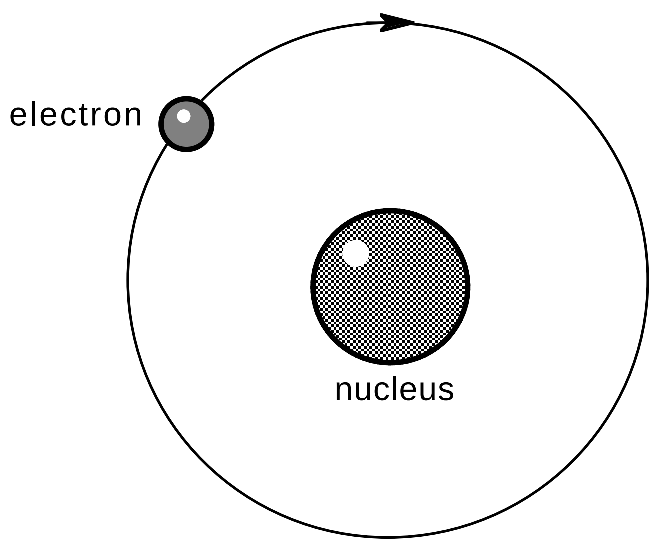

Figure 5. The Bohr atom.

Two familiar phenomena associated with the quantum theory of light are fluorescence and phosphorescence.

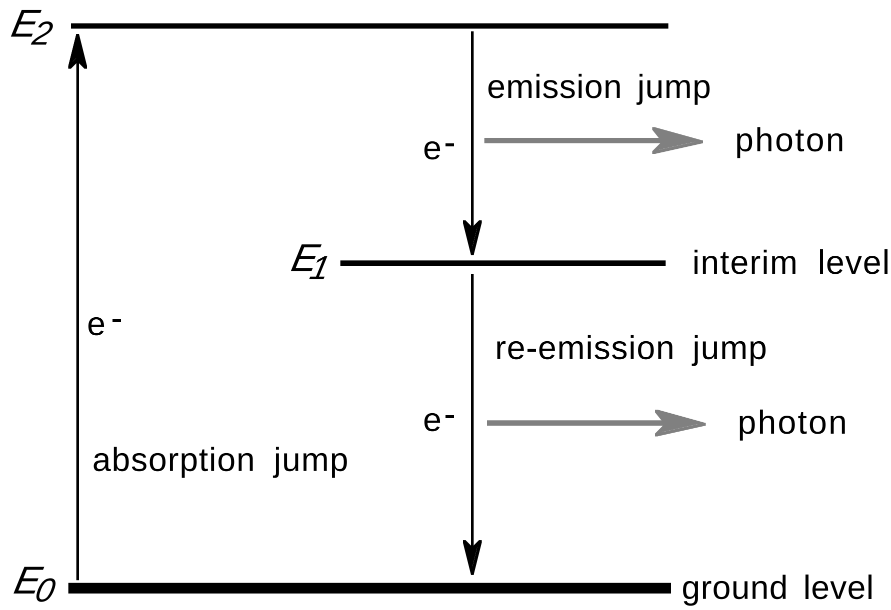

Figure 6. In fluorescence an excited electron falls back to ground level through an intermediate level.

Light shining on the material moves an electron from E_0 to E_2. The electron falls from E_2 to E_1 emitting a photon (figure 6). There is speedy remission of light from the interim level. Note that since $E_2-E_0>E_2-E_1$, less energy is emitted in dropping to the interim level than was absorbed in moving the electron to the upper level. This means that relatively short wavelength (high energy) light causes the absorption while long wavelength (low energy) light is emitted in falling to the interim level. Thus in fluorescence, blue light goes in, yellow light comes out.

There are many practical applications of fluorescence. In eye care, for example, fluorescent dyes are used to visualize corneal scratches, tear pooling behind a contact lens, and blood through retinal and iris vessels. At one time certain invisible bifocals had fluorescent markings.

In phosphorescence, on the other hand, the electron stays in a metastable state for a while, the light emission continuing sometime after the exciting source is removed. A variety of glow-in-the-dark knick-knacks make use of phosphorescence.

WAVE-PARTICLE DUALITY

So how do we reconcile the wave theory, which accounts for interference and diffraction so well, with the particle theory which accounts for spectra and the photoelectric effect?

Answer is best done mathematically. In essence it consists of interpreting the intensity distributions of diffraction theory as probabilities, the probability of a photon landing in a particular location being proportional to the intensity at the point. This concept is called wave-particle duality.

To understand duality better, consider an experiment in which light waves polarized at 45° are passed through a vertical polarizer, as shown in figure 7.

By Malus' law, half the luminous flux and hence half the photons go through the polarizer. But what happens to an individual photon? You can't split a photon so an individual photon either goes through or doesn't go through. The odds of its going through are 50-50. But since all the photons hitting the polarizer are identical, what determines whether a particular photon goes through or not?

According to quantum mechanics, the photon initially exists in *both* states of polarization. Only when it encounters the polarizer does the photon pick one or the other. The choice of polarization is purely random for any individual photon, but for a large number of photons we will achieve the 50–50 division predicted by Malus' law.

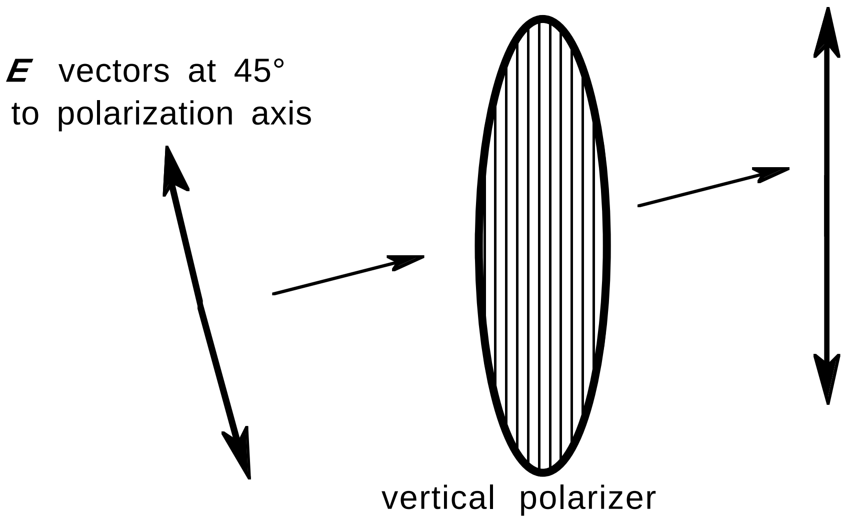

Figure 7. Light polarized at 45° passing through a vertical polarizer.

But why should duality only apply to photons? In fact, it doesn't. Louis de Broglie extended the quantum hypothesis to all matter including electrons, protons, etc. A practical consequence was the electron microscope which uses electron waves instead of light waves to get higher resolution.

*But wait a minute! Didn't my optics teacher say that light travels in straight lines, in **rays**, not some sort of undulating, zig-zagging **waves**?*

Optics teachers never lie! Light *does* travel in straight lines--sort of. In fact light really *is* a particle-wave phenomenon. Straight line propagation is an approximation to the actual behavior of light, a very useful approximation for large scale effects. Just don't look too closely at the edges of those shadows...