Matter can absorb any amount of energy.

Light is a wave.

An electron is a particle.

Energy and matter are unrelated.

Energy and waves

We usually determine of the energy in an ocean wave by measuring its height, but the energy delivered by a series of waves is expressed not only by examining the amplitude of the wave, but also the frequency of the wave.

UV light is higher in frequency than visible light; which is, in turn, higher in frequency than infrared light.

$$\mathbf{c} = \lambda \cdot \nu$$

speed = wavelength •frequency

speed m/s = wavelength m•frequency 1/s

Quantization of energy in

Black Body radiation

When an object is heated it radiates energy. We have all seen and felt this phenomenon. Some radiation cannot be seen by us, but we can feel it; a wood burning stove radiates infrared light. We can feel the heat from the stove, and a simple experiment demonstrates that the heat we feel comes from light waves. To stop the heat you only have to hold an object between your face and the stove. As objects get hotter they glow like the burner of an electric. As objects continue to be heated they glow brilliantly like the tungsten filament in a light bulb.

Black body radiation cannot be explained using classical physics.

Max Plank saved us from the ultraviolet catastrophe by suggesting that maybe matter had to absorb energy in discrete steps. That is matter cannot absorb any amount of energy it chooses , rather matter can only absorb certain amounts of energy. The energy that could be absorbed or released is then expressed as:

$$\Delta E = n \bullet h \bullet \nu$$

(ν is the frequency of the light energy being absorbed or released)

- n is a whole number; i.e., 1,2,3,4...

- h is a constant (Planks constant 6.626 x $^{10-34}$ J•s which determines the size of the step).

What does this mean for our picture of oscillators...
Now an oscillator is not allowed to absorb any amount of energy. Any oscillator of a certain frequency can only have certain values as specified by $n \bullet h \bullet \nu$.

Compare a low energy oscillator, i.e. one that produces infrared light, to a high energy oscillator, one that produces ultraviolet light.

oscillator(IR) = $n \bullet (6.626 \times 10^{-34}\ J \bullet s)\ (3 \times 10^{12}\ s^{-1}) = n\ (2 \times 10^{-21}\ J)$

oscillator(UV)= $n \bullet (6.626 \times 10^{-34}\ J \bullet s)\ (3 \times 10^{16}\ s^{-1}) = n\ (2 \times 10^{-17}\ J)$

So, it takes approximately 1,000 x as much energy before UV oscillators even start going.

The photoelectric effect

Another phenomenon which classical thinking cannot explain is The Photoelectric Effect.

draw photoelectric picture with wave
table with light color, amount of current, energy of electrons

Shine white light on sodium and current flows.

Several observations were made about the photoelectric effect...

- If the light is made brighter then more current flows through the ammeter.

- If blue light is used a current flows.

- If yellow light is used current flows.

- If red light is used no current flows no mater how bright the light is.

- The electrons produced by the blue light have more energy than the electrons produced by the yellow light.

Summing up observations

- There is a frequency below which no current flows, and higher frequency light makes more energetic electrons (not more electrons).

- The amount of current, number of electrons, increases with increasing light intensity.

Can this result be explained by the classical description of light; that is, light is a wave? No.

We know that when two lights are shining on a table more energy is hitting the surface of the table. Thinking classically, if the intensity is high enough then the amount of energy being absorbed by the sodium should be enough to push an electron out, but this does not happen.

What if light was quantized; that is, what if light delivered its energy in small packets called photons.

Implications:

- The frequency of the light determines the energy of the photon, packet of energy.

- The intensity of light is determined by the number of photons.

draw wave vs. particle (different chalk board)

The light energy is now transferred by collisions of photons with matter; in this case, the matter is an electron.

draw close-up metal

If the photon has enough energy then it collides with the electron and the electron is pushed free of the solid. This is what happens when a yellow photon hits the electron.

If a photon does not have enough energy then the electron does not gain enough energy to get free. This is what happens when a red photon hits the electron. Furthermore, if we turn up the intensity of the red light, each photon still does not have enough energy to knock an electron free. (The odds of two photons striking the electron is so small that it does not happen.)

If a blue photon hits and electron the electron will be ejected since a blue photon has more energy than a yellow photon. Since a blue photon has more energy than a yellow photon, the extra energy goes into increasing the kinetic energy of the electron.

This relationship is described mathematically:

$$\frac{1}{2} mv^2 = h\nu - \Phi$$

Φ is the work function of the metal; i.e., the amount of energy required to remove and electron.
$h\nu$ is the energy of the photon

Electrons have **wavelike** character.

X-rays and a crystal

> If a beam of X-rays is shined on a crystal a diffraction pattern forms. If a beam of electrons is shined on a crystal a diffraction pattern forms.
>
> The crystal scatters the X-rays, and, because of the regular organization of the crystal, the scattered X-rays interfere with each other constructively and destructively. Since a diffraction pattern forms when a beam of electrons passes through a crystal the electrons must be behaving like X-rays. That is the electrons are behaving like waves and interfering constructively and destructively.

A **particle**, an electron, acts like a **wave**.

In fact, we can measure its wavelength. (deBroglie Equation)

$$\lambda = \frac{h}{mv}$$

be careful the book uses ν for both v and ν.

> In microscopy, magnification is important, but resolution is even more important. Due to the wavelength of visible light, there is a limit to the resolution that visible light can achieve. Electron microscopes use electrons because when electrons are traveling at the right speed they have a short wavelengths. Very good electron microscopes use extremely fast electrons because the electrons will have very short wavelengths. Very short wavelengths allows the microscope to resolve very small details.

Turning Classical Physics on its ear…

Light acts like a particle...

- The Compton effect, X-rays push around electrons.

- The photoelectric effect.

Electrons act like waves....

- An electron beam shot through a nickel crystal produces a diffraction pattern like light going through a grating (oil puddle)

- Beams of electrons act like light...electron microscopes.

Energy acts like matter...

- Energy must be delivered in discrete packages, photons.

- Nuclear reactions inter-convert matter and energy

OK, lets use some of these ideas to tackle the atom. When we last left the atom we had a centralized nucleus and an electron floating/circling around.

Lets take that hydrogen atom and put electricity through it; this is a gas discharge tube. The hydrogen emits light. But the light looks different than regular light.

White light is made up of all sorts of different colors (ROYGBIV), and when white light (sun-light) passes through a prism we can see all the different colors.

When light produced by H atoms passes through a prism we do not see ROYGBIV. We only see four lines. (red 656, green 486, blue 434, and violet 410 nm).

If light can cause electrons to jump out (photoelectric effect), then electrons jumping around can emit photons. The photons emitted are only of certain frequencies so the electrons must only be allowed to have certain energies. The energy levels of the electron must be quantized.

So, the energy of the electrons orbital are quantized.

draw picture of H atom with circular orbits

Energy released when an electron goes from high energy to lower energy is proportional to the frequency of the light that is released.

$$\Delta E = h\nu$$

So, the amount of energy between the two energy levels when purple light is released is...

Purple is 410 nm so...

$$E = h\ c/(410 \times 10^{-9}\ \mathrm{m})$$

$$E = (6.626 \times 10^{-34}\ \mathrm{J \bullet s})(7.312 \times 10^{14}\ \mathrm{s^{-1}})$$

$$E = 4.845 \times 10^{-19}\ \mathrm{J} \qquad (4.8449)$$

Is the energy of the photon emitted. What is the change in energy for the electron?

$$E_{\mathrm{photon}} = -\Delta E_{\mathrm{electron}}$$

So, $\Delta E_{\mathrm{electron}} = -4.845 \times 10^{-19}\ \mathrm{J}$