

## A Little Modern Physics

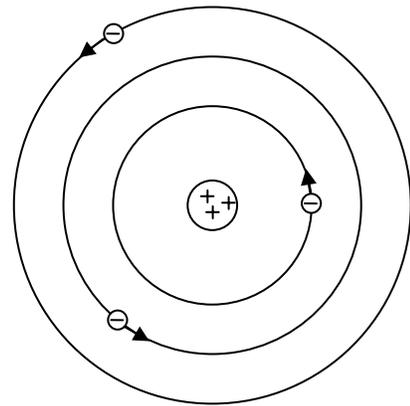
"Modern" physics means physics discovered after 1900; i.e. twentieth-century physics.

The late nineteenth century (roughly 1880 – 1900) was a time of blissful ignorance for physicists. Many physicists believed that Newton's mechanics and Maxwell's E&M could explain everything. Boy, were they wrong!

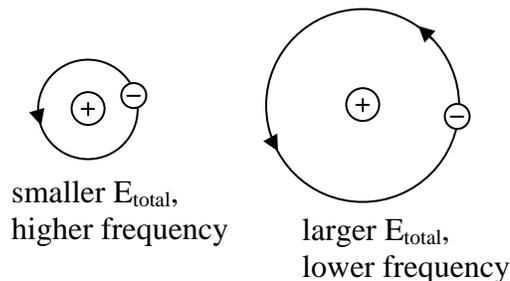
Three revolutions in our understanding of the physical world occurred in the 20<sup>th</sup> century:

- 1) Special Relativity, a theory of space and time (Einstein 1905)
- 2) General Relativity, a theory of gravity (Einstein, 1916)
- 3) Quantum Mechanics, a theory of the behavior of atoms (Planck, Einstein, Bohr, Heisenberg, Schrodinger, Born, Dirac, Pauli, ..., 1900-1928)

In 1911, Ernest Rutherford (New Zealand/Britain) did an experiment that showed that an atom consists of a small, heavy, positively-charged nucleus, surrounded by small light electrons. The electrons are held in orbit around the positive nucleus by the coulomb force (similar to a planet in orbit around the sun, held by the gravitational force).



The electron has a total energy  $E_{\text{tot}} = KE + PE$ . Classical E&M and Newton's mechanics predicts that the electron can have any total energy. One can show that higher energy corresponds to a larger radius orbit with a longer period  $T$  (lower frequency  $f = 1/T$ ).

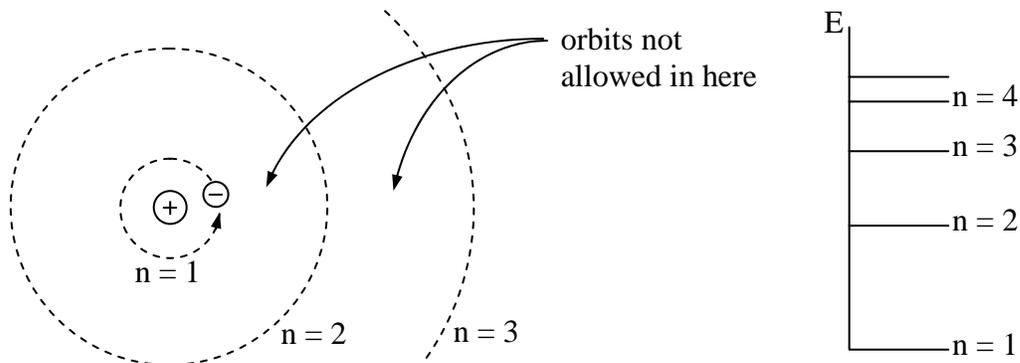


But if the electron can have any total energy, it can orbit with any frequency. And the atom can then give off light of any frequency. (Recall that if a charges shakes with frequency  $f$ , it gives off light of that same frequency  $f$ .) However, this prediction conflicts with experiment.

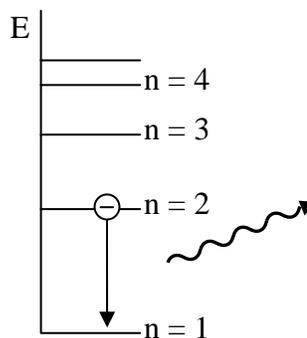
Experimentally, it is found that atoms only give off light at certain specific frequencies. Each

element (H, He, C, N, O, etc) emits a pattern of light at particular frequencies. The pattern of frequencies give a unique fingerprint which can be used to identify the element producing the light.

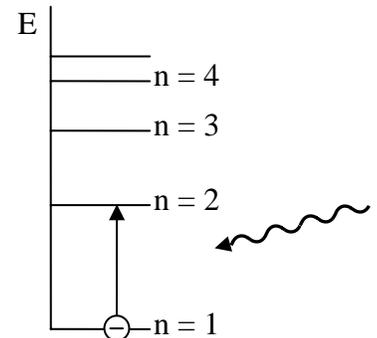
In the early 20<sup>th</sup> century (roughly 1918–1928), a new theory called **Quantum Mechanics**, was developed to explain the behavior of atoms. Quantum mechanics predicts that only certain electron energies are allowed in an atom. Classical mechanics predicts that any energy is possible, and so the allowed energies form a *continuum*; quantum mechanics predicts that only certain energies are allowed and so the energies are *quantized*, that is, discrete. The allowed energies are labeled with a *quantum number*  $n$ . The quantum number  $n = 1$  is the label for the lowest allowed energy state, called the *ground state*. Higher energy states ( $n = 2, 3$ , etc) are *excited states*. The separation between energy levels is usually about a few eV's (1 eV = 1 electron-volt =  $1.6 \times 10^{-19}$  J )



Light is emitted from the atom when the atom makes a transition from a higher-energy state to a lower energy state. Light is absorbed by the atom when it makes a transition from a lower-energy state to a higher-energy state.



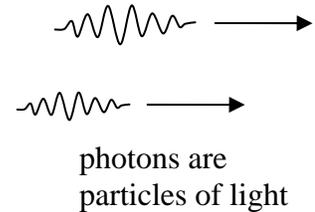
transition to lower  $n$ ,  
light emitted



light absorbed,  
transition to higher  $n$

Isaac Newton (around 1700) believed that light was a particle (like a little pellet) that always travels in straight lines called rays. In 1801, the English scientist Thomas Young performed the famous "double-slit" experiment that showed that light was a wave of some kind. Around 1860, Scottish physicist James Clerk Maxwell developed a theory which showed that light is an electromagnetic wave. So Newton was wrong, right? Actually, he was partially correct.

Quantum mechanics predicts that light is both a wave and a particle. It has both wave-like properties (constructive and destructive interference) and it has particle-like properties. If you look real closely, a beam of light appears to be made up of a stream of particles called **photons**. The photon is the smallest possible unit of light. You cannot have an amount of light smaller than one photon. (Yes, this is weird. Einstein was the one who first explained the photon concept, but he was mighty unhappy about it.)

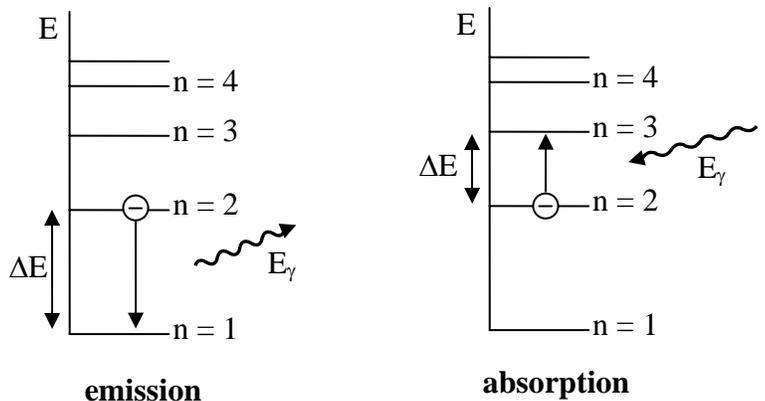


The energy of a single photon is given by the formula

$$E_{\gamma} = hf = h \frac{c}{\lambda}$$

where  $f$  is the frequency of the light and  $h$  is a constant, called Planck's constant (after Max Planck, German scientist, c.1900),  $h = 6.64 \times 10^{-34}$  J·s. The greek letter gamma ( $\gamma$ ) is the symbol traditionally used to indicate a photon, so the energy of a photon is written  $E_{\gamma}$ . Another useful number to know is  $hc = 1240$  eV·nm; this allows easy conversion between the energy of a photon in eV and its wavelength in nm.

When light is absorbed or emitted by atoms, the light is almost always absorbed or emitted as a single photon. The wavelength of the light is then easily related to the energy difference of the initial and final states of the atom, according to the formula



$$\Delta E = |E_f - E_i| = E_\gamma = h \frac{c}{\lambda}$$

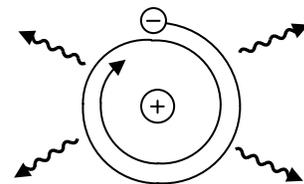
This is just a statement of conservation of energy. In emission, the energy lost by the atom goes into making the photon. In absorption, the energy gained by the atom came from the energy of the absorbed photon.

**Example.** What is the energy (in eV) of visible light? The wavelength of green light is about 550 nm (the center of the visible spectrum). Energy  $E_\gamma = (hc) / \lambda = (1240 \text{ eV}\cdot\text{nm})/550 \text{ nm} \approx 2.3 \text{ eV}$ . It just so happens that the energy levels of the outermost electron in atoms are usually separated by a few eV, so transitions between energy levels in atoms usually result in visible light.

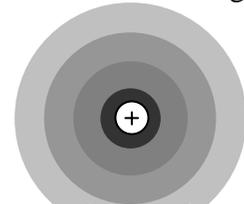
**Example.** Can a microwave oven or a cell-phone communications antenna (both of which emit microwave radiation) cause cancer? Answer: The wavelength of microwaves is about  $\lambda = 10 \text{ cm} = 0.1 \text{ m} = 10^8 \text{ nm}$ . The photon energy that this produces is  $E_\gamma = (hc) / \lambda = (1240 \text{ eV}\cdot\text{nm})/10^8 \text{ nm} \approx 10^{-5} \text{ eV} = 0.00001 \text{ eV}$ . Chemical bonds in molecules are a few eV. In order to cause a cancer, we must break a chemical bond in a cell. The energy of a microwave photon is about 100,000 time too small to do this. Microwaves cannot cause cancer.

Among the problems solved by Quantum Mechanics, that was mysterious from the point of view of classical mechanics, was the stability of atoms. In the classical view, the electron orbits the nucleus. As the electron "shakes" around and around the nucleus, it should radiate light, giving up energy. As it gives up energy, it should spiral into the nucleus, making the atom small and smaller.

In QM, the allowed energy states are completely stable. When the electron is in one of the allowed energy states, it doesn't really shake, it just sort of sits there quietly. In QM, the electron is not a particle in orbit. Rather it is an "electron cloud" which hovers, motionless,



Classically, an electron in an atom should radiate and spiral inward as it loses energy.



QM says that an electron in an atom exists as a stationary "electron cloud".

around the nucleus. This electron cloud is called the "wavefunction". Only when the electron makes a transition from one state to another, does the electron shake and give off light (in the form of single photons).

One other question that QM answers: Why do hot solids (like a tungsten light bulb filament) emit a continuous range of wavelengths (full rainbow) while individual atoms only emit specific wavelengths. QM predicts that when 2-atoms form a molecule (which occurs when their electron clouds overlap), there are twice as many allowed energies for the 2-atom molecule as there are for the single atom. In a 3-atom molecule there are 3 times as many levels. In a solid with  $10^{23}$  (Avogadro's number) atoms, there are so many allowed levels that they form a continuum and essentially any energy transition can occur, producing any wavelength of light.

