Essl 290 2021

Lecture 40

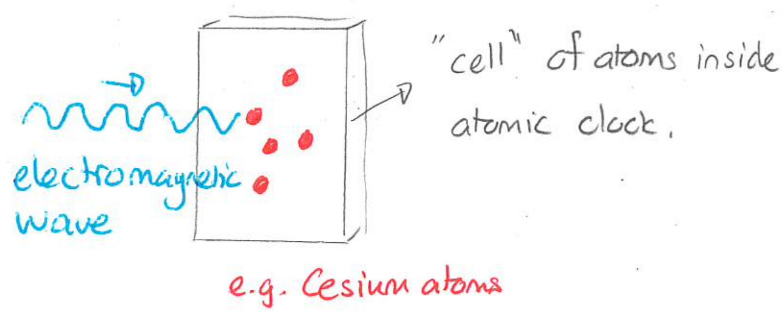
Fri: Short Assignment

Read Barrett 154 – 160

Atomic Clocks

The state of art quartz clocks have an accuracy of about $10\mu s = 0.000010 s$ per day. This easily exceeds the requirements for ordinary daily timekeeping and even the timekeeping required for radio and telephone communications.

Nonetheless this is insufficient for some current tasks and technologies. There is a new class of clocks, called atomic clocks, that can provide the necessary precision. Roughly these clocks use the interplay between atoms and electromagnetic waves to attain very precise timekeeping.



A basic understanding of these involves:

1) electromagnetic waves
2) quantum physics of atoms.

Electromagnetic waves.

An electromagnetic wave is an example of a class of objects called waves. These are readily illustrated by considering waves on a string or a slinky.

Demo: PhET W.o.a.S.

* No end
* No damping
* Create propagating wave

For timekeeping and atomic physics there are two important wave characteristics:

1) wave speed = speed with which pattern propagates

$$= \frac{\text{distance traveled}}{\text{time taken}}$$

2) frequency $\approx$ number of crests passing a given location per second.

The usual units of frequency are Hertz.

1 Wave speed and frequency

The instructor will run the animation and time how long it takes a crest to travel a given distance

a) Determine the speed of the wave.

5cm 4.23S

$$\text{speed} = \frac{\text{distance}}{\text{time}}$$

$$= \frac{5\text{cm}}{4.23\text{s}} = 1.18\text{cm/s}$$

b) How long would it take this wave to travel 20 cm?

$$\text{time} = \frac{\text{distance}}{\text{speed}} = \frac{20\text{cm}}{1.18\text{cm/s}} = 16.92\text{s}$$

The instructor will record the time taken for a certain number of crests to pass through the window.

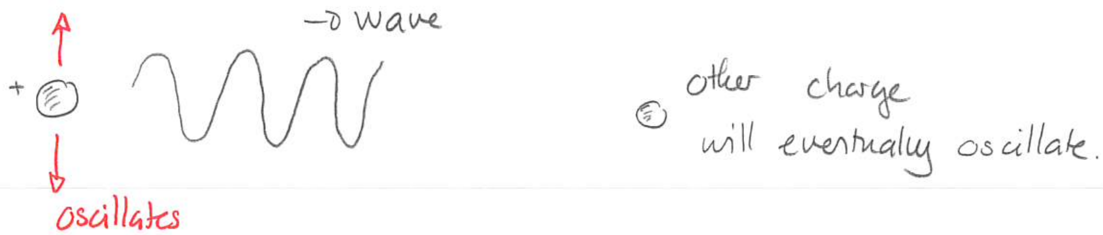
c) Determine the frequency of the wave.

10 crests took.

20.136

$$\text{frequency} = \frac{10}{20.13\text{s}} = 0.497\text{Hz}.$$

An electromagnetic wave consists of a wave of electric and magnetic fields. Roughly these are produced by oscillating charges



In a vacuum these travel at the speed of light, 3.0×10^8 m/s and their speed is similar in air.

Example: Determine how long it takes an electromagnetic wave to travel 200m (roughly 200 yards).

Answer: $\text{speed} = \dfrac{\text{distance}}{\text{time}} \Rightarrow \text{time} = \dfrac{\text{distance}}{\text{speed}}$

$$= \frac{200\text{m}}{3.0 \times 10^8} = 6.7 \times 10^{-6}\text{s}$$

This is very short!

Electromagnetic waves exist in a large range of frequencies. The "spectrum" of electromagnetic waves can be classified into regions depending on the frequencies. Given regions interact with different types of matter in specific ways

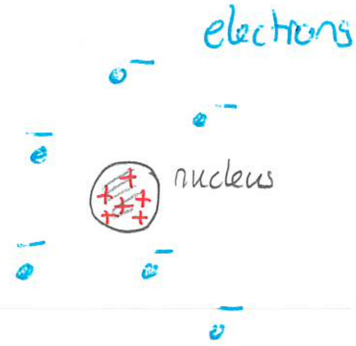
Demo: NASA Spectrum

Examples are:

1) radio waves 10^4 Hz → 10^8 Hz ≡ 10kHz → 100 MHz
2) visible light 10^{15} Hz.

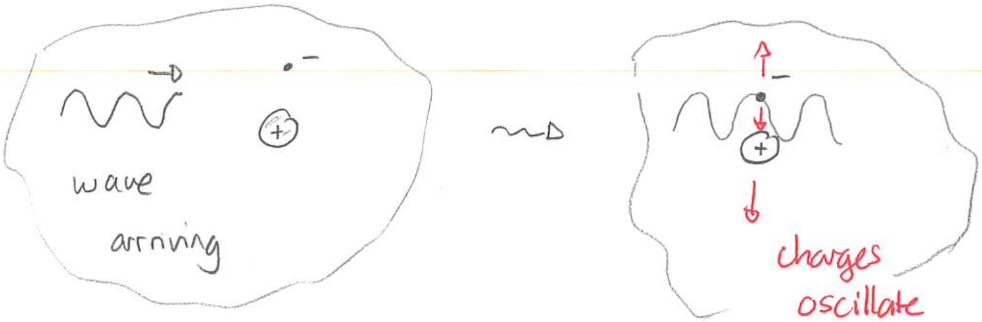
Atoms and electromagnetic waves

All atoms consist of a positively charged nucleus surrounded by negatively charged electrons.



Carbon atom.

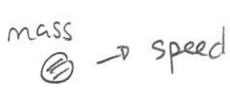
We would expect such atoms to be able to produce electromagnetic waves and also to respond to electromagnetic waves. So for an electromagnetic wave that is incident on an atom



There is a long history in physics of how to describe this interaction. The description that works best is provided by quantum physics and this refers to the energy of the atom.

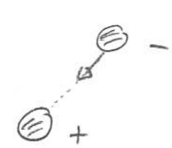
What is energy? In classical physics there are two relevant types of energy, illustrated for the electron.

Kinetic energy



kinetic energy = $\frac{1}{2}$ x mass x speed

Potential energy

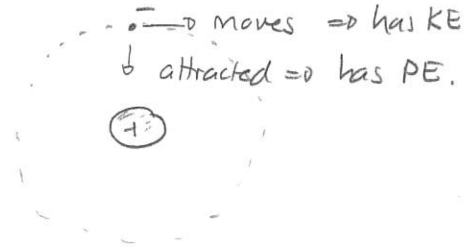


describes interaction between charges

closer charges are => lower potential energy

further " " => higher " "

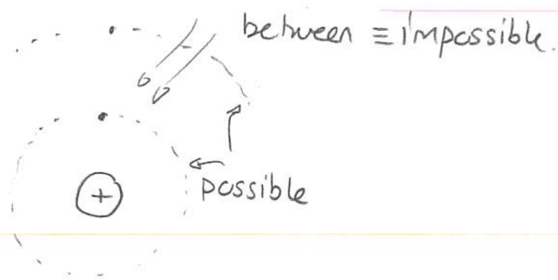
If we consider an electron orbiting a nucleus then the total energy is the sum of the two types. In classical physics these would depend on the radius of orbit.



Any energy is possible in this case, provided it is negative.

What quantum theory predicts is:

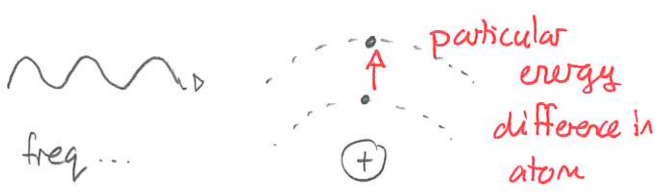
1) only certain energies are possible. (as though only some orbits are possible). These are associated with states



2) when electromagnetic radiation is incident on the atom, the <u>change in energy</u> is

$$\text{energy absorbed} = \underbrace{6.63\times10^{-34}\ \text{J.s}}_{\text{always same.}} \times \text{frequency of EM wave}$$

This means that if the frequency corresponds to a possible change in energy of the atom, then the EM wave will be absorbed. If the frequency does not correspond to a possible change the the wave will not be absorbed



atom energy difference $= 6.63\times10^{-34}\ \text{Js} \times \text{freq}$

$\Downarrow$

wave absorbed

atom energy diff $\neq 6.63\times10^{-34}\ \text{J.s} \times \text{freq.}$

$\not\Downarrow$

wave not absorbed.