Lesson 32: Birth of Quantum Mechanics

End of an Era...

At the end of the 1800s, physicists looked back at a period of 300 years of great growth…

- Newton had explained the motion of objects here on earth (and in the heavens).
- Maxwell had put together electricity and magnetism in his work on electromagnetic radiation.
- Thomson had figured out the mass of atomic particles.
- ...and more!

Altogether, most physicists believed that they had pretty much figured out the whole universe! They were willing to admit that there were still a few questions, but for the most part they were sure they could answer those problems based on what was already known. It was felt that it was only a matter of time (and not much time) before it would all be cleared up… right?

Wrong.

All of the physics you have studied up till now is called "Classical Physics."

- It works great for the kind of physics we've looked at, and you can keep on using it for those kinds of questions.
- The problem was that classical physics (as we now call it) could not explain a few nagging questions in physics right around the end of the 1800's.
  - One of these problems involved something called **blackbody radiation**.

Blackbody Radiation

A blackbody is an object that perfectly absorbs all wavelengths of EMR that strike it.

- This means that all EMR, from the lowest frequency AC radiation to the highest cosmic rays, will perfectly be absorbed by the object.
  - It's called a blackbody, since objects colored black absorb all *visible* light that falls on them. True blackbodies work even better than this, but it seemed like a good name.
- This EMR being absorbed is really energy that the blackbody is absorbing.

Blackbody radiation was also called **cavity radiation** at one time. In this model we imagine a hollow sphere with a single hole drilled in the side (the cavity), through which the EMR enters.

This energy is also perfectly re-emitted, released by the object, as EMR.

- According to classical physics, as the frequency of the emitted EMR increases, so should the intensity.
  - As more and more energy from the EMR was absorbed, it would cause the atoms of the blackbody to vibrate faster and faster at higher and higher frequencies.
  - These vibrating atoms (made of charged particles) would release higher and higher frequencies of more and more intense EMR.
- This classical physics explanation of the emitted EMR could be drawn as a graph (*Illustration 1*).

The problem is, this doesn't happen!

- Instead, the intensity of the emitted radiation does increase, until it reaches a particular frequency that depends on the temperature, and then drops.

- The peak frequency is the reason why different objects at different temperatures appear as different colors, like the red hot burner on a stove.
  - The higher the temperature, the higher the peak frequency shifts up to.
  - So the shift in visible light as the temperature increases is from red to violet.

> So, why don't you ever see a burner on a stove glowing green? As the colors shift higher and higher, most of the colors eventually end up being emitted strongly, so they all blend into white light.

- We also have a generic graph of this (for no particular temperature) on the graph in *Illustration 1*.

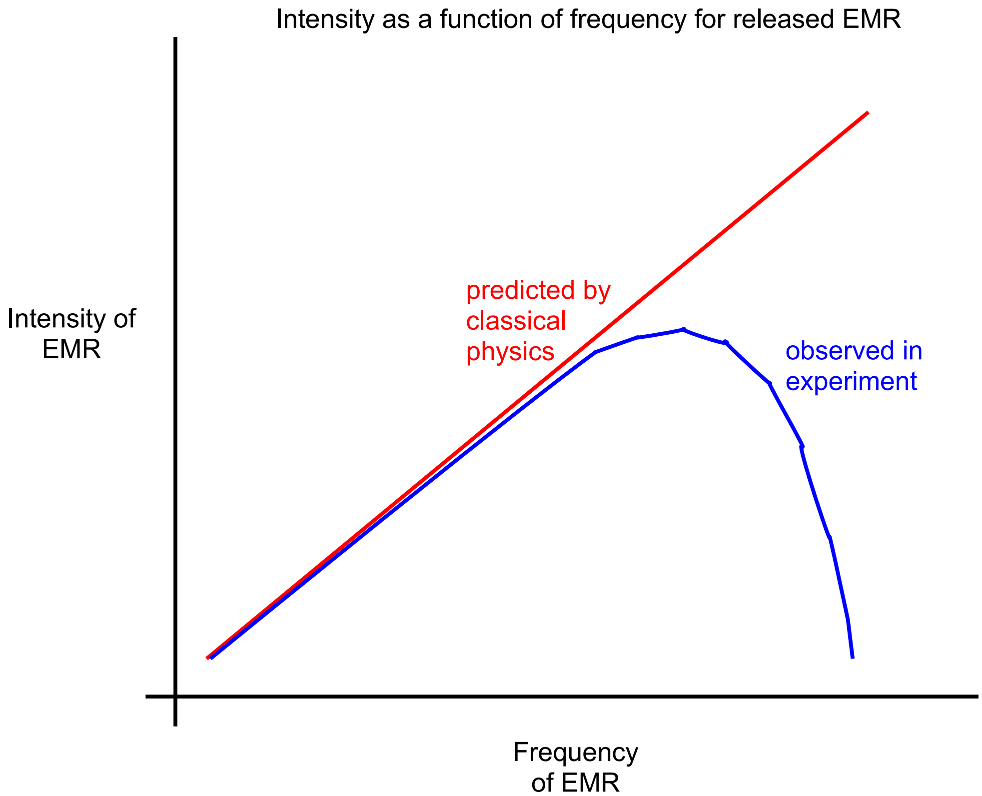

Illustration 1: Blackbody radiation prediction and reality.

Physicists could not explain why the graph suddenly drops off, or why it peaks at the particular frequencies at particular temperatures.

- Some of the best minds of the time worked on this, people like Wilhelm Wien, Lord Rayleigh, and Sir James Jeans.
  - Never heard of these guys? Doesn't surprise me. Although they made important contributions in physics, their attempts at blackbody radiation failed to come up with an explanation.
- Because the frequency that the graph drops off at corresponds roughly to the frequency of ultraviolet radiation, this problem became known as the **Ultraviolet Catastrophe**.

Max Planck

Illustration 2: Max Planck

Late in the year 1900, Max Planck (pronounced "Plonk," not kidding) came up with a new idea that would solve the problems everyone was having trying to explain blackbody radiation.

- Up to this point everyone was assuming that those little vibrating electrons (thought to be absorbing and then re-emitting the blackbody radiation) could vibrate at any frequency.
- Planck suggested that there is a minimum amount of energy that a particular frequency of EMR can transfer to the matter.
- This smallest individual "piece" of energy was called a **quantum**.

Quanta is the plural form of **quantum.** So a bunch of individual pieces of energy is called quanta.

The idea of pieces of energy, **quanta**, was used to explain the shape of blackbody radiation graphs.

- Planck found that a very simple formula could be used to calculate the quantum at a particular frequency of EMR…

$$E = hf$$

E = energy of the radiation (J)
h = Planck's Constant = 6.63e-34 J·s
f = frequency of the EMR (Hz)

Warning! Two Special Notes!
This formula is the amount of energy emitted by a single "piece" of radiation. To have multiple pieces, the formula would look like…

$$E = nhf$$

n = number of "pieces" of radiation emitted

Sometimes we measure the energy in electron volts, so we use a different value for Planck's Constant, h = 4.14e-15 eV·s . Only use this value if you have a really good reason to.

Planck was saying that energy is not continuous, but instead is **quantized**, coming in tiny pieces.

- This is sort of like when you look at a picture in the newspaper.
  - On a big scale it *looks* like a continuous picture.
  - If you can get down to the little details you'll see it's *actually* made up of little dots that blend together. Quanta.

Example 1: **Determine** the smallest amount of energy from a light source that emits light at a frequency of 4.50e14 Hz.

E = hf
E = 6.63e-34 (4.50e14)
E = 2.9835e-19 = 2.98e-19 J

It is normal to state this answer in Joules. If we had calculated it with the other value of Planck's Constant we would have had the answer 1.86 eV.

Example 2: **Determine** the minimum energy transferred by a light source with a 212 nm wavelength in electron volts.

Remember the universal wave equation can apply to EMR...

$$v = f\lambda$$
$$c = f\lambda$$
$$f = \frac{c}{\lambda}$$

This can be substituted into Planck's formula...

$$E = hf = \frac{hc}{\lambda}$$
$$E = \frac{4.14\text{e-}15(3.00\text{e}8)}{212\text{e-}9}$$
$$E = 5.85849 = 5.86\,eV$$

Albert Einstein

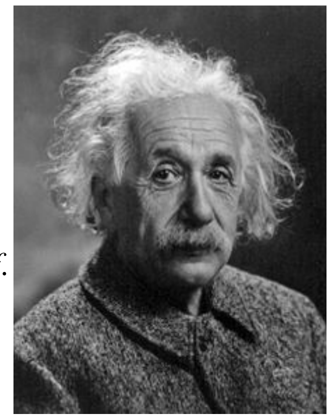

Illustration 3: Albert Einstein... ya mighta heard of him.

In 1905 an unknown physicist named Albert Einstein came up with an idea that built on what Planck had said.

- Planck thought that his ideas of quanta and E = hf was all about how matter absorbed and emitted energy.
  - Remember, he was focused on explaining blackbody radiation.
- Einstein suggested that these ideas were primarily about the *light itself*.
  - He figured that light itself was where it all started, that the light itself was made up of individual pieces.
  - The reason this was so radical an idea was because it meant that light was acting like a **particle**.
  - The light particles were eventually named **photons**.

This idea was not immediately accepted by everyone, since there was so much evidence that light acted as a wave, not a particle.

- As we will see in later lessons, the amount of evidence that light had a particle nature increased to a point it couldn't be ignored.
- This does not mean that we abandon the wave nature. Instead we will bring the two ideas together.

Photon comes from the Greek word for light. Einstein originally called photons a "light quantum." The chemist Gilbert N. Lewis came up with the name photon.

Example 3: You buy a laser at the store and read on the label that it has a frequency of 4.38e15 Hz. The label also says that it runs at 4.06 mW. **Determine** how many photons it can release in one second.

This is the total energy being released as a bunch of individual photons come out of the laser each second. We can calculate how many photons by using the Power formula from Physics 20 and the special version of Planck's formula that has "n" for the number of photons in it...

$$E = nhf$$
$$Pt = nhf$$
$$P = \frac{\Delta E}{t} \qquad n = \frac{Pt}{hf}$$
$$\Delta E = P t \qquad n = \frac{4.06\text{e-}3(1)}{6.63\text{e-}34(4.38\text{e}15)}$$
$$n = 1.3981005\text{e}15 = 1.40\text{e}15 \ photons$$

Homework

p706 #1-3
p707 #1-3
p708 #1-2