Lecture 32 (Intro to Quantum and Photoelectric Effect)

Physics 262-01 Spring 2019

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Always look where you haven't.

- When we look around us carefully, we discover new aspects of the universe.
- Even when it is believed that science explains everything that we have already seen, nature rarely fails to surprise us.
- Our next subject of study has a beautiful history that makes this very clear – as scientists made more and more careful measurements, the current understanding of the world (Classical Physics) started to fall apart.
- This, despite the overwhelming successes of Classical Physics!

Rise of Quantum Mechanics Time-Line (Partial, of course)

1855 Maxwell's equations predicts EM waves
1886 Hertz's radio waves unifies EM waves and optics
1887 Hertz first sees electrons emitted from a cathode due to UV light
1887 Michelson-Morley experiment null result for ether
1893 Wien's law for blackbody spectral density
1895 Röntgen discovers X-rays
1896 Mme. Curie discovers radioactivity
1896 Zeeman effect
1897 Thompson discovers electron
1900 Rayleigh-Jeans approximation for blackbody spectral density
1900 Plank resolution of blackbody problem by interaction between matter and radiation only occurring in quanta of hv
1902 Lenard discovers photoelectric effect
1905 Einstein resolves photoelectric effect by quanta of light (solves blackbody also)
1905 Einstein special relativity rejects absolute time
1910 Millikan's oil drop experiment quantifies elementary electric charge
1911 Rutherford describes atomic nucleus with electron cloud
1912 Willson cloud chambers see trajectories of charged particles
1912 von Laue confirms wave nature of X-rays by scattering off crystals
1913 Geiger counter
1913 Bohr's quantum theory of spectra (quantized angular momentum)
1914 Millikan photoelectric experiment confirms Einstein using sodium
1914 Meyer and Gerlach confirm photoelectric effect on metallic dusts
1916 Einstein publishes his paper on General Relativity
1922 Compton scattering photons off electrons confirms particle nature of light
1922 Stern-Gerlach experiment demonstrates space quantization
1923 Bohr's Correspondence principle
1924 Pauli's exclusion principle
1925 de Broglie postulates matter waves
1926 Schödinger's wave equation
1927 Davisson-Germer experiment confirms de Broglie matter waves by scattering electrons off of crystals
1927 Born statistical interpretation of wavefunction
1928 Dirac relativistic wave equation and prediction of positron

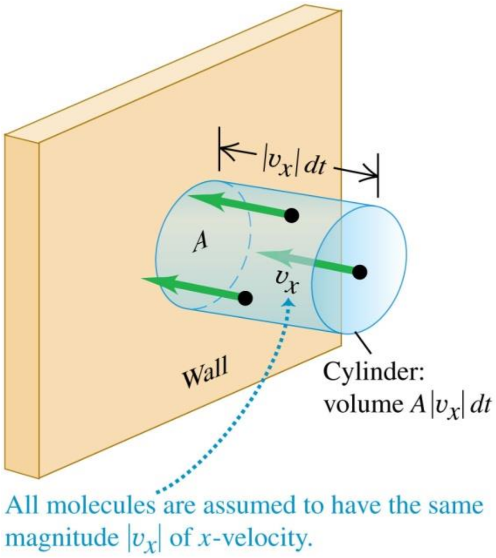
Heat Capacities

- To begin our foray into the quantum world, we will begin with thermodynamics.
- Remember the ideal gas equation? $pV = nRT$
- The pressure can be calculated from the average translation kinetic energy of the atoms by considering their collisions with the container.
- A key aspect of this derivation is that the energy content in the gas is equally shared among all degrees of freedom – in the ideal monatomic gas case, 3 degrees for the 3 directions of motion.

The pressure can be related to the average molecular speed:

$$p = \frac{Nmv_x^2}{V} = \frac{1}{3}\frac{Nm\left(v^2\right)_{avg}}{V} = \frac{2}{3}\frac{N}{V}\left(\frac{1}{2}m\left(v^2\right)_{avg}\right) \Rightarrow$$

$$pV = \frac{2}{3}N\left(KE_{tr}\right)_{avg} = \frac{2}{3}\left(KE_{tr}\right)$$



Heat Capacities

- But, if we compare this result to the ideal gas law taken from experiment, then:

$$pV = \frac{2}{3} KE_{tr} = nRT \Rightarrow$$

$$KE_{tr} = \frac{3}{2} nRT = 3\left(\frac{1}{2} nRT\right)$$

- Let us now return to the idea of heat capacity. Recall:

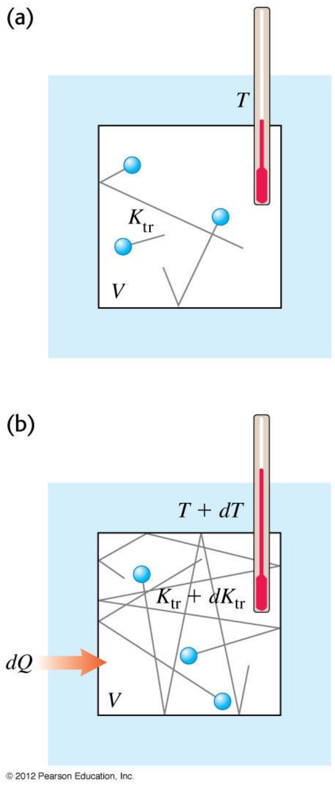
$$Q = nC\Delta T$$

- At constant volume (so that the gas does no work), the heat that enters the system will raise its temperature by raising the average kinetic energy.

- Then, we have:

$$nC_V dT = \frac{3}{2} nRdT \Rightarrow$$

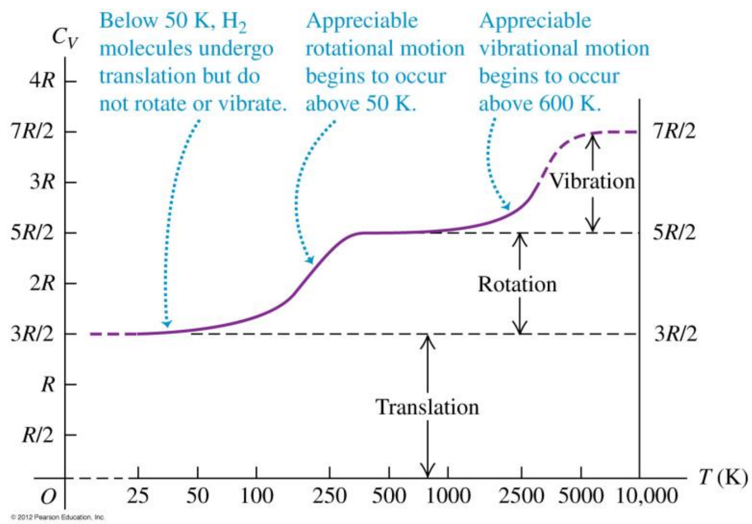
$$\boxed{C_V = \frac{3}{2} R}$$



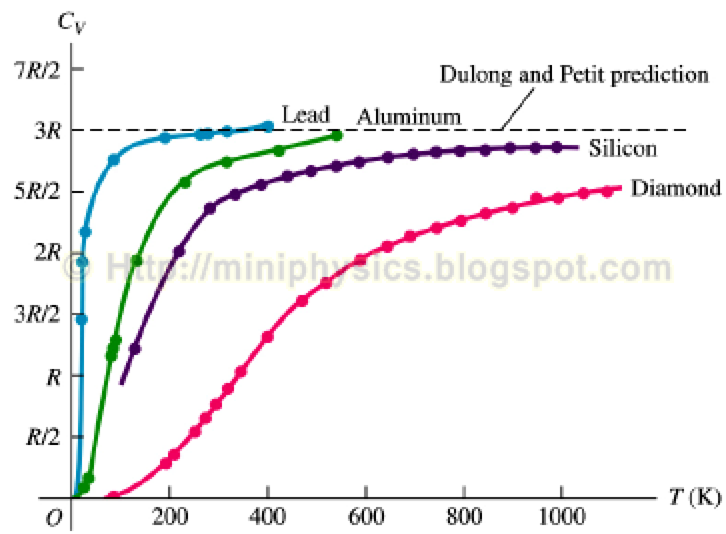
Heat Capacities

- This heat capacity formula works well for monatomic gas, but when you apply the same principles to a diatomic gas, or a solid, you find something unexpected – temperature dependence.
- Let's take the diatomic gas as an example…

Diatomic gas



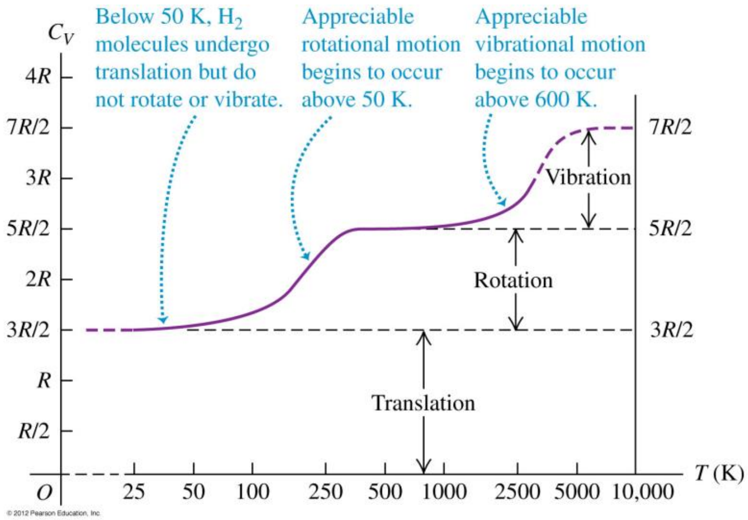
Solids

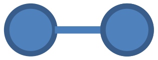


Heat Capacities

- There are actually seven (non-trivial) degrees of freedom in which energy can be stored in a diatomic molecule:
  - 3 for translational kinetic energy (the **only** ones available to an ideal monatomic gas).
  - 2 for rotational motion (does not add to temperature).
  - And 2 for vibrational motion (kinetic + potential energy) (does not add to temperature).

Diatomic gas

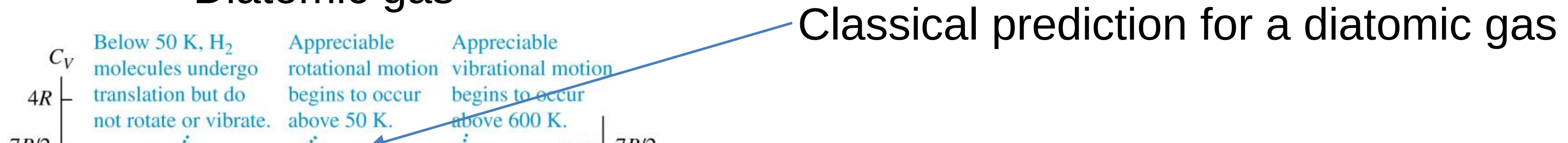


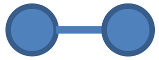


Heat Capacities

- This means that you have to add more energy to get the same change in translational kinetic energy, and hence temperature.
- But it appears that these degrees of freedom aren't available at all temperatures! Why?
- This was not expected at all in Classical Physics.

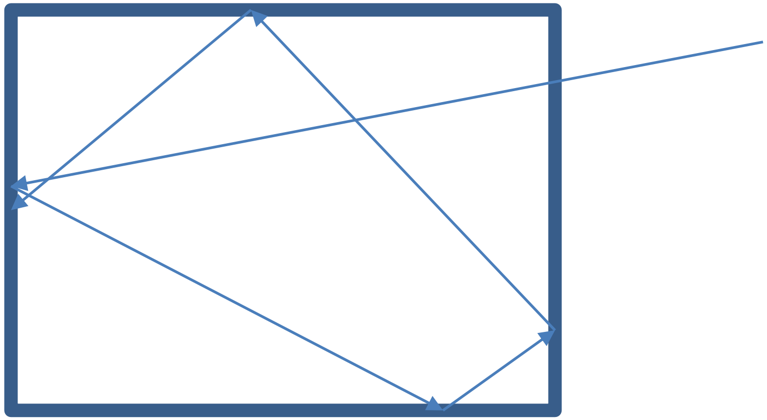
Diatomic gas





Black-Body Radiation

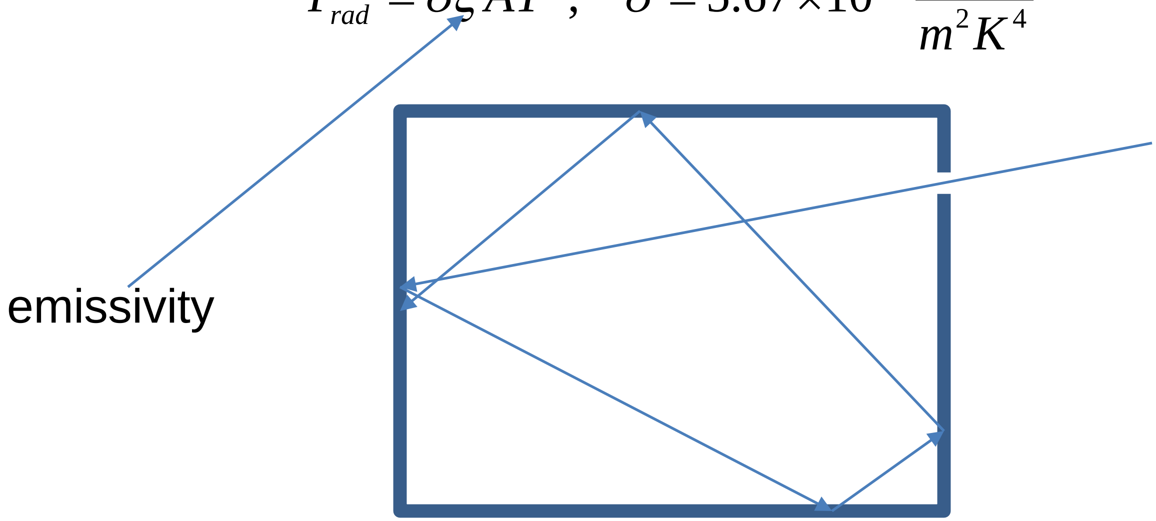
- In the late 1800s, people were looking for the first time at the spectrum (wavelengths) of light emitted from hot objects.
- As a way to idealize the situation, they considered "black bodies" – objects that would absorb all wavelengths of light (don't want to consider reflection and refraction).
- One type of black-body would be a cavity with a small hole. All light would enter the small hole and be trapped inside the cavity.
- The question then would be when the electromagnetic field is in thermal equilibrium with the box, what would be the spectrum of light coming out of the hole?



Black-Body Radiation

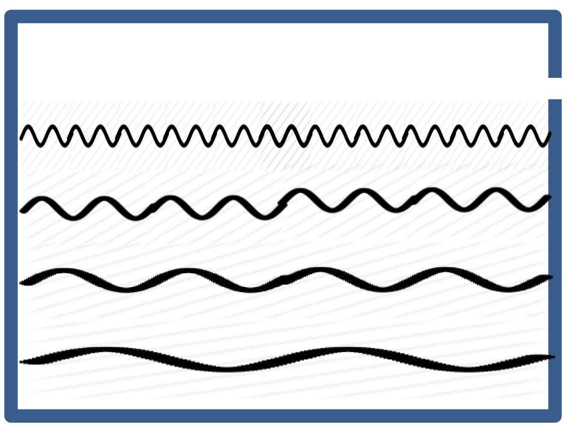
- Experimentally, the power emitted by a body depends upon its area, the emissivity (how well it radiates or absorbs), and its temperature.
- The power can be derived from **CLASSICAL** laws of **thermodynamics** and is given by the Stefan-Boltzmann Law:

$$P_{rad} = \sigma \xi A T^4, \quad \sigma = 5.67 \times 10^{-8} \frac{W}{m^2 K^4}$$



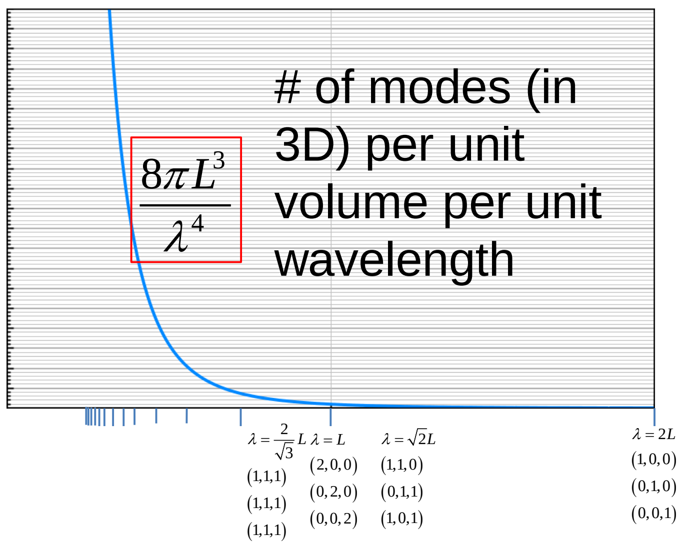
Black-Body Radiation

- To calculate the power emitted using the idea of equipartition of energy, two things are needed:
  - The number of ways you can put a particular wavelength in the cavity (number of modes per unit wavelength).
    - This grows quickly as you go to shorter wavelengths
  - The amount of energy that goes into each mode.
    - Classically, this is just kT with $k = \frac{R}{N_A}$.



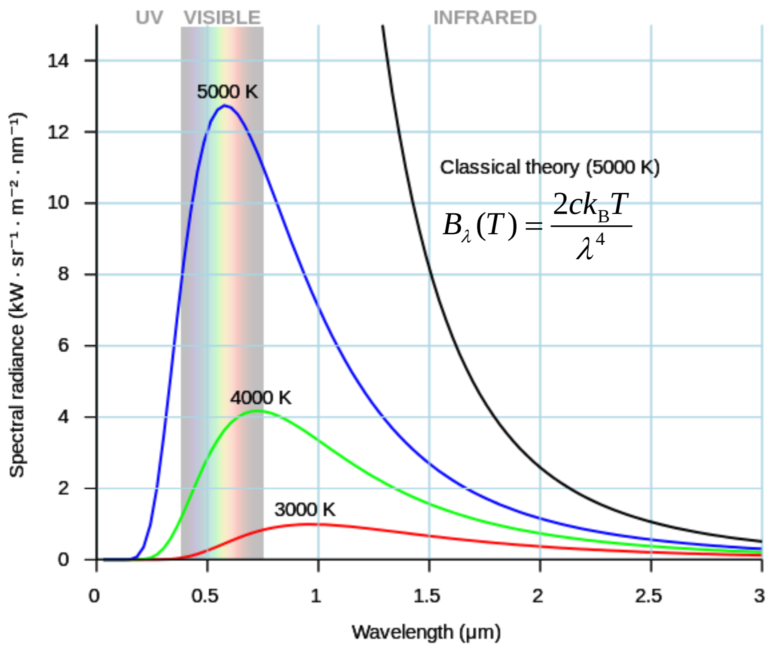
$$\lambda = \frac{2L}{n}, \quad n = 1, 2, 3$$

The spacing between allowed wavelengths gets smaller with increasing n



Black-Body Radiation

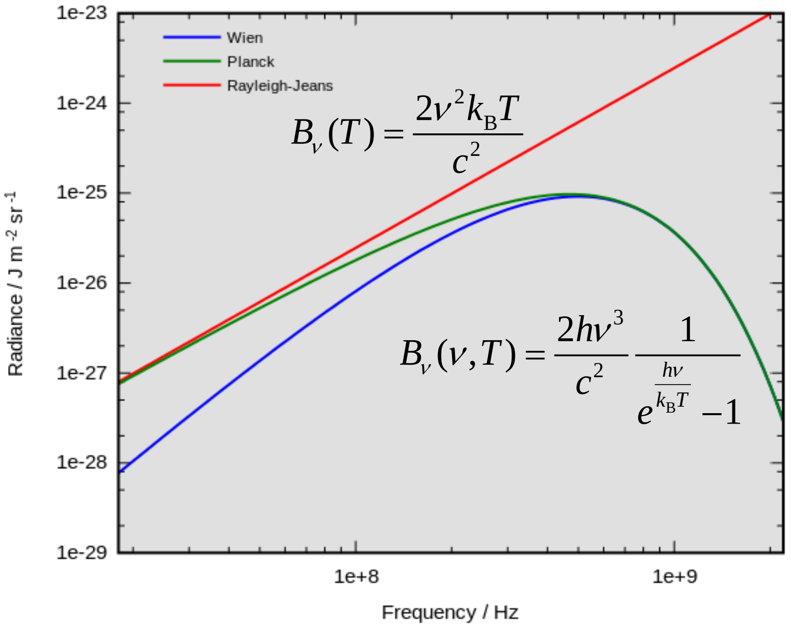
- There are two problems with this classical calculation:
  - It gives an infinite power!
  - And (obviously) doesn't even come close to the experimental data.
- This was called the ultraviolet catastrophe.



"Black body" by Darth Kule - Own work. Licensed under Public Domain via Commons - https://commons.wikimedia.org/wiki/File:Black_body.svg#/media/File:Black_body.svg

Black-Body Radiation

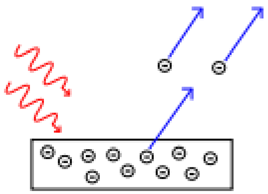
- Max Planck (and others) tried to fit the experimental spectrum with a functional form that gave the appropriate cutoffs at small wavelengths (or high frequencies, as shown below).
- But, at first at least, they didn't offer any theoretical explanation for this functional form.
- Later, he hypothesized that the electromagnet waves could only oscillate in discrete amplitudes such that the energy of the waves were quantized as $E = nh\nu$.
- This gave a statistical interpretation of his exponential factor in the denominator, but still had no other theoretical motivation behind it.



Note that in this plot, we are look at frequency, not wavelength, and it is a log-log plot!

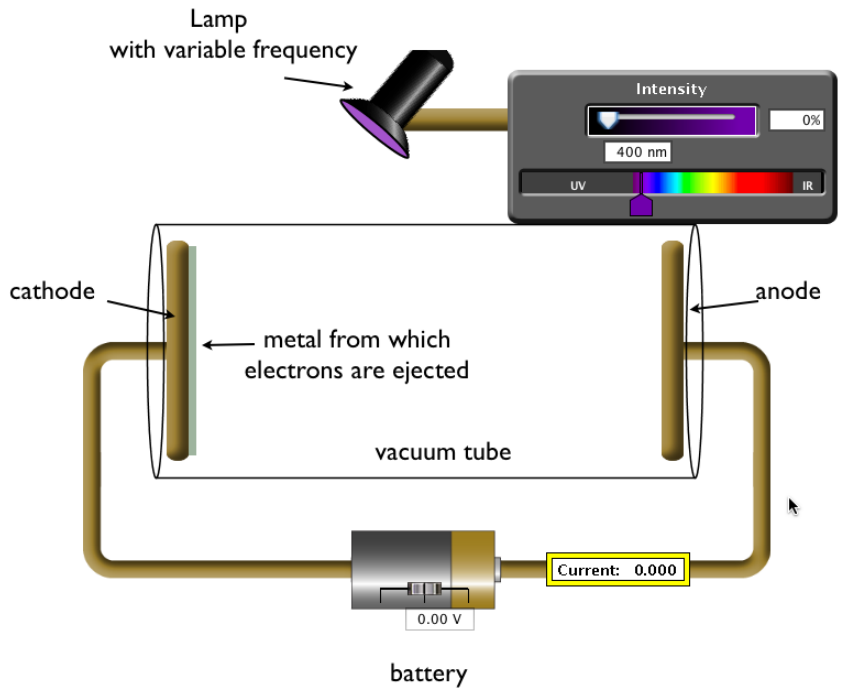
Photoelectric Effect

- Another area that was being investigated around the same time was the interaction between light and metallic surfaces.
- It was noticed that when light struck the surface of certain metals, it would give off electrons.
- This was called the photoelectric effect, and it was being studied as a function of everything that they could think of to change:
  - The particular metal used.
  - The wavelength of light used.
  - The intensity of light used.
  - And more…



Photoelectric Effect Experimental Setup

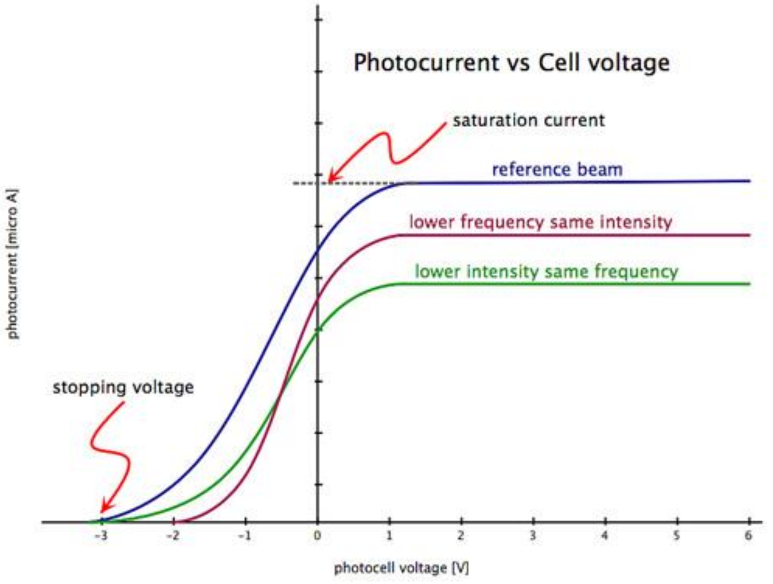
- A typical experimental setup of the photoelectric effect is shown below.
  - We can adjust the wavelength and intensity of the light.
  - The electrons emitted from the cathode are collected at the anode. We can adjust the voltage between them to measure the kinetic energy of the electrons after they are emitted.
  - And we can change out the cathode to see how these things are affected by using different materials.
  - We can also measure any time delay between turning on the light and seeing a current.



Photoelectric Effect Results

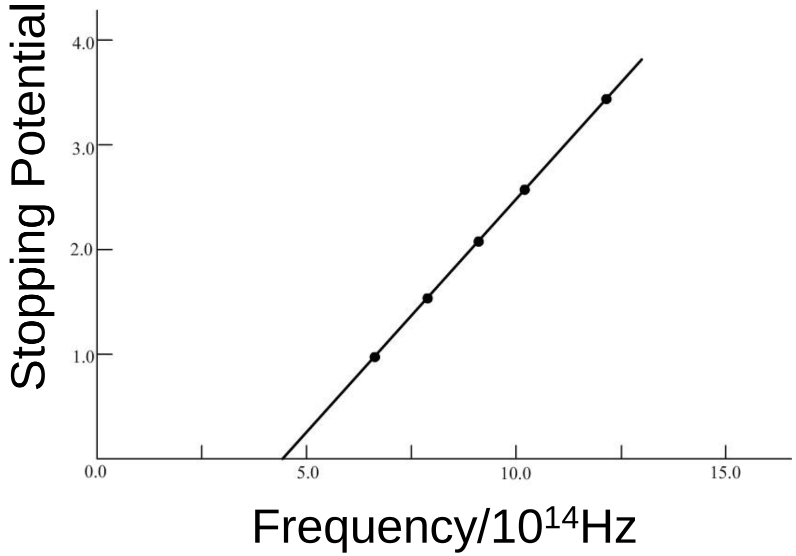
- Now, if we look at the current as a function of the voltage between the cathode and anode (labeled photocell voltage below) we see (blue line):
  - Above a certain positive voltage, and for a fixed intensity, the current remains constant.
  - All electrons that make it out of the cathode are accelerated and make it to the anode and are measured as a current.
  - As the voltage is lowered, some electrons don't make it to the anode – the current is reduced.
  - Even with negative voltage, there is some current, until at some point the current goes to zero.
- If we lower the intensity (green line):
  - The saturation current is lowered, but the point at which the current becomes zero remains the same.

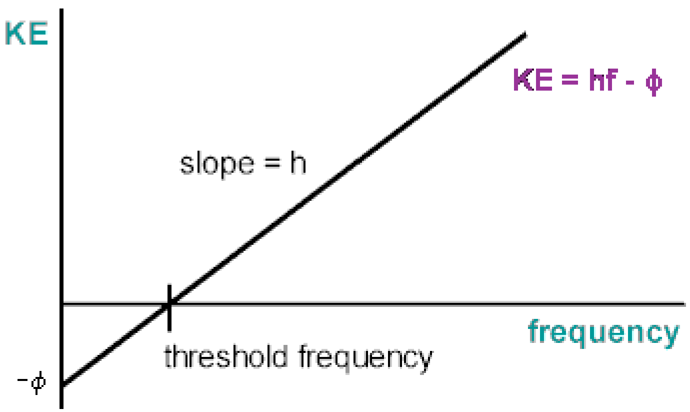
- It turns out that **the stopping voltage** stays the same regardless of intensity for a particular cathode material, but is different for different cathode materials.
- The stopping potential for a particular cathode material also changes depending on the frequency of light shining on it (red line):
  - Lower frequencies have stopping potentials closer to zero.
- Below some frequency for a certain cathode material, no current is seen regardless of intensity or voltage.
- Regardless of intensity, there is no time delay between turning on the light and measuring a current



Understanding the Results

- The stopping potential as a function of the frequency (for a particular cathode) turns out to be linear.
- Different cathodes have the same slope, ***h***, but cross the horizontal axis at a different point.
- If we think of the stopping potential as the maximum kinetic energy which an emitted electron has after leaving the surface, then the linear function has the form: $KE_{\max} = hf - \phi$
- Where ϕ is called the work function and is only dependent on the cathode material – it is the amount of energy needed to just get an electron out of the surface.





Classical Wave Expectations

- What was the classical physics expectations for this experiment?
  1. The energy carried by an electromagnetic wave is dependent on its intensity (~amplitude of electric field squared), not on the frequency, so there should be current at all frequencies with sufficient magnitude, and the current should depend on the intensity, not on the frequency.
  2. Since the minimum energy to knock out an electron (the work function ϕ) could be built up over time, at low intensities one should see a time delay between turning on the light and seeing the current.
  3. The stopping potential should increase with increasing intensity, and should be independent of frequency.
- Needless to say, the experimental results were astonishing at the time!