PHY293 Lecture #9

November 13, 2017

1. Units in Atomic/Quantum Physics
   - When dealing with very small/light objects (single protons or electrons) convenient to use commensurate units
   - Most common unit in atomic, nuclear and particle physics is the electron-volt (eV)
   - The amount of kinetic energy an electron (charge 1 object) received passing through a potential difference of 1V
     - Atomic physics: atomic electron binding energies are measured in eV
     - Nuclear physics: neutron and proton binding energies in nucleii are measured in keV
     - Particle physics: the amount of energy required to make new particles: Muon: 100 MeV, Proton 1 GeV, Higgs boson 125 GeV
     - Given that $E = mc^2$ for a particle of mass m at rest it is conventional to quote particle masses in units of eV/c^2 (or MeV/c^2 or GeV/c^2 for most of the fundamental particles)
       - The electron mass is 511 keV/c^2
       - The proton mass is 0.938 GeV/c^2
2. Blackbody radiation
   - A "blackbody" is in thermal equilibrium with its surroundings. It absorbs all incoming radiation and emits radiation with a characteristic set of wavelengths that depends only on its temperature
   - Everything radiates (human beings, stove elements, even the sun) but at different wavelengths
   - Humans are in infra red, stove elements visible and infra-read, sun in broad spectrum including UV and higher
   - Classically the amount of radiation at high frequencies (short wavelengths) grows without bound
     - Classical statistical mechanics + E&M: $\frac{dU}{df} \propto k_B T f^2$ (Raleigh Jeans law)
     - Is unbounded at large frequencies (or at low wavelengths as per the figure appended at the end of these notes)
     - Works OK, if you cut it off at arbitrary wavelengths (see fig) – could re-scale things to get a pretty good approximation to the dashed curve.
   - Planck showed that problem could be resolved if the only energies that could be associated with EM radiation was limited to integer multiples of hf
     - h became known (is still known) as Planck's constant: 6.63×10^{-34} J s
     - For any frequency there is a minimum energy hf (ie. 1 times hf)
     - This cuts off the power distribution with the form $\frac{dU}{df} \propto \frac{hf}{e^{hf/k_B T} - 1} f^2$
     - Goes to 0 as f goes to infinity, gives Raleigh-Jeans expression for low frequencies
     - Physical conclusion is that for any given wavelength there is a minimum energy – light is quantised
     - Planck won Nobel Prize in 1918 for this work
   - Note the most probable wavelength decreases with increasing temperature (actually as $1/\lambda$)
   - While the most probable frequency increases, linearly with/proportional to, temperature
   - Coblentz (1916) extracted $h = 6.57 \times 10^{-34}$ J s (less than 1% away from modern value)
3. The Photo-electric effect
   - Metals emit electrons when exposed to light – experimental observations well before 1900
   - Classically lightwaves would impart energy to electrons in the metal continuously
     - Expect that for lower intensities (light wave amplitudes) or lower energies (frequencies according to Planck) predict fewer electrons ejected
     - In both cases there is less energy available to eject electrons ("eject" means emerge with some kinetic energy)
     - Might also expect some time lag for sufficiently low amplitude (dim) light – time to build up enough energy to eject first electron (ie. some sort of resonant behaviour which builds up and 'breaks' the electron/nucleus binding in the atom.
     - Might expect that increasing the intensity (brightness) of the light could extract electrons from the metal even at lower frequencies.

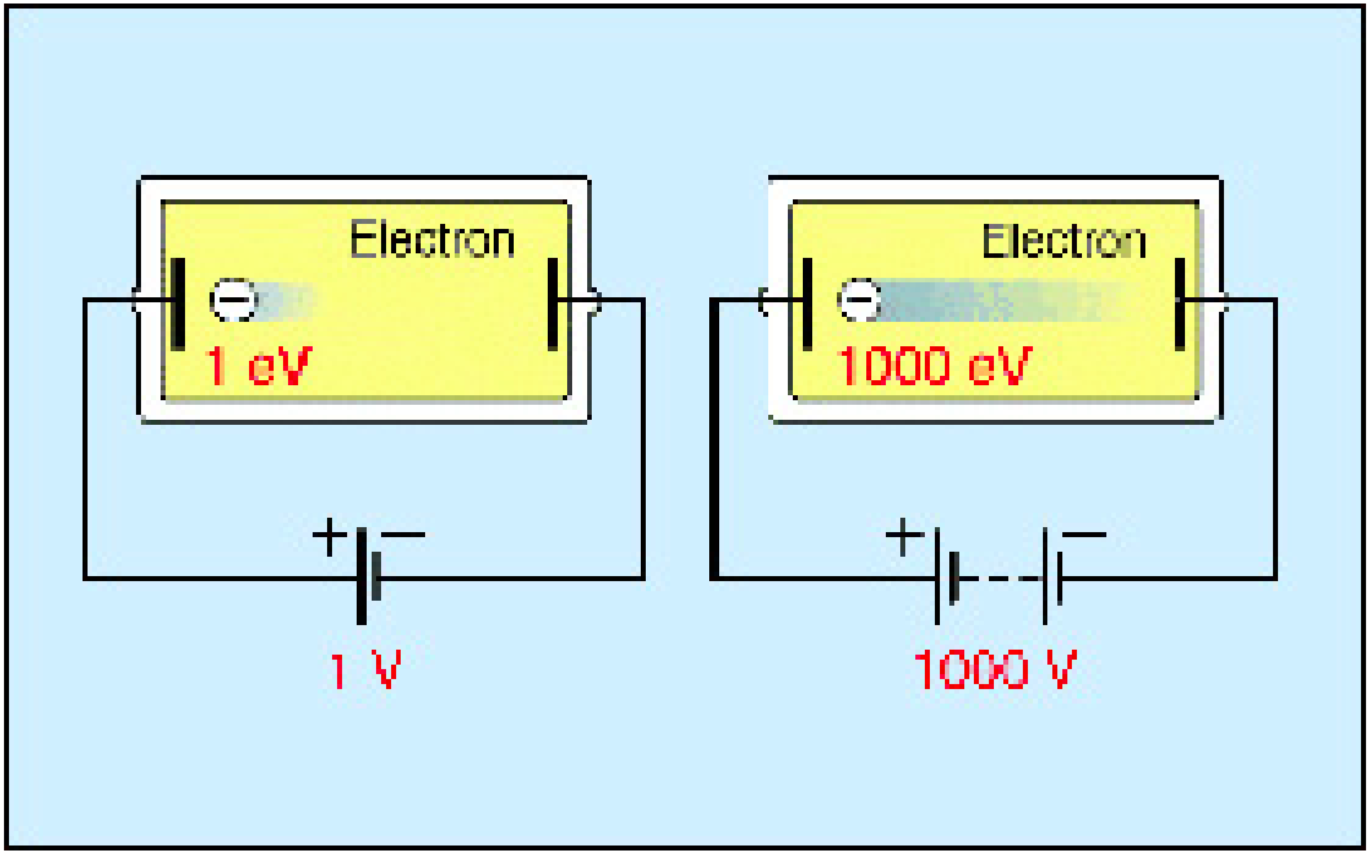
- Not what is seen experimentally
- Consider online simulation (http://phet.coloradoedu/en/simulation/photoelectric)
  - Play with light intensity, light colour (ie wavelength of 1/frequency) and stopping voltage
  - Look at some of the graphs (I vs. intensity, I vs. wavelength and electron energy vs. frequency)
  - Can also try 3 or 4 different metals + a mystery metal
- What is seen experimentally is that below some incident frequency **no** electrons are emitted (independent of intensity or duration of exposure)
- Einstein explained this by saying light came in discrete packets: Photons, each with energy $h\nu$
- This was what he actually won his Nobel Prize for (paper in 1905, prize in 1921).
- Milikan (Nobel Prize in 1923 for 'oil drop' experiment – quantisation of charge) verified Einstein's conjecture experimentally.
- Ejection of an electron from a metal requires enough energy to overcome the 'work function" (binding energy of electron in metal).
- Einstein hypothesized that this happened when a **single** photon of energy $h\nu$ had more energy than the work-function.
  - The single photon transfers all its energy (or doesn't). If it is more than the work function then
  - The kinetic energy of the 'free electron' after it emerges from the metal is: $E_{kinetic} = h\nu - \Phi$
  - There is no dependence on the brightness of the light source – except that a brighter source has more photons. But if the frequency is too low, then you can't make up for it by using a brighter light – no electrons will be emitted unless $h\nu > \Phi$.
  - Here Φ is the energy lost to the work-function (extracting the electron with kinetic energy = 0)
- Try to calculate the velocity of electron given the wavelengths in the diagram
- NB. Electrons are pretty non-relativistic – why? (Consider the energies involved and the mass of the electron).

- Calculations like these with photons often convenient to have conversion factor (from Js to eV nm ... as an example).
- Problem 3.27 in the text book (maybe assigned in PS6?) asks you to show that $hc = 1240$ eV nm
- These are the right units for photons since $E = h\nu = \frac{hc}{\lambda}$ so if you are given energy in eV or wavelength in nm you can easily predict the other. hc is often the 'constant of nature' that comes up in quantum mechanical phenomena/problems.
- Photoelectric effect graph: slope gives h (Planck's constant)
- From Milikan data conclude $h = 4.1 \times 10^{-15}$ eV s (current value 4.136)
- The known work function for sodium is 2.28 eV which gives a cutoff frequency of 5.5×10^{14} Hz

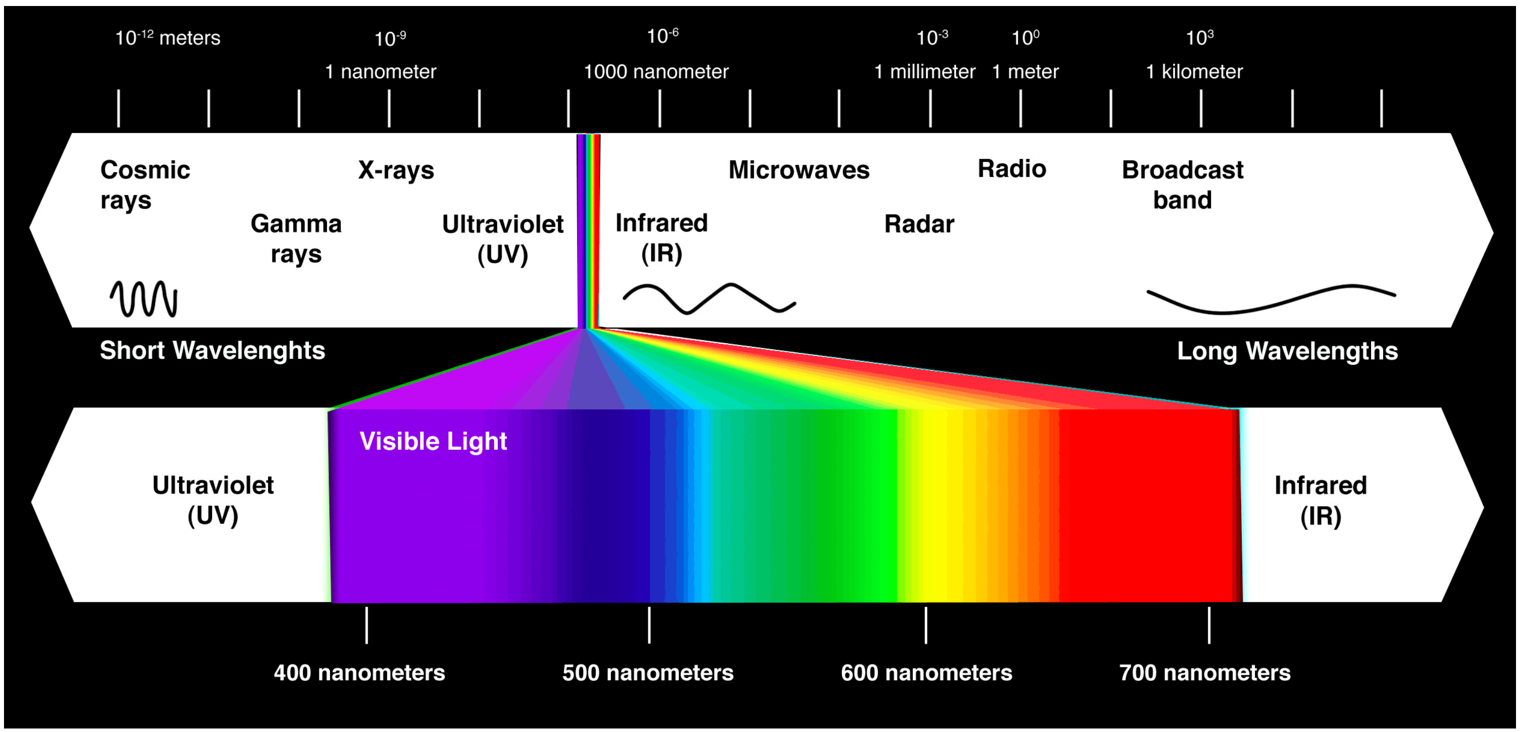
4. Applications of the Photo-electric effect

- Photomultipliers – detect single photons (and multiply the resulting electrons to make a measurable signal)
- Widely used in atomic, nuclear and particle physics.
- Night vision goggles – photo-cathode is followed by micro-channel plate electron multiplication and the fluorescent (green) screen

The Electron Volt



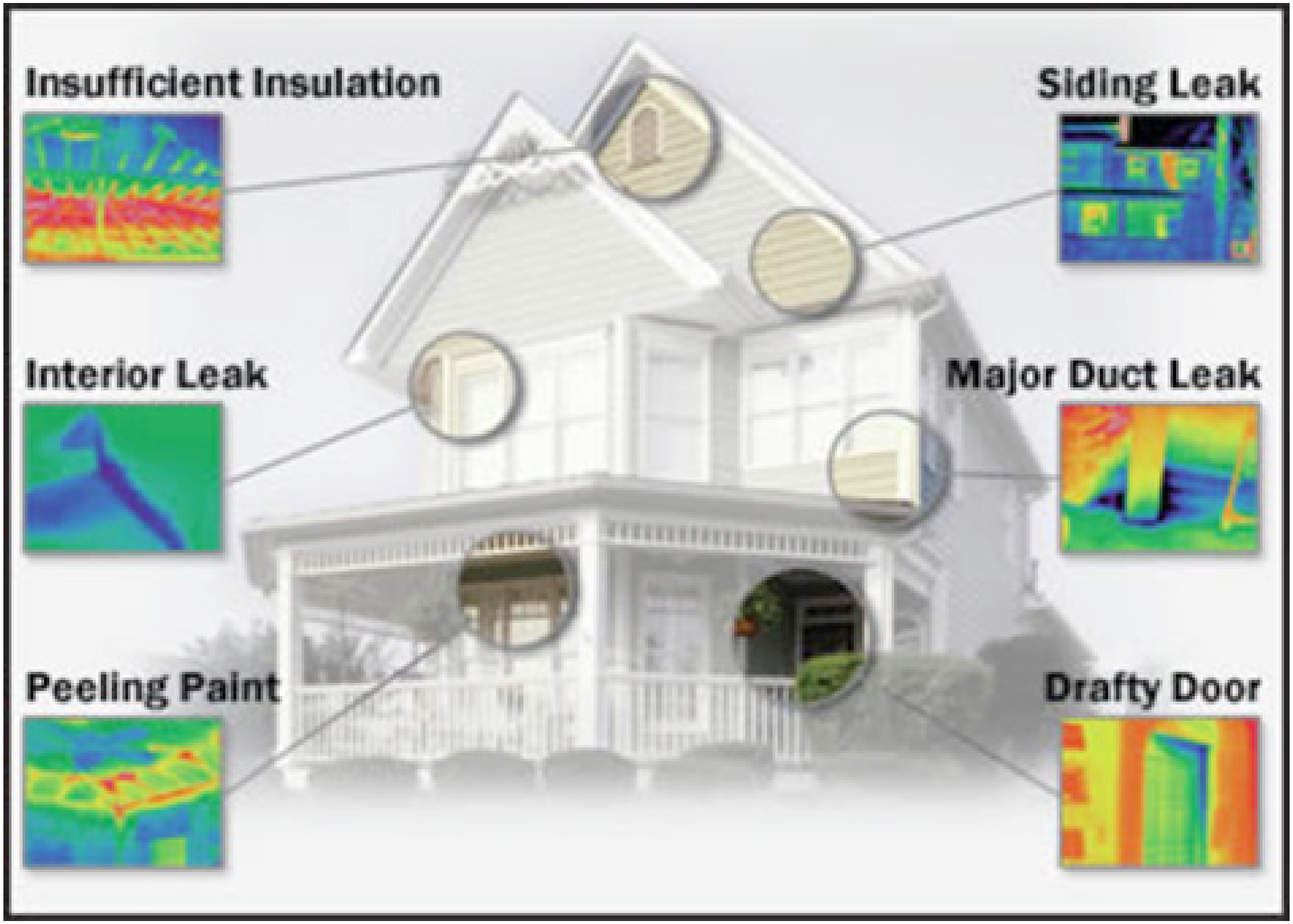
Light Specturm



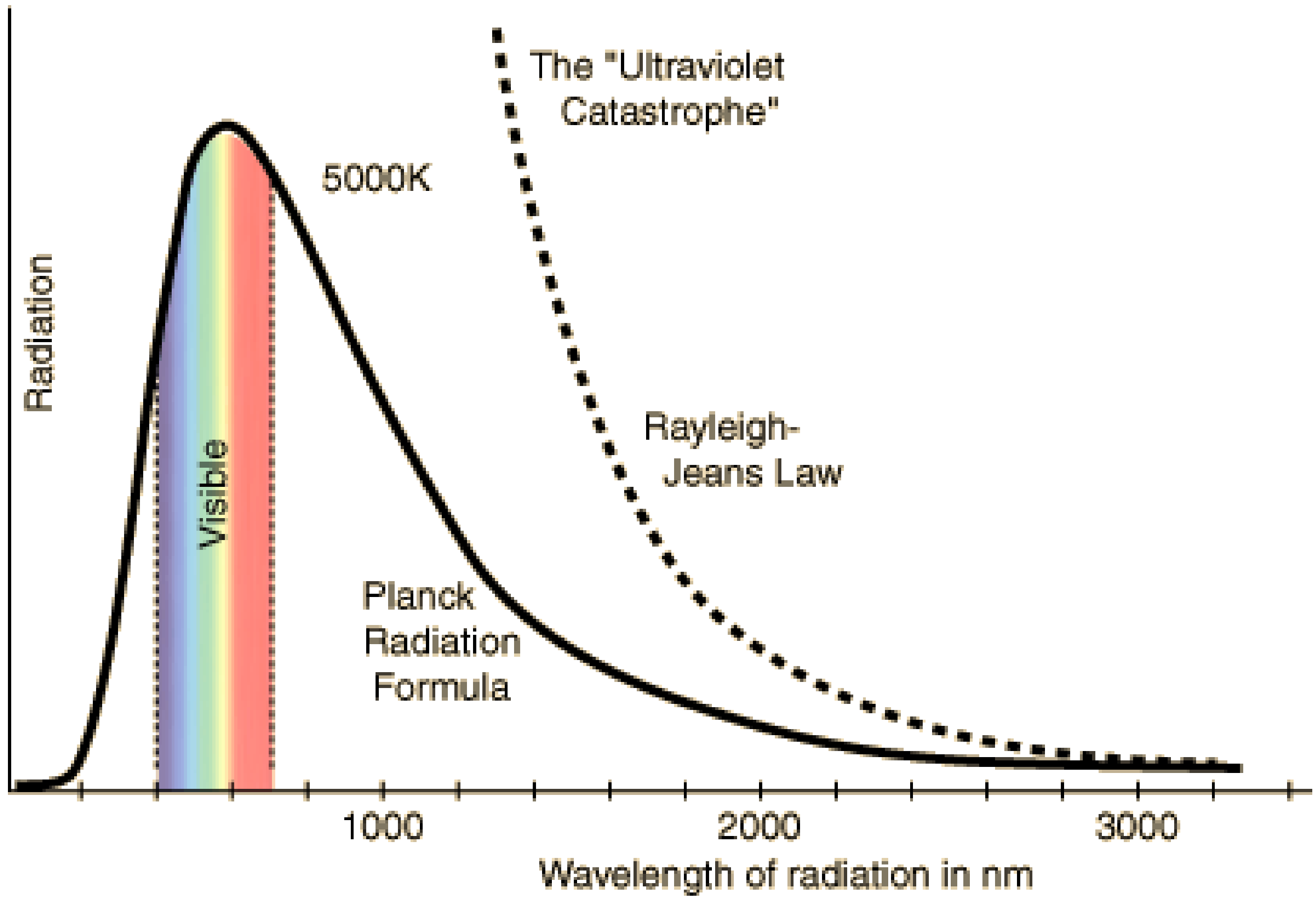
Wavelengths and Energies

Table 1: Gamma Rays and the Electromagnetic Spectrum			
Name of Wave	**Wavelength (m = meters)**	**Frequency (Hz)**	**Energy per Photon (eV)**
AM Radio	10^{2}	10^{6}	10^{-9}
FM, TV	1	10^{8}	10^{-7}
Radar	10^{-1}	10^{9}	10^{-6}
Microwaves	10^{-2}	10^{10}	10^{-5}
Infrared	10^{-5}	10^{13}	10^{-2}
Visible Light	10^{-7}	10^{15}	1
Ultraviolet	10^{-8}	10^{16}	10^{1}
X-Rays	10^{-10}	10^{18}	10^{3}
Gamma Rays	10^{-13}	10^{21}	10^{6}

Thermal Images



Classical Black Body Radiation Spectrum



Temperature Dependence

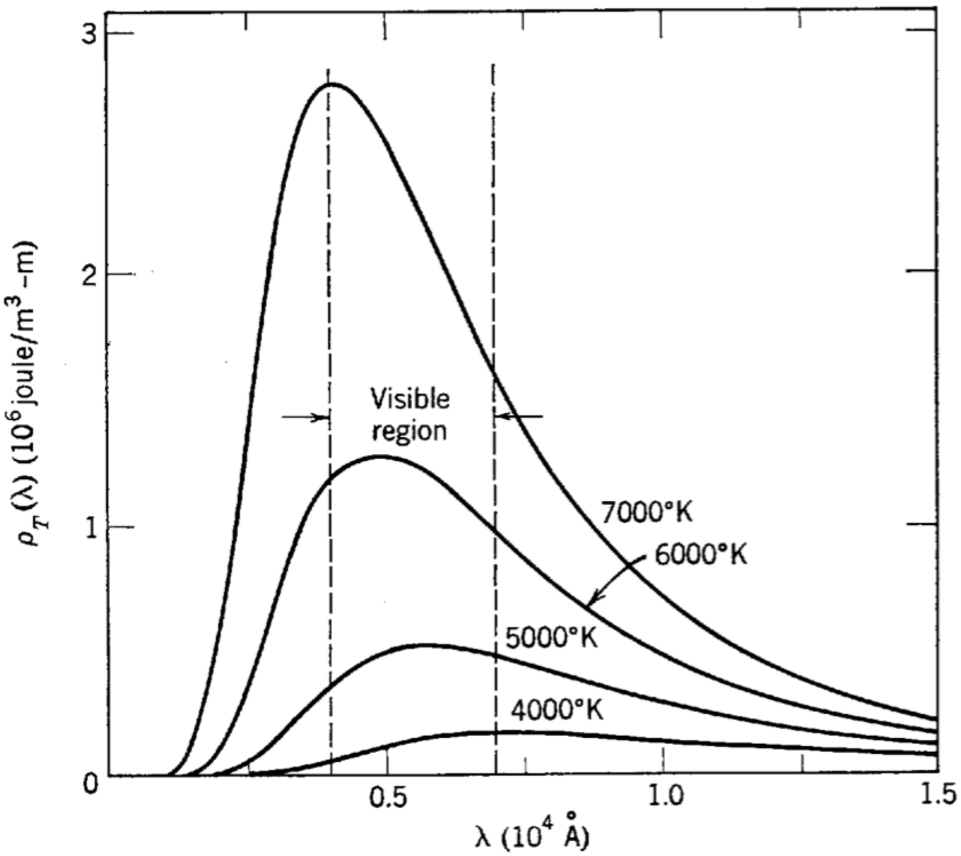


Figure 1-12 Planck's energy density of blackbody radiation at various temperatures as a function of wavelength. Note that the wavelength at which the curve is a maximum decreases as the temperature increases.

Frequency Dependence

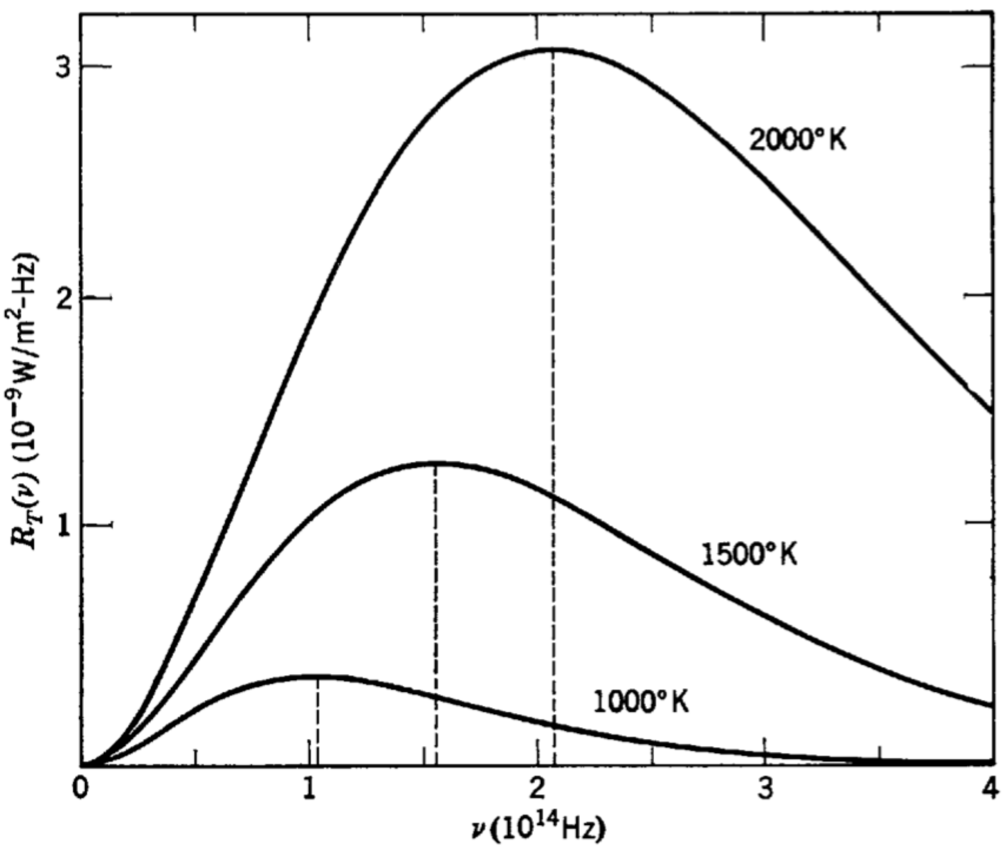


Figure 1-1 The spectral radiancy of a blackbody radiator as a function of the frequency of radiation, shown for temperatures of the radiator of 1000°K, 1500°K, and 2000°K. Note that the frequency at which the maximum radiancy occurs (dashed line) increases linearly with increasing temperature, and that the total power emitted per square meter of the radiator (area under curve) increases very rapidly with temperature.

Coblentz Measurement (1916)

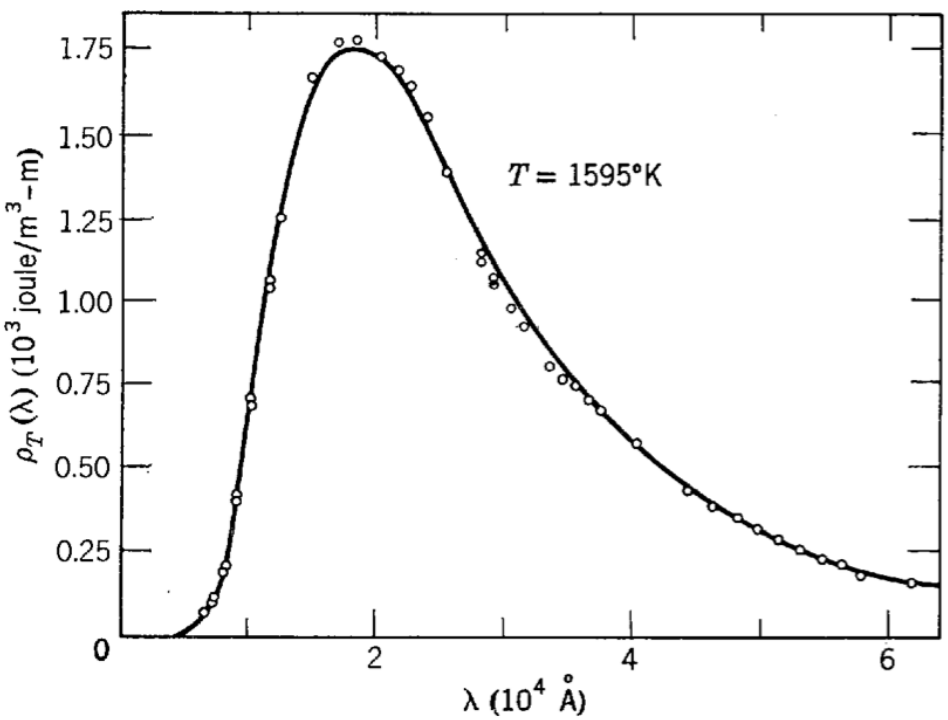
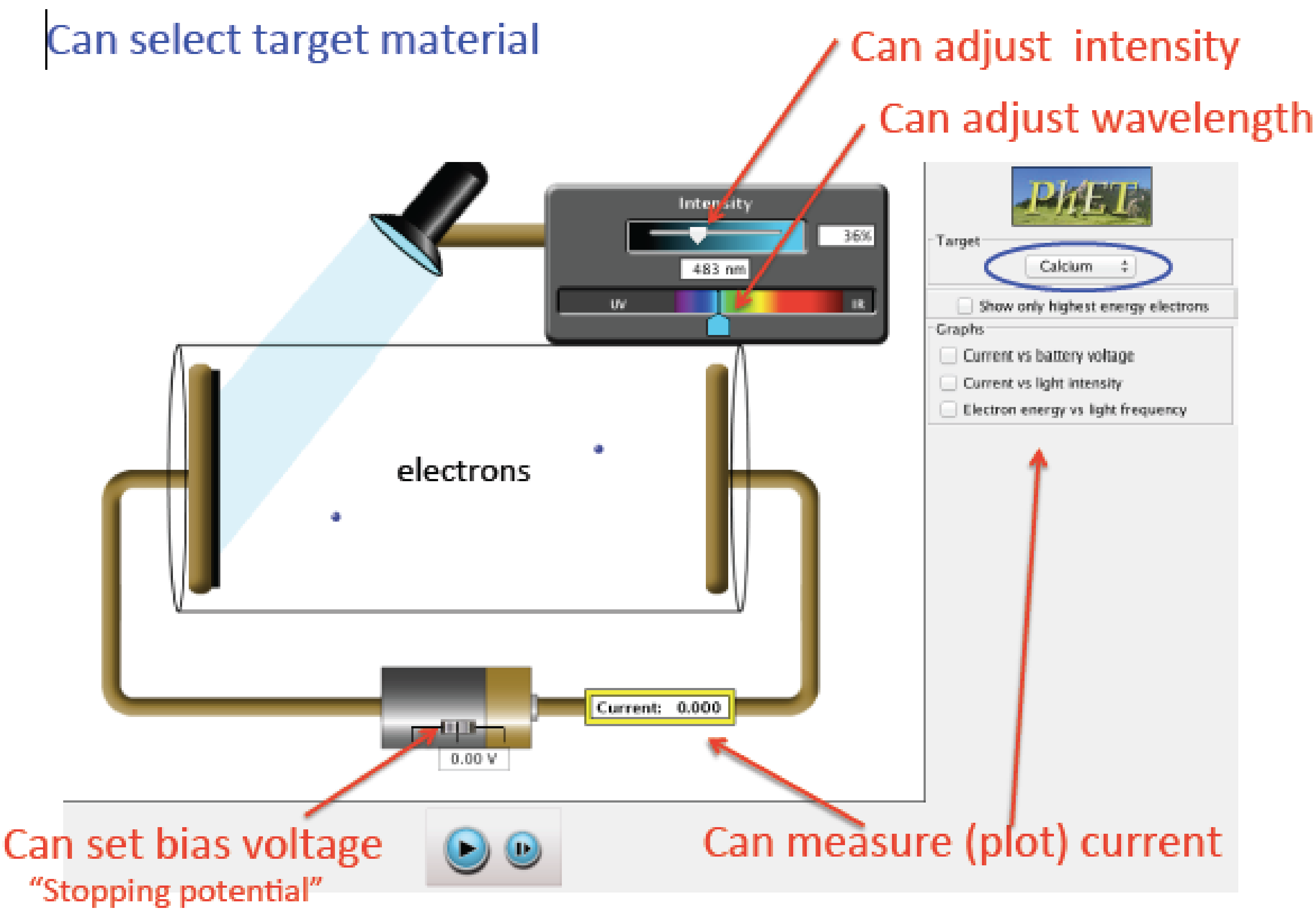
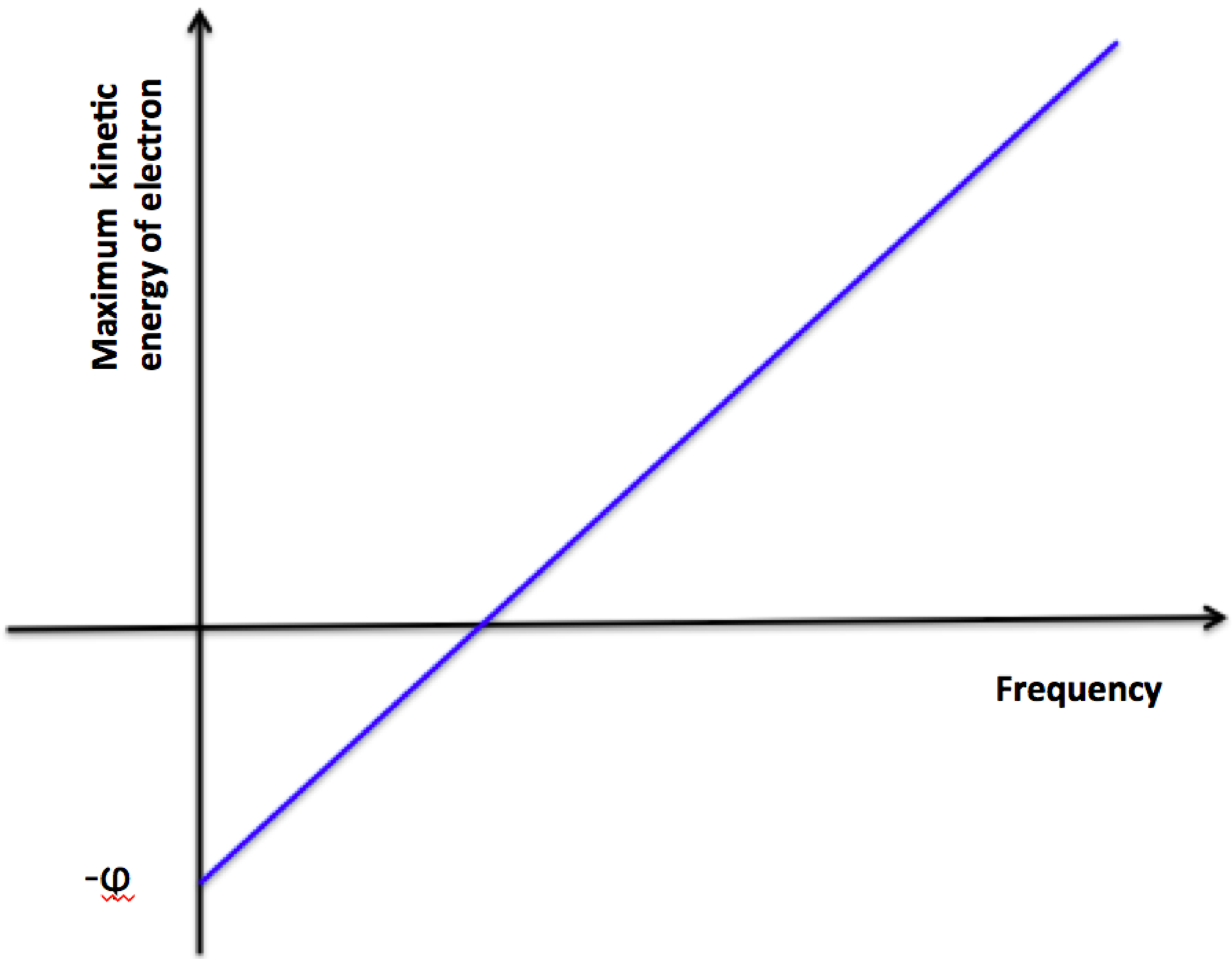


Figure 1-11 Planck's energy density prediction (solid line) compared to the experimental results (circles) for the energy density of a blackbody. The data were reported by Coblentz in 1916 and apply to a temperature of 1595°K. The author remarked in his paper that after drawing the spectral energy curves resulting from his measurements, "owing to eye fatigue it was impossible for months thereafter to give attention to the reduction of the data." The data, when finally reduced, led to a value for Planck's constant of 6.57×10^{-34} joule-sec.

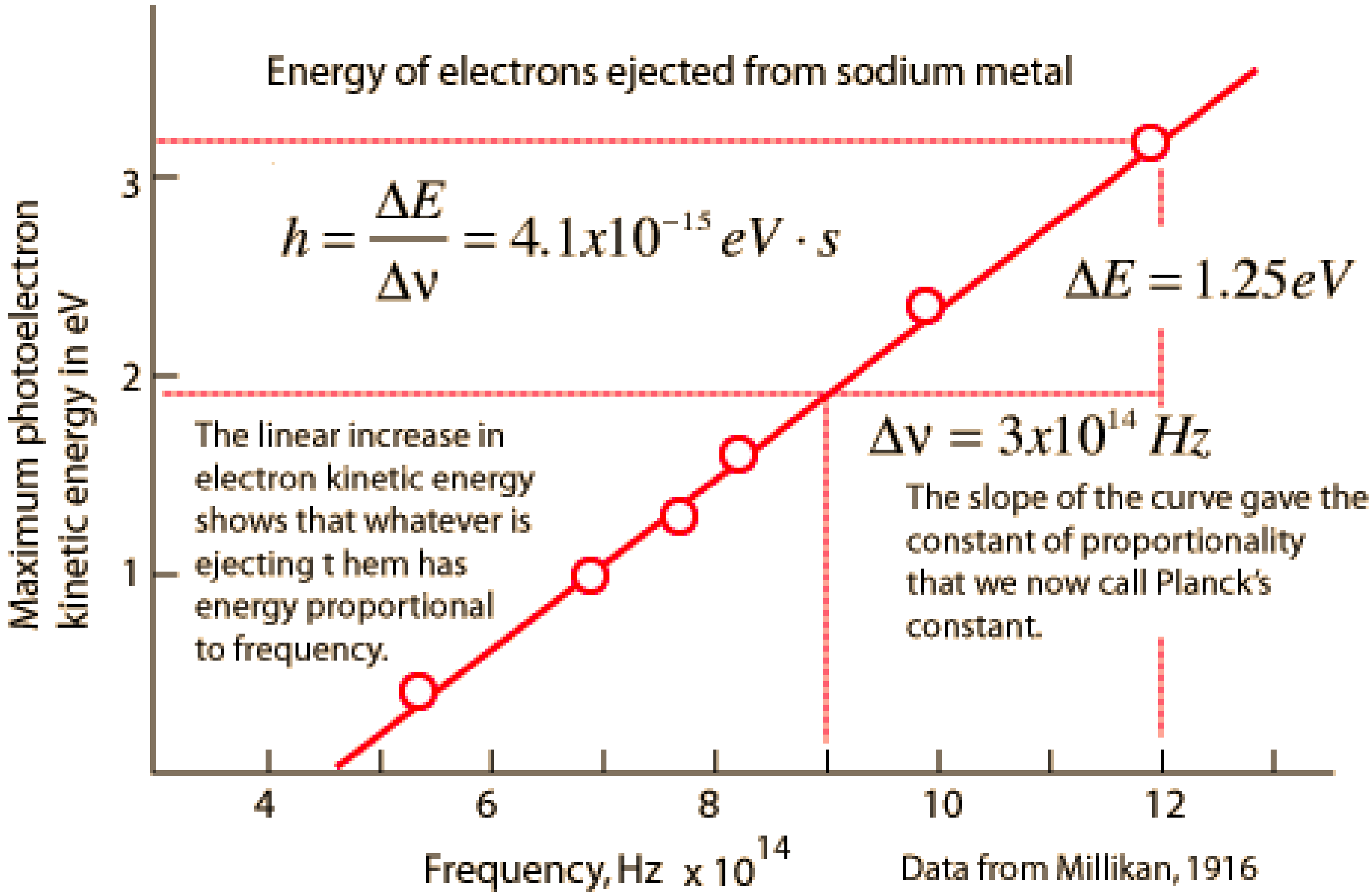
Photoelectric Effect Simulation



Photoelectric Effect cartoon

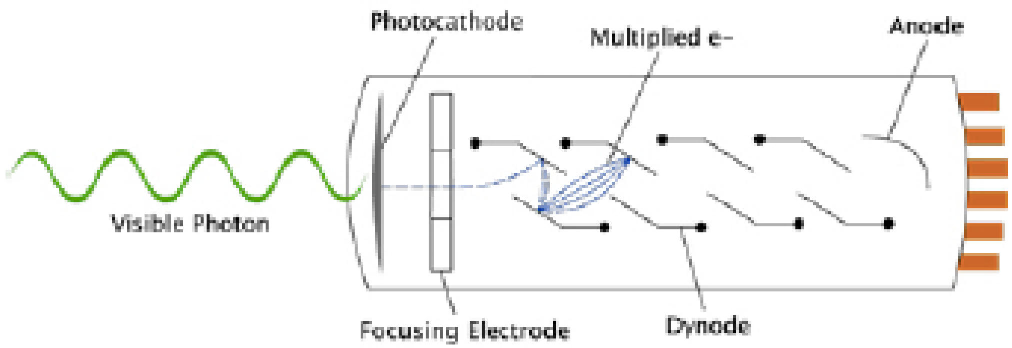


Milikan Data

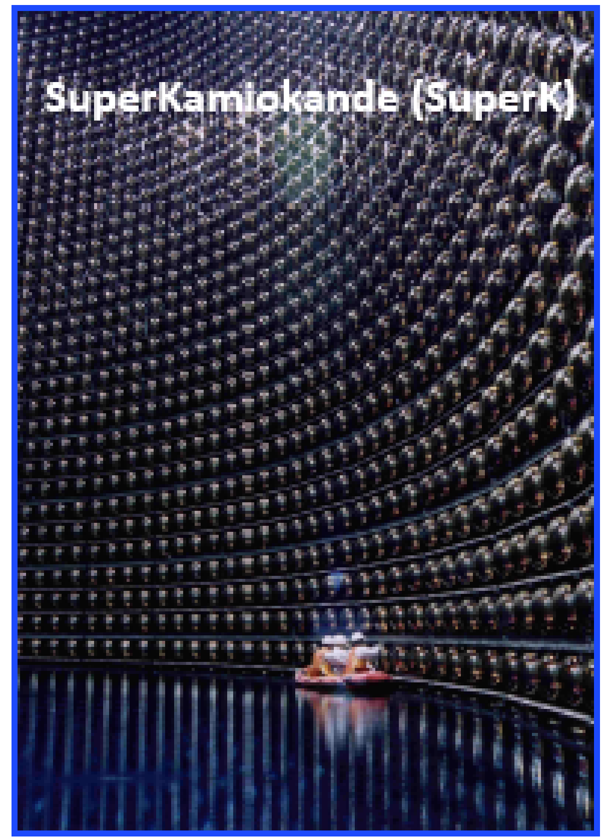


Photomultipliers

now).



Dynodes: secondary emission (electron multiplication)



Night Vision Goggles