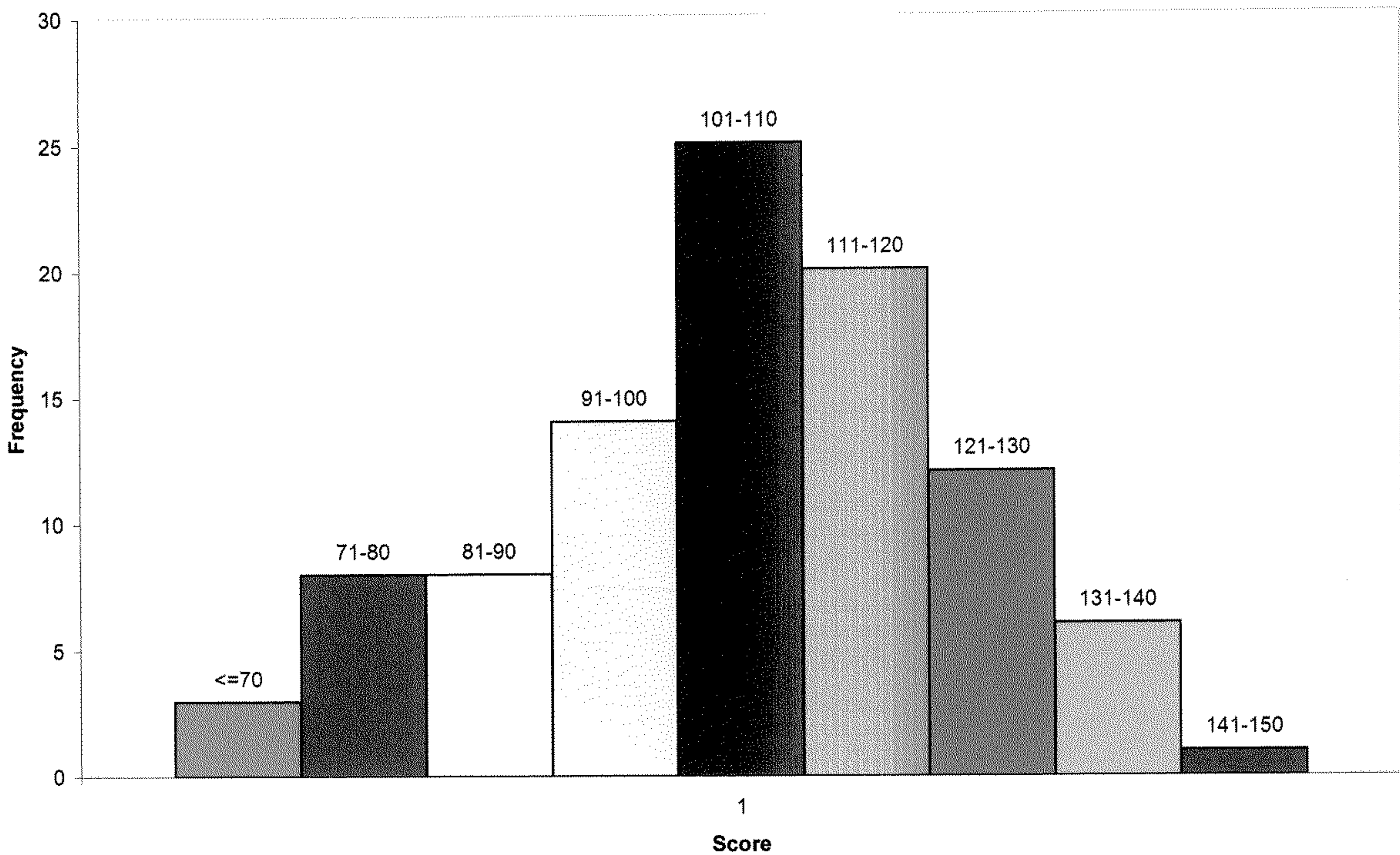
Lecture

5/10/05

Midterm 2



30
25
20
15
10
5
0
Frequency
<=70
71-80
81-90
91-100
101-110
111-120
121-130
131-140
141-150
1
Score

Outline

- The Photon Model
  - Recap
  - Units: the eV
- Are Photons Real? Two experiments
  - The photoelectric effect
  - X-rays
- Reconciling with the wave model

Einstein's Photon Equations

- Einstein (1905) suggested that photons carry both energy and momentum according to the equations:

$$E = \hbar\omega \qquad\qquad p = \hbar k$$

$$\text{(Recall } \omega = \frac{2\pi}{T} = 2\pi f \quad k = \frac{2\pi}{\lambda}\text{)}$$

- This equations are somewhat peculiar. We tend to think of the left side of the equations as particle properties and the right side as wave properties.
- Einstein was the first to suggest that some objects in the world have both wave and particle properties.

A New Unit: The eV

- Since we will now be working with atomic and molecular scales, units developed for macroscopic objects are inconvenient.
- Instead we introduce as a unit the energy an electron gains by traveling through a potential difference of 1 Volt.

$$U = e\Delta V$$

$$e = 1.6 \times 10^{-19}\ \mathrm{C}$$

$$1\ \mathrm{eV} \equiv 1.6 \times 10^{-19}\ \mathrm{J}$$

The Connection to Chemistry

- The chemical unit for energy is the calorie (1 cal = 4.19 J)
- Since the eV is appropriate for a single electron, let's scale down our calorie by the number of atoms in a mole. ($N_0 = 6.023 \times 10^{23}$)

Optional FYI

$$1\ \text{cal/mole} = \frac{4.19\ \text{J}}{6.023\times10^{23}\ \text{atoms/mole}} = 0.7\times10^{-23}\ \text{J/atom}$$

$$1\ \text{kcal/mole} = 0.07\times10^{-19}\ \text{J/atom}$$

$$1\ \text{kcal/mole} = 0.07\times10^{-19}\ \frac{\text{J}}{\text{atom}}\ \frac{1\ \text{eV}}{1.6\times10^{-19}\ \text{J}} = 0.04\ \text{eV/atom}$$

$$1\ \text{eV/atom} = 25\ \text{kcal/mole}$$

The Wavelength of Light

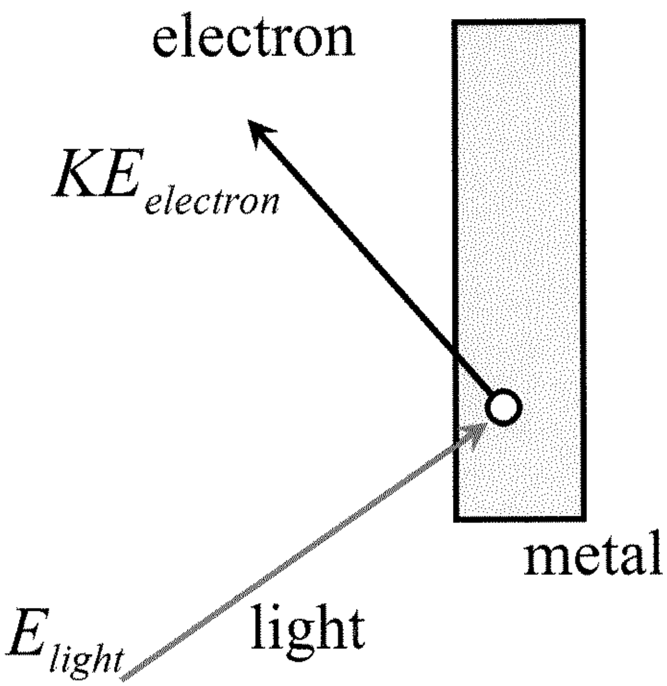
$$E = \hbar\omega = hf = \frac{hc}{\lambda} = \frac{124\,\text{eV - nm}}{\lambda}$$

- The energy of red light ($\lambda \sim 600$ nm) is ~ 0.2 eV.
- The energy of UV light ($\lambda \sim 200$ nm) is ~0.6 eV.

The Photoelectric Effect

- Einstein then predicted that when light was used to knock electrons out of a metal, it would show some strange properties.
- Electrons are bound in a metal, just like they are bound in an atom or molecule.
- It takes a certain amount of energy (called the *Work function*, ϕ) to extract the electron. (Analogous to the ionization energy of an atom.)
- The work function is a characteristic property of a metal.

The Photoelectric Effect



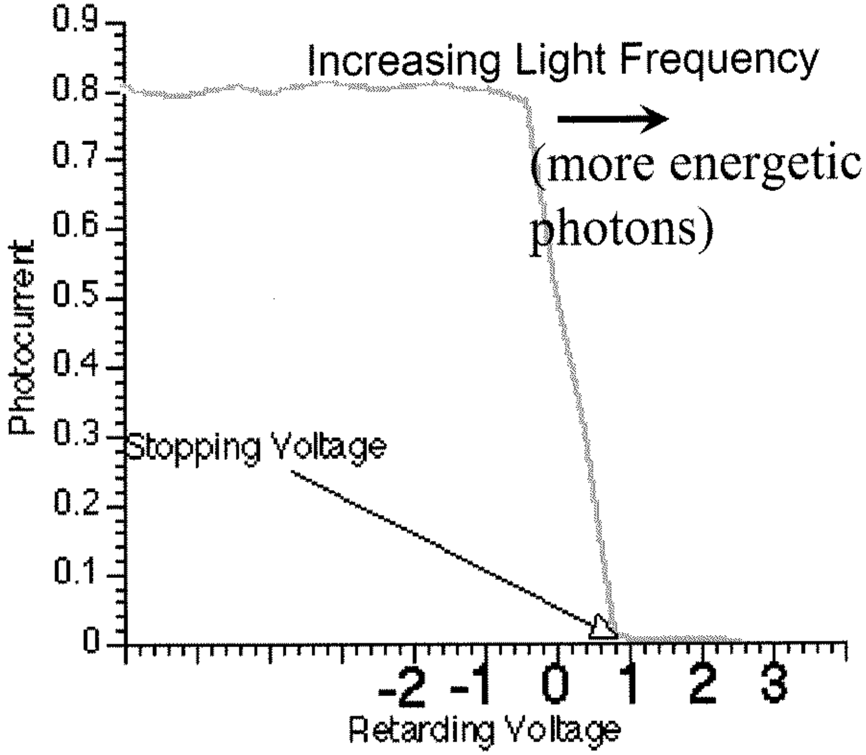
$$KE_{electron} = E_{light} - \phi$$

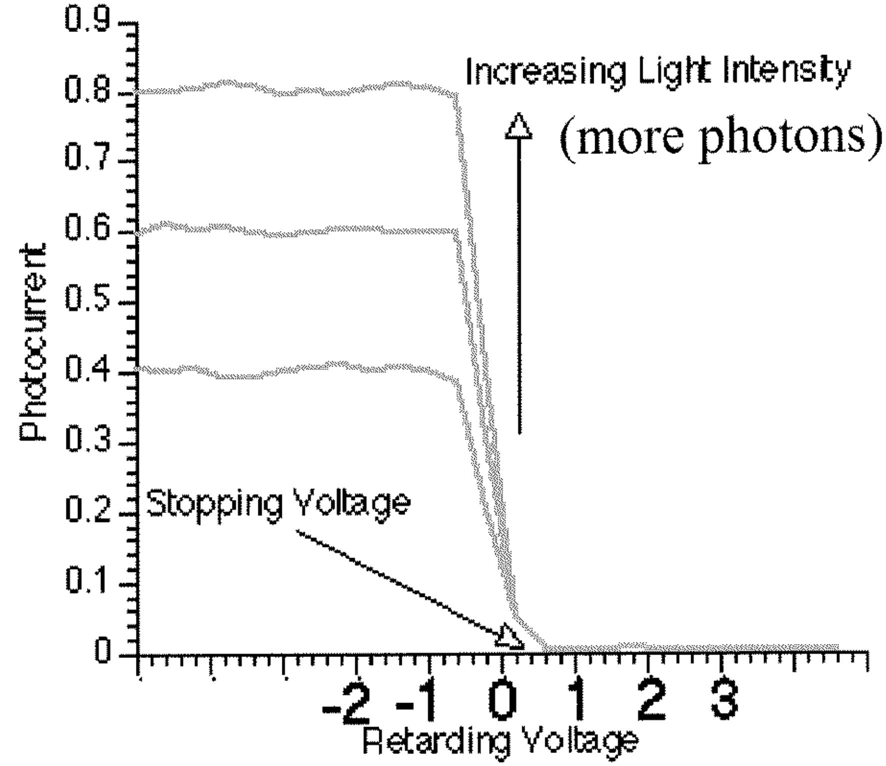
$$E_{light} = hf$$

Peculiar Results: Einstein's Predictions

- The electron emission should begin as soon as the light is turned on.
- The stopping potential should only depend on the frequency of the light, not on its intensity.
- The size of the current should only depend on the intensity, not on the frequency.
- The size of the current should be independent of the voltage.

Results



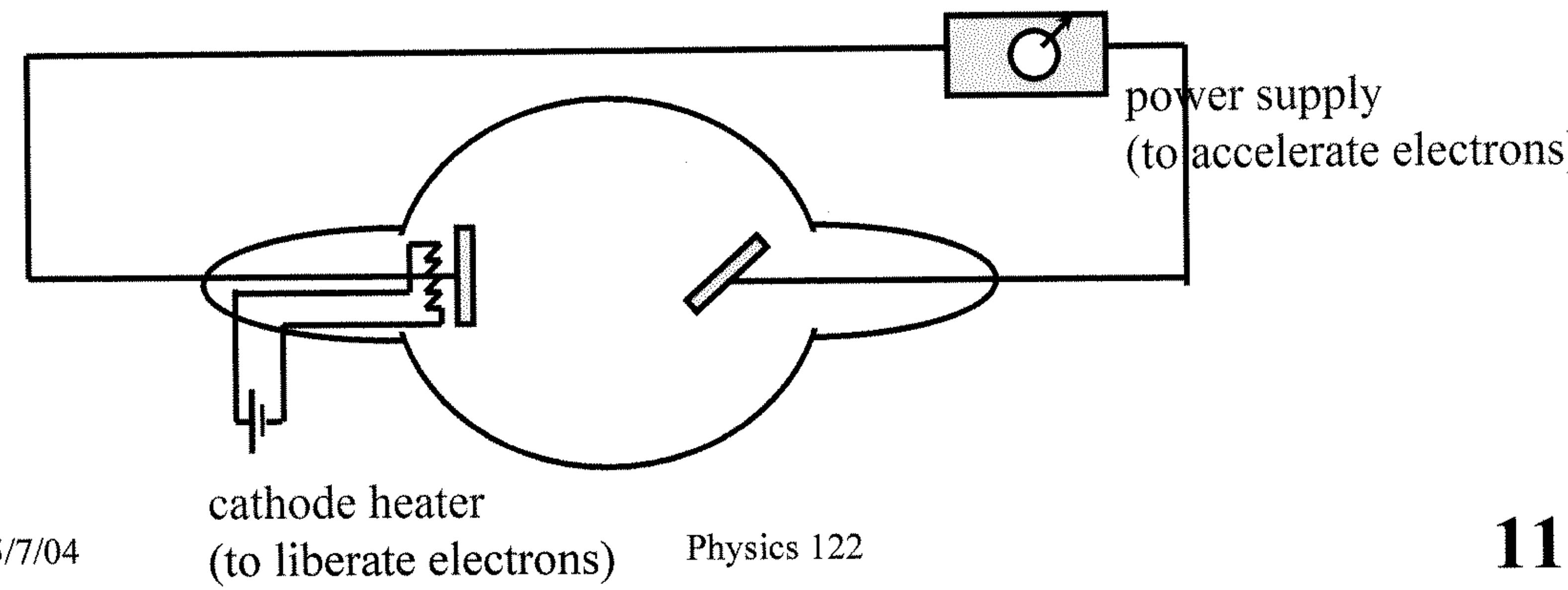


Einstein's predictions were confirmed by Millikan in 1916. Einstein won the Nobel prize for this work in 1921.

http://www.chembio.uoguelph.ca/educmat/chm386/rudiment/tourexp/photelec.htm

Creating High Energy Photons: X-Rays

- If high speed electrons are slammed into metal, the slow down quickly and emit high energy EM waves
  – X-rays.
- The photons of these X-rays have energies ranging from about 100 eV up to about 100,000 eV.



Biological Applications: Hodgkin

- Dorothy Crowfoot Hodgkin (1910-1994) was a pioneer in the use of x-ray scattering to determine the structure of organic molecules including:
  - penicillin,
  - Vitamin B-12, and
  - insulin.
- She won the 1964 Nobel Prize in Chemistry for this work.

Biological Applications: Franklin

- Rosalind Franklin (1910-1957) used x-ray scattering on DNA.
- Crick and Watson relied heavily on her results to interpret the structure of DNA.
- She died before the Nobel Prize was awarded for understanding DNA in 1958. She might well have shared the prize had she lived.

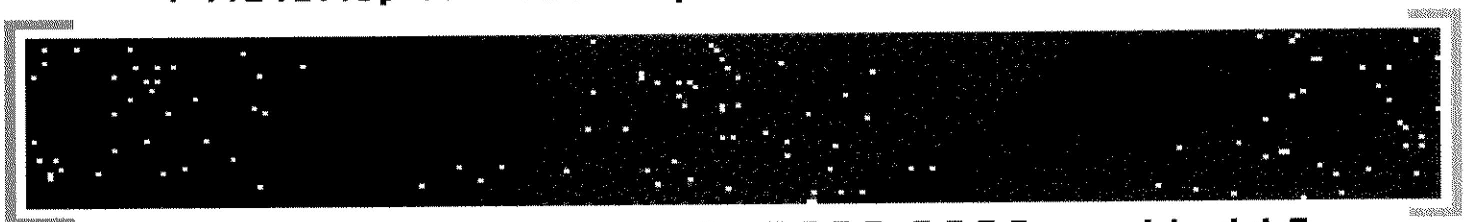
Reconciling Photons and the Wave Model: Starting Quantum Physics

- The photoelectric effect and the photon picture seem to contradict the wave model -- but relies on it.
- What if we pass photons through a double-slit but with a low enough energy density that we expect only one photon in the system at a time.
- What would the pattern look like?

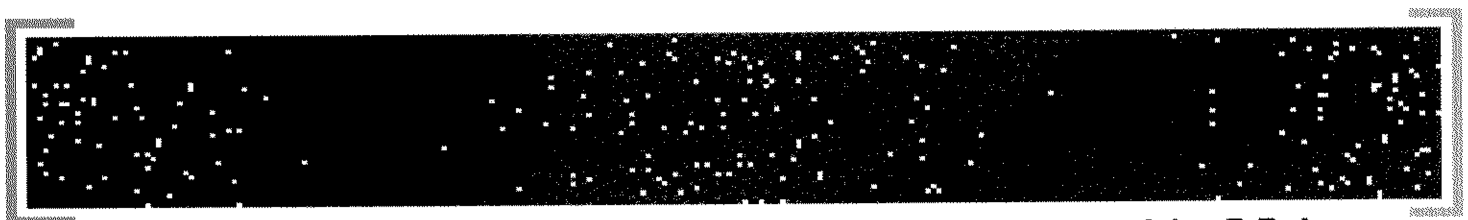
http://phys.educ.ksu.edu/vqm/html/doubleslit/

Results

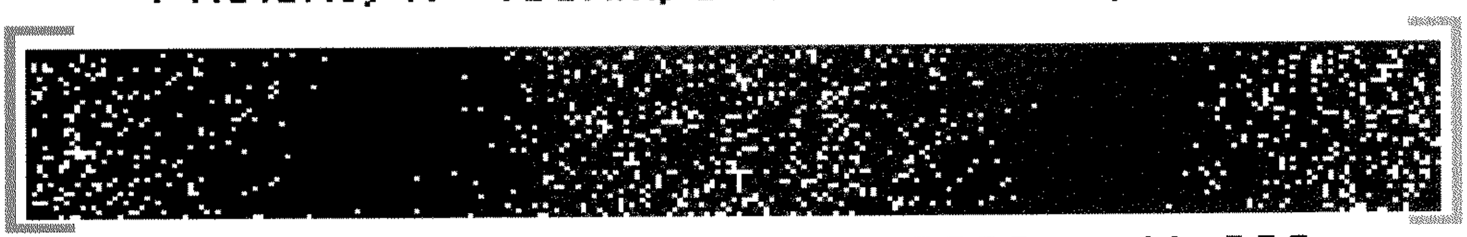
Photons, W=498nm, S=9960.0000nm, N=37



Photons, W=498nm, S=9960.0000nm, N=119



Photons, W=498nm, S=9960.0000nm, N=234



Photons, W=498nm, S=9960.0000nm, N=996

E=Energy, W=Wavelength, S=Slit Separation, N=# Particles

Both Particle and Wave Properties are Displayed

- Individual photons strike the target individually and are detected as tiny spots.
- Individual photons still follow an interference pattern – but at random.
- The intensity of an EM wave only tells us the *probability* of finding a photon at a particular place.

Photons, W=498nm, S=9960.0000nm, N=4033