Modern physics

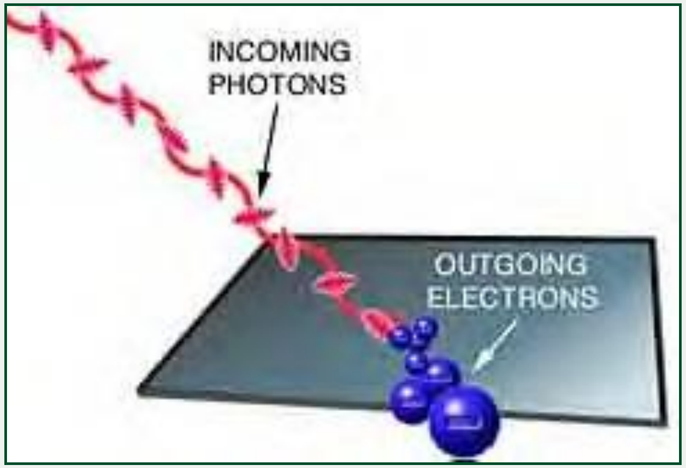
Lecture 4

The photoelectric effect

To be a wave or a particle? That is the question.

Quick overview:

- In the photoelectric effect, you hit target with EM radiation and electrons fly out!
- The electrons ejected from the target are called “photoelectrons”



Classical Physics

Observations

Brighter light more photo electron

Photo emission not completely dependent on Amplitude or brightness

Supposed to be dependent on Amplitude square

Photo emission starts beyond cut off wavelength or frequency

Classical Physics unable to explain

Photoelectric Effect

Metal Foil

Photoelectric Effect

Metal Foil

Photoelectric Effect

- As blue light strikes the metal foil, the foil emits electrons.

Photoelectric Effect

Photoelectric Effect

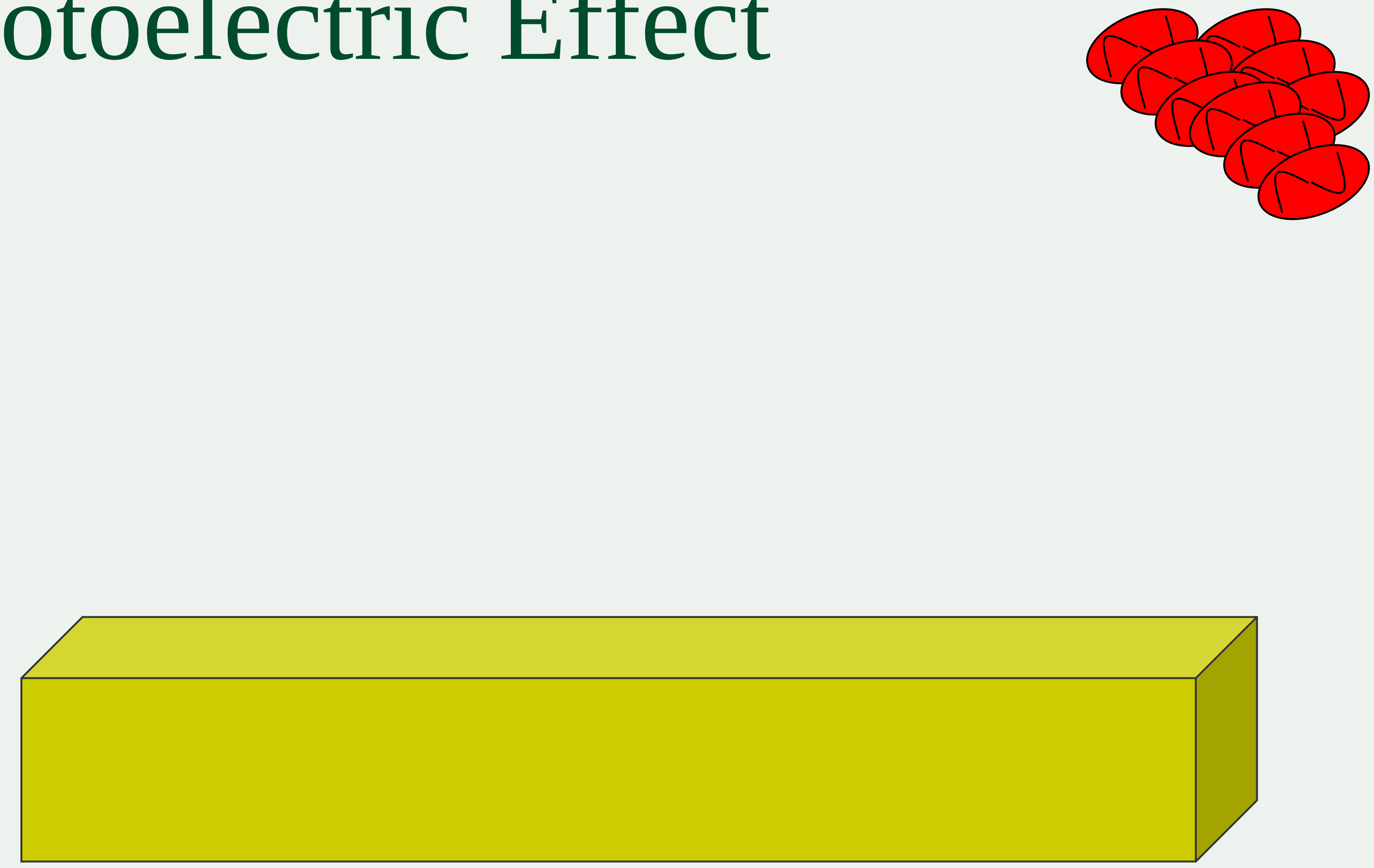
- When red light hits the metal foil, the foil does not emit electrons.
- Blue light has more energy than red light.
- How could we get more energy into the red light?
- Try increasing the brightness (classical physics).

Photoelectric Effect

Photoelectric Effect

- Well, that didn't work!
- Maybe its still not bright enough.

Photoelectric Effect



Photoelectric Effect

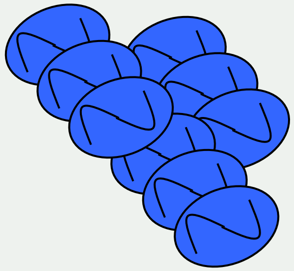
- Still not working.
- What happens with brighter blue light?

Photoelectric Effect

Photoelectric Effect

- More blue light means more electrons emitted, but that doesn’t work with red.

Photoelectric Effect



Photoelectric Effect

- Wave theory cannot explain these phenomena, as the energy depends on the intensity (brightness)
- According to wave theory bright red light should work!

  - ***<u>BUT IT DOESN'T!</u>***

- Einstein said that light travels in tiny packets called ***quanta.***
- The energy of each quanta is given by its frequency

frequency

$$E=h\nu$$

Energy

Planck's constant

- Each metal has a minimum energy needed for an electron to be emitted.
- This is known as the ***work function, W.***
- So, for an electron to be emitted, the energy of the photon, $h\nu$, must be greater than the work function, W.
- The excess energy is the *kinetic energy, E* of the emitted electron.

EINSTEIN’S PHOTOELECTRIC EQUATION:-

$$E = h\nu - W$$

$$h\nu = E_{KE} + W$$

If ν_0 is the cut off frequency then work function can be termed as

$$W = h\nu_0$$

Therefore,

$$E_{KE} = h(\nu - \nu_0)$$

Photon energy in terms of electron volts,

$$E_p = h\nu = \nu 6.626\times 10^{-34}\, Joules$$

$$E_p = \left(\frac{6.626\times 10^{-34}}{1.602\times 10^{-19}}\right)\nu = \nu(4.136\times 10^{-15})eV$$

In terms of wavelength, $$E_p = \frac{1.24\times 10^{-6}}{\lambda}eV$$

Ultra violet light of wavelength 350 nm and intensity 1.00 W/m^2 is directed at a potassium surface. W for potassium is 2.2 eV

a) Find the maximum Kinetic Energy of the photo electrons
b) If 0.50 percent of the incident photons produce photo electrons, how many are emitted per second if the potassium surface has an area of 1.00 cm^2

Part a

Photon energy

$$E_p = \frac{1.24\times10^{-6}}{350\cdot10^{-9}} eV = 3.5eV$$

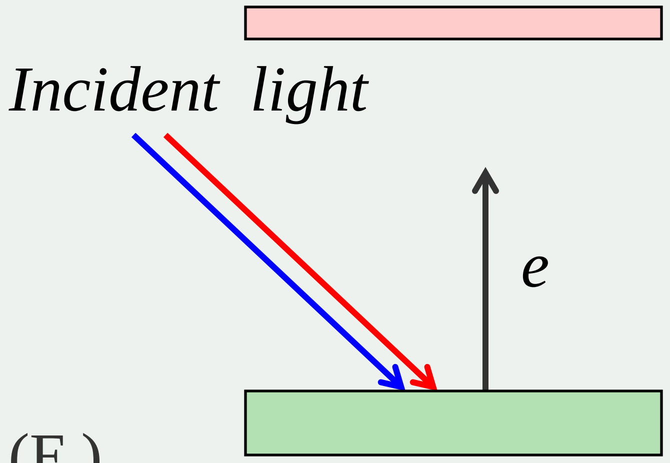
Max Kinetic energy

$$E_{KE} = h\nu - h\nu_0 = (3.5-2.2)eV = 1.3eV$$

Part b

Objective: Find the number of photo electrons

- Find the number of photons/sec impinging on the surface
- Conversion ratio is given already



Find energy of single photon (E_p)
Find energy of total photons/sec impinging (E_t)
Divide E_t by E_p

Energy of a single photon,

$$E_p = \frac{6.626\times10^{-34}}{350\times10^{-9}}\times3\times10^{8} = 5.68\times10^{-19}\,J$$

Total number of photons in incident light per second,

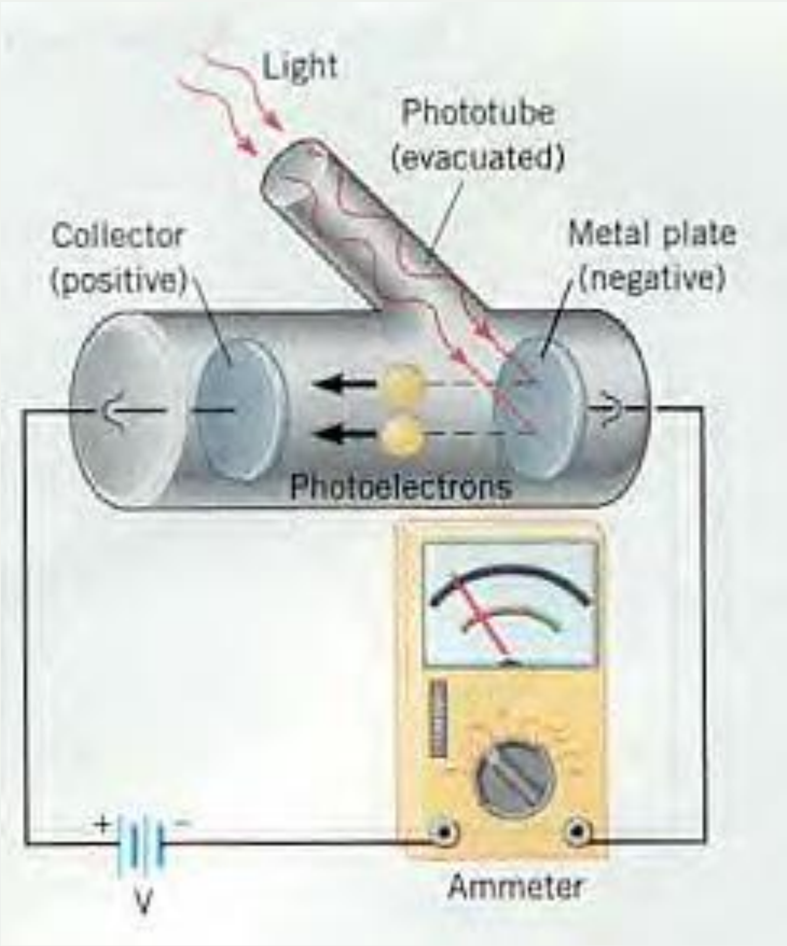
$$n_p = \frac{E/t}{E_p} = \frac{(P/A)(A)}{E_p} = \frac{(1.00W/m^2)(1.00\times10^{-4}m^2)}{5.68\times10^{-19}\,J/photon}$$

$$n_p = 1.76\times10^{14}\,photons/s$$

Rate of photo electron emission would be,

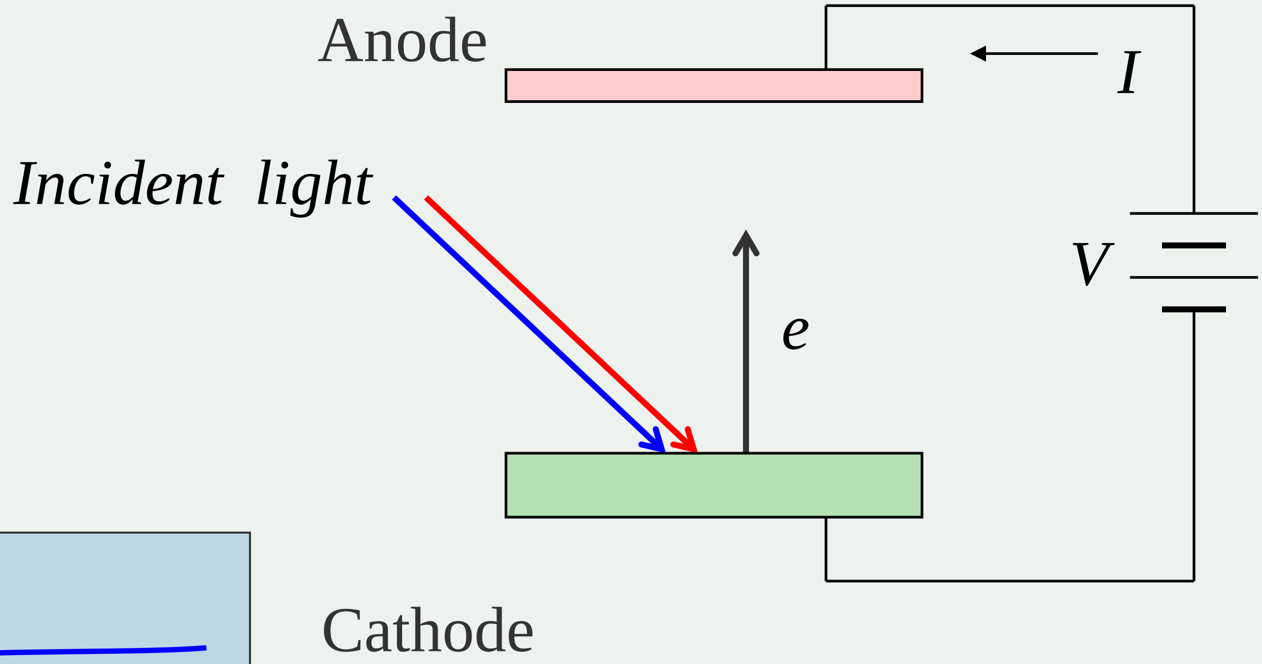
$$n_e = (0.0050)n_p = 8.8\times10^{11}\,photoelectrons/s$$

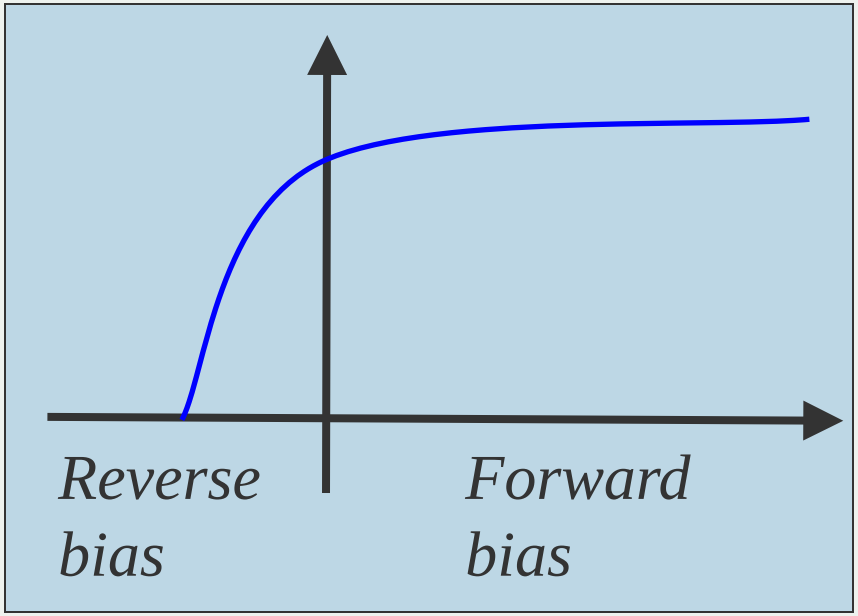
The setup



- An adjustable voltage is applied. Voltage can be forward or reverse biased (which slows down the electrons)
- Ammeter records the current arising due to Photoelectrons, termed as photo current

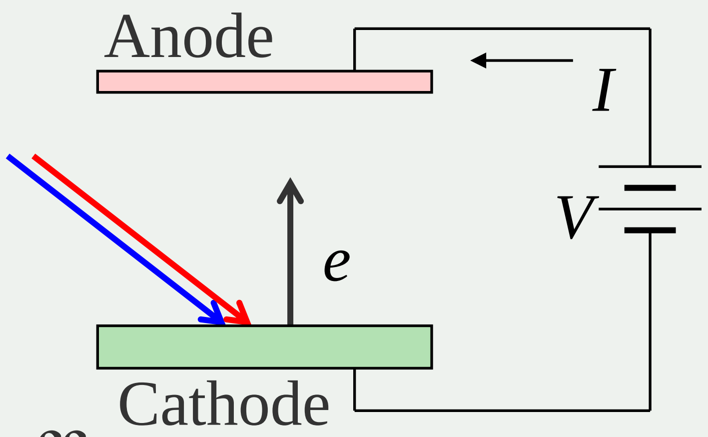
Schematic of Photo electric setup





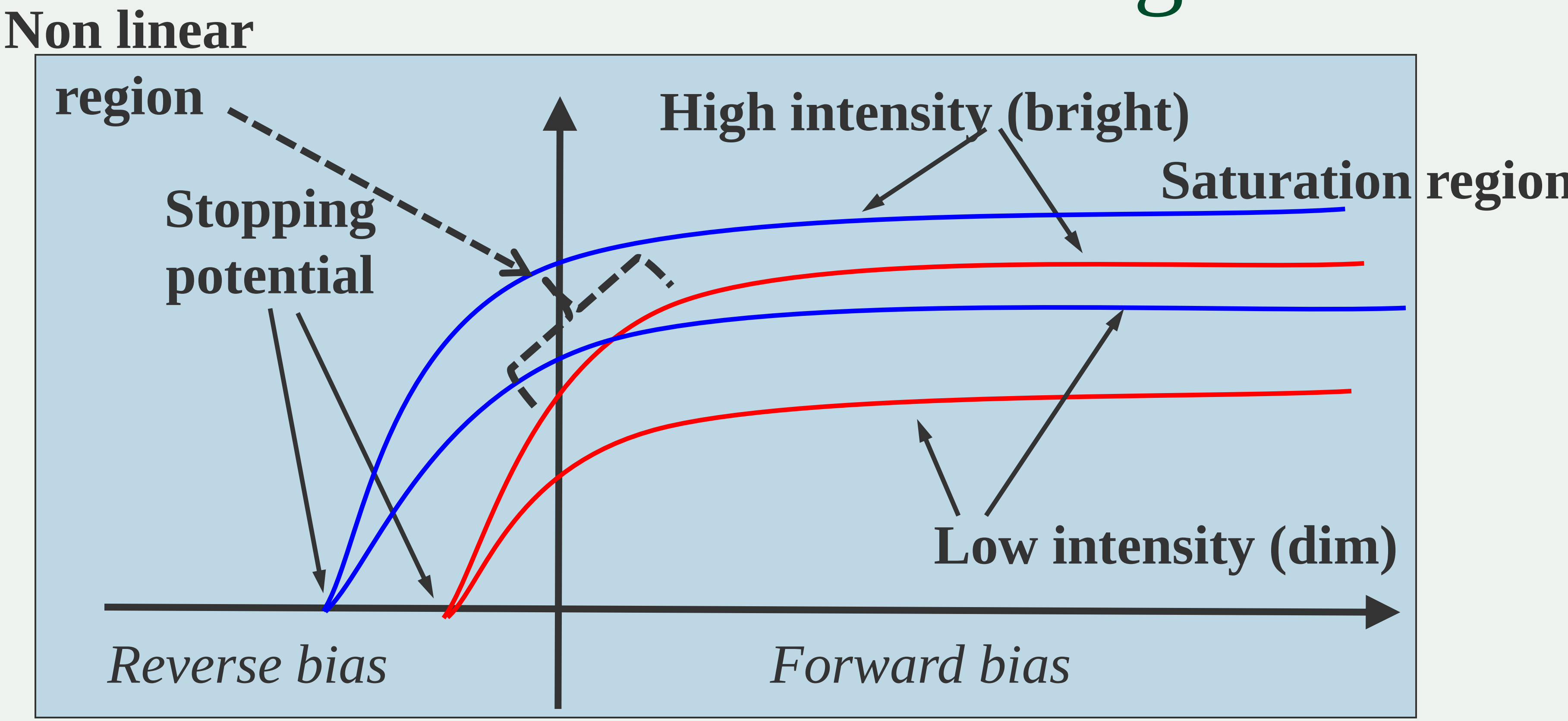
Experimentally obtained results:

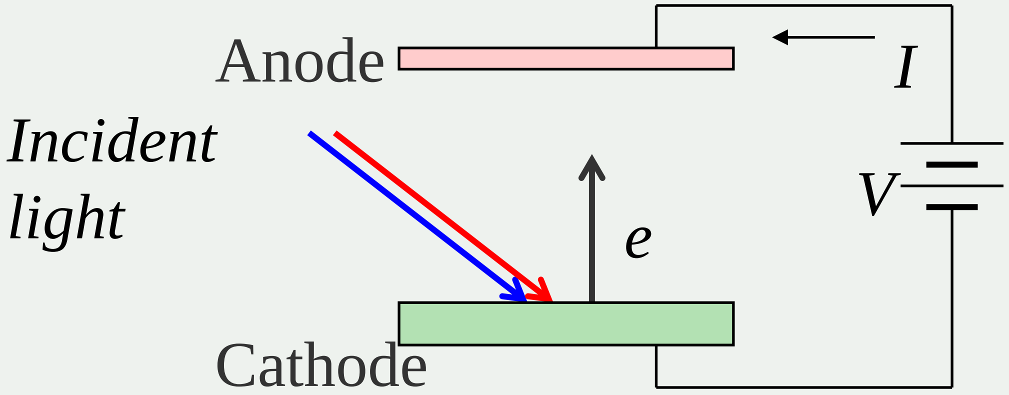
- If photoelectrons get ejected when you shine monochromatic light on the target, the current increases when you increase the intensity (brighter light = more photoelectrons)
- BUT… below a "cutoff frequency" no photoelectrons get ejected no matter how great the intensity of the incident radiation

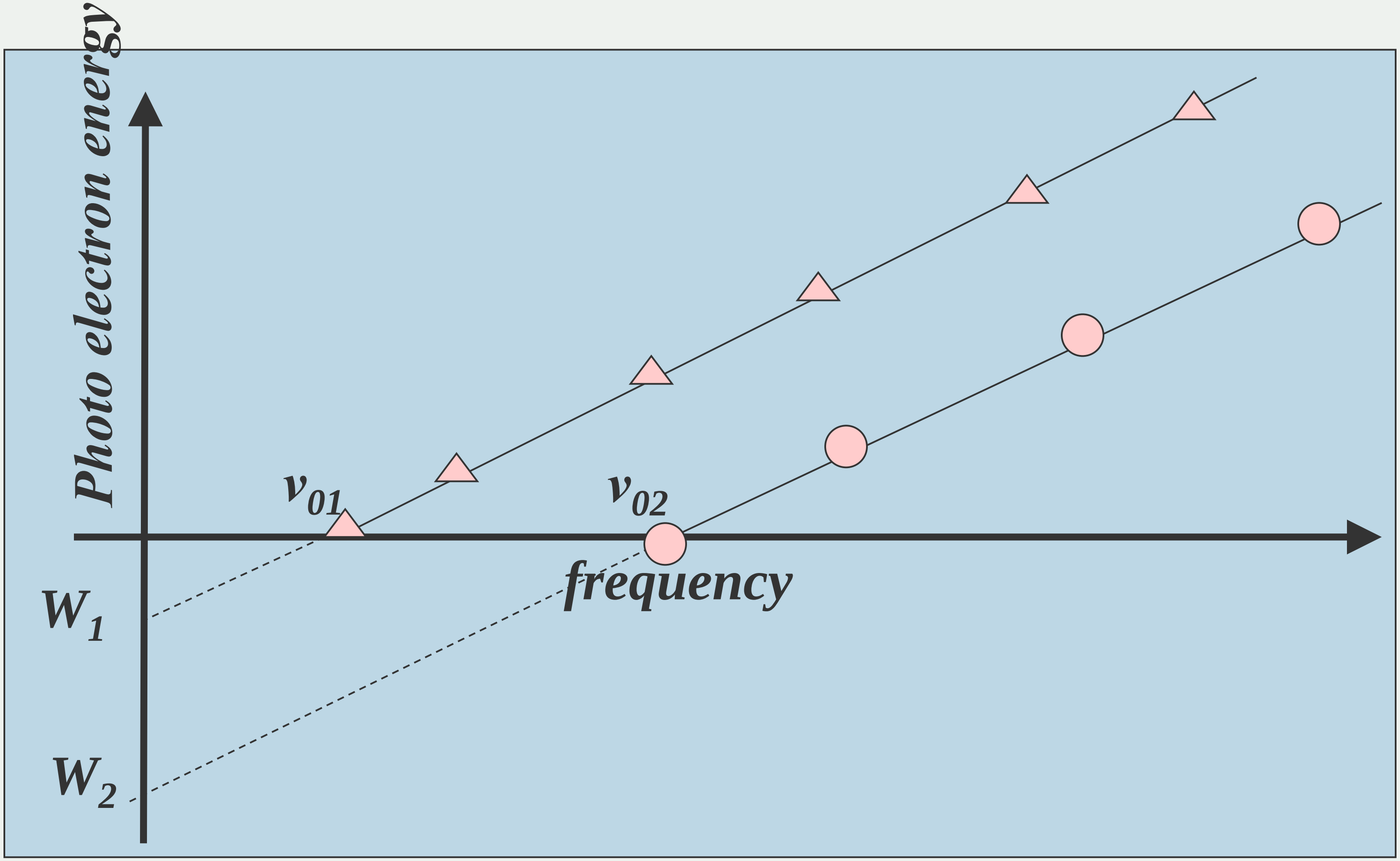


- AND…for frequencies above the cutoff, decreasing the radiation to very low intensities does not completely eliminate the production of photo electrons

Current vs. Bias voltage

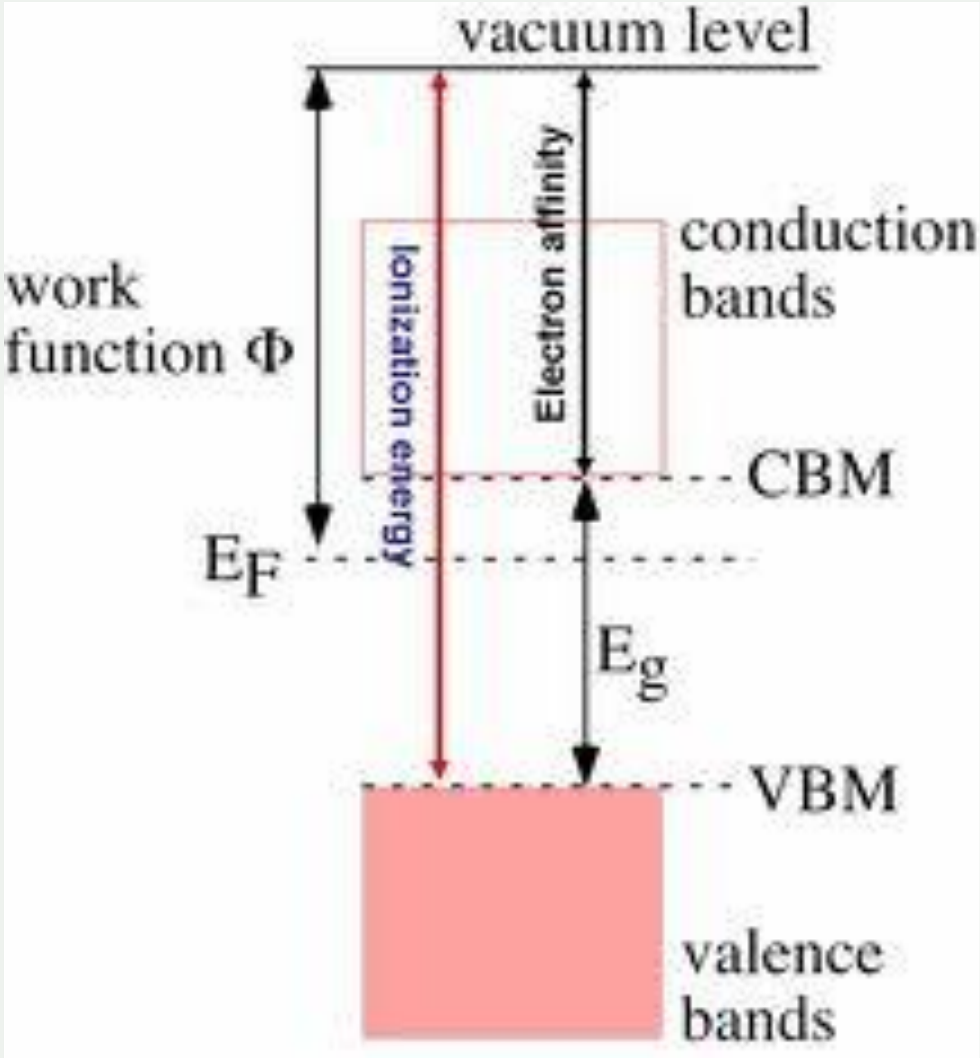






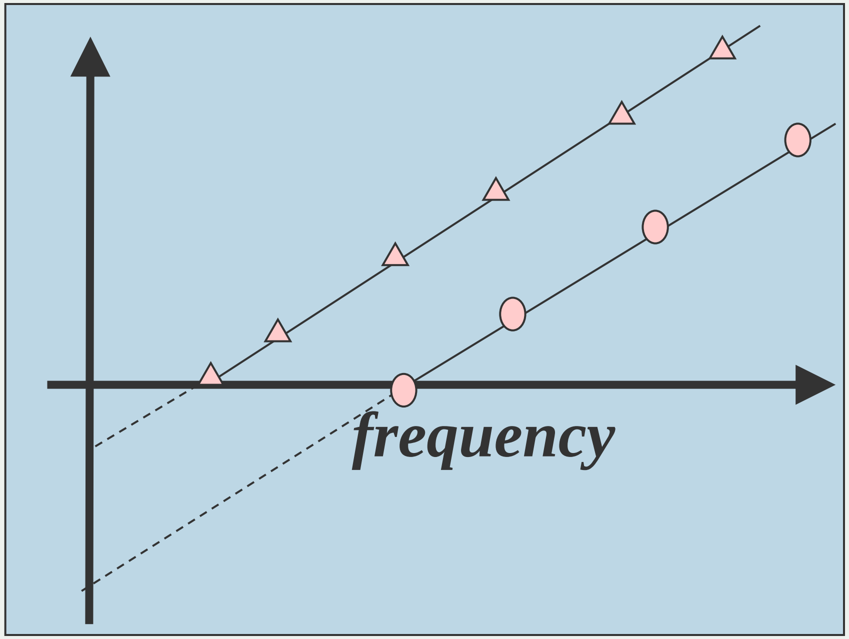
ν_{01} ν_{02} gives information about what?

$$E = h\nu - W$$



- Work functions for some metals:
  - Na: 2.28 eV
  - Co: 3.90 eV
  - Al: 4.08 eV
  - Pb: 4.14 eV
  - Zn: 4.31 eV
  - Fe: 4.50 eV
  - Cu: 4.70 eV
  - Ag: 4.73 eV
  - Pt: 6.35 eV

Interpretation



- Slope is same for all targets
- y intercept is different for different target materials.
- $e\Delta V = hf - \phi_{metal}$
- ϕ is the "work function" of the metal…the mininum amount of energy required to remove an electron.
- $h = 6.63 \times 10^{-34}$ is Planck's Constant!

Interpretation (continued)

- Planck's EM "quanta" turn out to be real after all! (?)
- Light comes in energy packets equal to hf
- Each packet acts more like a particle than a wave
- These light "particles" are called ***photons***
- Rather than continuously absorbing wave radiation the target is being bombarded by photons like tiny billiard balls!

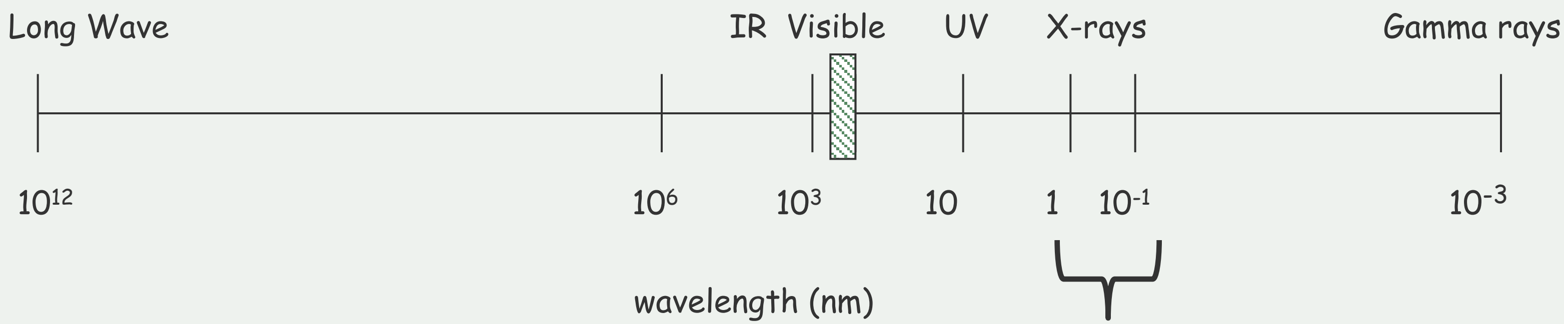
APPLICATIONS

- The photoelectric effect can be used to measure light.
  - Camera light meter

- It can also generate electricity.
  Photovoltaic cell

Modern physics

X-rays and X rays diffractions



$\lambda \sim 0.5$ nm

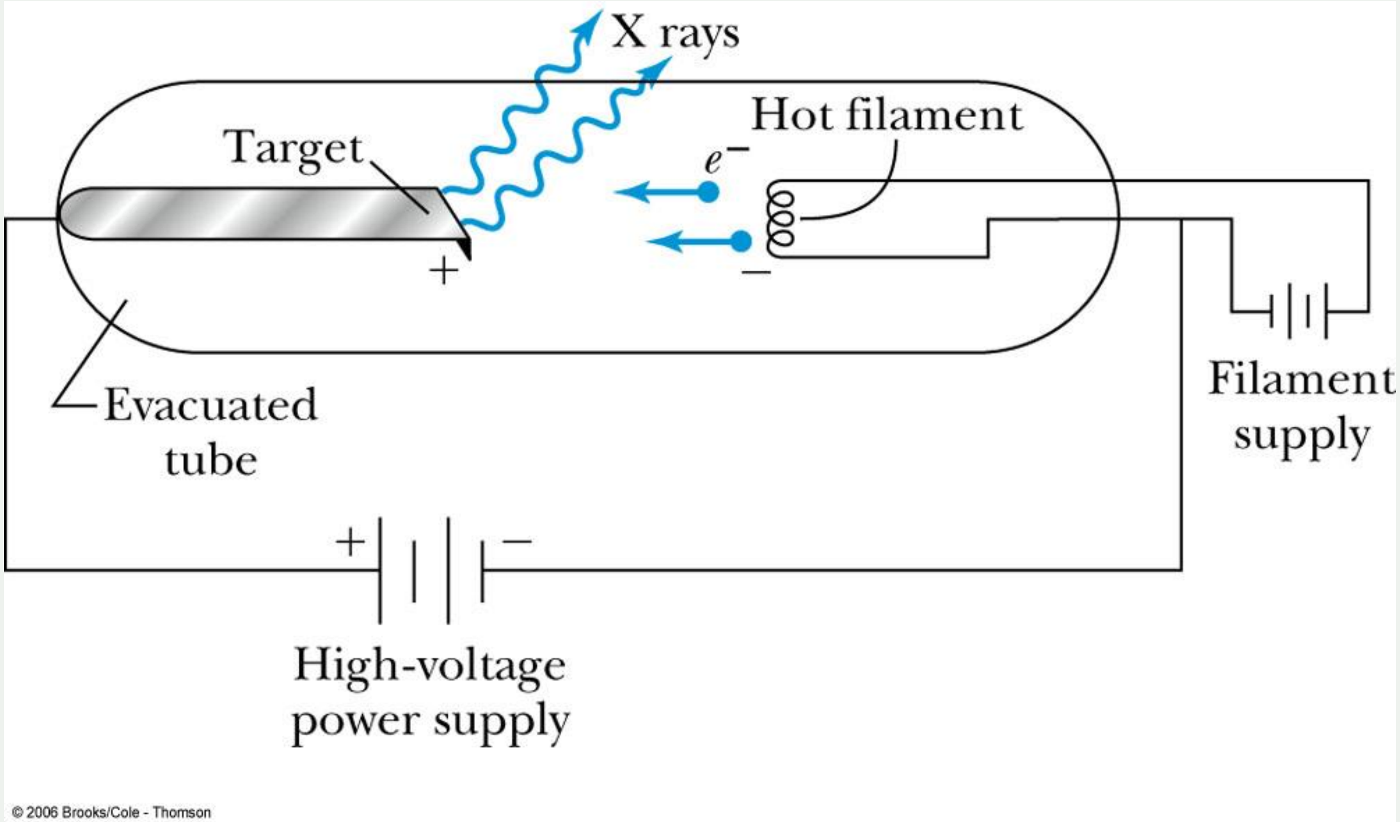
Frau Rontgen's Hand

- X-rays are produced when electrons are accelerated and collide with a target
  - Bremsstrahlung x-rays
  - Characteristic x-rays

- X-rays are sometimes characterized by the generating voltage
  - 0.1-20 kV soft x-rays
  - 20-120 kV diagnostic x-rays
  - 120-300 kV orthovoltage x-rays
  - 300 kV – 1 MV intermediate energy x-rays
  - > 1MV megavoltage x-rays

X-ray Tube

- A simplified x-ray tube (Coolidge type) shows the idea behind most x-ray tubes today



X-rays

White or Bremsstrahlung radiation

Any amount of energy can be lost up to a max. amount

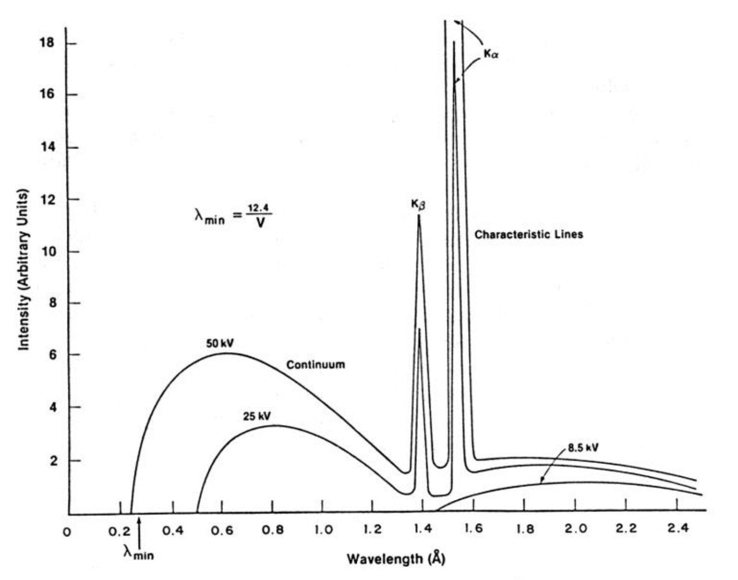
Continuous variation of wavelength

Characteristic radiation

Specific energies absorbed

Specific x-ray wavelengths emitted

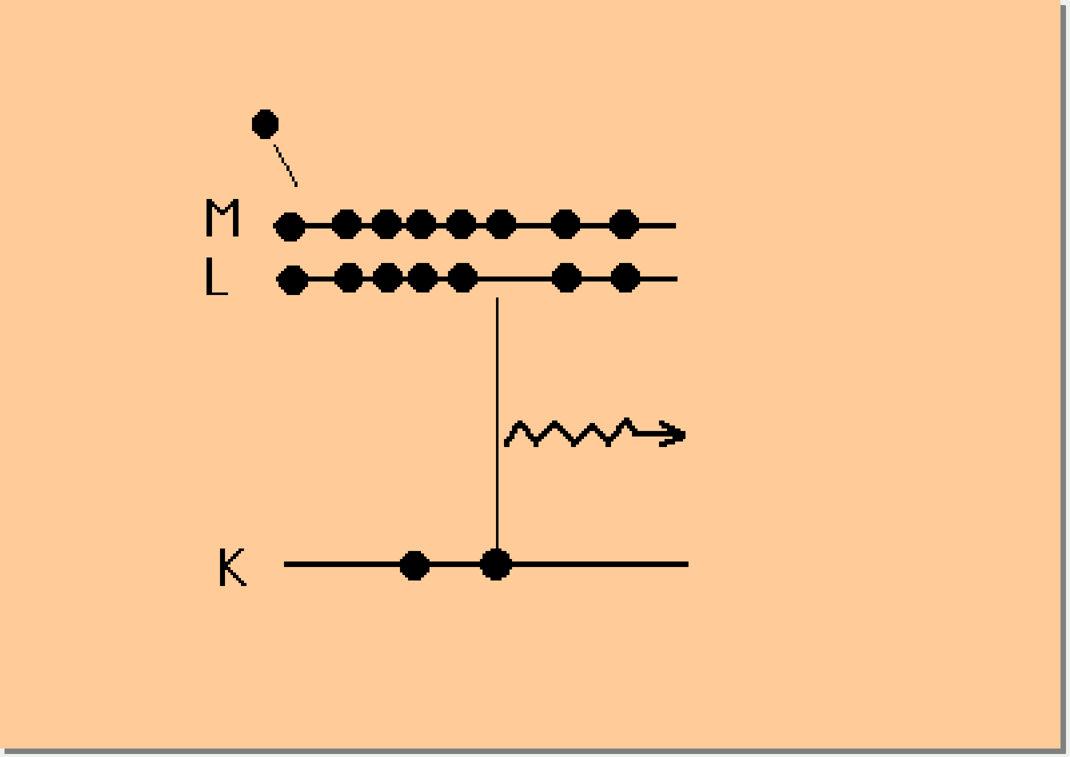
Wavelengths characteristic of target atom type



Continuous and characteristic radiation for copper.

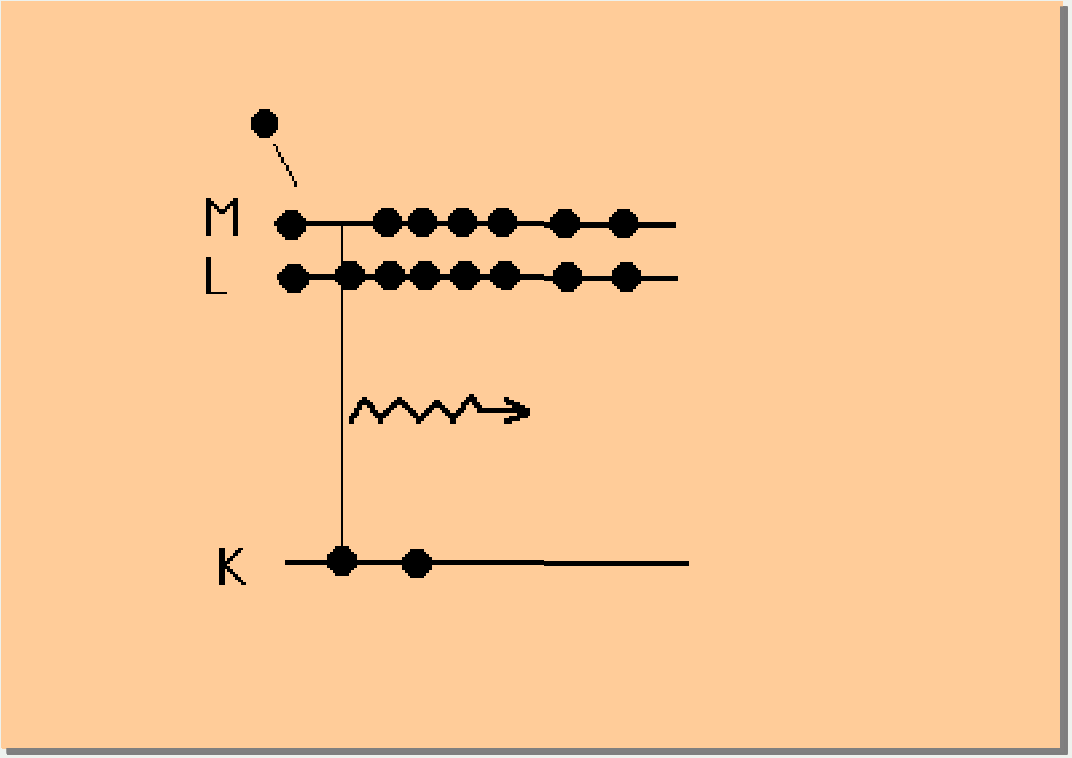
X-rays

Mechanism



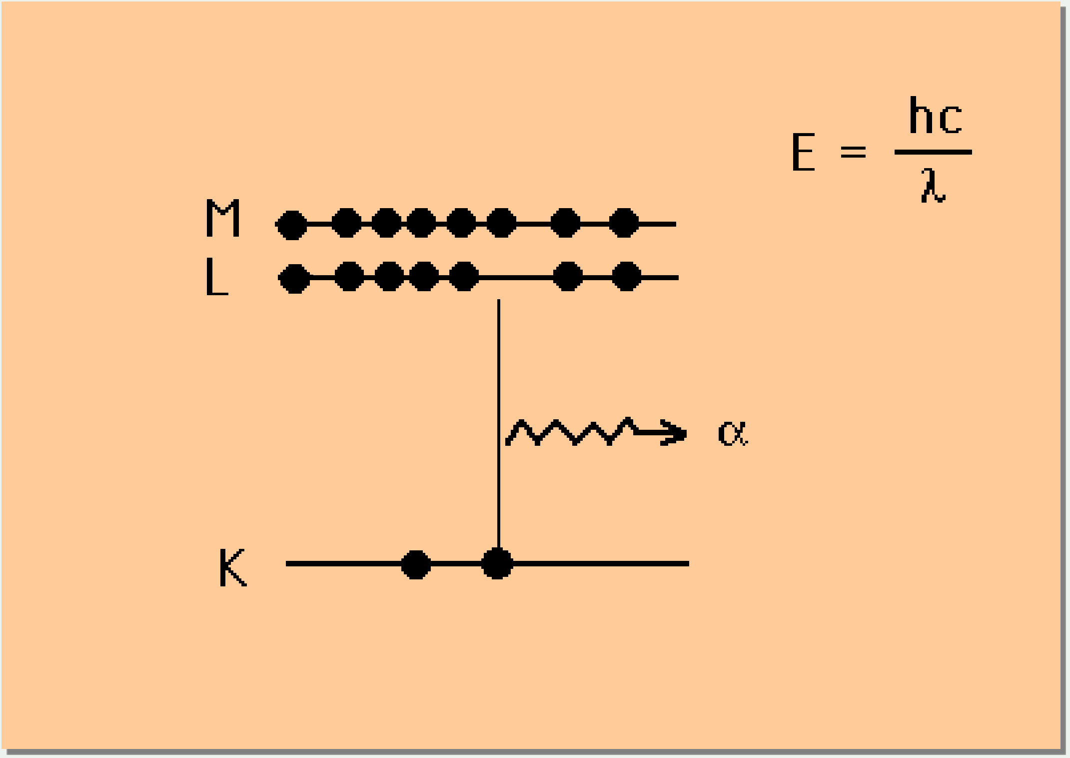
X-rays

Mechanism



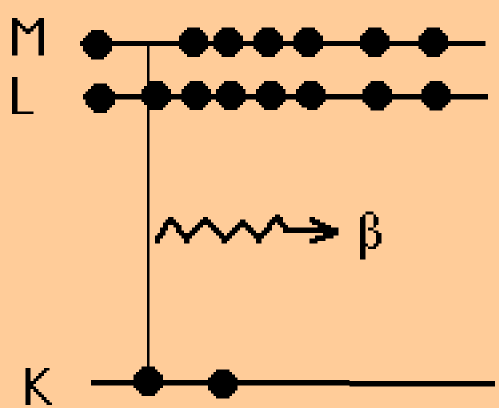
X-rays

Mechanism



X-rays

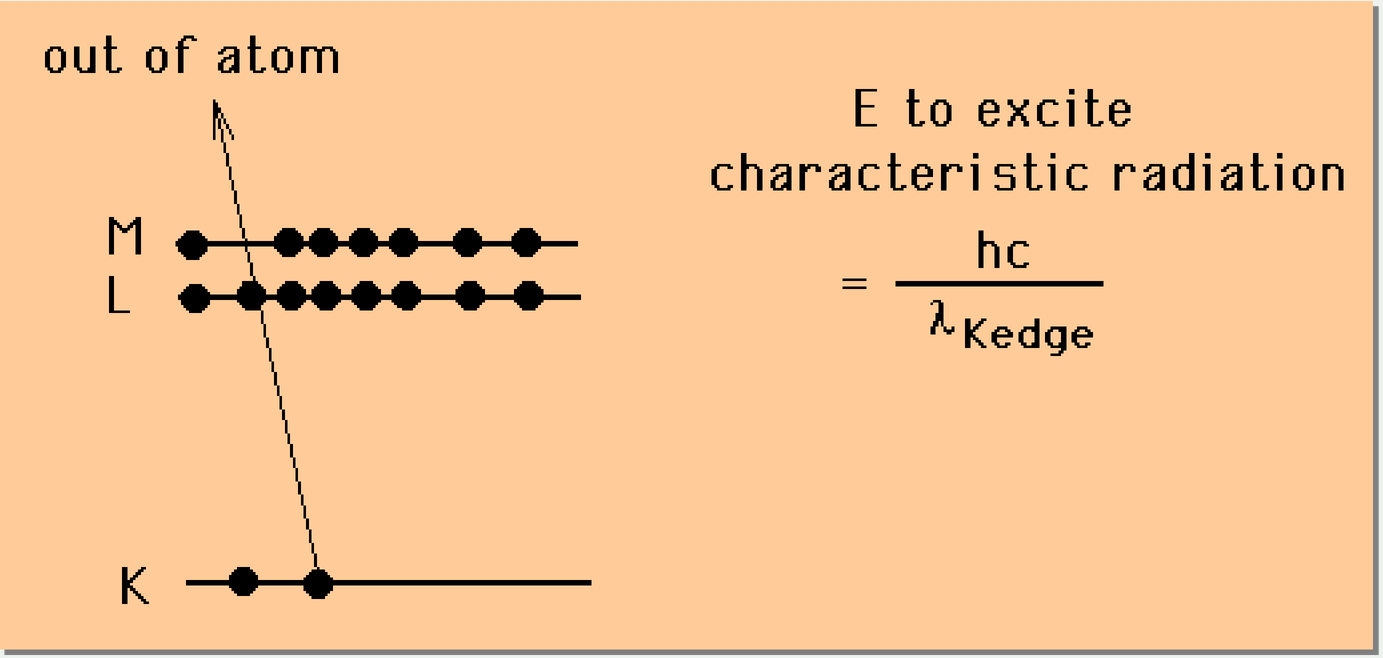
Mechanism



$$E = \frac{hc}{\lambda}$$

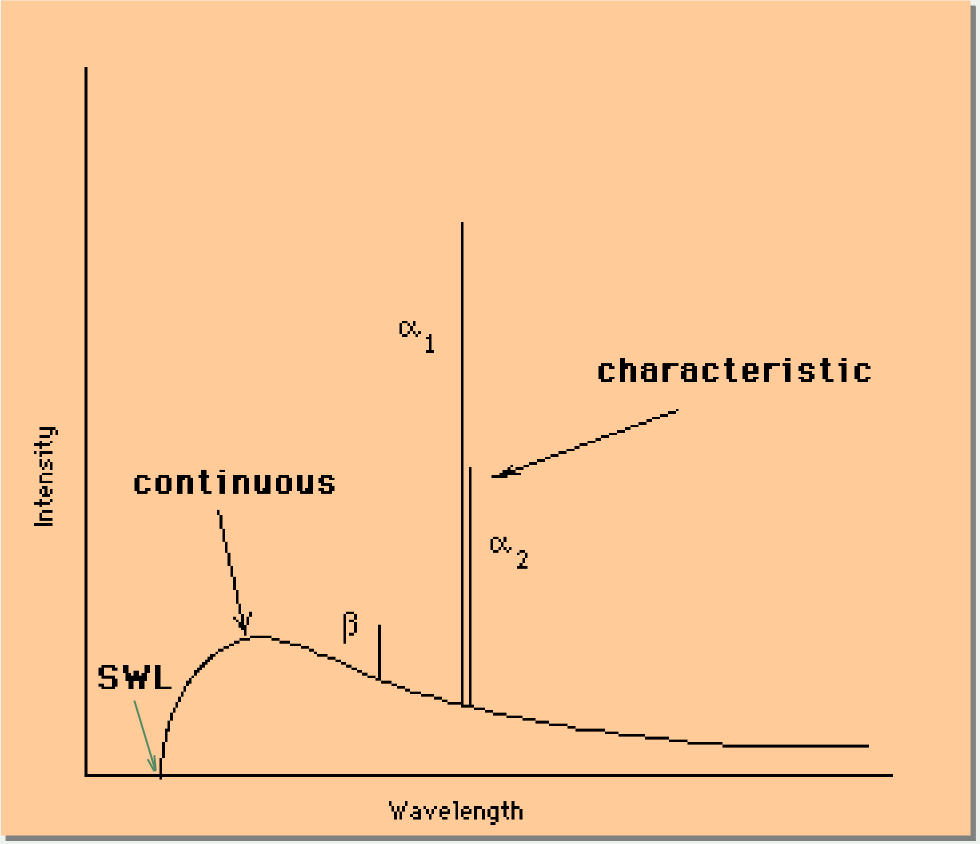
X-rays

Mechanism



X-rays

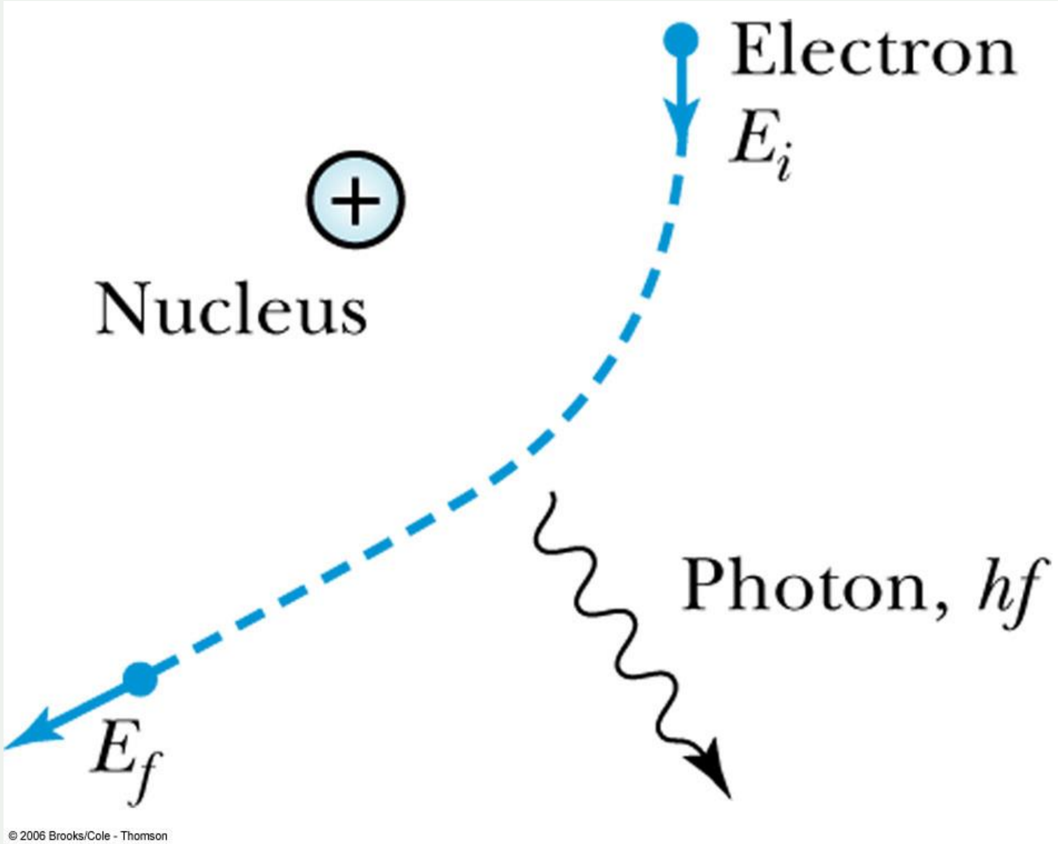
Typical tube spectrum



Target Metal	**λ Of K_α radiation (Å)**
Mo	0.71
Cu	1.54
Co	1.79
Fe	1.94
Cr	2.29

Bremmstrahlung

- Bremsstrahlung x-rays occur when electrons are (de)accelerated in the Coulomb field of a nucleus

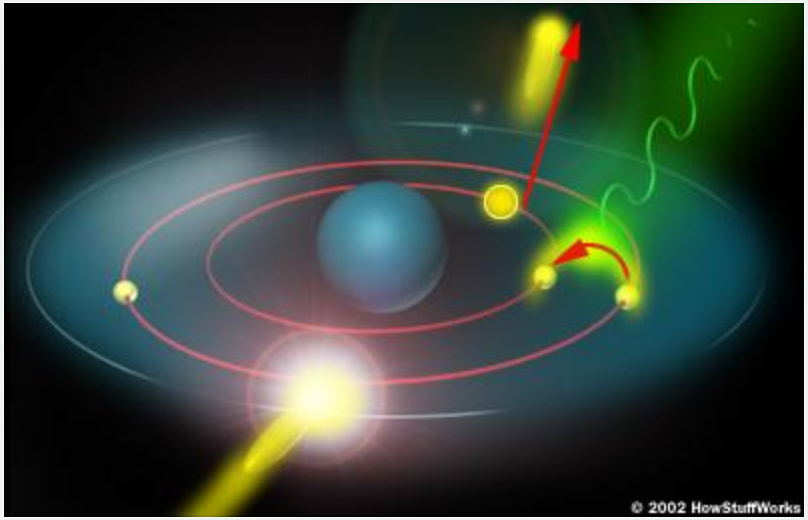


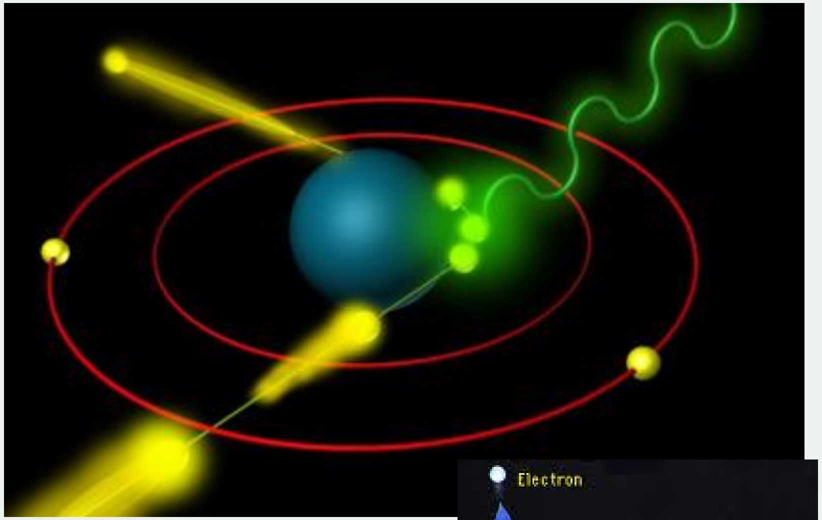
How are X-Rays produced? Physical picture

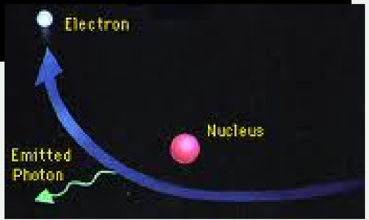
Electron radiative interactions:

- Characteristic x-rays:
  - Electron ejects an inner-shell electron
  - Reorganization generates x-ray

- Bremsstrahlung x-rays
  - Electron “grazes" nucleus, slows down
  - Energy loss generates x-ray (primary source of x-rays from an x-ray tube)







Energy Calculations

- What is the minimum potential in KV that is required to excite Cu K-series radiation from a Cu-target X-ray tube?
- Absorption edge of Cu = 1.380Å
- $E = hc/\lambda = (6.60\ 10^{-34})(3*10^{8})/(1.380*10^{-10})$
- $E = 1.435*10^{-15}$ joule
- $E = 1.435*10^{-15} / 1.6016*10^{-19} = 8958$ ev
- The potential on the tube must exceed 8.958 KV

$$\nu = \frac{c}{\lambda} \quad (1)$$

$$E = h\nu \quad (2)$$

$$E = \frac{hc}{\lambda} \quad (3)$$

$$E = \frac{12.398}{\lambda} \quad (4)$$

- X-rays may be described as waves and particles, having both wavelength (λ) and energy (*E*)
- Substituting (1) into (2) yields (3), the relationship between wavelength and energy.
- In the equations at left:
  - *E* is the energy of the electron flux in KeV
  - *h* is Planck's constant (4.135×10^{-15} eV)
  - *v* is the frequency
  - *c* is the speed of light (3×10^{18} Å/s)
  - λ is the wavelength in Å
- In (4) all constants are substituted

Summary of X-ray Properties

- X-rays are considered both particles and waves, i.e., consisting of small packets of electromagnetic waves, or photons.

- X-rays produced by accelerating HV electrons in a vacuum and colliding them with a target.

- The resulting spectrum contains (1) continuous background (Bremsstrahlung;“white X-rays”), (2) occurrence of sharp lines (characteristic X-rays), and (3) a cutoff of continuum at a short wavelength.

- X-rays have no mass, no charge (vs. electrons)

X Ray Diffraction

Introduction

Motivation:

- **X-ray diffraction is used to obtain structural information about crystalline solids.**
- **Useful in biochemistry to solve the 3D structures of complex biomolecules.**

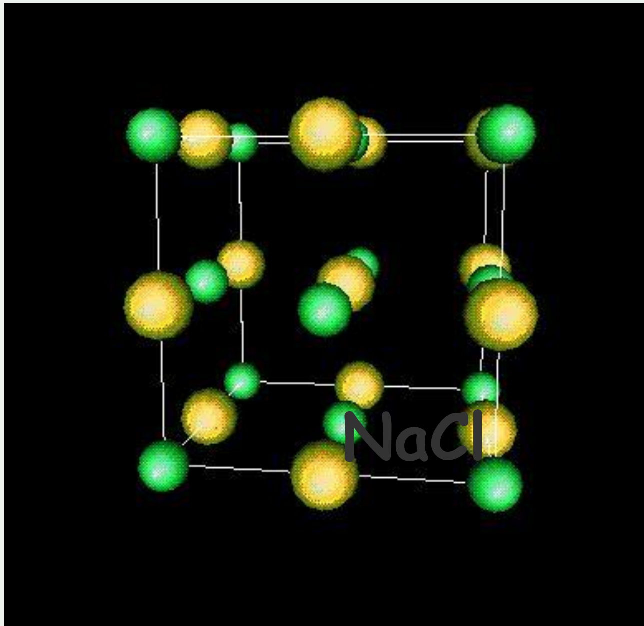
X-ray diffraction is important for:

- **Solid-state physics**
- **Biophysics**
- **Medical physics**
- **Chemistry and Biochemistry**

X-ray Diffractometer

How Diffraction Works

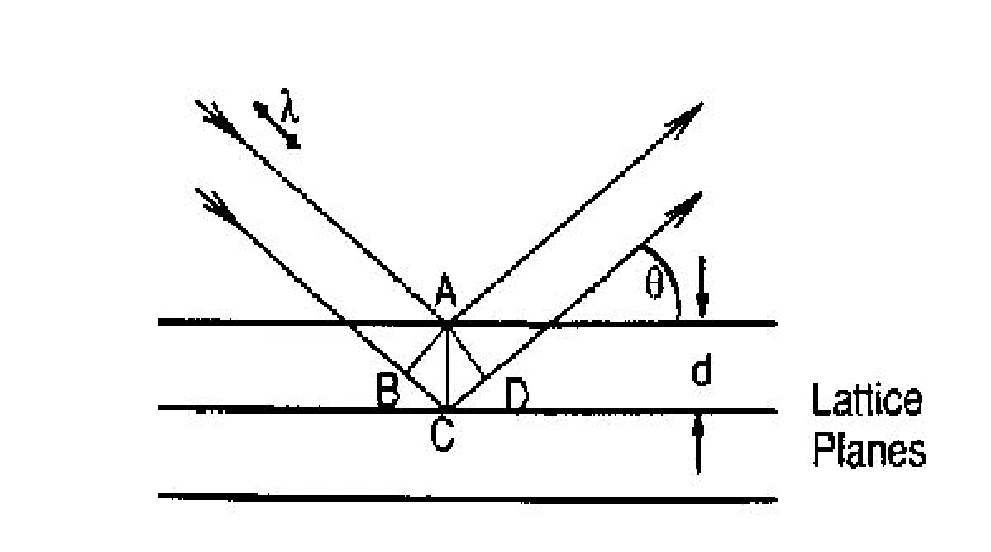
- Wave Interacting with a Single Particle
  - Incident beams scattered uniformly in all directions
- Wave Interacting with a Solid
  - Scattered beams interfere constructively in some directions, producing diffracted beams
  - Random arrangements cause beams to randomly interfere and no distinctive pattern is produced
- Crystalline Material
  - Regular pattern of crystalline atoms produces regular diffraction pattern.
  - Diffraction pattern gives information on crystal structure



Diffraction

- Diffraction is the coherent scattering of waves from a periodic array of scatterers.
- The wavelength of light is about half a micron
- The wavelengths of X-rays is about the same as the interatomic distances in crystals.
- Crystals diffract X-rays.

X-Ray Diffraction



- Atoms separated by distance **d** will scatter in phase when the path length difference is an integral number of wavelengths.
- Path length difference B-C-D = $n\lambda$
- $n\boldsymbol{\lambda} = 2\mathbf{d} \sin\theta$

- Similar principle to multiple slit experiments
- Constructive and destructive interference patterns depend on lattice spacing (d) and wavelength of radiation (λ)
- By varying wavelength and observing diffraction patterns, information about lattice spacing is obtained

How Diffraction Works: Schematic

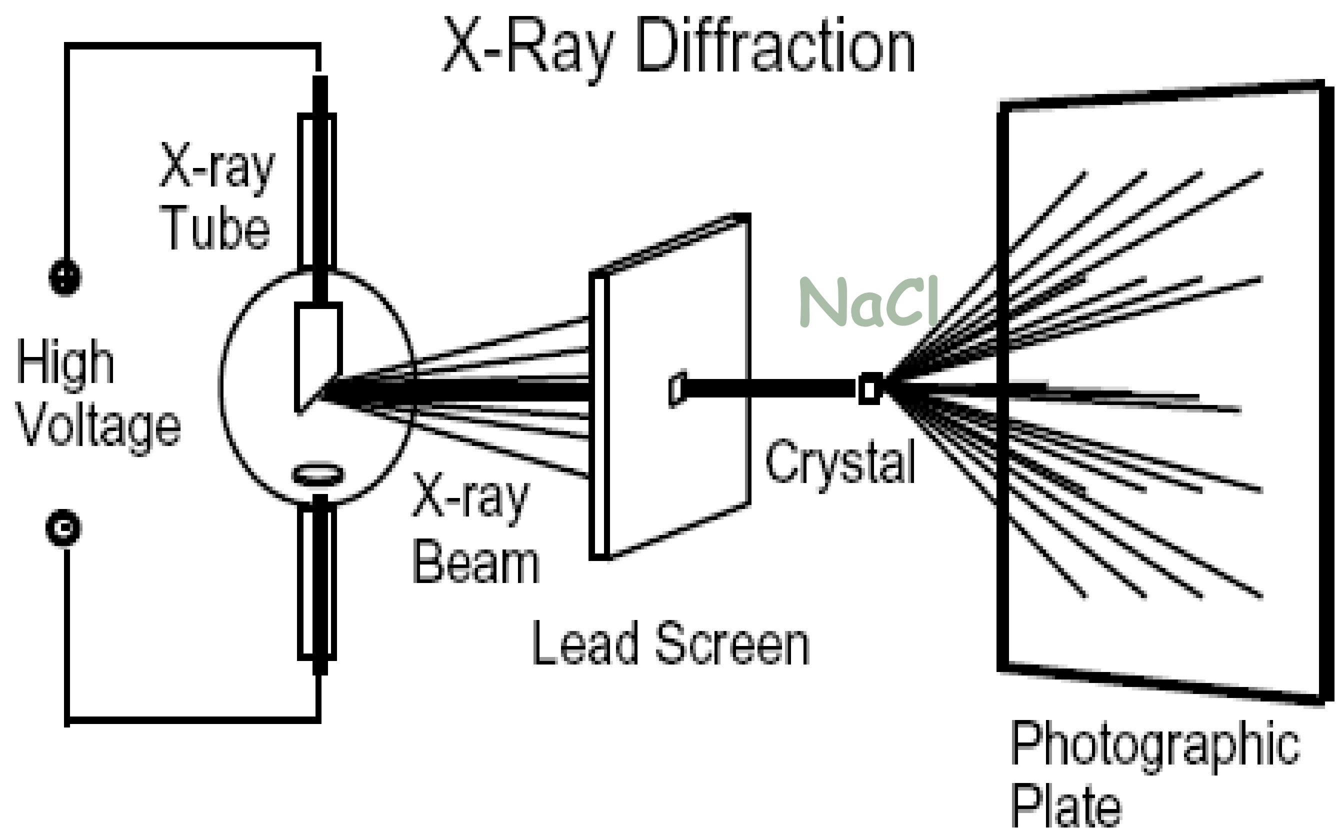


Figure 2. A schematic of X-ray diffraction.

How Diffraction Works: Schematic

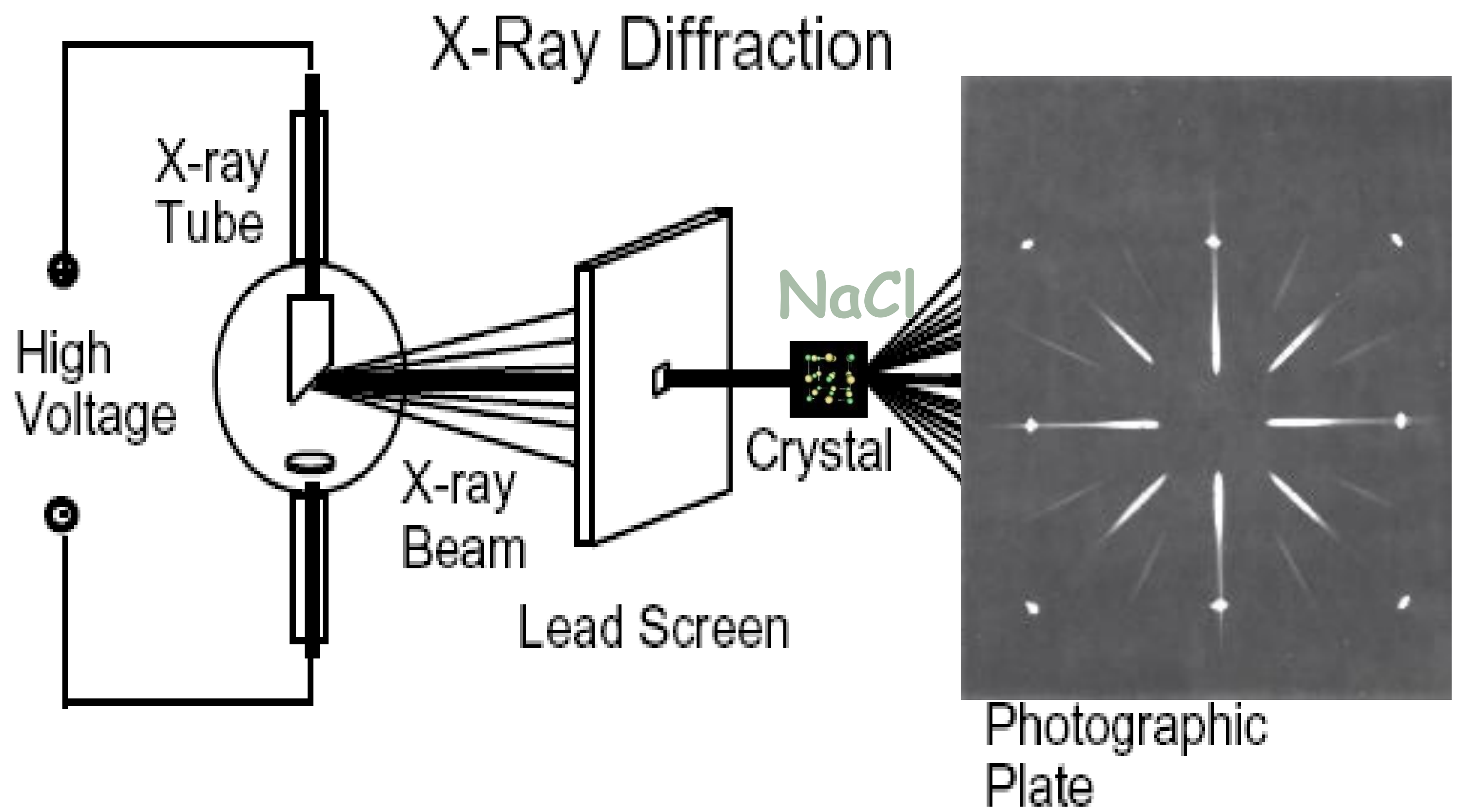


Figure 2. A schematic of X-ray diffraction.