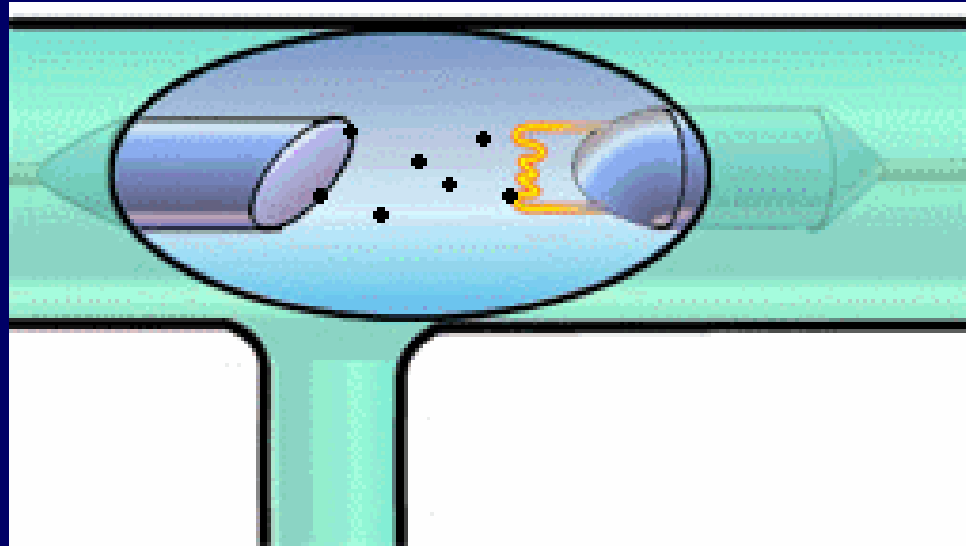


Physics 102: Lecture 26

X-rays





X-Rays



Photons with energy in approx range **100eV to 100,000eV**.

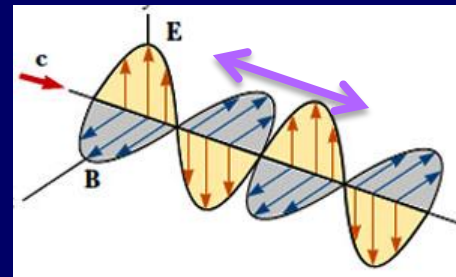
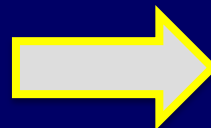
This large energy means they mostly go right through you (except for your bones and some soft tissue).

0.01 nm to 10 nm

What are the wavelengths?

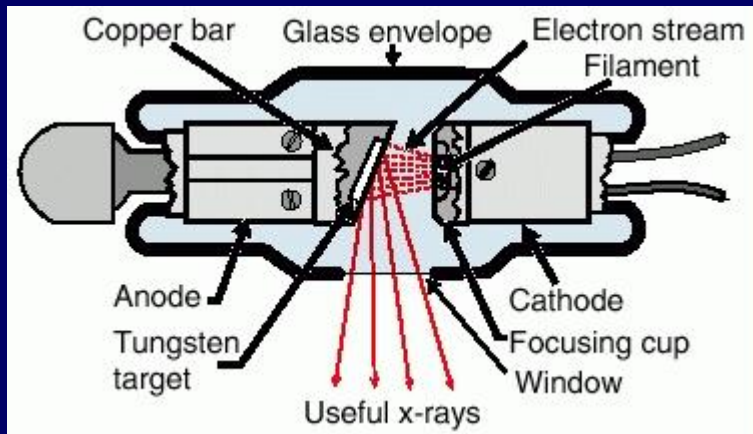
$$\lambda = \frac{hc}{E} = \frac{1240 \text{ eV} \cdot \text{nm}}{E}$$

$$\frac{1240 \text{ eV} \cdot \text{nm}}{100000 \text{ eV}} \approx .01 \text{ nm}$$



$$\frac{1240}{100} \approx 10 \text{ nm}$$

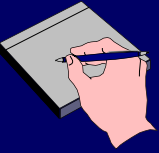
From Electrons to X-Rays



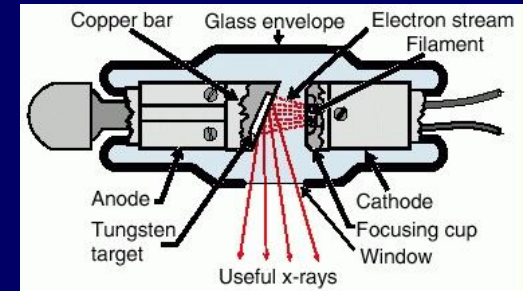
- Take high energy electrons and slam them into a target (any heavy element, usually tungsten)

Example

Electron Tubes



- **Electron** is accelerated through a voltage difference (from - “cathode” to + “anode”) to give it some energy...



An electron is accelerated through a potential difference of 70,000 V. How much energy does it emerge with?

Recall from Lecture 3: $EPE = V q$

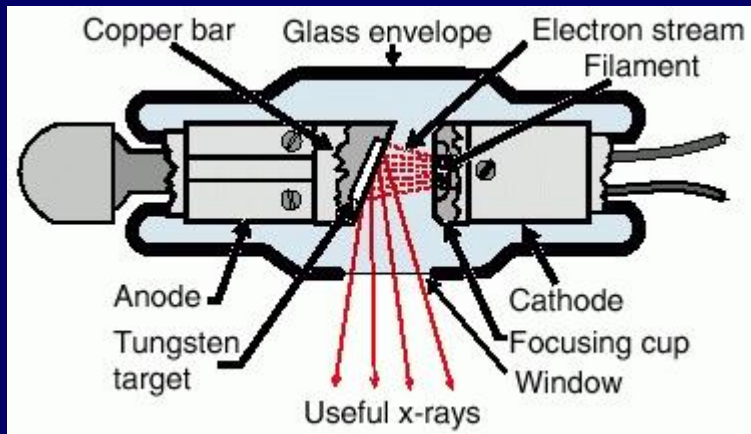
$$KE = EPE = (70,000 \text{ V}) (1 e^-) = 70,000 \text{ eV}$$

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

$$= 11.2 \times 10^{-14} \text{ J}$$

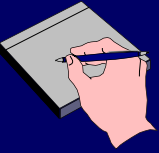
EPE of voltage gap becomes K.E. for electron!

From Electrons to X-Rays

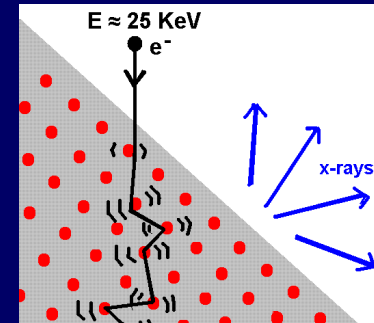
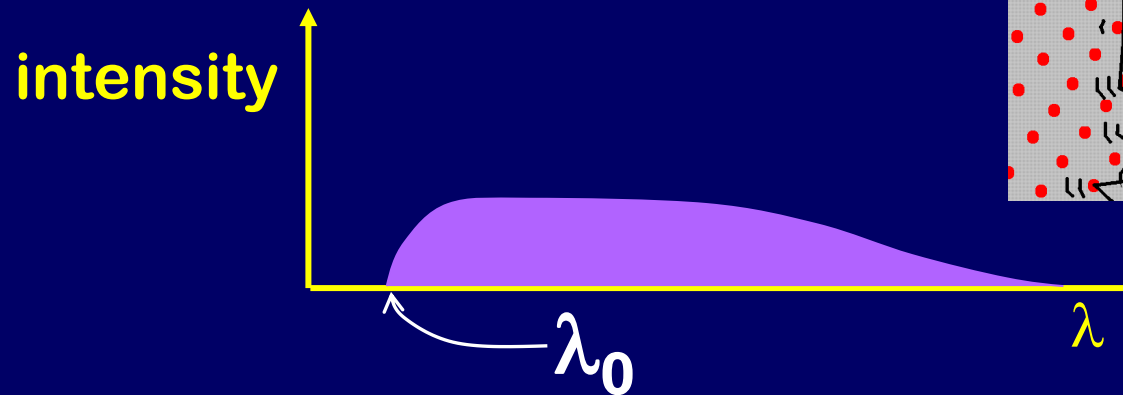
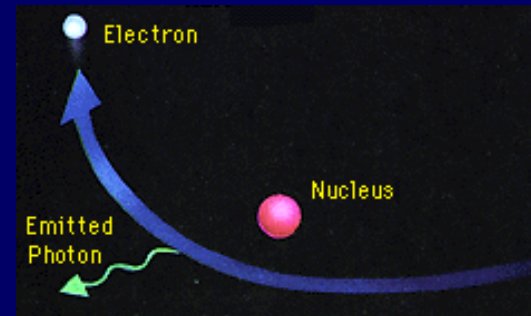


- Take high energy electrons and slam them into a target (any heavy element, usually tungsten)
- 2 kinds of X-Rays are produced:
 - “Bremsstrahlung”
 - “Characteristic”

Bremsstrahlung X-Rays



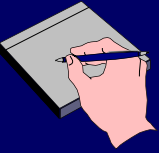
- **Electron hits atom and slows down, losing kinetic energy.**
 - Energy emitted as photon
- **Electron hitting atom makes many photons (X-Rays), all with different energy.**
 - Many different wavelengths.



- **If all of electron's energy is lost to a single photon, photon has maximum energy (minimum wavelength).**
 - Minimum X-Ray wavelength = λ_0 .

Example

Bremsstrahlung Practice

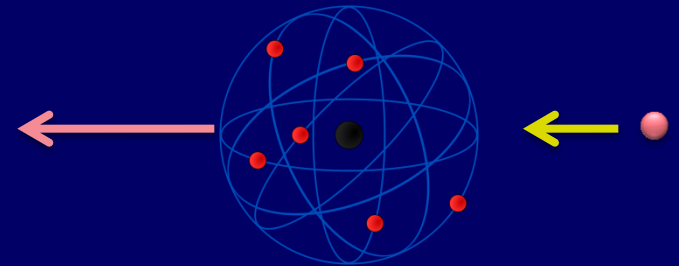


An electron is accelerated through 50,000 volts

What is the minimum wavelength photon it can produce when striking a target?

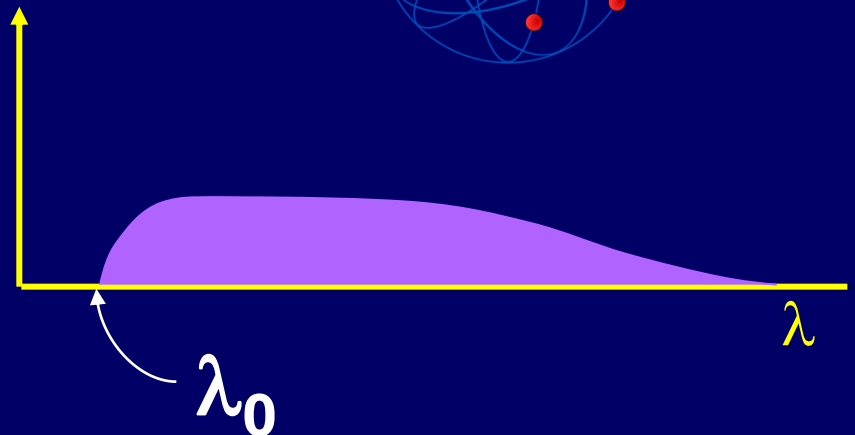
Minimum wavelength \longleftrightarrow Maximum energy

Electron loses ALL of its energy in one collision and emits one photon.



intensity

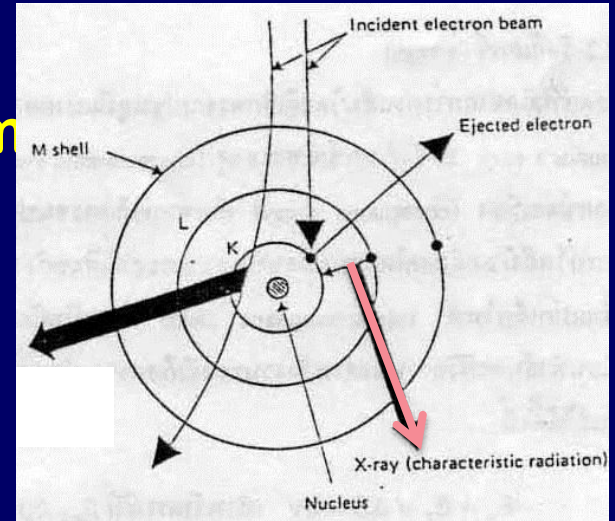
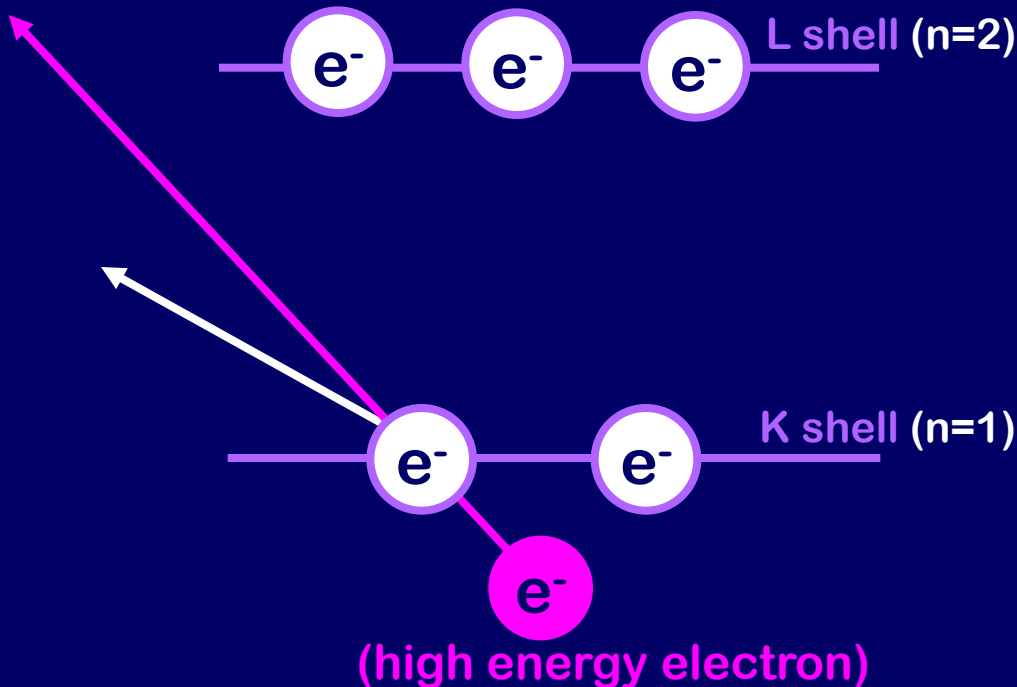
$$\lambda_0 = \frac{hc}{E} = \frac{1240}{50,000} = .0248 \text{ nm}$$



Characteristic X-Rays

Electron knocks one of the two K shell (ground state) electrons out of an atom

L ($n=2$) or higher shell electron falls down to K shell (ground state) and x-ray photon is emitted



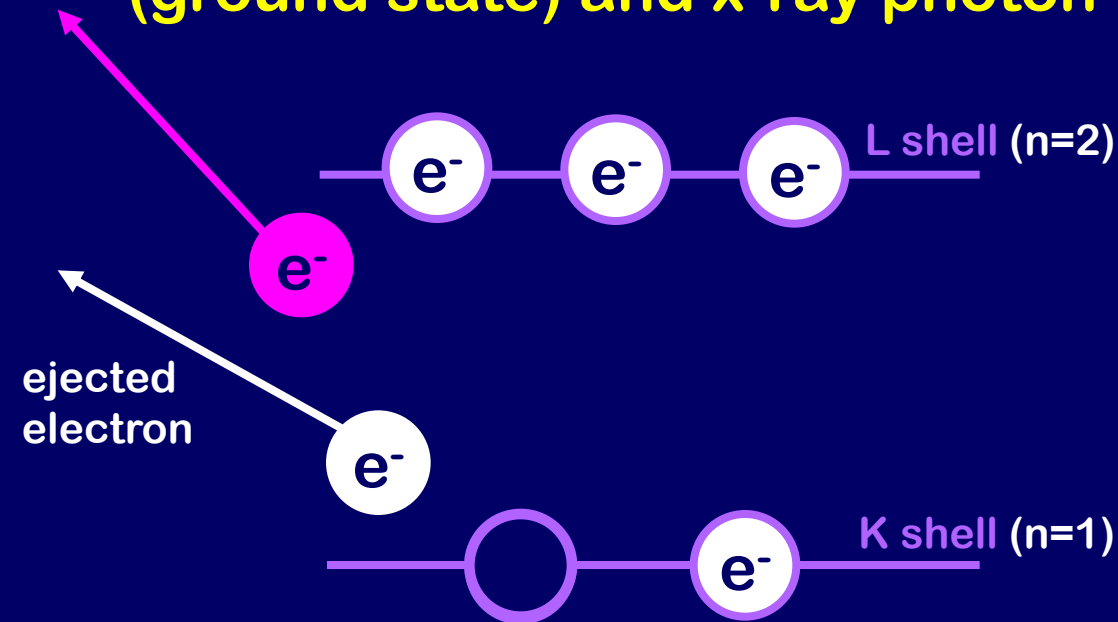
Characteristic x-ray nomenclature

$n=1$	"K shell"
$n=2$	"L shell"
$n=3$	"M shell"

Characteristic X-Rays

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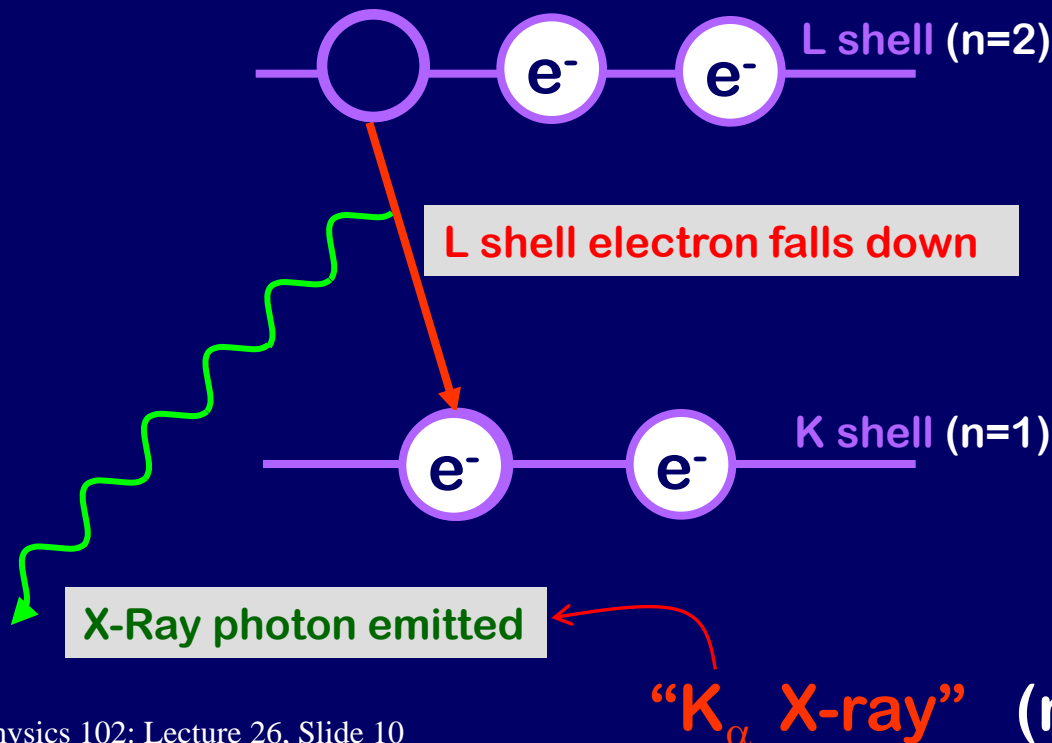
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Characteristic x-ray nomenclature

$n=1$	"K shell"
$n=2$	"L shell"
$n=3$	"M shell"

" K_α X-ray" ($n=2 \rightarrow n=1$ transition)

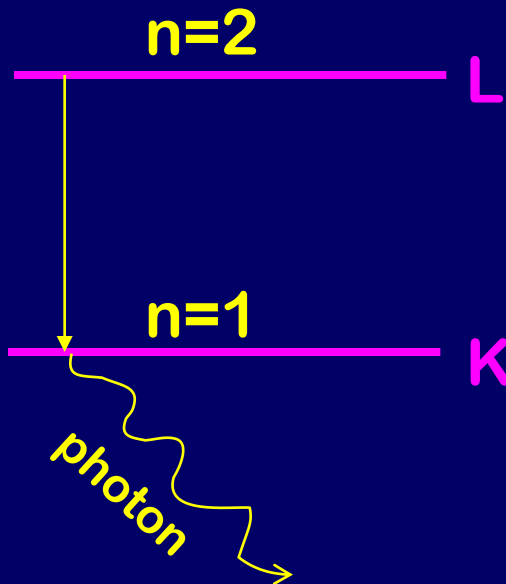
Example

K_{α} X-Rays

Estimate the energy of K_{α} X-rays off of a silver (Ag) target ($Z=47$).

Better formula for inner-shell electrons in multi-electron atoms

$$E_n = \frac{(-13.6)(Z-1)^2}{n^2}$$



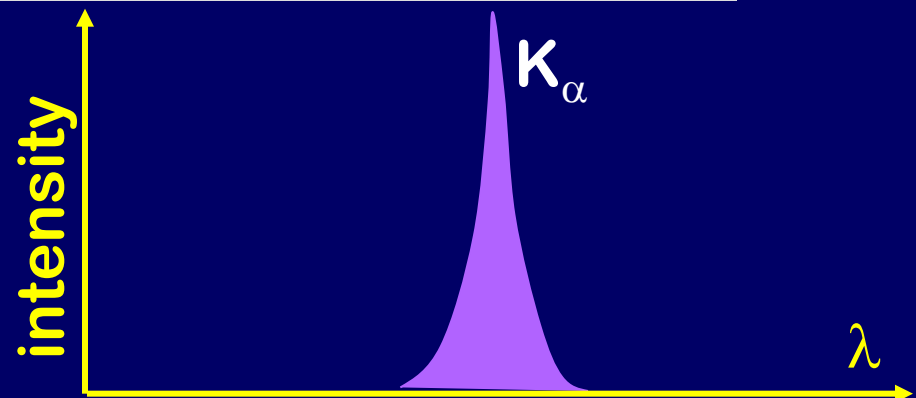
$$E_L = -13.6\text{eV}(47-1)^2 \frac{1}{2^2} = -7.2\text{keV}$$

$$E_K = -13.6\text{eV}(47-1)^2 \frac{1}{1^2} = -28.8\text{keV}$$

$$E(K_{\alpha}) = E_L - E_K = 21.6\text{keV}$$

(vs. 21.7 keV Expt)

Not bad!



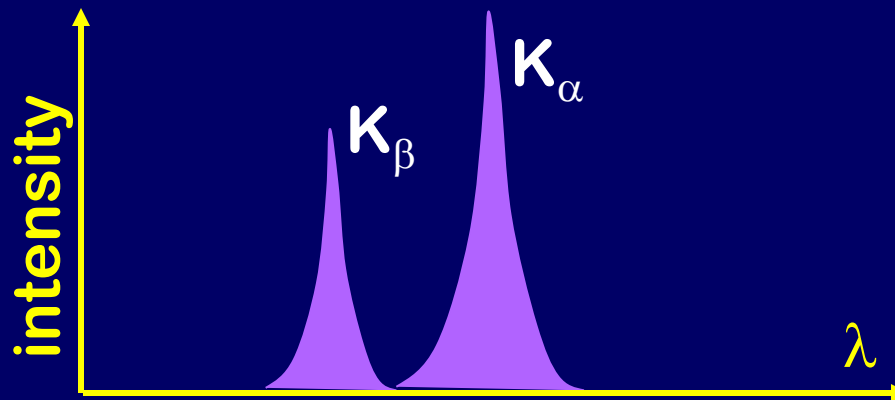
K_β X-Rays

K_α X-rays come from $n=2 \rightarrow n=1$ transition.

What about $n=3 \rightarrow n=1$ transition?

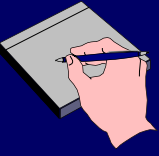
Not as likely, but possible. Produces K_β X-Rays!

K_β X-Rays are higher energy (lower λ) than K_α .
(and lower intensity)

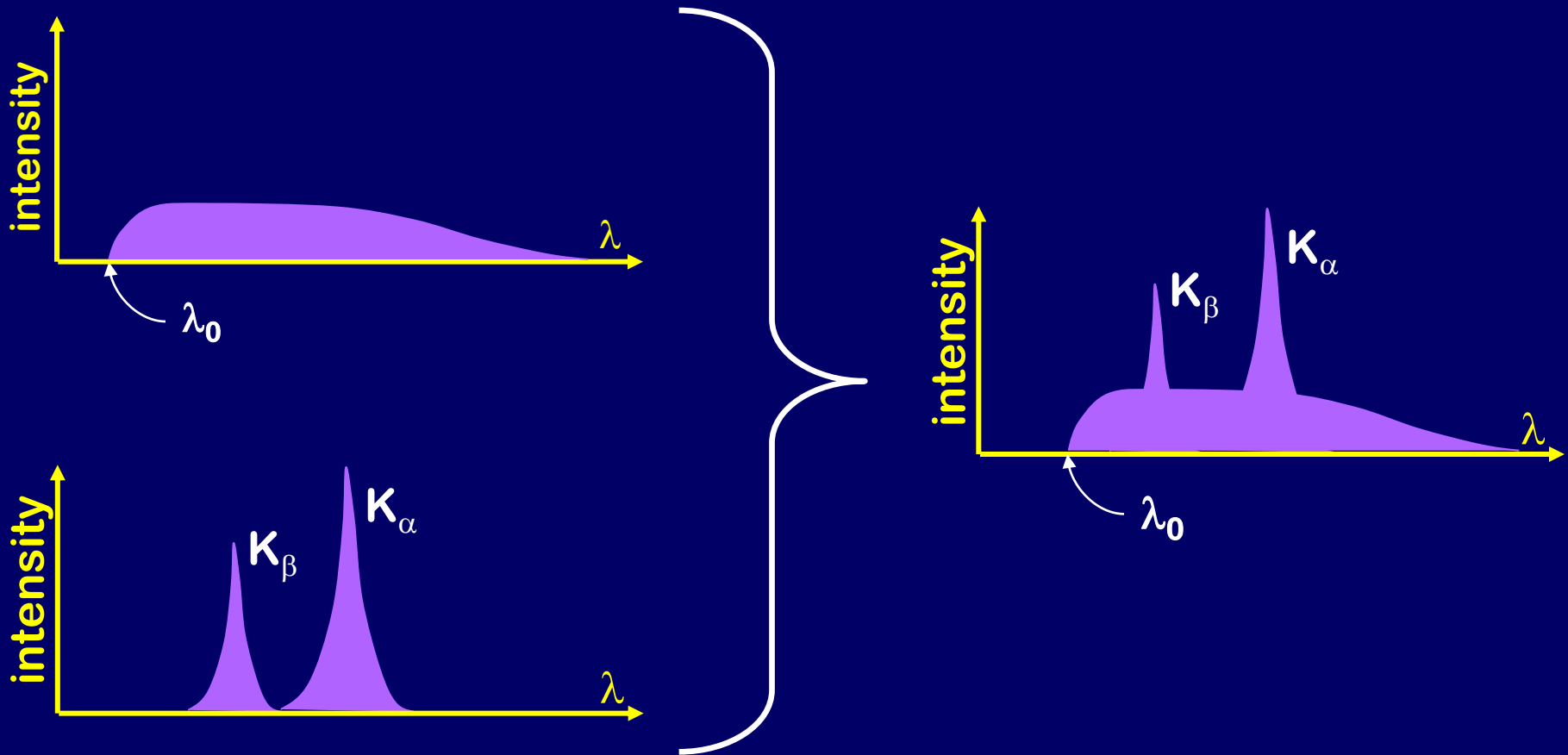


Different elements have different Characteristic X-Rays

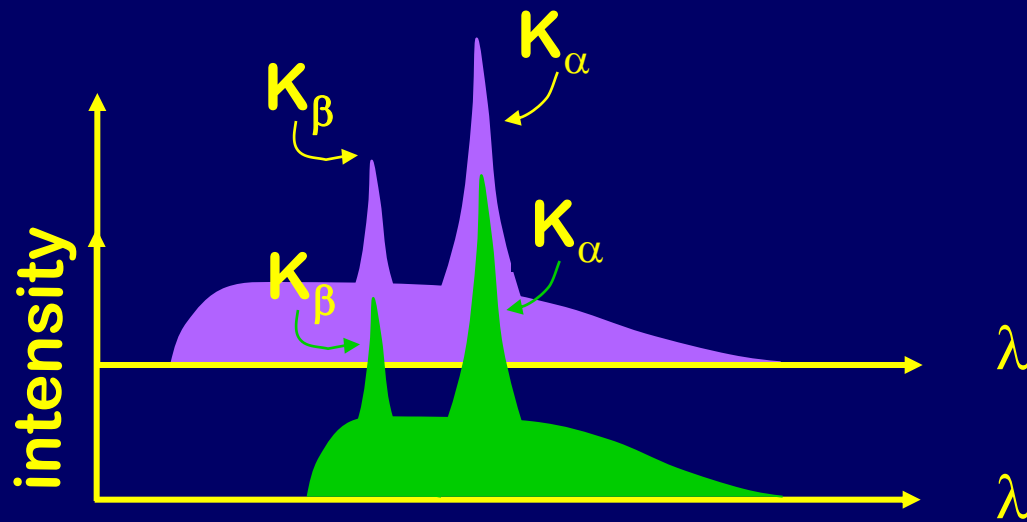
All Together Now...



Bremsstrahlung **X-Rays** and Characteristic **X-Rays** both occur at the same time.



Checkpoint 1

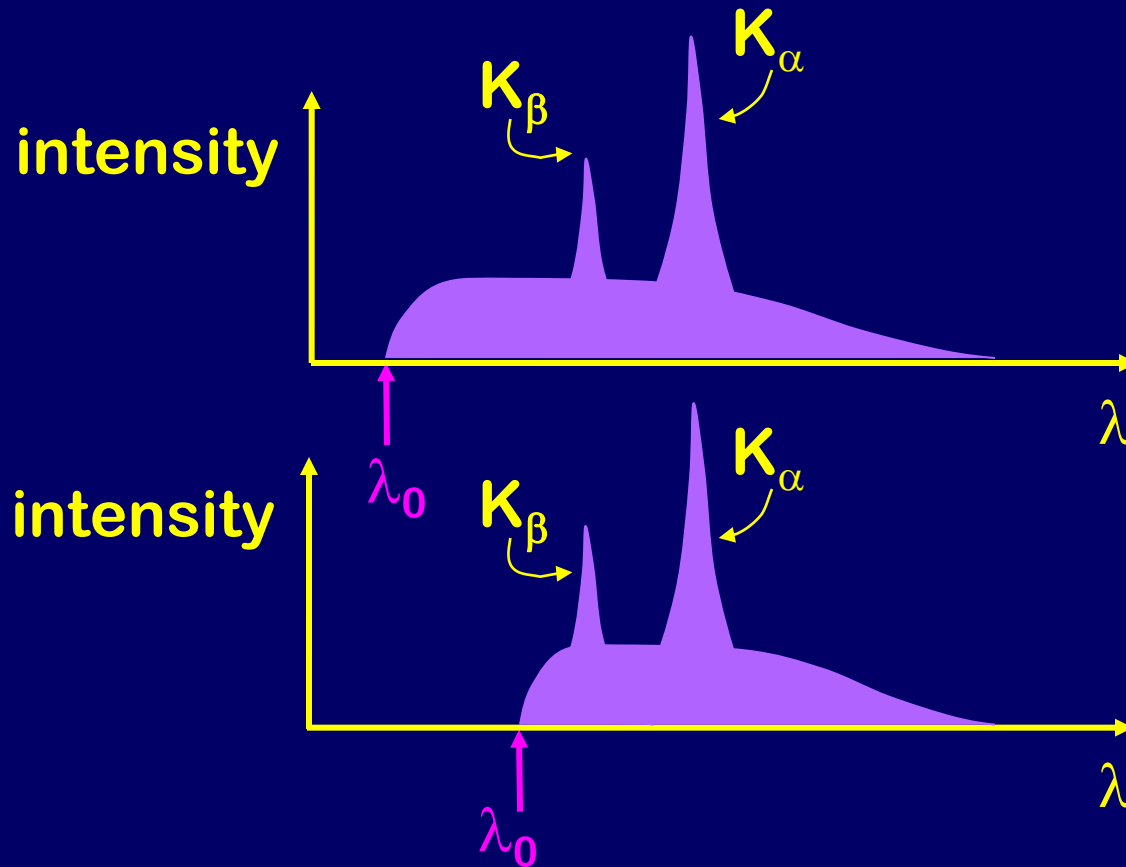


These two plots correspond to X-Ray tubes that:

- (1) Are operating at different voltages
- (2) Contain different elements
- (3) Both
- (4) Neither



ACT: X-Rays I



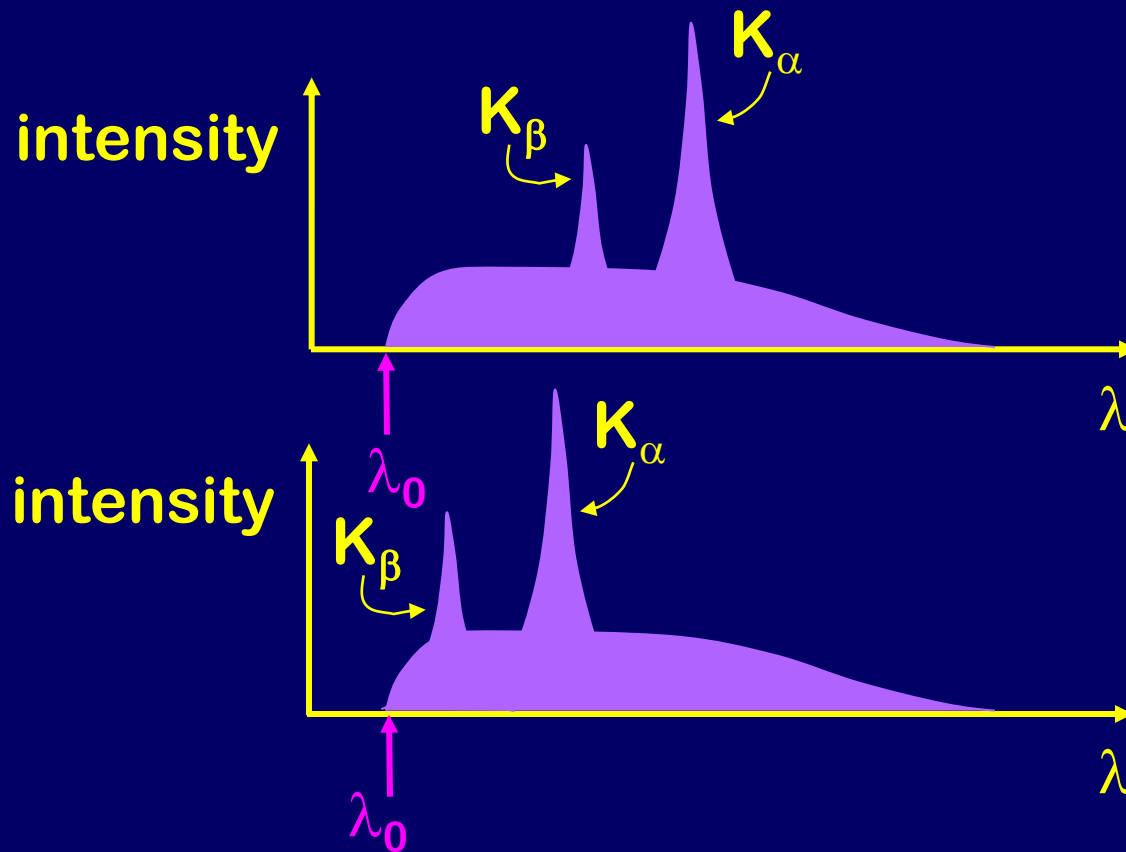
Which graph corresponds to the tube being operated at the higher voltage?

1) Top

2) Bottom



ACT: X-Rays II



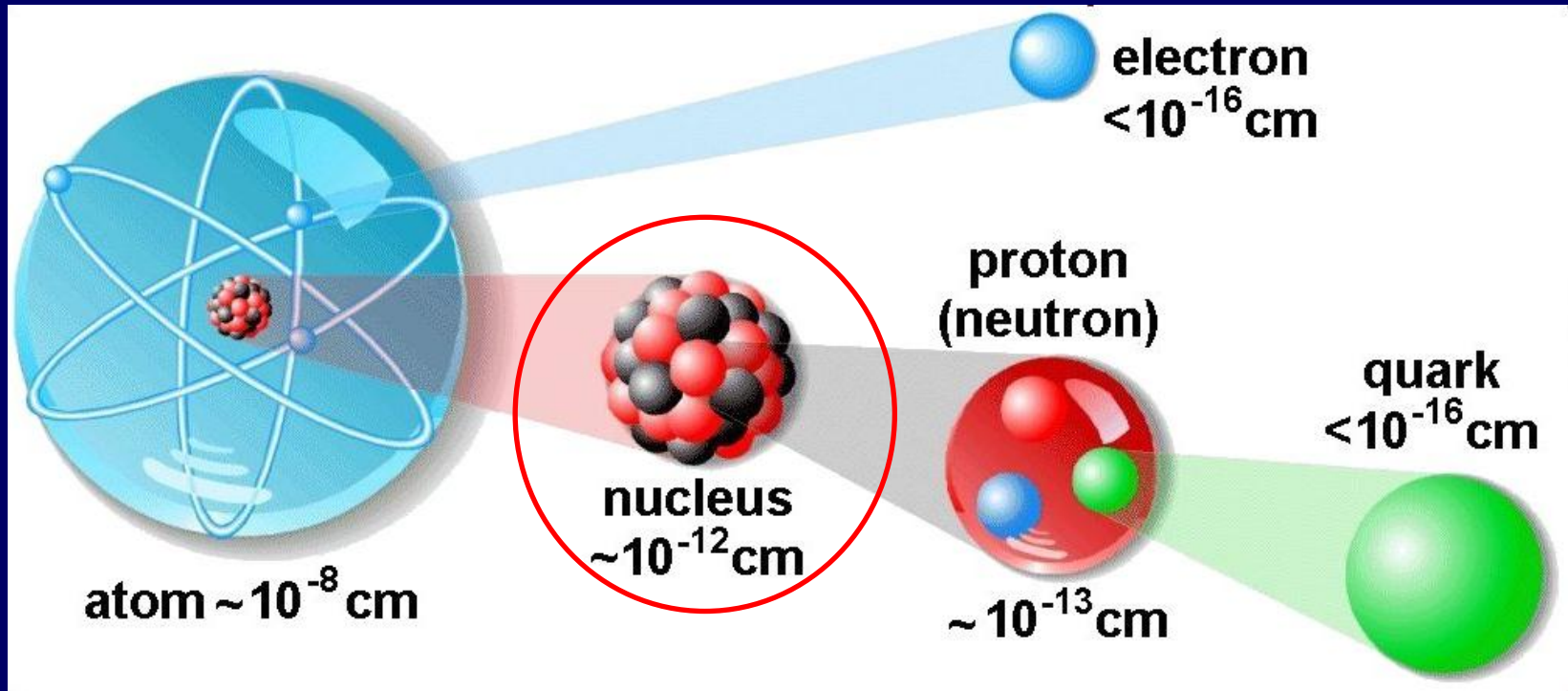
The top spectrum comes from a tube with a silver target (Ag, $Z=47$). What is the bottom target?

1) Pd, $Z=46$

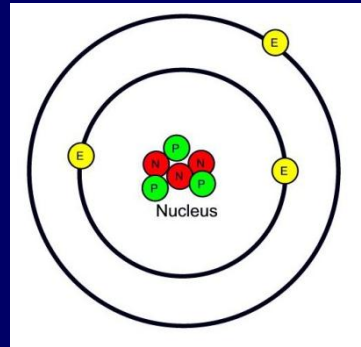
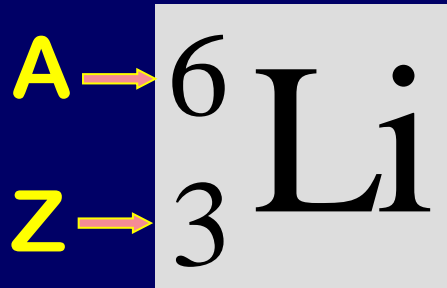
2) Ag, $Z=47$

3) Cd, $Z=48$

From atoms to nuclei to nucleons to quarks: The hierarchy of sizes



Nuclear Physics



Nucleus = Protons + Neutrons
nucleons

Z = proton number (“atomic number”)

Gives chemical properties (and name)

N = neutron number (different “isotopes”)

A = nucleon number (atomic mass number)

Gives you mass density of element

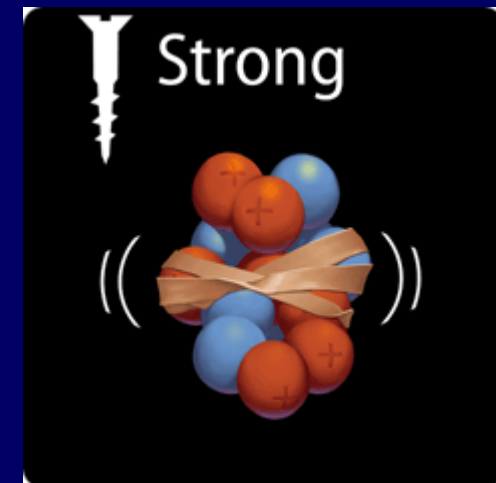
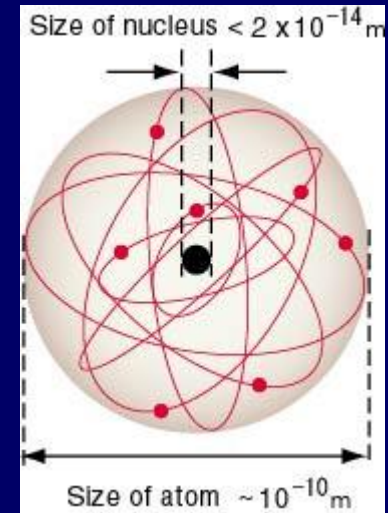
$\rightarrow A = N + Z$

Strong Nuclear Force

- Rutherford experiment shows that all the positive charge is contained in a small nucleus
 - Size \sim few $\times 10^{-15}$ m (few fm)
- Estimate EPE of two protons separated by 1 fm

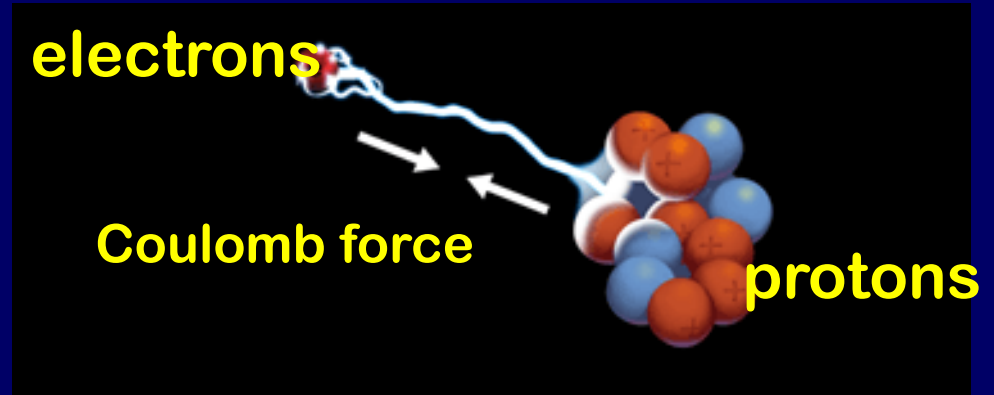
$$\begin{aligned}\text{EPE} &= kq^2/r \\ &= (9 \times 10^9)(1.6 \times 10^{-19})^2/10^{-15} \\ &= 2.3 \times 10^{-13} \text{ J} \\ &= 1.44 \times 10^6 \text{ eV} = 1.44 \text{ MeV}\end{aligned}$$

- The force that binds protons and neutrons together to form a nucleus must be very strong in order to overcome Coulomb repulsion!
- But the force acts over very short distances—of order few fm: force between atoms insignificant

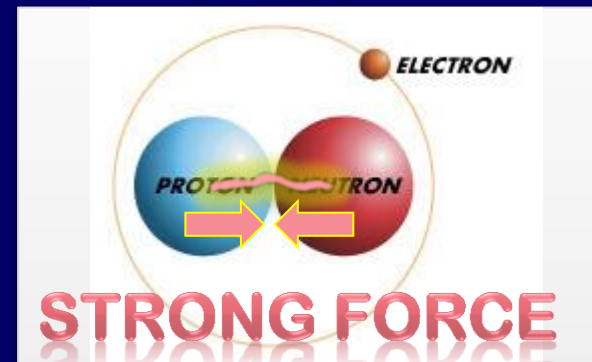


Strong Nuclear Force

Hydrogen atom:
Binding energy
= 13.6 eV (electron to nucleus)



Simplest Nucleus:
Deuteron = neutron + proton
(nucleus of deuterium, isotope of H)

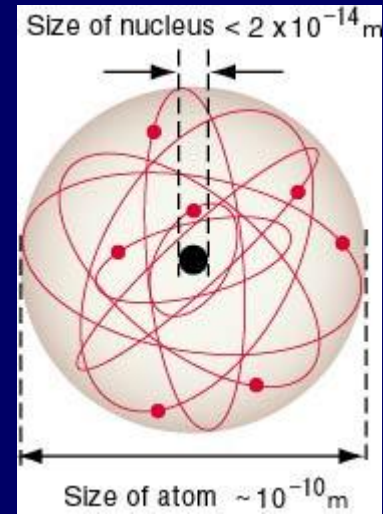


Binding energy of deuteron = $2.2 \times 10^6 \text{ eV}$ or 2.2 MeV ! That's around 200,000 times bigger!

Smaller is Bigger!

Comparing Nuclear and Atomic sizes

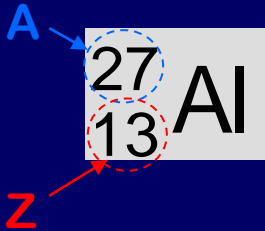
Hydrogen Atom: Bohr radius $5.29 \times 10^{-11} \text{ m}$



Nucleus with nucleon number $r \approx A^{1/3} \cdot (1.2 \times 10^{-15} \text{ m})$

A:

Example



has radius $r \approx 3.6 \times 10^{-15} \text{ m}$

Note the **TREMENDOUS** difference

Nucleus is 10^4 times smaller
and binding energy is 10^5 times larger!