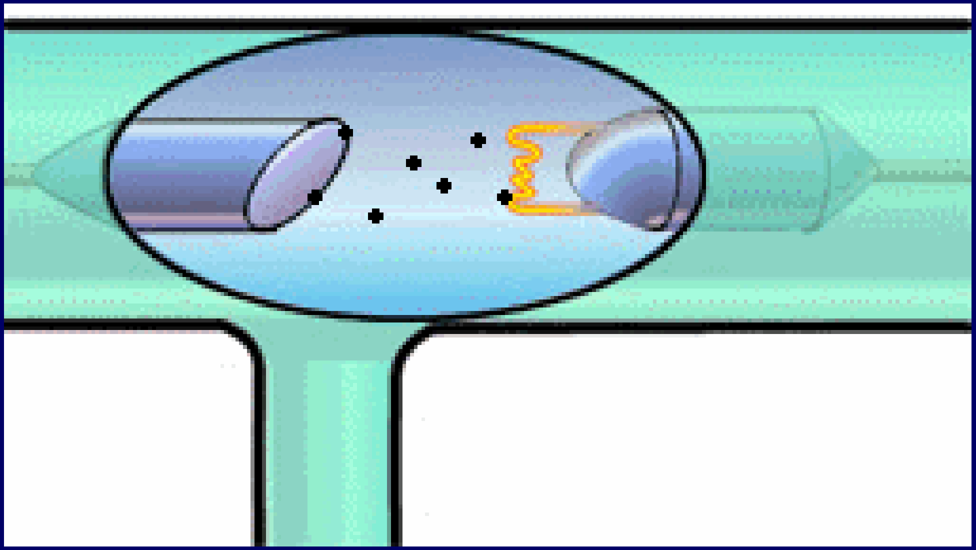
Physics 102: Lecture 26

X-rays



End-of-semester info

- Final exam info:
  - A1: Thursday, May 15, 1:30-4:30pm
  - A2: Friday, May 9, 1:30-4:30pm
  - Approximately 50 questions
  - Cumulative (all material from semester covered evenly)
  - Problems from text for material after exam 3
    - CH 26 P13, 15
    - CH 27 P1,9,17,19,35,39,45,49
    - CH 28 P35,37,43
    - CH 19 Concept 1,2 P35,37
- CHECK GRADEBOOK!

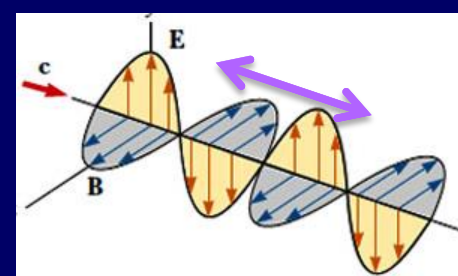
X-Rays

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?

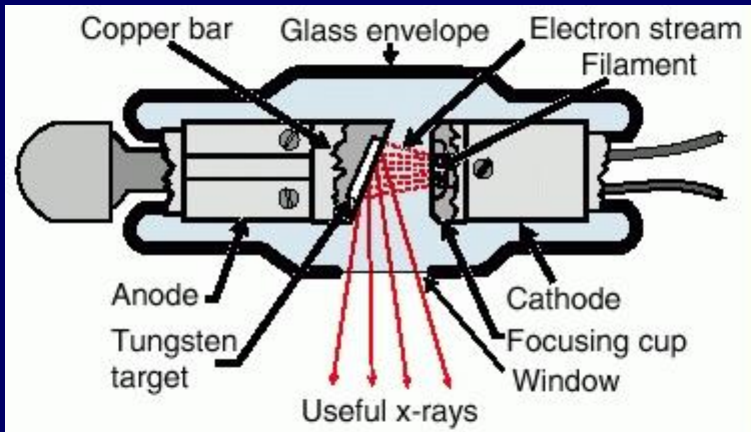


$$\lambda = \frac{hc}{E} = \frac{1240\ \text{eV}\cdot\text{nm}}{E}$$

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

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

From Electrons to X-Rays

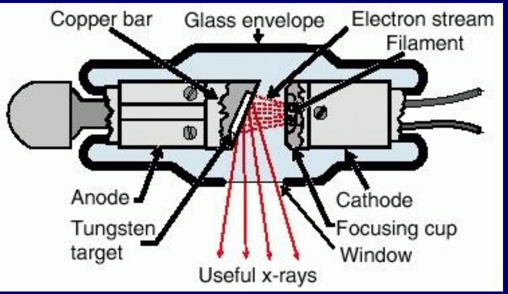


- **Take high energy electrons and slam them into a target (any heavy element, usually tungsten)**

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: $\boxed{EPE = V\,q}$

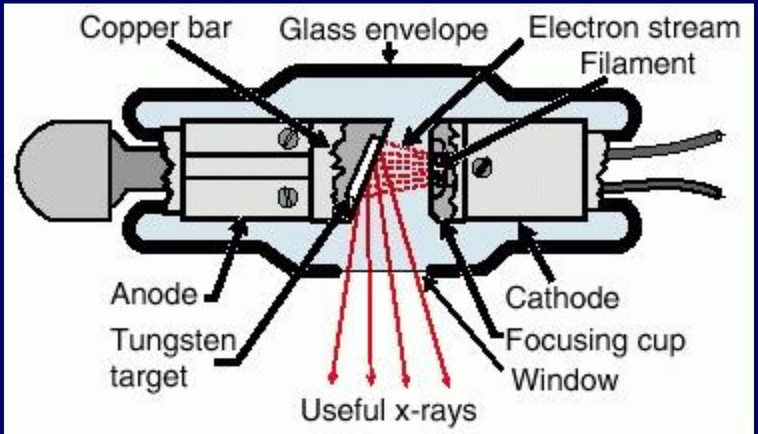
$$KE = EPE = (70{,}000\ V)\ (1\ e^-) = 70{,}000\ eV$$

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

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

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

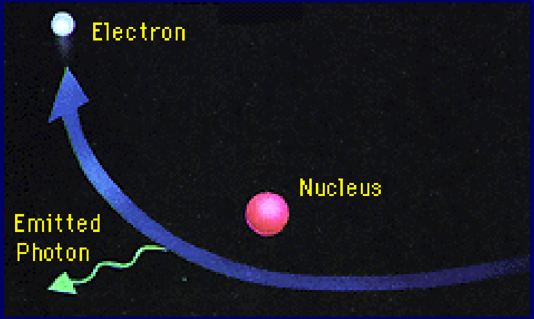
From Electrons to X-Rays



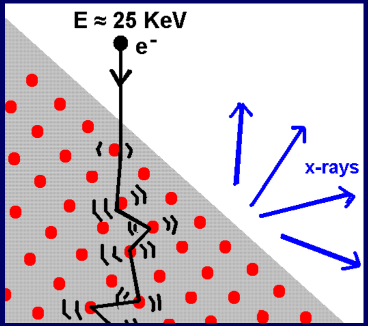
- **Take high energy electrons and slam them into a target (any heavy element, usually tungsten)**
- **2 kinds of X-Rays are produced:**
  - **"Bremsstrahlung"**
  - **"Characteristic"**

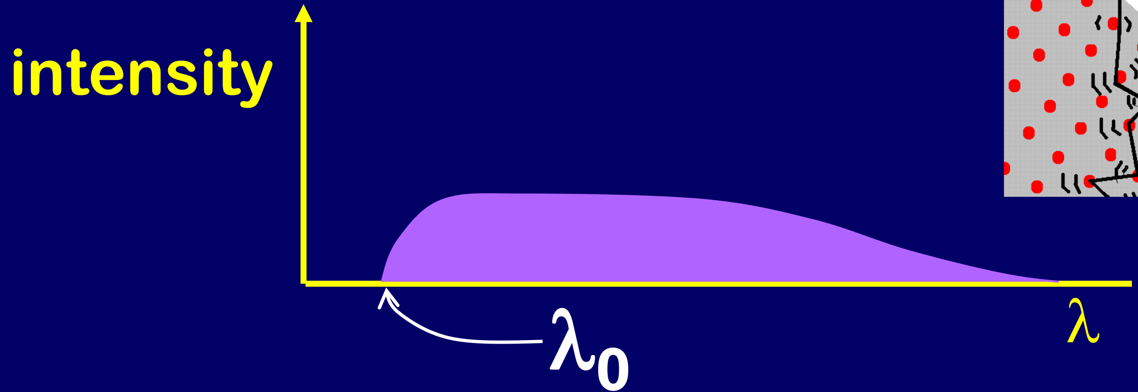
Bremsstrahlung X-Rays

- **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.**

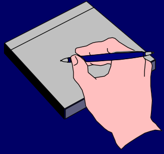




- **If all of electron's energy is lost to a single photon, photon has maximum energy (minimum wavelength).**
  - **Minimum X-Ray wavelength = λ_o.**

Example

Bremsstrahlung Practice

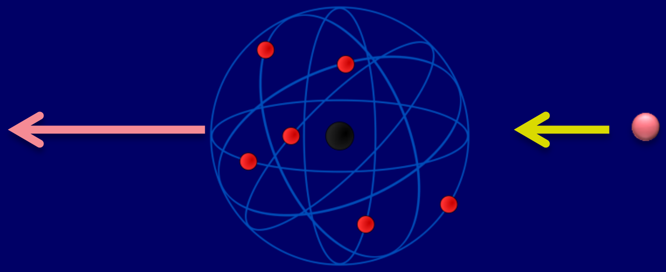


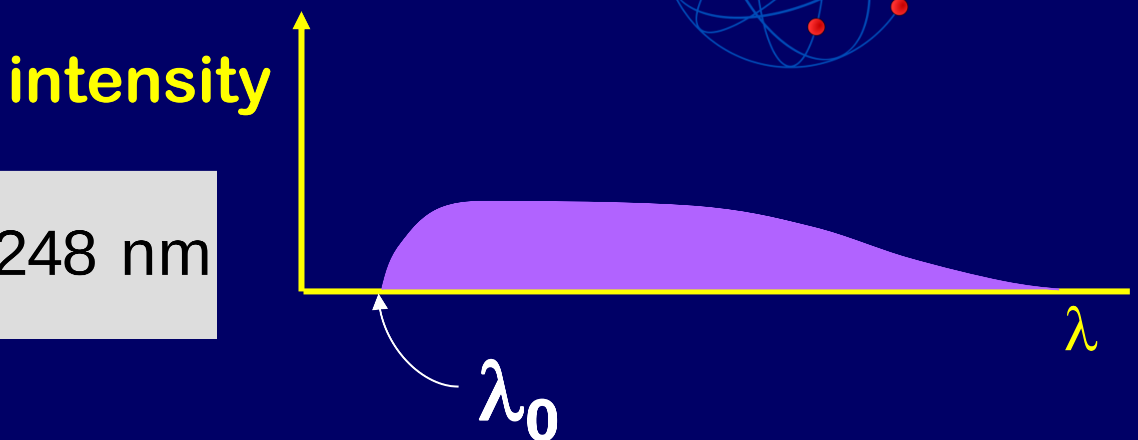
An electron is accelerated through 50,000 volts

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.

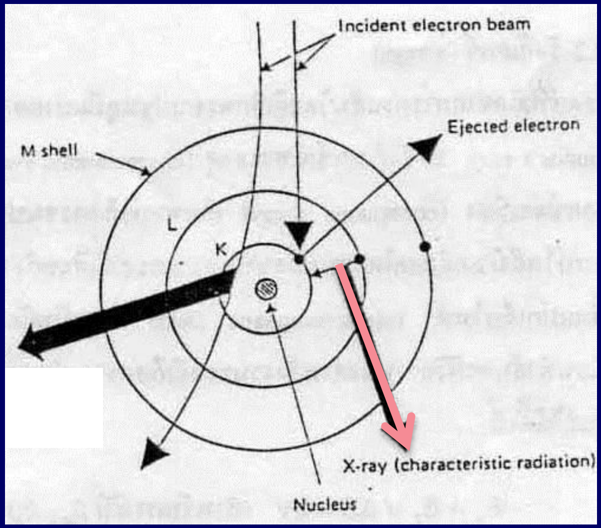




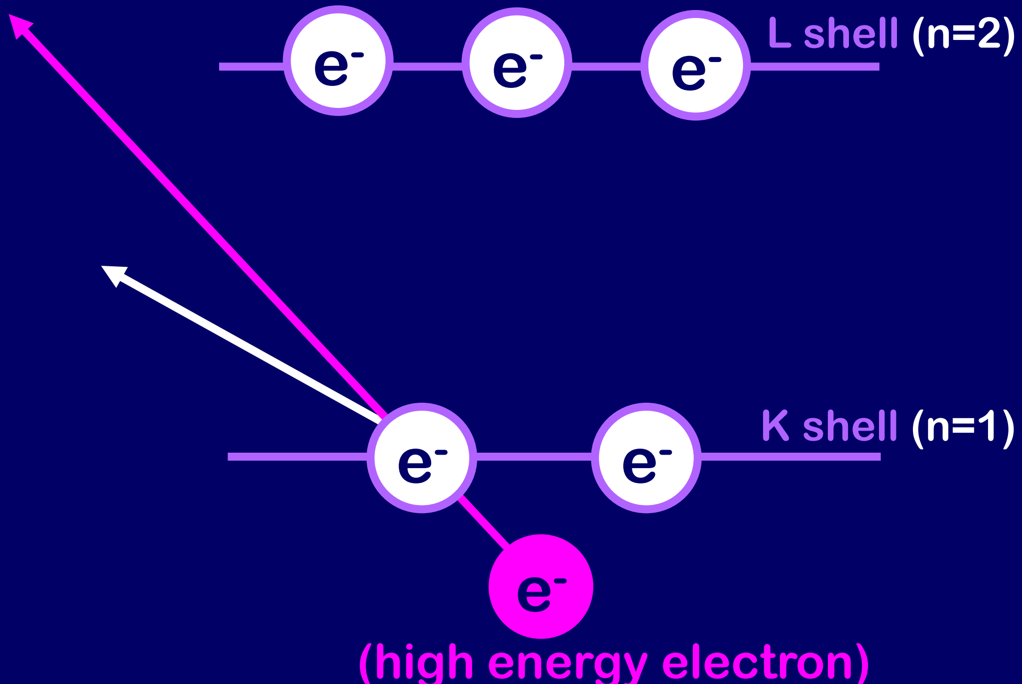
$$\lambda_0 = \frac{hc}{E} = \frac{1240}{50,000} = .0248 \text{ nm}$$

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"

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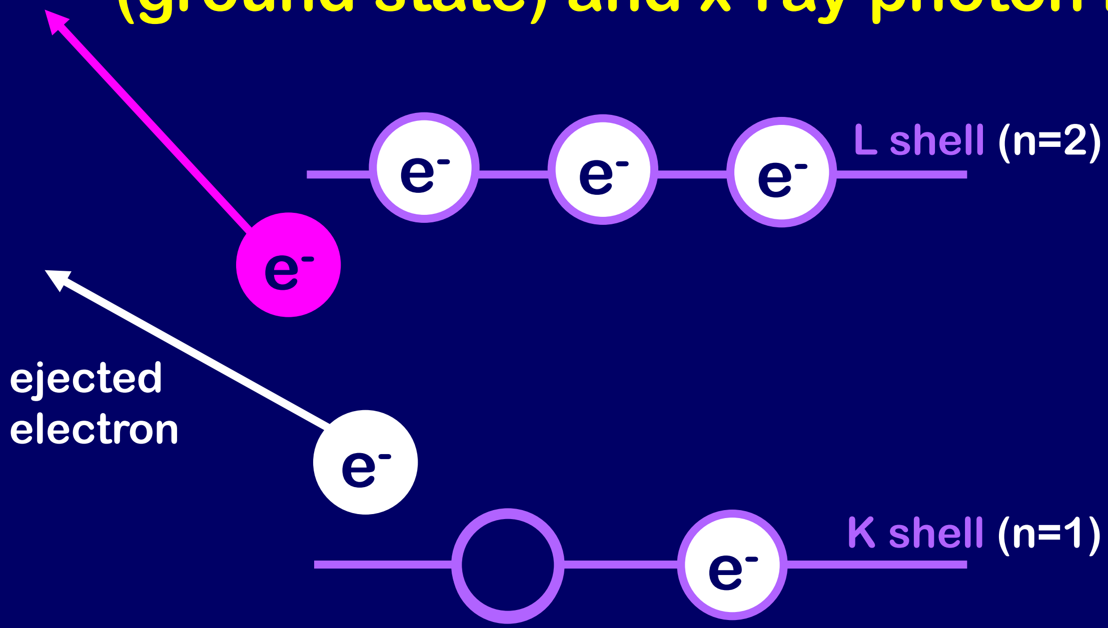

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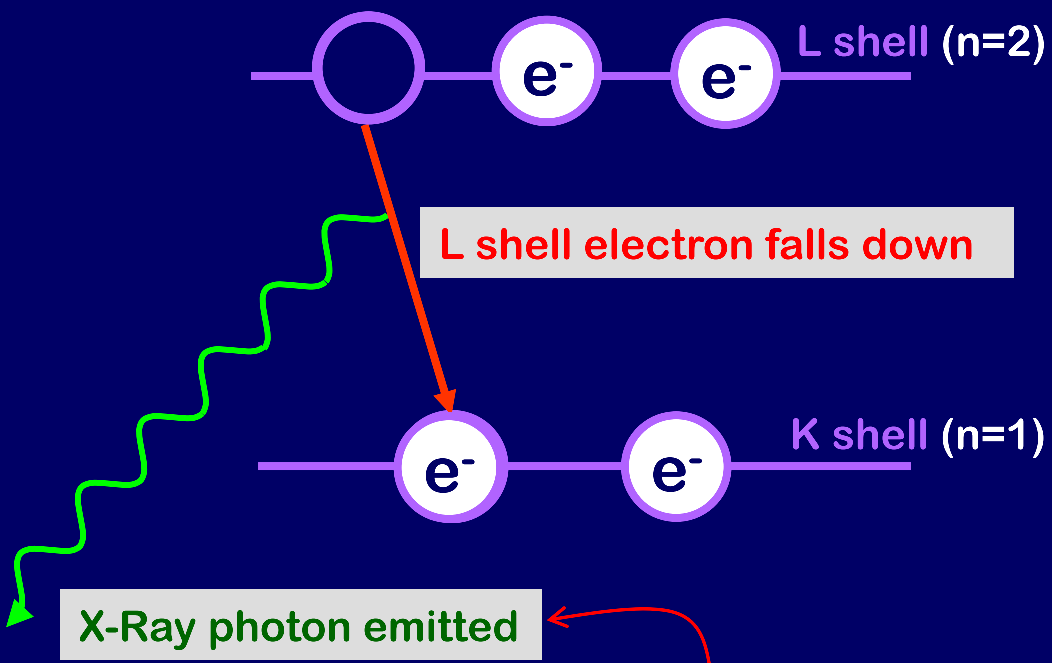


Characteristic x-ray nomenclature

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

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

Example

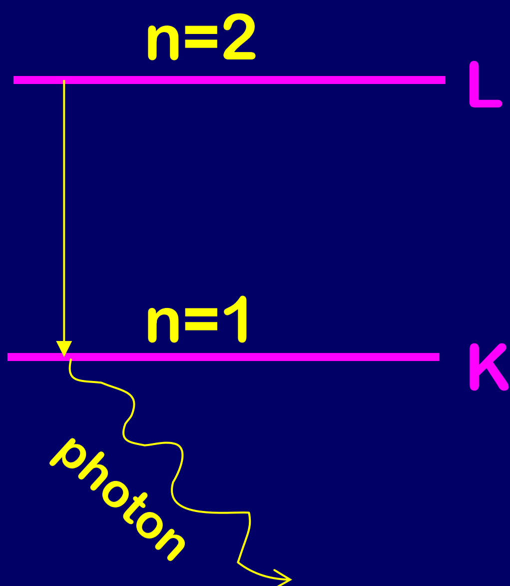
K_α X-Rays

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

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

Careful! the formula assumed a *single electron* bound to just a positive nucleus.



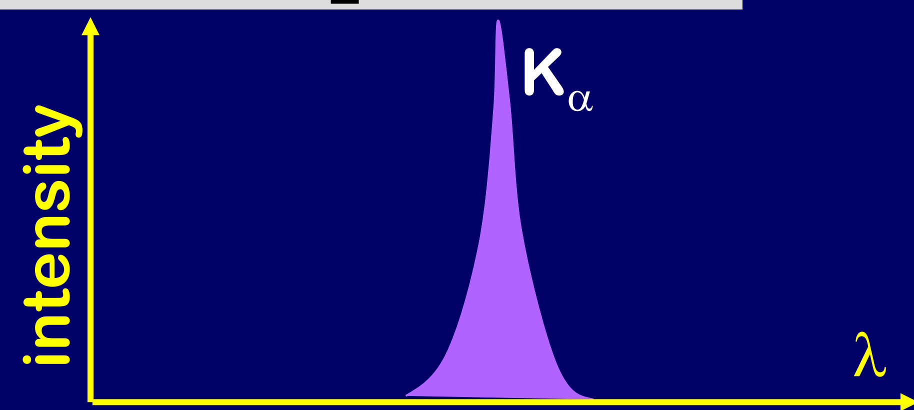
$$E_L = -13.6\text{eV}(47-1)^2\frac{1}{2^2} = -7.2\text{keV}$$

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

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

(vs. 21.7 keV Expt)

Not bad!



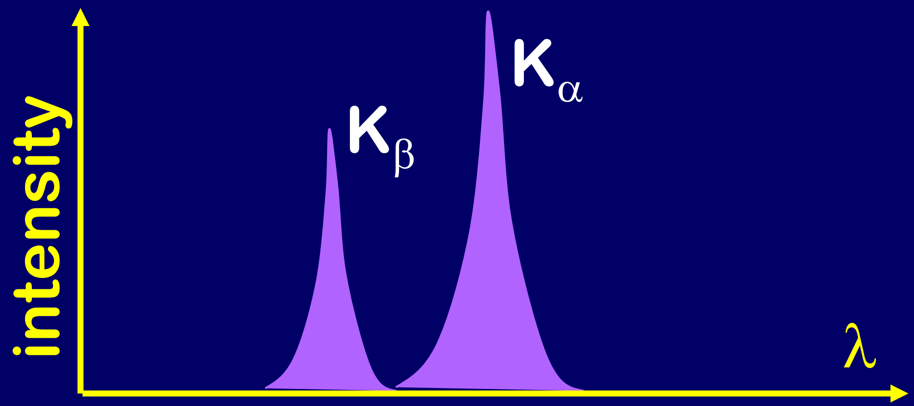
K_β X-Rays

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

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

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

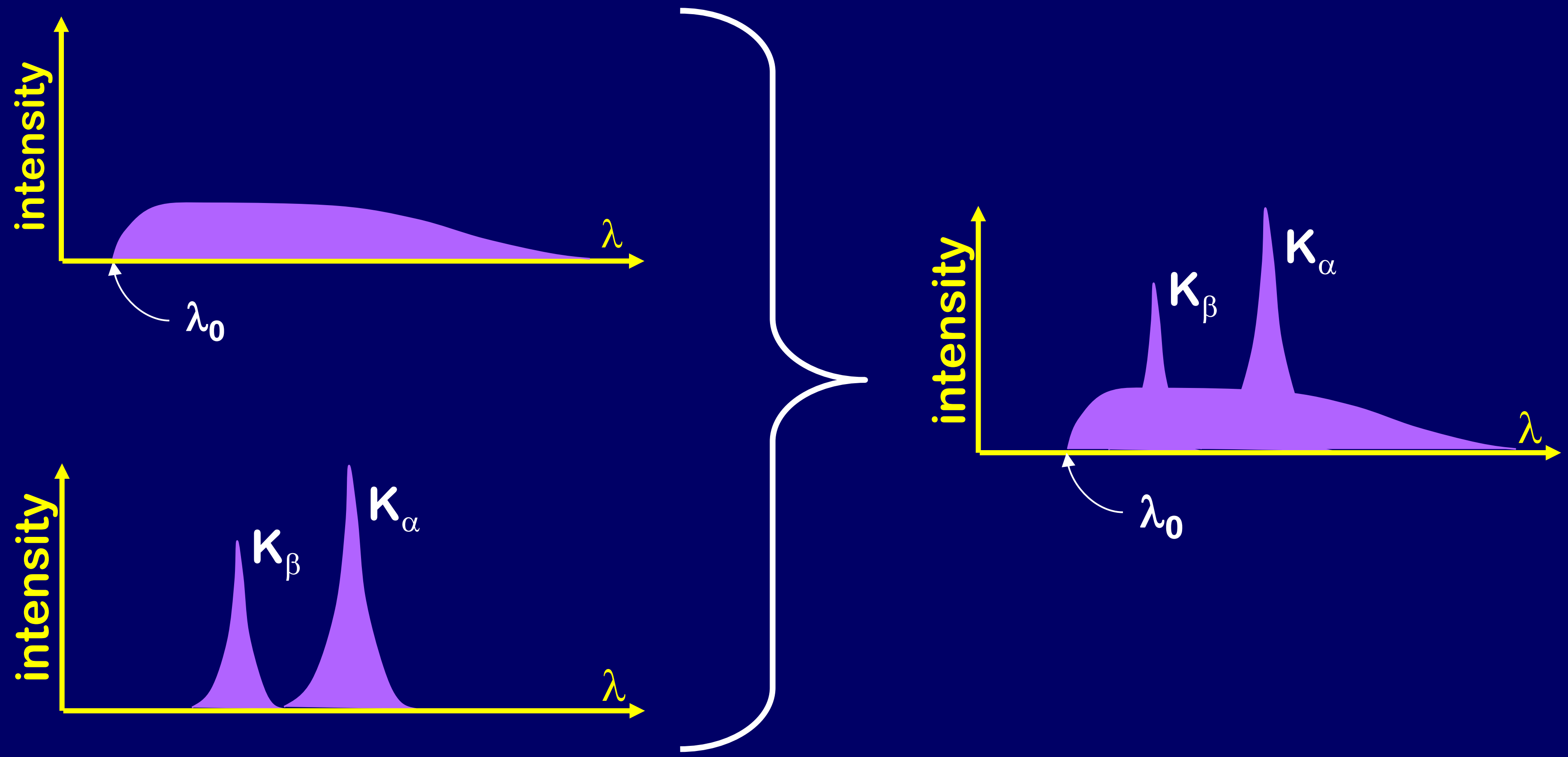
K_β X-Rays are higher energy (lower λ) than K_α.
(and lower intensity)



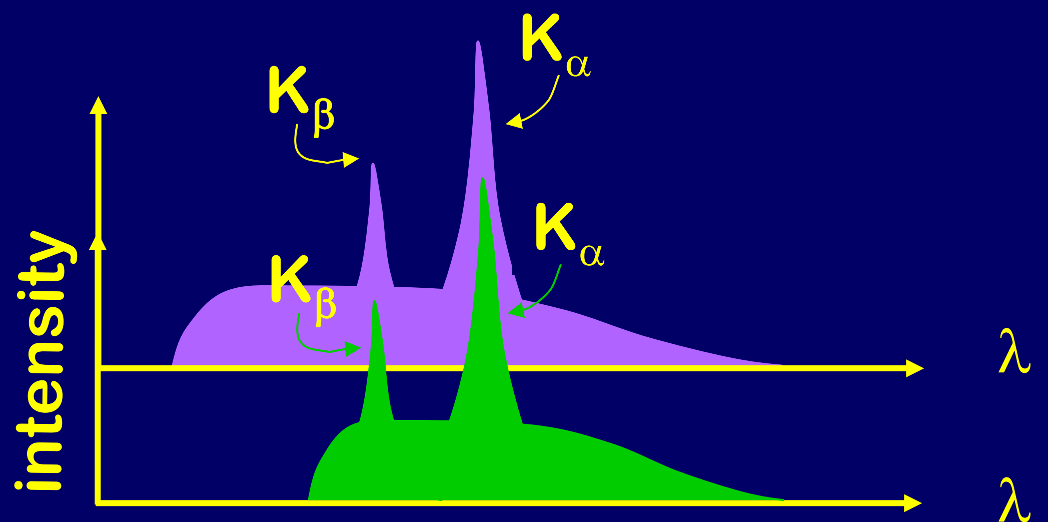
Different elements have different Characteristic X-Rays

All Together Now...

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



ACT: Checkpoint 1



These two plots correspond to X-Ray tubes that:

(A) Are operating at different voltages

(B) Contain different elements

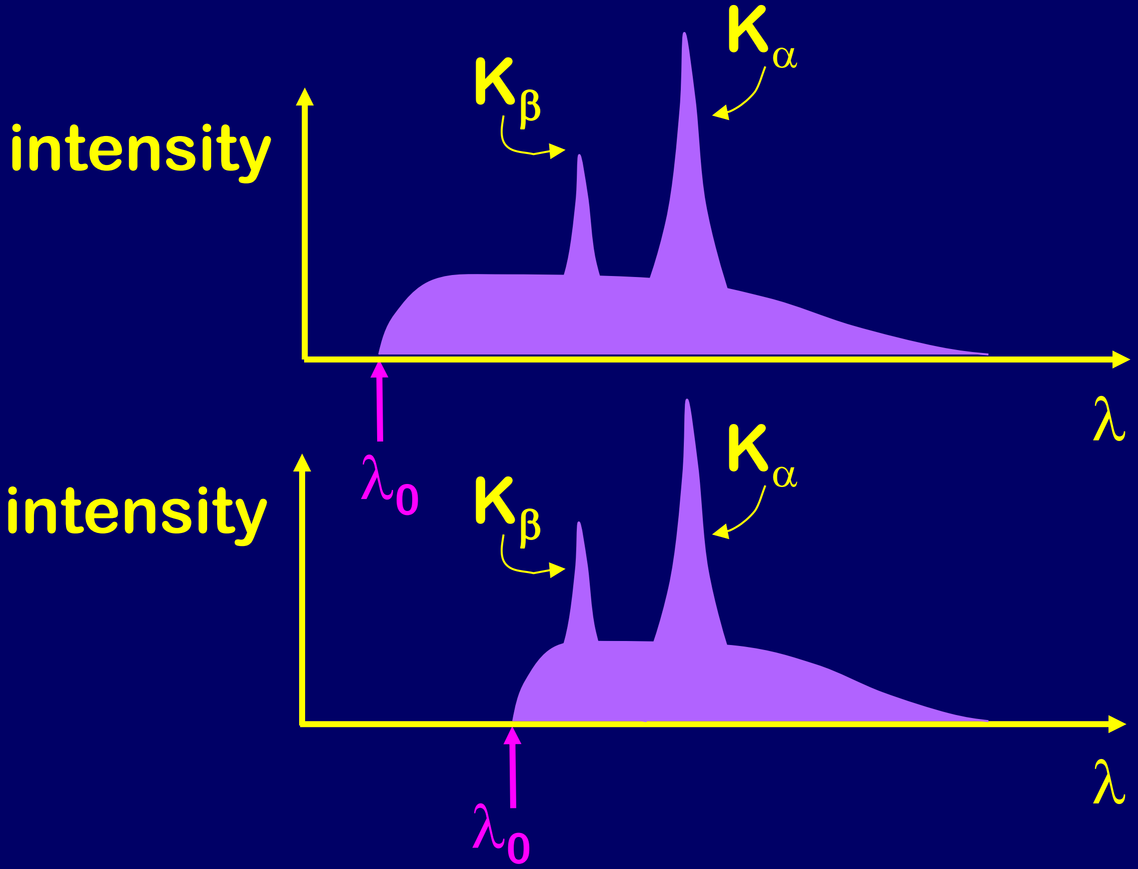
(C) Both

(D) Neither

K_α and K_β are the same

λ_o is different

ACT: X-Rays I



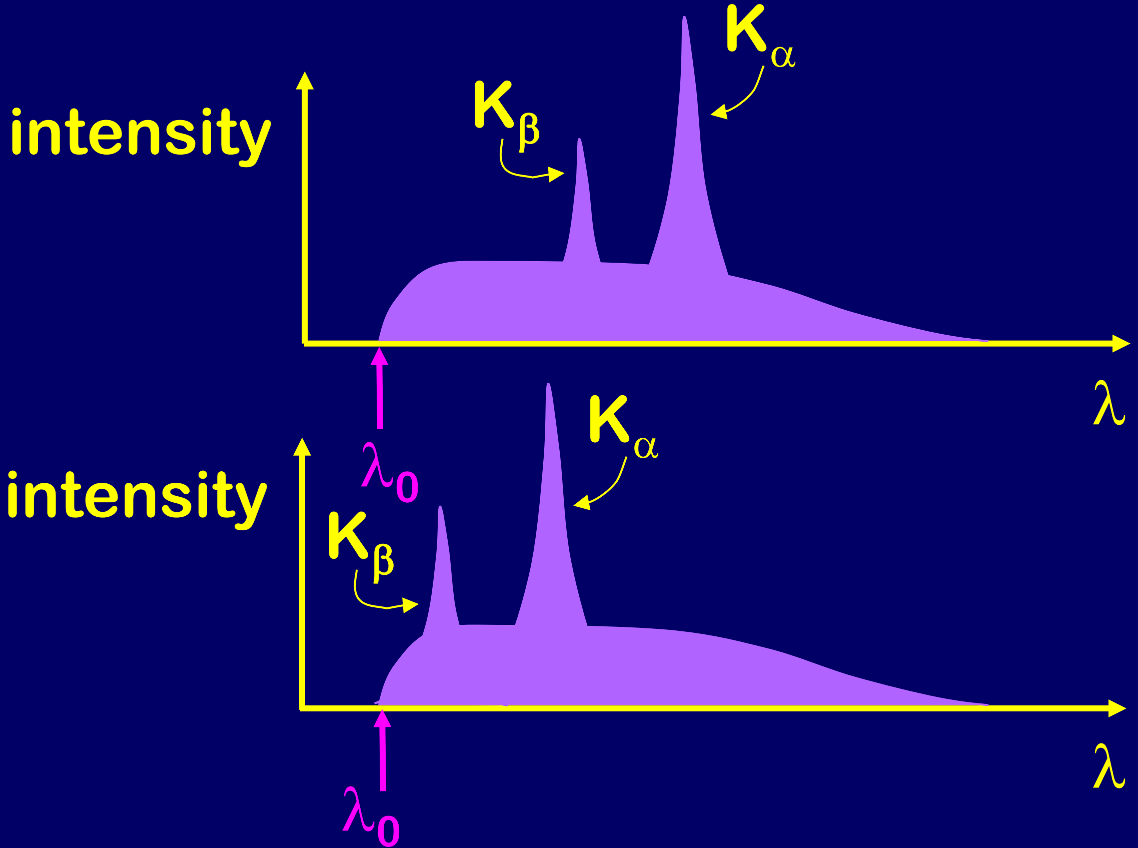
K_α and K_β are the same for each!

Higher voltage means higher energy x-ray photon can be produced, or smaller maximum wavelength, λ_0.

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

A) Top **B) Bottom**

ACT: X-Rays II



λ_o is the same for each!

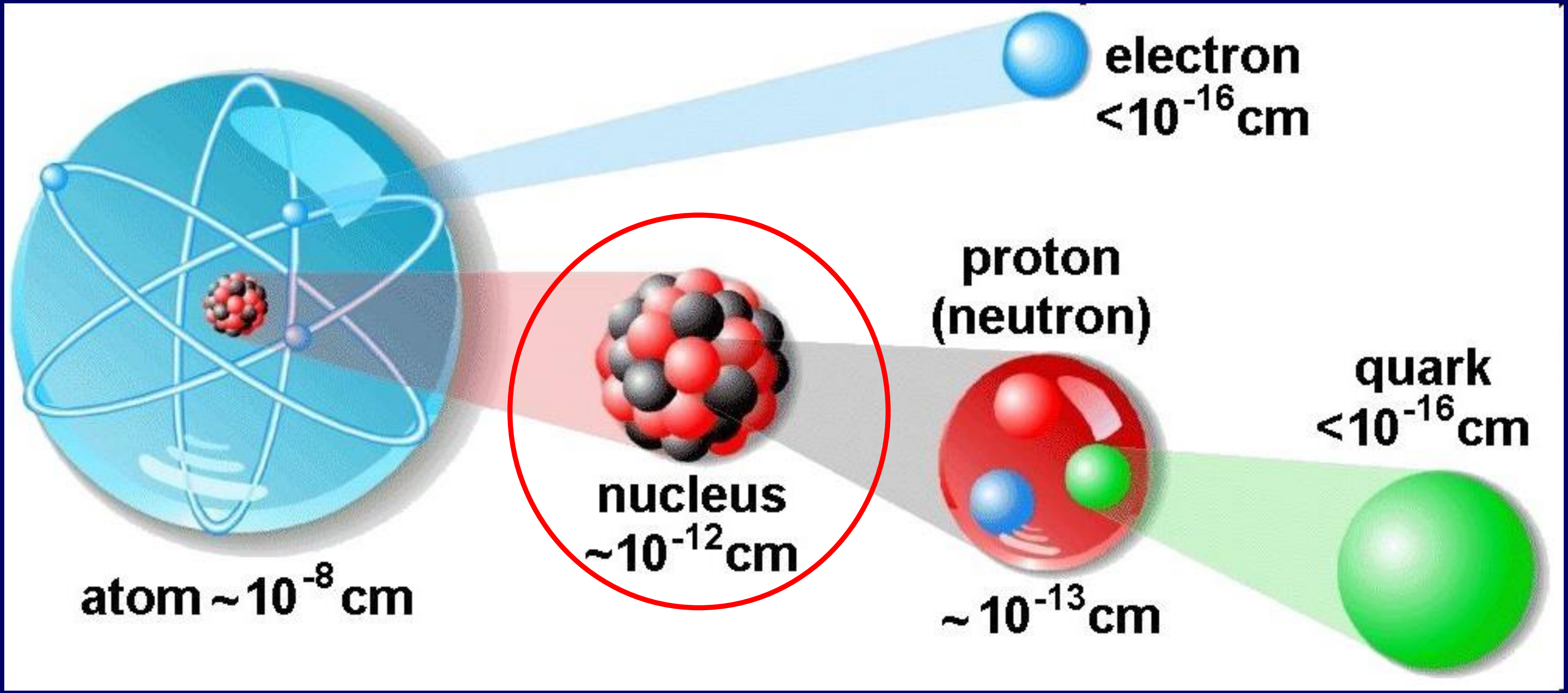
Energy of characteristic X-ray is proportional to $(Z-1)^2$.

Higher energy = higher Z

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

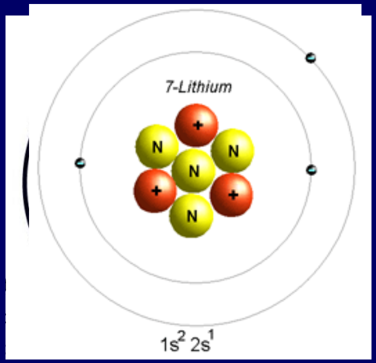
A) Pd, Z=46 B) Ag, Z=47 C) Cd, Z=48

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



Nuclear Physics

A → $^{7}_{3}\mathrm{Li}$ ← Z



Nucleus = $\underbrace{\text{Protons + Neutrons}}_{\text{nucleons}}$

Z = proton number ("atomic number")

Gives chemical properties (and name)

N = neutron number (different "isotopes")

A = nucleon number (atomic mass number)

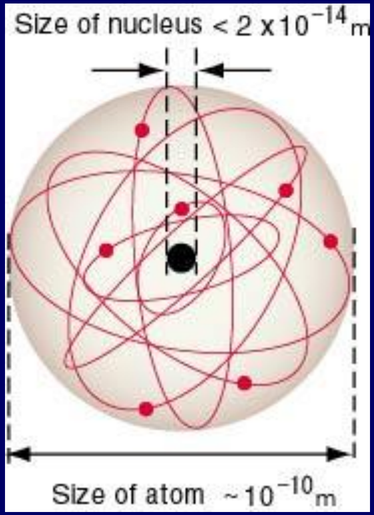
Gives you mass density of element

→ **A=N+Z**

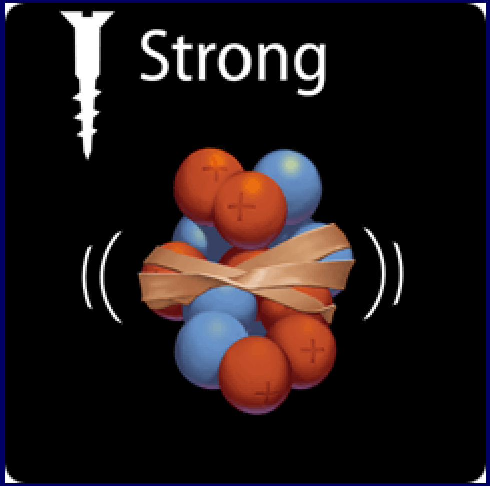
Strong Nuclear Force

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

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

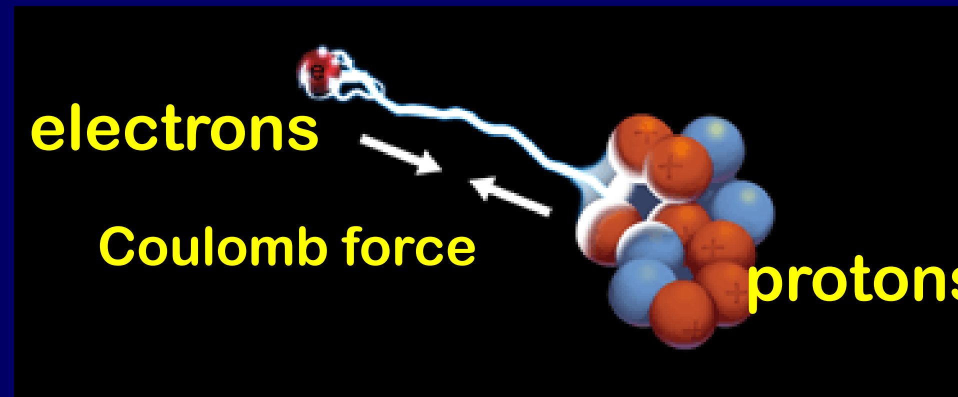


- The force that binds protons and neutrons together to form a nucleus must be very strong in order to overcome Coulomb repulsion!
- But the force acts over very short distances—of order few fm: force between atoms insignificant

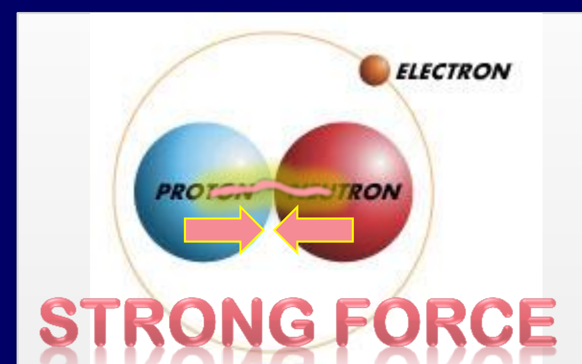


Strong Nuclear Force

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

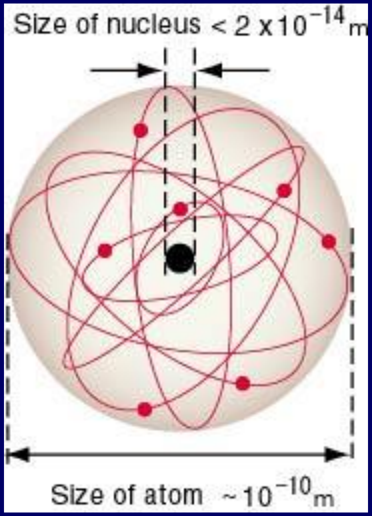


Simplest Nucleus:
Deuteron=neutron+proton
(nucleus of deuterium, isotope of H)



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

Smaller is Bigger!



Comparing Nuclear and Atomic sizes

Hydrogen Atom: Bohr radius = 5.29×10^{-11} m

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

Example

A

Z

$^{27}_{13}\text{Al}$ **has radius** $r \approx 3.6 \times 10^{-15}$ m

Note the TREMENDOUS difference

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

See you next time!