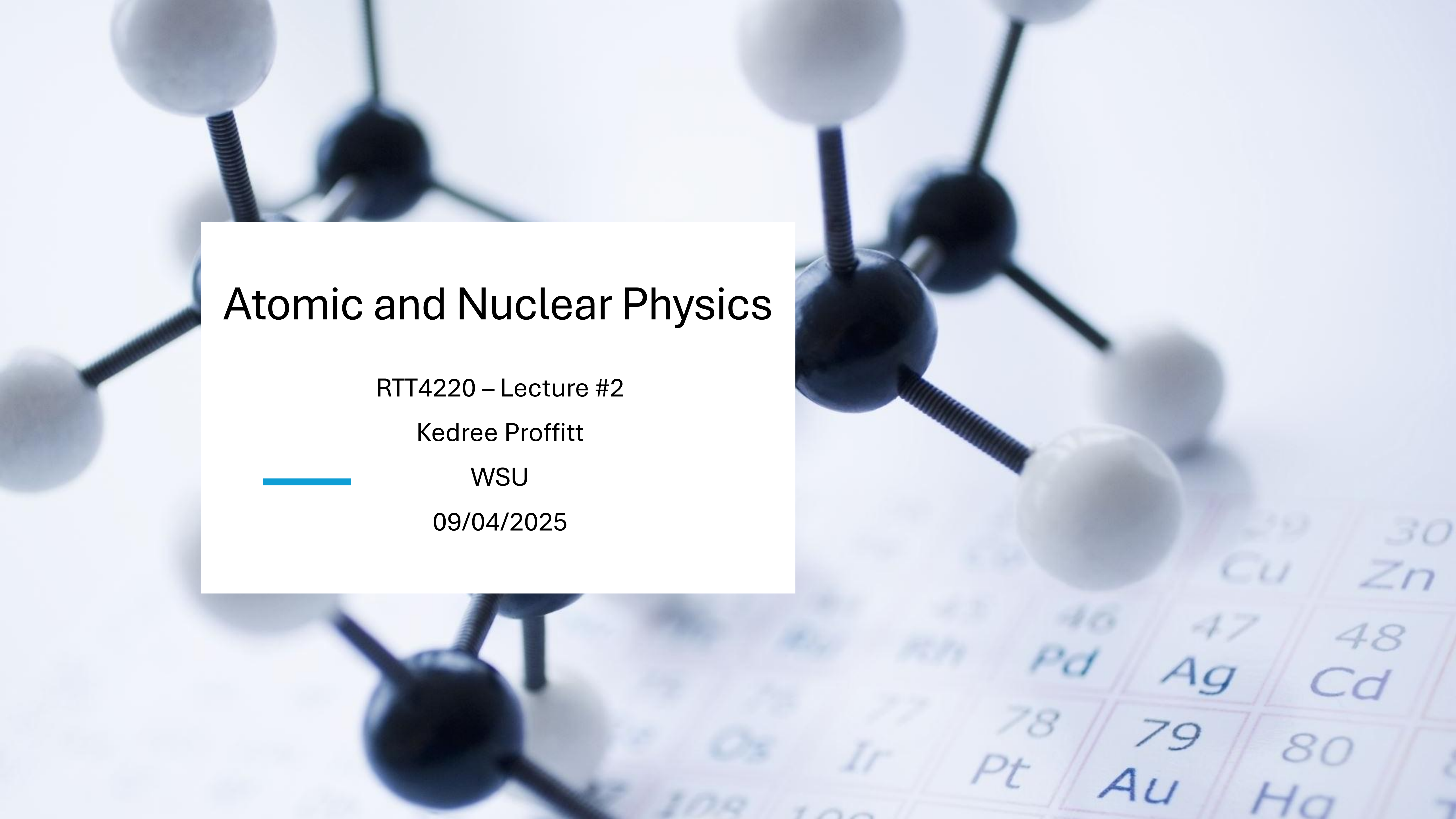


# Atomic and Nuclear Physics

RTT4220 – Lecture #2

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WSU

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# The Nucleus

How nucleating!

# Discovery of Atoms

X-rays and radioactivity discovered BEFORE Rutherford Atom Model (1895 – **Roentgen**, 1896 – **Becquerel**)

Next model says atoms consist of a nucleus of positive charge with a negative charge outside (1910 – **Rutherford**)

Under Rutherford's model the shell should collapse, Bohr's Model introduces electron SHELLS with Pauli's Exclusion Principle (1913 – **Bohr**, 1925 – **Pauli**)

Modern model says the electrons exist in wibbly wobbly timey wimey cloud

# Nuclear Composition

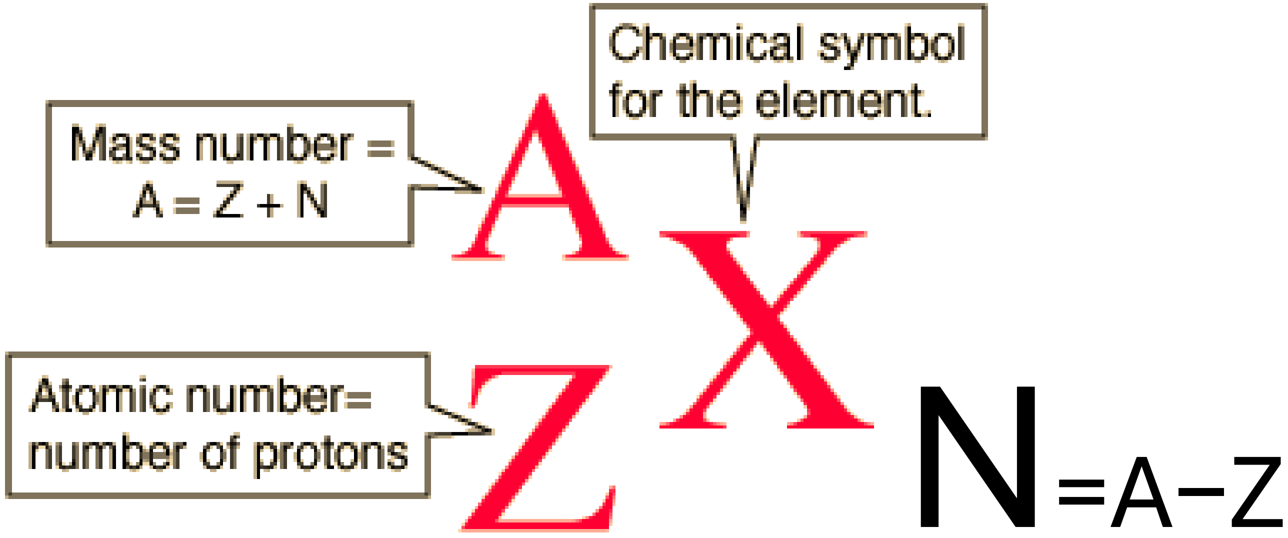
- Atoms are made of PROTONS ($P$), NEUTRONS ($N$), and ELECTRONS ($e^-$)
- Protons and neutrons are NUCLEONS
- Nuclear density is VERY HIGH, electron cloud density is VERY LOW (mostly empty, like space!)

| | | Mass | |
|---|---|---|---|
| **Particle** | **Charge*** | **u** | **MeV** |
| Proton | +1 | 1.007276 | 938.272 |
| Neutron | 0 | 1.008665 | 939.565 |
| Electron | −1 | 0.000549 | 0.511 |

*One unit of charge is equivalent to $1.602 \times 10^{-19}$ coulombs.

# Nuclear Notation

- Standard Notation shown below
- Common notation omits Z and N. In text form it looks like: Co-60 or Cobalt-60



# Nuclear Families

Isomers – Same element and # nucleons, different energy state

(Tc-99 / Tc-99m)

Isobars – Same # nucleons, different element

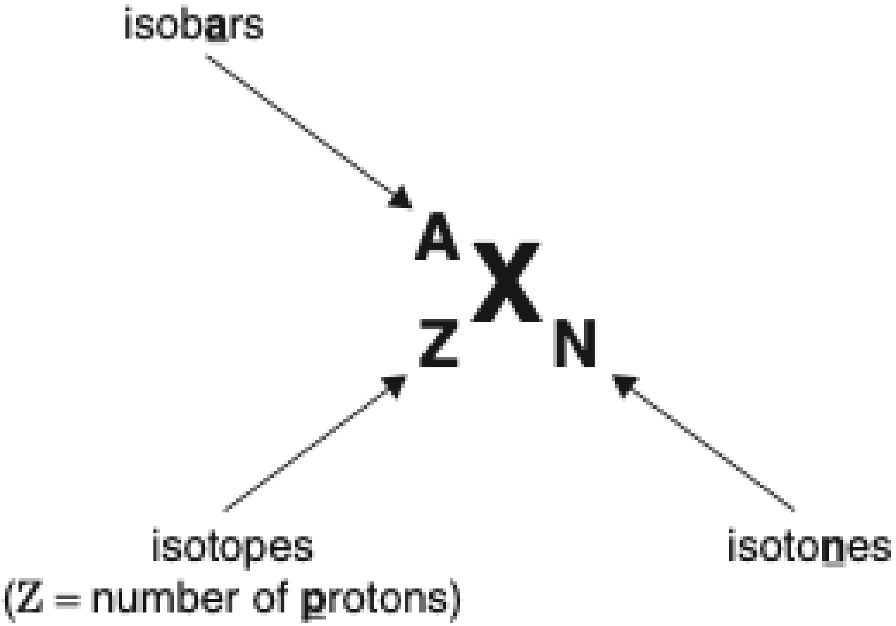
(Ca-40 / K-40)

Isotones – Same # neutrons, different element

(B-12 / C-13)

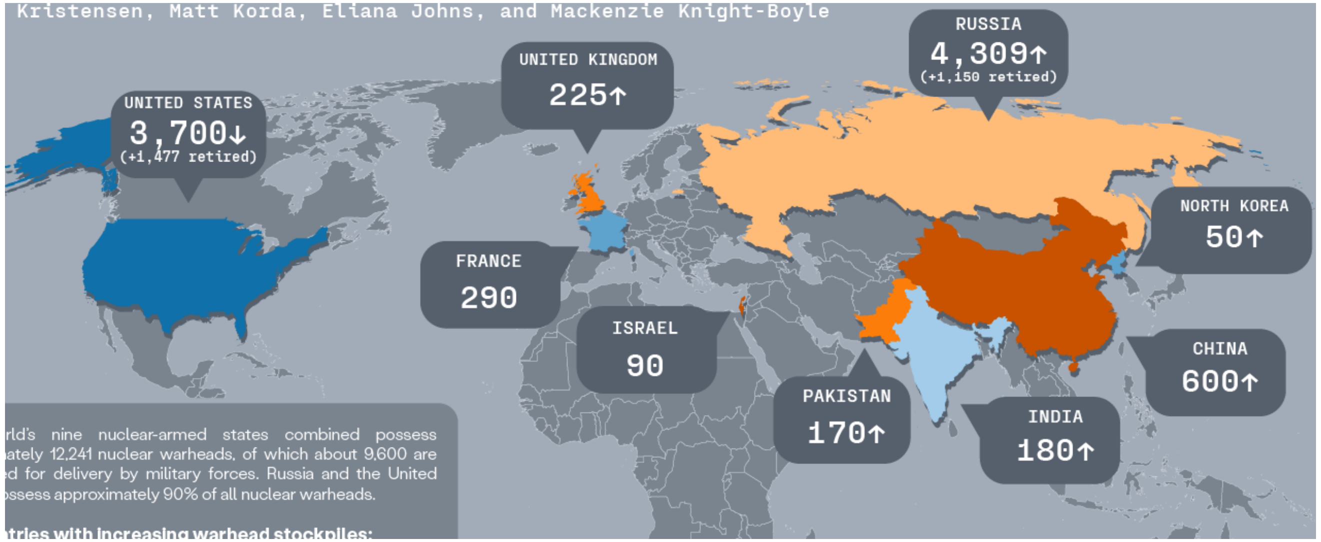
Isotopes – Same element, different # nucleons

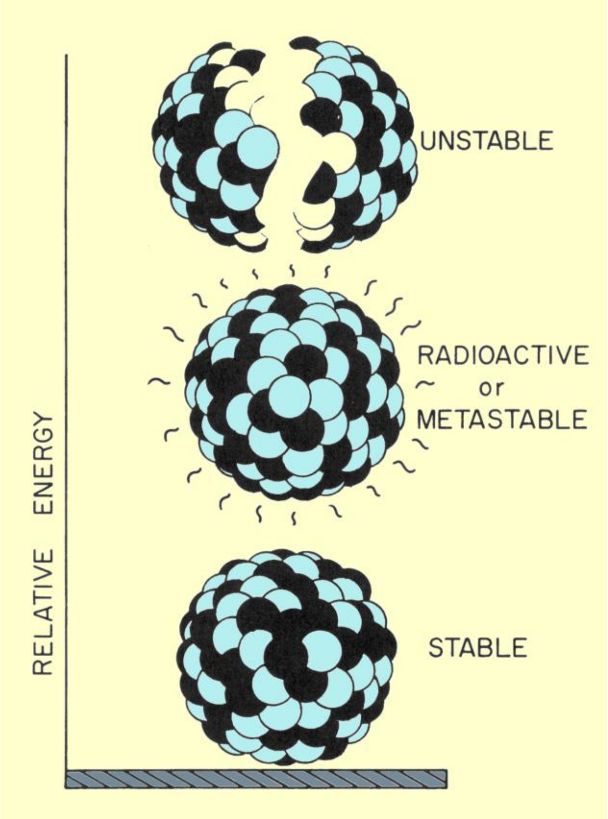
(Co-59 / Co-60)



# Nuclear States

- Three general states:
  - Stable (Ground)
  - Metastable
  - Excited
- Excited states are transitory (very short lived)
- Metastable states are longer lived (dividing line about 1 picosecond)
- Ground state is the lowest energy (most stable)
- Tc-99m is a famous metastable state

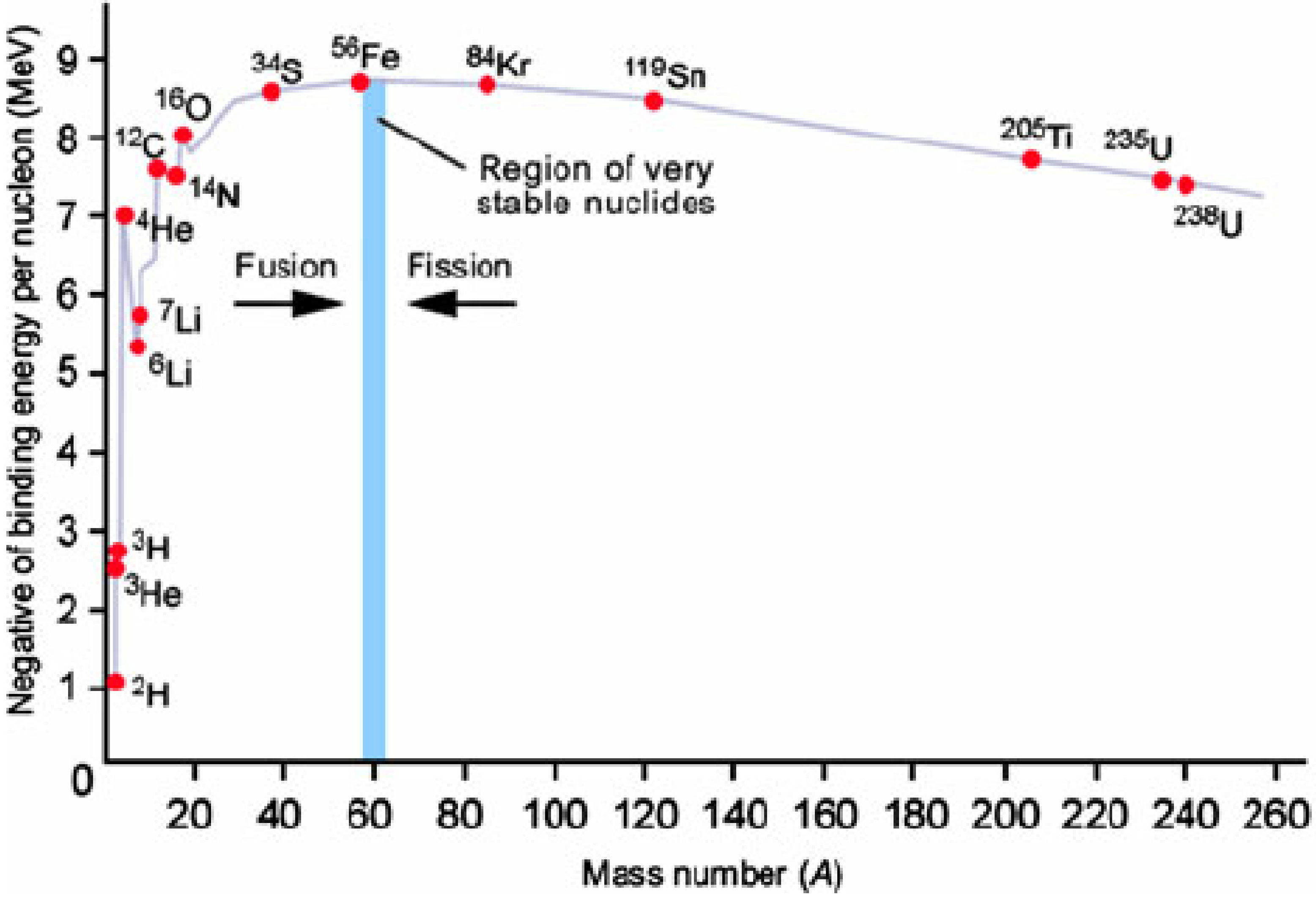


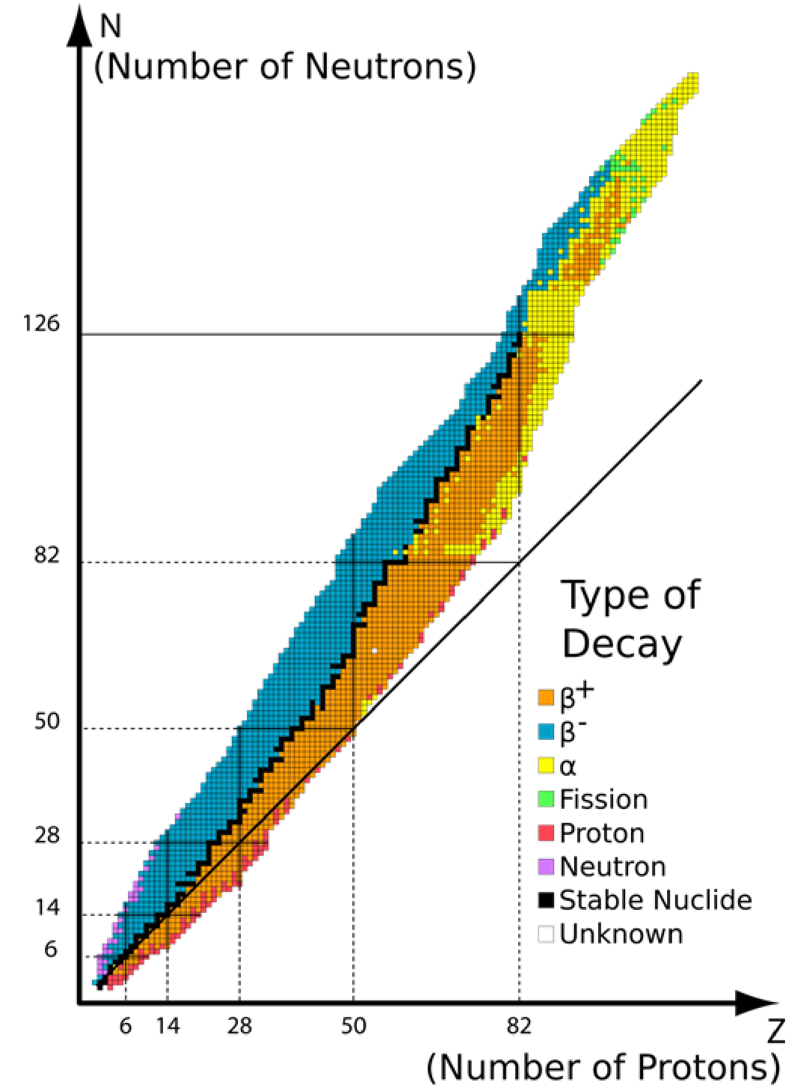
# Nuclear Stability

- BINDING ENERGY is the energy required to take a nucleon out of the nucleus (energy required to break apart nucleus)
- Binding energy per nucleon is a useful metric
  - Peaks at A~=60
- Atoms have stable isotopes despite the “tug-of-war” between nuclear forces and electromagnetic repulsion (gluons vs positive charge)
- The LINE OF STABILITY follows a weird trend:
  - Light Elements → # Neutrons ~= # Protons
  - Heavy Elements → # Neutrons ~= 1.5x # Protons (For every 2 protons, 3 neutrons)
  - Even numbered Proton/Neutron atoms tend to be more stable (“Magic Numbers”)

# Binding Energy Per Nucleon



# Line of Stability




**Nuclear Stability**

Decay will occur in such a way as to return a nucleus to the band (line) of stability.

The most stable nuclide is Iron-56

If Z > 83, the nuclide is radioactive

Graphic – Wikimedia user : Napy1kenobi

# Mass Energy Equivalence

- Don’t think too much into it
- We can represent energy as mass and vice versa

$$\boxed{E = mc^2}$$

# Mass Energy Equivalence Practice - 1

Prove that 1 amu is approximately 932 MeV using Einstein's Mass Energy Equivalence Equation

$$E = mc^2 \rightarrow E = (1.661 \times 10^{-27}\ \mathrm{kg}) \times \left(3 \times 10^8\ \frac{\mathrm{m}}{\mathrm{s}}\right)^2$$

$$= 1.49 \times 10^{-10}\ \mathrm{J} \rightarrow \frac{1.49 \times 10^{-10}}{1.6 \times 10^{-19}}\ \frac{\mathrm{eV\ J}}{\mathrm{J}} = 9.32 \times 10^8\ \mathrm{eV} = 932\ \mathrm{MeV}$$

This rule of thumb is very useful!

# Mass Energy Equivalence Practice - 2

What is the energy representation of an electron's rest mass in keV?

$$E = mc^2 \rightarrow E = (9.1 \times 10^{-31}\ \text{kg}) \times \left(3 \times 10^8\ \frac{m}{s}\right)^2$$

$$= 8.19 \times 10^{-14}\ \text{J} \rightarrow \frac{8.19 \times 10^{-14}}{1.6 \times 10^{-19}}\ \frac{\text{eV J}}{\text{J}} = 5.11 \times 10^5\ \text{eV} = 511\ \text{keV}$$

# Mass Defect and Binding Energy

- The MASS DEFECT is used to find the BINDING ENERGY of a nucleus
- Calculate mass defect in amu, use Einstein's Equation to convert mass defect into binding energy
- Nuclear mass (sum of all nucleon mass') ≠ Experimental mass

$$\boxed{\Delta m = (Z \times m_P + N \times m_N) - m_{exp}}$$

$$\boxed{\mathbf{BE} = \Delta m \times c^2}$$

# Binding Energy Practice

| Mass | Energy (amu) |
|---|---|
| Total Mass O-16 | 15.994914 |
| Total Mass O-19 | 19.003578 |
| Neutron Rest Mass | 1.00866 |
| Proton Rest Mass | 1.00727 |

Calculate the binding energy of Oxygen-16 and Oxygen-19, compare their binding energies per nucleon and predict which is more stable using that binding energy or another concept. Oxygen-16 and Oxygen-19 have 8 protons and 8/11 neutrons, respectively.

$$\mathrm{BE}_{\mathrm{O}-16} = \big((8 \times 1.00727) + (8 \times 1.00866)\big) - 15.994914 = 0.132526\ \mathrm{u} \cong 123\ \mathrm{MeV}$$

$$\mathrm{BE}_{\mathrm{O}-19} = \big((8 \times 1.00727) + (11 \times 1.00866)\big) - 19.003578 = 0.149842\ \mathrm{u} \cong 140\ \mathrm{MeV}$$

The binding energy per nucleon is then 7.688 MeV/amu for O-16 and 7.368 MeV/amu for O-19. O-19 will be less stable than O-19, this can be inferred from O-16’s “double magic” number or how O-19 diverges from the line of stability (Z~=N for light elements).

# The Electrons

Electrifying?

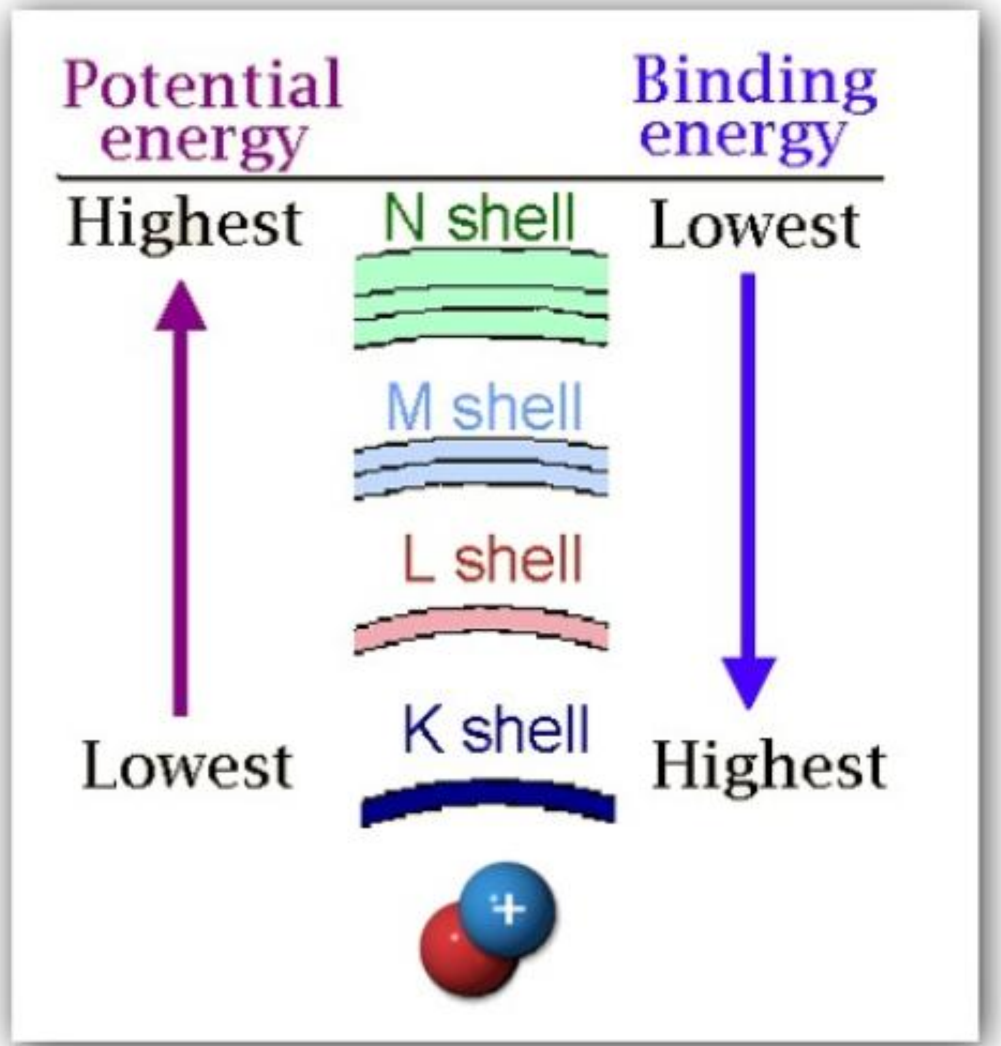
# Electron Shells

- Each SHELL is comprised of SUBSHELLS which are comprised of ORBITALS which are occupied by ELECTRONS
  - Shells → Subshells → Orbitals → Electrons
- We give these letters and numbers to describe them:
  - **Shells:** Principle Quantum Number $\boldsymbol{n}$ (1: K-Shell, 2: L-Shell…)
  - **Subshells:** Orbital Angular Momentum Quantum Number $\boldsymbol{l}$ $(0, 1, \ldots n-1)$
  - **Orbitals:** Magnetic Quantum Number $\boldsymbol{m_l}$ ($\pm l$ integers and 0)
  - **Electrons:** Electron Spin Quantum Number $\boldsymbol{m_s}$ $\left(\pm\frac{1}{2}\right)$

# Electron Binding Energy

- Electrons “occupy” lowest energy states first (K-shell → L-shell…)
- Binding Energy is the energy required to remove an electron from an atom
- Binding energy relies on a few factors:
  - Increases as the nucleus gains charge
  - Decreases as electrons occupy FURTHER orbitals
- As electrons transition from excited to deexcited state (i.e. L→K), the energy released is the difference in binding energies
- We use Energy level diagrams to represent these transitions

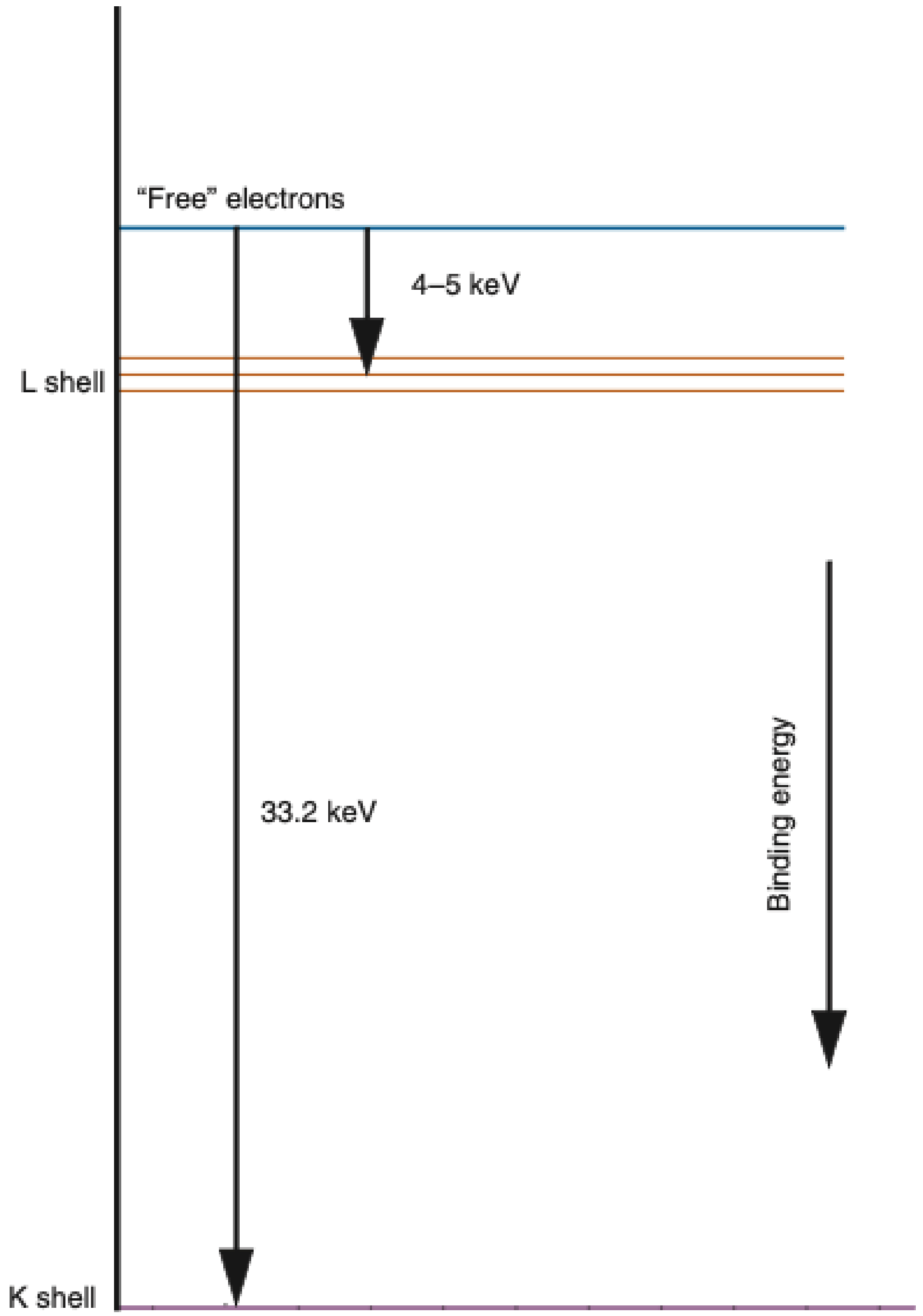
# Electron Binding Energy



# Electron Binding Energy

The energy level diagram at the right shows the various binding energies for Iodine electrons.

$$\boldsymbol{\Delta E = E_y - E_x}$$



# Electron Binding Energy Practice

What would be the energy released from an Iodine electron deexcitation from the L-shell to the K-shell?

$$\Delta E = E_y - E_x \rightarrow \Delta E = 33.2\ \text{keV} - 5?\ \text{keV} \cong 28\ \text{keV}$$

*The discrepancy is because the spin of an electron interacts with the angular momentum (spin-orbit coupling). The number of possible binding energies is found by:* $2n - 1$

*Typically, these are denoted by:* $L_1 2s$, $L_2 2p_{1/2}$, $L_3 2p_{3/2}$, *etc.*

# Characteristic Radiation

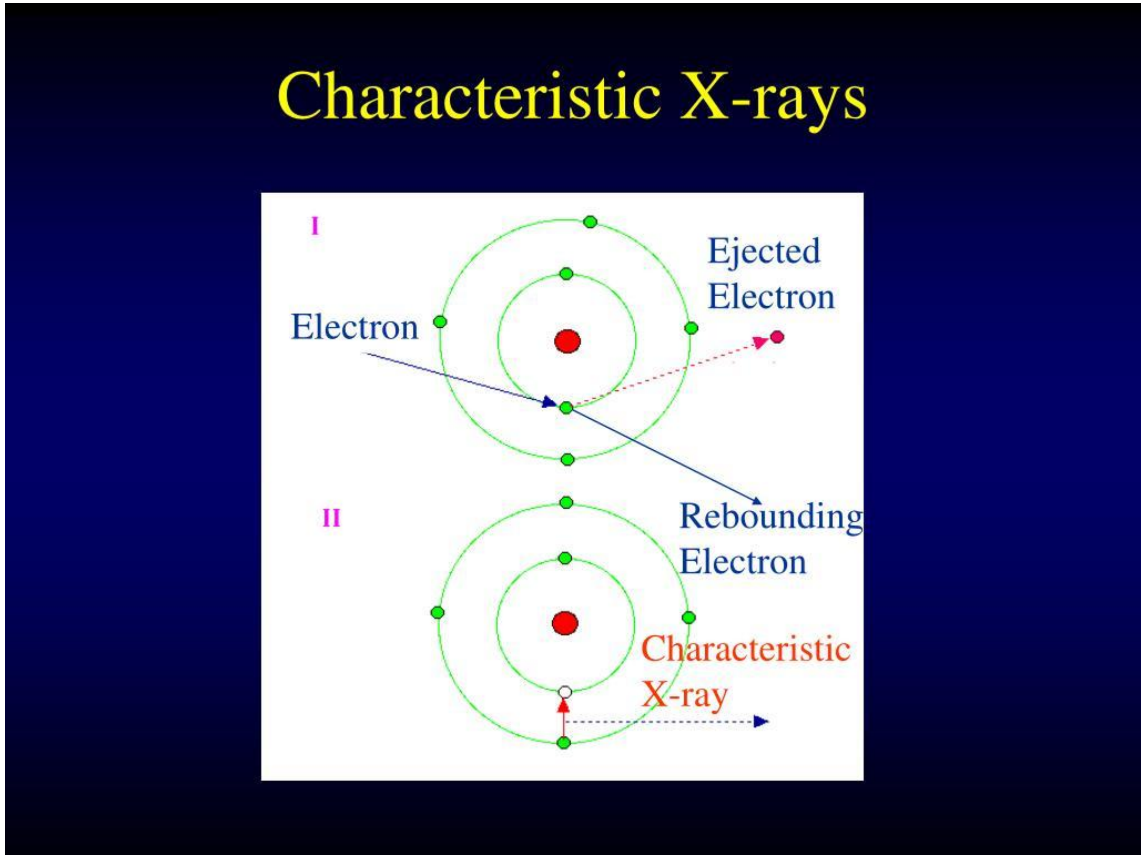
The emitted energy of an electron transition is in the form a photon called CHARACTERISTIC RADIATION

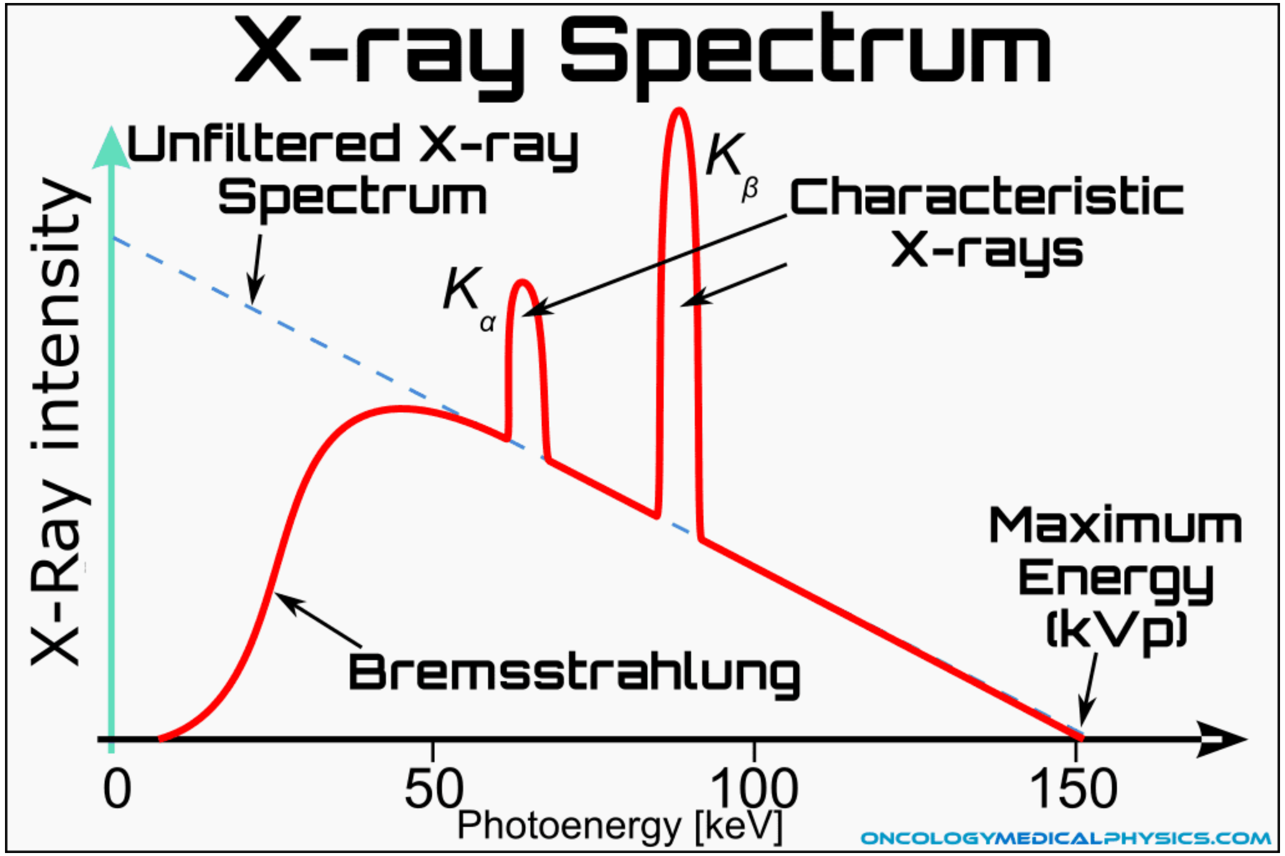
Characteristic X-rays are unique for given atomic and electric states (things get funky IRL)

For most cases the char. x-rays are well-known and predictable

Each ELEMENT has predetermined binding energies due, thus a unique array of char. x-rays

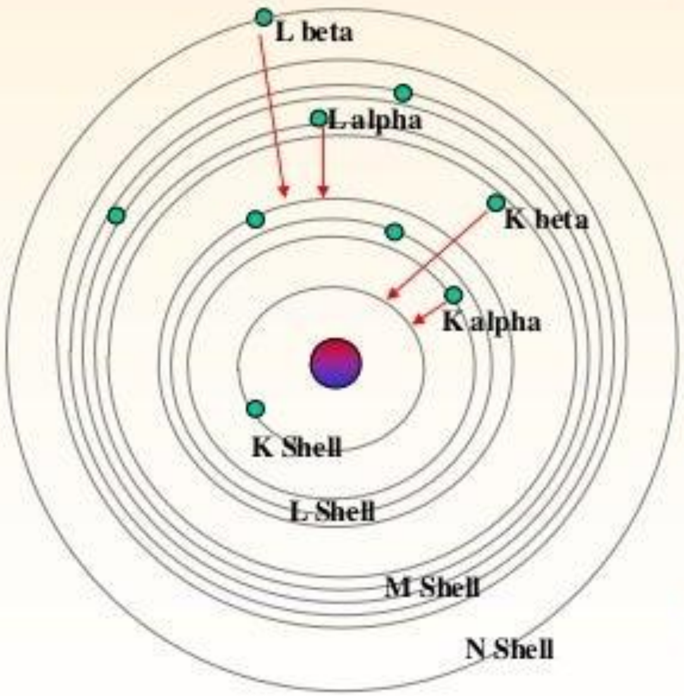
# Characteristic Radiation



# Characteristic Radiation Notation

## K & L Spectral Lines




- **K - alpha lines:** L shell e- transition to fill a vacancy in K shell. Most frequent transition, hence most intense peak.
- **K - beta lines:** M shell e- transitions to fill a vacancy in K shell.
- **L - alpha lines:** M shell e- transition to fill a vacancy in L shell.
- **L - beta lines:** N shell e- transition to fill a vacancy in L shell.

# Auger Effect

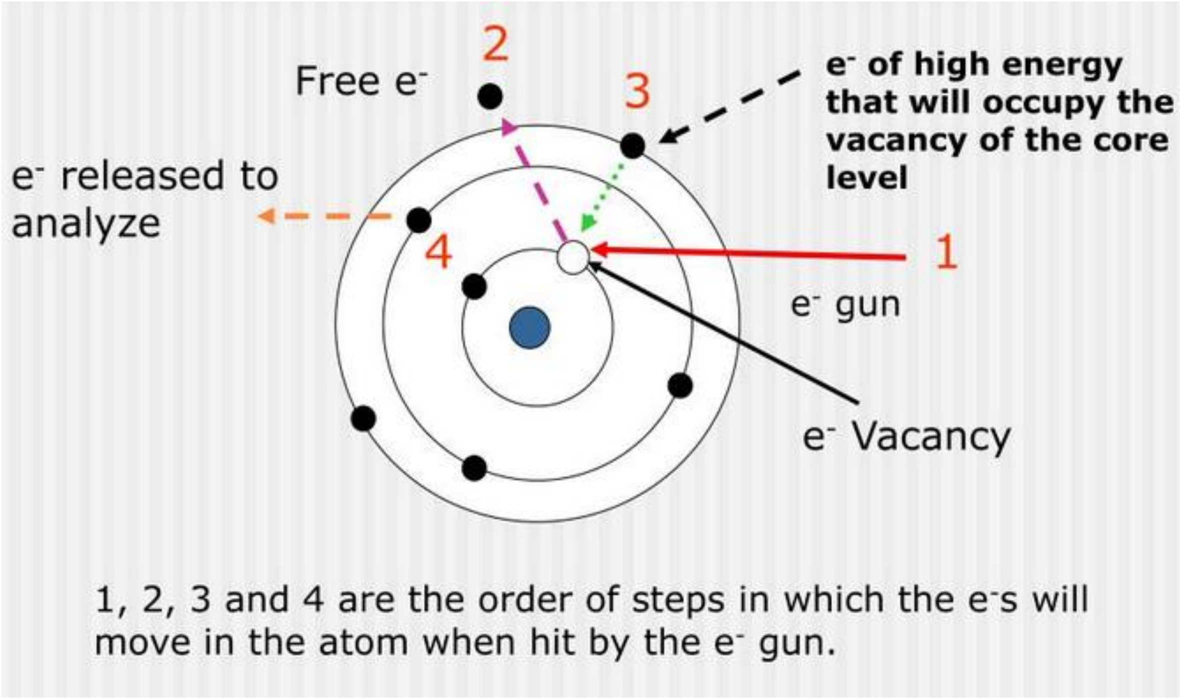
- A **competing** process to Characteristic Radiation
- An AUGER ELECTRON is emitted instead of an x-ray
- Results in TWO orbital vacancies → more Char. Radiation/Auger
- The kinetic energy of the Auger Electron is (roughly):

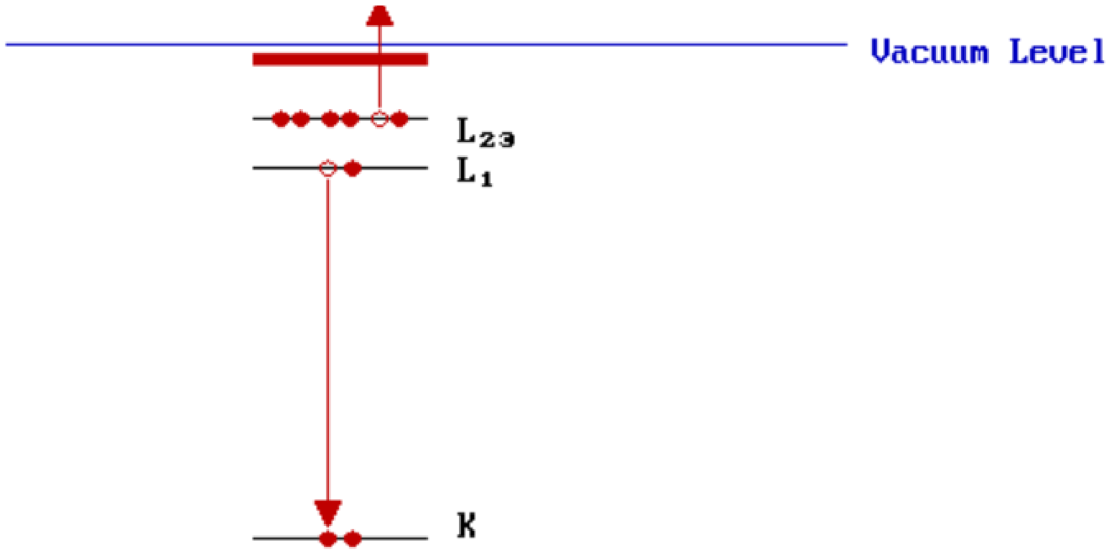
$$\boxed{\mathbf{KE_A} = \mathbf{BE_C} - (\mathbf{BE_{V1}} + \mathbf{BE_{V2}})}$$

# Auger Effect

Example:

$$KE_A = BE_K - (BE_{L1} + BE_{L23})$$



# Fluorescent Yield

- Defined as the probability of CHARACTERISTIC RADIATION (vs Auger Effect) for a vacancy
  - Hence, *Fluoro-*
  - Use $\omega$ for total, $\omega_K$ and $\omega_L$ for K-Shell and L-Shell
- Heavier elements have HIGHER $\omega$

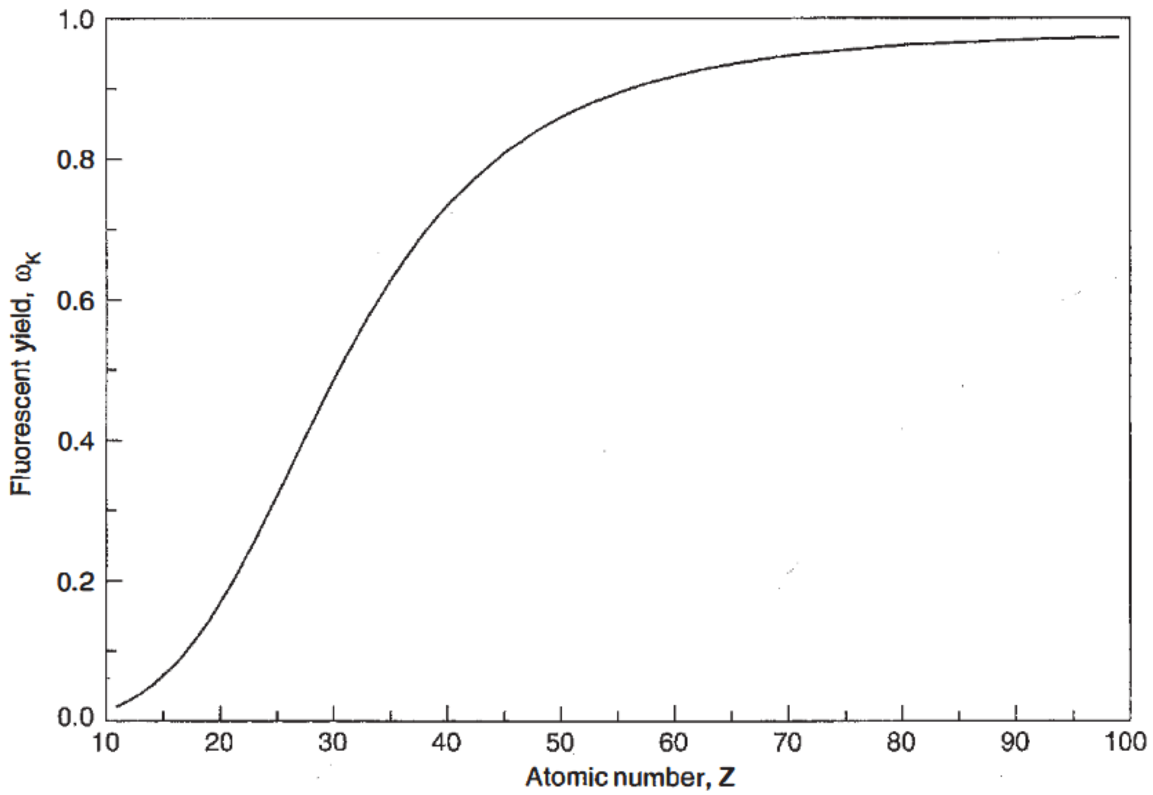



**Figure 2–6.** Fluorescent yield, $\omega_K$, or probability that an orbital electron shell vacancy will yield characteristic x rays rather than Auger electrons, versus atomic number Z of the atom. (Data from Hubbell JH, Trehan PN, Singh N, et al: A review, bibliography, and tabulation of K, L, and higher atomic shell x-ray fluorescence yields. J Phys Chem Ref Data 23:339–364, 1994.)