Physics of the nucleus and radioactive decay

a) Physics of the nucleus
- i) Nuclear nomenclature (isotope, isobar, isotone, isomer)
- ii) Nuclear stability
- iii) Radioactivity

b) Radioactive decay modes
- i) Gamma emission
- ii) Alpha decay
- iii) Beta decay
  - (a) Beta minus
  - (b) Beta plus (positron)
  - (c) Electron capture
- iv) Isomeric transition: 99m Tc

Review : Atom and Nucleus

- All matters are made of atoms
- Atoms are composed of three elementary (subatomic) particles;

  → **elections, protons, and neutrons**

  - Electron : negatively charged particle (1.6 x 10^{-9} C) with a mass of 0.9 x 10^{-27} g
  - Proton : positively charged (equal in amount of electron) with m_p=1.6726 x 10^{-24} g ~ **2000 x m_e**
  - Neutron : no charge, m_n =1.6747 x 10^{-24} g, slightly heavier than a proton

- Atoms are electrically neutral

  → the same number of electrons and protons

Concept from Special Relativity

- Total energy of a particle = rest-mass energy + kinetic energy

$$E = m_o c^2 + Q$$

- Speed of light, $c = 3x\ 10^8$ m/sec

  - Mass energy of an electron or positron = **511 keV**
  - Mass energy of a proton = 938.3 MeV
  - Mass energy of a neutron = 939.6 MeV
  - Mass of a photon (quantum of E.M. radiation) = 0
  - Mass of a neutrino (weakly interacting particle) ~ 0

Review : Standard Notation and Definition

A : atomic number
= Z+N

$${}^{A}_{Z}X_{N}$$

Z: number of protons

N: number of neutrons

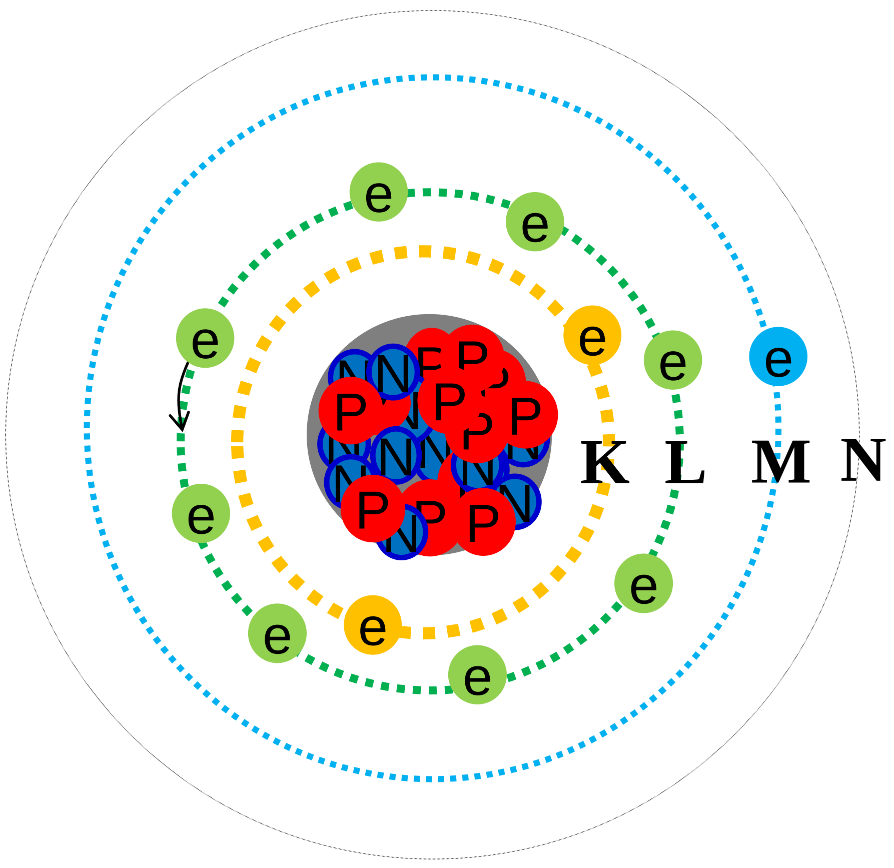
<u>Example:</u>

Carbon :	${}^{11}_{6}C_{5}$	${}^{12}_{6}C_{6}$	${}^{13}_{6}C_{7}$	${}^{14}_{6}C_{8}$
Iodine :	${}^{123}_{53}I_{70}$	${}^{124}_{53}I_{71}$	${}^{125}_{53}I_{72}$	${}^{127}_{53}I_{74}$
	${}^{129}_{53}I_{76}$	${}^{131}_{53}I_{78}$	${}^{135}_{53}I_{82}$	

Review: Simplified drawing of atomic structure

Nucleus : Protons (+) and Neutron (no charge) are at the center

Negatively charged electrons orbiting the nucleus over the surface of spherical shells of different radii.



Sodium with
11 electrons
11 protons
12 neutrons

$^{23}_{11}Na_{12}$

Quantized Binding energy (Na)
K-shell : -1.072 keV
L-shell : -0.063 keV
M-shell : -0.001 keV

Nuclear nomenclature (Isotopes, Isotones, Isobars)

<u>Isotopes:</u> Same number of <u>protons</u>, e.g., ${}^{12}_{6}C_{6}$ and ${}^{14}_{6}C_{8}$

<u>Isotones</u>: Same number of <u>neutrons</u>, e.g., ${}^{14}_{6}C_{8}$ and ${}^{15}_{7}N_{8}$

<u>Isobars</u>: Same number of <u>nucleons</u>, e.g., ${}^{15}_{8}\mathbf{O}$ and ${}^{15}_{7}\mathbf{N}$
(Atomic mass)

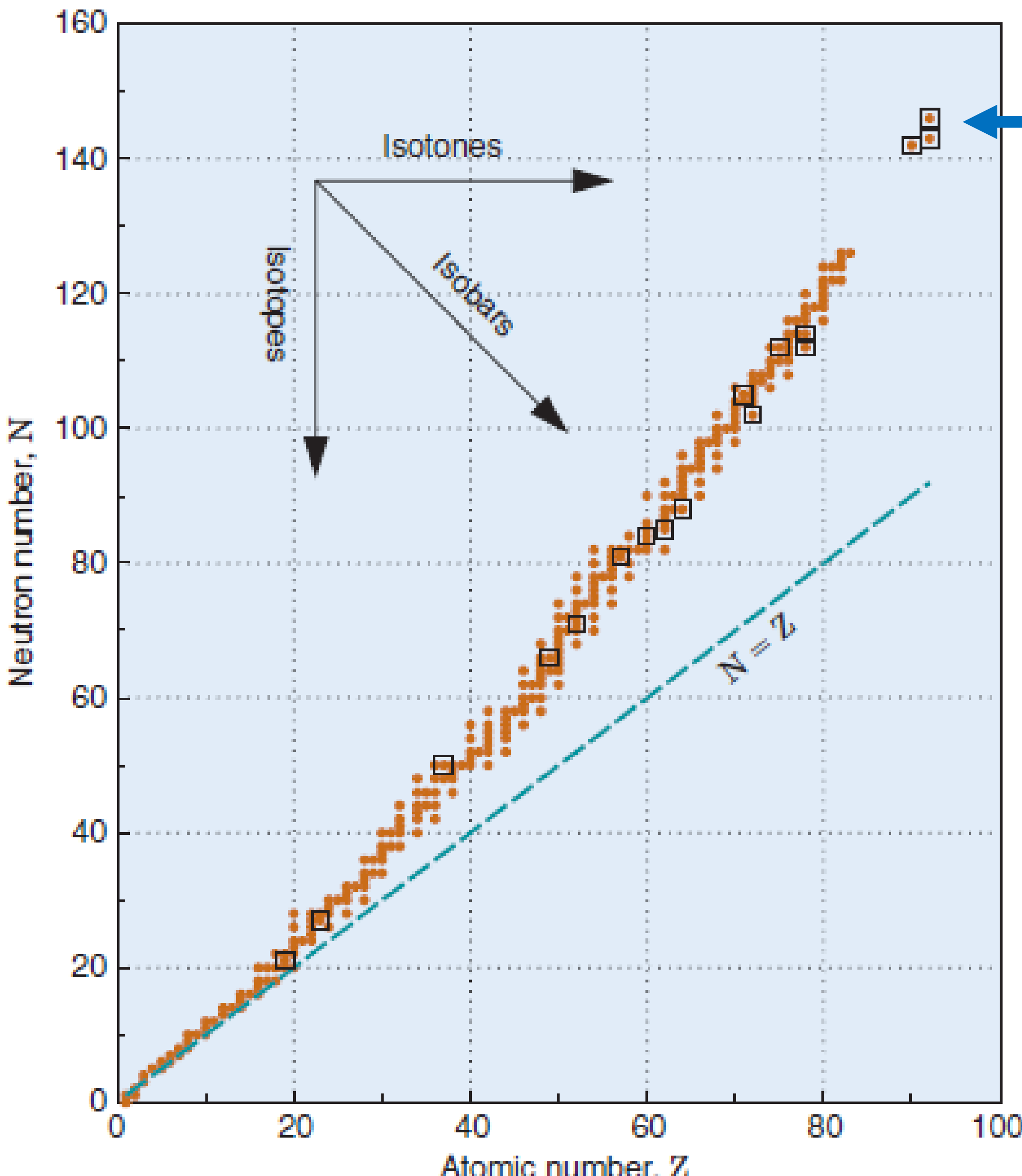
A **<u>nuclide</u>** is any identifiable atomic species with a definite number of protons (Z) and neutrons (N)

→ with unique **<u>nuclear properties</u>**

Nuclear Structure

- How do protons and neutrons stay together?
  - Repulsive *electrical forces* exist between positively charged protons
  - Counteracting very strong forces of attraction, called *nuclear forces* between any two protons and neutrons
  - Electrical and Nuclear Force compete
  - Nuclear energy levels are also quantized
  - Nucleons are arranged in spherical shells inside the nucleus
    - Interpretation is more complex than for atomic levels.

Nuclear stability (Band or line of stability) : natural nuclides



(# Proton)

Very long-lived naturally occurring unstable nuclides

Cherry, p16

Nuclear Stability

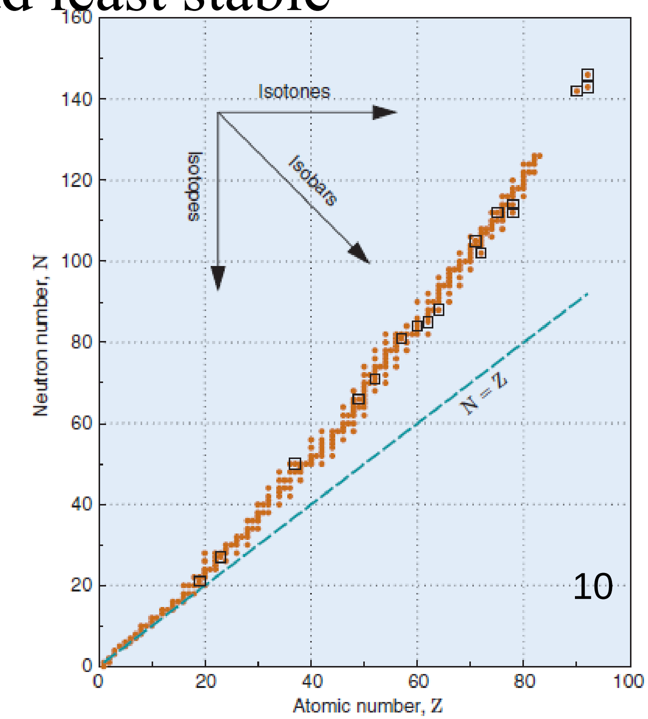
- 253 nuclides are considered stable, and ~33 are very long lived…
- N ~ Z for low Z, stable elements (e.g., ${}^{12}_{6}C_6$, ${}^{16}_{8}O_8$).
- N ~ 1.5 Z for heavy stable elements (e.g., ${}^{208}_{82}Pb_{126}$, ${}^{251}_{99}Es_{152}$).

  Extra neutrons required to overcome repulsive forces from large number of protons in heavy nuclei.
- Even-even (p-n) nuclei more stable; odd-odd least stable

165 stable e-e : $\boxed{{}^{12}_{6}C_6}$ $\boxed{{}^{208}_{82}Pb_{126}}$

109 stable e-o : $\boxed{{}^{195}_{78}Pt_{117}}$

4 stable o-o : $\boxed{{}^{2}_{1}H_1}$ $\boxed{{}^{6}_{3}Li_3}$ $\boxed{{}^{10}_{5}B_5}$ $\boxed{{}^{14}_{7}N_7}$



Beginning of Nuclear Medicine

- A Physicist (Henri Becquerel) **discovered natural radioactivity** in 1896
    - the uranium emitted radiation without an external source of energy

- In 1898, Physicists, Marie and Pierre Curie discovered another radioactive element, Radium

- In 1934, **Artificial (or manmade) radioactivity** was produced by Curie and Joliet.

    a radioactive isotope of phosphorus (P) by bombarding aluminum with alpha particles. $\longrightarrow$ $\boxed{{}^{30}_{15}P_{15}}$

    - ✓ Prompted the invention of cyclotron and reactors
    - ✓ Now many radionuclides are commercially available

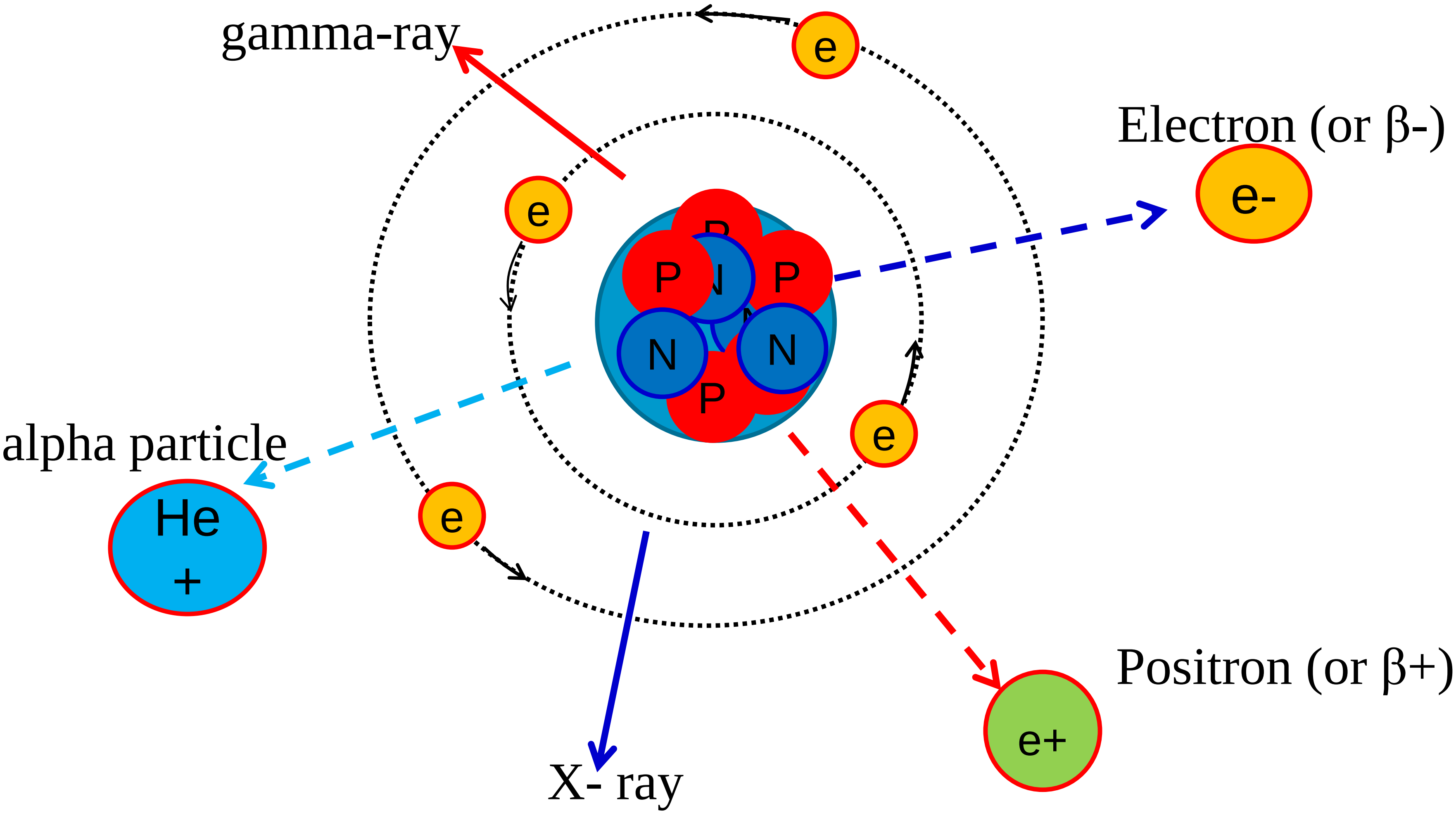
Nuclear Structure

protons and neutrons (nucleons) are arranged in spherical shells inside the nucleus

→ quantized energy level

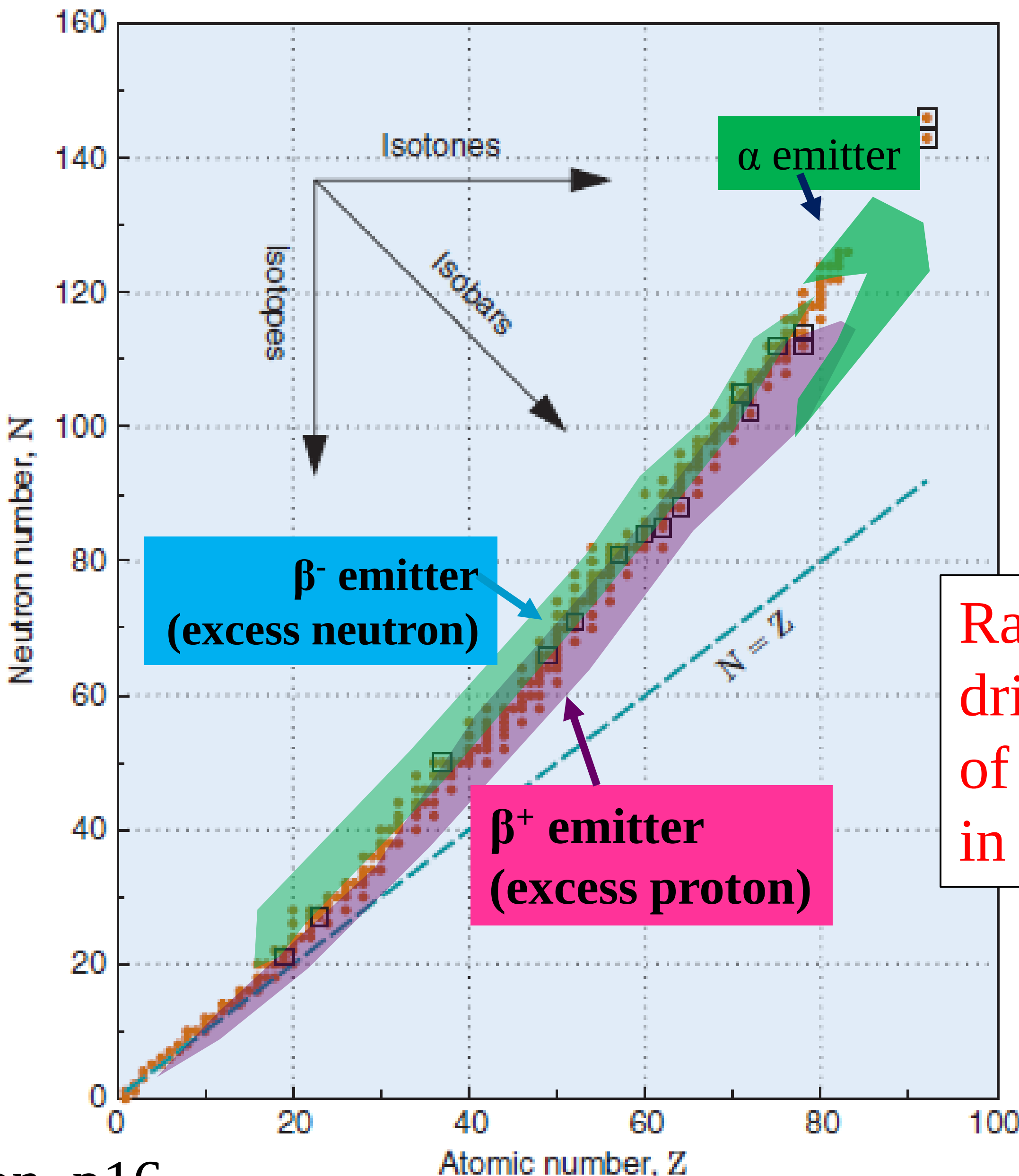
- Nucleons can be excited to higher energy shells by absorption of energy from outside of nucleus
  - Most stable arrangement of nucleons yields **ground state**.
  - Excited states (*) are unstable. Generally very short lifetimes (picoseconds) before transformation to some other state.
  - Metastable states (*m*) are unstable, but have a long lifetime before transformation. Also called **isomeric states**.

Radioactive Decay



Radionuclides try to become stable by emitting electromagnetic radiation or charged particles (α, β, γ, x-ray,)

Nuclear stability (Band or line of stability)



Radioactive decay is driven by the number of protons and neutrons in the nucleus

Sorenson, p16

Radioactivity: General concepts

- Radionuclide: radioactive nucleus (**parent**) that decays to **daughter**
- Daughter has higher binding energy than parent
- Radioactive decay is **spontaneous** (exact moment not predictable).
- Nuclear decay obeys **Charge, Energy**, & Momentum conservation
- **Radionuclide** (generally preferred term) vs. **radioisotope**.
- Unique properties of radionuclides:
  - mode of decay
  - energies of all emissions
  - lifetime (**half-life,** $T_{1/2}$) and **transition energy** (Q).

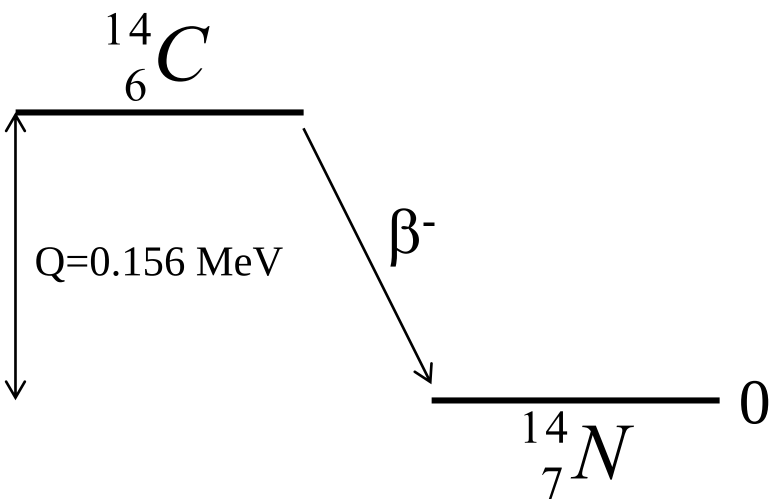
    $T_{1/2}$: the time for half of the radionuclides to decay
    Q : total mass-energy

Extra neutrons - Decay by β⁻ emission $n \rightarrow p + \beta^- + \bar{\nu}$

Excess of neutrons → a neutron is converted into a proton and the excess energy is released as an electron (β^-) and an antineutrino

$$ {}^{A}_{Z}X_{n} \rightarrow {}^{A}_{Z+1}Y_{n-1} + \beta^- + \bar{\nu} $$

Beta Decay scheme Diagram



(drawn towards the right since Z increases by 1)

$T_{1/2}$=5730 yrs

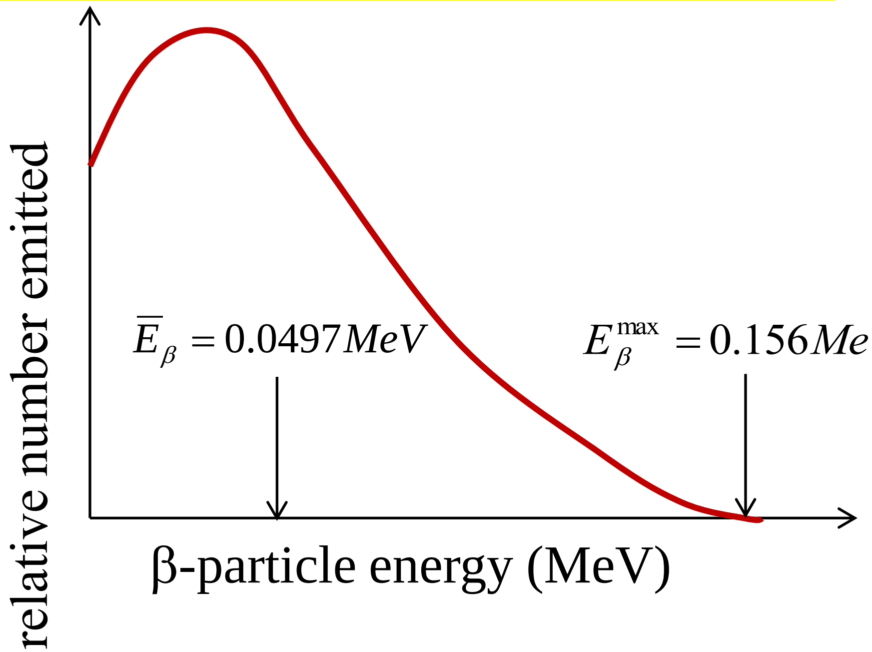
- ✓ **Mass number** "A" does not change because the total number of nucleons in the nucleus does not change.
  → isobaric decay mode
- ✓ Parent and daughter are isobars
- ✓ Parent and daughter represent <u>different elements</u>
  → **transmutation** of elements

Extra neutrons - Decay by β^- emission

- Antineutrino : to satisfy the law of energy conservation
- Sharing of energy between β^- and $\overline{\nu}$ is random

  → electron is emitted with varying energy, i.e., spectrum

Beta Energy Spectrum of ^{14}C



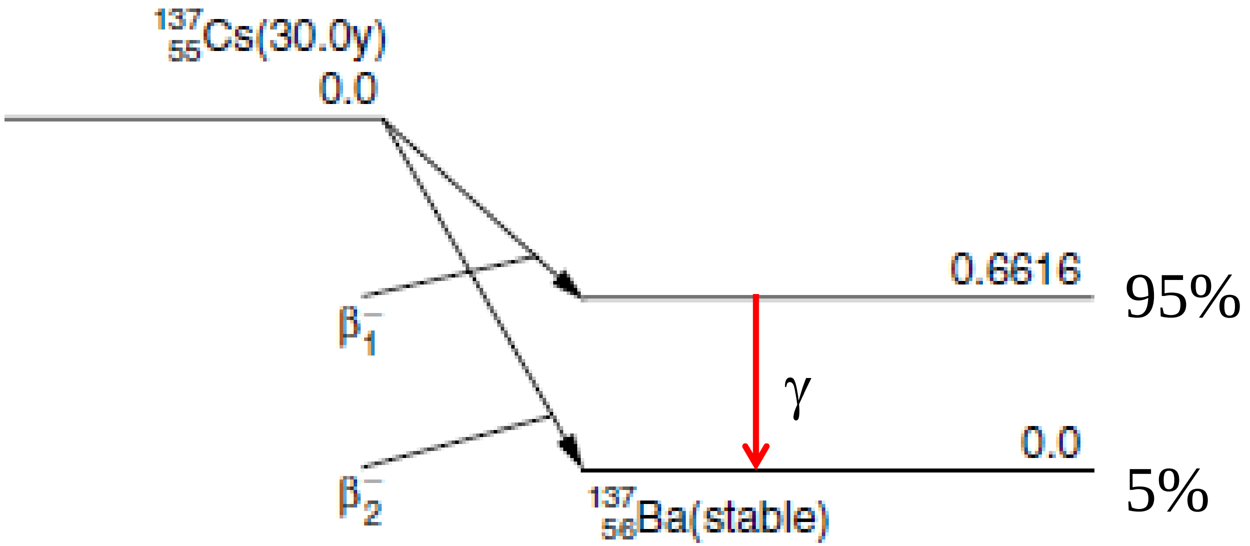
- Average energy of the beta particle : $\overline{E}_\beta \approx \frac{1}{3} E_\beta^{max}$

  → 2/3 to antineutrino

Extra neutrons : Decay by (β^-, γ) emission

a daughter nucleus in an **excited state** rather than in the ground state.

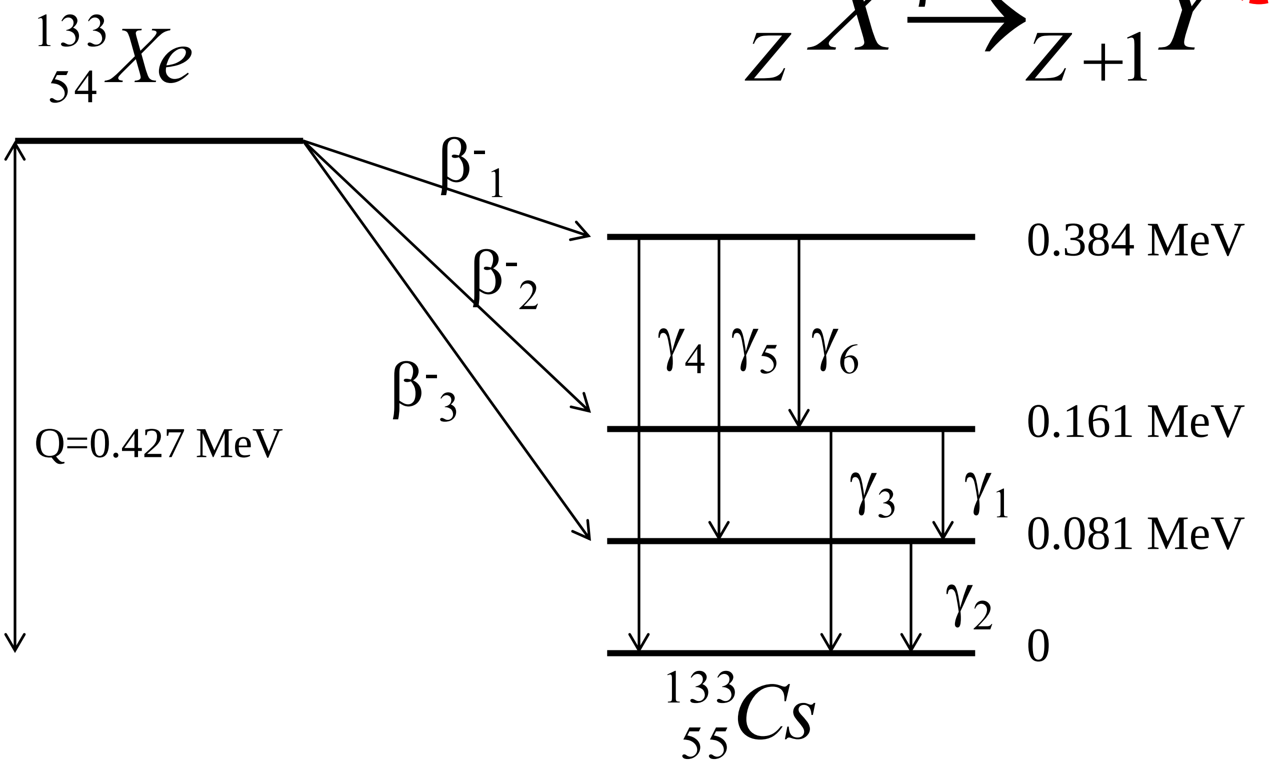
$$ {}^{A}_{Z}X \xrightarrow{\beta^-} {}^{A}_{Z+1}Y^{*} \xrightarrow{\gamma} {}^{A}_{Z+1}Y $$



Extra neutrons : Decay by (β^-, γ) emission

Many excited states

$${}^{A}_{Z}X \xrightarrow{\beta^-} {}^{A}_{Z+1}Y^{*} \xrightarrow{\gamma} {}^{A}_{Z+1}Y$$



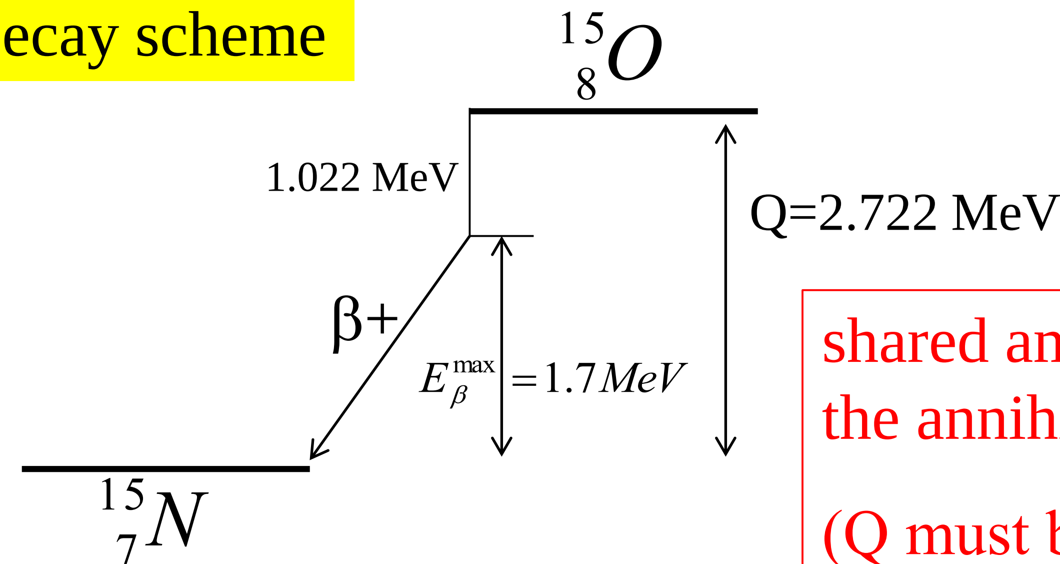
^{131}I also emits betas and gammas → therapy and imaging

Extra protons - Decay by positron emission $p \rightarrow n + \beta^{+} + \nu$

A proton inside the nucleus is converted into a neutron and the excess energy is emitted as a **<u>positron</u>** and a <u>neutrino</u>

$$ {}^{A}_{Z}X_{n} \rightarrow {}^{A}_{Z-1}Y_{n+1} + \beta^{+} + \nu $$

Decay scheme



shared among positron, neutrino, and the annihilation photons.

(Q must be ≥1.022 MeV = 2 $m_e c^2$)

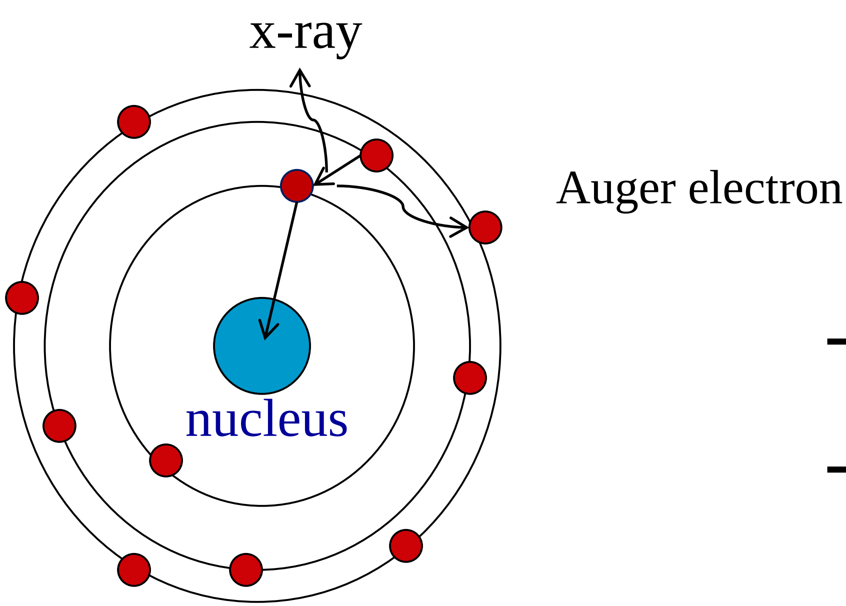
(drawn towards the left since Z decreases by 1)

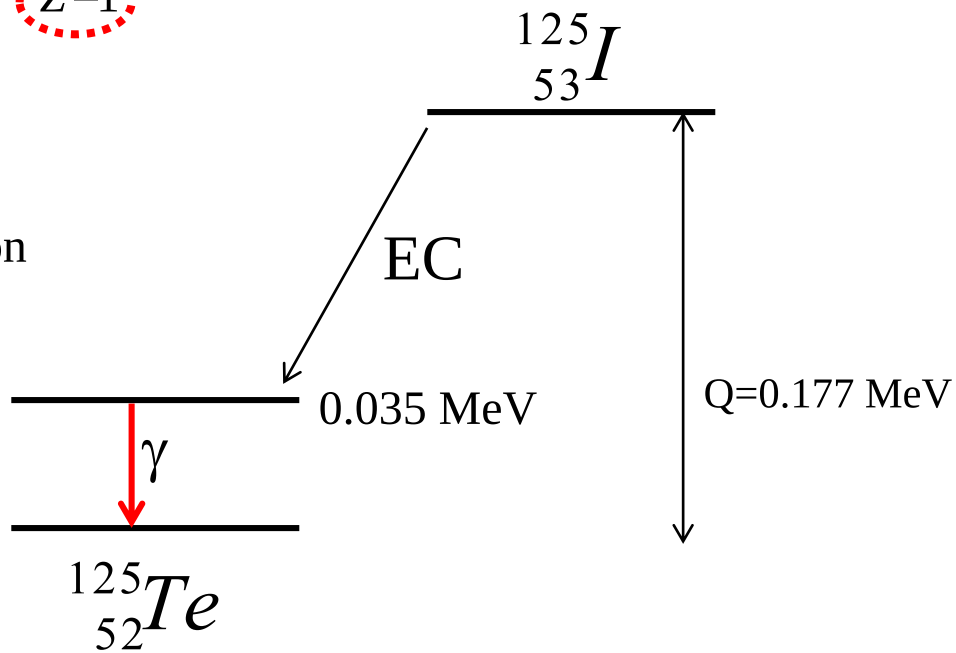
Mass energy of an electron or positron = **511 keV**

Extra protons - Decay by electron capture (EC) $p^{+}+e^{-}\rightarrow n^{o}+\nu+energy$

A proton inside the nucleus is converted into a neutron by capturing an electron from one of the atomic shells, and the excess energy is release as a neutrino

$$^{A}_{Z}X+e^{-}\rightarrow {}^{A}_{Z-1}Y+\nu$$

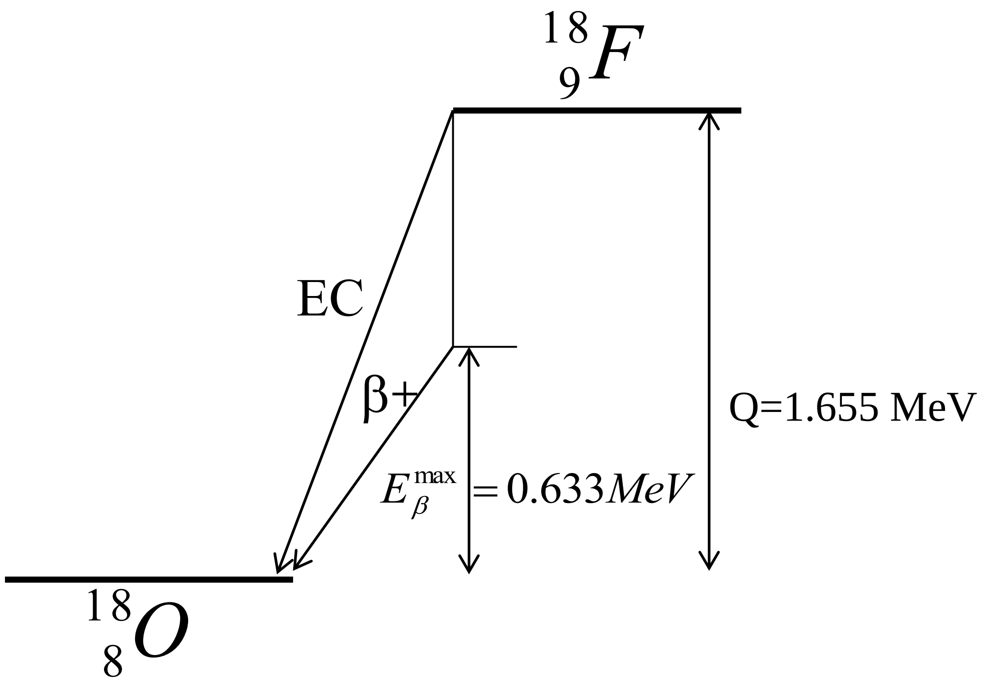




^{125}I emits low energy gamma, x-ray, and Auger electrons → therapy

EC nuclear medicine examples: ^{67}Ga, ^{111}In, ^{123}I, ^{201}Tl

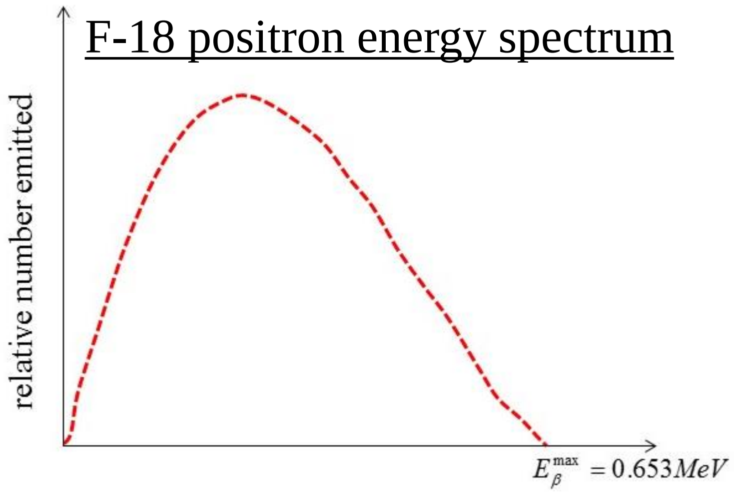
Extra protons : Competitive β^+ and EC decay



For F-18:

Probability (β^+) = 97%

Probability (EC) = 3%



Another nuclear medicine example: ^{11}C

Probability (β^+) = 99.75%

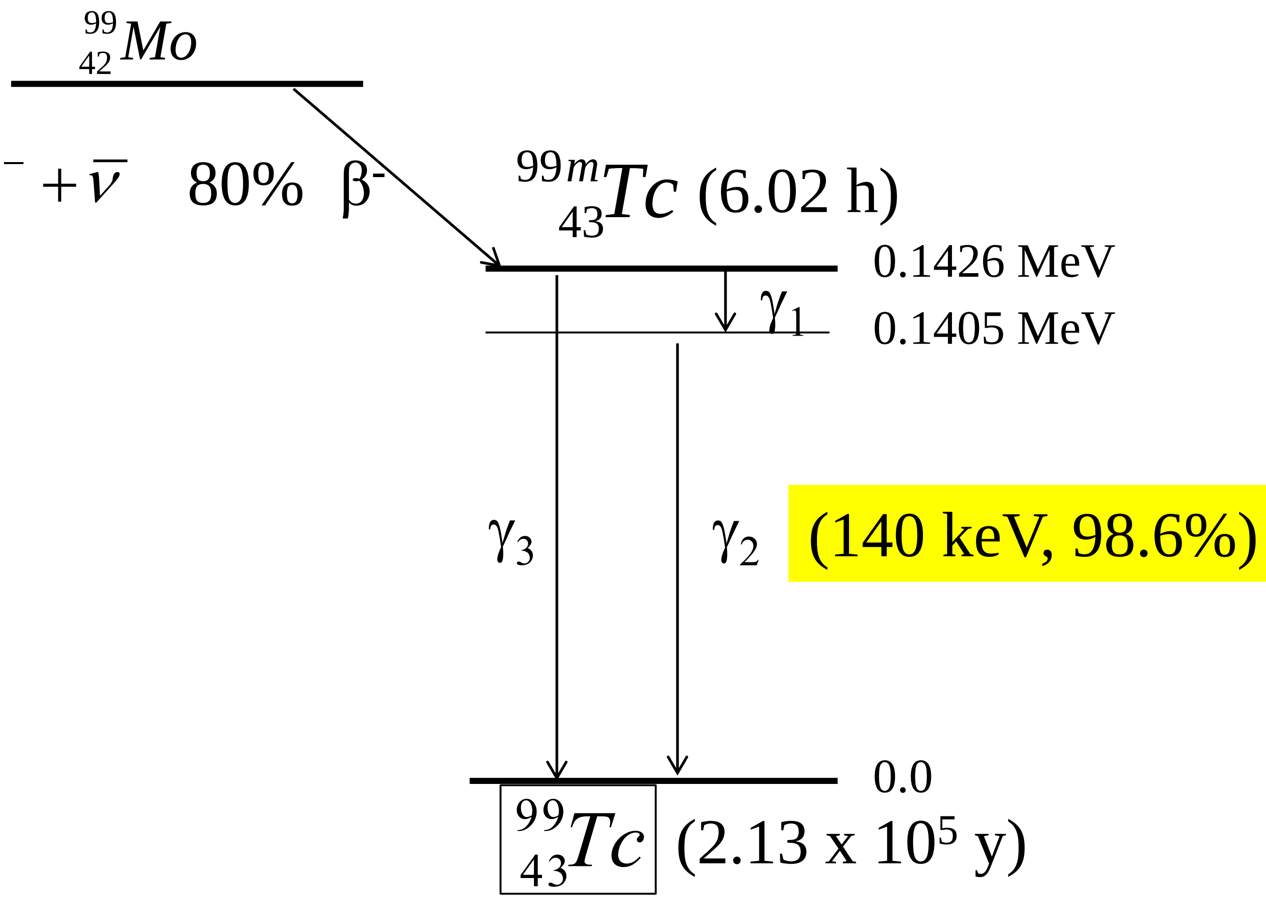
Probability (EC) = 0.25 %

Metastable Radionuclide

The daughter nucleus of a radioactive parent may be formed in a “long-lived” metastable or isomeric state.

$$^{99}_{42}Mo \rightarrow {}^{99m}_{43}Tc + \beta^- + \bar{\nu}$$

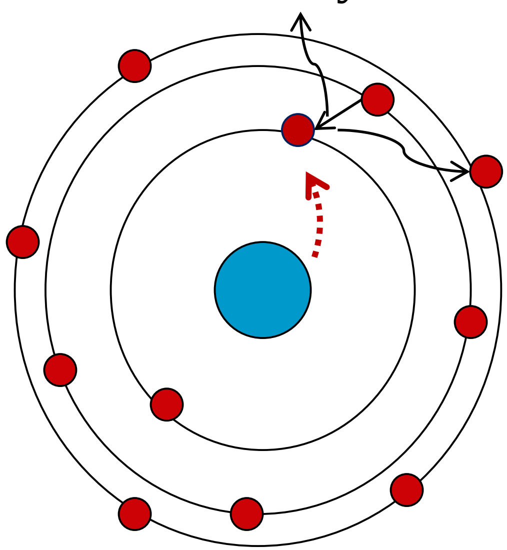
$T_{1/2}$= 67 hrs



(no change in Z)

Internal Conversion (IC)

- ❑ The excess energy is transferred to an orbital electron,
  → orbital electron is ejected.
- ❑ No γ ray emission as if it is internally absorbed



Emission of electrons, x-rays, and Auger electrons

Metastable nuclides always emit a certain number of conversion electrons (ce)

Metastable Radionuclide

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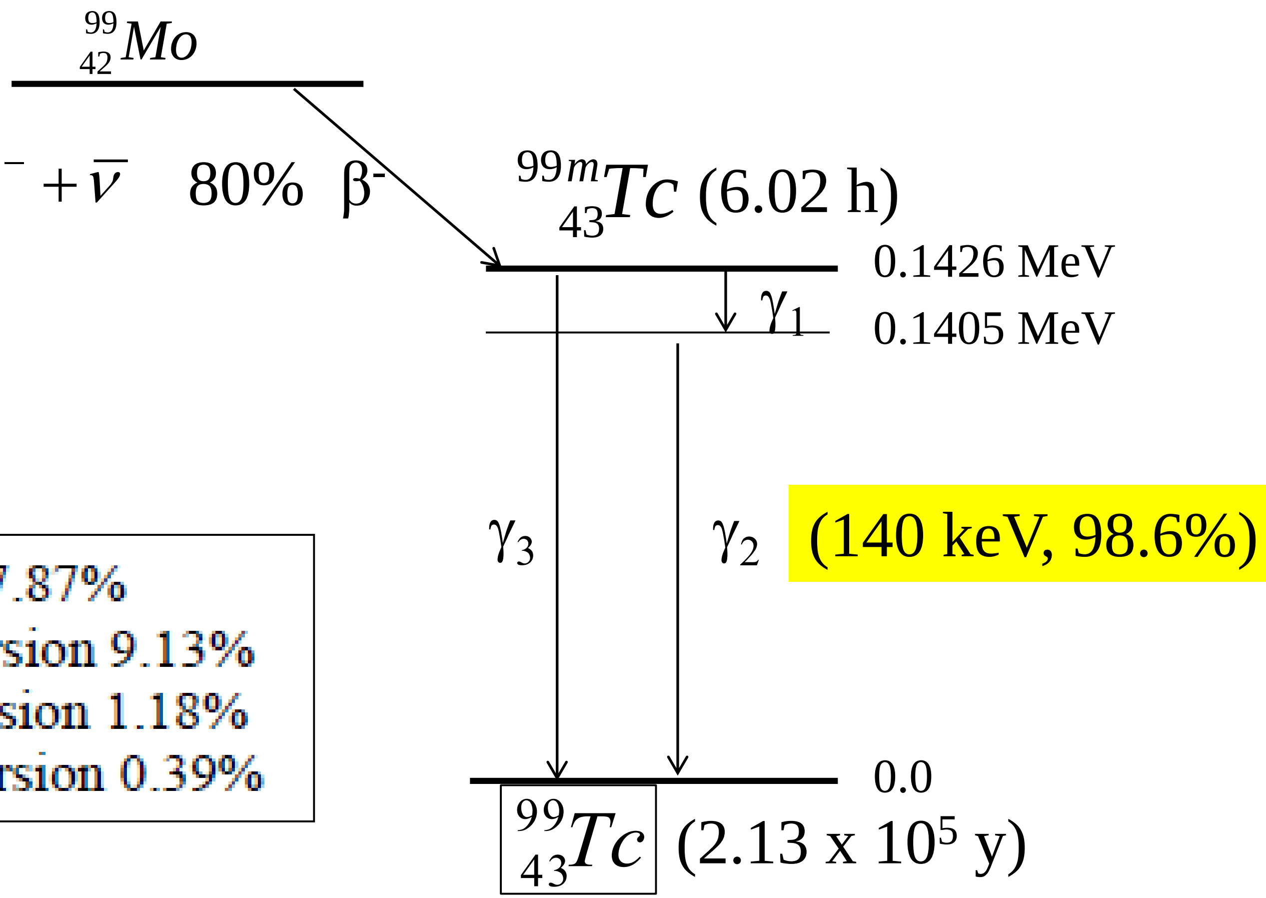


gamma photon 87.87%
K-internal conversion 9.13%
L-internal conversion 1.18%
M-internal conversion 0.39%

(no change in Z)

Decay by α-particle emission

- occurs mostly in heavy nuclides, e.g., uranium, radon..
- **α-particle** : helium atom with 2 protons and 2 neutrons, ${}_{2}^{4}He_{2}$

$$ {}_{Z}^{A}X \rightarrow {}_{Z-2}^{A-4}Y + \alpha $$

- After α-decay, the atomic number of the nucleus is reduced by 2 and the mass number by 4.
- The range of the α-particles : very short, ~ 0.03 mm in body tissue.
- Some α-emitters are used in therapy.

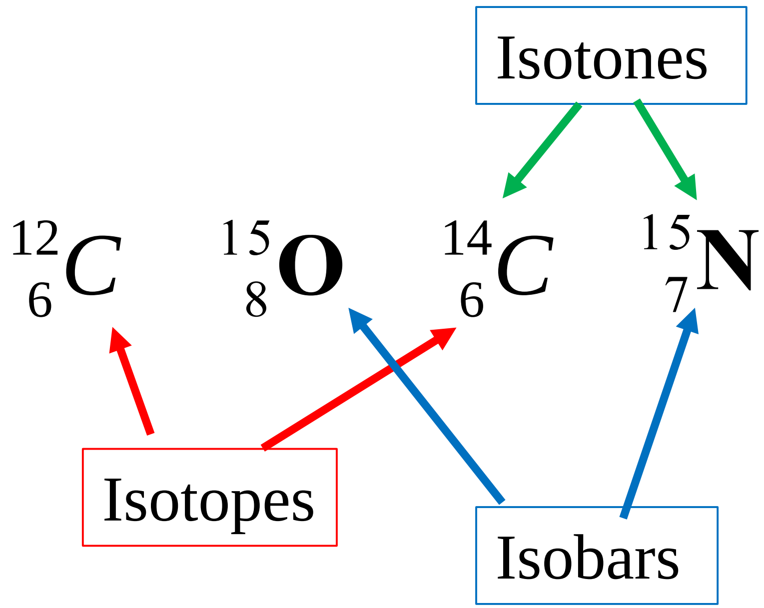
targets bone metastases, prostate cancer

$$ {}_{88}^{223}Ra \rightarrow {}_{86}^{119}Rn + \alpha $$

Summary

- Excess of neutrons, Same A, Z→ Z+1
    - beta minus (β^-) emission (with continuous energy spectrum)
    - β^- and γ emission
- Excess of protons : Same A, Z→ Z-1
    - beta plus (positron, β^+) emission
        - β^+ and γ emission
    - Electron capture (EC)
        - EC and γ emission
        - EC and γ emission, x-ray, Auger electrons
    - β^+ and EC
- Metastable radionuclides
    - γ emission + x-ray, electrons via internal conversion
    - Parent and daughter are isomers.

1. Identify the pair of isotopes, isobars, and isotones from the following nuclides



2. What decay mode are radionuclides with an excess number of neutrons are likely to undergo?
   a. electron capture
   b. beta-minus decay
   c. isomeric transition
   d. Positron decay

3. Einsteinium (Es) has an atomic number of 99. How many neutrons are present in the nucleus of ^{251}Es?

a. 99
b. 251
c. 152
d. 350