The Nucleus and Radioactive Decay

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Reminder: Concept from Special Relativity

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

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

- 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

Reminder: Atomic Energy Levels

- Energy levels of atomic electrons are **quantized**.
- Pauli exclusion principle determines max. number per shell

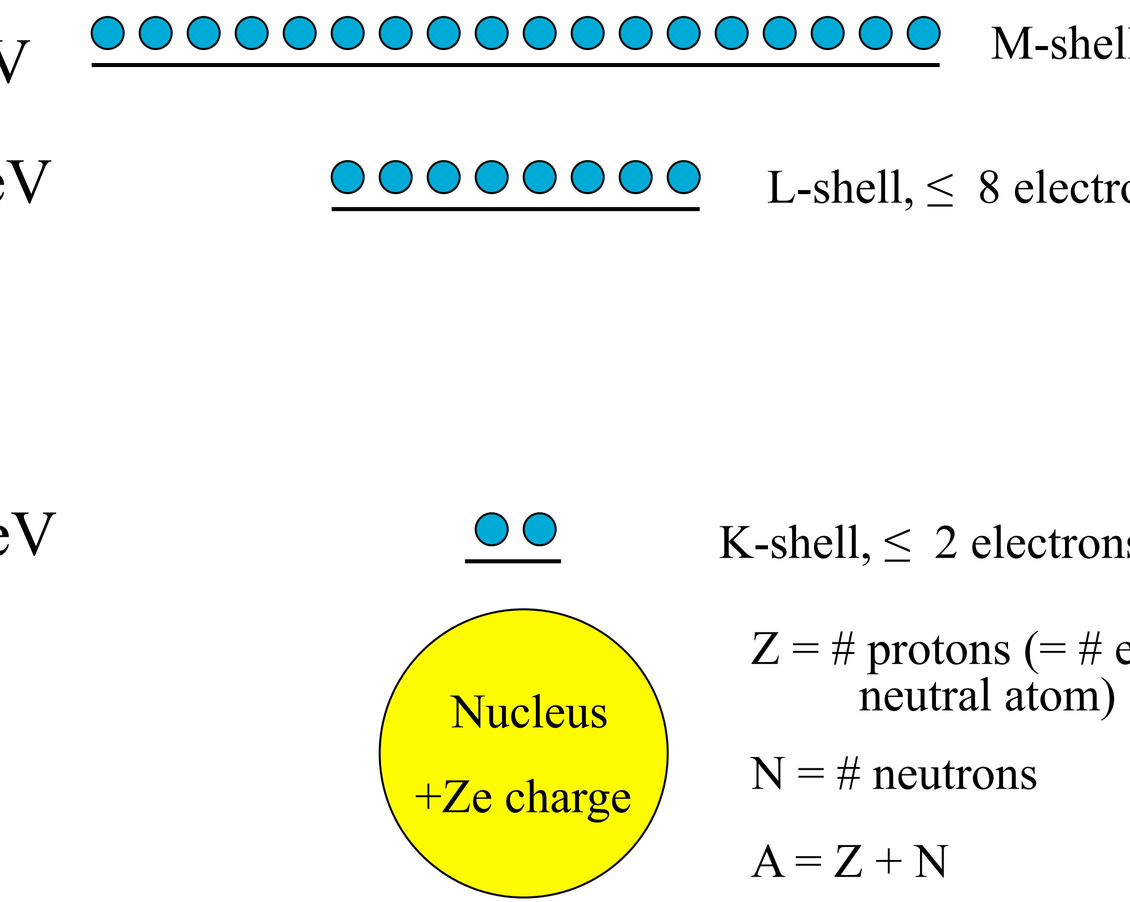
Binding energy = 0 for free electrons

$E_{free} = 0$

$E_M = -3$ keV — M-shell, ≤ 18 electrons

$E_L = -12$ keV — L-shell, ≤ 8 electrons

$E_K = -69$ keV — K-shell, ≤ 2 electrons



Z = # protons (= # electrons for neutral atom)

N = # neutrons

A = Z + N

Reminder: Standard Notation and Definitions

(ABR core study guide 17.a.i)

Example: Stable gold.

$^{197}_{79}\mathbf{Au}_{118}$ 79 protons (Z), 118 neutrons (N), 197 nucleons (A)

Isotopes, Isotones, Isobars:

Isotopes: Same number of protons, e.g., $^{12}_{6}\mathbf{C}$ and $^{14}_{6}\mathbf{C}$

Isotones: Same number of neutrons, e.g., $^{14}_{6}\mathbf{C}$ and $^{15}_{7}\mathbf{N}$

Isobars: Same number of nucleons, e.g., $^{15}_{8}\mathbf{O}$ and $^{15}_{7}\mathbf{N}$

<u>Key points: Nuclear Energy Levels and Transitions</u>

- Nuclear energy levels are also quantized.

- Interpretation is more complex than for atomic levels.

- Electromagnetic and Strong Force compete with each other.

- Most stable arrangement of nucleons yields **<u>ground state</u>**.

- Excited states are unstable. Generally very short lifetimes before transformation to some other state.

- Metastable states are unstable, but have a long lifetime before transformation. Also called **<u>isomeric states</u>**. One or more **<u>gamma rays</u>** are often emitted when a metastable state decays to a more stable state. **X-rays** arise from **<u>atomic</u>** transitions, whereas **gamma rays** arise from **<u>nuclear</u>** transitions.

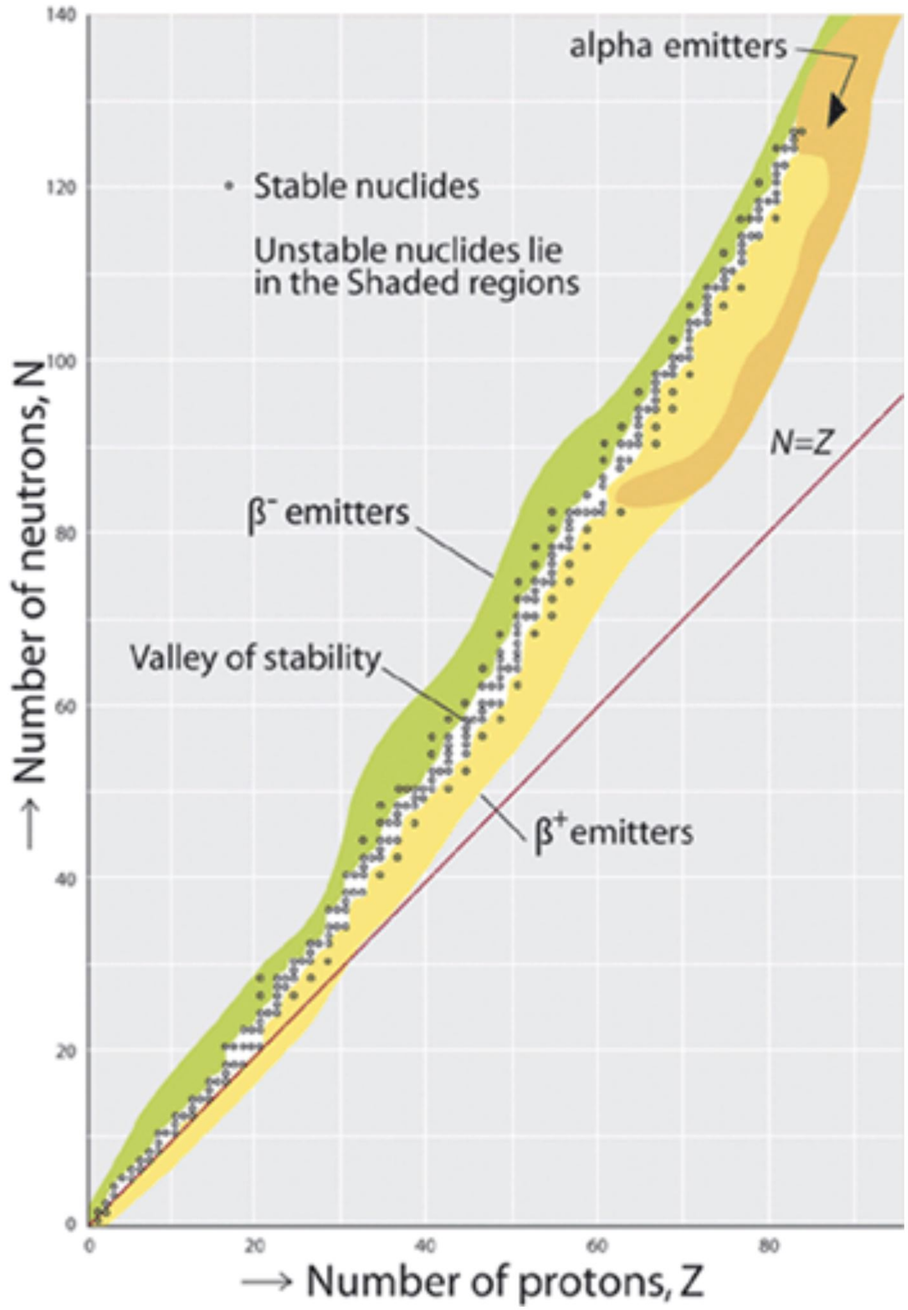
- ^{99m}Tc (metastable) and ^{99}Tc are isomers of each other.

- 10^{-12} seconds is approximate transition from unstable to metastable.

Modes of Radioactive Decay

- Nuclear stability and general concepts
- Effects on chemistry
- β^- emission
- $\beta^- + \gamma$ emission
- isomeric transition and internal conversion
- electron capture (EC)
- β^+ decay and competition with EC
- α decay

(ABR core study guide 17.a.ii)



(From: http://ec.europa.eu/research/energy/fi/fi_bs/article_1172_en.htm)

<u>Nuclear Stability</u> (ABR core study guide 17.a.ii)

1. N ~ Z for low Z, stable elements (e.g., $^{12}_{6}C$).
2. N ~ 1.5 Z for heavy stable elements (e.g., $^{216}_{83}Bi$).
   - Extra neutrons required to overcome repulsive forces from large number of protons in heavy nuclei.
3. If N > line-of-stability, nucleus is <u>proton deficient</u>:

   -> β^- decay likely ($n^o \rightarrow p^+ + \beta^- + \bar{\nu}$)

   If N < line-of-stability, nucleus is <u>neutron deficient</u>.

   -> β^+ decay likely ($p^+ \rightarrow n^o + \beta^+ + \nu$)

   (electron capture also likely)
4. Even-even nuclei more stable; odd-odd least stable (165 stable e-e, 109 stable e-o; only 4 stable o-o nuclei)
5. More tightly bound nuclei (high E_b/A) generally more stable.

Radioactivity: General concepts **(ABR core study guide 17.a.iii)**

1. Terminology: radioactive nucleus = **parent**; product = **daughter**.

2. Radioactive decay is **spontaneous** (exact moment not predictable).

3. Mass -> Mass + Energy (Q) in radioactive decay (atomic masses)

4. **Radionuclide** (generally preferred term) vs. **radioisotope**.

5. Unique properties of radionuclides:

    - mode of decay and energies of all emissions

    - lifetime (**half-life**) and **transition energy** (Q).

Chemistry Considerations

- Chemical reactions usually involve outermost orbital electrons.

- Radioactive decay primarily involves the nucleus.

- Can generally substitute any isotope (stable or radioactive) in a molecule or in a given chemical reaction.

- Minor exceptions:

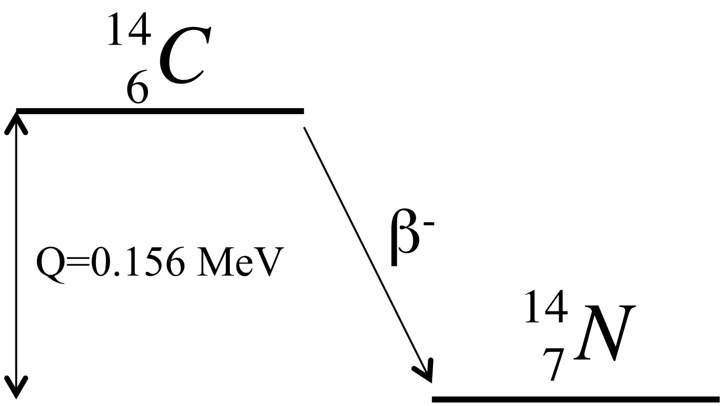
  1. Isotope effect (purely a mass effect; radioactivity irrelevant)

  2. Orbital binding energies can be altered a little by molecular interactions. Therefore, half-life of decays involving orbital electrons can be altered.

Decay by β^- emission (ABR core study guide 17.b.iii(a))

$$(n^{o} \rightarrow p^{+} + \beta^{-} + \bar{\nu})$$

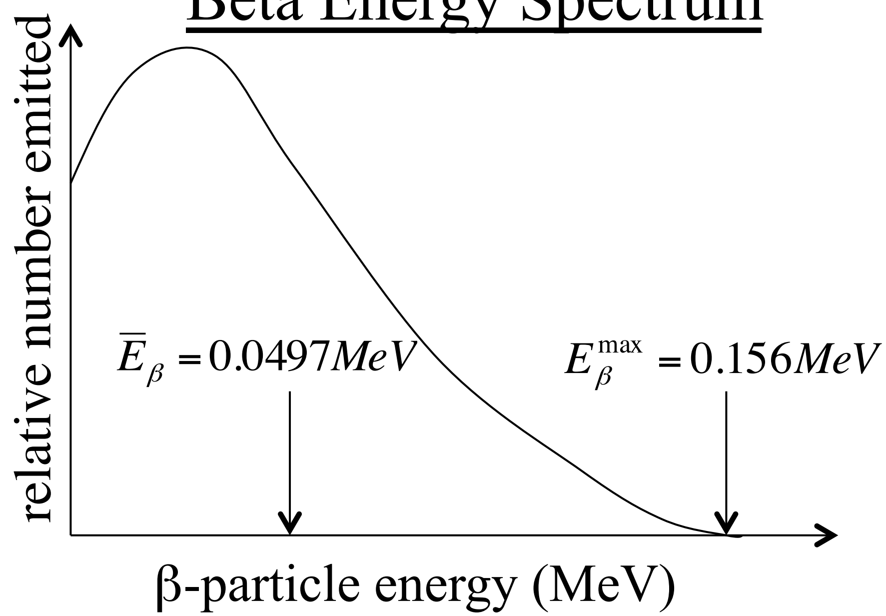
$$ {}^{A}_{Z}X \xrightarrow{\beta^-} {}^{A}_{Z+1}Y $$



Beta Decay Diagram

(drawn towards the right since Z increases by 1)

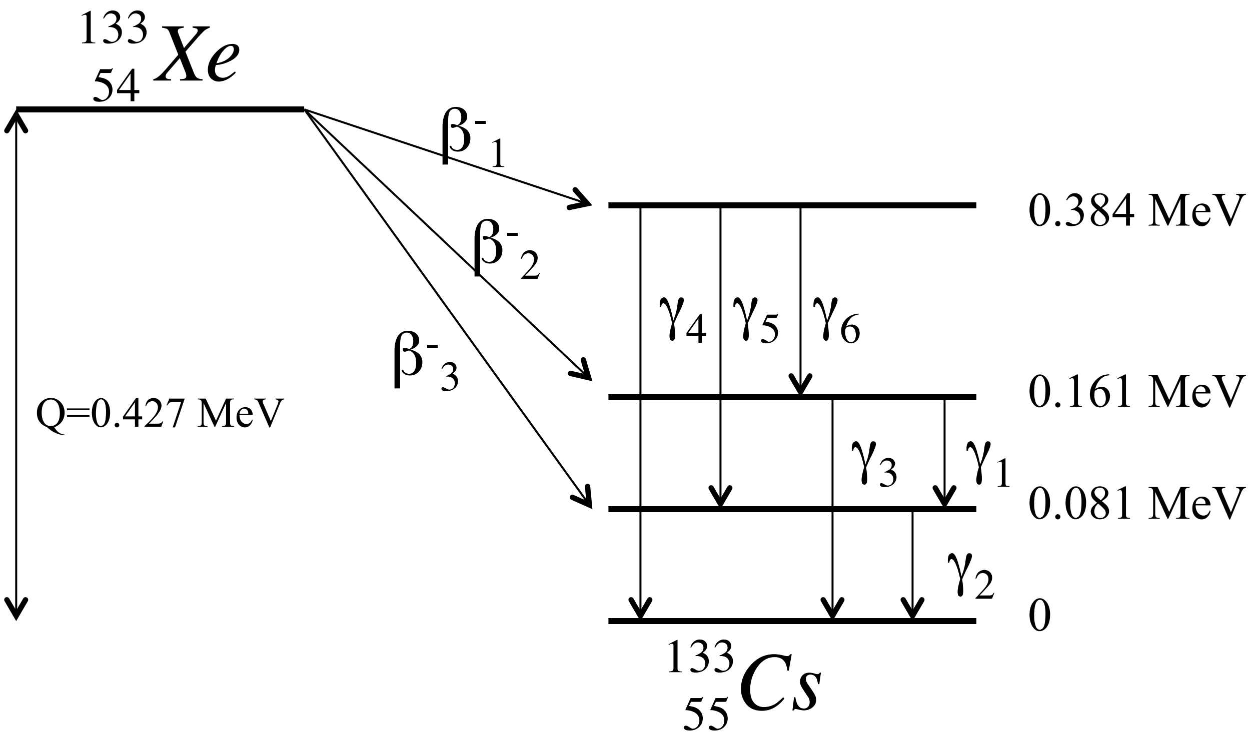
Beta Energy Spectrum



Decay by (β^-, γ) emission (ABR core study guide 17.b.i and 17.b.iii(a))

$(n^o \rightarrow p^+ + \beta^- + \bar{\nu})$

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



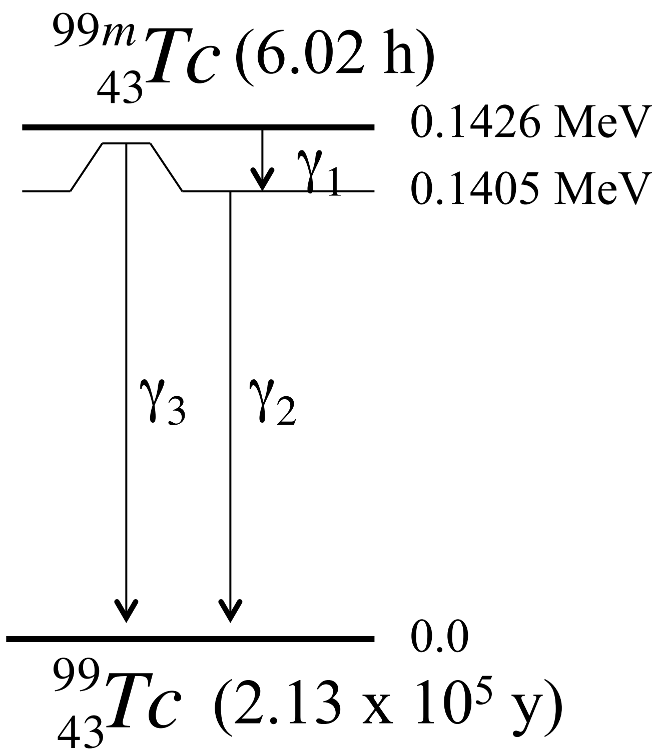
Another nuclear medicine example: ^{131}I

Isomeric Transition (IT) and Internal Conversion (IC)

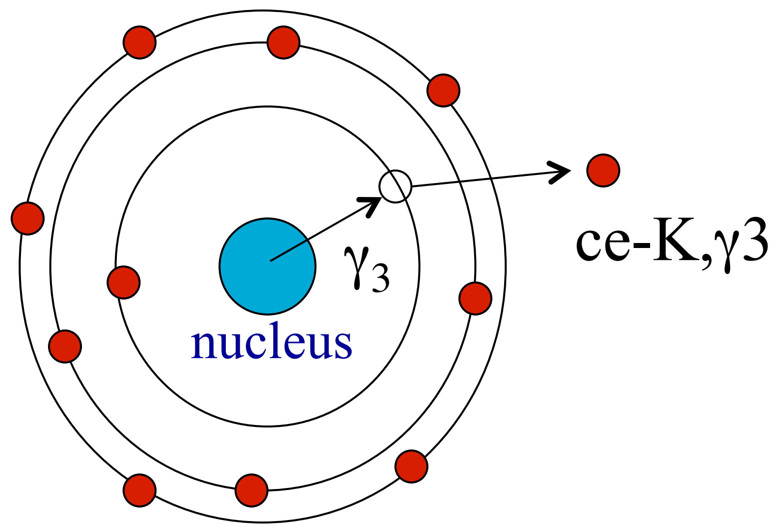
(ABR core study guide 17.b.iv)

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

metastable state



(no change in Z)



K-shell conversion yield

α_K = prob(ce-K)/prob(γ)

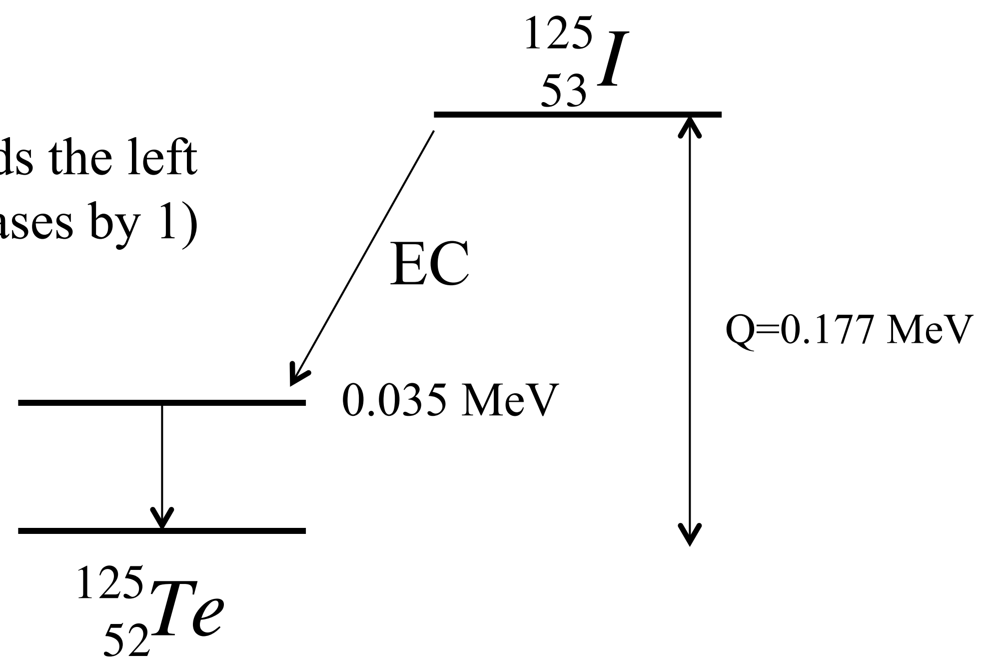
(Internal conversion is followed by emission of characteristic x-rays and/or Auger electrons.)

Decay by electron capture (EC) **(ABR core study guide 17.b.iii(c))**

($p^{+} + e^{-}$ -> $n^{o} + \nu$ + energy)

$$ {}^{A}_{Z}X \xrightarrow{\text{EC}} {}^{A}_{Z-1}Y $$

(drawn towards the left since Z decreases by 1)



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

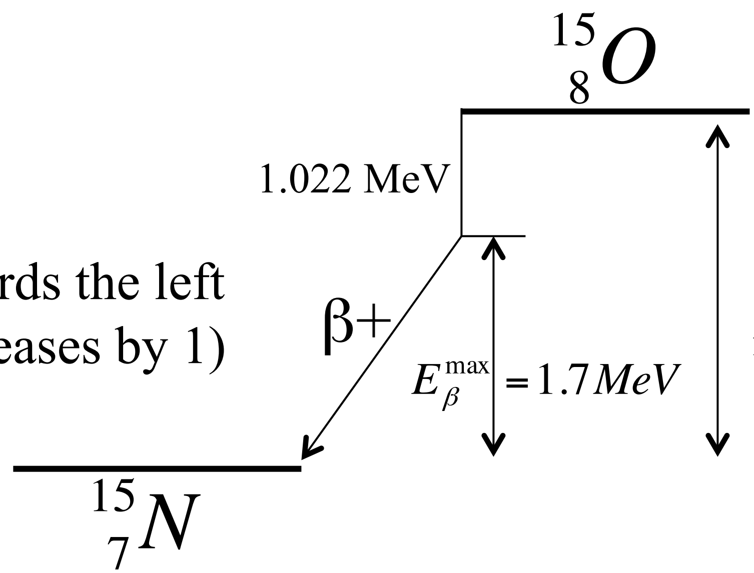
Decay by positron emission (ABR core study guide 17.b.iii(b))

($p^+ \to n^o + \beta^+ + \nu$ + energy)

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

(followed by positron-electron annihilation: $\beta^+ + e^- \to \gamma + \gamma$)

(drawn towards the left since Z decreases by 1)



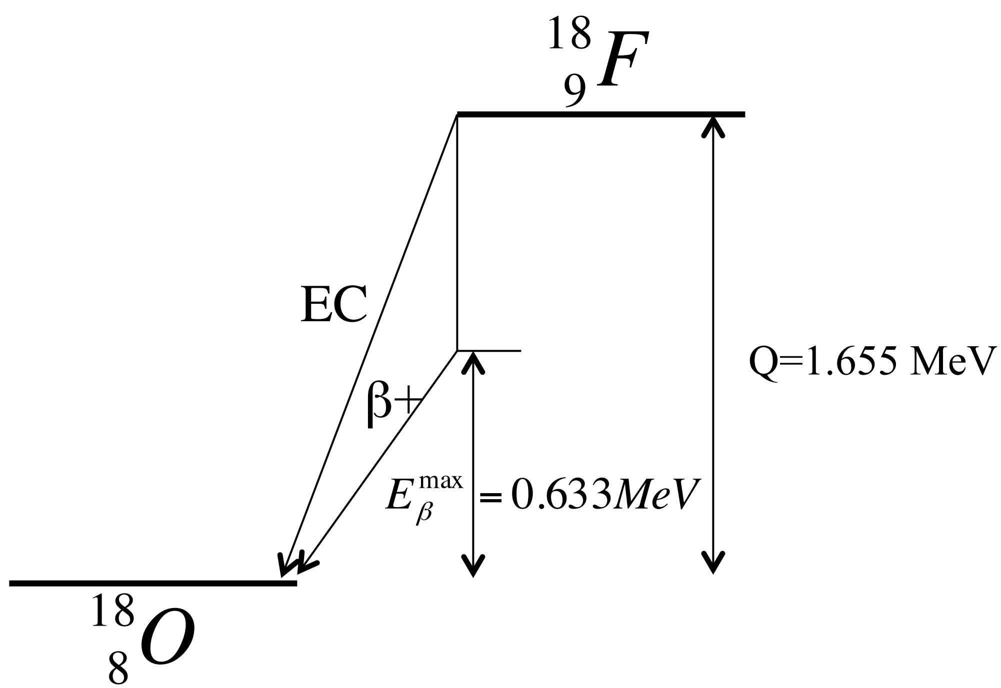
Q=2.722 MeV, divided among positron, neutrino, and the annihilation photons.

(Q must be $\geq$1.022 MeV = 2 $m_e c^2$)

Another nuclear medicine example: ^{13}N

Competitive β⁺ and EC decay

(ABR core study guide 17.b.iii(b) and 17.b.iii(c))



<u>For F-18</u>:

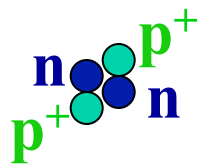
Prob(EC) = 3%

Prob (β+) = 97%

Another nuclear medicine example: ^{11}C

Decay by α-particle emission

(ABR core study guide 17.b.ii))

α-particle : 

(nucleus of helium atom)

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

(Some α-emitters may be useful for radiation therapy.)