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Nuclear diagnostics and Magnetic Resonance Imaging

Week 1; Lecture 1; Section 2: Nuclear medicine

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Section 2

Nuclear medicine

What is “nuclear diagnostics” (aka nuclear medicine)?

Imaging using radio-isotopes:

- Introduce radionuclide into the body:
  - A ‘radiotracer’ is usually introduced into the body on a ‘radiophamaceutical’;
  - Detectors external to body used to ‘image’ distribution of radiotracer within body;
  - Spatial distribution depends on ‘take-up’ of radiopharmaceutical in tissue.
- ND (NM) usually ‘emission imaging’ . . .
  to be contrasted with conventional x-ray imaging which is ‘transmission imaging’.

Sensitivity!

- Goal is to use such a small amount of radiotracer that biological system under investigation is not perturbed.

Radiopharmaceuticals

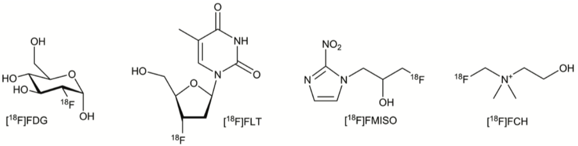
Enormous field! Beyond the scope of this course; some examples later.

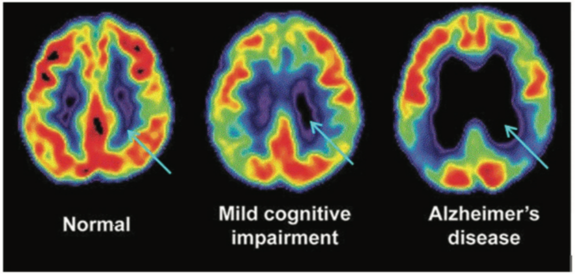
Consider the radiopharmaceutical as a means of delivering an isotope to a particular location:

- Compound tagged with a radionuclide;
- Accumulation, rate of uptake and clearance related to physiological, biochemical and/or molecular processes;
- Carrier molecule designed to target organ or function;
- Radionuclide required to produce emissions that can be detected outside the body;:
  - Require penetrating radiation: primary gammas, photons produced in positron annihilation;
- Radionuclides delivered in tiny amounts: nanograms:
  - Require sensitive detectors.
- Administration:
  - Intravenous, inhalation, subcutaneous, oral

Radiopharmaceuticals: an example

Delivering ^{18}F, and exploitation in diagnosis of Alzheimer's disease using PET.





http://real.mtak.hu/41305/1/225_247_BRC_2015_Vol_2.pdf

Radioactivity '101'

- Radioactivity is an intrinsic property of unstable nuclei;
- Quantum-mechanical process: uniform probability of decay;
- Radioactive decays:
  - Electromagnetic: de-excitation yielding photons . . . gammas;
  - Weak:
    - $N \rightarrow N' + e^- + \bar{\nu}_e$
    - $N \rightarrow N' + e^+ + \nu_e$ $\leftarrow$ the basis of PET.
  - Strong: e.g. α-decay; not of use for ND (NM).
- Isotopes have the same number of protons;
- Isotones have the same number of neutrons;
- Isobars have the same number of nucleons.

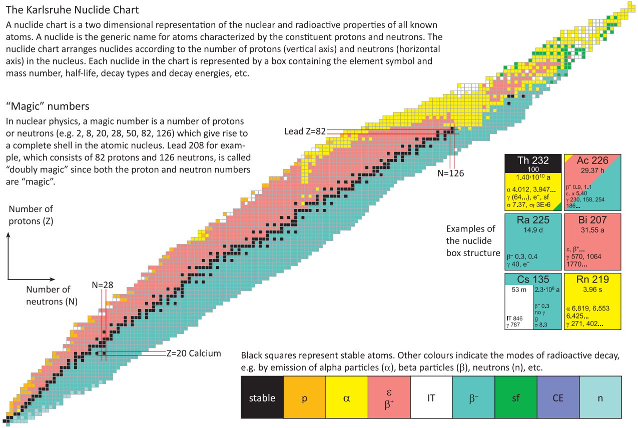
Nuclei and decay modes

The Karlsruhe Nuclide Chart

A nuclide chart is a two dimensional representation of the nuclear and radioactive properties of all known atoms. A nuclide is the generic name for atoms characterized by the constituent protons and neutrons. The nuclide chart arranges nuclides according to the number of protons (vertical axis) and neutrons (horizontal axis) in the nucleus. Each nuclide in the chart is represented by a box containing the element symbol and mass number, half-life, decay types and decay energies, etc.

"Magic" numbers

In nuclear physics, a magic number is a number of protons or neutrons (e.g. 2, 8, 20, 28, 50, 82, 126) which give rise to a complete shell in the atomic nucleus. Lead 208 for example, which consists of 82 protons and 126 neutrons, is called "doubly magic" since both the proton and neutron numbers are "magic".



Black squares represent stable atoms. Other colours indicate the modes of radioactive decay, e.g. by emission of alpha particles (α), beta particles (β), neutrons (n), etc.

stable	p	α	ε β^+	IT	β^-	sf	CE	n

https://www.epj-n.org/articles/epjn/full_html/2019/01/epjn180014/epjn180014.html

β decay

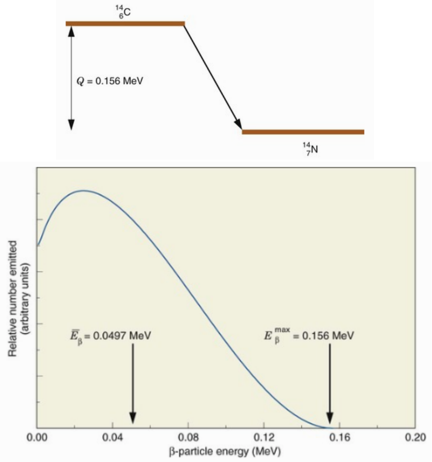
Underlying process: $n \rightarrow p + e^- + \bar{\nu}_e$

$$ {}^A_Z X \xrightarrow{e^-(\beta^-)} {}_{Z+1}{}^A Y $$

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

Kinematics requires neutral atoms, hence e^- on LHS.

Continuous electron-energy spectrum due to 3-body decay.



(β, γ) decay

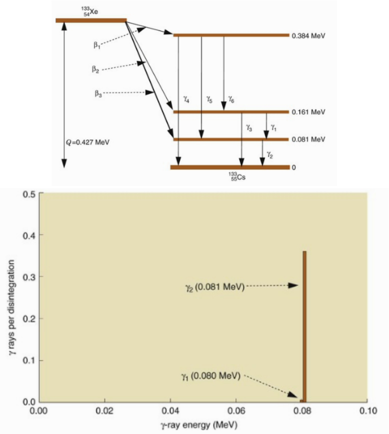
β absorbed in short distance; no use for ND (NM).
Exploit de-excitation γs.

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

β-decay leaves Y in excited state—indicated by '$*$'.

Discrete photon energy or energies.

Electron from β decay absorbed in tissue.



Isomeric transition (IT)

Daughter nuclide produced in long-lived, 'metastable' state.
Again, exploit de-excitation γs.

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

β-decay leaves Y in metastable excited state—indicated by 'm'.

Discrete photon energy or energies.

IT identical to decay by γ production, except that lifetime is much longer.

Important example:

$$ {}^{99}Mo \xrightarrow{\beta^-} {}^{99m}Tc \xrightarrow{\gamma} {}^{99}Tc $$

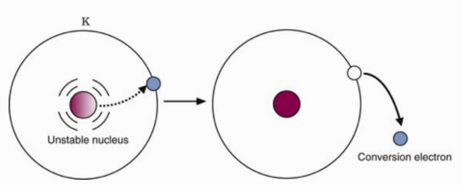
$\tau_{1/2}$ = 66 hrs $\quad$ $\tau_{1/2}$ = 6 hrs

Halflife of ^{99}Tc is 211 millennia:

- Decay rate of ^{99}Tc is low; but
- Clearly important to ensure 'waste' radionuclide is excreted.

Internal conversion (IC)

$$^{A}_{Z}X^{*} \xrightarrow{\text{IC}} {}^{A}_{Z}X + e$$



Nucleus in an excited state or a meta-stable excited state may decay such that:

- Energy from nuclear is transition transferred to orbital electron which is emitted;
- Electron emitted has an energy typical of a nuclear transition;
- Orbital vacancy is filled creating characteristic X-rays or Auger electrons.

In a sense, the γ that might have been emitted is 'internally converted' into an electron.

Positron emission

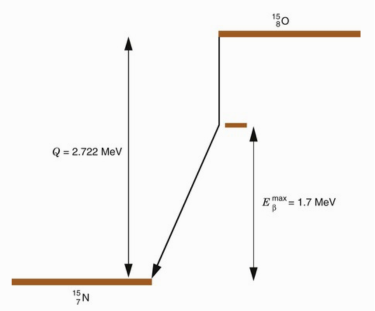
Underlying process: $p \rightarrow n + e^{+} + \nu_e$

$$ {}^{A}_{Z}X \xrightarrow{e^{+}(\beta^{+})} {}_{Z-1}^{\;\;A}Y $$

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

Kinematics requires neutral atoms,
hence e^{-} on RHS.
[Orbital electron 'lost' from atom after decay]

Continuous electron-energy spectrum due to 3-body decay.



$$
\begin{aligned}
Q &= 2.72\,\mathrm{MeV} \\
&= 2m_e c^2 + E_{\beta}^{\mathrm{max}} \\
&= 1.022\,\mathrm{MeV} + 1.7\,\mathrm{MeV}
\end{aligned}
$$

Summary

Radiopharmaceuticals are designed to deliver radio-isotopes to particular locations in the body

Emission imaging requires that the radionuclide produces penetrating radiation (γ-rays)

Decay modes exploited in ND (NM):

- Beta decay – especially β^+ decay
- (β, γ) decay
- Isomeric transition (IT)
- Internal conversion (IC)