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Nuclear diagnostics and Magnetic Resonance Imaging

Week 1; Lecture 2; Radionuclides, production methods, γ-camera introduction

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Section 1

Radionuclides for nuclear medicine

A practical matter . . .

A "Goldilocks" problem:

- Lifetime: neither:
  Too long—too small a fraction of decays used for imaging;
  Too short—too small a fraction delivered for imaging
- Practical lifetimes for imaging: minutes (seconds) to days
  - Longer-lived isotopes have applications in therapy
- Decay products 'sufficiently' penetrating:
  - Imaging requires external detection of radiation
- Radiation must emerge from the body:
  - Without leaving an unacceptably large dose . . . and . . .
  - With properties that make it easy to detect . . . and . . .
  - Pointing back to the origin of the radiation

Desirable properties of radioisotopes

- α-emitters are not suitable for imaging;
  Range too small, deposit too much dose
- γ-emitters: γ energy in range $50 < E_\gamma < 600\,\text{keV}$;
  Low-energy photons have large interaction probability so unlikely to leave body, simply deposit dose
- Beta emitters: e^- absorbed or lose energy and scatter, not used for imaging;
  If absorbed, e^- simply deposits dose, reducing rate that could be detected.
  Energy loss and scattering of high-energy e^- destroys pointing accuracy and make e^- hard to detect.
- e^+ emitters exploited in positron-emission tomography;
  Signal (back-to-back photons) from e^+e^- annihilation.

Radiopharmaceuticals – examples

Nuclide	Compound	Measurement	Example of clinical use
^{99m}Tc	^{99m}Tc-methylene diphosphonate (MDP)	Bone metabolism	Metastatic spread of cancer
^{99m}Tc	Sestamibi, Tetrofosmin	Myocardial perfusion	Coronary artery disease
^{99m}Tc	MAG3, DTPA	Renal function	Kidney disease
^{99m}Tc	HMPAO, EDC	Cerebral blood flow	Neurologic disorders
^{131}I	Sodium Iodide	Thyroid function	Thyroid disease
^{67}Ga	Gallium citrate	Sequestered in tumours	Tumour localization
^{111}In	Labelled white blood cells	Sites of infection	Detecting inflammation
^{18}F	Fluorodeoxyglucose	Glucose metabolism	Cancer, neurological disorders and myocardial diseases
^{13}N	Ammonia	Myocardial perfusion	Coronary artery disease

Summary of section 1

Nuclear decay processes exploited in nuclear medicine:

- γ emitters; $50 < E_\gamma < 600\,\text{keV}$;
- e^+ emitters

Lifetimes . . . "from minutes to days"

Section 2

Methods for the production of radionuclides

Methods for the production of radionuclides; overview

Nuclear reactor:

- Neutron capture
- Fission fragments

Radionuclide generators:

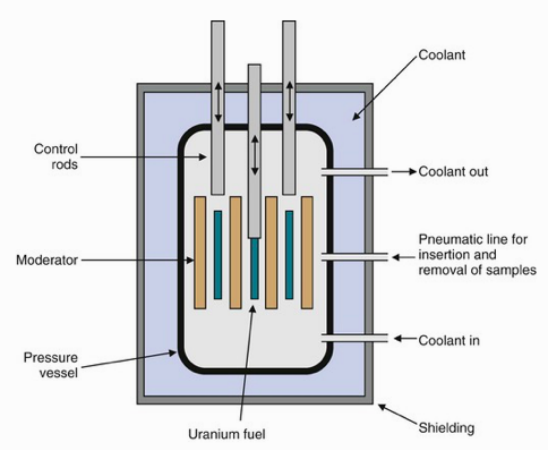
- Portable devices widely used in hospitals
- Require materials produced in nuclear reactors or accelerators

Accelerator:

- Cyclotron
- Active area of research:
  - Related areas of research within the CCAP

Nuclear reactor; one-slide outline

- Graphite or D_2O moderator surrounds fissionable fuel cells
- Control rods, commonly boron, shield or expose fuel cells
- Position of fuel cells & control rods determine rate of chain reaction
- Ports in core allow insertion of samples for irradiation



Used to generate fission products or perform neutron activation

Nuclear reactor: radionuclides produced by 'neutron activation'

Fission of ^{235}U produces neutrons which bombard samples introduced into the core.

Neutron activation produces:

- Neutron-rich radionuclides, which usually undergo beta decay
- Product is chemically identical to parent material:
  - Product therefore can not be separately chemically;
  - Results in lower purity and lower activity than other production methods

Example reactions:

- $^{31}\mathrm{P}(n,\gamma)^{32}\mathrm{P}$
  - Capture of n produces $^{32}\mathrm{P}^{*}$ which decays to $^{32}\mathrm{P}$ emitting a γ
- $^{50}\mathrm{Cr}(n,\gamma)^{51}\mathrm{Cr}$

Nuclear reactor: production of ^{125}I

^{125}I *is* produced via neutron activation and *can* be chemically separated, vis:

$$^{124}\mathrm{Xe}(n,\gamma)^{125}\mathrm{Xe} \underbrace{\xrightarrow{\text{EC or } \beta^-}}_{T_{\frac{1}{2}}=17\,\mathrm{hr}} {}^{125}\mathrm{I}$$

Nuclear reactor: production via fission fragments

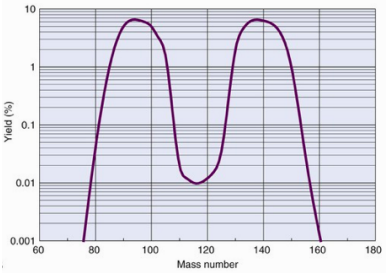
Fission fragments:

- Have bimodal distribution in A
- Excess of neutrons, hence tend to undergo β^- decay until stable nucleus is produced

If long-lived isotope is produced it can be chemically extracted, e.g.:

$$^{99}_{39}\mathrm{Y} \xrightarrow{\beta^-(1.5\,\mathrm{s})} {}^{99}_{40}\mathrm{Zr} \xrightarrow{\beta^-(21\,\mathrm{s})} {}^{99}_{41}\mathrm{Nb} \xrightarrow{\beta^-(15\,\mathrm{s})} {}^{99}_{42}\mathrm{Mo}$$

Halflife of ^{99}Mo is 65.9 hr, long enough to allow it to be extracted and incorporated in radionuclide generator to produce $^{99\mathrm{m}}$Tc



Radionuclide generators

Parent-daughter radionuclide pair in an apparatus that permits separation and extraction of the daughter from the parent

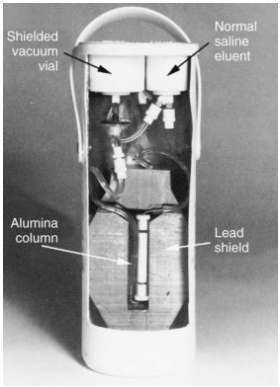
$T_P > T_D$ so that daughter product is replenished continuously by the decay of the parent and may be extracted repeatedly

Provides a local supply of short-lived radionuclides without needing a cyclotron or nuclear reactor

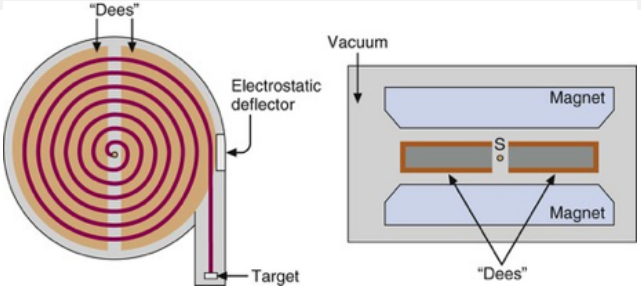
Radionuclide generator: ^{99m}Tc for imaging

$$^{99}\text{Mo} \xrightarrow{\beta^-;\ T_{\frac{1}{2}}=66\ hr} {}^{99m}\text{Tc} \xrightarrow{\gamma;\ T_{\frac{1}{2}}=6\ hr} {}^{99}\text{Tc}$$

- ^{99}Mo bound to an alumina column in form of molybdate ion (MoO_4^-)
- ^{99m}Tc, the decay product, is not bound to column; it is chemically different
- ^{99m}Tc is eluted from column with 5–25 ml saline
- 75–85% of available ^{99m}Tc can be extracted
- Typically used for one week
- Often refereed as a 'Molly' or a 'Cow'



Accelerator: cyclotron



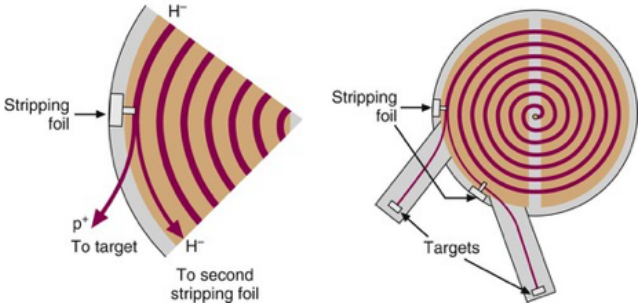
Cyclotron frequency, f:

$$f = \frac{qB}{2\pi m}$$

where q is ion charge, B the magnetic field strength, and m is ion mass.

Extraction is at a single, pre-determined, energy.

Accelerator: cyclotron



Schematic of H^- ion cyclotron showing stripping foils and targets.

Compact biomedical cyclotron

Medical cyclotrons often located near PET scanner due to short lifetimes of radionuclides that are produced.

Examples of cyclotron-produced radionuclides

Product	Decay Mode	Common Production Reaction	Natural Abundance of Target Isotope* (%)	Energy Threshold (MeV)†
^{11}C	β^+, EC	^{14}N(p,α)^{11}C	99.6	3.1
		^{10}B(d,n)^{11}C	19.9	0
^{13}N	β^+	^{16}O(p,α)^{13}N	99.8	5.5
		^{12}C(d,n)^{13}N	98.9	0.35
^{15}O	β^+	^{14}N(d,n)^{15}O	99.6	0
		^{15}N(p,n)^{15}O	0.37	—
^{18}F	β^+, EC	^{18}O(p,n)^{18}F	0.20	2.57
		^{20}Ne(d,α)^{18}F	90.5	0
^{67}Ga	(EC,γ)	^{68}Zn(p,2n)^{67}Ga	18.8	5.96
^{111}In	(EC,γ)	^{109}Ag(α,2n)^{111}In	48.2	—
		^{111}Cd(p,n)^{111}In	12.8	—
^{123}I	(EC,γ)	^{122}Te(d,n)^{123}I	2.6	—
		^{124}Te(p,3n)^{123}I	4.8	—
^{201}Tl	(EC,γ)	^{201}Hg(d,2n)^{201}Tl	13.2	—

Radioisotopes produced using cyclotron beams.
Decay schemes and production reactions are given.

Summary of section 2

Production methods:

- Nuclear reactor
- Radionuclide generators, e.g. “molly cow”
- Accelerator