Chapter 18

Radioactivity and Nuclear Transformation

Activity

- Number of radioactive atoms undergoing transformation per unit time

  $$A = -\,dN/dt = \lambda N$$

- 1 **Curie(Ci)** = 3.7×10^{10} disintegration/sec
- 1 **Becquerel(Bq)** = 1 disintegration/sec
  - SI unit
- Diagnostic range: 0.1 ~ 30mCi
- Therapeutic range: 300mCi

Decay Constant & Half Life

- Radioactive decay is random process
  - Decay constant : λ
  - $A = - dN/dt = \lambda N \rightarrow N=N_0e^{-\lambda t} \rightarrow N=N_0 2^{-t/T_{p1/2}}$
- Physical half life
  - $\mathbf{T_{p1/2}}=0.693/\lambda$
  - Fraction of second ~ billions of year
  - Hours or days for medical purpose

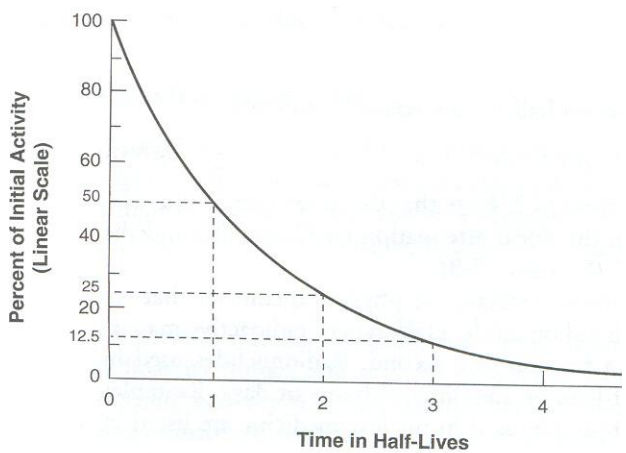
Radionuclide	$T_{p1/2}$
Fluorine 18(^{18}F)	110 min
Technetium99m(^{99m}Tc)	6.02 hr
Iodine123(^{123}I)	13.27 hr
Indium(^{111}In)	2.81 d
Thallium 201(^{201}Tl)	3.04 d
Iodine131(^{131}I)	8.02 d
Phosphorus 32(^{32}P)	14.26 d
Iodine125(^{125}I)	59.41 d
Cobalt 57(^{57}Co)	271.79 d

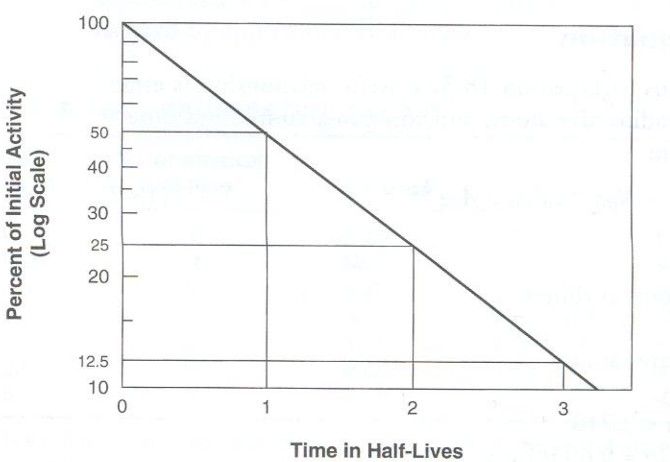
Decay Equation

- $N_t = N_0 e^{-\lambda t} \rightarrow A = -\, dN_t/dt = \lambda N_0 e^{-\lambda t} = A_0 e^{-\lambda t}$
  - Activity also decay exponentially

Ex) Remain activity of 500uCi ^{111}**In** after 2 days

- Half life = 2.81 days → $\lambda = 0.693/2.81 = 0.246\ day^{-1}$
- $A = A_0 e^{-\lambda t} = 500 e^{-(0.246)(2)} = 306 (uCi)$





Nuclear Transformation

- Radioactive Decay
  - Radiation emission during spontaneous decay
  - Until to reach stable nuclide
    - Parent nuclide → daughter nuclide
- Decay types
  1. Alpha decay
  2. Beta-minus emission
  3. Beta-plus(positron) emission
  4. Electron capture
  5. Iosmeric transition

     same molecular formula
     but different structural
     formulas

Alpha Decay

- ${}_{Z}^{A}X \rightarrow {}_{Z-2}^{A-4}Y^{-2} + {}_{2}^{4}He^{+2}$ **+ transition energy**
  - Increase in N/Z ratio

  Ex) ${}_{86}^{220}Rn \rightarrow {}_{84}^{216}Po + {}_{2}^{4}He^{+2}$ + 6.4MeV

  134/86=1.56 **132/84=1.57**

- Mostly with heavy nuclides (A>150)
  - Followed by gamma emission and X-ray emission
- Heaviest and least penetrating
  - 1cm/MeV in air, 100um in tissue
  - Cannot penetrate dead layer of skin
  - Not used in medical imaging

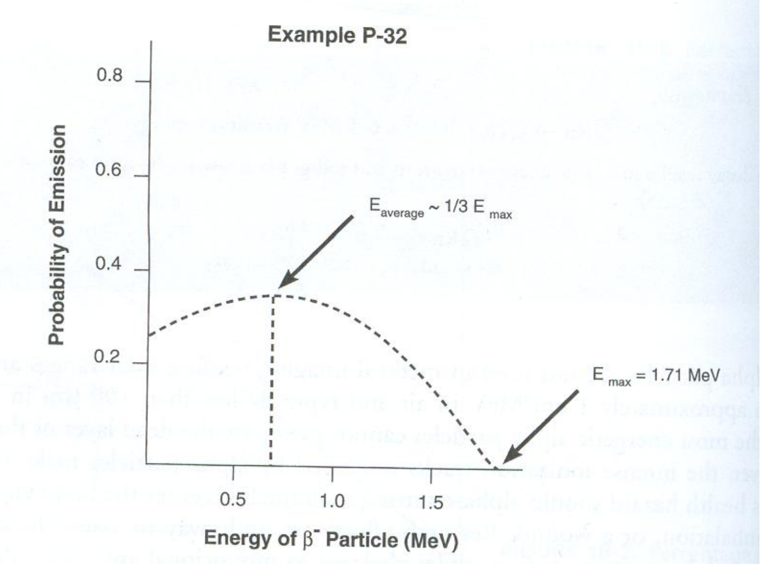
Beta-Minus(Negatron) Decay

- $_{Z}^{A}X \rightarrow {}_{Z+1}^{A}Y^{+} + \beta^{-} + \nu^{-}$ + **transition energy**
  - β^{-} : identical to electron, discrete maximal energy
  - ν^{-} : antineutrino, neutral subatomic particle smaller mass than electron, rarely interact with mater
  - Increase in Z, no change in A (isobaric transitions)

Ex) $_{15}^{32}P \rightarrow {}_{16}^{32}S + \beta^{-}$

17/15=1.13 16/16=1.00

- Radionuclide having excess number of neutrons
  - High N/Z ratio



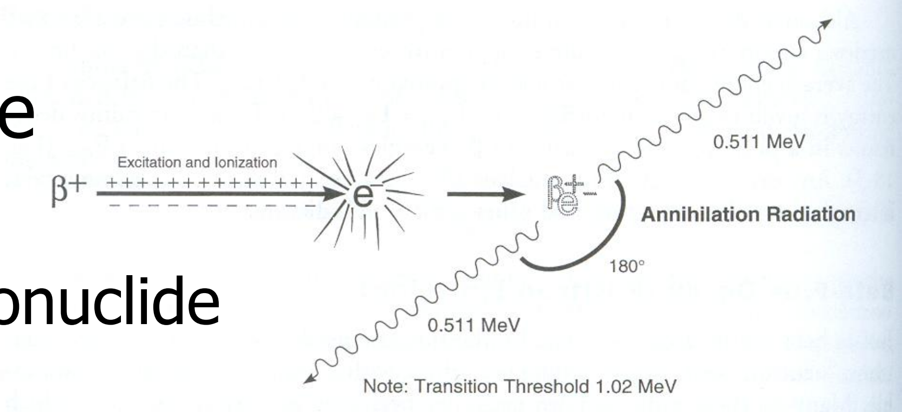
Beta-Plus Decay

- ${}_{Z}^{A}X \rightarrow {}_{Z-1}^{A}Y^{-} + \beta^{+} + \nu$ + **transition energy**
  - β^{+} : **positron**, poly energetic spectrum,
    - annihilation with electron, 180°-2 γ ray of 0.511MeV
  - ν : neutrino, antiparticle with antineutrino
  - Decrease Z by 1, no change in A (isobaric transitions)

Ex) ${}_{9}^{18}F \rightarrow {}_{8}^{18}O + \beta^{+}$

9/9=1.00 **10/8=1.25**

- Neutron poor radionuclide
  - Low N/Z ratio
  - Accelerator produced radionuclide



Electron Capture Decay

- Alternative to beta plus decay
  - For neutron poor radionuclide
  - Energy difference btw nuclides lower than threshold to produce positron
- **$_{Z}^{A}X + e^{-} \rightarrow {}_{Z-1}^{A}Y^{-}$ + transition energy**
  - Capture orbital electron of K or L shell
  - Followed by characteristic radiation from outer shell
    - Using for imaging
  - Decrease Z by 1, no change in A (isobaric transitions)

Thallium Mercury

Ex) $_{81}^{201}Tl + e^{-} \rightarrow {}_{80}^{201}Hg$ + energy

120/81=1.48 **121/80=1.51**

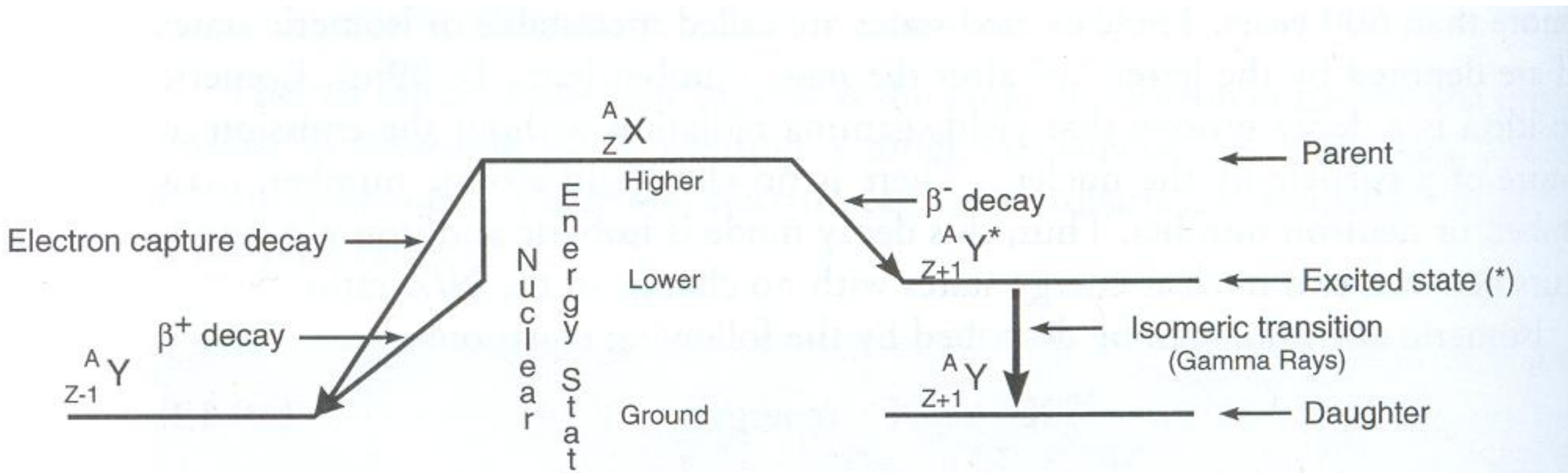
Isomeric Transition

- Not directly into stable state
  - Through excited state: meta state, isomeric state
  - Half life: 10^{-12} sec ~600 years
- Metastate → stable state + gamma ray
- **$_{Z}^{Am}X$ → $_{Z}^{A}X$ + transition energy**
  - No change in atomic(proton) number
  - No change in neutron number
  - No change in mass number

  Ex) Tc-99m

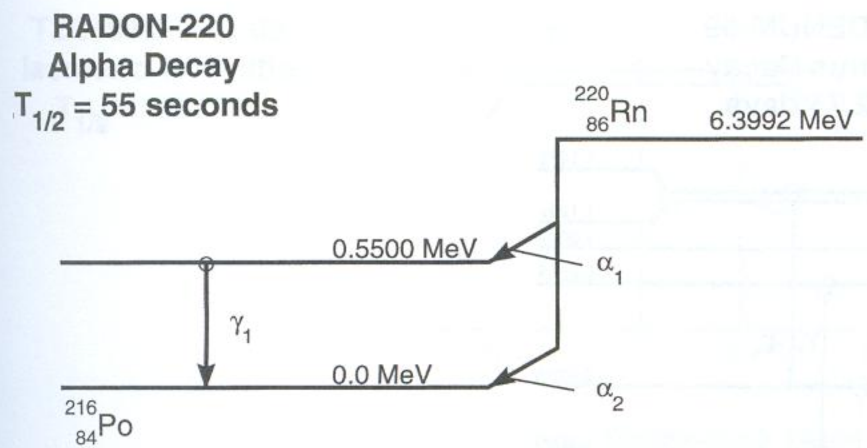
Decay Schemes

- Decay: unique characteristic of the nuclide
- Parent/daughter nuclide, mode of decay, energy level, radiation emission



Decay Scheme of Radon-220

- Alpha decay
- $T_{p1/2}$=55sec
- ${}_{86}^{220}Rn \rightarrow {}_{84}^{216}Po$
- α_1(0.07%)
  - Followed by isomeric decay
- α_2(99.93%)
  - Directly to ground state
- Decay data table



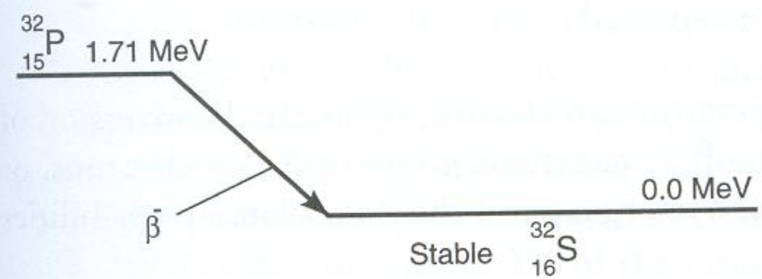
Decay Data Table

Radiation		Mean Number per Disintegration	Mean Energy per Particle (MeV)
Alpha	1	0.0007	5.7470
Recoil Atom		0.0007	0.1064
Alpha	2	0.9993	6.2870
Recoil Atom		0.9993	0.1164
Gamma	1	0.0006	0.5500

Decay Scheme of ^{32}P

- β^- decay
- $T_{p1/2}$=14.3 days
- Into stable ^{32}S
- E_{max}=1.71MeV
- Pure beta emitter
- Using as therapeutic agent

PHOSPHORUS-32
Beta-Minus Decay
$T_{1/2}$ = 14.3 days

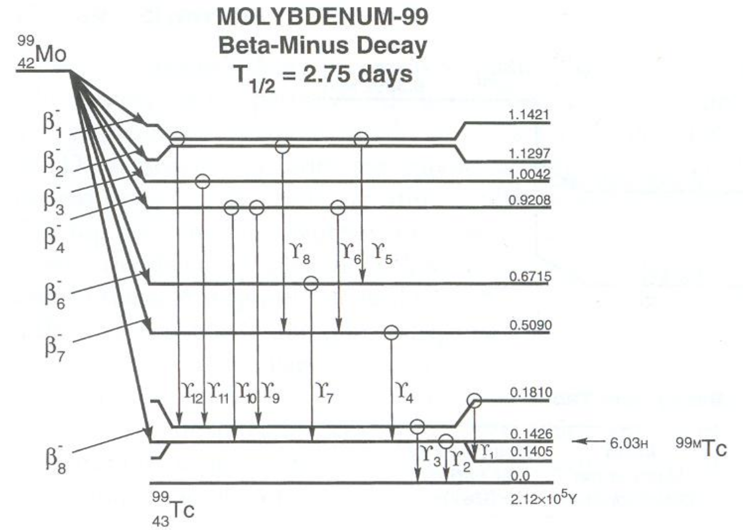


Decay Data Table

Radiation	Mean Number per Disintegration	Mean Energy per Particle (MeV)
Beta Minus	1.000	0.6948

Decay Scheme of ^{99}Mo

- β^- decay
  - Followed by isomeric decay
- $T_{p1/2}$=2.75 days
- Into stable ^{99}Tc
  - Intermediate ^{99m}Tc
- Decay data table



Decay Data Table

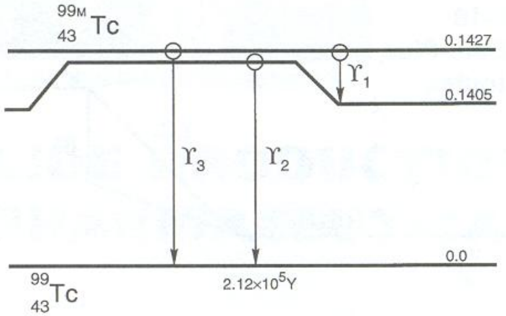
Radiation		Mean Number per Disintegration	Mean Energy per Particle (MeV)	Radiation		Mean Number per Disintegration	Mean Energy per Particle (MeV)
Beta Minus	1	0.0012	0.0658	Gamma	4	0.0143	0.3664
Beta Minus	3	0.0014	0.1112	Gamma	5	0.0001	0.3807
Beta Minus	4	0.1850	0.1401	Gamma	6	0.0002	0.4115
Beta Minus	6	0.0004	0.2541	Gamma	7	0.0005	0.5289
Beta Minus	7	0.0143	0.2981	Gamma	8	0.0002	0.6207
Beta Minus	8	0.7970	0.4519	Gamma	9	0.1367	0.7397
Gamma	1	0.0130	0.0405	K Int Con Elect		0.0002	0.7186
K Int Con Elect		0.0428	0.0195	Gamma	10	0.0479	0.7782
L Int Con Elect		0.0053	0.0377	K Int Con Elect		0.0000	0.7571
M Int Con Elect		0.0017	0.0401	Gamma	11	0.0014	0.8231
Gamma	2	0.0564	0.1405	Gamma	12	0.0011	0.9610
K Int Con Elect		0.0058	0.1194	K Alpha-1 X-Ray		0.0253	0.0183
L Int Con Elect		0.0007	0.1377	K Alpha-2 X-Ray		0.0127	0.0182
Gamma	3	0.0657	0.1810	K Beta-1 X-Ray		0.0060	0.0206
K Int Con Elect		0.0085	0.1600	KLL Auger Elect		0.0087	0.0154
L Int Con Elect		0.0012	0.1782	KLX Auger Elect		0.0032	0.0178
M Int Con Elect		0.0004	0.1806	LMM Auger Elect		0.0615	0.0019
				MXY Auger Elect		0.1403	0.0004

FIGURE 18-8. Principal decay scheme of molybdenum-99.

Decay Scheme of ^{99m}Tc

- Isomeric transition
- $T_{p1/2}$=6.02 hrs
- 140.5keV, 142.7keV
- Detection for imaging

TECHNETIUM 99M
Isomeric Transition
$T_{1/2}$ = 6.02 hrs.

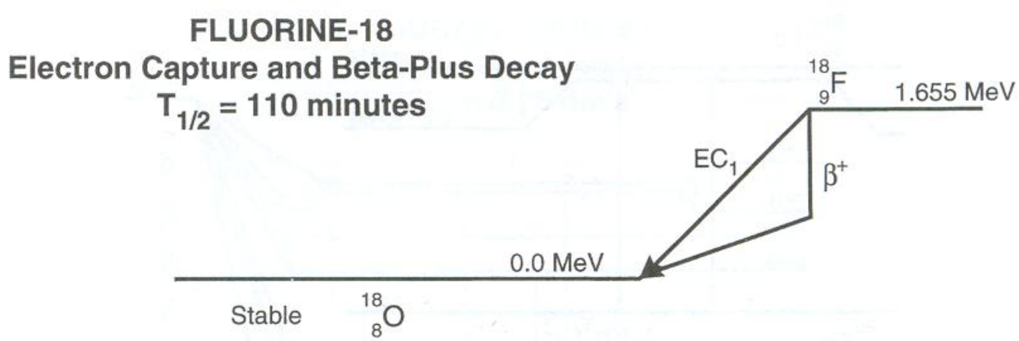


Decay Data Table

Radiation		Mean Number per Disintegration	Mean Energy per Particle (MeV)
Gamma	1	0.0000	0.0021
M Int Con Elect		0.9860	0.0016
Gamma	2	0.8787	0.1405
K Int Con Elect		0.0913	0.1194
L Int Con Elect		0.0118	0.1377
M Int Con Elect		0.0039	0.1400
Gamma	3	0.0003	0.1426
K Int Con Elect		0.0088	0.1215
L Int Con Elect		0.0035	0.1398
M Int Con Elect		0.0011	0.1422
K Alpha-1 X-Ray		0.0441	0.0183
K Alpha-2 X-Ray		0.0221	0.0182
K Beta-1 X-Ray		0.0105	0.0206
KLL Auger Elect		0.0152	0.0154
KLX Auger Elect		0.0055	0.0178
LMM Auger Elect		0.1093	0.0019
MXY Auger Elect		1.2359	0.0004

Decay Scheme of ^{18}F

- β^+ decay(97%) +electron capture(3%)
- Followed by annihilation: 2 gamma rays
- Most widely using in PET



Decay Data Table

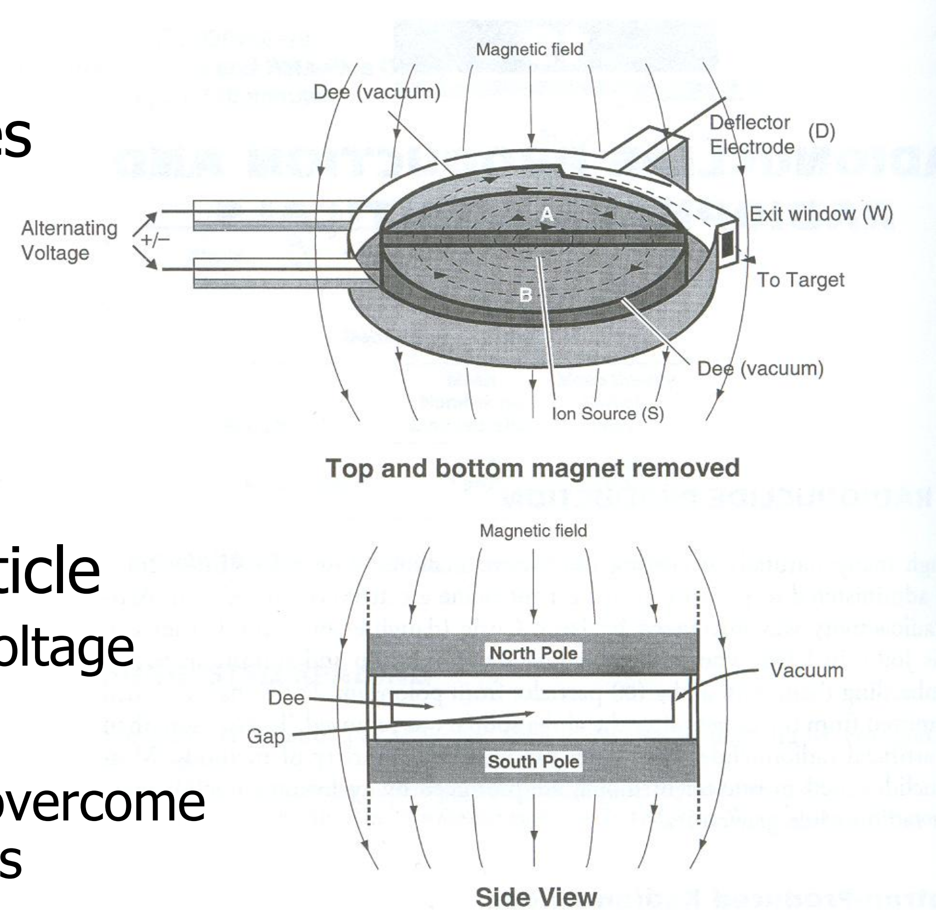
Radiation	Mean Number per Disintegration	Mean Energy Particle (MeV)
Beta Plus	0.9700	0.2496
Annih. Radiation	1.9400	0.5110

Chapter 19

Radionuclide Production and Radiopharmaceuticals

Radionuclide Production

- Artificially produced
  - More than 2500 nuclides
  - Cyclotron
  - Nuclear reactor
  - Radionuclide generator
- Cyclotron
  - Accelerate charged particle
    - By Multiply alternating voltage
  - Bombard to a target
    - Require high energy to overcome repulsive force of nucleus



Nuclear Reaction

- Gallium-67 production
  - Bombarding 20MeV proton into zinc-68
  - Gallium-67 with emitting 2 neutrons

  $_{30}^{68}\mathbf{Zn}\ (p,2n)\ _{31}^{67}\mathbf{Ga}$

- Iodine-123 production

  $_{53}^{127}\mathbf{I}\ (p,5n)\ _{54}^{123}\mathbf{Xe} \xrightarrow[T_{1/2}\ 2hr]{EC} {}_{53}^{123}\mathbf{I}$ ($T_{1/2}$ =13.27 hr)

  $_{54}^{124}\mathbf{Xe}\ (p,2n)\ _{55}^{123}\mathbf{Cs} \xrightarrow[T_{1/2}\ \sim 1sec]{EC\ or\ \beta+} {}_{54}^{123}\mathbf{Xe} \xrightarrow[T_{1/2}\ 2hr]{EC} {}_{53}^{123}\mathbf{I}$

- Indium-111 production

  $_{47}^{109}\mathbf{Ag}\ (\alpha,2n)\ _{49}^{111}\mathbf{In}$, $_{48}^{111}\mathbf{Cd}\ (p,n)\ _{49}^{111}\mathbf{In}$ ($T_{1/2}$ =2.81d)

  $_{48}^{112}\mathbf{Cd}\ (p,2n)\ _{49}^{111}\mathbf{In}$

Nuclear Reaction

- Cobalt-57 production: ${}_{26}^{56}\mathbf{Fe}$ (d,n) ${}_{27}^{57}\mathbf{Co}$ ($T_{1/2}$ =271.8d)
- Thallium-201 production

$${}_{81}^{203}\mathbf{Tl}\ \ (p,3n)\ {}_{82}^{201}\mathbf{Pb} \xrightarrow[T_{1/2}\sim 9.4\text{ hr}]{\text{EC or }\beta+} {}_{81}^{201}\mathbf{Tl}\ (T_{1/2} = 3.04\text{d})$$

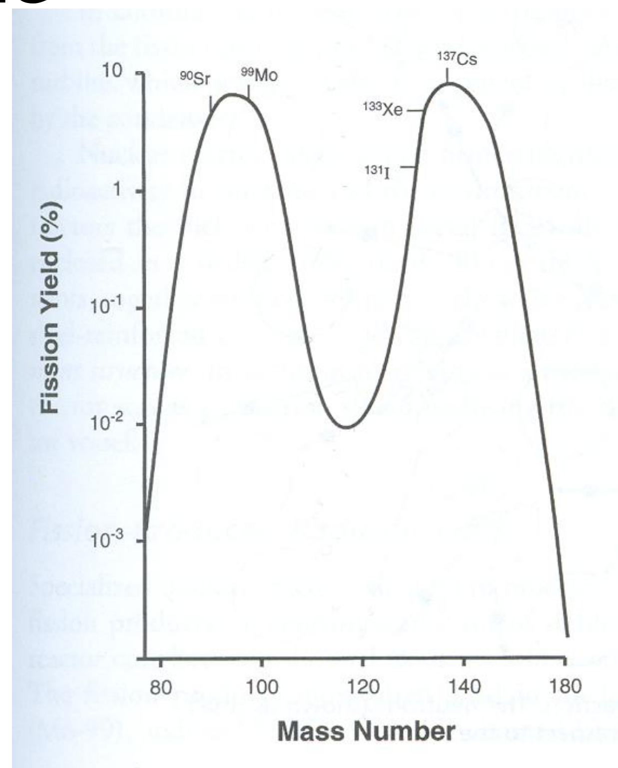
- Using hospital based cyclotron
  - Short half life
  - Fluorene-18: ${}_{8}^{18}\mathbf{O}$ (p,n) ${}_{9}^{18}\mathbf{F}$ ($T_{1/2}$=110min)
  - Nitrogen-13: ${}_{6}^{12}\mathbf{C}$ (d,n) ${}_{7}^{13}\mathbf{N}$ ($T_{1/2}$=10min)
  - Oxygen-15: ${}_{7}^{14}\mathbf{N}$ (d,n)${}_{8}^{15}\mathbf{O}$, ${}_{7}^{15}\mathbf{N}$(p,n)${}_{8}^{15}\mathbf{O}$ ($T_{1/2}$=2min)
  - Carbon-11: ${}_{5}^{10}\mathbf{B}$ (d,n) ${}_{6}^{11}\mathbf{C}$ ($T_{1/2}$=20.4min)

Nuclear Reactor

- Using neutron: uncharged
  - Can penetrate nucleus without high energy
  - 2 methods: Nuclear fission, neutron activation
- **Nuclear fission**
  - Splitting of atom into two smaller nuclei
  - Need energy to overcome nuclear binding energy
    - By absorption of neutrons
  - U-235: most widely using

U-235

- ${}^{235}_{92}U + {}^{1}_{0}n_{thermal} \rightarrow {}^{134}_{50}Sn + {}^{99}_{42}Mo + 3{}^{1}_{0}n_{fast} + \gamma + \sim 200MeV$
- Wide range of fragment nuclide
  - 200 radionuclide
  - Btw Z=70 & Z=160
- Neutron rich products
  - β- decay
- Medical use
  - Mo-99, I-131, Xe-133

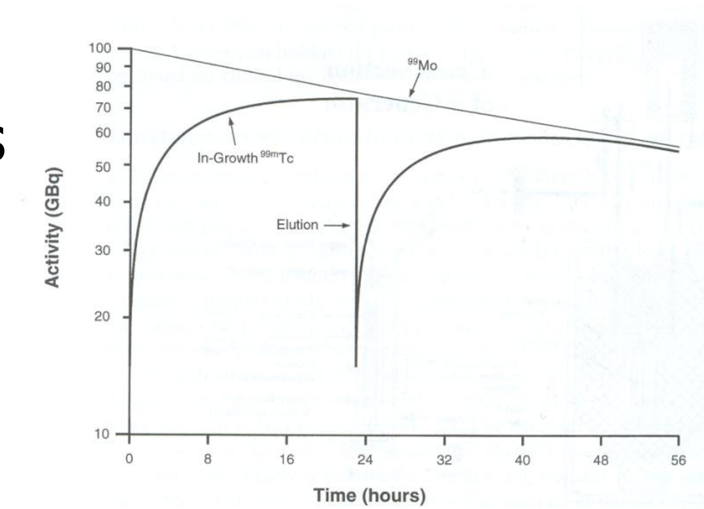


Neutron Activation

- Using neutron produced by fission
- Bombarding stable target material
- Capture neutron and emit γ ray
  - (n, γ) reaction
  - Decay with β- decay
  - Phosphorus-32: $^{31}P\ (n, \gamma)\ ^{32}P$ ($T_{1/2}$=14.3 days)
  - Chromium-51: $^{50}Cr\ (n, \gamma)\ ^{51}Cr$ ($T_{1/2}$=27.8 days)
- Difficult to separate chemically from target isotope
  - Limit in concentration

Radionuclide Generator

- Holding parent nuclide that daughter can easily be separated
  - Tc-99m: widely using in medicine ($T_{1/2}$=6 hrs)
    - Impractical to store weekly
  - Store parent nuclide Mo-99 ($T_{1/2}$=67 hrs)
- Chemically separate Tc-99m
  - Transient equilibrium: 23 hours
    - Production rate=decay rate
  - Separate every morning
  - Weekly store



Comparison

Characteristic	**Cyclotron**	**Fission**	**Neutron Activation**	**Generator**
Particle	p, d, α	n	n	By decay
Product	Neutron poor	Neutron excess	Neutron excess	Neutron poor/ excess
Decay mode	Positron emission, electron capture	Beta-minus	Beta-minus	Several modes
Carrier free?	yes	yes	no	yes
High specific activity	yes	yes	no	yes
Relative cost	high	low	low	low
Nuclides	^{201}Tl, ^{123}I, ^{63}Ga, ^{18}F, ^{15}O, ^{57}Co,	^{99}Mo, ^{131}I, ^{133}Xe	^{32}P, ^{51}Cr, ^{125}I, ^{111}In, ^{89}Sr, ^{153}Sm	^{99m}Tc, ^{82}Rb, ^{68}Ga

Radiopharmaceuticals

- Radionuclide + Pharmaceuticals → Radiopharmaceuticals
  - By injecting into freeze-dried pharmaceuticals
- Nuclear medicine imaging
  - **Tc-99m:** most widely in nuclear medicine
  - ^{123}I, ^{67}Ga, ^{111}In, ^{133}Xe,^{201}Tl
- Clinical PET imaging
  - Positron emission pharmaceuticals
  - **^{18}F** as fluorodeoxyglucose(FDG): 85%
  - ^{11}C, ^{13}N, ^{15}O, ^{68}Ga ^{82}Rb,

Ideal Radiopharmaceuticals

- Low radiation dose
  - Few particulate emission, abundance of clinically useful photons(~140KeV)
  - Compromise among patient attenuation, spatial resolution, detection efficiency
  - Effective half-life
    - Long enough for imaging, short enough to minimize dose
- High target/Non-target activity
  - Clinically useful uptake and clearance: **hot/cold** spot
- Safety, Convenience, Cost-Effective
  - Carrier free, shelf life….

Mechanism of Localization

- Compartmental Localization
  - Into anatomical compartment for abnormal opening finding
    - Xe-133 gas inhalation into lung
    - Tc-99m labeled RBC into circulatory system
- Cell Sequestration 격리
  - RBC withdraw → label with Tc-99m and damage → reinject
  - Measure spleen's ability to remove damaged RBC

Mechanism of Localization

- Passive Diffusion
  - Disruption of Blood-Brain Barrier by trauma, neoplasm
    - Normally block radiopharmaceuticals
- Metabolism
  - FDG: glucose analogue & follow glucose metabolism
- Active transport
  - Transport using energy against gradient
    - Iodine in thyroid gland, Thallium in muscle
- Capillary blockage
  - Tc-99m-MAA block to assess pulmonary perfusion