Joint CI-JAI advanced accelerator lecture series

Imaging and detectors for medical physics

Lecture 4: Radionuclides

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Course layout

Day	AM 09.30 – 11.00	PM 15.30 – 17.00
Week 1		
6th June	Lecture 1: Introduction to medical imaging	Lecture 2: Detectors for medical imaging
7th June	Lecture 3: X-ray imaging	
8th June		Tutorial
Week 2		
13th June	Lecture 4: Radionuclides	
14th June	Lecture 5: Gamma cameras	Lecture 6: SPECT
16th June	Lecture 7: PET	
Week 3		
22nd June	Tutorial	

Books & references

1. N Barrie Smith & A Webb
   Introduction to Medical Imaging
   Cambridge University Press
2. Edited by M A Flower
   Webb's Physics of Medical Imaging
   CRC Press
3. A Del Guerra
   Ionizing Radiation Detectors for Medical Imaging
   World Scientific
4. W R Leo
   Techniques for Nuclear and Particle Physics Experiments
   Springer-Verlag

Nuclides live charts

- http://www.nndc.bnl.gov/nudat2/
- https://www-nds.iaea.org/relnsd/vcharthtml/VChartHTML.html

Nuclear medicine imaging

- Imaging of radioactive decay products of a radiopharmaceutical (radiotracer) introduced into the body → emission imaging (as opposed to X-ray imaging = transmission imaging)
- Spatial distribution depends on how radiopharmaceutical interacts with tissues in the body
- Administration of radiopharmaceutical:
  1. Intravenous injection into bloodstream
  2. Inhalation into lungs
  3. Subcutaneous administration
  4. Oral administration

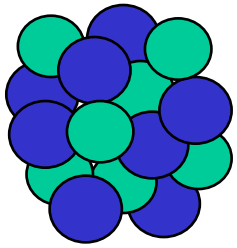
Nuclear medicine imaging techniques

- SPECT = Single Photon Emission CT = Single Photon Emission Computed Tomography
- PET = Positron Emission Tomography
- ~~Planar scintigraphy~~

Nuclide notation

Nucleus

- Formed of nucleons



neutron
proton

- Nucleons:
  - proton = particle with positive charge
  - neutron = particle with zero charge

Notation

Element X

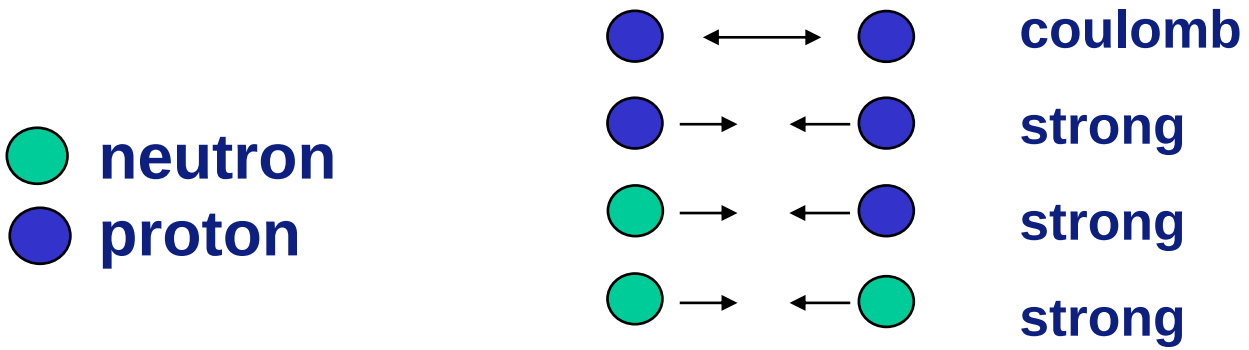
$$ {}^{A}_{Z}X $$

A = mass number = number of protons + neutrons

Z = atomic number = number of protons

Isotopes of an element = nuclides with same number of protons (same Z) but different number of neutrons (different A)

Forces within the nucleus



- In stable nuclei forces are well balanced
- In unstable nuclei there are too many neutrons or protons → forces are not balanced → nucleus is prone to undergo nuclear rearrangement and decay
- Line of stability
  - For low Z: $N \approx Z$
  - For high Z: $N \approx 1.5 \times Z$
  - No stable nuclei for $Z > 82$ (Lead)

Radioactivity

- Intrinsic property of unstable nuclei that have too many neutrons or protons → unstable nuclei emit particles or γ-rays to become more stable
- Definitions:
  1. Radionuclide = nuclide that is unstable and undergoes radioactive decay
  2. Radioisotope = radioactive isotope
  3. Radioactive disintegration or decay = spontaneous change in nucleus composition with associated emission of energy to reach a more stable state
  4. Radiotracer = radiopharmaceutical

Radioactive decay law

- Number of radioactive atoms in a sample decreases with time:

$$\frac{dN}{dt} = -\lambda t$$

- $N(t)$ = number of atoms left at given time t decreases exponentially:

$$N(t) = N_0 \exp(-\lambda t)$$

N_0 = number of atoms at $t = 0$

$\lambda[s^{-1}]$ = decay constant

$\exp(-\lambda t)$ = decay factor

Decay constant

- Probability that any individual radioactive atom will undergo decay per unit time
- Statistical definition → average rate of decay
- Exercise:

  Q: If $\lambda = 0.01\ s^{-1}$ on average how many atoms undergo radioactive decay per unit time?

(Radio)activity Q

Ref. 1 – Chapter 3.2 and Ref. 2 – Chapter 5.4.1

- (Radio)activity Q = number of disintegrations per s = rate of change of number N of radioactive nuclei

$$Q = -\frac{dN}{dt} = \lambda N$$

- Units for Q:
  1. SI unit = Bequerel (Bq)

     1 Bq = 1 disintegration per second
  2. Curies (Ci) = named after Pierre Curie and defined as number of disintegrations per second from 1 gramme of ^{226}Ra

     1 Ci = 3.7×10^{10} disintegrations per second = 3.7×10^{10} Bq

(Radio)activity Q decay law

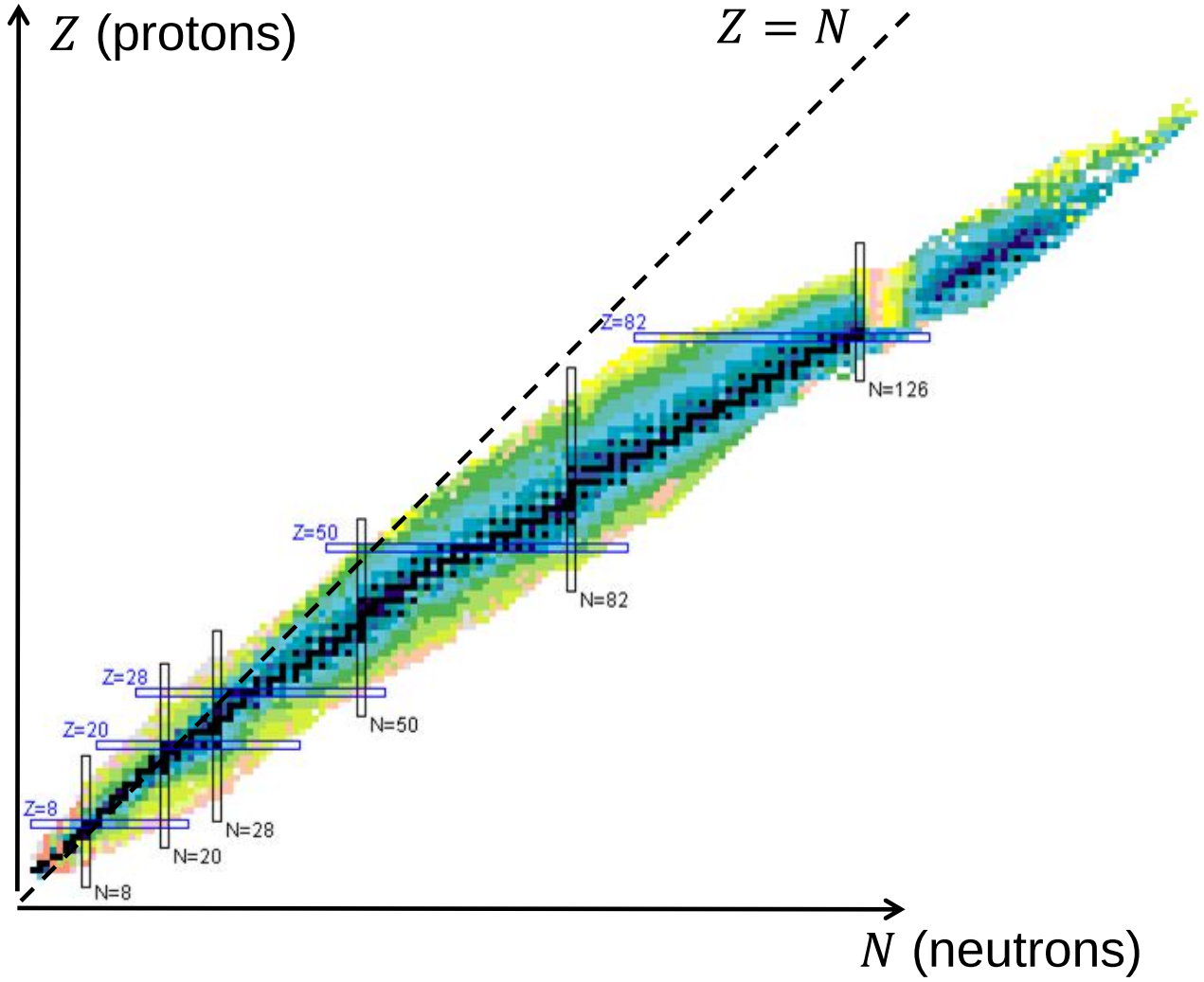
- (Radio)activity Q decreases with time too
- Exercise:

  Q: Determine the (radio)activity Q decay law

Half-life

- Half-life $\tau_{1/2}$ = time required for Q to drop to half (50%) of its initial value $\rightarrow$ $\tau_{1/2}$ is independent of N
- Exercise: Calculate relation between $\tau_{1/2}$ and λ and express Q as function of $\tau_{1/2}$

Atomic half-lives



Half-life (seconds)

> 1e+15	1e-01
1e+10	1e-02
1e+07	1e-03
1e+05	1e-04
1e+04	1e-05
1e+03	1e-06
1e+02	1e-07
1e+01	1e-15
1e+00	< 1e-15
unknown	

Courtesy Piero Posocco (Imperial College)

Biological and effective half-life

- In many cases excretion of radiotracer from tissue follows an exponential decay law → biological half-life $\tau_{1/2,bio}$ used to characterise the decay → $\tau_{1/2,bio}$ gives a measure of how long radiotracer remains in the body
- Effective half-life $\tau_{1/2,eff}$ given by:

$$\tau_{1/2,eff} = \frac{\tau_{1/2} \cdot \tau_{1/2,bio}}{\tau_{1/2} + \tau_{1/2,bio}}$$

→ $\tau_{1/2,eff}$ always less than the shorter between $\tau_{1/2}$ and $\tau_{1/2,bio}$

Exercise

- Q: Two patients undergo nuclear medicine scans. One receives a dose of radiotracer A with $\tau_{1/2} = 6$ h and the other a dose of radiotracer B with $\tau_{1/2} = 24$ h. If dose of radiotracer A is $3 \times$ dose of radiotracer B and $\tau_{1/2,bio}$ of A is 6 h and of B 12 h, at what time the radioactivity in the body of the two patients is the same?

Radioactive decay modes

Ref. 2 – Chapter 5.4.3

- α^{+2} decay
- β^{-} decay
- β^{+} decay
- Electron Capture (EC)
- Isomeric transitions
  - Radiative α^{+2}, β^{-} and β^{+} decays
  - Radiative EC
- Internal conversion (IC)

α^{+2} decay

- High A radionuclide emits α-particle = helium nucleus = +2 charge
- Most energy distributed between:
  1. Daughter nucleus = recoil energy
  2. α-particle = kinetic energy = 4÷8 MeV → travels few μm in tissue
- If nucleus left in excited state → de-excitation is through emission of γ-rays
- Not use in medical imaging (shallow penetration in tissue) but as sealed X- or γ-rays sources in therapy

β^- decay

- Neutron-rich radionuclide ejects β^- particle = e^- = −1 charge in the process:

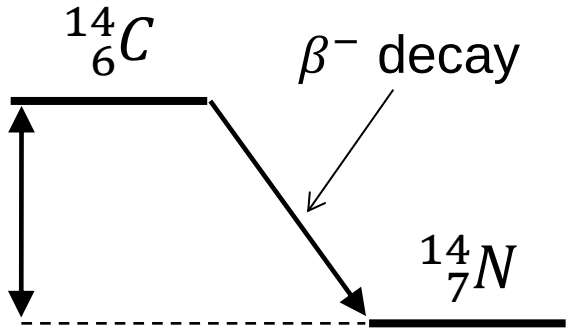
$$n \rightarrow p + e^- + \bar{\nu}$$

- Three-body decay → energy spectrum of e^- = continuum up to a maximum
- $Z \rightarrow Z + 1$, A and atomic weight remain the same
- e^- penetration in tissue < 2 mm → not used in medical imaging

Example

$$^{14}_{6}C \xrightarrow{\beta^- \text{decay}} {}^{14}_{7}N + \beta^- + \bar{\nu} + E$$

E = shared randomly between $\bar{\nu}$ and kinetic energy of β^-

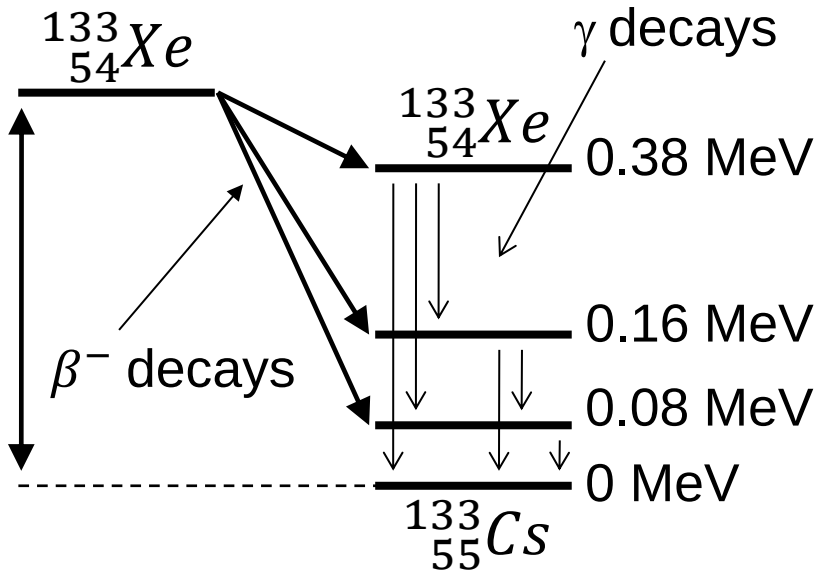


Radiative β^- decay (β^-, γ)

- If following β^- decay daughter nuclide is produced in excited state $X^* \rightarrow$ prompt de-excitation to more stable state through emission of γ rays
- $Z \rightarrow Z+1,\ A$ and atomic weight remain the same
- Typical energy of γ rays = $50 \div 500$ keV $\rightarrow$ useful for imaging
- Disadvantage: patient still exposed to β^- particle $\rightarrow$ dose

Example

$$^{133}_{54}Xe \xrightarrow{\beta^-} {}^{133}_{55}Cs^* \xrightarrow{\gamma} {}^{133}_{55}Cs$$



β^+ decay

- Proton-rich or neutron deficient radionuclide ejects β^+-particle = e^+ = +1 charge in the process:

$$p \rightarrow n + e^+ + \nu$$

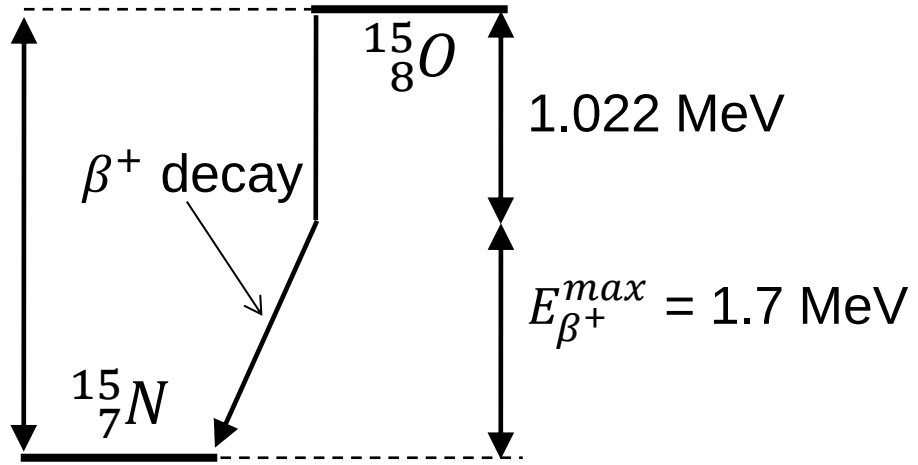
- Three-body decay → energy spectrum of e^+ = continuum up to a maximum
- $Z \rightarrow Z - 1,\ A$ and atomic weight remain the same
- e^+ travels ~1 mm in tissue → comes to rest → combines with atomic e^- → 2 back-to-back 511 keV γ-rays
- If daughter nuclide is produced in excited state → de-excitation is through emission of γ-rays

Example

$$^{15}_{6}O \xrightarrow{\beta^+\text{decay}} {}^{15}_{7}N + \beta^+ + \nu + E$$

E = shared randomly between ν and kinetic energy of β^+

Average kinetic energy $\langle E_{\beta^+} \rangle \cong E_{\beta^+}^{max}/3$



Electron Capture (EC) and radiative Electron Capture (EC, γ)

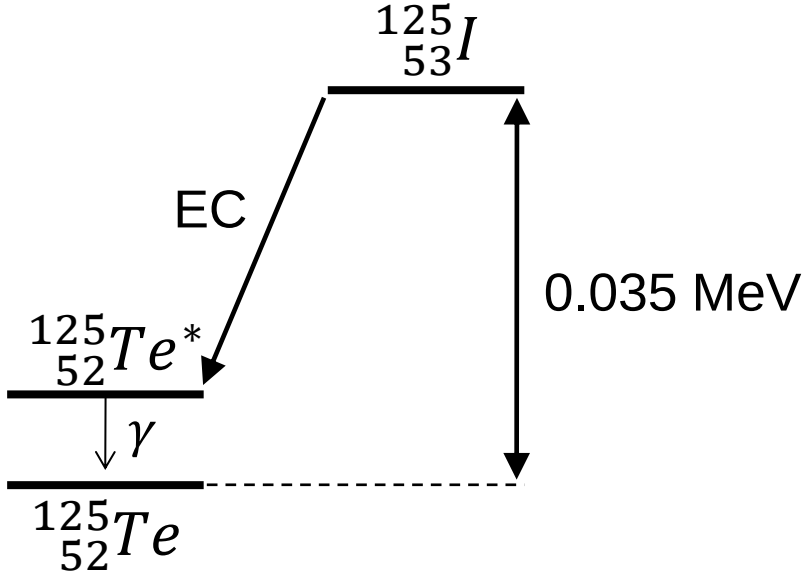
- In proton-rich radionuclide inner orbital (K-shell) e^- = closer to nucleus, captured within nucleus:

$$p + e^- \rightarrow n + \nu + E$$

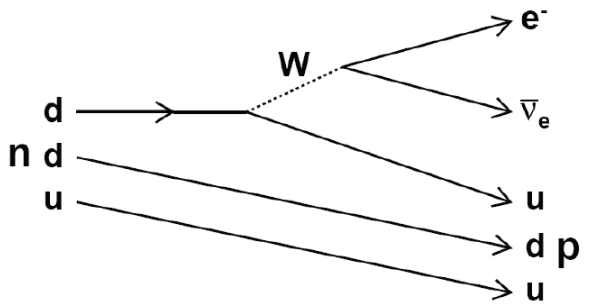
- $Z \rightarrow Z - 1$
- e^- from outer orbital fills vacancy $\rightarrow$ emission of X-ray characteristic of daughter nuclide = can be useful for imaging if high enough E
- The higher Z the closer to the nucleus are the e^- shells $\rightarrow$ probability of EC increases with Z
- If daughter nuclide is produced in excited state $X^* \rightarrow$ de-excitation is through emission of γ-rays

Example

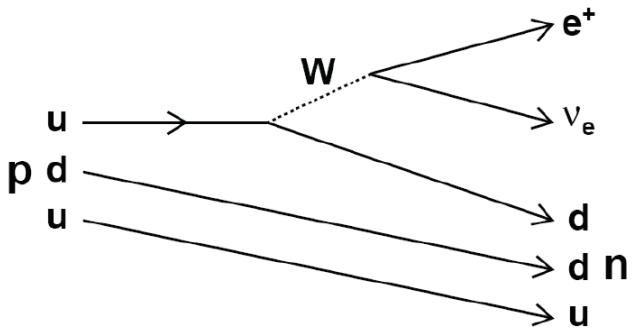
$$^{125}_{53}I + e^- \xrightarrow{EC} {}^{125}_{52}Te^* + \nu + E \xrightarrow{\gamma} {}^{125}_{52}Te$$



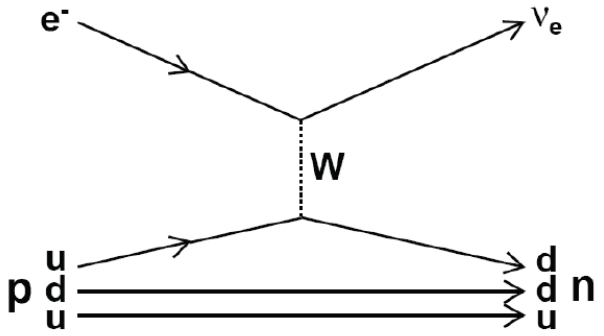
Feynman diagrams for β^-, β^+ decays and EC



$$ {}^{A}_{Z}X \xrightarrow{\beta^-} {}^{A}_{Z+1}Y + \mathrm{e}^- + \bar{\nu}_e $$



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



$$ {}^{A}_{Z}X + \mathrm{e}^- \xrightarrow{EC} {}^{A}_{Z-1}Y + \nu_e $$

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β emitters

(β^-, γ) emitters[1]			
Nuclide	Half-life	$\langle E_\beta \rangle$ (MeV)	E_γ (keV)
^{60}Co	5.27 yrs	0.096	1173, 1332
^{131}I	8.04 days	0.192	364
^{133}Xe	5.24 days	0.101	81
^{137}Cs	30.00 yrs	0.173	662

β^+ emitters			
Nuclide	Half-life (min)	$E_{\beta^+}^{max}$ (MeV)	$\langle \beta^+ range \rangle$ in water (cm)
^{11}C	20.30	0.961	0.103
^{13}N	10.00	1.190	0.132
^{15}O	2.07	1.720	0.201
^{18}F	110.00	0.635	0.064

[1]Only dominant β^- and γ emissions shown

EC and (EC, γ) radionuclides

EC radionuclides		
Nuclide	Half-life	E_{X-ray} (keV)
^{125}I	60.1 days	~30
^{201}Tl	3.04 days	~70

(EC, γ) radionuclides		
Nuclide	Half-life	E_{γ} (keV)
^{57}Co	270 days	122, 136
^{67}Ga	78.3 h	93, 185
^{111}In	2.83 days	171, 245
^{123}I	13.2 h	159

Isomeric transitions (IT) and metastable states

- Excited state in which daughter nuclide can be produced called isomeric state
- Sometimes radiative decays from isomeric state to ground state are called isomeric transition
- Isomeric transitions can take from fractions of seconds (short-lived states) to many years (long-lived states)
- Long-lived isomeric states are called metastable states ${}^{A}_{Z}X^{m}$

Example

- ${}^{99}Tc^{m}$ most common example of metastable isotope used in nuclear medicine
- Decay chain:

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

Half-life for β^- decay = 66 h

Half-life for isomeric transition = 6 h

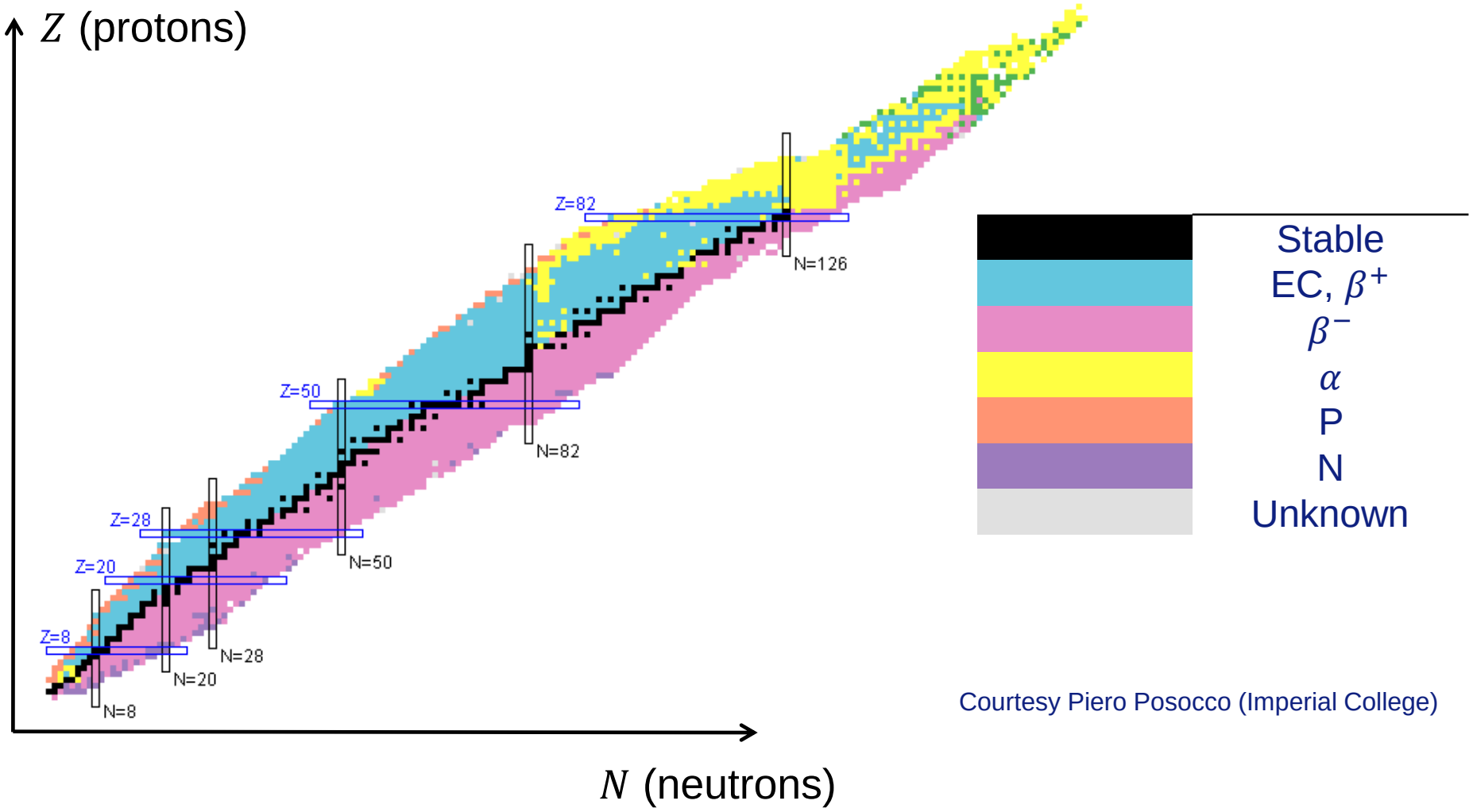
Internal Conversion (IC)

- γ-ray emitted in isomeric transition interacts with atomic e^- → e^- is ejected = conversion electron
- Interaction is usually with K-shell e^- as they are closest to nucleus
- Conversion e^- has kinetic energy E:

$$E = E_\gamma - E_{binding}$$

- e^- from outer shell fills vacancy → characteristic X-ray emitted
- X-ray emitted can interact with other outer shell e^- → e^- get ejected if $E_{X-ray} > E_{binding}$ = Auger e^-

Radioactive decay table



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Production of radionuclides

Ref. 2 – Chapter 5.4.2

- Man-made production:
  1. Neutron capture = neutron activation
  2. Nuclear fission
  3. Charged-particle bombardment
  4. Radioactive decay
- Naturally-occurring radionuclides

Man-made production technologies

- Nuclear reactors:
  1. Neutron capture = nuclear absorption
  2. Nuclear fission
- Accelerators:
  1. Charged-particle bombardment
- Radionuclide generators:
  1. Radioactive decay

Neutron capture / nuclear absorption

- Radionuclides produced when neutron absorbed by atomic nucleus

$$neutron + nucleus \rightarrow radionuclide$$

- For neutron to be captured E_n needs to be low in the range $0.03 \div 100$ eV = thermal neutrons
- Radionuclides produced predominantly neutron rich $\rightarrow$ decay mainly by β^-
- Production system:
  1. Nuclear reactor: creates thermal neutrons
  2. Target: placed inside field of thermal neutrons

Neutron capture reaction chain

- Neutron capture leaves nucleus excited → de-excitation via emission of γ-ray:

$$n + {}^{A}X \rightarrow {}^{A+1}X + \gamma$$

$$\text{Notation: } {}^{A}X(n,\gamma){}^{A+1}X$$

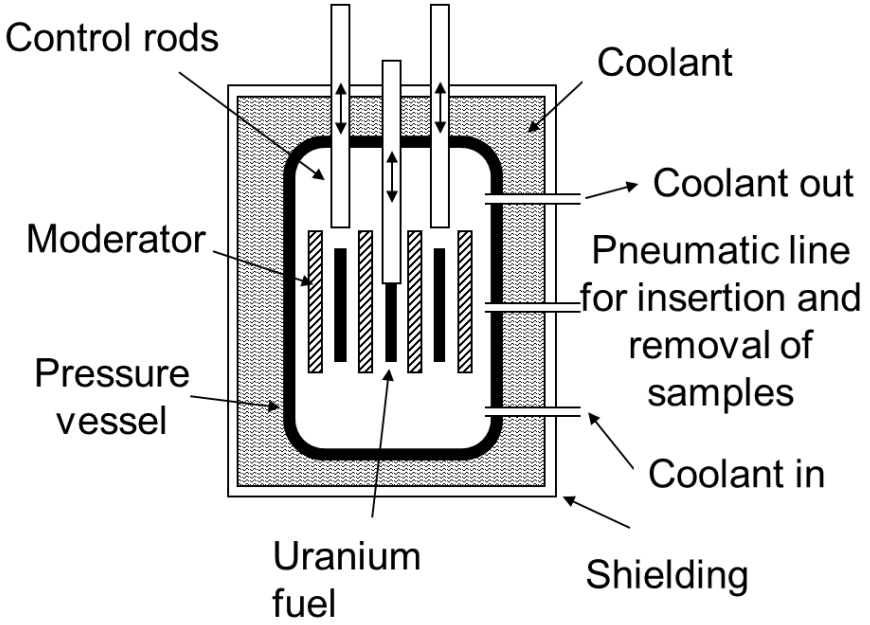
- Radionuclide produced = isotope of target material = same Z but $A + 1$ → very difficult to separate → low purity and activity
- Exception that can be easily separated: ${}^{125}I$ from decay of ${}^{125}Xe$ with half-life 17 h:

$${}^{124}Xe(n,\gamma){}^{125}Xe \xrightarrow{\text{EC } or\ \beta^+} {}^{125}I$$

Nuclear fission

- Nuclear fission process:
  1. Heavy nuclei (^{232}Th, ^{235}U, ^{237}U, ^{239}Pu and others with $A > 92$) are irradiated with thermal neutrons = neutron bombardment → absorb neutrons → become unstable
  2. Unstable nuclei undergo fission = break up into two lighter nuclei of approximately similar atomic weight
- Fission-produced nuclides have $28 < A < 65$
- Radionuclides produced predominantly neutron rich → decay mainly by β^-
- Fission products can be separated chemically with high specificity → high quality radiopharmaceuticals

Nuclear reactor



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Fission of ^{235}U or heavily enriched ^{235}U giving:

1. Fission products
2. Thermal neutrons → can be used to create radionuclide by neutron capture

- Main components:
  1. Fuel cells: contain fissionable material
  2. Moderator: commonly graphite or D_2O surrounding fuel cells = slows down neutrons
  3. Control rods: commonly boron exposing or shielding fuel cells = heavy neutron absorbers
  4. Ports in reactor core: allow samples to be inserted for irradiation with neutrons
- Position of fuel cells and control rods determine rate of chain reaction

Reactor-produced radionuclides

Nuclear absorption				
Radionuclide	**Production reaction**	**E_γ (keV)**	**Half-life**	**σ (Barn)**
^{51}Cr	$^{50}Cr(n,\gamma)^{51}Cr$	320	27.7 days	15.8
^{59}Fe	$^{58}Fe(n,\gamma)^{59}Fe$	1099	44.5 days	1.28
^{99}Mo	$^{98}Mo(n,\gamma)^{99}Mo$	740	66.02 h	0.13
^{131}I	$^{130}Te(n,\gamma)^{131}Te \rightarrow {}^{131}I$	364	8.04 days	0.29

Nuclear fission			
Radionuclide	**E_γ (keV)**	**Half-life**	**Fission yield (%)**
^{99}Mo	740	66.02 h	6.1
^{131}I	364	8.05 days	2.9
^{133}Xe	81	5.27 days	6.5
^{137}Cs	662	30 yrs	5.9

Charged-particle bombardment

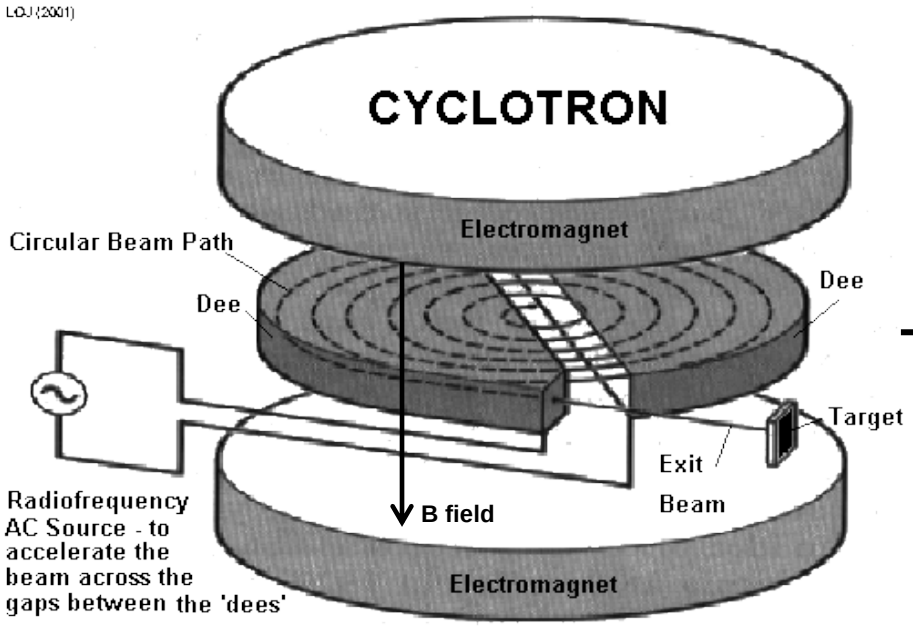
- Radionuclides produced through interaction of charged particles ($H^{\pm}, D^{+}, {}^{3}He^{2+}, {}^{4}He^{2+}$) with nuclei of stable atoms

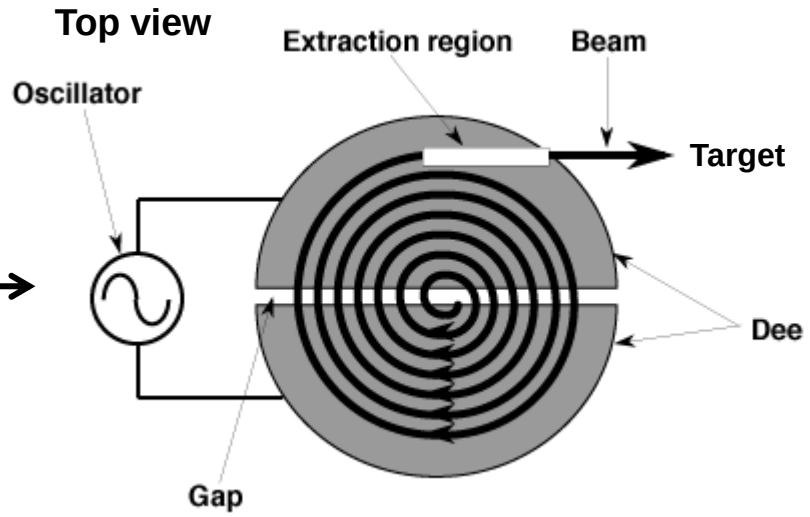
  $$charged\ particle + nucleus \rightarrow radionuclide$$

- Radionuclides produced predominantly neutron deficient $\rightarrow$ decay by β^{+} or EC
- Production system:
  1. Accelerator: kinetic $E_{charged\ particle}$ needs to be high enough to overcome nucleus (+) electrostatic repulsion
  2. Target

Accelerators

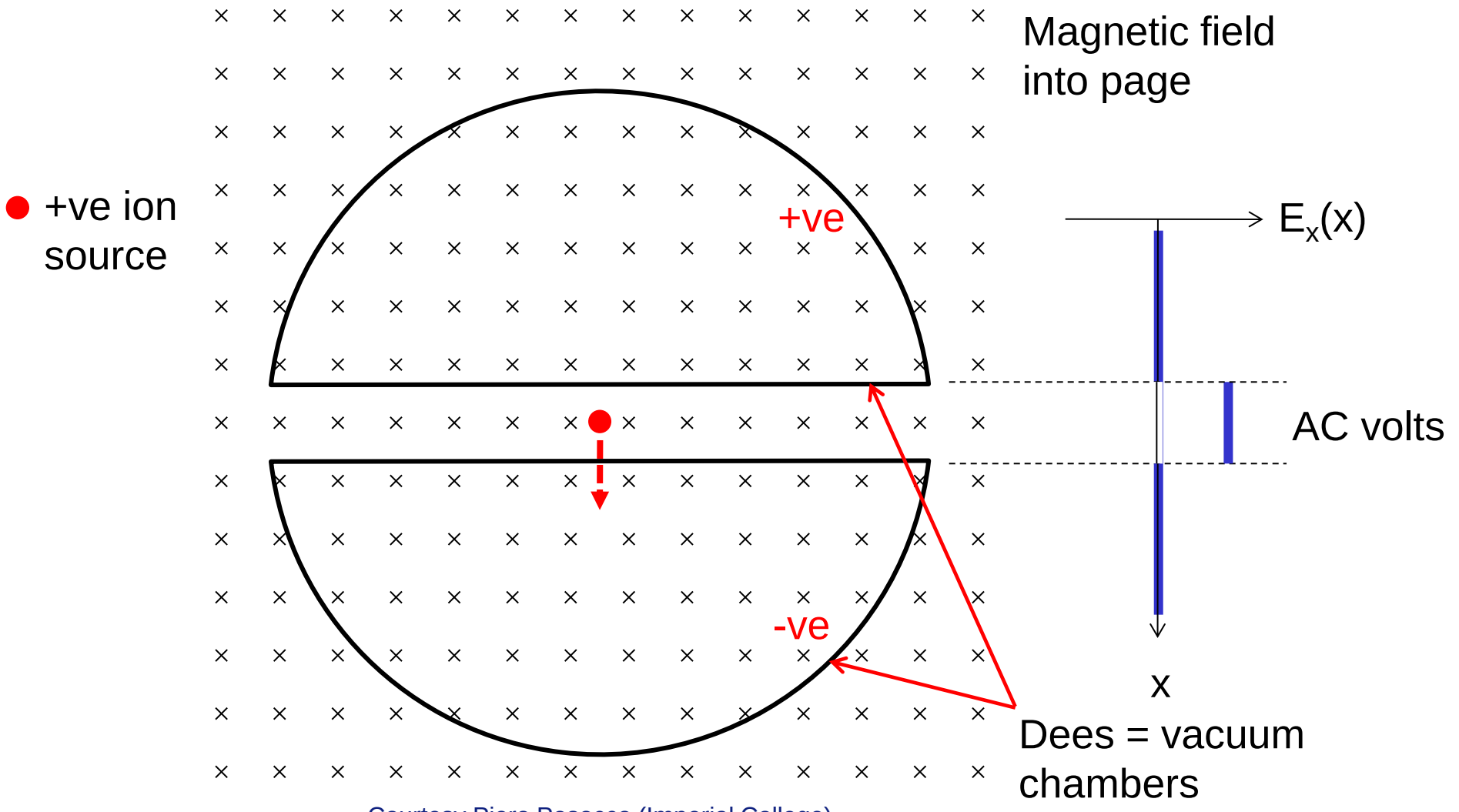
- Two basic types used for medical imaging:
  1. Cyclotron → most commonly used and usually located near hospitals due to radionuclide short half-lives
  2. Linear accelerator





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

Path of +ve ion in cyclotron



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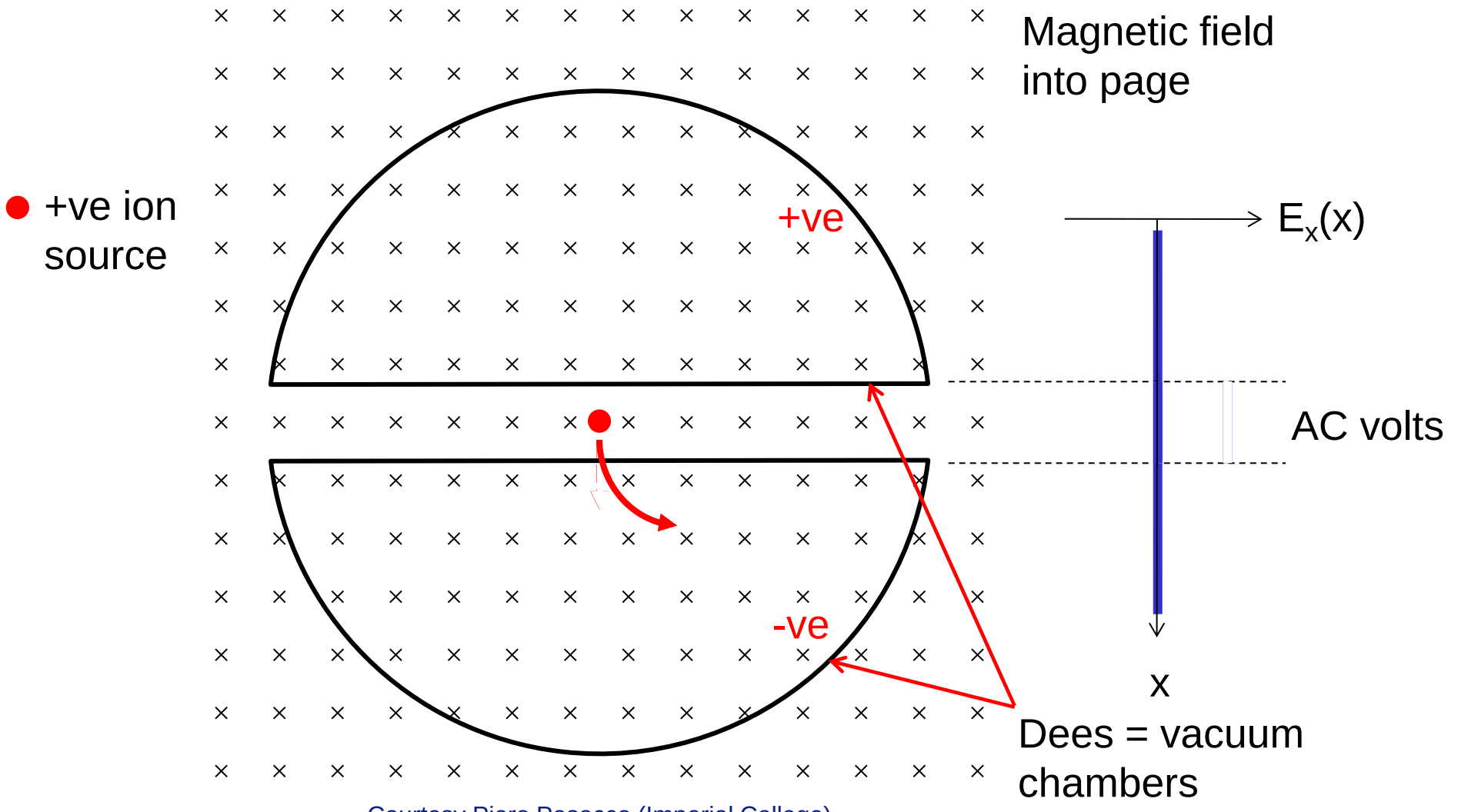
Path of +ve ion in cyclotron



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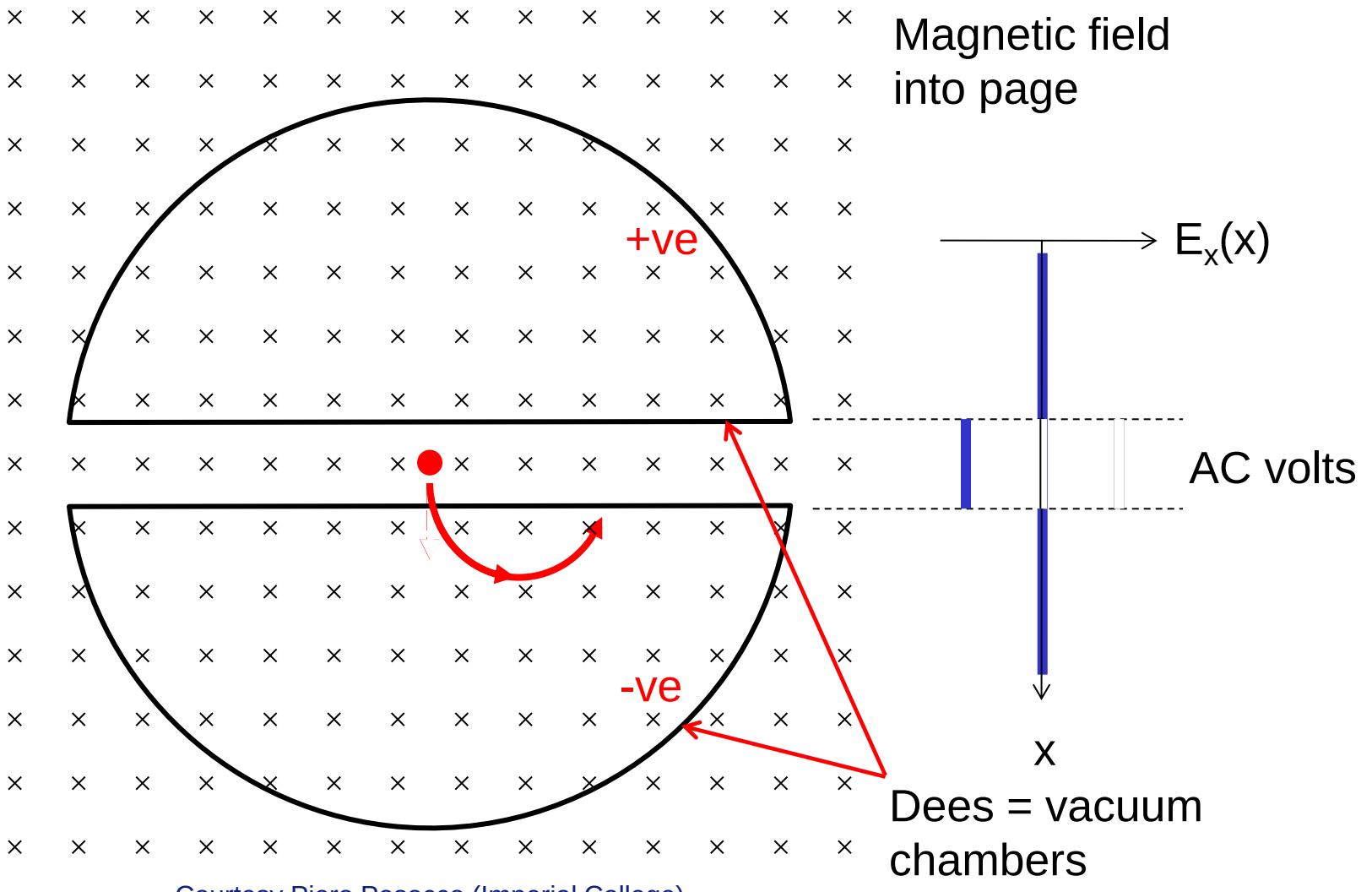
Path of +ve ion in cyclotron

- +ve ion source



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Compact biomedical cyclotron

Power supplies and
Target support unit

Retractable shields

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Accelerator-produced radionuclides

Radionuclide	Principal γ-ray E_γ (keV)[1]	Half-life	Production reaction
^{11}C	511	20.4 min	$^{14}N(p,\alpha)^{11}C$
^{13}N	511	9.96 min	$^{13}C(p,n)^{13}N$
^{15}O	511	2.07 min	$^{15}N(p,n)^{15}O$
^{18}F	511	109.7 min	$^{18}O(p,n)^{18}F$
^{67}Ga	93, 184, 300	78.3 h	$^{68}Zn(p,2n)^{67}Ga$
^{111}In	171, 245	67.9 h	$^{112}Cd(p,2n)^{111}In$
^{120}I	511	81 min	$^{127}I(p,8n)^{120}Xe \rightarrow {}^{120}I$
^{123}I	159	13.2 h	$^{112}Te(p,2n)^{123}I$ $^{127}I(p,5n)^{123}Xe \rightarrow {}^{123}I$
^{124}I	511	4.2 days	$^{124}Te(p,n)^{124}I$
^{201}Tl	68÷80.3	73 h	$^{203}Tl(p,3n)^{201}Pb \rightarrow {}^{201}Tl$

[1]511 keV γ-rays come from β^+ decay

Radioactive decay

- Radioactive decay of parent radionuclide can lead to:
  1. Unstable nuclide = radioactive nuclide = daughter radionuclide
  2. Stable nuclide
- Z of radionuclide daughter depends on decay type
- Good radionuclides for medical imaging:
  1. Daughter is short-lived and has Z different from parent → can be easily separated
  2. Parent has sufficiently long half-life for production, processing and shipment

Radionuclide generator

- The generator:
  1. Receives in input radionuclides produced from nuclear reactors or accelerators
  2. Contains:
     a) Chemical separation system of daughter radionuclide from parent radionuclide: chromatographic techniques most common
     b) Extraction system
- Main features:
  1. Portable → provides local supply of short-lived radionuclides without a nearby accelerator or nuclear reactor
  2. Daughter product replenished continuously by decay of parent → can be extracted repeatedly

Generator-produced radionuclides

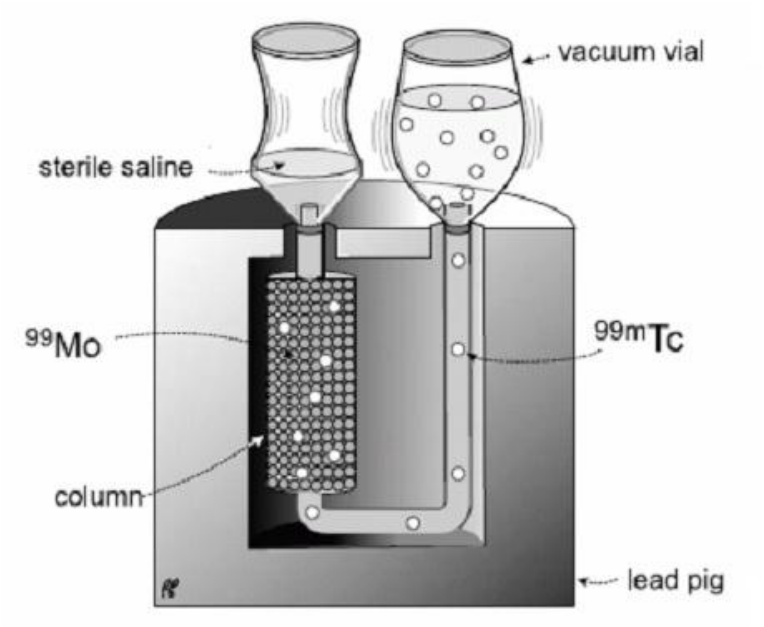
Parent P	Parent half-life	Mode of decay P → D	Daughter D	Daughter decay mode	Daughter half-life	Daughter γ E_γ (keV)
^{62}Zn	9.1 h	β^+ EC	^{62}Cu	β^+ EC	9.8 min	511 1173
^{68}Ge	280 days	EC	^{68}Ga	β^+ EC	68 min	511 1080
^{81}Rb	4.7 h	EC	^{81}Kr	IT	13 s	190
^{82}Sr	25 days	EC	^{82}Rb	EC β^+	76 s	777 511
^{99}Mo	66.02 h	β^-	$^{99}Tc^m$	IT	6.02 h	140
^{113}Sn	115.1 days	EC	$^{113}In^m$	IT	1.66 h	392
$^{195}Hg^m$	40 h	IT EC	$^{195}Au^m$	IT	30.6 s	262

$^{99}Mo - {}^{99}Tc^{m}$ generator

Ref. 1 – Chapters 3.4 and 3.5

- $^{99}Tc^{m}$ most common radioisotope used in nuclear medicine:

$$^{99}Mo \xrightarrow[Half-life=66\,h]{} {}^{99}Tc^{m} \xrightarrow[Half-life=6.02\,h]{} {}^{99}Tc + 140\ \text{keV}\ \gamma$$



- Also called a Molly or Cow
- Typically used for one week
- ^{99}Mo bound to alumina column as molybdate ion ($(NH_4)_2MoO_4^-$)
- $^{99}Tc^{m}$:
  - Chemically different → not bound to column → eluted from column with 5÷25 ml saline
  - 75÷85% of available $^{99}Tc^{m}$ extracted

Equation for number of $^{99}Tc^m$ atoms produced with generator

$$\underset{(N_1)}{^{99}Mo} \xrightarrow{\lambda_1} \underset{(N_2)}{^{99}Tc^m} \xrightarrow{\lambda_2} \underset{(N_3)}{^{99}Tc}$$

- Number N_1 of ^{99}Mo atoms decreases with time from N_0 due to decay:

$$N_1 = N_0 e^{-\lambda_1 t}$$

- Number N_3 of ^{99}Tc atoms increases with time due to decay of $^{99}Tc^m$
- Number N_2 of $^{99}Tc^m$ atoms has two components = one decreases with time due to $^{99}Tc^m$ own decay, other increases with time due to ^{99}Mo decay → first order differential equation for N_2:

$$\frac{dN_2}{dt} = \lambda_1 N_1 - \lambda_2 N_2 \rightarrow \frac{dN_2}{dt} + \lambda_2 N_2 = \lambda_1 N_1$$

With boundary condition: $N_2 = 0$ at $t = 0$

Solution of first order differential equation for N_2

- Solution of first order differential equation for N_2 made of two terms:

$$N_2 = Ce^{-\lambda_2 t} + De^{-\lambda_1 t}$$

1. Homogeneous: $N_2 = Ce^{-\lambda_2 t}$
2. Particular: $N_2 = De^{-\lambda_1 t}$

- From boundary condition $\rightarrow C = -\frac{\lambda_1 N_0}{\lambda_2 - \lambda_1}$
- Solving particular solution for $D \rightarrow D = \frac{\lambda_1 N_0}{\lambda_2 - \lambda_1}$
- Final solution of first order differential equation for N_2:

$$N_2 = -\frac{\lambda_1 N_0}{\lambda_2 - \lambda_1} e^{-\lambda_2 t} + \frac{\lambda_1 N_0}{\lambda_2 - \lambda_1} e^{-\lambda_1 t}$$

$$\boxed{N_2 = \frac{\lambda_1 N_0}{\lambda_2 - \lambda_1}\left(e^{-\lambda_1 t} - e^{-\lambda_2 t}\right)}$$

Radioactivity Q of $^{99}Tc^{m}$ produced with the generator

- Radioactivity Q of $^{99}Tc^{m}$ produced with the generator given by:

$$Q = \lambda_2 N_2$$

- Using solution for N_2 the radioactivity Q is finally given by:

$$Q = \lambda_2 \frac{\lambda_1 N_0}{\lambda_2 - \lambda_1}\left(e^{-\lambda_1 t} - e^{-\lambda_2 t}\right) = \frac{\lambda_1 \lambda_2 N_0}{\lambda_2 - \lambda_1}\left(e^{-\lambda_1 t} - e^{-\lambda_2 t}\right)$$

$N_0 =$ number of ^{99}Mo at $t = 0$

$\lambda_1 = {}^{99}Mo$ decay constant $= \frac{\ln 2}{\tau^1_{1/2}} = \frac{\ln 2}{66} = 0.0105\ \mathrm{h}^{-1}$

$\lambda_2 = {}^{99}Tc^{m}$ decay constant $= \frac{\ln 2}{\tau^2_{1/2}} = \frac{\ln 2}{6} = 0.116\ \mathrm{h}^{-1}$

- Radioactivity proportional to difference of two exponentials = one governing increase in $^{99}Tc^{m}$ due to ^{99}Mo decay and other decrease in $^{99}Tc^{m}$ due to its decay

Naturally-occurring radionuclides

- Very long-lived elements
- Mainly very heavy elements

Nuclide	Abundance (%)	Half-life (yrs)
^{40}K	0.01	1.26×10^{9}
^{87}Rb	27.8	4.88×10^{10}
^{232}Th	100	1.40×10^{10}
^{235}U	0.7	7.04×10^{8}
^{238}U	99.3	4.46×10^{9}

- $\rightarrow$ Not useful for imaging

Choice of radionuclides for imaging

Ref. 2 – Chapter 3.4.4

- Desirable physical characteristics of radionuclides for nuclear medicine imaging:
  1. Physical half-life:
     a. Long enough to allow:
        1) Preparation of radiopharmaceuticals
        2) Completion of imaging procedures
     b. Short enough to ensure dose to patient and staff is minimised
  2. Decay via isomeric transition = produces γ rays with:
     a. High photon yield → good counting statistics
     b. Suitable E_γ
  3. Absence of particulate emission (α or β particles) → no unnecessary dose to patients

Emitted photon energy

- Emitted photon energy critical and chosen as "compromise" for various reasons:
  1. High enough E_γ so that:
     a. Photon is able to efficiently escape the body
     b. Photopeak is easily separated from scattered radiation
  2. Low enough E_γ so that:
     a. Detection efficiency is still good
     b. Do not penetrate thin collimator septa → thickness of collimator septa not too big
     c. Photons are not too difficult to shield and to handle

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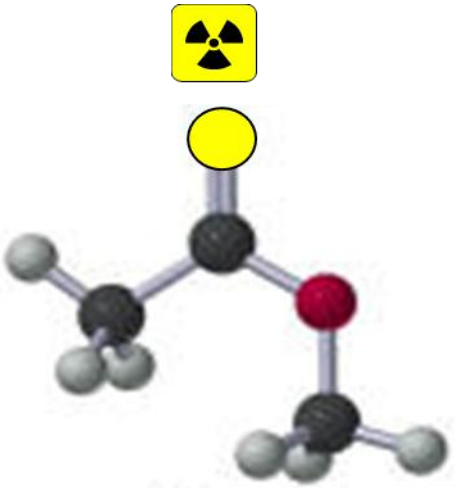
Commonly used radionuclides for imaging

Nuclide	Decay mode	Product	E (keV)	Half-life	Imaging system	Comment
^{11}C	β^+	γ	511	20 min	PET	
^{13}N	β^+	γ	511	10 min	PET	
^{15}O	β^+	γ	511	2 min	PET	
^{18}F	β^+	γ	511	110 min	PET	~80% of all PET imaging (FDG)
^{67}Ga	EC	γ	93, 185, 300	3.3 days	γ-camera, SPECT	
^{82}Rb	β^+	γ	511	1.25 min	PET	
$^{99}Tc^m$	IT	γ	140	6.0 h	γ-camera, SPECT	> 80% of all nuclear medicine imaging
^{111}In	EC	γ	172, 247	2.8 days	γ-camera, SPECT	Used for longer term studies
^{123}I	EC	γ	159	13 h	γ-camera, SPECT	
^{201}Tl	EC	X-ray	68÷80	3.0 days	γ-camera, SPECT	

Radiopharmaceuticals

Ref. 2 – Chapter 5.4.5



Courtesy Piero Posocco (Imperial College)

- Radiopharmaceutical = radioactive compound (biomolecule or drug) of suitable quality to be safely administered humans for diagnosis, therapy or research
- Radiopharmaceutical composition:
  1. Usually radionuclide + pharmaceutical compound
  2. Some exceptions:
     a. No associated pharmaceutical compound, for ex. ^{133}Xe gas
     b. Pharmaceutical component = counter ion, for ex. NaI

Radiopharmaceutical chemistry and biology

Ref. 2 – Chapters 5.4.5, 5.4.6 5.4.7 and 5.4.8

- Radiolabelling = “attach” the radionuclide to the pharmacological compound
- Distribution of radiopharmaceutical within living system depends on various factors including:
  1. 3D structure and size of the molecule
  2. Blood flow
- Quality control:
  1. Biological purity: toxicity, sterility and apyrogenicity
  2. Radiopharmaceutical purity: radionuclide, radiochemical and chemical purity

Choice of radiopharmaceuticals for imaging

- Characteristics of radiopharmaceuticals for nuclear medicine imaging:
  1. Accumulation / rate of uptake or clearance of radiopharmaceutical should be related to a physiologic, biochemical or molecular process, target or function
  2. No pharmacological or toxicological effects on system / organ under study → concentration usually subpharmacological (micromolar to nanomolar)
  3. High uptake in target tissue compared with non-target tissue = specificity → lower required dose + increase image contrast
  4. Half-life appropriate for the duration of the study
  5. Easily synthesised or labelled
  6. Sufficiently long shelf life before and after radiolabelling
  7. Be of required pharmaceutical quality

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Some common radiopharmaceuticals

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