

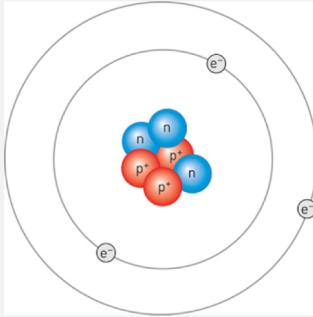
Biophysics I

13. Nuclear radiations

Liliom, Károly

01. 12. 2023.

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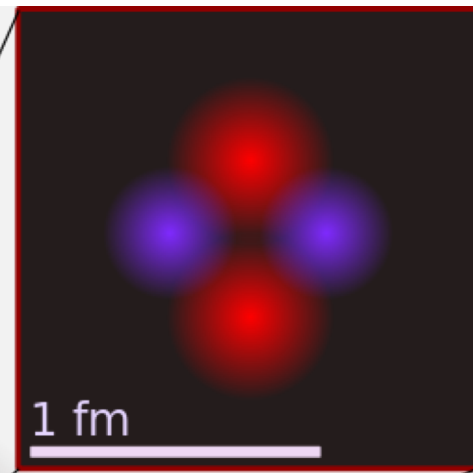
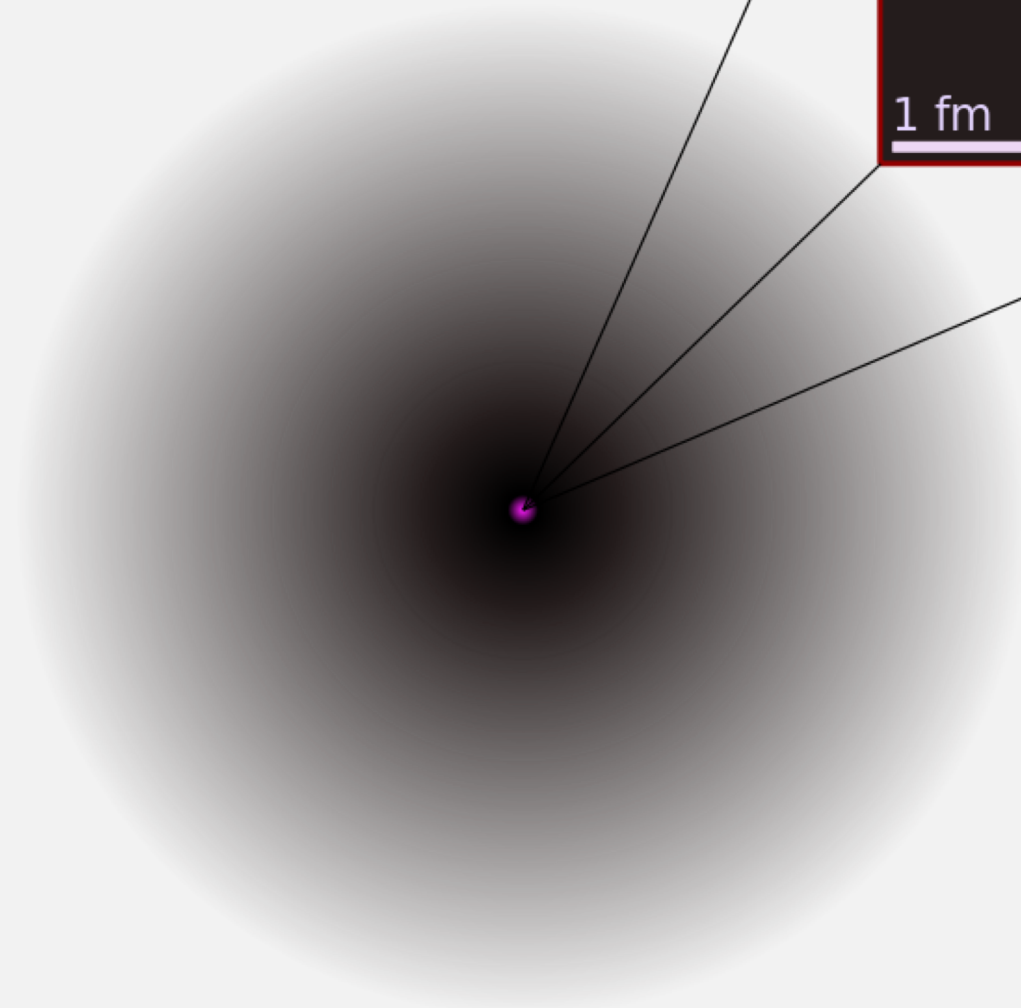
Constituents of atoms

Particle	Symbol	Resting Energy (MeV)	Relative Charge*	Mass (kg)	Relative Mass (AMU)**
electron	e	0.51100	1-	9.11×10^{-31}	5.4858×10^{-4}
proton	p	938.272	1+	1.6726×10^{-27}	1.0072765
neutron	n	939.566	0	1.6749×10^{-27}	1.0086649

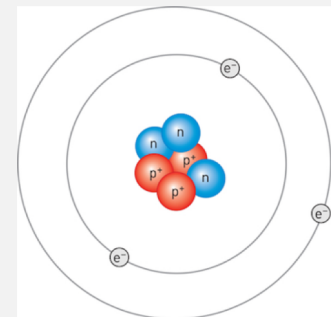
* electrons have an electric charge of $-1.602 \times 10^{-19} \text{ C}$

**The atomic mass unit is defined as 1/12 of the carbon (^{12}C) atom

Nucleus size



$$1 \text{ \AA} = 100,000 \text{ fm}$$

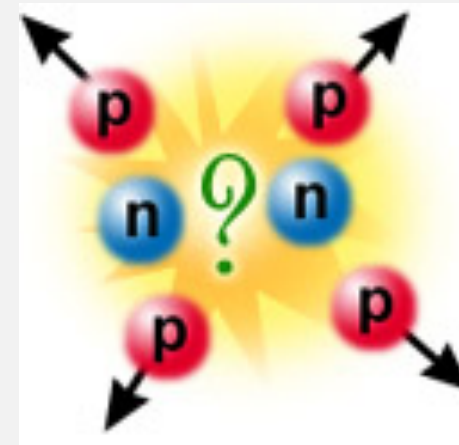


Nuclear stability

There are very large *repulsive electrostatic forces* between protons

should cause the nucleus to fly apart

It must be an attractive force be present within the nucleus!



Rutherford, 1911 – nuclear force: an attractive force acting on short distances within the nucleus, independent of charges, and stronger than the Coulomb forces.

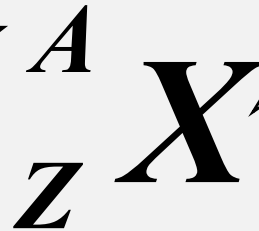
The hypothesis of neutron (discovered by Chadwick in 1932)

Nuclear notation

Mass number

$$A = Z + N$$

*Chemical symbol for
the element*



*Atomic number =
Number of protons*



N = number of neutrons
nucleon = proton or neutron

Nuclear stability

$$\Delta M = [Zm_p + (A-Z)m_n] - M(A,Z)$$

The mass defect (or mass deficit) problem: the mass of a nucleus is less than the mass of its constituent nucleons. The difference can be explained by Einstein's law of mass-energy equivalence:

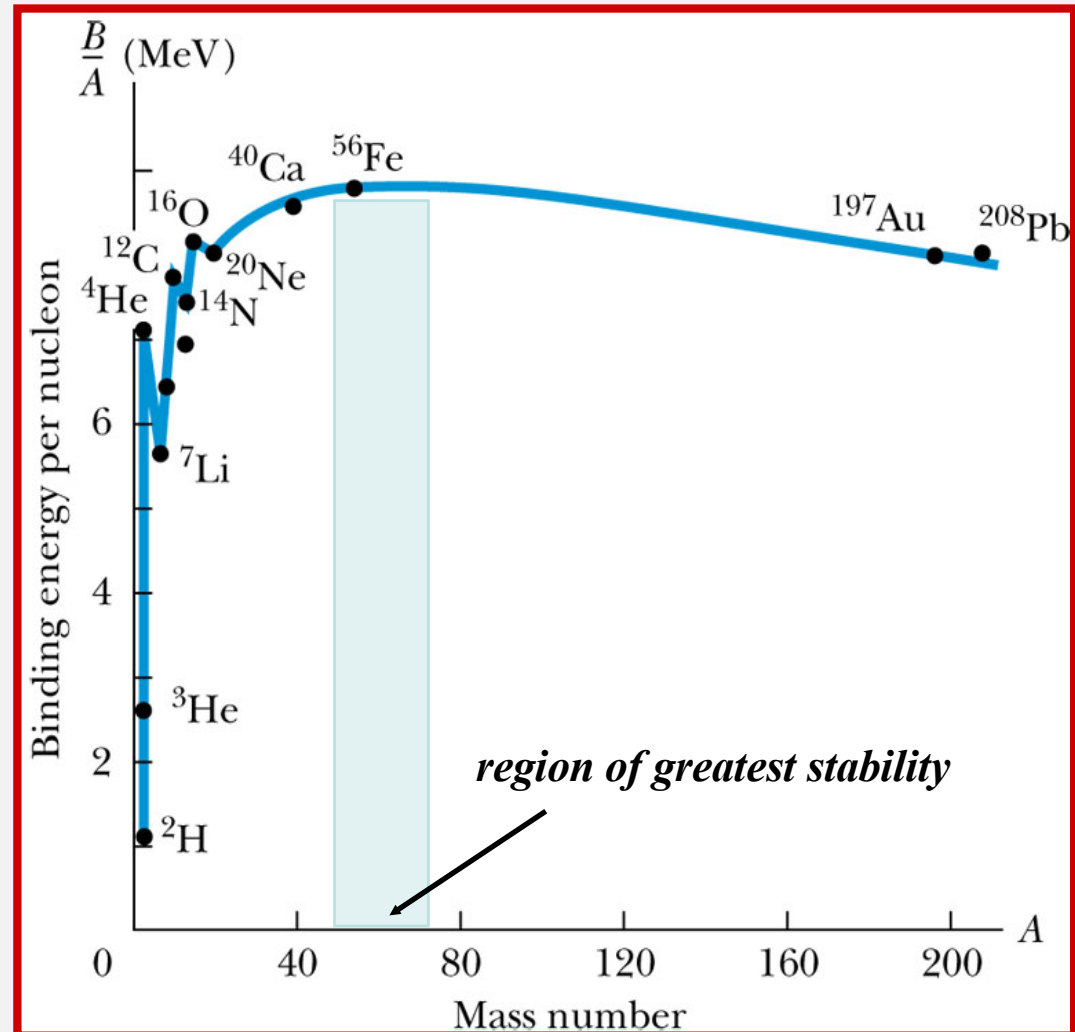
$$\Delta E = \Delta M c^2$$

The energy corresponding to the mass defect is the binding energy of the nucleons.

Binding energy per nucleon

- The curve increases rapidly
- Sharp peaks for the even-even nuclei for ${}^4_2\text{He}$, ${}^{12}_6\text{C}$, and ${}^{16}_8\text{O}$
- Maximum is around $A=56$

nucleon = proton or neutron



Isotopes

Greek *isos topos* = *equal place*

Isotopes of an element have nuclei with

- the same number of protons
- different numbers of neutrons
- different mass number

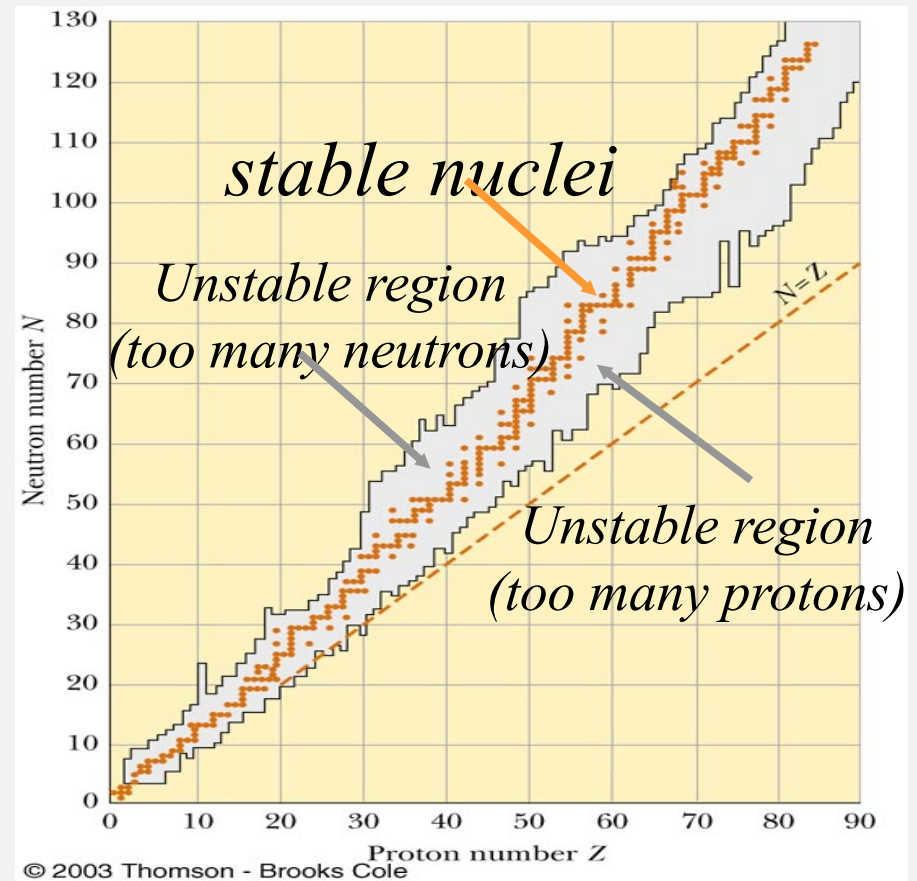
isotope = equal place = equal atomic number

Mendeleev's Periodic Table of Elements

1 IA		Table of Common Polyatomic Ions										Element categories					State of matter at 25 °C					18 VIIIA					
		<div>acetate chlorate hydroxide nitrate permanganate</div> <div>$C_2H_3O_2^-$ ClO_3^- OH^- NO_3^- MnO_4^-</div> <div>carbonate chromate dichromate</div> <div>CO_3^{2-} CrO_4^{2-} $Cr_2O_7^{2-}$</div> <div>silicate sulfate thiosulfate</div> <div>SiO_3^{2-} SO_4^{2-} $S_2O_3^{2-}$</div> <div>arsenate phosphate</div> <div>AsO_4^{3-} PO_4^{3-}</div> <div>ammonium hydronium</div> <div>NH_4^+ H_3O^+</div>										<div><div>Alkali metals</div><div>Alkaline-earth metals</div><div>Transition metals</div><div>Other metals</div></div> <div><div>Hydrogen</div><div>Semiconductors</div><div>Halogens</div><div>Noble gases</div><div>Other nonmetals</div></div>					<div>Gas Liquid Solid Artificially prepared Unknown</div> <div>13 14 15 16 17</div> <div>IIIA IVA VA VIA VIIA</div>					2					
1	<div>H</div> <div>1.008</div> <div>1</div>																5 6 7 8 9					10					
2	<div>Li</div> <div>6.941</div> <div>2-1</div>	<div>Be</div> <div>9.0122</div> <div>2-2</div>																13 14 15 16 17					18				
3	<div>Na</div> <div>22.990</div> <div>2-3</div>	<div>Mg</div> <div>24.305</div> <div>2-2</div>																31 32 33 34 35					36				
4	<div>K</div> <div>39.098</div> <div>2-8-1</div>	<div>Ca</div> <div>40.078</div> <div>2-8-2</div>	<div>Sc</div> <div>44.956</div> <div>2-8-9-2</div>	<div>Ti</div> <div>47.867</div> <div>2-8-10-2</div>	<div>V</div> <div>50.942</div> <div>2-8-11-2</div>	<div>Cr</div> <div>51.996</div> <div>2-8-13-1</div>	<div>Mn</div> <div>54.938</div> <div>2-8-13-2</div>	<div>Fe</div> <div>55.845</div> <div>2-8-14-2</div>	<div>Co</div> <div>58.933</div> <div>2-8-15-2</div>	<div>Ni</div> <div>58.693</div> <div>2-8-16-2</div>	<div>Cu</div> <div>63.546</div> <div>2-8-18-1</div>	<div>Zn</div> <div>65.39</div> <div>2-8-18-2</div>	<div>Ga</div> <div>69.723</div> <div>2-8-18-3</div>	<div>Ge</div> <div>72.64</div> <div>2-8-18-4</div>	<div>As</div> <div>74.922</div> <div>2-8-18-5</div>	<div>Se</div> <div>78.96</div> <div>2-8-18-6</div>	<div>Br</div> <div>79.904</div> <div>2-8-18-7</div>	<div>Kr</div> <div>83.80</div> <div>2-8-18-8</div>									
5	<div>Rb</div> <div>85.468</div> <div>2-8-18-1</div>	<div>Sr</div> <div>87.62</div> <div>2-8-18-2</div>	<div>Y</div> <div>88.906</div> <div>2-8-18-9-2</div>	<div>Zr</div> <div>91.224</div> <div>2-8-18-10-2</div>	<div>Nb</div> <div>92.906</div> <div>2-8-18-12-1</div>	<div>Mo</div> <div>95.94</div> <div>2-8-18-13-1</div>	<div>Tc</div> <div>(98)</div> <div>2-8-18-14-1</div>	<div>Ru</div> <div>101.07</div> <div>2-8-18-15-1</div>	<div>Rh</div> <div>102.91</div> <div>2-8-18-16-1</div>	<div>Pd</div> <div>106.42</div> <div>2-8-18-18</div>	<div>Ag</div> <div>107.87</div> <div>2-8-18-1</div>	<div>Cd</div> <div>112.41</div> <div>2-8-18-2</div>	<div>In</div> <div>114.82</div> <div>2-8-18-3</div>	<div>Sn</div> <div>118.71</div> <div>2-8-18-4</div>	<div>Sb</div> <div>121.76</div> <div>2-8-18-5</div>	<div>Te</div> <div>127.60</div> <div>2-8-18-6</div>	<div>I</div> <div>126.90</div> <div>2-8-18-7</div>	<div>Xe</div> <div>131.29</div> <div>2-8-18-8</div>									
6	<div>Cs</div> <div>132.91</div> <div>2-8-18-18-1</div>	<div>Ba</div> <div>137.33</div> <div>2-8-18-18-2</div>											<div>Hf</div> <div>178.49</div> <div>2-8-18-32-10-2</div>	<div>Ta</div> <div>180.95</div> <div>2-8-18-32-11-2</div>	<div>W</div> <div>183.84</div> <div>2-8-18-32-12-2</div>	<div>Re</div> <div>186.21</div> <div>2-8-18-32-13-2</div>	<div>Os</div> <div>190.23</div> <div>2-8-18-32-14-2</div>	<div>Ir</div> <div>192.22</div> <div>2-8-18-32-15-2</div>	<div>Pt</div> <div>195.08</div> <div>2-8-18-32-17-1</div>	<div>Au</div> <div>196.97</div> <div>2-8-18-32-1</div>	<div>Hg</div> <div>200.59</div> <div>2-8-18-32-2</div>	<div>Tl</div> <div>204.38</div> <div>2-8-18-32-3</div>	<div>Pb</div> <div>207.2</div> <div>2-8-18-32-4</div>	<div>Bi</div> <div>208.98</div> <div>2-8-18-32-5</div>	<div>Po</div> <div>(209)</div> <div>2-8-18-32-6</div>	<div>At</div> <div>(210)</div> <div>2-8-18-32-7</div>	<div>Rn</div> <div>(222)</div> <div>2-8-18-32-8</div>
7	<div>Fr</div> <div>(223)</div> <div>2-8-32-18-8-1</div>	<div>Ra</div> <div>(226)</div> <div>2-8-32-18-8-2</div>											<div>Rf</div> <div>(261)</div>	<div>Db</div> <div>(262)</div>	<div>Sg</div> <div>(266)</div>	<div>Bh</div> <div>(264)</div>	<div>Hs</div> <div>(277)</div>	<div>Mt</div> <div>(268)</div>	<div>Uun</div> <div>(281)</div>	<div>Uuu</div> <div>(272)</div>	<div>Uub</div> <div>(285)</div>	<div>Uut</div> <div>(284)</div>	<div>Uuq</div> <div>(289)</div>	<div>Uup</div> <div>(288)</div>	<div>Uuh</div> <div>(291)</div>	<div>Uus</div> <div>(294)</div>	<div>Uuo</div> <div>(294)</div>
Selected Oxidation States																											
Atomic Number																											
Symbol																											
Electron Configuration																											
<div>21</div> <div>Sc</div> <div>44.956</div> <div>2-8-9-2</div>																											
57 58 59 60 61 62 63 64 65 66 67 68 69 70 71																											
<div>La</div> <div>138.91</div> <div>57</div> <div>Ce</div> <div>140.12</div> <div>58</div> <div>Pr</div> <div>140.91</div> <div>59</div> <div>Nd</div> <div>144.24</div> <div>60</div> <div>Pm</div> <div>(145)</div> <div>61</div> <div>Sm</div> <div>150.36</div> <div>62</div> <div>Eu</div> <div>151.96</div> <div>63</div> <div>Gd</div> <div>157.25</div> <div>64</div> <div>Tb</div> <div>158.93</div> <div>65</div> <div>Dy</div> <div>162.50</div> <div>66</div> <div>Ho</div> <div>164.93</div> <div>67</div> <div>Er</div> <div>167.26</div> <div>68</div> <div>Tm</div> <div>168.93</div> <div>69</div> <div>Yb</div> <div>173.04</div> <div>70</div> <div>Lu</div> <div>174.97</div> <div>71</div>																											
89 90 91 92 93 94 95 96 97 98 99 100 101 102 103																											
<div>Ac</div> <div>227</div> <div>89</div> <div>Th</div> <div>232.04</div> <div>90</div> <div>Pa</div> <div>231.04</div> <div>91</div> <div>U</div> <div>238.03</div> <div>92</div> <div>Np</div> <div>(237)</div> <div>93</div> <div>Pu</div> <div>(244)</div> <div>94</div> <div>Am</div> <div>(243)</div> <div>95</div> <div>Cm</div> <div>(247)</div> <div>96</div> <div>Bk</div> <div>(247)</div> <div>97</div> <div>Cf</div> <div>(251)</div> <div>98</div> <div>Es</div> <div>(252)</div> <div>99</div> <div>Fm</div> <div>(257)</div> <div>100</div> <div>Md</div> <div>(258)</div> <div>101</div> <div>No</div> <div>(259)</div> <div>102</div> <div>Lr</div> <div>(262)</div> <div>103</div>																											

Nuclear stability chart

- Light nuclei are most stable if $N=Z$
- Heavy nuclei are most stable when $N > Z$
As the number of protons increases, the Coulomb force increases and so more neutrons are needed to keep the nucleus stable
- No nucleus is stable when $Z > 83$



What does it mean „unstable”?

Radioactive decay



Antoine Becquerel
1903 Nobel Prize in Physics
for discovering radioactivity



Image of Becquerel's
photographic plate which has
been fogged by exposure to
radiation from an uranium salt.
The shadow of a metal
Maltese Cross placed between
the plate and the uranium salt
is clearly visible. (1896)

Radioactive decay

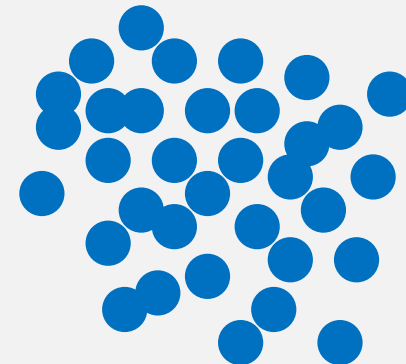
- *Radioactivity* is the spontaneous release of energy in the form of particles or electromagnetic waves
- Experiments suggested that radioactivity was the result of the decay of unstable nuclei
- Three types of radiation can be emitted
 - Alpha (α) particles
 - Beta (β) particles
 - Gamma (γ) rays

Characteristics of radioactive decay

- it is a *statistical process* – individual disintegrations occur

randomly

- it results in a decrease over time of the initial number of unstable (radioactive) nuclei



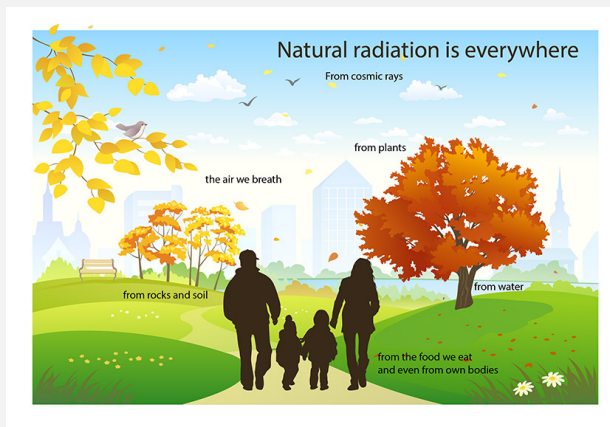
Characteristics of radioactive decay

Activity: $\Lambda = \left| \frac{\Delta N}{\Delta t} \right|$ *N: number of nuclei to be decayed*
t: time

Activity = number of nuclei decayed in a unit time

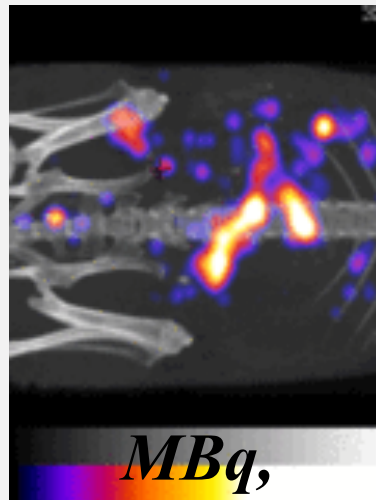
unit: becquerel (Bq) 1Bq = 1 decay/sec

background



kBq,

diagnostics



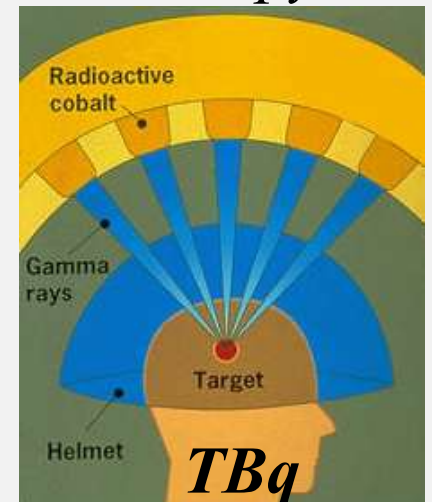
MBq,

laboratory practice



GBq,

therapy



TBq

Radioactive decay law

Differential form:

$$\frac{\Delta N}{\Delta t} = -\lambda N$$

solution

λ : decay constant, characteristic for isotopes (1/s)

Integral form:

$$N = N_0 e^{-\lambda t}$$

N_0 : number of radioactive nuclei at $t=0$,

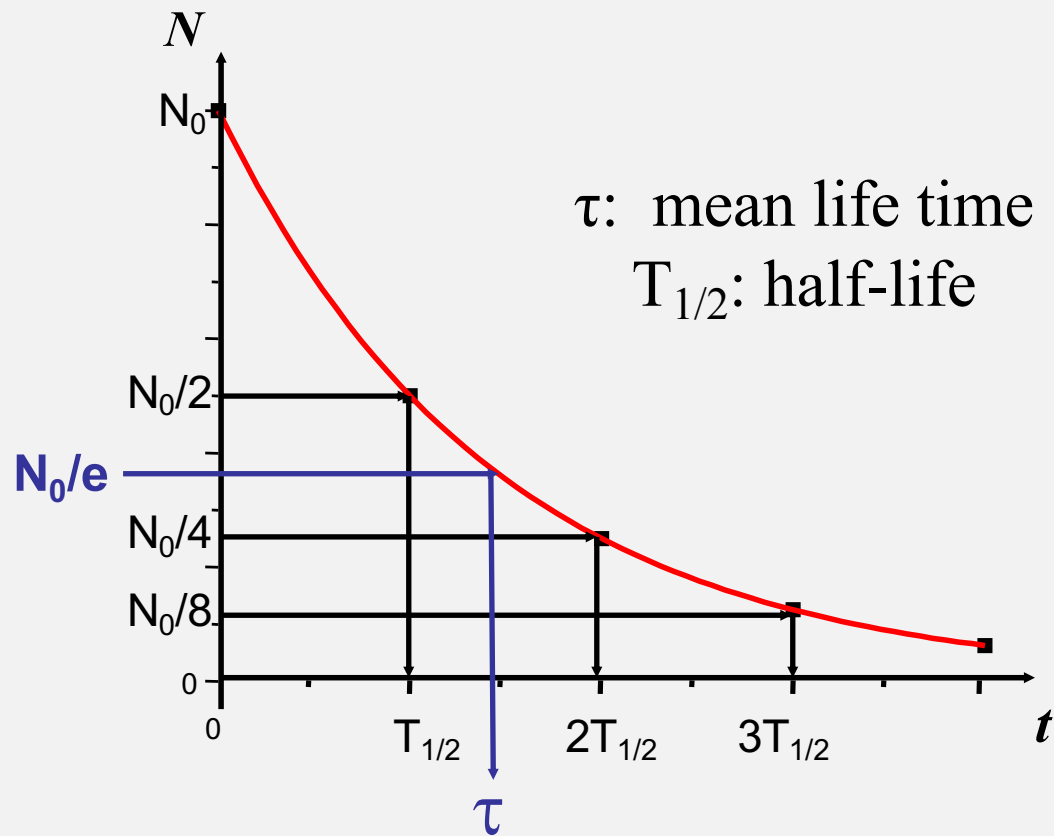
N : number of remaining radioactive nuclei at a later time t

Activity depends both on the type of isotope and on the size of the population of unstable (radioactive) nuclei

Specific activity: activity in a unit mass of isotope (Bq/kg)

Graphical representation

$$N = N_0 e^{-\lambda t}$$



If $t = \tau$



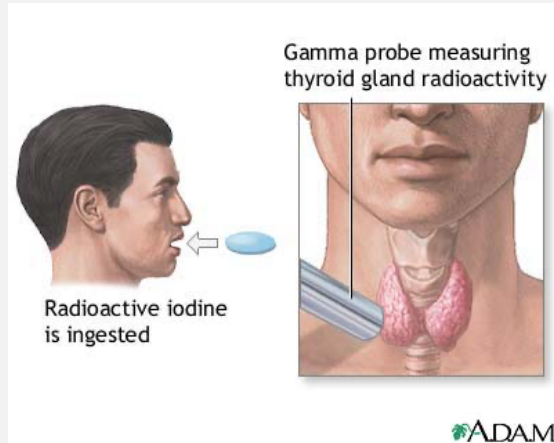
$$N_0 / e = N_0 e^{-\lambda \tau}$$



$$\lambda = \frac{1}{\tau}$$

$$\text{If } t = T_{1/2} \longrightarrow N_0 / 2 = N_0 e^{-\lambda T_{1/2}} \longrightarrow \lambda = \frac{\ln 2}{T_{1/2}} = \frac{0.693}{T_{1/2}}$$

Half-lives in Medical Practice

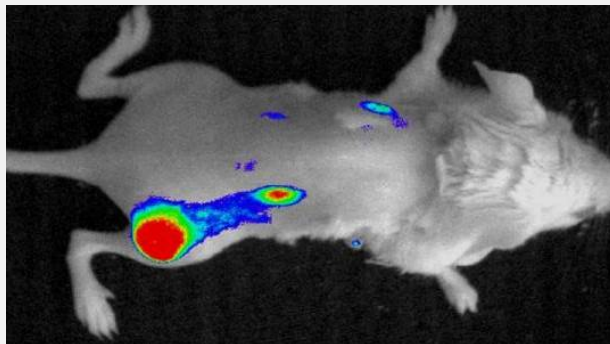
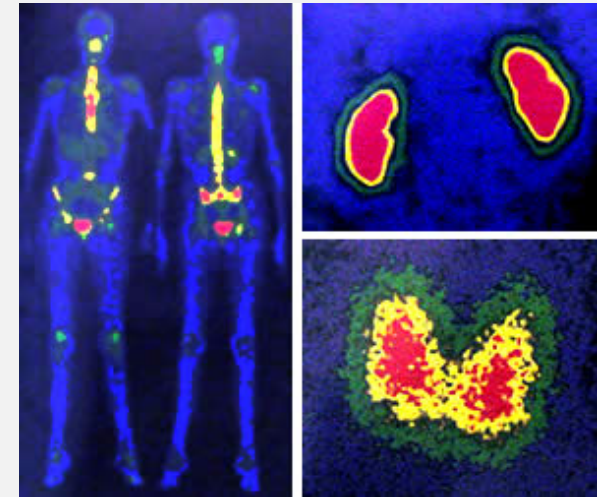


Iodine - 131 (^{131}I) - $T_{1/2} = 8$ days

Thyroid treatment

Technetium-99m ($^{99\text{m}}\text{Tc}$) - $T_{1/2} = 6$ hours

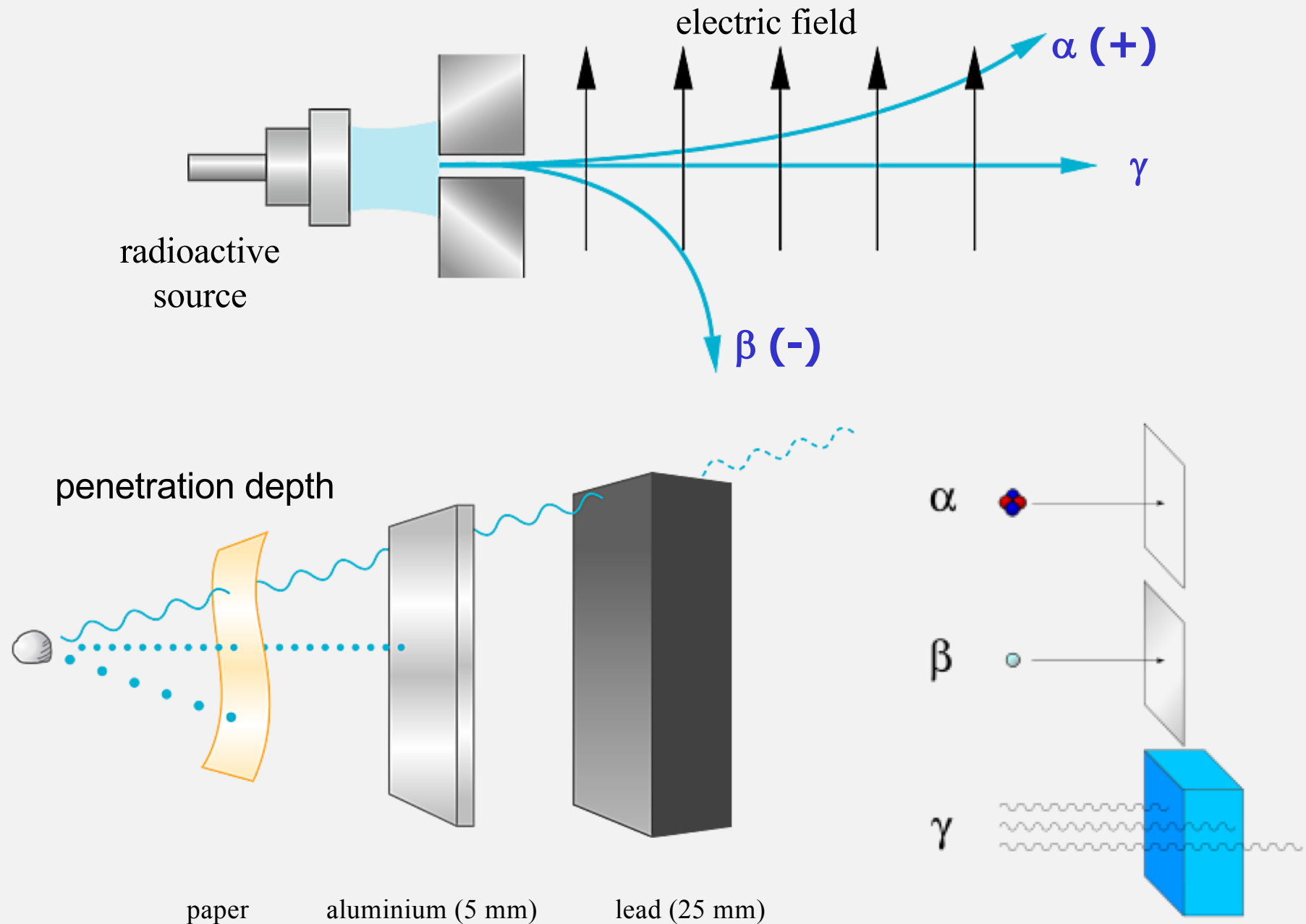
Isotope diagnostics



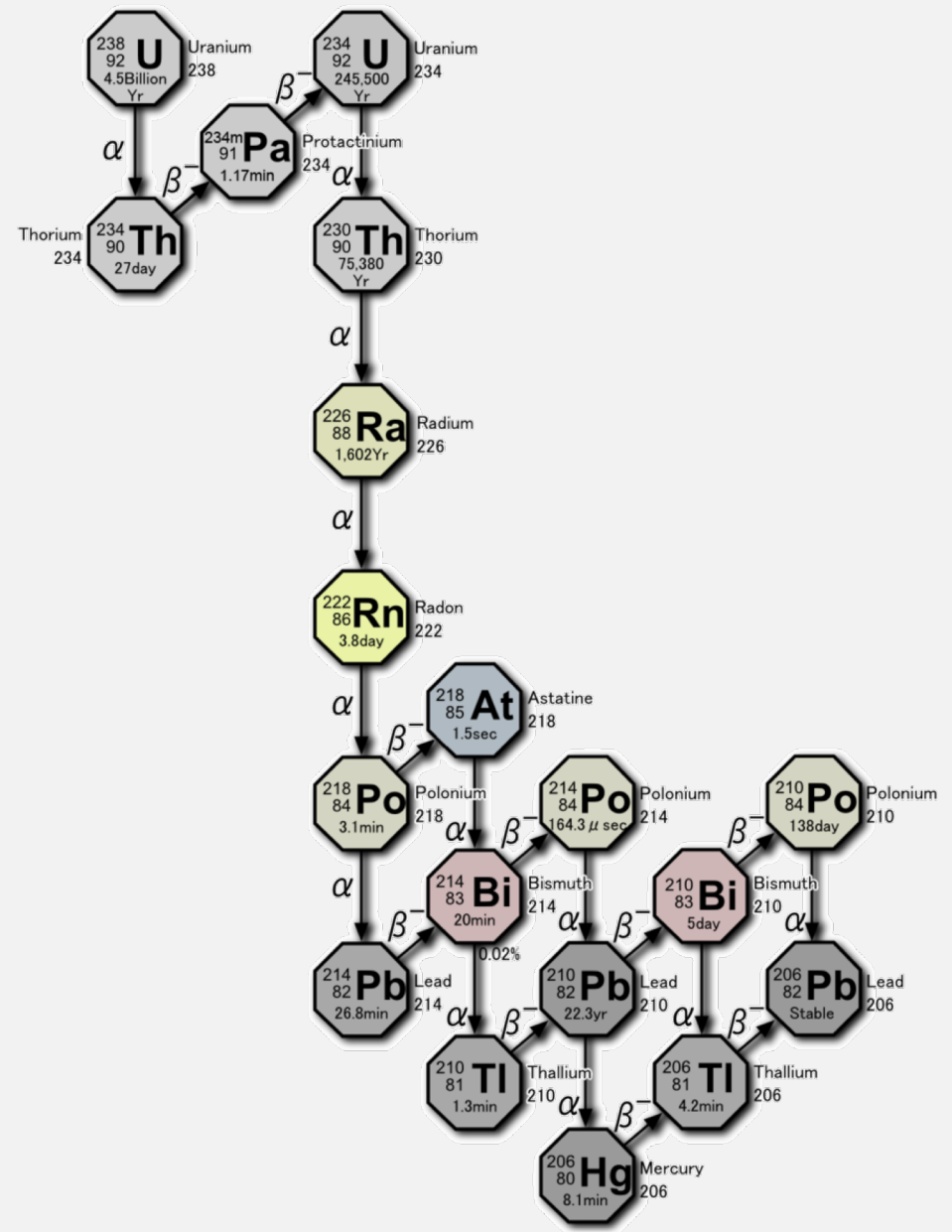
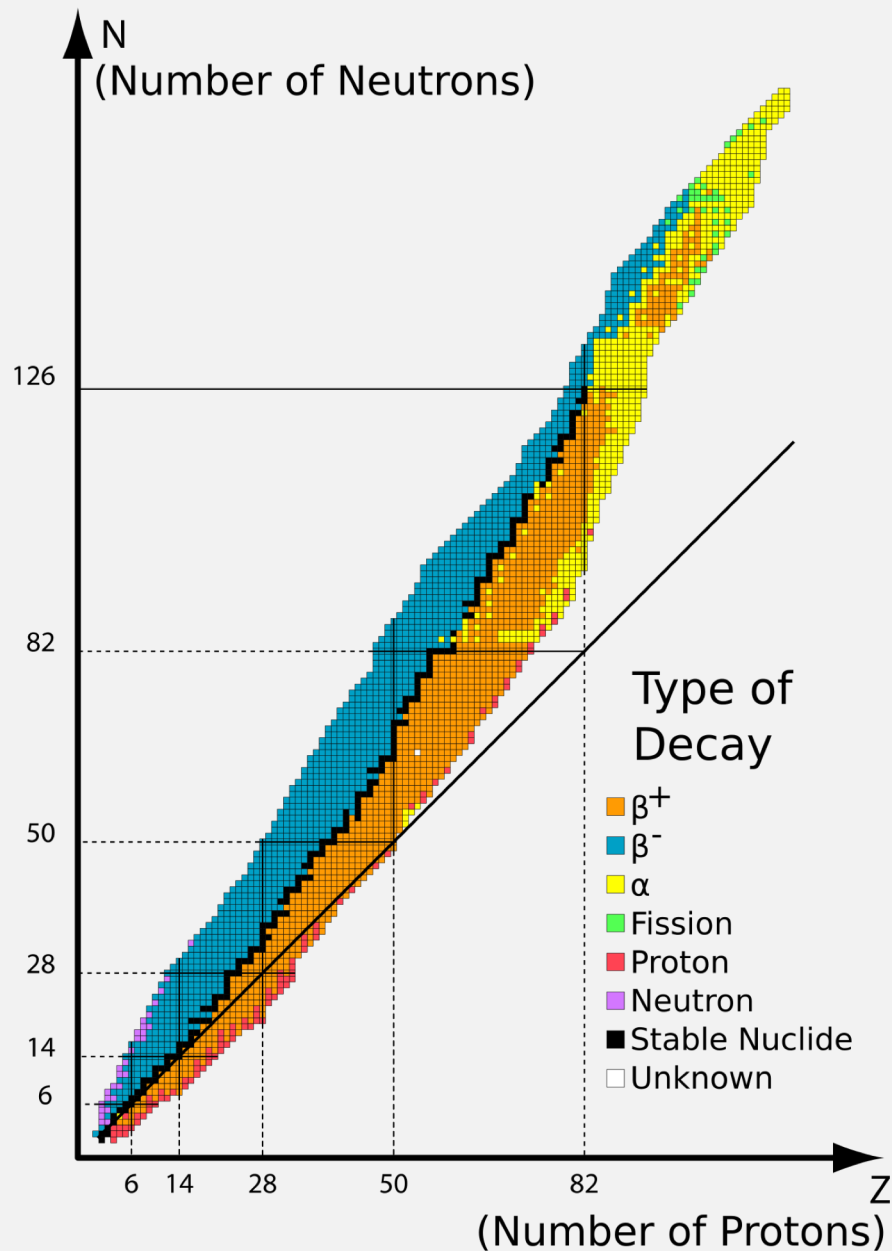
Gold-198 (^{198}Au) - $T_{1/2} = 2.7$ days

Tumor therapy

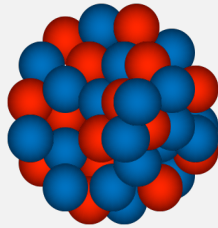
Types of radioactive decay



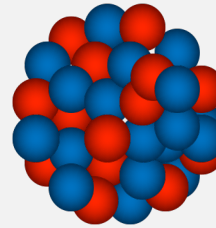
Types of radioactive decay



α decay



parent nucleus

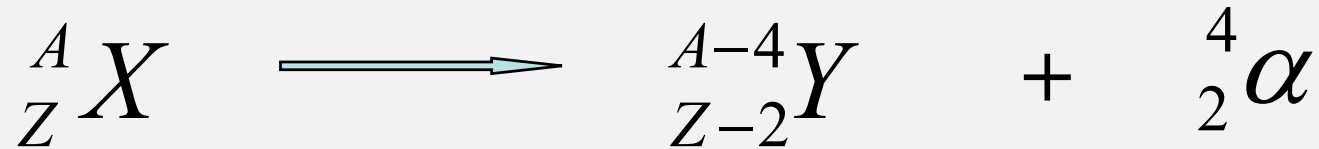


daughter nucleus

+



α particle



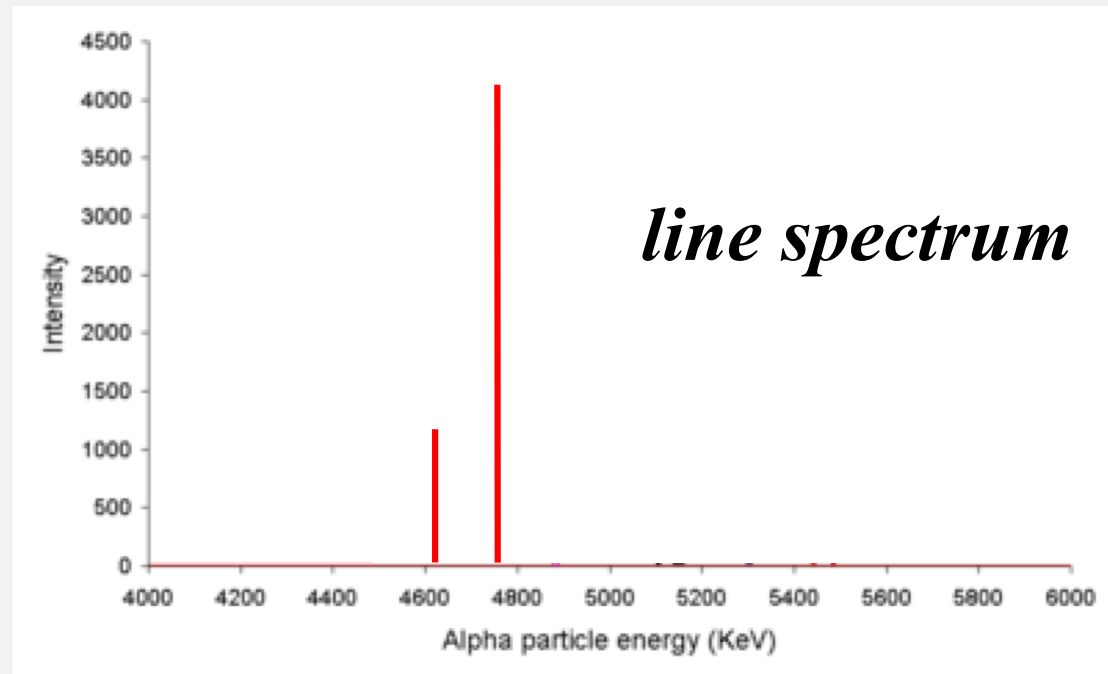
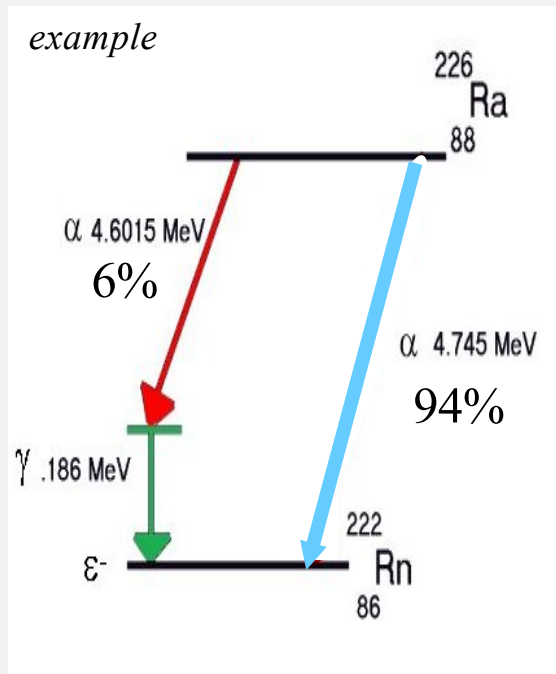
α particle is a nucleus of helium containing two neutrons and two protons

Heavy nuclei ($A > 150$) can disintegrate by emission of an α particle

example:

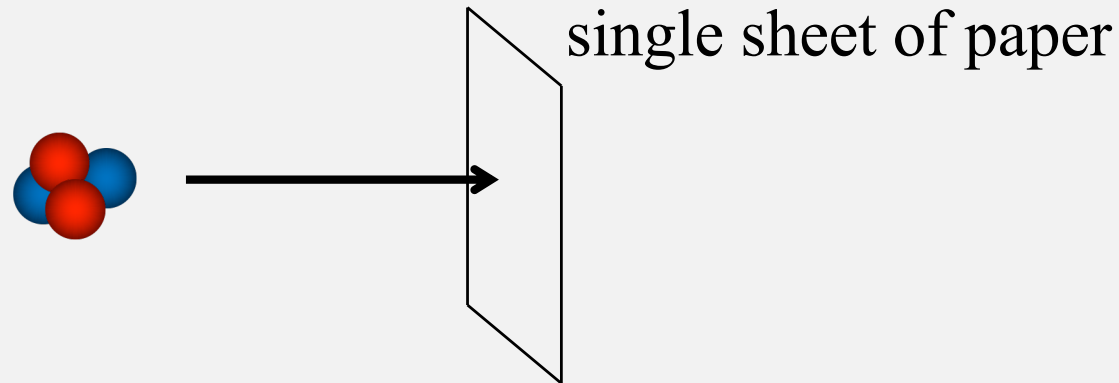


Energy spectrum of α radiation



Energy levels are characteristic for the nucleus

Penetration depth of α particles

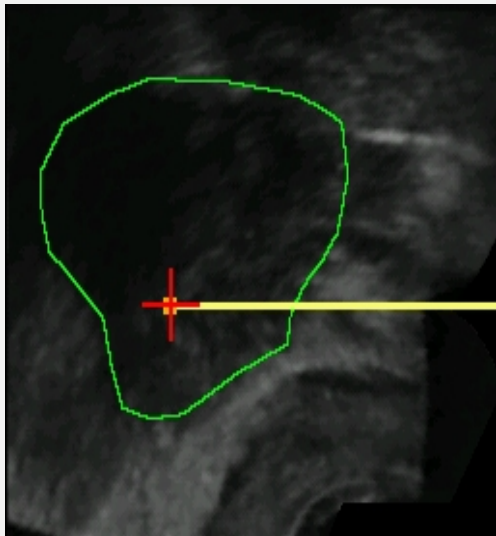


absorber	density	alpha range
air (STP)	1.2 mg/cm ³	3.7 cm
paper (20lb)	0.89 g/cm ³	53 μ m
water (soft tissue)	1.0 g/cm ³	45 μ m

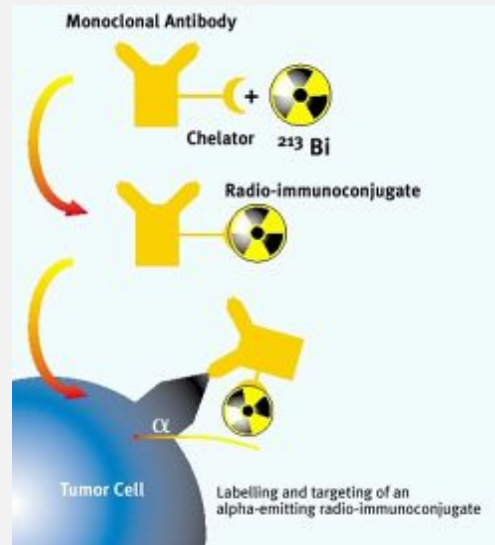
Medical application of α radiation

Diagnostics: none

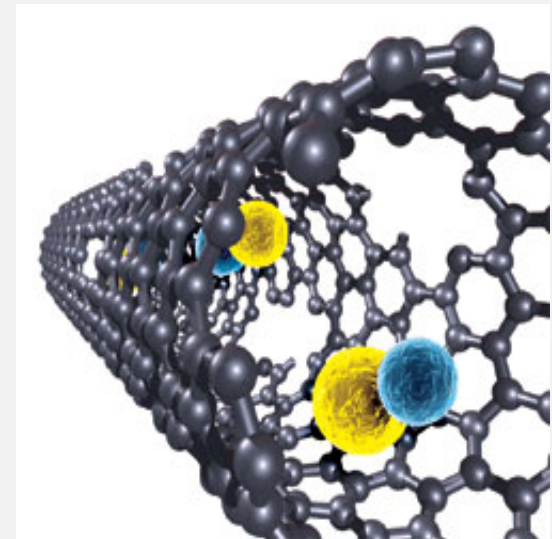
Targeted alpha **therapy** of cancer



Seed implantation
by needle



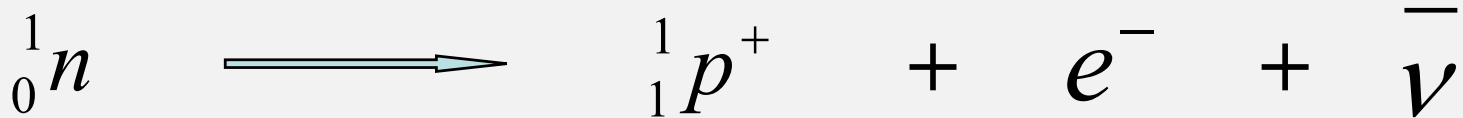
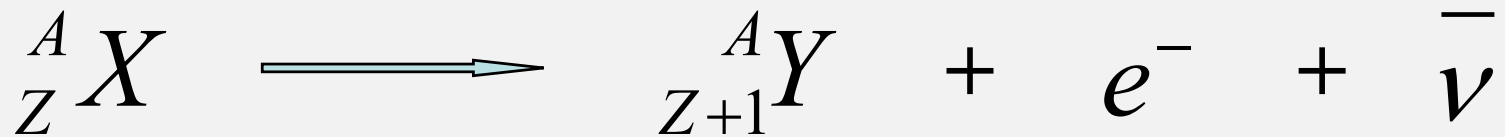
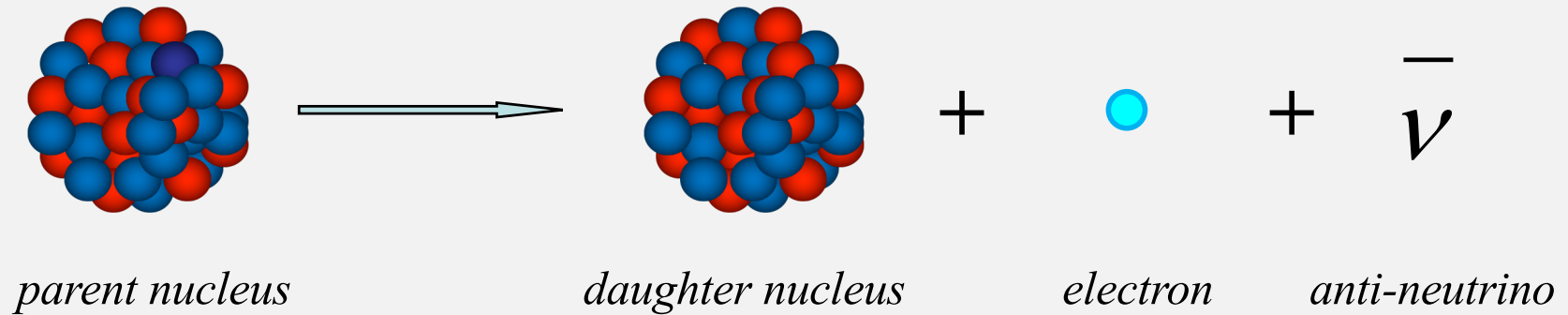
Monoclonal
antibody



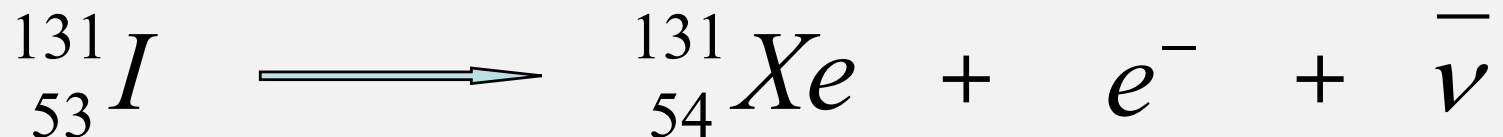
Carbon nano-tube

β decay

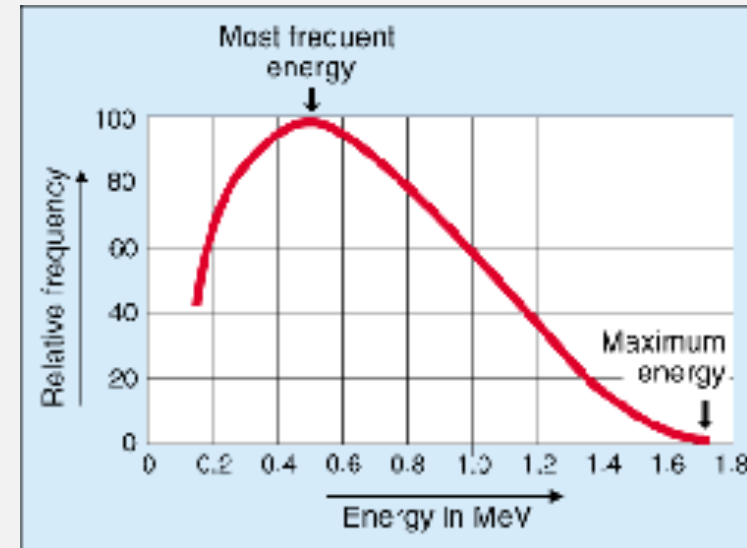
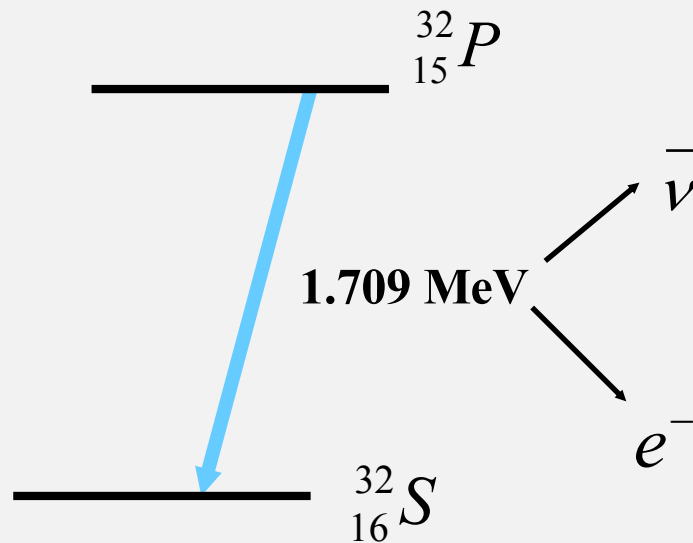
1. Neutron excess: β^- decay



example:



Energy spectrum of β radiation

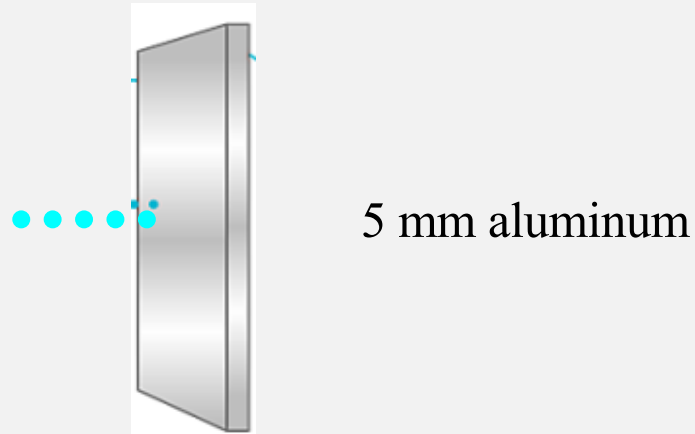


Energy distribution of the β^- particles emitted during the β^- decay of ^{32}P .

continuous spectrum

with a maximum kinetic energy for the β particle

Penetration depth of β^- particles

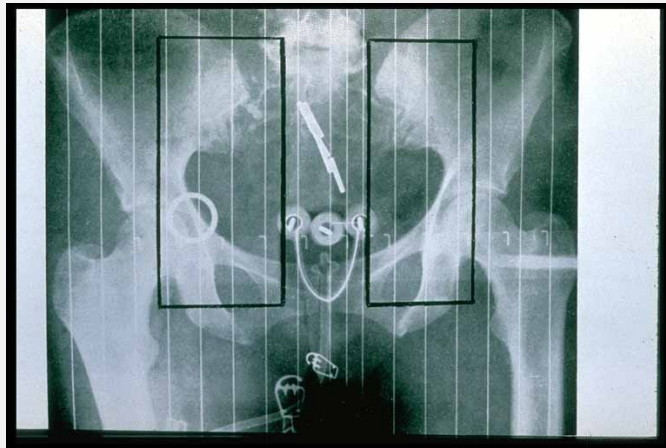


<i>absorber</i>	<i>density</i>	<i>maximum beta range</i>	
		<i>(2.3 MeV)</i>	<i>(1.1 MeV)</i>
air	1.2 mg/cm ³	8.8 m	3.8 m
water (soft tissue)	1.0 g/cm ³	11 mm	4.6 mm
aluminum	2.7 g/cm ³	4.2 mm	2.0 mm
lead	11.3 g/cm ³	1.0 mm	0.4 mm

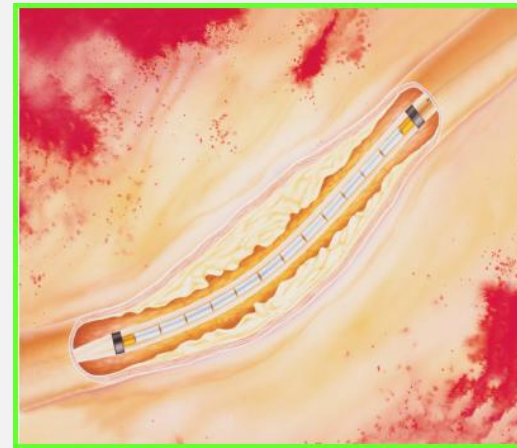
Medical application of β^- radiation

Diagnostics: none

Targeted therapy: hyperthyroidism, thyroid, prostate, and several other types of cancer



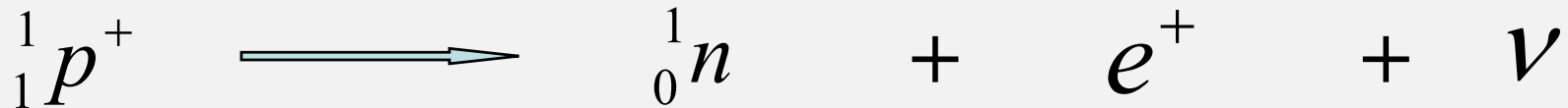
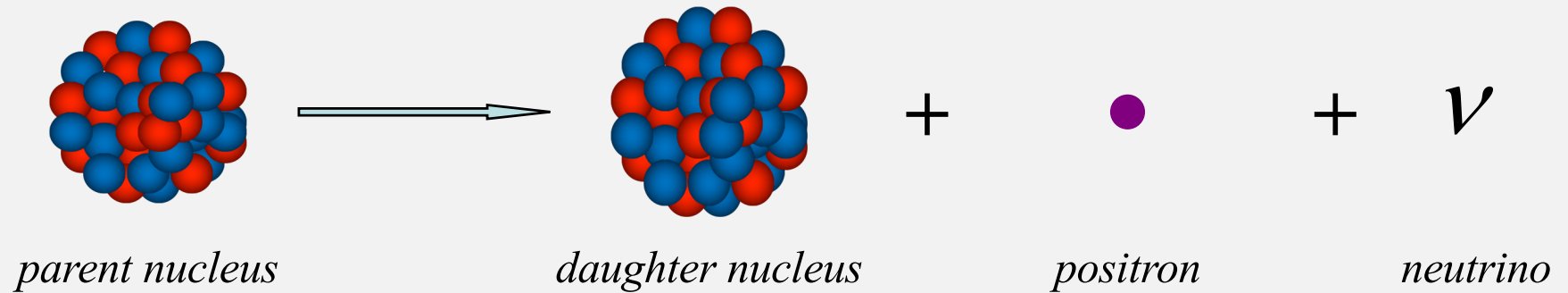
Brachytherapy:
implants into the
tumours



Endovascular
irradiation

β decay

2. Proton excess: β^+ decay



example:



Annihilation - particle-antiparticle pairs annihilate each other

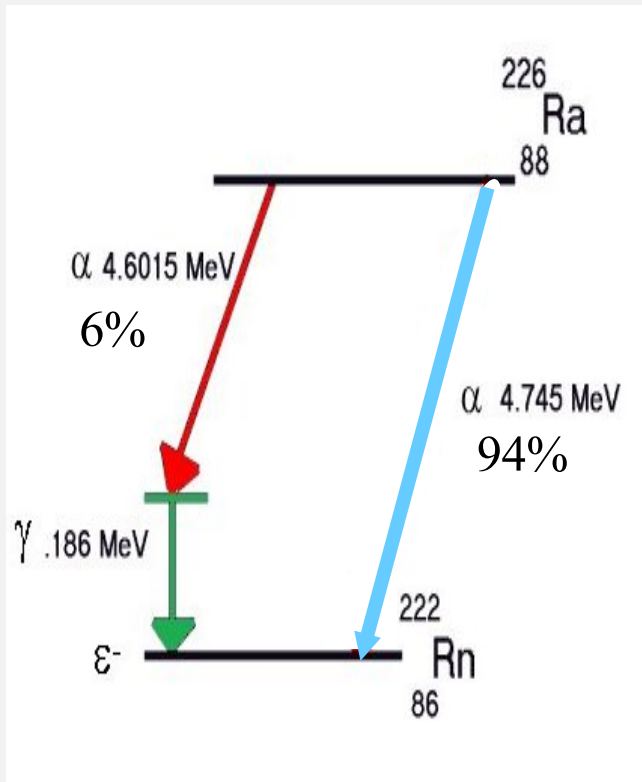


1. Conservation of momentum: two photons with opposite direction are produced
2. Energy balance:

$$m_e c^2 + m_p c^2 = 2 h f$$

mass-energy equivalence

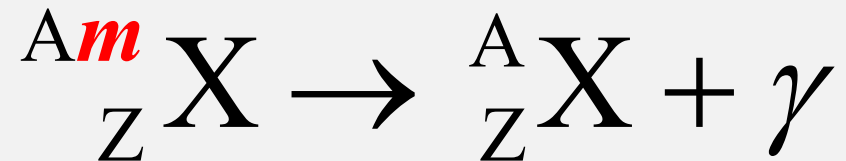
γ decay – Isomeric transition



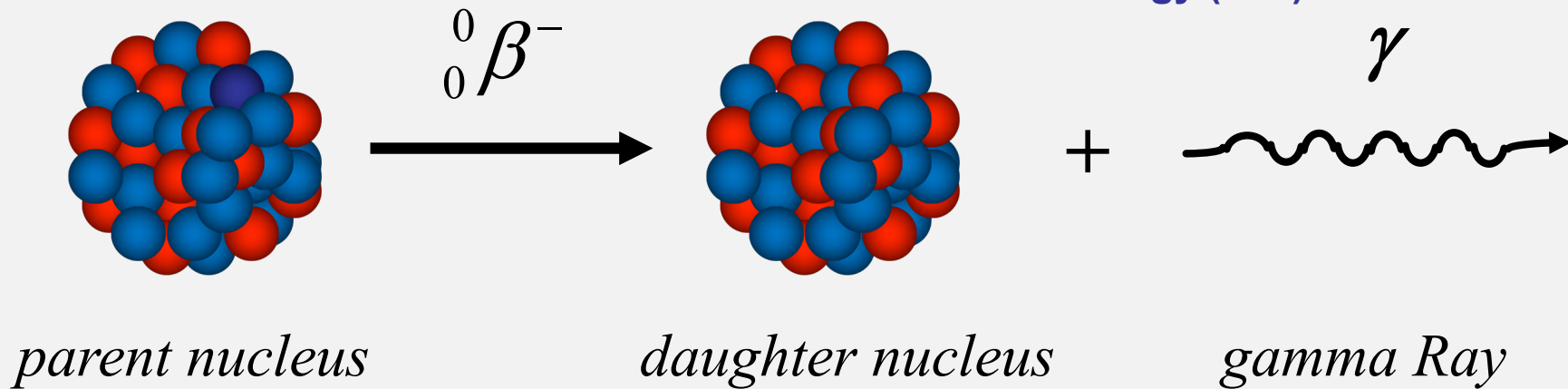
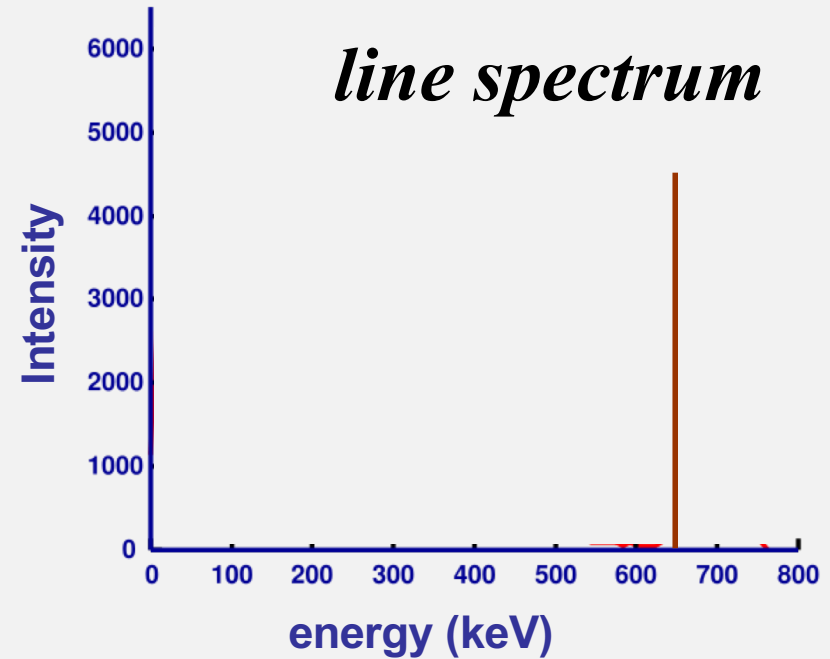
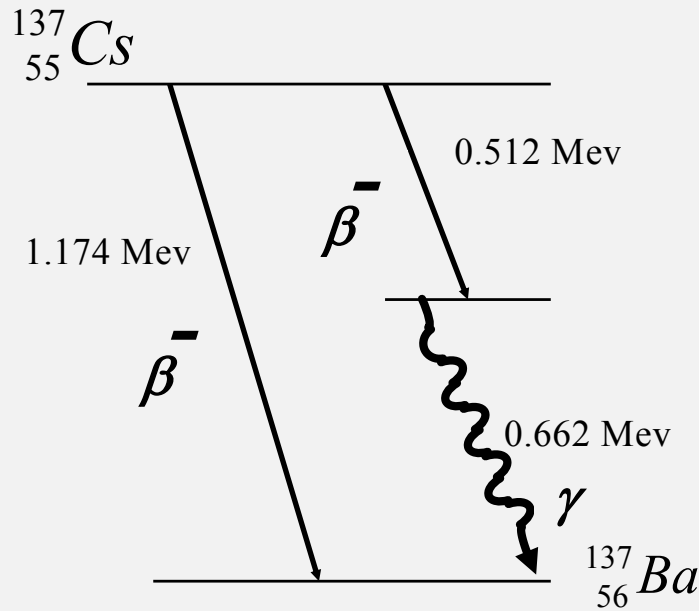
Sometimes the newly formed isotopes (after α or β decay) appear in the excited state.

Excited nuclides release the excess of energy by emission of gamma rays.

half-life ranging from hours up to more than 600 years

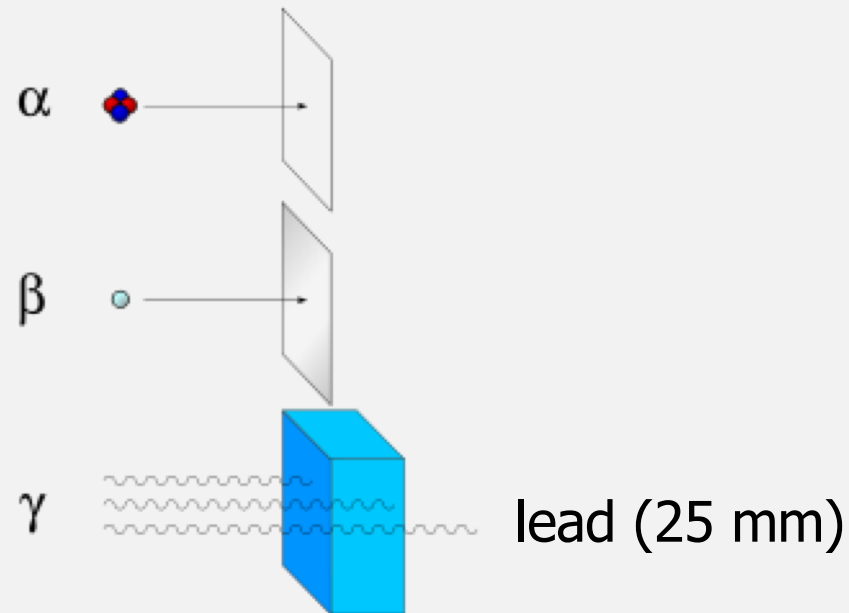


Energy spectrum of γ radiation



Energy is characteristic for the nucleus

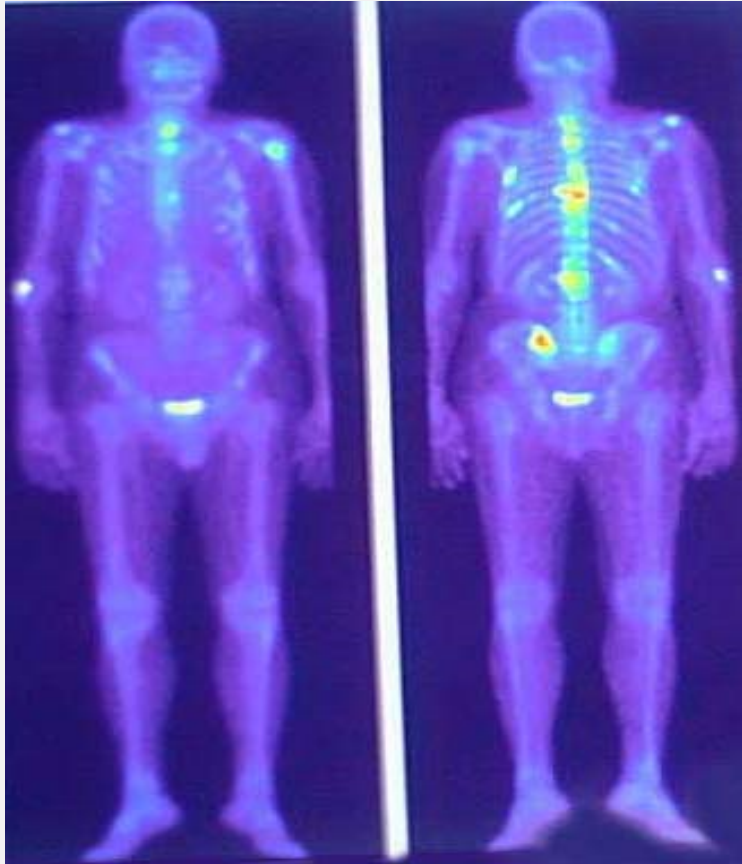
Penetration depth of γ radiation



Penetration depth is higher than that of α or β particles, but it is highly energy dependent.

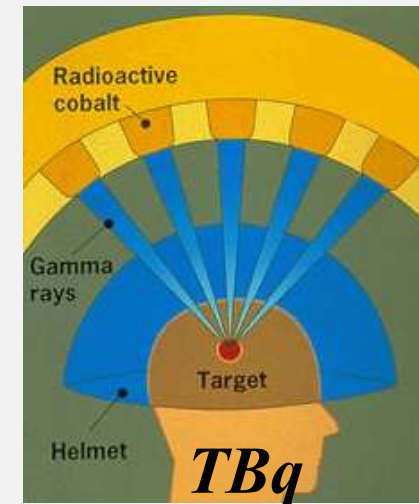
Gamma rays can travel **hundreds of meters in the air** and can easily pass **through people (~dm)**.

Medical application of γ rays



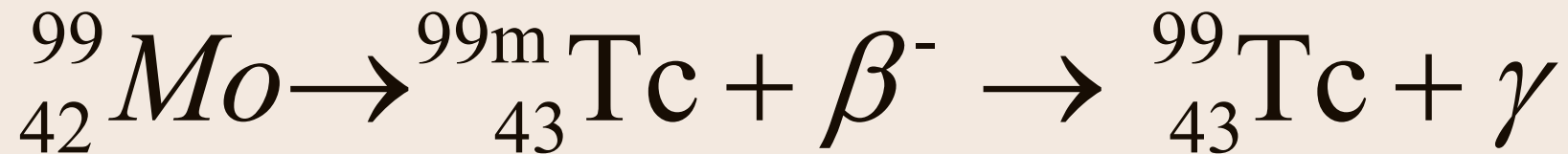
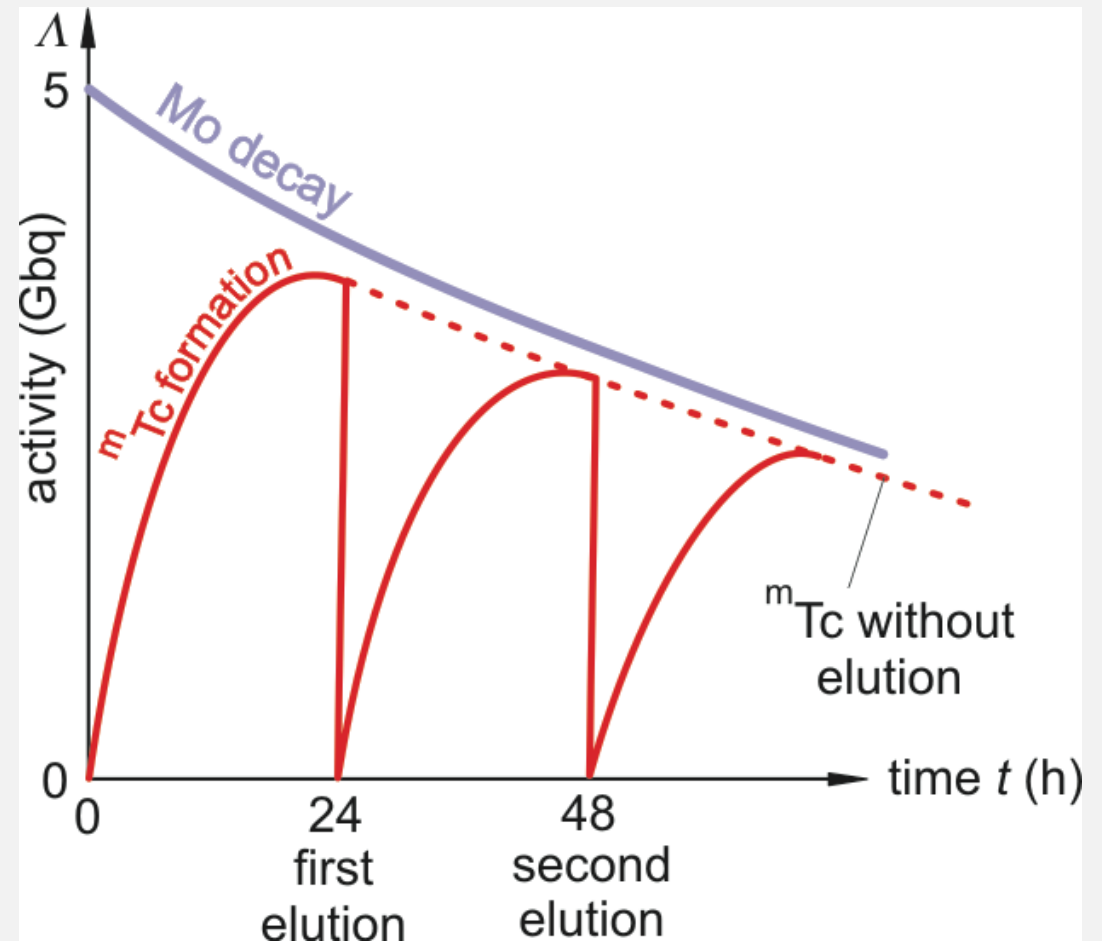
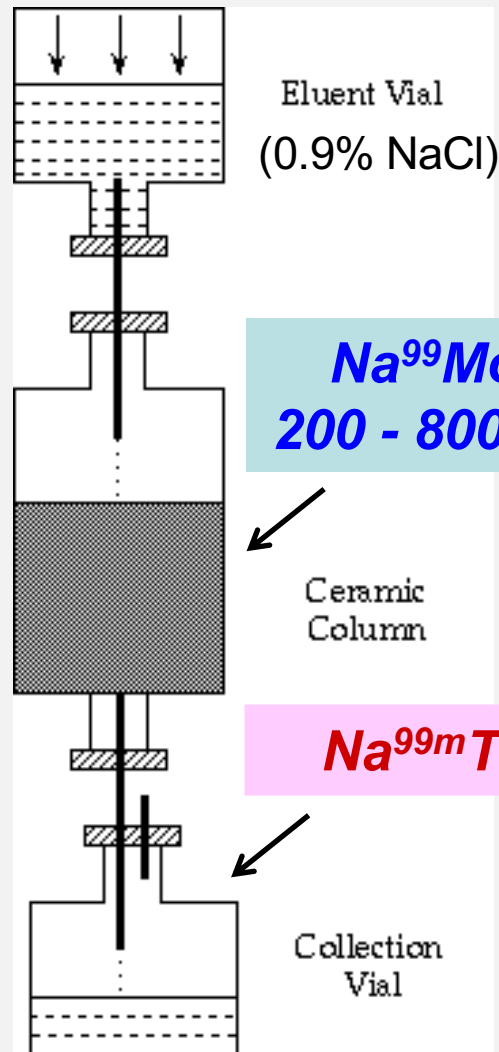
*Bone scan using
 ^{99m}Tc labeled
phosphate compound*

therapy: γ -knife



Diagnostics: ideal for isotope diagnostics

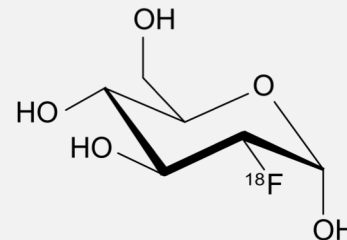
Technetium-99m generator



$T_{1/2}=67$ hours

$T_{1/2}=6$ hours

<i><u>Isotope</u></i>	<i><u>radiofarmacon</u></i>	<i><u>organ</u></i>	<i><u>function</u></i>
$^{99}\text{Tc}^m$	sodium pertechnetate	brain	blood flow
$^{99}\text{Tc}^m$	albumin-linked	lung	blood flow
$^{99}\text{Tc}^m$	colloidal suspension	kidney	metabolism
$^{99}\text{Tc}^m$	phosphate/pyrophosphate	bone	metabolism
^{123}I	iodine	thyroid gland	metabolism
^{123}I	hippurate	kidney	metabolism
^{133}X	X gase	lung	breathing
^{18}F	fluorodeoxyglucose		metabolism



Checklist

Composition and stability of the nucleus

Origin of nuclear force

Radioactive decay law – differential and integral form

Decay constant, half-life, mean life time

Types of nuclear radiation and their characteristics

Damjanovich, Fidy, Szöllősi: Medical Biophysics

I. 1.5

1.5.1

1.5.2

1.5.4

II.3.2

3.2.1

3.2.2

3.2.3

3.2.4