

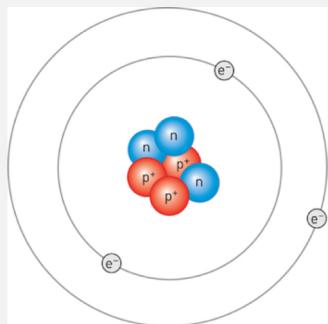
Biophysics I

13. Nuclear radiations

Liliom, Károly

03. 12. 2021.

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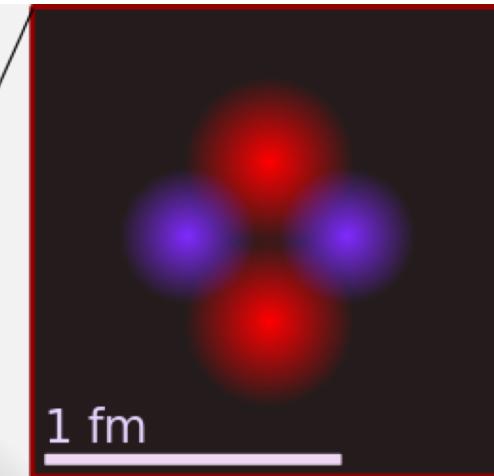
Constituents of atoms

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

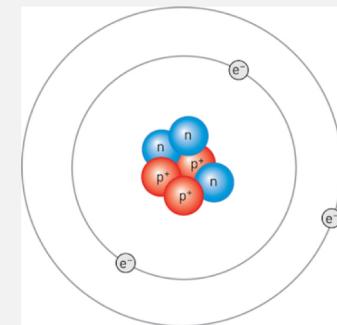
* electrons have an electric charge of $-1.602 \times 10^{-19} \text{ C}$

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

Nucleus size



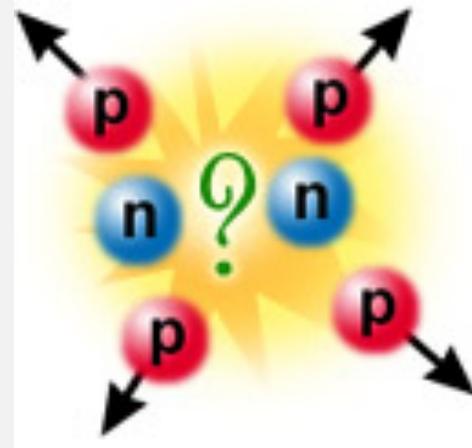
$1 \text{ \AA} = 100,000 \text{ fm}$



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)

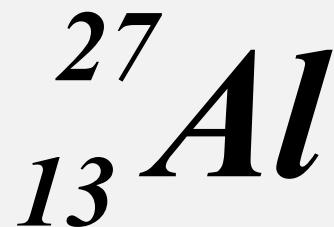
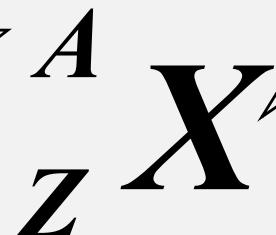
Nuclear notation

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:

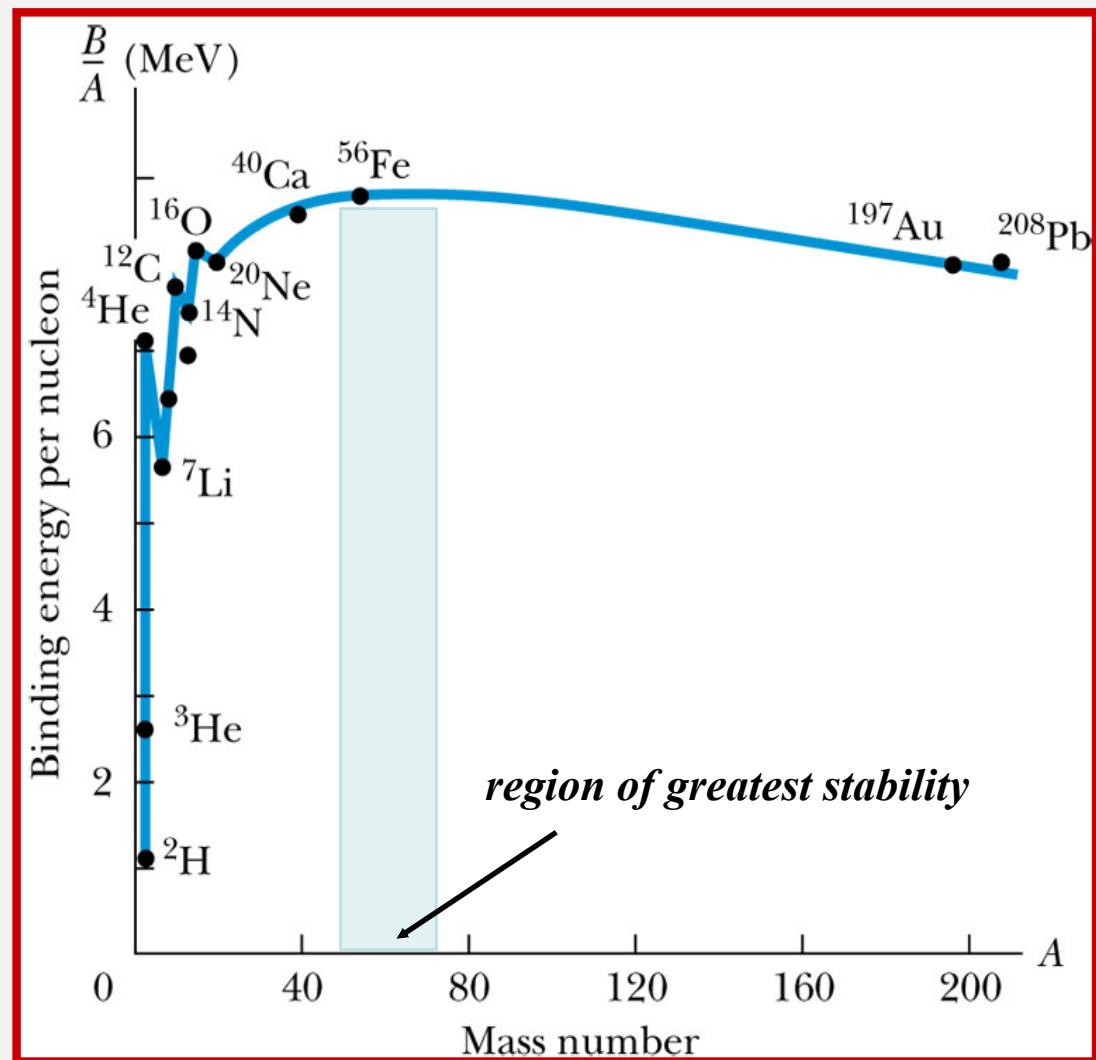
$$\Delta E = \Delta Mc^2$$

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 nuclides ${}^4_2\text{He}$, ${}^{12}_6\text{C}$, 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

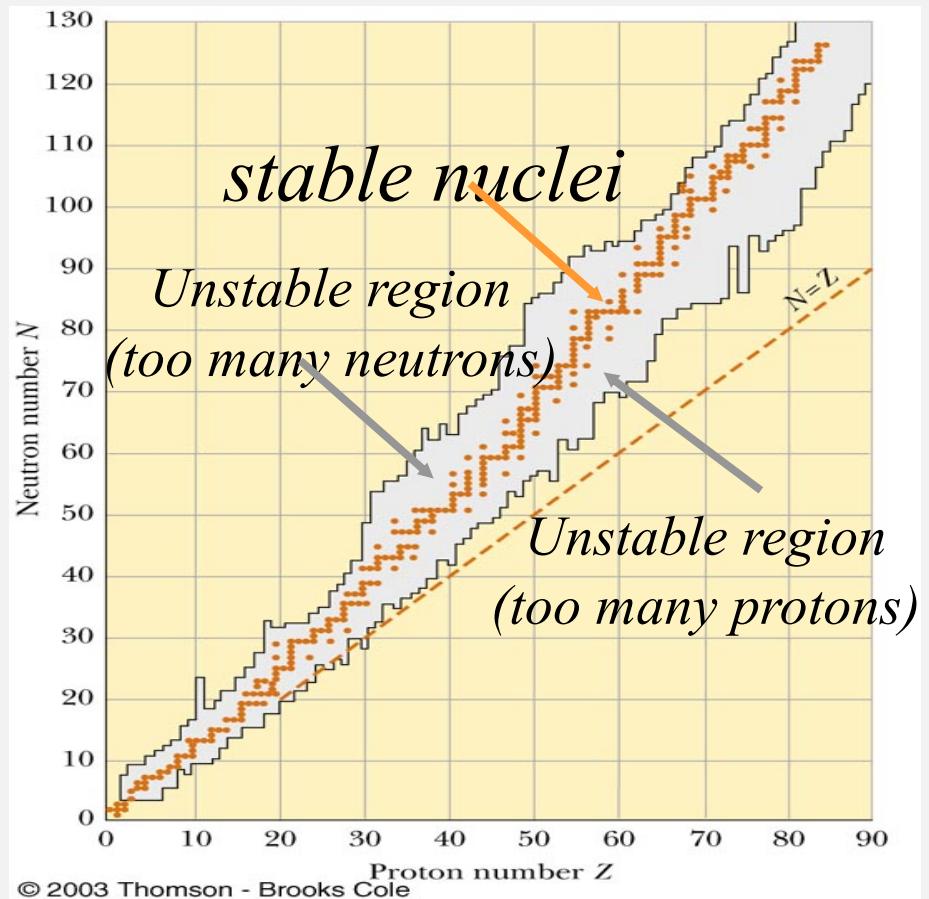
Mendeleev's Periodic Table of Elements

1 IA	Table of Common Polyatomic Ions																		Element categories	State of matter at 25 °C							18 VIIIA																															
1 H 1.008 1	acetate	C ₂ H ₃ O ₂ ⁻	silicate	SiO ₄ ⁴⁻	13 III A	B 10.811 2-3	Gas	14 IV A	C 12.011 2-4	Liquid	15 VA	N 14.007 2-5	Solid	16 VIA	O 15.999 2-6	Artificially prepared	17 VIIA	F 18.998 2-7	Unknown	He 4.003 2	Noble gases																																					
2 Be 9.0122 2-2	chlorate	ClO ₃ ⁻	sulfate	SO ₄ ²⁻	5 IIIB	Al 26.982 2-3	Hydrogen	6 IVB	Si 28.086 2-4	Alkali metals	7 VB	Fe 55.845 2-5	Alkaline-earth metals	8 VI B	Zn 65.39 2-6	Transition metals	9 VII B	Br 35.453 2-7	Halogens	10 Ne 20.179 2-8	Other metals																																					
3 Na 22.990 2-8-1	hydroxide	OH ⁻	thiosulfate	S ₂ O ₃ ²⁻	11 VIIIB	Ge 72.64 2-8-18-5	Semiconductors	12 IB	Cu 63.546 2-8-18-1	Hydrogen	13 I B	Sn 118.71 2-8-18-4	Noble gases	14 IIB	Ga 69.723 2-8-18-2	Other nonmetals	15 II B	As 74.922 2-8-18-3	Other nonmetals	16 III B	S 78.96 2-8-18-6	Other nonmetals	17 IV B	Se 79.904 2-8-18-7	Other nonmetals	18 V B	Ar 39.948 2-8-8	Other nonmetals																														
4 K 39.098 2-8-8-1	nitrate	NO ₃ ⁻	permanganate	MnO ₄ ⁻	19 VIIIB	Ge 72.64 2-8-18-5	Hydrogen	20 I C	Ca 40.078 2-8-2	Semiconductors	21 II C	Sc 44.956 2-8-2	Alkaline-earth metals	22 III C	Ti 47.867 2-8-10-2	Transition metals	23 IV C	V 50.942 2-8-11-2	Transition metals	24 V C	Cr 51.996 2-8-15-1	Transition metals	25 VI C	Mn 54.938 2-8-13-2	Transition metals	26 VII C	Fe 55.845 2-8-14-2	Transition metals	27 VIII C	Co 58.933 2-8-15-2	Transition metals	28 I IA	Ni 58.693 2-8-16-2	Transition metals	29 II IA	Cu 63.546 2-8-18-1	Transition metals	30 III IA	Zn 65.39 2-8-18-2	Transition metals	31 IV IA	Ga 69.723 2-8-18-1	Transition metals	32 V IA	Ge 72.64 2-8-18-5	Transition metals	33 VI IA	As 74.922 2-8-18-3	Transition metals	34 VII IA	Se 78.96 2-8-18-6	Transition metals	35 VIII IA	Br 79.904 2-8-18-8	Transition metals	36 VIII IB	Kr 83.80 2-8-18-8	Transition metals
5 Rb 85.468 2-8-18-8-1	dichromate	Cr ₂ O ₇ ²⁻	chromate	CrO ₄ ²⁻	37 VIIIB	Rb 85.468 2-8-18-8-2	Halogens	38 I C	Sr 87.62 2-8-18-2	Noble gases	39 II C	Y 88.906 2-8-18-9-2	Noble gases	40 III C	Zr 91.224 2-8-18-10-2	Noble gases	41 IV C	Nb 92.906 2-8-18-12-1	Noble gases	42 V C	Tc (98) 101.07 2-8-18-13-1	Noble gases	43 VI C	Ru 102.91 2-8-18-14-1	Noble gases	44 VII C	Rh 106.42 2-8-18-15-1	Noble gases	45 VIII C	Pd 107.87 2-8-18-15-2	Noble gases	46 VIIIA	Ag 112.41 2-8-18-16-2	Noble gases	47 VIIIB	Cd 114.82 2-8-18-18-2	Noble gases	48 I IA	In 118.71 2-8-18-18-4	Noble gases	49 II IA	Sn 121.76 2-8-18-18-5	Noble gases	50 III IA	Sb 127.60 2-8-18-18-6	Noble gases	51 IV IA	Te 126.90 2-8-18-18-7	Noble gases	52 V IA	I 131.29 2-8-18-18-8	Noble gases	53 VI IA	Xe 131.29 2-8-18-18-8	Noble gases			
6 Cs 132.91 2-8-18-18-8-1	carbonate	CO ₃ ²⁻	35 VIIIB	56 I C	Ba 137.33 2-8-18-18-8-2	Hydrogen	72 II C	Hf 178.49 2-8-18-32-10-2	Semiconductors	73 III C	Ta 180.95 -18-32-12-2	Alkaline-earth metals	74 IV C	W 183.84 -18-32-12-2	Transition metals	75 V C	Re 186.21 -18-32-13-2	Transition metals	76 VI C	Os 190.23 -18-32-13-2	Transition metals	77 VII C	Ir 192.22 -18-32-15-2	Transition metals	78 VIII C	Pt 195.08 -18-32-17-1	Transition metals	79 VIIIA	Au 196.97 -18-32-18-1	Transition metals	80 VIIIB	Hg 200.59 -18-32-18-2	Transition metals	81 VIIIA	Tl 204.38 -18-32-18-3	Transition metals	82 VIIIB	Pb 207.2 -18-32-18-4	Transition metals	83 VIIIA	Bi 208.98 -18-32-18-5	Transition metals	84 VIIIB	Po (209) -18-32-18-6	Transition metals	85 VIIIA	At (210) -18-32-18-7	Transition metals	86 VIIIB	Rn (222) -18-32-18-8	Transition metals							
7 Fr (223) -18-32-18-8-1	dichromate	Cr ₂ O ₇ ²⁻	104 VIIIB	87 I C	Ra (226) -18-32-18-8-2	Hydrogen	105 II C	Rf (261)	88 III C	Db (262)	106 IV C	Sg (266)	107 V C	Bh (264)	108 VI C	Hs (277)	109 VII C	Mt (268)	110 VIII C	Uun (281)	111 VIIIA	Uub (272)	112 VIIIB	Uut (285)	113 VIIIA	Uuq (289)	114 VIIIB	Uup (288)	115 VIIIA	Uuh (291)	116 VIIIB	Uus (294)	117 VIIIA	Uuo (294)	118 VIIIB	Uuo (294)																						
<p>Selected Oxidation States</p> <p>Atomic Number</p> <table border="1"> <tr> <td>21</td> <td>Sc</td> <td>44.956 2-8-2</td> </tr> </table> <p>Symbol</p> <p>Electron Configuration</p> <p>Atomic Mass</p>																											21	Sc	44.956 2-8-2																													
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<table border="1"> <tr> <td>57 La 138.91</td> <td>58 Ce 140.12</td> <td>59 Pr 140.91</td> <td>60 Nd 144.24</td> <td>61 Pm (145)</td> <td>62 Sm 150.36</td> <td>63 Eu 151.96</td> <td>64 Gd 157.25</td> <td>65 Tb 158.93</td> <td>66 Dy 162.50</td> <td>67 Ho 164.93</td> <td>68 Er 167.26</td> <td>69 Tm 168.93</td> <td>70 Yb 173.04</td> <td>71 Lu 174.97</td> </tr> </table>																											57 La 138.91	58 Ce 140.12	59 Pr 140.91	60 Nd 144.24	61 Pm (145)	62 Sm 150.36	63 Eu 151.96	64 Gd 157.25	65 Tb 158.93	66 Dy 162.50	67 Ho 164.93	68 Er 167.26	69 Tm 168.93	70 Yb 173.04	71 Lu 174.97																	
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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 „not stable”?

Radioactive decay



Antoine Becquerel
1903 Nobel Prize in Physics
for discovering radioactivity



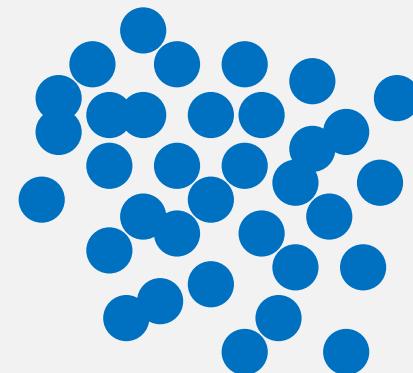
Image of Becquerel's photographic plate which has been fogged by exposure to radiation from a uranium salt. The shadow of a metal Maltese Cross placed between the plate and the uranium salt is clearly visible. (1896)

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



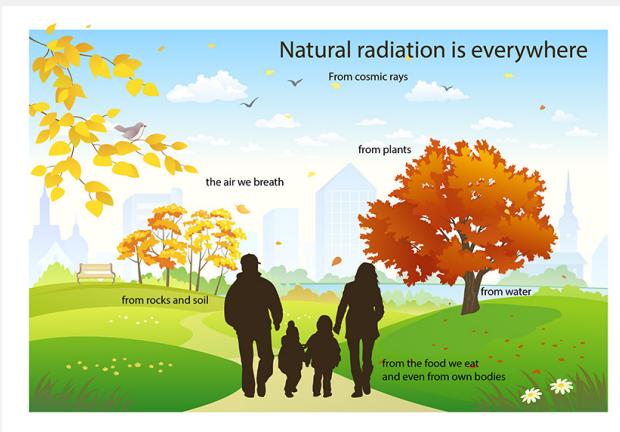
Characteristics of radioactive decay

$$\text{Activity: } \Lambda = \left| \frac{\Delta N}{\Delta t} \right| \quad \begin{array}{l} N: \text{number of nuclei} \\ \text{to be decayed} \\ t: \text{time} \end{array}$$

Activity = number of nuclei decayed in a unit time

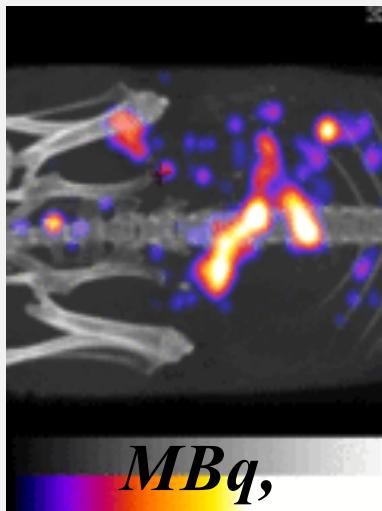
unit: bequerel (Bq) 1Bq = 1 decay/sec

background



kBq,

diagnostics



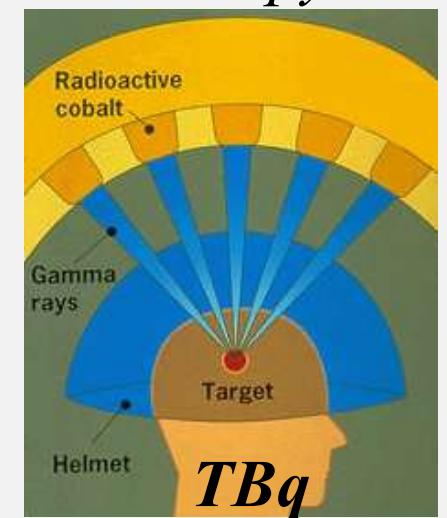
MBq,

*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 $t=0$,

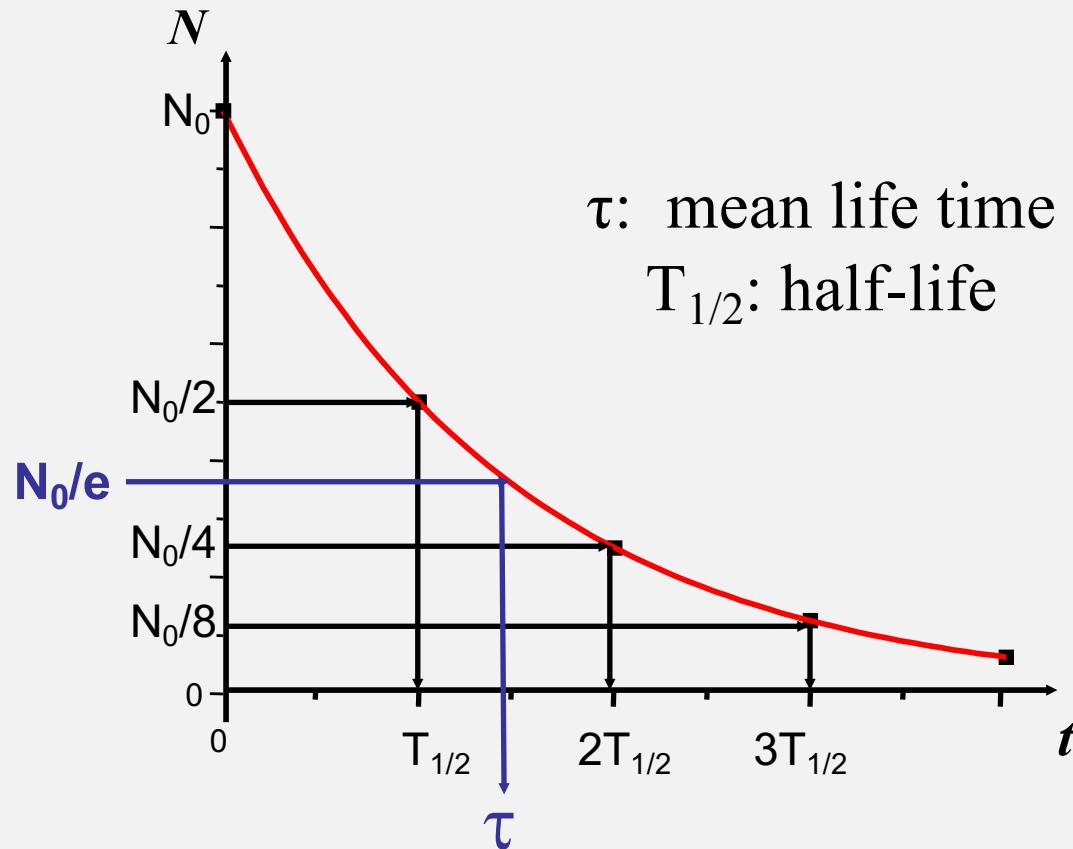
N : number of remaining radioactive nuclei at a later time t

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 $t = \tau$



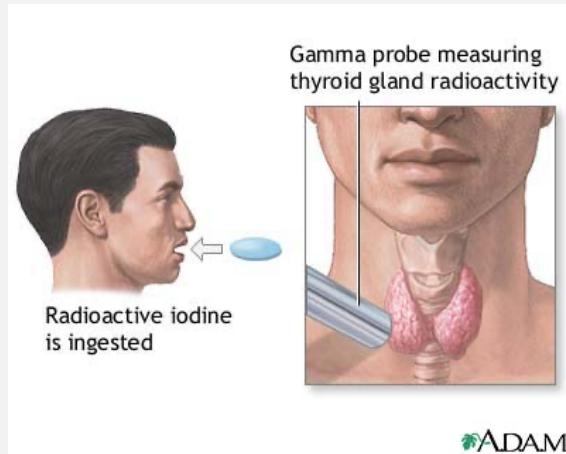
$$N_0 / e = N_0 e^{-\lambda \tau}$$



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

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

Half-lives in Medical Practice

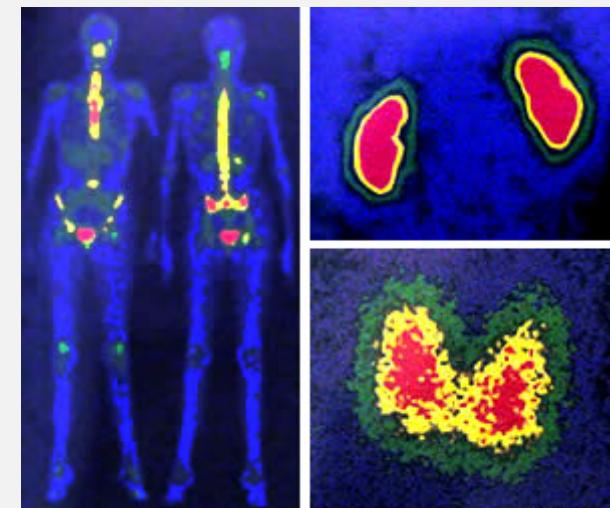
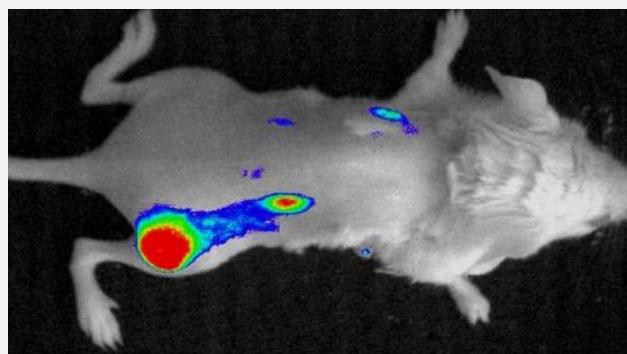


Iodine - 131 (^{131}I) - $T_{1/2} = 8 \text{ days}$

Thyroid treatment

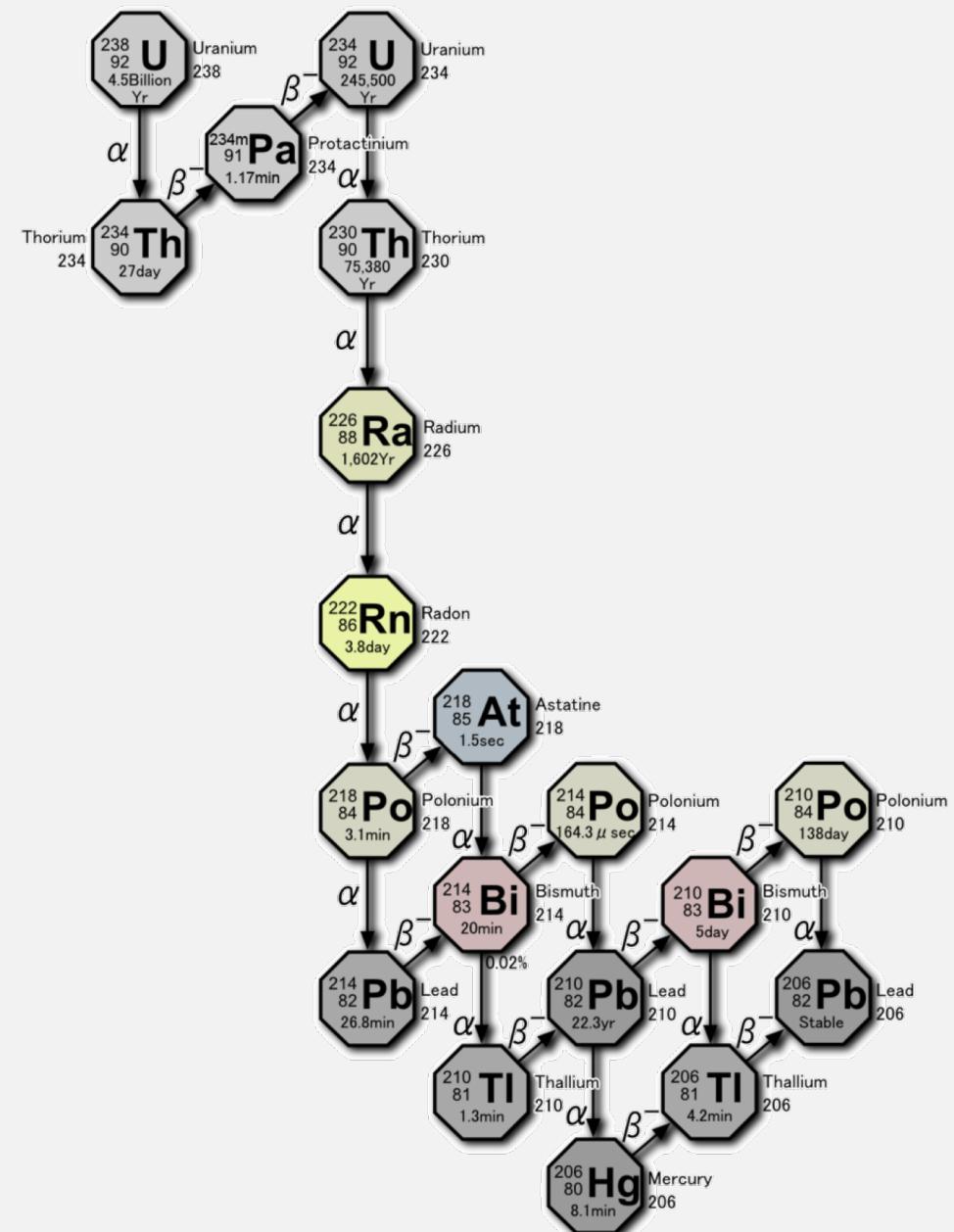
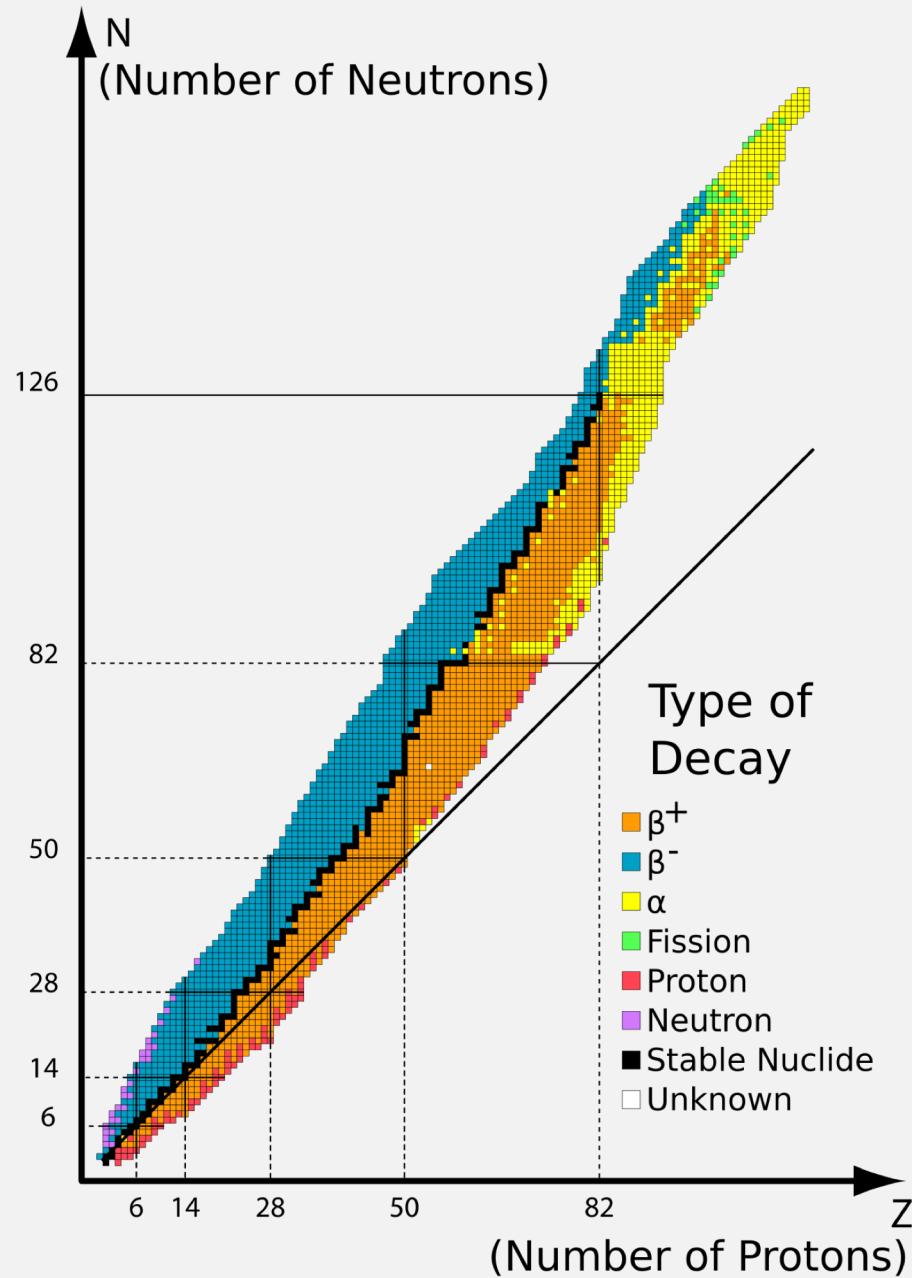
Technetium-99m ($^{99\text{m}}\text{Tc}$) – $T_{1/2} = 6 \text{ hours}$

Isotope diagnostics

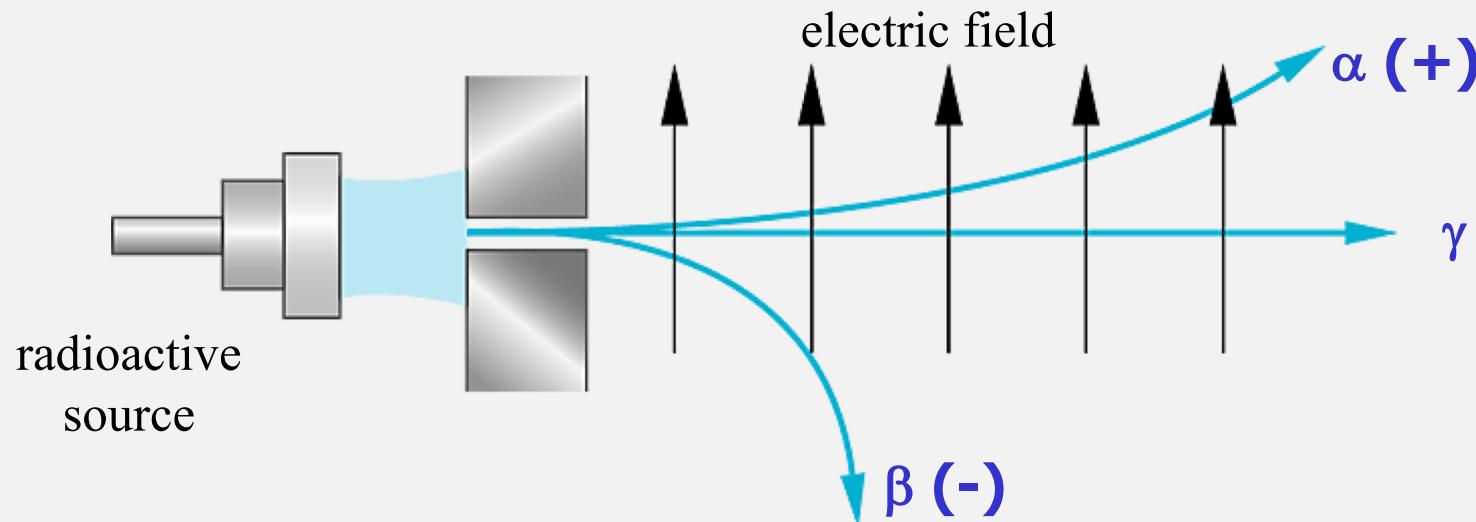


Gold-198 (^{198}Au) - $T_{1/2} = 2.7 \text{ days}$
Tumor therapy

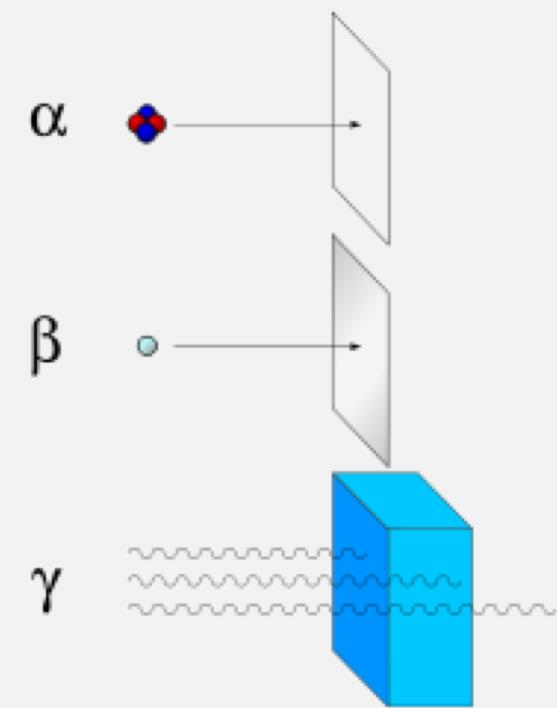
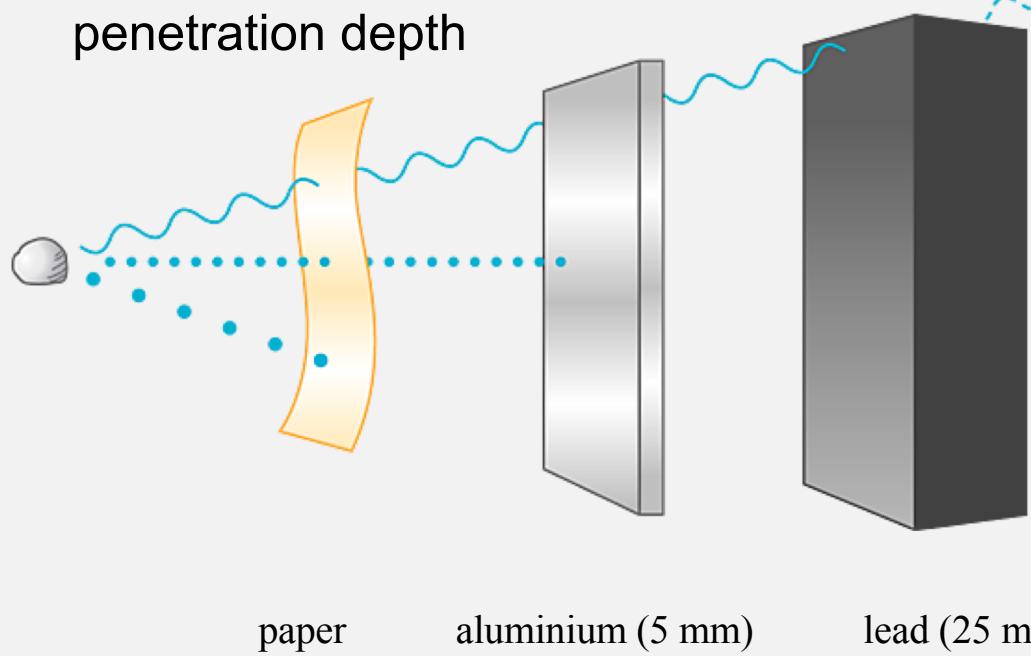
Types of radioactive decay



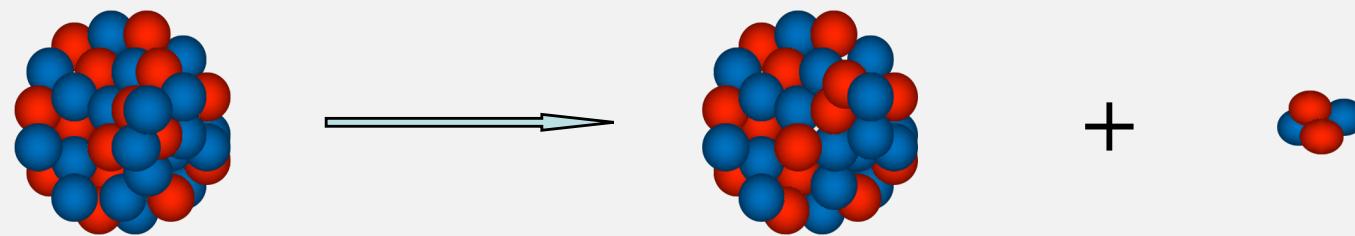
Types of radioactive decay



penetration depth



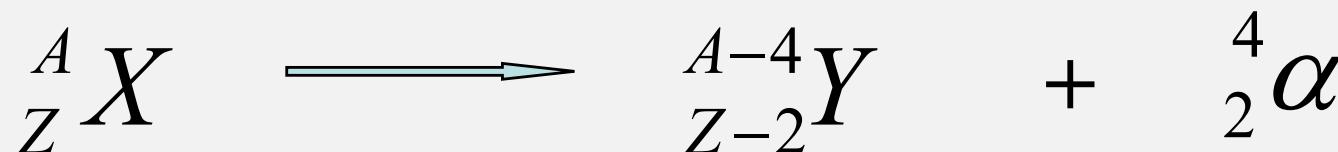
α decay



parent nucleus

daughter nucleus

α particle



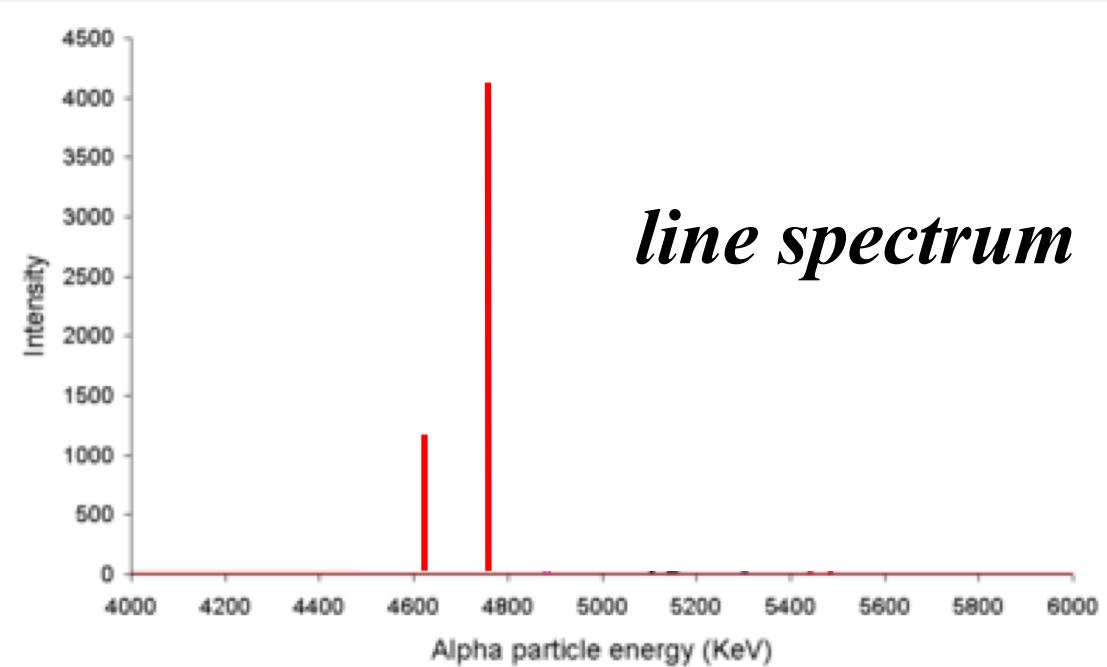
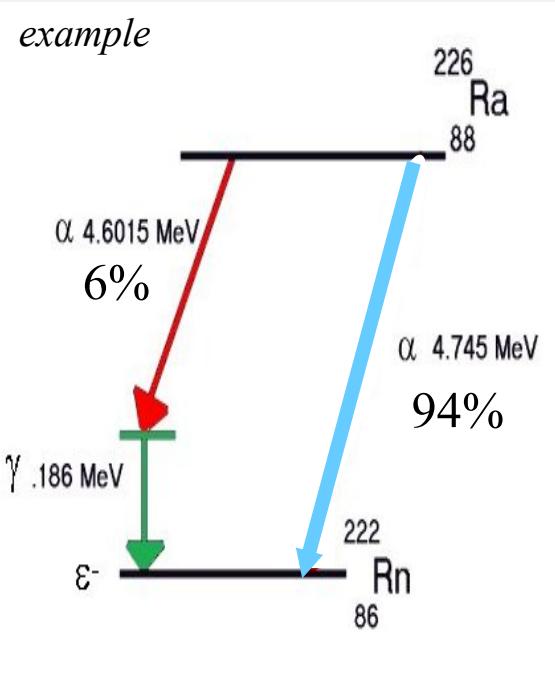
α particle is a nucleus of helium containing two neutrons and two protons

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

example:



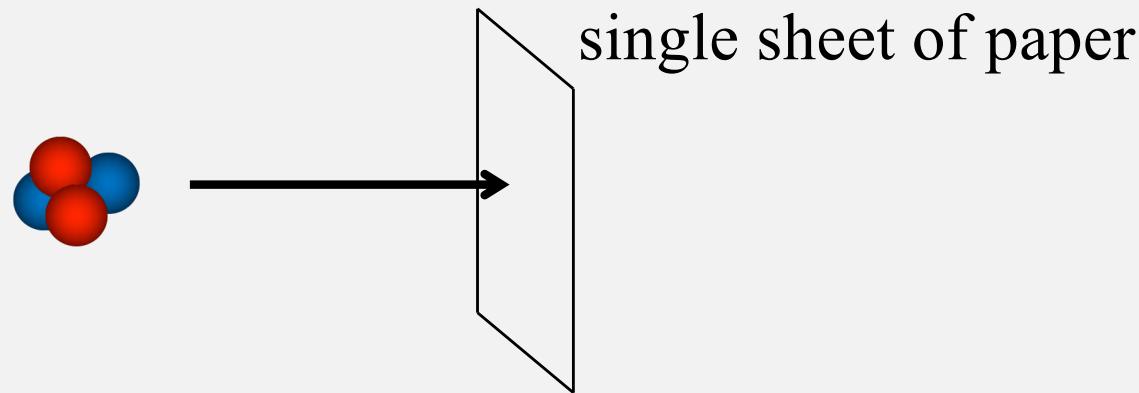
Energy spectrum of α radiation



line spectrum

Energy is characteristic for the nucleus

Penetration depth of α particles

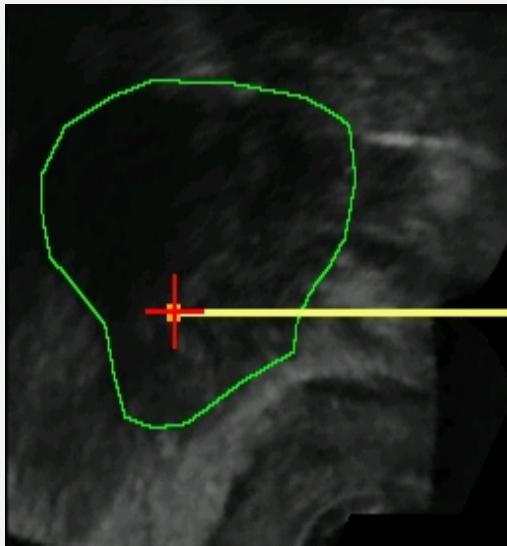


absorber	density	alpha range
air (STP)	1.2 mg/cm ³	3.7 cm
paper (20lb)	0.89 g/cm ³	53 μ m
water (soft tissue)	1.0 g/cm ³	45 μ m

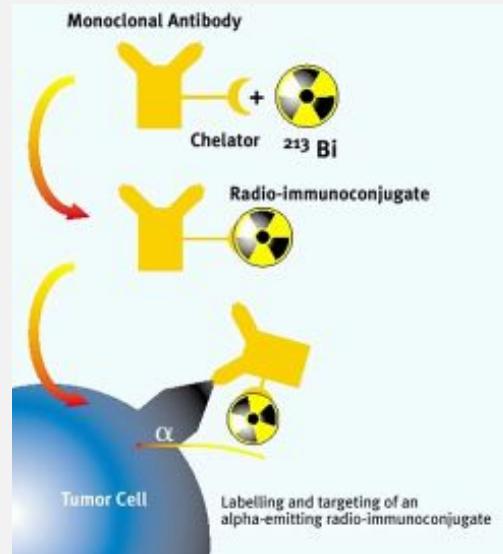
Medical application of α radiation

Diagnostics: none

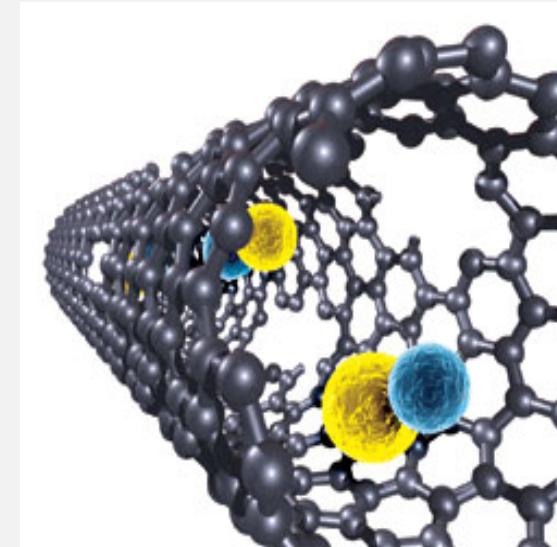
Targeted alpha **therapy** of cancer



Seed implantation
by needle



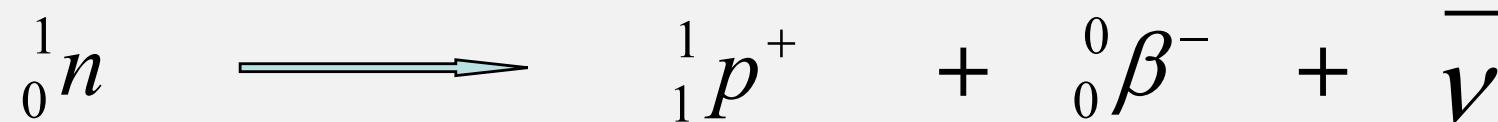
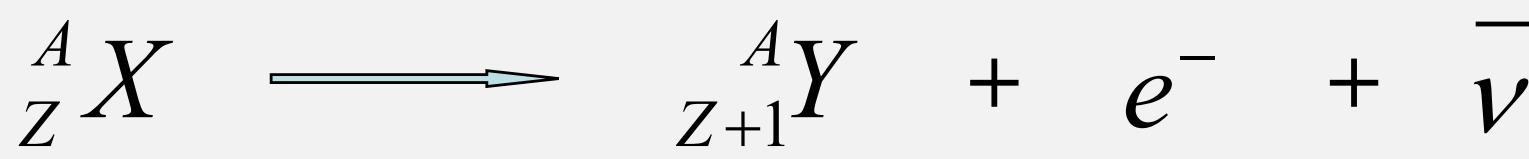
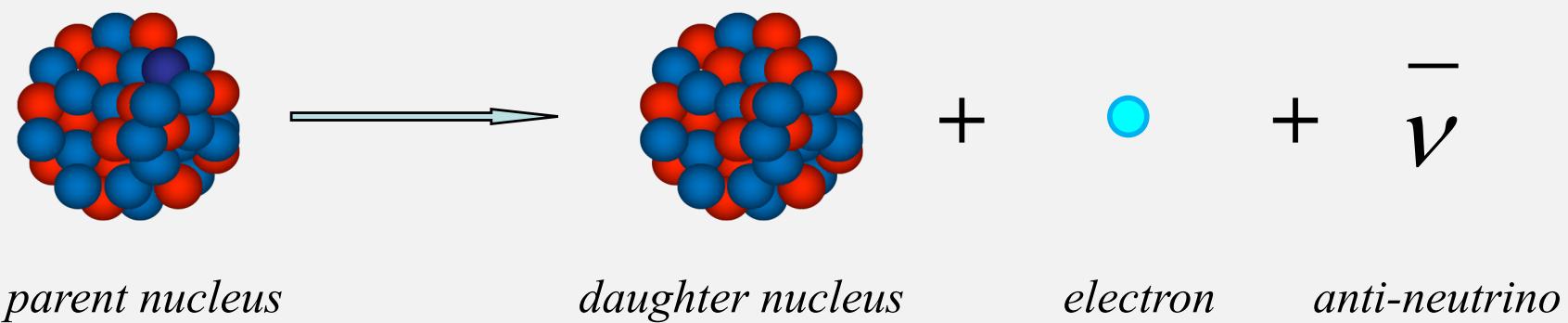
Monoclonal
antibody



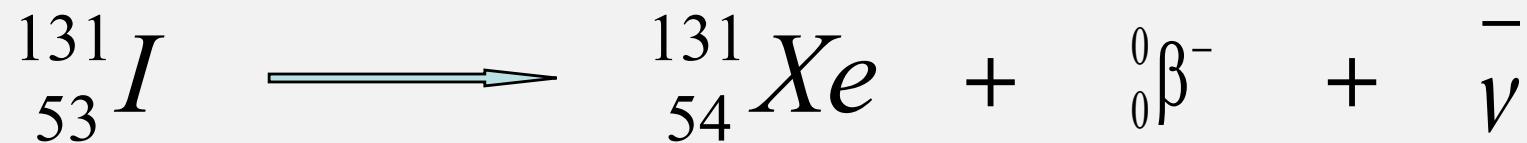
Carbon nano-tube

β decay

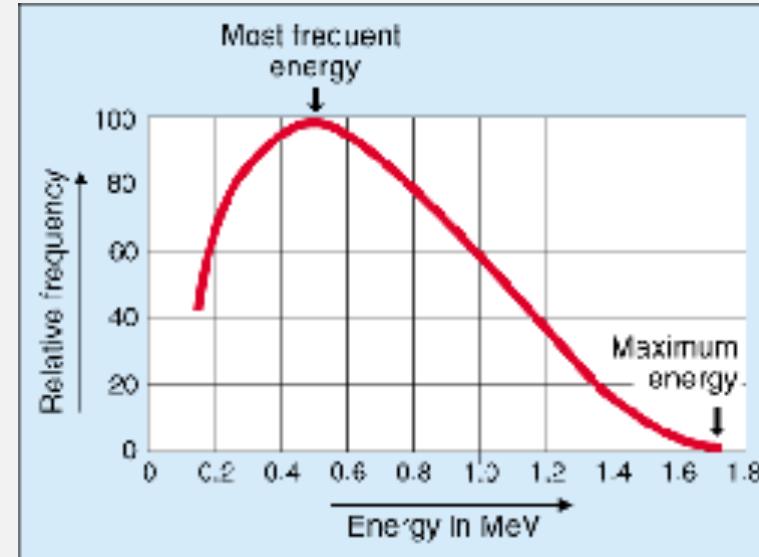
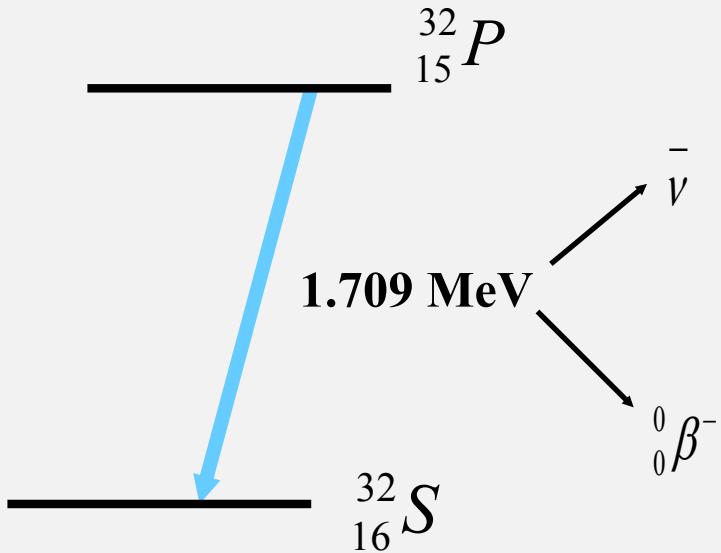
1. Neutron excess: β^- decay



example:



Energy spectrum of β radiation

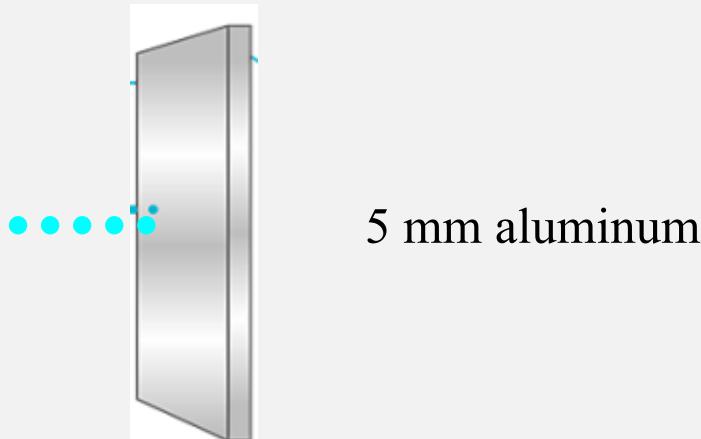


Energy distribution of the β - particles emitted during the β - decay of ^{32}P .

continuous spectrum

with a maximum kinetic energy for the β particle

Penetration depth of β^- particles

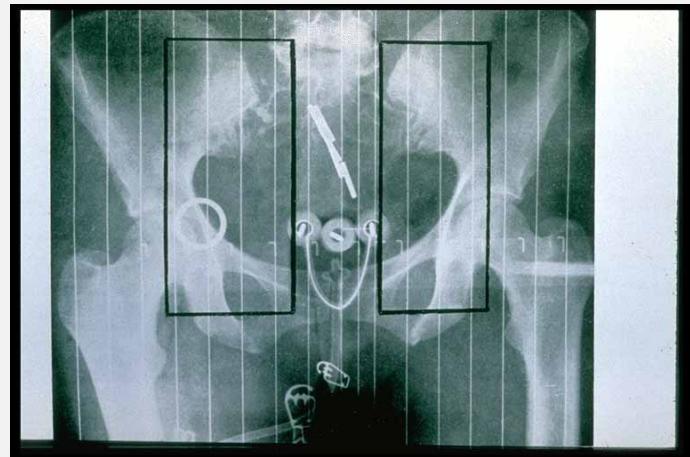


<i>absorber</i>	<i>density</i>	<i>maximum beta range (2.3 MeV)</i>	<i>(1.1 MeV)</i>
air	1.2 mg/cm ³	8.8 m	3.8 m
water (soft tissue)	1.0 g/cm ³	11 mm	4.6 mm
aluminum	2.7 g/cm ³	4.2 mm	2.0 mm
lead	11.3 g/cm ³	1.0 mm	0.4 mm

Medical application of β^- radiation

Diagnostics: none

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



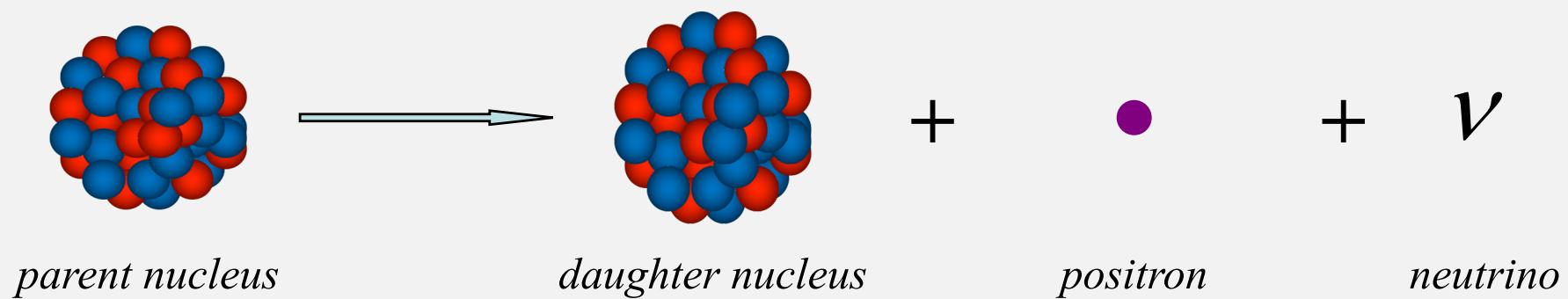
Brachytherapy:
implants into the
tumours



Endovascular
irradiation

β decay

2. Proton excess: β^+ decay



example:



Annihilation - particle-antiparticle pairs annihilate each other

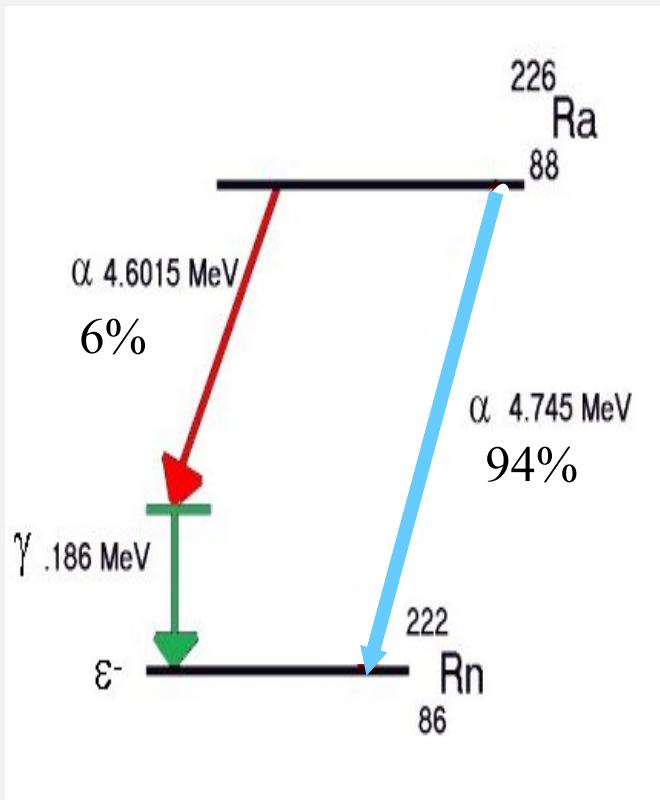


1. Conservation of momentum: two photons with opposite direction are produced
2. Energy balance:

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

mass-energy equivalence

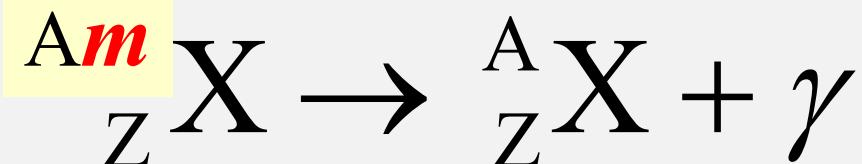
γ decay – Isomeric transition



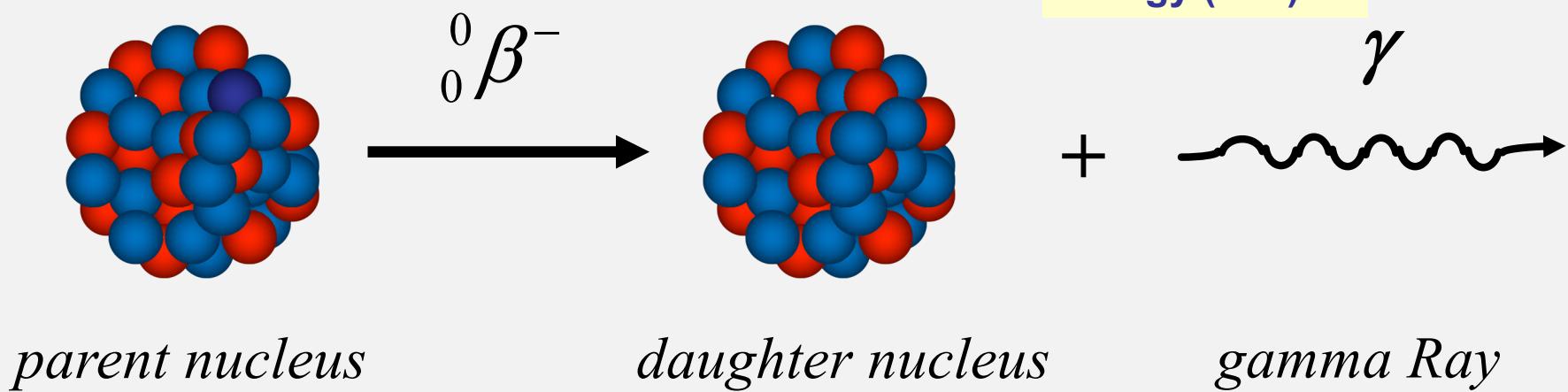
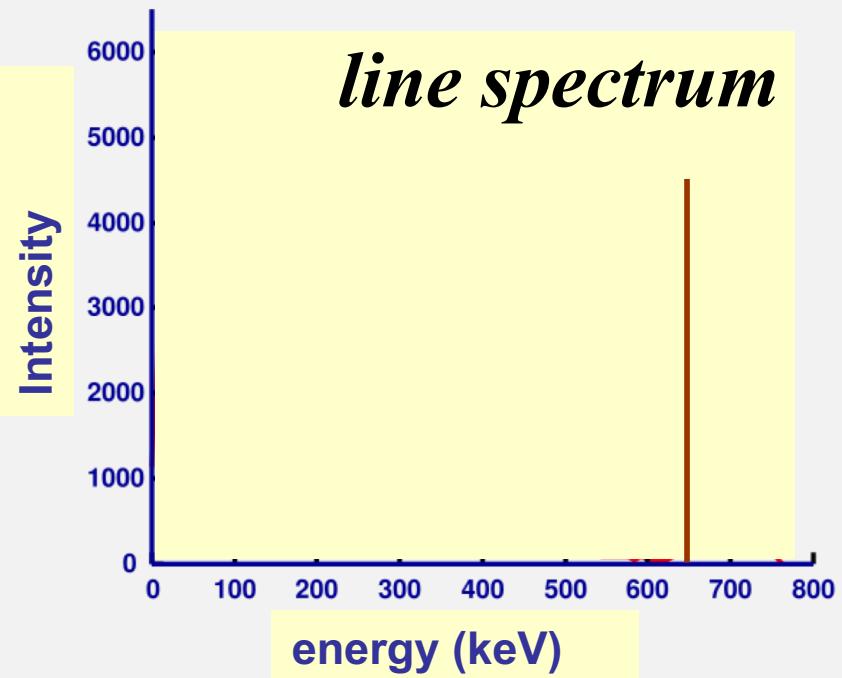
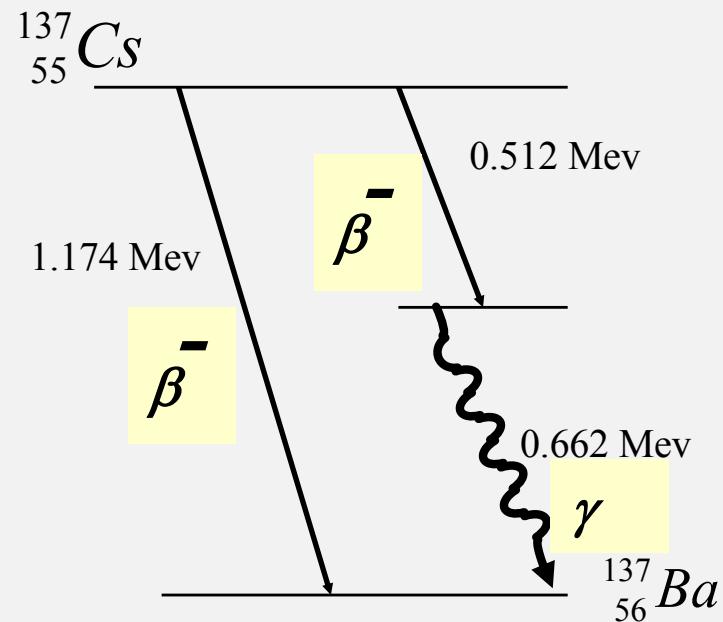
Sometimes the newly formed isotopes (after α or β decay) appear in the excited state.

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

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

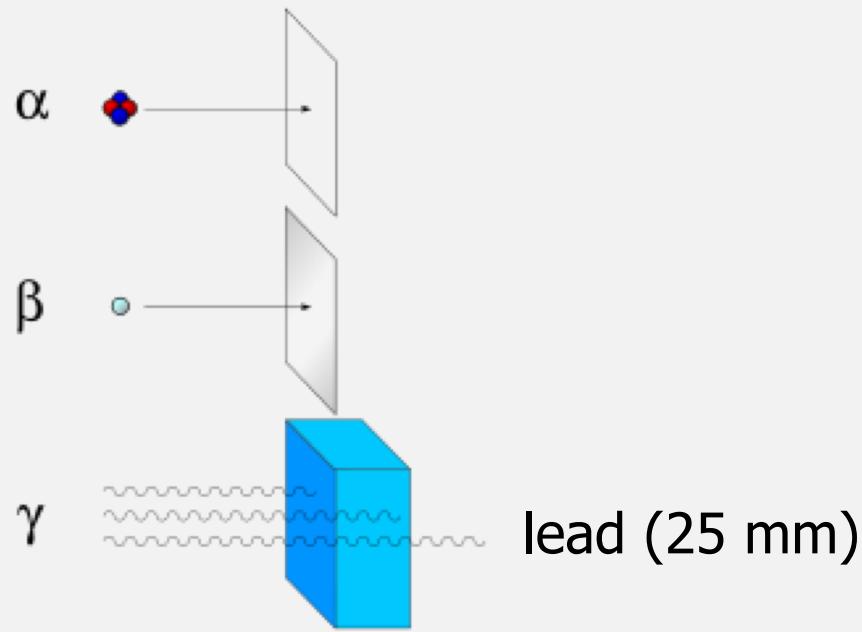


Energy spectrum of γ radiation



Energy is characteristic for the nucleus

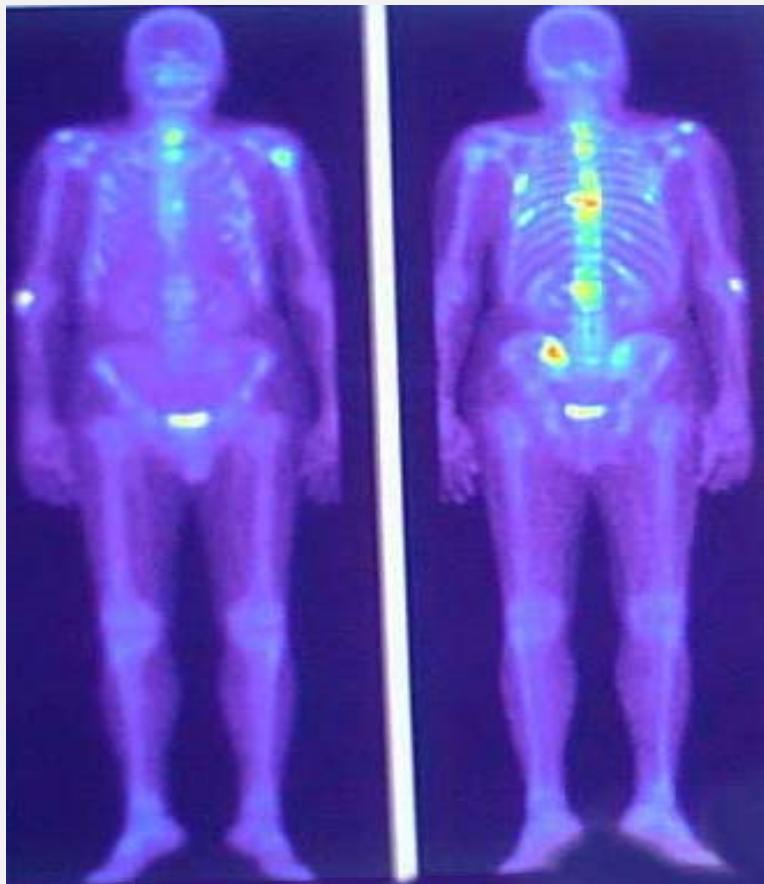
Penetration depth of γ radiation



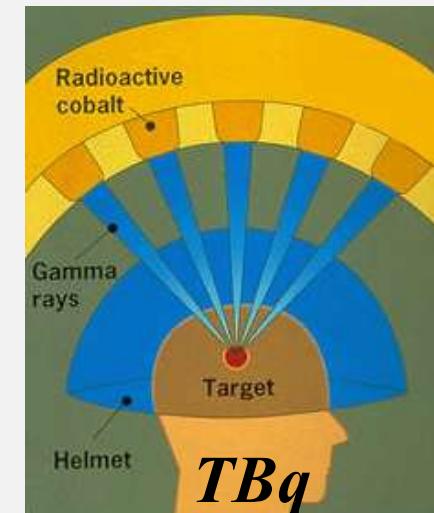
Penetration depth is higher than that of α or β particles, but it is highly energy dependent.

Gamma rays can travel from **hundreds of meters in the air** and can easily go right **through people (\sim dm)**.

Medical application of γ rays

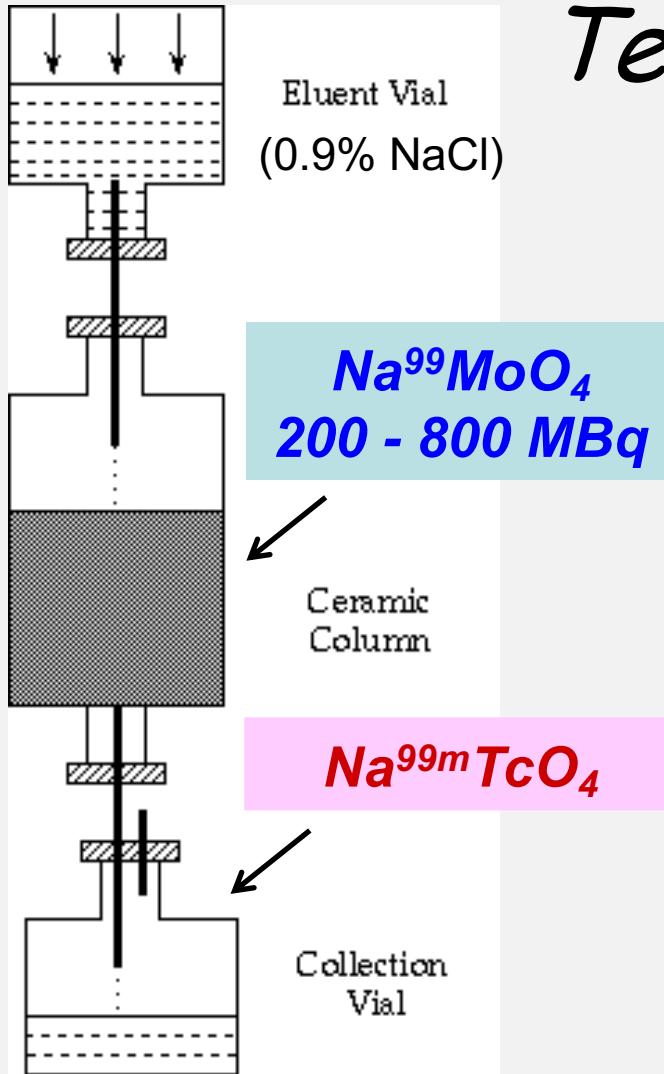


therapy: γ -knife

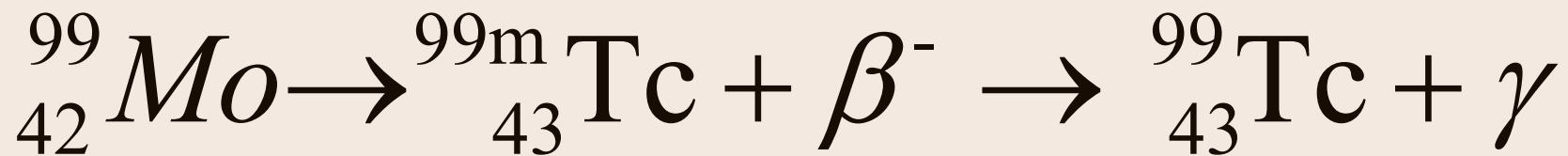
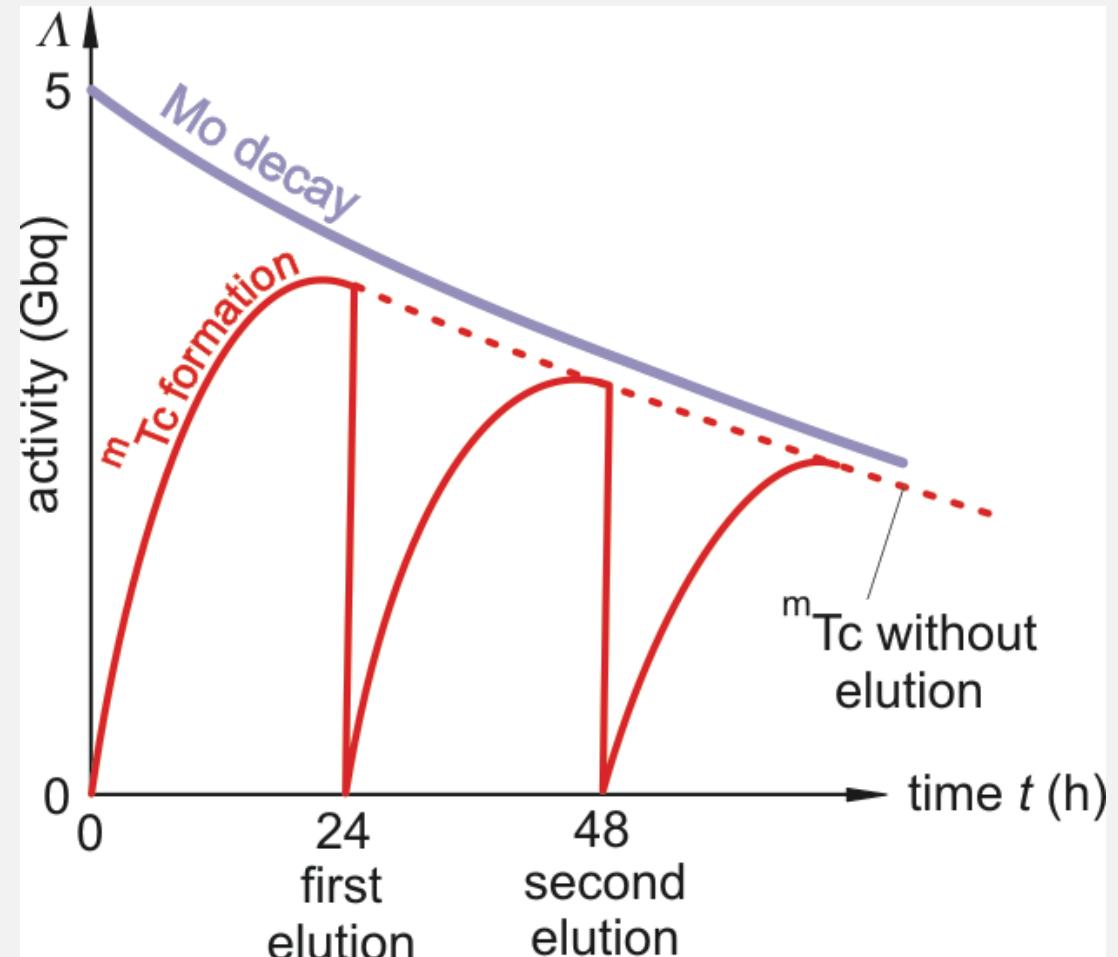


*Bone scan using
 ^{99m}Tc labeled
phosphate compound*

Diagnostics: ideal for isotope diagnostics



Technetium-99m generator



$T_{1/2}=67$ hours

$T_{1/2}=6$ hours

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