

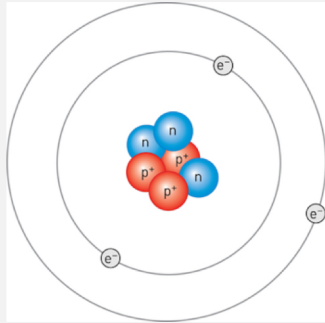
# Biophysics I

## 13. Nuclear radiations

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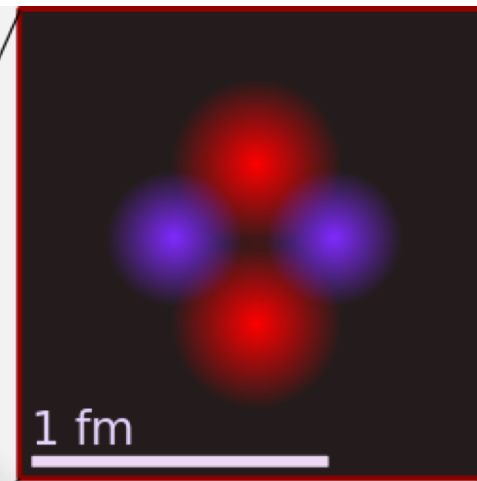
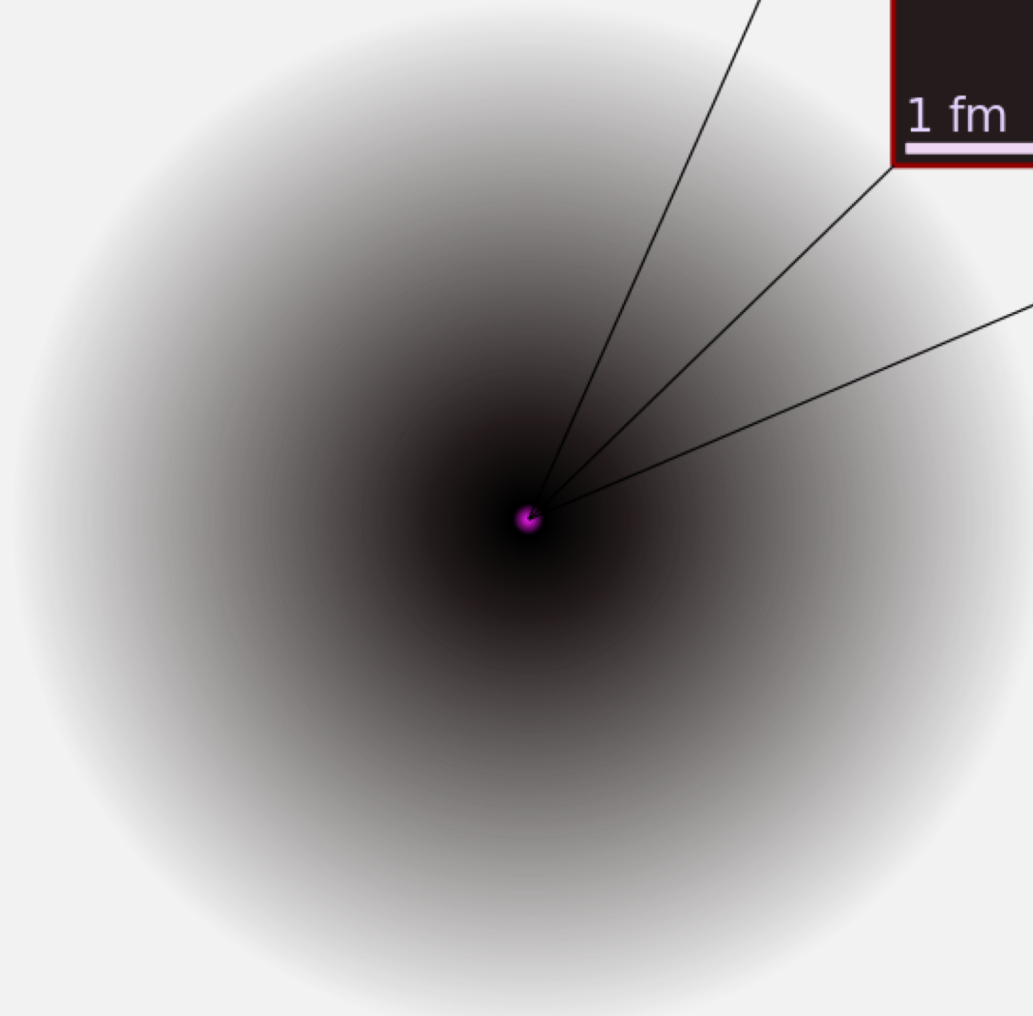
# Constituents of atoms

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

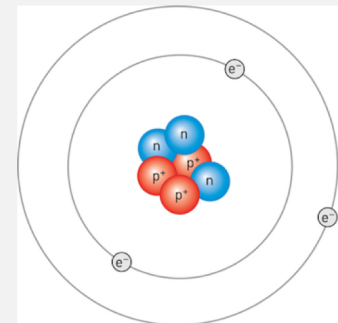
\* electrons have an electric charge of  $-1.602 \times 10^{-19} \text{ C}$

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

# Nucleus size



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

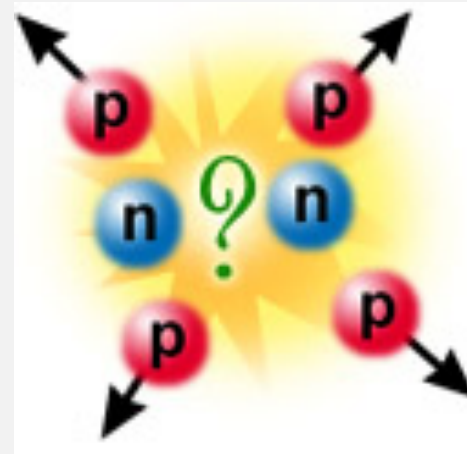


# Nuclear stability

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.

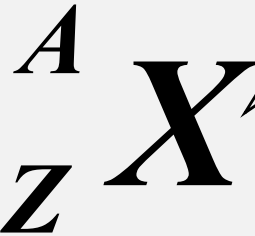
The hypothesis of neutron (discovered by Chadwick in 1932)



# Nuclear notation

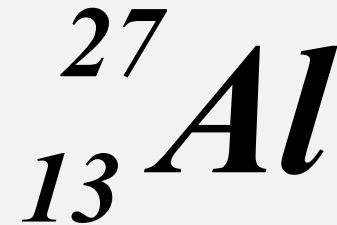
*Mass number*

$$A = Z + N$$



*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:

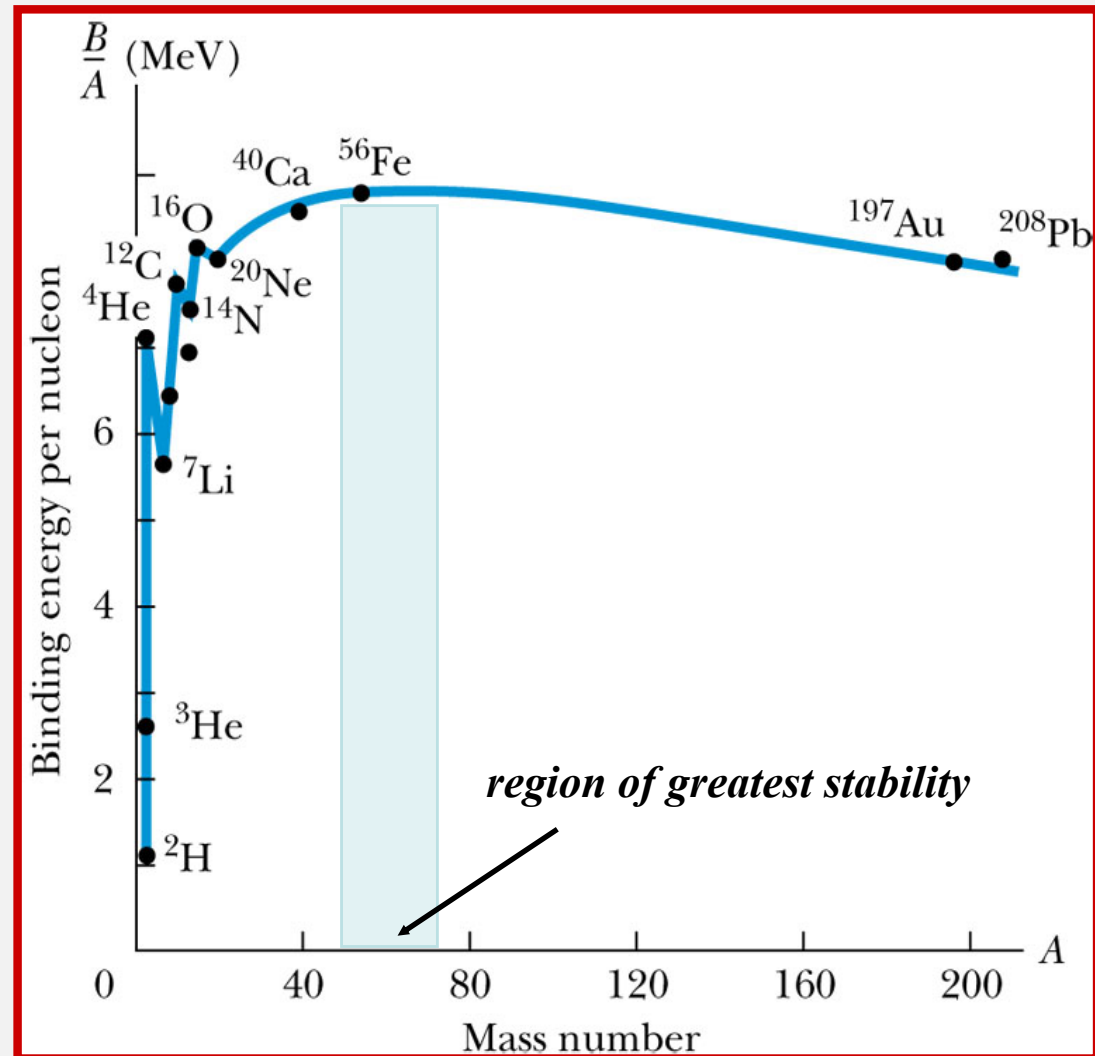
$$\Delta E = \Delta M c^2$$

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

1  
H  
1.008  
1

2  
He  
4.003  
2

2  
IIA

3  
Li  
6.941  
2-1

4  
Be  
9.0122  
2-2

3  
IIIB

11  
Na  
22.990  
2-8-1

12  
Mg  
24.305  
2-8-2

4  
IVB

19  
K  
39.098  
2-8-8-1

20  
Ca  
40.078  
2-8-8-2

5  
VB

37  
Rb  
85.468  
2-8-18-8-1

38  
Sr  
87.62  
2-8-18-8-2

6  
VIB

55  
Cs  
132.91  
2-8-18-18-8-1

56  
Ba  
137.33  
2-8-18-18-8-2

7  
VIIB

87  
Fr  
(223)  
-18-32-18-8-1

88  
Ra  
(226)  
-18-32-18-8-2

8  
VIII

21  
Sc  
44.956  
2-8-9-2

22  
Ti  
47.867  
2-8-10-2

23  
V  
50.942  
2-8-11-2

24  
Cr  
51.996  
2-8-13-1

25  
Mn  
54.938  
2-8-13-2

26  
Fe  
55.845  
2-8-14-2

27  
Co  
58.933  
2-8-15-2

28  
Ni  
58.693  
2-8-16-2

29  
Cu  
63.546  
2-8-18-1

30  
Zn  
65.39  
2-8-18-2

31  
Ga  
69.723  
2-8-18-3

32  
Ge  
72.64  
2-8-18-4

33  
As  
74.922  
2-8-18-5

34  
Se  
78.96  
2-8-18-6

35  
Br  
79.904  
2-8-18-7

36  
Kr  
83.80  
2-8-18-8

37  
Rb  
85.468  
2-8-18-8-1

38  
Sr  
87.62  
2-8-18-8-2

39  
Y  
88.906  
2-8-18-9-2

40  
Zr  
91.224  
2-8-18-10-2

41  
Nb  
92.906  
2-8-18-11-1

42  
Mo  
95.94  
2-8-18-13-1

43  
Tc  
(98)  
2-8-18-14-1

44  
Ru  
101.07  
2-8-18-15-1

45  
Rh  
102.91  
2-8-18-16-1

46  
Pd  
106.42  
2-8-18-18

47  
Ag  
107.87  
2-8-18-18-1

48  
Cd  
112.41  
2-8-18-18-2

49  
In  
114.82  
2-8-18-18-3

50  
Sn  
118.71  
2-8-18-18-4

51  
Sb  
121.76  
2-8-18-18-5

52  
Te  
127.60  
2-8-18-18-6

53  
I  
126.90  
2-8-18-18-7

54  
Xe  
131.29  
2-8-18-18-8

55  
Cs  
132.91  
2-8-18-18-8-1

56  
Ba  
137.33  
2-8-18-18-8-2

57  
La  
138.91  
2-8-18-32-18-8-2

58  
Ce  
140.12  
-18-32-13-2

59  
Pr  
140.91  
-18-32-12-2

60  
Nd  
144.24  
-18-32-13-2

61  
Pm  
(145)  
-18-32-14-2

62  
Sm  
150.36  
-18-32-15-2

63  
Eu  
151.96  
-18-32-17-1

64  
Gd  
157.25  
-18-32-18-1

65  
Tb  
158.93  
-18-32-18-2

66  
Dy  
162.50  
-18-32-18-3

67  
Ho  
164.93  
-18-32-18-4

68  
Er  
167.26  
-18-32-18-5

69  
Tm  
168.93  
-18-32-18-6

70  
Yb  
173.04  
-18-32-18-7

71  
Lu  
174.97  
-18-32-18-8

72  
Hf  
178.49  
2-8-18-32-10-2

73  
Ta  
180.95  
-18-32-11-2

74  
W  
183.84  
-18-32-12-2

75  
Re  
186.21  
-18-32-13-2

76  
Os  
190.23  
-18-32-14-2

77  
Ir  
192.22  
-18-32-15-2

78  
Pt  
195.08  
-18-32-17-1

79  
Au  
196.97  
-18-32-18-1

80  
Hg  
200.59  
-18-32-18-2

81  
Tl  
204.38  
-18-32-18-3

82  
Pb  
207.2  
-18-32-18-4

83  
Bi  
208.98  
-18-32-18-5

84  
Po  
(209)  
-18-32-18-6

85  
At  
(210)  
-18-32-18-7

86  
Rn  
(222)  
-18-32-18-8

87  
Fr  
(223)  
-18-32-18-8-1

88  
Ra  
(226)  
-18-32-18-8-2

89  
Ac  
227  
2-8-18-32-18-8-2

90  
Th  
232.04  
-18-32-13-2

91  
Pa  
231.04  
-18-32-12-2

92  
U  
238.03  
-18-32-13-2

93  
Np  
(237)  
-18-32-14-2

94  
Pu  
(244)  
-18-32-15-2

95  
Am  
(243)  
-18-32-17-1

96  
Cm  
(247)  
-18-32-18-1

97  
Bk  
(247)  
-18-32-18-2

98  
Cf  
(251)  
-18-32-18-3

99  
Es  
(252)  
-18-32-18-4

100  
Fm  
(257)  
-18-32-18-5

101  
Md  
(258)  
-18-32-18-6

102  
No  
(259)  
-18-32-18-7

103  
Lr  
(262)  
-18-32-18-8

104  
Rf  
(261)  
2-8-18-32-18-8-2

105  
Db  
(262)  
-18-32-13-2

106  
Sg  
(266)  
-18-32-12-2

107  
Bh  
(264)  
-18-32-13-2

108  
Hs  
(277)  
-18-32-14-2

109  
Mt  
(268)  
-18-32-15-2

110  
Uun  
(281)  
-18-32-17-1

111  
Uuu  
(272)  
-18-32-18-1

112  
Uub  
(285)  
-18-32-18-2

113  
Uut  
(284)  
-18-32-18-3

114  
Uuq  
(289)  
-18-32-18-4

115  
Uup  
(288)  
-18-32-18-5

116  
Uuh  
(291)  
-18-32-18-6

117  
Uus  
(294)  
-18-32-18-7

118  
Uuo  
(294)  
-18-32-18-8

Table of Common Polyatomic Ions

acetate  
chlorate  
hydroxide  
nitrate  
permanganate

$\text{C}_2\text{H}_3\text{O}_2^-$   
 $\text{ClO}_3^-$   
 $\text{OH}^-$   
 $\text{NO}_3^-$   
 $\text{MnO}_4^-$

silicate  
sulfate  
thiosulfate  
arsenate  
phosphate

$\text{SiO}_3^{2-}$   
 $\text{SO}_4^{2-}$   
 $\text{S}_2\text{O}_3^{2-}$   
 $\text{AsO}_4^{3-}$   
 $\text{PO}_4^{3-}$

carbonate  
chromate  
dichromate

$\text{CO}_3^{2-}$   
 $\text{CrO}_4^{2-}$   
 $\text{Cr}_2\text{O}_7^{2-}$

ammonium  
hydronium

$\text{NH}_4^+$   
 $\text{H}_3\text{O}^+$

Alkali metals  
Alkaline-earth metals  
Transition metals  
Other metals

Hydrogen  
Semiconductors  
Halogens  
Noble gases  
Other nonmetals

State of matter at 25 °C

Gas  
Liquid  
Solid  
Artificially prepared  
Unknown

13  
IIIA  
14  
IVA  
15  
VA  
16  
VIA  
17  
VIIA

18  
VIIIA

Selected Oxidation States

Atomic Number

Symbol

Electron Configuration

21  
Sc  
44.956  
2-8-9-2

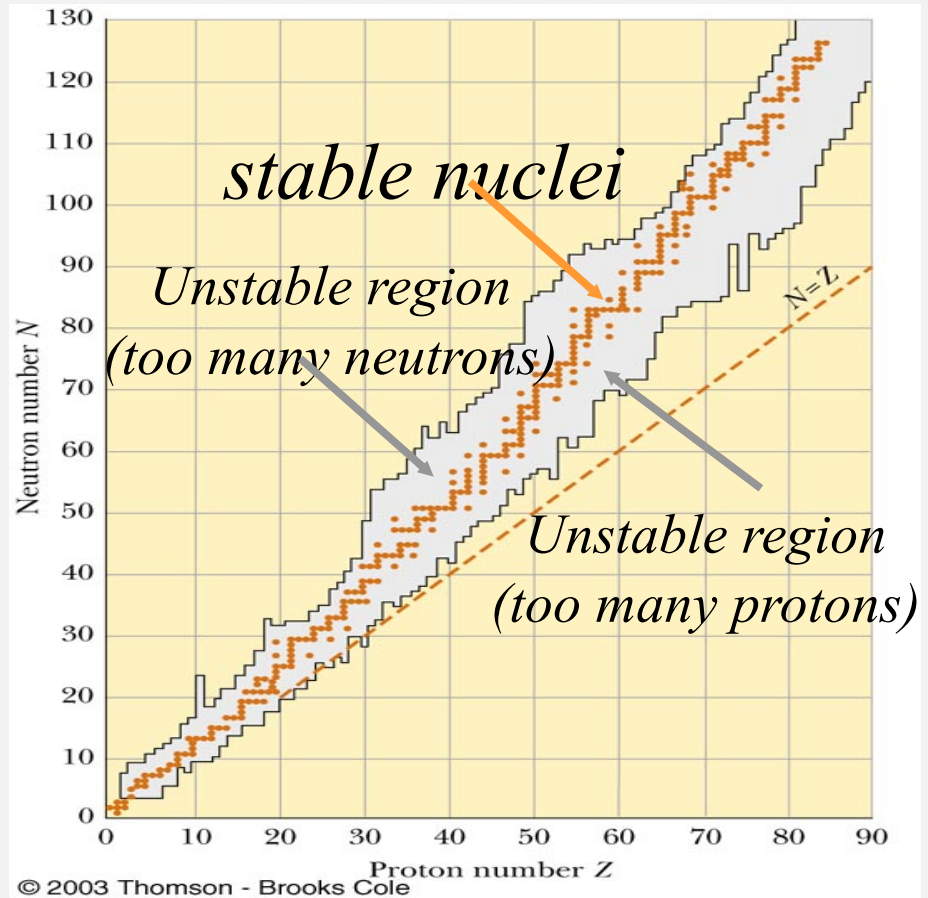
From Russia with      

# 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

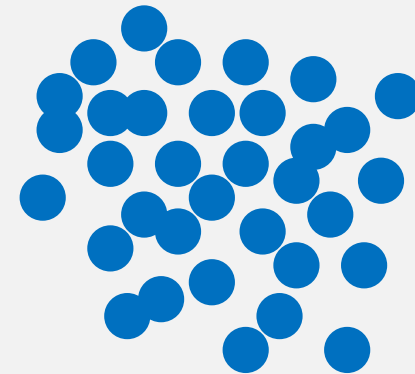
- *Radioactivity* is the spontaneous release of energy in the form of particles or electromagnetic waves
- Experiments suggested that radioactivity was the result of the decay of unstable nuclei
- Three types of radiation can be emitted
  - Alpha ( $\alpha$ ) particles
  - Beta ( $\beta$ ) particles
  - Gamma ( $\gamma$ ) 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

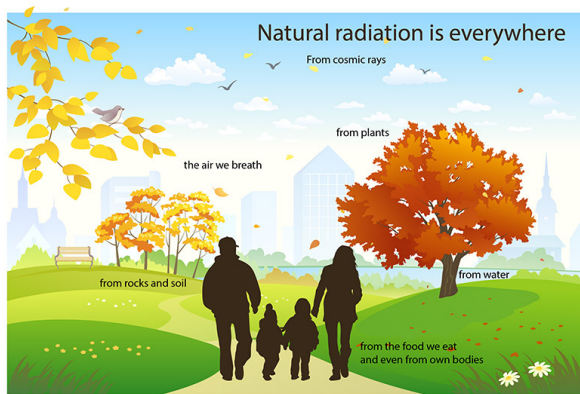
**Activity:**  $\Lambda = \left| \frac{\Delta N}{\Delta t} \right|$

*N: number of nuclei to be decayed*  
*t: time*

*Activity = number of nuclei decayed in a unit time*

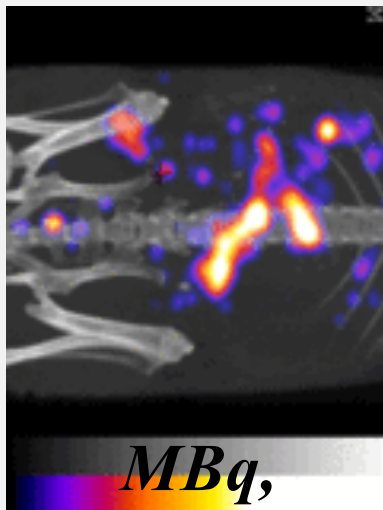
*unit: becquerel (Bq)    1 Bq = 1 decay/sec*

*background*



*kBq,*

*diagnostics*



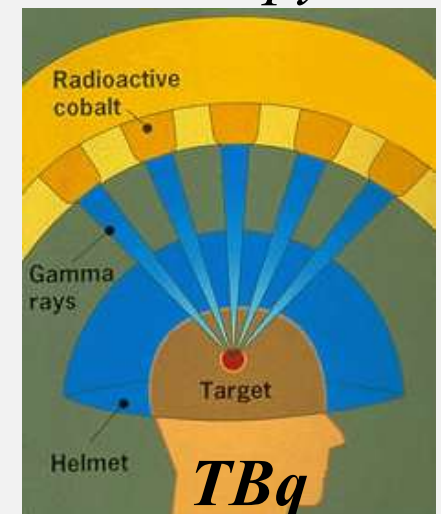
*MBq,*

*laboratory practice*



*GBq,*

*therapy*



*TBq*

# Radioactive decay law

**Differential form:**  $\frac{\Delta N}{\Delta t} = -\lambda N$

solution

$\lambda$  : decay constant, characteristic for isotopes (1/s)

**Integral form:**  $N = N_0 e^{-\lambda t}$

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

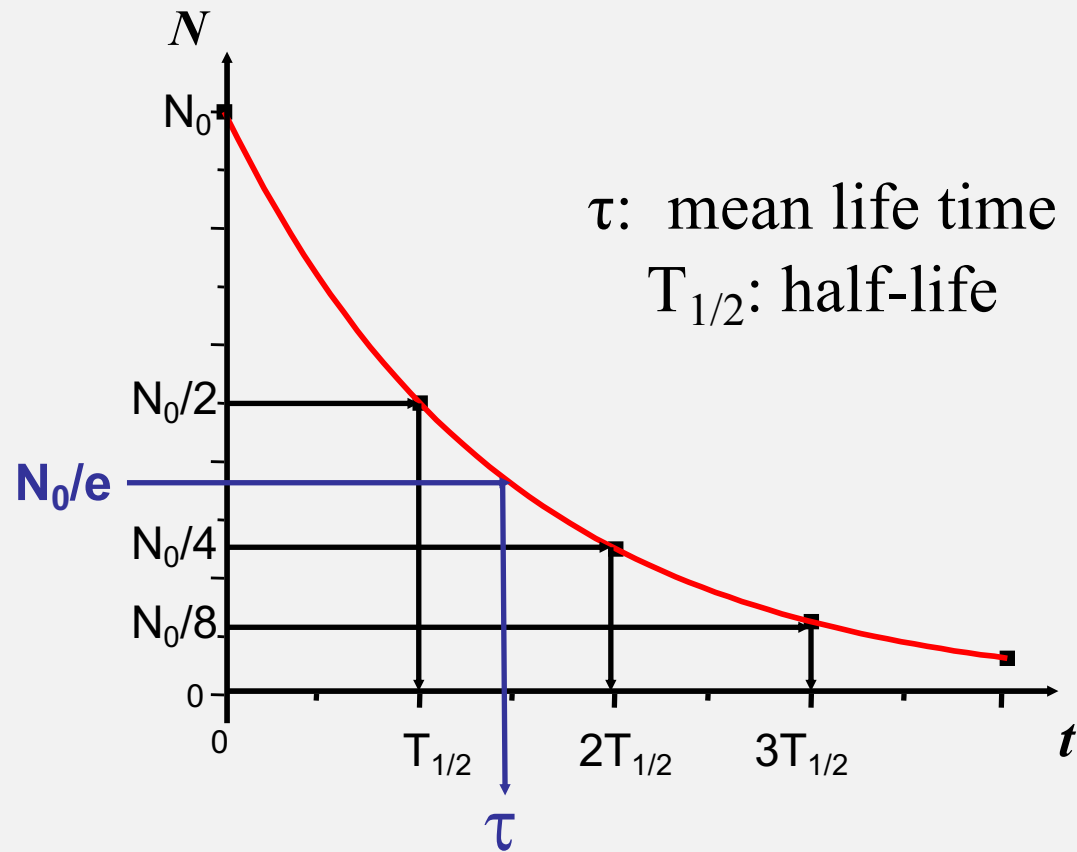
$N$ : number of remaining radioactive nuclei at a later time  $t$

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  $t = \tau$



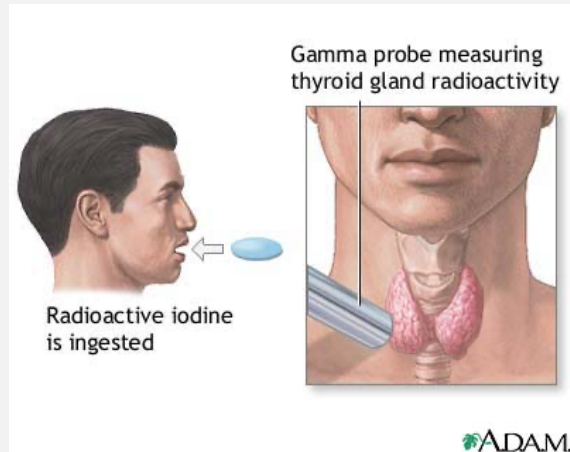
$$N_0 / e = N_0 e^{-\lambda \tau}$$



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

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

# Half-lives in Medical Practice

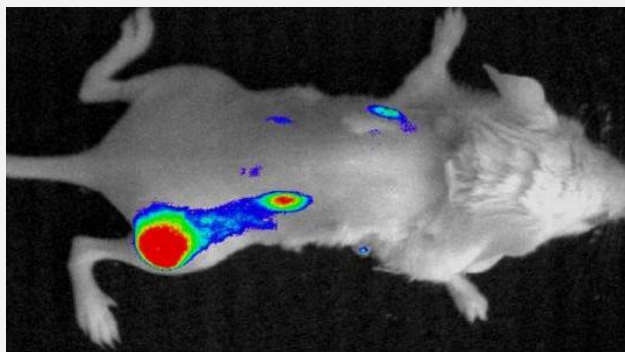
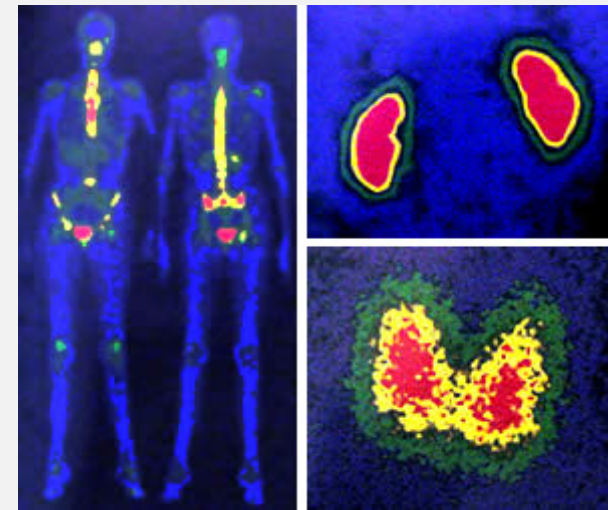


*Iodine - 131 ( $^{131}\text{I}$ ) -  $T_{1/2} = 8 \text{ days}$*

*Thyroid treatment*

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

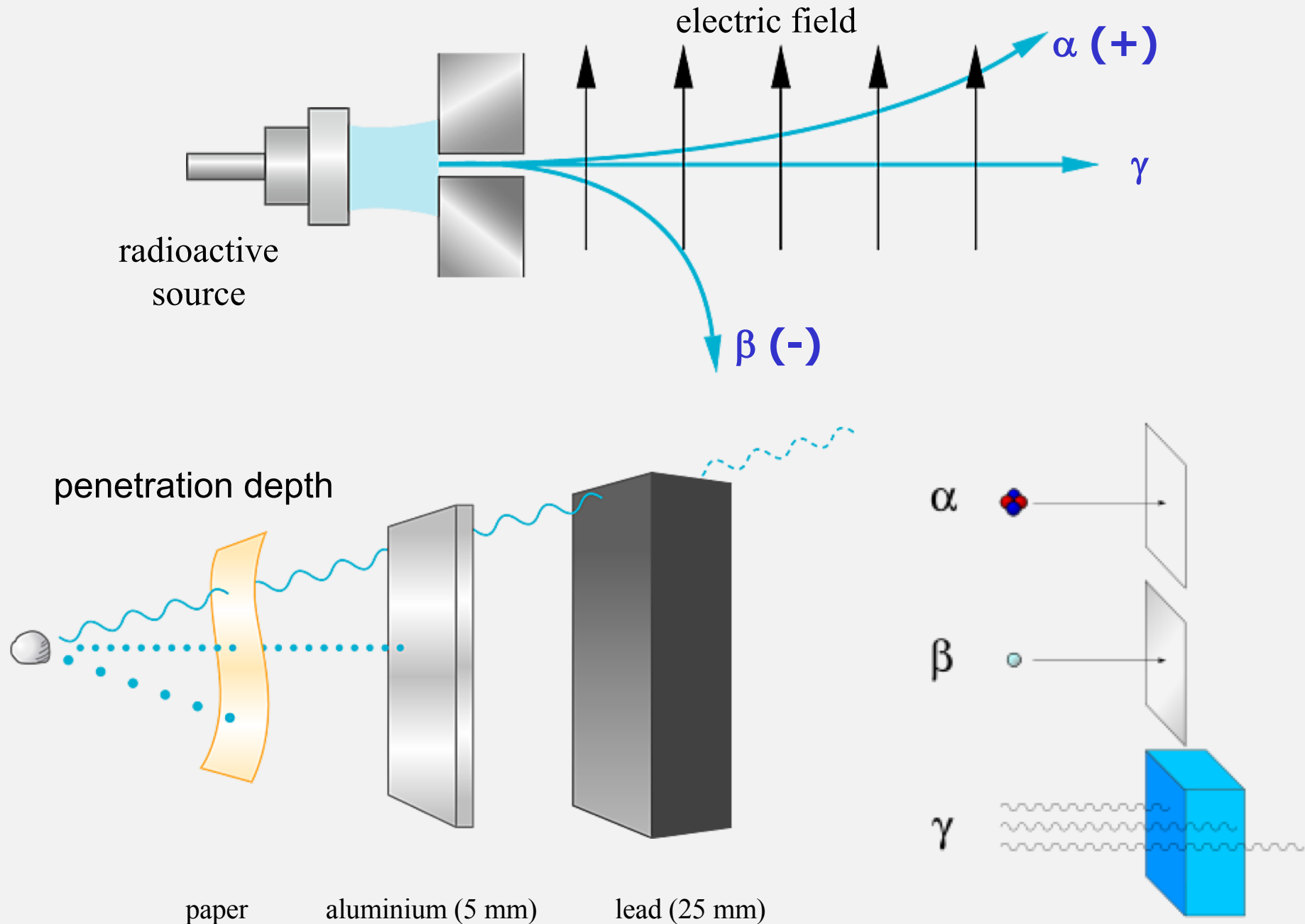
*Isotope diagnostics*



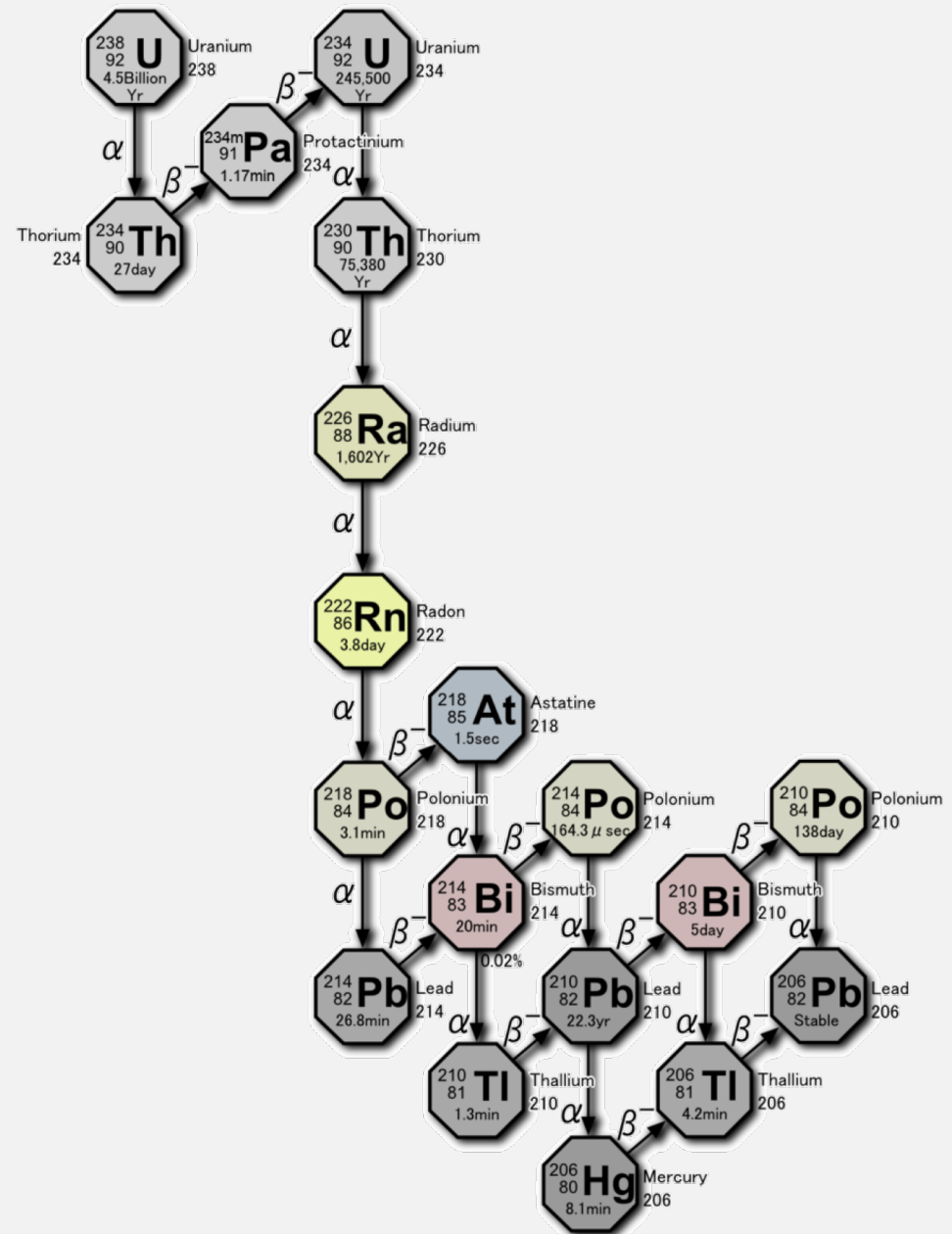
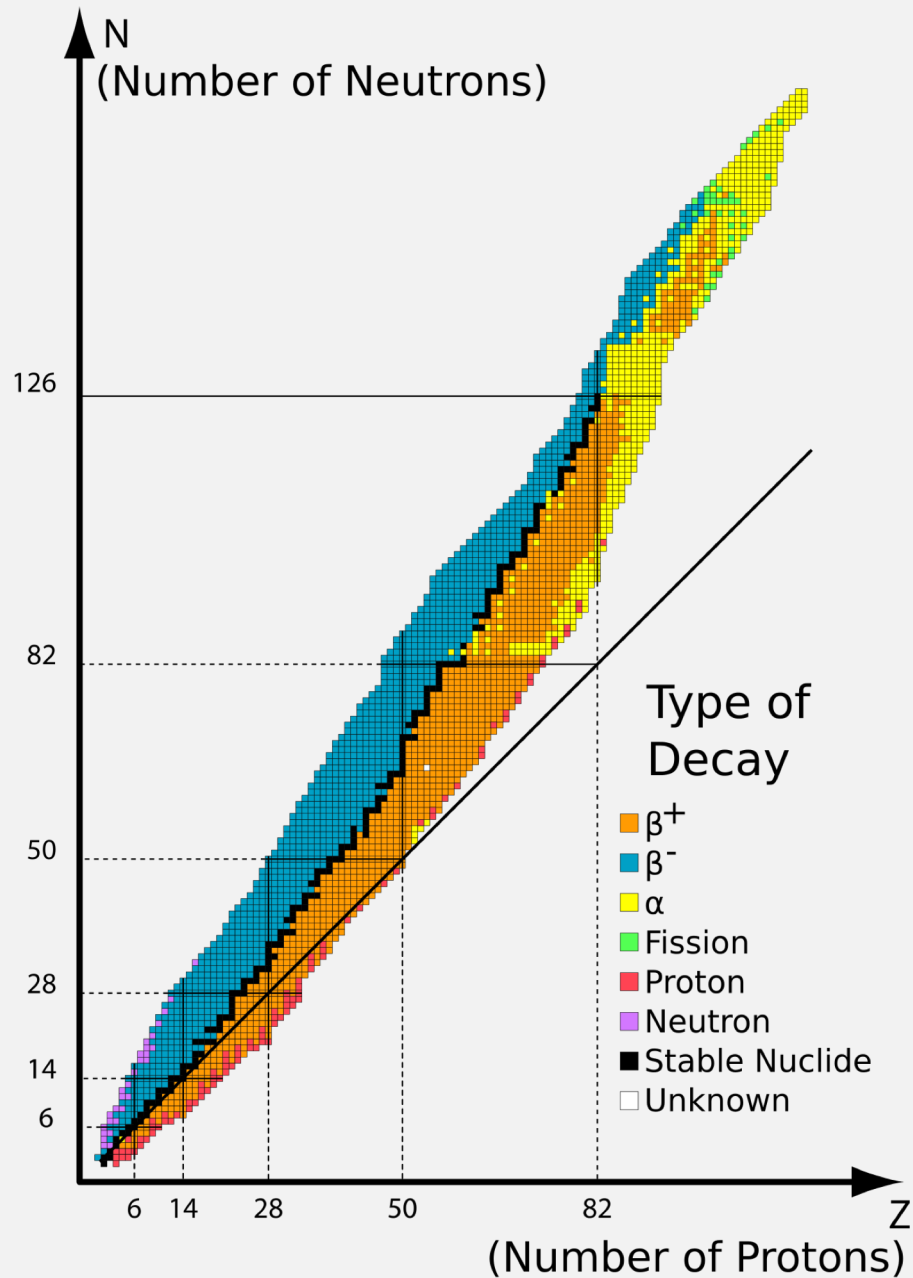
*Gold-198 ( $^{198}\text{Au}$ ) -  $T_{1/2} = 2.7 \text{ days}$*

*Tumor therapy*

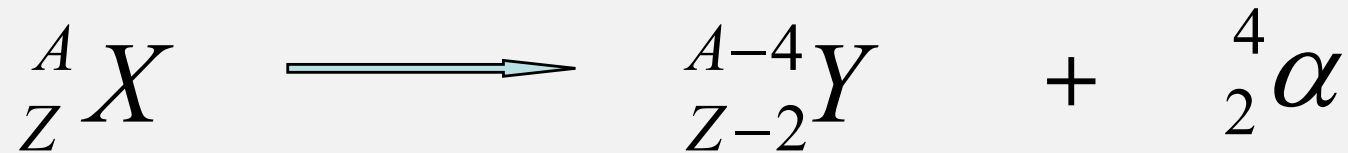
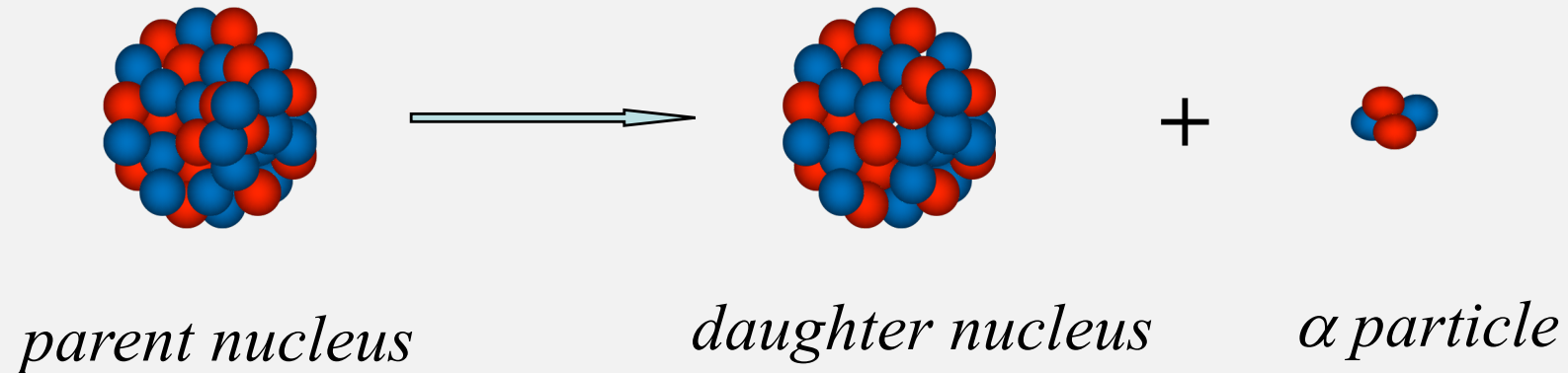
# Types of radioactive decay



# Types of radioactive decay



# $\alpha$ decay



**$\alpha$  particle** is a nucleus of helium containing two neutrons and two protons

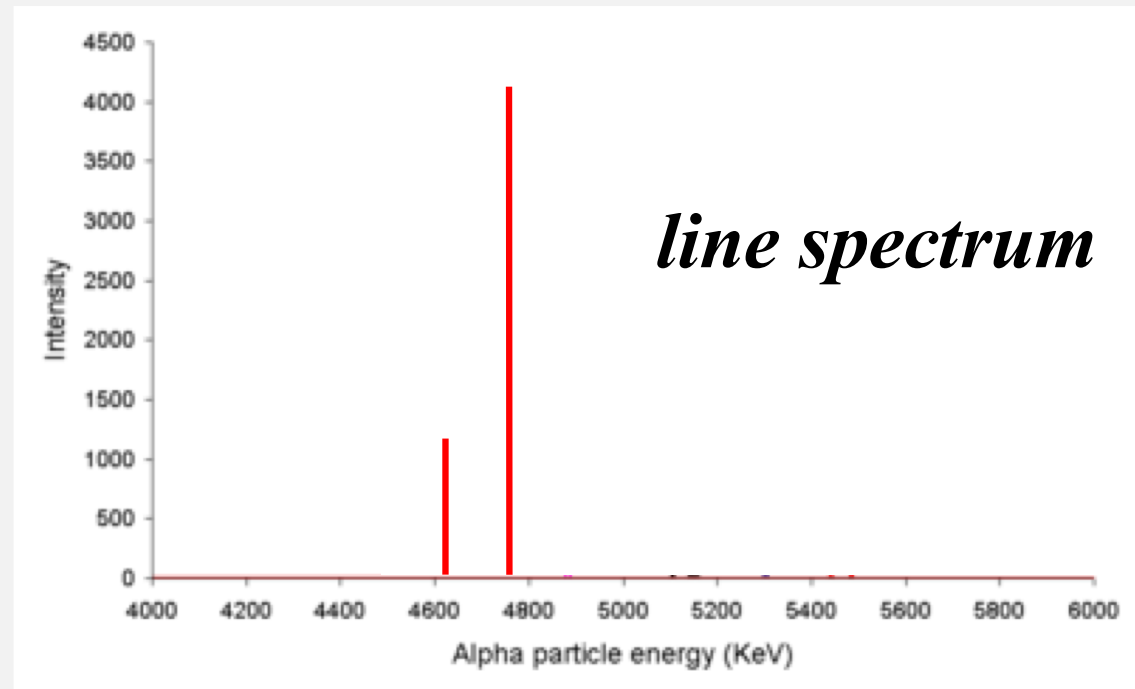
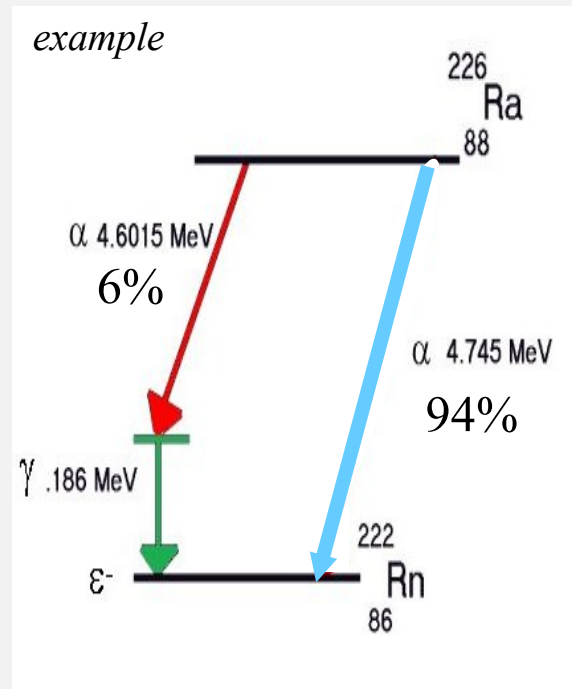
Heavy nuclei ( $A > 150$ ) can disintegrate by emission of an  $\alpha$  particle

*example:*



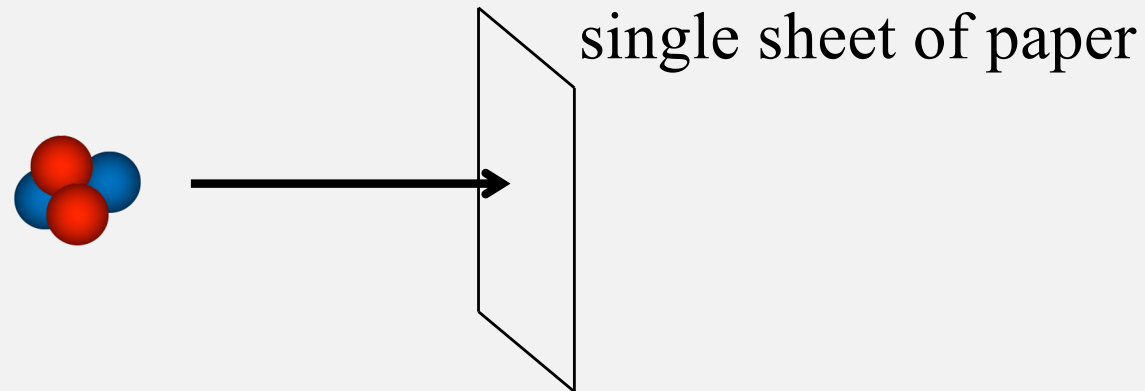


# Energy spectrum of $\alpha$ radiation



*Energy levels are characteristic for the nucleus*

# Penetration depth of $\alpha$ particles

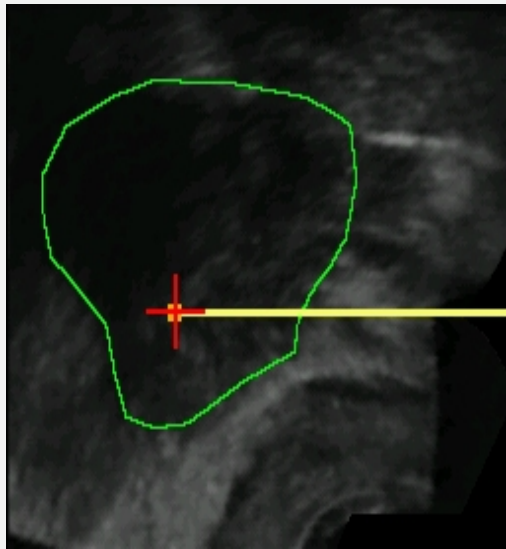


absorber	density	alpha range
air (STP)	1.2 mg/cm <sup>3</sup>	3.7 cm
paper (20lb)	0.89 g/cm <sup>3</sup>	53 $\mu$ m
water (soft tissue)	1.0 g/cm <sup>3</sup>	45 $\mu$ m

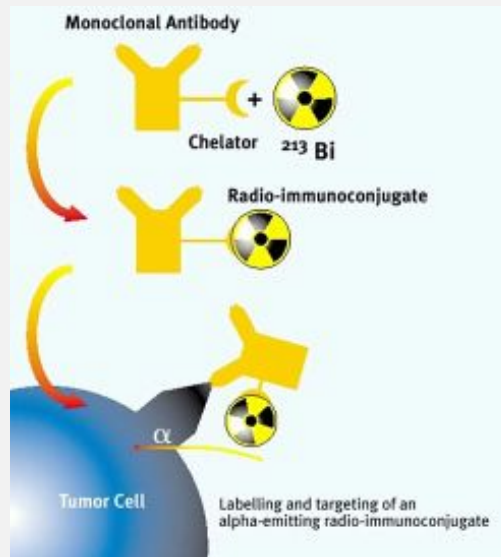
# Medical application of $\alpha$ radiation

Diagnostics: none

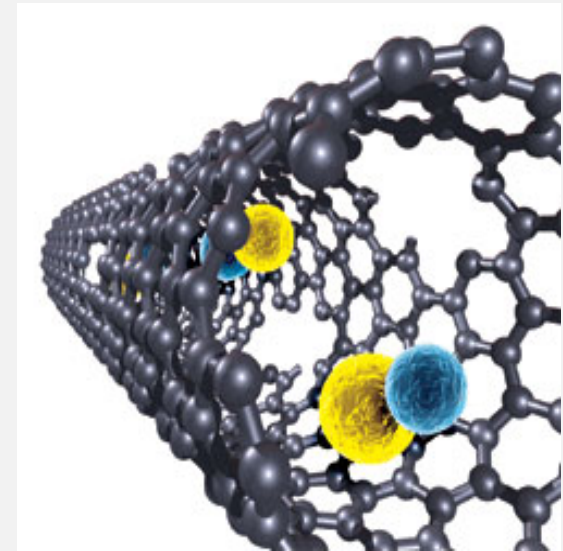
Targeted alpha **therapy** of cancer



Seed implantation  
by needle



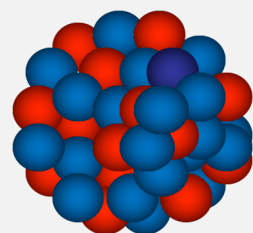
Monoclonal  
antibody



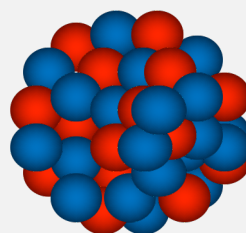
Carbon nano-tube

# $\beta$ decay

## 1. Neutron excess: $\beta^-$ decay



*parent nucleus*



*daughter nucleus*

+

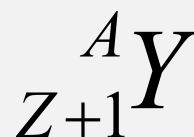
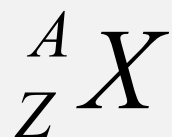


*electron*

+



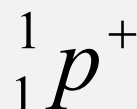
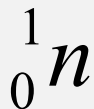
*anti-neutrino*



+



+



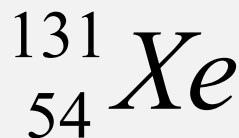
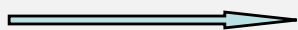
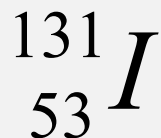
+



+



*example:*



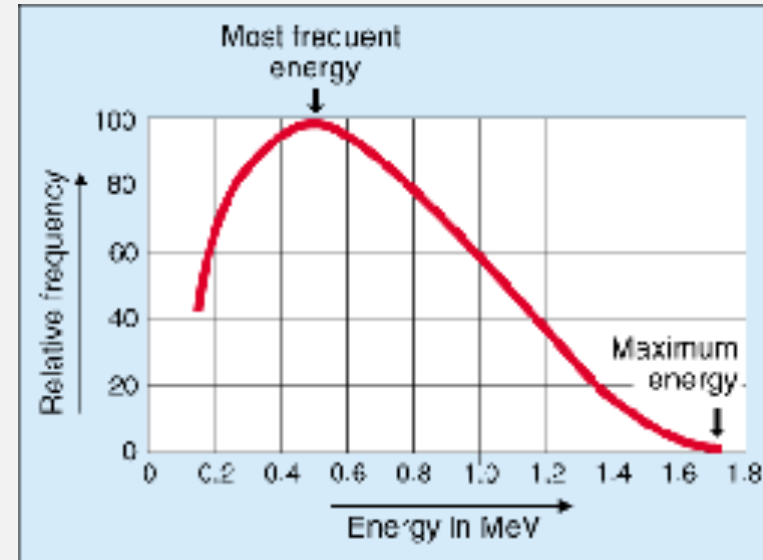
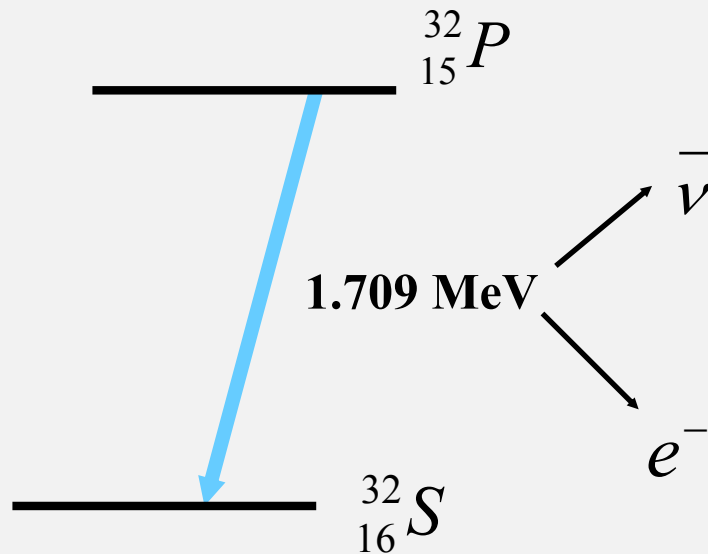
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+



# Energy spectrum of $\beta$ radiation

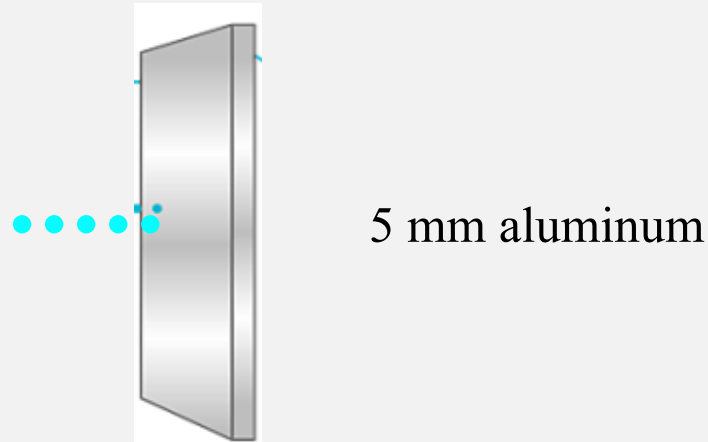


*Energy distribution of the  $\beta^-$  particles emitted during the  $\beta^-$  decay of  $^{32}\text{P}$ .*

***continuous spectrum***

with a maximum kinetic energy for the  $\beta$  particle

# Penetration depth of $\beta^-$ particles

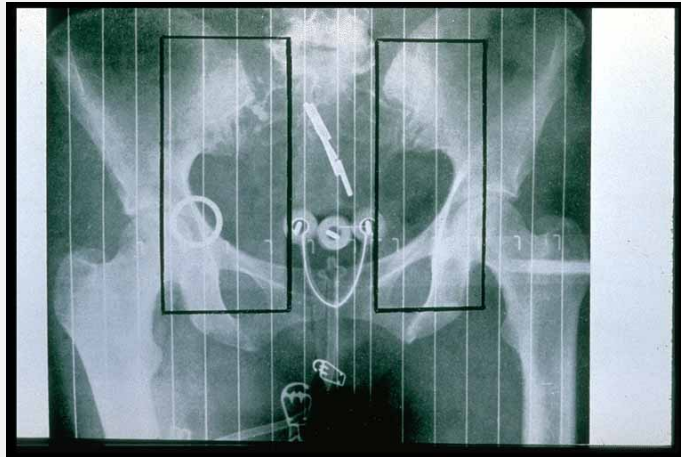


<b><i>absorber</i></b>	<b><i>density</i></b>	<b><i>maximum beta range</i></b>	
		<b><i>(2.3 MeV)</i></b>	<b><i>(1.1 MeV)</i></b>
air	1.2 mg/cm <sup>3</sup>	8.8 m	3.8 m
water (soft tissue)	1.0 g/cm <sup>3</sup>	11 mm	4.6 mm
aluminum	2.7 g/cm <sup>3</sup>	4.2 mm	2.0 mm
lead	11.3 g/cm <sup>3</sup>	1.0 mm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

# Medical application of $\beta^-$ radiation

Diagnostics: none

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



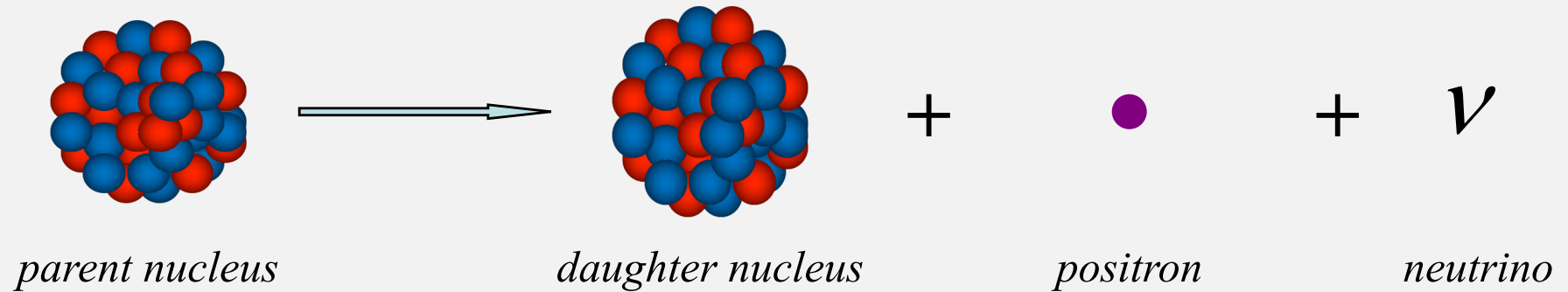
Brachytherapy:  
implants into the  
tumours



Endovascular  
irradiation

# $\beta$ decay

## 2. Proton excess: $\beta^+$ decay



example:





# Annihilation - particle-antiparticle pairs annihilate each other

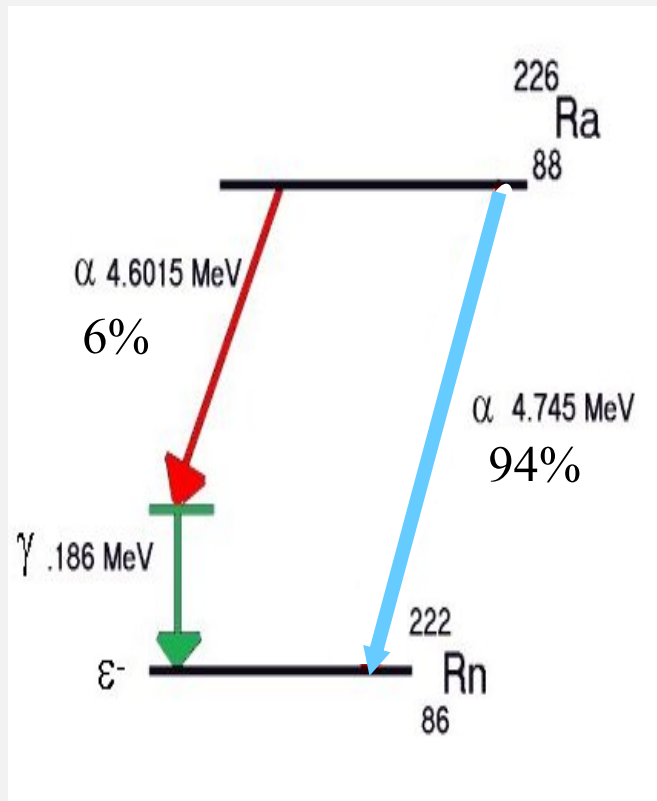


1. Conservation of momentum: two photons with opposite direction are produced
2. Energy balance:

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

*mass-energy equivalence*

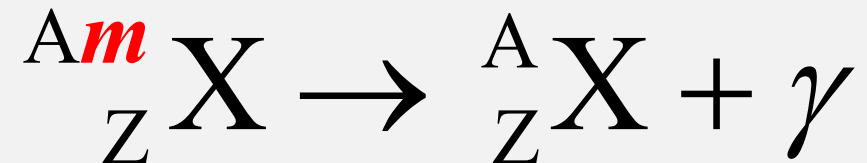
# $\gamma$ decay – Isomeric transition



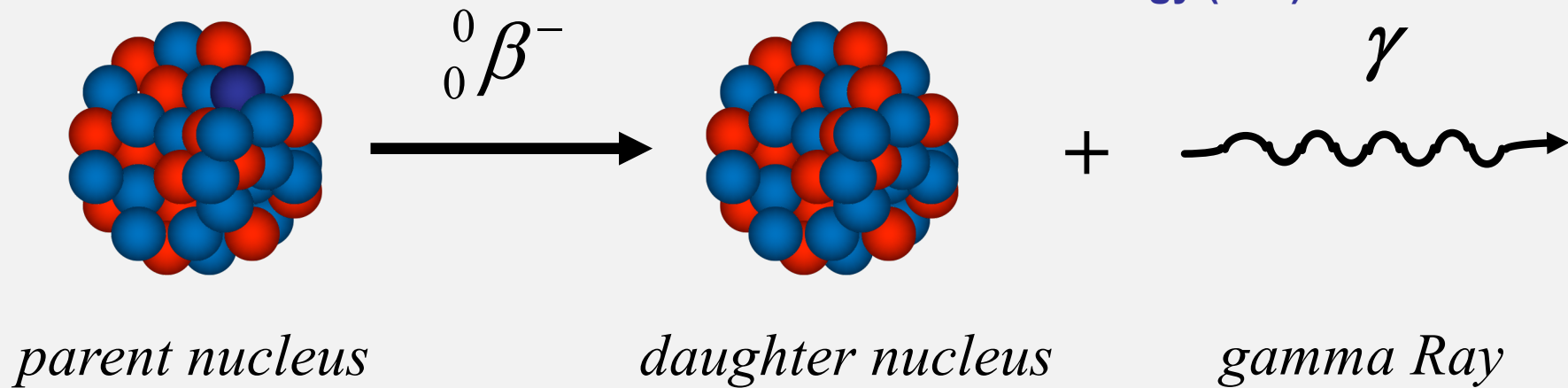
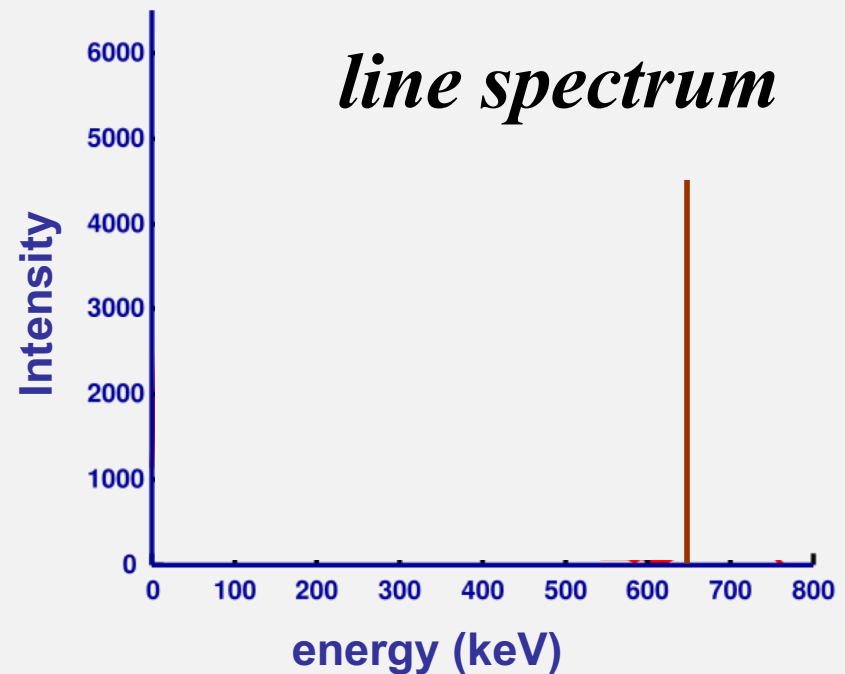
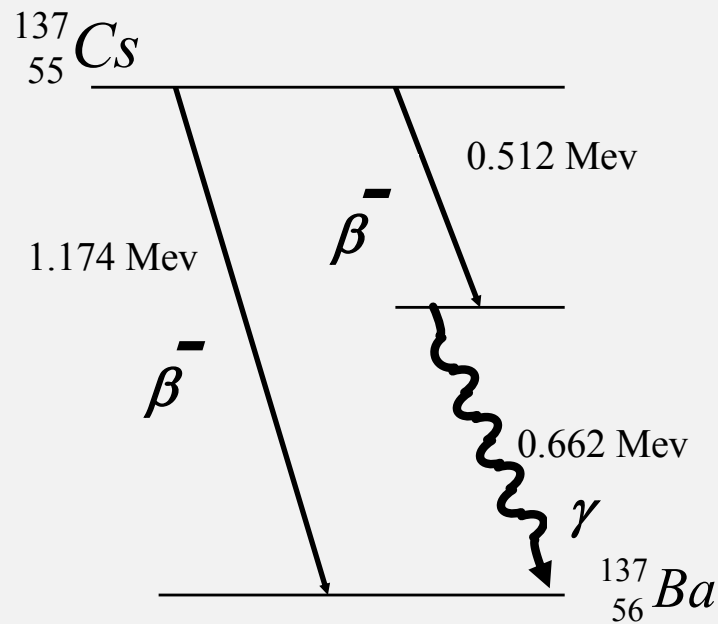
Sometimes the newly formed isotopes (after  $\alpha$  or  $\beta$  decay) appear in the excited state.

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

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

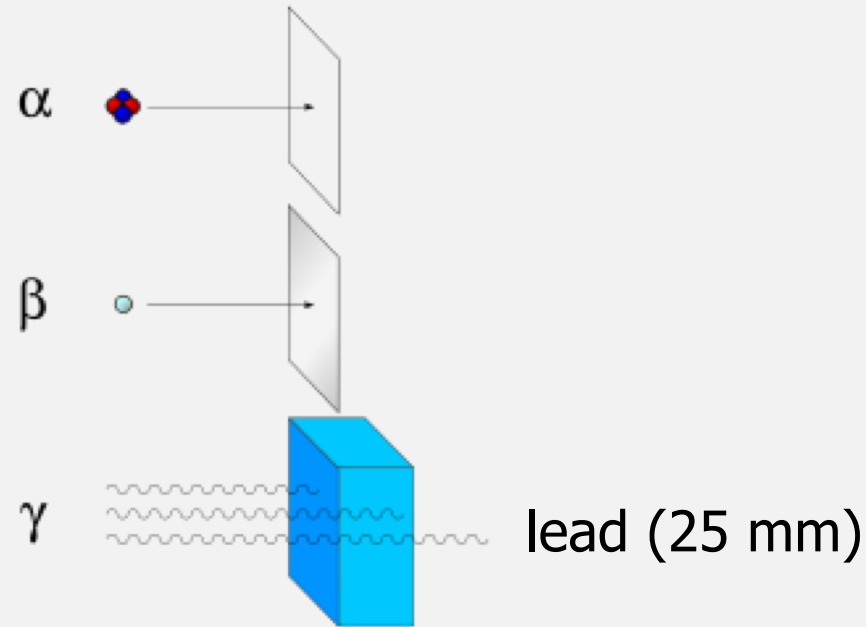


# Energy spectrum of $\gamma$ radiation



*Energy is characteristic for the nucleus*

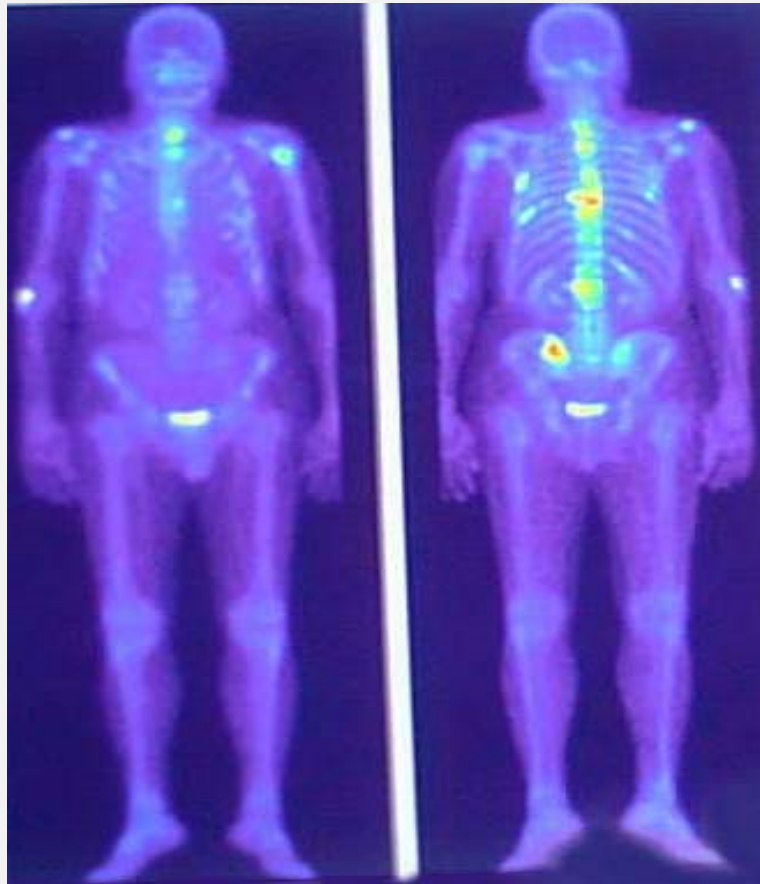
# Penetration depth of $\gamma$ radiation



Penetration depth is higher than that of  $\alpha$  or  $\beta$  particles, but it is highly energy dependent.

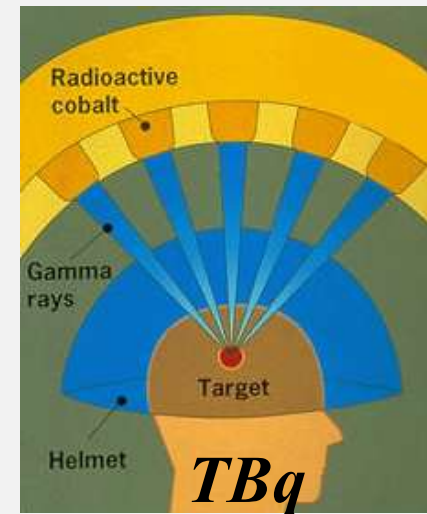
Gamma rays can travel **hundreds of meters in the air** and can easily pass **through people (~dm)**.

# Medical application of $\gamma$ rays



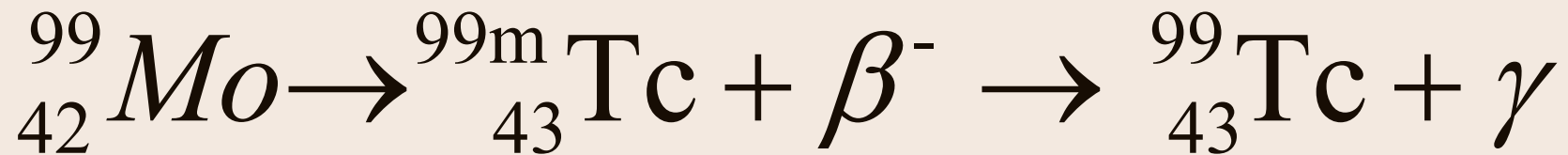
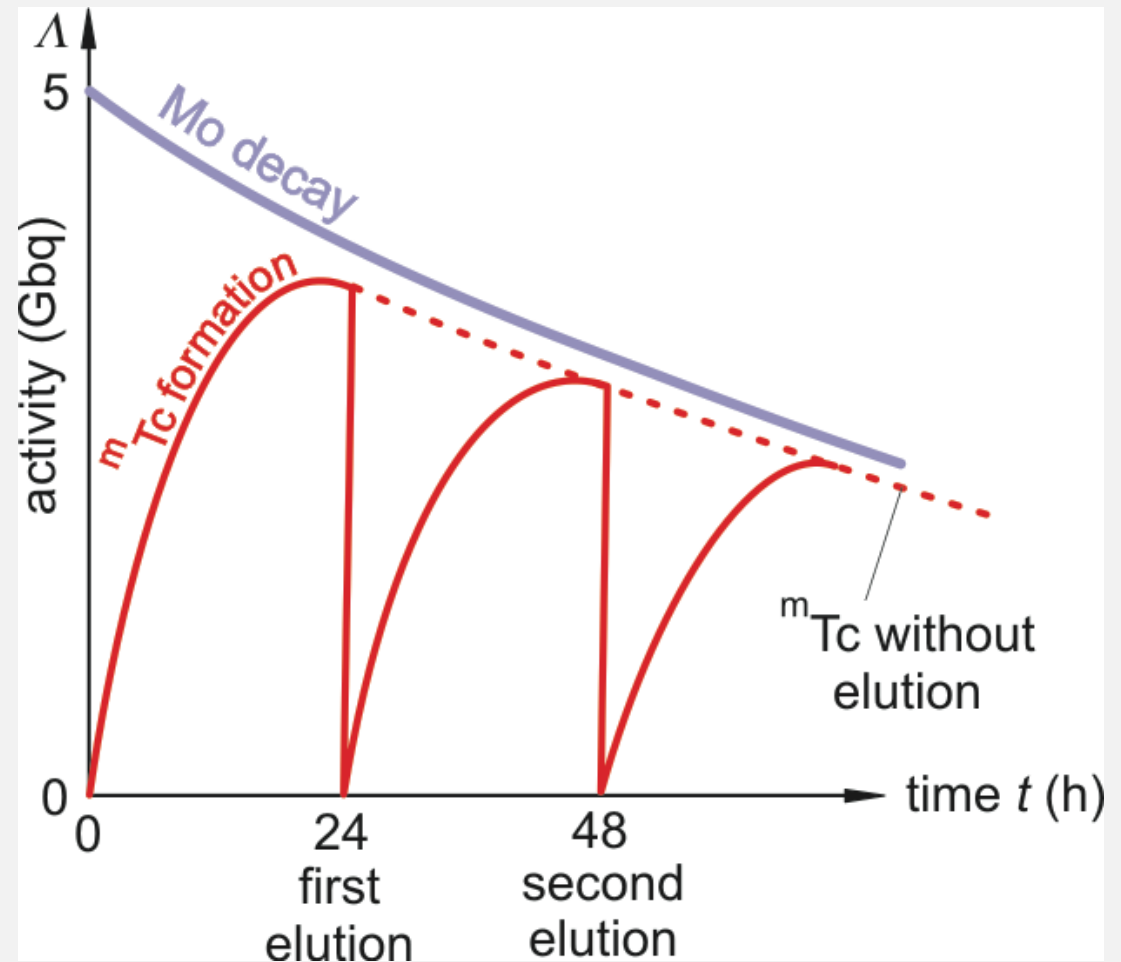
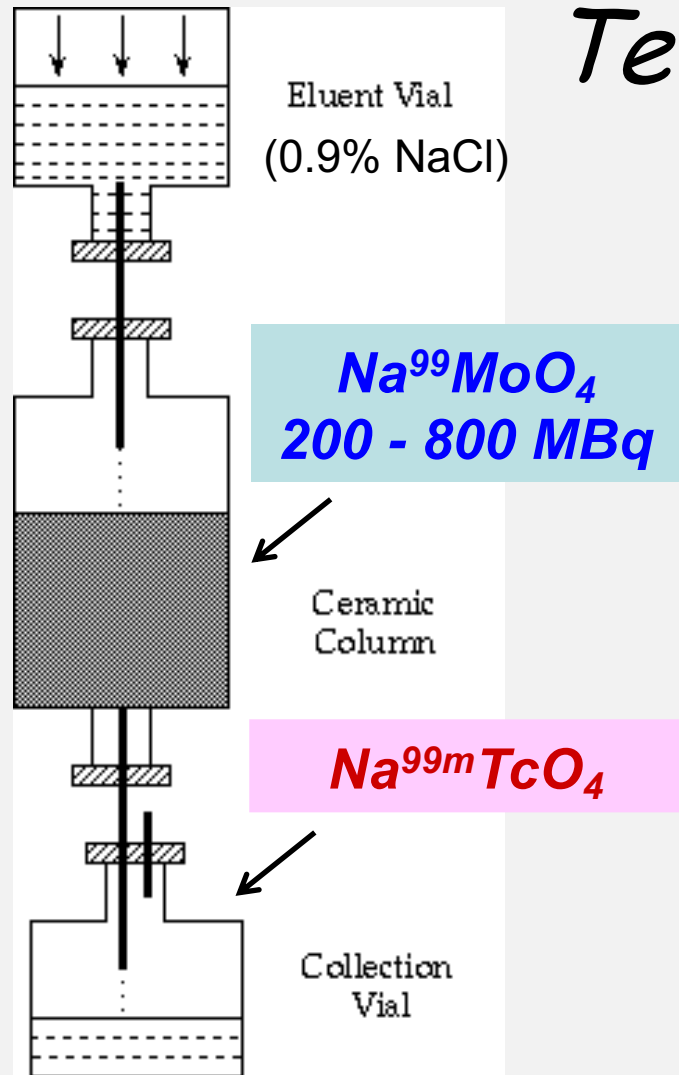
*Bone scan using  
 $^{99m}\text{Tc}$  labeled  
phosphate compound*

*therapy:  $\gamma$ -knife*



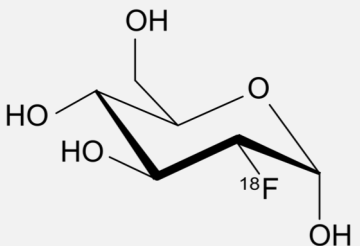
Diagnostics: ideal for isotope diagnostics

# 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
$^{123}\text{I}$	iodine	thyroid gland	metabolism
$^{123}\text{I}$	hippurate	kidney	metabolism
$^{133}\text{X}$	X gase	lung	breathing
$^{18}\text{F}$	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