

Nuclear radiation, radioactive isotopes

Constituents of atoms

Particle	Symbol	Rest 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	0	1.6726×10^{-27}	1.0072765
neutron	n	939.566	1+	1.6749×10^{-27}	1.0086649

* electrons have an electric charge of -1.602×10^{-19} C

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

Nuclear notation

Mass number

$$A = Z + N$$

Chemical symbol for
the element

$^{27}_{12}\text{Al}$

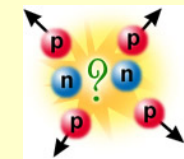
Atomic number =
Number of protons

N = number of neutrons

Nuclear stability

- There are very large *repulsive electrostatic forces* between protons

These forces should cause the nucleus to fly apart



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

It must be that a different type
of force exists within the
nucleus



1911 Rutherford, Geiger and Marsden

Nuclear stability

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

Instead of two separate conservation laws, a single conservation law states that the sum of mass and energy is conserved. Mass does not magically appear and disappear at random. A decrease in mass will be accompanied by a corresponding increase in energy and vice versa.

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

Another, short-range force is present, called the *nuclear force* (Rutherford, 1911)

Nuclear stability

- Another, short-range force is present, called the *nuclear force* (Rutherford, 1911)

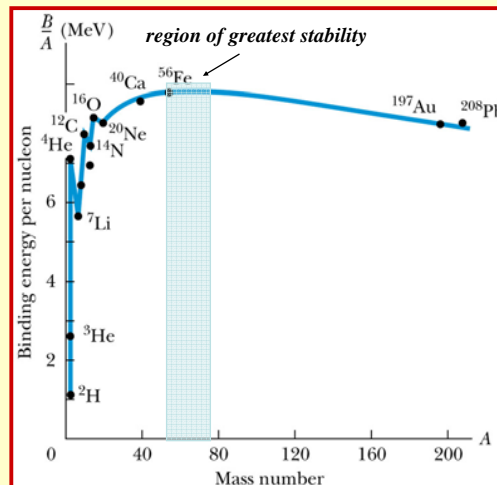
This is an *attractive force* that acts between all nuclear particles
The nuclear attractive force is stronger than the Coulomb repulsive force at the short ranges within the nucleus

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

The nuclear force is
- independent of charge
- the range of action is extremely short (~fm)

Binding energy per nucleon

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



Nuclear stability

*The balance of proton and neutron number
is extremely important for the stability of the nucleus*

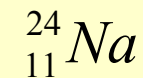
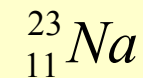
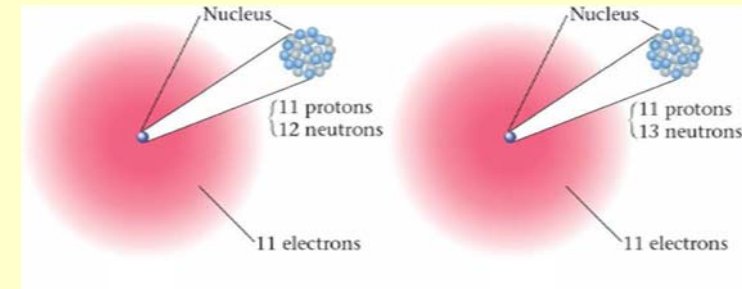
Isotopes

Greek *isos topos* = *equal place*

Isotopes of an element have nuclei with

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

Example of isotopes

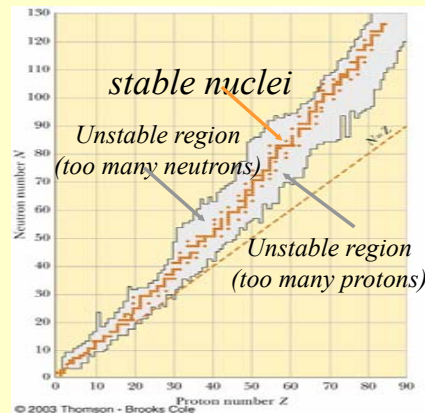


What is/are the stable combination(s)? 1:1 ?

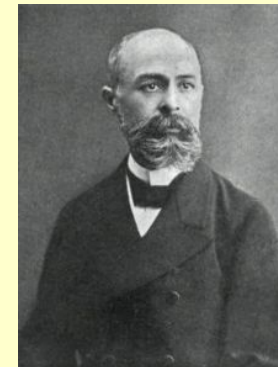
Nuclear stability chart

- Light nuclei are most stable if $N=Z$
- Heavy nuclei are most stable when $N > Z$

As the number of protons increase, the Coulomb force increases and so more nucleons are needed to keep the nucleus stable



- No nucleus is stable when $Z > 83$



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

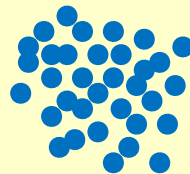
- *Radioactivity* is the spontaneous release of energy in the form of radioactive particles or waves
- Experiments suggested that radioactivity was the result of the decay, or disintegration, of unstable nuclei
- Three types of radiation can be emitted
 - Alpha (α) particles
 - Beta (β) particles
 - Gamma (γ) rays (Rutherford 1896, see details later)

- The nuclides, as with most things in nature, want to be at their *lowest energy state* which is a stable nucleus.
- Radioactive decay occurs in nuclides where the *nucleus is unstable*.

• *The nuclide reaches its stable state by undergoing radioactive decay.*

Characteristics of radioactive decay

- it is *statistical process* — individual disintegrations occur *randomly*
- it results in a decrease over time of the original amount of the radioactive nuclei



decrease of the original amount of the radioactive nuclei over time

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

number of nuclei decayed in a unit time

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

Typical activities in the practice

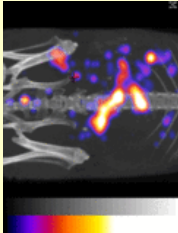
kBq,

natural
background



MBq,

in vivo
diagnostics



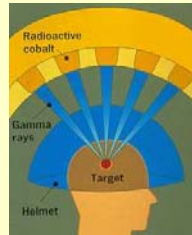
GBq,

laboratory
practice



TBq

therapy



Radioactive decay law

$$\text{Differential form} \quad \left| \frac{dN}{dt} \right| = -\lambda N$$

λ : decay constant (measure: 1/s)
constant for a certain isotope

Activity depends both on the

- size of the population of radioactive atoms
- type of the isotope

$$\left| \frac{dN}{dt} \right| = -\lambda N$$

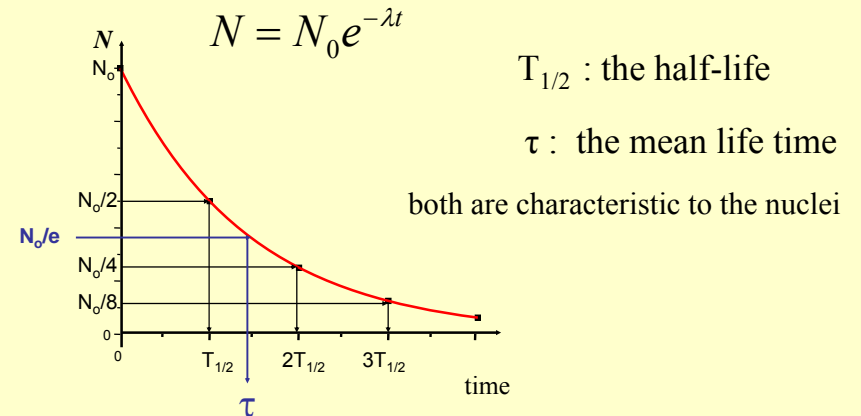
Solution of this equation yields

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

Integral form

N_0 : number of radioactive nuclei at $t = 0$,
 N : the number radioactive of nuclei remaining
after a period t

Graphical representation

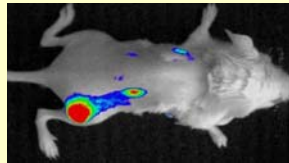
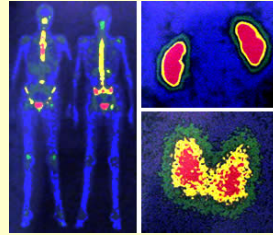


Half-lives in Medical Uses



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

Further considerations

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

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

$$\lambda = \frac{\ln 2}{T_{1/2}} = \frac{0.693}{T_{1/2}}$$

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

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

Definition of decay constant

Alteration of activity in time

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

$$\Lambda = \lambda N$$

$$\Lambda = \Lambda_0 e^{-\lambda t}$$

Specific activity : activity in a unit mass (Λ/m),
 unit: Bq / kg

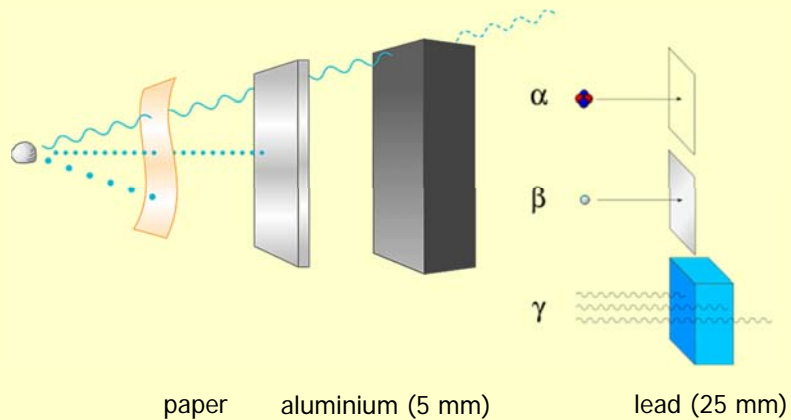
Characteristics of radioactive isotopes

Activity : depends both on the nucleus and the size of its population

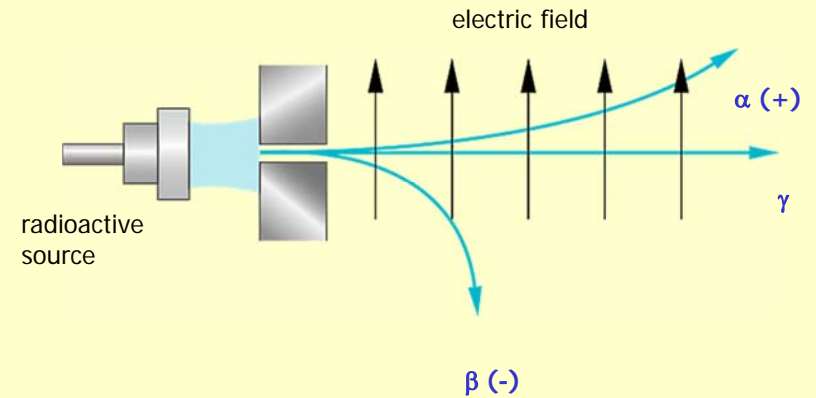
Half-life : physical parameter of each radioactive isotope

Type of radiation : physical characteristic of the nucleus

Types and nature of nuclear radiation

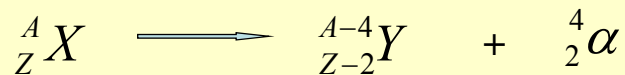
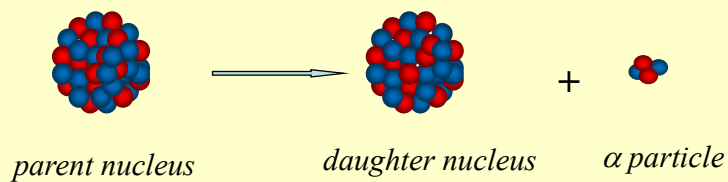


Deflection of radiation in electric field



Radiation from a radium source is split by an electric field.

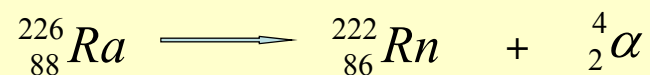
α decay



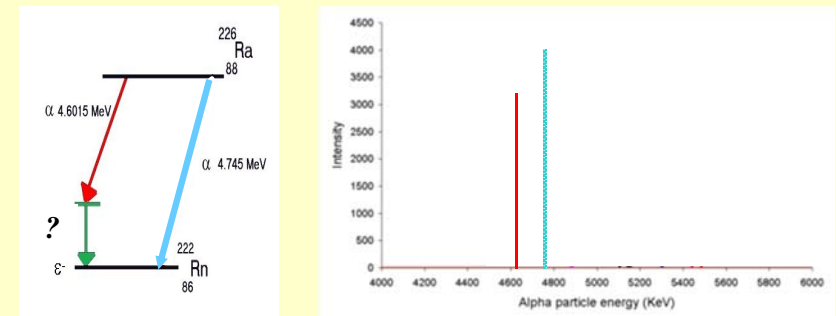
α particle is a nucleus of helium containing two neutrons and two protons

Heavy nuclei with mass numbers higher than 150 can disintegrate by emission of an α particle

example



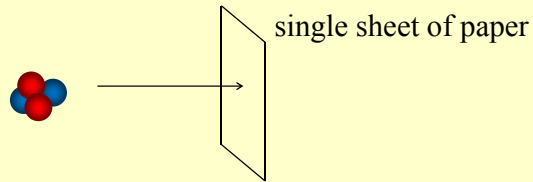
Energy spectrum of α radiation



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

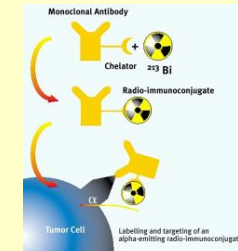
Medical application of α radiation

Diagnostics: none

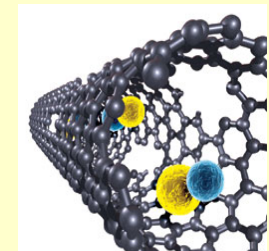
Targeted alpha **therapy** of cancer



Seed implantation
by needle



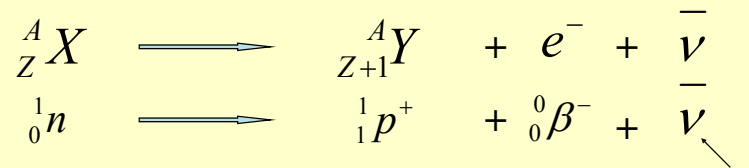
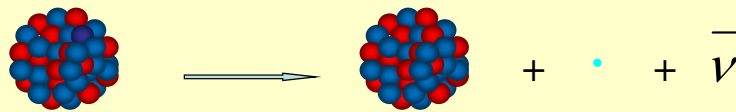
Monoclonal
antibody



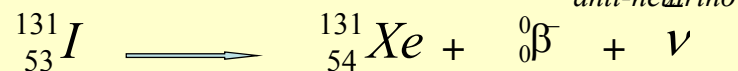
Carbon nano-tube

β decay

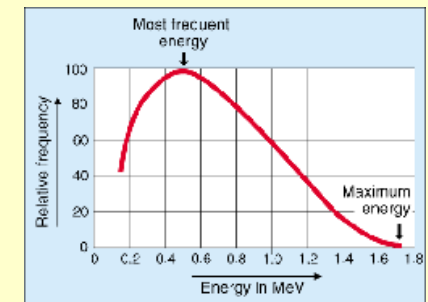
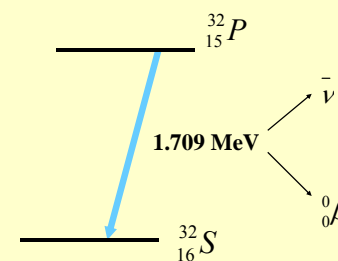
1. Neutron excess: β^- decay



example



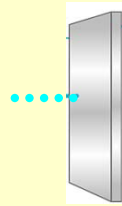
Energy spectrum of β radiation



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

continuous spectrum
with maximum kinetic energy for the
 β particle

Penetration depth of β^- particles



5 mm aluminum

absorber	density	maximum beta range (2.3 MeV) (1.1 MeV)	
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 and several other types of cancer



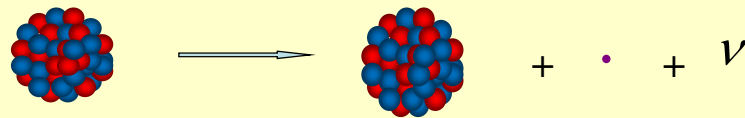
Brachytherapy:
implants into the
tumours



Endovascular
irradiation

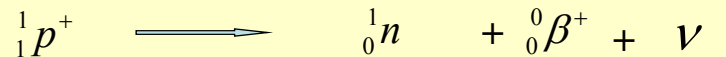
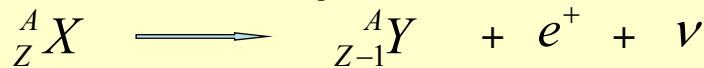
β decay

2. Proton excess: β^+ decay

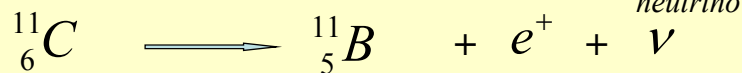


parent nucleus

daughter nucleus

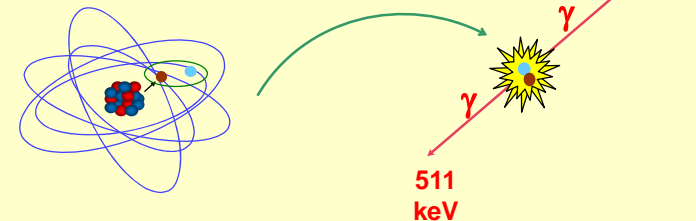


example



neutrino

Annihilation - particle-antiparticle pairs can annihilate each other



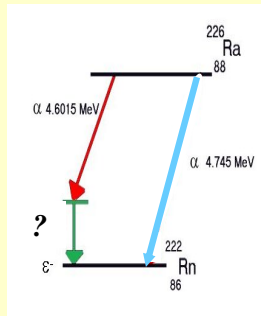
1. Conservation of momentum : two photons with opposite direction are produced

2. Energy balance:

$$m_e c^2 + m_p c^2 = 2 hf$$

mass - energy equivalence

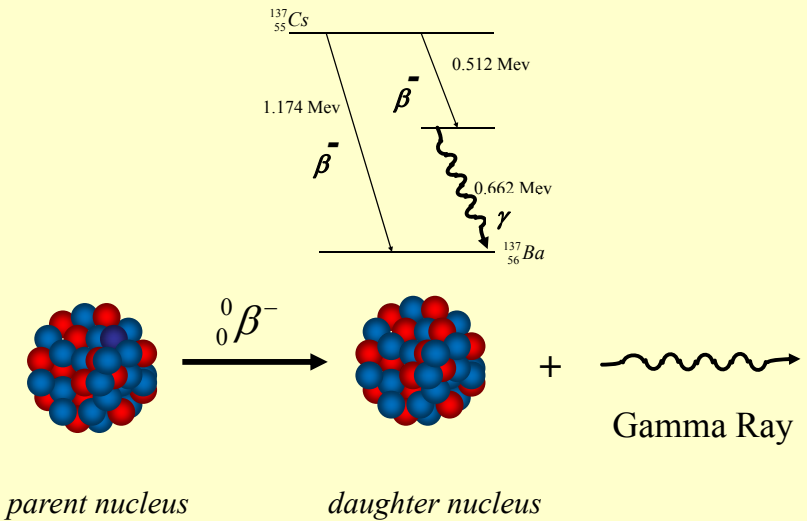
γ decay



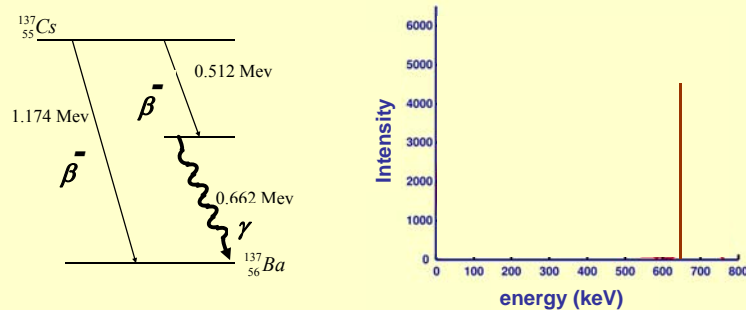
Sometimes the newly formed isotopes (after α or β decay) appear in the excited stat.

Excited nuclides have tendency to release the excess of energy by

electromagnetic radiation - emission of gamma rays.



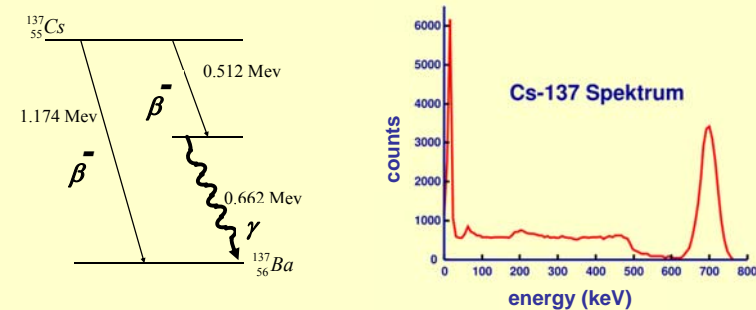
Energy spectrum of γ radiation



line spectrum

Energy is characteristic for the nucleus

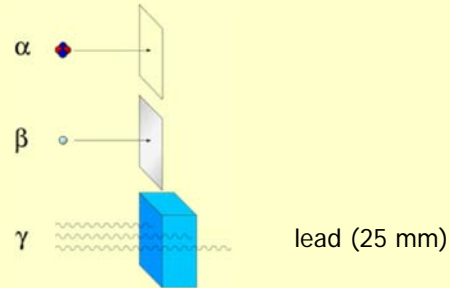
Energy spectrum of γ radiation



line spectrum

Energy is characteristic for the nucleus

Penetration depth of γ radiation



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

Gamma rays can travel from **1 to 100s of meters in the air** and can easily go right **through people (~dm)**.

Timing of γ emission

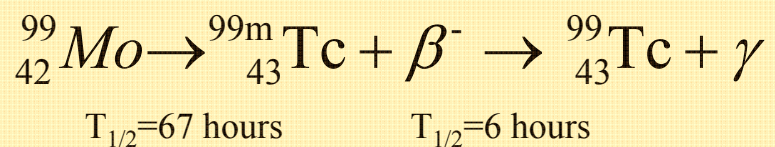
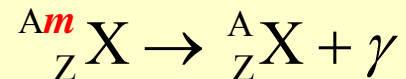
Lifetime of the excited nucleus:

1. Prompt γ decay: $\sim 10^{-13} - 10^{-18} \text{ s}$

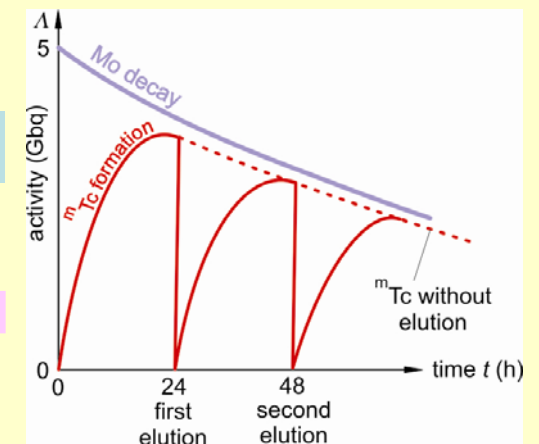
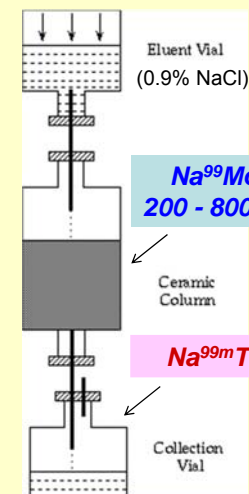
2. Isomeric transition: $\geq 10^{-10} \text{ s}$

Isomeric transition

Some excited states may have a half-lives ranging from hours up to more than 600 years

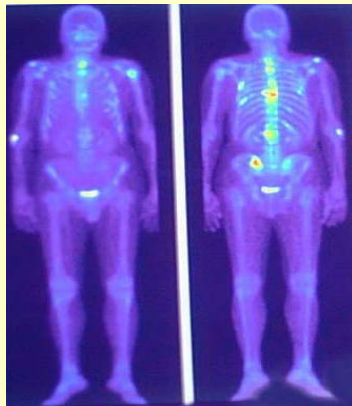


Technetium-99m generator



Medical application

Diagnostics: ideal for isotope diagnostics



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

<u>Radionuclide</u>	<u>Compound</u>	<u>Organ</u>	<u>Function</u>
^{99m} Tc	sodium pertechnetate	brain	blood flow
^{99m} Tc	coagulated albumin	lung	blood flow
^{99m} Tc	colloidal suspension	liver	liver function
^{99m} Tc	complex phosphate	bone	bone metabolisms
^{99m} Tc	red blood cells	heart	blood circulation
¹²³ I	iodide	thyroid	metabolisms
¹²³ I	hippuran	kidneys	renal function
¹³³ X	gas	lungs	ventilation

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