La Radioattività

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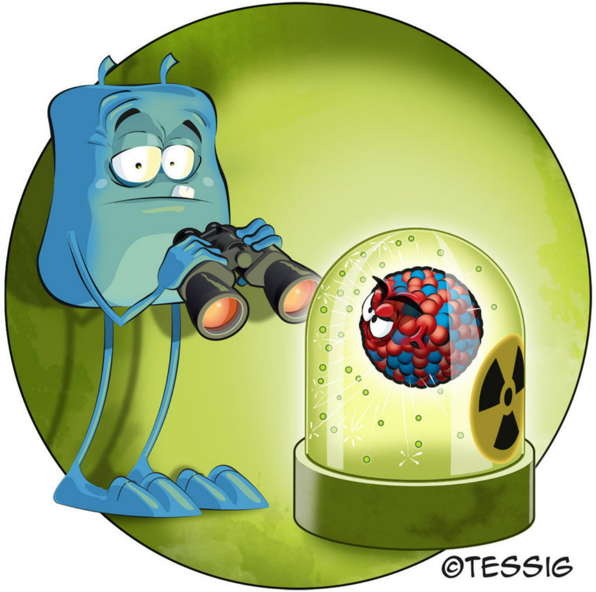


Cos’è la Radioattività ?

“La radioattività è il fenomeno di trasformazione spontanea (chiamata **decadimento**) di un **nucleo instabile** in un altro nucleo, accompagnato dall’ emissione di **particelle** e/o di **radiazione.**”

Un po’ di storia….

- 1895, W.C. Roentegen

Studiando i **raggi catodici** (ovvero la corrente che scorre in un tubo a vuoto) ed utilizzando un tubo ricoperto di carta nera in una stanza buia, Roentegen notò che un foglio di carta ricoperto della sostanza chimica detta platinocianide di bario diventava **fluorescente** (ovvero emetteva luce) anche se posizionato alla distanza di 2 metri dal tubo a raggi catodici.

→ Scoperta dei **Raggi X**

Un po’ di storia….

- 1896, H. Becquerel

Becquerel osservò che delle lastre fotografiche (ricoperte di un foglio di alluminio per proteggerle dalla luce) di annerivano se poste vicino al solfato di Uranio.

Ne dedusse che l’Uranio emette dei raggi in grado di attraversare il foglio di Alluminio. Dimostrò anche che questa **radiazione** era indipendente da qualunque condizione esterna (luce, calore, etc) ma era proprietà intrinseca dell’Uranio.

- 1898, Pierre and Marie Curie

osservarono che la radiazione emessa aumentava con l’aumentare della quantità di **Uranio** o **Torio**. Chiamarono queste sostanze “**radioattive**” ed il processo di emissione “**radioattività**”. Scoprirono inoltre altri elementi radioattivi: il **Polonio** ed il **Radio**.

Un po' di storia….

- 1913, Ernest Rutherford

  bombardando gli atomi con particelle alfa osservò che alcun particelle era riflesse all'indietro. Egli fu in grado di misurare il raggio del nucleo e di formulare la rima descrizione della struttura dell'atomo.

- 1919, Ernest Rutherford

  utilizzando particelle alfa di alta energia fu in grado di separare l'atomo bersaglio in due atomi; realizzò così la prima reazione nucleare e scoprì il protone.

- 1932, J. Chadwick

  dimostrò l'esistenza del neutrone e ne determinò la massa.

Un po’ di storia….

- 1897, J.J. Thomson

  utilizzando il tubo a raggi catodici fu in grado di identificare l’elettrone.

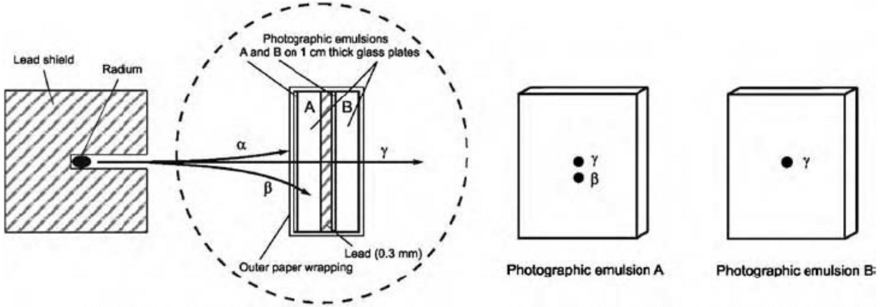
- 1899, Ernest Rutherford

  scoprì la radiazione alfa e beta e le caratterizzò studiando il loro potere di penetrazione nei materiali; poi scoprì che gli atomi che emettono radiazione alfa o beta cambiano la loro natura e diventano più leggeri.

- 1900, Paul Villard

  scoprì la radiazione gamma

(denominata in questo modo da Rutherford)



(a) Experimental arrangement

(b) Emulsions after chemical development

Un po' di storia….

- 1932, W.K. Heisenberg

  formulò la teoria dettagliata dell'atomo e del nucleo.

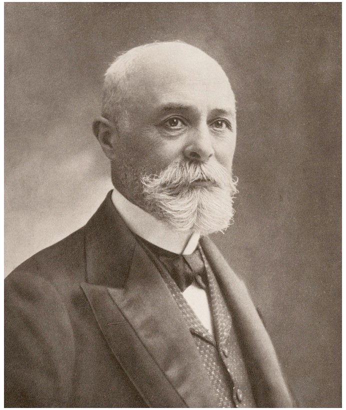
- 1928, George Gamow

  spiegò il decadimento alfa considerando l'effetto tunnel nel nucleo

- 1934, Enrico Fermi

  propose una teoria per spiegare il decadimento beta introducendo una nuova forza (l'interazione debole) in grado di trasformare un neutrone in un protone e vice-versa. La particella neutra emessa nel decadimento fu chiamata da Fermi neutrino.

Un po’ di premi Nobel….



Marie Skłodowska in Curie
Pierre Curie ed Henri Becquerel
Premio Nobel in Fisica **1903**

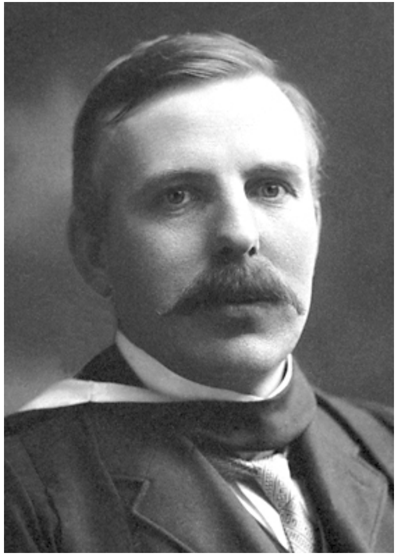
"in riconoscimento degli straordinari servizi che hanno reso con le loro ricerche condivise sui fenomeni di radiazione, scoperti dal professor Henri Becquerel"

Un po' di premi Nobel….

Joseph John Thomson
1856 - 1940
Premio Nobel in Fisica 1906

"per i grandi meriti dei suoi studi scientifici sulla conduzione elettrica nei gas”

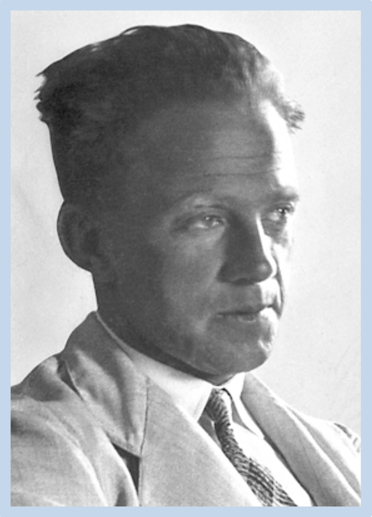
Un po’ di premi Nobel….



Ernest Rutherford
1871 - 1937
Premio Nobel in Chimica 1908

"per lo studio della disintegrazione degli elementi e la chimica delle sostanze radioattive”

Un po’ di premi Nobel….



Werner Karl Heisenberg
1901 - 1976
Premio Nobel in Fisica 1932

"per la creazione della meccanica quantistica, la cui applicazione, tra l'altro, ha portato alla scoperta delle forme allotropiche dell'idrogeno"

Un po' di premi Nobel….

James Chadwick
1891 - 1974
Premio Nobel in Fisica 1935

"per la scoperta del neutrone"

Il Modello Atomico

- Il Modello di Rutherford: l'atomo è costituito da una nuvola di elettroni distribuiti intorno ad un nucleo carico positivamente, composto da protoni e neutroni.

  le dimensioni della nuvole di elettroni sono dell' ordine di 10^{-8} cm

  le dimensioni del nucleo sono dell' ordine di 10^{-12} - 10^{-13} cm

- Le dimensioni del NUCLEO:
  - Quando l'angolo di diffusione di una particella α è pari a π, tutta la sua energia cinetica viene trasformata in energia potenziale nel campo elettrico del nucleo, ad una distanza molto vicina al raggio nucleare R_N

$$\Delta E_\alpha = -E_\alpha = V(R_N) = -\frac{2Ze^2}{R_N} \qquad R_N = \frac{2Ze^2}{E_\alpha}$$

$e^2 = 1.44\ MeV \cdot fm \qquad Z \approx 80 \qquad E_\alpha \approx 10\ MeV$

$$R_N \approx 10^{-12} cm$$

$$R = r_0 A^{1/3} \quad \text{with} \quad r_0 = 1.2\ \text{fm}$$

Il Nucleo Atomico

- Nuclide: ${}^{A}_{Z}X_{N}$
    - X: elemento chimico
    - Z: numero atomico (number di electroni)
    - A: numero di massa (numero totale di neutroni, N, e protoni, Z)
    - N = A-Z (può essere omesso)
- Isotopi: nuclei con lo stesso valore di Z (stesso elemento chimico, X);
    - Examples: ${}^{12}Ca$, ${}^{13}Ca$, ${}^{14}Ca$
- Isotoni: nuclei con lo stesso valore di N
    - Examples: ${}^{2}_{1}H$, ${}^{3}_{2}He$ ${}^{12}_{6}C$, ${}^{15}_{7}N$, ${}^{14}_{8}O$
- Isobari: nuclei con lo stesso valore di A
    - Examples: ${}^{14}_{6}C$, ${}^{14}_{7}N$ ${}^{130}_{56}Ba$, ${}^{130}_{52}Te$, ${}^{130}_{48}Cd$

Il Nucleo Atomico

- La massa del nucleo $M_N(A,Z)$ assume un valore dato da:

$$M_N(A,Z)=Zm_p + (A-Z)m_n - B_N(A,Z)$$

$B_N(A,Z)$ (> 0 per definizione) è il difetto di massa o energia di legame

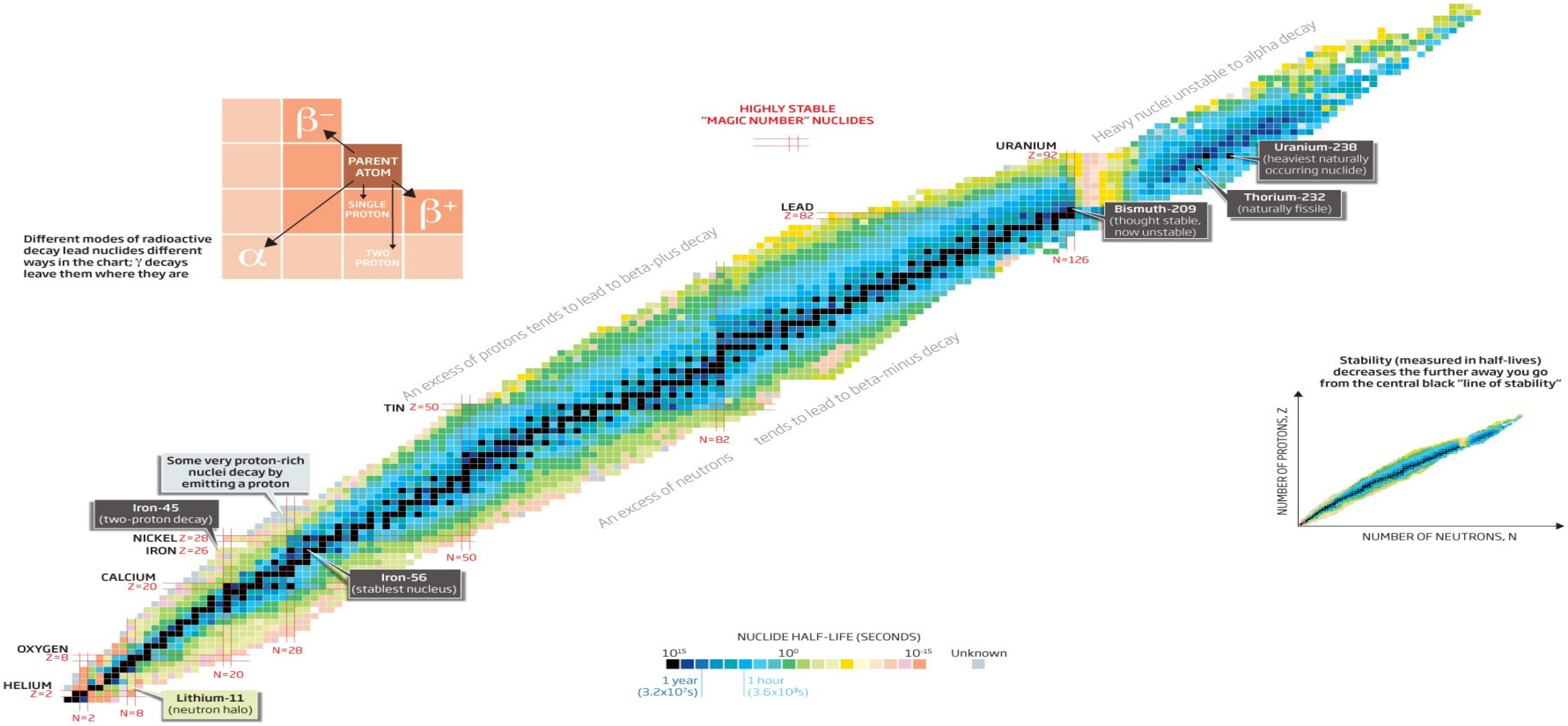
- La massa atomica $M_A(A,Z)$ è il valore della massa dell' atomo, inclusi gli elettroni

$$M_N(A,Z)=M_A(A,Z) - Zm_e + B_e(Z)$$

La massa atomica può essere misurata con uno spettrometro di massa; sottraendo la massa degli elettroni ed aggiungendo la loro energia di legame (minore del keV) si ottiene la massa nucleare

- L'eccesso di massa: $\Delta = M_A(A,Z) - A \cdot u \Rightarrow \Delta = 0$ per il ^{12}C
- Nella tabella di massa atomica si trova: $M_A(A,Z)$, $B_N(A,Z)$, l'Eccesso di Massa(Δ)

Carta dei Nuclei

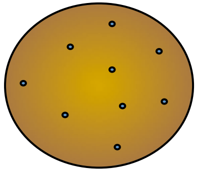


Evoluzione temporale della conoscenza sui costituenti primi della materia

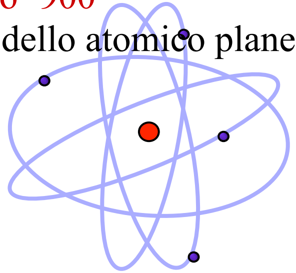
Dall'atomo indivisibile ai quarks

Fine '800
L'atomo

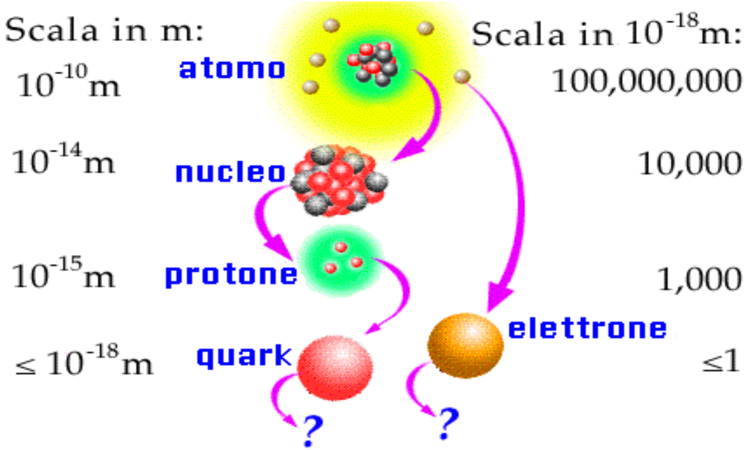
Inizio '900
Il modello atomico di Thomson



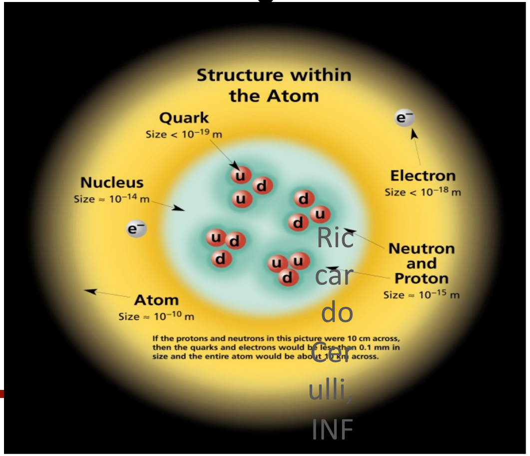
Inizio '900
Il modello atomico planetario



Anni 30
La struttura del nucleo atomico



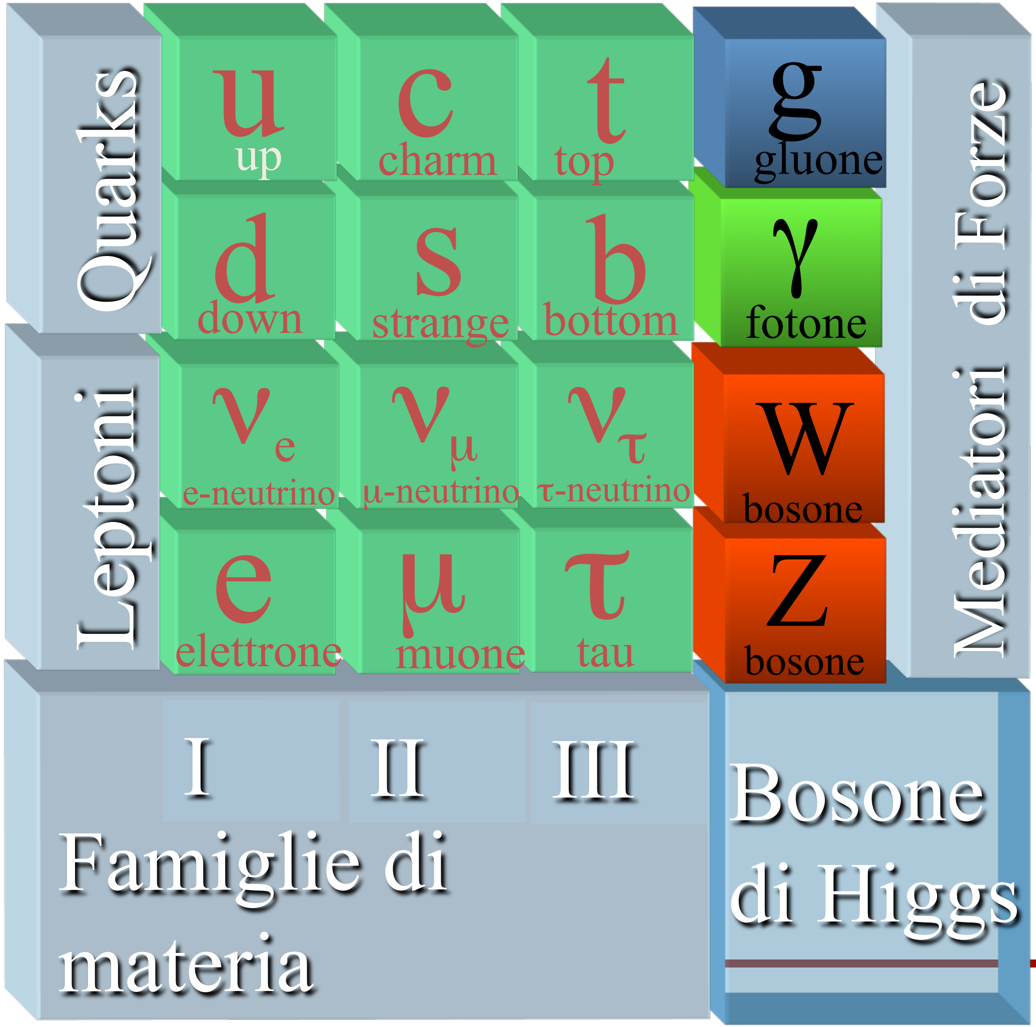
Fine '900
La struttura subnucleare a quark



If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

Il protone ha una massa 1800 volte maggiore di quella dell'elettrone

Foto di famiglia al completo … (?!)



Il Modello Standard

Costituenti materiali

4 Forze

Radioactive Phenomena

- Known and artificially produced nuclei : ~ 2700
- Stable nuclei: ~ 270, no spontaneous physical process able to transform them
- Un-stable nuclei transform spontaneously through physical processes named **radioactive decays**
- In a radioactive decay an unstable nucleus decay into a more stable state with release of energy

Radioactive Phenomena

- A decay is a probabilistic process
- A nucleus can undergo different decay processes
- The time behavior of the decay is independent of the processes
- The Q value of a reaction or a decay is defined as:

$$Q = (\Sigma m_{\mathrm{i}} - \Sigma m_{\mathrm{f}})c^2$$

difference of initial and final mass of the nuclei

Q > 0 decay is allowed

Main nuclear decay processes

- α decay (typical for A>210):

$$A(Z,N) \longrightarrow A'(Z-2,N-2) + A''(2,2)$$

- β^+, β^- decay (for nuclei with neutron excess or defect)

$$A(Z,N) \longrightarrow A(Z+1,N-1) + e^- + \bar{\nu}$$

$$A(Z,N) \longrightarrow A(Z-1,N+1) + e^+ + \nu$$

- $2\beta^+$, $2\beta^-$ decay (observed in few nuclei)

$$A(Z,N) \longrightarrow A(Z-2,N+2) + 2e^+ + 2\nu$$

$$A(Z,N) \longrightarrow A(Z+2,N-2) + 2e^- + 2\bar{\nu}$$

- γ emission (transition from an level to a lower one)

$$A^*(Z,N) \longrightarrow A(Z,N) + \gamma$$

Main nuclear decay processes

- Spontaneous fission (for heavy nuclei)

$$A(Z,N) \longrightarrow A'(Z',N') + A''(Z'',N'') + kn$$

$$A' + A'' + k = N' + N'' + Z' + Z'' + k = A$$

- Proton or Neutron emission

$$A(Z,N) \longrightarrow A'(Z-1,N) + p$$

$$A(Z,N) \longrightarrow A'(Z,N-1) + n$$

- Light nuclei decay (A > 4) (observed in heavy nuclei)

$$A(Z,N) \longrightarrow A'(Z',N') + A'(Z'',N'')$$

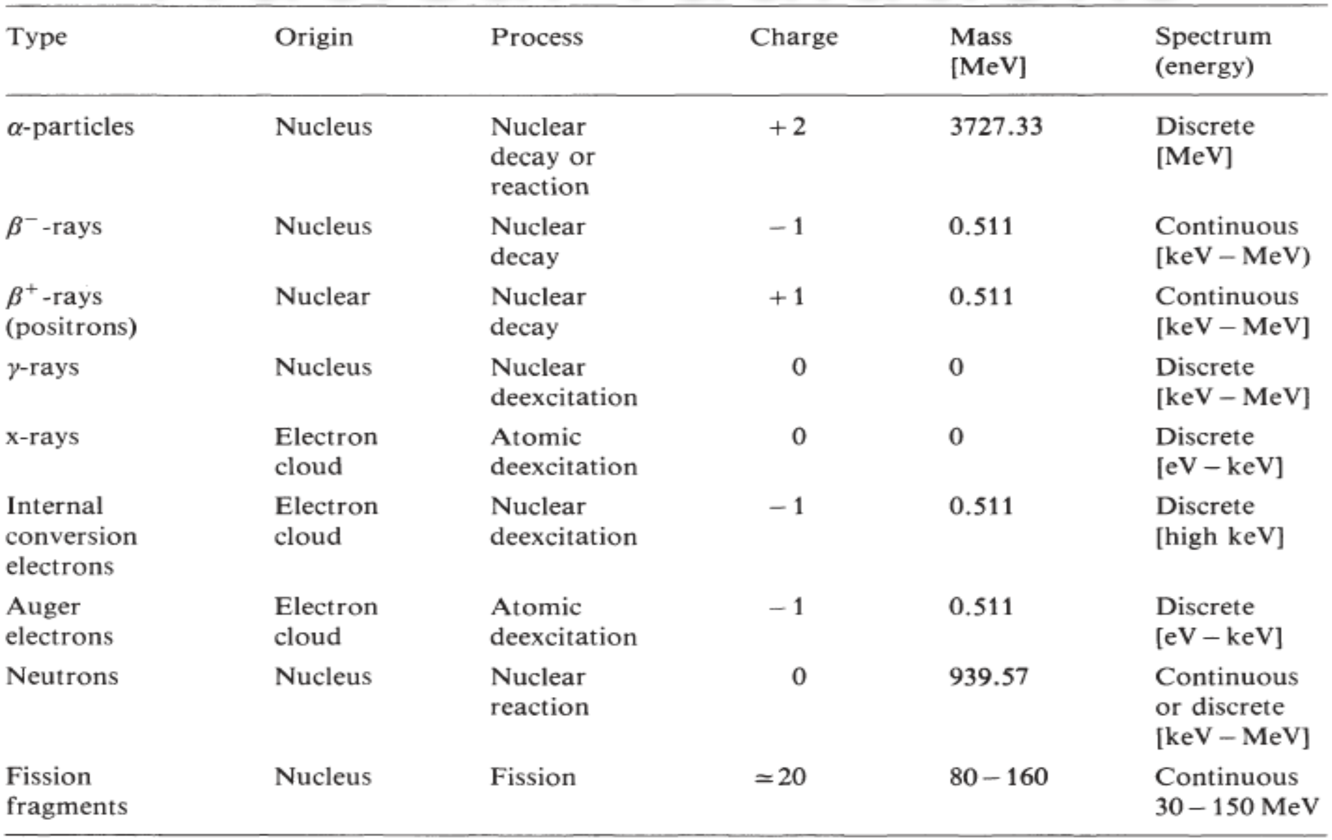
Main nuclear decay processes

- Electron Capture (as a β^+ decay with e^- in left side):

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

- Annihilation radiation: when a e^+ annihilate with e^- in matter or detector medium, 2 (E=511 keV) photons are emitted in opposite directions
- Internal conversion: nuclear excitation energy is transferred to an atomic electron rather than emitted as a photon; e^- are monoenergetic with energy equal to the difference between the excitation energy and electron binding energy. e^- can belong to K-shell, L-shell., etc. (group of IC lines, from keV to MeV)
- Auger electrons: excitation in the electron shell transferred to an atomic electron rather than to characteristic x-ray; the e^- are monoenergetic (few keV)

Nuclear radiations



Type	Origin	Process	Charge	Mass [MeV]	Spectrum (energy)
α-particles	Nucleus	Nuclear decay or reaction	$+2$	3727.33	Discrete [MeV]
β^--rays	Nucleus	Nuclear decay	-1	0.511	Continuous [keV – MeV)
β^+-rays (positrons)	Nuclear	Nuclear decay	$+1$	0.511	Continuous [keV – MeV]
γ-rays	Nucleus	Nuclear deexcitation	0	0	Discrete [keV – MeV]
x-rays	Electron cloud	Atomic deexcitation	0	0	Discrete [eV – keV]
Internal conversion electrons	Electron cloud	Nuclear deexcitation	-1	0.511	Discrete [high keV]
Auger electrons	Electron cloud	Atomic deexcitation	-1	0.511	Discrete [eV – keV]
Neutrons	Nucleus	Nuclear reaction	0	939.57	Continuous or discrete [keV – MeV]
Fission fragments	Nucleus	Fission	$\simeq 20$	80 – 160	Continuous 30 – 150 MeV

Activity Units

Activity of a source (A): number of decay per unit time

$A = dec/sec$

$1\ Becquerel\ (Bq) = 1 disintegration/sec$

Traditional unit, Curie defined as the activity of 1 g of ^{226}Ra

$1\ Curie\ (Ci) = 3 \cdot 10 \uparrow 10\ disintegration/sec$

α decay

- α decay processes

$$A_1(Z,N) \longrightarrow A_2(Z-2,N-2) + \alpha \longrightarrow {}^4He$$

- Strong and e.m. interaction

- Quantum mechanics effect (tunnel effect)

- Give information about nuclear properties: charge, dimension, angular momentum, parity, isospin levels, etc.

- Energy and $T_{1/2}$ range:

$$4\ MeV < E_\alpha < 9\ MeV$$

$$10^{-7}\ s < T_{1/2} < 10^{10} y$$

β decay

- β decay processes
  - ✓ β^-: $A(Z,N) \longrightarrow A(Z+1,N-1) + e^- + \overline{\nu}$
  - ✓ β^+: $A(Z,N) \longrightarrow A(Z-1,N+1) + e^+ + \nu$
  - ✓ EC: $A(Z,N) + e^- \longrightarrow A(Z-1,N+1) + \nu$
- Weak interaction
- Electron (positron) can have a kinetic energy from *0* to E_{max}:

  E_{max} range from *26 keV* (^{187}Re) to ≈ 20 *MeV*

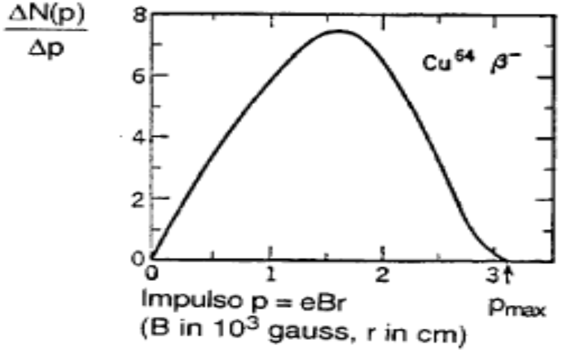
  $T_{1/2} \approx 10^{-2}$ *s* - 10^{17}*y* (few nuclei have $T_{1/2} > 10^5$ *y*)

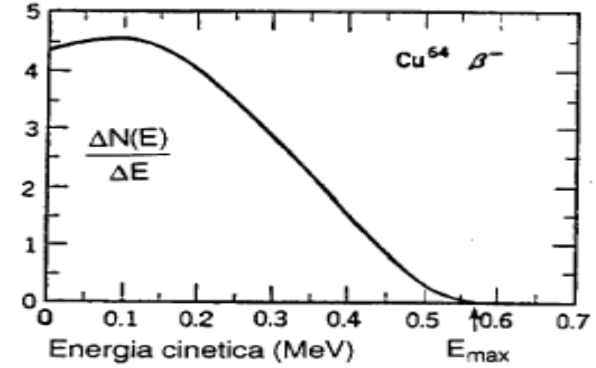
  $^{115}_{49}In \quad (10^{14}\,a)$, $\qquad ^{113}_{48}Cd \quad (10^{15}\,a)$, $\qquad ^{50}_{23}V \quad (10^{17}\ a)$

β decay

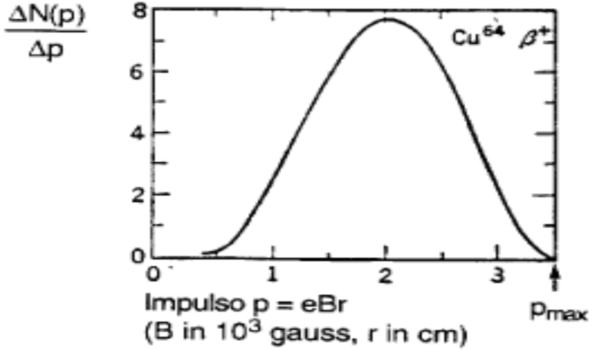
- Spectrum and dN/dE

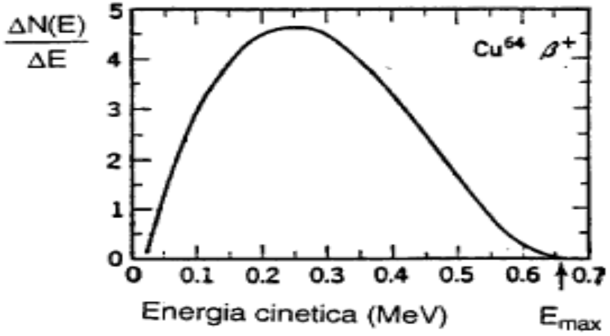
^{64}Cu, β^-





^{64}Cu, β^+





β decay

Q value calculation:

$$
\begin{aligned}
&\beta^- && M(A,Z) = M(A,Z+1) + T_A + m_e + T_e + E_{\overline{\nu}}\\
&\beta^+ && M(A,Z) = M(A,Z-1) + T_A + m_e + T_e + E_{\nu}\\
&CE && M(A,Z) + m_e - B_e \approx M(A,Z) + m_e =\\
& && \qquad = M(A,Z-1) + T_A + E_{\nu}
\end{aligned}
$$

$$
\begin{aligned}
&\beta^- && Q_{\beta-} = M(A,\,Z) - M(A,\,Z+1) - m_e =\\
& && \qquad = T_A + T_e + E_{\overline{\nu}} > 0\,,\\
&\beta^+ && Q_{\beta+} = M(A,\,Z) - M(A,\,Z-1) - m_e =\\
& && \qquad = T_A + T_e + E_{\nu} > 0\,,\\
&CE && Q_{CE} = M(A,\,Z) - M(A,\,Z-1) + m_e =\\
& && \qquad = Q_{\beta+} + 2m_e = T_A + E_{\nu} > 0\,.
\end{aligned}
$$

β decay

When β+ is allowed, EC is allowed too

$Q_{EC} = Q_{\beta+} + 2m_e$ when $Q_{\beta+} > 0$ → $Q_{EC} > 0$

Case with $Q_{\beta-} > 0$, $Q_{EC} > 0$, $Q_{\beta+} > 0$

$$^{64}_{29}Cu \begin{cases} \xrightarrow{\beta^+} {}^{64}_{28}Ni & 20\% \\ \xrightarrow{CE} {}^{64}_{28}Ni & 40\% \\ \xrightarrow{\beta^-} {}^{64}_{30}Zn & 40\% \end{cases}$$

Case with: $Q_{EC} > 0$ and $Q_{\beta+} < 0$

$$^{7}_{4}Be \xrightarrow{CE} {}^{7}_{3}Li \quad 100\%$$

For Free neutron the decay into proton is allowed

$$n \longrightarrow p + e^- + \overline{\nu} \qquad Q_{\beta-} = m_n - m_p - m_e = 782\ keV > 0$$

Free proton is **stable**

$$p \longrightarrow n + e^+ + \nu \qquad Q_{\beta+} = m_p - m_n - m_e = -1.81\ MeV < 0$$

γ decay

$$A_i \longrightarrow A_f + \gamma$$

i initial state
f final state

- γ emission when configuration of charge or current or magnetic moment changes
- in the nucleus orbital motion of protons changes the charge distribution; magnetic moment depends on the orbital motion and on magnetic moment of p and n

$$10\,keV \;\le\; E_\gamma \;\le\; 5\,MeV$$

$$0 = p_f + p_\gamma$$

$$E_i \equiv M_i c^2 = E_f + E_\gamma = M_f c^2 + T_f + E_\gamma$$

$$T_f \;=\; \frac{1}{2}\frac{E_\gamma^2}{M_f c^2} \ll \; E_\gamma$$

$$E_\gamma \ll M_f c^2 \;\approx\; A\,938\,MeV$$

$$\boxed{E_\gamma = M_i c^2 - M_f c^2}$$

Environmental Radioactivity

Origin of radiation

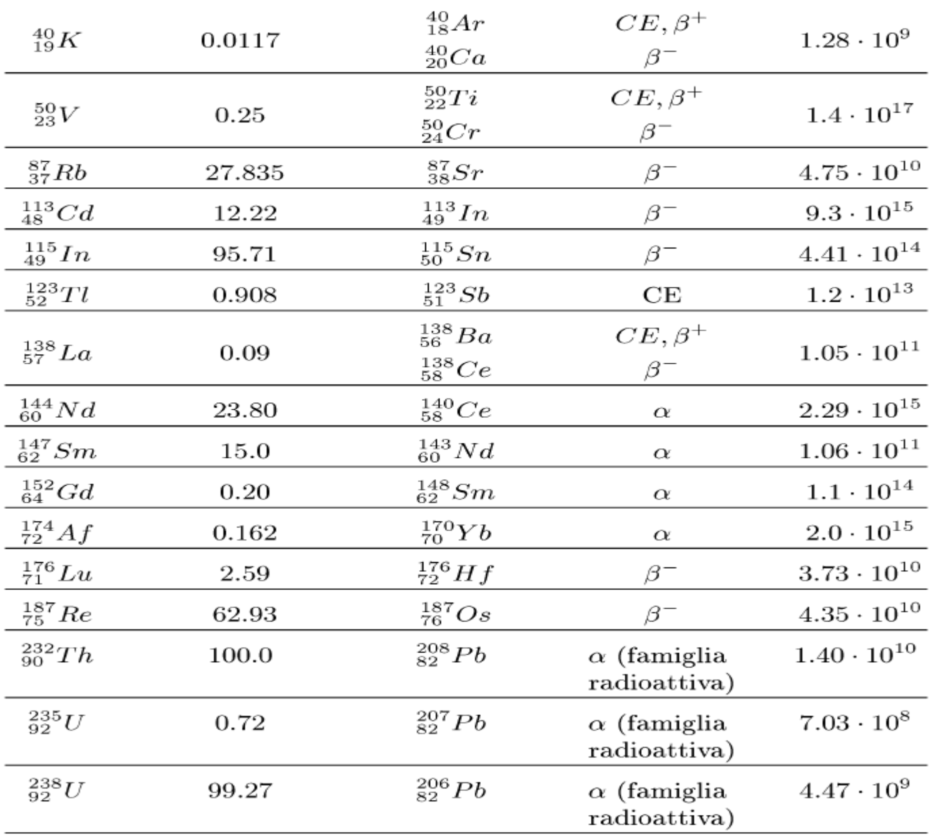
- natural: radioactive nuclei present (in trace) in the material, in the living being, in the air, etc.…
- cosmic: radiation coming from the Extraterrestrial sources (Stars, …)
- artificial: produced in laboratory (reactor, accelerator, medical devices)

Natural Radioactive nuclei: **≈75 nuclei**

primordial: present in the Earth since the formation of the Solar System

cosmogenic: produced in the interaction between the cosmic ray and the atoms in the Earth

Primordial radioactive nuclei



Nuclide	Isotopic abundance	Stable nuclei produced in the decay	decay process	Half-Life (yr)
${}^{40}_{19}K$	0.0117	${}^{40}_{18}Ar$ ${}^{40}_{20}Ca$	CE, β^+ β^-	$1.28 \cdot 10^9$
${}^{50}_{23}V$	0.25	${}^{50}_{22}Ti$ ${}^{50}_{24}Cr$	CE, β^+ β^-	$1.4 \cdot 10^{17}$
${}^{87}_{37}Rb$	27.835	${}^{87}_{38}Sr$	β^-	$4.75 \cdot 10^{10}$
${}^{113}_{48}Cd$	12.22	${}^{113}_{49}In$	β^-	$9.3 \cdot 10^{15}$
${}^{115}_{49}In$	95.71	${}^{115}_{50}Sn$	β^-	$4.41 \cdot 10^{14}$
${}^{123}_{52}Tl$	0.908	${}^{123}_{51}Sb$	CE	$1.2 \cdot 10^{13}$
${}^{138}_{57}La$	0.09	${}^{138}_{56}Ba$ ${}^{138}_{58}Ce$	CE, β^+ β^-	$1.05 \cdot 10^{11}$
${}^{144}_{60}Nd$	23.80	${}^{140}_{58}Ce$	α	$2.29 \cdot 10^{15}$
${}^{147}_{62}Sm$	15.0	${}^{143}_{60}Nd$	α	$1.06 \cdot 10^{11}$
${}^{152}_{64}Gd$	0.20	${}^{148}_{62}Sm$	α	$1.1 \cdot 10^{14}$
${}^{174}_{72}Af$	0.162	${}^{170}_{70}Yb$	α	$2.0 \cdot 10^{15}$
${}^{176}_{71}Lu$	2.59	${}^{176}_{72}Hf$	β^-	$3.73 \cdot 10^{10}$
${}^{187}_{75}Re$	62.93	${}^{187}_{76}Os$	β^-	$4.35 \cdot 10^{10}$
${}^{232}_{90}Th$	100.0	${}^{208}_{82}Pb$	α (famiglia radioattiva)	$1.40 \cdot 10^{10}$
${}^{235}_{92}U$	0.72	${}^{207}_{82}Pb$	α (famiglia radioattiva)	$7.03 \cdot 10^8$
${}^{238}_{92}U$	99.27	${}^{206}_{82}Pb$	α (famiglia radioattiva)	$4.47 \cdot 10^9$

- Nuclei with **half-life** larger than the age of the Earth
- Nuclei belonging to a **radioactive chain** with parent nucleus having half-life larger than the age of the Earth
- **^{40}K** responsible of the largest part of radioactivity in the human body; it contributes for 1/3 of the natural radioactivity

Main radioactive chains

^{238}U ($T_{1/2}$ = 4.468 10^9 y) ^{235}U ($T_{1/2}$ = 7.038 10^8 y) ^{232}Th ($T_{1/2}$ = 1.39 10^{10} y)

- Mass number of the nuclei belonging to these 3 families can be expressed as:
  - *4n (^{232}Th)*
  - *4n + 2 (^{238}U)*
  - *4n + 3 (^{235}U)*

n = integer

- The family with mass number *4n + 1:* artificially discovered, ^{237}Np
- It is not present in Nature because the half-life of its daughter nuclei are smaller than the age of the Earth; Np has an half-life of 10^6 yr. The only nuclide of this chain that is present is ^{209}Bi (stable)
- Because of the high $T_{1/2}$ of the primordial nuclei, the daughter nuclei are in equilibrium

The activity of the daughters (X) are the same as the primordial nucleus (A)

$$\boxed{\frac{n_X}{n_A} = \frac{T^X_{1/2}}{T^A_{1/2}}}$$

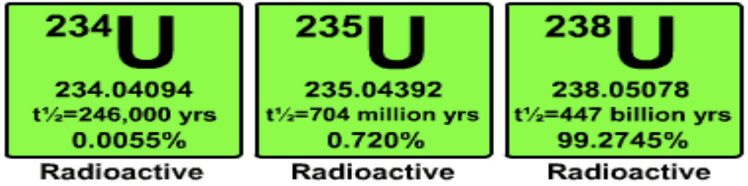
Constant in all the material containing A

Uranium

- It is a metal, silver colored, ductile and malleable, ρ = 19,05 g/cm^3

- There exists 25 Uranium isotopes (A=211-225)

- Most abundant isotopes:



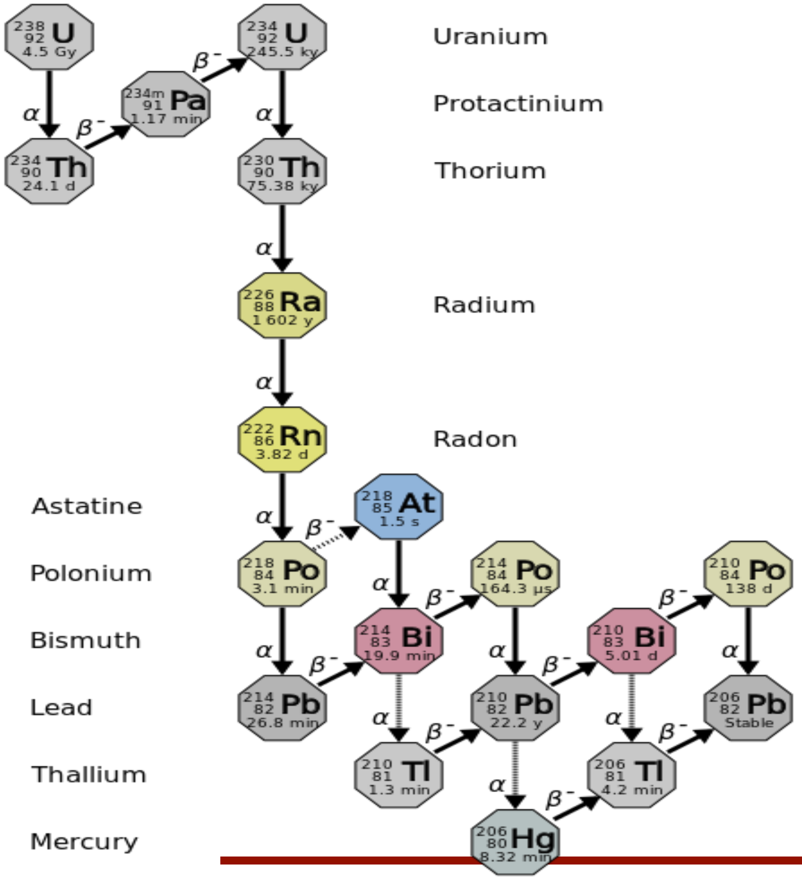
^{234}U	^{235}U	^{238}U
234.04094	235.04392	238.05078
t½=246,000 yrs	t½=704 million yrs	t½=447 billion yrs
0.0055%	0.720%	99.2745%
Radioactive	Radioactive	Radioactive

- Uranium isotopes are present in all the Earth surface and materials

- Fundamental in nuclear reactors:
  - ^{235}U is fissile (to induced fission)
  - ^{238}U is fertile not fissile, it can capture neutrons producing ^{239}Pu (fissile)
  - To be used in reactors U is enriched in ^{235}U at 3-4% level

- Uranium depleted (by ^{235}U) is used for bullets with high penetration power

^{238}U decay chain



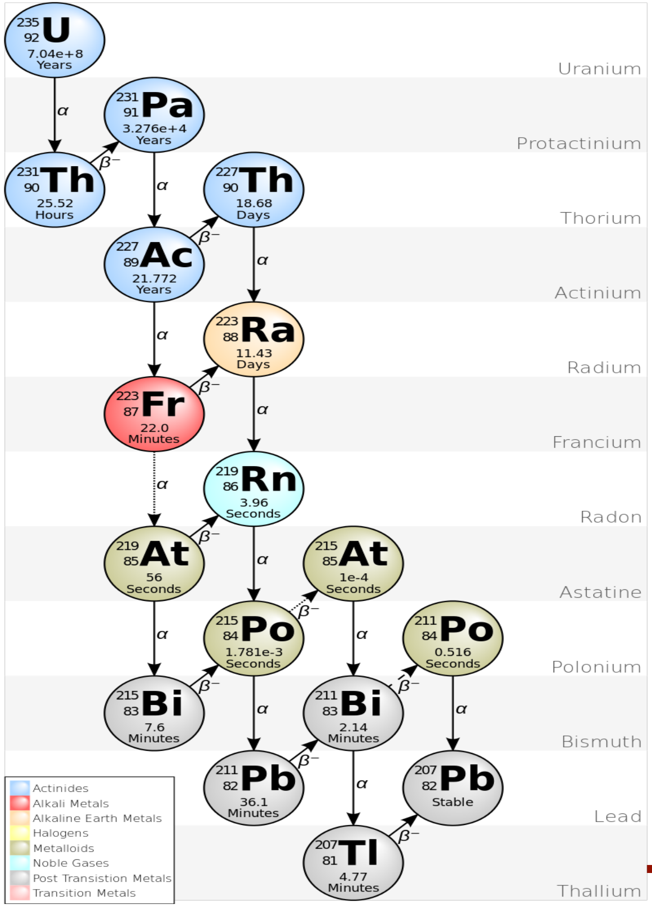
- ^{226}Ra: $T_{1/2}$ short enough to have sizeable activity, short enough to neglect its decreases in time
- ^{222}Rn ($T_{1/2}$ = 3.82 d): radioactive gas (the only natural radioactive gas at room temperature); important for the environment
- From the decay of ^{222}Rn, the ^{210}Pb is produced, it is heavy and can deposit on surface and has a long half life
- Terminate with Stable Lead Element

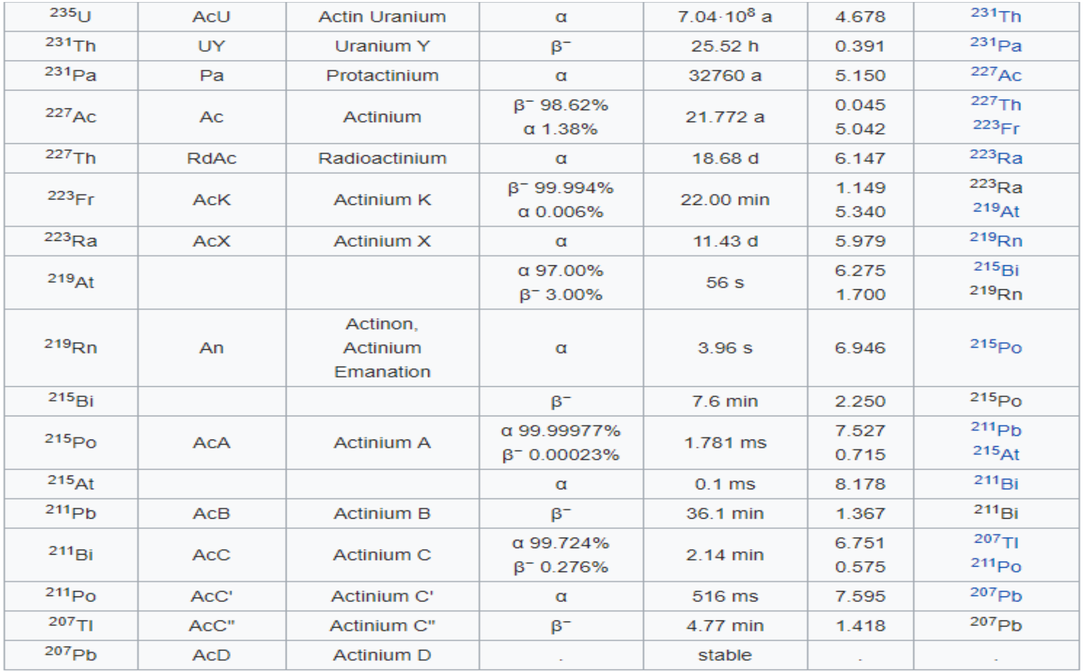
^{235}U decay chain

actinium series

$4n + 3$; $n = 58, 57, 56 \ldots, 51$

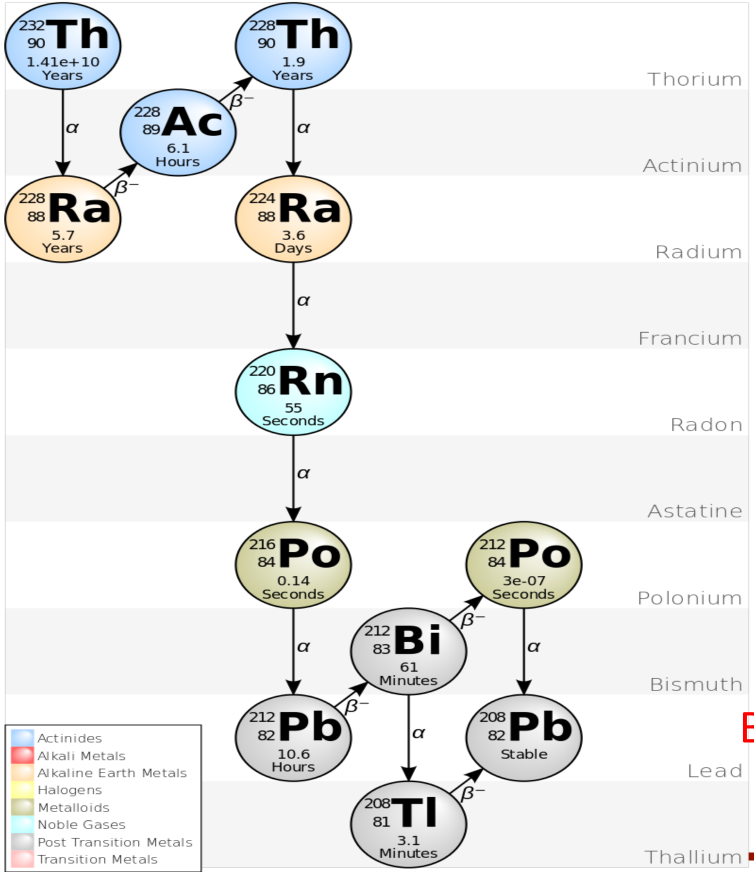
Terminate with Stable Lead Element





^{235}U	AcU	Actin Uranium	α	7.04·10^{8} a	4.678	^{231}Th
^{231}Th	UY	Uranium Y	β⁻	25.52 h	0.391	^{231}Pa
^{231}Pa	Pa	Protactinium	α	32760 a	5.150	^{227}Ac
^{227}Ac	Ac	Actinium	β⁻ 98.62% α 1.38%	21.772 a	0.045 5.042	^{227}Th ^{223}Fr
^{227}Th	RdAc	Radioactinium	α	18.68 d	6.147	^{223}Ra
^{223}Fr	AcK	Actinium K	β⁻ 99.994% α 0.006%	22.00 min	1.149 5.340	^{223}Ra ^{219}At
^{223}Ra	AcX	Actinium X	α	11.43 d	5.979	^{219}Rn
^{219}At			α 97.00% β⁻ 3.00%	56 s	6.275 1.700	^{215}Bi ^{219}Rn
^{219}Rn	An	Actinon, Actinium Emanation	α	3.96 s	6.946	^{215}Po
^{215}Bi			β⁻	7.6 min	2.250	^{215}Po
^{215}Po	AcA	Actinium A	α 99.99977% β⁻ 0.00023%	1.781 ms	7.527 0.715	^{211}Pb ^{215}At
^{215}At			α	0.1 ms	8.178	^{211}Bi
^{211}Pb	AcB	Actinium B	β⁻	36.1 min	1.367	^{211}Bi
^{211}Bi	AcC	Actinium C	α 99.724% β⁻ 0.276%	2.14 min	6.751 0.575	^{207}Tl ^{211}Po
^{211}Po	AcC'	Actinium C'	α	516 ms	7.595	^{207}Pb
^{207}Tl	AcC"	Actinium C"	β⁻	4.77 min	1.418	^{207}Pb
^{207}Pb	AcD	Actinium D	.	stable	.	.

^{232}Th decay chain



4n; n=58, 57, 56 ..., 52

- 28 Th Isotopes A = (210 -237)
- Most abundant radioactive natural element in the crust (3 times Uranium)
- It is a metal, ductile and malleable
- It is a fertile nucleus, bombarding with neutrons it can give ^{233}U that is fissile

BiPo event

$$^{212}\mathrm{Bi} \xrightarrow{\overset{\beta^-}{(64.1\%)}} {}^{212}\mathrm{Po} \xrightarrow{\overset{\alpha}{(100\%)}} {}^{208}\mathrm{Pb}$$

E_m=2.25 MeV
T1/2 = 60.6 m

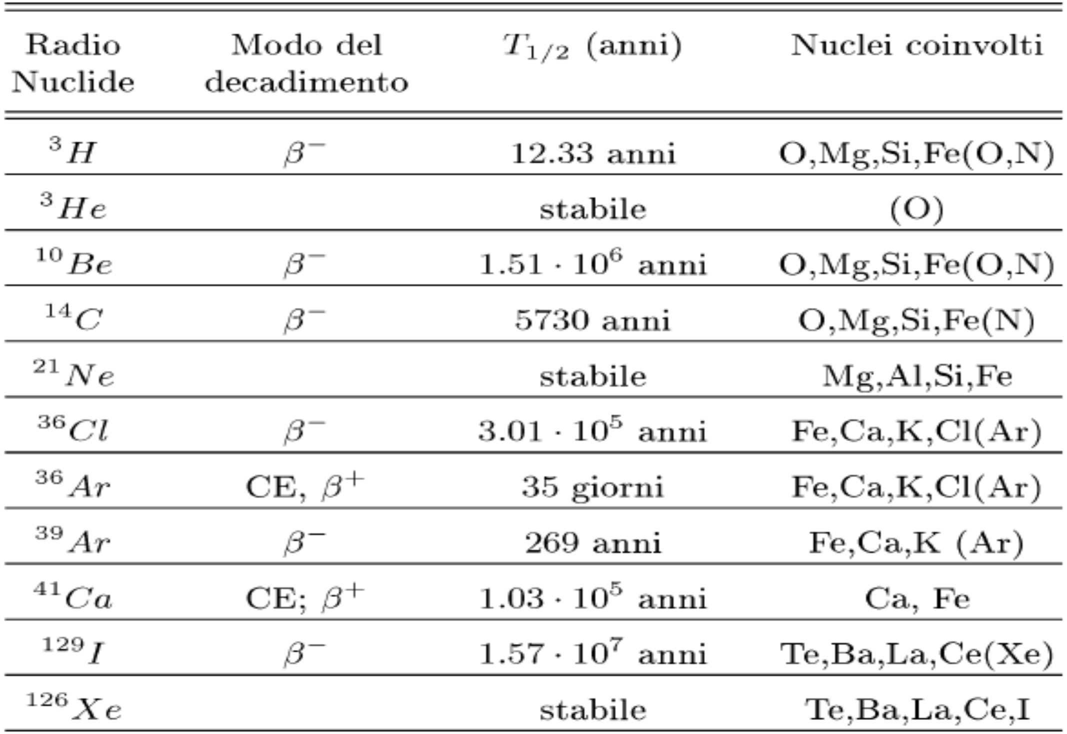
E=8.8 MeV
$T_{1/2}$ =299 ns

Cosmogenic Nuclei

- The Earth surface is bombarded by particles (p, n, γ, e^+, e^-, ν, ...) coming from the space and from the high atmosphere
- Primary cosmic rays are particles produced in different sources in the Universe travelling in the space
- When a cosmic ray reach the Earth , it can interact with nuclei of the atmosphere producing particles and/or cascade reaching the Earth surface
- Radioactive nuclei can be produced by the interaction of primary or secondary cosmic rays with the nuclei of the Earth
- These radioactive nuclei are called cosmogenic

Cosmogenic Nuclei

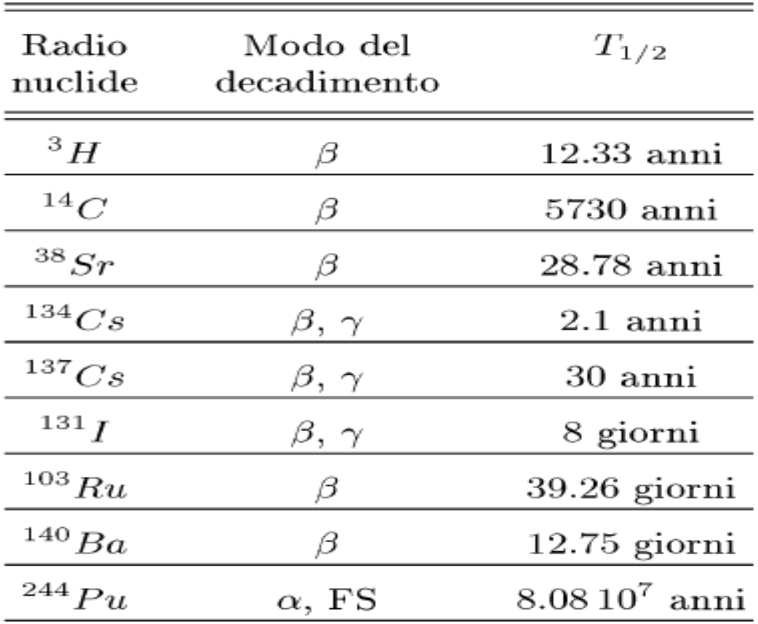
Most important



Radio Nuclide	Modo del decadimento	$T_{1/2}$ (anni)	Nuclei coinvolti
^{3}H	β^-	12.33 anni	O,Mg,Si,Fe(O,N)
^{3}He		stabile	(O)
^{10}Be	β^-	$1.51 \cdot 10^6$ anni	O,Mg,Si,Fe(O,N)
^{14}C	β^-	5730 anni	O,Mg,Si,Fe(N)
^{21}Ne		stabile	Mg,Al,Si,Fe
^{36}Cl	β^-	$3.01 \cdot 10^5$ anni	Fe,Ca,K,Cl(Ar)
^{36}Ar	CE, β^+	35 giorni	Fe,Ca,K,Cl(Ar)
^{39}Ar	β^-	269 anni	Fe,Ca,K (Ar)
^{41}Ca	CE; β^+	$1.03 \cdot 10^5$ anni	Ca, Fe
^{129}I	β^-	$1.57 \cdot 10^7$ anni	Te,Ba,La,Ce(Xe)
^{126}Xe		stabile	Te,Ba,La,Ce,I

Artificial Radionuclides

- Can be produced:
  - Fission processes in reactors (A= 70-160)
  - Nuclear explosion
  - Collision at accelerators
- They are source of α, β, ν, γ, e+, e-
- Present in the environment in very low concentration; can be released in accident or nuclear explosion
- Some of them are also cosmogenic
- Iodine, Cesium, Rubidium and Barium product of nuclear explosion (Chernobyl 1985)

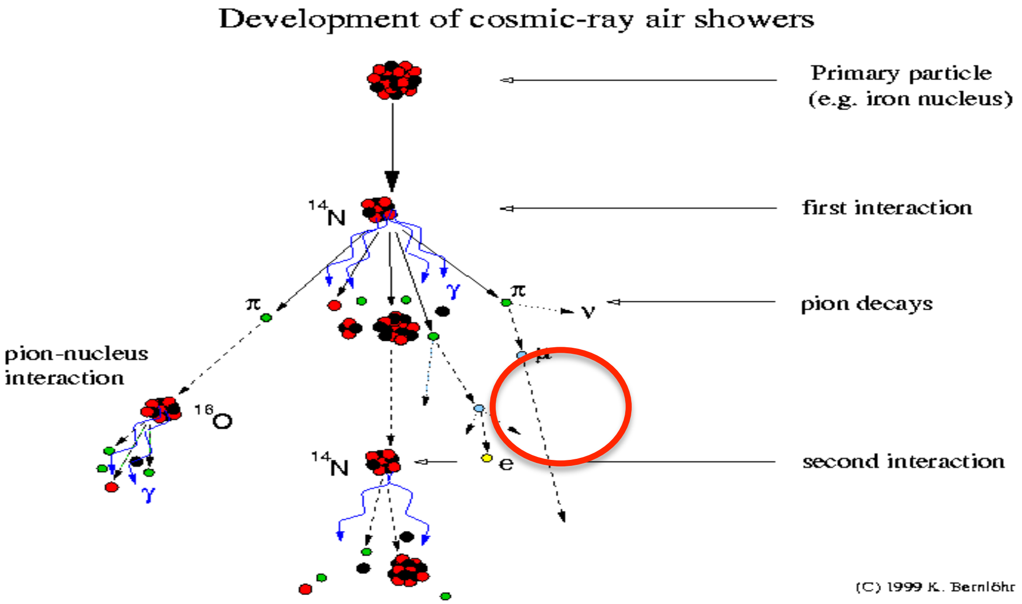


Radio nuclide	Modo del decadimento	$T_{1/2}$
^{3}H	β	12.33 anni
^{14}C	β	5730 anni
^{38}Sr	β	28.78 anni
^{134}Cs	β, γ	2.1 anni
^{137}Cs	β, γ	30 anni
^{131}I	β, γ	8 giorni
^{103}Ru	β	39.26 giorni
^{140}Ba	β	12.75 giorni
^{244}Pu	α, FS	$8.08\,10^{7}$ anni

Cosmic Rays

- Discovered in 1912 by Victor Hess with a balloon experiment
- The Earth surface is bombarded by high energy particles (p, n, γ, e^+, e^-, ν, ...) coming from the space and from the high atmosphere
- **Primary** cosmic rays are particles produced in astrophysical sources in the Universe travelling in the space (e^-, p, He, C, O, Fe, nuclei synthesized in stars)
- **Secondary** cosmic rays are particles produced in the interaction of primary cosmic ray with interstellar medium (Li, Be, B, …)
- When a cosmic ray reach the Earth , it can interact with nuclei of the atmosphere producing secondary particles and/or cascade reaching the Earth surface and, eventually, penetrating the Earth crust
- Cosmic ray are influenced by the solar wind and when they enter in the Earth atmosphere are subjected to the terrestrial magnetic field that can deflect them
- Primary cosmic ray can be produced in the Galaxy or by extra-galactic sources
- The origin of cosmic rays (in particular very high energy cosmic rays) is not fully understand

Cosmic Rays



- p and e^- near the top of atmosphere are primary
- Other particles produced in the interaction of primary with air
- μ and ν produced in the decay chain of charged mesons (π)
- e^- and γ produced in the decay of neutral mesons

$\pi^- \to (e)\mu^- + \text{anti}(\nu)$
$\pi^+ \to \mu^+ + \nu_\mu$
$\pi^0 \to 2\,\gamma$

$\mu^+ \to e^+ + \nu_e$
$\mu^- \to e^- + \text{anti}(\nu_e)$

$T_{1/2}(\mu) = 2.2 \times 10^{-6}$ s