

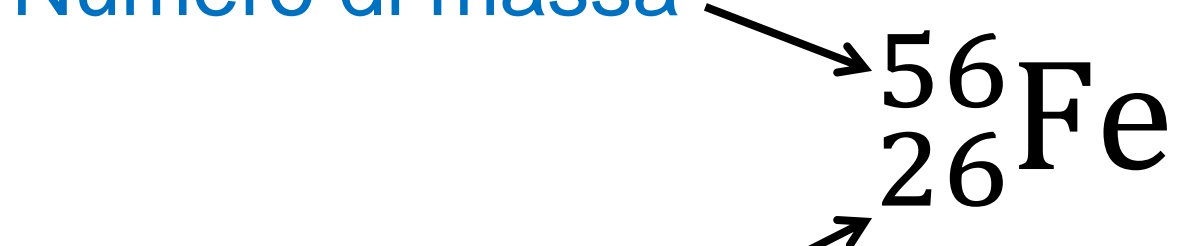
Massa del protone \approx massa del neutrone
 $= 1.672 \times 10^{-27}$ kg
 ≈ 1836 volte la massa dell'elettrone

Carica dell'elettrone $= 1,602 \times 10^{-19}$ C

Protone: 2 quark up ($2 \times +2/3$) + 1 quark down ($-1/3$)

Neutrone: 1 quark up ($+2/3$) + 2 quark down ($2 \times -1/3$)

Numero di massa



Numero atomico

Energia di legame nucleare

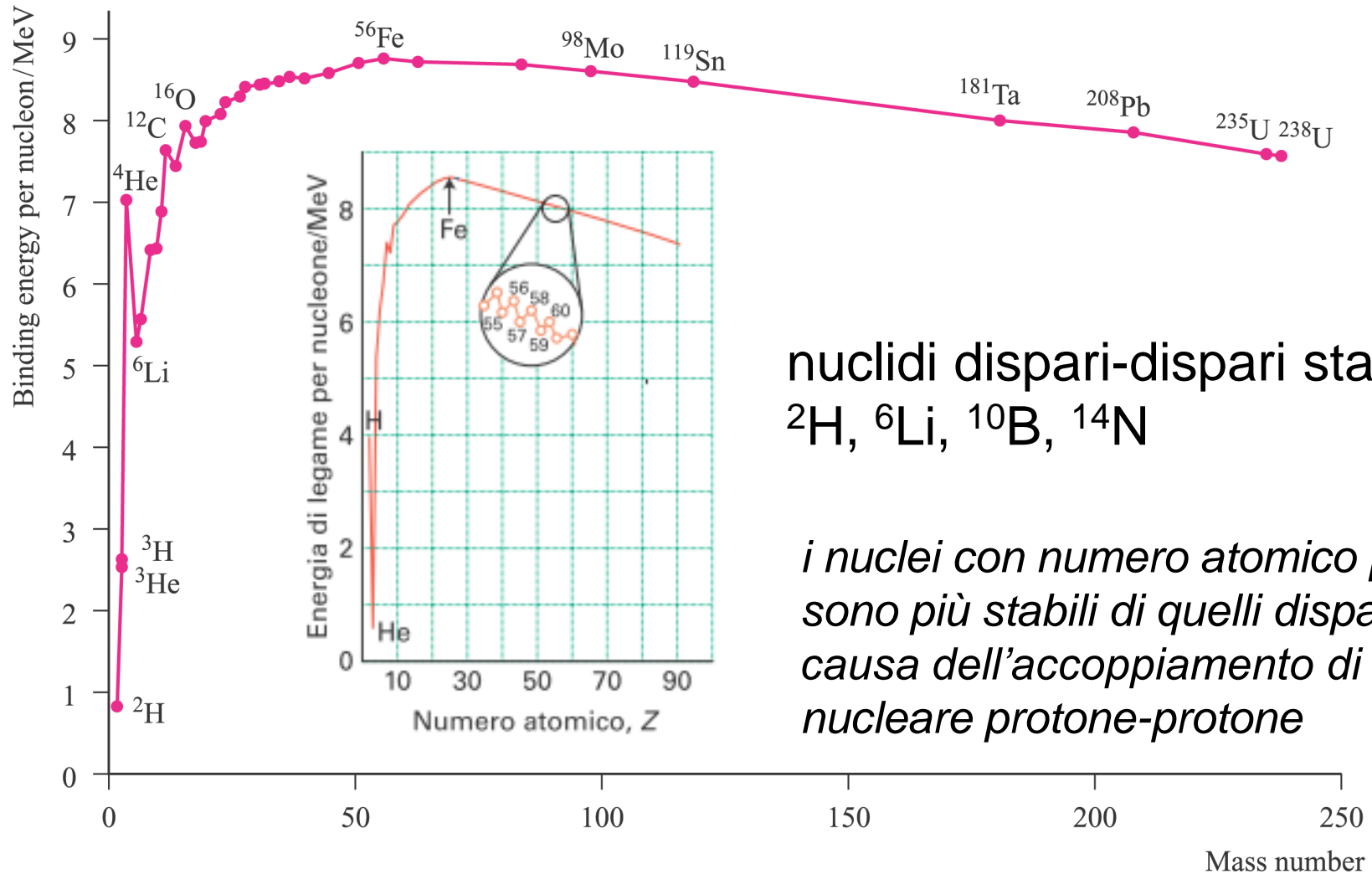
$$\Delta E = \Delta mc^2$$

$$c = 2.998 \times 10^8 \text{ m s}^{-1}$$

1 mole ${}^7\text{Li}$: $3.79 \times 10^9 \text{ kJ}$

1 mole butano (combustione): 2857 kJ

Energia per nucleone



nuclidi dispari-dispari stabili:
 ${}^2_1\text{H}$, ${}^6_3\text{Li}$, ${}^{10}_5\text{B}$, ${}^{14}_7\text{N}$

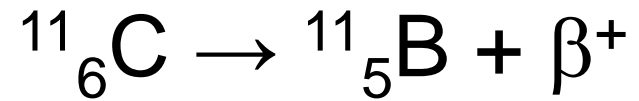
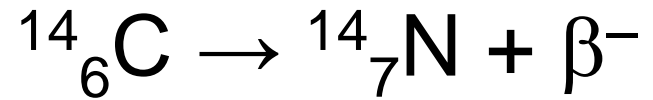
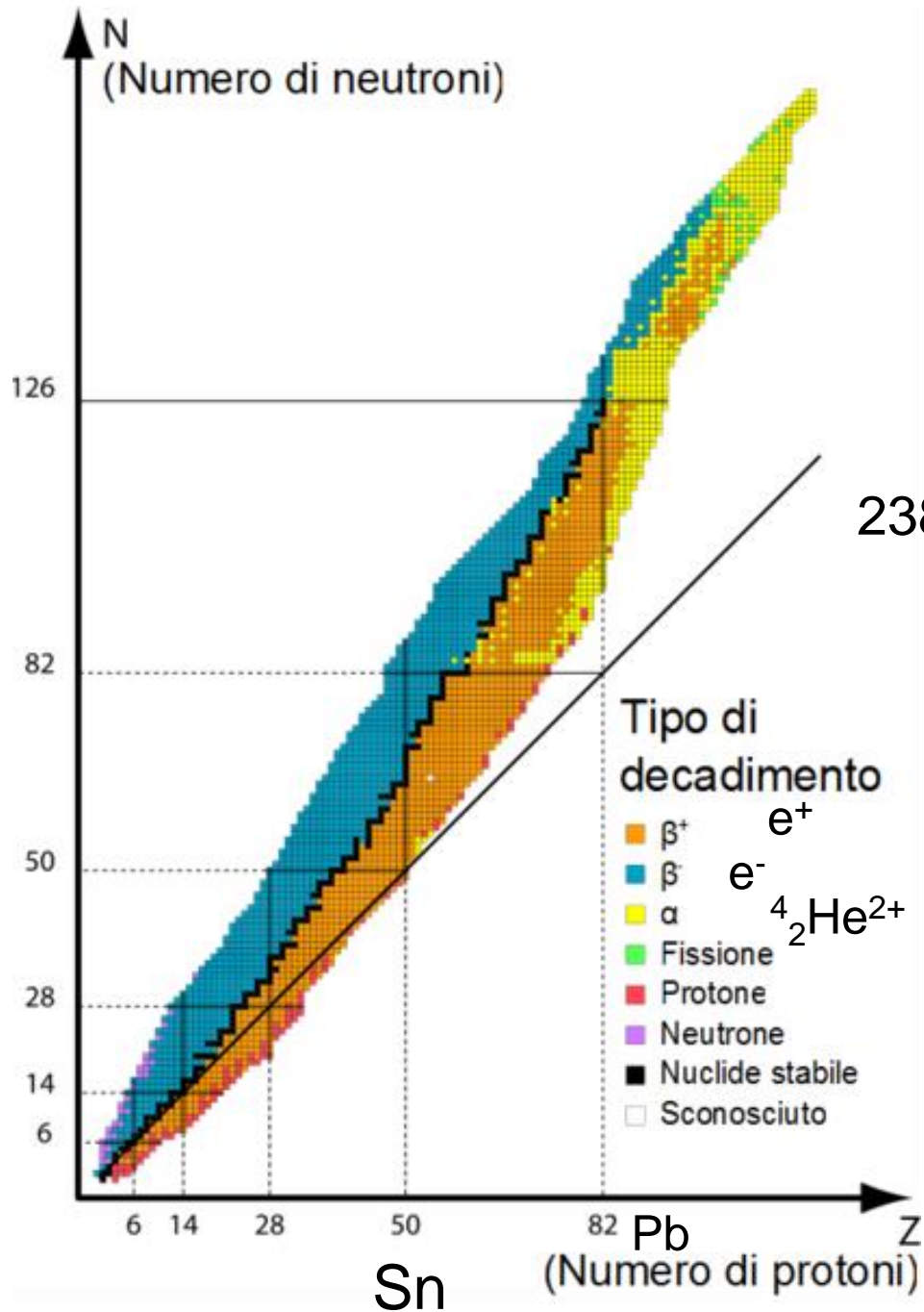
i nuclei con numero atomico pari sono più stabili di quelli dispari a causa dell'accoppiamento di spin nucleare protone-protone

Numeri magici (di nucleoni): 2, 6, 8, 20, 28, 50, 82, 126

Nuclei doppiamente magici: ${}^4_2\text{He}$, ${}^{16}_8\text{O}$, ${}^{40}_{20}\text{Ca}$, ${}^{208}_{82}\text{Pb}$

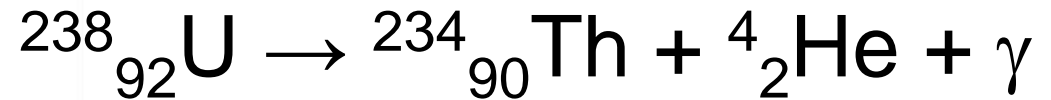
Processi spontanei nei nuclei radioattivi

- Emissione di particelle (α , β^- , β^+)
- Cattura di elettroni
- Emissione di radiazioni (raggi X, γ)
- Fissione



$$\Delta E > 1.022 \text{ MeV}$$

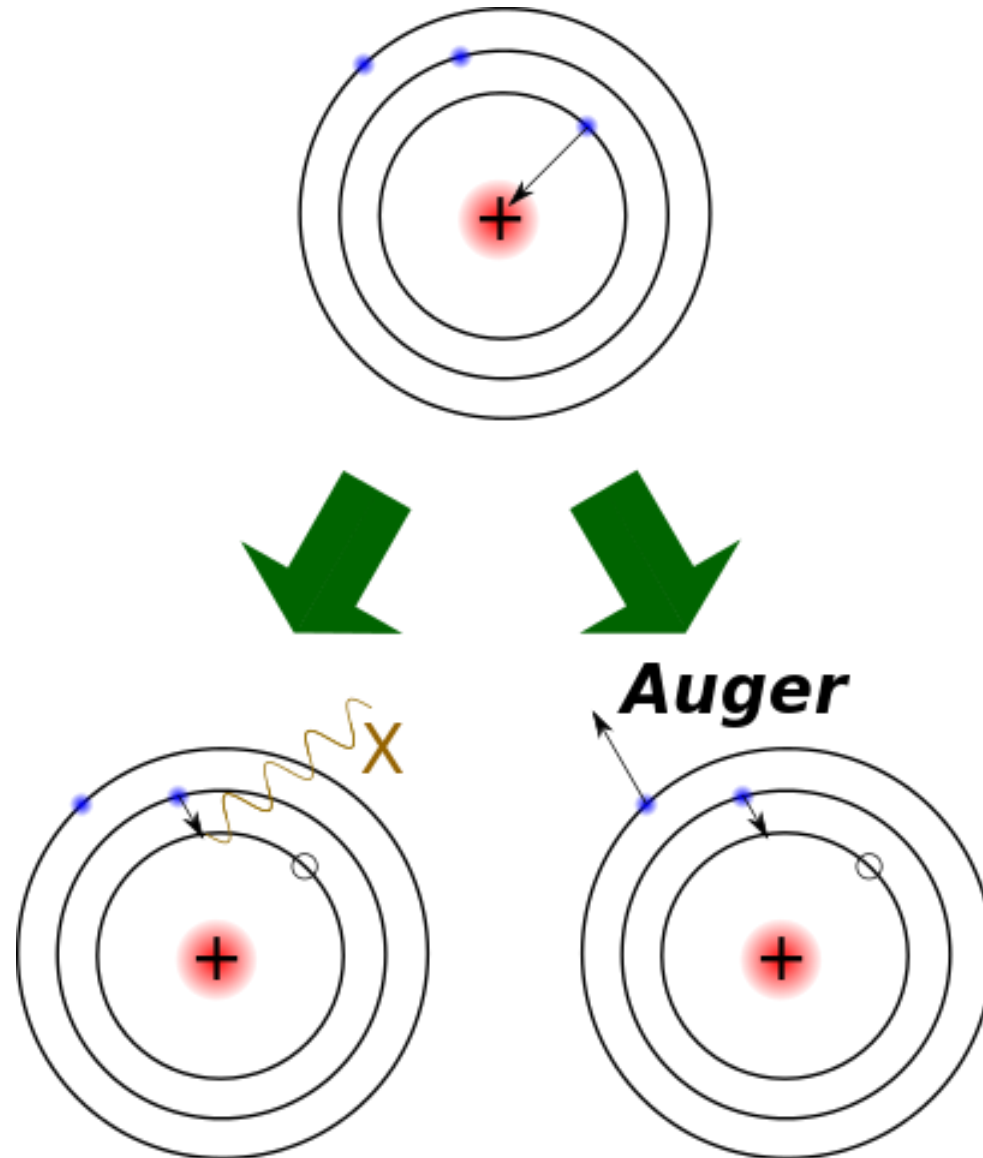
se $\Delta E < 1.022 \text{ MeV} \rightarrow \text{EC}$



Live Chart of Nuclides

<https://www-nds.iaea.org/relnsd/vcharthtml/VChartHTML.html>

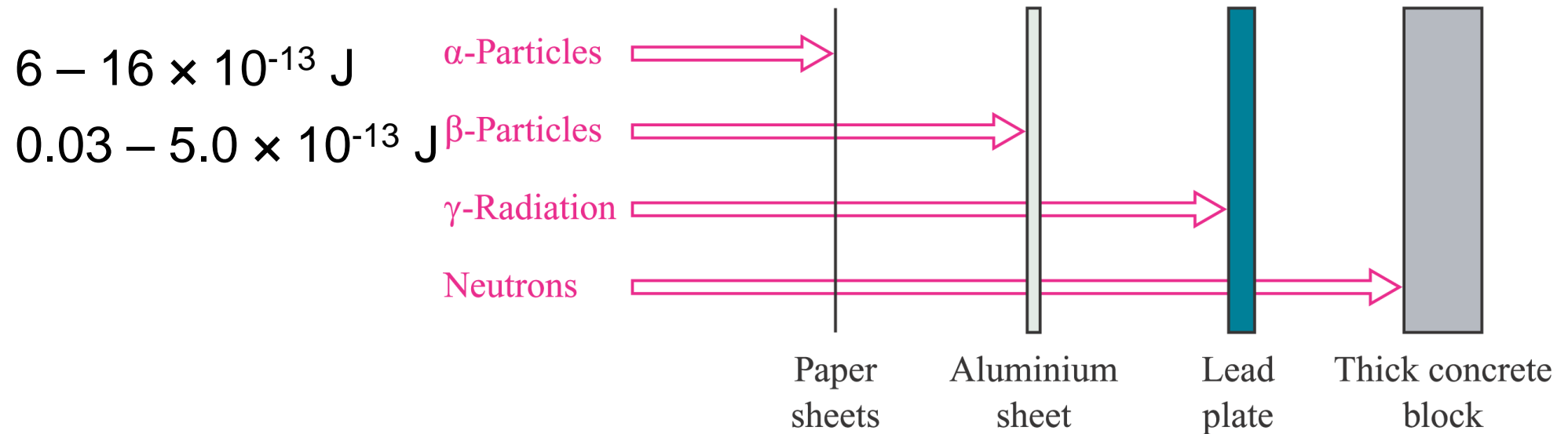
Electron capture (EC)



unità di misura della radioattività

1 becquerel (Bq) = una disintegrazione nucleare per secondo (SI)

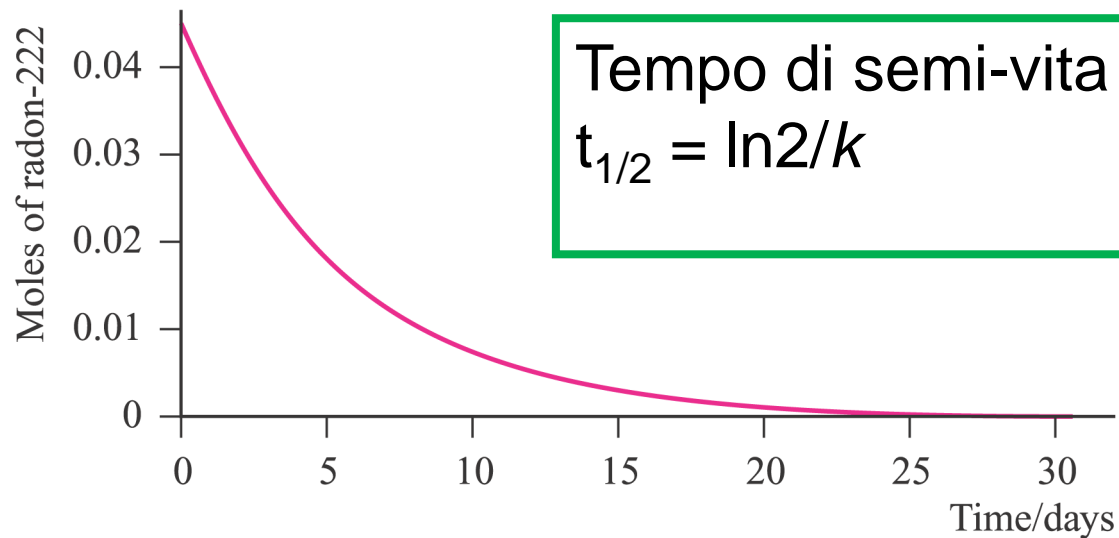
1 Ci (Curie) = 3.7×10^{10} Bq



^{210}Po , emettitore α , caso *Litvinenko* 2006

Decadimento radioattivo del primo ordine di ^{222}Rn

$$N/N_0 = e^{-kt}$$



$$\ln N - \ln N_0 = -kt$$

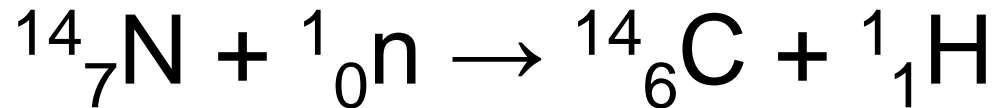
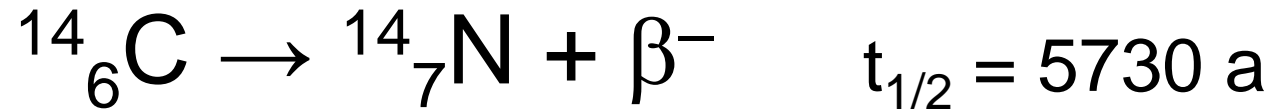
$$\ln N/2 - \ln N = -kt_{1/2}$$

$$\ln 2 = kt_{1/2}$$

$$t_{1/2} = \ln 2/k$$

Datazione con il carbonio-14

(W. F. Libby, Nobel 1960)

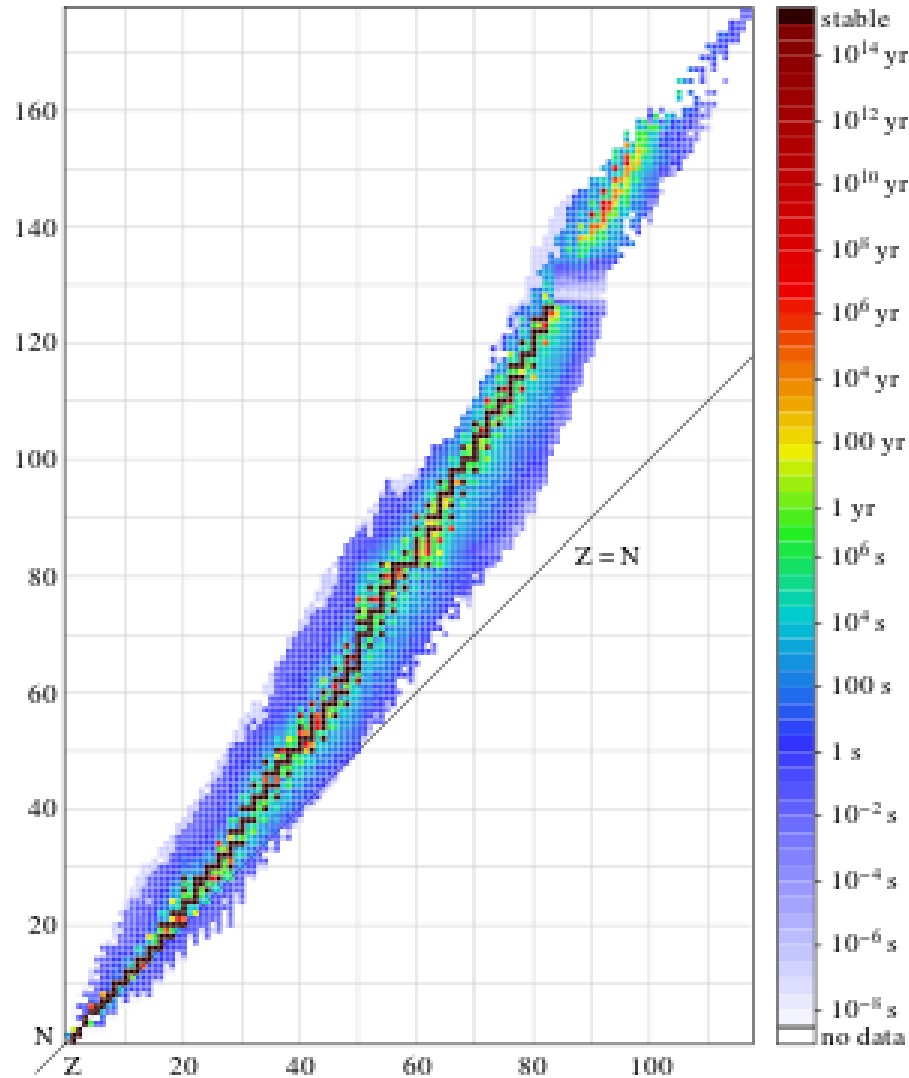


Radiazioni cosmiche

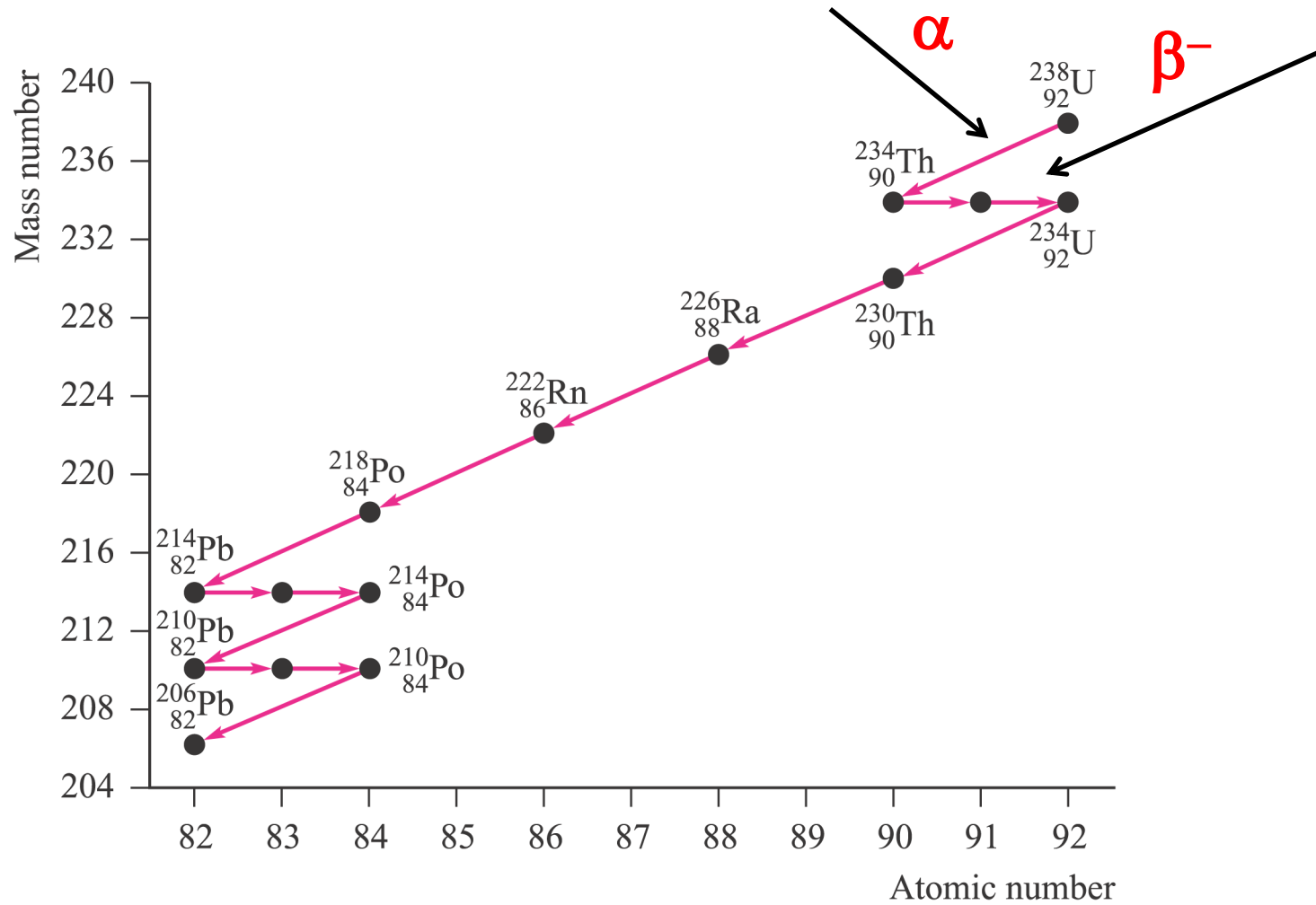


Datazione di un manufatto in base alla misura del rapporto ${}^{14}\text{C}:{}^{12}\text{C}$

Emivite degli isotopi



Decadimento in serie



Nuclide	Symbol	Particle emitted	Half-life
Uranium-238	${}_{92}^{238}\text{U}$	α	4.5×10^9 yr
Thorium-234	${}_{90}^{234}\text{Th}$	β^-	24.1 d
Protactinium-234	${}_{91}^{234}\text{Pa}$	β^-	1.18 min
Uranium-234	${}_{92}^{234}\text{U}$	α	2.48×10^5 yr
Thorium-230	${}_{90}^{230}\text{Th}$	α	8.0×10^4 yr
Radium-226	${}_{88}^{226}\text{Ra}$	α	1.62×10^3 yr
Radon-222	${}_{86}^{222}\text{Rn}$	α	3.82 d
Polonium-218	${}_{84}^{218}\text{Po}$	α	3.05 min
Lead-214	${}_{82}^{214}\text{Pb}$	β^-	26.8 min
Bismuth-214	${}_{83}^{214}\text{Bi}$	β^-	19.7 min
Polonium-214	${}_{84}^{214}\text{Po}$	α	1.6×10^{-4} s
Lead-210	${}_{82}^{210}\text{Pb}$	β^-	19.4 yr
Bismuth-210	${}_{83}^{210}\text{Bi}$	β^-	5.0 d
Polonium-210	${}_{84}^{210}\text{Po}$	α	138 d
Lead-206	${}_{82}^{206}\text{Pb}$	None	Non-radioactive

Tavola periodica con gli elementi colorati secondo l'emivita del loro isotopo più stabile

		Group																		
		I	II											III	IV	V	VI	VII	VIII	
1		1 H																		2 He
2		3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne	
3		11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar	
4		19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr	
5		37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe	
6		55 Cs	56 Ba	*	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn	
7		87 Fr	88 Ra	**	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo	
* Lanthanides		57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu				
** Actinides		89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr				




-  Elementi stabili
-  Elementi radioattivi con isotopi di emivita > 4 milioni di anni. Radioattività molto piccola, se non trascurabile
-  Elementi radioattivi che possono presentare bassi rischi per la salute. I loro isotopi più stabili hanno emivite tra 800 e 34 000 anni.

Tavola periodica con il numero degli isotopi stabili

1 H 1																	2 He 2																												
3 Li 3	4 Be 2																	5 B 5	6 C 2	7 N 2	8 O 3	9 F 1	10 Ne 2																						
11 Na 1	12 Mg 3																	13 Al 1	14 Si 3	15 P 1	16 S 4	17 Cl 2	18 Ar 4																						
19 K 2	20 Ca 4	21 Sc 0	22 Ti 2	23 V 1	24 Cr 3	25 Mn 1	26 Fe 4	27 Co 1	28 Ni 2	29 Cu 2	30 Zn 4	31 Ga 1	32 Ge 2	33 As 1	34 Se 2	35 Br 2	36 Kr 4																												
37 Rb 1	38 Sr 2	39 Y 0	40 Zr 2	41 Nb 1	42 Mo 3	43 Tc 0	44 Ru 2	45 Rh 1	46 Pd 2	47 Ag 1	48 Cd 2	49 In 1	50 Sn 4	51 Sb 1	52 Te 2	53 I 1	54 Xe 4																												
55 Cs 1	56 Ba 2	57 La 0	72 Hf 2	73 Ta 1	74 W 3	75 Re 1	76 Os 2	77 Ir 1	78 Pt 2	79 Au 1	80 Hg 2	81 Tl 1	82 Pb 4	83 Bi 1	84 Po 0	85 At 0	86 Rn 4																												
87 Fr 0	88 Ra 0	89-90 Ac 0	91-92 Th 0	93-94 Pa 0	95-96 U 0	97-98 Np 0	99-100 Pu 0	101-102 Am 0	103-104 Cm 0	105-106 Bk 0	107-108 Cf 0	109-110 Es 0	111-112 Fm 0	113-114 Md 0	115-116 No 0	117-118 Lr 0																													
<table border="1"> <tr> <td>58 Ce 2</td> <td>59 Pr 1</td> <td>60 Nd 2</td> <td>61 Pm 0</td> <td>62 Sm 2</td> <td>63 Eu 1</td> <td>64 Gd 2</td> <td>65 Tb 1</td> <td>66 Dy 2</td> <td>67 Ho 1</td> <td>68 Er 2</td> <td>69 Tm 1</td> <td>70 Yb 2</td> <td>71 Lu 1</td> </tr> <tr> <td>90 Th 0</td> <td>91 Pa 0</td> <td>92 U 0</td> <td>93 Np 0</td> <td>94 Pu 0</td> <td>95 Am 0</td> <td>96 Cm 0</td> <td>97 Bk 0</td> <td>98 Cf 0</td> <td>99 Es 0</td> <td>100 Fm 0</td> <td>101 Md 0</td> <td>102 No 0</td> <td>103 Lr 0</td> </tr> </table>																		58 Ce 2	59 Pr 1	60 Nd 2	61 Pm 0	62 Sm 2	63 Eu 1	64 Gd 2	65 Tb 1	66 Dy 2	67 Ho 1	68 Er 2	69 Tm 1	70 Yb 2	71 Lu 1	90 Th 0	91 Pa 0	92 U 0	93 Np 0	94 Pu 0	95 Am 0	96 Cm 0	97 Bk 0	98 Cf 0	99 Es 0	100 Fm 0	101 Md 0	102 No 0	103 Lr 0
58 Ce 2	59 Pr 1	60 Nd 2	61 Pm 0	62 Sm 2	63 Eu 1	64 Gd 2	65 Tb 1	66 Dy 2	67 Ho 1	68 Er 2	69 Tm 1	70 Yb 2	71 Lu 1																																
90 Th 0	91 Pa 0	92 U 0	93 Np 0	94 Pu 0	95 Am 0	96 Cm 0	97 Bk 0	98 Cf 0	99 Es 0	100 Fm 0	101 Md 0	102 No 0	103 Lr 0																																

339 nuclidi in natura sulla terra

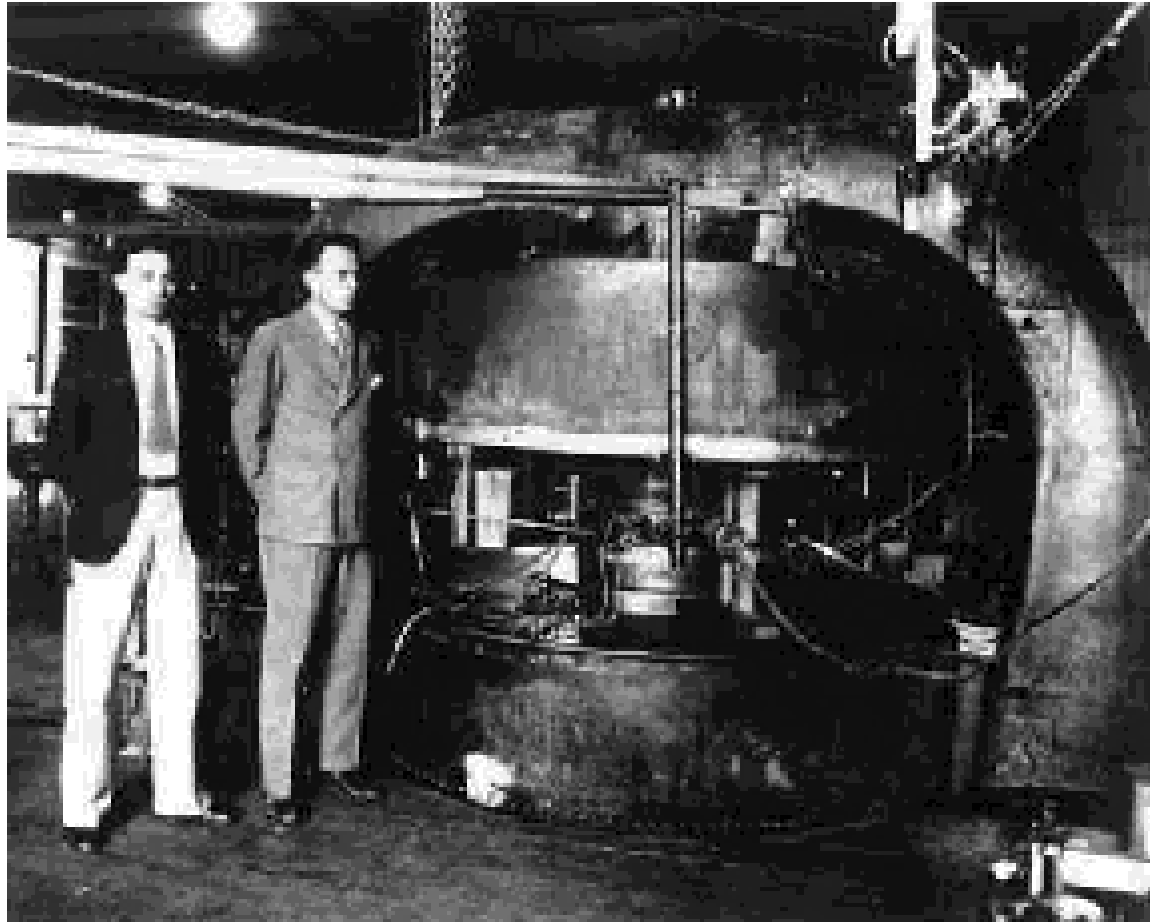
di cui:

- 255 nuclidi stabili
- 33 nuclidi radioattivi primordiali ($t_{1/2} > 80$ Ma)
- 51 nuclidi radioattivi ($t_{1/2} < 80$ Ma) figli o cosmogenici

255+33 = 288 nuclidi primordiali

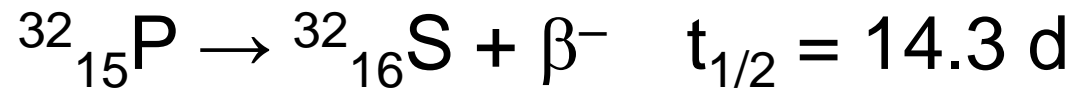
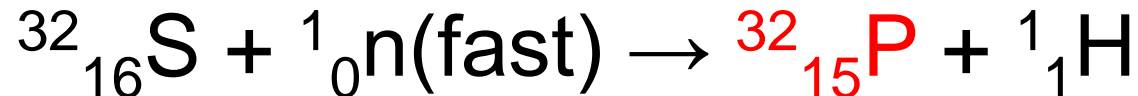
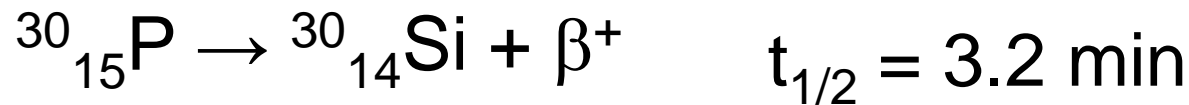
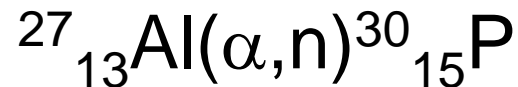
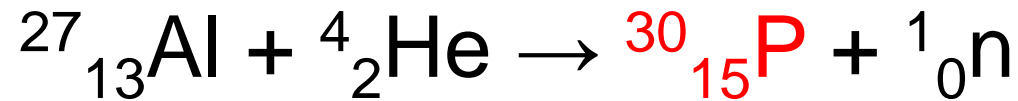
26 elementi con 1 solo nuclide stabile (25 con Z dispari)

Il primo ciclotrone (Ciclotrone Lawrence, 1931) Acceleratore di particelle cariche



Isotopi artificiali

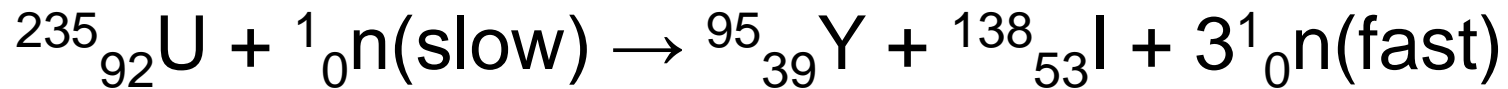
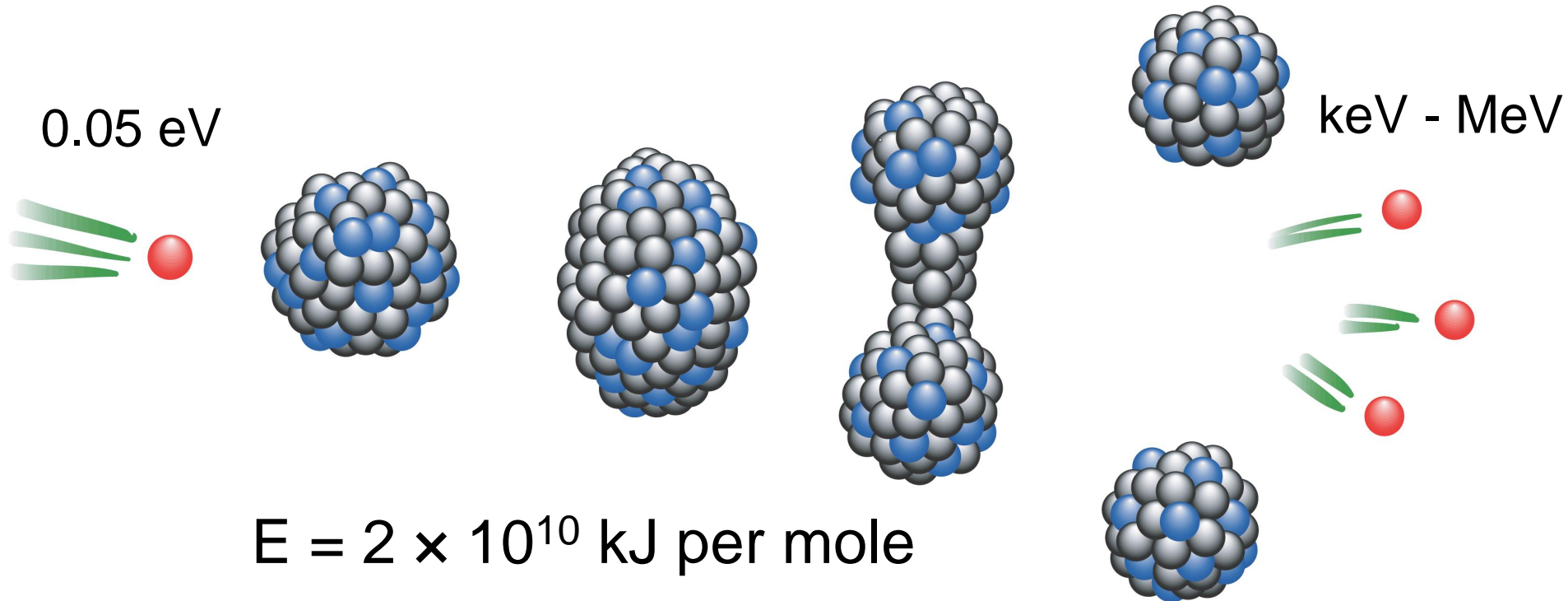
Le reazioni nucleari avvengono con la **conservazione del numero atomico e del numero di massa**



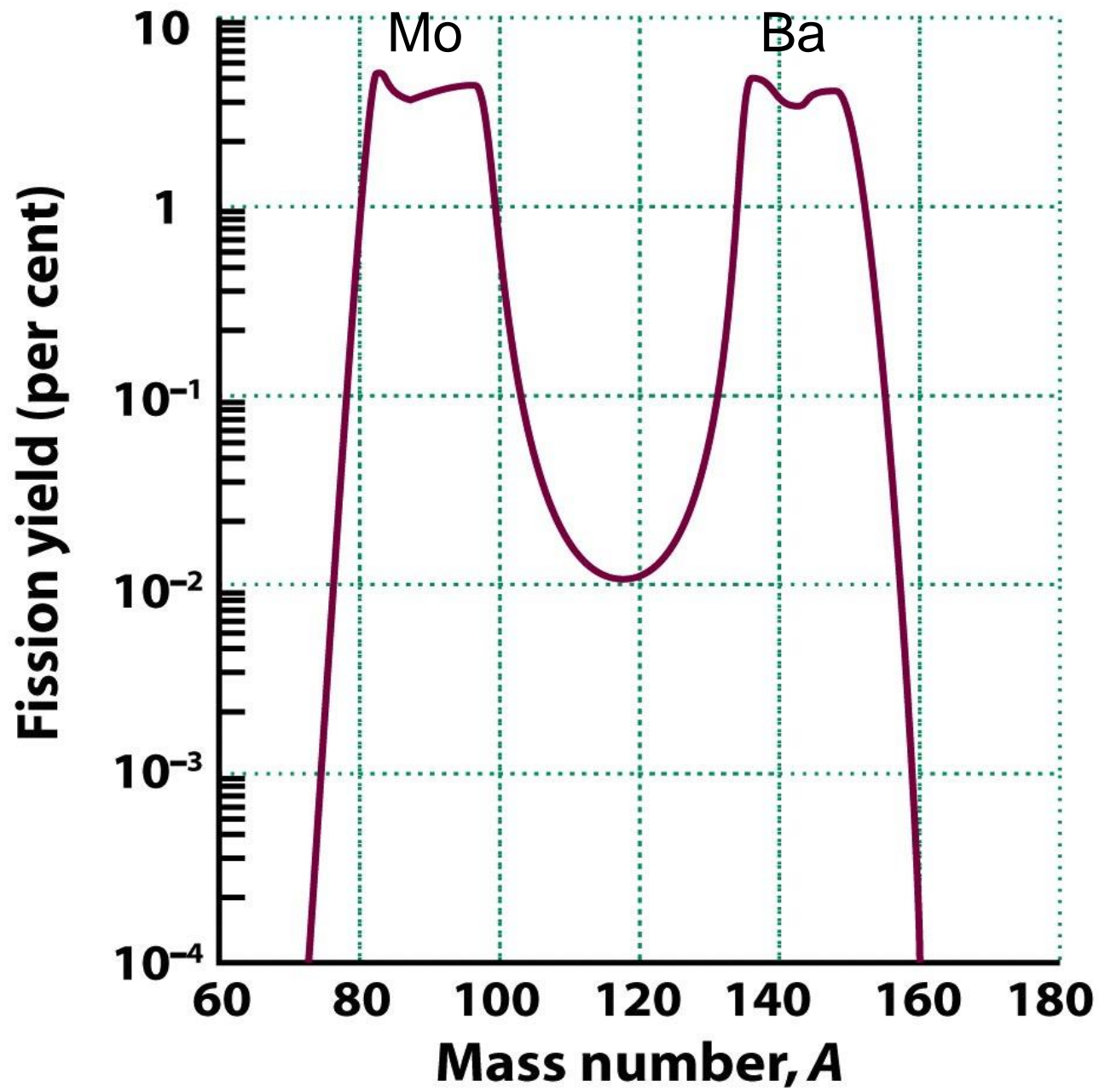
Reazione (n,γ)

Reazione (n,γ)

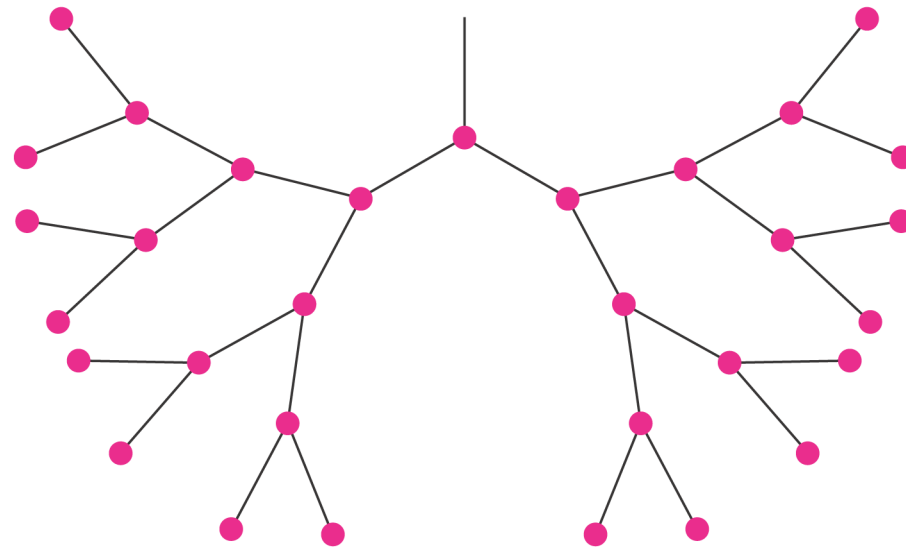
Bombardamento di un nucleo di ^{235}U con neutroni termici



^{235}U = ca. 0.72% dell'uranio naturale



Reazione a catena



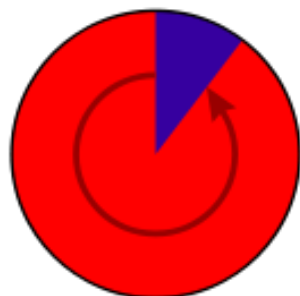
- Grafite o D_2O per rallentare i neutroni
- Acciaio al boro, carburo di boro o carburo di cadmio per catturare i neutroni (B e Cd hanno alte sezioni d'urto per la cattura)



Natural uranium
> 99.2% U-238
0.72% U-235

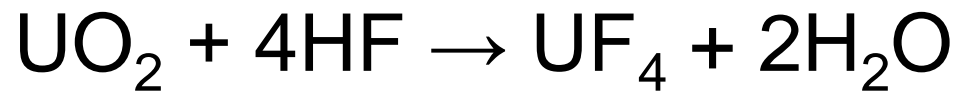
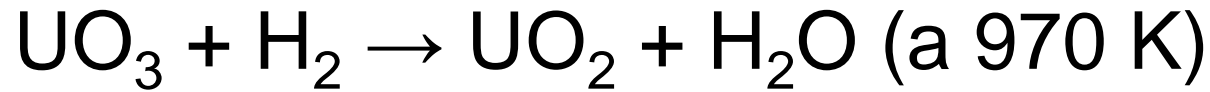


Low-enriched uranium
(reactor grade)
3-4% U-235

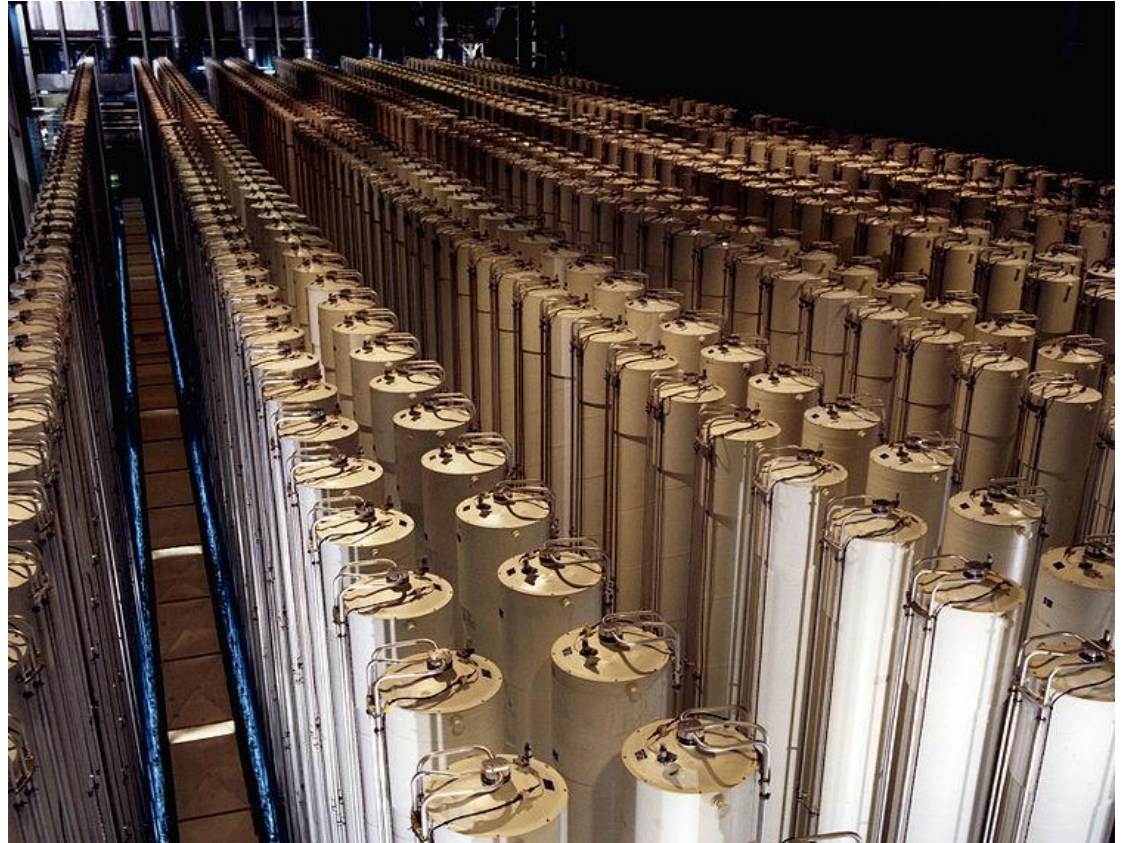


Highly enriched uranium
(weapons grade)
90% U-235

Trasformazione dell'uranile in UF₆



Centrifughe per la separazione della miscela di ²³⁵UF₆ e ²³⁸UF₆ sfruttando la legge di Graham



Radiopharmaceuticals

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graph TD; A([Radiopharmaceuticals]) --> B([Radiodiagnostics]); A --> C([Radiotherapeutics]);
```

Radiodiagnostics

γ -emitters (SPECT)
positron-emitters (β^+) (PET)
 $10^{-6} - 10^{-8}$ M

Radiotherapeutics

α or β^- emitters

Isotopes suitable for nuclear imaging

1 H Hydrogen		<div style="display: flex; justify-content: space-between; align-items: center;"> <div style="writing-mode: vertical-rl; transform: rotate(180deg);">Short Half-Life</div> <div style="background-color: #0070C0; color: white; padding: 5px; border: 1px solid black;">PET Isotopes</div> <div style="writing-mode: vertical-rl; transform: rotate(180deg);">Long Half-Life</div> </div> <div style="display: flex; justify-content: space-between; align-items: center; margin-top: 5px;"> <div style="background-color: #C00000; color: white; padding: 5px; border: 1px solid black;">SPECT Isotopes</div> </div>																2 He Helium					
3 Li Lithium	4 Be Beryllium																	5 B Boron	6 C Carbon	7 N Nitrogen	8 O Oxygen	9 F Fluorine	10 Ne Neon
11 Na Sodium	12 Mg Magnesium																	13 Al Aluminum	14 Si Silicon	15 P Phosphorus	16 S Sulfur	17 Cl Chlorine	18 Ar Argon
19 K Potassium	20 Ca Calcium	21 Sc Scandium	22 Ti Titanium	23 V Vanadium	24 Cr Chromium	25 Mn Manganese	26 Fe Iron	27 Co Cobalt	28 Ni Nickel	29 Cu Copper	30 Zn Zinc	31 Ga Gallium	32 Ge Germanium	33 As Arsenic	34 Se Selenium	35 Br Bromine	36 Kr Krypton						
37 Rb Rubidium	38 Sr Strontium	39 Y Yttrium	40 Zr Zirconium	41 Nb Niobium	42 Mo Molybdenum	43 Tc Technetium	44 Ru Ruthenium	45 Rh* Rhodium	46 Pd Palladium	47 Ag Silver	48 Cd Cadmium	49 In Indium	50 Sn Tin	51 Sb Antimony	52 Te Tellurium	53 I Iodine	54 Xe Xenon						
55 Cs Cesium	56 Ba Barium	57-70 Lanthanides	71 Lu* Lutetium	72 Hf Hafnium	73 Ta Tantalum	74 W Tungsten	75 Re* Rhenium	76 Os Osmium	77 Ir Iridium	78 Pt Platinum	79 Au Gold	80 Hg Mercury	81 Tl Thallium	82 Pb Lead	83 Bi Bismuth	84 Po Polonium	85 At Astatine	86 Rn Radon					
87 Fr Francium	88 Ra Radium	89-102 Actinides	103 Lr Lawrencium	104 Rf Rutherfordium	105 Db Dubnium	106 Sg Seaborgium	107 Bh Bohrium	108 Hs Hassium	109 Mt Meitnerium	110 Ds Darmstadtium	111 Rg Roentgenium	112 Cn Copernicium	113 Uut Ununtrium	114 Fl Flerovium	115 Uup Ununpentium	116 Lv Livermorium	117 Uus Ununseptium	118 Uuo Ununoctium					

E
Element

Denotes an element
with isotopes suitable for
both PET and SPECT

E
Element

Denotes an element
with multiple isotopes with
different physical half-lives

*Isotopes typically used for radiotherapy with which SPECT is also possible but not common — e.g., ¹⁷⁷Lu, ¹⁰⁵Rh, ¹⁸⁶Re, etc. — have been omitted.