NE585
NUCLEAR FUEL CYCLES
Nuclear engineering basics
1

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Learning objectives

Demonstrating fundamental concepts in nuclear physics

Analyzing decay data to identify radionuclides

Summarizing different decay mechanisms

Book – Chapter 2

Learning nodes

Relativity

Atomic structure

Binding energy

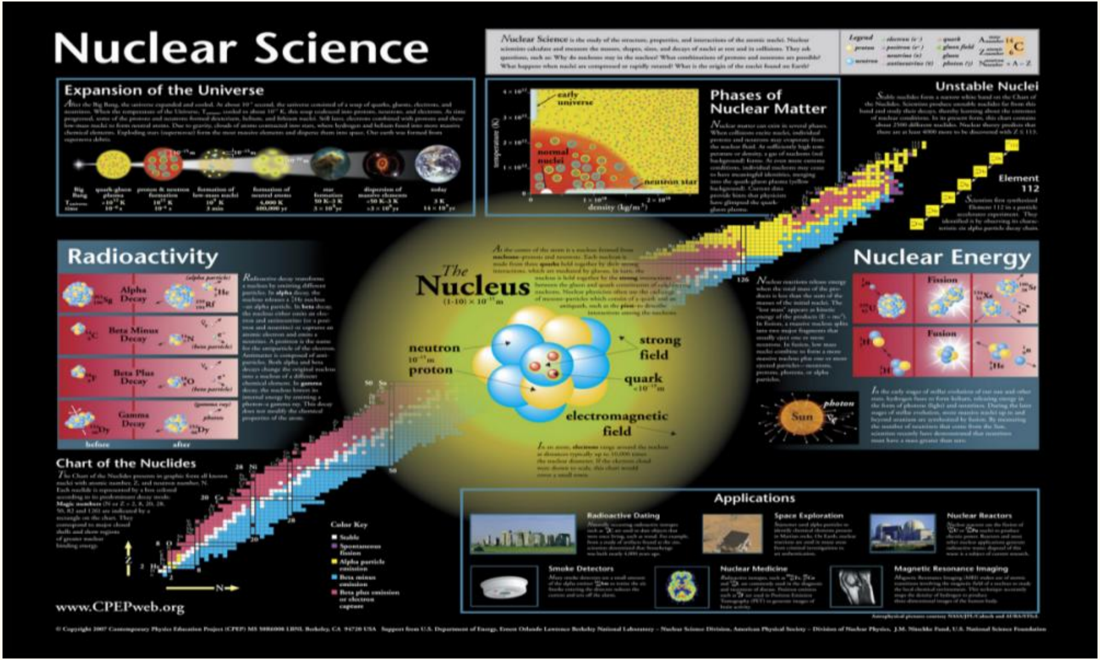
Q-value

Radioactivity

Chart of the nuclides

Decay chains

Half life


Nuclear Science
Expansion of the Universe
Phases of Nuclear Matter
early universe
normal nuclei
neutron star
Unstable Nuclei
Element 112
Radioactivity
Alpha Decay
Beta Minus Decay
Beta Plus Decay
Gamma Decay
before
after
The Nucleus
neutron
proton
strong field
quark
electromagnetic field
Nuclear Energy
Fission
Fusion
photon
Sun
Chart of the Nuclides
Color Key
Applications
Radioactive Dating
Space Exploration
Nuclear Reactors
Smoke Detectors
Nuclear Medicine
Magnetic Resonance Imaging
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Relativity

We apply energy from nuclear reactions and radiation interactions with matter

$$E_{REST} = m_0 c^2 \tag{1}$$

$$E = mc^2 \tag{2}$$

Rest mass energy for an electron – 0.511 *MeV*

Save that for later

Energy released or energy injected

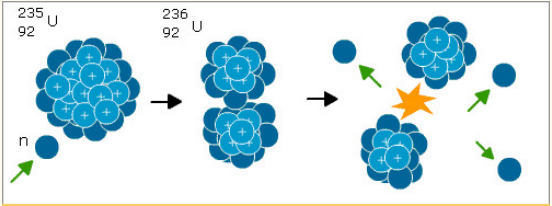
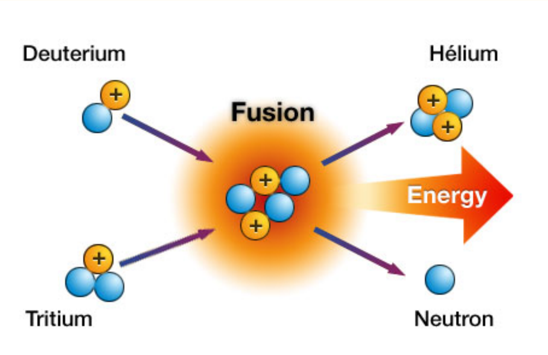


fig1. Induced fission of U-235



Determine the energy of a fusion neutron that is not at rest

$$m = \frac{m_0}{\sqrt{1 - (\frac{v^2}{c})^2}} \rightarrow E = mc^2 \tag{3}$$

With $v = 5.2 \times 10^7\ m/s$, that is about $0.17c$; not negligible

So we have to compute the not rest mass

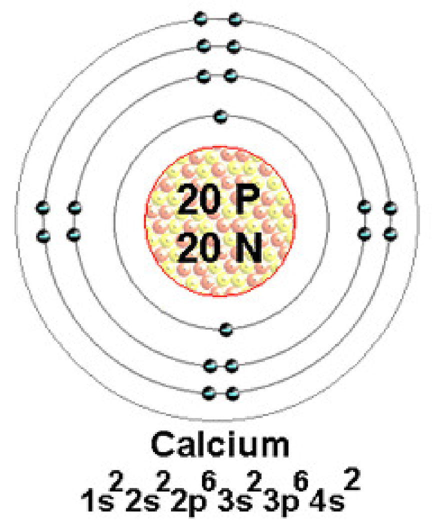
$m_0(n) = 1.674927211 \times 10^{-27}\ kg$

Fusion neutron at that speed has $E = 14.5\ MeV$

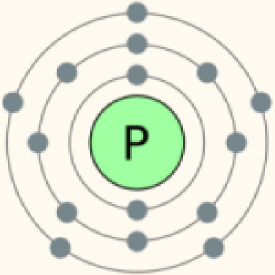
For relativistic calculations use MeV

Atomic structure

The shell model describes how subatomic particles are arranged

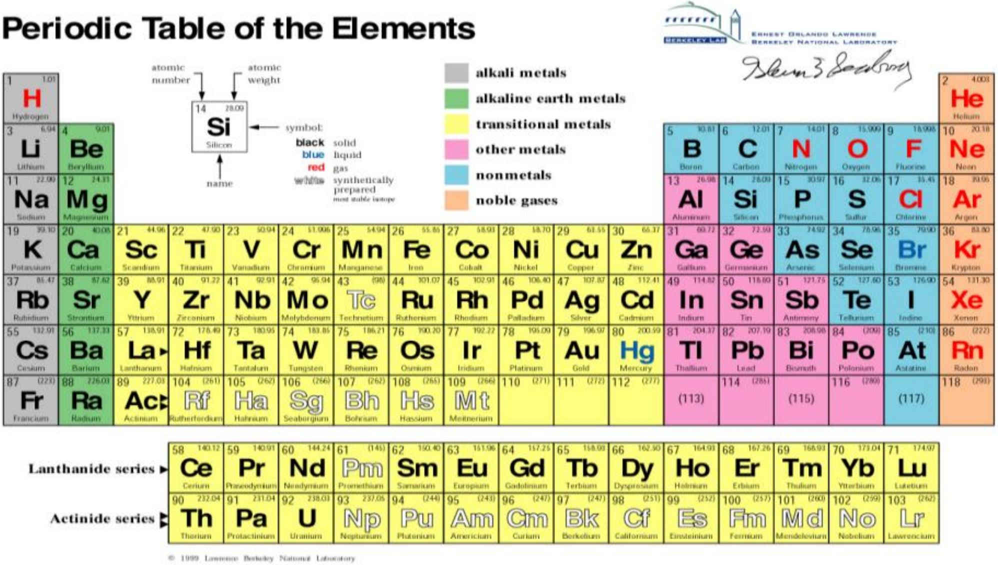


15: Phosphorus 2,8,5



Notation

$$^{A}_{Z}Q_{A-Z} = ^{235}_{92}U_{143}$$


Periodic Table of the Elements
Ernest Orlando Lawrence Berkeley National Laboratory
Berkeley Lab
alkali metals
alkaline earth metals
transitional metals
other metals
nonmetals
noble gases
atomic number
atomic weight
14 28.09 Si Silicon
symbol:
name
black solid
blue liquid
red gas
white synthetically prepared
most stable isotope
1 H 1.01 Hydrogen
2 He 4.003 Helium
3 Li 6.94 Lithium
4 Be 9.01 Beryllium
5 B 10.81 Boron
6 C 12.01 Carbon
7 N 14.01 Nitrogen
8 O 15.999 Oxygen
9 F 18.998 Fluorine
10 Ne 20.18 Neon
11 Na 22.99 Sodium
12 Mg 24.31 Magnesium
13 Al 26.98 Aluminum
14 Si 28.09 Silicon
15 P 30.97 Phosphorus
16 S 32.06 Sulfur
17 Cl 35.45 Chlorine
18 Ar 39.95 Argon
19 K 39.10 Potassium
20 Ca 40.08 Calcium
21 Sc 44.96 Scandium
22 Ti 47.90 Titanium
23 V 50.94 Vanadium
24 Cr 51.996 Chromium
25 Mn 54.94 Manganese
26 Fe 55.85 Iron
27 Co 58.93 Cobalt
28 Ni 58.70 Nickel
29 Cu 63.55 Copper
30 Zn 65.37 Zinc
31 Ga 69.72 Gallium
32 Ge 72.59 Germanium
33 As 74.92 Arsenic
34 Se 78.96 Selenium
35 Br 79.90 Bromine
36 Kr 83.80 Krypton
37 Rb 85.47 Rubidium
38 Sr 87.62 Strontium
39 Y 88.91 Yttrium
40 Zr 91.22 Zirconium
41 Nb 92.91 Niobium
42 Mo 95.94 Molybdenum
43 Tc (98) Technetium
44 Ru 101.07 Ruthenium
45 Rh 102.91 Rhodium
46 Pd 106.40 Palladium
47 Ag 107.87 Silver
48 Cd 112.41 Cadmium
49 In 114.82 Indium
50 Sn 118.69 Tin
51 Sb 121.75 Antimony
52 Te 127.60 Tellurium
53 I 126.90 Iodine
54 Xe 131.30 Xenon
55 Cs 132.91 Cesium
56 Ba 137.33 Barium
57 La 138.91 Lanthanum
72 Hf 178.49 Hafnium
73 Ta 180.95 Tantalum
74 W 183.85 Tungsten
75 Re 186.21 Rhenium
76 Os 190.20 Osmium
77 Ir 192.22 Iridium
78 Pt 195.09 Platinum
79 Au 196.97 Gold
80 Hg 200.59 Mercury
81 Tl 204.37 Thallium
82 Pb 207.19 Lead
83 Bi 208.98 Bismuth
84 Po (209) Polonium
85 At (210) Astatine
86 Rn (222) Radon
87 Fr (223) Francium
88 Ra 226.03 Radium
89 Ac 227.03 Actinium
104 Rf (261) Rutherfordium
105 Ha (262) Hahnium
106 Sg (266) Seaborgium
107 Bh (262) Bohrium
108 Hs (265) Hassium
109 Mt (266) Meitnerium
110 (271)
111 (272)
112 (277)
(113)
114 (285)
(115)
116 (289)
(117)
118 (293)
Lanthanide series
58 Ce 140.12 Cerium
59 Pr 140.91 Praseodymium
60 Nd 144.24 Neodymium
61 Pm (145) Promethium
62 Sm 150.40 Samarium
63 Eu 151.96 Europium
64 Gd 157.25 Gadolinium
65 Tb 158.93 Terbium
66 Dy 162.50 Dysprosium
67 Ho 164.93 Holmium
68 Er 167.26 Erbium
69 Tm 168.93 Thulium
70 Yb 173.04 Ytterbium
71 Lu 174.97 Lutetium
Actinide series
90 Th 232.04 Thorium
91 Pa 231.04 Protactinium
92 U 238.03 Uranium
93 Np 237.05 Neptunium
94 Pu (244) Plutonium
95 Am (243) Americium
96 Cm (247) Curium
97 Bk (247) Berkelium
98 Cf (251) Californium
99 Es (252) Einsteinium
100 Fm (257) Fermium
101 Md (260) Mendelevium
102 No (259) Nobelium
103 Lr (262) Lawrencium
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Binding energy

There are four fundamental forces of interaction

Gravity – Obvious

Strong nuclear – Holds the nucleus together

Electromagnetic – Basically electrons & magnetism

Weak nuclear – Changes the flavor of quarks

To blow out a nucleus, a lot of energy is needed

Would it be constant or variable per nucleus?

Why would you want to blow out the nucleus?

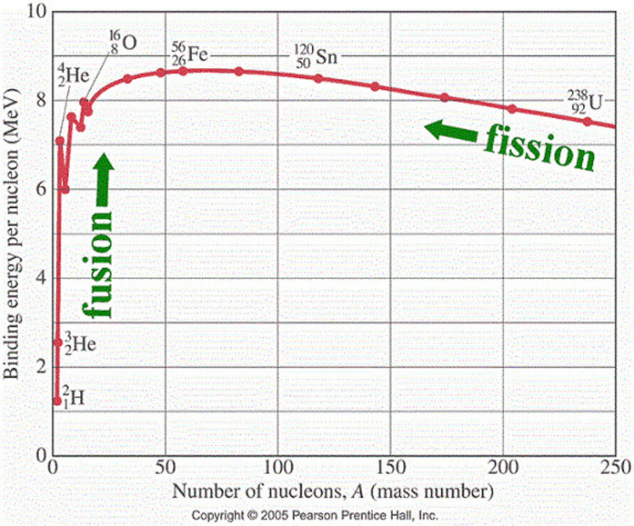
$$\Delta m = (A - Z)m_n - Zm_p - M \tag{4}$$

$$\Delta m(^{239}_{94}Pu) = 1759\ MeV = 7.40\ \frac{MeV}{nucleon} \tag{5}$$

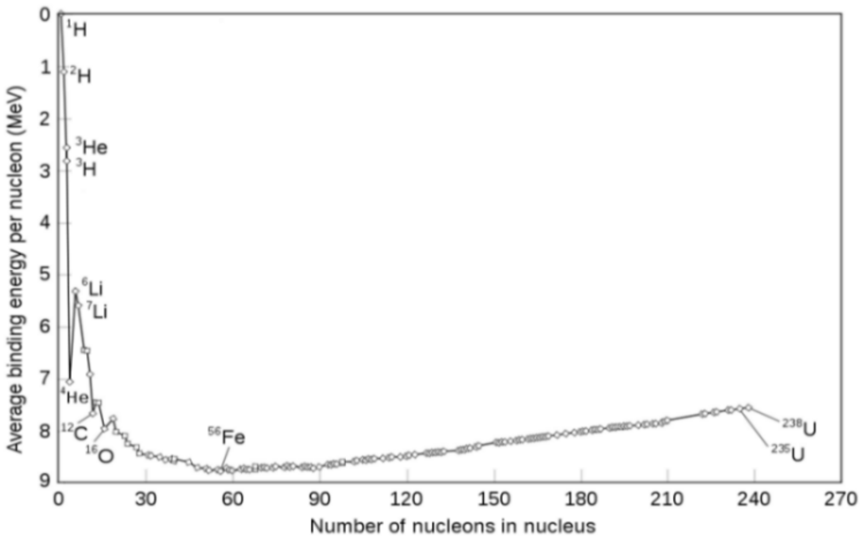
This energy corresponds to a velocity of 0.88c

$931.5\ \frac{MeV}{amu}$

Binding energy is used to compare atomic stability, reaction energy, probability of fission/fusion



Light nuclei get more stable by fusion; heavy nuclei get more stable by fission



Q-value

The Q-value for a reaction indicates energy requirements

$$ {}^{6}_{3}Li\ (n, \alpha)\ {}^{3}_{1}H \tag{6} $$

$$ {}^{6}_{3}Li + {}^{1}_{0}n \rightarrow {}^{4}_{2}\alpha + {}^{3}_{1}H \tag{7} $$

(1) Conservation of nucleons

(2) Conservation of charge

(3) Conservation of momentum

(4) Conservation of energy

Compute the Q value for this reaction

$$^6_3Li + ^1_0 n \rightarrow ^4_2 \alpha + ^3_1 H \tag{8}$$

$$Q = [(M_{Li} + M_n) - (M_\alpha + M_H)]c^2 \tag{9}$$

$$Q = 4.78\ MeV \tag{10}$$

$Q > 0 \rightarrow ?$

$Q < 0 \rightarrow ?$

What is the energy of fission from thorium and uranium fuel cycles?

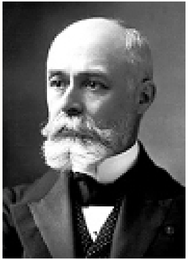
$$^{1}_{0}n + ^{235}_{92}U \rightarrow ^{92}_{36}Kr + ^{141}_{56}Ba + ^{1}_{0}n + ^{1}_{0}n + ^{1}_{0}n \tag{11}$$

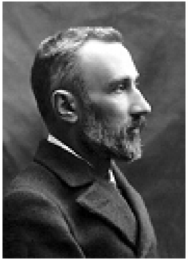
$$^{1}_{0}n + ^{233}_{92}U \rightarrow ^{92}_{36}Kr + ^{141}_{56}Ba + ^{1}_{0}n \tag{12}$$

For comparison, burning a carbon atom releases 4 eV

Radioactivity

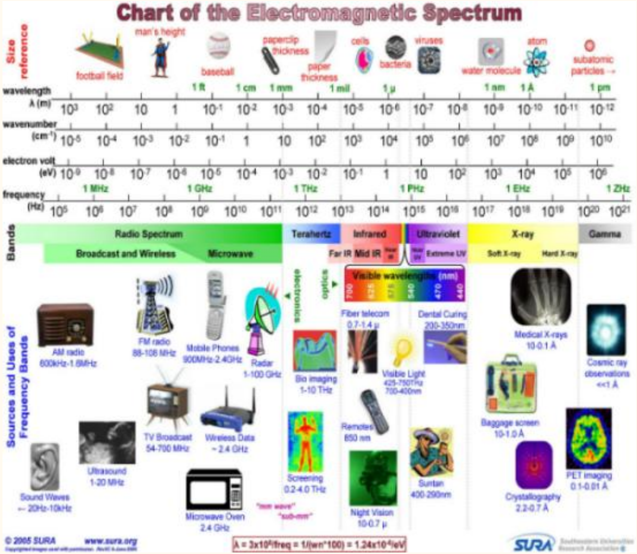
Scientists in late 1800s made discoveries which would change the course of science, medicine, and history in the 20th Century



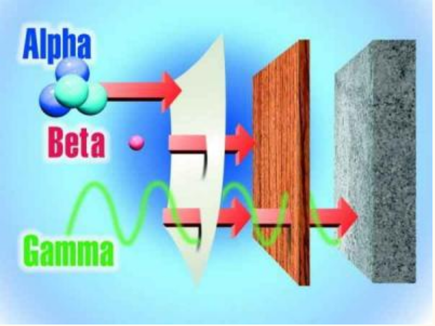


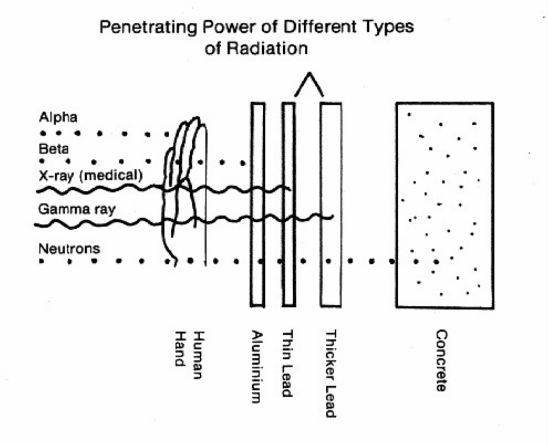
The Nobel Prize in Physics 1903 was divided, one half awarded to Antoine Henri Becquerel "*in recognition of the extraordinary services he has rendered by his discovery of spontaneous radioactivity*", the other half jointly to Pierre Curie and Marie Curie, née Sklodowska "*in recognition of the extraordinary services they have rendered by their joint researches on the radiation phenomena discovered by Professor Henri Becquerel*".

Radiation is energy as particles or electromagnetic waves, like sunshine



Radiation is energy as particles or electromagnetic waves





Radiation is energy as particles or electromagnetic waves

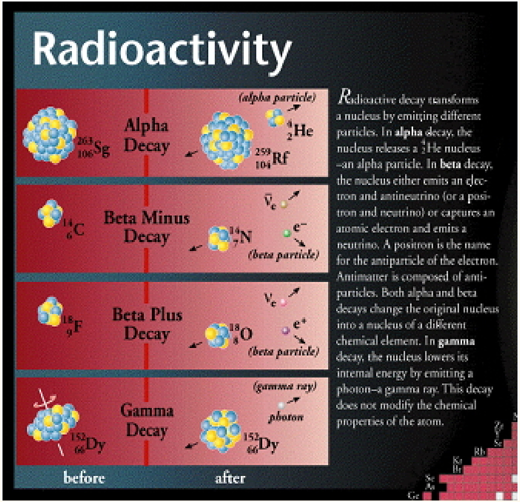
Charged particles are –

- protons (+)
- alpha (++)
- beta (+/-)
- heavy ions (varying)
- U,Pu (3+,4+,5+,6+)

Neutrons have no charge, but are also ionizing

Ionizing rays are x-rays, g-rays, cosmic rays

Ernest Rutherford discovered the three main kinds of radioactive decay (Chemistry Nobel 08)



Alpha particle decay is the ejection of a helium atom from a heavy nucleus

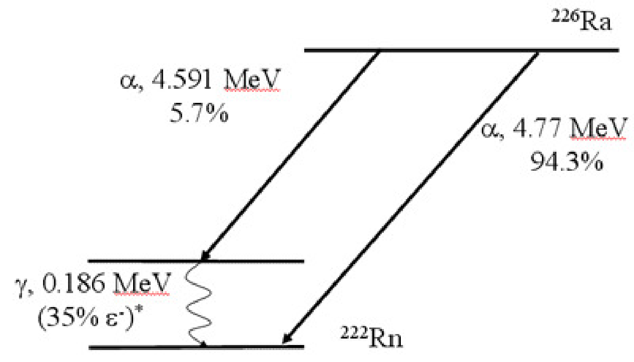
$$^{238}_{92}U \rightarrow ^{234}_{90}Th + ^{4}_{2}\alpha \tag{13}$$

$$Q = 4.268\ MeV \tag{14}$$

Sometimes nucleus decays to excited state and then emits a gamma ray (for any kind of radiation)

Discrete energy spectrum

Some % decay at certain energy



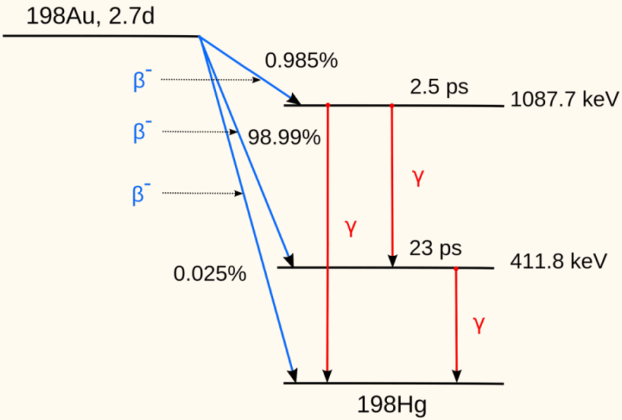
^{226}Ra
α, 4.591 MeV
5.7%
α, 4.77 MeV
94.3%
γ, 0.186 MeV
(35% ε^{-})*
^{222}Rn

β^- particle decay occurs for unstable nuclei with excessive neutrons

$$ {}^{19}_{8}O \rightarrow {}^{19}_{9}F + \beta^- + \overline{\nu} \tag{15} $$

The neutron is converted to a proton and a beta negative (electron) and anti-neutrino (momentum) are ejected

Sometimes nucleus decays to excited state and then emits a gamma ray (for any kind of radiation)

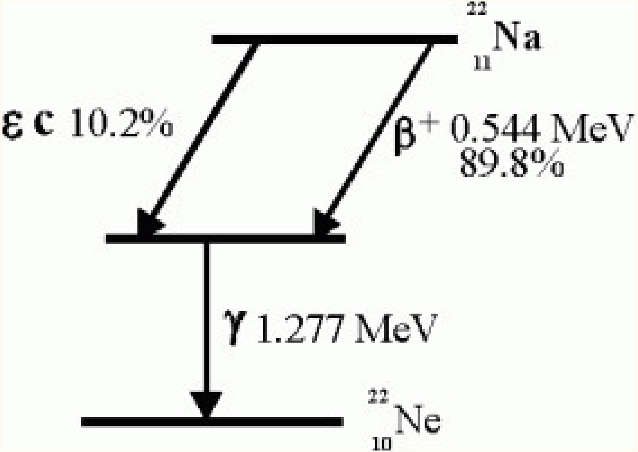

198Au, 2.7d
0.985%
β-
2.5 ps
1087.7 keV
β-
98.99%
β-
γ
γ
23 ps
411.8 keV
0.025%
γ
198Hg

β^+ particle decay occurs for unstable nuclei with deficient neutrons

$$ {}^{11}_{6}C \rightarrow {}^{11}_{5}B + \beta^+ + \nu \tag{16}$$

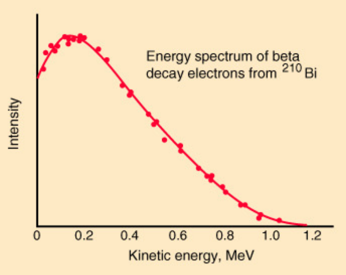
The proton is converted to a neutron and a beta positive (positron) and neutrino (momentum) are ejected

Sometimes nucleus decays to excited state and then emits a gamma ray (for any kind of radiation)



$^{22}_{11}Na$
ε c 10.2%
β+ 0.544 MeV
89.8%
γ 1.277 MeV
$^{22}_{10}Ne$

In both forms of beta decay, the energies are exhibited by a continuous energy spectrum



$$\overline{E}(\beta^-) = 0.3E_{MAX} \tag{17}$$

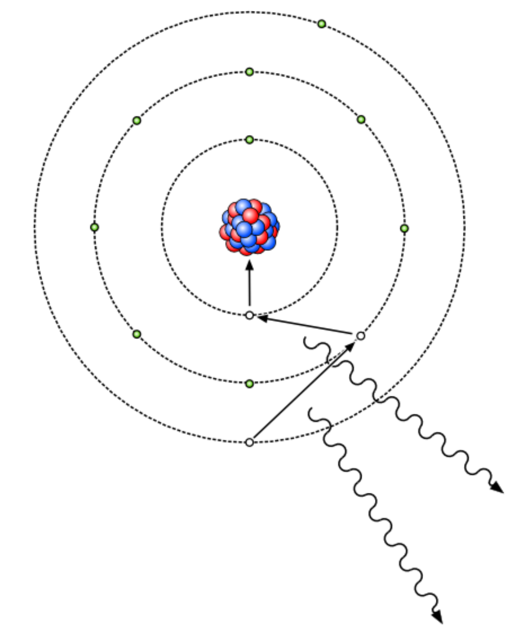
$$\overline{E}(\beta^+) = 0.4E_{MAX} \tag{18}$$

Electron capture also occurs for unstable nuclei with deficient neutrons

$$^{22}_{11}Na \rightarrow \epsilon^{-} + ^{22}_{10}Ne + \nu \tag{19}$$

The K shell electron (not free) is absorbed by the nucleus to convert the proton to a neutron

Sometimes nucleus decays to excited state and then emits a gamma ray (for any kind of radiation)



Electron capture and β^+ are competing processes

$$ {}^{22}_{11}Na \rightarrow \epsilon^- + {}^{22}_{10}Ne + \nu \tag{20} $$

$$ {}^{22}_{11}Na \rightarrow {}^{22}_{10}Ne + \beta^+ + \nu \tag{21} $$

$$ Q = 2.842\ MeV \tag{22} $$

$Q > 1.022\ MeV$ positron favored

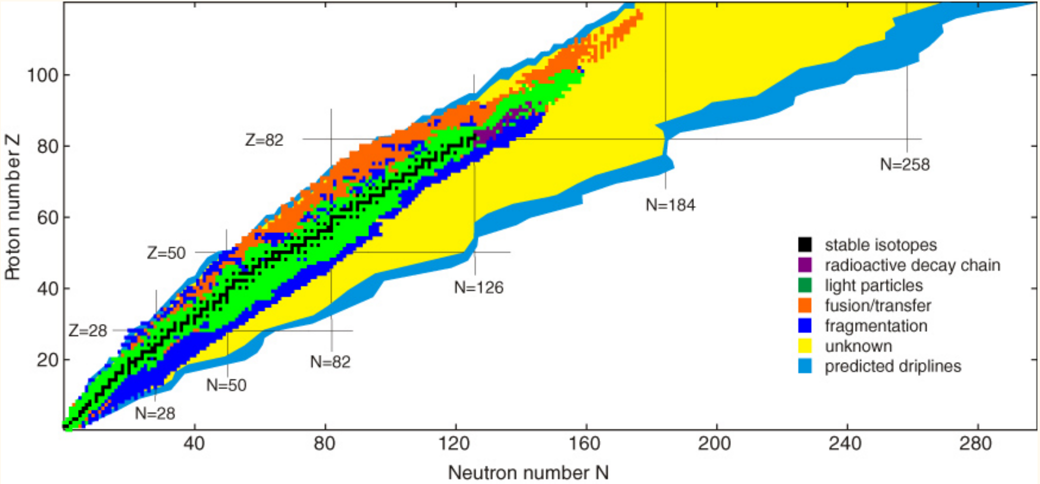
$Q < 1.022\ MeV$ electron capture favored

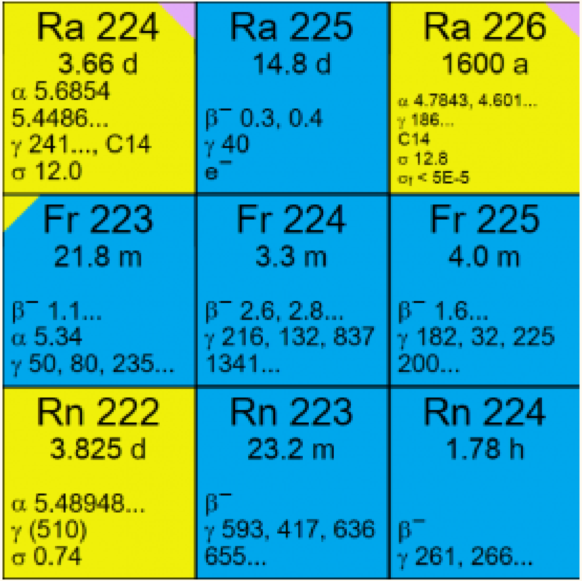
Why?

γ-ray emission is not a decay mode, but superfast de-excitation of the nucleus

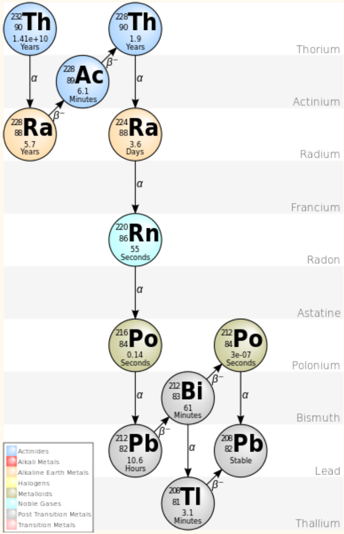
Interactions of gamma rays with matter is a very important branch of nuclear physics

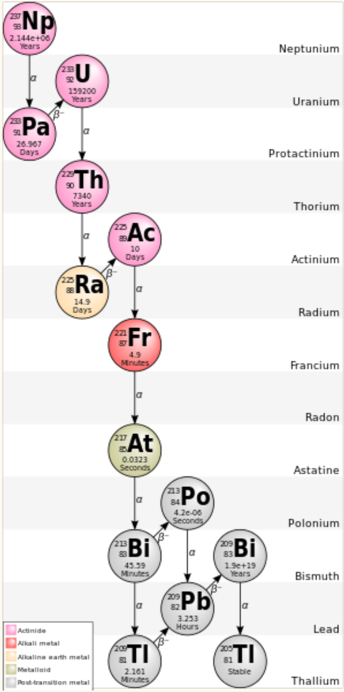
Chart of the nuclides

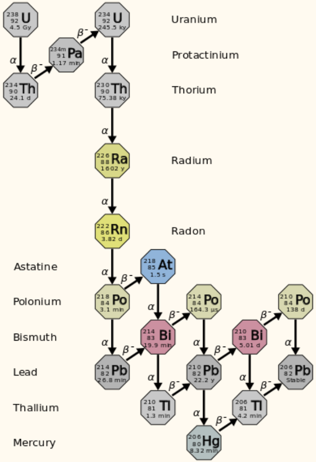

Proton number Z
Neutron number N
100
80
60
40
20
40
80
120
160
200
240
280
Z=82
Z=50
Z=28
N=28
N=50
N=82
N=126
N=184
N=258
stable isotopes
radioactive decay chain
light particles
fusion/transfer
fragmentation
unknown
predicted driplines


Ra 224
3.66 d
α 5.6854
5.4486...
γ 241..., C14
σ 12.0
Ra 225
14.8 d
β⁻ 0.3, 0.4
γ 40
e⁻
Ra 226
1600 a
α 4.7843, 4.601...
γ 186...
C14
σ 12.8
σf < 5E-5
Fr 223
21.8 m
β⁻ 1.1...
α 5.34
γ 50, 80, 235...
Fr 224
3.3 m
β⁻ 2.6, 2.8...
γ 216, 132, 837
1341...
Fr 225
4.0 m
β⁻ 1.6...
γ 182, 32, 225
200...
Rn 222
3.825 d
α 5.48948...
γ (510)
σ 0.74
Rn 223
23.2 m
β⁻
γ 593, 417, 636
655...
Rn 224
1.78 h
β⁻
γ 261, 266...

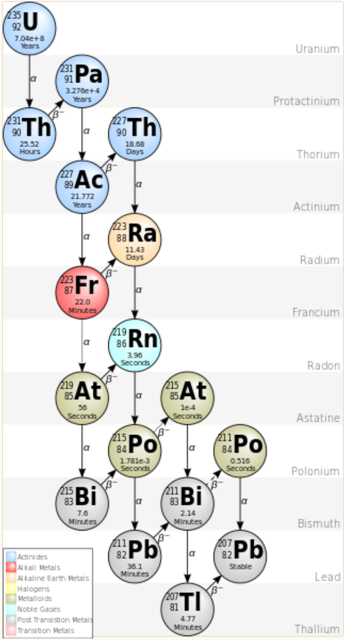
Decay chains


232 90 Th 1.41e+10 Years
228 90 Th 1.9 Years
Thorium
228 89 Ac 6.1 Minutes
Actinium
228 88 Ra 5.7 Years
224 88 Ra 3.6 Days
Radium
Francium
220 86 Rn 55 Seconds
Radon
Astatine
216 84 Po 0.14 Seconds
212 84 Po 3e-07 Seconds
Polonium
212 83 Bi 61 Minutes
Bismuth
212 82 Pb 10.6 Hours
208 82 Pb Stable
Lead
208 81 Tl 3.1 Minutes
Thallium
α
β−
Actinides
Alkali Metals
Alkaline Earth Metals
Halogens
Metalloids
Noble Gases
Post Transition Metals
Transition Metals


237 93 Np 2.144e+06 Years
233 92 U 159200 Years
233 91 Pa 26.967 Days
229 90 Th 7340 Years
225 89 Ac 10 Days
225 88 Ra 14.9 Days
221 87 Fr 4.9 Minutes
217 85 At 0.0323 Seconds
213 84 Po 4.2e-06 Seconds
213 83 Bi 45.59 Minutes
209 83 Bi 1.9e+19 Years
209 82 Pb 3.253 Hours
209 81 Tl 2.161 Minutes
205 81 Tl Stable
α
β−
Neptunium
Uranium
Protactinium
Thorium
Actinium
Radium
Francium
Radon
Astatine
Polonium
Bismuth
Lead
Thallium
Actinide
Alkali metal
Alkaline earth metal
Metalloid
Post-transition metal



Uranium
Protactinium
Thorium
Radium
Radon
Astatine
Polonium
Bismuth
Lead
Thallium
Mercury
238 92 U 4.5 Gy
234 92 U 245.5 ky
234m 91 Pa 1.17 min
234 90 Th 24.1 d
230 90 Th 75.38 ky
226 88 Ra 1602 y
222 86 Rn 3.82 d
218 85 At 1.5 s
218 84 Po 3.1 min
214 84 Po 164.3 μs
210 84 Po 138 d
214 83 Bi 19.9 min
210 83 Bi 5.01 d
214 82 Pb 26.8 min
210 82 Pb 22.2 y
206 82 Pb Stable
210 81 Tl 1.3 min
206 81 Tl 4.2 min
206 80 Hg 8.32 min
α
β⁻


235 92 U 7.04e+8 Years
231 91 Pa 3.276e+4 Years
231 90 Th 25.52 Hours
227 90 Th 18.68 Days
227 89 Ac 21.772 Years
223 88 Ra 11.43 Days
223 87 Fr 22.0 Minutes
219 86 Rn 3.96 Seconds
219 85 At 56 Seconds
215 85 At 1e-4 Seconds
215 84 Po 1.781e-3 Seconds
211 84 Po 0.516 Seconds
215 83 Bi 7.6 Minutes
211 83 Bi 2.14 Minutes
211 82 Pb 36.1 Minutes
207 82 Pb Stable
207 81 Tl 4.77 Minutes
α
β⁻
Uranium
Protactinium
Thorium
Actinium
Radium
Francium
Radon
Astatine
Polonium
Bismuth
Lead
Thallium
Actinides
Alkali Metals
Alkaline Earth Metals
Halogens
Metalloids
Noble Gases
Post Transition Metals
Transition Metals

Half life

A radioactive isotope decays with a unique characteristic time

Decay is stochastic, characterized by Poisson distribution

So the decay of any one radionuclide cannot be predicted

The probability per time that a nucleus will decay is a constant

Decay is described by a Poisson process

Occurrences are randomly distributed in time

What is the 'occurrence' here?

Homogeneous, long term decay rate is constant

$$\mu \equiv \lambda \Delta t \tag{23}$$

$$P(n) = e^{-\mu} \cdot \frac{\mu^n}{n!} \tag{24}$$

What is the expected value and variance of the distribution?

A radioactive isotope decays with a unique characteristic time

$n(t)$ atoms at t have decayed in dt

$$\lambda n(t)dt \tag{25}$$

The number of atoms that decay on average in the interval $t, (t + dt)$ can be expressed as –

$$-dn(t) = \lambda n(t)dt \tag{26}$$

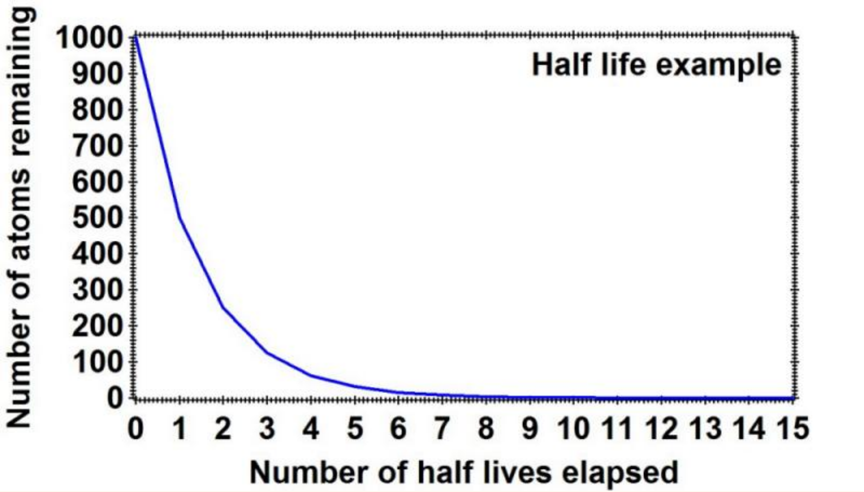
You should be able to solve this for $n(0) = n_0$

Radionuclides are characterized by half life

$$t_{\frac{1}{2}} = \frac{ln2}{\lambda} \tag{27}$$

Half life can be derived from the decay law

A radionuclide is ‘negligible’ after 10 half-lives have elapsed



Why would this be important?

How was half-life discovered?

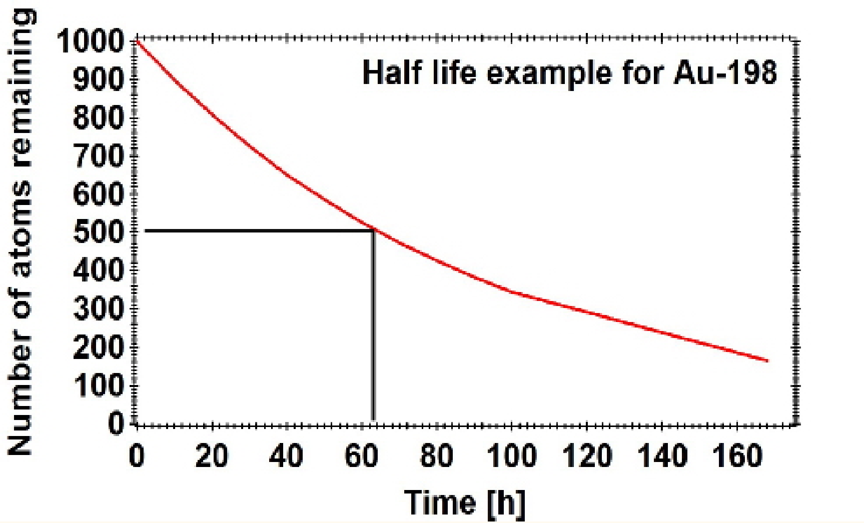
Rutherford discovered alpha and beta particle decay

In the course of, he noticed that there was a characteristic time

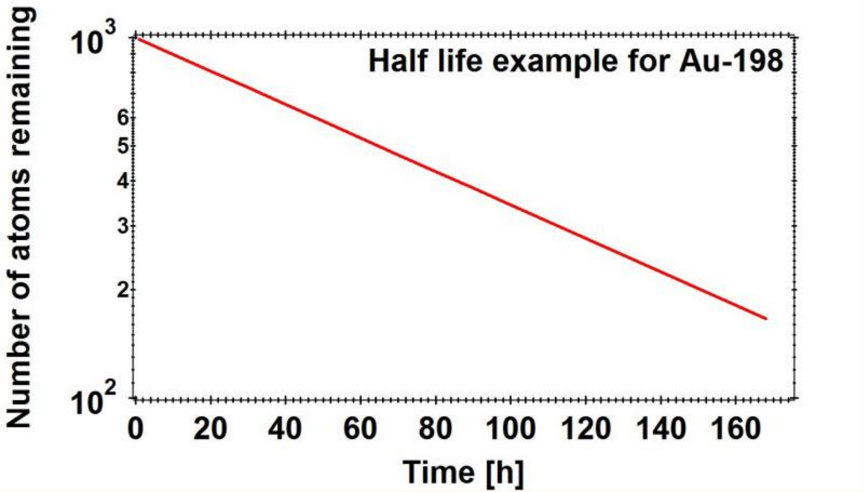
Basically observed decay time was the same for each atom

Experiments with thorium led to the discovery of radon

Then observing the radon gas led to the decay/half-life (65 s)


Half life example for Au-198
Number of atoms remaining
1000
900
800
700
600
500
400
300
200
100
0
0
20
40
60
80
100
120
140
160
Time [h]

Engineers like straight lines



Slope of the line is the decay constant


Pets on leash
only