Elements and Isotopes

A = Mass / nucleon number
A = number of protons + neutrons
$A = Z + N$
Z = Atomic / Proton number, nuclear charge

Frederick Soddy
(1877-1956)
NP in Chem. 1921

Element = set of atoms, same Z
Nuclide = set of atoms, same A and Z
Isotopes = set of nuclides of an element
Isobars = nuclides, same A, different Z (^{14}C-^{14}N; ^{3}H-^{3}He)
Isotons = nuclides, same number of neutrons, $N = A – Z$
Isomers = same nuclides, different content of energy

Isotopes

Isotopes set of nuclides of an element

2600 nuclides (stable and radioactive)
340 nuclides found in Nature
270 stable and 70 radioactive, other artificial

Monoisotopic elements:
^{9}Be, ^{19}F, ^{23}Na, ^{27}Al, ^{31}P, ^{59}Co, ^{127}I, ^{197}Au

Polyisotopické elements :
^{1}H, ^{2}H (D), ^{3}H (T)
^{10}B, ^{11}B

Sn has the highest number of **stable** isotopes – 10

$^{112, 114, 115, 116, 117, 118, 119, 120, 122, 124}$Sn

Stability of Nuclei

Stability with respect to radioactive decay is given by the number of protons and neutrons - Zone of stability

Light nuclides are stable for Z ~ N

Only ^{1}H and ^{3}He have more p than n.

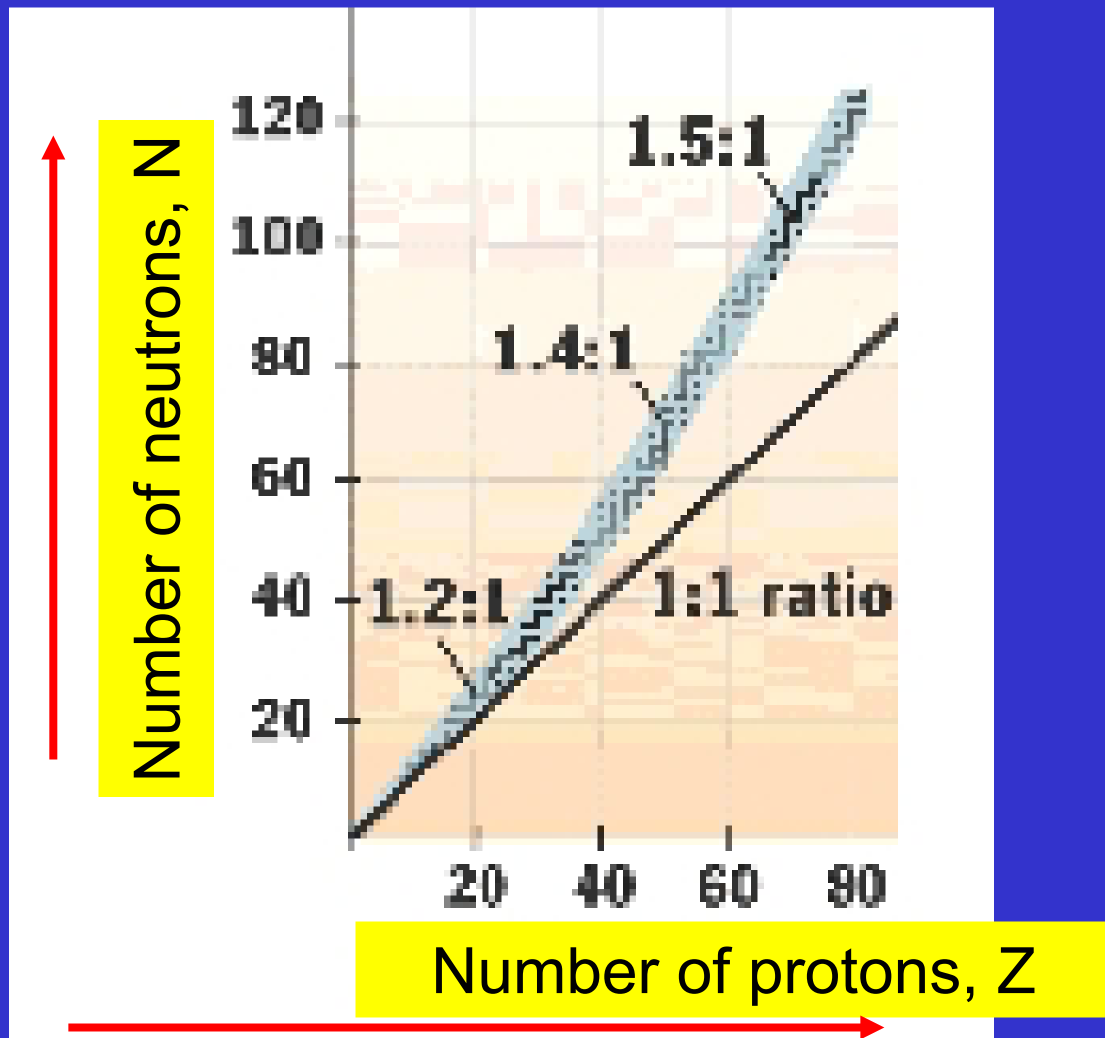
^{2}H, ^{4}He, ^{6}Li, ^{10}B, ^{12}C, ^{14}N, ^{16}O, ^{20}Ne, ^{24}Mg, ^{28}Si, ^{32}S, ^{36}Ar and ^{40}Ca
Have the same number of p and n

All other nuclides have **more** n than p   N > Z

Mattauch Rule: Of two isobars that differ by 1 in Z, one is radioactive.

^{40}Ar ^{40}Ca $\Delta Z = 2$ ^{40}Ar ^{40}K ^{40}Ca $\Delta Z = 1$ ^{40}K is radioactive.

Stability of Nuclei



Stability of Nuclei

In some elements, radioactive isotopes exist in Nature with a long half life ^{40}K, 0.012%, 1.3 10^{10} years

Elements with Z ≤ 83 (Bi) have at least 1 stable isotope

Z = 43 (Tc), 61 (Pm) do not exist in Nature

Artificial radioactive isotopes prepared by nuclear reactions

Nuclides with Z ≥ 84 (Po) are all **unstable** with respect to radioactive decay = **radioactive elements**

Magic Numbers

Z	N	Number of stable isotopes
even	even	168
even	odd	57
odd	even	50
odd	odd	4

Aston's Rule: Elements with even Z have more isotopes, elements with odd Z have no more than 2 isotopes, one of then unstable, elements with odd number of nucleons (A) have only one stable isotope (^{19}F, ^{23}Na, ^{27}Al, ^{31}P).

Only ^{2}H, ^{6}Li, ^{10}B,^{14}N, ^{40}K, ^{50}V, ^{138}La, ^{176}Lu have odd number of both p and n.

Magic Numbers

Magic Numbers = 2, 8, 20, 28, 50, 82 and 126

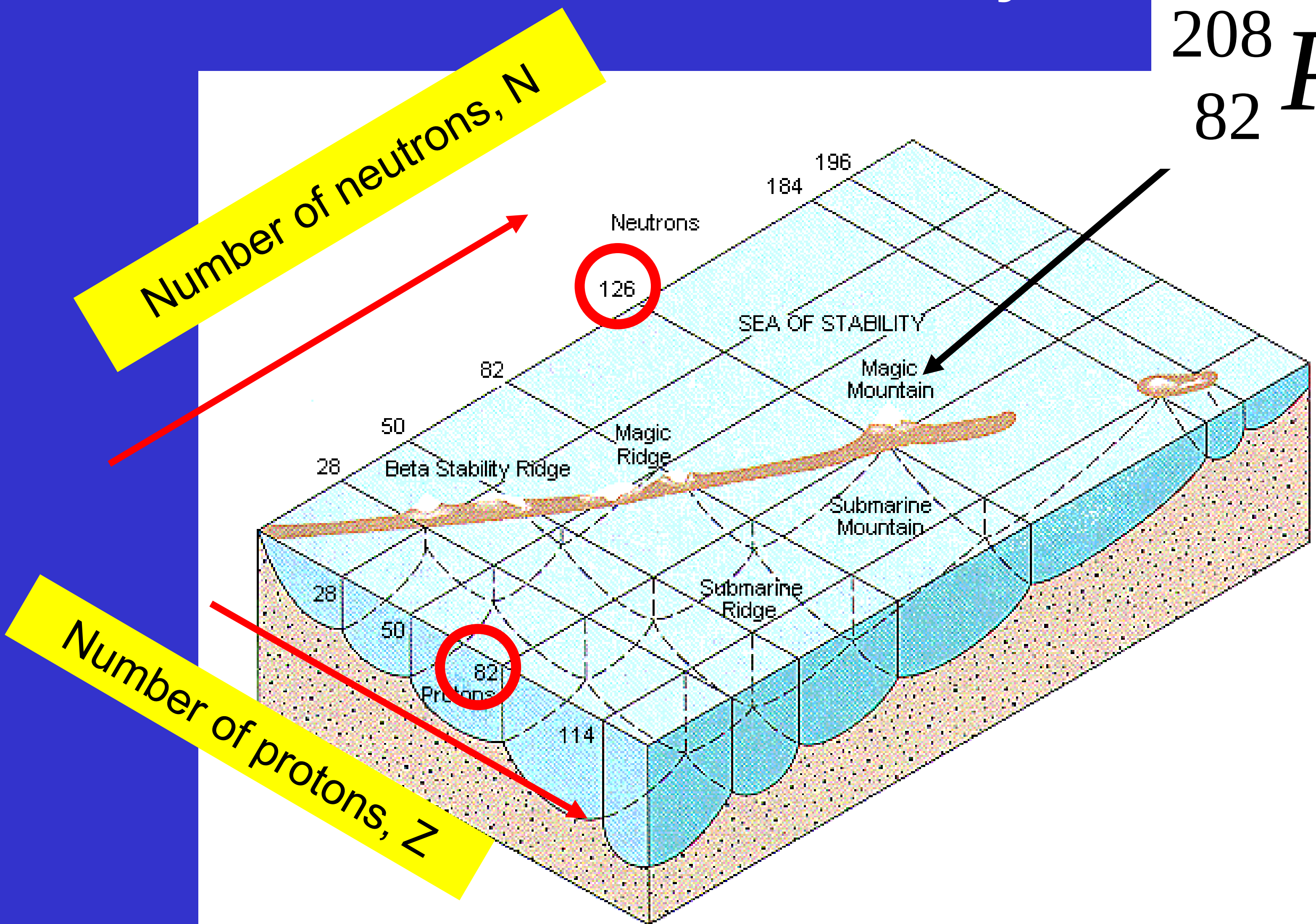
Elements with Z = magic number have a large number of stable isotopes; when an isotope is radioactive, it has a long half life

Sn Z = 50, 10 stable isotopes

Nuclides ^{4}He, ^{16}O, ^{40}Ca, ^{48}Ca and ^{208}Pb have magic number of both p and n = very stable nuclides

Island of Stability

$^{208}_{82}Pb$



Mass of Electron and Nucleons

Symbol	*m* / kg	*m* / u
e	$9.11\ 10^{-31}$	0.0005486
p	$1.673\ 10^{-27}$	1.007276
n	$1.675\ 10^{-27}$	1.008665

1 *amu* = $1.6606\ 10^{-27}$ kg

Mass Defect

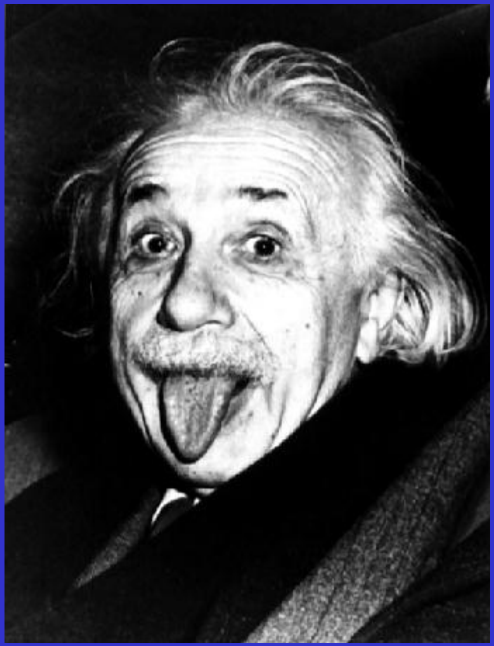
Nucleus mass is always smaller than the sum of masses of nucleons

$M_j < Z\ m_p + (A–Z)\ m_n$

Mass loss $\Delta m < 0$
[Δm in amu units]

Binding energy of nucleus
$E_b = – \Delta m\ c^2$

$E_b = – 931.5\ \Delta m$ [MeV]



NP in Physics 1921

Binding Energies of Nuclei, E_b

Nuclide	E_b, MeV
^{2}H	2.226
^{4}He	28.296
^{14}N	104.659
^{16}O	127.619
^{40}Ca	342.052
^{58}Fe	509.945
^{206}Pb	1622.340
^{238}U	1822.693

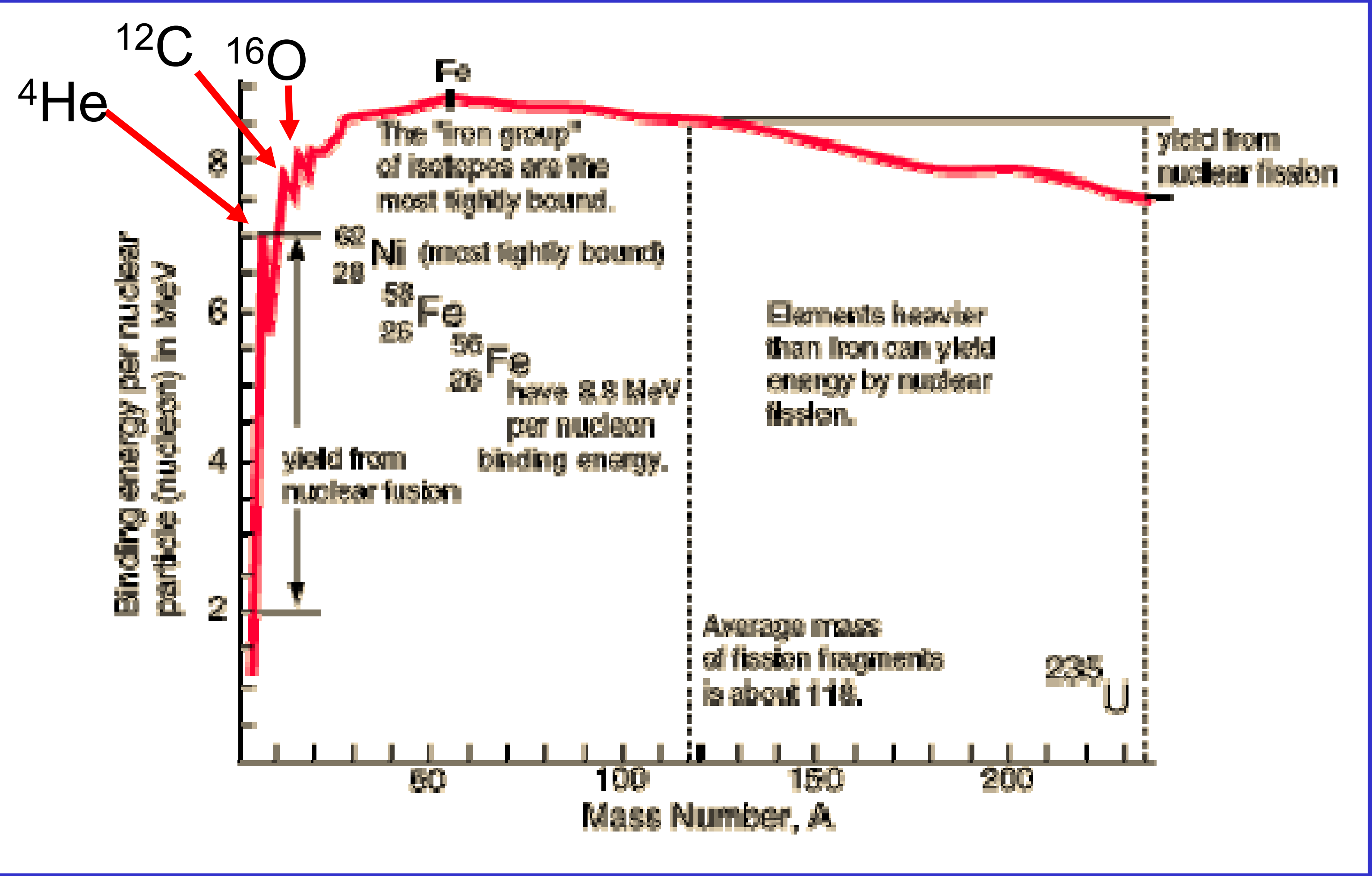
Binding Energy per One Nucleon, $E_b(n)$

Nuclide	$E_b(n)$, MeV	E_v, MeV
^{2}H	1.113	2.226
^{4}He	7.074	28.296
^{14}N	7.476	104.659
^{16}O	7.976	127.619
^{19}F	7.779	147.801
^{40}Ca	8.551	342.052
^{55}Mn	8.765	482.070
^{58}Fe	8.792	509.945
^{62}Ni	8.795	545.259
^{206}Pb	7.875	1622.340
^{238}U	7.658	1822.693

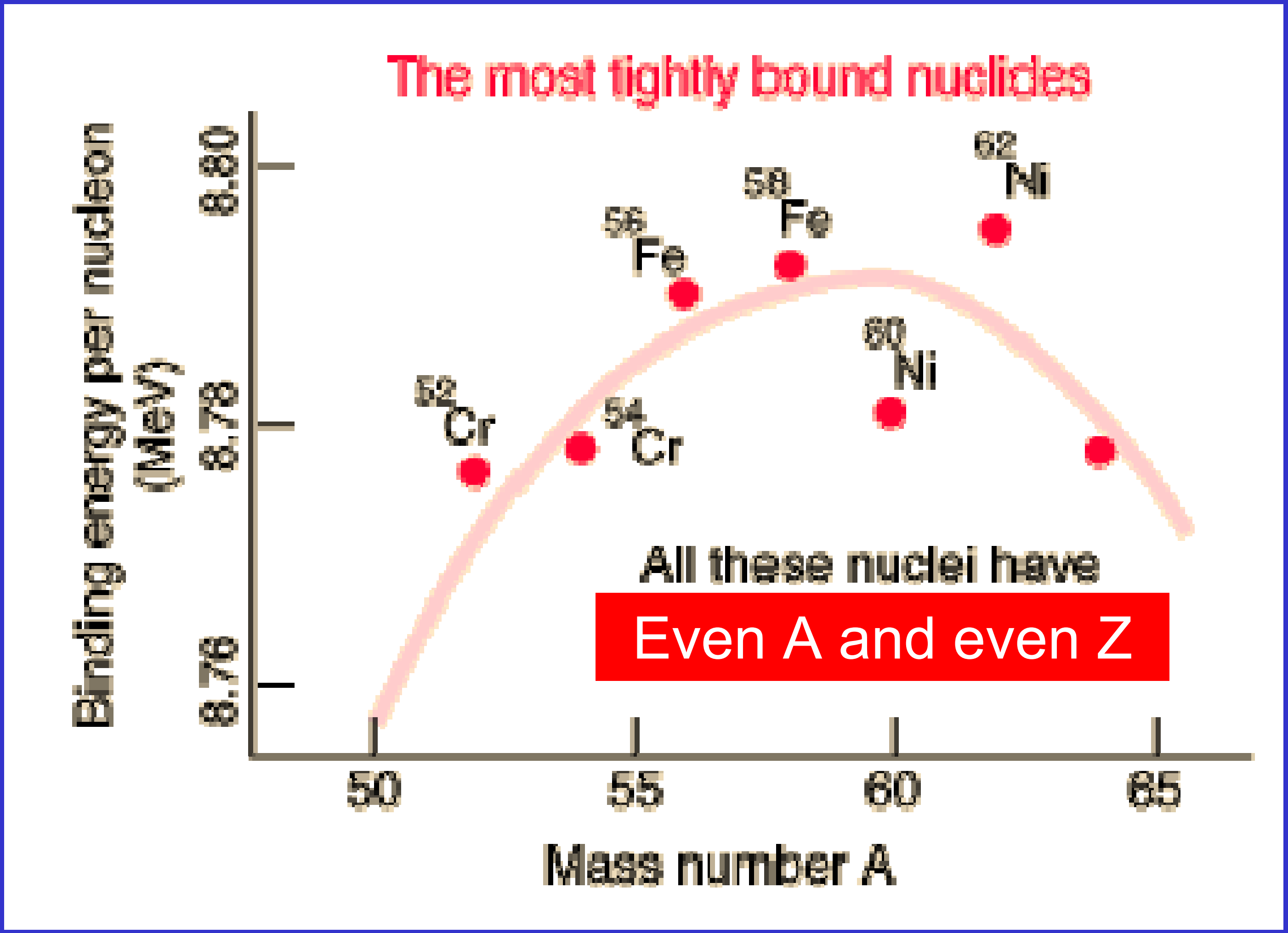
$E_b(n) = E_b / A$

Energy for removing of one nucleon

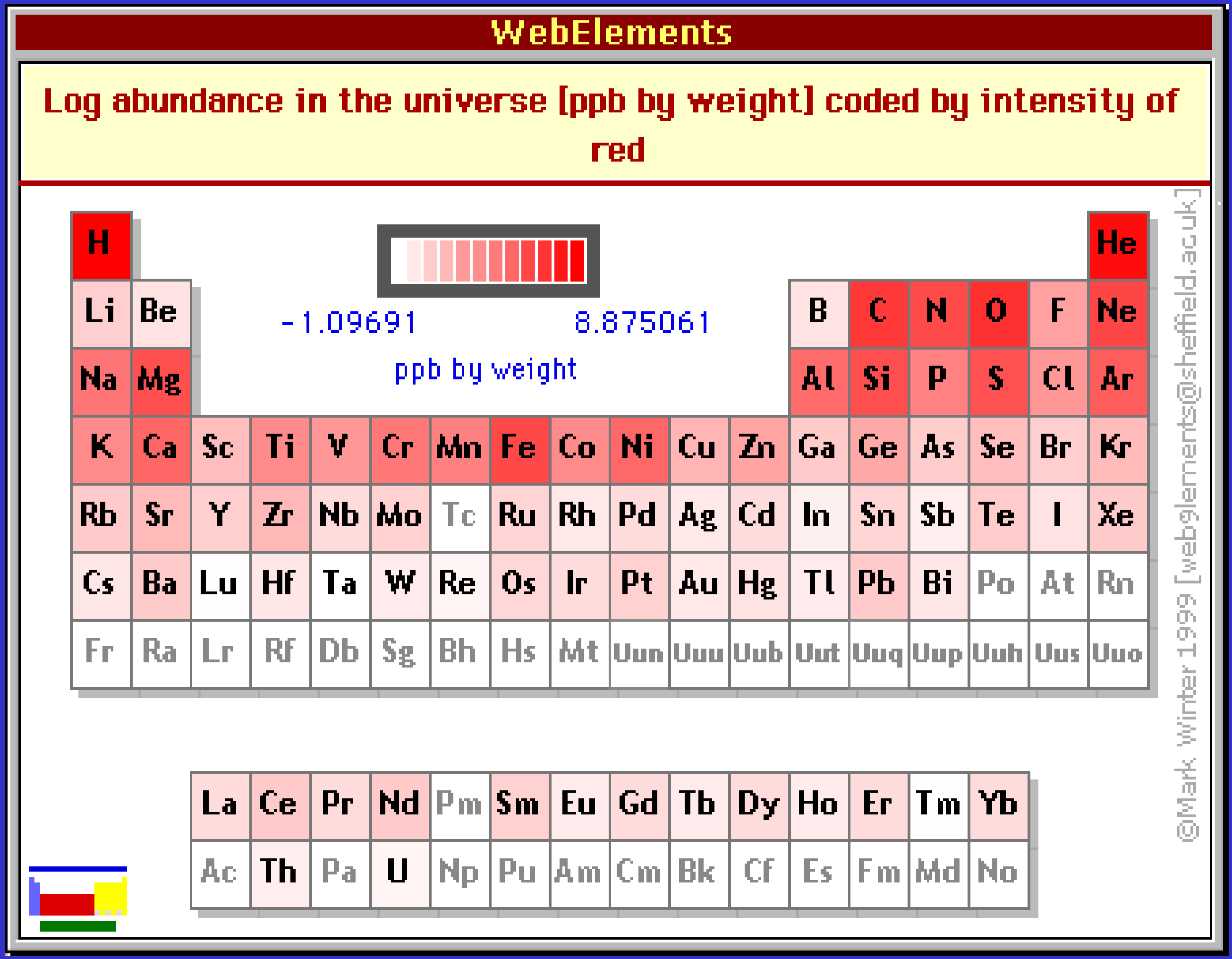
Binding Energy per Nucleon, $E_b(n)$



Binding Energy per Nucleon



Elements in the Universe



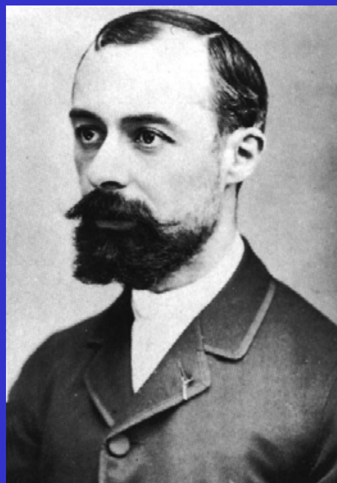
Binding Energies of Nucleus and Chemical Bond

Binding Energy per Nucleon for ^{58}Fe 8.792 MeV

Bond Energy for C-H 411 kJ mol^{-1} = 4.25 eV

Nuclear binding energies are 10^6 times bigger than chemical bond energies.

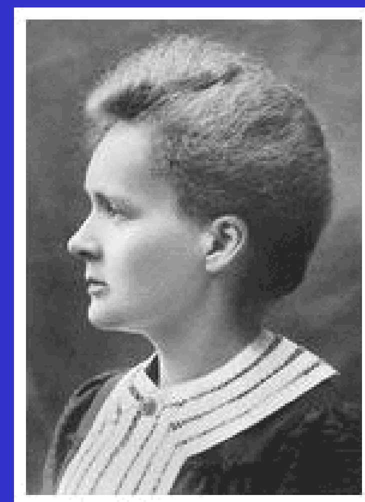
1 eV (molecule)$^{-1}$ = 96.485 kJ mol^{-1}

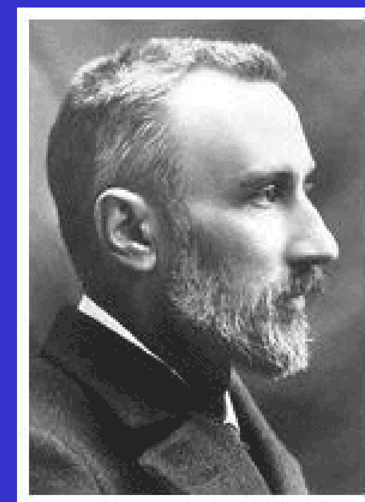


Discovery of Radioactivity

Uranium,
Thorium

Antoine Henri Becquerel
(1852-1908)





Radium, Polonium

Marie Curie (1867-1934)
Pierre Curie (1859-1906)

Discovery of radioactivity 1896
NP in Physics 1903

NP in Physics 1903
M. C. NP in Chemistry 1911

Radioactivity

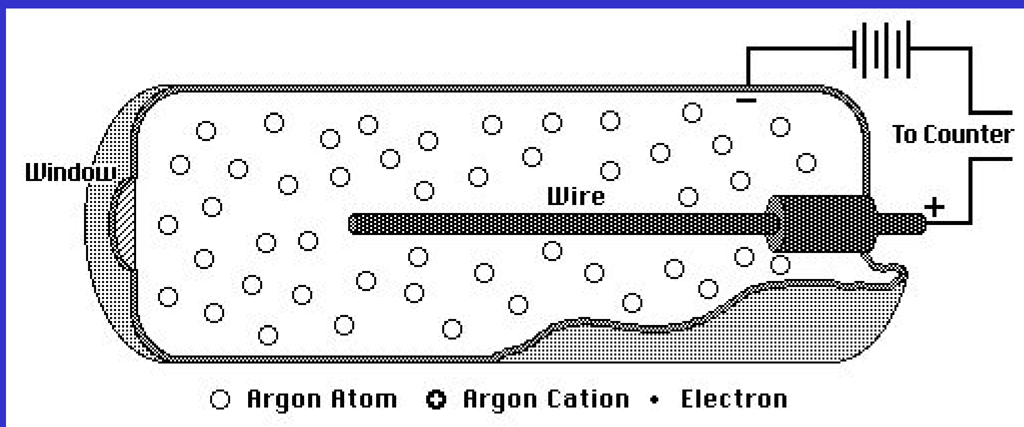
If a nucleus possesses too little/much of neutrons →

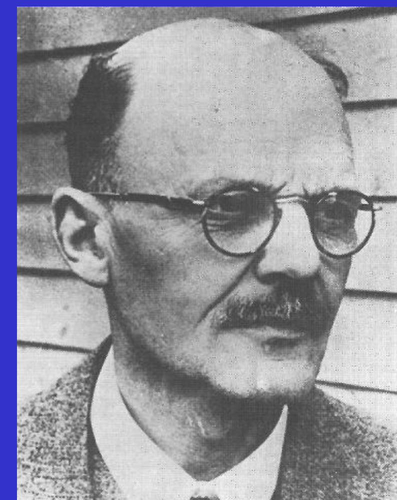
Radioactivity = transformation of some nuclei to other nuclei with emission of small particles and energy (exo)

Radioactivity = spontaneous process, products have a lower energy content and are more stable than the original nuclei

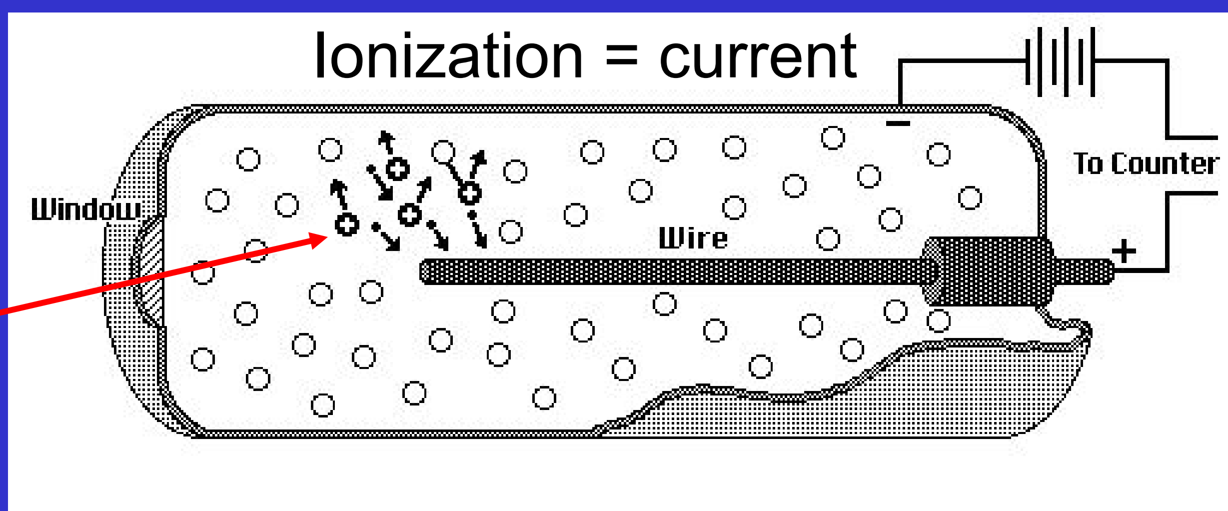
Geiger counter

Geiger Counter





Hans Geiger
(1882-1945)



particle

Measurement of Radioactivity

Radioactivity
1 Bq (becquerel) = 1 decay per 1 s
(^{40}K in human body 4 kBq)
1 Ci (curie) = 3.7 10^{10} Bq

Radiaton Dose
1 Gy (gray) = absorption of 1 J in 1 kg of tissue
1 Gy = 100 rad

Effective Dose
1 Sv (sievert) = 1 Gy $\times$ Q factor
1 Sv = 100 rem

3 Sv = LD 50/30
dose from cosmic radiation and natural background radiation in ČR = 2 mSv/year

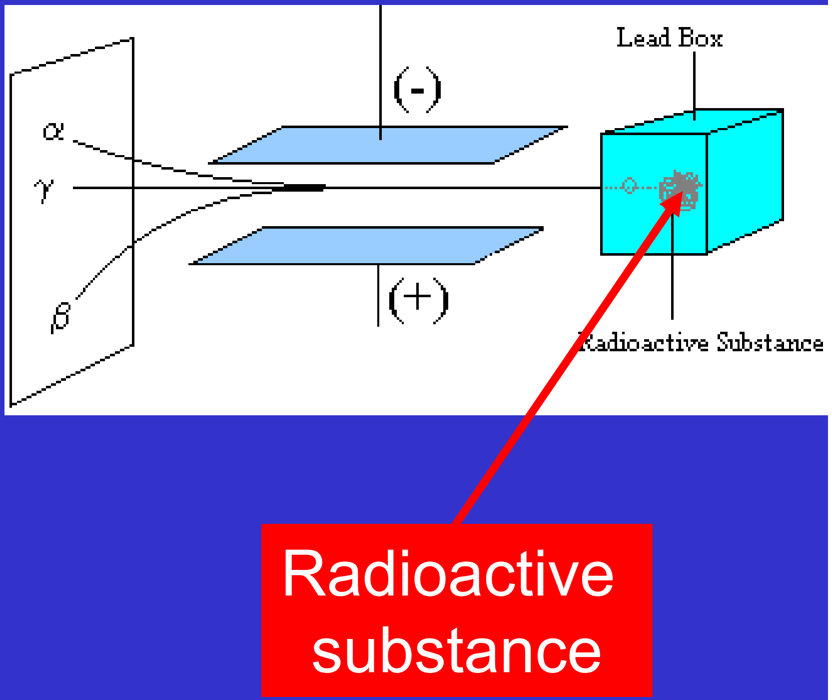
Nuclear Reactions

Rutherford – deflection of radioactive rays in electric and magnetic fields

Alpha = positive charge
Beta = negative charge
Gama = neutral

Formation of a new nuclide

Shift rules – changes in Z and N



Alpha Radiation $^{4}_{2}He$

Heavy nuclei

Alpha particle speed = 10% c

Low penetration, several cm in air, stopped by a sheet of paper

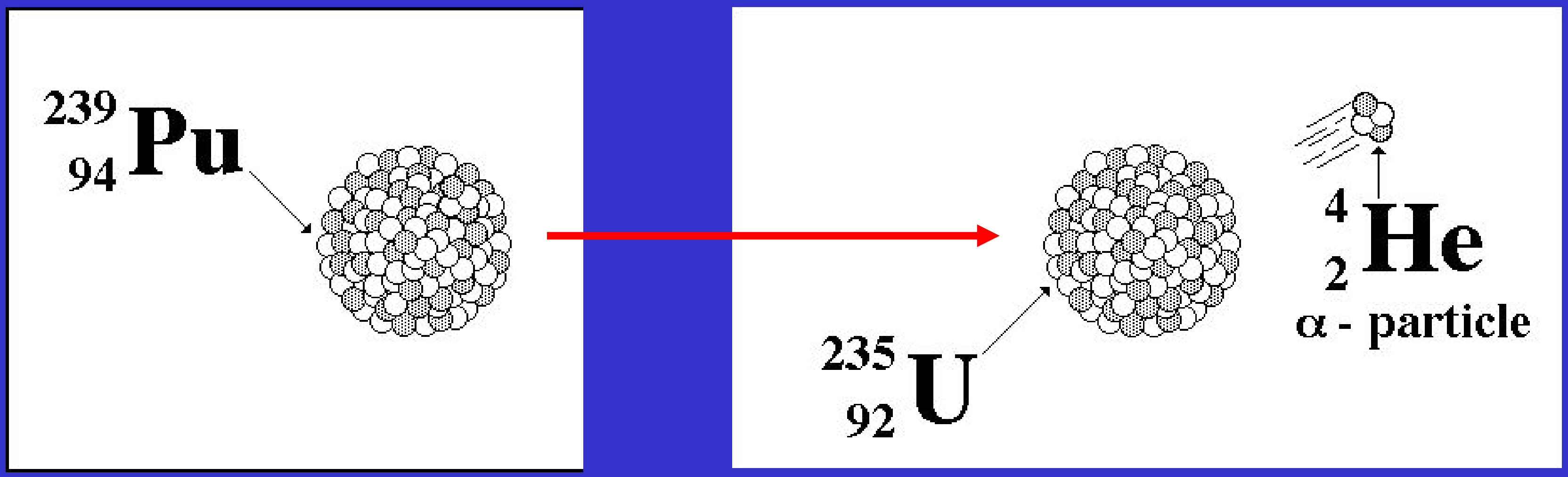
Very harmful to cells in case of inhalation

$$^{222}_{86}Rn \rightarrow ^{218}_{84}Po + ^{4}_{2}He$$

Alpha Radiation

A shift of two elements to the left in periodic table

$$^{A}_{Z}N_1 \longrightarrow {}^{A-4}_{Z-2}N_2$$



Alpha Radiation

Radium-226

Curium-240

$$ {}^{A}_{Z}N_1 \longrightarrow {}^{A-4}_{Z-2}N_2 $$

Uranium-232

Gold-185

Thorium-230

Americium-241 (smoke detectors)

Polonium-210

Beta Radiation $^{0}_{-1}e$

Nuclei with excess of neutrons, lack of protons

Beta particles are electrons (but not from e cloud !!!)

Decay of neutrons

$$^{1}_{0}n \rightarrow {}^{1}_{1}p + {}^{0}_{-1}e$$

e speed = 90% c

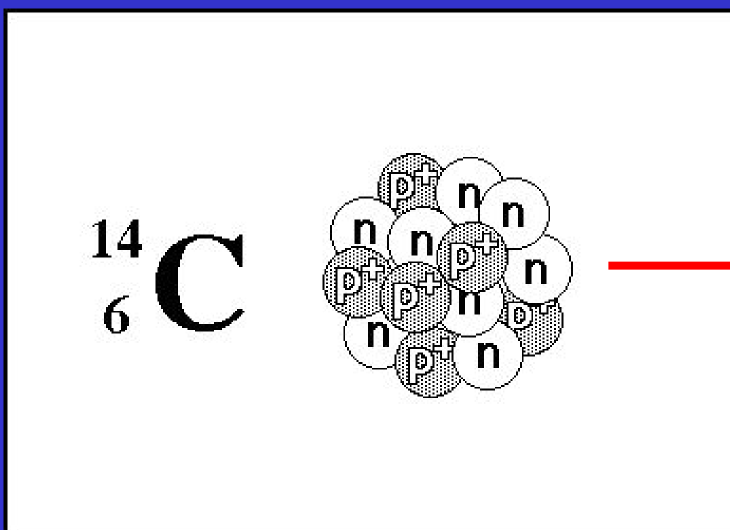
Penetration of several m in air
Stopped by 1cm of Al foil

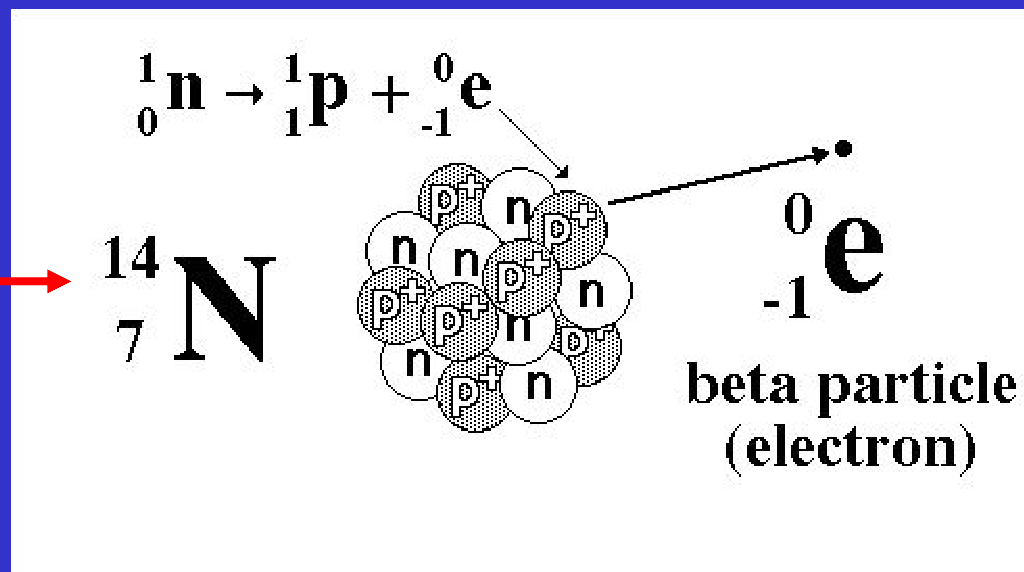
$$^{14}_{6}C \rightarrow {}^{14}_{7}N + {}^{0}_{-1}e$$

Beta Radiation

A shift of one element to the right in periodic table

$$^{A}_{Z}N_1 \longrightarrow \, ^{A}_{Z+1}N_2$$





Beta Radiation

Krypton-87

Zinc-71

Silicon-32

Cobalt-60

Magnesium-27

Sodium-24

Iron-59

Phosphor-32

$$^{A}_{Z}N_1 \longrightarrow {}^{A}_{Z+1}N_2$$

Gamma Radiation

Nuclei with excess of energy

Electromagnetic radiations with very short wavelength
High energy, MeV

Speed of light

Deep penetration, 500 m in air

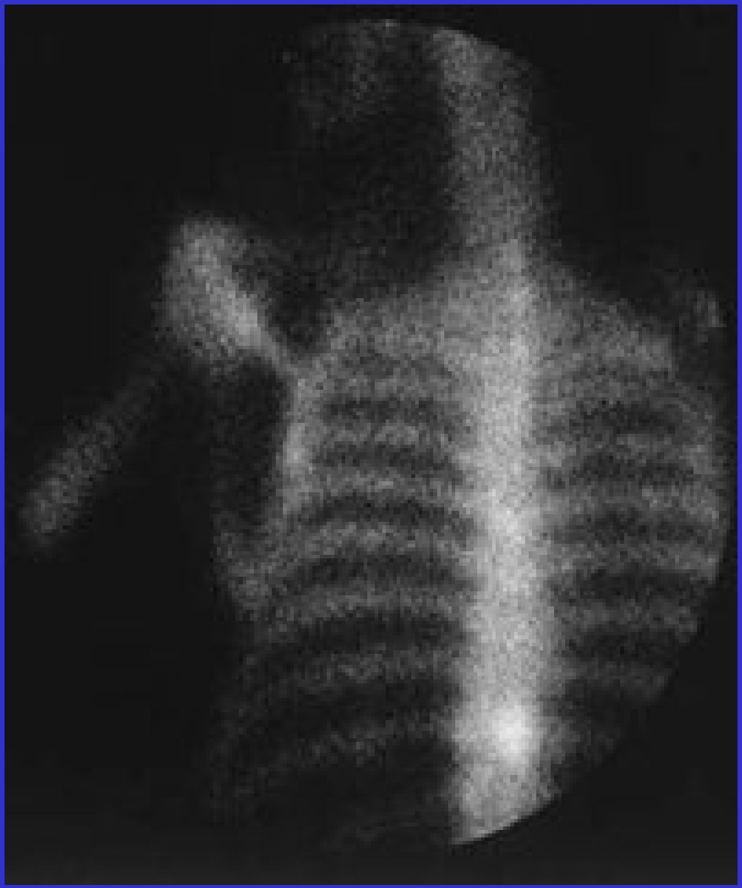
$^{m99}Tc \rightarrow {}^{99}Tc + \gamma$

Tracers

Gyorgy Hevesy 1913

NP 1943

$^{m99}Tc \rightarrow {}^{99}Tc + \gamma$



Positron Emission $^{0}_{1}e$

Nuclei with excess of protons, lack of neutrons

$$^{1}_{1}p \rightarrow ^{1}_{0}n + ^{0}_{1}e$$

$$^{11}_{6}C \rightarrow ^{11}_{5}B + ^{0}_{+1}e$$

Positron (antiparticle) recombines in 10^{-10} s

Very small penetration

Anihilation $_{1}e + _{-1}e \rightarrow \gamma$

$$^{A}_{Z}N_1 \longrightarrow ^{A}_{Z-1}N_2$$

A shift of one element to the left in periodic table

Positron Emission

Rubidium-81

Germanium-66

Praseodymium-140

Neon-18

Oxygen-15

Nitrogen-13

Copper-59

$$^{A}_{Z}N_1 \longrightarrow {}^{A}_{Z-1}N_2$$

Electron Capture

An electron from atom's electron cloud is captured by nucleus, e transforms p to n,
e from outer shell drops to the hole and emits gamma

$$ {}^{1}_{1}p + {}^{0}_{-1}e \rightarrow {}^{1}_{0}n $$

Nuclei with Z > 83 cannot stabilize by beta emission, positron emission, or electron capture

$$ {}^{A}_{Z}N_1 \qquad {}^{40}_{19}K + {}^{0}_{-1}e \rightarrow {}^{40}_{18}Ar \qquad {}^{A}_{Z-1}N_2 $$

A shift of one element to the left in periodic table

Electron Capture

Rubidium-83

Vanadium-48

Gallium-67

Beryllium-7

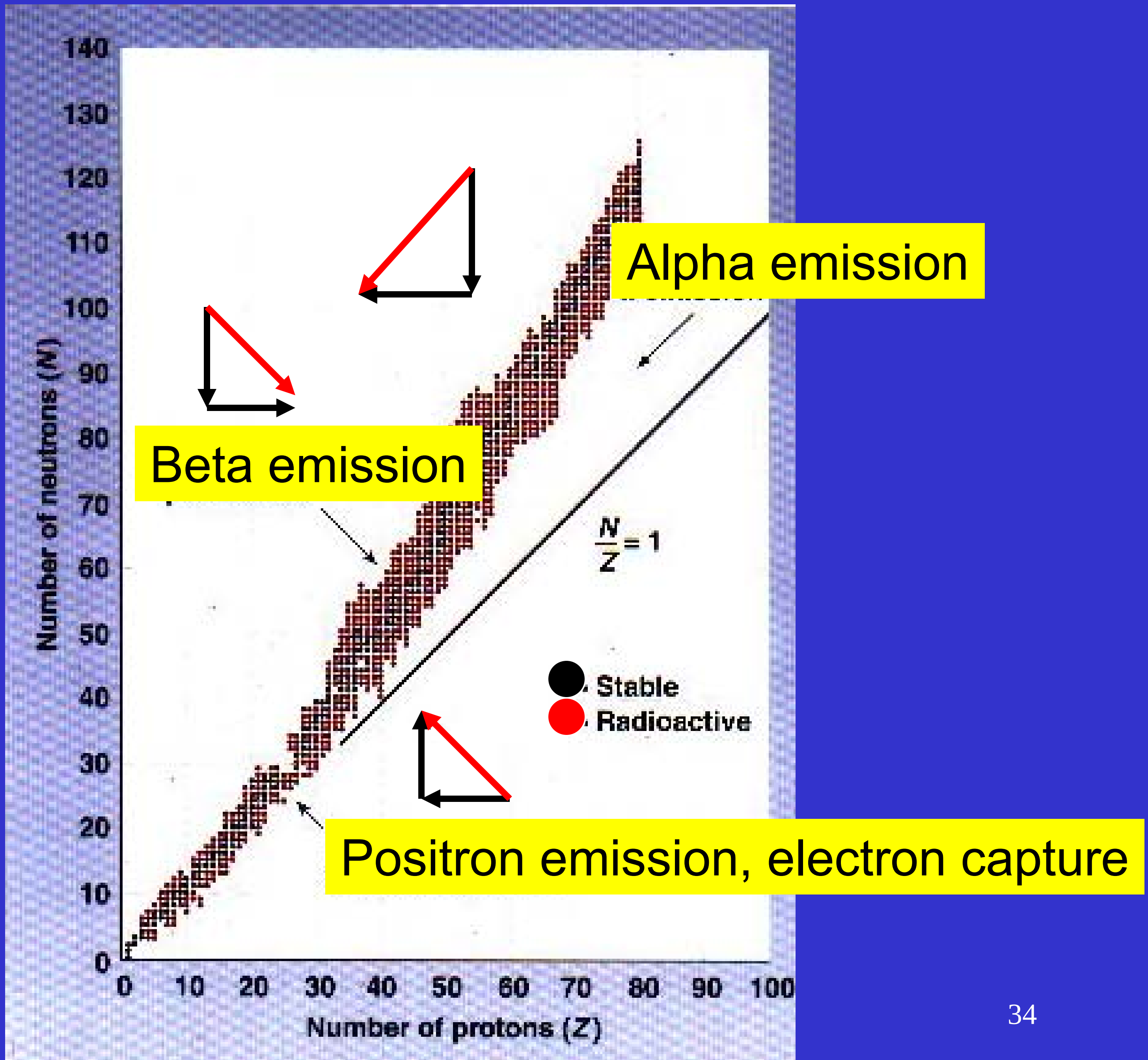
Calcium-41

Cobalt-57

Selenium-72

$$^{1}_{1}p + ^{0}_{-1}e \rightarrow ^{1}_{0}n$$

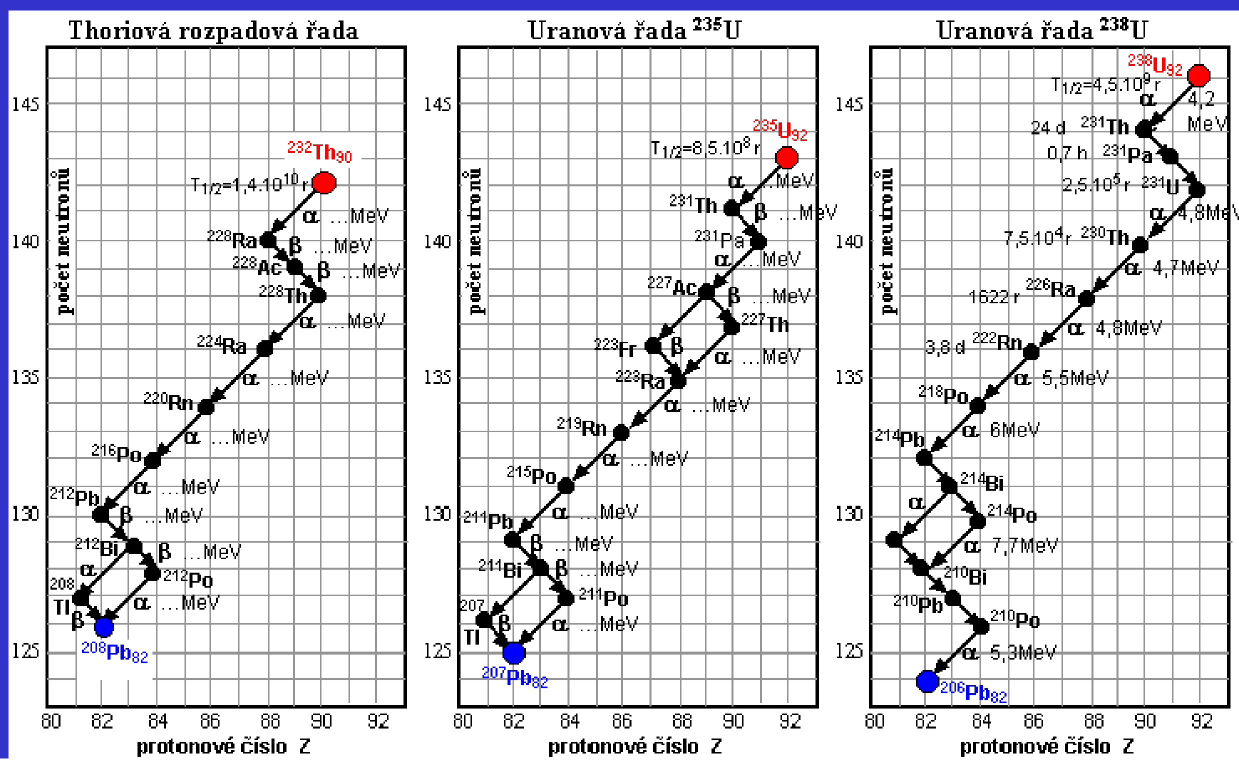
$$^{A}_{Z}N_1 \longrightarrow ^{A}_{Z-1}N_2$$



Alpha emission
Beta emission
Positron emission, electron capture
Number of neutrons (N)
Number of protons (Z)
N/Z = 1
Stable
Radioactive
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140

Nuclear Disintegration Series

Thorium ^{232}Th - ^{208}Pb	A = 4n
Neptunium (artificial) ^{241}Pu - ^{209}Bi	A = 4n+1
Uranium ^{238}U - ^{206}Pb	A = 4n+2
Actinuranium ^{235}U - ^{207}Pb	A = 4n+3



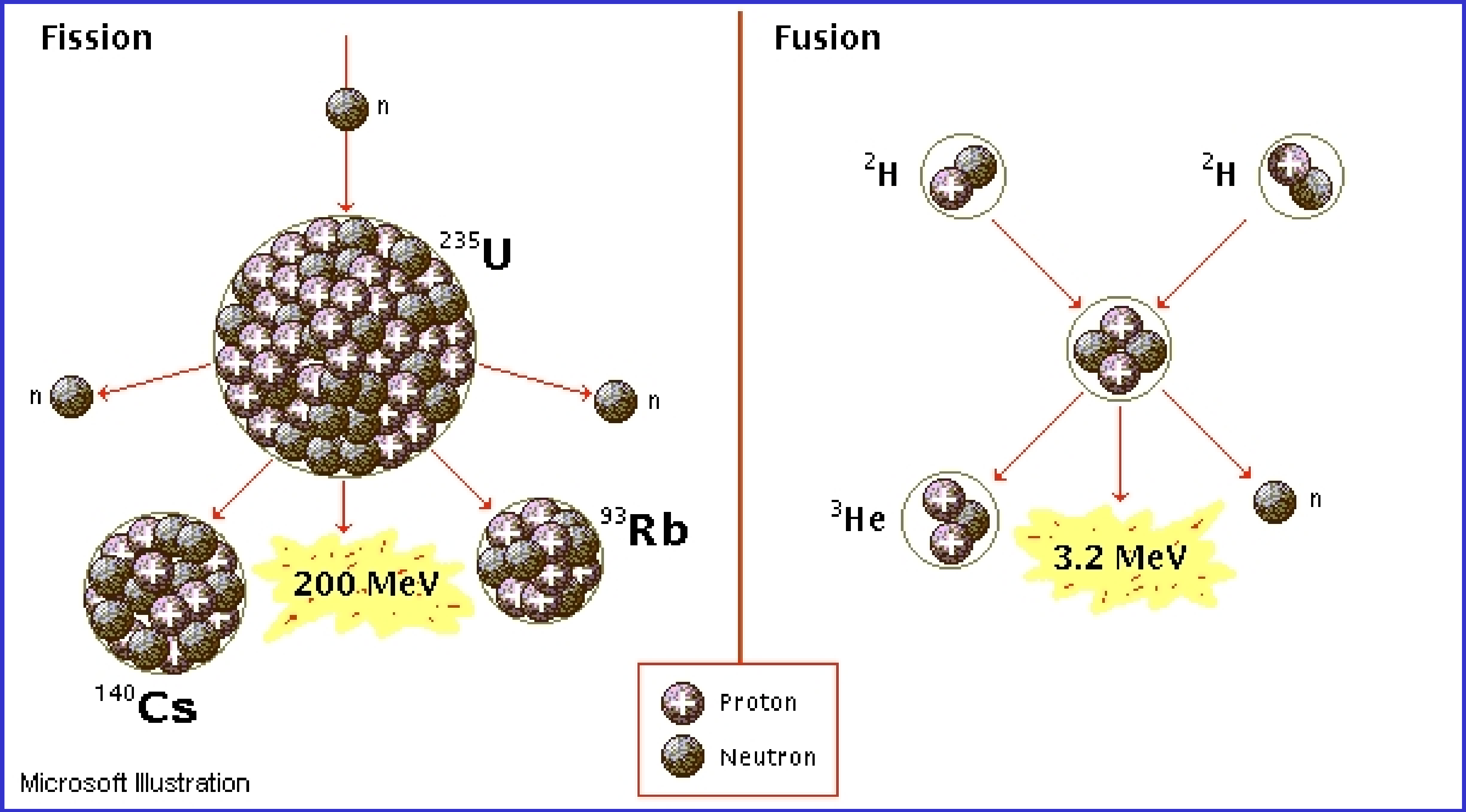
Spontaneous Fission

A heavy nucleus disintegrates to 2-3 fragments and one or more neutrons

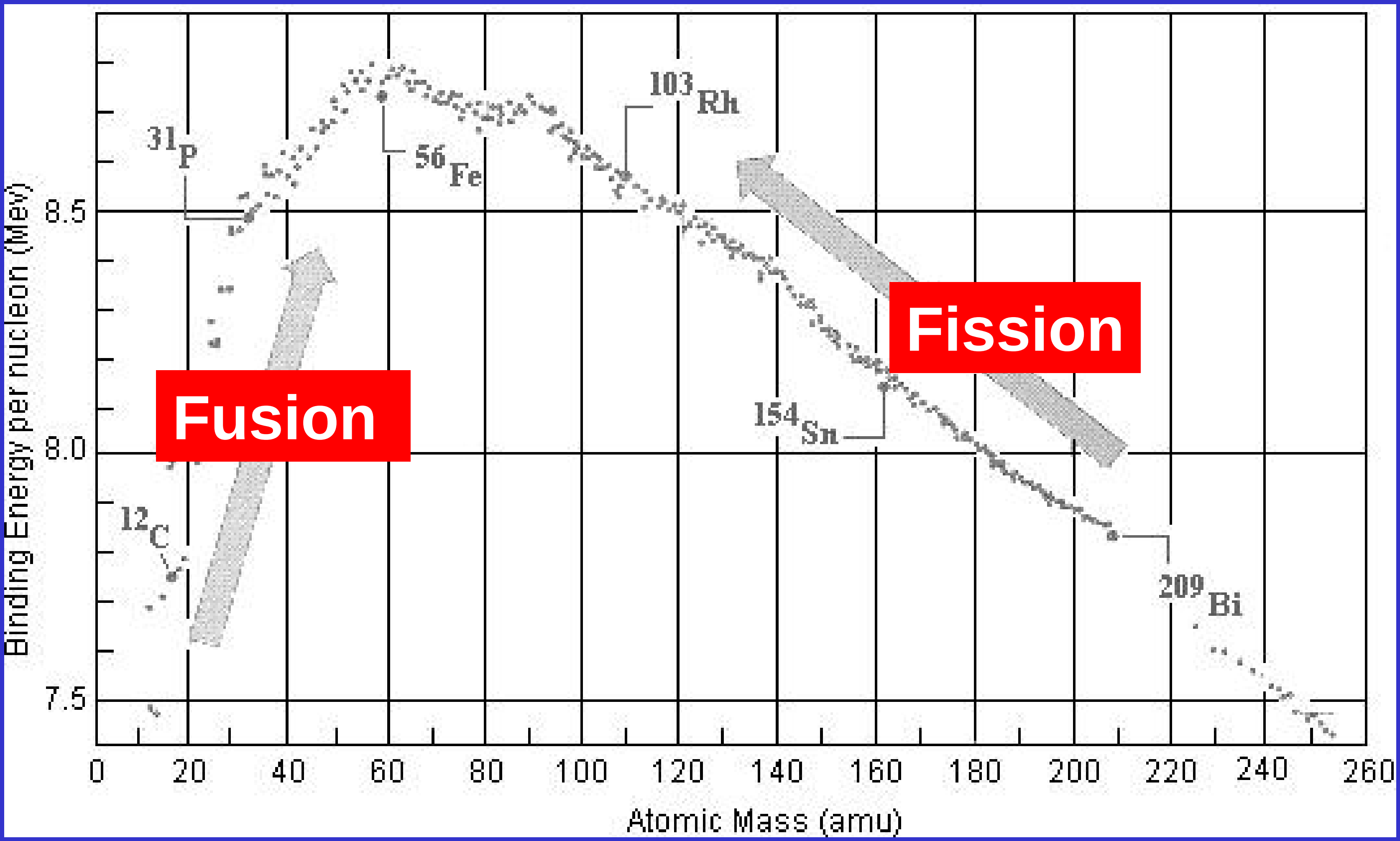
Nuclear Fusion and Fission

Nuclear Fission

Nuclear Fusion



Nuclear Fusion and Fission



Nuclear Synthesis in the Universe

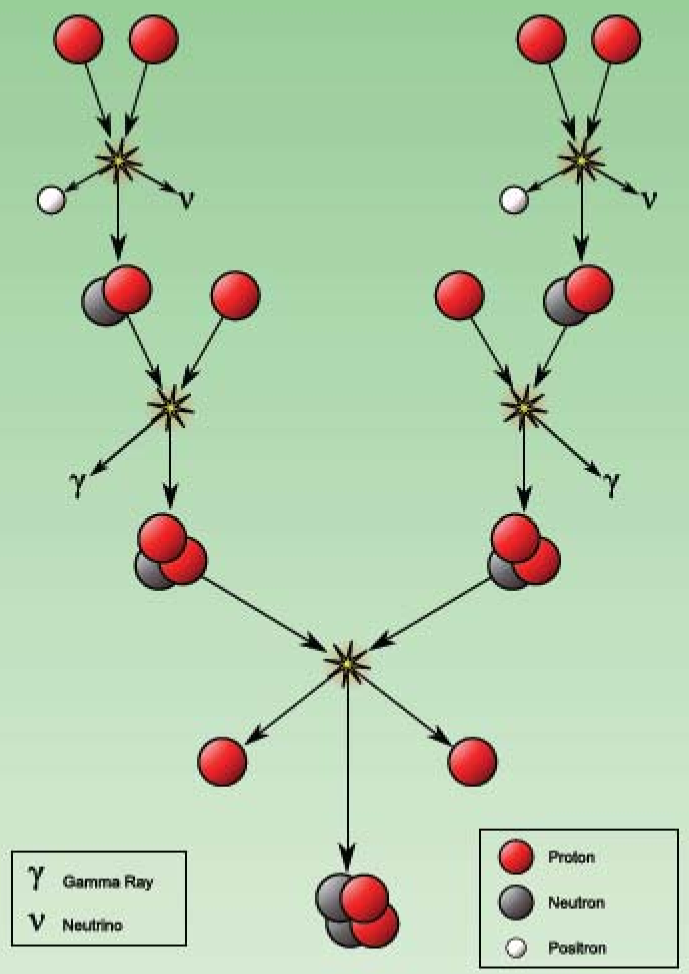
Big Bang $^{1}n \rightarrow {}^{1}H + e^{-}$

Sun (temperature = 2 ×10^{6} K inside, energy form PP or CN cycle)

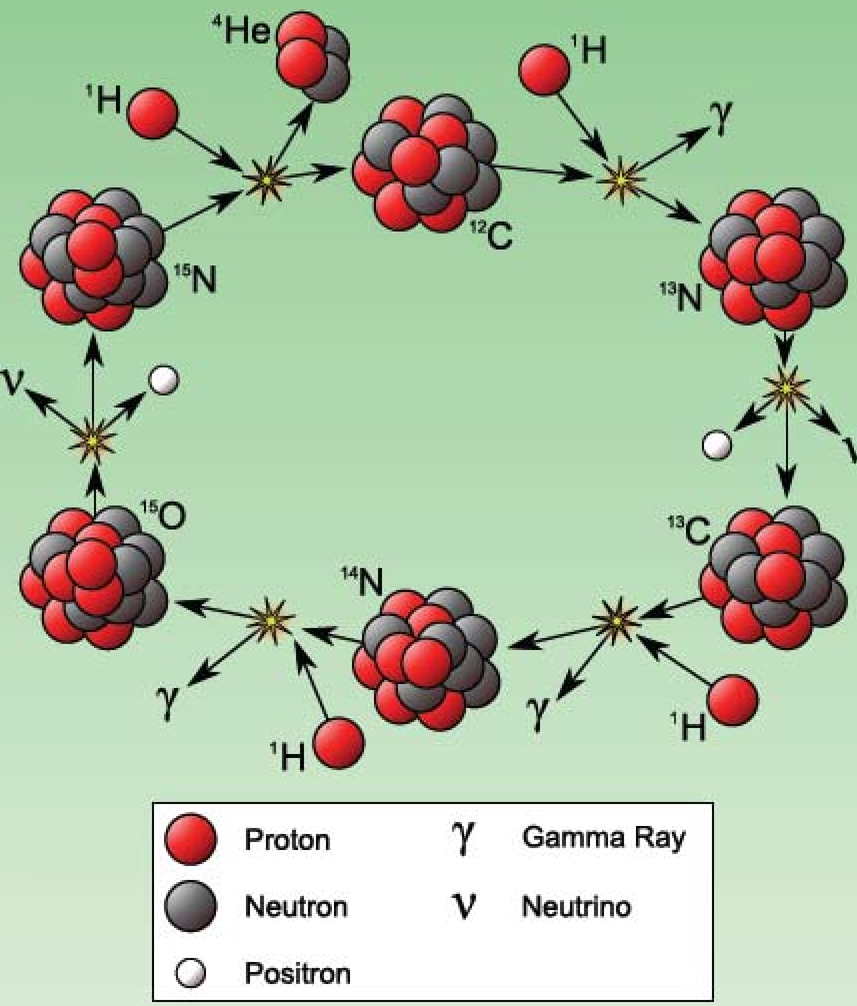
PP cycle

$^{1}H + {}^{1}H \rightarrow {}^{2}H + e^{+} + \nu + 0.42$ MeV
$^{1}H + {}^{2}H \rightarrow {}^{3}He + \gamma + 5.49$ MeV
$^{3}He + {}^{3}He \rightarrow {}^{4}He + 2\ {}^{1}H + 12.86$ MeV
$^{3}He + {}^{1}H \rightarrow {}^{4}He + e^{+}$
$e^{+} + e^{-} \rightarrow \gamma + 1.02$ MeV

PP cycle



CN cycle



Nuclear Synthesis in the Universe

Sun $\rightarrow$ red giant $\rightarrow$ white dwarf

$^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma + 1.59$ MeV

$^{4}He + {}^{4}He \rightarrow {}^{8}Be$

$^{7}Be + p \rightarrow {}^{8}B + \gamma + 13$ MeV

$^{8}B \rightarrow {}^{8}Be + \gamma + e^{+} + 10.78$ MeV

$^{8}Be + {}^{4}He \rightarrow {}^{12}C$

$^{12}C + {}^{4}He \rightarrow {}^{16}O$

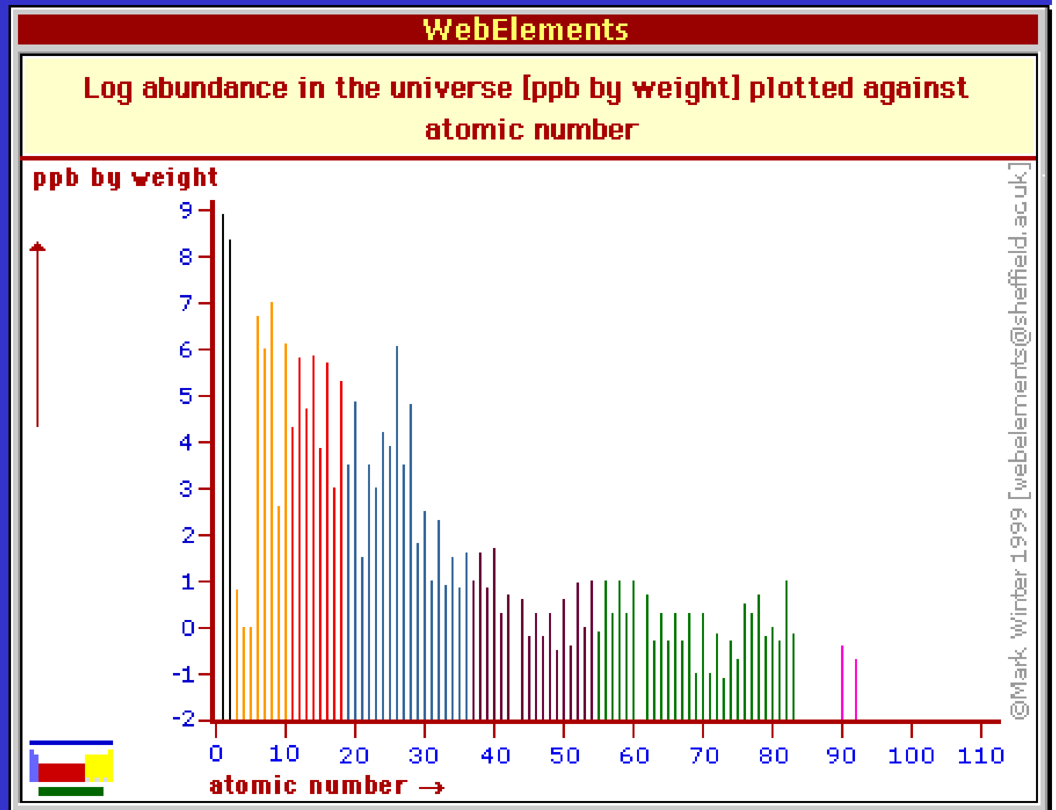
Nuclear Synthesis in the Universe

Heavy stars

$^{12}C \rightarrow$ Ne, Mg

$^{16}O \rightarrow$ Si, S

Si $\rightarrow$ ^{58}Fe



Fe nuclei are the most stable, what next?

Supernova explosion high neutron fluxes

Fe + n $\rightarrow$ Au $\rightarrow$ Pb $\rightarrow$ U

Thermonuclear Reactions

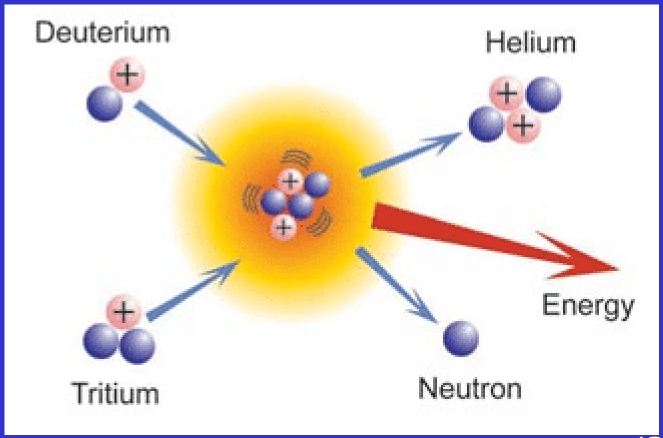
$$^{2}H + {}^{2}H \rightarrow {}^{3}He + n + 3.3\ MeV$$

$$^{2}H + {}^{2}H \rightarrow {}^{3}H + p + 4.0\ MeV$$

$$^{3}H + {}^{2}H \rightarrow {}^{4}He + n + 17.6\ MeV$$

ITER Cadarache, France

National Ignition Facility, USA

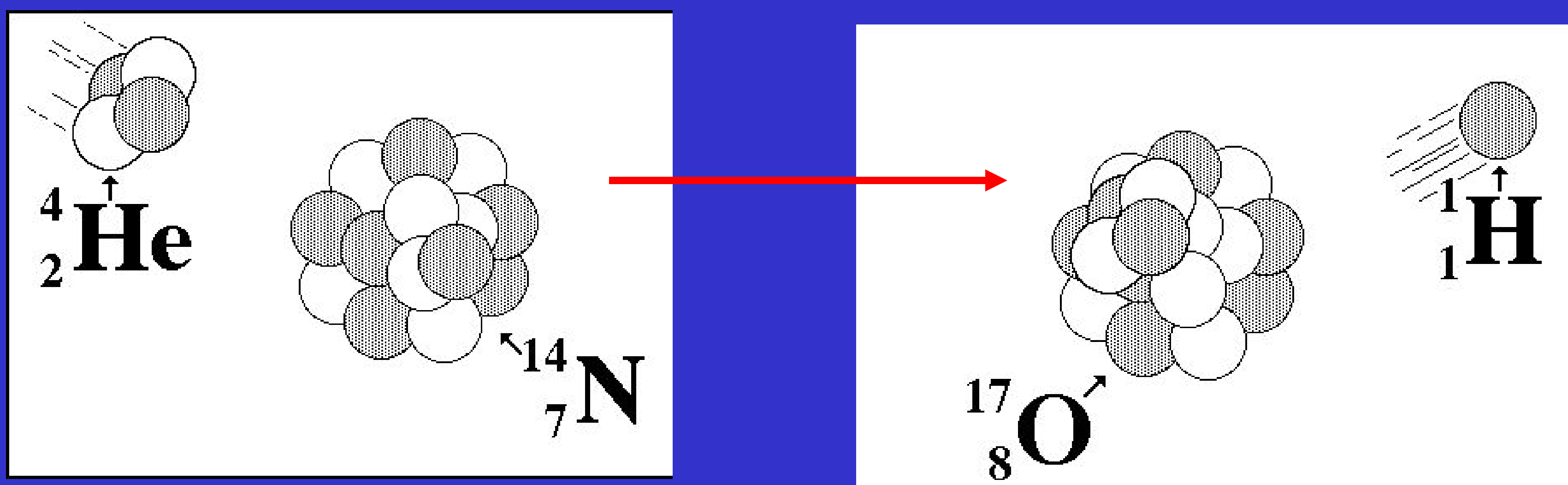


Transmutations

1919, Rutherford, 1st artifical synthesis of an element

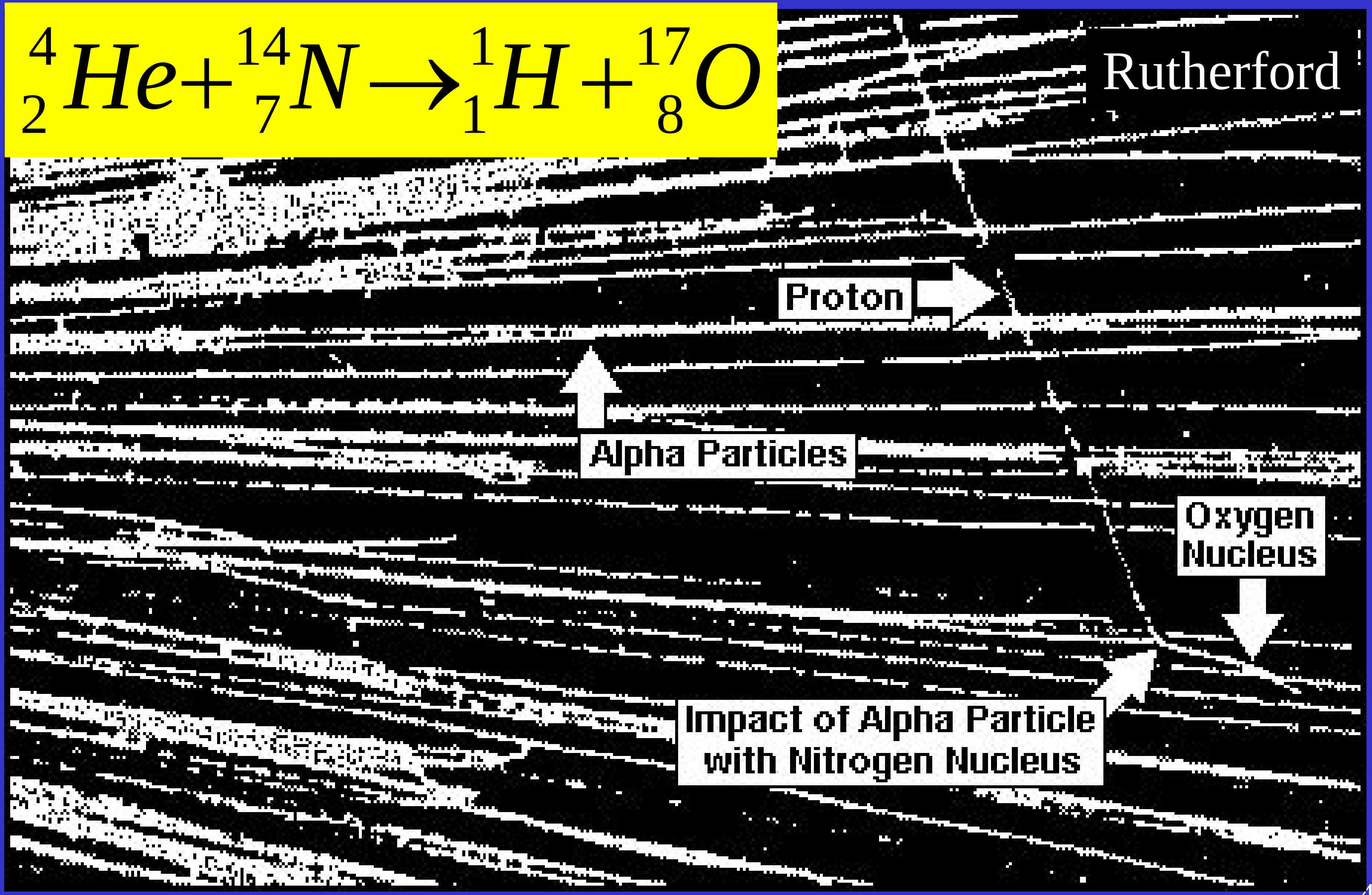
$$^{4}_{2}He + ^{14}_{7}N \rightarrow ^{1}_{1}H + ^{17}_{8}O$$

$^{14}N(\alpha, p)^{17}O$



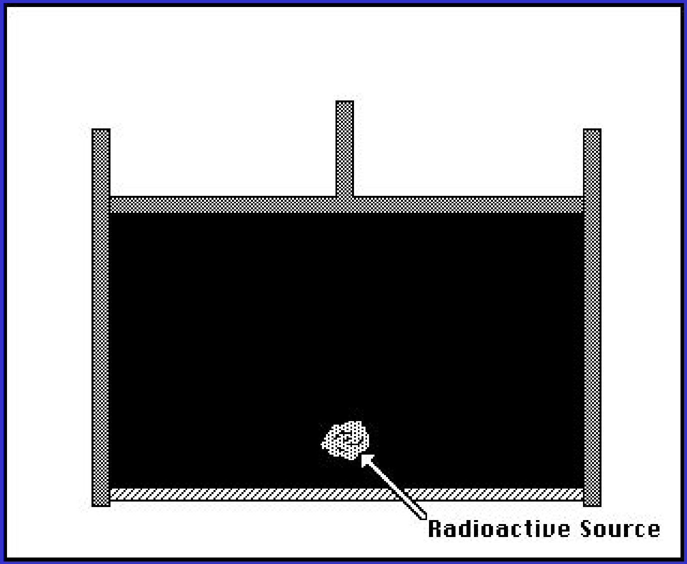
Transmutations

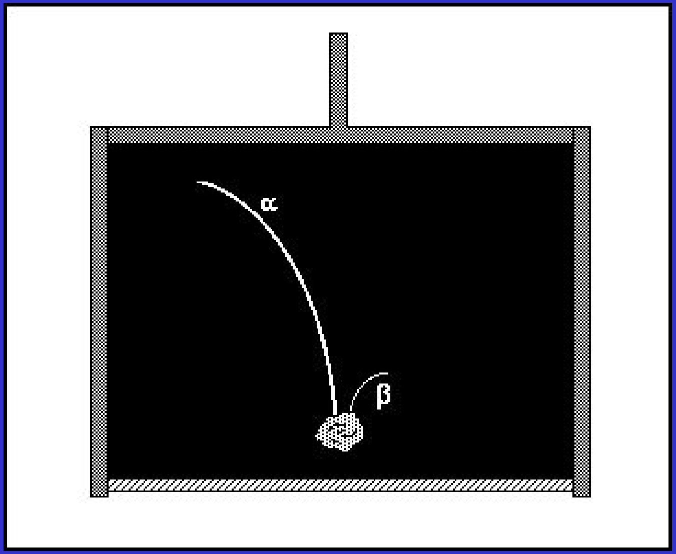
$$^{4}_{2}He + ^{14}_{7}N \rightarrow ^{1}_{1}H + ^{17}_{8}O$$



Wilson Cloud Chamber

Charles Wilson (1869-1959) NP in Physics 1923





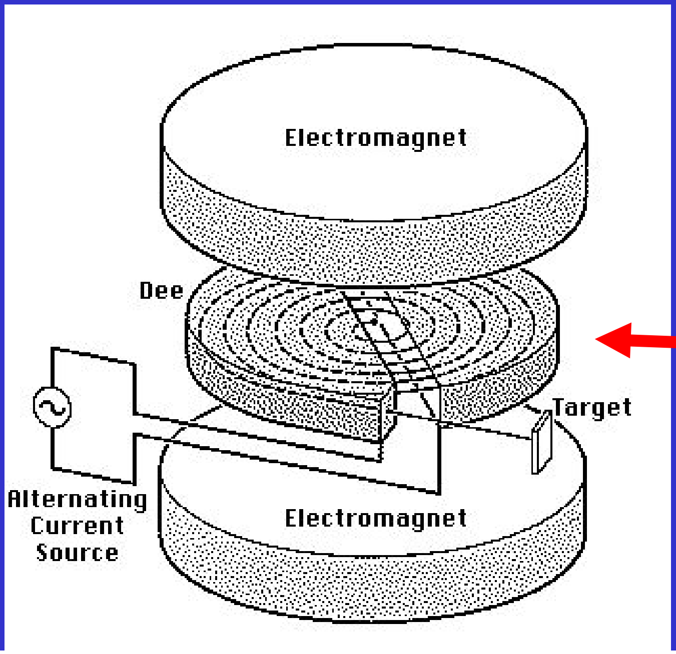
Gas (air, He, Ar,...)
and vapors of water or
ethanol in a chamber,
piston for volume change

Expansion, cooling,
supersaturated vapor,
particles ionize gas atoms,
condensation – trail

Cyclotron

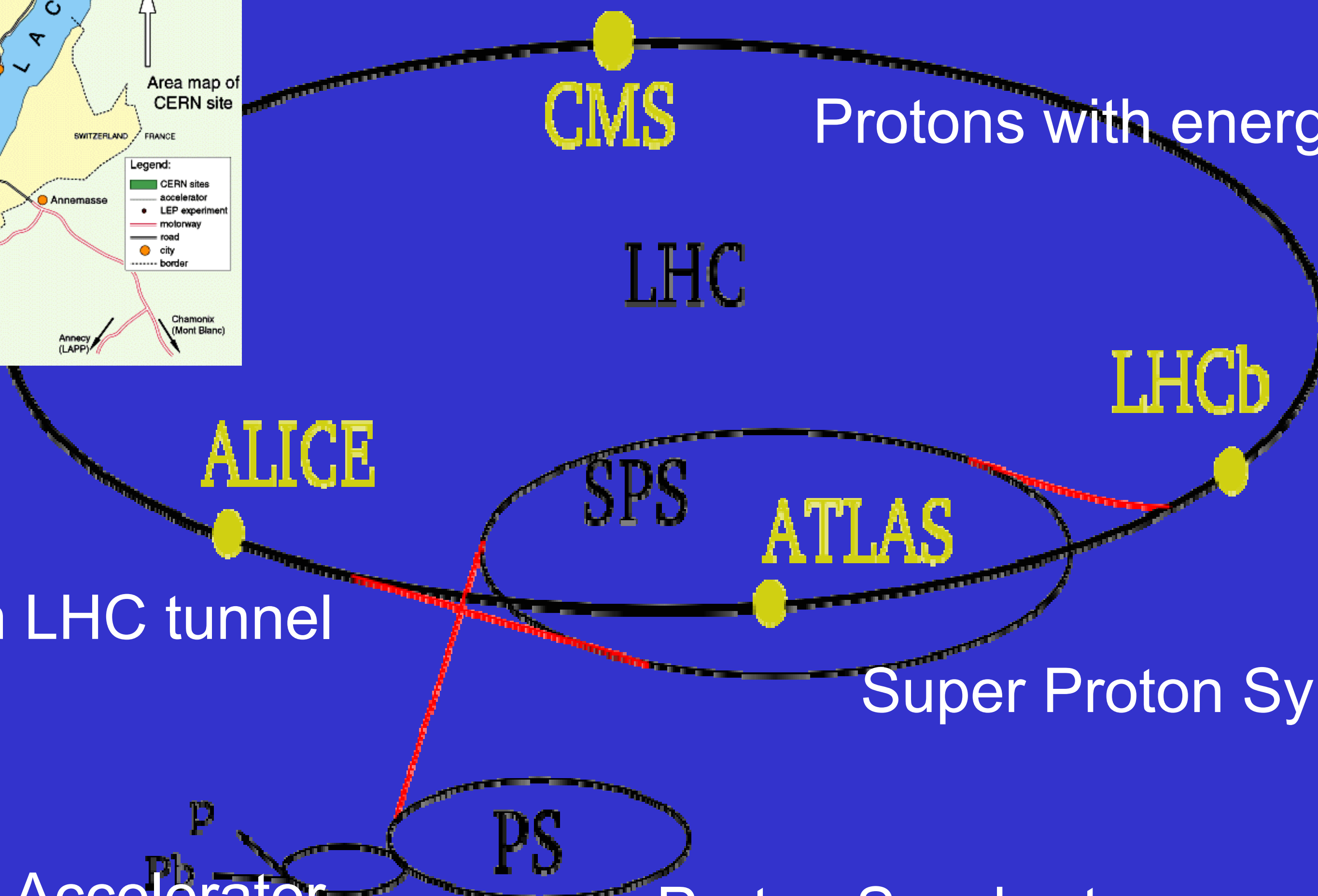
1929
Accelerator of positive ions (H^+, D^+, ...)
Pass thru potential step,
alternating pos/neg charging of Dees,
Circular movement in magnetic field,
energies up to 100 MeV

Ernest O. Lawrence
(1901-1958)
NP in Physics 1939



Hollow electrodes Dees

Large Hadron Collider



Protons with energies 7 TeV

27 km LHC tunnel

Super Proton Synchrotron

Linear Accelerator
(protons and ions)

Proton Synchrotron

Nuclear Fission

1932
John D. Cockcroft (1897-1967)
and Ernest T. S. Walton (1903-1995)

Cascade accelerator, protons 800 keV

The 1st splitting of a stable nucleus by an accelerated particle

$$ {}_{1}^{1}H + {}_{3}^{7}Li \rightarrow {}_{2}^{4}He + {}_{2}^{4}He $$

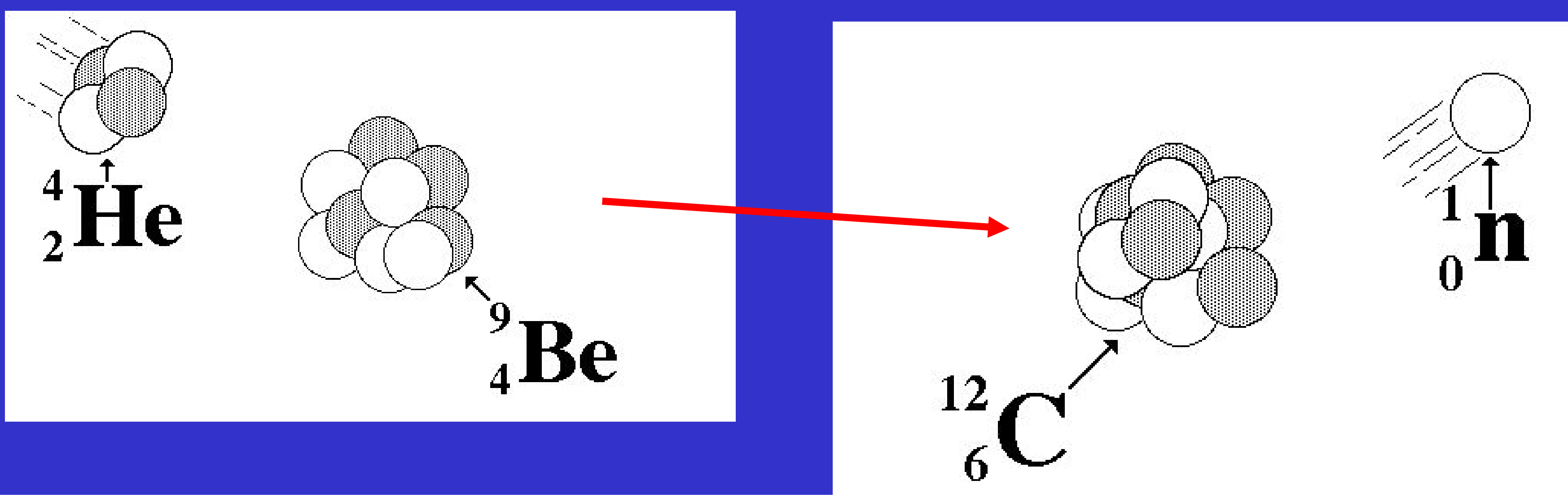
1951 joint NP in Physics

1932 **Discovery of a Neutron**

$$ {}^{4}_{2}He + {}^{9}_{4}Be \rightarrow {}^{12}_{6}C + {}^{1}_{0}n $$

James Chadwick
(1891-1974)
NP in Physics 1935

neutron = particle with zero charge, spin ½
m = 1.67470 10^{-27} kg



Transmutations

Cyclotron

$$ {}_{2}^{4}He + {}_{92}^{238}U \rightarrow {}_{94}^{239}Pu + 3\,{}_{0}^{1}n $$

Bombardment with neutrons

$$ {}_{27}^{59}Co + {}_{0}^{1}n \rightarrow {}_{27}^{60}Co $$

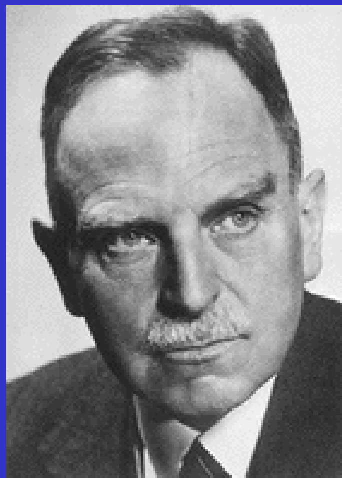
Artificial Radioactivity

1933

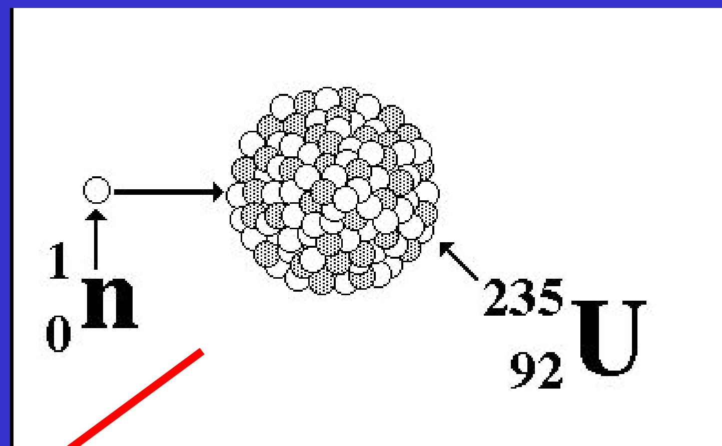
Frederic and Irene Joliot-Curie
(1900-1958)   (1897-1956)

$$ {}_{2}^{4}He + {}_{13}^{27}Al \rightarrow {}_{15}^{30}P + {}_{0}^{1}n $$

$$ {}_{15}^{30}P \rightarrow {}_{14}^{30}Si + {}_{+1}^{0}e $$

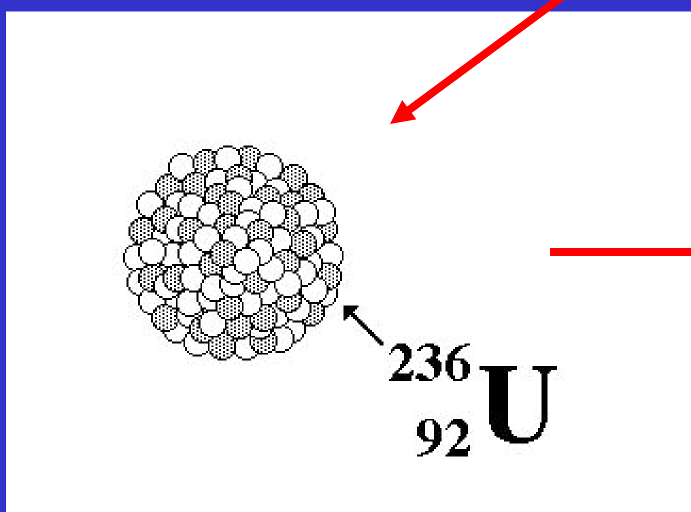


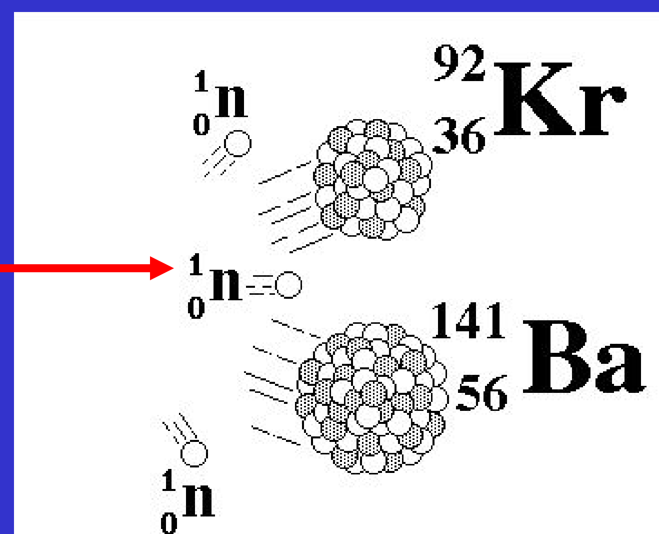
Nuclear Fission



^{235}U, 0.71%
Slow neutrons

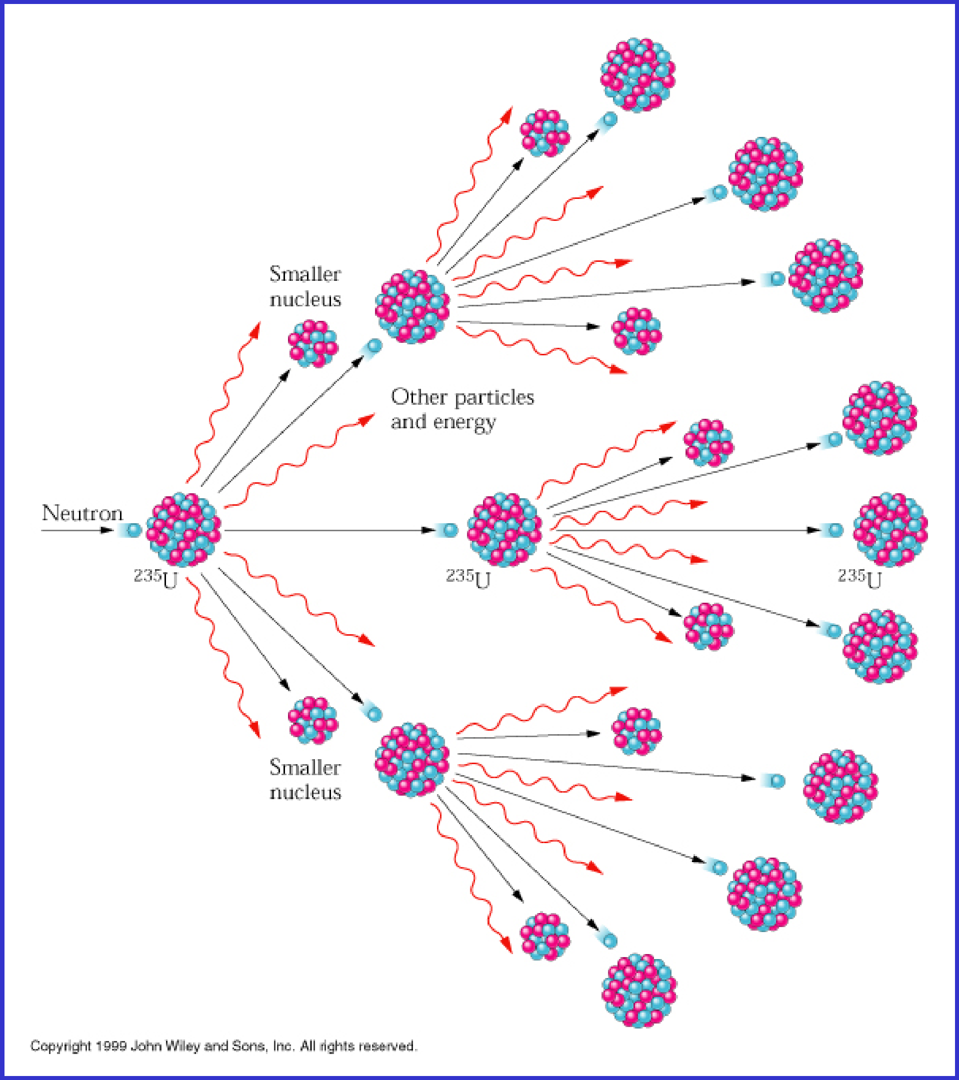
Otto Hahn
(1879-1968)
NP in Physics 1944





190 MeV

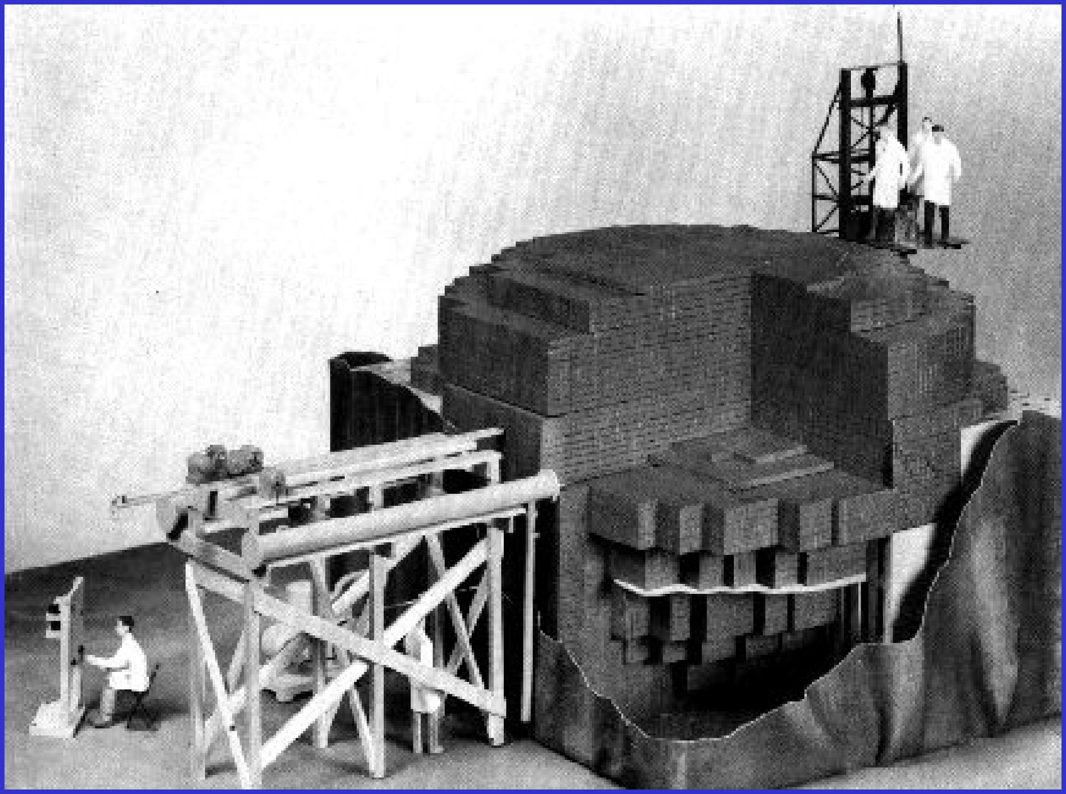
Chain Reaction



Nuclear Reactor

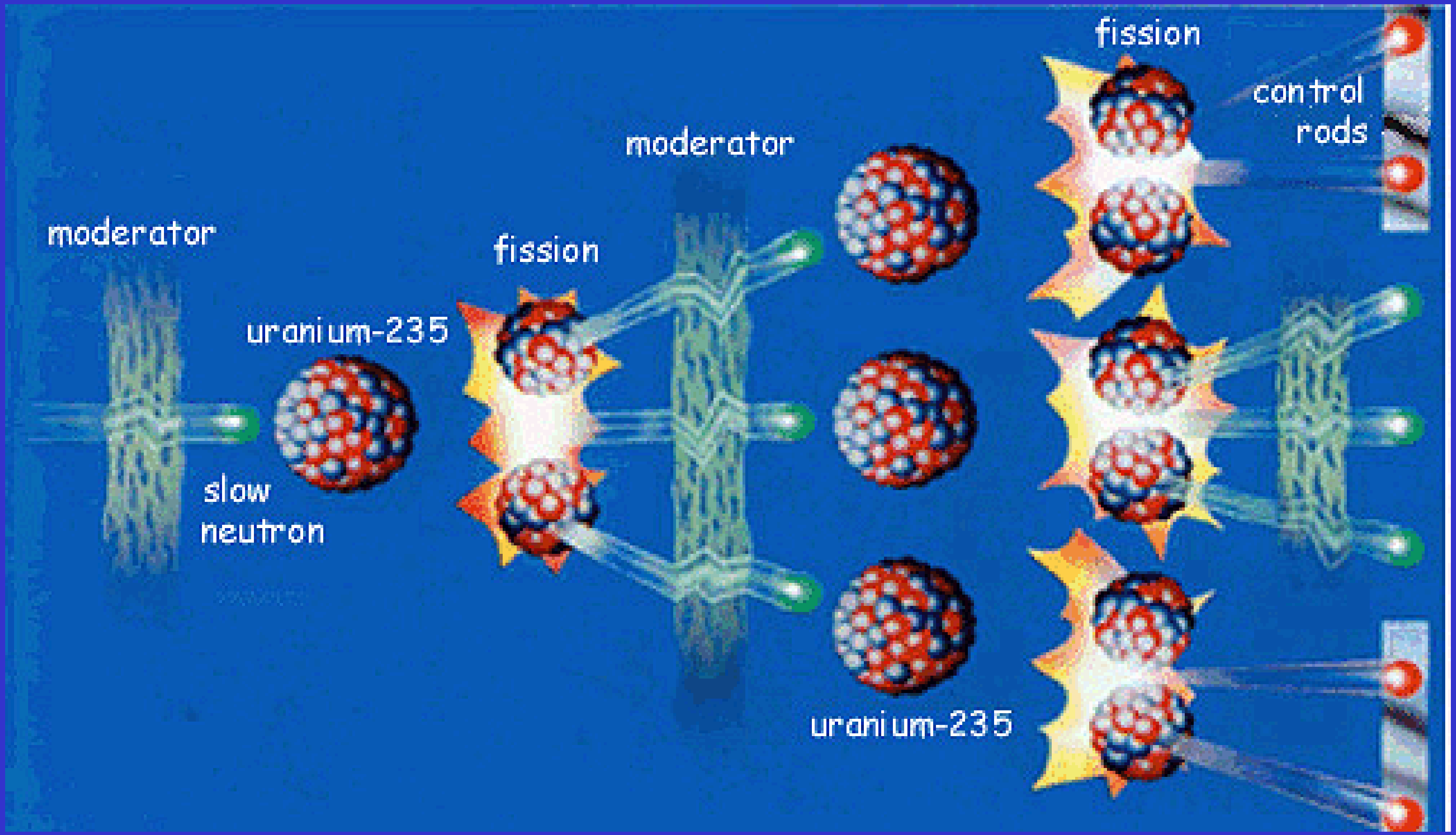
1942 Chicago

1st Fission reaction of ^{235}U



Enrico Fermi
(1901-1954)
NP in Physics 1938

Controlled Fission Reaction of ^{235}U



Moderator = slowing of neutrons – graphite
Cd absorbs neutrons – captures n

Transuranium Elements

Untill 1940 heaviest natural element Z = 92 (U)
$Z \geq 93$ (Np) transuranium, only artificial

1940 the 1st artificial = ${}^{239}_{93}Np$

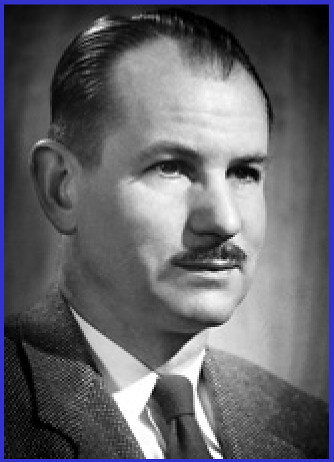
Bombardment with neutrons
${}^{238}U + n \rightarrow {}^{239}U \rightarrow {}^{239}Np + e$

${}^{239}_{94}Pu$

Adress of Glenn Seaborg
Sg, Lr, Bk, Cf, Am

Glenn T. Seaborg
(1912- 1999)

Joint NP
in Chemistry 1951



Edwin M. McMillan
(1907- 1991)

Synthesis of Transuranium Elements

Bombardment with positive ions

^{4}He, ^{12}C, ^{15}N, ^{18}O, ...

Synthesized transuranium elems to Z = 118

$^{208}_{82}Pb + ^{62}_{28}Ni \rightarrow ^{269}_{110}Ds + ^{1}n$ $t_{1/2} = 270$ ms

$^{208}_{82}Pb + ^{64}_{28}Ni \rightarrow ^{271}_{110}Ds + ^{1}n$

$^{209}_{83}Bi + ^{54}_{24}Cr \rightarrow ^{262}_{108}Bh + ^{1}n$

Joint Institut of Nuclear Research, Dubna, Russia
GSI (Gesellschaft fur Schwerionenforschung), Germany
LBL (Lawrence Berkeley Lab), USA

Synthesis of Transuranium Elements

Bombardment with positive ions

^{4}He, ^{12}C, ^{15}N, ^{18}O, ... ^{70}Zn

Synthesized transuranium elems to Z = 118

$^{249}_{97}Bk + ^{48}_{20}Ca \rightarrow ^{293}_{117}X + 3\ ^{1}n$

The last named element

$^{208}_{82}Pb + ^{70}_{30}Zn \rightarrow ^{278}_{112}Cn \rightarrow ^{277}_{112}Cn + ^{1}n$

GSI (Gesellschaft fur Schwerionenforschung), Germany

Kinetics of Radioactive Decay

$-dN/dt = k\,N$

$dN/N = -k\,dt$

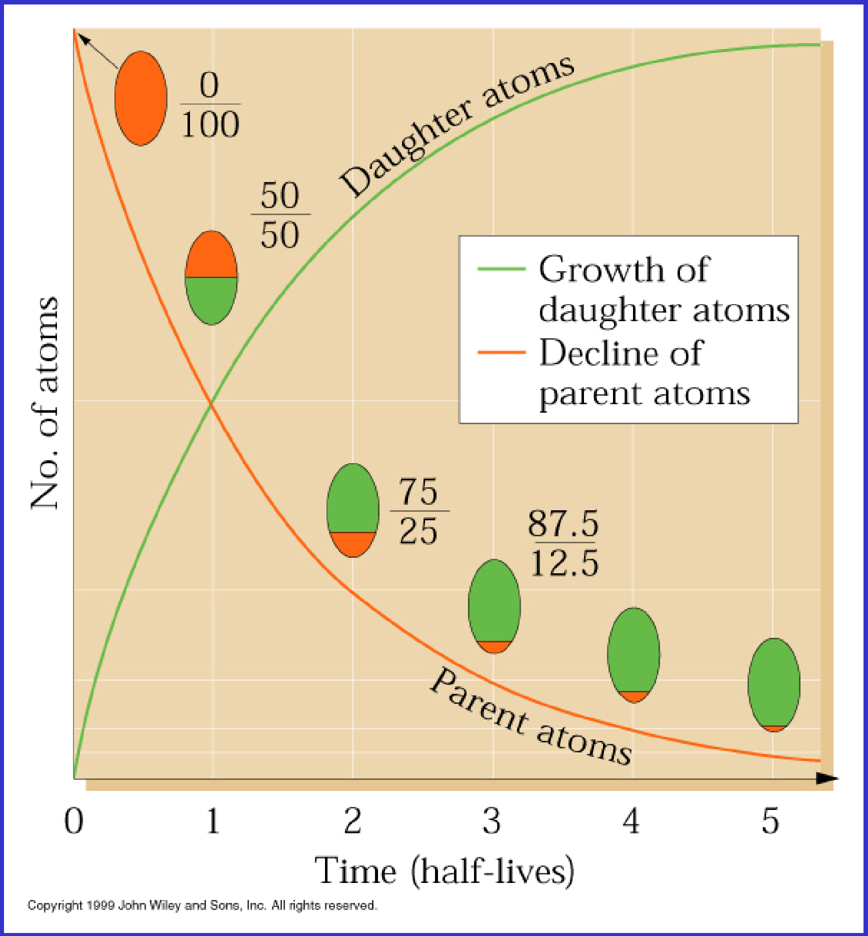
Integrate
$t = 0 \quad N = N_0$

$\ln(N/N_0) = -k\,t$

$N/N_0 = \exp(-k\,t)$

$N = N_0 \exp(-k\,t)$

N



t

Half-life, $t_{1/2}$

$t = t_{1/2} \quad N = N_0/2$

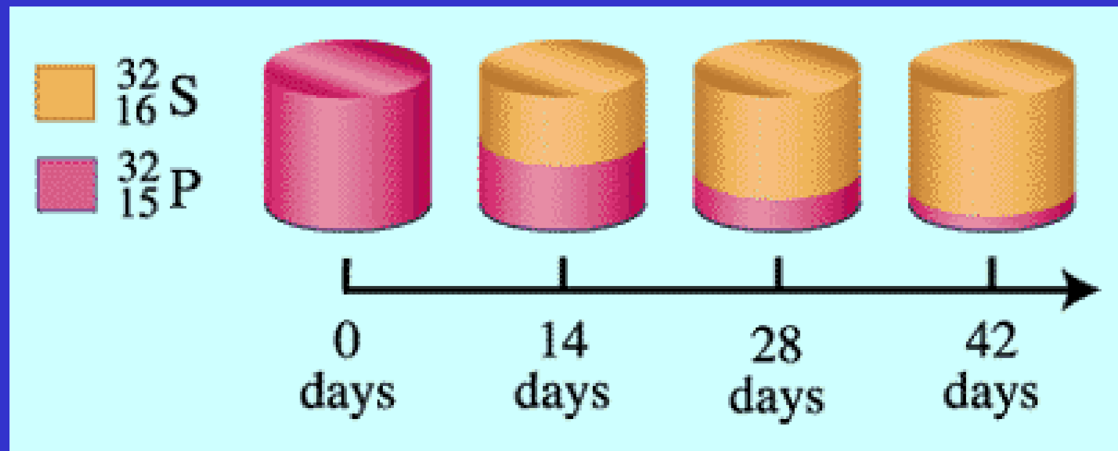
$\ln(N/N_0) = -k\, t$

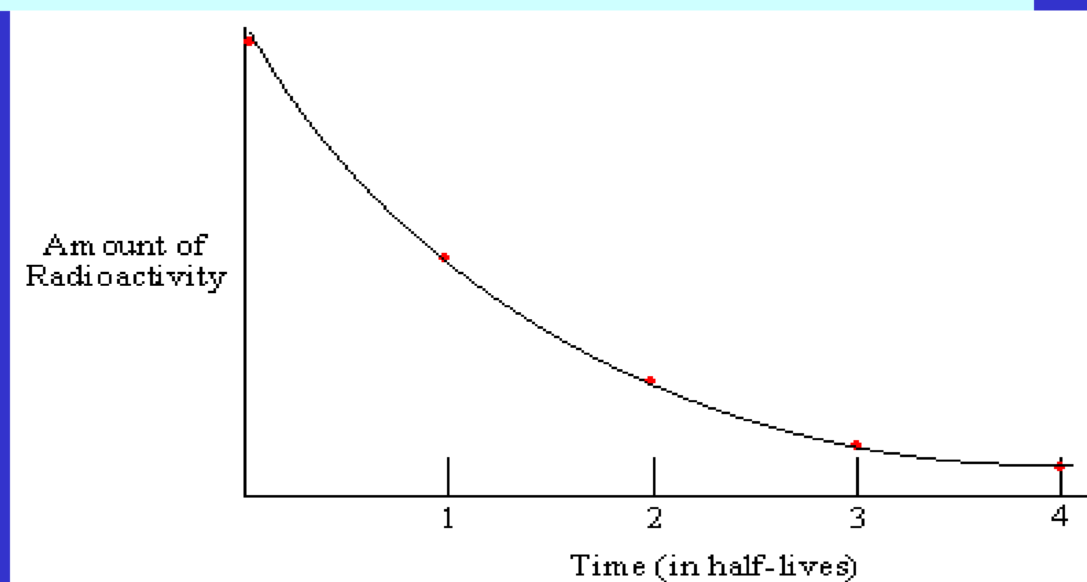
$\ln(1/2) = -k\, t_{1/2}$

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

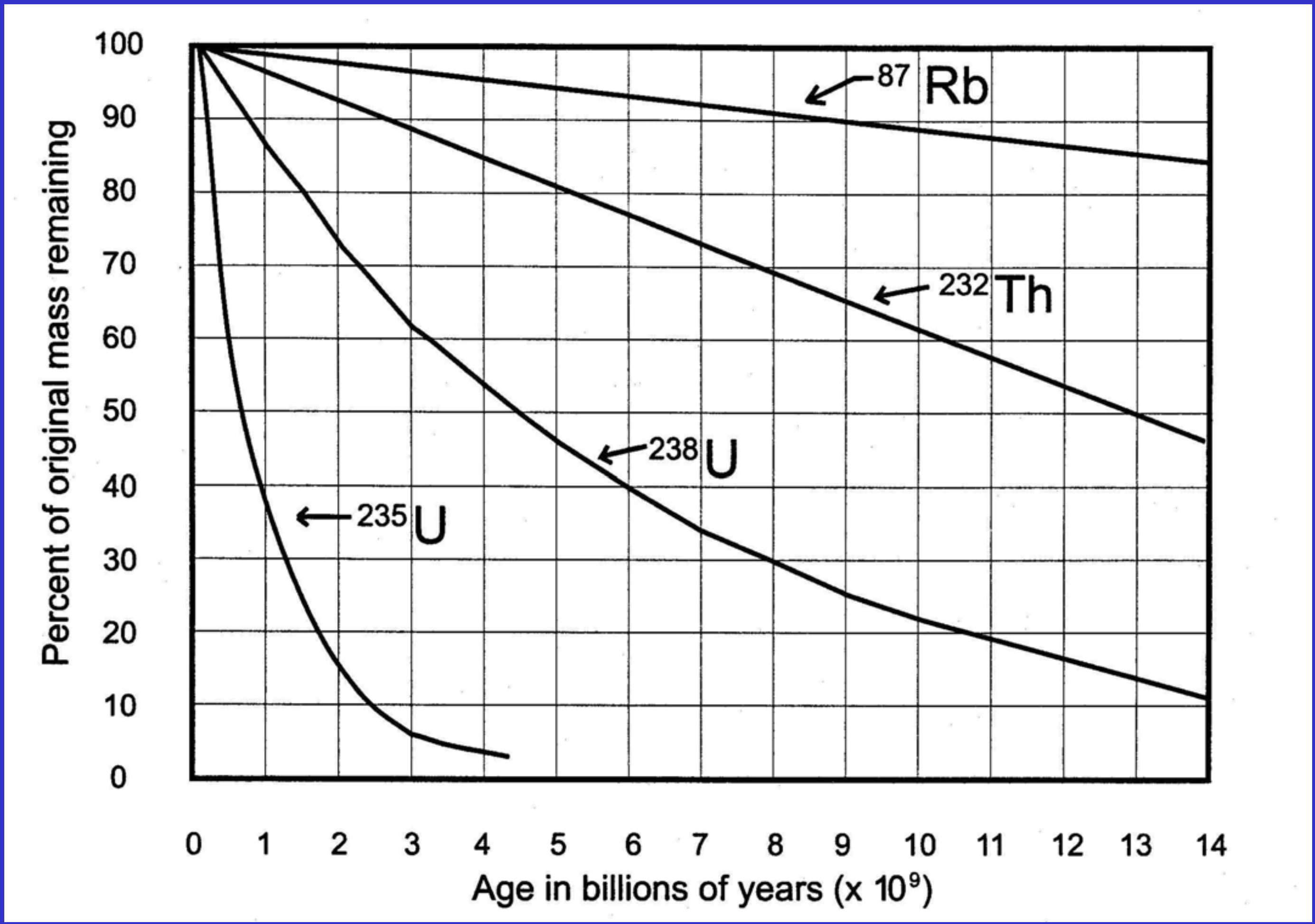
$k = \ln(2) / t_{1/2}$

$\ln(N/N_0) = -t \ln(2) / t_{1/2}$





Half-life, $t_{½}$



Percent of original mass remaining
100
90
80
70
60
50
40
30
20
10
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14
Age in billions of years (x 10⁹)
87 Rb
232 Th
238 U
235 U

Carbon Dating ^{14}C

Willard Libby (1908-1980)
NP in Chemistry 1960

^{14}C continually produced in high atmosphere

$^{14}_{7}N + ^{1}_{o}n$ (cosmic radiation) $\rightarrow ^{14}_{6}C + p^{+}$

Decays by beta emission
with half-life of 5730 y

$^{14}_{6}C \rightarrow ^{14}_{7}N + ^{0}_{-1}e$

In atmosphere and living plants (CO_2, photosynthesis), established equilibrium concentration of ^{14}C. After death of organism, concentration of ^{14}C decreases. $^{14}C/ ^{12}C$ established by mass spectrometry