同位素地质年代学与放射成因同位素地球化学

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课程内容安排

第一节

1. 引言
2. 核素物理与同位素
3. 同位素衰变原理与概念

第二节

4. 实验室介绍
5. 超净化实验室和同位素化学分离纯化
6. 质谱计原理和同位素比值测量

第三节

7. 同位素地球化学示踪原理
8. 岩石圈和地幔同位素特征

第四节

9. 同位素年代学基本原理
10. Rb-Sr和Sm-Nd定年方法

第五节

11. U-Pb定年方法

第六节

12. Ar-Ar定年方法

13. 其它定年方法

第七节

14. 应用实例

1）欧洲华力西造山带

2）大别－苏鲁超高压造山带

3）土耳其北部特提斯造山带

第八节

答疑和测验

Introduction to

Isotope Geochemistry

Isotope geochemistry has grown over the last 40 years to become one of the most important fields in the Earth Sciences as well as in Geochemistry.

White (1998)

The growth in the importance of **Isotope Geochemistry** reflects its remarkable success in attacking fundamental problems of Earth Science, as well as in astrophysics and physics.

White (1998)

Isotope Geochemistry has played an important role in transforming geology from a qualitative, observational science to a modern quantitative one.

The impact of **Isotope Geochemistry** on: ore genesis, petrogenesis, crustal evolution, mantle dynamics, global tectonics and geodynamics, volcanology, hydrology, oceanic circulation, paleontology, anthropology and archeology, paleoclimate, environmental protection and monitoring, monitors of the cosmic ray flux, etc.

Isotopes in Geosciences

- Stable Isotope Geochemistry
- Radiogenic Isotope Geochemistry

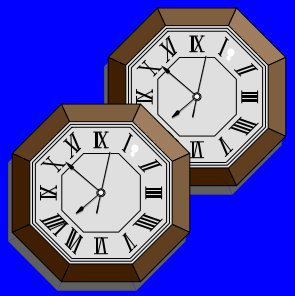
Applications of Radiogenic Isotopes

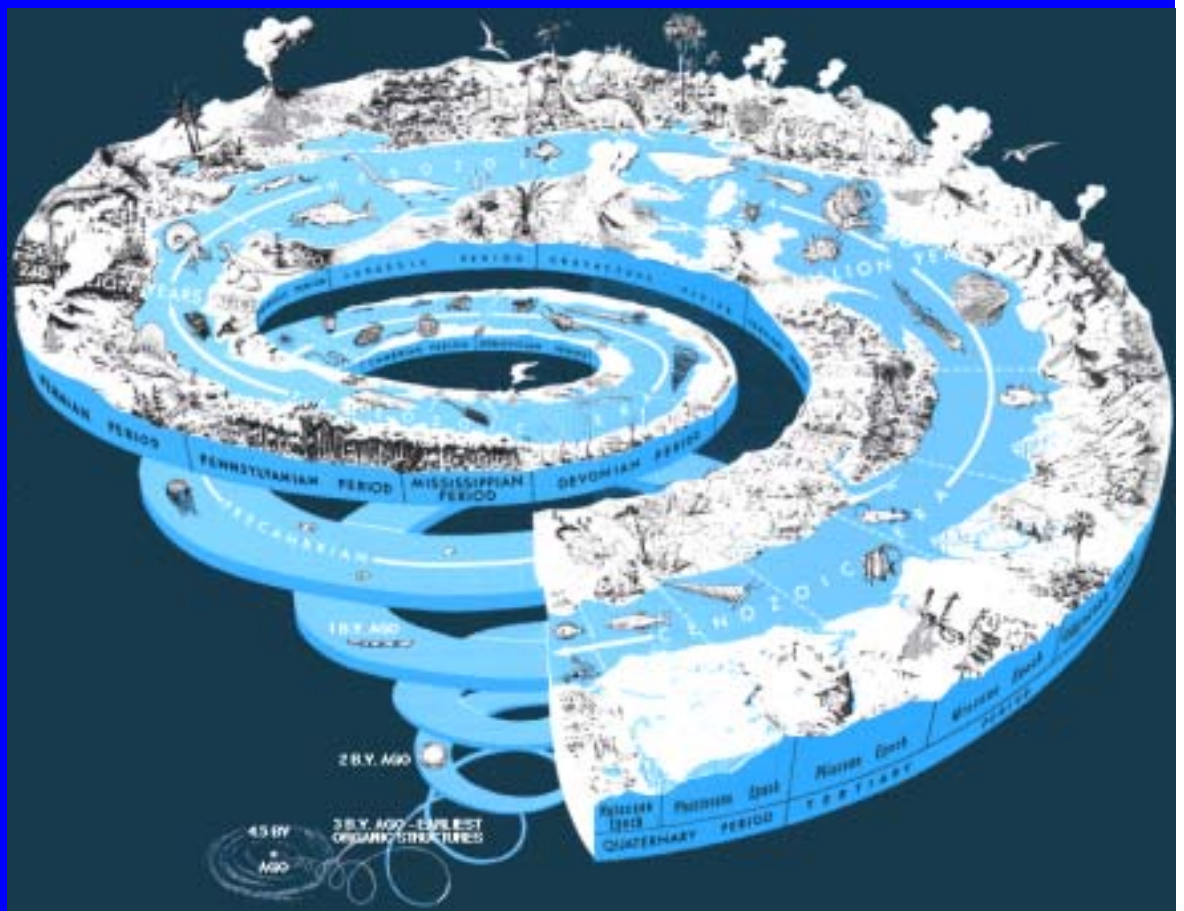
1. Geochronology
2. Isotope Tracer

Isotope Geochronology



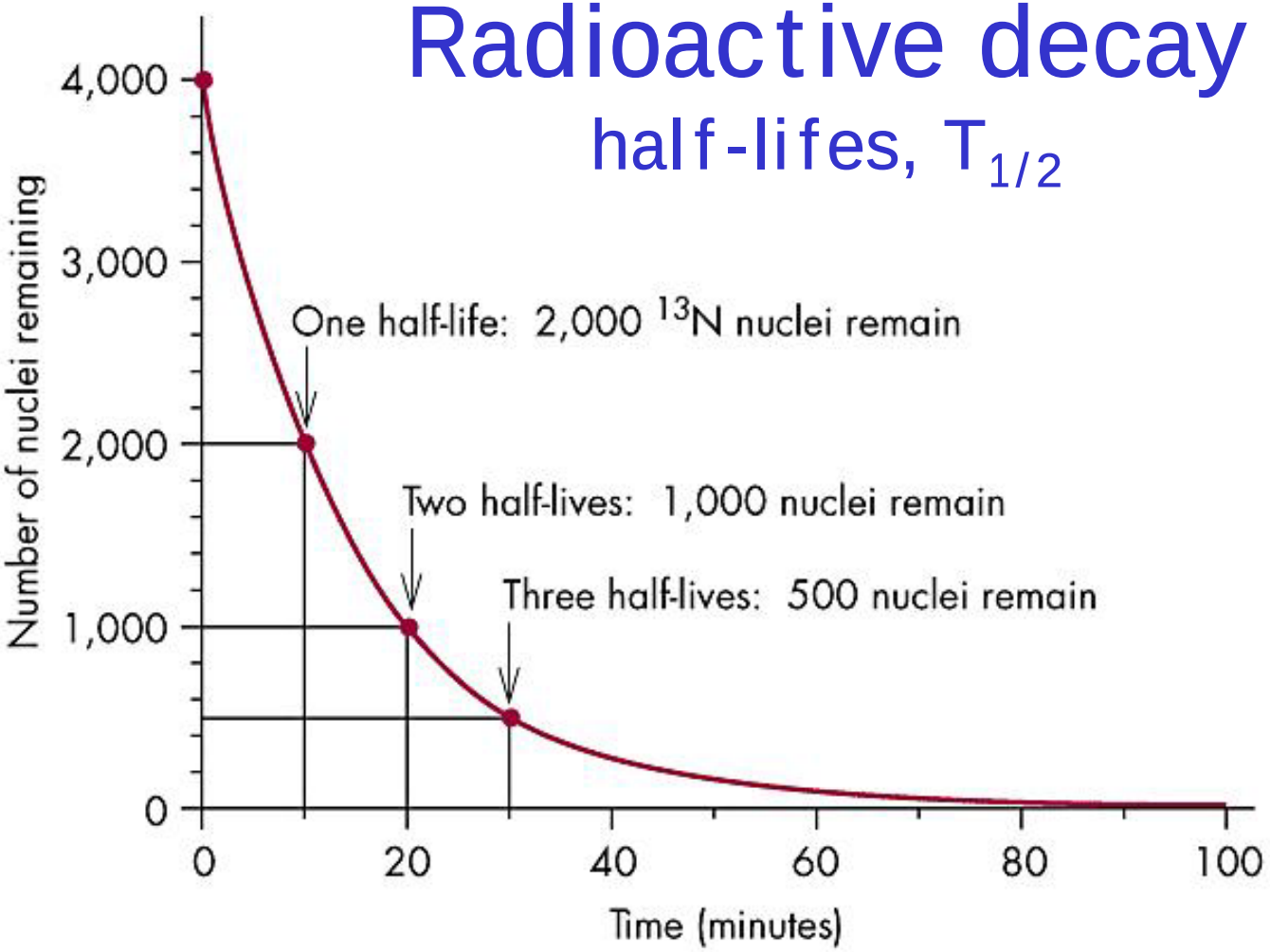
Radiometric dating -
A time machine
to the past

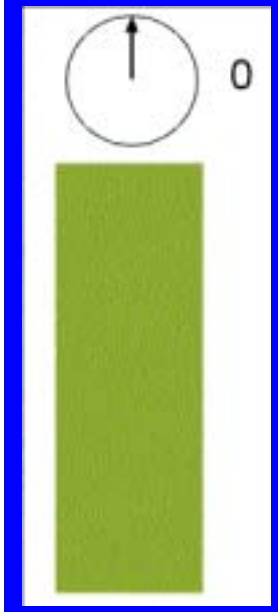




Radioactive decay

half-lifes, $T_{1/2}$





if it is possible to determine the ratio of the PARENT and DAUGHTER atoms, it is then possible to determine how long ago the decay process started → age determination

Radioactive decay

- Rate of decay is proportional to the number of decaying nuclei
- Integrate to find the change in N with time

$$\frac{dN}{dt} = -\lambda N$$

$$\frac{dN}{N} = -\lambda \cdot dt$$

Radioactive decay

- Integrate:

$$\int_{N_o}^{N(t)} \frac{1}{N}\, dN = -\int_0^t \lambda\, dt$$

- Find N(t):

$$N = N_o \cdot e^{-\lambda \cdot t}$$

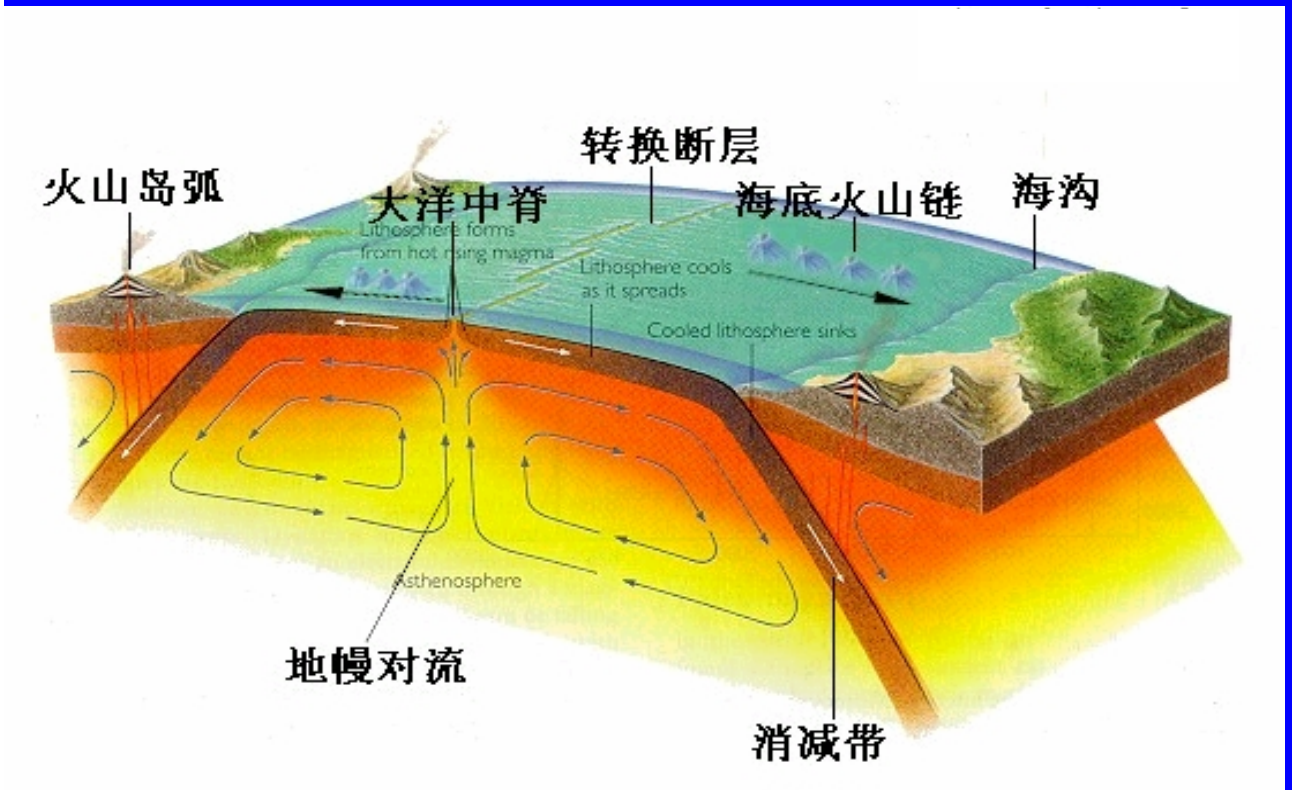
Parent-Daughter system:

$$D = D_0 + N\,(e^{\lambda t} - 1)$$

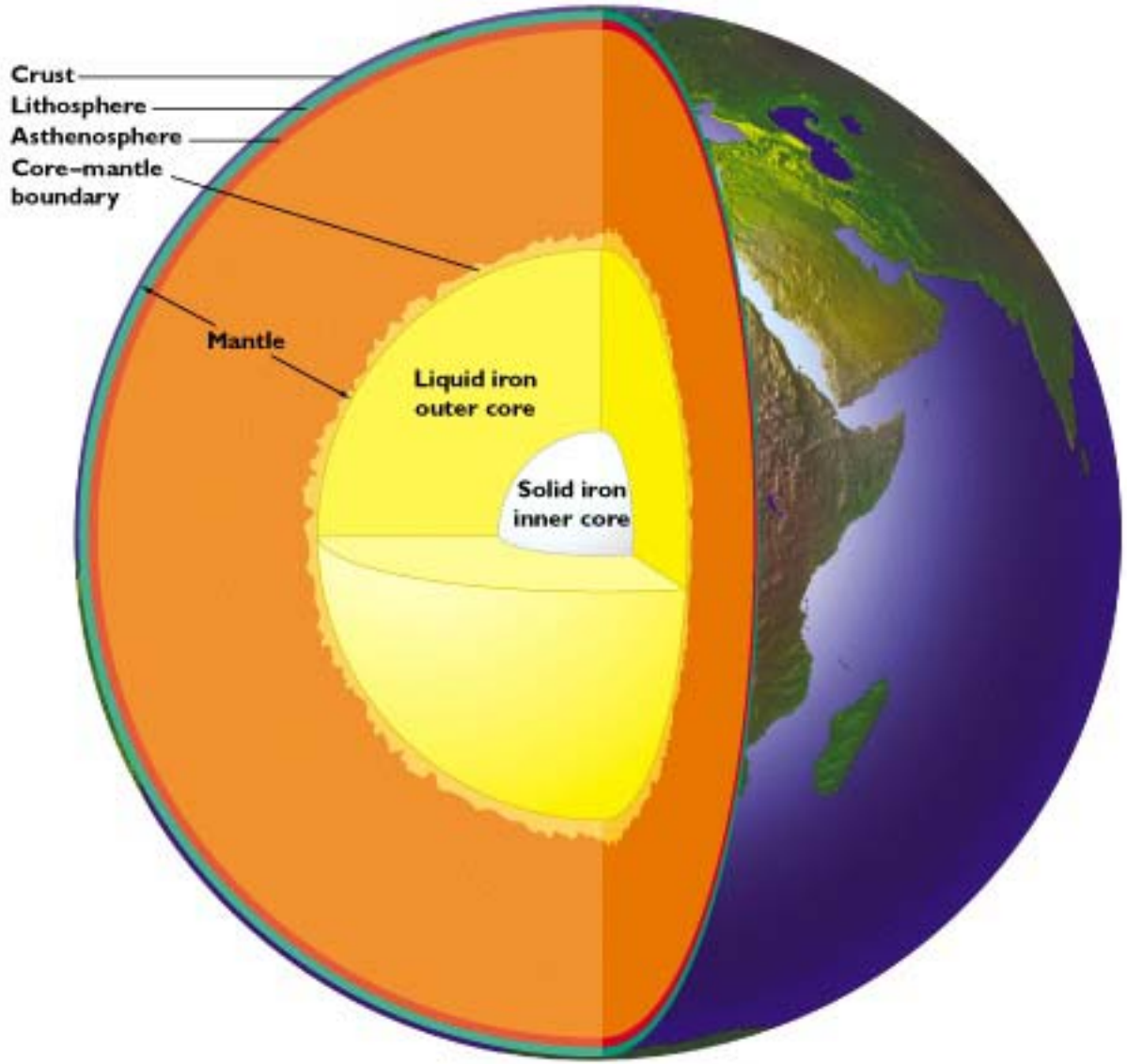
Isotope Tracer

How do we know where the rocks came from?





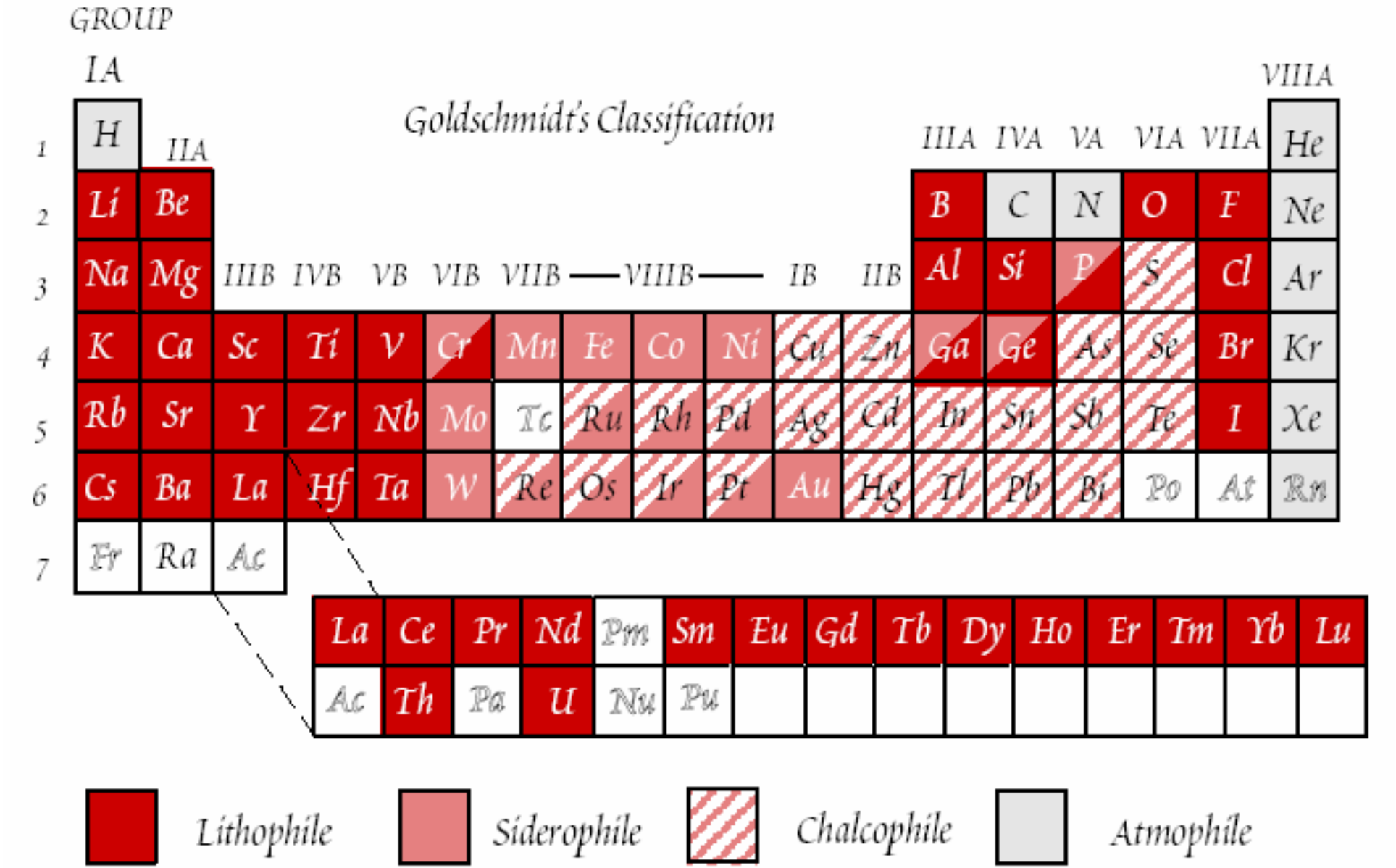
The Earth's Interior

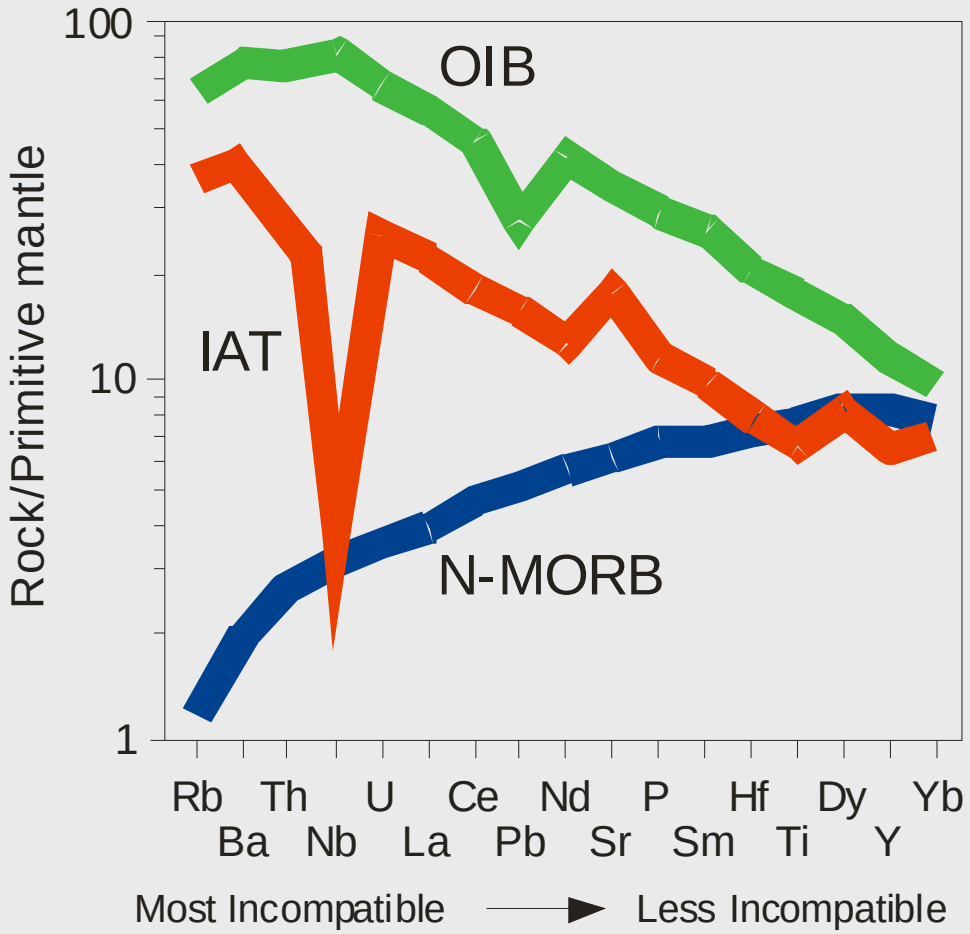


Goldschmidt's classification of the elements

亲铁元素	亲硫元素	亲石元素	亲气元素
Siderophile	Chalcophile	Lithophile	Atmophile
Fe*, Co*, Ni*	(Cu), Ag	Li, Na, K, Rb, Cs	(H), N, (O)
Ru, Rh, Pd	Zn, Cd, Hg	Be, Mg, Ca, Sr, Ba	He, Ne, Ar, Kr, Xe
Os, Ir, Pt	Ga, In, Tl	B, Al, Sc, Y, REE	
Au, Re†, Mo†	(Ge), (Sn), Pb	Si, Ti, Zr, Hf, Th	
Ge*, Sn*, W‡	(As), (Sb), Bi	P, V, Nb, Ta	
C‡, Cu*, Ga*	S, Se, Te	O, Cr, U	
Ge*, As†, Sb†	(Fe), Mo, (Os)	H, F, Cl, Br, I	
	(Ru), (Rh), (Pd)	(Fe), Mn, (Zn), (Ga)	

*Chalcophile and lithophile in the earth's crust
†Chalcophile in the earth's crust
‡Lithophile in the earth's crust


GROUP
IA
IIA
IIIB
IVB
VB
VIB
VIIB
VIIIB
IB
IIB
IIIA
IVA
VA
VIA
VIIA
VIIIA
Goldschmidt's Classification
1
2
3
4
5
6
7
H
He
Li
Be
B
C
N
O
F
Ne
Na
Mg
Al
Si
P
S
Cl
Ar
K
Ca
Sc
Ti
V
Cr
Mn
Fe
Co
Ni
Cu
Zn
Ga
Ge
As
Se
Br
Kr
Rb
Sr
Y
Zr
Nb
Mo
Tc
Ru
Rh
Pd
Ag
Cd
In
Sn
Sb
Te
I
Xe
Cs
Ba
La
Hf
Ta
W
Re
Os
Ir
Pt
Au
Hg
Tl
Pb
Bi
Po
At
Rn
Fr
Ra
Ac
La
Ce
Pr
Nd
Pm
Sm
Eu
Gd
Tb
Dy
Ho
Er
Tm
Yb
Lu
Ac
Th
Pa
U
Np
Pu
Lithophile
Siderophile
Chalcophile
Atmophile



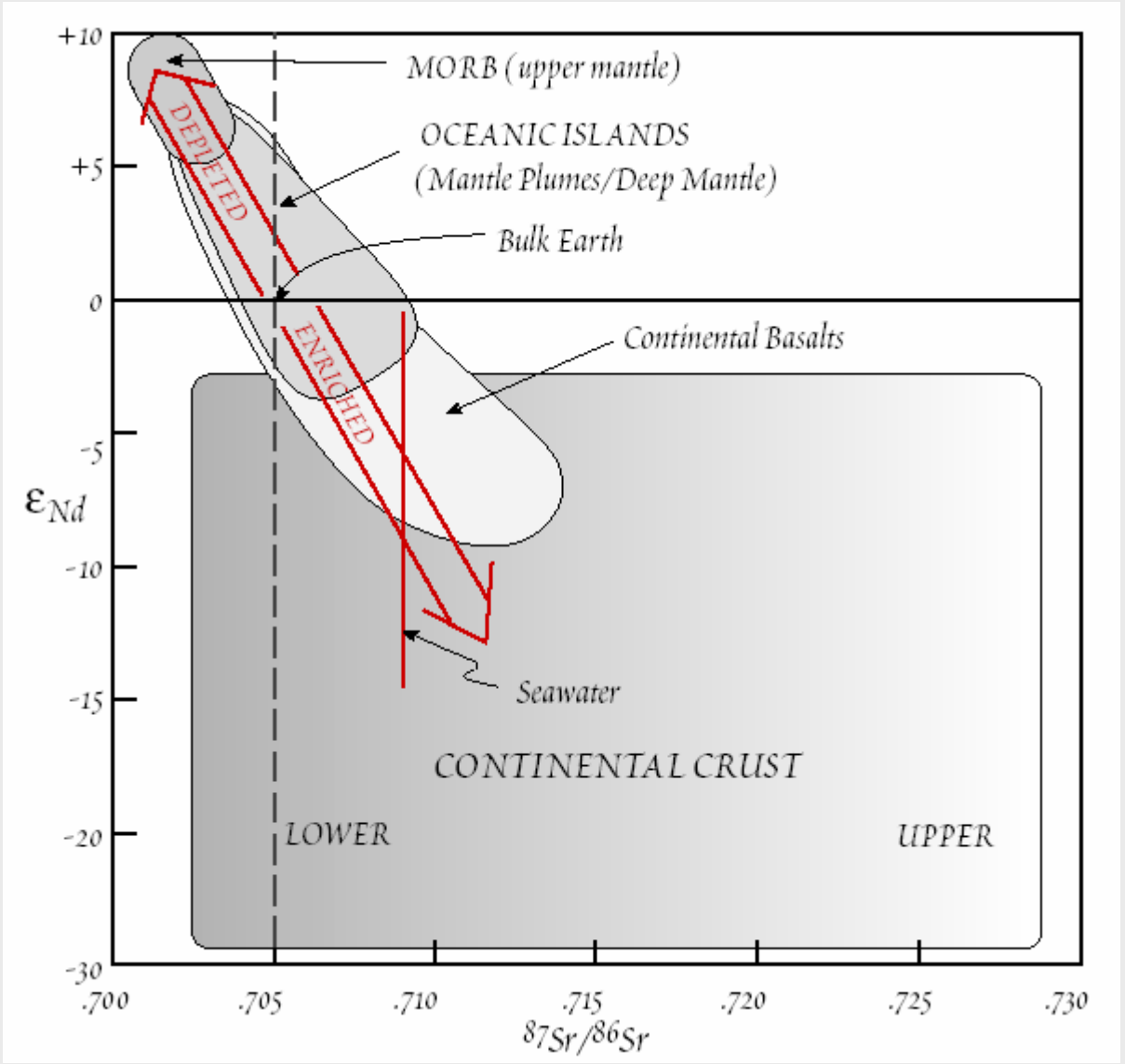
Schematic profiles of basalts from different tectonic settings

MORB

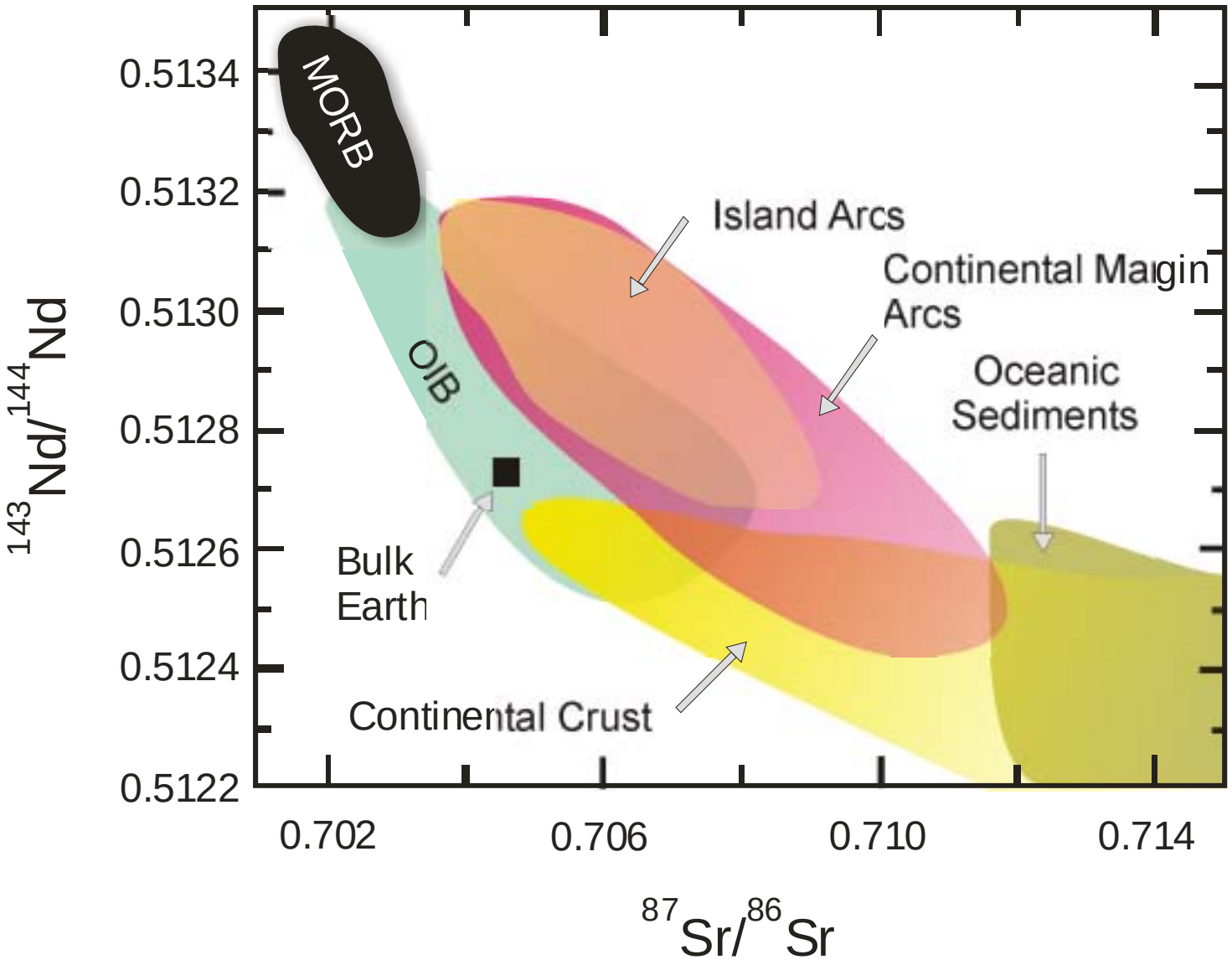
OIB

Island Arc Basalt

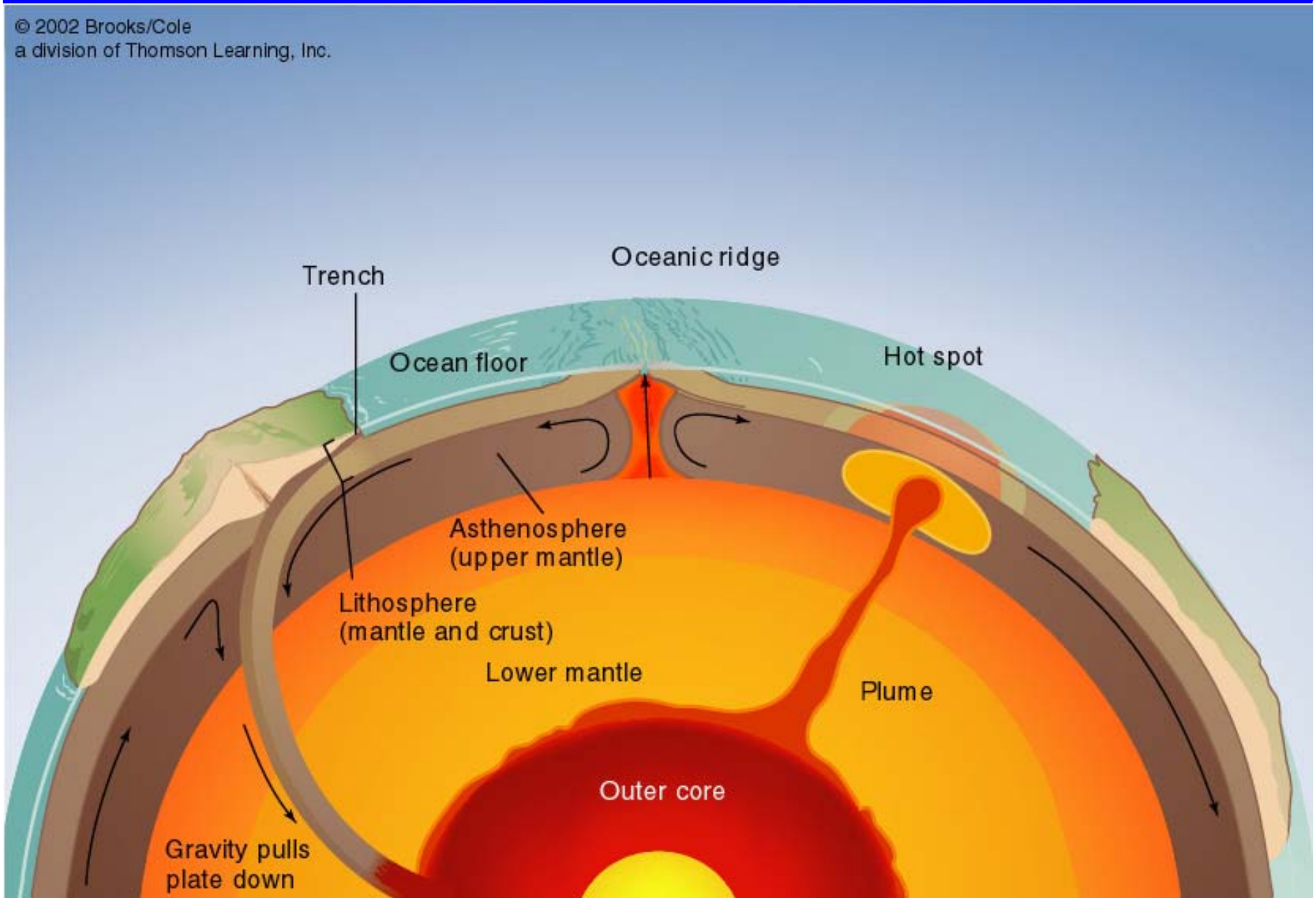
Sr and Nd isotopic systematics of the crust and mantle



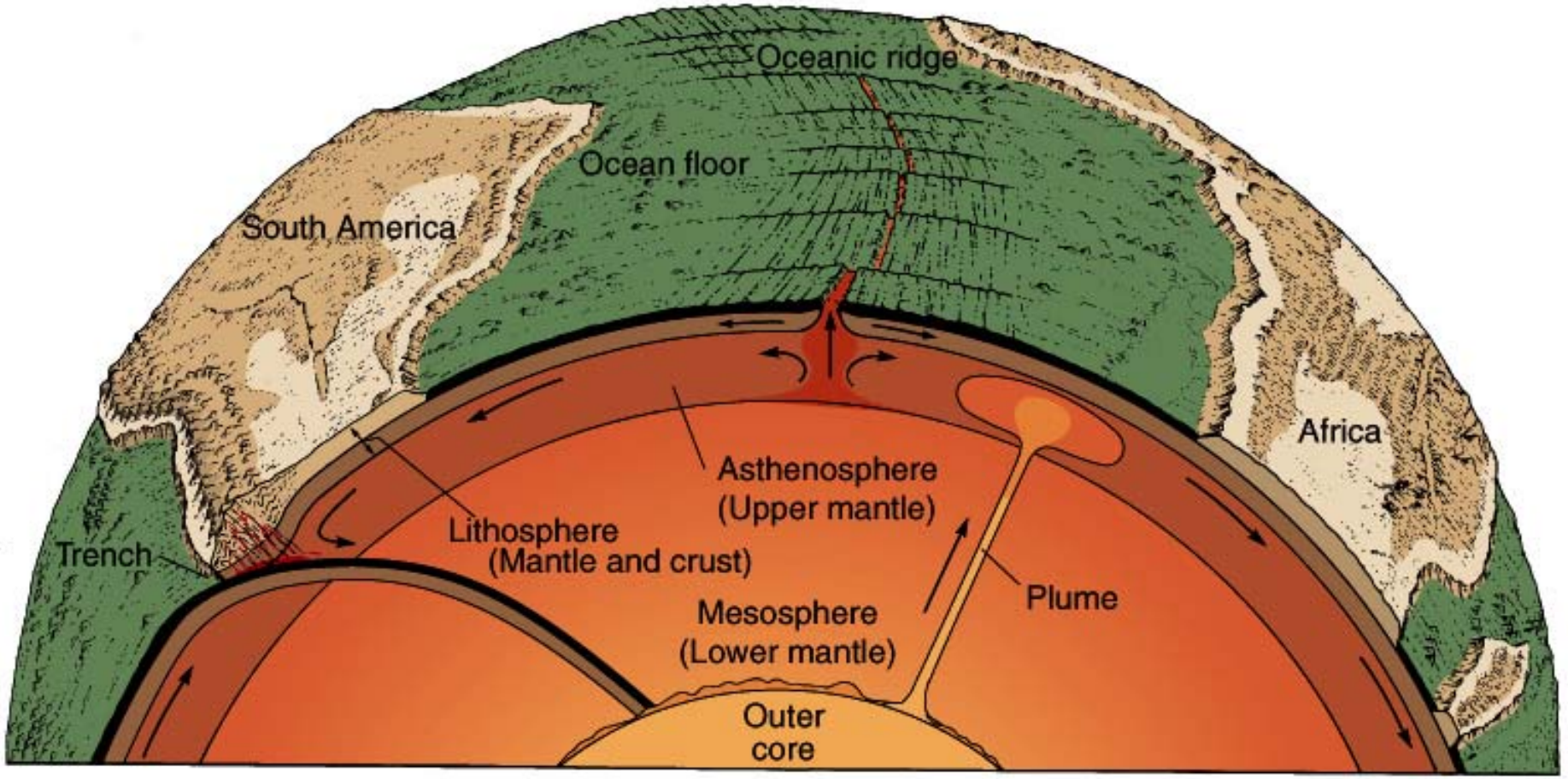
Correlation of Sr-Nd isotopic composition



An overview of the tectonic system

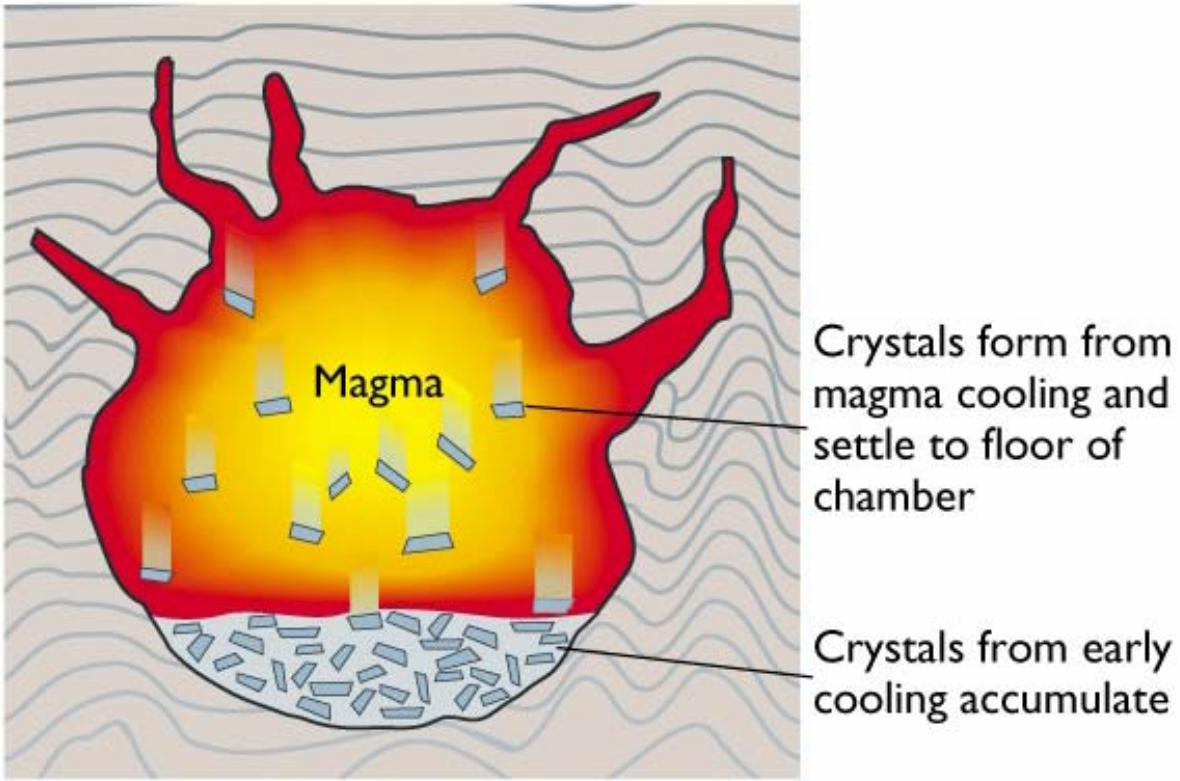


An overview of the tectonic system



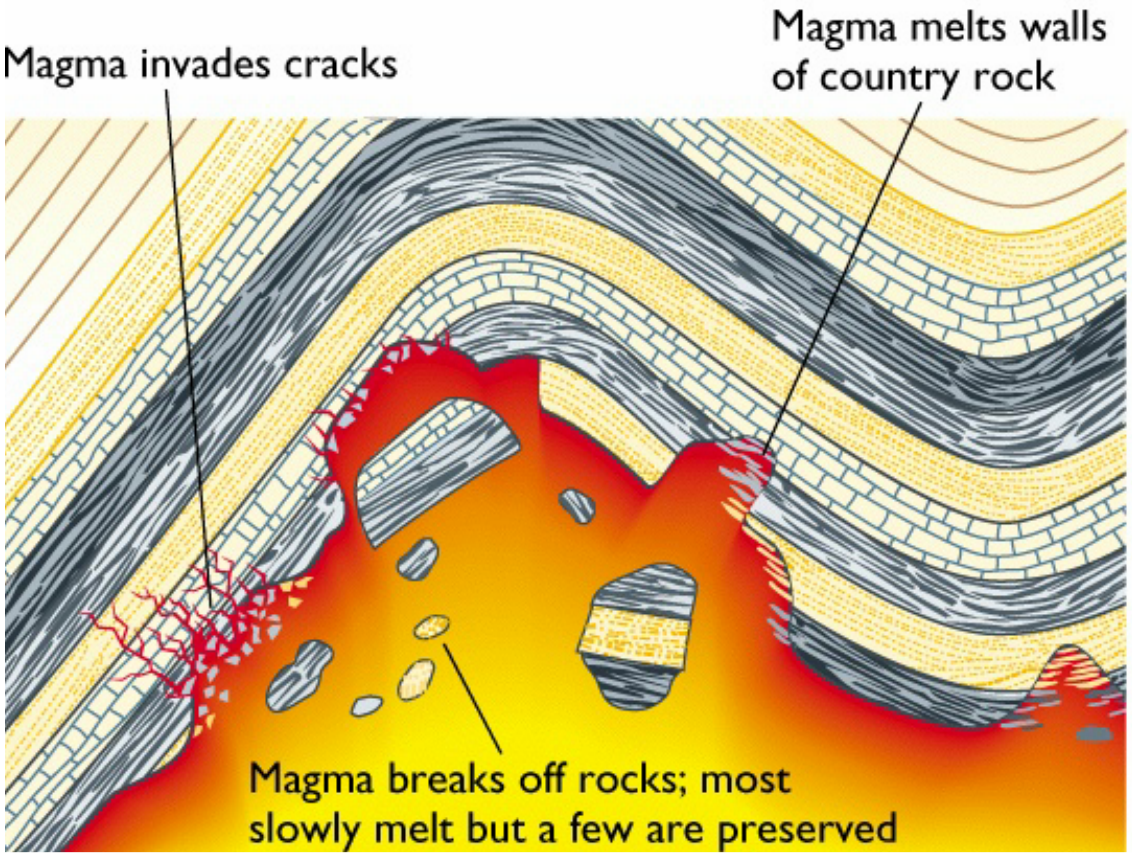
Magma Differentiation

- Fractional Crystallization
  - Separation of crystals from liquid
  - Gravitative settling or flotation play a significant role



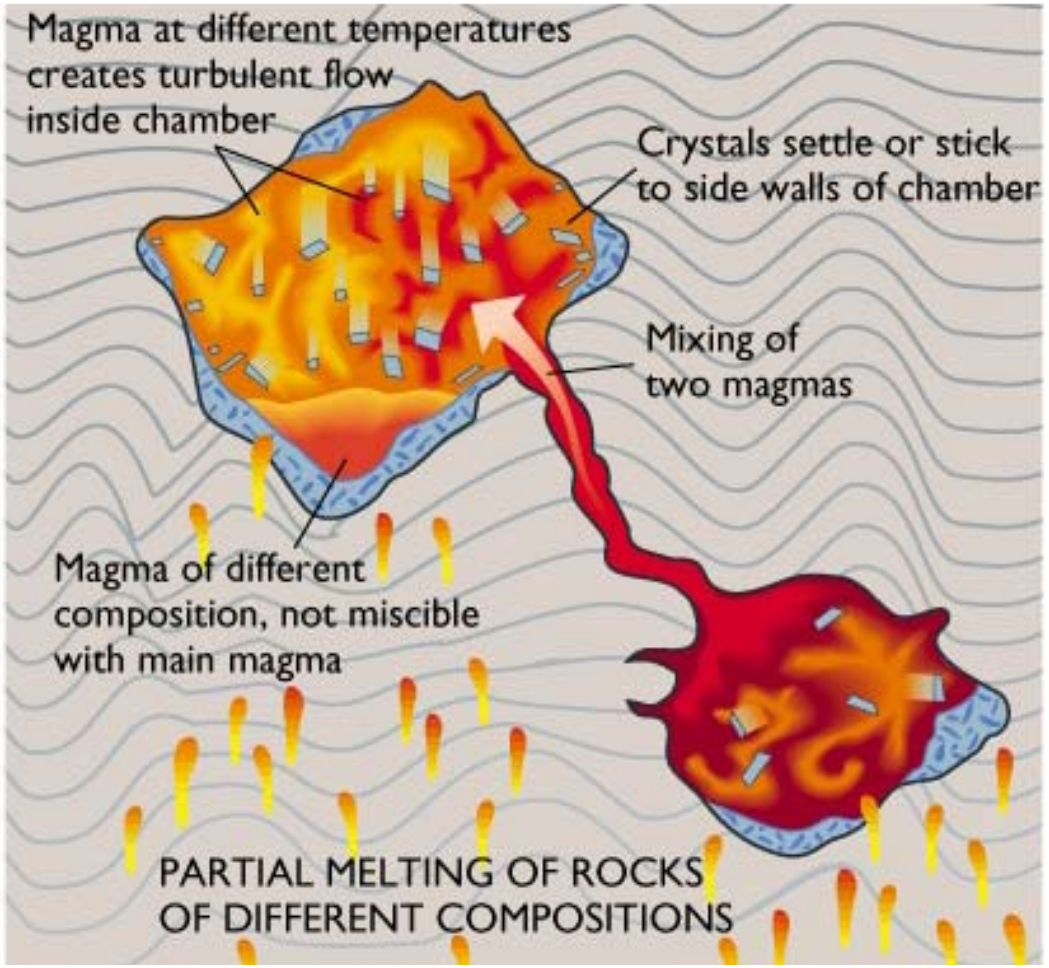
Magma Differentiation

- Assimilation +/- Fractional Crystallization



Magma Differentiation

- Magma Mixing



Physics of the Nuleus

Early Views of the Atom

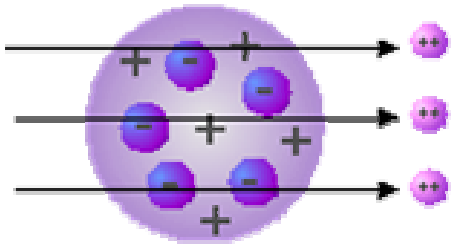
Dalton's atomic theory of matter (1807)

- All matter consists of atoms – smallest particle of an element
- All atoms of a given element, such as gold, are identical
- Atoms of different elements have different masses

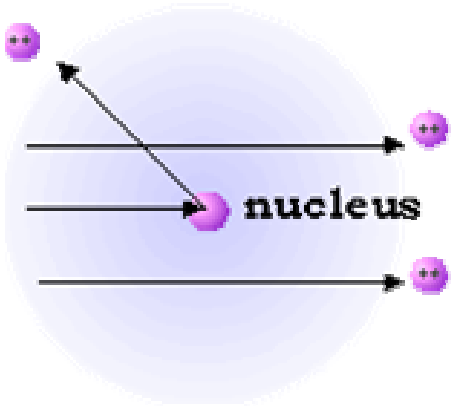


The Atom

- **Thomson's Atom:**
  - ❖ Diffusive mass and charge



- **Rutherford's Atom**
  - ❖ Concentrated mass and positive charge at the nucleus
  - ❖ Electrons roam through empty space around nucleus

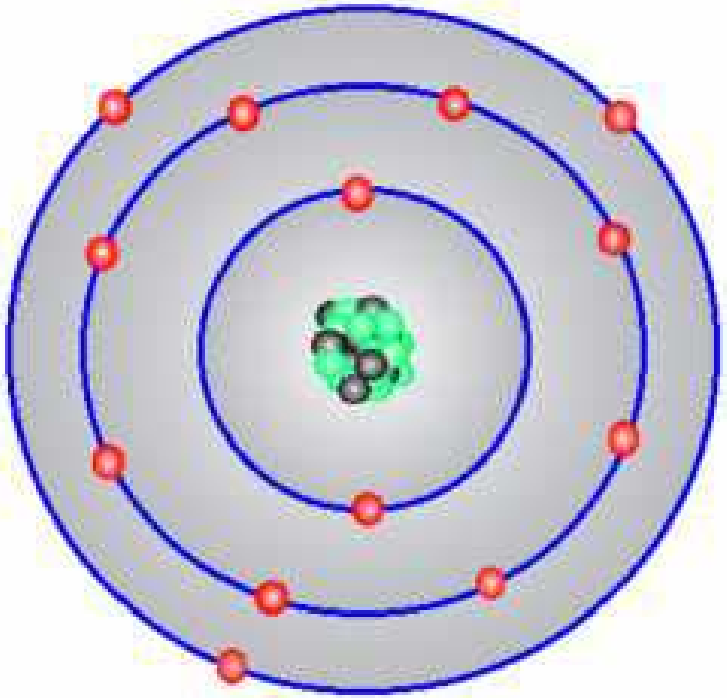


Bohr model of the atom

The Bohr model is a 'planetary' type model.

Each principal quantum represents a new 'orbit' or layer.

The nucleus is at the center of the model.



Component of an atom

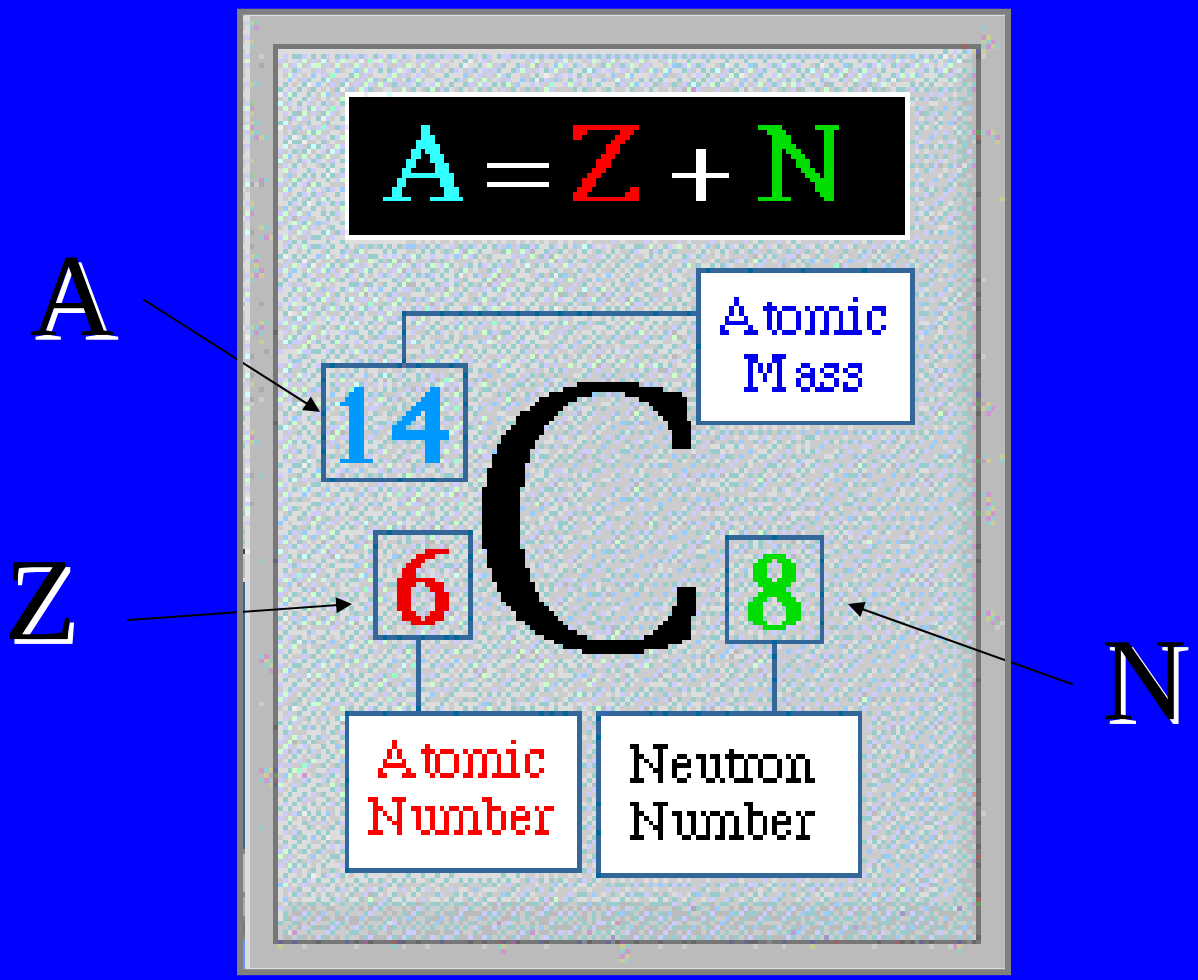
for geochemists' interest

Proton (Z)

Neutron (N)

Electron (E)

The Nuclear Symbol



Atoms of an element have identical number of proton and identical number of electron

Atoms of an element have identically chemical feature

Weight of an atom =
number of proton + neutron

(A = Z + N)

Atoms of an element can have
different number of neutron

Atoms of an element can have different weight

For instance:

Atom1: Weight (A_1) = Z + N_1

Atom2: Weight (A_2) = Z + N_2

Such atoms are **isotopes**

Isotopes

- Elements with the same atomic number (number of protons or electrons) but different mass number (number of nucleons) are isotopes

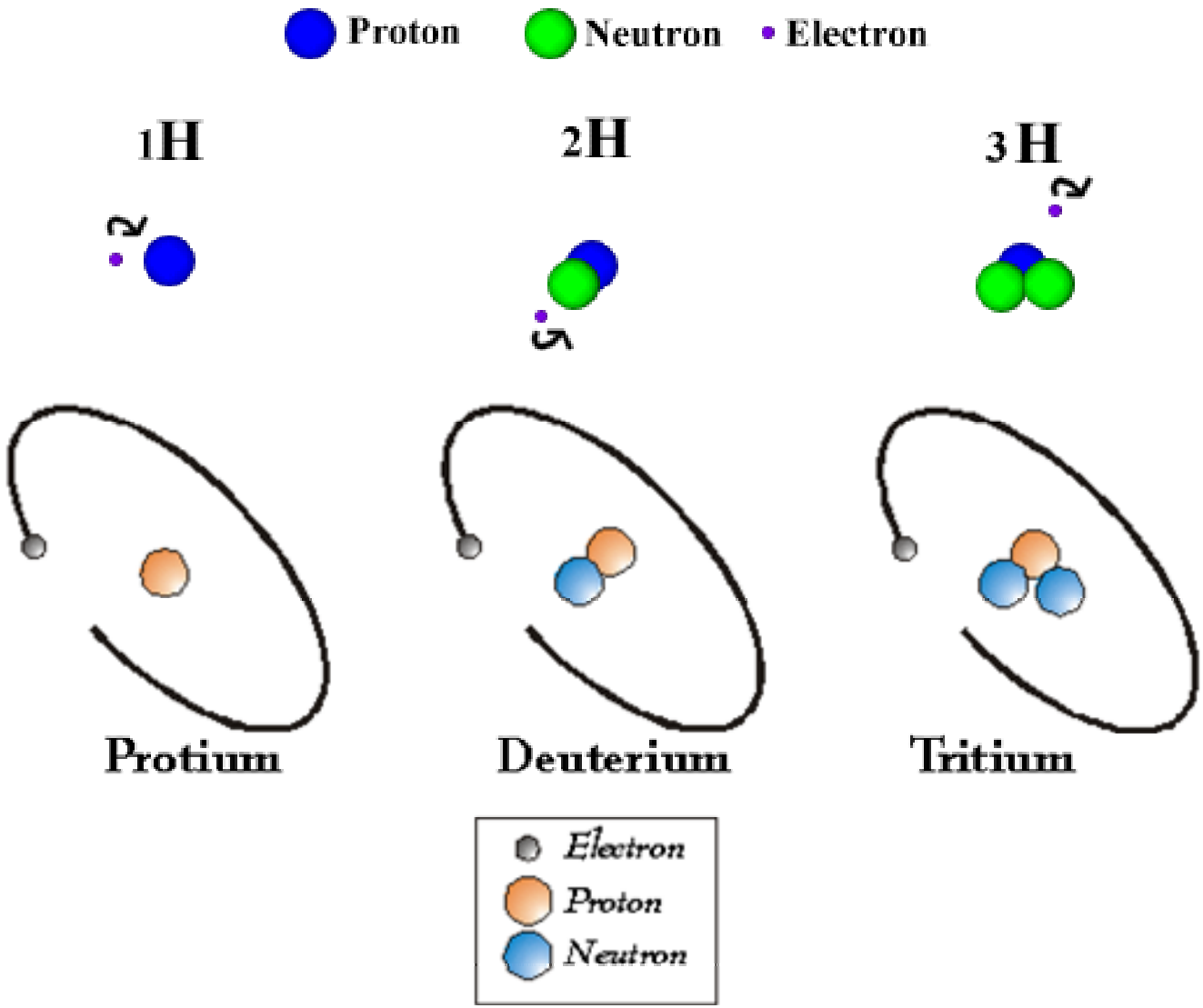
- Isotopes of an element differ only in the number of neutrons

Isotopes

- If we compare different isotopes of the same element:

  - The number of protons and electrons are the same, i.e. atomic number, Z, is the same
  - The number of neutrons are different
  - The number of nucleons (protons and neutrons) are different, i.e. mass number, A, is different

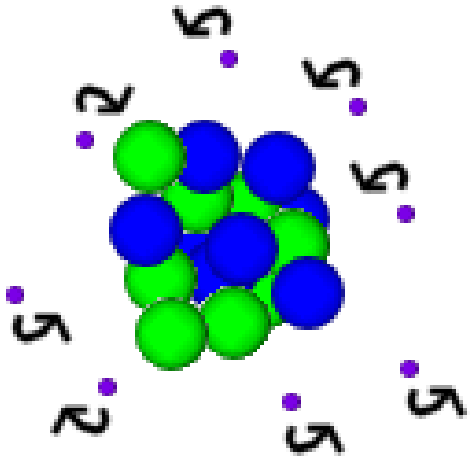
The Three Isotopes of Hydrogen



Oxygen-16
(8 protons, 8 neutrons)

Proton Electron

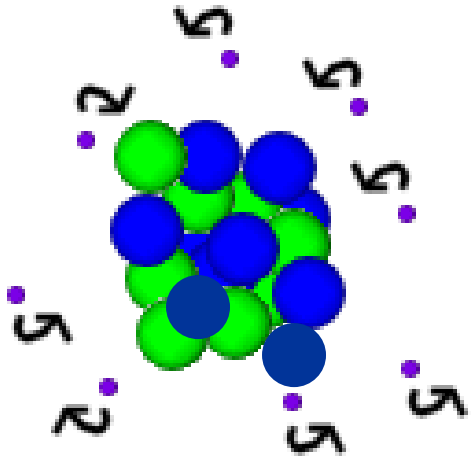
Neutron



Oxygen-18
(8 protons, 10 neutrons)

Proton Electron

Neutron



Isotopes

- isotopes: same Z, different M

$^{1}_{1}H$ $^{2}_{1}H$ $^{3}_{1}H$ $^{12}_{6}C$ $^{13}_{6}C$ $^{14}_{6}C$ $^{235}_{92}U$ $^{238}_{92}U$

- isotopic abundance: $\frac{\text{\# atoms of isotope present}}{\text{\# atoms of element present}}$

isotope	natural abundance	mass (amu)
carbon-12	98.89 %	12.000000
carbon-13	1.11 %	13.003354

average mass: 12.01_{11} amu

Average atomic mass

Potassium atomic number 19

$$^{39}K = \frac{93.26}{100} * 38.964 \text{ amu} = 36.338 \text{amu}$$

$$^{40}K = \frac{0.012}{100} * 39.964 \text{ amu} = 0.0048 \text{ amu}$$

$$^{41}K = \frac{6.73}{100} * 40.962 \text{ amu} = 2.757 \text{ amu}$$

Average atomic mass for K = 39.10 amu

Isobar

Different elements have the same weight number (A), but different Z

example: ^{87}Rb, Z=37, N=50

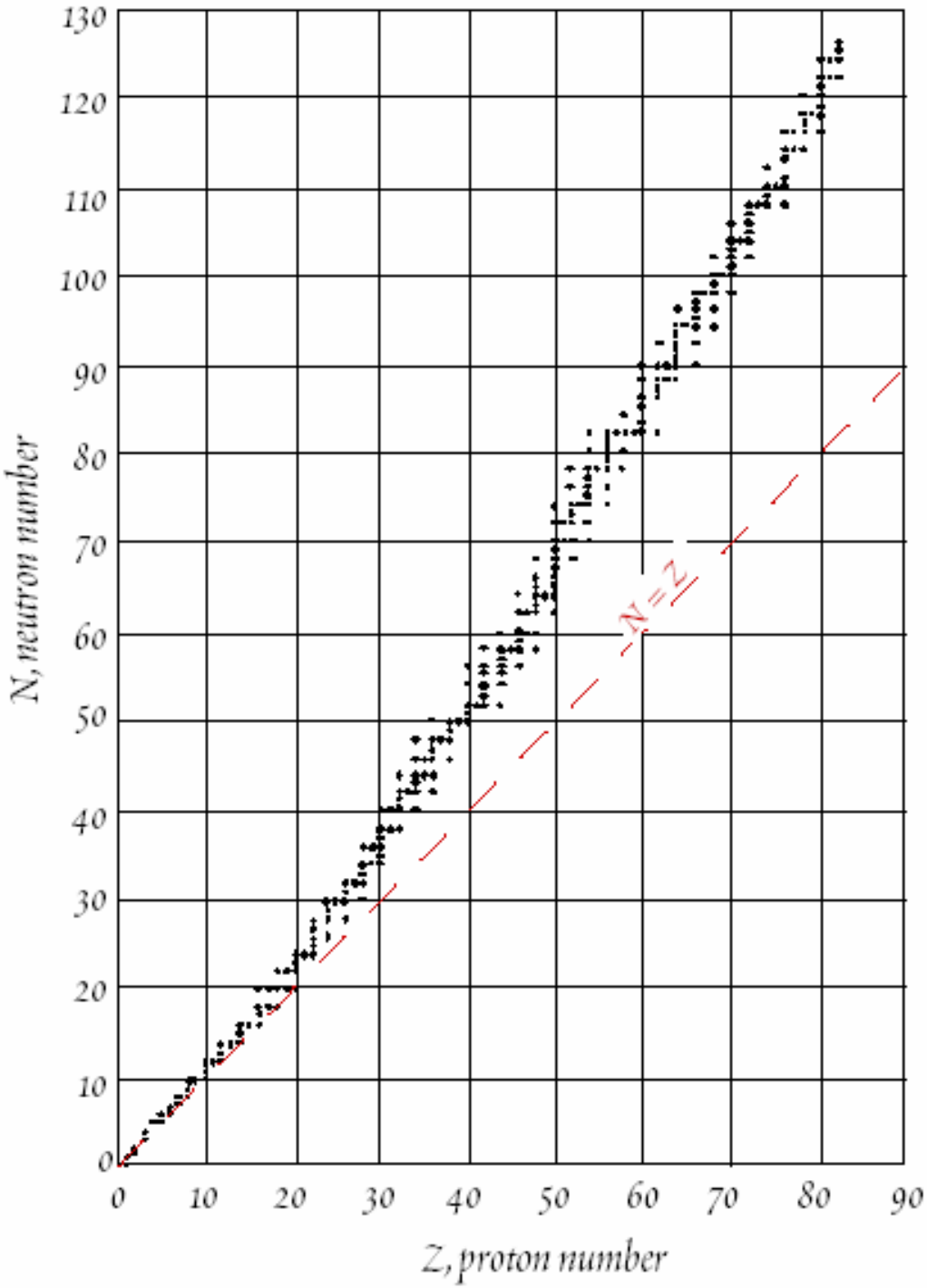
^{87}Sr, Z=38, N=49

Proton: 1.007593 daltons or amu (atomic mass units)
$=1.6726231 \times 10^{-27}$ kg

Neutron: 1.008982 daltons or amu

Electron: 0.000548756 daltons or amu
$=9.10083897 \times 10^{-31}$ kg

Neutron number vs. proton number for stable nuclides



Binding energy

- When protons and neutrons combine, mass is lost to energy – Binding energy
- The binding energy of a nucleus can be found based on

$$E = mc^2$$

A more useful version of the equation is

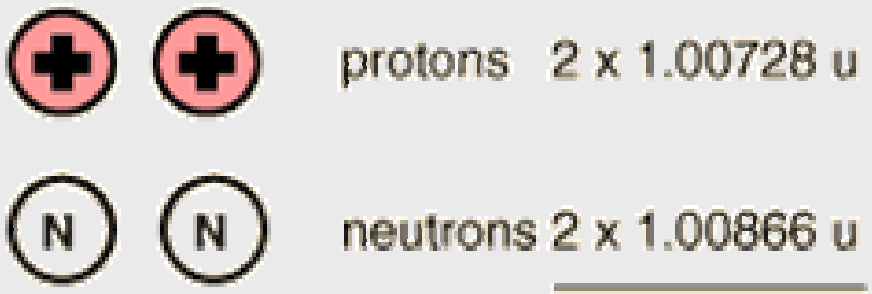
$$\Delta E = \Delta mc^2$$

where

ΔE = the binding energy

Δm = mass difference between the nucleus and the separate nucleons

Binding energy



protons 2 x 1.00728 u

neutrons 2 x 1.00866 u

Mass of parts 4.03188 u



Alpha particle

Mass of alpha 4.00153 u

$1\ u = 1.66054 \times 10^{-27}\ kg = 931.494\ MeV/c^2$

Binding energy per neucleon (E_b)

$$Eb = (W-M)*C^2/A$$

Mass decrement: $\delta = W-M$

M： actual mass of atom

W: sum of the mass of constituent particles of atom

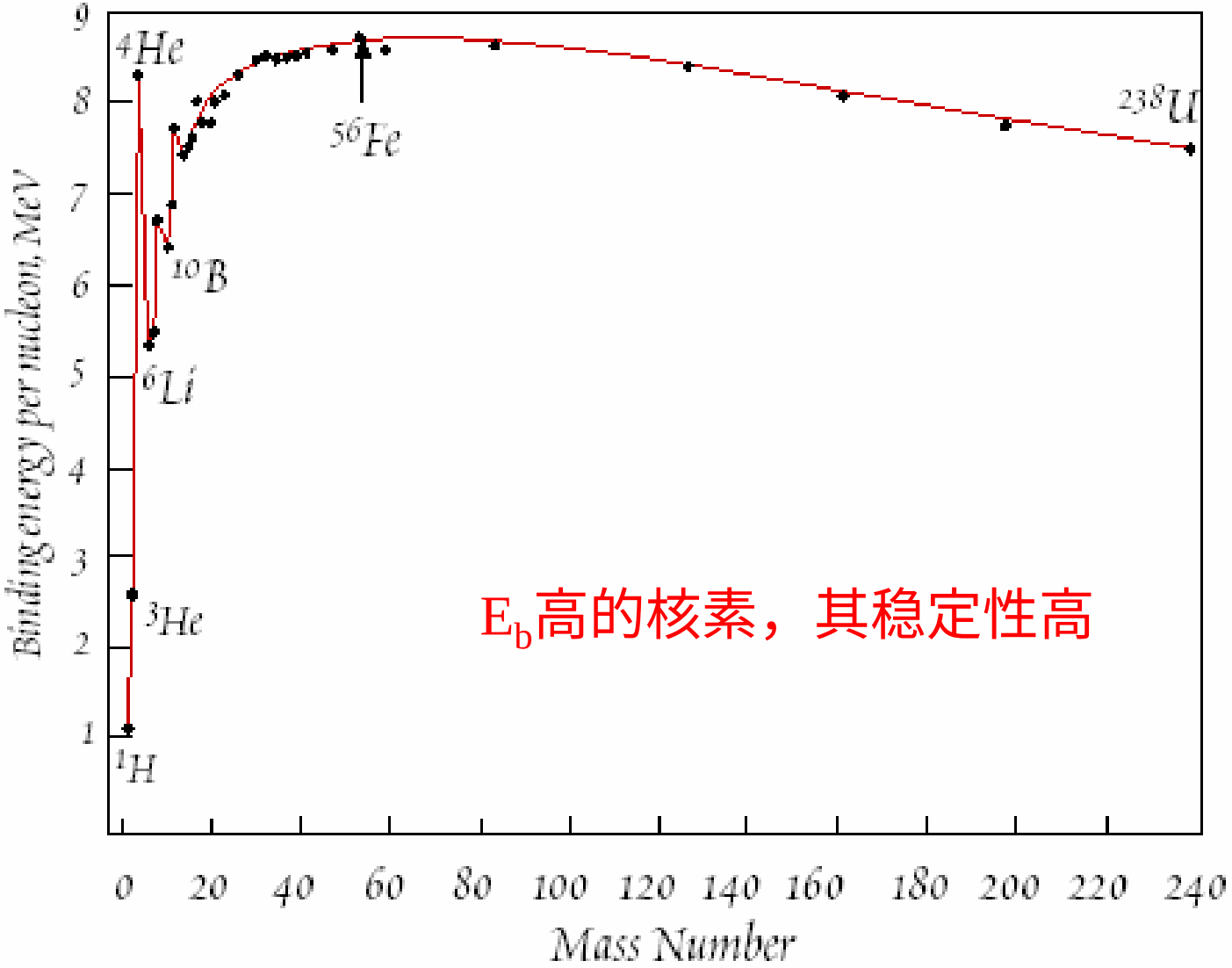
Example of ^4He: $W = 2m_p + 2m_n + 2m_e = 4.034248$ daltons

M = 4.003873 daltons

d = 0.030375 daltons

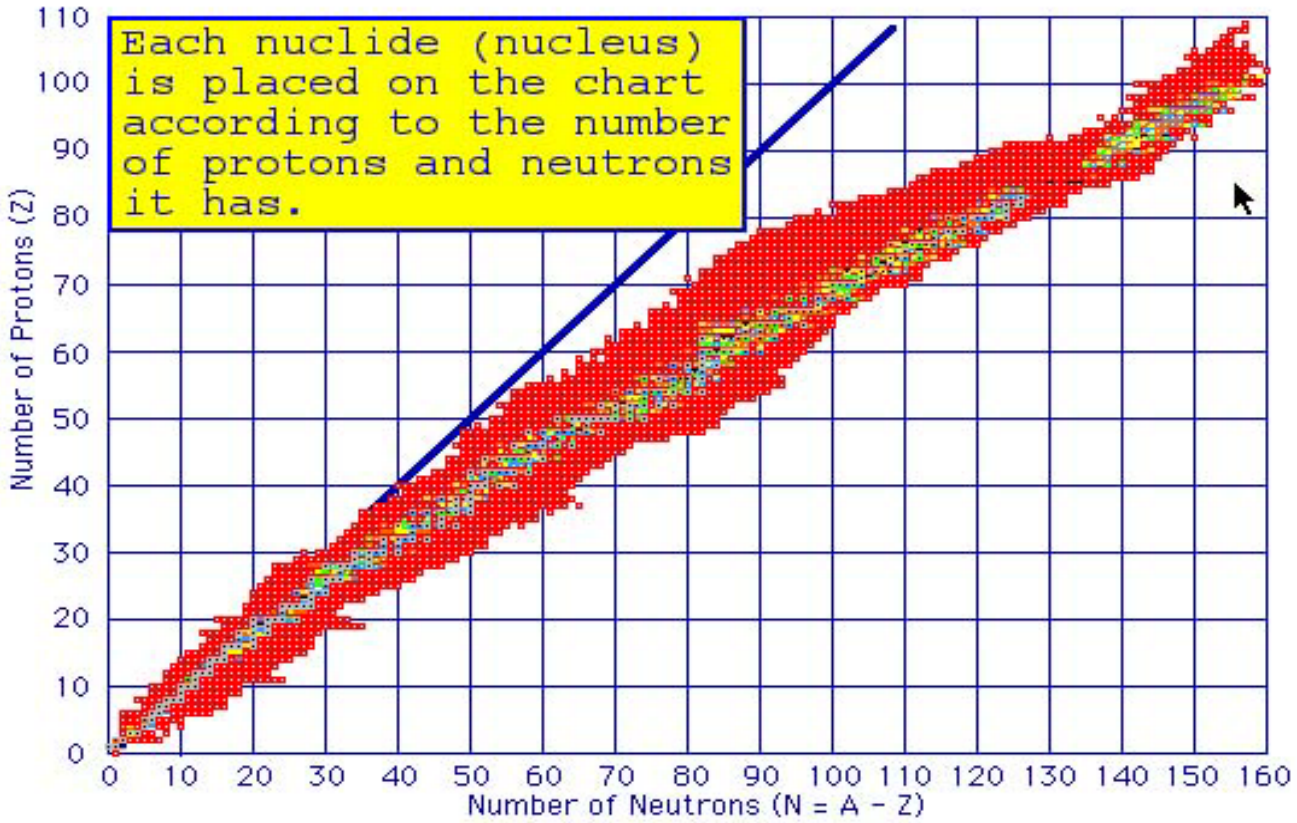
Eb = 7.07 MeV

Binding energy per nuleon (E_b)



E_b高的核素，其稳定性高

Chart of the Nuclides



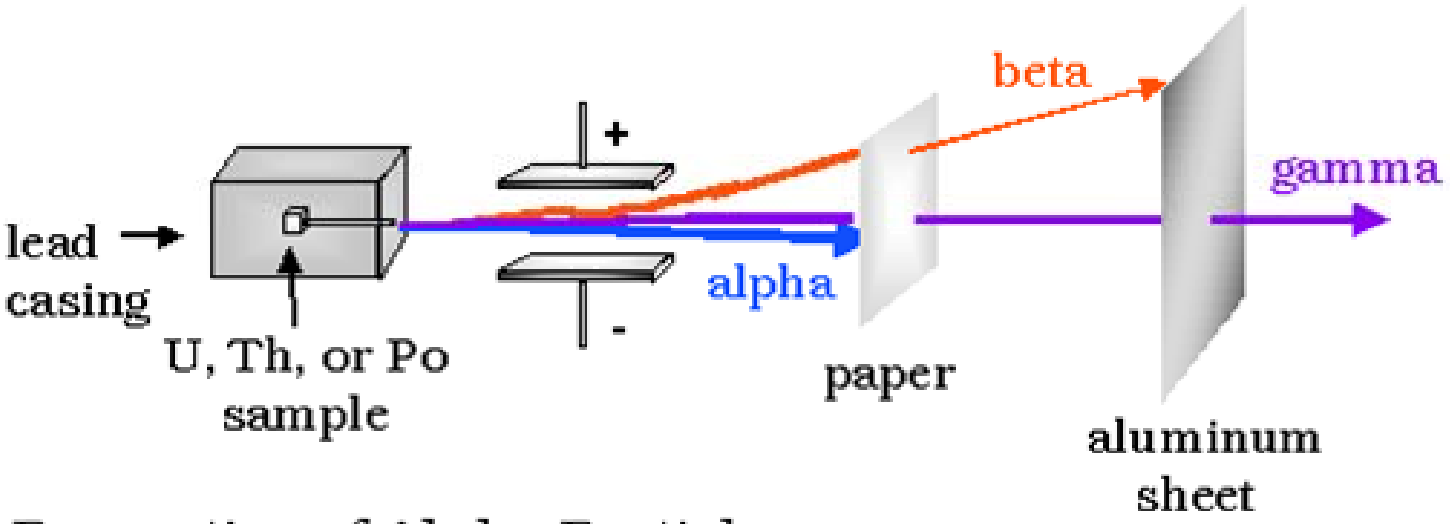
Radioactivity

- **A property of some nuclei in which they undergo a transformation to a lower (more stable) energy state**
- **This is commonly observed by the spontaneous emission of particles and/or energy from a nucleus**
- **First observed by Henry Becquerel in 1896**
- **So why does it happen?**

Reasons for a decay

- Too many nucleons
  characterized by α-emission
- Too many protons
  β^+ emission or electron capture
- Too many neutrons
  β^-emission
- Too much energy
  emission of a γ-ray. Typically associated with other types of emission

Major types of radioactive decay



Properties of Alpha Particles:

- much more massive than electrons
- positively charged
- expose photographic film

Decay trends

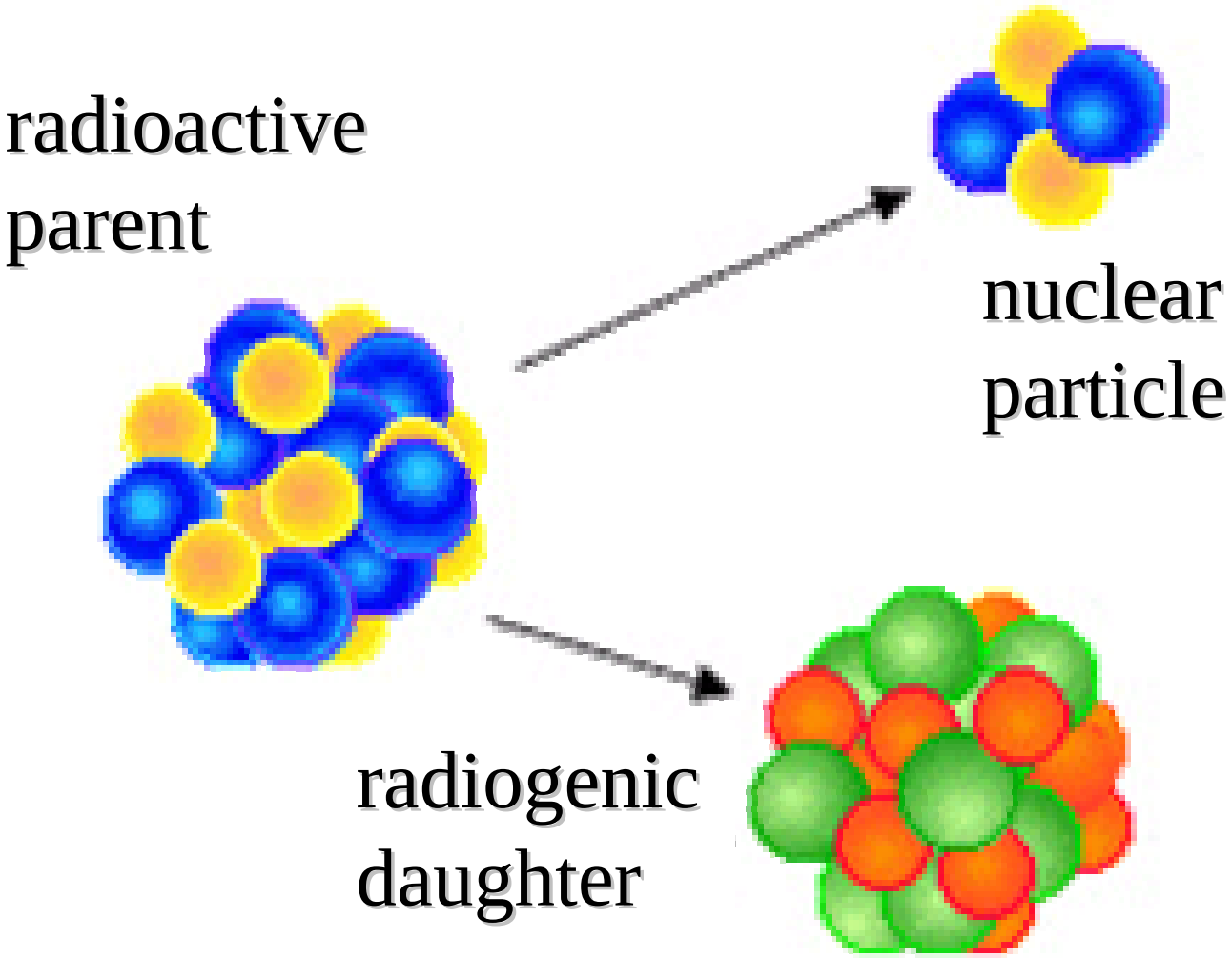
Naturally occurring radioactive isotopes

All are alpha emitters.

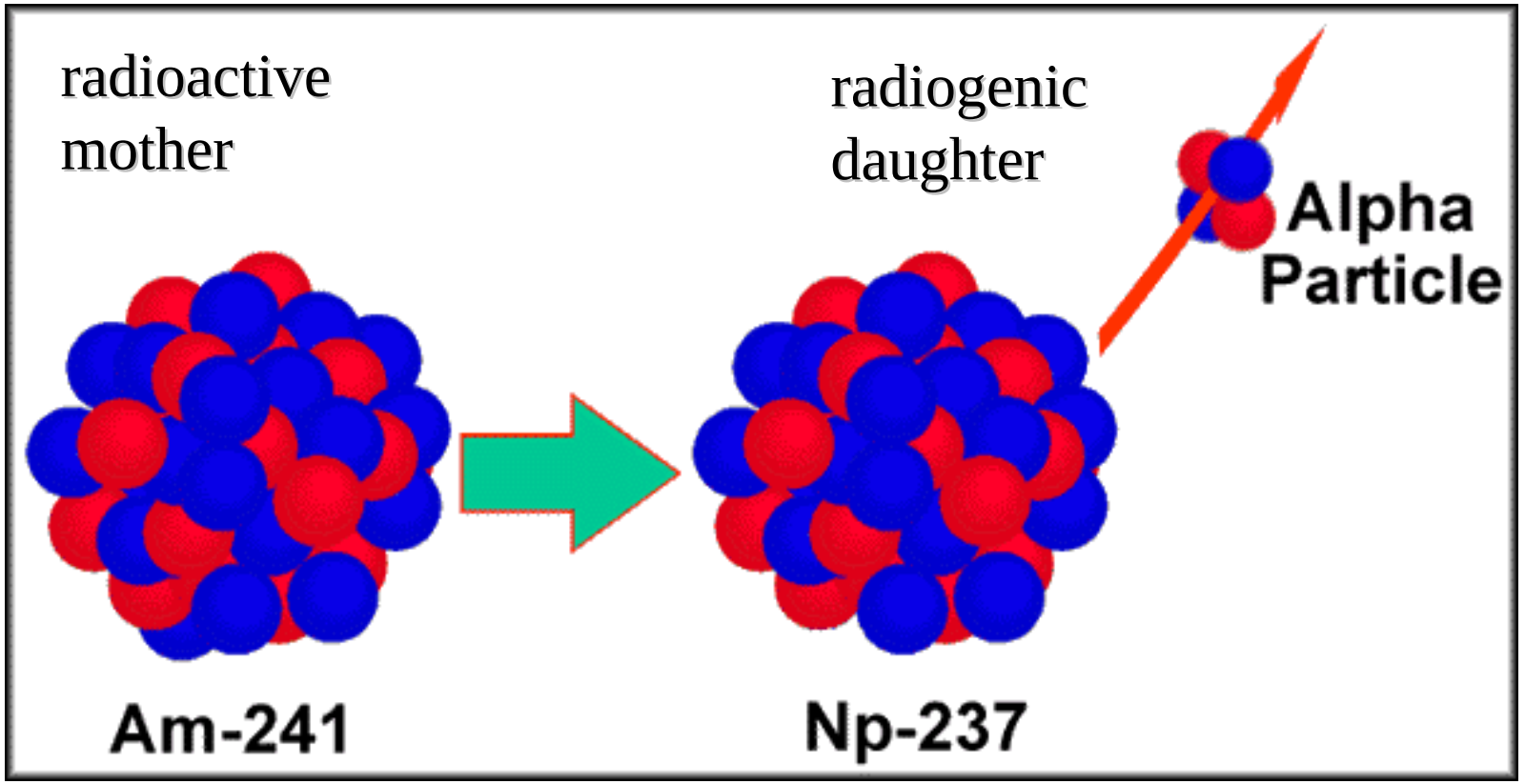
Too many nucleons.

$$ {}^{A}_{Z}X \longrightarrow \alpha + {}^{A-4}_{Z-2}A $$

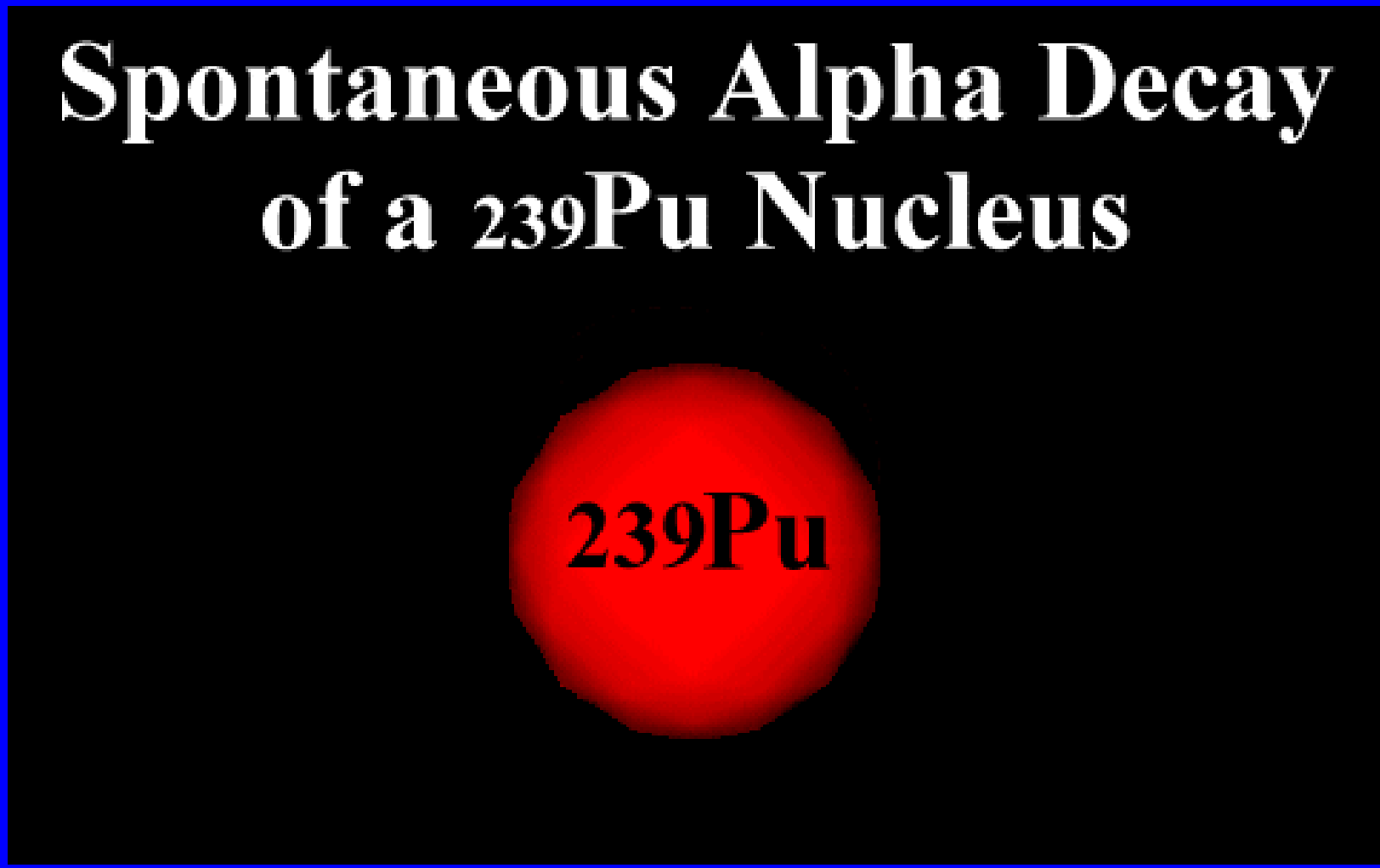
This is a quick way to reduce the number by 4. Multiple steps may be required to complete the process - decay series.


radioactive
parent
nuclear
particle
radiogenic
daughter

Alpha (α) Decay:



Alpha (a) Decay



Decay trends

Neutron rich isotopes

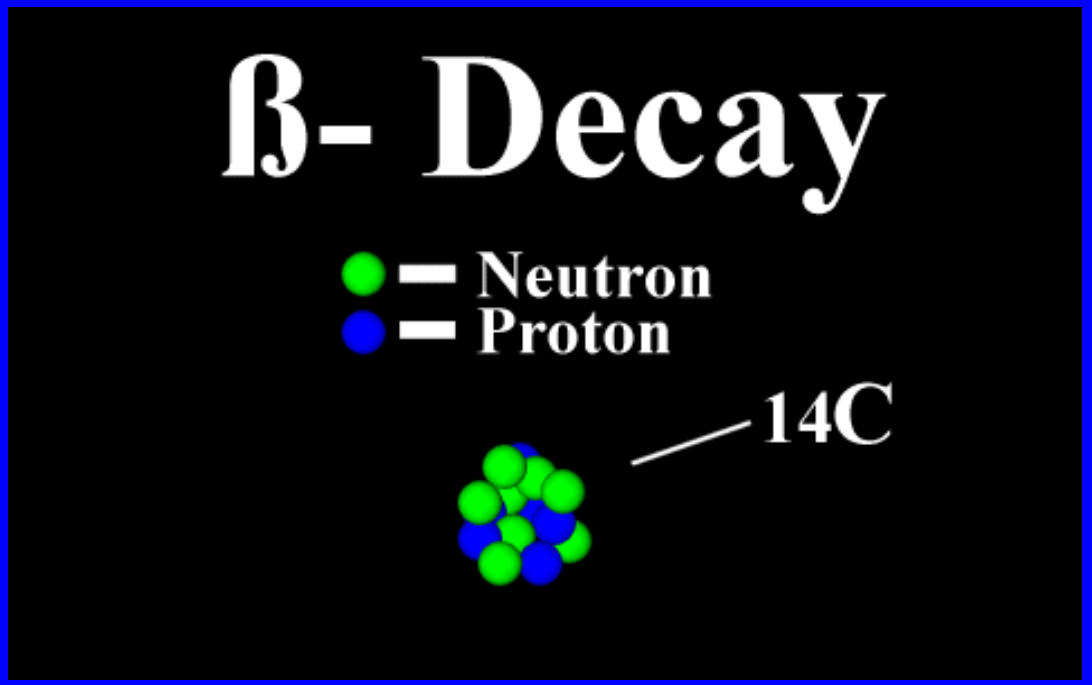
Prefer β^- emission

$$ {}^{A}_{Z}X \longrightarrow \beta^- + {}^{A}_{Z+1}A $$

In essence, we are converting a neutron to a proton.

Beta ($ß$)$^-$ Decay:

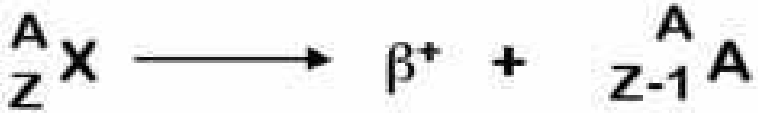

$^{14}_{6}C$
Beta Minus Decay
$\bar{\nu}_e$
$^{14}_{7}N$
e^-
(beta particle)


ß- Decay
Neutron
Proton
14C

Decay trends

Proton rich isotopes

Prefer β^+ or ε emission



$$ {}^{A}_{Z}X \longrightarrow \beta^+ + {}^{A}_{Z-1}A $$

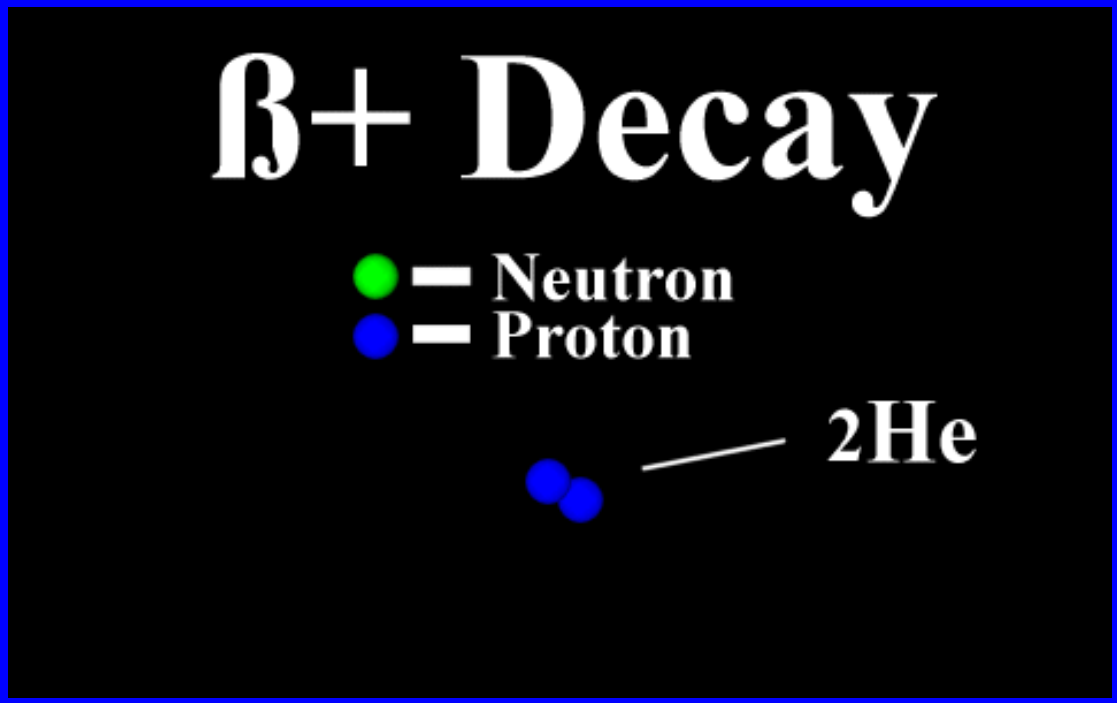


$$ {}^{A}_{Z}X \xrightarrow{EC} {}^{A}_{Z-1}A $$

In essence, we are converting a p to an n - trying to get back to the zone of stability.

Beta $(ß)^+$ Decay

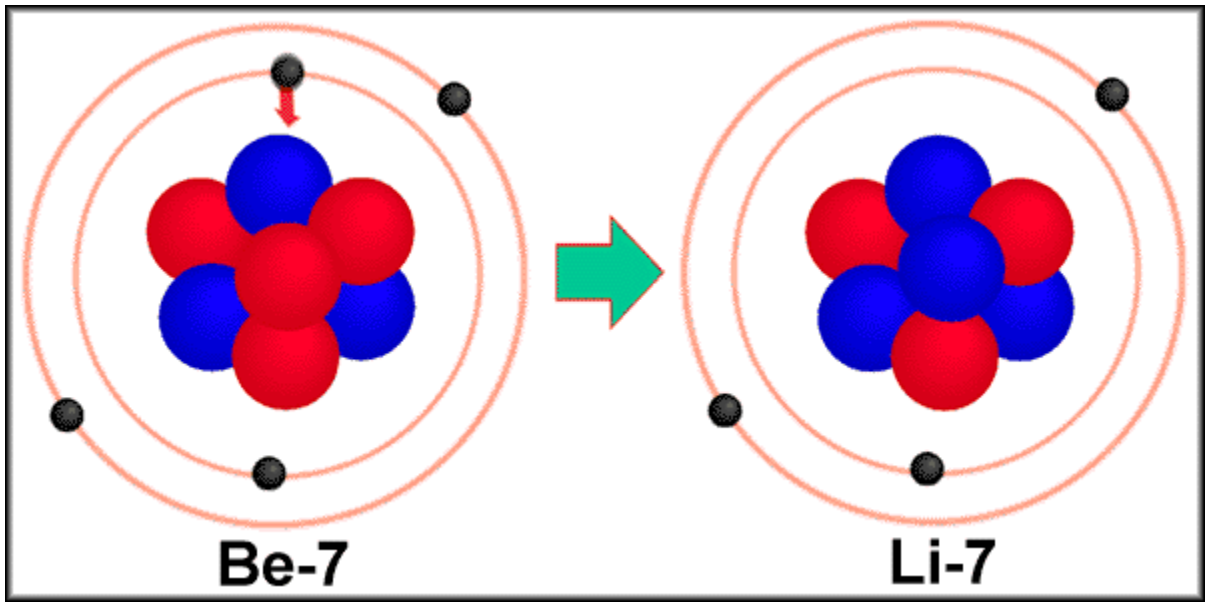

$^{18}_{9}F$
Beta Plus Decay
ν_e
e^+
$^{18}_{8}O$
(beta particle)


ß+ Decay
Neutron
Proton
2He

Electron Capture

A parent nucleus may capture one of its orbital electrons and emit a neutrino

Most commonly, it is a K-shell electron which is captured, and this is referred to as K-capture

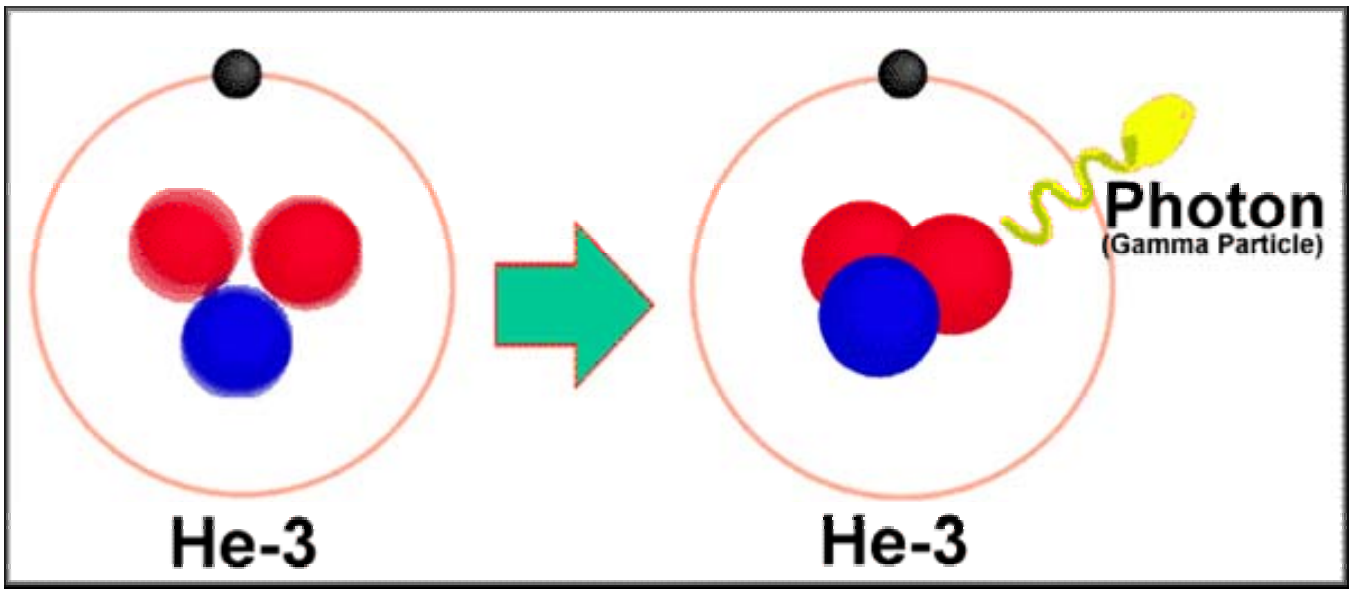


$$^{7}_{4}Be + ^{0}_{-1}e \dashrightarrow ^{7}_{3}Li + \nu$$

Gamma (γ) Decay

Gamma radioactivity is composed of electromagnetic rays.

It is distinguished from x-rays by the fact that it comes from the nucleus.



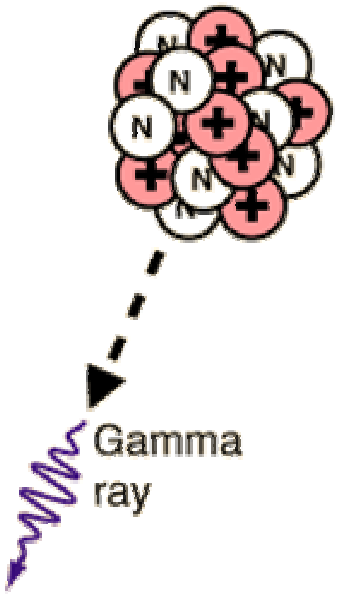
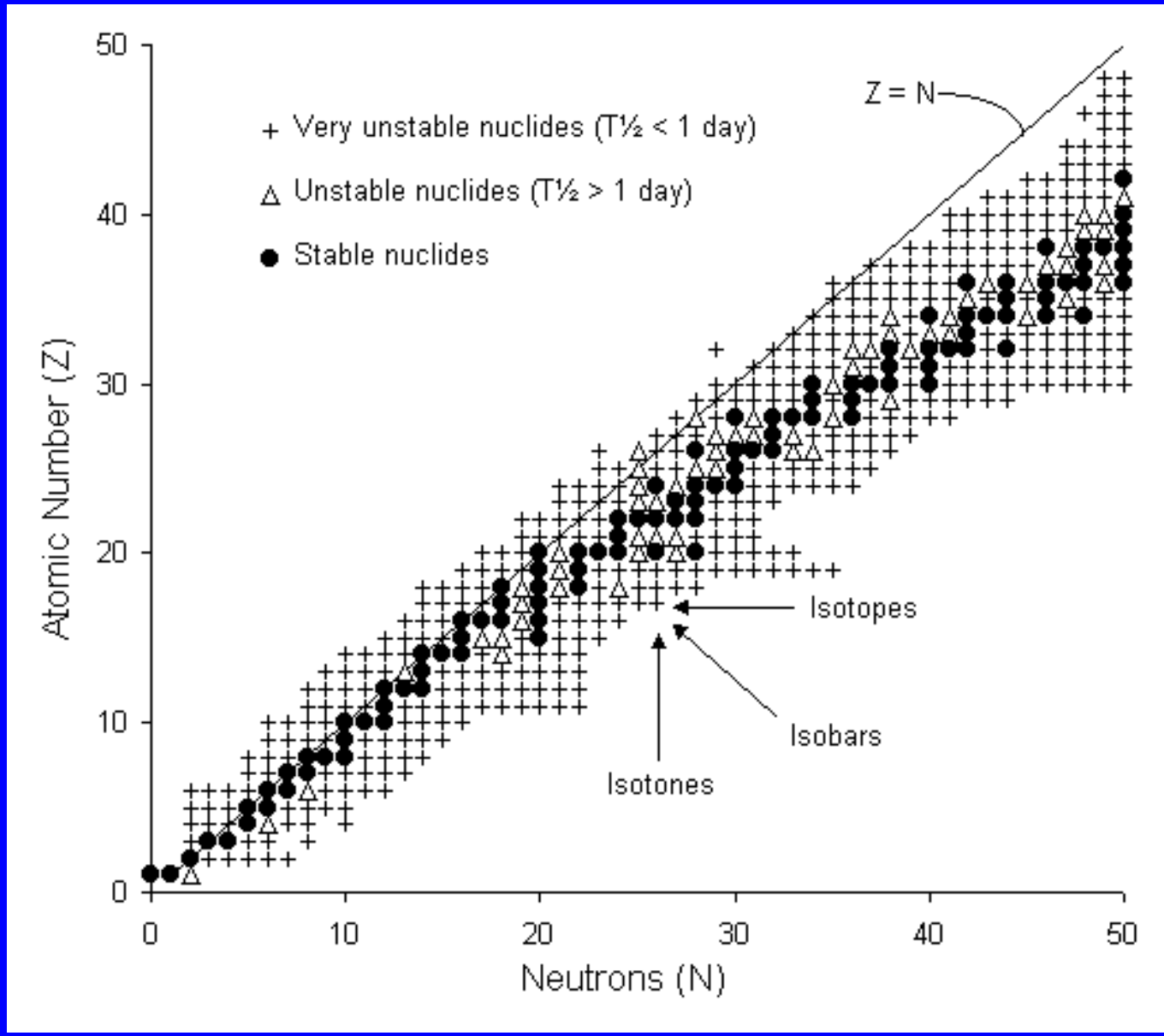


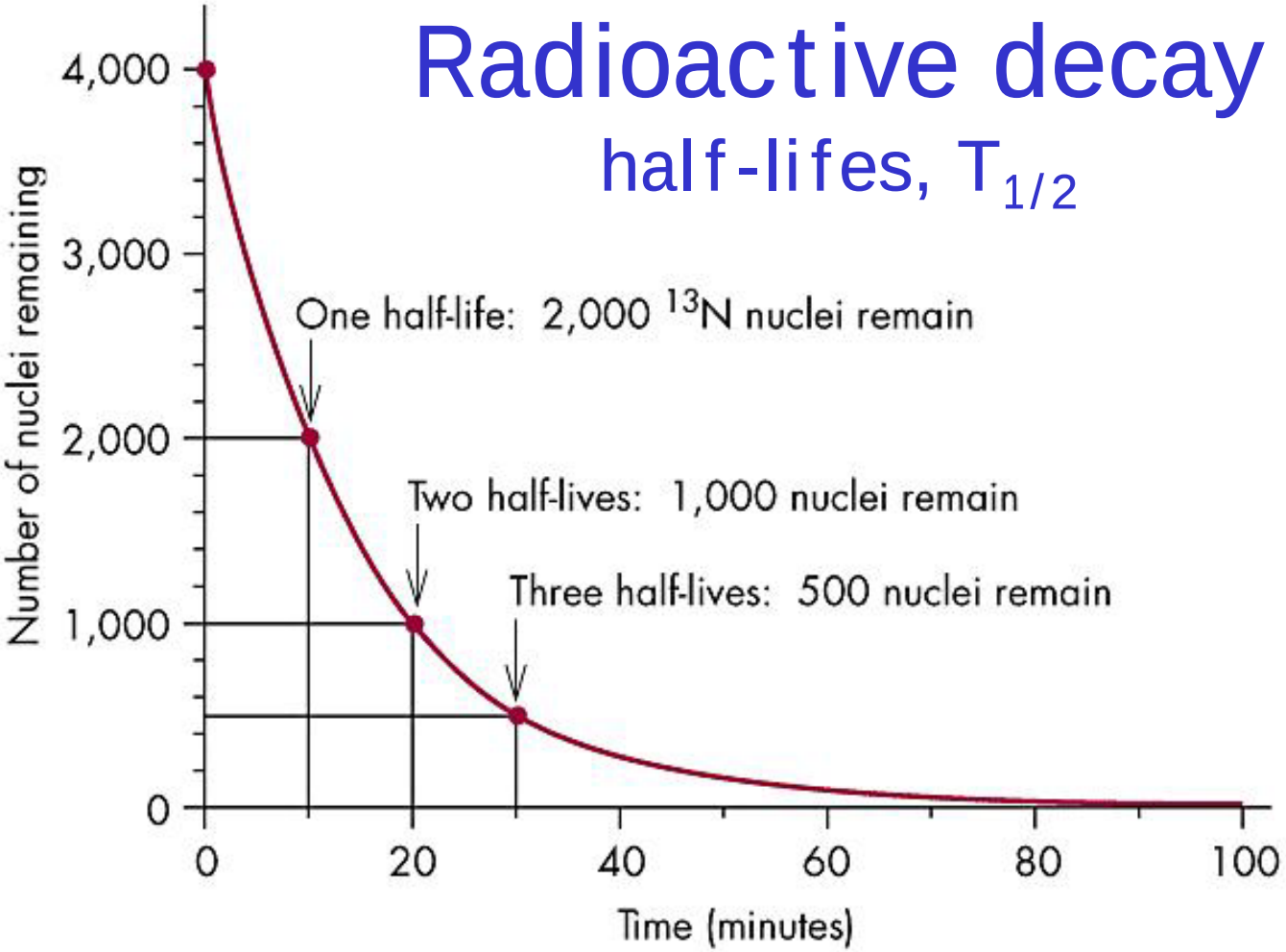
Chart of the Nuclides

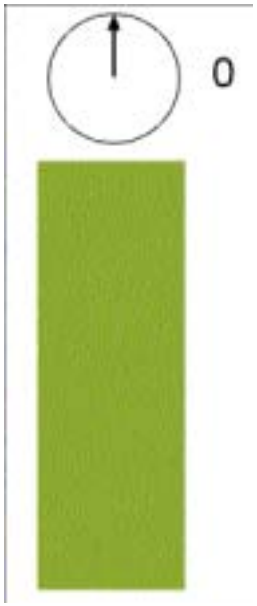


Concept of Isotope Decay

Radioactive decay

half-lifes, $T_{1/2}$





- if it is possible to determine the ratio of the PARENT and DAUGHTER atoms, it is then possible to determine how long ago the decay process started → age determination, last lecture

Basic equation of radioactive decay:

$$\frac{dN}{dt} = -\lambda N$$

λ is the decay constant, which we define as the probability that a given atom would decay in some time dt. It has unit of time^{-1}

$$\int_{N_0}^{N} \frac{dN}{N} = \int_{0}^{t} -\lambda dt$$

where N_0 is the number of atoms of the radioactive, or parent, isotope present at time t=0.

$$\ln \frac{N}{N_0} = -\lambda t$$

$$\frac{N}{N_0} = e^{-\lambda t} \quad \text{or} \quad N = N_0 e^{-\lambda t}$$

Suppose we want to know the amount of time for the number of parent atoms to decrease to half the original number, i.e.:

t when $N/N_0 = 1/2$. Setting N/N_0 to 1/2

$$\ln\frac{1}{2} = -\lambda t_{1/2} \quad \textbf{OR} \quad \ln 2 = \lambda t_{1/2}$$

Half-life time $t_{1/2}$ $\quad t_{1/2} = \dfrac{\ln 2}{\lambda}$

The decay of the parent produces some daughter, or radiogenic nuclides. The number of daughters produced is simply the difference between the initial number of parents and the number remaining after time t:

$$D = N_0 - N$$

$$D = Ne^{\lambda t} - N = N(e^{\lambda t} - 1)$$

This tells us that the number of daughters produced is a function of the number of parents present and time.

In general, there are some atoms of the daughter nuclide around to begin with (t = 0), a more general expression is:

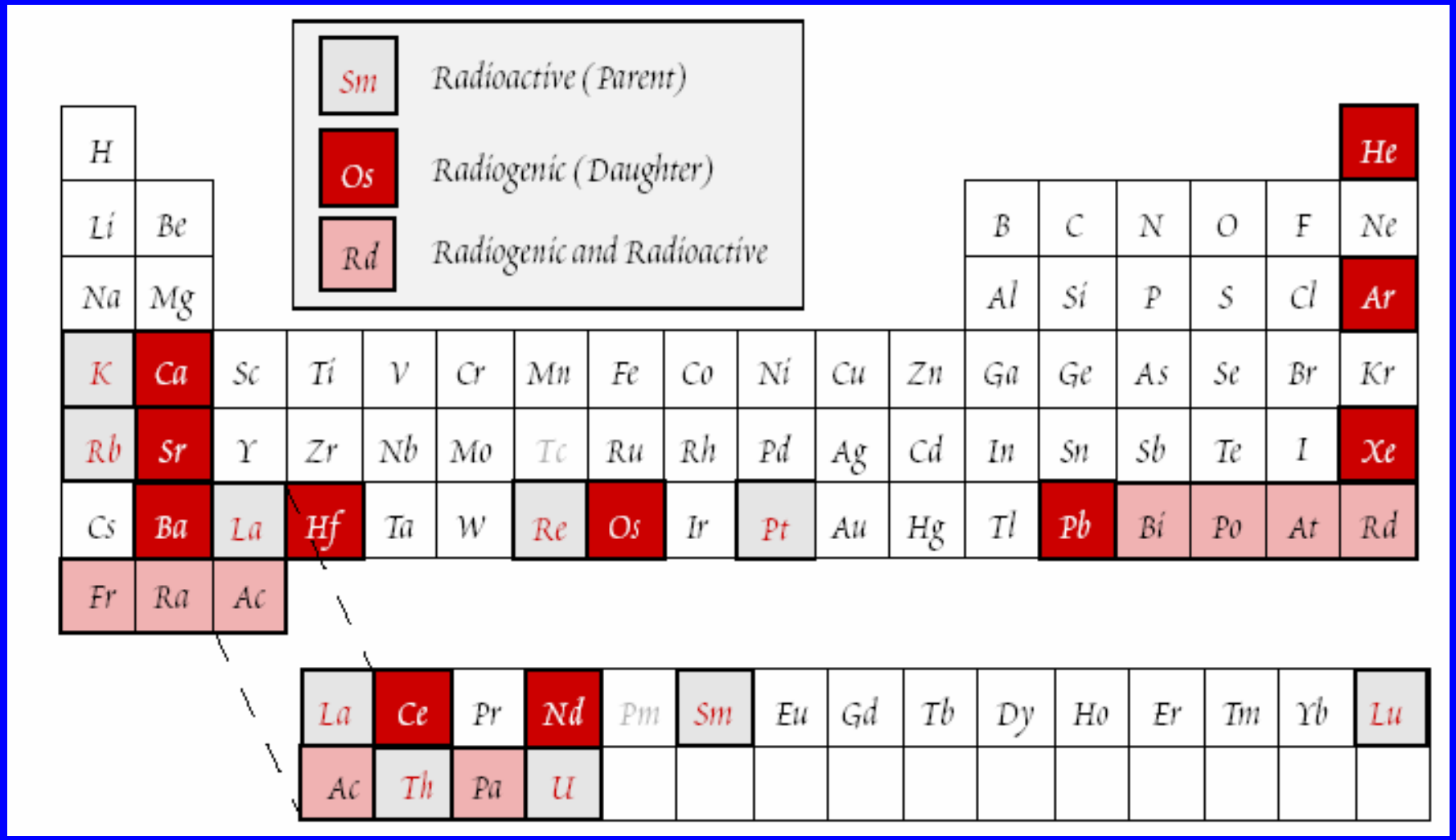
$$\mathbf{D = D_0 + N(e^{\lambda t} - 1)}$$

where D_0 is the number of daughters originally present

e.g., $$^{87}Sr = {}^{87}Sr_0 + {}^{87}Rb(e^{\lambda t} - 1)$$

$$^{87}Sr/^{86}Sr = (^{87}Sr/^{86}Sr)_0 + {}^{87}Rb/^{86}Sr(e^{\lambda t} - 1)$$

Figure: **Periodic Table showing the elements having naturally occurring radioactive isotopes and the elements produced by their decay**



Clocks in the rocks

Geochronology

Methods relying on the decay of naturally occurring radiogenic isotopes:



Parent isotope		Daughter isotope
1. Potassium-40	->	Argon-40
2. Rubidium-87	->	Strontium-87
3. Uranium-235	->	Lead-207
4. Uranium-238	->	Lead-206
5. Thorium-232	->	Lead-208

TABLE: Geologically Useful Long-Lived Radioactive Decay Schemes

Parent	Decay Mode	λ	Half-life	Daughter	Ratio
^{40}K	β^+, e.c, β^-	$5.543 \times 10^{-10} y^{-1}$	$1.28 \times 10^{9} yr$	^{40}Ar, ^{40}Ca	$^{40}Ar/^{36}Ar$
^{87}Rb	β^-	$1.42 \times 10^{-11} y^{-1}$	$4.8 \times 10^{10} yr$	^{87}Sr	$^{87}Sr/^{86}Sr$
^{138}La	β^-	$2.67 \times 10^{-12} y^{-1}$	$2.59 \times 10^{11} yr$	^{138}Ce, ^{138}Ba	$^{138}Ce/^{142}Ce$, $^{138}Ce/^{136}Ce$
^{147}Sm	α	$6.54 \times 10^{-12} y^{-1}$	$1.06 \times 10^{11} yr$	^{143}Nd	$^{143}Nd/^{144}Nd$
^{176}Lu	β^-	$1.94 \times 10^{-11} y^{-1}$	$3.6 \times 10^{10} yr$	^{176}Hf	$^{176}Hf/^{177}Hf$
^{187}Re	β^-	$1.64 \times 10^{-11} y^{-1}$	$4.23 \times 10^{10} yr$	^{187}Os	$^{187}Os/^{188}Os$, $^{187}Os/^{186}Os$
^{190}Os	α	$1.54 \times 10^{-12} y^{-1}$	$4.50 \times 10^{11} yr$	^{186}Os	$^{186}Os/^{188}Os$
^{232}Th	α	$4.948 \times 10^{-11} y^{-1}$	$1.4 \times 10^{10} yr$	^{208}Pb, ^{4}He	$^{208}Pb/^{204}Pb$, $^{3}He/^{4}He$
^{235}U	α	$9.849 \times 10^{-10} y^{-1}$	$7.07 \times 10^{8} yr$	^{207}Pb, ^{4}He	$^{207}Pb/^{204}Pb$, $^{3}He/^{4}He$
^{238}U	α	$1.551 \times 10^{-10} y^{-1}$	$4.47 \times 10^{9} yr$	^{206}Pb, ^{4}He	$^{206}Pb/^{204}Pb$, $^{3}He/^{4}He$

Note: the branching ratio, i.e. ratios of decays to ^{40}Ar to total decays of ^{40}K is 0.117. The production of ^{3}He from ^{147}Sm decay is insignificant compared to that produced by decay of U and Th. ^{147}Sm and ^{190}Pt also produces ^{4}He, but a trivial amount compared to U and Th.

Clocks in the rocks

Cosmogenic isotopes

Methods relying on the isotopes produced by cosmic rays:

1. Tritium
2. Carbon-14
3. Beryllium-10
4. Aluminium-26
5. Chlorine-36



Other methods

Methods relying on disequilibrium within the U-series decay chain

Lead-210

谢谢！