Week 3 Lecture 1 – Ages from Isotope Ratios

Nuclear Decay

-- Decay Law

-- Simplest form of kinetics

-- Sequential Decay (three groups)

-- Radioactive dating, Ages & Natural Activities

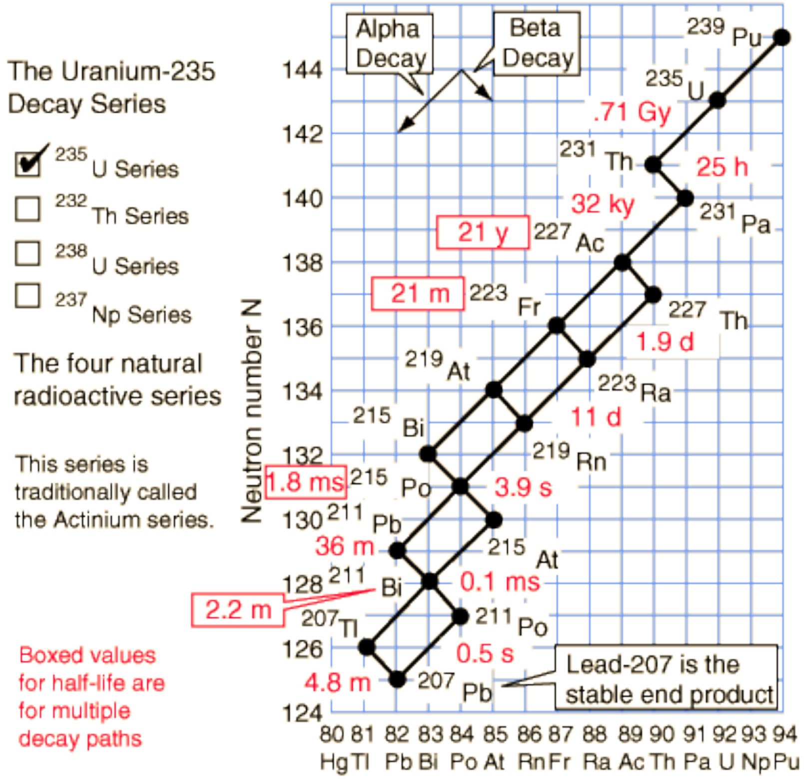
The Persistence of Memory, S. Dali (1931)

Primordial Isotopes - 1

There are a few radioisotopes with very long half-lives that can be used to evaluate the age of a geological sample – given the right conditions.

“Natural Decay Series” – there are four series (sets) of heavy elements linked by the fact that alpha decay changes the mass number by four units but beta decay cannot change the mass number.

^{232}Th (14 Gyr) and all daughters have A= 4n [^{208}Pb]
^{237}Np (2.3 Myr) leads the (4n)+1 series [extinct, ^{209}Bi]
^{238}U (4.5 Gyr) heads the (4n)+2 series [^{206}Pb]
^{237}U (0.71 Gyr) heads the (4n)+3 series [^{207}Pb]



http://hyperphysics.phy-astr.gsu.edu/hbase/Nuclear/radser.html

Measure ratio of Pb to U and compare it to the equilibrium ratio…

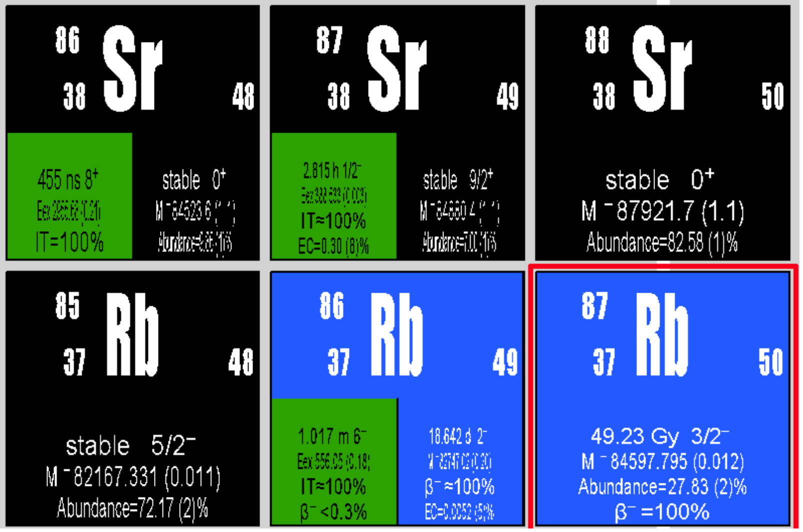
1) The U and Pb were distributed evenly when the material (rock) was being formed.
2) The material did not undergo a chemical change during its life. (no gain/loss of U & Pb)

Measure Pb isotopic ratios [note that ^{204}Pb is stable]

1) The isotopic variations are due to feeding by the radioactive decay.
2) The material underwent (no more than) one purification of Pb during its life.

Primordial Isotopes - 2

There are a few radioisotopes with very long half-lives that can be used to evaluate the age of a geological sample – given the right conditions.



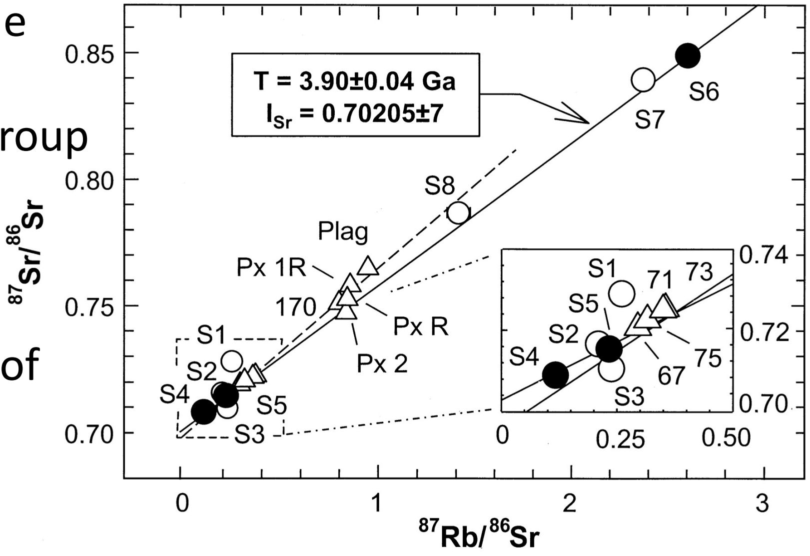
The Rb-Sr Isochron: ^{87}Rb is long-lived and decays to ^{87}Sr (β-); strontium has several other stable isotopes to provide a reference measurement of the amount of daughter present when the material (rock) was formed.

Measure atomic ratio of ^{87}Rb/^{87}Sr and compare to ^{87}Sr/^{86}Sr. This plot is called a concordance and all the data should fall on a straight line if the samples were created at the same time in the past. Cf. Figure 3.12 in the textbook.

Measure isotopic ratios [note that two isotopes in this group are stable], assume:

1) The isotopic variations are due to feeding by the radioactive decay.
2) The material did not undergo a chemical separation of Rb from Sr during its life.

Note that a similar isochron is ^{40}K/^{40}Ar where one might worry more about chemical separation over time.



Random example: Martian Meteorite from Borg, et al. Science 286 (1999) 90

Cosmogenic (recently produced) Isotopes

^{14}C “dating” … ^{14}C ($T_{½}$ = 5730 yr) is created in upper atmosphere by a secondary nuclear reaction between neutrons and ^{14}N. The free carbon atom usually ends up bound into CO_2. The $^{14}CO_2$ comes into equilibrium with the atmosphere and then the biosphere. Every living thing has the equilibrium amount of ^{14}C activity per gram of stable carbon isotopes (^{12}C and ^{13}C). The activity is usually quoted as a “specific activity” because the source is not pure – in preindustrial times: 0.226Bq/gram of carbon. [The specific activity of pure ^{14}C is 4460 mCi/g.] Once the organism dies, it goes out of equilibrium, and the amount of ^{14}C decreases.

Cosmic rays
Solar wind, etc.

$$^{1}_{1}p(high\,energy) + (^{14}N, ^{16}O, etc.) \rightarrow {}^{1}n(high\,energy) + residues\ldots$$

$$^{1}n + ^{14}_{7}N \rightarrow ^{1}_{1}p^{+} + ^{14}_{6}C^{-} + Q \qquad Q = \Delta_{n} + \Delta_{14N} - (\Delta_{H} + \Delta_{14C}) = 0.626\,MeV$$

$$^{14}_{6}C \rightarrow ^{14}_{7}N^{+} + e^{-} + \overline{\upsilon} + Q_{\beta} \qquad Q = \Delta_{14C} - \Delta_{14N} = 0.156\,MeV$$

$$T_{1/2} = 5730\,yr$$

$$A(t) = A_{o}e^{-\lambda t} = \frac{A_{o}}{2^{t/T_{1/2}}}$$

The understanding and application of these ideas lead to the Nobel Prize in Chemistry for W. Libby in 1960

http://www.radiocarbon.org/

Modern ^{14}C Analysis

Recall that the activity is proportional to the number of atoms, and in this case with a long half-life:

$$A(t) = \lambda N(t) \rightarrow \frac{N(t)}{A(t)} = \frac{1}{\lambda}$$

It was realized about 30 years ago that an extremely sensitive Mass Spectrometer could measure the number of atoms present in a sample when the level of activity is far below a measureable activity. (This lead to a MacArthur Award to R. Mueller in 1982.)

The difficulty is to separate the stable and ubiquitous ^{14}N from the rare ^{14}C atoms. Here one applied the fundamental chemical difference between these elements to separate them in a high energy mass spectrometer.

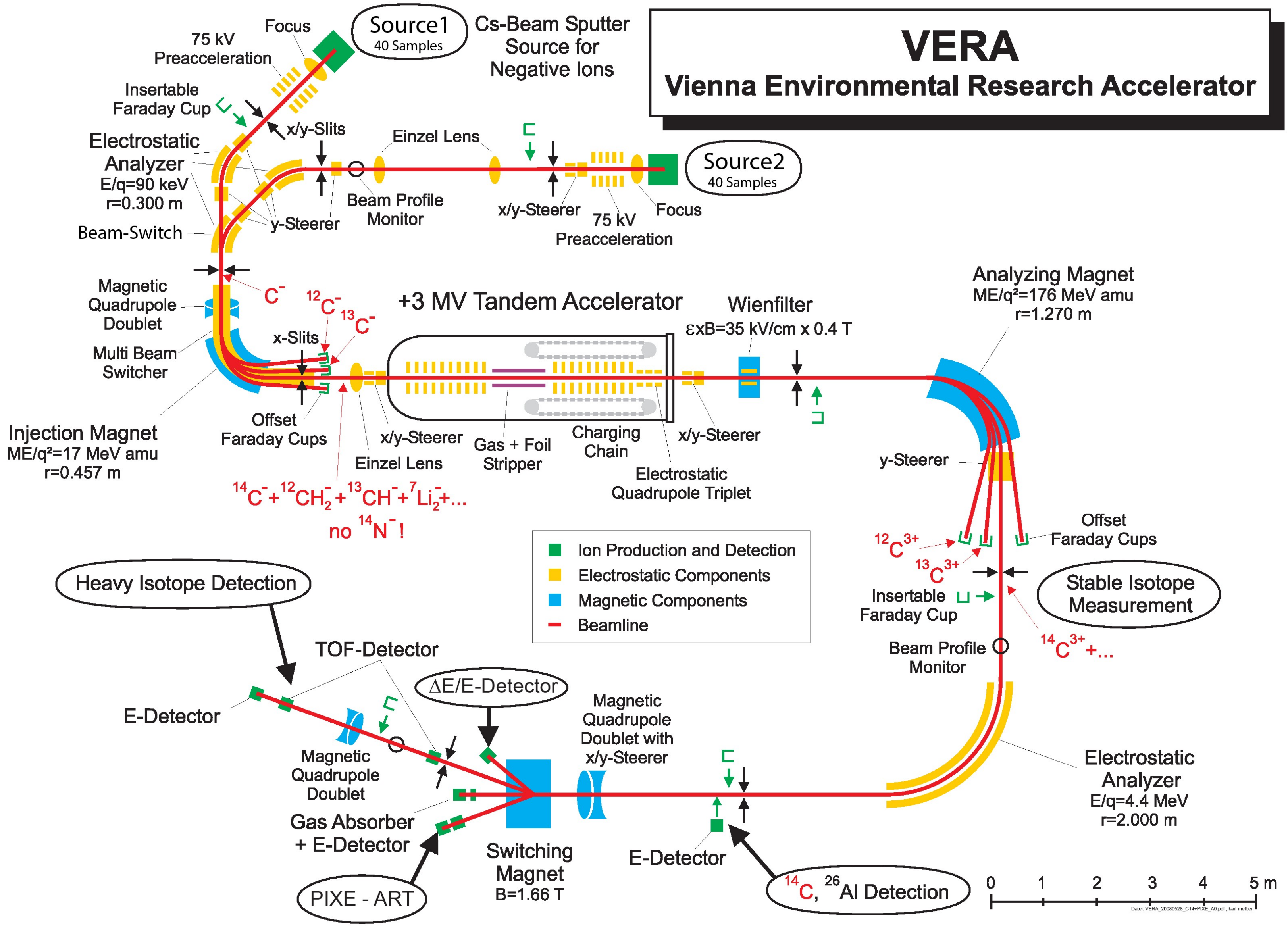
Today there is a large number of AMS laboratories that will analyze the ^{14}C content for you.

http://www.radiocarbon.org/Info/ams-labs.htm

http://owww.phys.au.dk/ams/

Modern ^{14}C Laboratory

MICHIGAN STATE UNIVERSITY



VERA

Vienna Environmental Research Accelerator

Source1
40 Samples
Cs-Beam Sputter Source for Negative Ions
Focus
75 kV Preacceleration
Insertable Faraday Cup
x/y-Slits
Electrostatic Analyzer
E/q=90 keV
r=0.300 m
Beam-Switch
y-Steerer
Beam Profile Monitor
Einzel Lens
x/y-Steerer
75 kV Preacceleration
Focus
Source2
40 Samples
Magnetic Quadrupole Doublet
Multi Beam Switcher
Injection Magnet
ME/q²=17 MeV amu
r=0.457 m
C^-
$^{12}C^-$
$^{13}C^-$
x-Slits
Offset Faraday Cups
x/y-Steerer
Einzel Lens
$^{14}C^- + {}^{12}CH_2^- + {}^{13}CH^- + {}^7Li_2^- + \ldots$
no $^{14}N^-$!
+3 MV Tandem Accelerator
Gas + Foil Stripper
Charging Chain
Electrostatic Quadrupole Triplet
x/y-Steerer
Wienfilter
εxB=35 kV/cm x 0.4 T
Analyzing Magnet
ME/q²=176 MeV amu
r=1.270 m
y-Steerer
Offset Faraday Cups
$^{12}C^{3+}$
$^{13}C^{3+}$
Insertable Faraday Cup
Stable Isotope Measurement
Beam Profile Monitor
$^{14}C^{3+} + \ldots$

🟩 Ion Production and Detection
🟨 Electrostatic Components
🟦 Magnetic Components
🟥 Beamline

Heavy Isotope Detection
TOF-Detector
E-Detector
Magnetic Quadrupole Doublet
ΔE/E-Detector
Gas Absorber + E-Detector
PIXE - ART
Switching Magnet
B=1.66 T
Magnetic Quadrupole Doublet with x/y-Steerer
E-Detector
^{14}C, ^{26}Al Detection
Electrostatic Analyzer
E/q=4.4 MeV
r=2.000 m
0 1 2 3 4 5 m

http://isotopenforschung.univie.ac.at/index.php?id=1570