

## “Radioactive Clocks” or Radiometric Dating

The time span of “relevant” events varies from a few centuries to billions of years

- historians
- archeologists,
- anthropologists,
- geologists,
- astrophysicists

### Radioactive Decay

- independent of the age of the nucleus
- unaffected by heat
- pressure,
- magnetic and electric influences
- in fact, all external forces.

*The basis for all radioactive dating methods is this constancy of decay rate.*

$$N = N_0 e^{-\lambda t}$$

- Radioactive clocks are widely used for the dating of archeological and geological and cosmic materials.
- The time elapsed since the incorporation of a “long-lived” radioactive element into a *closed system* can be inferred from the residual activity or from the amount of elements formed in the decay.

### Uncertainties:

- What is the amount of the daughter present when the rocks were formed?
- Have any parent or daughter atoms been added or lost during the process?

### Some Naturally occurring Radioactive Isotopes and their Half-lives

<b>Radioactive Isotope (Parent)</b>	<b>Product (Daughter)</b>	<b>Half-life (years)</b>
Samarium-147	Neodymium-143	106 billion
Rubidium-87	Strontium-87	48.8 billion
Rhenium-187	Osmium-187	42 billion
Lutecium-176	Halfnium-176	38 billion
Thorium-232	Lead-208	14 billion
Uranium-238	Lead-206	4.5 billion
* Potassium-40	Argon-40	1.26 billion
Uranium-235	Lead-207	0.7 billion
Beryllium-10	Boron-10	1.52 million
Chlorine-36	Argon-36	300,000
* Carbon-14	Nitrogen-14	5730
Uranium-234	Thorium-230	248,000
Thorium-230	Radium-226	75,400

## Radiocarbon dating

The radiocarbon method was developed by a team of scientists led by the late Professor Willard F. Libby of the University of Chicago in the late 1940s.

Libby later received the Nobel Prize in Chemistry in 1960:

*"for his method to use Carbon-14 for age determinations in archaeology, geology, geophysics, and other branches of science."*

According to one of the scientists who nominated Libby as a candidate for this honour;

*"Seldom has a single discovery in chemistry had such an impact on the thinking of so many fields of human endeavour. Seldom has a single discovery generated such wide public interest."*

## Carbon-14

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See 1<sup>st</sup> and 2<sup>nd</sup> figures in Hyperphysics, "*Carbon Dating*." [cited 26 March 2004].  
<http://hyperphysics.phy-astr.gsu.edu/hbase/nuclear/cardat.html>

- $^{14}\text{C}$  is produced in the upper atmosphere:
- cosmic ray bombardment of molecules produces neutrons
- $^{14}\text{N}(\text{n,p})^{14}\text{C}$  reaction produces  $^{14}\text{C}$
- $^{14}\text{C}$  combines with  $\text{O}_2$  to form  $\text{CO}_2$
- $^{14}\text{CO}_2$  equilibrates with  $^{12}\text{CO}_2$  and is incorporated into organic matter
- Carbon dating only applicable to matter which was living

## **$^{14}\text{C}$ Equilibrium Activity**

Living organisms continually exchange  $\text{CO}_2$  with the atmosphere

- At equilibrium with the atmosphere
- Assumes that rate of  $^{14}\text{C}$  production is constant (not true)

$$\frac{{}^{14}_6\text{C}}{{}^{12}_6\text{C}} \approx 1.3 \times 10^{-12}$$

Specific Activity of  $^{14}\text{C}$   $\sim 15$  Bq/gram total carbon

$^{14}\text{C}$  half-life = 5730 years

Beta-minus emission to  $^{14}\text{N}$

Beta energy = 0.016 MeV (not very penetrating), will not come out of solid samples

Samples usually oxidized to form  $\text{CO}_2$

$^{14}\text{C}$  in the gas is counted

Required large samples (1-2 g carbon) and long counting times (up to 15 hours)

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See 3rd figure in Hyperphysics, “*Carbon Dating*.” [cited 26 March 2004].  
<http://hyperphysics.phy-astr.gsu.edu/hbase/nuclear/cardat.html>

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$$N = N_0 e^{-\lambda t}$$

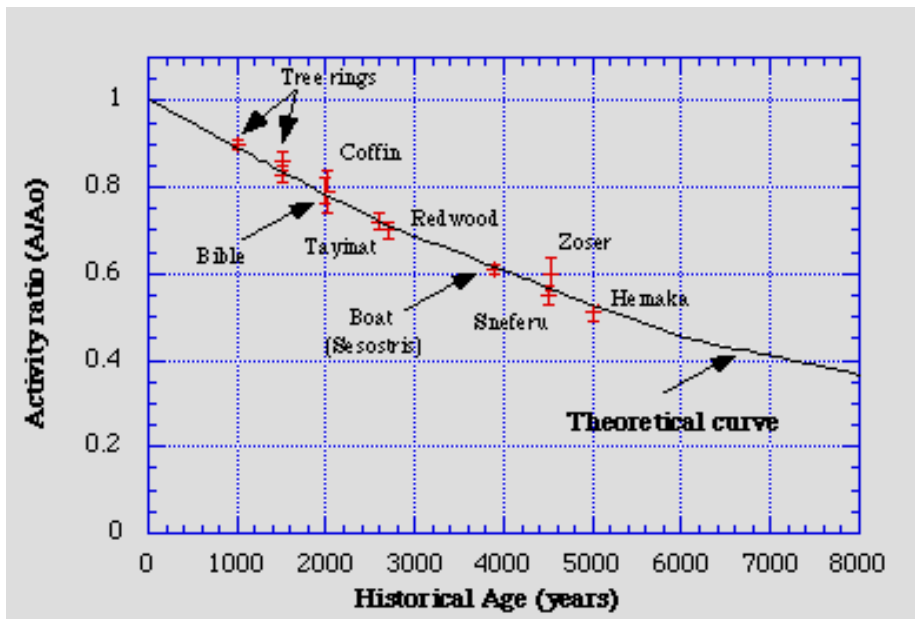


Figure 1: The "Curve of Knowns" after Libby and Arnold (1949). The first acid test of the new method was based upon radiocarbon dating of known age samples primarily from Egypt (the dates are shown in the diagram by the red lines, each with a  $\pm 1$  standard deviation included). The Egyptian King's name is given next to the date obtained. The theoretical curve was constructed using the half-life of 5568 years. The activity ratio relates to the carbon 14 activity ratio between the ancient samples and the modern activity. Each result was within the statistical range of the true historic date of each sample.

The original measurements of Libby were calibrated by using organic samples of known age—including historical artifacts from Egypt.

## Corrections required

### *Tree rings*

- Bristlecone Pines
- Some living specimens > 4000 years old
- Dead specimens overlap back to ~ 8000 years old
- ***Same samples*** used for  $^{14}\text{C}$  dating

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Corrections are needed for ages greater than ~ 2000 years.

E.g.,  $^{14}\text{C}$  date of 3000 B.C.  
Corrected date = 3650 B.C.

### Suess Effect or Industrial Effect (Hans Suess, 1950)

- Burning of fossil fuel since ~ 1890 has added  $^{12}\text{CO}_2$  to the atmosphere
- Effectively dilutes the  $^{14}\text{C}/^{12}\text{C}$  ratio by ~2%
- 1890 wood was used as a calibration standard and corrected for decay to 1950.

### Nuclear Weapons

- Weapons testing in the atmosphere produces enormous amounts of neutrons
- Neutrons interact with nitrogen producing  $^{14}\text{C}$  through the same  $^{14}\text{N}(n,p)^{14}\text{C}$  reaction.
- Maximum effect was in ~ 1963
- The amount of  $^{14}\text{C}$  in the atmosphere was ***doubled!***
- Ratio is returning to “normal”

## Accelerator Mass Spectrometry: A more sensitive approach

15 Bq/g beta count rate for a 1 gram sample, when there are actually  $\sim 10^{12}$  atoms of  $^{14}\text{C}$  present in the 1 gram sample is not very efficient.

Accelerator Mass Spectrometry counts all atoms: the ratio of  $^{14}\text{C}$  to  $^{12}\text{C}$  can be directly measured.

Sensitivity  $\sim 10^{-15}$  in the  $^{14}\text{C}/^{12}\text{C}$  ratio has been achieved

Modern techniques require only mg samples.

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See 1<sup>st</sup> figure in Hyperphysics, "*Mass Spectrometer*." [cited 26 March 2004].  
<http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/maspec.html>.

contaminants of mass 14:

$^{14}\text{N}$

$^{12}\text{CH}_2$

$^{13}\text{CH}$

removed during the sputtering, acceleration, stripping process..

## The Shroud of Turin

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- Said to be the burial cloth of Christ.
- Bears faint impression (in 3D) of a naked crucified man.
- Libby offered to carbon date the Shroud in the 1940s (sample size required was too large)
- AMS techniques: 1988 3 samples dated in three separate laboratories
- 1290-1390 A.D. dates widely publicized
- (see <http://www.shroud.com>) The dating controversy continues...

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Fig. 1 in Damon, P.E. et al. "Radiocarbon Dating of the Shroud of Turin." *Nature* 337 (1989): 611-615.

The shroud samples (0.25 inch x 0.25 inch ) and three control samples were put in encoded stainless steel cylinders and taken back to the three laboratories. The age of the shroud, as determined by the  $^{14}\text{C}/^{12}\text{C}$  ratio measured by AMS, was found to be 1290-1390 AD (95% confidence) in a widely publicized series of 'blind' measurements at 3 AMS labs throughout the world.

## Potassium-40/Argon-40 Method

$^{40}\text{K}$ : half-life =  $1.2 \times 10^9$  years

Major Advantage: offers a means to eliminate daughter atoms present at time=0.

- $^{40}\text{K} \rightarrow ^{40}\text{Ar}$  daughter is a noble (non-reactive) gas
- $^{40}\text{Ar}$  is assumed to be completely volatilized in igneous rocks.

Crystals: no gas exchange

- All  $^{40}\text{Ar}$  present within the crystal must have been created in situ by  $^{40}\text{K}$  decay.

The “Age Equation” (show that this is equivalent to  $N = N_0 e^{-\lambda t}$ )

$$t = \frac{1}{\lambda} \ln \left( 1 + \frac{D}{P} \right)$$

where  $t$  is the age of the rock or mineral specimen,  
 $D$  is the number of atoms of a daughter product today,  
 $P$  is the number of atoms of the parent isotope today,  
 $\ln$  is the natural logarithm (logarithm to base  $e$ ), and  
 $\lambda$  is the appropriate decay constant.

(The decay constant for each parent isotope is related to its half-life,

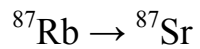
$t^{1/2}$  by the following expression:  $t^{1/2} = \frac{\ln 2}{\lambda}$ )

**Oldest terrestrial rocks:  $\sim 3.8 \times 10^9$  years**

**Oldest meteor/moon rocks:  $\sim 4.5 \times 10^9$  years**

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Graph: "The Rubidium - Strontium System"

## The Isochron Method



- Three other non-radiogenic isotopes of Sr usually present along with  $^{87}\text{Sr}$
- $^{84}\text{Sr}$ ,  $^{86}\text{Sr}$ ,  $^{88}\text{Sr}$
- The ratio of  $^{87}\text{Sr}/^{87}\text{Rb}$  increases over time
- $^{87}\text{Sr}$  ratios to  $^{84}\text{Sr}$ ,  $^{86}\text{Sr}$   $^{88}\text{Sr}$  also increase
- Plotted ratios form straight lines
- Slope proportional to the age of the sample

## The Age of the Earth

Some of the oldest rocks on earth are found in Western Greenland. Because of their great age, they have been especially well studied. The table below gives the ages, in billions of years, from twelve different studies using five different techniques on one particular rock formation in Western Greenland, the Amitsoq gneisses.

<b>Technique</b>	<b>Age Range (billion years)</b>
uranium-lead	3.60±0.05
lead-lead	3.56±0.10
lead-lead	3.74±0.12
lead-lead	3.62±0.13
rubidium-strontium	3.64±0.06
rubidium-strontium	3.62±0.14
rubidium-strontium	3.67±0.09
rubidium-strontium	3.66±0.10
rubidium-strontium	3.61±0.22
rubidium-strontium	3.56±0.14
lutetium-hafnium	3.55±0.22
samarium-neodymium	3.56±0.20