'HEADS' OR 'TAILS'?: HOW GEOLOGISTS DETERMINE ABSOLUTE AGE
ACEPT RADIOMETRIC AGE DETERMINATION MODULE

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STUDENT MATERIAL

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Introduction

How do we know that the Earth is about 4.55 billion years old, or that the dinosaurs died out about 65 million years ago, or that man first evolved 3 to 4 million years ago? Geologists have used methods of absolute age determination to decipher these facts. The determination of the absolute age of rocks is one of the most important achievements in the geological sciences. A geologist may determine the relative ages of rocks in a sequence of rocks by looking at various (stratigraphic) relationships between the rock layers and by comparing the fossils (if any) present in those layers. However, determining the absolute age of a rock layer, that is the actual time in years before today that the rock was formed, requires other methods. These age determination methods make up the field called geochronology.

The most important and versatile absolute age determination method is radiometric age determination, in which the time-dependent decay of radioactive isotopes is used to determine the age of a rock. Radioactive decay is simply the spontaneous changing (decay) of an atom of one element into an atom of another element. Radioactive decay is also an important aspect of the nuclear waste disposal issue because the length of time it is necessary to sequester the waste depends on the decay rates of the materials produced in a nuclear reactor. In nuclear medicine, radioactive decay of atoms is used in methods of imaging parts of the body and internal organs as well as in treating certain types of disease.

In this exercise, we will explore some of the characteristics of radioactive decay for several isotopic systems. The decay rates of the isotopes will be modeled in a simple experiment using coin flipping.

The area surrounding the Awash River in northern Ethiopia is one of the world's richest areas for fossils of early human ancestors. During the 1970's a partial skeleton named 'Lucy' and a group of 13 individuals named 'First Family' of the species Australopithecus afarensis were unearthed in sedimentary layers in this area (see Figure 1). Determination of the age of theses specimens has been a problem until recently (Walter, 1994).

Objectives

1. To discover the characteristic time dependence of radioactive decay by examing the decay of several radioactive isotopes.
2. To develop an explanation for the nature of the decay-time curves by analogy with a coin tossing experiment.

Materials

- Graph paper
- Data tables provided here
- Pennies and container for shaking them
- Calculator
- Figure illustrating the positions of ash layers and early human fossils.

Procedure

1. In the tables given below (Table 1) are listed the number of parent atoms and daughter atoms as a function of time for several isotopic systems. Working with another student, plot the data for two of the systems. Carefully observe the shapes of the curves and the time dependence. Then join another pair of students who have plotted different systems and discuss your observations and interpretations. What are the shapes of the curves? What is similar and what is different about the curves for the different systems? Why do they have this particular shape, as opposed to some other possible shape? As a group try to generate one or more hypotheses that explain why the curves have the shapes that they do.

2. a) In your groups of four, get a bunch of pennies (100 to 200) and a container in which to shake them up. Shake up the pennies and let them drop randomly onto the table top. Count and record the number of 'heads-up' and the number of 'tails-up' pennies. Remove the 'tails-up' pennies from the group. Then, take only the 'heads-up' pennies, shake them up and let them drop again. As before, count and record the number of 'heads-up' and the number of 'tails-up' pennies. What are the total numbers of 'heads' and 'tails', including all the 'tails' obtained in previous flips of the coins? Separate the 'tails' pennies from the group, and continue until there are no more 'heads-up' pennies. Then as a group discuss the results. How do the results of this penny flipping exercise relate to the isotopic decay examples plotted in Step 1?
b) If you are given a container that contains 240 pennies, of which 42 are 'heads' and the remainder are 'tails', can you tell how many coin flips the system has undergone? How does the number of times the coins have been tossed relate to the time scale of the plots in Step 1?
3. Examine the stratigraphic sequence depicted in Figure 1. To bracket the age of the early human fossils, we will use the ^{40}K-^{40}Ar system to determine the ages of volcanic ash layers above and below the fossil-containing layer. ^{40}K decays to ^{40}Ar with a half life of 1.25×10^9 years; the decay constant $\lambda = \ln 2/t_{1/2} = 5.543 \times 10^{-10}$ yrs^{-1}. You are able to extract some potassium-rich crystals from the upper and lower volcanic ash layers (see Figure 1). You analyze the crystals and obtain the data in Table 2. Use these data and the equation given to you by the instructor to determine the age of the ash layers. (^{40}K has a second decay pathway that results in formation of ^{40}Ca, so in Table 2, the data for ^{40}K concentration are corrected for

Table 1a. Radioactive Decay of ^{131}I

^{131}I - ^{131}Xe Decay, 10,000 atoms initially		
time (days)	131I(t)	131Xe(t)
0.00	10000	0
2.00	8416	1584
4.00	7083	2917
6.00	5962	4038
8.00	5017	4983
10.00	4223	5777
12.00	3554	6446
14.00	2991	7009
16.00	2517	7483
18.00	2119	7881
20.00	1783	8217
22.00	1501	8499
24.00	1263	8737
26.00	1063	8937
28.00	895	9105
30.00	753	9247
32.00	634	9366
34.00	533	9467
36.00	449	9551

Table 1b. Radioactive Decay of ^{59}Fe

^{59}Fe - ^{59}Co Decay, 10,000 atoms initially		
time (days)	$^{59}Fe(t)$	$^{59}Co(t)$
0.00	10000	0
10.00	8558	1442
20.00	7324	2676
30.00	6268	3732
40.00	5364	4636
50.00	4590	5410
60.00	3928	6072
70.00	3362	6638
80.00	2877	7123
90.00	2462	7538
100.00	2107	7893
110.00	1803	8197
120.00	1543	8457
130.00	1321	8679
140.00	1130	8870
150.00	967	9033
160.00	828	9172
170.00	708	9292
180.00	606	9394

Table 1c. Radioactive Decay of ^{90}Sr

^{90}Sr - ^{90}Y Decay, 10,000 atoms initially		
time (years)	$^{90}Sr(t)$	$^{90}Y(t)$
0.00	10000	0
10.00	7881	2119
20.00	6210	3790
30.00	4894	5106
40.00	3857	6143
50.00	3039	6961
60.00	2395	7605
70.00	1888	8112
80.00	1487	8513
90.00	1172	8828
100.00	924	9076
110.00	728	9272
120.00	574	9426
130.00	452	9548
140.00	356	9644
150.00	281	9719
160.00	221	9779
170.00	174	9826
180.00	137	9863

Table 1d. Radioactive Decay of ^{14}C

^{14}C - ^{14}N Decay, 10,000 atoms initially		
time (yrs)	$^{14}C(t)$	$^{14}N(t)$
0	10000	0
1.00E+03	8861	1139
2.00E+03	7851	2149
3.00E+03	6956	3044
4.00E+03	6164	3836
5.00E+03	5462	4538
6.00E+03	4839	5161
7.00E+03	4288	5712
8.00E+03	3799	6201
9.00E+03	3366	6634
1.00E+04	2983	7017
1.10E+04	2643	7357
1.20E+04	2342	7658
1.30E+04	2075	7925
1.40E+04	1839	8161
1.50E+04	1629	8371
1.60E+04	1443	8557
1.70E+04	1279	8721
1.80E+04	1133	8867

Table 1e. Radioactive Decay of ^{235}U

^{235}U - ^{207}Pb Decay, 10,000 atoms initially		
time (years)	$^{235}U(t)$	$^{207}Pb(t)$
0	10000	0
2.00E+08	8212	1788
4.00E+08	6744	3256
6.00E+08	5538	4462
8.00E+08	4548	5452
1.00E+09	3735	6265
1.20E+09	3067	6933
1.40E+09	2519	7481
1.60E+09	2069	7931
1.80E+09	1699	8301
2.00E+09	1395	8605
2.20E+09	1146	8854
2.40E+09	941	9059
2.60E+09	773	9227
2.80E+09	634	9366
3.00E+09	521	9479
3.20E+09	428	9572
3.40E+09	351	9649
3.60E+09	289	9711

Table 1g. Radioactive Decay of ^{87}Rb

^{87}Rb - ^{87}Sr Decay, 10,000 atoms initially		
time (years)	$^{87}Rb(t)$	$^{87}Sr(t)$
0	10000	0
1.00E+10	8676	1324
2.00E+10	7528	2472
3.00E+10	6531	3469
4.00E+10	5667	4333
5.00E+10	4916	5084
6.00E+10	4266	5734
7.00E+10	3701	6299
8.00E+10	3211	6789
9.00E+10	2786	7214
1.00E+11	2417	7583
1.10E+11	2097	7903
1.20E+11	1820	8180
1.30E+11	1579	8421
1.40E+11	1370	8630
1.50E+11	1188	8812
1.60E+11	1031	8969
1.70E+11	895	9105
1.80E+11	776	9224

Table 1f. Radioactive Decay of ^{40}K

^{40}K-^{40}Ar Decay, 10,000 atoms initially		
time (yrs)	$^{40}K_{eff}(t)$	$^{40}Ar(t)$
0	10000	0
2.50E+08	8706	1294
5.00E+08	7579	2421
7.50E+08	6599	3401
1.00E+09	5745	4255
1.25E+09	5001	4999
1.50E+09	4354	5646
1.75E+09	3791	6209
2.00E+09	3300	6700
2.25E+09	2873	7127
2.50E+09	2501	7499
2.75E+09	2178	7822
3.00E+09	1896	8104
3.25E+09	1651	8349
3.50E+09	1437	8563
3.75E+09	1251	8749
4.00E+09	1089	8941
4.25E+09	948	9052
4.50E+09	826	9174