Classroom notes for: Radiation and Life

Lecture 11

98.101.201

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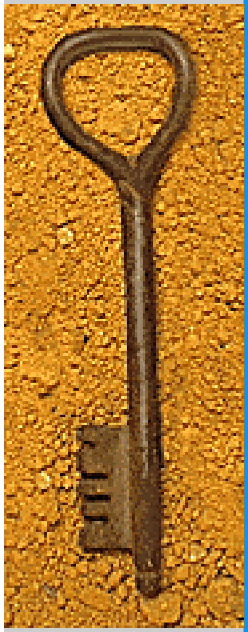
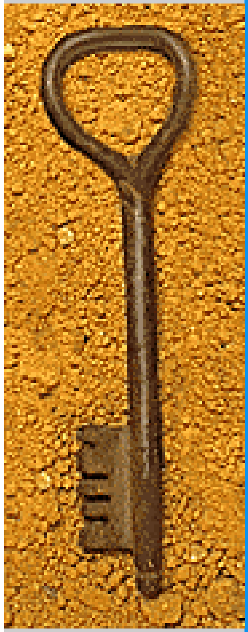


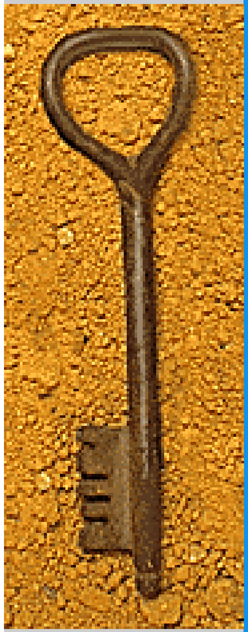
Radioactive Decay Series (“Chains”)

- A radioactive isotope (radioisotope) can decay and transform into another radioisotope.
- This may happen several times before one of the radioisotopes in the chain decays to something stable.
- For example, U-238 has a decay chain that is 15 steps long.

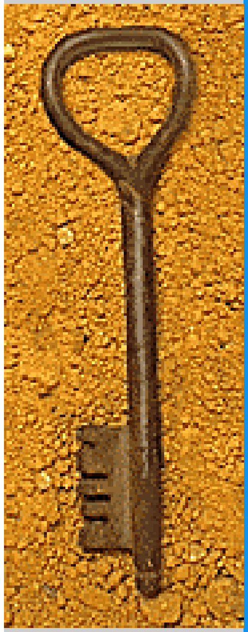


				change in:	
isotope	Z	A	decay mode	Z	A
${}_{92}$U-238	92	238	α	-2	-4
${}_{90}$Th-234	90	234	β	+1	0
${}_{91}$Pa-234	91	234	β	+1	0
${}_{92}$U-234	92	234	α	-2	-4
${}_{90}$Th-230	90	230	α	-2	-4
${}_{88}$Ra-226	88	226	α	-2	-4
${}_{86}$Rn-222	86	222	α	-2	-4
${}_{84}$Po-218	84	218	α		
			total:	-8	-20

- Check the math: the difference U-238 and Po-218 is Z=8 and A=20. This decay series finally ends with stable ${}_{82}$Pb-206 (incidentally, ${}_{83}$Bi-209 is the heaviest occurring stable isotope).
- The Curies had to sort through many different materials to isolate radium and polonium!



- If we start with 1000 atoms of U-238; after one half-life, we have 500 atoms of uranium, but less than 500 atoms of Th-234, because as soon as the U-238 decays to Th-234, the thorium itself starts decaying. Thus in uranium deposits, you'll find all the other elements in the chain mixed in.
- It will be a very long time before all of the uranium has transformed to lead, however. The U-238 decay chain is still active today, because only one U-238 half-life has elapsed since the formation of the earth.
- Some radioisotopes are not in a series, and decay directly to stable nuclei.
- ${}_{1}$H-3-- -> ${}_{2}$He-3 + ${}_{-1}\beta + \nu$ + Q t-½ = 12.32 year
- ${}_{6}$C-14-- -> ${}_{7}$N-14 + ${}_{-1}\beta + \nu$ + Q t-½ = 5730 years



These two radioisotopes are not left over from the earth's creation; they are produced naturally in the upper atmosphere as a result of nuclear reactions induced by cosmic radiation.

(*Radiation Safety and Control, Volume 2*, French and Skrable, p. 10)

$_{7}\text{N-14} + {}_{0}\text{n-1} \rightarrow {}_{6}\text{C-14} + {}_{1}\text{p-1}$

$_{3}\text{Li-6} + {}_{0}\text{n-1} \rightarrow {}_{3}\text{H-3} + {}_{2}\alpha\text{-4}$

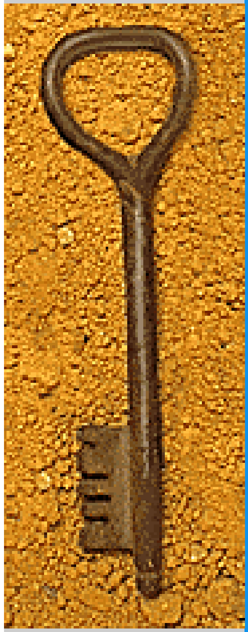
An Aside: Carbon-14 Dating

All living organisms have small amounts of $_{6}$C-14 in them

This is because a certain percentage of all carbon is the radioactive isotope carbon-14 ; it's created by the action of cosmic rays.

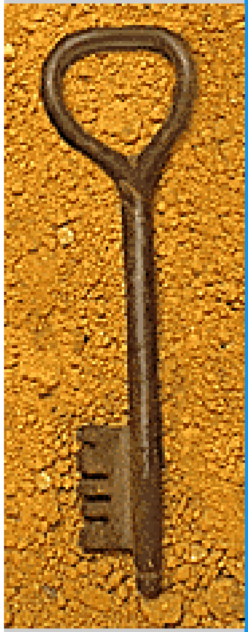
The $_{6}$C-14 that decays to stable $_{7}$N-14 or is excreted is balanced by $_{6}$C-14 that is brought into the organism's body as part of it's normal carbon intake.

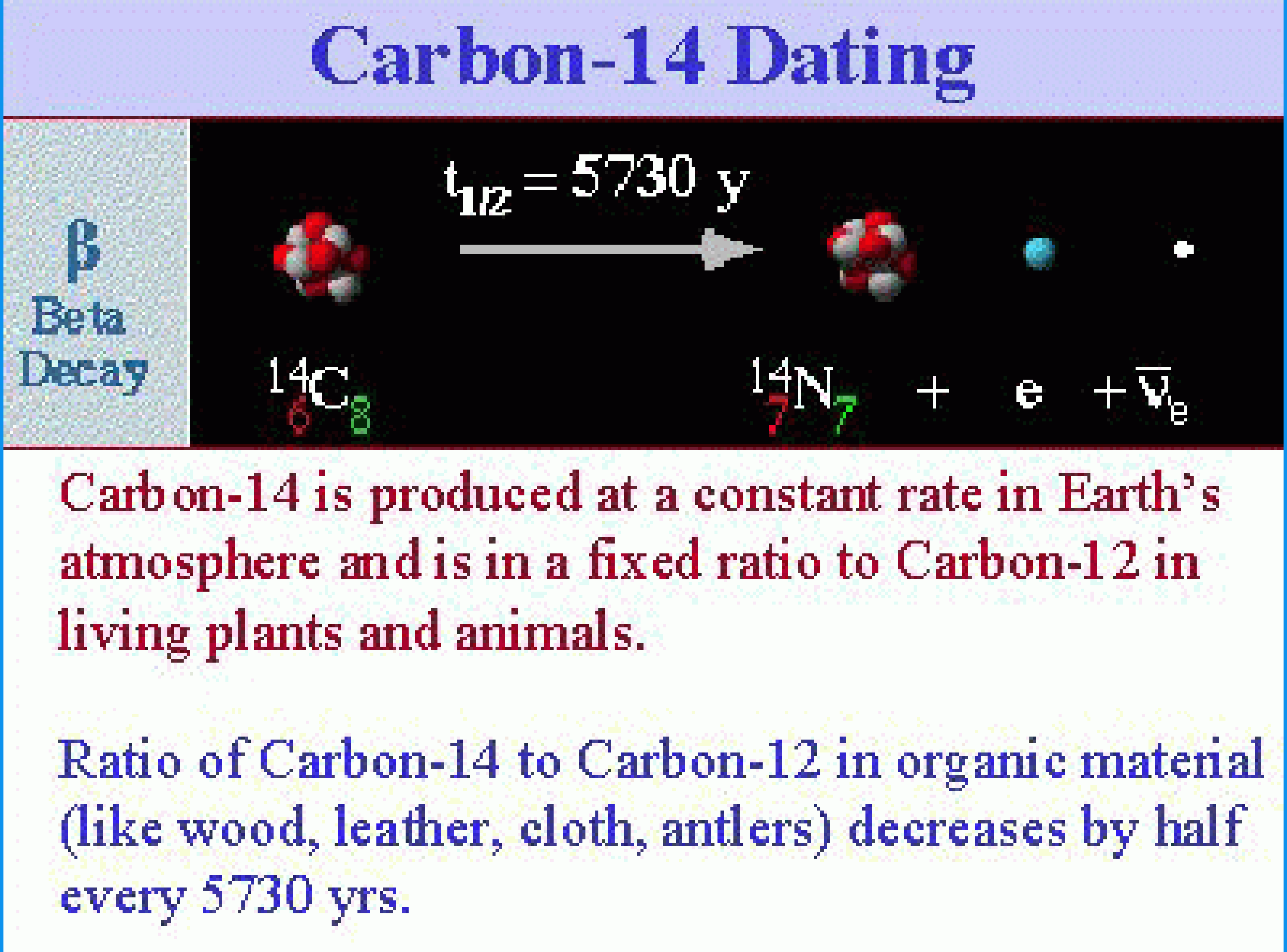
Thus, each organism has a specific amount of $_{6}$C-14.



- For example, suppose the ratio of ${}_{6}$C-14 to ${}_{6}$C-12 is 1/100 (hypothetically). However, by measuring the radioactivity emitted by the carbon-14 in the dead organism, we find the ratio is now only 1/200 (half of what it should be). That means one half-life has elapsed, so the organism died 5730 years ago.
- Obviously, this technique will usually only work for once-living organisms or other organic matter. A bronze artifact simply won’t have enough carbon in it (and certainly not enough ${}_{6}$C-14 in it) to allow it to be dated.
- This technique also doesn’t work well beyond about 50,000 years (9-10 half-lives) because much of the radioactive carbon has decayed to nitrogen by that point.

The Nuclear Reaction





Carbon-14 Dating

β

Beta Decay

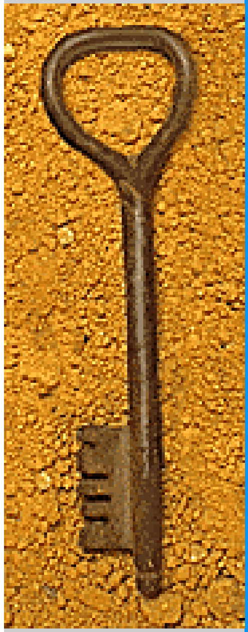
$t_{1/2} = 5730$ y

$$^{14}_{6}\mathrm{C}_{8} \longrightarrow {}^{14}_{7}\mathrm{N}_{7} + e + \bar{\nu}_e$$

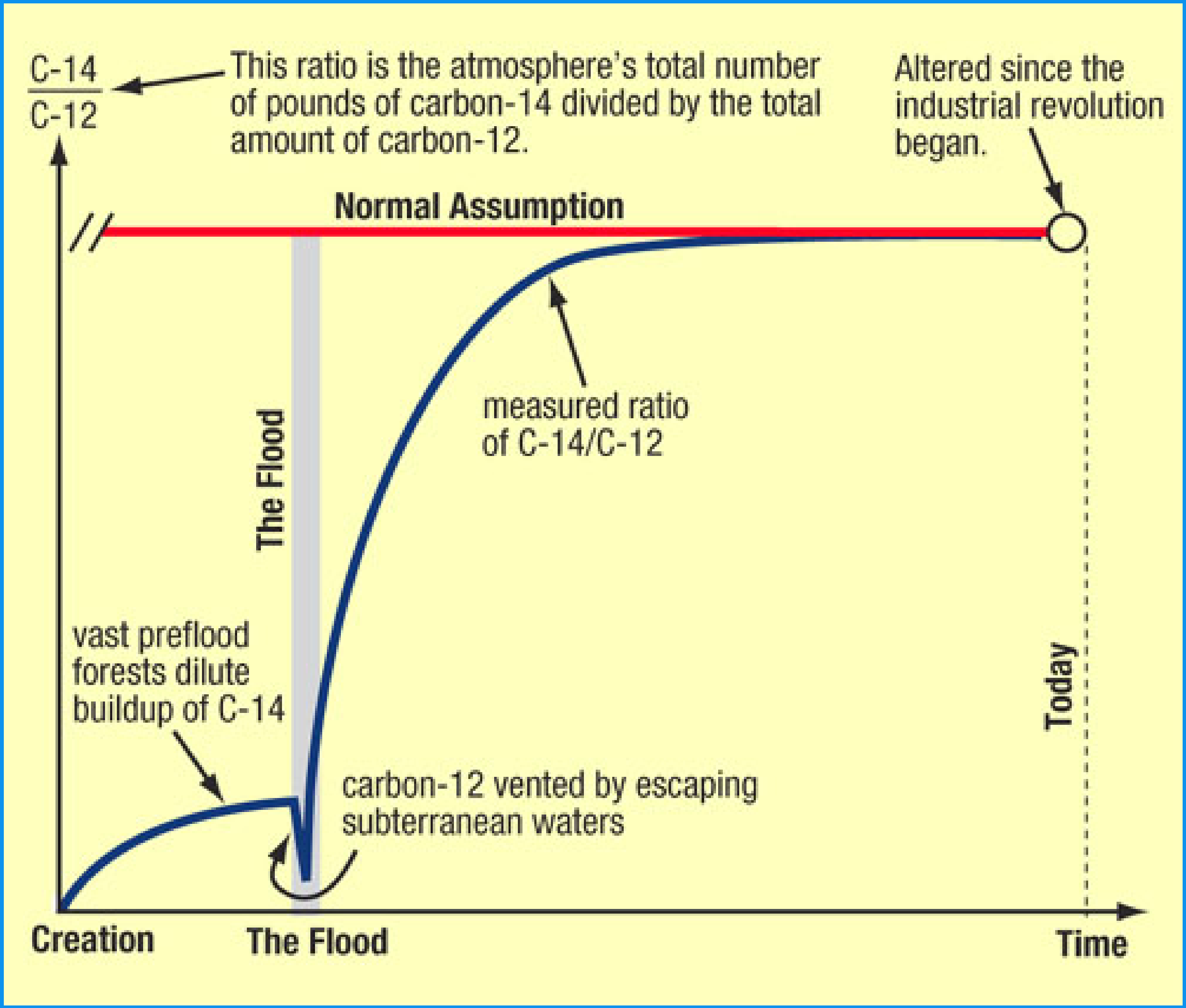
Carbon-14 is produced at a constant rate in Earth's atmosphere and is in a fixed ratio to Carbon-12 in living plants and animals.

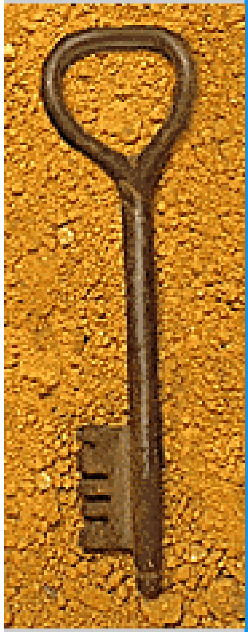
Ratio of Carbon-14 to Carbon-12 in organic material (like wood, leather, cloth, antlers) decreases by half every 5730 yrs.

http://www.astro.virginia.edu/class/oconnell/astr121/test/im/carbon_14_dating.gif



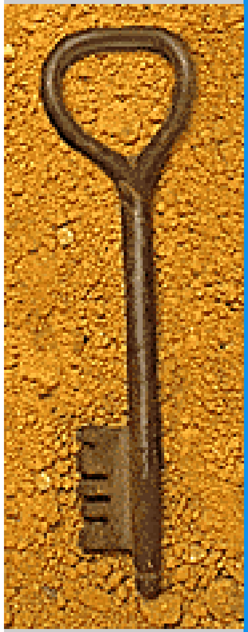
What is wrong with this picture?





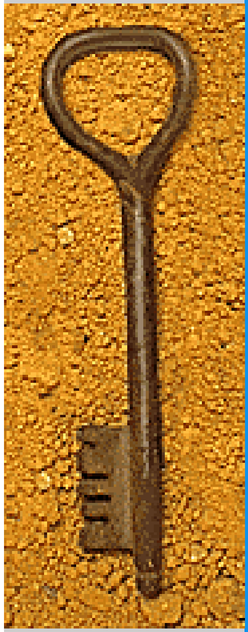
Back to the Curies

- Now we can understand the puzzling properties of polonium and radium discussed earlier (remember the Curies?)
  - The amount of polonium in their sample decreased by ½ over regular time intervals.
- Radioactive materials undergo spontaneous decay with a specific half-life (that varies with each radionuclide).
  - Note that the word radionuclide essentially has the same meaning as radioisotope.
  - No chemical or physical treatment could alter the amount of radioactivity produced by a given amount of polonium or radium.
- Radioactivity is a result of interactions within the nucleus; standard chemical and physical treatment (as was available circa 1900) cannot alter the nucleus.
  - Radioactivity seemed to violate the principle of conservation of energy.
  - By E=mc^2, the conservation of mass-energy.

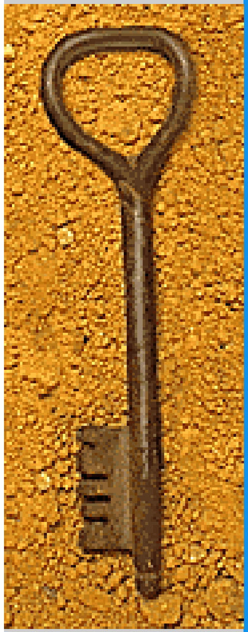


Activity

- Activity is the amount of radiation being emitted per unit time (per second, per minute, per year…) by a radioactive material.
- It is typically measured in decays (disintegrations) per second (dps) or decays per minute (dpm).
  - Other units of activity include:
  - 1 becquerel (abbreviated Bq) = 1 dps; and
  - 1 curie (abbreviated Ci) = 3.7 x 10^{10} becquerel = 3.7 x 10^{10} dps.
- In Pierre Curie’s honor, the 1910 Radiology Congress chose the curie as the basic unit of radioactivity: the quantity of radon in equilibrium with one gram of radium. (http://www.accessexcellence.org/AE/AECCC/historical_background.html)
- As a rough rule-of-thumb (ROT), one curie represents a large amount of activity, one mCi represents a moderate activity, and one becquerel is a very tiny amount of activity.



- Activity depends on:
- the number of radioactive atoms; and
  - This makes sense intuitively; the more atoms that are present in a radioactive material, the greater will be the sample’s activity.
- the half-life of the radionuclide.
  - This also makes sense upon reflection; a material with a short half-life decays very quickly, which means it must be emitting radiation in large amounts (it has a high activity).
  - We can represent this dual dependence mathematically.



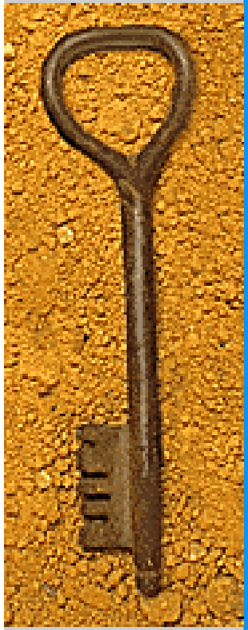
We can represent this dual dependence mathematically.

Activity (A) = .693 / half-life (t- ½) x number of atoms in radioactive material (N)

The constant .693 is an artifact of choosing to work with half-lives when performing the calculus that allows you to derive this mathematical expression.

- To express activity in dps, then t- ½ will be the half-life in seconds.
- To express activity in dpm, then t- ½ will be the half-life in minutes.

N will be huge even for very small amounts of radioactive material; for instance, one gram of water contains 3.34556×10^{22} H_2O molecules. That's quite a few molecules for .035, or about 1/30th of one ounce!



Consider an Example That Demonstrates the Dual Dependence

5 g of U-238

t- ½ = 4.51 x 10^9 yr or 1.42 x 10^{17} sec

N = 1.265 x 10^{22} atoms

A = .693 / (1.42 x 10^{17}) x (1.265 x 10^{22})

A = 6.17 x 10^4 dps (Bq)

A = 1.67 μCi

Compare this with 1 g of Co-60 (this is an equivalent number of atoms).

1 g of $_{27}$Co-60

t- ½ = 5.27 yr or 1.66 x 10^8 sec

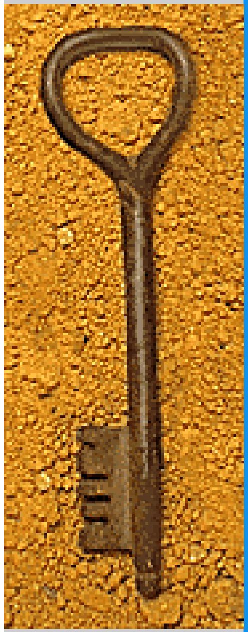
N = 1 x 10^{22} atoms

A = .693/(1.66 x 10^8) x (1 x 10^{22})

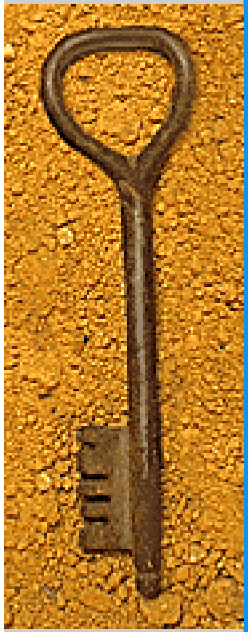
A = 4.17 x 10^{13} dps (Bq)

A = 1.13 x 10^3 Ci

Thus, for roughly equal numbers of atoms, the activities differed by a factor of about 1 x 10^9.

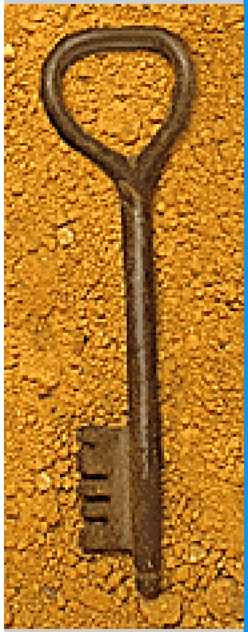


- Remember that activity depends upon the number of atoms in the sample as well; so you can pile up more uranium atoms to get a larger activity. However, it would take about 3.4 billion grams (~770 tons) of U-238 to match the activity of 1 g of Co-60!
- The Co-60 has a much shorter half-life (about one billion times shorter), so it decays much more quickly.
- The activity of the Co-60 decreases by ½ every 5.27 years.
- After 105 years, the activity of the Co-60 has decreased to ~ 1,000 µCi (a factor of one-million decrease).
- The activity of the U-238 remains essentially unchanged after 105 years, and is still 1.67 µCi.



Absorbed Dose

- When discussing the term "dose" with students, be careful to use the term properly. Often, when speaking of absorbed dose (or dose equivalent- both of which are explained below), the term "exposure" will be used. However, exposure is defined very precisely and narrowly, and should only be used in a specific context. For instance, to ask "What was my exposure for the year?" is improper. The correct question to ask would be "What was my dose equivalent for the year?"
- The term "exposure", strictly speaking, is defined as the quantity of charge liberated per unit mass in air by photons between the energies of 10 keV and 3 MeV. In this sense, "exposure is the ionization equivalent of collision kerma in air". (*Heath Physics*, March 2002, p. 376)



Absorbed dose is the energy absorbed by matter as ionizing radiation interacts with it (a somewhat simplistic definition that works for the purposes of this class).

This tern is ordinarily defined for ionizing radiation only- if you are warmed by your oven, for instance, this is not an absorbed dose.

- The units of absorbed dose are as follows.

The historical unit of absorbed dose is the “rad”. The term “rad” is an initialism for “radiation absorbed dose”. (*Heath Physics*, March 2002, p. 375) It was originally defined as 100 ergs (an outdated measure of energy) of ionizing radiation absorbed per gram of target material. (*Radiation Detection and Measurement*, Knoll, p. 61) Alternately:

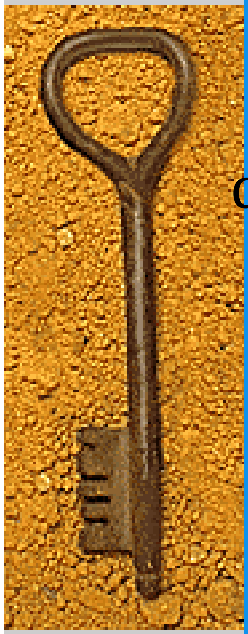
1 rad = .01 joules of ionizing radiation absorbed per kilogram of target matter (1 rad = .01 J/kg).

In terms of SI units:

1 gray (Gy) = 1 joule of ionizing radiation absorbed per kg of target matter (1 Gy = 1 J/kg). (*Radiation Detection and Measurement*, Knoll, p. 61)

Thus, 1 Gy = 100 rad.

Calculating Absorbed Dose



To calculate the absorbed dose, we must answer four questions.

- –What is the energy (E) of the radiation?
- –Calculate the “Q-value” of the originating reaction, and use this to calculate the energy of each individual particle or photon that is emitted (remember that Q is the overall energy of the reaction).
- –What is the activity (A) of the source?

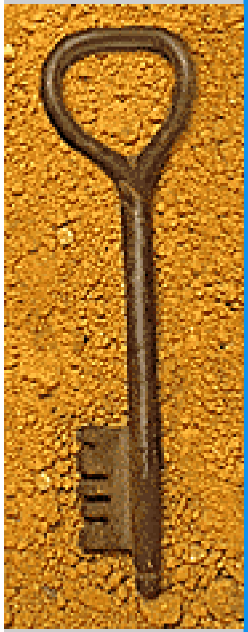
Remember, activity is usually measured in dps.

- How long was the irradiation?

The irradiation time will usually be measured in seconds.

- What is the fraction of emitted ionizing radiation that is actually absorbed?

Determining this fraction actually involves rather complex math (geometry and calculus); the concept can be understood readily on an intuitive level, however, if you consider a small radiation source positioned first close to the body then far away from it

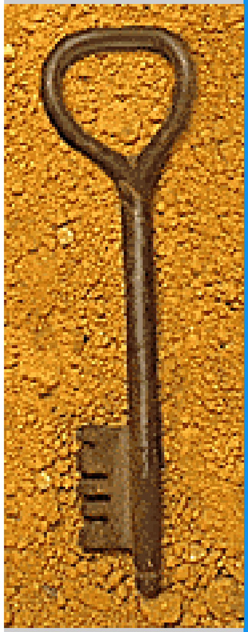


Dose Equivalent

To understand the health effects (risk) to biological organisms posed by a particular dose of ionizing radiation, we must know one more thing: the type of radiation. This is because different types of ionizing radiation will have different effects on biological organisms.

Each type of ionizing radiation is therefore assigned a quality factor (Q), depending upon how damaging it is.

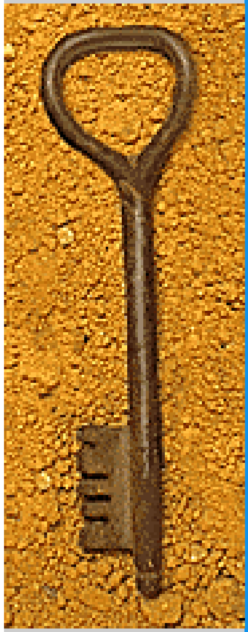
radiation	Q
α particles	20
neutrons	10 (average)
β particles	1
x-rays/γ-rays	1



Note that Q as used in this context differs from the Q-value of a nuclear reaction.

Roughly speaking, Q is assigned by using x-rays/gamma-rays as the baseline and arbitrarily giving them a quality factor of 1; other types of ionizing radiation are compared to x-rays/g-rays and assigned an appropriately scaled quality factor. The quality factor for alpha particles could just as easily have been assigned as 1, in which case x-rays would have a Q of 1/20th.

Values of Q are selected from experimental values of the relative biological effectiveness (RBE), which is the ratio of x- or g-ray dose to that of the radiation in question giving the same kind and degree of biological effect. (*Introduction to Radiological Physics and Radiation Dosimetry*, Attix, p. 34)



Note that Q as used in this context differs from the Q-value of a nuclear reaction.

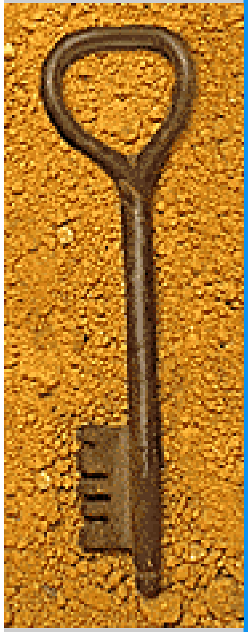
absorbed dose	radiationQ	dose equivalent	
1 rad	alpha	20	20 rems
1 rad	gamma	1	1 rem

Three points are illustrated by this example.

Q has the units of rems/rad or sieverts/gray. (*Heath Physics*, March 2002, p. 382)

The amount of energy absorbed hasn’t actually increased (in fact it’s equal); we’re simply trying to gauge the relative biological damage to tissue by measuring radiation in rems. Apparently, alpha particles are more damaging to biological organisms than are gamma ray photons.

- Thus, one sievert of (ionizing) radiation produces a constant biological effect regardless of the type of radiation. (Radiation and Life, Hall, http://www.uic.com.au/ral.htm)
- The term “rem” is an initialism that originally meant “roentgen equivalent mammal” and later “roentgen equivalent man”. (*Heath Physics*, March 2002, p. 375)



The correct plural of “rem” is “rems”.

It obviously only makes sense to discuss the dose equivalent in rems for living organisms, because the quality factor used to determine the number of rems is based on the biological effects of the ionizing radiation.

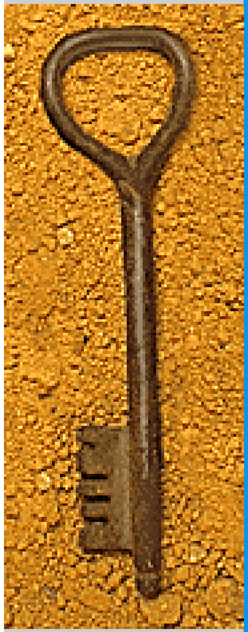
So you can see that activity alone doesn’t determine the risk posed by ionizing radiation. It is only of many factors you need to know to determine the dose equivalent in rems; the rem is the true measure of risk for a biological organism.

- For instance, one curie is a huge amount of radiation, but it may not translate to a large dose equivalent.

The dose received by standing one foot away from a one-curie Co-60 source for one hour will be large, because Co-60 emits energetic gamma rays.

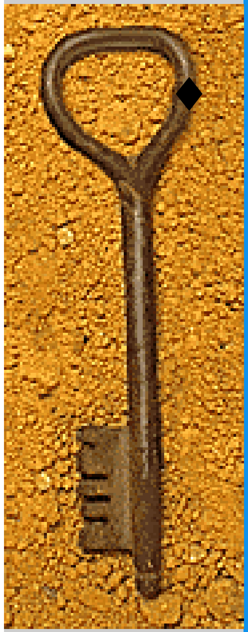
- The dose received by standing one foot away from a one-curie tritium source will essentially be nil, because the beta particles emitted by the tritium will not even be energetic enough to escape whatever material (plastic or glass) that is being used to encapsulate the tritium.

This is an important point, because many people believe that a large activity (a large number of curies) implies a greater risk.



- It’s interesting to note that the total amount of energy absorbed doesn’t have to be very large for ionizing radiation to have a very damaging effect
  - 400 rems of x-rays could kill a person if absorbed over the whole body.
- If this were heat energy instead of x-rays, this amount of energy would be equivalent to the amount of heat absorbed from drinking a cup of hot coffee.
  - Why is this? Consider the way in which the energy is delivered. Infrared tends to be delivered to the atom or a molecule as a whole (many molecules have both vibrational and rotational resonances in the infrared), while x-ray photons deliver their energy in tightly packed punches directly to the orbital electrons, and thus can knock them out. The rabbit analogy (infrared as five pound of sand, x-rays as a five-pound rock) serves well here.
  - Note: when discussing absorbed energy, it is correct to use rads, rather than rems, because the rem *is not* a unit of energy; however, say 400 rems to the students in this instance to avoid confusion, since the students were just told to use rems when discussing biological organisms that have absorbed ionizing radiation.

Time, Distance, and Shielding



- There are three ways to minimize absorbed dose (or dose equivalent if discussing biological organisms).
  - *Minimize* the amount of time irradiated by the source.
  - *Maximize* the distance from the source.
- Recall our previous discussion, in which we posed the question: "what is the fraction of emitted ionizing radiation that is actually absorbed?"
- Distance is one of the factors to consider when calculating that fraction; it's a purely geometrical effect that has nothing to do with shielding.
- Consider holding a button source (that emits gamma rays) directly against your chest versus standing six feet away from it; the fraction of emitted radiation that you absorb will quite obviously be less in the latter case.
  - *Maximize* the shielding between the source and the target.
- We've already established a rough rule-of-thumb regarding what types of shielding are able to stop the various types of ionizing radiation.