Lecture 25

Radioactivity
Radiation Health Effects
Radioactive Dating
Medical Imaging
There are 4 natural "decay chains". Each features a relatively long lived "mother" nucleus α (and β) decaying through a series of much shorter life time "daughter" nuclei ultimately to a nucleus near Pb.

Uranium/radium series: \(^{238}\text{U}\) (4.5 billion years) \(\rightarrow^{206}\text{Pb}\)

Thorium series: \(^{232}\text{Th}\) (\(t_{1/2} = 14\) billion years) \(\rightarrow^{208}\text{Pb}\)

Neptunium series: \(^{237}\text{Np}\) (2 million years) \(\rightarrow^{209}\text{Bi}\) (10\(^{19}\) years!) \(\rightarrow^{205}\text{Tl}\)

Actinium series: \(^{235}\text{U}\) (0.7 billion years) \(\rightarrow^{207}\text{Pb}\)
Radioactivity Health Effects

Radioactive decays typically produce decay products of α's, β's, γ's, and neutrons (from various nuclear reactions), all of which can have biological effects.

The basic problem is that when these energetic particles pass through matter, they can ionize matter, knocking out atomic electrons, breaking molecules, damaging DNA, and killing cells, if there is enough radiation.

The basic strategies for dealing with this are:

• source reduction: avoid generating radioactive material
• time: minimize time of exposure to radioactive material
• distance: keep as far away as you can
• shielding: keep material that absorbs radiation between you and radiation sources
Ionizing radiation doses are measured in Grays or Sieverts.

Gray refers to the amount of energy absorbed per kg of tissue:

1 Gray = 1 Gy = 1 J/kg

Because different types of radiation have different biological effects for the same energy deposited, there is another unit that takes this “quality factor” into account:

- $\gamma$: 1 Sievert (Sv) = 1 Gy
- $\beta$: (1.0-1.5) Sv / 1 Gy
- $\alpha$: (3-5) Sv / 1 Gy
- $\alpha$: 20 Sv / 1 Gy

Other sources:

- <1%
- Occupational: 0.3%
- Fallout: <0.3%
- Nuclear fuel cycle: 0.1%
- Miscellaneous: 0.1%

From human activity: 18%

- Cosmic: 8%
- Terrestrial: 8%
- Internal: 11%
- Medical x rays: 11%
- Nuclear medicine: 4%
- Consumer products: 3%
- Radon: 55%

Natural: 82%
Typical annual radiation dose is \( \approx 2 \text{ mSv/year}. \)

Radiation workers are allowed up to 50 mSv/year.

A one-time exposure of about 5 Sv kills about 50% of people.

Smaller exposures cause cataracts, kill skin, increase cancer risks, etc.

For smaller "chronic" doses, the effects of radiation are much more poorly known. The typical standard is the "linear no-threshold" model: The number of cancers in a population is most likely directly proportional to the radiation exposure.

Sadly, much of the information comes from Hiroshima & Nagasaki nuclear attacks, nuclear shipyard workers, and the Chernobyl nuclear accident.
Radon

- Radioactive decay products in rocks that are solids safely stay trapped in the rock.
- One of the decay products, radon, is a radioactive noble gas and lives long enough to migrate out of the rock into your basement air or well water.
- The EPA estimates that radioactive radon causes 21,000 deaths / year due to lung cancer. An indoor radon level of 4 pCi/liter = 150 Becquerels/m³ is considered the “action threshold”, above which corrective action should be taken.
- Does this mean that levels below 4 pCi/liter are safe? Not at all. At 2 pCi/liter, we just have half as many long-term cancer deaths, which is clearly not safe for the thousands of people who get lung cancer from radon exposure.

Radon level in this house increased dramatically from one day to the next, because furnace turned on.
Radioactive Dating

Because radioactive materials decay exponentially, if we can reliably estimate the initial radioactivity of a material, and measure the current radioactivity, we can tell how old it is.

\[ N = N_0 e^{-\lambda t} \quad \Leftrightarrow \quad \frac{dN}{dt} = -\lambda N_0 e^{-\lambda t} \]

A common example is $^{14}C$, with a half-life of 5730 years, and is constantly generated by cosmic rays interacting with $^{14}N$ in the atmosphere. For this reason, the fraction of $^{14}C$ in carbon contained in living matter is roughly constant.

Biological systems constantly absorb $^{14}C$ until death, so measuring $^{14}C$ content determines when things died. $^{14}C$ dating is useful for archeology and "ancient" history, good to about 60,000 years.
\(^{238}\text{U}\) has a half life of 4.47 billion years, and is useful in dating extremely old inorganic systems like rocks.

This dating method is based on measuring the ratio of \(^{238}\text{U}\) to the reaction end product, \(^{206}\text{Pb}\).

It is not useful for biological systems - which generally do not contain uranium, nor is it useful for dating “young” materials, for which hardly any \(\text{U}\) has decayed.

Other schemes, involving various radioisotopes, exist that cover many different ranges in age.
Application: Powering Space Probes

Most satellites and planetary exploration vehicles have been powered by solar panels. Problem: no power at night during winter, in the shade.

More robust alternative: Radioisotope Thermoelectric Generators use electricity produced from the heat generated by decay of $^{238}$Pu or other isotopes.
Nuclear Magnetic Moments

Just like the electron, protons and neutrons have spin angular momentum, and an associated magnetic moment.

In the case of the neutron, this is evidence that the neutron, despite having overall charge zero, is made up of positively and negatively charged constituents (quarks!)

Nuclear magnetic moments arise from the proton and neutron moments, as well as their orbital motions.

Applications:

• Nuclear Magnetic Resonance (spectroscopy)
• Magnetic Resonance Imaging (medical diagnostics)
Magnetic Resonance Imaging (MRI)

(a) Protons, the nuclei of hydrogen atoms in the tissue under study, normally have random spin orientations.

In the presence of a strong magnetic field, the spins become aligned with a component parallel to $\vec{B}$.

A brief radio signal causes the spins to flip orientation.

As the protons realign with the $\vec{B}$ field, they emit radio waves that are picked up by sensitive detectors.

(b) Since $\vec{B}$ has a different value at different locations in the tissue, the radio waves from different locations have different frequencies. This makes it possible to construct an image.

(c) An electromagnet used for MRI

- Main coil supplies uniform $B$ field.
- $x$ coil varies $B$ field from left to right.
- $z$ coil varies $B$ field from head to toe.
- $y$ coil varies $B$ field from top to bottom.
- Transceiver sends and receives signals that create image.
Medical Imaging Applications

- MRI: radiation dose = zero!
- X-ray image: radiation dose ≈ 0.4 mSv
- X-ray CT scan: Use multiple images and computer processing to generate 3D view. Radiation dose ≈ 15 mSv.
- PET scan (positron emission tomography): Patient ingests positron-emitting material, Imaging equipment detects emitted positrons. Radiation dose ≈ 14 mSv.