Nuclear Physics 3

Effects of radiation:

We talked last term about the ways that a nucleus can de-excite:

α: "Breakup" by throwing off an α-particle = \(^4\)He

β: Lose a neutron by transforming it to a proton, \( n \rightarrow p^+ + e^- + \bar{\nu} \)

or \( p^+ + e^- \rightarrow n + \nu \) = electron capture

or \( p^+ \rightarrow n + e^+ + \nu \)

γ: A high energy photon.

We also talked about the rate for these processes that is measured -- or quantified -- by the half-life.

\[ t_{1/2} = \frac{\ln 2}{\lambda} \]

and

\[ N(t) = N(0) e^{-\lambda t} \]

and

\[ \frac{dN}{dt} = -\lambda N \] is the decay rate.
That decay rate is also called the "activity" as in radioactivity.

More activity means more decays, and more energy released, per time.

Activity is measured in Curies \( \equiv Bq = B~c~q~u~e~v~e \)

1 curie \( \equiv 3.7 \times 10^{10} \) disintegrations per second

That may seem like an odd unit. It is, because it was defined as the activity of 1 gram of radium. Not particularly useful nowadays but if you find a radioactive source, it will be labelled as \( X \) mCi or \( Y \) pCi.

You are active yourself due to various unstable components e.g., \(^{14}C\).

If you have \( \sim 1 \) kg of carbon in you, and there are \( \sim 12 \) decays/minute/gram of carbon, then your activity is

\[
\frac{12,000 \text{ Bq}}{60} = 200 \text{ Bq} \approx 5 \times 10^{-8} \text{ Ci} = 50 \text{ nCi}
\]
So, is that bad?

First, it is better than not eating, even if all food is radioactive (at least some "4C).

Second, what actually happens when radiation hits you? It depends...

\( \alpha \) particles are helium nuclei, so they are relatively heavy, and doubly charged. That makes them ionizes matter easily. So they dump all their kinetic energy into ionization in a short distance.

Visible light reflects -- just atomic excitation.
UV light ionizes, and dis-associates molecules.
Ionizing radiation does "the same" to many atoms/molecules.
\( \alpha \) particles are effective but short range (e.g. blocked by clothing and outer skin, just don't eat/inhale it).

\( \beta \) particles are electrons. They ionize atoms as well, but less aggressively. So they penetrate farther.

\( \gamma \)'s are photons and so they tend to interact in one spot and ionize there -- giving an electron a hard tick. It then ionizes further.
DEMO 88-30: absorption of β & γ's.

So, since the different types deposit energy differently, we want measures that take that into account.

Roentgen measures exposure that a source could produce.
\[ 1 \text{R} = 1.6 \times 10^{12} \text{ ion pairs per gram of air} \]

Rarely used, at least by me, instead:
\[ \text{Rad} = \text{radiation absorbed dose} \]
measures what is actually absorbed.

\[ 1 \text{ rad} = 10^{-2} \text{ J/kg} \]

You might think that 1 rad is small since 0.01 J/kg is tiny -- a negligible temperature change e.g.

But, since the energy is dis-associating your molecules, not just heating them, it can be a big dose.

To set the scale, ~300 rads is lethal (to 50% level).
The REM (Roentgen Equivalent in Man) gives a measure of dose equivalent including "enhancement" or "quality" factor increases for α particles and neutrons since they do more damage per rad. (1 Sv = 100 rem)

Some relevant doses:

- A chest x-ray ~ 30 mrem (~3 for dental)
- Natural background ~ 300 mrem/year (cosmics + U/Th)
- Man made sources (other than medical) ~ 10 mrem/year
- A typical trans-polar flight ~ 1-10 mrem
Fission

Recall that $^{238}$U has a half-life of $\approx 4.5 \times 10^9$ yrs.

But, if you hit it with a neutron it may spontaneously decay by splitting not just into Th and an α, but into two large pieces -- this process is called fission.

It is more complicated than just that, but not too far off... details coming.

If we add a neutron $^{238}$U becomes $^{239}$U and its inexcited state from the neutron's energy.

If the nucleon's motion pushes them far enough out, then electrostatic repulsion drives them apart.
It is not a particularly useful energy generating scheme to have to trigger each atom's decay by specifically hitting it with a high energy neutron.

We want a "chain reaction" that is self-sustaining, like burning wood produces heat to burn more wood.

So, enter two modifications: $^{235}$U and thermal neutrons.

$^{235}$U is a different isotope of uranium that has a smaller barrier, so it can be excited into fission by low energy neutrons.

Thermal neutrons are ones with low energy, $K = \frac{3}{2} kT = 0.04 \text{ eV} \ (at \ room \ temperature)$. These are easily absorbed by the nucleus (no charge to repel).

Thermal neutrons readily are absorbed by $^{235}$U and it readily fissions. ($^{238}$U only fissions readily with higher energy neutrons, which are less readily absorbed).

So, both $^{235}$U in thermal neutrons and it will fission.
When it fissions, it does not usually split 50/50

50/50 is in fact quite unlikely.

Note that $^{235}\text{U}$ has $N/Z \approx 1.6$ which is far above the stable ratio for the decay products, so these daughters tend to be radioactive and decay by $\beta$ decay to rid themselves of the excess neutrons.

And during the initial breakup -- fission -- a few neutrons tend to be released directly. In fact, 2.47 neutrons are released, on average.

These neutrons can then be absorbed by other $^{235}\text{U}$ nuclei and cause them to fission → chain reaction.

Energy released is $\sim 1\text{ MeV}$ (per nucleon) $\rightarrow \sim 200\text{ MeV}$ C.F. $\sim 10$ eV for chemistry
Fission reactors.

So, fission of one $^{235}U$ produces enough neutrons to generate more fissions. But controlling the reaction requires overcoming several difficulties.

1). **Neutron leakage.** Some of the neutrons will "leak" out of the fuel.

   Leakage is proportional to surface area $\propto r^2$

   Neutron production is proportional to volume $\propto r^3$.

   So, decrease surface area/volume by increasing size $\Rightarrow$ critical mass.

2). Fast neutrons. The neutrons produced have energies of order MeV while we want slow neutrons, E=1eV. So we need to slow them. This is done with a "moderator" = a material that the neutrons can scatter off of and so lose energy.

   It shouldn't absorb them -- just slow them.

   Water is a good choice, since its hydrogen (protons) is light, same mass as neutrons, for effective energy transfer.
3). Neutron capture. Some neutrons can be captured by other nuclei, particularly heavy elements such as the daughters of previous fissions (that build up over time).

And, more importantly, the $^{238}\text{U}$ that is mixed with the $^{235}\text{U}$ fuel.

$^{235}\text{U}$ is only $\approx 0.7\%$ of naturally occurring $\text{U}$. The rest is $^{238}\text{U}$ that only fissions with fast neutrons—and then rarely. So it doesn’t help the reaction go. Rather it hinders by neutron capture. In particular, it likes to absorb neutrons with $K\approx$ a few eV. So, fuel rods are used to

- produce fission in the rod
- neutrons leave the rod at high KE.
- slow to thermal energy in the surrounding water (staying away from $^{238}\text{U}$)
- then enter another neighboring fuel rod when safely below the capture energy (for $^{238}\text{U}$) and get captured by $^{235}\text{U}$. 
4). Low $^{235}\text{U}$ fraction in naturally occurring uranium. So, it must be enriched by (thankfully) complicated means. 0.2% to 3% is sufficient and typical for a power reactor.

5). A control mechanism. One wants to be able to turn the power up and down, and shut it off when necessary -- equivalent to controlling gasoline or air intake.

This is accomplished with control rods made of neutron absorbing material (e.g. cadmium). Since many of the neutrons are produced by decay of fission products (on time scales of seconds) these rods need only be controlled at that time scale, not the extremely fast fission time scale.

Some comments on engineering:
- primary/secondary cooling loops
- coolant for low $T_c \Rightarrow$ high eff.
- fail safes.
- waste typ
First man-made reactor at U Chicago 12/2/45.

First reactor on earth, though, was not man-made.

A uranium mine in Africa was found to be depleted of $^{235}U$, 0.4% instead of 0.7%.

It was filled with isotopes that are fission products descendants -- far down the chain after all decays.

If the uranium deposit was porous, it could fill with groundwater acting as a moderator to slow the neutrons.

The heated water would boil off, and loss of the moderator stops the reaction.

The only problem is that this only works with enriched uranium. ~3% $^{235}U$, not ~0.7%.

$^{238}U$ has a half-life of $4.5 \times 10^9$ years

$^{235}U$ has a half-life of $0.7 \times 10^9$ years.

So, about $2 \times 10^9$ years ago, $^{235}U$ was naturally 3% abundance, and such a reactor could proceed easily. (At formation, ~4.5 x 10^9 y, the abundance was 30%).