CALCULATING
RADIATION EXPOSURE

ACTIVITY units

1 **Bequerel (Bq)** ≡ 1 radioactive decay per second.

An isotope with a ***half-life*** of $T_{½}$ has a ***mean lifetime*** of

$$\tau = T_{½}/\ell n 2 \quad \text{(where} \quad \ell n 2 = 0.6931478\ldots)$$

and a ***decay rate*** of $\lambda = 1/\tau$

so a sample of N such nuclei will have an ***activity*** of

$$A = \lambda N = N \ell n 2 / T_{½} \text{ Bq}$$

(if $T_{½}$ is measured in *seconds*)

But it matters what the isotopes decay *into*!

Activity of 1 gram of Uranium

A sample of N atoms of an isotope with a ***half-life*** of $T_{½}$ has an ***activity*** of $A = N\,\ell n 2 / T_{½}$ Bq (if $T_{½}$ is measured in *seconds*). Note: the *activity is higher* if the *lifetime is shorter*. (But not for long!)

Natural uranium is roughly 99% ^{238}U, with a half-life of 4.468 billion years, and 1% ^{235}U with a half-life of 0.7 billion years. Both decay by α-emission. From this and their masses we can calculate the number N of both isotopes in 1 g of natural uranium and the activity of same, namely $A \approx$ 13,000 Bq.

That sounds like a lot, but if you had a 1 gram block of U metal (a 3.74 mm cube) none of the short-ranged α-particles would make it out of the block unless they were within a few µm of the surface, and those would stop in a few cm of air.

On the other hand, if you ground it to a fine powder and dispersed it so that people could *inhale* the particles, those alphas might do some lung damage! *How much*, exactly?

DOSE units

1 **rad** ≡ 100 erg/g (energy deposited per unit mass)

1 ***gray*** (***Gy***) ≡ 100 **rad** ≡ 1 J/kg. (standard international unit)

*R*elative *B*iological *E*ffectiveness (*RBE*) "fudge factor":

- X-rays, γ-rays & β-rays (fast electrons): *RBE* = 1 (by definition)
- Slow neutrons: average *RBE* ≈ 3. (Variable!)
- Fast neutrons, protons & α-rays: *RBE* = 10.
- Fast heavy ions: *RBE* = 20.

REM (***R***, *R*oentgen *E*quivalent to *M*an):

R ≡ *RBE* × **rad**.

(1 mR ≡ 1 *milliREM* ≡ 10^{-3} R.)

sievert (***Sv***, standard international unit):

Sv ≡ *RBE* × ***Gy*** = 100 ***R***

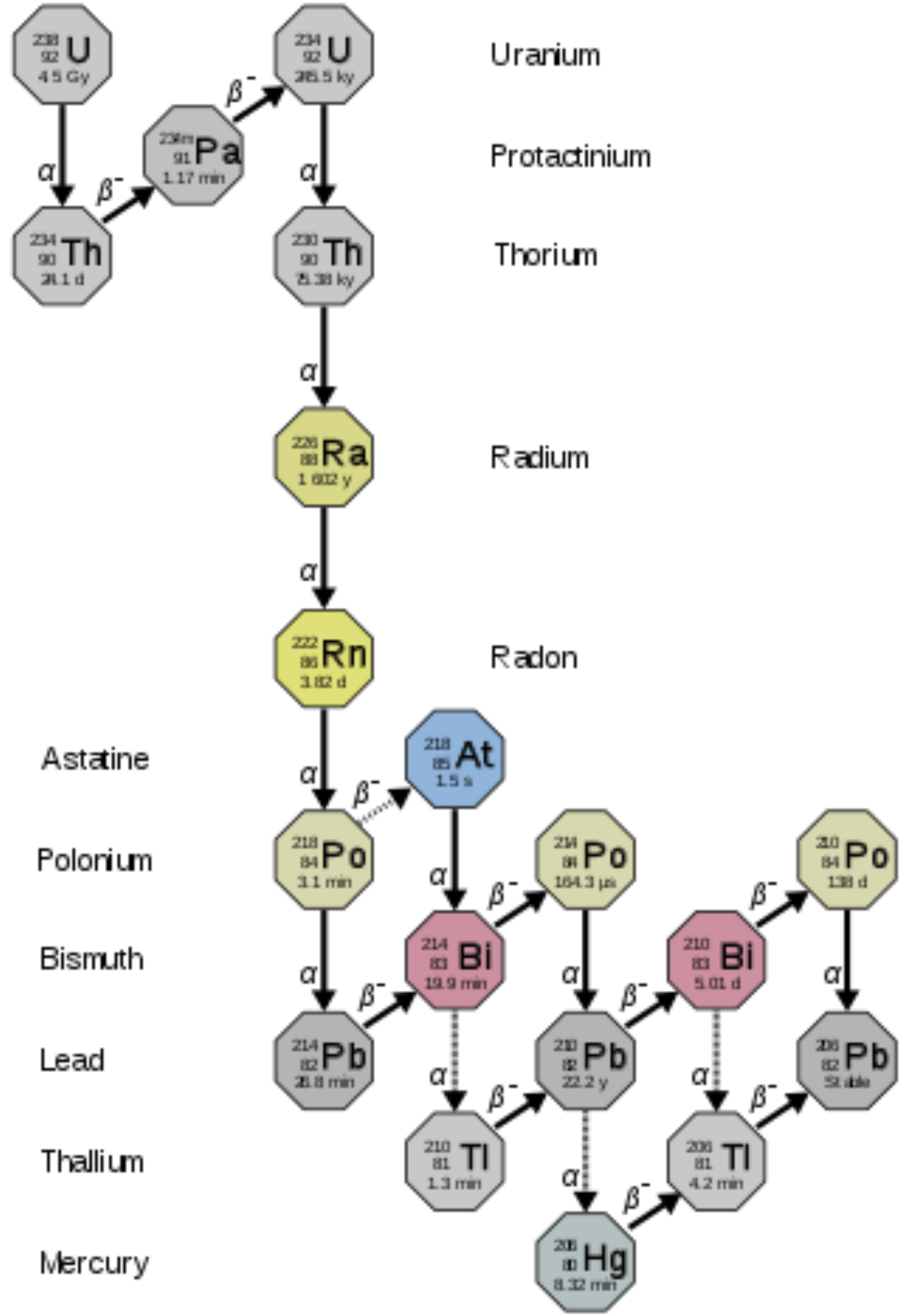
DOSE from 1 gram of Uranium

As mentioned earlier, the dose from 1 gram of natural uranium held at arm's length with tongs is exactly *zero*, because none of the alphas make it to you. So let's suppose you ground it up into a fine dust and breathed it *all* into your lungs, where the kinetic energy of the alphas would all get deposited in your lung tissue.

How much energy is that? Alphas from ^{238}U decay have an energy of 4.267 MeV or 0.684×10^{-12} J; those from ^{235}U have about the same, 4.679 MeV. So the 13,000 alphas produced per second from your gram of natural uranium deposit 0.897×10^{-8} J/s in your lungs. In one *year* that would add up to 0.283 J deposited fairly uniformly in your lungs, which have a mass of about 1 kg. So that's 0.283 Gray per year. Alphas have an RBE of over 10, so we finally arrive at a meaningful **dose**: **3 Sieverts per year**, 30 Sv per decade or 300 Sv per century. After a few millennia it would get to be a *huge* dose! In a few billion years it would taper off, though.

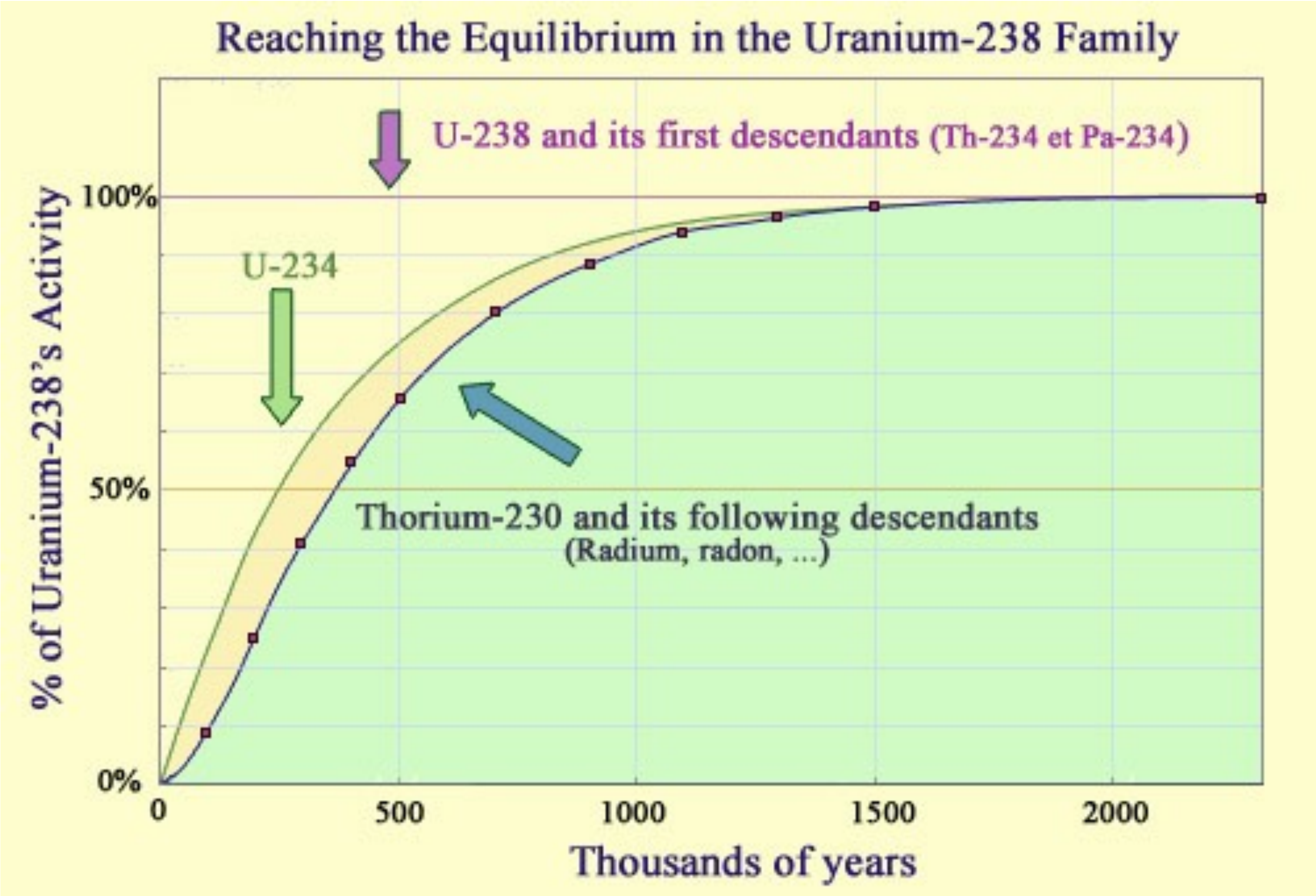
But wait… is that ***all*** the energy deposited?

^{238}U decay chain



CHANGING Dose from 1g of ^{238}U

The dose from the initial α-decay of 1 gram of pure ^{238}U is 3 Sv/year, or 50 mSv/week, but that's not the end of the story. The "daughter" nucleus, ^{234}Th, β-decays into ^{234}Pa in 24 days, and ^{234}Pa quickly β-decays into ^{234}U, which has a half-life of 0.245 million years, eventually α-decaying to ^{230}Th and on down to lead. During the first 100 years, the net dose would be increased by only those two βs, with RBEs of 1, so 3.2 Sv/y.



How ***bad*** would ***this*** be for your lungs?

EFFECTS of Penetrating *Radiation*

- **Instant Death**: ~ **50** Sieverts [Sv] "*whole-body*" can wipe out the central nervous system (CNS) *when delivered all at once*.
- **Overnight Death**: ~ **9** Sv whole-body may accomplish the same thing in about a day.
- **Ugly Death**: ~ **5** Sv → severe *radiation sickness* (nausea, hair loss, skin lesions, *etc*.) as short-lived cells fail to provide new generations to replace their normal mortality. Complications (infection) often kill. Some recover completely but may develop leukemia years later; offspring (if any) may have genetic mutations.
- **Sub-Acute Exposures**: ~ **1** Sv whole-body delivered all at once → no immediate symptoms, but possible leukemia (rarely, years later).

Back to our 1 gram of Uranium

Okay you've ground it up and breathed it into your lungs, where it delivers a dose of **3.2 Sieverts per year**. If 3.2 Sv were delivered *all at once* (or in less than a week) you might get cancer in a decade or so. But you only get about 0.054 Sv (54 mSv) in any given week.

Why does the ***rate*** of delivery matter?
Because of what ionizing radiation ***does***
and how your cells ***respond***.

Ionizing Radiation → DNA Strand Breaks

Single strand breaks (SSBs) usually *heal* in *milliseconds*.

NIH: SSBs occur *naturally* more than 10,000 times a day in any single mammalian cell.

Double strand breaks (DSBs) can take longer to heal, and may even be *permanent*, causing…

- **Cell Reproductive Death** [most common]

  Cells usually survive for their natural lifetimes — a few days for hair follicles, skin and mucous membrane cells; "forever" for brain cells and some muscle cells.

- **Genetic Mutation** [most subtle]

  Damaged *gamete* cells → *mutations* (usually fatal to foetus; almost always detrimental to the individual offspring…)

- **Cancer** [most unpleasant]

  Runaway replicative zeal of a misguided cell…

Revisiting our 1 g of Uranium

A dose of **3.2 Sv/year** is only about 54 mSv/week. While this is probably undesirable, you'd have a good chance of being basically unaffected… if it were not for the ***chemical*** toxicity of uranium — which depends critically on its oxidation state — and the fact that inhaling 1 g of ***any*** **metal** into your lungs is apt to produce nasty effects having little to do with either radiation or chemistry.

The *relative* toxicity of radioactivity, chemicals and irritants is frequently ignored.

Why there is so much disagreement

It is hard to calculate how much harm is done by a given amount of radioactivity. We can fairly easily calculate the ***activity*** of a certain amount of a given radioisotope, and then we can fairly easily find how much *energy* its ionizing radiation deposits *per kg* of flesh; but the same energy deposited by one type of particles can be an order of magnitude worse for you than the same amount of energy deposited by another type of particles; and it makes a *huge* difference whether that energy is deposited *all at once* or spread out over time, because *the damage* ***heals***. Moreover, many of these "fudge factors" are based on empirical observations that are not rigorously quantitative.

As a result, it's very tempting to make qualitative ***comparisons***, especially with "natural background radiation". But even then we have disagreements on how a *low* dose should be compared with a *high* dose….

Thresholds and Linearity

We have data on the survivors of *Hiroshima* and *Nagasaki*. We also have data on the people exposed to high radiation levels at *Chernobyl*. We know roughly how much their probability of (*e.g.*) thyroid cancer was heightened over time by exposure to Iodine-131, and we know how many suffered immediate effects of "radiation sickness". What we *don't* know so well is how people are affected by much *lower* levels of radiation exposure. One reason for this is that we don't have a "**control group**" of people who are not exposed to *any* radiation. There are no such people! Your *bones* are radioactive.

One model is "***LNT***" — a simple ***L***inear model with ***N***o ***T***hreshold: that is, we assume there is *no such thing* as a "*harmless*" amount of radiation and that the probability of harm is *proportional* to the radiation dose. This model has the advantage of simplicity.

The "***Threshold***" model assumes that the "normal background" radiation level is *harmless*, and may even be *beneficial* up to a point ("***hormesis***"). There is actually some evidence for the latter.