PH2233 Fox : Lecture 23
Chapter 41 (bits) : Radioactivity

Radioactivity : Why?

Here we look briefly at why a nucleus or particle would decay. We'll be looking at energy in various forms, and down at this scale there are a couple of mass and energy units that are commonly used. This material summarizes the key points from **sections 41-1 and 41-2** in the textbook.

Atomic mass unit : The mass of a single ${}^{12}_{6}C$ atom is taken to be exactly 12 u (atomic mass units), which makes $1\ u = 1.6605 \times 10^{-27}\ kg$.

Energy equivalent : Einstein postulated that mass can be converted into energy with the equivalence $E = mc^2$, so a mass of 1 u represents an energy of $E = (1.6605 \times 10^{27}\ kg)(2.9979 \times 10^8\ m/s)^2 = 1.49236 \times 10^{-10}\ J$ or further converting to electron volts (eV), this would be: $E = (1.49236 \times 10^{-10}\ J) \times \frac{1\ eV}{1.6022 \times 10^{-19}\ J} = 931.5\ MeV$.

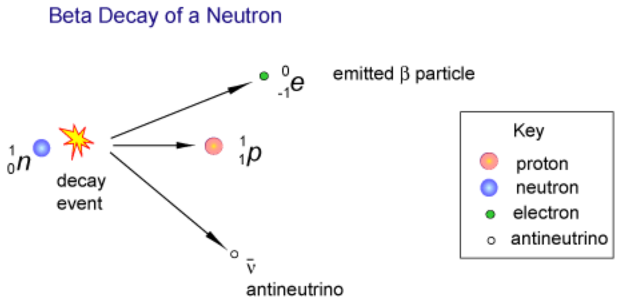
Down at the level of atoms and elementary particles then, masses are often given in terms of their energy equivalent: $m = E/c^2$. Something with a mass of 1 u would have a mass in these terms of $931.5\ MeV/c^2$. In that form that actually is units of mass. People get tired of writing that unit symbol out all the time and you'll very often see this quoted as simply $931.5\ MeV$.

Masses in Kilograms, Atomic Mass Units, and MeV/c^2			
Object	kg	u (Da)	MeV/c^2
1 u	1.6605×10^{-27}	1.0	931.494893
electron	9.1094×10^{-31}	0.00054857991	0.510998950
proton	1.67262×10^{-27}	1.007276467	938.272088
neutron	1.67493×10^{-27}	1.008664915	939.565420
${}^{1}_{1}H$		1.007825032	938.78307
${}^{2}_{1}H$		2.014101778	1876.12393
${}^{3}_{1}H$		3.016049281	2809.43212
${}^{3}_{2}He$		3.016029322	2809.41353
${}^{4}_{2}He$		4.002603254	3728.40133

So what does this have to do with nuclear decay? ⇒ Binding Energy

A hydrogen atom consists of a proton and an electron, but if we add up the masses of those two entities we get a number that is very slightly higher than the actual mass of a hydrogen atom. The reason for this is that we need to include **all** the energy in this atom to get it's mass, which means we need to include the (negative) electric potential energy that's also present. It's only 13.6 eV of energy, but that's enough to hold the electron in place, and is called it's **binding energy** : something external needs to hit the electron with that much energy (or more) in order to separate it from the proton.

(NOTE: the table above has the most accurate values I could find, which are slightly different from what I used in some the examples that follow...)



Neutron decay : Let's apply this process to the neutron. It has a mass of 939.57 MeV/c^2. If we add up the masses of it's parts (proton plus electron plus anti-neutrino, which has a mass of a small fraction of a single electron volt, so we'll ignore it), we have $938.27 + 0.511 = 938.78\ MeV/c^2$. That's **less** than the mass of the neutron itself, so nothing stops the neutron from breaking up into its constituent parts, and releasing 0.0084 amu (about 0.78 MeV/c^2) of energy in the process (mostly carried off by the electron in the form of β^- radiation). It's a pretty small energy difference, so this reaction isn't sudden. The half-life for a free neutron is about 610 sec, or slightly over 10 min.

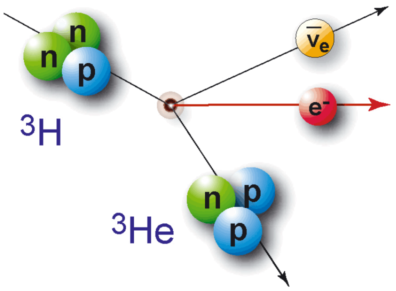
Deuterium Atom : Let's look at a simple deuterium atom: a hydrogen atom that has a neutron as well as a proton in the nucleus. A single $^{2}_{1}H$ atom has a mass of 2.0141017436981201 amu. If we add the masses of a proton, neutron and electron though, they total up to 2.0164899613591842 amu which is *slightly* higher. The actual mass is about 2.22 MeV/c^2 lower than it 'should' be. Why? Remember when we looked at the hydrogen atom, we had to include the (negative) electrical potential energy between the proton and electron to get the right mass for the $^{1}_{1}H$ atom and now we have a new force to account for: the **strong nuclear force** between the proton and the neutron. The (negative) potential energy related to this force is creating this difference.

Can the deuterium atom decay? If it ejects the neutron, we're left with a normal $^{1}_{1}H$ atom with a mass of 1.007825 amu plus a neutron with a mass of 1.00866 amu for a total mass of 2.0165 amu which is higher than the mass of a deuterium atom (2.0141 amu), so this decay isn't allowed by conservation of energy.

We can look at other possible decays, but all result in a picture where the total energy after the decay is higher than we started with. There aren't any paths available for deuterium to decay, so it's completely stable.

Tritium Atom : Let's look at $^{3}_{1}H$: a hydrogen atom that has **two** neutrons in its nucleus. The mass of a single tritium atom is 3.0160492 amu (about 2809.44.. MeV). It we add the masses of one proton plus two neutrons plus one electron, we get 3.024606 amu (about 2817.4 MeV). The actual mass is **lower** by about 8 MeV, representing the negative potential energy of the strong nuclear force present. We can't split the tritium atom into it's constituent parts without adding this much energy to the system.

That doesn't mean that tritium is stable though, and it isn't. What if instead of breaking the nucleus up entirely, we look at other possible transition? Suppose one of the neutrons decays into a proton, leaving a nucleus with 2 protons and 1 neutron (the $^{3}_{2}He$ isotope of helium).



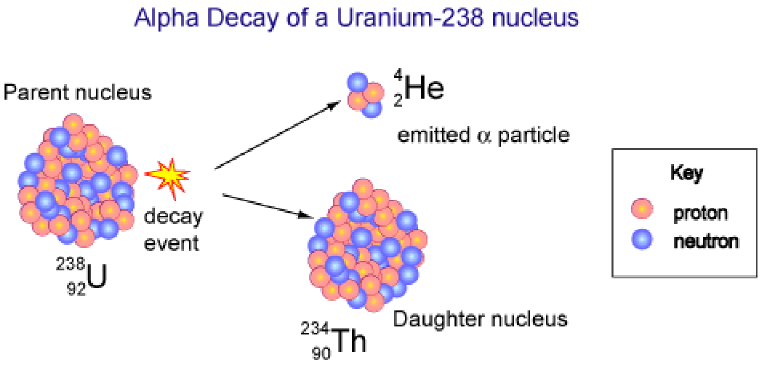
If we add all the masses of the resulting parts, we get 3.0160289 u (or 2809.43.. MeV) which is **lower** than the mass of the tritium atom we started with, so this decay mode is allowed by conservation of energy. This 'decay' would actually release about 0.02 MeV of energy, which the electron produced in the neutron decay can carry off with it. It's a very small energy difference though, so tritium actually ends up with a half-life of about 12.33 $years$.

(The resulting ${}^3_2He$ atom is entirely stable. Any decay path we think of involves an increase in energy, so conservation of energy prevents them from happening. This particular isotope of helium is the only atom that has more protons than neutrons, and it has a major advantage in nuclear **fusion** because it produces NO radiation as a byproduct, unlike other possible fusion 'fuel' like deuterium or tritium. It is believed that the Moon could be a significant source of ${}^3_2He$ thanks to being constantly replenished by cosmic rays and the solar wind. This idea is exploited in the Apple TV show 'For all Mankind'.)

$\boxed{\textbf{Helium-4 Atom}}$: Let's compare a (normal) ${}^4_2He$ atom to it's constituent parts. A single helium-4 atom has a mass of 4.002603 amu. It's made of two protons, two neutrons, and 2 electrons, and adding up those masses we get 4.032980 u, which is more than the mass of the resulting atom. The difference is 0.030377 u or 28.3 MeV. That's how much energy it would take to split the Helium nucleus up into it's separate components. The $-28.3\ MeV$ of 'missing mass' is due to the **binding energy** (potential energy) related to the strong nuclear force.

We can look at all possible decays paths (ejecting a neutron, converting a proton into a neutron, etc) and everything yields a configuration with a higher energy than we started with, so this isotope of helium has no 'allowed' decay paths. It's completely stable.

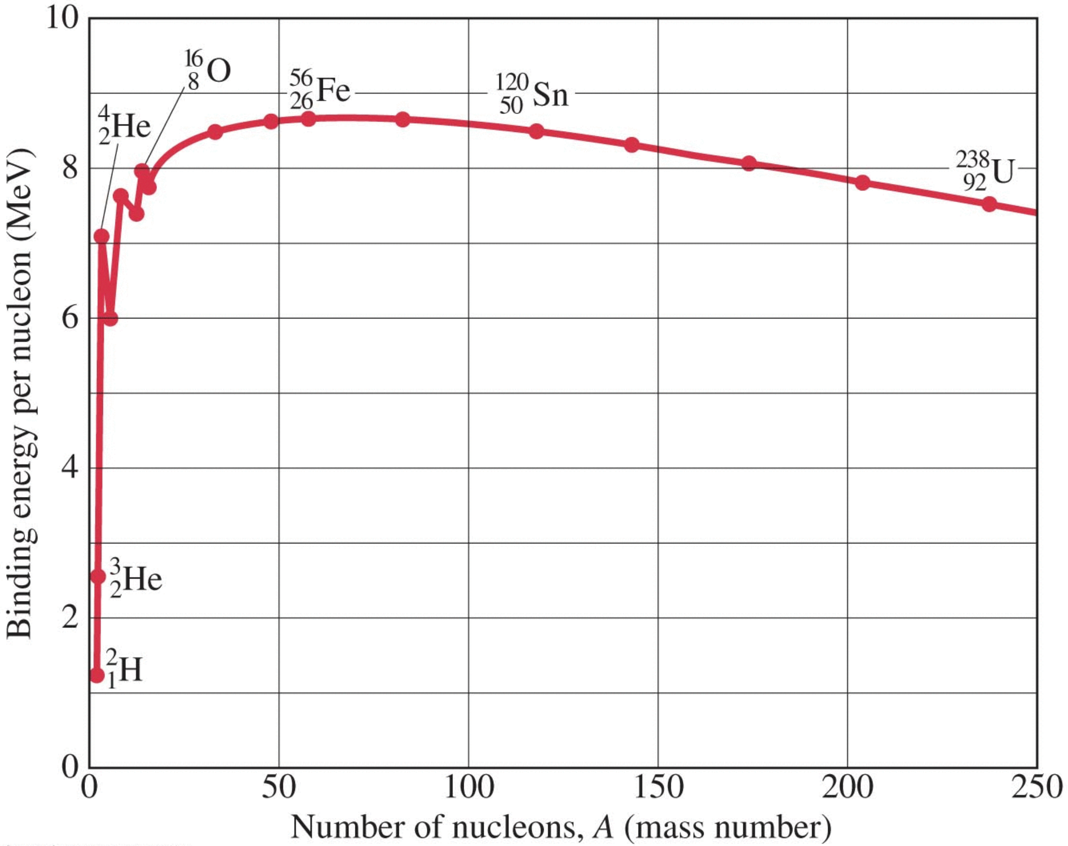
$\boxed{\textbf{Uranium-238}}$: This atom is radioactive and decays by emitting an alpha particle (Helium nucleus): ${}^{238}_{92}U \rightarrow {}^{234}_{90}Th + {}^4_2\alpha$
If we add up all the constituent parts (92 protons and electrons plus $238 - 92 = 146$ neutrons) this atom <u>should</u> have a mass of 239.98 u but actually has a mass of only 238.0508 u, which is almost 2 u or $(2\ u)(931.5\ MeV/u) = 1863\ MeV$ lower. That implies that the **binding energy** of this nucleus is 1863 MeV: we would need to inject that much energy to split this nucleus into it's underlying parts.



That doesn't imply it's stable though, and it's not since it decays via α radiation into thorium-234. If we add the mass of a thorium-234 nucleus plus an alpha particle (helium nucleus) we get 238.046 u which is actually slightly lower than the mass of the initial uranium-238 nucleus. That opens up the possibility for this decay mode. It's such a small drop in energy though (only 4.6 keV) that it doesn't happen abruptly: the half-life of this isotope of uranium is over 4 billion years.

These sorts of calculations barely scratch the surface, and don't give much insight on which decay path a particular unstable nucleus might take. In fact a given nucleus might decay in multiple different ways, each with a different probability of occurring.

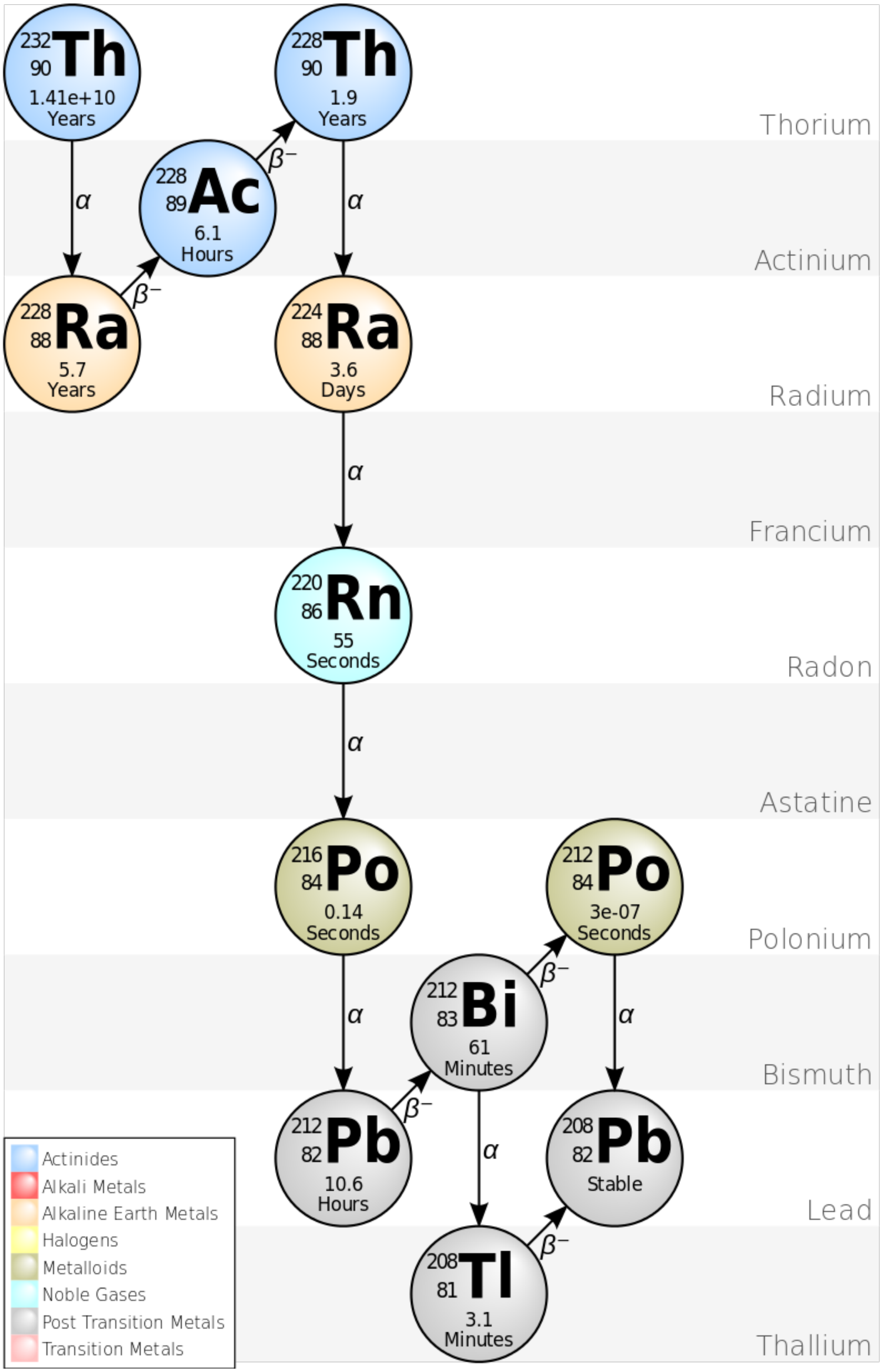
Let's end with one final figure. Let's take the binding energy of the $^{238}_{92}U$ nucleus we computed before and divide that by the number of nucleons (protons plus neutrons, so here that would be 238): $(1863\ Mev)/238 = 7.83\ MeV/nucleon$. This is called the **binding energy per nucleon** and is graphed below:



The higher the number, the more binding energy there is and the more stable the nucleus is. The curve peaks around Iron. For any atom over to the right, they can increase their stability by radioactively decaying into something to their left. It doesn't mean they **will** decay, but at least energy considerations alone do open up that pathway. **The graph to the right of Iron (Fe) is the realm of radioactivity and nuclear fission.**

For elements to the 'left' of Iron in the figure, it looks like they need to move to the right to achieve greater stability. This is the realm of **nuclear fusion**. Combining two deuterium nuclei to form a helium nucleus results in a more stable entity: a higher binding energy, which means that energy is released if we can force two deuterium nuclei to 'fuse' into helium. That's (very) hard to do since the deuterium nuclei will repel each other with considerable electrical force until they get close enough for the strong nuclear force to take over. **The tremendous pressures in the core of the Sun are sufficient to allow it, and it's the main source of energy produced by the Sun.** On Earth, this has been an active area of research for decades now, and if it can be made to work there are no dangerous byproducts (just some helium gas, and there are plenty of commercial uses for that).

Many isotopes don't make it directly to a stable final product but take a meandering path, called a 'decay chain' or 'decay series'. Here is the $^{232}_{90}Th$ (thorium) series:



Attenuation (shielding)

In this section, we will look at **radiation shielding**, which is a part of the lab on radioactivity. This topic is scattered across paragraphs in multiple sections of this book, so the key concepts are summarized here.

Review

The first section described some of the common types of radioactivity (α, β, and γ radiation) and the radioactive decay law:

Radioactive atoms remaining: $N(t) = N_o e^{-\lambda t}$

Activity: $R(t) = |dN/dt| = R_o e^{-\lambda t}$ (other books often use $A(t)$ instead of $R(t)$)

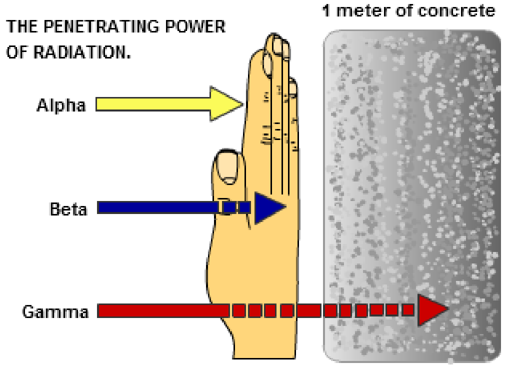
which led to the concept of half-life: $t_{1/2} = \frac{ln(2)}{\lambda}$.

Attenuation of Radiation

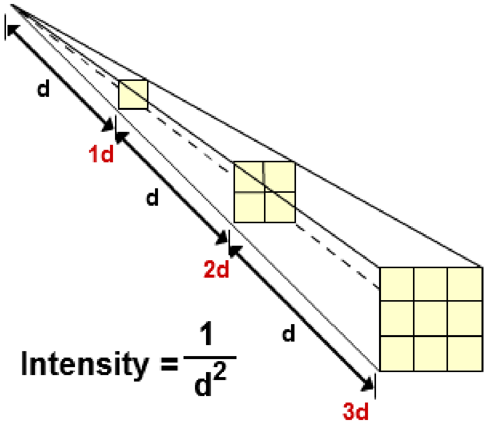
All the types of radiation we introduced will interact with matter, being absorbed to various degrees, thus reducing the activity (count rate) of the radiation, and/or it's energy, both of which can affect it's impact (positive and negative) on other materials.

(See the NDE and Wikibooks links on Canvas, which is the source for most of this material.)

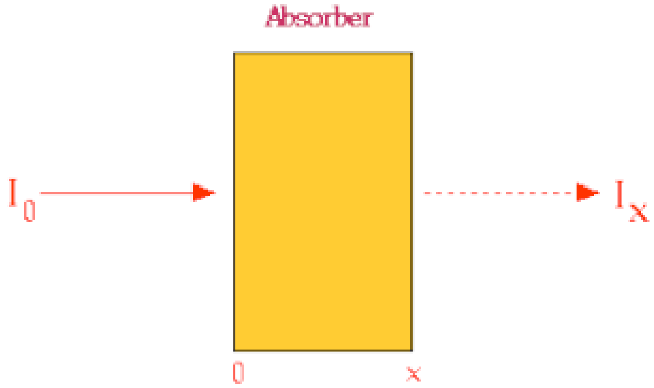
Because of their double charge and relatively slow velocity, α particles have a short range even in air (a few cm) and particularly in denser materials like tissue (fractions of a mm). β particles may have lower energies but since m_e is so small they can have much higher velocities and penetrate further (meters in air, cm in tissue). γ rays, X-rays, and neutrons have no charge and can pass easily through air and tissue.



In addition to the physical attenuation introduced by the radiation travelling through some material, we do still have the attenuation due to the radiation spreading out as we move farther from the source. If the source is emitting radiation uniformly in all directions (or in a cone spreading out with distance), the intensity (activity per area) falls off with the usual $1/r^2$ behaviour as well. Here, we will focus on the physical attenuation aspects (shielding).



The radioactive particles interact with the material they are passing through, colliding with the atoms or nuclei in the material. If look in the calculus limit of a very thin sheet of material and double the thickness we double the chances for the radiation to interact with the material, so the activity should drop in proportion to the thickness (in this thin sheet limit). (NOTE: this source uses I to represent the intensity.) If one (thin) thickness reduces the intensity by 1 percent, doubling the thickness doubles the number of interactions, reducing the intensity by 2 percent, for example.

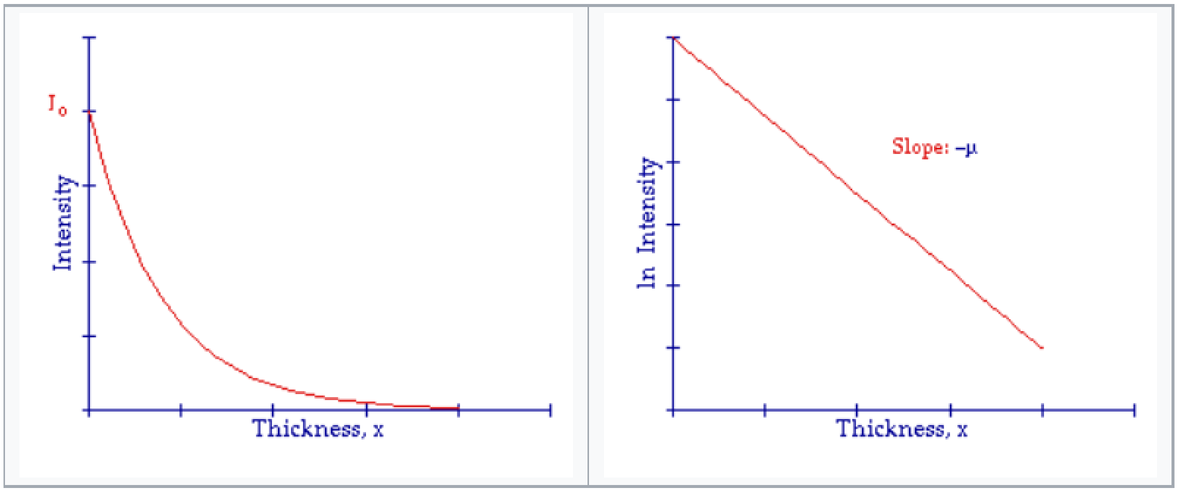


We can write this as $\frac{\Delta I}{I} \propto \Delta x$ and since the intensity is **decreasing** we write this as (in the calculus limit): $\frac{dI}{I} = -\mu dx$. Integrating both sides, $\int_{I_o}^{I(x)} \frac{dI}{I} = -\mu \int_0^x dx$ which yields $\boxed{I(x) = I_o e^{-\mu x}}$.

The parameter μ is called the **linear attenuation coefficient** and has units of inverse distance (properly inverse meters, but often seen as inverse centimeters or even inverse millimeters).

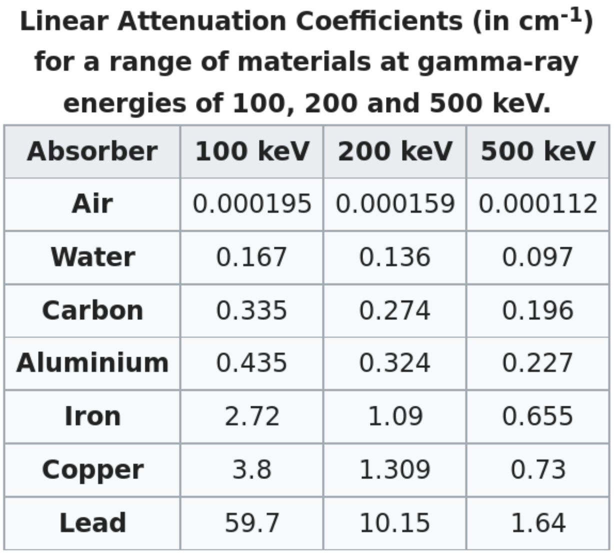
NOTE: a related quantity which is sometimes encountered in this field is the **mass attenuation coefficient**, which is poorly named because it is actually the ratio of the linear attenuation coefficient μ and the **density** of the material: $\boxed{\mu/\rho}$

Graphical representation of the dependence of radiation intensity on the thickness of absorber: Intensity versus thickness on the left and the natural logarithm of the intensity versus thickness on the right.



This aspect of the lab involves placing varying thicknesses and types of materials between the source and the Geiger counter and measuring the activity, which can then be used to determine the attenuation coefficient. That wasn't part of the lab, but you could now go back and re-use parts of your data to determine the μ and $x_{1/2}$ values for some of the materials you used.

Linear attenuation coefficients (note units) for some materials. Note that μ depends on the type of radiation and also on how energetic it is. This table shows μ for a γ radiation at a few selected energies that might be encountered in medical uses.



Linear Attenuation Coefficients (in cm^{-1}) for a range of materials at gamma-ray energies of 100, 200 and 500 keV.

Absorber	100 keV	200 keV	500 keV
Air	0.000195	0.000159	0.000112
Water	0.167	0.136	0.097
Carbon	0.335	0.274	0.196
Aluminium	0.435	0.324	0.227
Iron	2.72	1.09	0.655
Copper	3.8	1.309	0.73
Lead	59.7	10.15	1.64

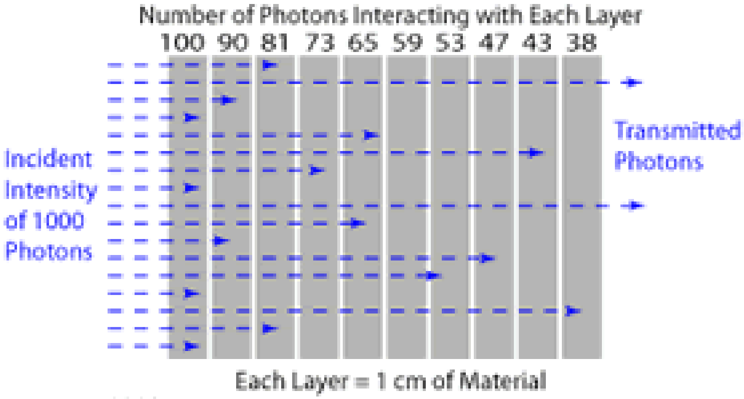
Half-Value Layer (thickness)

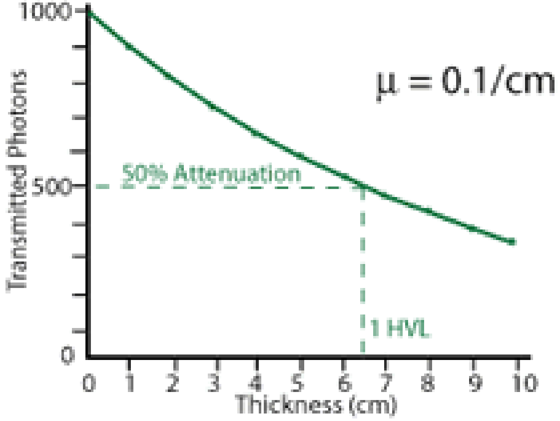
Just as with the exponential decay we had with activity, it's sometimes more convenient to work with a sort of half-life, but here we define the **half-value layer** (HVL) as the thickness of the material that will reduce the intensity by half.

$I(x) = I_o e^{-\mu x}$ so the thickness where $I(x) = 0.5 I_o$ will be when $0.5 = e^{-\mu x}$ or $x = \frac{ln(2)}{\mu} = \frac{0.693}{\mu} = HVL$, giving the thickness that will reduce the intensity in half.

Note that $\boxed{x_{1/2}}$ is sometimes used to represent this thickness.

$$x_{1/2} = HVL = \frac{0.693}{\mu}$$





Example: Rutherford Experiment

Around 1911, Rutherford and others fired α particles (from the radioactive decay of uranium) through very thin gold foils and found the vast majority of them went straight through, hinting that atoms consisted of mostly empty space with a nucleus about $100,000$ times smaller in diameter than the atom itself.

The thinnest gold foils used were about $0.00004\ cm$ thick. If 99% of the α radiation passes through one layer of this foil, determine the attenuation coefficient and the half-value layer (thickness) for how gold attenuates α radiation at this energy level.

The intensity of radiation passing through a thickness x should behave as: $\boxed{I(x) = I_o e^{-\mu x}}$.

In this experiment, apparently with $x = 0.00004\ cm$ the intensity drops by just one percent, so $I(x) = 0.99 I_o$ at $x = 0.00004\ cm$:

$0.99 I_o = I_o e^{-(\mu)(0.00004\ cm)}$ or $0.99 = e^{-(\mu)(0.00004)}$. Taking the natural log of each side: $ln(0.99) = -(\mu)(0.00004\ cm)$ so $\mu = -ln(0.99)/(0.00004\ cm)$ and finally $\mu = 251.25\ cm^{-1}$.

The 'half-value layer' (the thickness needed to cut the intensity in half) is:
$x_{1/2} = \frac{0.693}{\mu} = \frac{0.693}{251.25\ cm^{-1}} = 0.00276\ cm.$

Each layer was $0.00004\ cm$ thick, so apparently $(0.00276\ cm)/(0.00004\ cm/layer) = 68.95\ layers$ of foil would be needed to cut the intensity in half.

As a check, if each layer reduces the intensity by a factor of 0.99, then 69 layers would reduce it by a factor of 0.99 raised to the power 69:
$factor = (0.99)^{69} = 0.49984$ (close enough to half).

If your calculator doesn't have an x^y function built in, you could do this with logs:
$factor = (0.99)^{69}$
taking the log of both sides: $ln(factor) = 69 * ln(0.99) = -0.69347..$
taking e^x of each side of the equation: $factor = e^{-0.69347} = 0.49984$.

Human skin thickness varies from about $0.5\ mm$ for the eyelids, so about $4\ mm$ for the heels on the bottom of our feet. The average skin thickness is about $2\ mm$ which is about 5000 times as thick as the gold foils used by Rutherford.

Our skin isn't made of gold of course, but it's 5000 times thicker than those foils and most α radiation is stopped by the outer layers of our skin. The α particles released in radioactive decay typically have energies in the MeV range, so this radiation can cause burns, cell damage, possibly skin cancer, and so on.

In fact even **air** molecules end up absorbing most of the α radiation before it has a chance to reach us. The HVL for air is about $3.7\ cm$

Example : Air as Shielding

If the HVL for α radiation for **air** is 3.7 cm, how much air would these particles have to travel through to reduce the intensity by a factor of 1000?

$I(x) = I_o e^{-\mu x}$

Here we want $I(x) = 0.001 I_o$ and $x_{1/2} = 3.7\ cm$ so $\mu = ln(2)/x_{1/2} = 0.187337\ cm^{-1}$

Leaving x in centimeters:

$0.001 I_o = I_o e^{-0.187337x}$ so $0.001 = e^{-0.187337x}$ and taking the natural log of both sides:

$ln(0.001) = -0.187337x$ and $x = -ln(0.001)/(0.187337) = 36.87\ cm.$

(Note: moving away from the source also reduces the intensity due to the $1/r^2$ effect: the radiation is being spread over a larger area as we move away from it. We'll include that effect in the example on the next page.)

Example : Sheets of Paper as Shielding

If the HVL for α radiation for **paper** is 53 μm, how many sheets of paper (each with a thickness of 0.07 mm) would reduce the intensity by a factor of 1000?

$53 \times 10^{-6}\ m$ is $0.053 \times 10^{-3}\ m$ or 0.053 mm so it looks like each sheet of paper, being slightly thicker than that, will reduce the radiation a bit more than a factor of 2.

Let's do this one a little differently than the previous example. By what factor will one sheet of paper reduce the intensity? Adding sheets brings in that factor again and again, so how many will it take to achieve a final intensity of 0.001? (I.e. reduced to $1/1000th$ of the original?)

$\mu = ln(2)/x_{1/2} = ln(2)/(53 \times 10^{-6}\ m) = 13078.25\ m^{-1}$

Then with $x = one\ sheet = 0.07\ mm = 0.07 \times 10^{-3}\ m = 7 \times 10^{-5}\ m$ we have:

$I(x) = I_o e^{-(13078.25\ m^{-1})(7\times 10^{-5})} = I_o e^{-0.915477} = (0.4003) I_o.$

Each sheet of paper reduces the intensity by a factor of 0.4003. How many sheets would reduce it to just 0.001 times the original intensity? $(0.4003)^n = 0.001$ so taking the log10 of each side: $(n)log(0.4003) = log(0.001)$ becomes $(-0.3976)(n) = -3$ and finally $n = 7.55\ sheets$ (well, can't really add a half-thickness sheet of paper, so I guess we'll have to use 8 sheets).

Example : Combination

Suppose the radiation travels through 37 cm of air **and** we hold 8 sheets of paper between us and the source. How much will the intensity be reduced?

We found that travelling through that much air reduced the intensity by a factor of 1000.

The 8 sheets of paper also reduces the intensity by a factor of 1000.

The net effect is the intensity gets multiplies by 0.001 by the air gap and another 0.001 thanks to the paper, for an overall reduction of $(0.001)(0.001) = 1 \times 10^{-6}$: a reduction of a factor of a million.

Only 1 in a thousand α particles makes it the given distance, and only 1 in a thousand of those make it through the paper.

Example : A More Realistic Scenario

Suppose we have a 1 Ci source of alpha radiation and we stand 1 meter away from it. What intensity will actually reach us?

1 Ci means the source is emitting 3.7×10^{10} particles per second, but they're being spread uniformly around a sphere of radius 1 meter, representing an area of $4\pi r^2 = 12.57\ m^2$. The **intensity** at this distance then would be $(3.7 \times 10^{10}\ s^{-1})/(12.57\ m^2) = 2.94 \times 10^9\ s^{-1}\ m^{-2}$.

If we're surrounded by **air** though, most of those α particles will actually be absorbed by the air. The HVL for α radiation in air is about 3.7 cm so if we're a meter away, the alphas are passing through $n = (100\ cm)/(3.7\ cm) = 27.03$ half-value-layer's worth of air, each of which is cutting the intensity in half, so what makes it all the way to us will only be: $(2.94 \times 10^9\ s^{-1}\ m^{-2}) \times (0.5)^{27.03} = 21.5\ s^{-1}\ m^{-2}$.

Distance is doing two things for us here: the radiation is spreading out as $1/r^2$, and the air between us and the source is absorbing the vast majority of the α particles that would have made it to us.

If we want to reduce it even further, we can add a thin layer of lead to our clothes (basically wear a lead-lined lab coat).

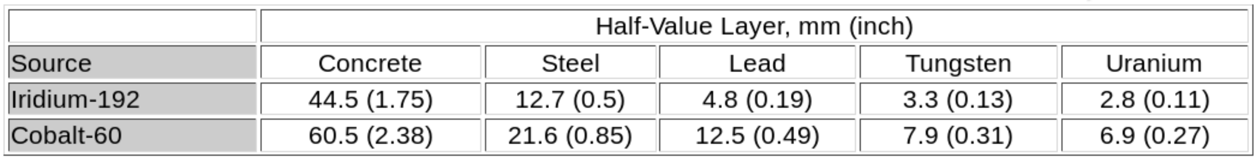
Beta Radiation

β radiation (whether β^- when a neutron becomes a proton, or β^+ where a proton becomes a neutron in the decay) is often in the MeV energy range also. They penetrate **much** farther than α radiation. The half-value layer thickness for air is on the other of **meters**, for skin about a centimeter, and for metals it's in the range of a few millimeters.

The **top half** of the table below shows the half-value thicknesses (in millimeters and inches) for a few materials and varying energies of β radiation. (The materials in this part of the table are radioactive materials sometimes used in cancer treatments.

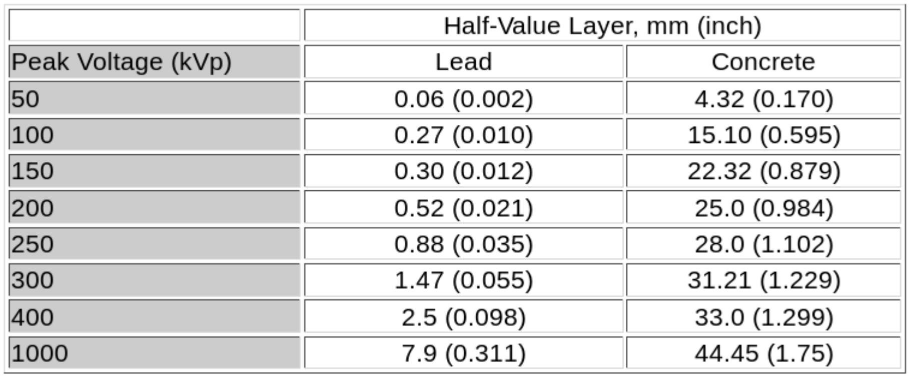
${}^{60}_{27}Co$ (cobalt-60) decays via β decay into an excited form of ${}^{60}_{28}Ni$ (nickel-60) which then emits γ rays of about 1.27 Mev and 1.33 Mev.

${}^{192}_{77}Ir$ (iridium-192) involves β decay (with the emitted electrons having energies of about 170 keV).



	Half-Value Layer, mm (inch)				
Source	Concrete	Steel	Lead	Tungsten	Uranium
Iridium-192	44.5 (1.75)	12.7 (0.5)	4.8 (0.19)	3.3 (0.13)	2.8 (0.11)
Cobalt-60	60.5 (2.38)	21.6 (0.85)	12.5 (0.49)	7.9 (0.31)	6.9 (0.27)

Approximate Half-Value Layer for Various Materials when Radiation is from an X-ray Source



	Half-Value Layer, mm (inch)	
Peak Voltage (kVp)	Lead	Concrete
50	0.06 (0.002)	4.32 (0.170)
100	0.27 (0.010)	15.10 (0.595)
150	0.30 (0.012)	22.32 (0.879)
200	0.52 (0.021)	25.0 (0.984)
250	0.88 (0.035)	28.0 (1.102)
300	1.47 (0.055)	31.21 (1.229)
400	2.5 (0.098)	33.0 (1.299)
1000	7.9 (0.311)	44.45 (1.75)

X-rays and Gamma Radiation

The **lower part** of the table above shows half-value thicknesses for various energies of X-rays (technically also γ rays, but generated directly without radioactivity).

Ultimately, the absorption (attenuation) of radiation depends on the type of radiation, it's energy, and the absorbing material. The use of radiation for cancer treatments can involve selecting the specific type such that it would pass through healthy tissue with very little absorption but then have a very high absorption coefficient in the cancer cells.

Example : γ radiation

Suppose we have a radioactive material emitting 0.1 μCi of 200 keV gamma rays.

- What intensity (counts per square meter) would we receive if we were standing 1 meter from this source?

  1 *curie* of activity means this source is emitting 3.70×10^{10} gamma rays per second, so our 0.1 $micro-Curie$ source is emitting 3.70×10^3 gamma rays per second ('micro' being a factor of 10^{-6} and the 0.1 value further reducing it by another factor of 10).

  This radiation is spreading over a sphere 1 meter in radius, which represents an area of: $4\pi r^2 = (4\pi)(1\ m)^2 = 12.566\ m^2$ so we have an intensity of: $I = (activity)/(area) = (3700\ counts/sec)/(12.566\ m^2) = 294\ s^{-1}\ m^{-2}$.

  (That 1 m^2 is about the cross-sectional area our body presents if we're facing the source, so we'd be receiving 294 gamma rays per second, spread over the part of our body facing the source.)

- Unfortunately, the HVL for gamma rays in air at this energy is over 50 meters so almost none of this radiation will be absorbed by the air. Almost the entire 294 gammas per square meter per second will hit us and we'll need to use some actual shielding to cut this down.

- If we are wearing a 2 mm thick layer of lead shielding, what intensity would we be exposed to?

  The intensity determined above is now striking a relatively thin (but still quite heavy) layer of lead just before hitting us. How much will this shielding attenuate the intensity falling on it?

  $I(x) = I_o e^{-\mu x}$ and here we have $x = 2\ mm$ of lead. Looking at one of the earlier tables, the attenuation coefficient for lead (for 200 keV gamma rays) is $\mu = 10.15\ cm^{-1}$. To minimize the conversions needed, let's use x in terms of centimeters instead of millimeters, so here we have $2\ mm = 0.2\ cm$ of lead.

  The intensity that makes it through the lead shielding then will be:

  $I = I_o e^{-\mu x} = (294) e^{-(10.15\ cm^{-1})(0.2\ cm)} = 38\ counts\ s^{-1}\ m^{-2}$.

  (We've cut the radiation level down by a factor of 7.6; wearing a shield twice as thick would cut it another factor of 7.6, so only about 5 gamma rays would hit us each second.)

- What if we have a different source with the same activity, but this one emits 500 keV gamma rays? What changes?

  The intensity at our distance was just the activity divided by the area, so that doesn't change.

  What happens when this intensity falls on our 2 mm lead shielding now? The absorption coefficient at this higher energy is much lower: $\mu = 1.64\ cm^{-1}$ so adding the lead apron only reduces the radiation reaching our body to:

  $I = I_o e^{-\mu x} = (294) e^{-(1.64)(0.2)} = 212\ counts\ s^{-1}\ m^{-2}$, which is hardly any reduction at all.

Both the **type** and **energy** of a given radioactive material go into determining what type of shielding is used.