Lesson 43: Alpha, Beta, & Gamma Decay

The late 1800s and early 1900s were a period of intense research into the new "nuclear" realm of physics.

In 1896 **Henri Becquerel** found that a sample of uranium he was doing experiments with had a special property.

- After he was done with a series of experiments using the uranium, he put it into a drawer with a photographic plate.
  - A photographic plate is a piece of glass covered in chemicals. It was used as the "film" in old style cameras.
- Becquerel was surprised to find out later that the uranium had caused the plate to be fogged up, as if it had been exposed to light.
- He correctly assumed that the uranium was emitting radiation similar to visible light.
  - He was even able to show that a magnetic field seemed to change the direction that this invisible radiation traveled.

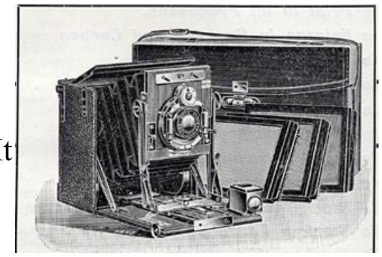

Illustration 1: An early camera with photographic plates.

Shortly after this, **Marie** and **Pierre Curie** isolated two other radioactive elements, polonium and radium.

- No matter what physical or chemical stresses they placed on these elements, they continued to emit radiation just like the uranium that Becquerel had used.
  - Since nothing they did could stop the radioactivity, they believed that the radioactivity must come from deep within the atom, in what we would today call the nucleus.

Did You Know?
In 1934 Marie Curie died of leukemia from years of exposure to radioactive elements. She received two Nobel Prizes, in Physics and Chemistry. The element polonium that she helped discover is named after her homeland, Poland.

We now know that radioactivity actually results from the decay (disintegration) of an unstable nucleus.

- This process fundamentally changes the nucleus of the element itself.
  - The radiation that we measure is evidence of events happening inside the nucleus.
  - In many cases this will actually result in the element changing to a different element, a process called **transmutation**.
- The reason these decays happen is because they result in more stable nuclei.

Ernest Rutherford and others started studying the radiation that was emitted by these elements.

- He found ***three*** distinct forms of radiation, originally divided up based on their ability to pass through certain materials and their deflection in magnetic fields...

  Alpha (α): could barely pass through a single sheet of paper. Deflected as a positive particle in a magnetic field.

  Beta (β): can pass through about 3mm of aluminum. Deflected as a negative particle in a magnetic field. *

  Gamma (γ): can pass through several centimetres of LEAD! Not deflected in a magnetic field.

* *Because of our modern understanding of what can happen in decays, we will have to examine **two** different kinds of beta decay later.*

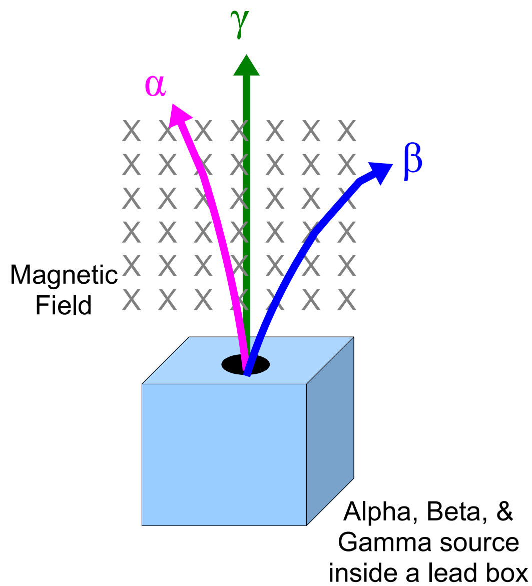

Illustration 2: Different types of radiation traveling through a magnetic field.

Alpha Radiation

Main Properties
Barely pass through a single sheet of paper.
Deflected as a positive particle in a magnetic field.
Highly ionizing α^{2+}.
Only dangerous if source is ingested.

The reason the alpha radiation has such a hard time even passing through a piece of paper is because it is not a form of EMR like we might expect. It is actually the nuclei of a helium atom $^{4}_{2}He$!

- During an alpha decay, a nucleus is able to reach a more stable state be allowing 2 protons and 2 neutrons to leave the nucleus.
    - This will result in a smaller nucleus, which is often the more stable arrangement.
- Because 2 protons and 2 neutrons are really just helium-4, the particle that is emitted is really helium-4.
    - Because this helium is "born" from a nuclear decay, we usually don't call it a helium atom. Instead we call it an **alpha particle**.

Alpha particles come out of the nucleus as just nucleons ***without any electrons***.

- So, each alpha particle has a charge of **+2e** .

The atom that originally went through the alpha decay has just lost some of its nucleons. That must change the element somehow.

- It's actually pretty easy to figure out what will happen as long as we apply the conservation of nucleons.

The Conservation of Nucleons

The total number of nucleons (protons plus neutrons) must remain the same before and after a nuclear decay reaction.

> **Warning!**
> The conservation of momentum, energy, and charge also still apply. The conservation of nucleons is just the newest conservation law that applies to the following situations.

We can write out what basically looks like a chemistry reaction to show how what we started with (the parent nucleus) **transmutates** according to a radioactive decay into another element (the daughter nucleus) and the emitted particle.

- It's not a chemistry equation though, since we are showing things that happen in the nucleus, and we can end up with different elements on each side.
- Just remember that we must end up with the same total number of nucleons as we started with.
- We also use the conservation of charge to show that we will end up with the same number of protons on both sides (and some other clever tricks later).

Example 1: The iridium-168 isotope is known to go through alpha decays. Write out a decay equation that shows this process.

Start by looking up iridium on your periodic table so that you can find out its atomic number. Then write down the most basic decay reaction; show what you started with (the iridium is your parent nucleus), and how it has decayed by emitting an alpha particle and some other nuclei.

$$^{168}_{77}Ir \rightarrow {}^{4}_{2}\alpha + X$$

Notice how on the left I have a total of 168 nucleons, of which 77 are protons. So far on the right side I've only shown 4 nucleons and 2 protons... woof! There's a bunch missing! They must be making up my unknown daughter nucleus, X. We can figure out the numbers for the daughter nucleus by just subtracting what we have (on the alpha particle) from what we had on the parent nucleus (the iridium).

Nucleons = A value = 168 – 4 = 164 ← Conservation of Nucleons
Protons = Z value = 77 – 2 = 75 ← Conservation of Charge

There's only one element on the periodic table that has 75 protons: rhenium. That means that the finished alpha decay reaction of iridium-168 should show...

$$^{168}_{77}\mathrm{Ir} \rightarrow {}^{4}_{2}\alpha + {}^{164}_{75}\mathrm{Re}$$

Parent Nucleus
Alpha Particle
Daughter Nucleus

	Parent Nucleus	Alpha Particle + Daughter
Conservation of Nucleons ($p^+ + n^o$)	**168**	4 + 164 = **168**
Conservation of Charge (p^+)	**77**	2 + 75 = **77**

In the process of alpha decay the total mass of the daughter nucleus plus the alpha particle is less than the mass of the original parent nucleus.

$$m_{parent} > m_{alpha} + m_{daughter}$$

- The “missing” mass isn’t really missing. It’s been turned into energy following Einstein’s formula $E = mc^2$.
  - This works out for our new understanding of conservation of mass and conservation of energy being interchangeable.
- The energy is found (mostly) in the kinetic energy of the alpha particle and daughter nucleus moving away from each other.
  - The alpha particle usually moves faster, since the alpha particle is almost always much lighter than the daughter nucleus.
  - Also keep in mind that if the parent nucleus was at rest, the alpha particle and daughter nucleus will travel off in opposite directions so that the **conservation of momentum** is obeyed.

Example 2: **Determine** how much energy is released when Uranium-238 decays to Thorium- 234 .
This is an alpha decay. The reaction for it would be...

$$^{238}_{92}U \rightarrow {}^{4}_{2}\alpha + {}^{234}_{90}Th$$

It is possible to look up the total masses of these atoms in your textbook (p.881) or on the internet.

For masses we get...

238.0508u → 4.0026u + 234.0436u

Add up the stuff on the right side...

238.0508u > 238.0462u

If we subtract them, we find that there is 0.0046u unaccounted for after the reaction has occurred. Since 1u = 1.66e-27 kg...

$E = mc^2 = (0.0046\text{u} \times 1.66\text{e-}27\text{kg/u})\,(3.00\text{e}8\text{m/s})^2 = 6.87\text{e-}13\ \text{J}$

We often state these answers in MeV (mega electron volts). First we would convert it to eV, and then MeV...

$$\frac{6.87\text{e-}13\,J}{1.60\text{e-}19\,J/eV} = 4.30\text{e}6\,eV = 4.30\text{MeV}$$

Beta Radiation

Main Properties
Barely pass through a sheet of foil.
Deflected as a negative particle (classic β^-) in a magnetic field.
Not as great an ionizing radiation.
Can penetrate about 1cm into a person.

Beta Negative Decay (β^-)

Beta decays happen in two ways, called beta negative and beta positive. Beta negative is the “classic” beta decay Rutherford observed. Beta positive decays are more rare. We will look at both.

Beta negative decay (β^-) happens during a process that at first seems crazy. A neutron falls apart and becomes a proton and an electron!

- This isn't as crazy as it sounds if you look at the facts. Remember earlier when we pointed out that neutrons have just a tiny bit more mass than protons? Now you know why. In the simplest terms, the neutron is made up of a proton and an electron stuck together.

- In the beta negative decay, the neutron becomes a proton (which stays in the nucleus) and an electron that goes flying out (the **beta particle**).
  - To make sure that you understand that the beta particle is not just a regular electron, but rather one that came from inside the nucleus, we will use the symbol $_{-1}^{0}\beta$.
  - Notice its A value is zero since it is not a nucleon, and its Z value -1 since it is the opposite charge of a proton.

Example 3: Write out the beta negative decay reaction for calcium-46.

As with the alpha decay in Example 1, first find your parent nucleus on the periodic table and write out a basic decay reaction...

$$_{20}^{46}Ca \rightarrow {}_{-1}^{0}\beta + X$$

Just like before, we figure out the A and Z values for our unknown daughter nucleus by subtracting what the beta particle has from the parent nucleus...

A = 46 – 0 = 46
Z = 20 - (-1) = 21

So our daughter nucleus must be scandium, the only element with 21 protons.

$$_{20}^{46}Ca \rightarrow {}_{-1}^{0}\beta + {}_{21}^{46}Sc$$

There is only one other thing we should put in our reactions for beta negative decay.

- When physicists first examined beta negative decays, they figured that since the electrons that are the beta particles are so light, they should just go shooting out of the nucleus at tremendous speeds (conservation of momentum & energy).
  - In reality, a lot of them moved really slow.
- In order to still have conservation laws obeyed, it was realized that a very small, neutral particle must also be emitted from the nucleus.
  - Today we call that particle an ***antineutrino*** and give it the symbol $\bar{v}$.
- So, we should really write the answer from Example 3 as...

$$_{20}^{46}Ca \rightarrow {}_{-1}^{0}\beta + {}_{21}^{46}Sc + \bar{v}$$

Did you know?
An antineutrino is an antimatter particle. Antimatter is different from regular matter because one characteristic (such as charge) is the exact opposite. Antineutrinos have a “spin” that is opposite to neutrinos.

If we wanted to just look at how the neutron changes into a proton, an electron, and an antineutrino, we could write it out as...

$$n^{o} \rightarrow p^{+} + {}_{-1}^{0}\beta + \bar{v}$$

Beta Positive Decays (β^+)

The other, rarer type of beta decay we examine is called beta positive.

- Beta positive is different from beta negative because the particles emitted are the exact opposite.
- For example, the beta positive decay emits a positive **positron**.
  - A **positron** is sometimes called an **antielectron**, since it is the

Positrons (β^+) have the exact same mass as an electron, but they have a +1e charge. Positrons are the antimatter version of electrons.

antimatter version of an electron. Antimatter is discussed in detail in Lesson 47.

- **Positrons** have the same mass as an electron, but their charge is +1e.
- We use the symbol β^+ to represent **positrons**, and in decay equations we write it as ${}^{0}_{1}\beta$.
- They are deflected as positive charges in a magnetic field (Rutherford did ***not*** observe these).

Following the trend of "everything is opposite," beta positive decays involve a proton decaying into a neutron and a positron, while also releasing a neutrino for conservation of momentum to be followed.

$$p^+ \longrightarrow n^o + {}^{0}_{1}\beta + \nu$$

- We can still use the rules for conservation of nucleons to figure out the products of a beta positive decay.

Example 4: Potassium-40 is known to go through beta positive decays. Write out the decay equation for this decay.

You should know the drill by now. We need to gather info on potassium-40 and then write out the decay.

$${}^{40}_{19}K \rightarrow {}^{0}_{1}\beta + X$$

Just like before, we figure out the A and Z values for our unknown daughter nucleus by subtracting what the beta particle has from the parent nucleus...

A = 40 – 0 = 40

Z = 19 - 1 = 18

So our daughter nucleus must be argon, the only element with 18 protons.

$${}^{40}_{19}K \rightarrow {}^{0}_{1}\beta + {}^{40}_{18}Ar + \nu$$

Notice the neutrino "ν" (no bar over the top) added at the end. This is the antiparticle of the antineutrino in the beta negative decay.

Inverse Beta Decays (aka Electron Capture)

Although not really one of the main forms of decay, we are looking at these **inverse beta decays** simply because of their similarity to beta negative decays.

- In this process a proton rich nucleus absorbs an electron from one of the inner energy levels.

$$p^+ + e^- \longrightarrow n^o + \nu$$

- Shown with nucleons values to prove conservation of nucleons we would have...

$${}^{1}_{1}p + {}^{0}_{-1}e \rightarrow {}^{1}_{0}n + \nu$$

Example 5: Rubidium-83 is known to go through electron captures. Write out the decay equation for this decay.

$${}^{83}_{37}Rb + {}^{0}_{-1}e \rightarrow {}^{83}_{36}Kr + \nu$$

Gamma Radiation (γ)

Main Properties
Only stopped by thick layers of lead.
Not deflected in a magnetic field.
Not an ionizing radiation.
True EMR… not a particle.

Gamma radiation can only be stopped by stuff like a few inches of lead.

- This is because unlike the other two forms of decay, gamma decays emit a form of EMR, not a particle.
- You will remember that gamma radiation is quite high up in the frequencies of the EM spectrum.
    - This allows it to pass through anything but the densest of matter.

Gamma decays happen most often after a alpha or beta decay.

- This happens because the nucleus has just been through a lot! Spitting out other subatomic particles, changing to a different element, and all that.
    - The nucleus is basically all jiggled up and needs to release some energy somehow.
    - An easy way to do this is to let off a gamma burst.
- Because we are releasing energy (not particles), the A and Z values stay the same.

Example 6: The argon-40 that was produced in Example 4 is in an excited state, so it releases a burst of gamma radiation. Write the equation for this.

$$^{40}_{18}Ar \rightarrow \gamma + ^{40}_{18}Ar$$

Decay Series

Anytime a nucleus decays, the daughter nucleus itself may still be unstable.

- In this case, the daughter nucleus is now the parent nucleus and will go through another decay.
- By this process a nucleus may go through several decays before reaching a nucleus stable enough to stay the same for a while.
    - This bunch of decays is called a **decay series**, and can be written several ways.

Example 7: Write a decay series for thorium-226 decaying to astatine-214.

Without looking stuff up we have no way of being certain which decays will happen, but we can make some guesses and see if we end up in the right spot. We will leave out any gamma decays here, since they do not change any of the nucleon numbers.

$$^{226}_{90}Th \rightarrow ^{4}_{2}\alpha + ^{222}_{88}Ra$$

$$^{222}_{88}Ra \rightarrow ^{0}_{-1}\beta + ^{222}_{89}Ac + \bar{v}$$

$$^{222}_{89}Ac \rightarrow ^{4}_{2}\alpha + ^{218}_{87}Fr$$

$$^{218}_{87}Fr \rightarrow ^{4}_{2}\alpha + ^{214}_{85}At$$

To save room, and since we can figure out what kind of decay happened from the products, we sometimes write a decay chain that skips the decay particles...

$$^{226}_{90}Th \rightarrow ^{222}_{88}Ra \rightarrow ^{222}_{89}Ac \rightarrow ^{218}_{87}Fr \rightarrow ^{214}_{85}At$$

Radiation Risks

You've probably seen a movie with a Geiger counter clicking like crazy as the people get near a radioactive source, or Homer Simpson glowing green after falling into the nuclear reactor.

- In real life there are radiation sources all around you. There is no big problem with this, since this natural background radiation has always been there. Biologically, life on Earth has always been exposed to these low levels of radiation.
- The problem is when people are exposed to large doses of radiation in extraordinary circumstances.
  - The levels a person is exposed to can be measured in a variety of units like:
    - **Rad**: A rad is the older unit used to describe each kilogram of tissue exposed absorbing 0.01 J of energy.
    - **Gray** (**Gy**): one Gray means each kilogram of material absorbs 1 Joule of energy. So, 1 Gy equals 100 rad.
    - **Sievert** (**Sv**): is a modified version of Grays, because it takes into account the Relative Biological Effectiveness (RBE) of a particular kind of radiation. The more dangerous a particular kind of radiation is to a person, the more the original Grays are multiplied to give Sieverts.
- In normal situations, a person can expect to be exposed to about 0.5 mSv in a year. Any exposure of about 6 Sv or higher will be fatal.

Radiation can cause damage to a human in two ways.

- **Radiation Sickness**
  Radiation sickness usually refers to a very large dose of radiation in a small period of time. The problem is that the radiation can **ionize** cells. This means that the radiation is knocking electrons off the cells, usually interfering with cell division.
  Many people that survived the initial blast of the bombs used at Hiroshima and Nagasaki died from radiation sickness a few days later.
- **Genetic Damage**
  The radiation can cause damage to the actual DNA of cells. This can result in cancer, which will usually show up after several years.

Since the three types of radiation have different abilities to penetrate matter, they represent different levels of risk to humans.

- ***Alpha*** has a high ionization rate, but can not easily penetrate matter. A layer of clothes or even the top layer of skin (which is dead anyways) can stop it. The alpha particles can only move through the air about 5 cm before being stopped. Alpha radiation is really only a danger if you either breathe in or swallow the source of the alpha radiation.
- ***Beta*** does not ionize as easily, but it can penetrate matter more easily, traveling about 0.50 m through the air and about 1 cm into a body. This means that although beta radiation can be a bit more of a risk, it is still most dangerous if the source is ingested.

- ***Gamma*** can easily penetrate your body, since it is EMR with a high frequency. Although it doesn't ionize much, it causes the most damage to a person. Even being near an unshielded source of gamma radiation for a short period of time is very dangerous!

Homework

p799 #1-3
p800 #1-3
p801 #1-3
p803 #1
p810 #11