Radioactive Decay

Radioactivity is the spontaneous disintegration of atomic nuclei. This phenomenon was first reported in 1896 by the French physicist Henri Becquerel. Marie Curie and her husband Pierre Curie contributed further to the understanding of radioactivity. Their research led to the discovery of two new radioactive elements, polonium and radium, and forced scientists to change their ideas about the structure of the atom.

Radioactivity is the result of an atom trying to reach a more stable nuclear configuration. The process of radioactive decay can be achieved via three primary methods; (1.) a nucleus can change one of its neutrons into a proton with the simultaneous emission of an electron (beta decay), (2.) by emitting a helium nucleus (alpha decay), or (3.) by spontaneous fission (splitting) into two fragments. Often associated with these events is the release of high energy photons or gamma rays.

Each individual radioactive substance has a characteristic decay period or half-life. A half-life is the interval of time required for one-half of the atomic nuclei of a radioactive sample to decay. The radioactive isotope cobalt 60, which is used in radiation cancer therapy, has a half-life of 5.26 years. Thus after that interval, a sample originally containing 16 grams of cobalt 60 would contain only 8 grams of cobalt 60 and would emit only half as much radiation. After another interval of 5.26 years, the sample would contain only 4 grams of cobalt 60. Half-lives can range from milliseconds to thousands of years.
Sometimes after undergoing radioactive decay, the new atom is still left in a radioactive form. This means that the atom will decay again as it attempts to reach a stable nuclear state.

Henri Becquerel and others observed three clearly different types of radiation, but no one knew exactly what any of them were, so they were simply named alpha (α), beta (β), and gamma (γ) for the first three letters of the Greek alphabet. It was only later that the radiation was shown to consist of familiar things: helium nuclei, electrons, and high-energy electromagnetic waves.

### Alpha Decay

In alpha decay, a positively charged particle, identical to the nucleus of helium 4, is emitted spontaneously. This particle, also known as an alpha particle, consists of two protons and two neutrons. It was discovered and named by Sir Ernest Rutherford in 1899. The release of an alpha particle (2 protons and 2 neutrons) decreases the mass number of the nucleus by 4.
Alpha decay usually occurs in heavy nuclei such as uranium or plutonium, and therefore is a major part of the radioactive fallout from a nuclear explosion. Since an alpha particle is relatively more massive than other forms of radioactive decay, it can be stopped by a sheet of paper and cannot penetrate human skin. A 4 MeV alpha particle can only travel about 1 inch through the air.
Although the range of an alpha particle is short, if an alpha decaying element is ingested, the alpha particle can do considerable damage to the surrounding tissue. This is why plutonium, with a long half-life, is extremely hazardous if ingested. Alpha particles do not travel far in air before being absorbed; this makes them very safe for use in smoke detectors, a common household item. The reason alpha decay occurs is because the nucleus has too many protons which cause excessive repulsion. In an attempt to reduce the repulsion, a Helium nucleus is emitted. The way it works is that the Helium nuclei are in constant collision with the walls of the nucleus and because of its energy and mass it will tunnel out of the nucleus. Here is an example of alpha emission with americium-241:

![Alpha Decay of Americium-241 to Neptunium-237](image)
Another example of an alpha decay which involves uranium-238:

\[
^{238}_{92}\text{U} \rightarrow ^{234}_{90}\text{Th} + ^4_2\text{He}
\]

This process of transforming one element to another is known as transmutation.
Beta Decay

This form of radioactive decay was discovered by Sir Ernest Rutherford in 1899, although the neutrino was not observed until the 1960s. Beta particles have all the characteristics of electrons. At the time of their emission, they travel at nearly the speed of light. A typical .5 MeV particle will travel about 10 feet through the air, and can be stopped by 1 to 2 inches of wood.

Atoms emit beta particles through a process known as beta decay. Beta decay occurs when a beta particle is released from a nucleus. A beta particle is an electron formed inside the nucleus when a neutron breaks apart. The other particle that forms when a neutron breaks apart is a proton. So beta decay produces a new atom with the same mass number as the original atom but with an atomic number one higher than the original atom.

Beta decay also occurs when the neutron to proton ratio is too great in the nucleus and causes instability. Two types of beta decay can occur. One type (positive beta decay) releases a positively charged beta particle called a positron, and a neutrino; the other type (negative beta decay) releases a negatively charged beta particle called an electron, and an antineutrino. The neutrino and the antineutrino are high energy elementary particles with little or no mass and are released in order to conserve energy during the decay process. Negative beta decay is far more common than positive beta decay.
An example of such a process is:

\[ ^{234}\text{Th} \rightarrow ^{234}\text{Pa} + ^{0}\text{e} \]

\[ ^{14}\text{C} \rightarrow ^{14}\text{N} + e^- + \bar{\nu}_e \]

\[ ^{14}_6\text{C} \rightarrow ^{14}_7\text{N} + e^- + \text{antineutrino} \]
In terms of safety, beta particles are much more penetrating than alpha particles, but much less than gamma particles.
**Gamma Decay**

The third class of radioactive decay is gamma decay, in which the nucleus changes from a higher-level energy state to a lower level. When a gamma ray is emitted by a nucleus, the nucleus does not change into a different nucleus. But because a gamma ray is an extremely high-energy wave, the nucleus makes a transition to a lower energy state. Similar to the energy levels for electrons in the atom, the nucleus has energy levels. Gamma decay occurs because the nucleus is at too high of an energy state. The nucleus falls down to a lower energy state and, in the process, emits a high energy photon known as a gamma particle. This particle has no mass and no charge and it travels at the speed of light.

While alpha and beta decays occur because there are either too much neutrons compared to protons or too much protons compared to neutrons in the nucleus (this is why the nucleus is unstable), gamma decay simply occurs because the nucleus is in an excited or highly energetic state and hence has to ‘relax’ a bit.
Here's a diagram of gamma decay with helium-3:

Gamma Decay of Helium-3

\[ ^{240}_{94}\text{Pu}^* \rightarrow ^{240}_{94}\text{Pu} \]

\( \gamma \)-radiation: high-energy electromagnetic waves
Gamma rays are more penetrating than either alpha or beta radiation, but less ionizing. Gamma rays from nuclear fallout would probably cause the largest number of casualties in the event of the use of nuclear weapons in a nuclear war. They produce damage similar to that caused by X-rays such as burns, cancer, and genetic mutations.

Because of the high penetrating capabilities of its emitted particles, gamma decay is considered the greatest threat among the three. Radioactive substances in laboratories are kept inside Lead-sealed cabinets. Some even have Lead-sealed lab rooms. This design is made specifically for the purpose of preventing gamma rays from passing through.
Penetrating Power of an alpha (\(\alpha\)) particle, beta (\(\beta\)) particle and a gamma ray (\(\gamma\))

Paper, Aluminum, Lead Foil

Alpha particles may be completely stopped by a sheet of paper, beta particles by aluminum shielding. Gamma rays can only be reduced by much more substantial barriers, such as a very thick layer of lead.
The trefoil symbol is used to indicate radioactive material.
X - Rays

On November 8, 1895, a German physicist, W. C. Roentgen was working with a cathode ray tube in his laboratory. He was working with tubes similar to our fluorescent light bulbs. He evacuated the tube of all air, filled it with a special gas, and passed a high electric voltage through it. When he did this, the tube would produce a fluorescent glow. Roentgen shielded the tube with heavy black paper, and found that a green colored fluorescent light could be seen coming from a screen setting a few feet away from the tube. He realized that he had produced a previously unknown "invisible light," or ray, that was being emitted from the tube; a ray that was capable of passing through the heavy paper covering the tube. Through additional experiments, he also found that the new ray would pass through most substances casting shadows of solid objects on pieces of film. He named the new ray X-ray, because in mathematics "X" is used to indicated the unknown quantity.

In his discovery Roentgen found that the X-ray would pass through the tissue of humans leaving the bones and metals visible. One of Roentgen’s first experiments late in 1895 was a film of his wife Bertha’s hand with a ring on her finger (shown below). The news of Roentgen’s discovery spread quickly throughout the world. Scientists everywhere could duplicate his experiment because the cathode tube was very well known during this period. In early 1896, X-rays were being utilized clinically in the United States for such things as bone fractures and gun shot wounds.
X-RAY GENERATION

So far our discussion has been primarily centered on radioactive elements, the structure of the atom, and the phenomenon of radioactivity. Where as gamma radiation is one of the products of nuclear decay of radioactive elements, X-rays are produced in high voltage electron tubes. X-rays can be produced in parcels of energy called photons, just like light.

**How do you generate an x-ray?**

To generate x-rays, we must have three things. We need to have a source of electrons, a means of accelerating the electrons at high speeds, and a target material to receive the impact of the electrons and interact with them.

X-rays are generated when free electrons give up some of their energy when they interact with the orbital electrons or nucleus of an atom. The energy given up by the electron during this interaction appears as electromagnetic energy known as X-radiation.
Radioactive Half-Life

The radioactive half-life for a given radioisotope is the time for half the radioactive nuclei in any sample to undergo radioactive decay. After one half-life there will be one half of the original sample left. After two half-lives, there will be one fourth the original sample, after three half-lives one eight the original sample, and so forth.

Radioactive decay is the process by which an unstable atomic nucleus loses energy by emitting ionizing particles or radiation. The emission is spontaneous in that the nucleus decays without collision with another particle. This decay, or loss of energy, results in an atom of one type, called the parent, transforming to an atom of a different type, named the daughter nuclide. For example: a carbon-14 atom (the "parent") emits radiation and transforms to a nitrogen-14 atom (the "daughter"). This is a random process on the atomic level, in that according to quantum mechanics it is impossible to predict when a given atom will decay. However given a large number of similar atoms the decay rate, on average, is predictable.

The half-life is defined in terms of probability. It is the time when the expected value of the number of entities that have decayed is equal to half the original number. For example, one can start with 10 radioactive atoms, wait its half-life, and measure whether or not it decays in that period of time. Perhaps it will and perhaps it will not. But if this experiment is repeated again and again, it will be seen that it decays within the half life 50% of the time.
The half life of beryllium 11 is 13.81 seconds. Let's say you start with 16 grams of 11Be. Wait 13.81 seconds, and you'll have 8 grams left; the rest will have decayed to boron 11. Another 13.81 seconds go by, and you're left with 4 grams of 11Be; 13.81 seconds more, and you have 2 grams.

The radioactive isotope cobalt-60, which is used for radiotherapy, has a half-life of 5.26 years. Thus after that interval, a sample originally containing 8 g of cobalt-60 would contain only 4 g of cobalt-60 and would emit only half as much radiation.

**Half Life Example (Interval of 10 minutes)**

If the half life of substance X is 10 minutes and substance X starts out at a total of 100 grams then
- at $t = 0$, the current amount = 100 grams
- $t = 10$ mins, current amount = 50 grams
- $t = 20$ mins, there is 25 grams
- $t = 30$ mins, 12.5 grams and so on and so forth.
The Electron Volt

The SI unit of energy, the joule, is too large a unit to be useful in atomic or nuclear physics. Accordingly we define the **electron volt (eV)**, the energy that an electron would acquire when accelerated through a potential difference of one volt. The electron is now known to have a charge of \(e = -1.60 \times 10^{-19} \text{ Coulombs}\) first measured by Millikan. Thus the electron volt is related to the joule by \(1 \text{ eV} = 1.602 \times 10^{-19} \text{ joules}\)

A watt, the SI unit of power is defined as one joule per second.

The total energy released by the fission of 1 atom of Uranium-235 is about 200 MeV which corresponds to \(3.2 \times 10^{-11} \text{ Joules}\).
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