Radioactive Decay

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1 Radioactive Decay

The rate at which radiation is emitted is called radioactive decay. We can show experimentally that radioactive decay is not affected by temperature, pressure, or any other physical or chemical means. The only way to increase radioactive decay, is to increase the amount of radioactive material that is decaying. This is the Law of Radioactive Decay.

Law of Radioactive Decay: The rate of radioactive decay depends only on the number of atoms of a radioactive substance present.

This makes it easy to predict the rate of decay:

Rate of Decay $= -\lambda N$
Where λ is called the decay constant, and N is the number of atoms present.

The rate of decay is the number of nuclear disintegrations per second. The unit of radioactive decay is therefore one disintegration per second, which we call the **Bequerel (Bq)**.

2 Half-life & Decay Constant

The time it takes for half of the atoms in the radioactive substance to disintegrate is called the half-life. It is a characteristic of the particular substance, and can be anywhere between a fraction of a second to millions of years.

So, a substance with a short half life should have a large decay constant, and a substance with a long half life should have a small decay constant (think about why this is).

We can show experimentally that they are inversely related with the following relationship:

$T_{\frac{1}{2}} = \frac{ln2}{\lambda}$

Problem: The decay constant of a certain radioactive isotope is $3.5 * 10^4 s^{-1}$. What is it's half life?
Ans: $1.98 * 10^-5s$.

3 Diversion: Energy Mass Equivalence

Until now, we have looked upon mass and energy as different things. Mass is a thing affected by gravity: we are made up of mass, we can touch things that have mass, we can detect mass by the phenomenon of weight. Energy, on the other hand, is something a little more elusive, but we can see it travel around in different forms. Potential, kinetic, heat, light, chemical, ect.

In his revolutionary paper on special relativity in 1905, Einstein suggested that mass and energy are not so different after all. In this model, we can think of mass almost as another, very dense type of energy that we can treat similarly to other types of energy that you've seen before. We can transfer "mass-energy" into other types of energy. The relationship between mass and energy is one of the most famous equations in all of physics:

$E_0 = mc^2$

where E_0 is the rest energy (the energy the particle has solely due to it's mass, not including kinetic, potential, or other energies), m is the mass in kilograms, and c is the speed of light.

This is the basis behind **nuclear fission**, which is how the sun shines, **nuclear fusion**, which is now current nuclear power plants and nuclear weapons work, and how CERN in Switzerland can create and detect new types of fundamental particles.

4 Nuclear Reactions

As we have talked about before, we can change atoms of one element into atoms of another element, by changing the number of protons. This may be through radiation, or otherwise. Similarly, we can change the isotope by changing the number of neutrons, or we can ionise the atom by changing the number of electrons.

We have also discussed energy-mass equivalence. The implication of this is that the conservation of mass, which was so fundamental to classical mechanics, is no longer valid, since mass can be turned into other forms of energy. Now, when discussing particles that obey quantum mechanics, we have some new conservation laws:

1. **Conservation of Electric Charge**: Electric charge cannot be created nor destroyed. Total charge of an isolated system before and after a reaction must be the same.

2. **Conservation of Mass-Energy**: While mass alone is no longer necessarily conserved, the total energy of the isolated system is still conserved if we take mass to be "rest energy", as defined by the mass-energy equivalence.

3. **Conservation of Momentum**: This one still holds from classical physics, thankfully!

5 Uses of Radioisotopes

Until now, we have only discussed naturally occurring radioactive materials, like uranium, radon and thorium, for example. These are very rare, especially since radioactive materials are inherently unstable and will break down and become non radioactive over time. A lot of the radioactive material on earth is man-made.

5.1 Artificial Radioactivity

It is possible to manufacture nuclei that are so unstable, they become radioactive, by bombarding non-radioactive isotopes with wither charged particles or neutrons. These particles get lodged in the atom, making it unstable and causing it to become radioactive. This is how we make radioisotopes for use in medicine and other industries.

5.2 Uses of Radioisotopes in Medicine

Gamma Ray Imaging is where gamma ray are used to produce photographic images inside the body, using the same principles as x-ray imaging we saw earlier.

Radiation from an artificial radioisotope is injected into the patient, which is detected by detectors outside. This is the principle behind PET (positron emission tomography) and SPECT (single photon emission computerised tomography) scans.

Radiotherapy: Since radiation kills living cells, it is sometimes used to kill cancer cells in a body. The radioisotope typically used here is cobalt-60, which is a gamma emitter. Sometimes gold-198 (which has a half life of 2.5 days) is inserted directly into tumors. The trade off here is that radiation kills any living cell, so reducing exposure of healthy cells is very important.

Sterilisation: Since radiation can kill any living cells, it's also sometimes used in hospitals for very heavy duty sterilisation of heat-sensitive materials like scalpels, bandages, or syringes. Gamma radiation can penetrate plastic, so you can prepack the equipment in plastic before sterilisation, and the packaging will keep it sterile until needed.

5.3 Industrial Uses of Radioisotopes

Smoke Detectors contain americium-241, which emits α particles that can ionise air. Ionised air can carry a current, so if ionised air is placed in a gap in a circuit, current will still flow. In the presence of smoke, smoke particles stick to the ions and reduce the flow of current. The lack of current is detected, and will trigger the smoke alarm.

Gamma Ray Photography works in a similar way to x-ray photography, but is more penetrating again. Any gamma ray source can be used, like cobalt-60 or iridium-192. This technique is often used for checking jet engines, aircraft frames or pipelines. The only thing is that the gamma ray source cannot be turned on and off the an x-ray source; they have to be stored in lead lined containers, and operators must be shielded when in use.

Food Irradiation: Bacteria, fungi, insects and parasites can spoil food. By exposing the food to high levels of gamma radiation, you can kill the microorganisms and sterilise it. This will make the food keep for longer.

5.4 Research uses

Carbon Dating: Neutrons in cosmic rays from space are constantly bombarding the earths atmosphere. Sometimes, this causes the abundant nitrogen-14 to become the radioactive isotope carbon-14. All living things contain a known amount of carbon, and a small, but usually constant fraction of that is carbon-14. Since we know the half-life of carbon-14, 5,760 years, we can