Prelab: Radioactivity and Radiation

Everyday thing: an X-ray image or CT scan, a nuclear power plant, natural background radiation.

It is physics: atoms can change their state or type, and when they do, they emit radiation.

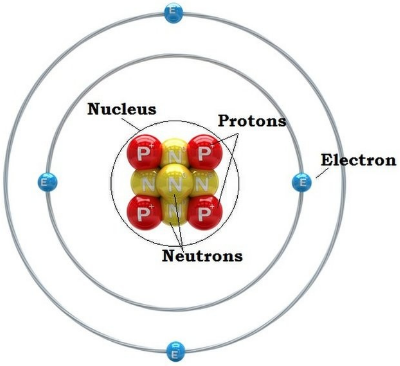
Atoms

Let's remind ourselves about **atoms**: an atom is the smallest constituent of normal matter that still has the properties of a chemical element.

Atoms are made of

- a **nucleus**, which is made up of **protons** and **neutrons**, and
- **electrons**, which form a "cloud" around the nucleus.

Protons are **positively** charged, and their charge is known as elementary charge *e*. Electrons are **negatively** charged, and their charge is exactly equal and opposite to the ones of protons, $-e$. Neutrons are **electrically neutral**. Thus, an electrically neutral atom has the same number of protons and electrons.



The Bohr model of the atom, with a nucleus in the center and electrons in orbits around the nucleus.

The electrons are held to the nucleus by the electrostatic force, since they are of opposite charge. Almost all of chemistry happens due to bonds formed by the electrons. Thus, as far as chemistry is concerned, the nucleus is mostly a bystander that keeps the electrons in place. Therefore, the **type** of element is determined by the **number of protons**: atoms with 1 proton are hydrogen (H), atoms with 2 protons are helium (He), atoms with 6 protons are carbon (C), etc.

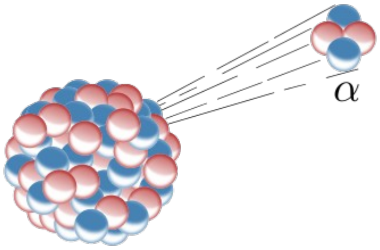
The nucleus contains almost all of the **mass** of the atom: a proton and a neutron have about the same mass, which is one **atomic mass unit** (a.m.u.). The electron only has a mass of 1/2000th of an a.m.u. Atoms with the same number of protons but different number of neutrons (i.e., different mass) are called **isotopes**. E.g., for hydrogen (1 proton), there are three main isotopes: hydrogen without neutrons (most common), hydrogen with one neutron (uncommon), hydrogen with two neutrons (very uncommon).

So, why do we have the neutrons? To answer this, let's first ask another question: since protons are positively charged, how come they stay together in the nucleus and are not ripped apart by electrostatic repulsion? The answer is that there exists a force, the **strong nuclear force**, which binds protons and neutrons together, and is, at very short distances, stronger than the electrostatic force. To get a stable atom, we thus need a balance of neutrons and protons.

Radioactive decay

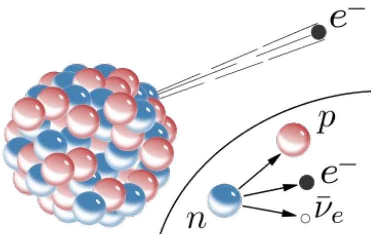
Radioactive decay is the process by which an unstable atomic nucleus **loses** potential energy and it converted to more stable one. Because energy is conserved, the energy lost is transferred to radiation. There are three types of radiation:

- **alpha radiation**: a small piece of the nucleus breaks off and is emitted, an “alpha particle”, which consists of two protons and two neutrons. This happens because the strong nuclear force only works on very short ranges, so as the nucleus becomes larger and larger, the risk of it being ripped apart by the electrostatic force increases.

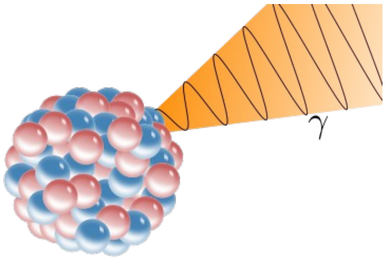
  alpha particles are heavy and highly charged, and thus very destructive to living cells and particularly to the DNA. Fortunately, they can only travel a few centimeters in air, and are shielded by a piece of paper and even the layer of dead skin cells that make up the epidermis. They are thus only dangerous when inhaled or ingested.

- **beta radiation**: the nucleus emits a “beta particle”, which is either an electron or a positron (the rare antimatter counterpart of an electron). This happens because there is a second force inside the nucleus, called the **weak nuclear force**. It basically allows a neutron to be transformed into a proton and an electron or a proton to be transformed into an neutron and a positron.

  Most beta particles can be stopped by a few millimeters of aluminium. (However, as they are shielded, beta electrons can emit secondary gamma rays, which are more penetrating.) They are not as destructive as alpha radiation, but still damages living tissue and DNA material.

- **gamma radiation**: as a result of alpha decay, beta decay, or nuclear fission, the nucleus may end up in a state where it strongly vibrates (similar to matter with high temperature). In this case, it can spontaneously give off some of this energy by emitting light of a very high frequency. This is gamma radiation.

  Gamma particles can only be shielded by thick layers of heavy materials, such as concrete or lead. Gamma radiation is the least destructive of the three types, but is still extremely dangerous to living organisms in high doses.

Exposure and Natural background radiation

>>> Watch this video: https://www.youtube.com/watch?v=TRL7o2kPqw0

We are all exposed to radiation all the time, which is called the **natural background radiation**. There are three main sources of this radiation:

- **inhalation** and **ingestion of radioactive elements**: radioactive elements are found throughout nature, and thus some of them are found in the air and in the food we eat. For instance, bananas are rich on potassium, and potassium has an isotope which emits beta radiation.

- **cosmic radiation**, which are mostly high-energy protons and ions coming partly from the sun, partly from outside the solar system and even distant galaxies. When they hit the Earth's atmosphere, they generate a shower of alpha, beta, and gamma particles, some of which hit the Earth's surface. Cosmic radiation depends on altitude, and is thus higher on mountains and on airplanes.
- **radiation from the ground**: the ground also contains radioactive elements (depending on the location).

The reason why we don't all drop dead from radiation poisioning or cancer as soon as we are born is that exposure to radiation is a game of chance: each alpha, beta, or gamma particle has a slim **chance** of hitting a cell in our body. Any such cell will in the most cases either repair itself or die. There is a slim chance that it hits the cell's DNA in a particular way, such that the cell mutates. Most mutated cells will usually just die, but there is a slim chance that a cancer cell is formed. Hundreds of thousands of cancer cells are scooped up by our immune system every day, but again, there is a slim chance that the cancer cell can fool the immune system and become a threat.

The risk associated with radiation thus depends on the amount of radiation deposited in our body, called the **radiation dose** *H*. It's SI unit is **Sievert** (**Sv**), which is radiation energy deposited per body mass or J/kg, usually corrected by a factor that accounts for the "danger" of the type of radiation and the part of the body irradiated. The dose from natural background radiation depends on the location, but is usually around **3 mSv** (milli-Sievert) **per year**.

The calculation of risk works about as follows: add up all radiation doses over the span of your life and subtract 5–50 mSv from each year's dose for your body's natural ability to cope with radiation damage.[1] Then for every 1000 mSv, your chances for developing cancer due to radiation increase by 5%.

For very high doses (> 1000 mSv) in a short term, there is also the acute risk from direct cell death that cannot be repaired in time. Acute (=short-term) doses of more than 4000 mSv are usually fatal.

Rough dose	Action
0.00005 mSv	Sleeping next to someone
0.0001 mSv	Eating a banana
0.0025 mSv	Max. from airport security screening
0.01 mSv	Set of dental X-rays
0.5 mSv	Mammogram
2 mSv	Annual dose for flight attendants
~ 3 mSv	**Annual dose from natural background radiation**
20 mSv	Full-body CT scan
50 mSv	Annual dose limit for radiation workers
1000 mSv	Cancer rink increased by 5%
1000 mSv	Maximum allowed radiation exposure for NASA astronauts over their career
5100 mSv	Fatal acute dose to Harry Daghlian in 1945 criticality accident
64000 mSv	Nonfatal dose to Albert Stevens spread over ~21 years, due to a 1945 plutonium injection experiment

Geiger counter

A Geiger counter is an instrument used for detecting and measuring ionizing radiation. It is widely used in applications such as radiation dosimetry, radiological protection, experimental physics, and the nuclear industry. It detects ionizing radiation such as alpha particles, beta particles, and gamma rays using the

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[1] *That figure is subject to intense debate in the scientific community. For a while people believed it was "0" (the so-called linear no-threshold model), but more recent work are consistent with a threshold of around 10 mSv.*

ionization effect produced in a Geiger–Müller tube, which gives its name to the instrument. In wide and prominent use as a hand-held radiation survey instrument, it is perhaps one of the world's best-known radiation detection instruments.

A Geiger counter consists of a Geiger-Müller tube (the sensing element which detects the radiation) and the processing electronics, which displays the result. The Geiger-Müller tube is filled with an inert gas such as helium, neon, or argon at low pressure, to which a high voltage is applied. The tube briefly conducts electrical charge when a particle or photon of incident radiation makes the gas conductive by ionization.

There are two types of detected radiation readout: counts or radiation dose. The counts display is the simplest and is the number of ionizing events detected displayed either as a count rate, such as "counts per minute" or "counts per second", or as a total number of counts over a set time period (an integrated total). The counts readout is normally used when alpha or beta particles are being detected.