RADIOACTIVE DECAY – Tutorial Script

What does it mean when we call a substance radioactive? Radioactive atoms are those with unstable nuclear configurations. As they naturally decay or turn themselves into stable atoms, high-energy particles or waves are emitted outward from a single point in all possible directions, a process known as radiation.

Before we go further, let's review a little chemistry. All materials are made of atoms. Any single atom contains three particles: **electrons**, **protons**, and **neutrons**. Collectively these are known as subatomic particles. Protons have a +1 charge; electrons a -1 charge; neutrons no charge. Protons and neutrons have the same mass – 1 atomic mass unit (or AMU); electrons have so little mass they are effectively equal to 0 AMU. In the center of an atom is a tiny nucleus, which contains all the **protons** and **neutrons**. Surrounding the nucleus are energy shells called orbitals, in which are found the **electrons**.

For an atom to be electrically neutral, it must have the same number of protons as electrons. If they are not equal, there's a net charge on the element, and it's considered an **ion**. Electrons can come and go in the outer shells, and this is what produces most of the interesting chemistry we see on the planet. For information on how electrons impact chemical bonding, watch the Water Molecule Shape video tutorial.

The **Periodic Chart of the Elements** tells us which types of atoms are found across our planet. The element that a substance is depends entirely on the number of protons. We call this number, the **atomic number**. For example, the element oxygen has 8 protons; gold, 79; mercury, 80; and uranium, 92. We can turn anything we want into gold if we can find a way to change the number of protons in the nucleus to 79. For example, if we can take one proton out of the mercury nucleus, the mercury atom becomes a gold atom. Turning mercury into gold was a task that alchemists tried to accomplish during the middle ages. Turns out, all they needed to do was find a way to pull a proton out of the nucleus. Not an easy task. Later in this video we'll show you how that happens naturally for some elements.

What about neutrons? Turns out, the number of neutrons can vary for any particular element. We call each such variation of an element an **isotope**. For example, 99.76% of all naturally occurring oxygen has 8 protons and 8 neutrons for a total mass of 16 AMU. Remember it's the protons and neutrons that provide the mass, and all of these mass particles are found in the tiny nucleus in the center. We call that isotope oxygen-16 (^{16}O). However, 0.20% of all naturally occurring oxygen is made of atoms with 8 protons and 10 neutrons. We call that isotope oxygen-18 (^{18}O). And 0.04% of all naturally occurring oxygen is made of atoms with 8 protons and 9 neutrons, oxygen-17 (^{17}O). All these isotopes are oxygen because they each have 8 protons. They differ only in the number of neutrons and thus their mass. The isotopes of oxygen are known as **stable isotopes** because they have stable nuclear configurations and don't naturally decay. Because of their differences in mass, they are powerful tools that geologists use to learn a lot about the history of our planet and the processes that took place in its past. For example, evaporation of a water molecule with a heavy oxygen is less likely than evaporation of one with a lighter one. We see evidence of this when we look at the oxygen isotope ratios in the water that has evaporated and the water that has remained. For more information, look to video tutorials on stable isotope geochemistry.

Let's look at Uranium. It has 4 abundant natural isotopes, all of which are radioactive, meaning they all decay over time into something more stable. For example, Uranium-238 (^{238}U), which represents 99.3% of all natural Uranium, decays with a **half-life** of about 4.5 billion years, into stable isotope Lead-206 (^{206}Pb). The half-life is the amount of time it takes for ½ the ^{238}U to turn into ^{206}Pb. The original radioactive element, ^{238}U, is known as the **parent**. The element it turns into, ^{206}Pb, is known as the **daughter**. ^{235}U is another isotope of Uranium, which represents 0.72% of naturally occurring Uranium, and it decays into ^{208}Pb with a half-life of about 700 million years. So there are two parent-daughter relationships within just the Uranium element – two different isotopes of Uranium that naturally radioactively decay with different half lives and thus providing different clocks.

So what is the decay process? How does radioactive decay actually happen? Through one of the following processes:

In **Alpha decay** the unstable nucleus spontaneously emits an **alpha particle** (α particle), 2 protons (p+) and 2 neutrons (n); this is the same as a Helium (He) ion. The result? Atomic number decreases by 2 (because it lost 2 p+); and atomic mass decreases by 4 (because it lost 2 p+ and 2n, which is 4 AMU). Because of the change in atomic number, the substance is now an entirely different element. For example, one alpha decay from ^{238}U will turn it into atomic number 90, which is Thorium. And with the loss of 4 AMU, the daughter product will be ^{234}Th.

But ^{234}Th is also radioactive and has a half-life of 24 days. It decays through a process known as **Beta decay** during which one neutron in the nucleus spontaneously emits a **beta particle** (β particle), which is essentially an electron trapped in a neutron. The neutron, therefore, turns itself into a proton. Let's go back to our review of subatomic particles and take an electron with a mass of effectively 0 and a -1 charge and add it to a proton, with a +1 charge and mass of 1 AMU. What do we get? A particle with a net charge of 0 and mass of 1 AMU – which is exactly what we know as a neutron. When a neutron kicks out its beta particle, its electron, its negative side, it transforms into a proton. Result? The atomic number increases by 1 (it gained a p+) – and it's a new element. Atomic mass stays same (because no mass was lost or gained: β particles or electrons have effectively no mass). Note: in addition to the electron or beta particle being emitted, there is also an antineutrino formed, which carries away excess decay energy.

Example: When ^{234}Th experiences Beta Decay, it gains a proton and loses a neutron. It becomes atomic number 91, Protactinium, atomic mass 234: ^{234}Pa. ^{234}Pa has a half-life of 1.2 minutes and through another beta decay becomes ^{234}U. Through a series of 7 more alpha decays and 4 beta decays, the final daughter product of U^{238} decay is lead-206, ^{206}Pb.

Another example of beta decay is what happens to radioactive Carbon-14 (^{14}C). Through beta decay ^{14}C becomes Nitrogen-14 (^{14}N) – note that during this decay, the atom went from atomic number 6, carbon, to 7, nitrogen.

A third kind of radioactive decay is **Beta or electron capture** in which a beta particle (β particle), which is essentially an electron, as we've already discussed, collides and fuses with a proton to become a neutron. The proton, therefore, turns itself into a neutron. Result? atomic number decreases by 1 (because it lost 1 p+) – so it's a new element. Atomic mass stays same (no mass lost or gained: β particle or electrons have effectively no mass). Note: in addition to the production of a neutron, a neutrino is emitted, carrying away excess decay energy. Also, the new element formed is in an excited state. The new element may emit one of these excited electrons, or those electrons might drop back into closer energy shells, accompanied by the emission of gamma radiation (γ) (equal to the energy difference between the two shells).

An example of electron or beta capture is the decay of potassium-40 (^{40}K) into argon-40 (^{40}Ar). The atomic number went down 1 from potassium (19 protons) to argon (18 protons), while the atomic mass stayed the same. The half-life of this decay process for ^{40}K is about 1.25 billion years.

How harmful is the radiation produced through radioactive decay? And what can we do to avoid it? Since there are natural sources of radioactive isotopes all around us, it's important to know what rocks we're building our structures on. If those rocks contain minerals rich in any radioactive elements, we want to be sure to ventilate well our basements. This is especially true when one of the intermediary steps in the decay process involves a gas, like Radon gas. Radon gas is produced as one of the steps in the decay process of ^{238}U.

High-energy radiation that can ionize atoms it encounters as it travels can be harmful to biological tissue. Ionization means that it's ripping electrons off atoms as the radiation moves past them. This can destroy cells (unless the cells can repair themselves, which of course takes energy and attention from the body's immune system) or it can cause the cell to mutate potentially into cancerous cells.

Alpha particles with a net charge of +2 will ionize the first thing they hit, thus they can't penetrate very far into a substance, and a single layer of clothing or paper will absorb them. Beta particles with a net charge of -1 can penetrate up to a millimeter or two in solids and liquids and several feet in air. It takes a few millimeters of a solid material to absorb beta particles and protect your skin from their damage. Gamma rays, on the other hand, because they are electrically neutral have less ionizing power, but that also means they can penetrate much further into biological organisms where they eventually cause damage to internal organs. Gamma rays can be stopped only by atoms with high cross-sectional interference, like lead or what's found in concrete. (*Note: the neutrinos and antineutrinos that we discussed earlier appear to have no interaction with matter and thus are not considered harmful to biological tissues. They move right through us.)

Since naturally radioactive isotopes can be trapped in different minerals as they form in rocks around the planet, their decay can be used as a clock to tell us the time that a particular mineral or rock formed. For more information refer to the Radiometric Dating video tutorial.

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