How Old is the Earth-Moon System

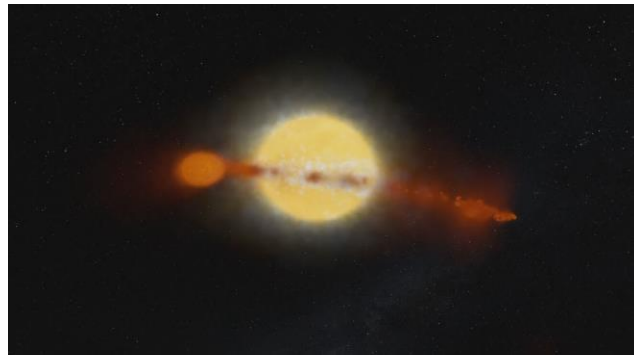
{Abstract: *In this chapter we cover the Giant Impact Hypothesis as the starting point for the age of the modern Earth-Moon system. We'll see a Fulldome illustration on what it might have looked like. We then cover Oxygen Fractionation and use water evaporation to show how it works. We build the Terrestrial Fractionation line and show that all oxygen on Earth falls on this line. We then show that meteors like Allende do not fit on the line, but Moon rocks do. We then begin our deeper dive into how we date rocks using Radiometric Dating with uranium and lead. We review the discovery of radiation with its alpha, beta and gamma rays. We cover half-life and the exponential law of radioactive decay including the uranium to lead decay chains. We also cover the Chemical Abrasion - Isotope Dilution - Thermal Ionization Mass Spectrometry (CA-ID-TIMS) method for dating zircon crystals in rocks found here on Earth. This includes a look at how the Memorial University of Newfoundland does it. We end with the age of the oldest Earth and Moon rocks.*}

Giant Impact Hypothesis

As the Earth formed, it was rotating on an axis perpendicular to the solar plane just like all the other planets. Today it's off by 23.5 degrees. The 1970s Apollo missions to the Moon collected 400 kg of moon rocks (that's 900 lbs. on Earth). These rocks showed a remarkable similarity to rocks here on Earth. This indicates that they were made at the same place. And analysis of the oldest Moon rocks show that they are the same age as the oldest rocks found on Earth. This indicates that they formed at the same time. (Later in this chapter, we'll cover just how rock analyses for similarities and age are done.)

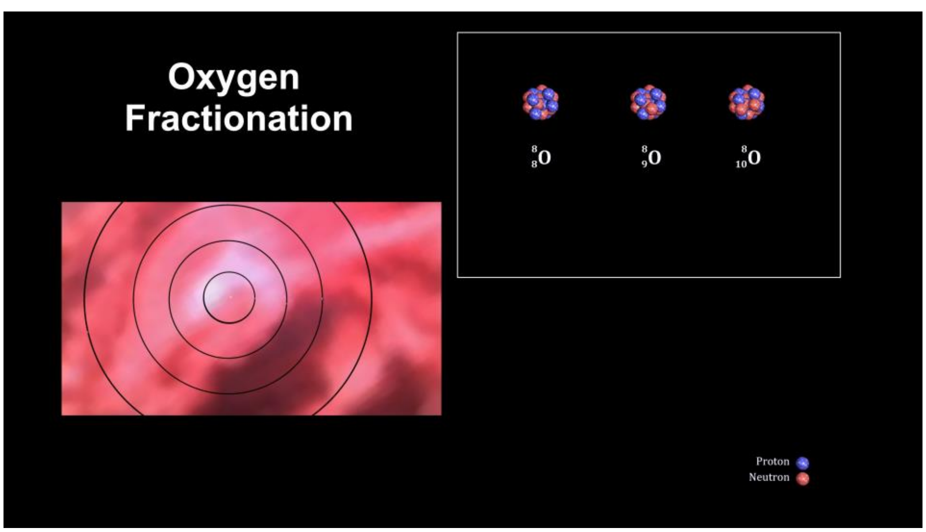
These, along with many other Earth-Moon system characteristics, support the idea that the Earth-Moon combination was the result of a massive collision called the Giant Impact Hypothesis. Here is an animation crated by Fulldome that illustrates how this may have looked. It's a hypothesis instead of a theory because there are a number of variations and not enough data is available to enable definitive selection of the right combination of possibilities.

The hypotheses that currently comes closest to what happened has it that a planet the size of Mars called Thea moved in from the outer solar system with major quantities of water and collided with the Earth shortly after it had formed. It hit at a 45^{o} angle traveling at around 4 km per second (that's 2.5 miles/s). The collision would have tilted the Earth, liquified, vaporized and homogenized the mantels of the two planets and ejected massive amounts of matter into space where it coalesced into the moon.

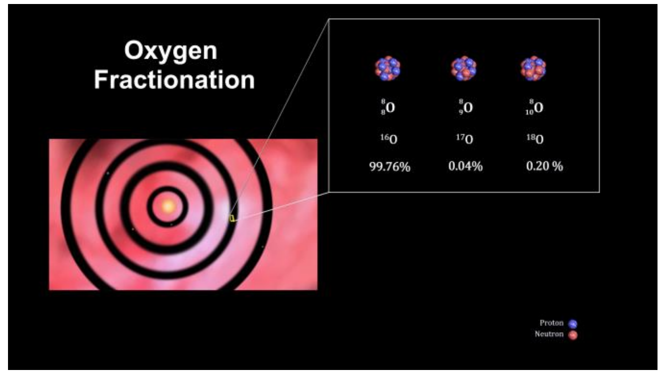


Oxygen Fractionation

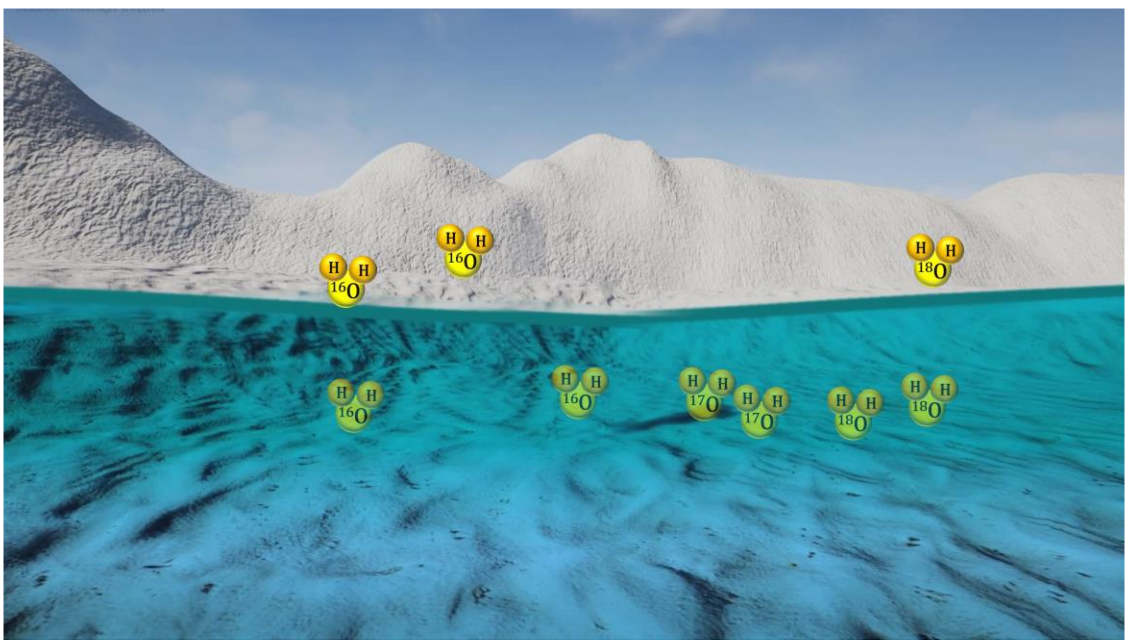
The key reason for this scenario is the similarity between rocks from Earth and the moon. We'll focus on oxygen. Among all the chemical elements, oxygen has a combination of properties that makes it uniquely important in solar system development studies. It's a principle constituent of most minerals, rocks and water. In addition, it's light enough (with 8 protons) to have three stable isotopes: One with 8 neutrons ^{16}O one with 9 neutrons ^{17}O and one with 10 neutrons ^{18}O. With modern mass spectrometers, we can accurately count atoms with different masses even if the difference is only one neutron. We'll cover mass spectrometers a bit later in the chapter.



Because oxygen combines to make gases like CO and H_2O water vapor and also combines to make solids like iron oxides and silicates, it would have separated into various reservoirs early in the solar system development with varying percentages of each isotope. This makes it a natural tracer for identifying different reservoirs and the objects they eventually formed. Here on Earth, we find that 99.76% of the oxygen is ^{16}O, 0.04% is ^{17}O, and 0.20 % is ^{18}O.



But physical processes can change these ratios for any particular sample. One of the best examples of this is water evaporation. The lighter isotope ^{16}O tends to evaporate faster than ^{18}O. This makes the ration of ^{18}O over ^{16}O larger in a water sample and smaller in an air sample. The same process will play out with ^{17}O proportionally by mass. The process is called isotopic fractionation.



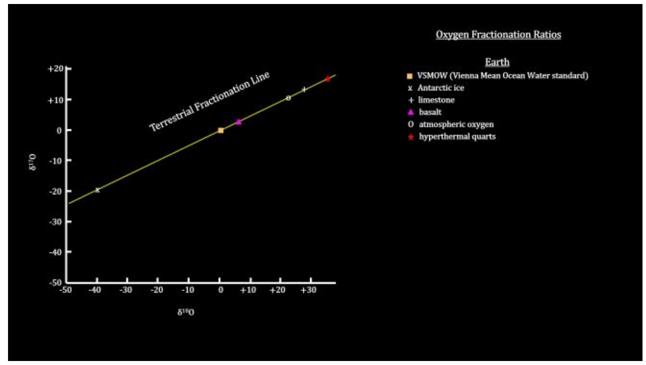
To take deviations like this into account, scientists measure the variations (δ) in the ratios of $^{17}O/^{16}O$ and $^{18}O/^{16}O$ against a standard called Vienna Standard Mean Ocean Water (VSMOW).

Fractionation

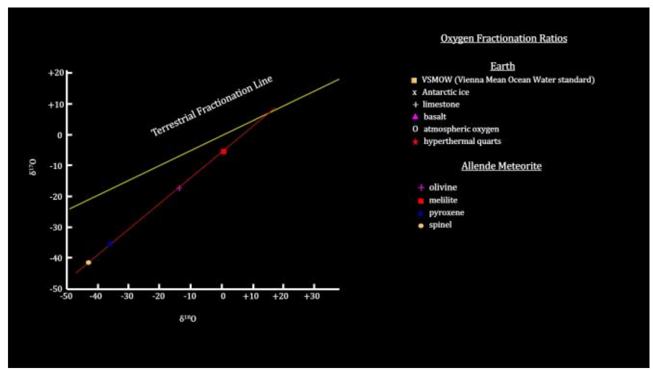
$$(^{17}O/^{16}O)_{VSMOW} = 379.9 \text{ (1 per 2632 parts)}$$
$$(^{18}O/^{16}O)_{VSMOW} = 2005.2 \text{ (1 per 498.7 parts)}$$

$$\delta^{17}O = [((^{17}O/^{16}O)_{sample} - (^{17}O/^{16}O)_{VSMOW})/(^{17}O/^{16}O)_{VSMOW}] \times 10^3$$
$$\delta^{18}O = [((^{18}O/^{16}O)_{sample} - (^{18}O/^{16}O)_{VSMOW})/(^{18}O/^{16}O)_{VSMOW}] \times 10^3$$

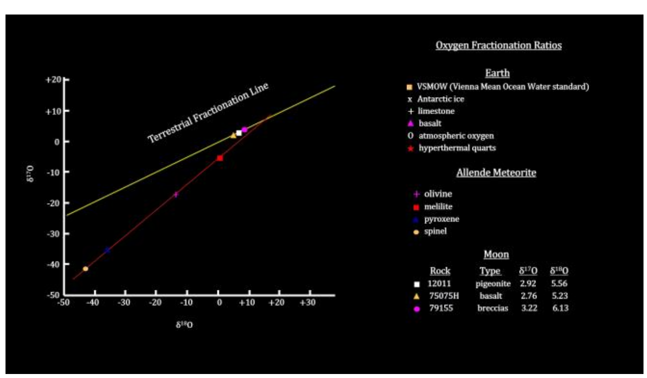
Here's a graph that maps the $^{17}O/^{18}O$ ratios for various substances: limestones, basalts, quarts, air and ice. Note that all the data points fall on a line. It's called the Terrestrial Fractionation Line. All oxygen on Earth fits on this line. Additionally, the fact that Earth's water fractionation is on the same line as the Earth's rock fractionation indicates that the water and rocks formed in the same place. [Any process that leads to a change in $\delta^{17}O$ will produce a change twice as large in $\delta^{18}O$, since the mass difference is one proton over two – making the slope of the line ½. Note that the vertical axis is stretched to accommodate the data points.]



The lines are quite different for meteorites. The Allende meteorite that struck Mexico is a good example. A number of minerals where examined. None of the oxygen isotope ratios fell on the terrestrial fractionation line. The Allende line is different because the oxygen isotope percentages in the volume of the circumstellar disk where the meteor formed were different.



A team of scientists from Switzerland and the US analyzed over 30 moon rock samples across 15 rock types from Apollo 11, 12, 15, 16, and 17. Every single one fit on the terrestrial fractionation line. Here we have shown just 3 of them. This indicates that the rocks on the moon and the rocks on the Earth formed in the same place. This in turn supports the idea that the Theia collision hit with sufficient force to homogenize the two planet's mantels. This also supports the idea that Theia brought us our water. We have already determined that the Earth's water and rocks formed in the same place. And, given that the Earth originally formed without water, Theia must have formed in the otter solar system with lots of water. When it collided, its water became a part of the homogenized mantels for the Earth and the Moon.



The reason all this is important for our 'how old is the Earth' purposes, is that the homogenized mantle would have been completely magma. Thus, the rocks that formed from this magma will be the oldest rocks on Earth. And the same would hold true for the Moon.

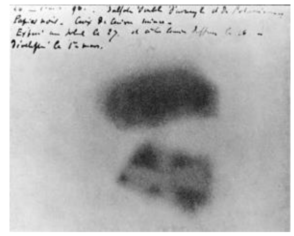
Radiometric Dating Intro

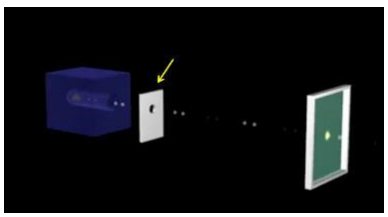
Determining the age of rocks is called geochronology. But before the early 20th century, there was no way to do it. In the 1920s, a British geologist named Arthur Holmes, the father of modern geochronology, came up with an accurate method called radiometric dating. The method requires that the rock contain at least some measurable amount of radioactive material such as Uranium and the lead it decays into. To understand how we can use the Uranium to date a rock, we'll go one level deeper into just how this dating method works. We'll cover; how we know what uranium radiates, how we know how long it takes uranium to decay, and how we measure how much uranium has decayed into lead in a rock sample.

We'll start with 'radiation' itself.

Nuclear Radiation (Radioactivity)

At the turn of the 20th century, radioactivity was discovered by the French scientist Henri Becquerel. Using Uranium salts, he was able to blacken a photographic plate. Here's a photograph of the plate.

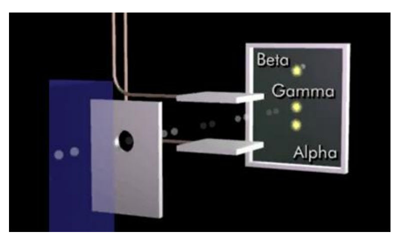




Further research by Becquerel, Ernest Rutherford, Madam Curie, and others discovered 3 types of radiation. Here's how they did it. A radiation source shines on a lead plate with a small hole in it to create a beam. The beam is directed at a florescent screen. The screen flashes when it is struck.

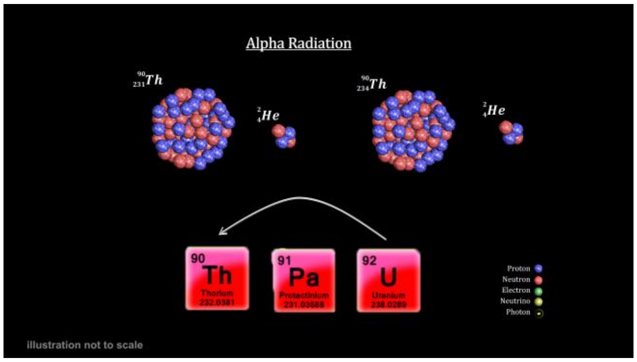
Without any electric field present, the beam illuminates a single point on the screen. When an electric field is applied, the beam is separated into three components. One is deflected upward by the electric field indicating that it consists of negatively charged particles. These were named beta rays.

One is deflected downward, but not as far as the Beta rays were deflected upward, indicating that it consists of positively charged particles that are more massive than beta rays. These were named Alpha rays. The radiation that continued to hit the center was not affected by the electric field and therefore has no charge. These emissions were named gamma rays.

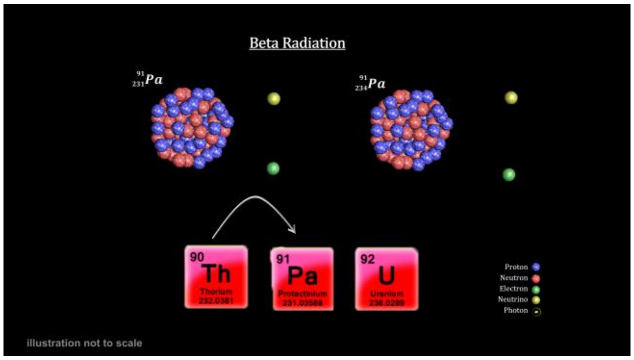


Radiation research has been going on in nuclear labs around the world ever since those days. What we know now is that alpha radiation comes from an unstable nucleus that disintegrates into a lighter nucleus and ejects an alpha particle which is always a helium nucleus - two protons and two neutrons. This is called alpha decay and it decreases the radiating atom's atomic mass number by 4 and it decreases the atom's atomic number by 2 changing its nature from one element to another.

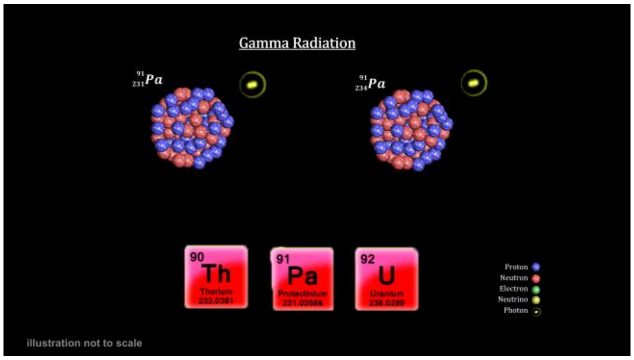
Focusing on Uranium, we see that alpha decay changes ^{235}U into ^{231}Th + ^{4}He, and the ^{238}U into ^{234}Th + ^{4}He.



Beta radiation comes from an unstable nucleus that ejects a neutrino and an electron - turning one proton into a neutron inside the nucleus and upping the atomic number by one while leaving the atomic mass number unchanged. This is called beta decay. Here we see that beta decay changes ^{231}Th into ^{231}Pa (Protactinium), and ^{234}Th into ^{234}Pa.

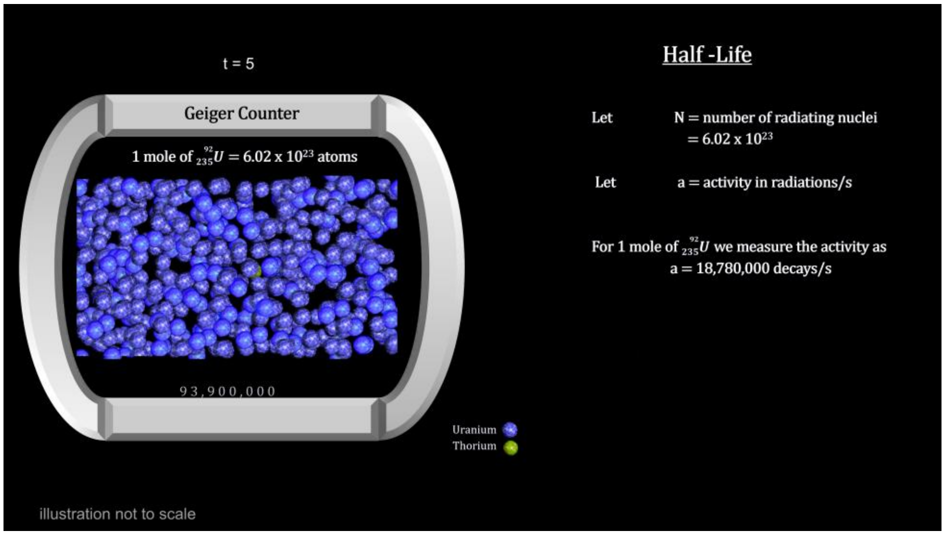


Gamma rays are extremely energetic photons and constitute the most dangerous form of radiation. They are produced when an excited nucleus returns to its ground state – much like when an excited electron around a nucleus produces a photon when it drops to its ground state. Only gamma ray photons have a million times more energy.

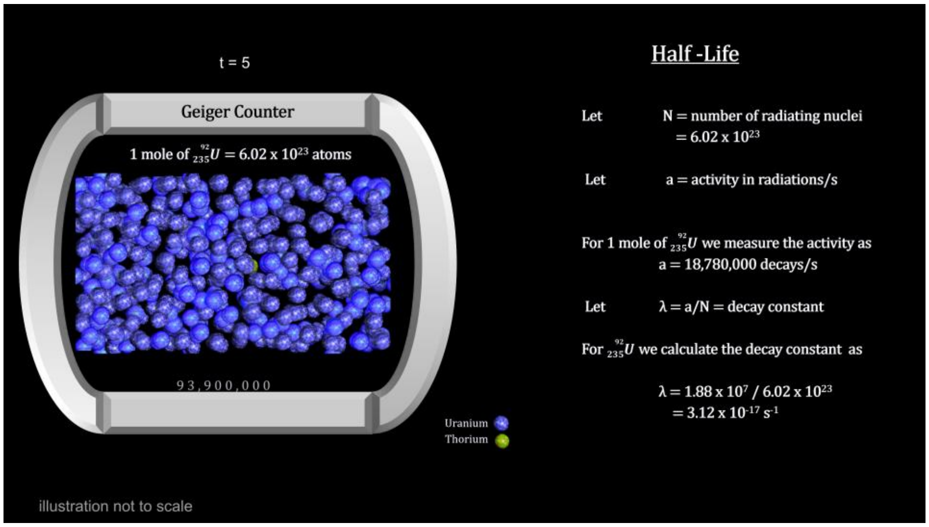


Half-Life

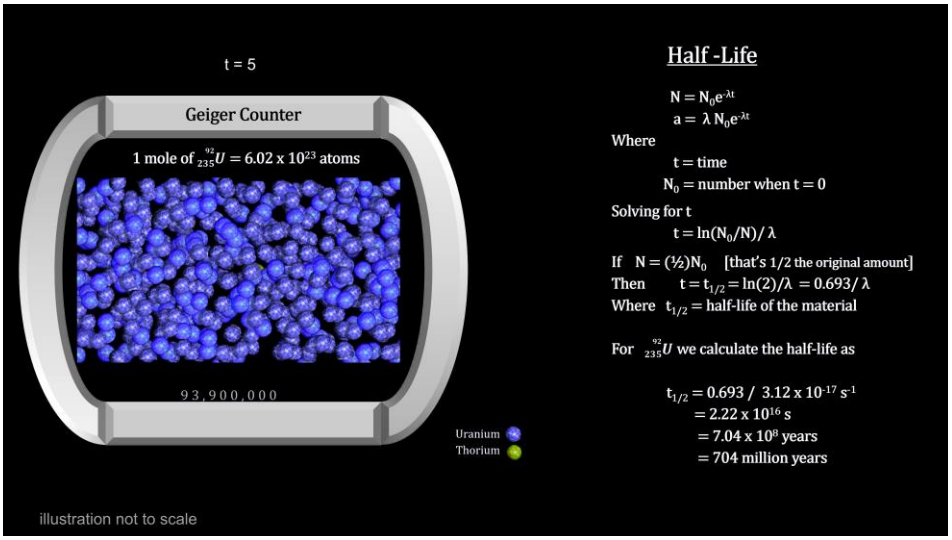
Here's a measured sample of U235. The rate at which unstable radioactive nuclei decay in a sample of material is called the *activity* of the sample. The greater the activity, the more nuclear decays per second. This is rather easily measured with devices like a Geiger counter. Here's a 5 second run illustration. Our U235 sample is decaying almost 19 million nuclei per second.



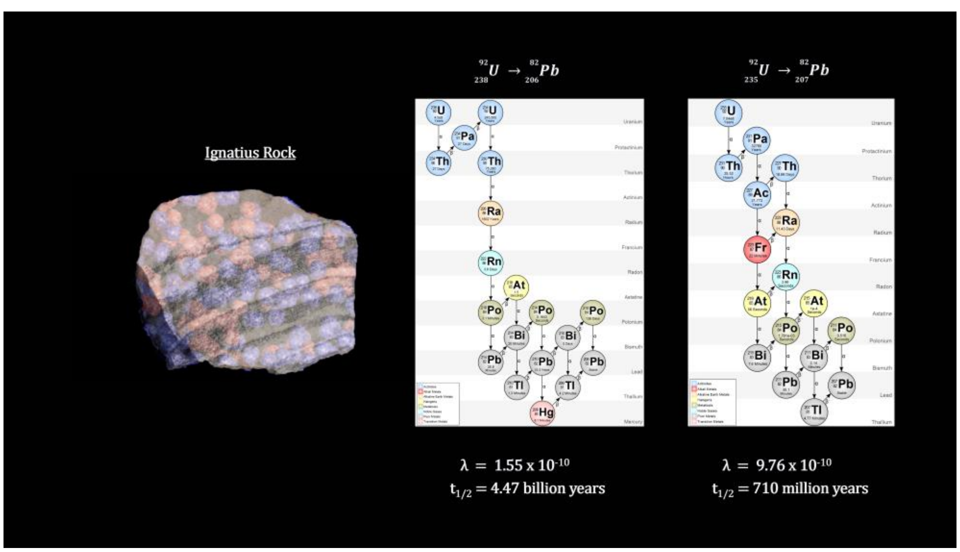
Given the number of radiating molecules in a sample, and measuring the activity, we can calculate the probability for any one molecule to decay in a second. This is called the decay constant. We find that the decay constant is always a small number, constant over time, and different for different materials. Here we have the decay constant for U235.



Both the activity rate and the number of radioactive nuclei vary over time. As a sample decays, the number of radioactive nuclei decreases. With fewer radioactive nuclei, the activity rate also decreases. From this we get the *exponential law of radioactive decay*. It tells us how the number of radioactive nuclei in a sample decreases with time. The *half-life* is the time that it takes for the material (and activity) to be reduced by half. For U235, we get a half-life of 704 million years.

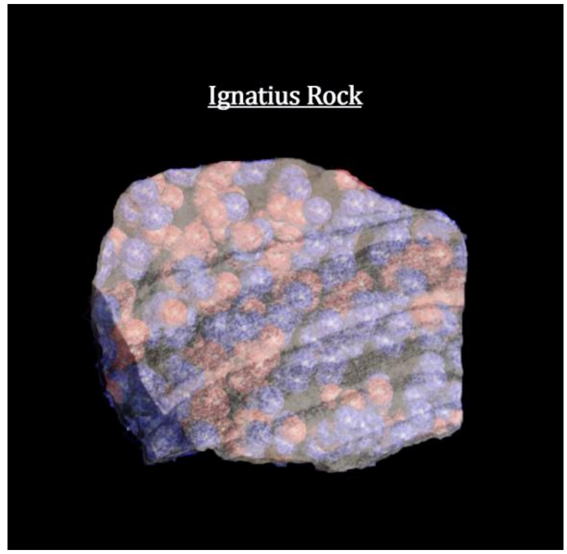


But the decay rate we need is not uranium to thorium, but the decay rate of uranium to lead. The two uranium to thorium decays we examined earlier become a pair of complex decay chains with some happening serially and some happening in parallel. But overall decay constants and half-lives have been measured and the fact that there are two paths gives us the opportunity to crosscheck when we find rocks with both types of uranium present.

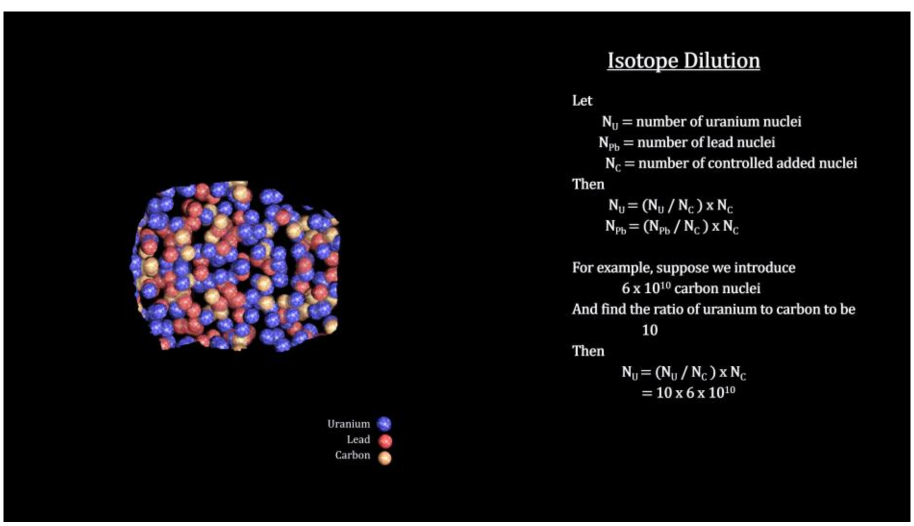


Isotope Dilution

We can use what we know about uranium decay to date rocks containing uranium. A significant complication arises when dealing with rocks compared to a controlled laboratory environment. In the lab, we controlled the number of atoms in a sample. But to accurately measure the number of atoms in a sample pulled from a rock taken from the curst of the Earth can be difficult.



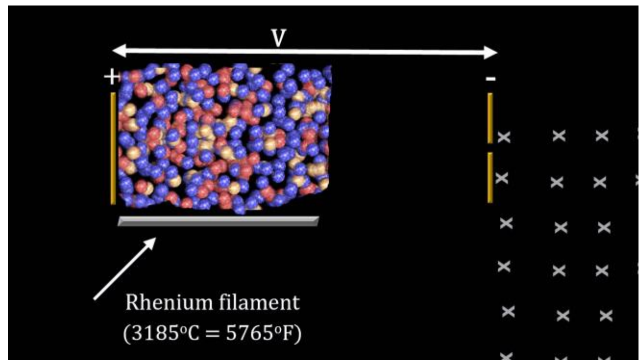
But there is a straight forward way to determine the number of atoms in a sample like this. All we need to do is add a measured amount of a different element; take a sample of the mixture; and measure the ratio of the sample to the additive or spike as it is sometimes called. This process is called isotope dilution. I've used carbon to illustrate the concept. In actual measurements, isotopes of uranium or lead not found in nature are used.



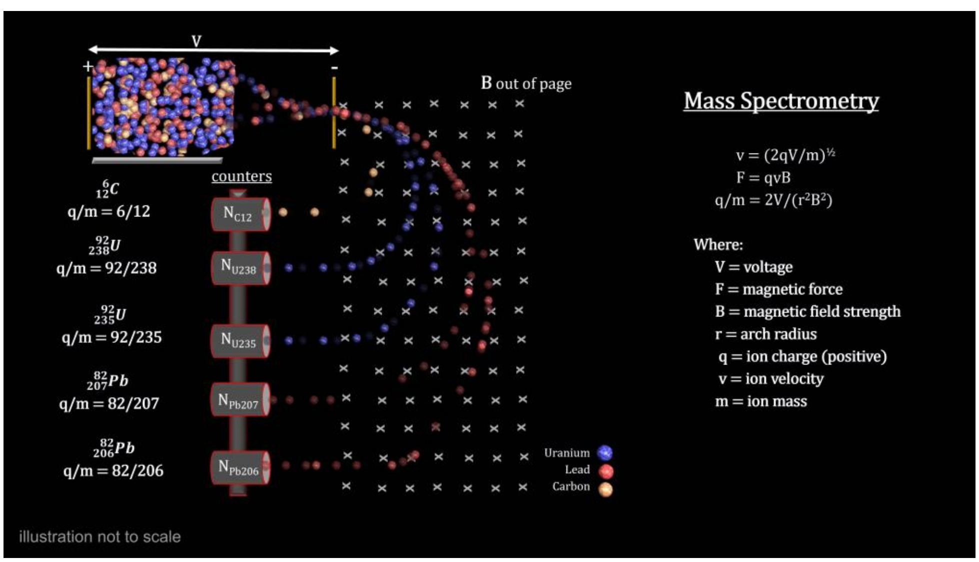
Mass Spectrometer

The actual measurement of the ratios is done with a mass spectrometer. Like a regular spectrometer breaks white light into its constituent parts, a mass spectrometer breaks a mixture of elements with different masses into sperate streams for counting. The first step is to take a small liquid sample (a nanogram up to microgram), and convert it into an ionized gas in a vacuum.

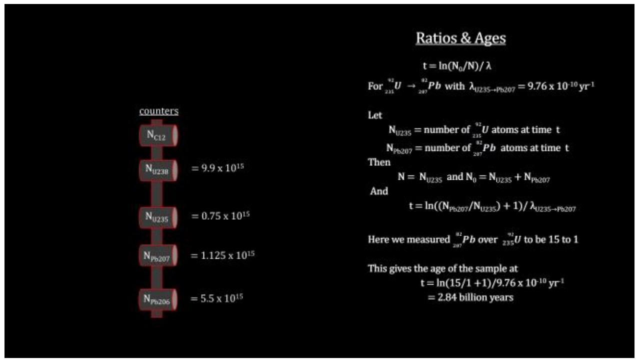
It's called Thermal Ionization. The sample is placed onto a filament which is then heated to very high temperatures. This simultaneously boils the liquid (desorbs it) and strips electrons from the sample making them positively charged. The best filament is rhenium, one of the rarest metals on Earth, because it holds on to its electrons at high temperatures. In this schematic, the electrons are attracted to the positive plate.



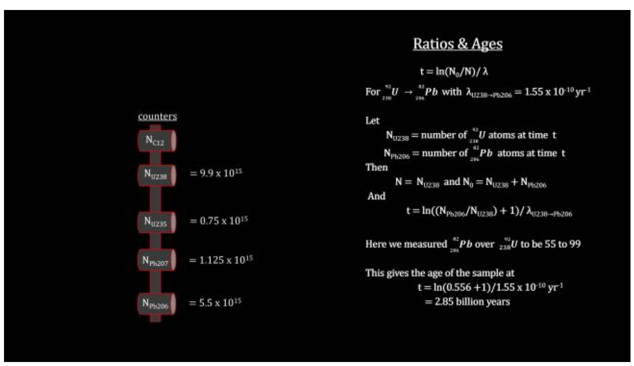
The remaining positively charged ions are attracted to the negative plate that has a small opening at its center. The ions then flow into a chamber containing a strong magnetic field. The ions will enter into circular curves according to their unique charge to mass ratios. **[**Remember that the charge will be the element's number (of protons), and its mass will be the mass of the protons plus neutrons.**]** This creates multiple streams with each stream containing the same ions. The mass spectrometer can run for hours capturing these streams and counting the numbers and producing the various ratios.



And as we have seen, these ratios give us the age of the rock. In our illustration, the counts for U235 and Pb207 came out at 15 to one lead over uranium. This produces an age calculation of 2.84 billion years.



The counts for U238 and Pb206 gave us a ratio of 55 to 99 lead over uranium. This produces an age calculation of 2.85 billion years. They are in agreement to within 0.35%. When they agree like this, you know you have a good measurement. This natural crosscheck gives geologists an extremely accurate dating method.

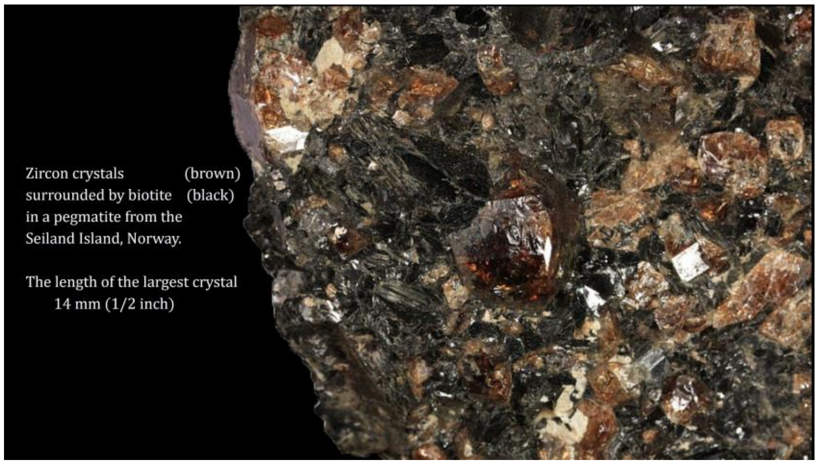


Dating Zircon

Calculating uranium to lead ratios in a lab is one thing. To do the same with a sample found in minerals in the Earth's crust is quite another. Uranium occurs naturally in low concentrations of a few parts per million in soil, rock, and water, all over the world. Over 150 uranium-bearing minerals have been identified out of about 5,400 minerals recognized by the International Mineralogical Association. Of all of these, Zircon is the most significant. Zircon crystals ($ZrSiO_4$) are the favorite mineral for U-Pb dating for several important reasons. First, its chemical structure is similar enough to Uranium to ensure that any adjacent uranium will be captured when the Zircon crystal forms. Second, lead is strongly excluded. Third, all lead created by Uranium decay will be trapped in the crystal. This gives us a clean sample where all the lead will have come from Uranium decay.

Forth, it traps uranium at a high temperature of 900°C (that's 1650ºF) early in the magma cooling phase. Fifth, it is physically very tough. This makes it resistant to geologic events. Sixth, it is very dense making it easily separated from crushed rock samples. And seventh, it is widespread in common igneous rocks formed by solidification of a molten magma.

A zircon mineral grain forms when it first cools from its liquid temperature to a solid – much like liquid water at its freezing point. This is called its trapping temperature because it traps elements like uranium and pushes out elements like lead. This makes it excellent for uranium dating purposes. It effectively sets the uranium-lead "clock" to zero. Lead atoms created by uranium decay are trapped in the crystal and build up in concentrations over time.



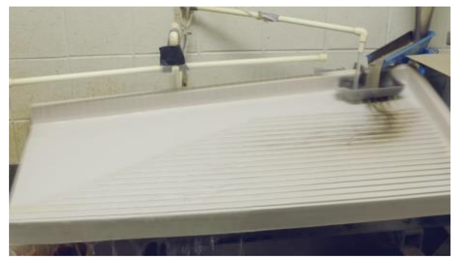
Producing high precision ratios of uranium to lead in a zircon crystal requires multiple steps including isotope-dilution, thermal ionization and mass spectrometry which we have just covered. And to start with, there is a procedure called 'Chemical Abrasion' to isolate the best zircon crystals in the rock. [The entire process is called Chemical Abrasion - Isotope Dilution - Thermal Ionization Mass Spectrometry or CA-ID-TIMS for short.]

Here's how the Memorial University of Newfoundland does it. First, of course, they find old looking rocks. The geology associated with this step is a science in its own right.

20 kg rock samples are typical. That's 44 pounds. Their first step is to wash and crush the rock into chip size pieces

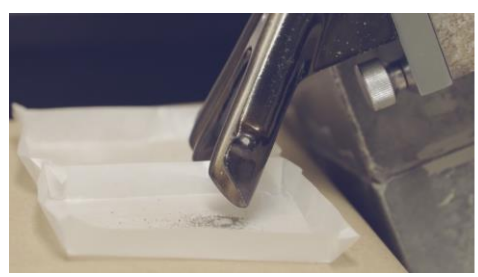
They pulverize the chips into a powder.

And pan the power to select only the densest particles. At this point, we're now down to around a few hundred grams of material. That's just 7 oz out of the original 44 pounds.



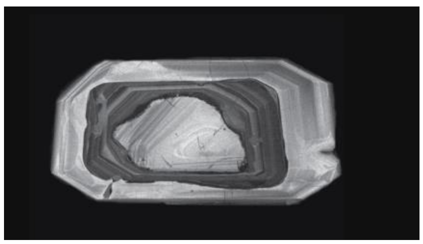
Then they further separate the minerals by density through a heavy liquid. The densest minerals will reach the bottom first. This takes advantage of zircon's extreme density over most other minerals. At this point, they have a few grams of zircon with a few other minerals.

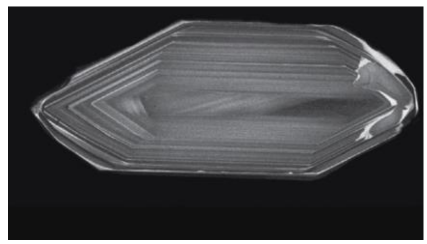
They then pass the remaining material through a magnetic field to separate out the grains with the most iron. At this point, they have a few milligrams of zircon with all other minerals removed.



Using jeweler's tweezers under a microscope, they manually select the very best 40 to 50 zircon crystals.

They put these under an electron microscope. This brings out the inner structure of each crystal. Some are damaged and discarded. Some are pristine and used.



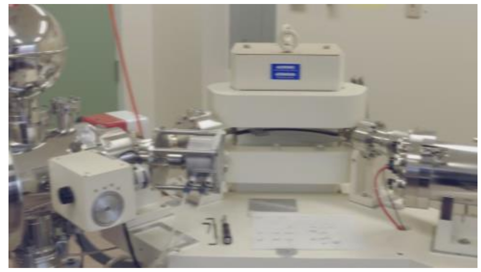


Each crystal is cleaned and put into a vial of hydrofluoric acid and baked for 3 days until dissolved. All the zircon molecular content is now in liquid form including silicon, zirconium, uranium and lead.

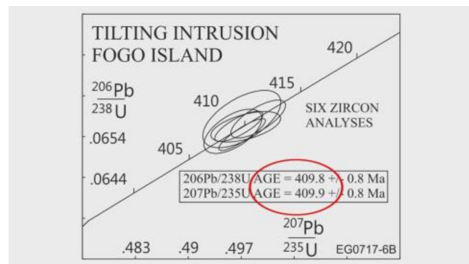
Then they use resins and acid washes to remove all the elements except uranium and lead. We're left with a single drop of water that contains all and only the uranium and lead in the original zircon crystal – usually around 10 to a 100 picograms. A picogram is a trillionth of a gram (10^{-12} grams).

The process they went through to get here is called Chemical Abrasion. The result is called the analyte – the substance to be analyzed. They then add a carefully measured amount of Pb205 to the analyte. This is the isotope-dilution step.

The analyte is then placed on the rhenium thermal ionization strip where it is rapidly converted from a drop of liquid to a gas at 1,500 C (that's 2700 F). In the process all the atoms have an electron stripped making them positively charged ions.



The now charged ions flow into the mass spectrometer. Over hours, the spectrometer reports the counts and ratios for each stream. These rations feed the equations that tell us the age of the rock they came from. This rock was 410 million years old.



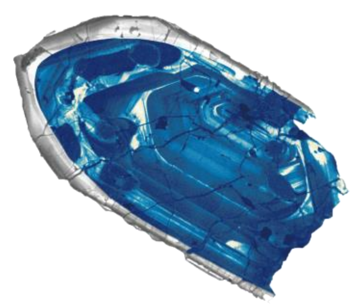
Oldest Earth and Moon Rocks

The oldest rocks on Earth come in three categories: 1) are the rocks that formed here when the magma from the great impact solidified; 2) the rocks we brought here from the moon; and 3) the rocks that landed here as meteorites. We'll cover the oldest rocks in each category.

The Jack Hills are a range of hills in Mid-West Western Australia about 800 kilometers (that's 500 mi) north of Perth. Zircons were found in sedimentary rocks indicating that they were sourced from pre-existing rocks which were then eroded by the weather. In January, 2001, Nature published an article on Curtin University's study of these Jack Hill zircon crystals. Using U-Pb zircon analyses, following standard operating techniques like the ones we just covered, they found the oldest solid Earth crust mater ever discovered at 4.356 billion years old. The Earth cannot be younger than this. [Note the close agreement between the two decay calculations. They are in complete concordance. This was approximately 90 million years older than the oldest known terrestrial material at that time.]

U-Pb isotopic analytical data

Spot	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{206}Pb/^{238}U$ age	$^{207}Pb/^{235}U$ age
36-1	0.965	71.9	4,356 Myr	4,355 Myr

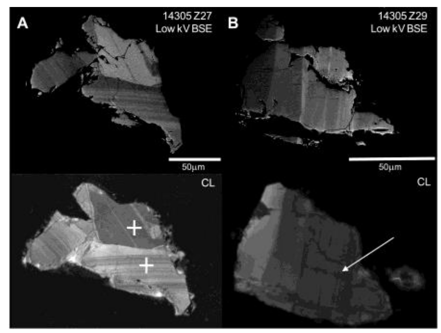


At the end of the first Apollo 14 EVA, a large soil sample was collected from the area near the lander. The bulk of the soil sample was scooped from a small crater. Sample 14163 was chosen as one of the reference soils for the lunar highland's suite.

Scientists used a chemical abrasion - isotope dilution - thermal ionization mass spectrometry analysis on zircon crystals in the sample like the process we used for our Earth rock sample. The oldest crystal (identified as z59), was found to be 4.3 billion years old. This is quite close to the oldest earth rock, indicting that they formed at the same time. We previously established via oxygen isotope ratios that they formed at the same place. These two findings constitute significant support for the Giant Impact hypothesis.

U-Pb isotopic analytical data

Sample	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{206}Pb/^{238}U$ age	$^{207}Pb/^{235}U$ age
14163 z59	0.954	70.12	4,319 Myr	4,330 Myr



But the Giant Impact idea remains a hypothesis. Dating methods are evolving. Different dating methods indicate different ages for moon rocks. The search for rocks on Earth continues. Another trip to the moon could change our view completely. But for now (in early 2020), the general scientific consensus is that the current version of the Earth is at least 4.3 billion years old and the Moon is close to the same age. This is interesting, but it does not tell us how long ago the earlier version of the Earth formed. For that, we need to date rocks that formed beyond the Earth. Rocks that never went through a melt and rehardening process like all the rocks on Earth and the Moon. For this, we need to examine meteorites.

Greek letters:

- α β γ δ ε ζ η θ ι κ λ μ ν ξ ο π ρ σ τ υ φ χ ψ ω
- Α Β Γ Δ Ε Ζ Η Θ Ι Κ Λ Μ Ν Ξ Ο Π Ρ Σ Τ Υ Φ Χ Ψ Ω

⇒ → ± ⊙ ∞ ↛ ∃ ∄ ∈ ∉ ∬ ∫ ≅ ≥ ≤ ≈ ≠ ≡ √ ∛ ~ ∝ ħ ÷