

## The Physics of Carbon 14

Last time, we saw that in certain circumstances, astronomical, archaeological and historical data can combine to yield powerful constraints on when certain events happened. However, these situations are very rare, and for more down-to-earth objects and events, age measurements must be made in some other way. Carbon-14 is one of the most famous and powerful methods for dating objects from human history and pre-history. Carbon-14 dating is also a good example of radiometric dating methods that we will encounter throughout these lectures. Therefore, we have two lectures dedicated to the subject. This lecture focuses on the physics and the principles behind Carbon-14 dating, while the next lecture will discuss what happens when this method is used in practice.

### 1 The General Idea

Carbon-14 dating was developed in the late 1940's by Willard F. Libby here at the University of Chicago (He won the Nobel Prize for this work in 1960). The basic concept is illustrated in figure 1. Carbon-14 is a heavy, unstable form of carbon, which decays (transforms into nitrogen) on a timescale of thousands of years. Carbon-14 is constantly being produced by cosmic rays colliding with air molecules in the atmosphere. From there, it enters the carbon cycle, where it is absorbed into the tissues of living creatures. Since living creatures constantly exchange carbon with the atmosphere (animals exhale carbon dioxide into the atmosphere and plants absorb carbon dioxide from the atmosphere via photosynthesis) they have about the same fraction of carbon in the form of Carbon-14 in their bodies as the atmosphere does.

After the organism dies, it no longer exchanges carbon with the atmosphere. Thus the unstable Carbon-14 in the material decays while no new carbon is absorbed to replace it. Therefore, the less Carbon-14 the material contains the older it is

### 2 Nuclear clocks

Carbon-14 dating is the most famous form of **radiometric dating**. All radiometric dating methods use the transformation/decay of the nuclei of particular atoms to measure age. As we will encounter several other radiometric methods in the course of these lectures, we will spend some time here covering the basic principles of nuclear decay.

#### 2.1 Definitions

The **nucleus** is the tiny core of an atom, where the positively charged **protons** and the neutral **neutrons** are found, and where most of the mass of the atom resides.

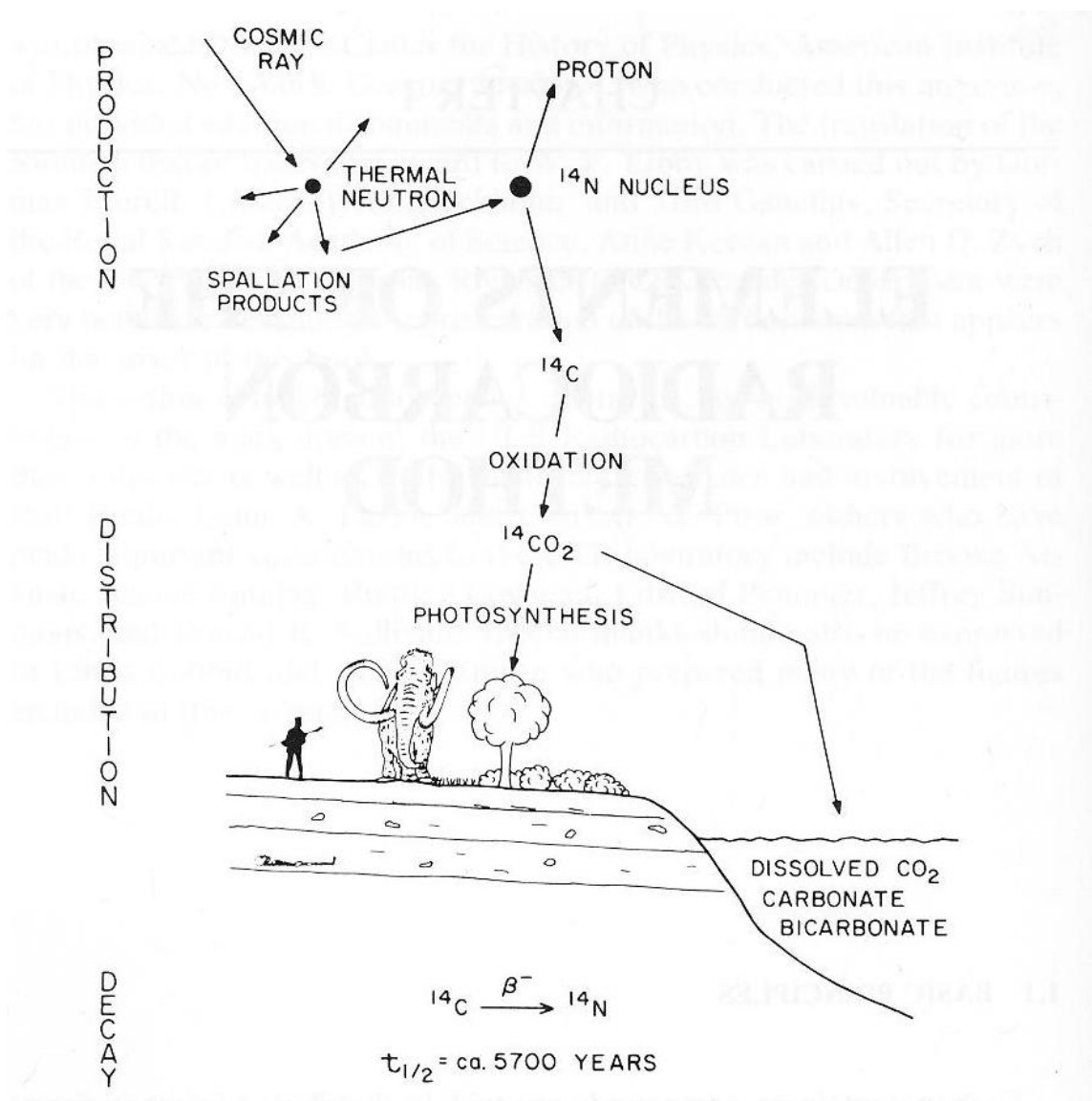


Figure 1: A summary of how Carbon-14 dating works, drawing from *Radiocarbon Dating* by Taylor.

Negatively charged **electrons** exist in a relatively dispersed cloud surrounding this nucleus. The number of electrons (usually) equals the number of protons and determines how the atom interacts with other atoms. Atoms with the same numbers of protons therefore have the same chemistry and are identified as the same **element**. Atoms with the same number of protons can differ in how many neutrons they contain. Since neutrons are neutral, they do not affect the chemistry of the atom but they do affect its mass. Atoms with the same number of protons but different numbers of neutrons are called different **isotopes** of the same element. For example, most carbon has 6 protons and 6 neutrons and is stable, while Carbon-14 is an isotope with 6 protons and 8 neutrons (the number 14 in the name refers to the total number of protons and neutrons in the nucleus) and is unstable.

## 2.2 $E = mc^2$ and the Nucleus

The forces holding the protons and neutrons together in the nucleus are rather curious. These forces must be strong enough to hold the positively charged protons together (remember, like charges repel). However, these forces must also operate only over a very short range, because they do not affect the interactions between atoms. The details of how these forces operate are very complicated and tricky to calculate. Fortunately, we can understand a lot about nuclear stability and decay without going into these details.

The famous equation  $E = mc^2$  provides a good starting point. The factor of  $c^2$  in this equation is just a constant number, so the critical part of this equation is that it identifies the mass  $m$  of an object with an energy  $E$ .

To understand the importance of this statement, realize what mass and energy mean in physics. **Mass** is a quantity intrinsic to an object that determines how it responds to forces. Give the same push, an object with less mass will move away more quickly than an object with more mass.

**Energy**, on the other hand is not necessarily intrinsic to an object. Energy can change form and can be transferred from one system to another. The central feature of energy is that it is conserved, which means it can neither be created nor destroyed, indeed, this is the basis of the definition of energy in physics. One, obvious form of energy is kinetic energy, or the energy of motion (the faster something moves the more kinetic energy it has). Since energy can change form, all other forms of energy can be interpreted as the potential to create motion in objects.

$E = mc^2$  states that an object with a certain mass must also have a certain energy (independent of any energy it has due to motion, etc.). This fact allows us to determine whether a nucleus is stable or not by comparing its mass to the mass of its component parts. For example, an ordinary carbon nucleus has 6 protons and 6 neutrons. However, the mass of the nucleus is about 1% smaller than the total mass of the 12 individual particles. The nucleus therefore has **less** energy than its component parts, and we would have to supply energy to the nucleus in order to pull it apart. The nucleus therefore cannot change into 12 isolated particles. on its own. On the other hand, if the nucleus could change in some way that the material left over after the transformation had less mass than the original nucleus, then no energy needs to be supplied to the system, and the nucleus could transform on its own.

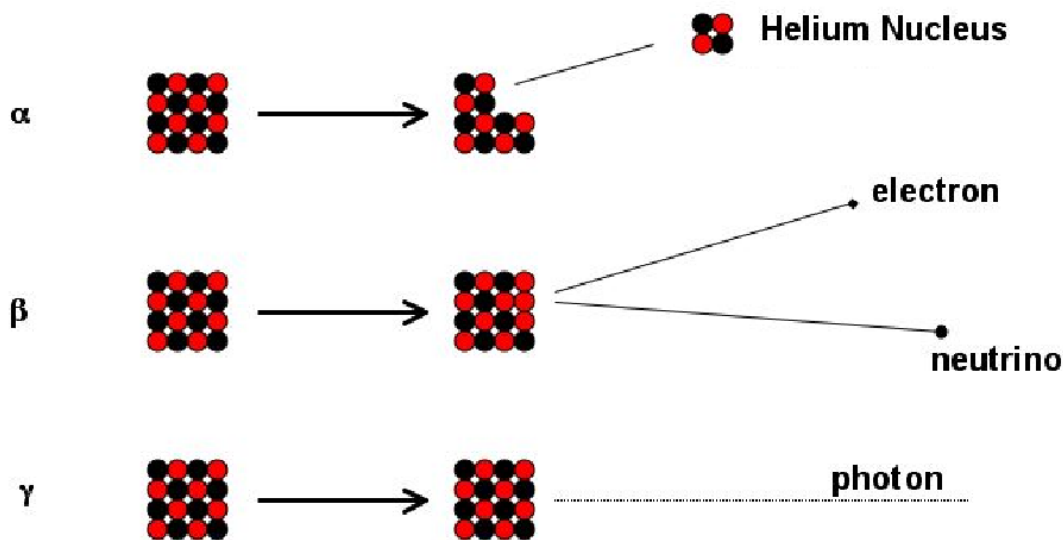


Figure 2: The three types of nuclear decay. On the left, we have nuclei, made up of protons (red/gray circles) and neutrons (black circles). These nuclei decay in different ways. At top we have alpha-decay, where the nucleus breaks into two pieces. In the middle we have beta-decay, where a neutron turns into a proton and emits an electron and a neutrino. At the bottom we have gamma decay, where the nucleus emits a photon. Carbon-14 undergoes beta-decay.

In practice, there are only three ways a nucleus can possibly change, (other transformations are not allowed because of various rules, such as that the total number of protons+neutrons cannot change) these are illustrated in figure 2 and are:

- **Alpha-decay**, where the nucleus splits into two parts (one part consisting of two protons and two neutrons).
- **Beta decay**, where a neutron in the nucleus converts into a proton, emitting an electron and a neutrino (various permutations on this process are also possible).
- **Gamma decay**, where the nucleus emits a photon.

Carbon-14 can decay because one of the above transformations results in a reduction in mass. A Carbon-14 nucleus contains 6 protons and 8 neutrons. The common isotope of nitrogen has 7 protons and 7 neutrons. Carbon-14 can therefore transform into nitrogen through a beta decay. Furthermore, nitrogen is slightly less massive than Carbon-14 (by about one part in 100,000), so no energy needs to be supplied to the nucleus for the transformation to happen. Therefore, Carbon-14 can and does decay into nitrogen spontaneously.

### 2.3 The Uncertain timing of a Half Life

What makes the decay of Carbon-14 and other unstable nuclei useful for measuring age is that these transformations have a characteristic timescale, known as the **half life**, which for Carbon-14 is about 5700 years. Say we have a sample of pure Carbon-14. After 5700 years (one half-life), half of the Carbon 14 atoms will have decayed

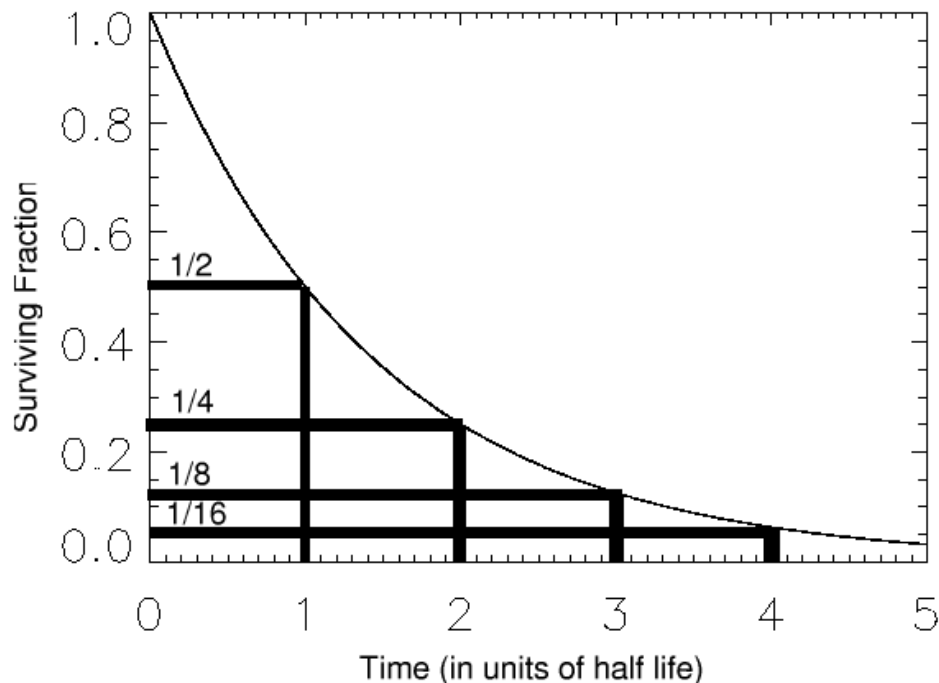


Figure 3: Half-life. Here we plot the fraction of undecayed material as a function of time, measured in units of half-life. After one half-life, half of the material has decayed. After another half-life, half of the remaining half has decayed, leaving one-quarter behind, and so on.

into nitrogen. After another 5700 years, half of the remaining half will have decayed, and so on and so forth. This simple and regular behavior, illustrated in figure 3 is clearly useful. However, this simplicity also hides a fundamental strangeness.

Consider a single atom of Carbon 14, it has a 1 in 2 chance of decaying into nitrogen in the next 5700 years. If it lasts that long, then it has a 1 in 2 chance of decaying in the following 5700 years, and so on. This means a Carbon-14 atom which has managed to survive for thousands of years and a Carbon-14 atom created yesterday are equally likely to decay in the next 5700 years. Therefore, the time at which any given atom of Carbon 14 decays is in some sense unpredictable.

What makes this unpredictability particularly odd is that the probability of an atom decaying has a half-life. To better understand why this is so strange, consider a more down-to-earth example of a system with a “half life”, illustrated in figure 4. Imagine we have a chamber filled with water, which has a narrow nozzle at the bottom. The total weight of water in the chamber pushes water through the nozzle, causing water to spew out of it at a fast rate. As the level of water in the chamber falls, there is less pressure on material in the nozzle, and the flow of water out of the tank slows.

Say the chamber starts out filled with one liter of water, and after one second half a liter of water has leaked out of the chamber through the nozzle. The chamber is therefore half full after one second. Since the amount of water in the chamber has

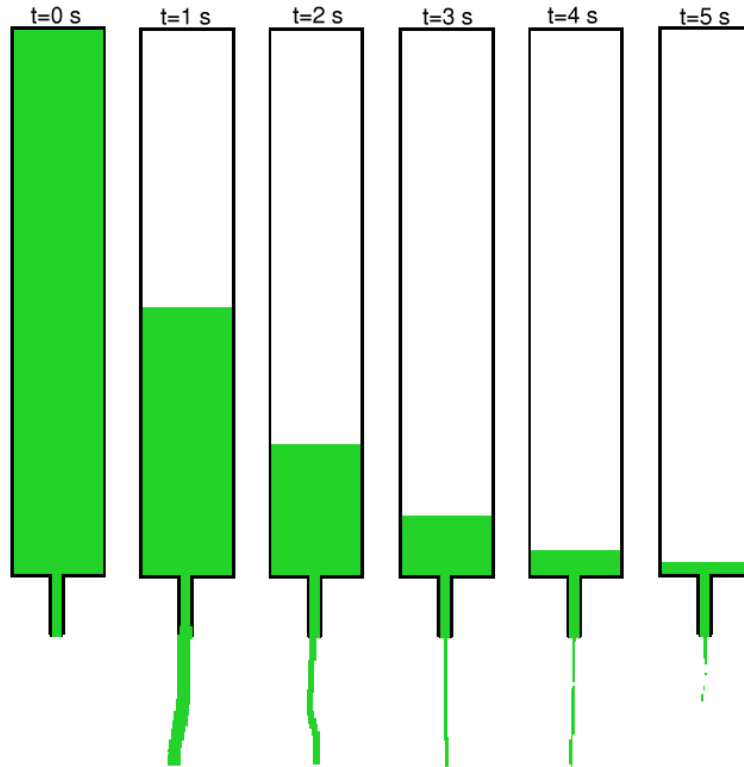


Figure 4: A system in classical physics with a half-life. This series of images shows a tank of water at a series of equally spaced times. Water in the tank is pushed out through a nozzle by the weight of material in the tank. Initially, the flow rate is high, but as the amount of material in the tank drops, the flow slows. The images show the amount of water left in the tank has a half-life (compare with figure 3)

been cut in half, the pressure forcing water through the nozzle is cut in half, and so the leak rate is also be half what it was when the chamber was full. Thus the amount of water leaving the chamber in the next second is half that of the previous second, that is  $1/4$  of a liter. This leaves  $1/4$  of a liter in the chamber, or half the volume that was present in the previous second. As this process continues, the amount of water in the chamber is cut in half every second. The volume of water in the chamber therefore has a “half life” of one second.

It is not too hard to think up other systems that have “half life”-like behavior. All you need is a system where how fast a parameter changes is proportional to the parameter itself (in the above example, the rate at which water leaks out of the tank is proportional to the amount of water in the tank). However, it is difficult to imagine a Carbon-14 nucleus behaving this way. A nucleus can be in only one of two states, either the nucleus has decayed or it has not decayed (it is either still Carbon 14 or it is nitrogen). There is no such thing as a partially decayed nucleus. We therefore cannot imagine the Carbon-14 gradually transforming into Nitrogen like the water gradually leaks out of the container. The transformation happens all at once, producing a “click” on a Geiger counter. However, it does appear that the **probability** that the decay happens behaves like the water flowing out of the container. This is a great example of the weirdness of quantum mechanics.

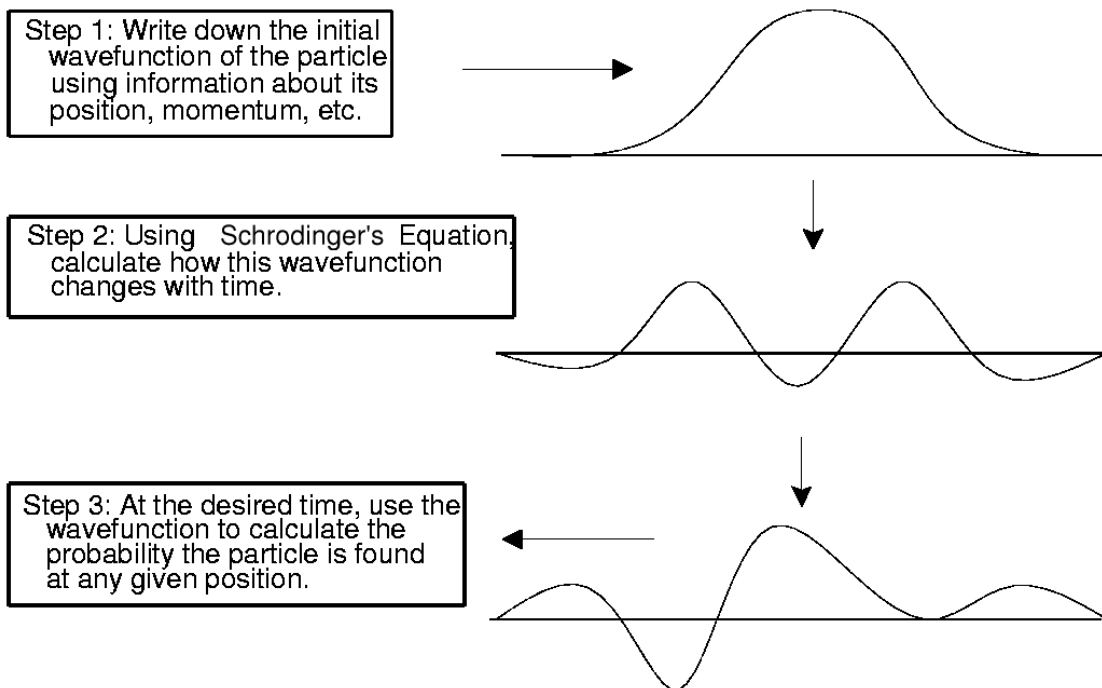


Figure 5: The usual procedure for quantum mechanical problems. A similar procedure can be used to calculate how probable it is for a Carbon-14 nucleus to have decayed after a fixed amount of time.

Quantum mechanics has a reputation for being a weird theory, but really it is a perfectly reasonable way to solve many physics problems. For example, say we have a particle at some position at some initial time, and we want to know where it will be 10 seconds later. Quantum mechanics tells us exactly how to solve this problem. First, based on the initial position, momentum etc. of the particle, we calculate something called a **wavefunction**. The wavefunction describes the probability the particle is at any given point. We have equations that tell us exactly how this wavefunction changes at time, so we can calculate what the wavefunction is after 10 seconds. This final wavefunction then gives us the probability that the particle is found at any given position (or moving in any given direction, etc.) Although we may not like that this method gives us probabilities and not a unique answer, following this procedure yield results that match experiments, so it is a perfectly good physical theory. (By analogy, we may not like Newton's laws, but that doesn't stop us from accepting and using them.)

In a similar way, quantum physics calculations can tell us the probability the an atom of Carbon 14 will decay in 1 year, 100 years, 1000 years or a million years. The way the relevant wavefunction changes with time gives rise to the observed half-life. Again, the procedure poses no real problems.

Now say instead of just coming back at a specific time and seeing if the nucleus has

decayed, we actually hang around watch the nucleus. At some time, the thing decays and causes a “click” on a Geiger counter. Obviously, something different happens at this time, since from then on, we know for sure the nucleus has decayed. But what exactly happened is not at all clear. Somehow, the steady, predictable evolution in the wavefunction collapses into some discrete event. The probability that this transition occurs is controlled by the wavefunction, but it happens at different times for different nuclei. Physicists still have trouble understanding exactly how and why this transition occurs. Indeed, this transition is responsible for most, if not all of the apparent “weirdness” of quantum mechanics (such as Schrodinger’s infamous Cat) . We cannot get into the details of these paradoxes here (they could form an entire lecture series in and of themselves), since we have to get back to the practical question of how to use Carbon-14 as a clock.

### 3 Measuring Age with Carbon-14

In addition to the half-life of Carbon-14, we need two pieces of information to calculate the age of some object: (1) How much Carbon-14 the object had to start with, and (2) How much Carbon-14 the object has now. Given these two numbers, we can calculate what fraction of the original Carbon-14 is left in the object. Then it is straightforward to determine how old the object is. For example, say an object originally contained 2 grams of Carbon-14 and now contains only 1 gram. The fraction of the original Carbon-14 remaining in the object is then  $1/2$ , so the object is one half-life, or about 5700 years, old.

In practice, the quantity that is measured is not the total amount of Carbon-14 in the object, since that depends on the size of the sample. What is instead measured is the **fraction** of carbon atoms in the object that are Carbon-14. Thus, we need to know the original and current Carbon-14 fractions to calculate the age of the object.

#### 3.1 How much Carbon-14 was in the object originally?

Without a time machine, one cannot directly measure the original Carbon-14 content of an object. However, based on how Carbon-14 is produced and absorbed into objects, it is reasonable to suggest that all living things had roughly the same fraction of their carbon atoms in the form of Carbon-14.

Until quite recently, most of Carbon-14 on earth was originally created by cosmic rays (since 1950, the Carbon-14 generated by nuclear weapons testing must be taken into account, but this need not concern us here). Cosmic rays are bare atomic nuclei (i.e. atoms without electrons) that fly through the universe at extremely high speeds, many approaching the speed of light.

The source of cosmic rays is still somewhat uncertain. Most of them certainly come from outside our solar system, however, it is difficult to be more specific than this. The problem is that the cosmic ray nuclei are charged particles, and there are magnetic fields in space. Just as an electro-magnet can be made by running a current through a coil of wire, moving charged particles (like electrons in a wire) are deflected as they move through magnetic fields (see Figure 6). Therefore, cosmic ray nuclei do not move on straight lines, but instead take complicated twisting paths between



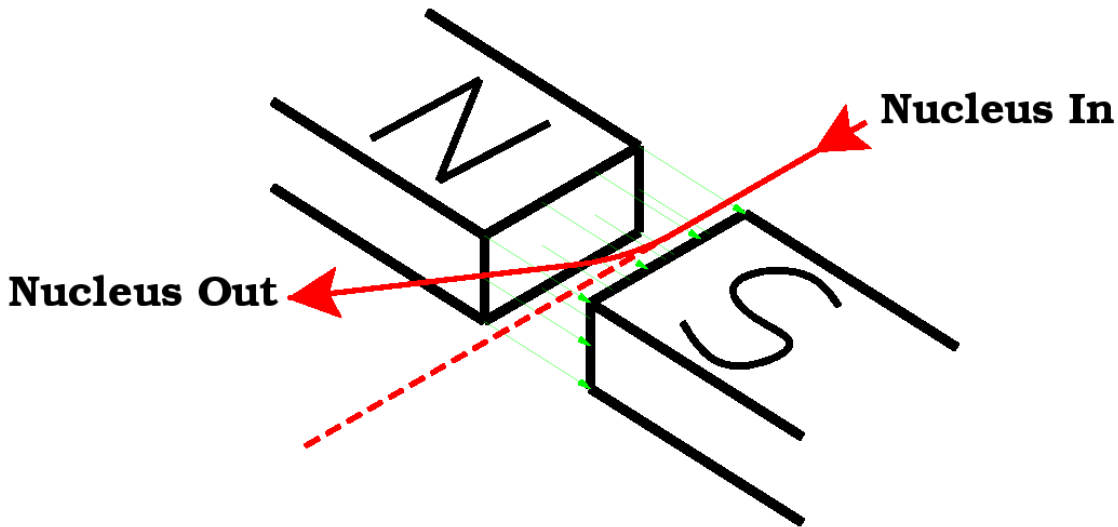


Figure 6: When a charged particle like a nucleus passes through a magnetic field, it is deflected. Magnetic fields in the galaxy similarly cause cosmic rays to move in complicated curving paths through space.

their source and earth, which makes it very difficult to reconstruct exactly where they originally came from.

When these particles do reach earth, they collide with atoms in our atmosphere. During these collisions, the huge kinetic energy of the cosmic ray is more than enough to break both colliding nuclei into their component parts. This energy is even sufficient to generate exotic subatomic particles. If the cosmic rays are traveling fast enough, the debris from this collision can contain enough kinetic energy to produce additional violent collisions, producing a shower of nuclei and subatomic particles.

Of particular interest here is that the debris of these collisions includes free neutrons. These neutrons rattle around in the atmosphere for a while and eventually they usually get stuck in the nucleus of a nitrogen atom (remember, our atmosphere is mostly composed of nitrogen). This happens relatively easily since the neutron does not have a charge, so it can get close to a nucleus without any trouble (unlike a proton, which would be repelled by the nucleus' positive charge). After capturing the neutron, the resulting nucleus has seven neutrons and eight protons. This perturbed nucleus is extremely unstable and quickly spews out the proton, leaving behind an atom of Carbon-14. (Note that the time between the absorption of the neutron and the expulsion of the proton is very short, this is therefore understood as a nuclear

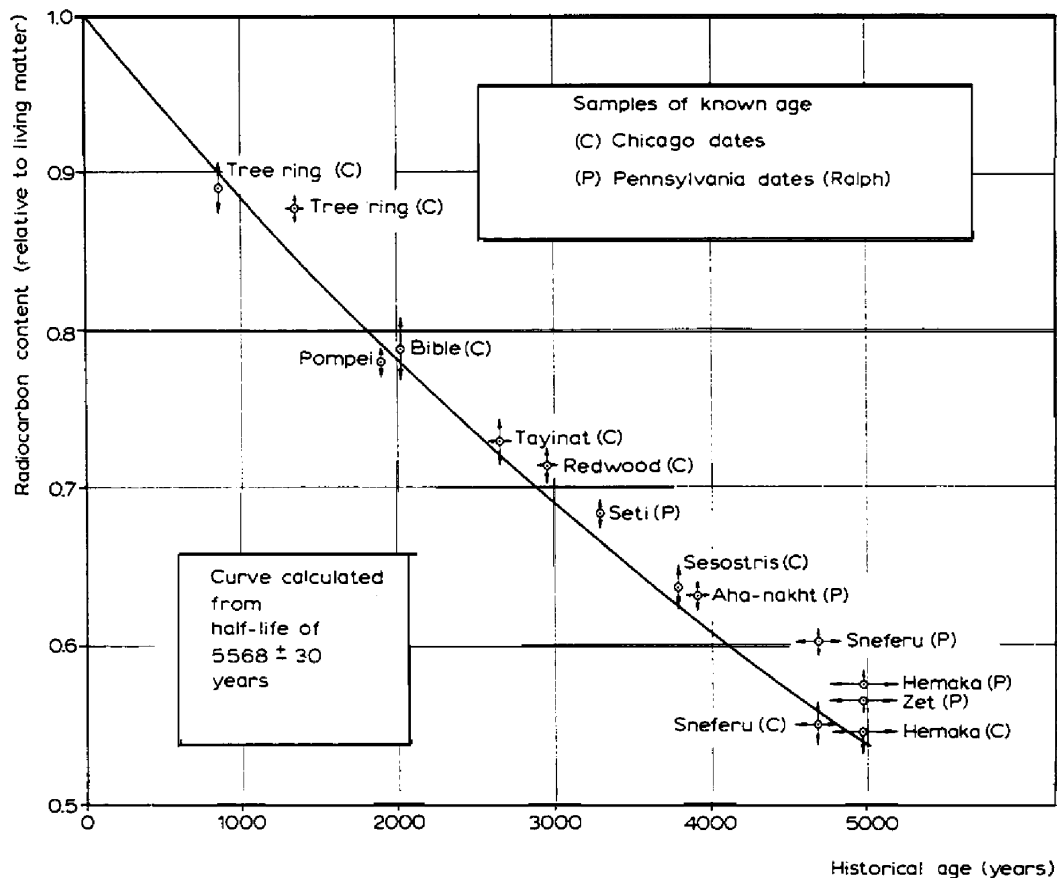


Figure 7: Libby's original "curve of knowns", which shows that older objects have less Carbon-14 activity, as expected. (Taken from Libby's Nobel Prize Lecture in 1960).

reaction, not a nuclear decay).

This Carbon-14 atom attaches itself to some oxygen atoms to form carbon dioxide. It then enters the carbon cycle, where it is absorbed into the tissues of living creatures. Since chemically Carbon-14 behaves like any other isotope of carbon, the fraction of carbon that is Carbon-14 in any organism should equal the fraction of carbon that is Carbon-14 in the atmosphere when the organism was alive.

Assuming the cosmic-ray flux on earth has been constant, we expect that all living things will have the same fraction of their carbon in the form of Carbon-14. This assumption is not unreasonable, but we still want to check that it is true. This will be the subject of the next lecture.

### 3.2 How much Carbon-14 is there in the object today?

In principle the present Carbon-14 content of an object is a straightforward measurement. However, the amount of Carbon-14 in living organisms is very small. There is only one part Carbon-14 for a trillion parts carbon. The measurement is therefore quite challenging.

The basic goal is to measure the fraction of carbon in the object that is Carbon-14.

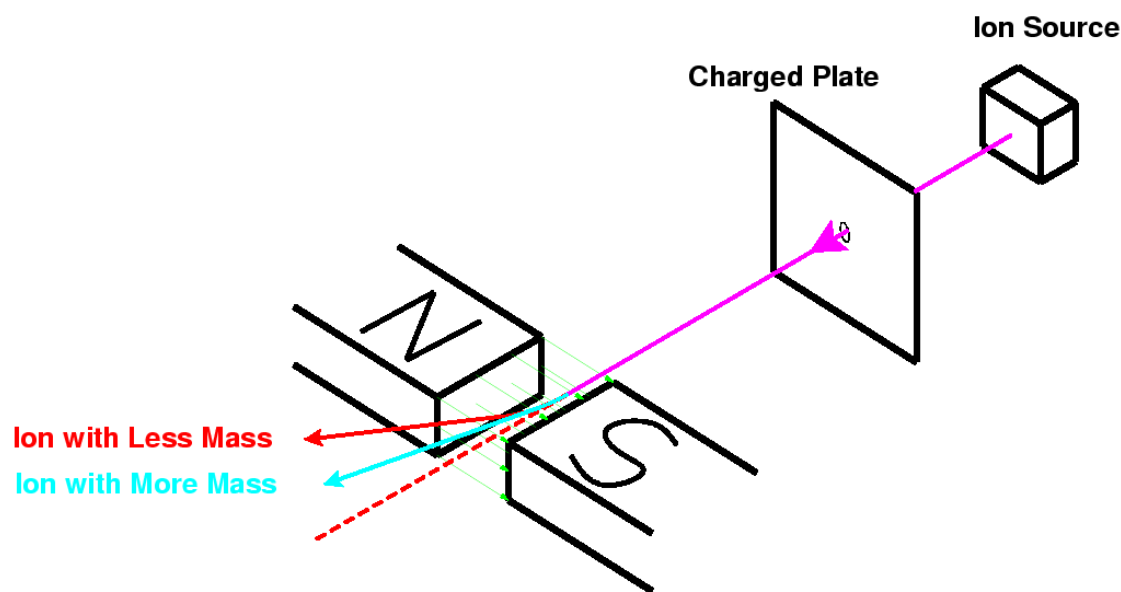


Figure 8: The basic idea of mass spectrometry. Ions generated from the sample are accelerated by being attracted to a charge plate. A hole in this plate lets the ions through to a magnet. This magnet deflects the ions, but more massive ions are deflected less, so the different mass ions can be isolated.

The carbon can be extracted from the material using a variety of chemical techniques. Isolating the Carbon-14, however, is a different matter. Carbon-14 has nearly the same chemical properties as the other carbon isotopes, so it cannot be easily isolated by chemical means. The measurement of the Carbon-14 fraction therefore must rely on the unique **physical** properties of this isotope: its larger mass and its radioactivity.

The original method of measuring the Carbon-14 fraction used by Libby relied on the radioactivity of these unstable nuclei. Each time an atom of Carbon-14 decays, it emits an electron, which can be detected with a Geiger counter. With this method, he was able to measure the current Carbon-14 content of a variety of objects of known age, as shown in figure 7. These data demonstrated that the Carbon-14 fraction in objects did in fact decrease with the age of the object, verifying that the original Carbon-14 content of living things was roughly constant in time.

The primary limitation to this method is that Carbon-14 decays very slowly. In one year, only 0.01% of the Carbon-14 atoms in a sample decays. So if we needed 1000 decays to estimate how much Carbon-14 is in the sample, and we were willing to wait a year to get the number, we would need 10 million Carbon-14 atoms in the sample. This method is therefore rather inefficient, and requires relatively large (1 gram) amounts of carbon to work.

Nowadays, small samples of material can be dated using **mass spectrometry**, which uses electric and magnetic fields to sort atoms by mass (see figure 8). First, individual atoms are released from the sample and ionized by adding or removing electrons from each atom. These atoms have a net charge, so they are attracted toward metal plates with an opposite charge. The atoms move faster and faster as they approach the metal plates. A hole in the plates lets the atoms go through to the

other side. They then enter an electromagnet. Just like cosmic rays are deflected by interstellar magnetic fields, this magnet exerts forces on the atoms. The mass of the atom then determines how much the atom responds to these forces. Therefore atoms with different masses take different trajectories through the magnetic fields. These atoms can then be isolated and counted separately.

Since the Carbon-14 fraction is extremely small, a special form of mass spectrometry is required, called an **accelerator mass spectrometry** or AMS. This technique uses multiple stages of acceleration and ionization, as well as several magnets to cleanly separate the Carbon-14 from all other possible atoms and molecules. This means the spectrometers used for Carbon-14 measurements are large beasts that exist only in specialized facilities.

The big advantage of AMS Carbon-14 dating is that all Carbon-14 atoms in a sample are counted, not just the ones that happen to decay. This method can be used with sample sizes as small as one 1 milligram. This means that many objects can be Carbon-14 dated without doing too much damage, and that even objects with small amounts of carbon (like steel tools) can potentially be dated with Carbon-14.

Carbon-14 is indeed a powerful tool for measuring the age of things, largely because it is based on a rather straightforward physics. However, as we will see in the next lecture, to obtain accurate age measurements from Carbon-14, we cannot rely on physics alone. Biology, archaeology and geology must be taken into consideration.

## 4 References

For a general overview of Carbon-14 dating, including a short history of Libby's work, see

- R.E. Taylor *Radiometric Dating* (Academic Press 1987)

For a historical introduction to nuclear physics, try

- G.I. Brown *Invisible Rays* (Sutton Publishing 2002)

For a popular introduction to Quantum Mechanics, I can recommend:

- John Gribbin *In Search of Schrodinger's Cat* (Bantam 1984)

For those intrepid folks wanting to know how to actually solve Quantum Mechanics Problems at college level, I recommend:

- D.J. Griffiths *Introduction to Quantum Mechanics* (Prentice Hall 1995)

A history of Accelerator Mass Spectrometry can be found

- H.E. Gove *From Hiroshima to the Iceman* (Institute of Physics 1999)

For more detail about Mass Spectrometry than anyone would ever want, see

- Claudio Tuniz et. al. *Accelerator Mass Spectrometry* (CRC 1998)