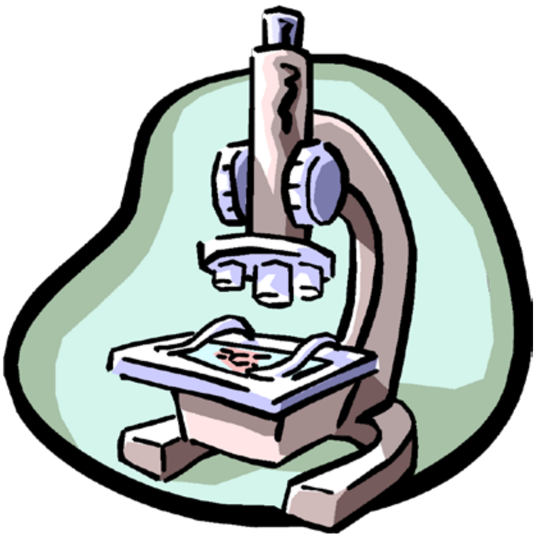
The *Scientists* and *Technologies*

Behind the Scene

By Lala Fujita and Jason Yang



Contents

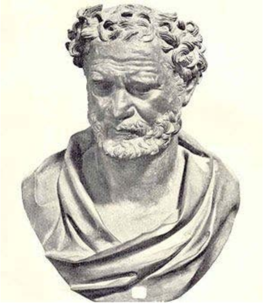
Case 0: A Brief Overview

Science textbooks nowadays tend to present scientific discoveries as given facts that scientists can easily look up in a series of almighty Encyclopedia of Sciences (similar to the one shown in **Figure 0-1**). However, textbooks that promote the omission of “the human side of science” inevitably create an illusion that all scientific knowledge came from the middle of nowhere. Not only is this a very inaccurate depiction of how scientific researches were done, it also gives out an impression that science is completely irrelevant to our everyday lives.

Figure 0-1: The Encyclopedia of Science & Technology published by McGraw Hill.

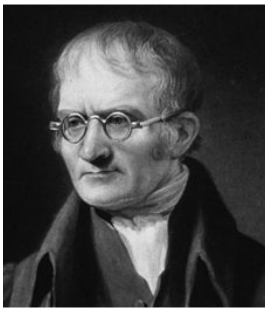
To better illustrate the procedures of scientific researches, as well as to honour the contributing scientists, you will be presented with 6 case studies that investigate the background stories of several physical, biological, and chemical discoveries in this study guide. All case studies here were chosen from milestone topics that will be discussed in Physics 11 – 12, Chemistry 11 – 12, and Biology 11 – 12. Should any of these case studies spark your interest in pursuing deeper study in their corresponding fields, feel free to discuss with your teacher or counsellor for more details about how to register to these courses.

In addition to the scientists behind the scenes, this study guide will also put emphasis on the importance of technological support behind each case study. This may come as a surprising statement to you, but there is a fine line between scientists and philosophers. In fact, the only thing that distinguishes a scientific theory from a philosophical claim is the scientific evidence obtained from a reproducible experiment. However, many of these experiments would not have been possible without the support from appropriate technology.


Democritus
(460 – 370 BC)


Antoine de Lavoisier
(1743 – 1794)


Joseph Louis Proust
(1754 – 1826)


John Dalton
(1766 – 1844)

For example, around the fifth century BC, Greek philosopher Democritus proposed that all matters are composed of small indivisible particles call atomos. Due to the lack of technological support, Democritus' claim was not based on any experimental data, and his claim was not very well accepted by the scholars back then because of it.

More than 2,000 years later, John Dalton proposed the very first scientific theory about atoms in 1803. Dalton was only able to develop his atomic theory after he studied the works of Antoine Lavoisier and Joseph Proust on the chemical compositions of tin oxides, which would not have been possible without the technology that supports chemical composition analysis. Based on the experimental data collected by Lavoisier and Proust, Dalton proposed that each chemical element consists of a single type of atom that could not be destroyed by any means. Dalton's publication of atomic theory marked the beginning of the scientific atomic theory.

Thus, a dedicated section on the insights of technological supports behind each case study will also be included to help you better appreciate all the behind the scenes stories of scientific discoveries.

Useful Links

John Dalton and Atomic Theory
https://courses.lumenlearning.com/introchem/chapter/john-dalton-and-atomic-theory/

Case 1: Compound Microscope (1595)

Relevant Topics

Biology 11 – Cell Theory

Physics 11 – Light and Geometric Optics

Zacharias Janssen
(1585-1632)

Robert Hooke
(1635-1703)

Matthias Schleiden
(1804-1881)

Theodor Schwann
(1810-1882)

In the cell theory unit of biological science, we learn that all living being on Earth is comprised of cells. Although this is considered a foundational knowledge today, scientists did not always know about cells. For thousands of years, the smallest thing human beings could see was about the thickness of a hair. In the year of 1595, Zacharias Janssen, possibly with the help of his father Hans Janssen since he was only a teenager back then, invented the first compound microscope (see Figure **1-1**).

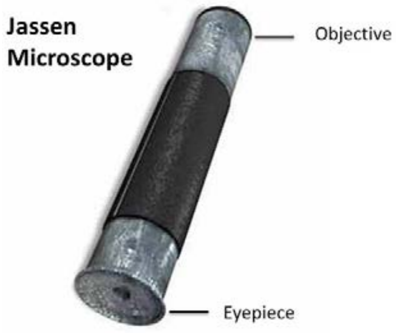


Figure 1-1: The first hand-held compound microscope by Hans and Zacharias Janssen

The Janssen microscope was capable of magnifying an object to approximately 3 times of its original size when the two lenses are properly aligned. Janssen's prototype microscope opened the door to microscopy, in which more and more scientists started exploring the formerly unknown and invisible world in the microscopic level.

Technological Insight

When an object is held between a convex lens and its focal point (F), an upright enlarged image of the object will be seen by the observer (see the left diagram in **Figure 1-2**). On the other hand, when an object is held between a convex lens' focal point (F) and twice its focal point (2F), an upside-down enlarged image of the object will be seen by the observer (see the right diagram in **Figure 1-2**)

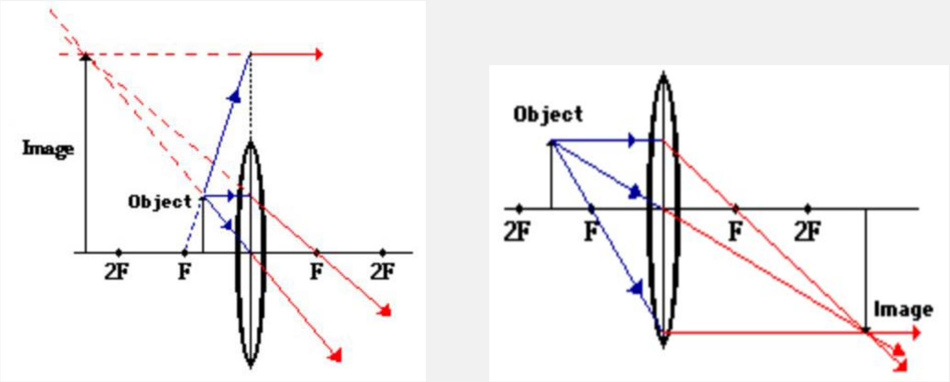


Figure 1-2: Ray diagram of convex lens

When two pieces of convex lenses are arranged in a way that the resulting upside-down enlarged image of the objective lens falls in between the eyepiece lens and its focal point, an upside-down enlarge image of the object will be seen by the observer (see **Figure 1-3**). This is the reason why when you move the slides, the image in the microscope moves in the opposite direction of your motion. Because more than one convex lens was used, the product microscope is called a compound microscope.

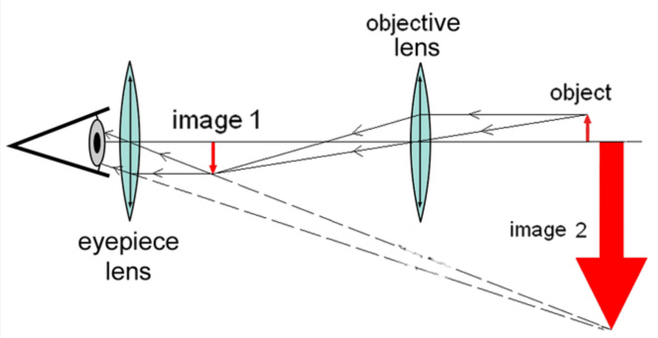


Figure 1-3: Mechanisms of a compound microscope

One advantage of compound microscope is that an object is enlarged twice: once by the objective lens, and once again by the eyepiece lens. For example, when a $4\times$ objective lens is paired with a $10\times$ eyepiece lens, the object will be enlarged 40 times its original size!

In the late 17th century, Robert Hooke improved the design of Janssen microscope by adding a stand for the microscope, as well as an oil lamp to illuminate the specimens (see **Figure 1-4**). Under optimal conditions, Hooke's microscope can magnify the object to approximately 50 times its original size.

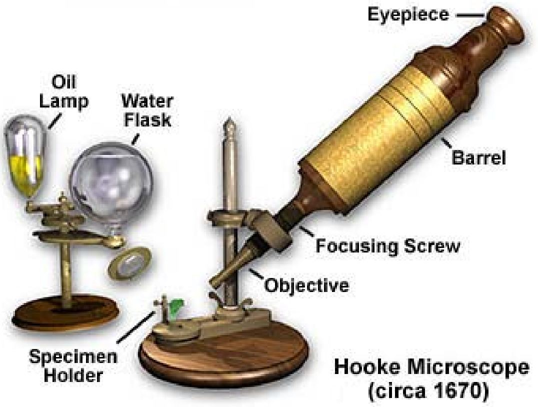


Figure 1-4: Hooke's revision of Janssen microscope.

The free-standing feature of Hooke microscope also allows Hooke to record copious specimens, such as fossils, diatoms, and other plant matters, into his book, *Micrographia*. In fact, the term "cell" was coined by Hooke after he observed a thin slice of wine cork with his microscope. To him, the cork sample looked as if it was made of tiny pores, which reminded him of the cells in a monastery (see **Figure 1-5**).

Figure 1-5: Comparison of monastery cells (left) and cork cells (right).

After reviewing over 200 years of researches done in the field of microscopy, Matthias Schleiden and Theodore Schwann co-founded the cell theory in 1839 and established that "the cell is the unit of structure in all living things," which is the foundation of the cell theory we learn today.

Useful Links

Janssen's Microscope

https://micro.magnet.fsu.edu/primer/museum/janssen.html

Converging Lenses - Ray Diagrams

https://www.physicsclassroom.com/class/refrn/u14l5da.cfm

History of the Cell: Discovering the Cell

https://www.nationalgeographic.org/article/history-cell-discovering-cell/12th-grade/

Cell Theory Timeline

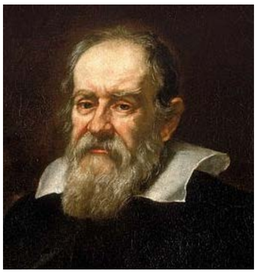
https://ib.bioninja.com.au/standard-level/topic-1-cell-biology/11-introduction-to-cells/cell-theory-history.html

Case 2: Fizeau–Foucault Apparatus (1849)

Relevant Topics

Physics 12 – Special Relativity

Chemistry 11 – Quantum Mechanical Model of Atoms



Galileo Galilei
(1564–1642)

Armand Hippolyte Louis Fizeau
(1819–1896)

Jean Bernard Léon Foucault
(1819–1868)

The speed of light ($2.99792 \times 10^8\, m/s$) is a crucial value in both Physics (special relativity) and Chemistry (modern atomic theory) fields. However, due to its extreme high value, scientists in the past were having hard time measuring it due to the lack of technological support. This is the main reason why prior to the 17th century, majority of scientists considered that the speed of light is infinite, and a light beam is able to travel any distance instantaneously.

Italian physicist Galileo Galilee was the first scientist to attempt to measure the speed of light in early 17th century. He devised an experiment in which two people with covered lanterns stood a known distance apart (see **Figure 2-1**). The first person uncovered the first lantern and as soon as the other person saw the light, the second person uncovered the second lantern. Standing beside the first person, Galileo attempted to record the time between lanterns' lights, but was unsuccessful because the distance involved was too small and light simply is traveling way too fast to be measured this way.

Figure 2-1: Galileo's attempt to measure the speed of light.

In mid-19th century, Armand Fizeau and Jean Foucault collaboratively built an apparatus (see **Figure 2-2 & 2-3**) in which a toothed wheel and a mirror were placed 8.6 km apart, and a bright light source was then used to send pulses of light between them. A partially reflecting mirror was placed near the toothed wheel so the returned light beam can reach the observer's eyes.

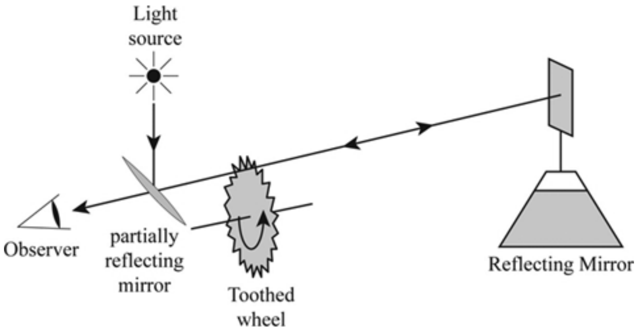


Figure 2-2: Side view of the Fizeau-Foucault apparatus.

Figure 2-3: Front view of the toothed wheel, partially reflecting mirror, and the observer.

Technological Insight

One crucial component of the Fizeau–Foucault apparatus is the **partially reflecting mirror** placed between the light source and the observer. The half-silvered mirror (more commonly known as the **beam splitter** in scientific research) is a special type of mirror that reflects a portion of the initial light beam, while allows the remaining portion of the initial light beam to pass through (see **Figure 2-4**).

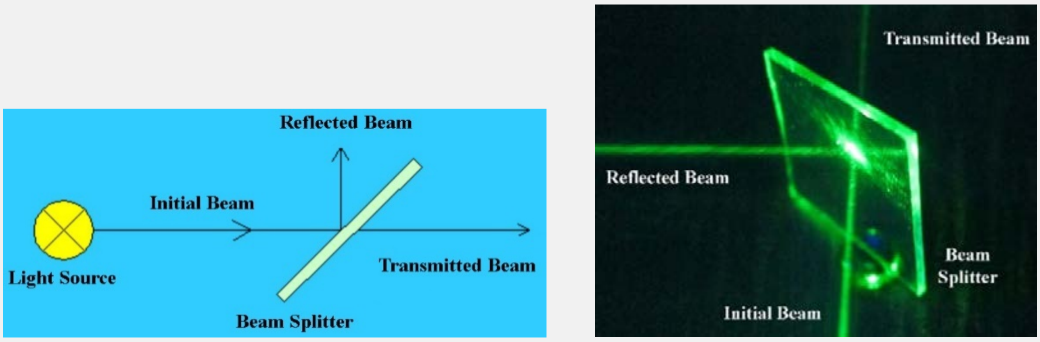


Figure 2-4: Illustration of how beam splitter functions.

> While it is uncertain who invented the beam splitter, the Fizeau–Foucault apparatus was the very first scientific experiment in the history that utilizes a beam splitter.

As illustrated in **Figure 2-5**, due to the rotation of the toothed wheel, small pulses of light beam were sent toward the distant mirror and then reflected back to the wheel. When the wheel was spun at a certain speed so that the time it takes for the pulse of light beam to travel to the distant mirror and back is the same as the time it takes for the toothed wheel to rotate to the next gap, the returned light pulse would pass through this gap and enters the observer's eyes. After several attempts, Fizeau and Foucault found that the rotation rate of $25.2\ \text{revolution}/s$ will allow them to see bright pulses of illumination in return.

When the apparatus is just started, the light source can initially pass through the gap in the toothed wheel.	As the wheel rotates, the light source is blocked by the tooth. Only a short pulse of light was sent to the mirror.	The pulse of light beam was then reflected by the distant mirror and return to the toothed wheel.

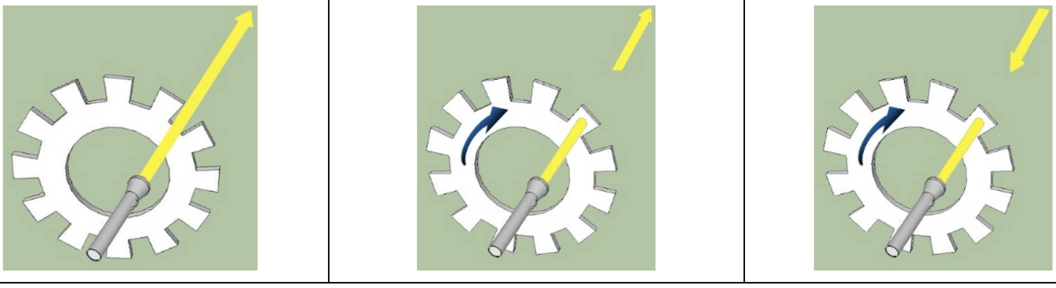


Figure 2-5: Mechanism of Fizeau-Foucault apparatus (half mirror part was omitted).

Based on the experimental setup, Fizeau and Foucault calculated that the speed of light was $3.133 \times 10^8\ m/s$ in 1849 (see *Speed of Light: Chopping Light Beams* in Useful Links for the actual calculation), which was only about 5% higher than the actual value obtained through modern technology.

After years of refining the apparatus and the experimental setup, Fizeau and Foucault eventually concluded that the speed of light was $2.99796 \times 10^8\ m/s$ in 1862 (still slightly off from the actual value, but the error is only 0.001%).

Useful Links

Who Determined the Speed of Light?

https://www.history.com/news/who-determined-the-speed-of-light

July 1849: Fizeau Publishes Results of Speed of Light Experience

https://www.aps.org/publications/apsnews/201007/physicshistory.cfm

Speed of Light: Chopping Light Beams

https://jarphys.wordpress.com/2014/05/04/speed-of-light-chopping-light-beams

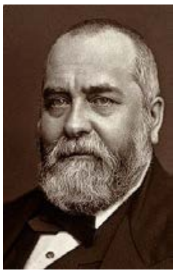
Case 3: Infrared Spectrometer (1905)

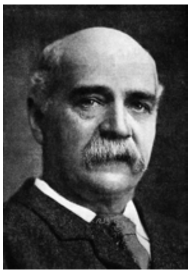
Relevant Topics

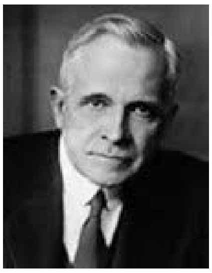
Chemistry 11 – Organic Chemistry

Physics 11 – Refraction of Light


William Herschel
(1738-1822)


Edward Festing
(1839-1912)


William Abney
(1843-1920)


William Coblentz
(1873-1962)

In organic unit of chemical science, we learn that there are various categories of organic compounds (see **Figure 3-1**). Applications of these organic compounds can easily be found in our everyday life. For example, esters often have pleasant smells, and are often used in perfumes and food additives. Ketone, on the other hand, are often good solvents, and are commonly used as nail polish remover or paint remover.

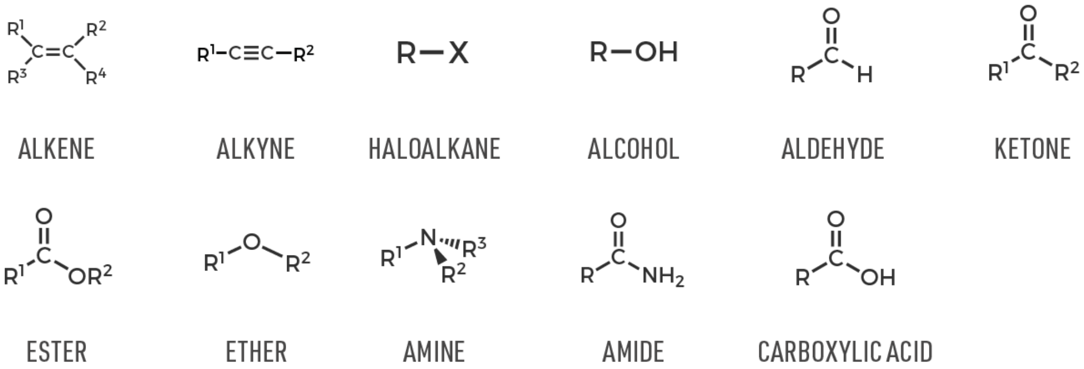


Figure 3-1: List of organic compound categories learned in chemistry

The definition of organic compounds is relatively simple: Any chemicals that were extracted from living things (with the exception of carbon dioxide gas and carbonate ions). While scientists prior to late 19th century were already very good at chemical composition analysis (determining how many carbon, hydrogen, nitrogen and oxygen atoms does a molecule have), they were having the hardest time figuring out the chemical structure of unknown organic compounds that they extracted from living organisms. For example, both ethanol and dimethyl ether have the same chemical composition of C_2H_6O (see **Figure 3-2**). It certainly does not help that both ethanol and dimethyl ether were volatile colourless liquids. In order to determine the structure of an unknown organic compound, we must first figure out what type of chemical bonds are present in their molecules.


dimethyl ether
ethanol

Figure 3-2: Possible structures of C_2H_6O

In 1881, William Abney and Edward Festing discovered that chemical compounds can absorb infrared light to "stretch and bend" their shapes. Depend on what type of chemical bond is present in the molecule, different wavelength of infrared light will be absorbed to cause motion. Using water as an example, when a specific wavelength of infrared light is shined on a water molecule, the molecule can absorb the light energy to undergo symmetric stretch (2,734 nm), asymmetric stretch (2,662 nm), or bend (6,269 nm) motions (see **Figure 3-3**).

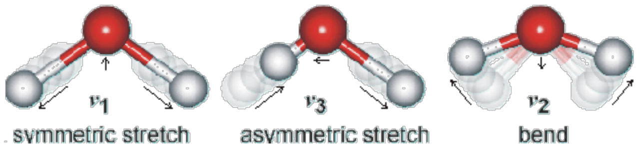


Figure 3-3: Water molecule's stretch and bend motions (scan the QR code for animation)

<u>Technological Insight</u>

Infrared light is a type of electromagnetic wave (similar to visible light). As its name suggests, it is just below the red light in the light spectrum (see **Figure 3-4**).

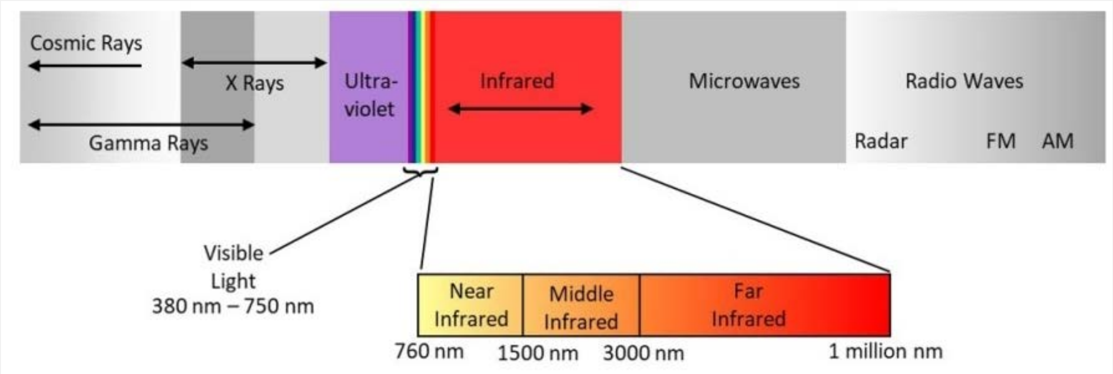


Figure 3-4: Electromagnetic spectrum with an emphasis on the infrared region.

Infrared light was discovered in 1800 by William Herschel. Puzzled by what colour of sunlight carries heat, Herschel set up an experiment to split the sunlight into various wavelengths of lights (see **Figure 3-5**). A narrow slit was made on a moving platform to allow only a single color of light to shine on thermometer #1. Thermometer #2, on the other hand, is placed in shadow to measure the ambient temperature. By moving the platform sideway, Herschel was able to compare how much temperature difference can each colour of light cause comparing to the ambient temperature.

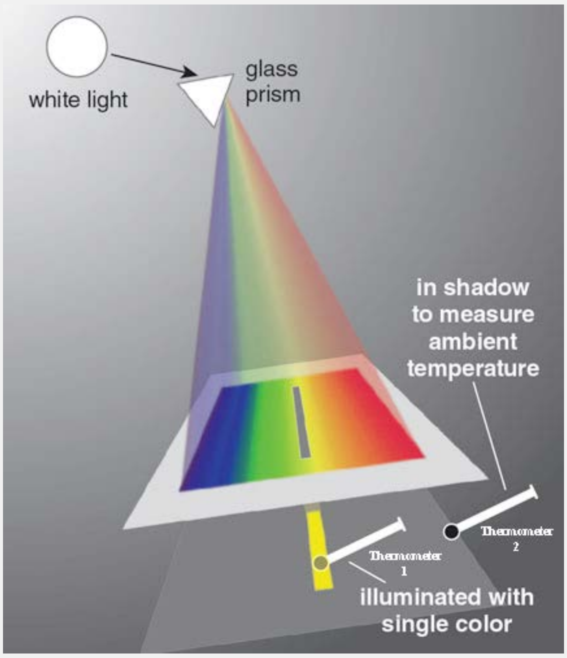


Figure 3-5: Herschel's experimental setup for his discovery of infrared light

To his surprise, the biggest temperature difference was observed when Herschel moved the platform beyond the red light region. Since the light was invisible to human eye, Herschel called it "radiant heat" in March 1800. The term "infrared light" did not enter scientific world until the 1880's, but the researchers were not able to trace who initially coined the term.

Herschel's experiment illustrated two things to the scientific world: a) it is possible to split sunlight into light waves beyond the visible light region, and b) by moving the platform sideway, it is possible to select what wavelength of infrared light to be shined on a test object. In another word, Herschel's experiment is what made the study of Infrared Spectroscopy possible in the 20th century.

In 1905, William Coblentz constructed the first infrared spectrometer that is capable of generating infrared light with wavelengths that ranged from 1,000 nm to 16,000 nm. As illustrated in **Figure 3-6**, a beam of infrared light with a selected wavelength (created using

Herschel's setup) is split in a way that half of the light beam goes through the chemical sample, and the other half goes through an empty reference. The two light beams are then directed back to a detector to check if there is any difference in light intensity. Should the chemical sample absorb any incoming infrared light, a decrease in light intensity (comparing to the reference) will be detected by the detector.

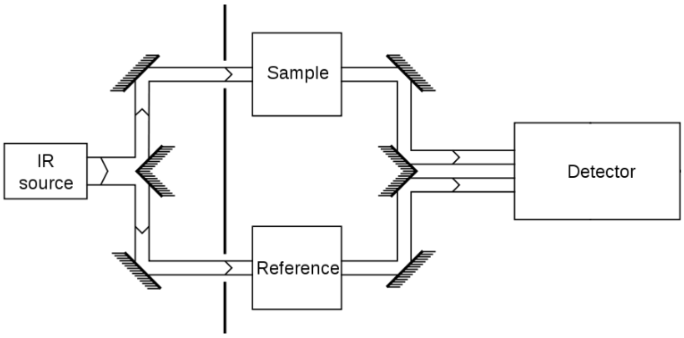


Figure 3-6: The mechanism of Coblentz infrared spectrometer

In addition to constructing the infrared spectrometer, Coblentz also published a large study of compounds that absorbs infrared light at various wavelengths. **Table 3-1** highlights a few common chemical bonds in organic compounds and their absorption wavelengths published by Coblentz.

Table 3-1: Absorption range of common chemical bonds in organic molecules

Chemical Bond	O – H	N – H	C = O	C = C	C – O
Absorption Wavelength (nm)	2700-2850	2800-3000	5500-6000	5900-6200	8700-9500

By looking at the infrared absorption data, we can deduce what type of chemical bond is present in an unknown organic compound, and hence work out the structure of the molecule accordingly. Coming back to our original question of how to determine the structure of an unknown compound with a chemical composition of C_2H_6O, all we needed to do is to check the infrared absorption data to see if O – H bond is present. If it is, then the unknown sample is ethanol. If O – H bond is not present, then the unknown compound must be dimethyl ether.

Figure 3-7: Returning to the possible structures of C_2H_6O

Useful Links

An Introduction to Near Infrared (NIR) Spectroscopy

https://www.impopen.com/introduction-near-infrared-nir-spectroscopy

Herschel and the Puzzle of Infrared

https://www.americanscientist.org/article/herschel-and-the-puzzle-of-infrared

Infrared Spectroscopy

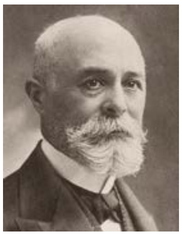
https://www2.chemistry.msu.edu/faculty/reusch/virttxtjml/spectrpy/infrared/infrared.htm

Case 4: Geiger-Marsden Apparatus (1908)

Relevant Topics

Chemistry 11 – Atomic Theory

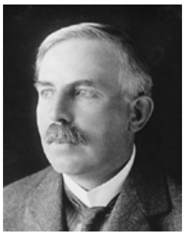
Physics 11 – Radioactive Decay



Antoine Henri Becquerel
(1852-1908)

Pierre Curie
(1859-1906)

Marie Curie
(1867-1934)



Ernest Rutherford
(1871-1937)

Johannes Hans Geiger
(1882-1945)

Ernest Marsden
(1889-1970)

The Geiger-Marsden experiment, also known as the Rutherford gold foil experiment, was a series of experiments performed between 1908 and 1913 by Hans Geiger and Ernest Marsden under the supervision of Ernest Rutherford. These experiments led to the discovery of the nucleus, which was a crucial piece of evidence that eventually ruled out J.J. Thomson’s plum pudding model of atom (see **Figure 4-1**).

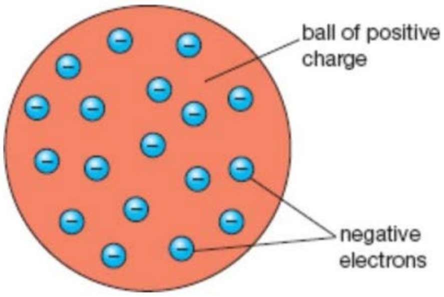


Figure 4-1: Thomson’s plum pudding model of an atom.

As illustrated in **Figure 4-2**, a radioactive source was enclosed in a lead block with a tiny hole facing toward the experimental setup. The enclosed radioactive source will constantly undergo radioactive decay to shoot out beams of positively charged particles (referred as the alpha particle at that time) toward all directions. However, only those traveling along a line toward the tiny hole will be able to leave the lead block and reach the gold foil. The circular fluorescent screen was made out of zinc sulfide, and it will give out tiny glowing flashes when it was struck by an alpha particle.

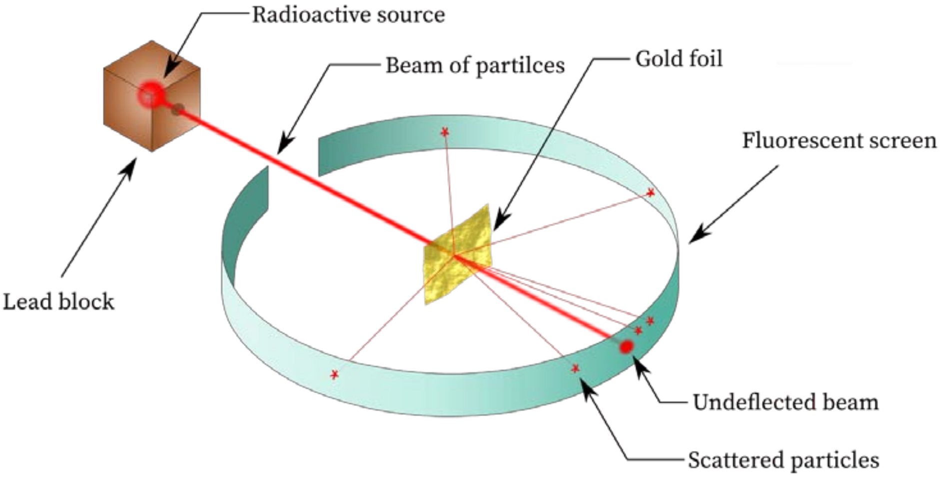


Figure 4-2: Illustration of the Geiger-Marsden apparatus.

Technological Insight

Inspired by Wilhelm Röntgen's discovery of X-ray (see **Case 5** for more detail) in 1895, Henri Becquerel began to suspect that the phosphorescent uranium salts (see **Figure 4-3**) he had been studying might be absorbing sunlight and reemitting it as X-rays (which turned out to be wrong). After a series of experiments, Becquerel discovered in 1896 that any uranium containing materials are able of spontaneously emitting a penetrating radiation similar to X-rays (without the presence of sunlight).

Figure 4-3: A sample of phosphorescent uranium nitrate crystal.

Becquerel initially thought his "uranium rays" were similar to X-rays, but his further experiments showed that unlike X-rays, which are neutral, his uranium rays could be deflected by electric or magnetic fields. In 1898, Marie and Pierre Curie began to study the strange uranium rays and soon found other elements (polonium, thorium, and radium) that are also spontaneously emitting uranium rays. Marie Curie was the person that coined the term "radioactivity" to describe the phenomenon of spontaneous emission of uranium rays.

In 1902, Ernest Rutherford managed to separate Becquerel's uranium rays into alpha ray (a beam of positively charged particles), beta ray (a beam of negatively charged particles), and gamma ray (a neutral electromagnetic wave). The radioactive source used in Geiger-Marsden apparatus was the radium chloride isolated by Marie Curie in 1902. Unlike other radioactive sources, such as uranium and polonium, radium does not occur naturally in nature. Marie Curie was able to isolate one-tenth of a gram of pure radium chloride after refining several tons of pitchblende (a highly complex mineral made of combination of up to 30 different elements, see **Figure 4-4**).

Figure 4-4: A sample of unrefined pitchblende.

The primary purpose of the Geiger-Marsden experiment was to verify whether Thomson's plum pudding model of an atom was correct. Should an atom resemble that of a fluffy plum pudding, the alpha particle beam should be able to penetrate the gold foil with minimal divergence (see left figure in **Figure 4-5**) similar to how a bullet would penetrate a muffin with ease.

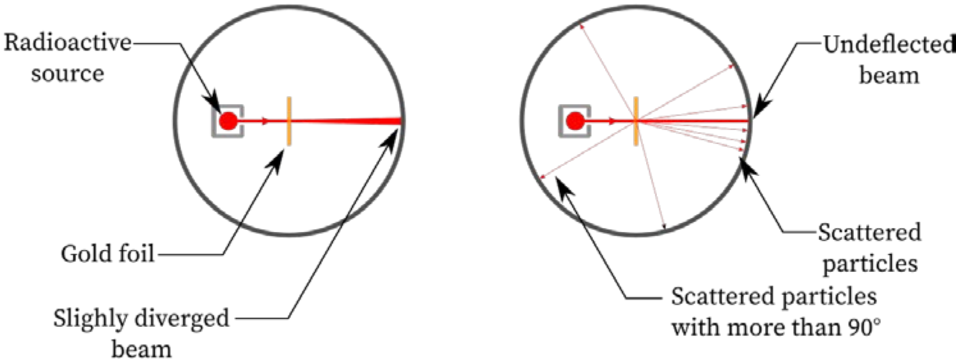


Figure 4-5: Predicted outcome based on Thomson's model (left) and Rutherford's model (right)

However, the experimental data Geiger and Marsden observed resembled the right figure in **Figure 4-5**. In 1913, Rutherford confirmed the presence of the nucleus and conceptualized the planetary model of an atom (see **Figure 4-6**).

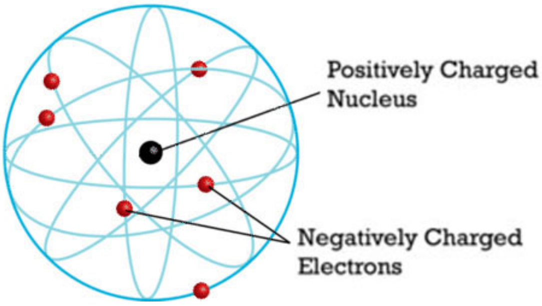


Figure 4-6: Rutherford's planetary model of an atom

The planetary model proposed that all positively charged matter of an atom is concentrated at the center of the atom called nucleus. The majority of the volume of an atom, on the other hand, was occupied by orbiting electrons similar to how planets orbits the sun.

Useful Links

Rutherford's Gold Foil Experiment
https://chemistrygod.com/gold-scattering-experiment

Henri Becquerel Discovers Radioactivity
https://www.aps.org/publications/apsnews/200803/physicshistory.cfm

Marie and Pierre Curie isolate radium
https://www.history.com/this-day-in-history/curies-isolate-radium

Case 5: X-Ray Diffractometer (1912)

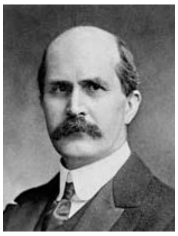
Relevant Topics

Biology 12 – Structure of DNA

Chemistry 11 – Organic Chemistry

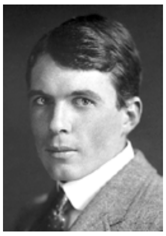
Physics 12 – Diffraction of Light

Wilhelm Röntgen
(1845-1923)



William Henry Bragg
(1862-1942)

Max von Laue
(1879-1960)



William Lawrence Bragg
(1890-1971)

Rosalind Elsie Franklin
(1920-1958)

In biological science, we learn that DNA (deoxyribonucleic acid) carries genetic information for living organisms and has double helical structure in 3D (see **Figure 5-1**).

Figure 5-1: 3D structure of DNA viewed from different angles.

The first X-ray picture of DNA crystal was taken in 1952 by Rosalind Franklin. Despite her contribution on X-ray analysis, Franklin was not named a prize winner for the Nobel Prize in 1962 because she passed away from ovarian cancer in 1958.

Unlike a typical X-ray image taken in hospitals, X-ray pictures taken on molecular level requires assistance from a specialized machine called X-ray diffractometer.

Technological Insight

From your dentist's clinic to airports' luggage inspection, the application of X-ray can be found in many places in our everyday life. Despite its versatility, the invention of X-ray was actually done accidentally by German physicist Wilhelm Röntgen in 1895. Similar to visible light, X-ray is also a type of electromagnetic wave (see **Figure 5-2**).

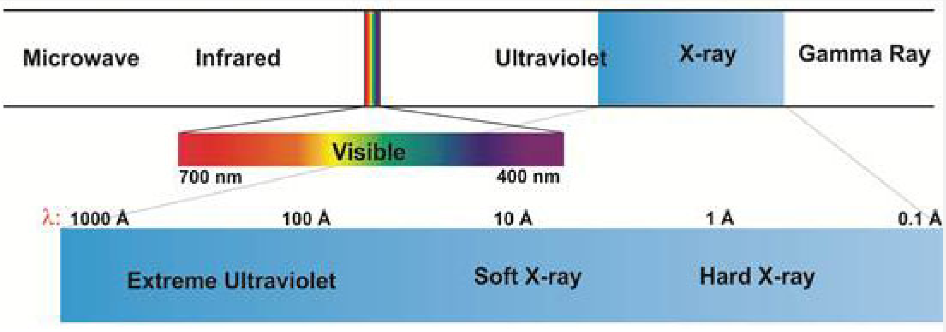
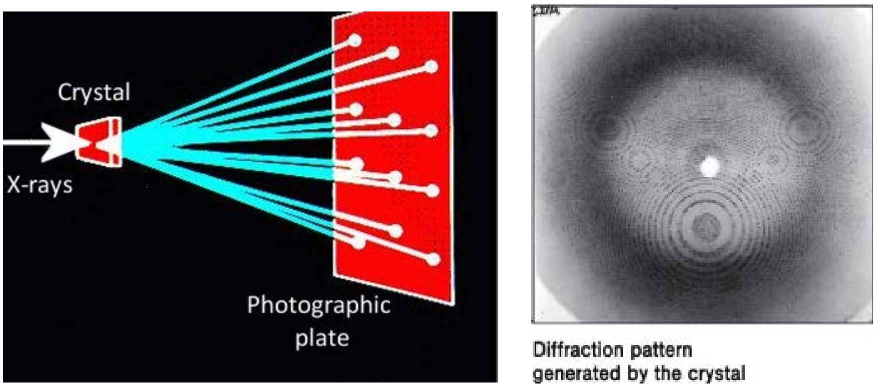


Figure 5-2: Electromagnetic spectrum with an emphasis on the x-ray region

Röntgen enlisted his wife for his first X-ray photos and captured images of the bones in her left hand and her wedding ring. The photo is known as the first röntgenogram (see **Figure 5-3**). Foreseeing the potential applications of X-ray, Röntgen deliberately chose not to patent his discovery. He believed that scientific advances should belong to the world instead of personal profit.

Figure 5-3: The first X-ray photo in the world (known as the röntgenogram).

In 1912, Max von Laue invented the first X-ray diffractometer and discovered that when a beam of X-ray is shined through a crystal, diffraction would take place and a pattern would be formed on a photographic plate (see **Figure 5-4**). The diffraction pattern will depend on the symmetrical arrangements of atoms in the crystal. von Laue's work suggested that it is possible for scientists to deduce the chemical structure of a molecule based on the diffraction pattern recorded on the photographic plate.



Diffraction pattern generated by the crystal

Figure 5-4: Mechanism of X-ray diffractometer.

In 1915, the father and son team of William H. Bragg and William L. Bragg founded X-ray Crystallography (a branch of science where scientists deduce the chemical structure of a molecule based on the X-ray diffraction pattern). Starting from simple inorganic crystals (such as table salt) to complex biological macromolecules (such as hemoglobin and DNA), the Braggs' research gave birth to modern Materials Science and Molecular Biology.

In addition to its application in biological science (such as determining 3D structures of proteins and enzymes), X-ray Crystallography is also frequently used in chemical science. Instead of deducing the structure of organic compounds based on their chemical composition and infrared absorption data (see **Case 3** for more detail), chemists can also utilize X-ray diffraction analysis to directly visualize a molecule's 3D structure. However, such technique only works for organic compounds that are capable of forming crystals due to the requirement of the X-ray diffractometer.

Useful Links

The Discovery of DNA's Structure

https://www.pbs.org/wgbh/evolution/library/06/3/l_063_01.html

Who Invented the X-Ray?

https://science.howstuffworks.com/innovation/inventions/who-invented-the-x-ray.htm

Biography of Max von Laue

https://www.britannica.com/biography/Max-von-Laue

Father of Crystallography

https://www.sciencedirect.com/science/article/pii/S1369702105007522

Case 6: Accelerator Mass Spectrometer (1939)

<u>Relevant Topics</u>

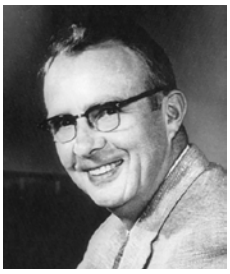
Biology 11 – Evidence for Macroevolution

Chemistry 11 – Isotope

Physics 11 – Radioactive Half Life

Joseph John Thomson
(1856-1940)

Willard Frank Libby
(1908-1980)



Luis Alvarez
(1911-1988)

Robert Cornog
(1912-1998)

In the evolution unit of biological science, we learn that fossils provide solid evidence for macroevolution. Fossils are the preserved remains or traces of animals, plants and other organisms from the past (see **Figure 6-1**). By studying fossils in chronological order, scientists can infer the lineages of those species and propose plausible progression of evolution.

Figure 6-1: Fossil of a seymouria (extinct).

You might be wondering: How exactly do scientists figure out whether a piece of fossil is older than one another or not? In order to answer that question, you need to learn about an experimental technique called carbon dating first.

In 1946, Willard Libby proposed an innovative method for determining the age of organic materials by measuring their content of carbon-14 (^{14}C), a naturally occurring radioactive isotope of carbon. Scientists referred this technique as radiocarbon dating, or carbon dating for short.

By studying the chemical composition of the atmosphere, Libby found that there is just one carbon-14 (^{14}C) atom per every 10^{12} regular carbon (^{12}C) atoms in air. Since majority of life forms on earth obtain their carbon from air (see **Figure 6-2**), any living organisms should also have the same ^{14}C to ^{12}C ratio inside their body as it does in air.

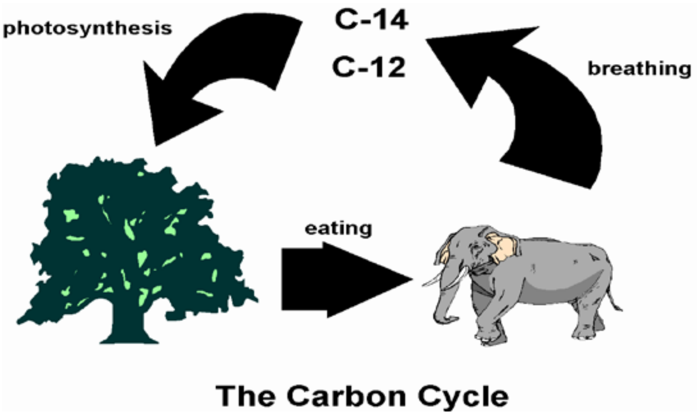


Figure 6-2: The carbon cycle for both ^{14}C and ^{12}C

However, after an organism died, it will no longer exchange its ^{14}C amount with the atmosphere through carbon cycle. Because ^{14}C is radioactive with a half life of 5700 years while ^{12}C is not radioactive at all, the ^{14}C to ^{12}C ratio of a dead organism will gradually decline over time (see **Figure 6-3**). By analyzing the amount of ^{14}C left in a fossil, scientists can calculate how many years ago did the organism passed away, and hence establish timelines for the fossil evidences.

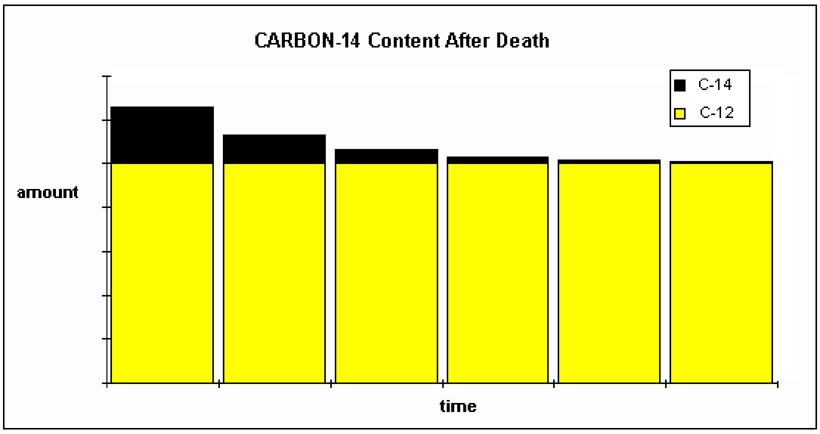


Figure 6-3: Diminishing ^{14}C after death (the ^{14}C to ^{12}C ratio was not drawn to scale).

Due to the mass difference between ^{14}C and ^{12}C, it would be beneficial for carbon dating technicians to develop an instrument that can automatically sort atoms by their atomic mass. As it turns out, an instrument called accelerator mass spectrometer is capable of doing just that!

Technological Insight

A mass spectrometer is defined as any device that operates by a process used to sort any given samples based on their molar mass. The first mass spectrometer (originally called a parabola spectrograph) was constructed in 1912 by J.J. Thomson.

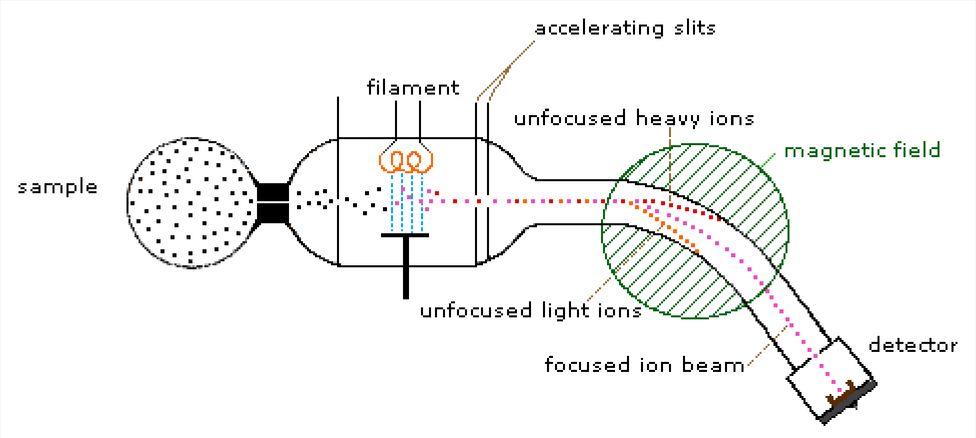


Figure 6-4: Mechanism of Thomson’s mass spectrometer.

Figure 6-4 shows a rough mechanism of how Thomson’s mass spectrometer works. As the sample molecules are directed to the filament chamber, highly energetic electrons emitted by the filament (illustrated as blue dots that showers downward) will start kicking off electrons inside the sample to make them positively charged (similar to how of billiard balls collide into on another on the pools table). After that, a set of accelerating slits will accelerate the positively charged sample into a magnetic field.

The magnetic field can be adjusted so that only ions with selected molar mass can pass through to reach the detector. For ions that are too heavy, the magnetic force is not strong enough to help it turn, so it collides into the outer wall of the instrument. For ions that are too light, on the other hand, the magnetic force is too strong and it causes the ion to collide into the inner wall. A detector is located at the end of the instrument to count the number of ions that actually made through the turn.

Although Thomson’s mass spectrometer might seem like a perfect solution for carbon dating technicians, there is actually a fundamental problem: Both carbon-14 (^{14}C, rare radioactive isotope of carbon) and nitrogen-14 (^{14}N, naturally occurring nitrogen) have the same molar mass of 14.00 g/mol. Because most organisms also contain abundant amount of nitrogen atoms in their body, there is no way for us to tell ^{14}C and ^{14}N apart in Thomson's mass spectrometer.

Fortunately, there is actually a minor mass difference between ^{14}C and ^{14}N when we increase the resolution of our measurement: ^{14}C has a molar mass of 14.003241 g/mol and ^{14}N has a molar mass of 14.003074 g/mol.

In 1939, Luis Alvarez and Robert Cornog constructed the first accelerator mass spectrometer (see **Figure 6-5**). In order to increase the resolution of Thomson's mass spectrometer, the resulted ion beam (with molar mass of roughly 14.00 g/mol) exiting magnetic field 1 is directed to a chamber of accelerating slits to acquire extremely high speed before entering magnetic field 2.

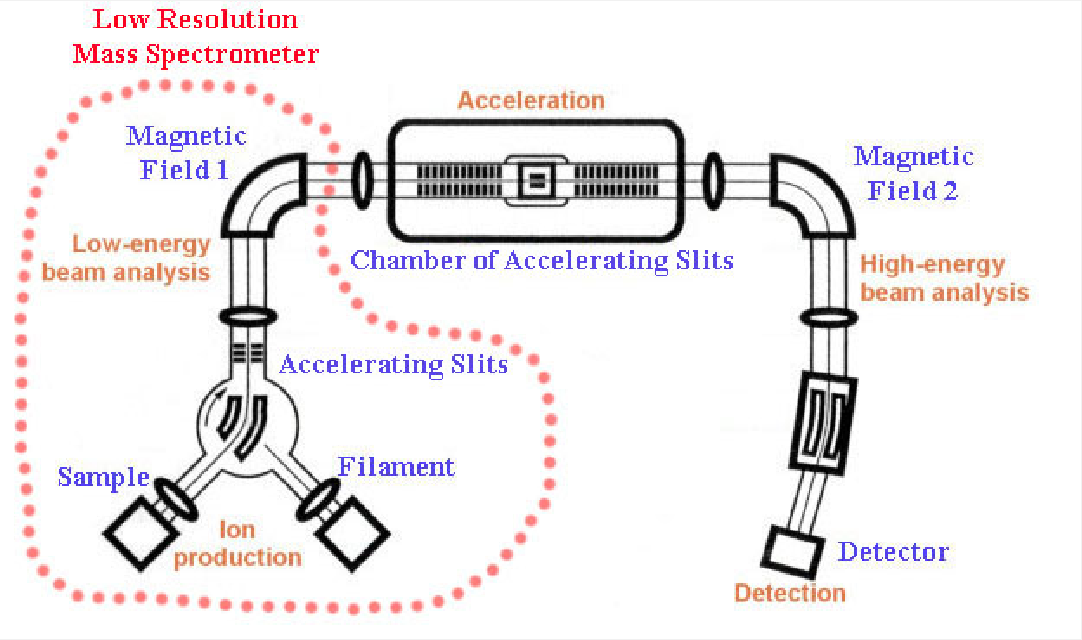


Figure 6-5: Mechanism of accelerator mass spectrometer

When the ions are travelling at such high speed, a slight difference in magnetic force will cause the ions to collide into the wall. Because ^{14}N is slightly lighter than ^{14}C, the magnetic force that is just right for ^{14}C would be too strong for ^{14}N. As a result, all ^{14}N ions will collide into the inner wall of the instrument and only ^{14}C will reach the detector. Carbon dating analysis will be possible after this step.

When Libby first presented radiocarbon dating, he estimated that the method should be able to measure ages up to 20,000 years. For samples older that than, the amount of ^{14}C remained in the sample is too little to be traced. However, with the advancement of accelerator mass spectrometer designs, scientists can now reliably date materials as old as 50,000 years.

Useful Links

The Fossil Record as Evidence for Evolution
https://tinyurl.com/yxdw3z6x

Understanding Radiocarbon Dating
http://unmaskingevolution.com/1-carbon14.htm

Willard Libby and Radiocarbon Dating
https://www.acs.org/content/acs/en/education/whatischemistry/landmarks/radiocarbon-dating.html

First Concept of Time-of-Flight Mass Spectrometer
https://www.aps.org/publications/apsnews/200104/history.cfm

Accelerator Mass Spectrometry
https://www.britannica.com/science/mass-spectrometry/Accelerator-mass-spectrometry

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