Landmark Lesson Plan:

Radiocarbon Dating and Willard Libby

Grades: 9-12
Subject Areas: Chemistry and History
Based on the National Historic Chemical Landmark on Willard Libby and Radiocarbon Dating
Principal author: Susan Cooper

The following inquiry-based student activities are designed for use in high school chemistry lesson planning, but they apply to all science subjects. Some middle school teachers may also find the lesson outline helpful if students have some understanding of nuclear chemistry, including half-life. The lesson plan will help students understand how we know the age of artifacts containing carbon. The final activity integrates writing as students are asked to summarize what they have learned about radiocarbon dating.

The content is designed as a ready-to-go lesson, easily implemented by teachers or their substitutes, to supplement a unit of study. Students will practice critical reading and writing skills as they develop a deeper understanding of the carbon cycle and radiocarbon dating.

All resources are available online at www.acs.org/LandmarkLessonPlans.

While these activities are thematically linked, each is designed to stand alone as an accompaniment for the article provided on pages three to five. Teachers may choose activities based on curricular needs and time considerations.

- Take a few minutes to introduce the lesson with a few conversation starters. How do we know the age of the funerary boat of an Egyptian pharaoh? How do we know how long ago the last ice sheets left North America?
- If you use the Anticipation Guide, do not distribute the article about radiocarbon dating until students have indicated their initial opinions or (for the optional engagement exercise) come up with their own ideas. Then distribute the article for students to check their answers and find the passage that supports or refutes their initial thoughts.
- For the remaining activities, distribute the exercise(s) selected for the class along with the article about radiocarbon dating and Willard Libby. Make sure students understand the directions for each activity. While students are reading, they should complete the exercise(s).
- For additional information about isotopes (and the final jigsaw activity), students may want to view the following video:
  What Are Isotopes? https://youtu.be/GyviEsmrVp0
- After all students have read the article and completed the exercise(s), use the Answer Guide for student feedback and further discussion.

Student Activities with Objectives

Anticipation Guide and Reading on "Radiocarbon Dating and Willard Libby"
(5 minute introduction, followed by 15-20 minutes of reading)

- Students confront their ideas about radiocarbon dating.

History Exercise: Timeline of Events
(10-15 minutes)

- Students chronologically order events mentioned in the reading.

Graphic Organizer(or Card Sort): What can be dated using radiocarbon dating? *and* **Graphic Organizer: Uses for Radiocarbon Dating**
(10-15 minutes)

- Students sort artifacts into those that can and can't be dated using radiocarbon dating methods, then they identify how different kinds of scientists might use radiocarbon dating.

Nuclear Equations and Writing: Let's Summarize!
(15-20 minutes)

- Students write nuclear equations for the formation and decay of 14C, and summarize the challenges Libby faced in demonstrating that his idea for radiocarbon dating worked.

Optional Jigsaw Summaries
(15-30 minutes)

- After reading the article, students work in groups on one of the suggested projects, then each group summarize their results to share with the class in a 1-minute presentation.

Radiocarbon Dating and Willard Libby

In 1946, Willard Libby developed a method for dating organic materials by measuring their content of carbon-14, a radioactive isotope of carbon. His radiocarbon dating method is now routinely used in archaeology and geology to determine the age of ancient artefacts that originated from living organisms. Libby's discovery, which earned him the Nobel Prize in Chemistry in 1960, has made it possible to develop more precise historical chronologies across geography and cultures.

Willard Libby's concept of radiocarbon dating

Willard Libby (1908–1980), a professor of chemistry at the University of Chicago, began the research that led him to radiocarbon dating in 1945.

He was inspired by physicist Serge Korff of New York University, who in 1939 discovered that bombardment of Earth's atmosphere by cosmic rays produces neutrons. Korff figured out that these neutrons react with nitrogen-14 (^{14}N) in the atmosphere to produce a proton and carbon-14, also known as radiocarbon or ^{14}C.

Libby reasoned that ^{14}C in the atmosphere would find its way into living matter, which would thus be tagged with the radioactive isotope. Theoretically, if he could detect the amount of ^{14}C in an object, he could establish the object's age using the half-life, or rate of decay, of the isotope. In 1946, Libby proposed this groundbreaking idea in the journal *Physical Review*.

Predictions about ^{14}C

The concept of radiocarbon dating focused on measuring the carbon content of organic objects, but in order to prove the idea Libby would need to work out the ebb and flow of carbon on Earth. Radiocarbon dating would be most successful if two important factors were true: that the concentration of ^{14}C in the atmosphere had been constant for thousands of years, and that ^{14}C moved readily through the atmosphere, biosphere, oceans and other reservoirs—in a process known as the carbon cycle.

In the absence of any historical data concerning the intensity of cosmic radiation, Libby simply assumed that it had been constant. He reasoned that a state of equilibrium must exist wherein the rate of ^{14}C production was equal to its rate of decay, dating back millennia. (Fortunately for him, this was later proven to be generally true, at least prior to the era of nuclear weapons.)

For the second factor, it would be necessary to estimate the overall amount of ^{14}C and compare this against all other isotopes of carbon. Based on Korff's estimation that just two neutrons were produced per second for each square centimeter of Earth's surface, each forming a ^{14}C atom, Libby calculated a ratio of just one ^{14}C atom per every 10^{12} carbon atoms on Earth.

Libby's next task was to study the movement of carbon through the carbon cycle. In a system where ^{14}C moves readily throughout the cycle, the ratio of ^{14}C to other carbon isotopes should be the same in a living organism as in the atmosphere.

However, the rates of movement of carbon throughout the cycle were not then known. Libby and graduate student Ernest Anderson calculated the mixing of carbon across these different reservoirs, particularly in the

University of Chicago

Willard Libby (right) with graduate student Ernest Anderson.

oceans, which constitute the largest reservoir. Their results predicted the distribution of ^{14}C across the carbon cycle and gave Libby encouragement that radiocarbon dating might actually work.

Detecting radiocarbon in nature

^{14}C was first discovered in 1940 by Martin Kamen and Samuel Ruben, who created it artificially using a cyclotron accelerator at the University of California Radiation Laboratory in Berkeley.

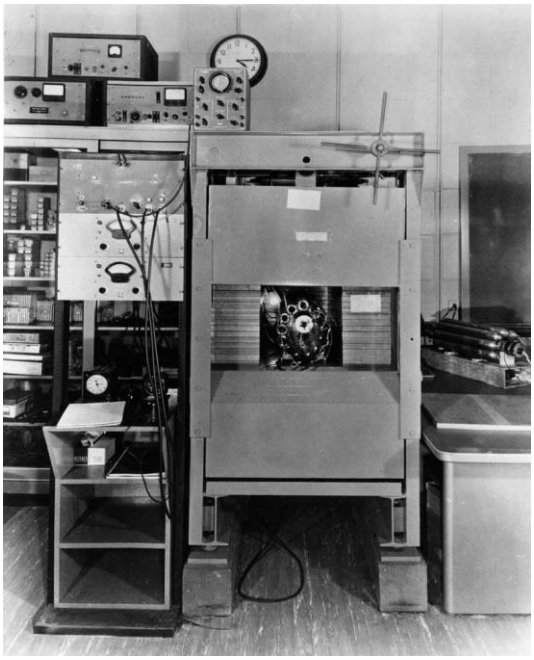
Further research by Libby and others estimated its half-life as 5,568 years (later revised to approximately 5,730 years), providing another essential factor in Libby's concept. But no one had yet detected ^{14}C in nature—at this point, Korff and Libby's predictions about radiocarbon were entirely theoretical. In order to prove his concept of radiocarbon dating, Libby needed to confirm the existence of natural ^{14}C, a major challenge given the tools then available.

At the time, no radiation-detecting instrument (such as a Geiger counter) was sensitive enough to detect the small amount of ^{14}C that Libby's experiments required. Libby reached out to Aristid von Grosse of the Houdry Process Corp. who was able to provide a methane sample that had been enriched in ^{14}C to a level that could be detected by existing tools.

Using this sample and an ordinary Geiger counter, Libby and Anderson established the existence of naturally occurring ^{14}C, matching the concentration predicted by Korff.

Although this method worked, it was slow and costly, so Libby's group developed an alternative.

University of Chicago



Libby's anti-coincidence counter. The circular arrangement of Geiger counters (center) detected radiation in samples while the thick metal shields on all sides were designed to reduce background radiation.

They surrounded the sample chamber with a system of Geiger counters calibrated to detect and eliminate the background radiation that exists throughout the environment.

The assembly was called an "anti-coincidence counter." When it was combined with a thick shield that further reduced background radiation and a novel method for reducing samples to pure carbon for testing, the system proved to be suitably sensitive.

Finally, Libby had a method to put his concept into practice.

Glossary

Carbon-14: Also known as radiocarbon or ^{14}C, this radioactive carbon isotope contains eight neutrons, or two more than ^{12}C, the most common form of carbon. Over time, ^{14}C decays into ^{14}N (along with an electron and antineutrino), so the relative amount of ^{14}C remaining in an artefact reveals its age.
Cosmic rays: High-energy particles that move through space at nearly the speed of light. They produce neutrons when they hit the atmosphere.
Half-life: The time for half the atoms in a radioactive sample to decay through radiation. For ^{14}C, the half-life is about 5,730 years, so a body that is 5,730 years old would contain half the ^{14}C and be half as radioactive as on the day the person died.
Isotope: Atoms consist of negatively charged electrons along with a nucleus that contains positively charged protons and neutral neutrons. Different isotopes of a given element — such as ^{12}C and ^{14}C — contain the same number of electrons and protons but a different number of neutrons. The sum of protons and neutrons is known as the mass number, which is 14 in the case of ^{14}C.
Organic material: Material that contains carbon.

Further reading

Students may wish to refer to these additional resources:

1960 Nobel Prize in Chemistry https://tinyurl.com/ACS-Nobel

Carbon-14 is 75±0 Years Old https://tinyurl.com/ACS-carbon14

How Does Radiocarbon Dating Work? https://tinyurl.com/ACS-dating

The "Radiocarbon Revolution"

The introduction of radiocarbon dating had an enormous influence on archaeology and geology, often referred to as the "radiocarbon revolution." Before Libby's technique was available, investigators in these fields used dating methods that were merely relative, such as comparing the layers of an archeological site in which artifacts were found, presuming that the layers had been laid down chronologically. However, this method simply places events in order without a precise numerical measure. By contrast, radiocarbon dating provided the first objective dating method—the ability to attach approximate numerical dates to organic remains.

This method helped to disprove several previously held beliefs, including the notion that civilization originated in Europe and diffused throughout the world. By dating man-made artifacts from Europe, the Americas, Asia, Africa and Oceania, archaeologists established that civilizations developed in many independent sites across the world. As they spent less time trying to determine artifact ages, archaeologists were able to ask more searching questions about the evolution of human behavior in prehistoric times.

Libby's work also contributed to geology. By using wood samples from trees once buried under glacial ice, Libby proved the last ice sheet in northern North America receded 10,000-12,000 years ago, not 25,000 years as geologists had previously estimated.

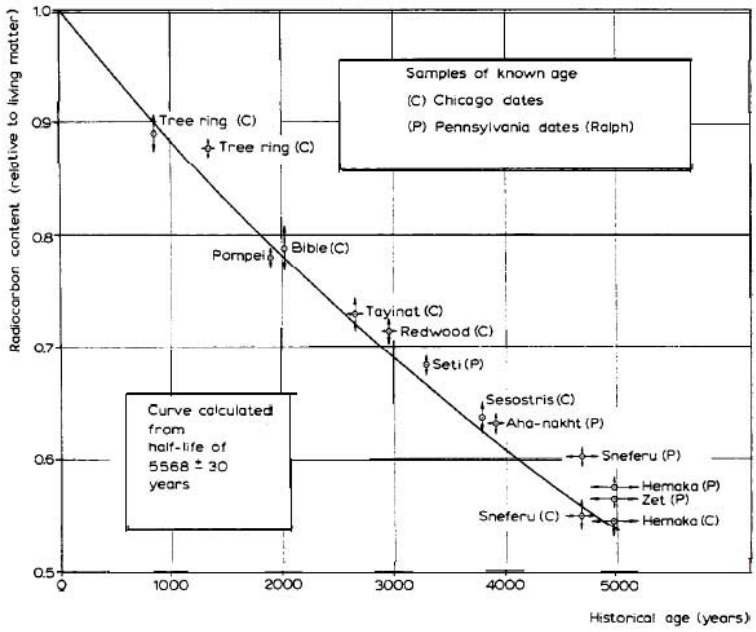
When Libby first presented radiocarbon dating to the public, he humbly estimated that the method may have been able to measure ages up to 20,000 years. With subsequent advances in the technology of ^{14}C detection, the method can now reliably date materials as old as 50,000 years.

Testing radiocarbon dating

The concept of radiocarbon dating relied on the assumption that once an organism died, it would be cut off from the carbon cycle. From then on, as a result of radioactive decay, its ^{14}C content would steadily diminish. Living organisms from the present day would have the same relative amount of ^{14}C as the atmosphere, whereas ancient sources that were once alive, such as coal beds or petroleum, would have no ^{14}C left. For organic objects of intermediate ages—between a few centuries and several millennia—an age could be estimated by measuring the relative amount of ^{14}C present in the sample and combining this information with the known half-life of ^{14}C.

To test the technique, Libby's group applied the anti-coincidence counter to samples whose ages were already known. Among the first objects tested were samples of redwood and fir trees, the ages of which were confirmed by counting their annual growth rings. The researchers also sampled artifacts from museums, such as a piece of timber from Egyptian Pharaoh Sesostris III's funerary boat, an object whose age was known from the record of its owner's death.

In 1949, Libby and Arnold published their findings in the journal *Science*, introducing the "Curve of Knowns." This graph compared the known age of artifacts with the estimated age as determined by the radiocarbon dating method. It showed all of Libby's results were similar to the known ages, thus proving the success of radiocarbon dating.



The "Curve of Knowns" compared the known age of historical artifacts associated with the Bible, Pompeii and Egyptian dynasties with their age as determined by radiocarbon dating. (Lower radiocarbon content indicates greater age.) The agreement between the two demonstrated the accuracy of the technique. This version was presented by Libby during his Nobel Lecture in 1960.

Student Name: _____ Date: _____ Period: _____

Anticipation Guide
Radiocarbon Dating and Willard Libby

Anticipation guides help engage students by activating prior knowledge and stimulating student interest before reading. If class time permits, discuss students' responses to each statement ***before*** they read the article. Then, ***while*** they read, students should look for evidence supporting or refuting their initial responses.

Directions: ***Before reading***, in the first column, write "A" or "D" indicating your agreement or disagreement with each statement. Then, ***while*** you read, compare your opinions with information from the article, which you'll use to write "A" or "D" in the second column. In the space under each statement, cite information from the article that supports or refutes your original ideas.

Me	Text	Statement
		1. The method for dating organic materials using radiocarbon dating was developed in the early 1900s.
		2. Carbon-14 (^{14}C) is produced naturally in the atmosphere when neutrons produced by cosmic rays react with nitrogen.
		3. The concentration of ^{14}C in the atmosphere was constant for thousands of years.
		4. Radioactive carbon (^{14}C) moves readily through the carbon cycle.
		5. ^{14}C was first discovered in the atmosphere.
		6. Libby's method used a system of Geiger counters to detect background radiation.
		7. Once an organism dies, the amount of ^{14}C it contains increases.

Student Name: _____ Date: _____ Period: _____

		8. Libby's method was tested using samples whose ages were known.
		9. Radiocarbon dating demonstrated that civilization originated in Europe.
		10. Radiocarbon dating can date materials more than 100,000 years old.

Optional Engagement Idea:

Instead of using the Anticipation Guide, consider this idea to engage your students in reading:

1. Ask students to share when they think the method of radiocarbon dating was developed and what technical obstacles the scientist who developed it might have had to overcome.
2. After this discussion, invite students to read the article to find more details about how Willard Libby developed the method of radiocarbon dating and how the method can be used.

Student Name: _____ Date: _____ Period: _____

Timeline: Radiocarbon Dating

Challenge students to put the following events in chronological order prior to reading. (The teacher could provide the events on strips of paper to make this easier.)

After their initial attempt at chronological ordering, students should re-order the events correctly using information from the article. Finally, students should summarize their learning about the history of radiocarbon dating in a short paragraph (3-5 sentences).

Directions: Using the article provided, put the following events in chronological order, with the earliest event "1" and the last event "7."

a. ____ Libby was awarded the Nobel Prize in Chemistry.

b. ____ Libby developed the method for radiocarbon dating.

c. ____ The Italian city Pompeii was destroyed by the eruption of Mount Vesuvius.

d. ____ The last ice sheet in northern North American receded.

e. ____ Carbon-14 was first discovered.

f. ____ Libby and Arnold published their method of radioactive carbon dating in the journal *Science*.

g. ____ Egyptian Pharaoh Sesostris III died.

Student Name: _____ Date: _____ Period: _____

Radiocarbon Dating

Directions: Sort the items below into those that can be dated using ^{14}C and those that cannot. Below the table, write one or two sentences explaining how you made your choices (what "rule" you used).

Artifact	Can be dated with ^{14}C	Cannot be dated with ^{14}C
Redwood tree cut down 2,000 years ago		
Redwood tree cut down in 1995		
Dugout canoe created in the 17th century		
Pottery shard		
Granite rock		
Cotton fabric from 18th century		
Lump of coal		
Seashell		
Seeds		

Explain how you made your choices:

Student Name: _____ Date: _____ Period: _____

Uses for Radiocarbon Dating

Directions: In the columns below, list at least five objects that researchers might want to date using radiocarbon dating.

Archaeology	Geology

Student Name: _____ Date: _____ Period: _____

Let's Summarize!

Radioactive elements like carbon-14 can change or "decay" into different elements by emitting forms of radiation such as alpha or beta particles. Alpha particles consist of protons and neutrons, while beta particles are electrons.

Nuclear equations show these transformations. Here are examples showing the decay of uranium-235 and iodine-131:

$$^{235}_{92}\mathrm{U} \longrightarrow {}^{231}_{90}\mathrm{Th} + {}^{4}_{2}\mathrm{He}$$

uranium-235 thorium-231 alpha particle

$$^{131}_{53}\mathrm{I} \longrightarrow {}^{131}_{54}\mathrm{Xe} + {}^{0}_{-1}\mathrm{e}$$

iodine-131 xenon-131 beta particle

Nuclear equations can also show the formation of radioactive elements. For instance, carbon-14 (which can also be written as $^{14}_{6}\mathrm{C}$), the radioactive type of carbon used in carbon dating, is formed from nitrogen-14 (written as $^{14}_{7}\mathrm{N}$) in the atmosphere. Over time, it decays back to nitrogen-14. These reactions involve neutrons (written as n), protons (written as p), and antineutrinos (written as $\bar{\nu}_{\mathrm{e}}$).

1. After reading the article, write the nuclear equation for the formation of carbon-14 in the atmosphere:

2. Write the nuclear equation for the decay of carbon-14:

After reading the article, write two paragraphs (or make a bulleted list) summarizing the following:

- Challenges Libby and his associates had to overcome to develop the radiocarbon dating method.
- Assumptions Libby made to demonstrate that radiocarbon dating worked.

Student Name: _____ Date: _____ Period: _____

Jigsaw Summaries

If students have access to the Internet, share the links below.

Prior to the Jigsaw activity, consider showing the video "What Are Isotopes" (https://youtu.be/GyviEsmrVp0) to the entire class

Students work in groups of 3-4 to view one of the suggested resources below, then summarize the content to share with the class in a 1-minute presentation. Each video is less than 5 minutes long.

1. ACS Reactions video: "Why Is Carbon the Key to Life (on Earth, Anyway)?" provides information about carbon's ability to form many different types of compounds, and astrochemists consider problems silicon-based life forms might have. https://youtu.be/VUiDwrM2YPI
2. ACS Reactions video: "How Do We Know the Age of the Earth?" describes past attempts to determine the age of the Earth and provides information about radioactive decay. https://youtu.be/7cFYPYaD4zQ
3. Chemical Heritage Foundation (CHF) video: "CHF Acquires Libby Shield" describes the steel shield and Geiger counters Libby used, as well as engineering obstacles he had to overcome. https://youtu.be/KdpasKqyGvc
4. National Museum of American History blog: "Carbon-14 is 75+/-0 Years Old" has archival photographs of the apparatus Libby used as well as information about Charles Tucek, who started a ^{14}C dating business. https://americanhistory.si.edu/blog/carbon-14
5. Scientific American video: "How Does Radiocarbon Dating Work?" (Instant Egghead #28) has information about the formation of ^{14}C and how it can be used to find out when plants and animals died. https://youtu.be/phZeE7Att_s

Anticipation Guide

Me	Text	Statement
	D	1. The method for dating organic materials using radiocarbon dating was developed in the early 1900s.
	A	2. Carbon-14 (^{14}C) is produced naturally in the atmosphere when neutrons produced by cosmic rays react with nitrogen.
	A	3. The concentration of ^{14}C in the atmosphere was constant for thousands of years.
	A	4. Radioactive carbon (^{14}C) moves readily through the carbon cycle.
	D	5. ^{14}C was first discovered in the atmosphere.
	A	6. Libby's method used a system of Geiger counters to detect background radiation.
	D	7. Once an organism dies, the amount of ^{14}C it contains increases.
	A	8. Libby's method was tested using samples whose ages were known.
	D	9. Radiocarbon dating demonstrated that civilization originated in Europe.
	D	10. Radiocarbon dating can date materials more than 100,000 years old.

Timeline: Radiocarbon Dating

Challenge students to put the following events in chronological order prior to reading. (The teacher could provide the events on strips of paper to make this easier.)

After their initial attempt at chronological ordering, students should re-order the events correctly using information from the article. Finally, students should summarize their learning about the history of radiocarbon dating in a short paragraph (3-5 sentences).

Directions: Using the article provided, put the following events in chronological order, with the earliest event "1" and the last event "7."

a. __7__ Libby was awarded the Nobel Prize in Chemistry. (1960)

b. __5__ Libby developed the method for radiocarbon dating. (1946)

c. __3__ The Italian city Pompeii was destroyed by the eruption of Mount Vesuvius. (79)

d. __1__ The last ice sheet in northern North American receded. (10,000-12,000 years ago)

e. __4__ Carbon-14 was first discovered. (1940)

f. __6__ Libby and Arnold published their method of radioactive carbon dating in the journal *Science*. (1949)

g. __2__ Egyptian Pharaoh Sesostris III died. (almost 4,000 years ago)

Radiocarbon Dating

Directions: Sort the items below into those that can be dated using ^{14}C and those that cannot. Below the table, write one or two sentences explaining how you made your choices (what "rule" you used).

Artifact	Can be dated with ^{14}C	Cannot be dated with ^{14}C
Redwood tree cut down 2,000 years ago	X	
Redwood tree cut down in 1995		X
Dugout canoe created in the 17th century	X	
Pottery shard		X
Granite rock		X
Cotton fabric from 18th century	X	
Lump of coal		X
Seashell	X	
Seeds	X	

Explain how you made your choices:

Answers will vary, but they should mention both of the following:

- The items must be organic (contain carbon).
- The items should be between about 100-50,000 years old.

Uses for Radiocarbon Dating

Directions: In the columns below, list at least five objects that researchers might want to date using radiocarbon dating.

Answers will vary. Potential responses are below.

Archaeology	Geology
• Human remains from native American sites • Tools containing wood or other organic material from ancient sites • Seeds from an ancient site • Fossils • Artefacts containing carbon from ancient burial sites	• Wood from glacial ice

Let's Summarize!

Radioactive elements like carbon-14 can change or "decay" into different elements by emitting forms of radiation such as alpha or beta particles. Alpha particles consist of protons and neutrons, while beta particles are electrons.

Nuclear equations show these transformations. Here are examples showing the decay of uranium-235 and iodine-131:

$$^{235}_{92}\mathrm{U} \rightarrow {}^{231}_{90}\mathrm{Th} + {}^{4}_{2}\mathrm{He}$$

uranium-235 thorium-231 alpha particle

$$^{131}_{53}\mathrm{I} \rightarrow {}^{131}_{54}\mathrm{Xe} + {}^{0}_{-1}\mathrm{e}$$

iodine-131 xenon-131 beta particle

Nuclear equations can also show the formation of radioactive elements. For instance, carbon-14 (which can also be written as $^{14}_{6}\mathrm{C}$), the radioactive type of carbon used in carbon dating, is formed from nitrogen-14 (written as $^{14}_{7}\mathrm{N}$) in the atmosphere. Over time, it decays back to nitrogen-14. These reactions involve neutrons (written as n), protons (written as p), and antineutrinos (written as $\bar{\nu}_{\mathrm{e}}$).

1. After reading the article, write the nuclear equation for the formation of carbon-14 in the atmosphere:

$$^{14}_{7}\mathrm{N} + \mathrm{n} \rightarrow {}^{14}_{6}\mathrm{C} + \mathrm{p}$$

nitrogen-14 neutron carbon-14 proton

2. Write the nuclear equation for the decay of carbon-14:

$$^{14}_{6}\mathrm{C} \rightarrow {}^{14}_{7}\mathrm{N} + {}^{0}_{-1}\mathrm{e} + \bar{\nu}_e$$

carbon-14 nitrogen-14 electron antineutrino

After reading the article, write two paragraphs (or make a bulleted list) summarizing the following:

- Challenges Libby and his associates had to overcome to develop the radiocarbon dating method.
- Assumptions Libby made to demonstrate that radiocarbon dating worked.

Challenges:

- Establish the existence of ^{14}C (with a Geiger counter).
- Create "anti-coincidence counter" to use with a thick shield to reduce background radiation.

Assumptions:

- ^{14}C in the atmosphere gets into living things.
- Distribution of ^{14}C in the atmosphere is the same as in living things.
- Age of once-living things can be established based on half-life of ^{14}C.
- Amount of ^{14}C is constant over time.
- Once an organism dies, it is cut off from the carbon cycle so amount of ^{14}C declines as time passes.

Rubric for Jigsaw summaries:

Score	Description	Evidence
4	Excellent	Complete; details provided; demonstrates deep understanding of scientific processes and how science relates to everyday life.
3	Good	Complete; few details provided; demonstrates some understanding of scientific processes and the relationship to everyday life.
2	Fair	Incomplete; few details provided; shallow understanding of scientific processes and relationship of findings to everyday life; some misconceptions evident.
1	Poor	Very incomplete; no details provided; many misconceptions evident.
0	Not acceptable	So incomplete that no judgment can be made about student understanding