
# NUCLEAR SCIENCE

BOY SCOUTS OF AMERICA

# Requirements

1. Do the following:
   a. Describe the biological effects and hazards of radiation to humankind, the environment, and wildlife. Explain the difference between acute and chronic effects. In your explanation, discuss the nature and magnitude of radiation risks to humans from nuclear power, medical radiation, and background radiation. Explain the measures required by law to minimize these risks.
   b. Describe the radiation hazard symbol and explain where it should be used. Tell why and how people must use radiation or radioactive materials carefully.
2. Tell the meaning of the following: ALARA, alpha particle, atom, background radiation, beta particle, contamination, curie and becquerel, gamma ray, half-life, ionization, quark, isotope, neutron, nuclear energy, nuclear reactor, particle accelerator, rad and gray, radiation, radioactivity, radon, rem and sievert, and X-ray.
3. Choose five individuals important to the field of atomic energy and nuclear science and explain each person's contribution.
4. Choose an element from the periodic table. Construct 3-D models for the atoms of three isotopes of this element, showing neutrons, protons, and electrons. Use the three models to explain the difference between atomic number and mass number. Then do the following:
   a. Make a drawing showing how nuclear fission happens, labeling all details. Draw another picture showing how a chain reaction could be started and how it could be stopped.
   b. Explain what is meant by a "critical mass."
5. Do any THREE of the following:
   a. Build an electroscope. Show how it works. Place a radiation source inside and explain any difference seen.
   b. Build a model of a reactor. Show the fuel, control rods, shielding, moderator, and any cooling material. Explain how a reactor could be used to change nuclear energy into electrical energy or make things radioactive.
   c. Using a radiation survey meter and a radioactive source, show how the measurements per minute change as the source gets closer to or farther from the radiation detector. Place three different kinds of materials between the source and the detector, then explain any differences in the measurements per minute. Explain how time, distance, and shielding can reduce the radiation dose.
   d. Obtain a sample of irradiated and non-irradiated foods. Prepare the two foods and compare their taste and texture. Store the leftovers in separate containers and under the same conditions. For a period of 14 days, observe their rate of decomposition or spoilage, and describe the differences you see on days 5, 10, and 14.
   e. Describe how radon is detected in homes. Discuss the steps taken for the long-term and short-term test methods, how to interpret the results, and explain when each type of test should be used. Explain the health concern related to radon gas and tell what steps can be taken to reduce radon in buildings.
   f. Visit a place where X-ray is used. Draw a floor plan of the room in which it is used. Show where the unit, the unit operator, and the patient would be when X-ray is used. Explain the precautions taken when X-ray is used and the importance of those precautions.

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g. Make a cloud chamber. Show how it can be used to see the tracks caused by radiation. Explain what is happening.

h. Visit a place where radioisotopes are being used. Using a drawing, explain how and why they are used.

i. Obtain samples of irradiated seeds. Plant them. Plant a group of non-irradiated seeds of the same kind. Grow both groups. List any differences you observe during a 30-day period. Discuss with your counselor what irradiation does to seeds.

j. Visit an accelerator (research lab) or university where people study the properties of the nucleus. After your visit, discuss what you have learned with your counselor.

6. Do ONE of the following:

   a. Give an example of each of the following in relation to how energy from an atom can be used: nuclear medicine, environmental applications, industrial applications, space exploration, and radiation therapy. For each example, explain the application and its significance to nuclear science.

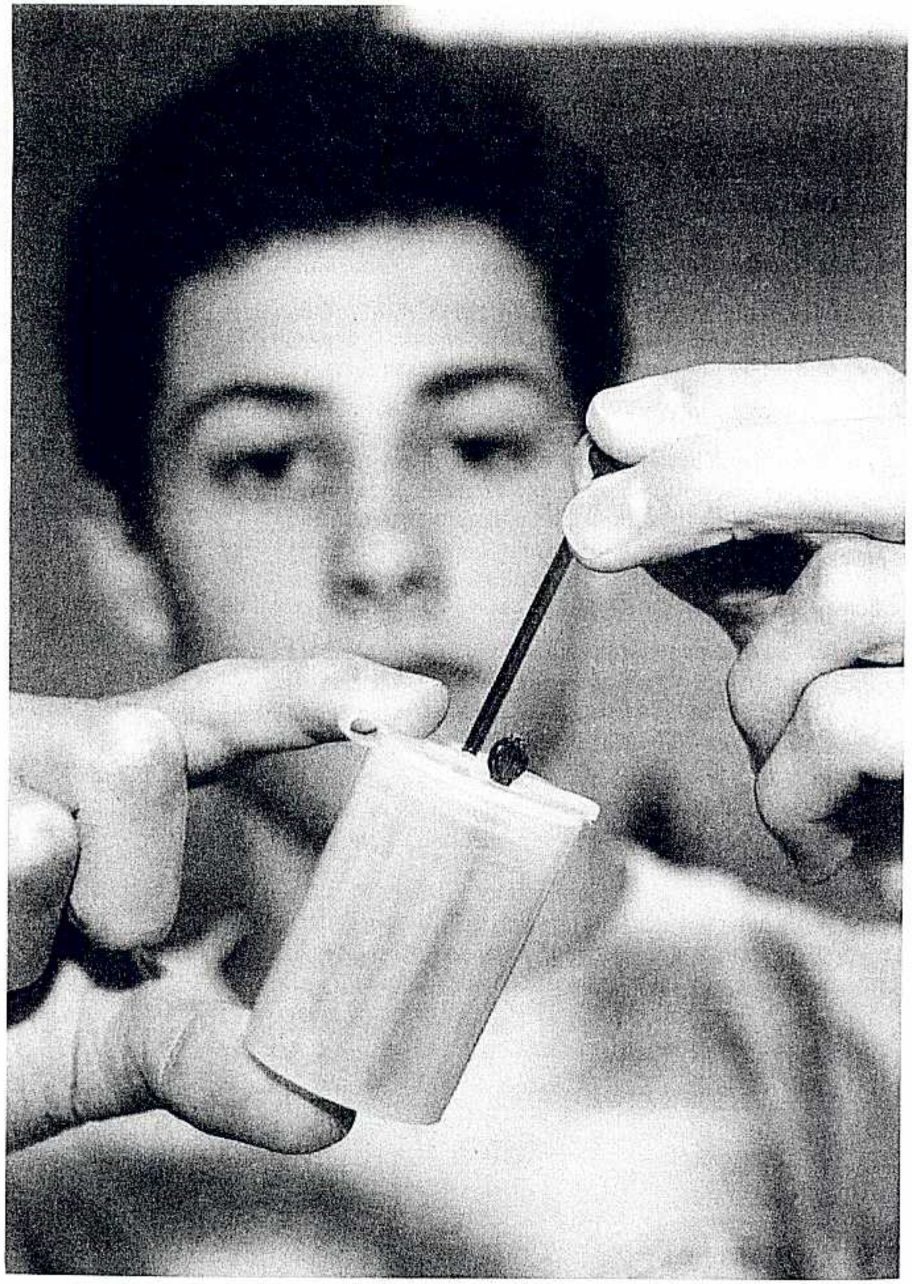
   b. Find out how many nuclear power plants exist in the United States. Locate the one nearest your home. Find out what percentage of electricity in the United States is generated by nuclear power plants, by coal, and by gas.

   c. Name three particle accelerators in the United States and describe the type of experiments each accelerator is designed to perform.

7. Find out about three career opportunities in nuclear science that interest you. Pick one and find out the education, training, and experience required for this profession and discuss this with your counselor. Tell why this profession interests you.



## Contents



# Nuclear Science: Going Beyond Chemistry

Science began when humans first sought to understand nature as the interactions of forces and matter. What causes seasons? What are stars? Why do we get sick? These questions once were dismissed as mysteries: Deities or spirits caused things to happen for reasons people could not understand. Science proposes to understand nature's materials and processes so we can predict and control events in our lives.

Over 2,000 years of science, researchers learned principles of matter and how it behaves. Within the last 200 years, we discovered that all substances are made of about 100 elements—each made of a unique kind of atom. Studying the characteristics of atoms and their interactions became the field of chemistry.

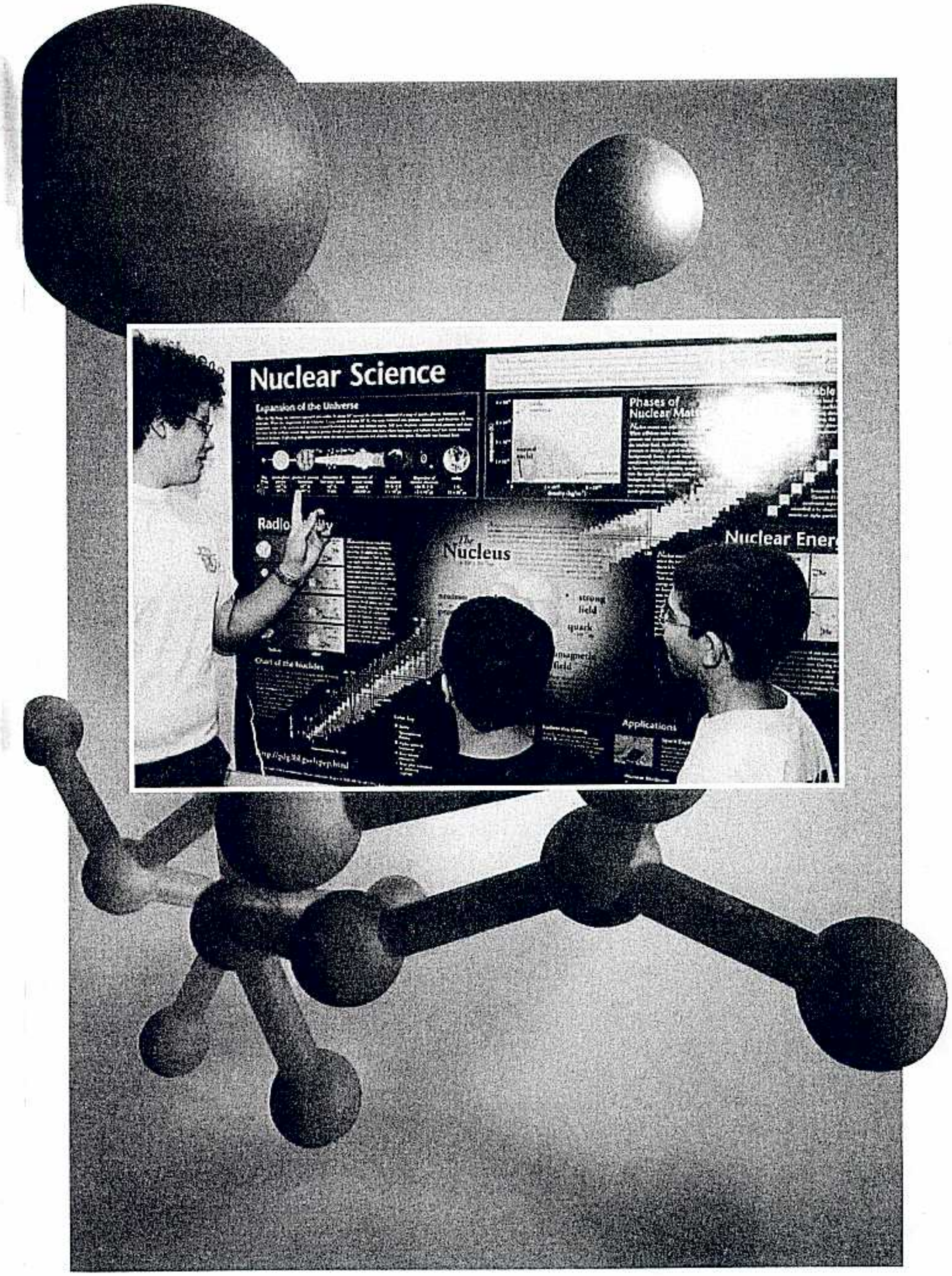
Physicists continued to try to understand the structure of atoms. They learned that all atoms are made of a few *subatomic* particles. Some atoms transform and give off *radiation*. Investigators moved atoms around using electrical charges and shot atoms or parts of atoms into each other, broke atoms down, and built them up. They built huge machines to break atoms apart to study their subatomic particles.

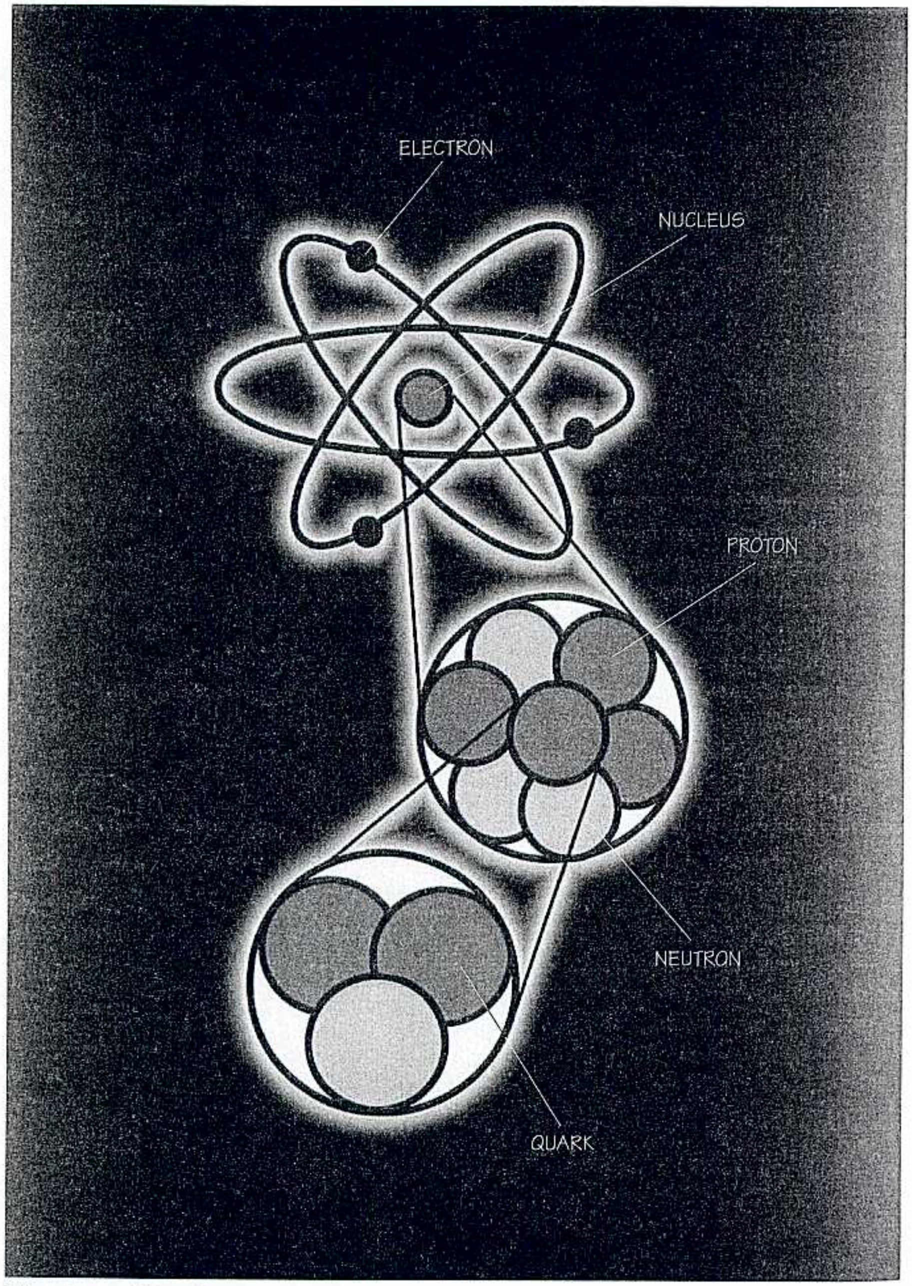
The study of atomic structure is still a part of the field of nuclear science. Nuclear science also

- Investigates natural and manufactured radiation—how they are produced and their practical uses
- Explains the principles applied to protect people from radiation
- Examines how atomic nuclei behave when they join together or split apart
- Seeks to understand the processes that occurred at the very beginning of the universe

Just as with science in general, nuclear science gives us a simpler—and at the same time more interesting—explanation of the natural world. The ultimate goal of nuclear science is to find out if there is one fundamental rule that explains how matter and forces interact. Earning the Nuclear Science merit badge is a chance for you to learn about this exciting field at the cutting edge of science today.

It doesn't take a nuclear physicist to understand the basics of nuclear science. A little background in chemistry and physics will help, but even for the nonscientific Scout, the Nuclear Science merit badge lies well within grasp.






**Structure of an atom**

# Atoms Then and Now

The first scientists to discuss atoms were Greeks who lived about 400 B.C. A Greek teacher, Leucippus, taught his students about atoms. His most famous student was Democritus. The Greeks believed that if you cut a piece of copper, and cut it again and again many times, you would finally end up with a piece of copper that could not be cut. This would be an *atom* of copper.

Democritus believed (mistakenly) that atoms were held together by little hooks.

An *atom* is the smallest piece or unit of an element having the properties of that element. *Elements* are fundamental substances that can't be broken into simpler substances by chemical means. Familiar elements include hydrogen, oxygen, iron, and gold. Each element consists of one basic kind of atom.

Many early scientists and philosophers did not believe the theory of atoms. Even Aristotle, one of the greatest thinkers in history, said there was no such thing. But the idea would not go away. The Roman philosopher Lucretius (circa 99–55 B.C.) wrote about nature and mentioned atoms in his Latin poem called *De Rerum Natura (On the Nature of Things)*.

Many scientists wrote in poems because there were few books, and poems were easier to remember.

Centuries passed, and atoms remained a part of scientific thought. In the 1500s and 1600s, well-respected men like Copernicus, Galileo, Francis Bacon, and Sir Isaac Newton began to disagree with the great Aristotle. They believed that atoms exist.

## John Dalton's Theory of Atoms

By 1803, an English schoolteacher had done much work to prove that atoms exist. He was the first to show how atoms work and to estimate the relative masses of different atoms. He added much to what scientists knew. John Dalton used his theory of atoms to explain how chemical reactions work.

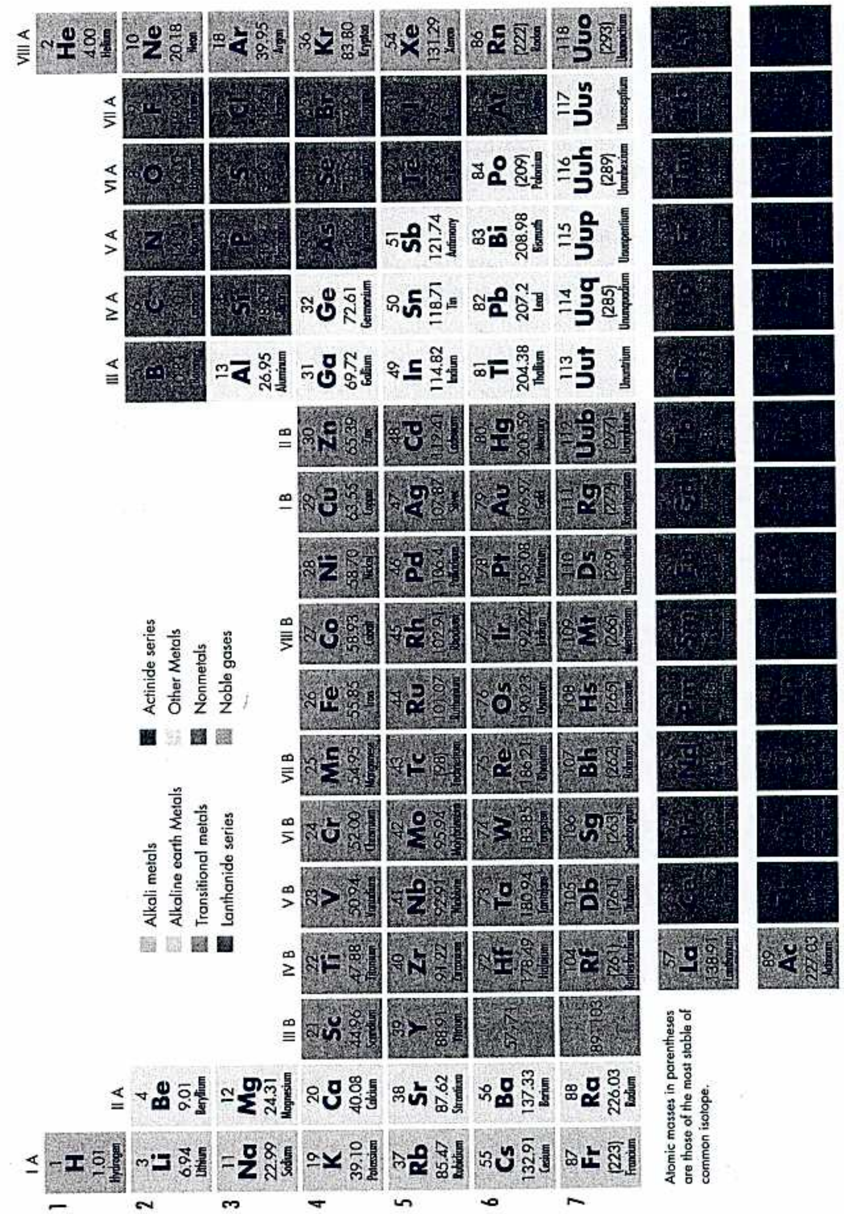
> Atoms are the smallest bit of an element. Different elements have atoms of different masses. (*Mass* is the quantity of matter that something contains. Your mass is always the same, while your weight might change if you go to a different place. In space, for instance, your weight would be zero, but your mass would be the same as it is on Earth.)

Amedeo Avogadro was an Italian who came up with a better way of measuring the mass of atoms. He showed that Dalton was on the right track but had made mistakes. Avogadro was a good scientist but not a good writer. Nobody understood much about his work until another Italian, Stanislao Cannizzaro, explained Avogadro's work in 1858.

> What Avogadro discovered the hard way in the 1800s—that scientists must be able to write clearly if they want others to understand their findings—is still true today.

Cannizzaro also added a new word to science: *molecule.* A molecule is what forms when atoms combine.

By the 1870s, scientists everywhere were studying atoms. In Russia, Dmitri Mendeleev put all atoms on a chart and showed that atoms could be divided into groups according to their similarities. Some of his ideas were wrong, but other scientists corrected his chart, and today it is known to scientists and students as the highly useful *periodic table* of the elements.




**The periodic table of the elements lists all the elements arranged by atomic number. Elements are grouped to show similar chemical characteristics.**

Any process that gives atoms an electric charge is called *ionization.*

## The Discovery of Ions and Electrons

Researchers continued to study the nature of atoms. Svante Arrhenius of Sweden found that some atoms carry an electric charge. These atoms could move through water and cause chemical reactions. He named them *ions,* from the Greek word for "traveler."

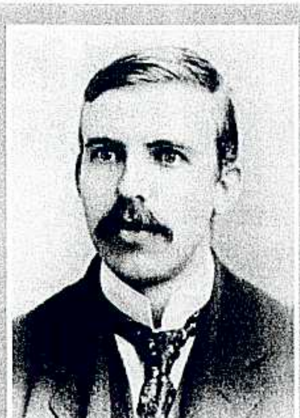
The Irish physicist G. Johnstone Stoney believed that electric current was actually the movement of extremely small, electrically charged particles. In 1891, he suggested these particles be called *electrons.* Electrons have a negative electric charge.

In 1897, British physicist J. J. Thomson proved the existence of electrons and showed that all atoms contain them. He believed (mistakenly) that the electrons were stuck in the atoms like raisins in a cake and (correctly) that ions were made when an atom had either too many or too few electrons.

## Isotopes—Alike but Different

Scientists learned more by studying different kinds of atoms. In 1903, Frederick Soddy was studying lead atoms in England. He found that there were three different forms of lead. Three different atoms all acted chemically like lead, but they had different masses.

Soddy named atoms of the same element with different masses *isotopes,* meaning "same place" in Greek. Though these atoms had different masses, they were in the same place on Mendeleev's chart.



**Sir Ernest Rutherford** (1871–1937) has been called the "father of nuclear physics." He discovered and named some of the field's fundamental concepts: alpha, beta, and gamma rays; the nucleus; the proton; and an element's half-life. In 1908, Rutherford won the Nobel Prize in chemistry for showing that radioactive elements actually become other elements when they decay—a finding that startled the scientific world. Most important was his discovery of the nucleus, the atom's core.



## Parts of the Atom

At about the same time, a scientist from New Zealand was making the first of his many important discoveries. Ernest Rutherford found that most of an atom is empty space with a tiny core in the center. He called this core the *nucleus* (plural, *nuclei*). Rutherford described the nucleus as being the middle of the atom, with the electrons going around the nucleus much like a swarm of bees.

By 1913, Danish physicist Niels Bohr had a new picture of the atom. He put the nucleus in the middle with the electrons traveling in many rings or orbits around it, like the orbits of the planets around the sun. Bohr's original model made a major advance in the understanding of the atom. It shows that the more energy an electron has, the farther from the nucleus the electron will be.

Some of Bohr's ideas had to be modified. By 1928, physicists had a more correct picture of the arrangement of electrons, thanks largely to the work of Erwin Schrodinger and Wolfgang Pauli of Austria and Max Born and Werner Heisenberg of Germany. Their work showed that electrons do not move in fixed orbits. Electrons travel in an unpredictable manner, but the general shape of an electron's movement does follow a pattern. One pattern is a sphere, while another is a dumbbell shape. The shape of the movement depends on the electron's energy and the type of *shell* the electron is in.

Also about 1913, Henry G. J. Moseley of England found a way to count the number of positive electric charges in a nucleus. He called the number of charges the *atomic number* of the atom.

Ernest Rutherford predicted scientists would soon find a piece of an atom that carried one positive charge. Rutherford proved himself correct with his discovery of the *proton* in 1914.

An electron *shell* is the region around the nucleus in which electrons of the same energy move.

The *atomic number,* or *Z,* is the number of protons in the nucleus of an atom. The number of protons determines the kind of element.

## The Neutron

During this period, William Harkins of the United States and Antoine-Philibert Masson of Australia were working on a big question. Why was Moseley's atomic number different from atomic mass? Rutherford read their work, did some of his own, and in 1920 said scientists would find a particle in the nucleus with no electrical charge.

Many experiments looked for the predicted neutral particle. Rutherford tried a new experiment with James Chadwick of England. It failed. Finally in 1932, 12 years after Rutherford's prediction, Chadwick found the *neutron*—a particle of an atom with no electric charge, about equal in size to a proton.

After the neutron's discovery, Werner Heisenberg suggested the nucleus was made of only protons and neutrons. Niels Bohr changed his model. Now he believed the nucleus was made of protons and neutrons and the electrons went around the nucleus in shells.

The discovery of the neutron gave scientists another way to describe an atom. The total number of protons and neutrons of an atom is the *mass number.* Isotopes, therefore, are atoms with the same atomic number (the same number of protons) but different mass numbers (different numbers of neutrons).

Today, the term *atomic mass* is used in place of the older term "atomic weight." It is the actual mass of the nucleus. The sum of the protons and neutrons in the nucleus of an atom is called the *mass number,* or *A.* If you round the atomic mass to the nearest whole number, that value is equal to the mass number. Oxygen, for example, with eight protons and eight neutrons, has a *mass number* of 16, while its *atomic mass* is 15.99491461 AMU (atomic mass units).

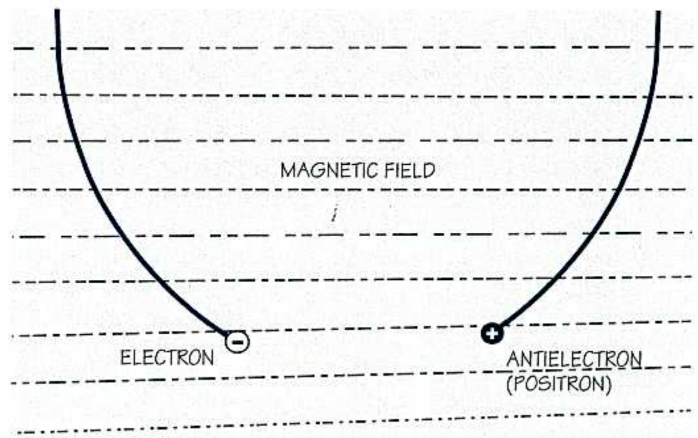
## What We Now Know

Recent decades have brought more discoveries about atoms. Giant *particle accelerators* bigger than city blocks explore the unseen world of the very small. Tiny particles that make up large particles have been identified. Almost undetectable "ghost" particles that zip through matter have been tracked down.

## Antimatter

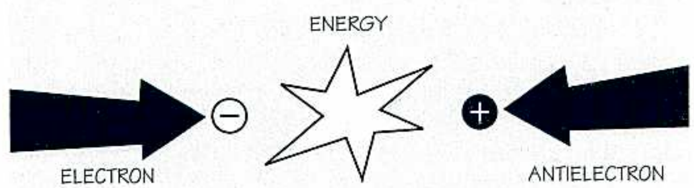
Even *antimatter* has been found to exist in the real world, not just in science fiction. In 1928, at age 26, theoretical physicist Paul Dirac wrote that for every kind of matter there existed an equal and opposite antimatter. He stated that when matter and antimatter came together, both would disappear. The only trace of their mutual annihilation would be a burst of energy left behind.

Dirac's prediction alerted scientists to the possibility of finding antimatter. In 1932 at the California Institute of Technology, Carl Anderson was studying cosmic ray *cloud chamber* photographs. One picture was of an electron that turned the wrong way. This *antielectron* behaved exactly the opposite of a normal electron. Anderson called it the *positron* because of its positive charge. (Normal electrons are negatively charged, remember.)




**Antimatter behaves exactly the opposite of its matter counterpart.**

Other scientists tracked down more antiparticles, and people began to wonder about the possible existence of antiworlds, antistars, or even an antiuniverse. Antimatter could be a tremendous source of energy. A tiny piece of matter meets an equal amount of antimatter, and *POW!*—no ashes, no waste, just pure energy.




**When matter meets antimatter, they both disappear in a burst of energy.**

**Richard Feynman** (1918–1988) is considered one of the most influential physicists of the 20th century. He described how charged particles (and their *antiparticles*) interact through *electromagnetic* force. To analyze these particle interactions, he developed diagrams and mathematical procedures to reveal their relationships. He shared the 1965 Nobel Prize in physics with S. I. Tomonaga and J. Schwinger.

## Neutrinos

In 1930 Wolfgang Pauli predicted a ghost particle that had no charge and almost no mass. Detecting it would be difficult because it didn't seem to "do" anything—unlike the electrically charged *alpha particles* and *beta particles,* which leave behind them a detectable trail of ions.

It took 26 years before Fred Reines and Clyde Cowan gathered hard evidence that *neutrinos,* the ghost particles, really exist. Six years later, in 1962, Leon Lederman, Melvin Schwartz, and Jack Steinberger used the Brookhaven National Laboratory accelerator to discover two types of neutrinos.

Neutrinos can pass through solid matter with only a slight chance of a collision. A beam of neutrinos can travel completely through Earth without losing intensity. The ability of neutrinos to penetrate matter makes them useful in the study of nuclear particles. Using particle accelerators, physicists have learned much about the makeup of neutrons and protons by observing rare collisions between neutrinos and atomic nuclei.

## The Modern Nucleus

In the years since Rutherford discovered the nucleus, physicists have learned that atomic nuclei come in many sizes and shapes. They can be round like a tennis ball or shaped like a football. On Earth, nuclei vary in size from hydrogen, with one proton, to uranium, with 238 protons and neutrons.

We know that protons and neutrons constantly move about inside the nucleus in different shells. Maria Goeppert-Mayer and J. Hans D. Jensen, cowinners of the 1963 Nobel Prize in physics, created the *nuclear shell model* to explain many of the nuclear properties. According to this model, nuclei "like" to have their shells filled. When a shell is filled, we say it has reached a "magic number." Magic nuclei are much more stable than their neighbors.

Often the nucleus behaves as if it were a raindrop. It can vibrate or, if shaped like a football, spin. Aage Bohr and Ben Mottelson described the motions of the nucleus and shared the 1975 Nobel Prize in physics for their work on the structure of the nucleus.

A *nuclide* is a nucleus that exists for a measurable length of time.

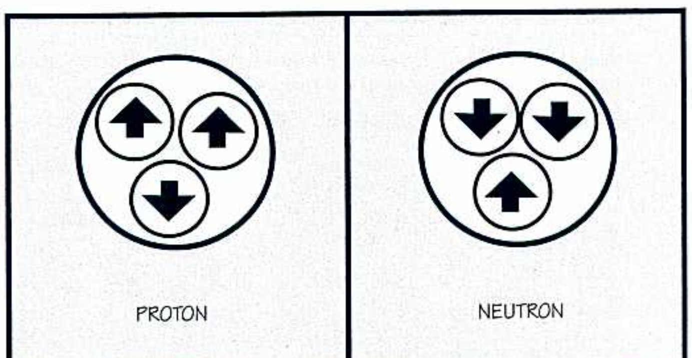
## Quarks and Gluons

In 1964, Murray Gell-Mann and George Zweig of the California Institute of Technology proposed that protons and neutrons were not *elementary* particles—they could be broken down further. Using particle accelerators, researchers shattered protons and neutrons into pieces Gell-Mann named *quarks.* In 1990, Jerome Friedman, Henry Kendall, and Richard Taylor shared the Nobel Prize in physics for showing that protons and neutrons do indeed have much smaller particles—quarks—inside them.

*Elementary particles* have no known smaller parts. Quarks, electrons, and neutrinos are elementary particles. Electrons and neutrinos belong to a group called *leptons.* They have no measurable size; physicists describe them as "pointlike."

Quarks comprise the protons and neutrons that make up the nucleus of every atom. Experiments have identified six quarks: *up* and *down*, which make up most everyday matter; and the much heavier *top, bottom, strange,* and *charm* quarks, which are unstable. Protons consist of two *up* quarks and one *down* quark. Neutrons have two *down* quarks and one *up* quark. Particles called *gluons* keep the quarks from flying away from each other. The theory of gluons and quarks as the building blocks of matter is the current theory of the structure of matter.

David Gross, David Politzer, and Frank Wilczek won the 2004 Nobel Prize in physics for showing how the attraction between quarks is strong when they are far apart but weak when they are close together. This discovery showed that a gluon provides the force that keeps quarks bound inside a nucleus and the force that keeps all nuclei together. The work is an important step toward providing a unified description of all the forces of nature, from the tiny distances within the atomic nucleus to the enormous expanse of the universe.



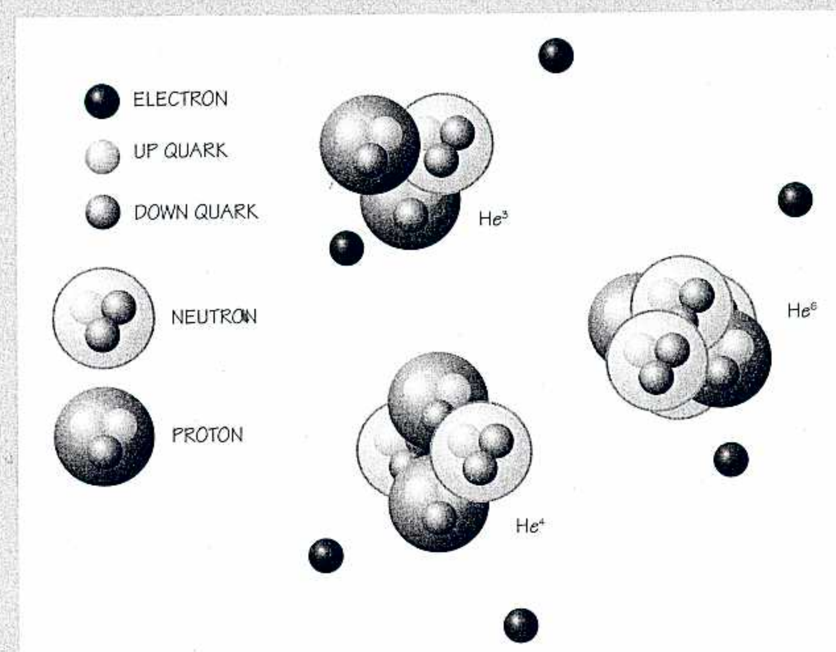

**Quarks form the fundamental building blocks of protons and neutrons. Gluons keep the quarks together.**

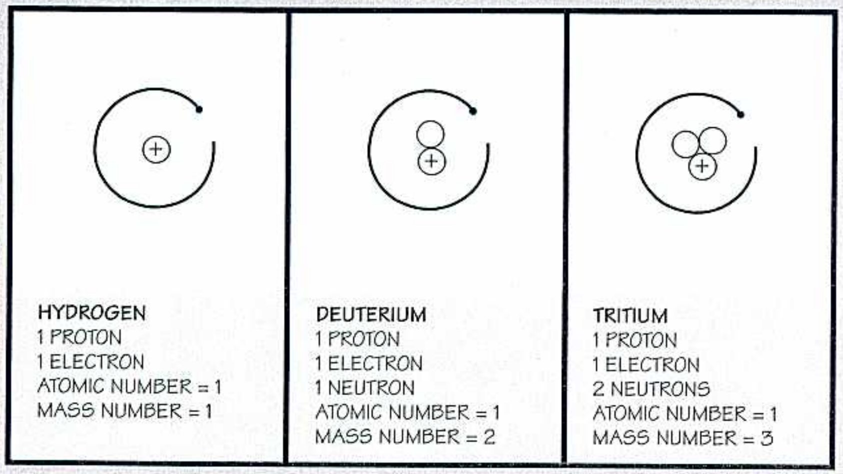
## Make 3-D Models of Isotopes

Models that can be touched are called *physical models.* You will make physical models of isotopes to help explain to your merit badge counselor the difference between mass number and atomic number.

Begin by studying pictures of the three isotopes of hydrogen. Hydrogen is the simplest and lightest element. Ordinary hydrogen has one proton, one electron, and no neutrons. In the two other hydrogen isotopes, the nucleus has one or two neutrons in addition to the proton.

Now use your imagination (and whatever materials are handy) to make a 3-D model of each isotope. One way would be to use table-tennis balls for protons and neutrons, which are big (compared to elementary particles) and about the same size. Darken or color the balls that represent neutrons. In the deuterium and tritium models, stick the protons and neutrons together tightly.






To represent the quarks that make the protons and neutrons, you can use marbles of two different colors—green for *up* quarks, for instance, and blue for *down* quarks. In each hollow table-tennis ball, cut a hole the size of a marble. For each proton, put two green marbles and one blue marble inside the ball. Push two blue marbles and one green marble into each neutron. (To help you remember which is which, label the green marbles *u* and the blue marbles *d*.) After inserting the marble quarks, cover the holes in the balls with clear tape.

Modeling the electron may be tricky. Electrons are constantly moving like race cars on a track. Also, electrons move very far from the nucleus. You would need to put the electron on the other side of your town to show the proper distance.

If you can't figure out a good way to represent the electron's movement around the nucleus, just use a piece of wire or a clear plastic drinking straw to attach the electron to your model. You might use marbles or candies for the electrons, which are much smaller than the protons and neutrons. The electron is so small that no one has ever been able to measure its size.

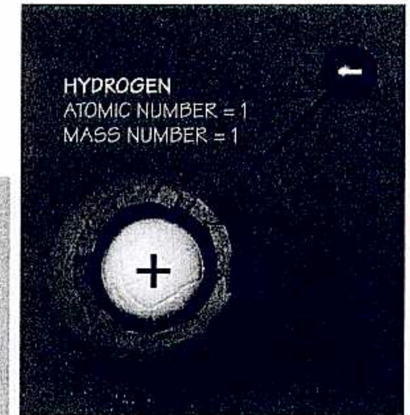
When you display your models to your counselor, be prepared to show that you understand the terms *nucleus, proton, neutron, quark, electron, isotope, atomic number,* and *mass number.* Also show that you know the electron is constantly moving, and (despite the straw or wire in your model) isn't physically fastened to the nucleus.

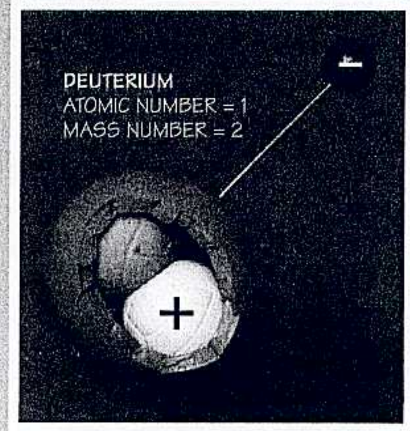


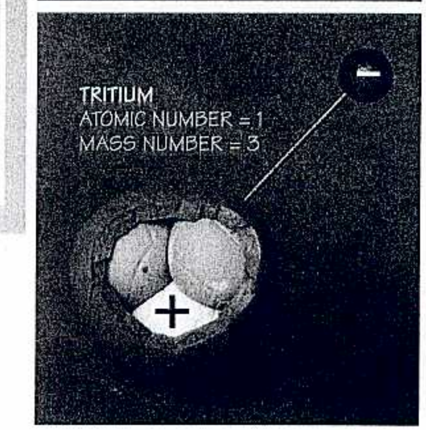
You might try other materials to make your models, such as balls of clay, painted balls of polystyrene foam, or different-sized marshmallows or candies. You could even bag the quarks in plastic wrap—some physicists describe protons and neutrons as "bags" containing quarks.

If you wish, you can make models of three isotopes of an element other than hydrogen. Try carbon-12, carbon-13, and carbon-14. These models will be considerably bigger and will require more materials than models of hydrogen.

In the nucleus of a real atom, extremely strong forces hold the protons and neutrons together. A huge amount of energy is concentrated in the nucleus because of these strong holding forces.



# Learn About Particle Accelerators

Particle accelerators, sometimes called atom smashers, are machines that can create beams of electrically charged particles and accelerate them to nearly the speed of light. This acceleration increases the particles' energy of motion. Think of the difference between catching a baseball that is gently underhanded to you and catching a fastball fired at you by a major-league pitcher. Energy is the universal container that holds things together. If you want to break open a container such as an atom or a proton to see what's inside, you must overcome that container's energy. From accelerators, scientists get the energy they need to break open and explore the makeup of atomic and subatomic particles.

**The Tevatron** at Fermi National Accelerator Laboratory (Fermilab, for short) in Batavia, Illinois, is the world's highest-energy particle accelerator and collider. Scientists use the Tevatron to smash beams of protons and antiprotons into one another. From out of the tiny cataclysmic fireballs come new clues about the most basic building blocks of matter and the forces acting on them.

**The Relativistic Heavy Ion Collider** at Brookhaven National Laboratory on Long Island in Upton, New York, is the world's largest facility for nuclear physics research. It is designed to accelerate ions to *relativistic* (near-light) speeds and smash them together. The goal is to re-create the super-hot, ultradense, souplike form of matter, called a *quark-gluon plasma,* that existed in the universe's first microseconds and set the stage for the formation of the universe as we know it.

**The B Factory** at the Stanford Linear Accelerator Center in Menlo Park, California, is used to accelerate and smash together beams of electrons and their antimatter counterparts, positrons. However, these two colliding beams are asymmetric, meaning they are not of equal energies, unlike the colliding beams of RHIC and the Tevatron. The asymmetric B Factory is designed to produce large quantities of *B mesons,* subatomic particles containing a *bottom quark.* Studying B mesons may help us know why the formation of matter was favored over antimatter in our universe.



**The Thomas Jefferson National Accelerator Facility (Jefferson Lab)** in Newport News, Virginia, is a fixed-target accelerator that creates a continuous stream of high-energy electrons. The machine steers the electrons into a nuclear target, which then shatters into smaller particles. Scientists analyze these fragments to measure and study the quark content of the nucleus.

Other particle accelerators operate at universities and national laboratories across the United States. Your counselor can help you find one to visit.

During your visit, ask questions. These will get you started.

- How does the accelerator work? Is it a linear accelerator (linac, for short) or a circular accelerator? What type of particles does it accelerate?
- How much energy does it take to run the accelerator?
- What type of experiments is this machine designed to do?
- What are the most exciting discoveries that have been made here?
- What types of people work here? What is it like to work here? What training do you need to get a job here?
- Are there radiation hazards around this machine? Why or why not? How are people protected from potential hazards?