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ABSTRACT

This book is one in a series of Interdisciplinary Approaches to Chemistry (IAC) designed to help students discover that chemistry is a lively science and actively used to pursue solutions to the important problems of today. It is expected for students to see how chemistry takes place continuously all around and to readily understand the daily problems facing them and their environment. Contents include: (1) "Basic Properties of Matter"; (2) "The Makeup of Our Solar System"; (3) "Nucleosynthesis and Stellar Evolution"; (4) "Radioactive Decay"; (5) "The Search for New Elements"; (6) "Uses of Radiation"; and (7) "Nuclear Power". (KHR)

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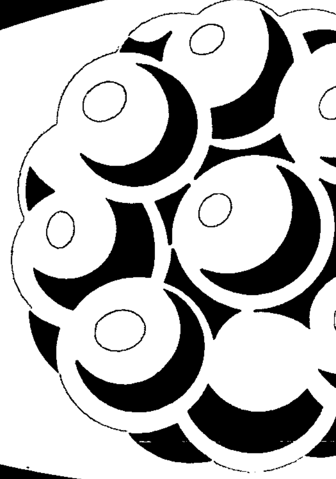
IAC

THE HEART OF MATTER

A NUCLEAR CHEMISTRY MODULE



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Vic Viola

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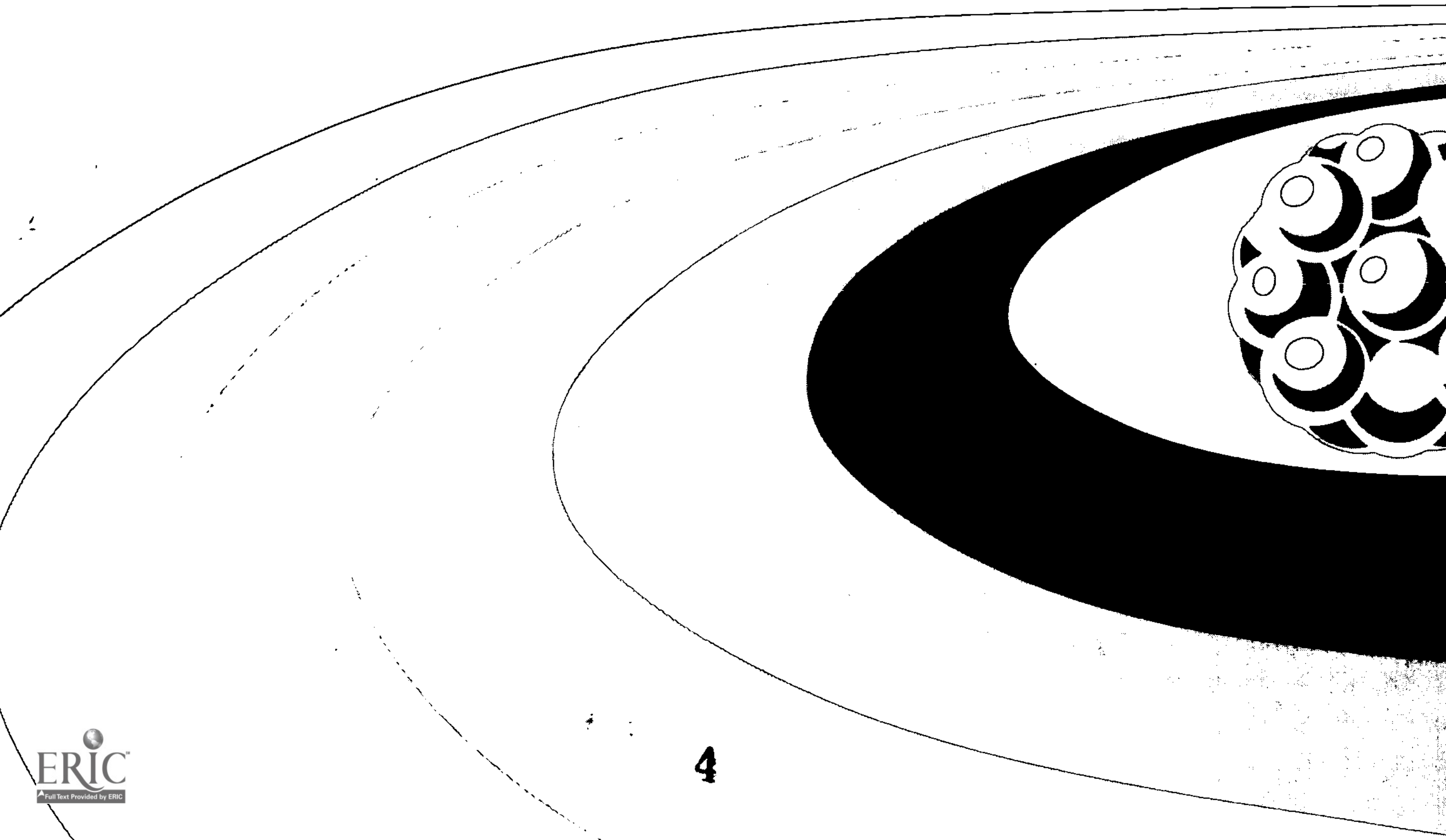

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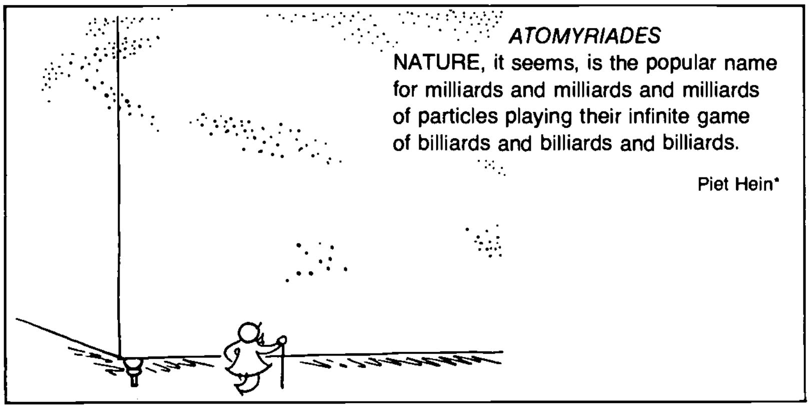
THE HEART OF MATTER:
A NUCLEAR CHEMISTRY MODULE

VIC VIOLA

Something funny happened to Vic Viola on the way from Abilene to Lawrence, Kansas. He wanted to be the "fastest pen" from Abilene to hit any school of journalism west of the Mississippi. Instead, Vic became the "fastest gun" with a cyclotron. His deadly aim with protons and alpha particles has won him a well-deserved reputation among his peers.

Some of his current research interests are studies of the origin of the elements lithium, beryllium, and boron in nature and their relation to theories of the expanding Universe. In addition he investigates nuclear reactions initiated by very heavy nuclei, such as krypton and xenon.

Busy as Vic is—playing with the Maryland cyclotron, teaching a class, writing a research report or a high-school chemistry module—he still finds time to jog a few miles every day. If you have any questions for Vic, your best bet may be an ambush as he rounds the dogleg on the seventh hole of the Maryland golf course.



ATOMYRIADES

NATURE, it seems, is the popular name
for milliards and milliards and milliards
of particles playing their infinite game
of billiards and billiards and billiards.

Piet Hein*

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PREFACE

Welcome to IAC Chemistry. Enjoy this year as you explore this important area of science. Chemistry is to be enjoyed, cultivated, comprehended. It is part of our culture, of our everyday lives.

Polymers, paints, pharmaceuticals, people, and pollution all have something in common—a chemical base. IAC Chemistry is relevant, interdisciplinary, student centered, and filled with important concepts and processes.

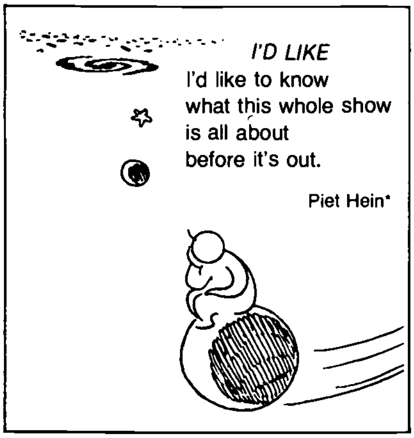
IAC will help you discover that chemistry is a lively science and being actively used to pursue solutions to the important problems of today. You will see how chemistry is taking place continuously all around. You will more readily understand the daily problems facing you and your environment.

Students throughout this country and in a number of other countries as well have let us know that they like and learn from the IAC modules. Classroom teachers have suggested changes to make them even better.

Since the IAC authors believe that student involvement in chemistry is very important, there are many activities that allow you to develop and apply chemistry concepts directly. We have tried to make the modules flexible, easy to read, and enjoyable, discussing everyday problems and adding a bit of humor that may help you remember some of the more important ideas. The Time Machines are intended to give you a sense of when the more important discoveries in chemistry happened in relation to other events.

Wonder—inquire—investigate. Think through all that you find here. But most of all—enjoy chemistry as you learn about the atoms, molecules, elements, and compounds that make up your universe. IAC is written for your learning pleasure.

Marjorie Gardner
Director, 1976–79
Interdisciplinary Approaches to Chemistry



I'D LIKE

I'd like to know
what this whole show
is all about
before it's out.

Piet Hein*

© 1966 by Piet Hein

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*Piet Hein is a Scandinavian poet who often served as a "mental Ping-Pong partner" for the famous chemist Niels Bohr.

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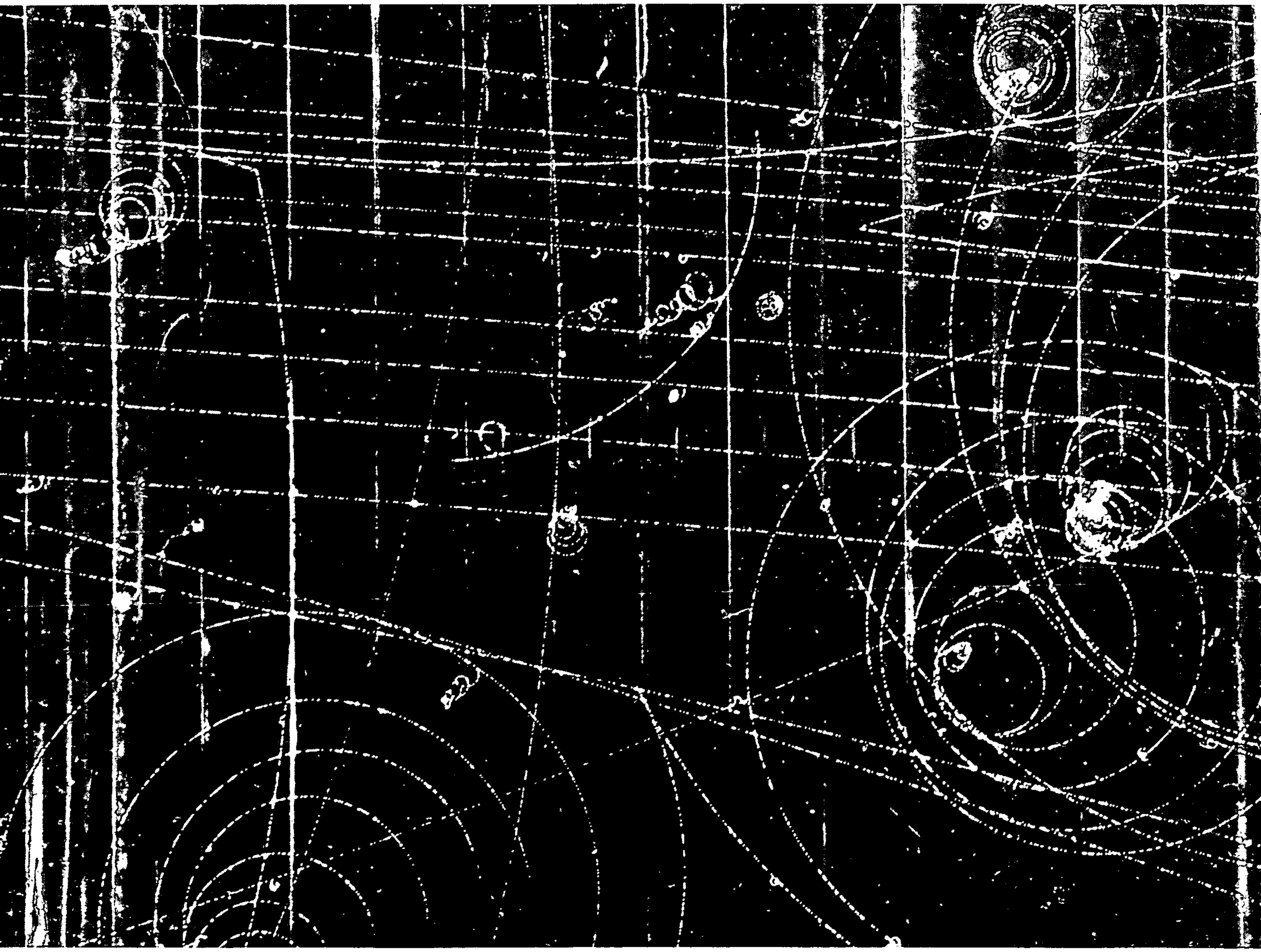
Basic Properties of Matter

How did the chemical elements in our environment come into existence? Are the elements that we find on Earth present everywhere in our solar system or in the Universe? When were the elements formed? These fundamental questions have stimulated the human imagination since the times of ancient philosophers, and they remain equally fascinating to scientists today.

The fundamental particles of matter are too small to be seen even with the most powerful microscopes. However, scientists can study these particles indirectly by using devices such as the "80-inch" Liquid Hydrogen Bubble Chamber at Brookhaven National Laboratory. The patterns in the photograph are tracks left by particles passing through the chamber.



Democritus *(above)* believed that all the matter in the Universe is made of indivisible particles, which he called atoms.

N-1 Elements: A Question of Beginning

The present-day search for answers to questions about the origin of the chemical elements has the advantage of years of research in many areas of science, such as chemistry, physics, astronomy, and geology. From the information that has been gathered, it is now possible to piece together a self-consistent *theory* to explain the formation of nature's elements. As you might imagine, given the great complexity of our Universe, this is not a simple task. Even today there is not complete agreement on all parts of the existing theory. Furthermore, even if a theory were proposed that would satisfy everyone, we could still not be sure it was correct. Why? Because it will never be possible to go back to the time when the elements were formed to check the evidence. Nonetheless, great progress has been made in the past twenty-five years toward the development of such a theory. It is the purpose of this module to discuss this theory as it now exists.

In order to discuss the origin of the elements, we must first consider the basic properties of matter. That is, what are the simplest particles and forces that can be used as the building blocks and binding substances of the elements? Next, the behavior of atomic nuclei must be considered, for *it is the nucleus that determines whether or not an element can exist in nature and what its chemical characteristics will be.* Also, is it possible that unknown "superheavy elements," beyond the known elements, exist in nature?*

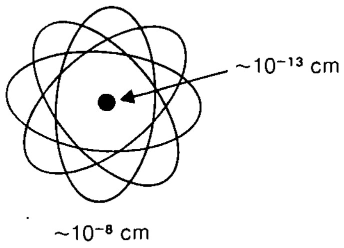
We must also consider the conditions present in stars, for we believe it is in the stars that the elements are synthesized. In describing nature's element-building processes, many other phenomena and applications are also encountered. Radioactivity, synthetic elements, nuclear reactors, and particle accelerators enter into the investigations of scientists. Whenever it is appropriate, we will include these subjects in our story of the origin of the elements.

Table 1: Comparative Sizes

Nuclei	$\sim 10^{-13}$ cm
Atoms	$\sim 10^{-8}$ cm
Bacteria	$\sim 10^{-3}$ cm
Person	$\sim 10^{2}$ cm
Earth	$\sim 10^{9}$ cm
Sun	$\sim 10^{11}$ cm

N-2 From the Smallest to the Largest

In our investigation of the origin of the elements we will discuss both the smallest and the largest objects known today—nuclei and stars. We can gain a perspective on the size of nuclei by examining their relationship to atoms. A simple way to do this is to imagine an atom to be the size of a baseball field. On that scale the nucleus of the atom would be about the size of a pinhead located somewhere around second base. In other words, the nucleus is about



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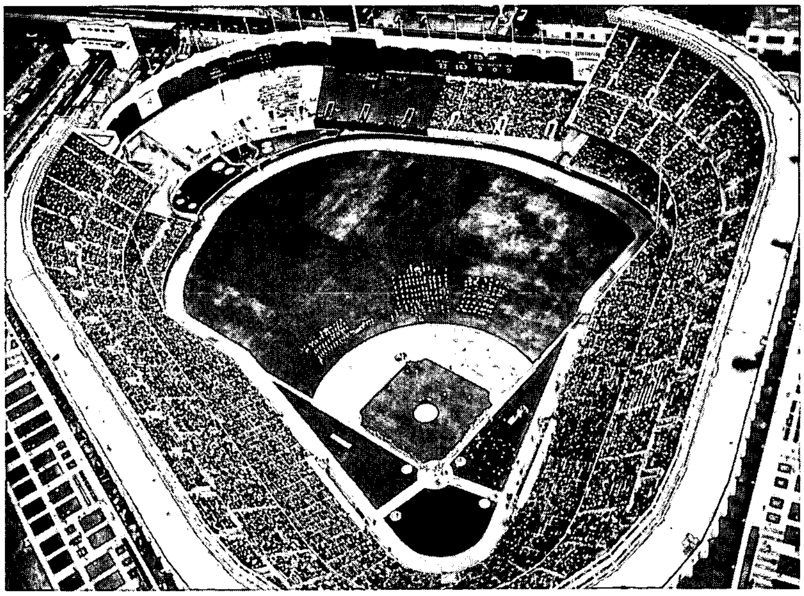
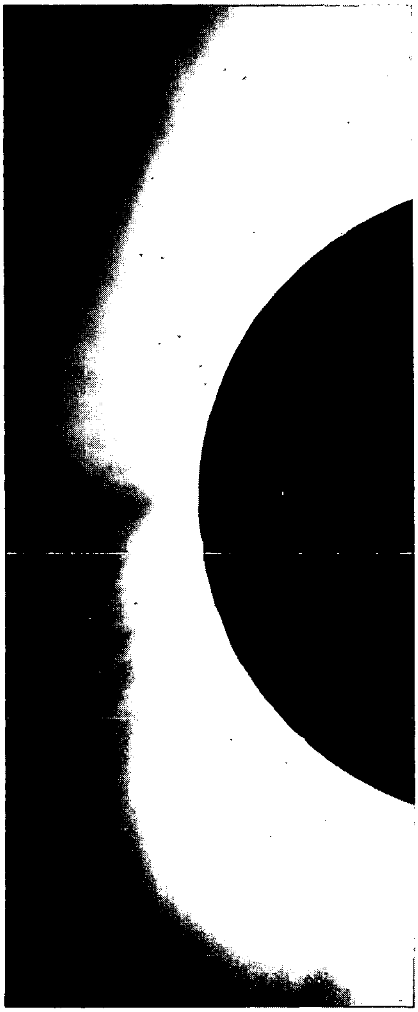
*See the *Periodic Table of the Elements* and the *Table of International Relative Masses* at the end of this module for an up-to-date listing of the elements.



A solar eclipse *(below)*, in which the moon passes in front of the Sun, dramatically illustrates the energy of the Sun's corona.

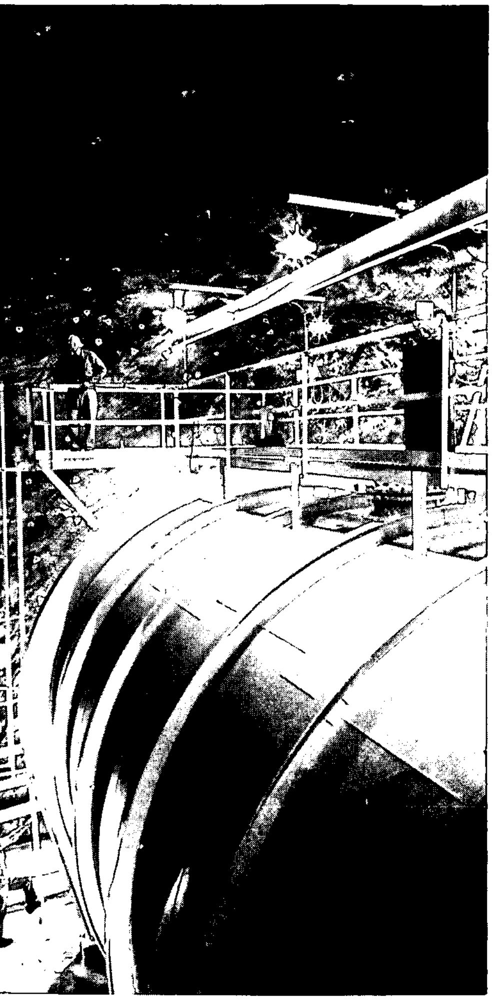


one hundred thousand times smaller than the whole atom (Table 1). A similar comparison can be made of the sizes of atoms and bacteria, or of the sizes of bacteria and a person. An atom is one hundred thousand times smaller than a bacterium. Similarly, a bacterium is one hundred thousand times smaller than a person. You could continue calculating in this manner to determine the size relationship between a nucleus and a star.

Scientists believe that most nuclei are synthesized by means of nuclear reactions that occur in stars such as our Sun. The term *stellar nucleosynthesis* is used to describe this process. To prepare for our study of nucleosynthesis, we must discuss further the structure of the atom and determine something about the simplest particles that are the "building blocks of matter." We will call these building blocks the *fundamental particles*. Next, we must also consider the "glue" that holds these building blocks together—that is, the forces that act upon the particles. Finally, it is important to consider the way these particles and forces interact with one another. A knowledge of these interactions is important, especially in studying the stars, where all kinds of processes can occur.

N-3 Fundamental Particles: Building Blocks

Among the most important fundamental particles for the purpose of our discussion are the *proton, neutron, electron,* and *photon* (Table 2). Protons and neutrons are the essential parts of atomic nuclei. Electrons combine with nuclei to form atoms. Photons, on the other hand, do not exist in atoms and nuclei but are produced when atoms and nuclei undergo changes from one form to another. The



This apparatus, which is about 1500 meters below the Earth's surface, helps scientists study solar neutrinos. While other particles are shielded from the tank by the Earth, neutrinos can be trapped in it for study.

photon is a type of radiation that has many names, depending upon its energy. Light rays are low-energy photons and X rays are high-energy photons; both are emitted from atoms. *Gamma rays* are still higher-energy photons emitted from nuclei. We will expand on our discussion of photons later in this module.

Table 2: FUNDAMENTAL PARTICLES INVOLVED IN STELLAR NUCLEOSYNTHESIS

Particle	Symbol	Mass		Electric Charge	Half-life
		u	*g*		
Proton	*p* or H	1.007 8252	1.6734×10^{-24}	+1	stable
Neutron	*n*	1.008 6654	1.6748×10^{-24}	0	12.8 min; stable inside nuclei
Electron	e	0.000 5486	9.1095×10^{-28}	−1	stable
Photon	depends on energy	0	0	0	stable

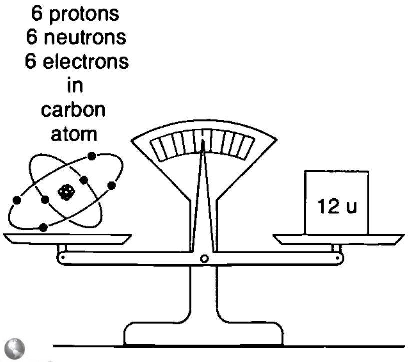
Note: For convenience, the mass of the proton listed here is actually that of the ^1_1H atom, that is, the proton plus an electron.

Although other so-called fundamental particles, such as mesons, neutrinos, and hyperons, have been observed experimentally, they are not essential to our discussion. One exception is the *positron*, which is an electron with a positive charge. The positron is an example of an *antiparticle* (a particle that has properties exactly the opposite of those of a normal particle). Antiparticles exist only under very special conditions. The positron will be discussed further in section *N-27*.

Three properties make it possible to distinguish one fundamental particle from another. These properties are *mass, electric charge,* and *half-life*. The *mass* of each of the particles is an extremely small number when expressed in grams. Consequently, it is helpful to express this quantity in terms of a unit called the *atomic mass unit* (u). This is defined in such a way that the mass of an atom is approximately equal to the number of neutrons and protons the atom contains, as we shall see later in sections *N-10* and *N-11*.

By using atomic mass units, you do not have to bother with awkward numbers. Scientists have agreed to use the carbon atom that contains six protons, six neutrons, and six electrons as a reference (Figure 1). They have assigned a mass of 12.000 000 u to the carbon atom instead of working with its mass in grams, which is 1.9925×10^{-23} g. The masses in Table 2 (expressed in atomic mass units) are computed on this assumption. Note that these masses are given in both grams and atomic mass units. Make comparisons of the particles in this table in the gram and the atomic mass unit systems of measuring mass.

Figure 1



Electric charge can be expressed in various units, but we will simply use the units of +1 (positive charge), −1 (negative charge), or 0 (no charge). The negatively charged electron should be familiar to us because it is the particle that travels in our electrical circuits and provides us with electrical energy.

Half-life is the term related to the lifetime of a group of particles or nuclei. We frequently refer to nuclei and particles as either *stable* or *radioactive* (unstable). Those nuclei or particles that remain unchanged with the passage of time are stable. Those nuclei or particles that spontaneously change, or *decay*, into more stable forms are radioactive. The characteristic time of radioactive decay is described in terms of half-life. One half-life is the length of time it takes half the particles or nuclei of a specific kind in a given sample to undergo radioactive decay. The neutron, as you will note in Table 2, is stable when it is inside a nucleus, but in free space (a vacuum) a neutron decays with a half-life of 12.8 minutes. Later on you will measure the half-life of a radioactive nucleus in the laboratory (section *N-28*).

The process of radioactive decay is a random one, very much like flipping a coin to see whether it comes up "heads" or "tails." If many coins are flipped at the same time, on the average 50 percent will come up heads and 50 percent tails. One way to illustrate the concept of half-life is by having the members of your class flip coins. Each coin can be considered to be a neutron in free space (or it can be considered to be a radioactive nucleus).

N-4 Heads/Tails and Half-life

miniexperiment

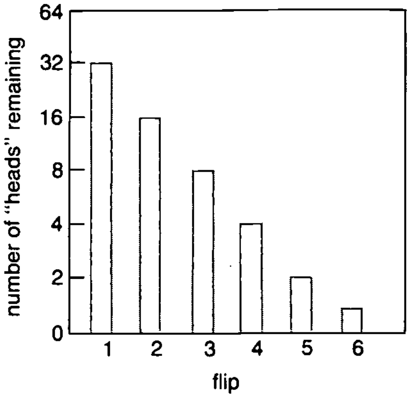
Initially you have as many neutrons (that is, coins) as there are students in the class. At a given signal, everyone flips a coin. *Each signaled flip is considered to be one half-life.* In reality, radioactive nuclei decay randomly during one half-life, but for our purposes the net result is the same if we flip the coins all at once.

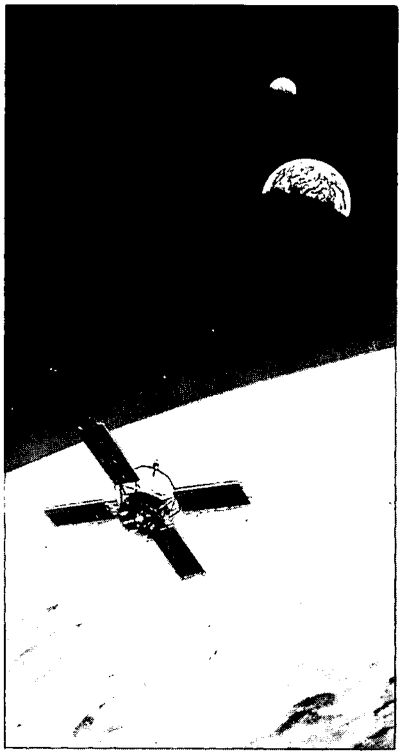
If you obtain heads, your neutron has survived and you will continue to flip. If you have tails, your neutron has decayed to a proton, and you drop out. After each signal, record the number of *tails* on a graph similar to the one in the margin.

Continue flipping the coins until everyone has been eliminated. (At this point one cycle of half-lives is complete, or in other words all the neutrons have decayed.) Then assume you have a fresh batch of neutrons and start a new cycle of half-lives with the entire class. Once again, keep flipping the coins until everyone is eliminated.

Continue flipping the coins for as many cycles as your class chooses. Then add the results of all cycles (for each half-life period). From your total results, how good is the assumption that half of the neutrons decay in one half-life? Do three-fourths decay in two half-lives?

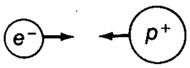
IDEAL RESULTS STARTING WITH 64 COINS





An artist's portrayal of the satellite *Mariner 9* in orbit around Mars. The Earth and its moon are shown in the distance. Mars' gravitational force holds *Mariner 9* in orbit. Earth's gravity holds the moon in orbit, while the sun's gravitational force keeps both Mars and Earth in their orbital paths.

ATTRACTION



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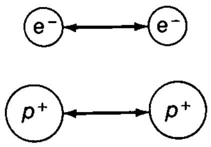
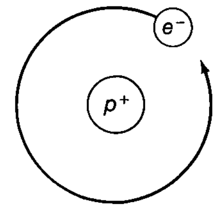


ATOM OF HYDROGEN



PROBLEM

Suppose there are 1024 neutrons in free space. How many neutrons and protons will there be after one half-life (the half-life of a neutron is 12.8 minutes)? One-half of 1024, or 512, neutrons will undergo decay to form 512 protons. There will be 512 remaining neutrons.

How many of the original 1024 neutrons will be present after another 12.8 minutes, that is, after two half-lives? How many *protons* will there be at this time?

Repeat this procedure for a total of ten half-lives.

N-5 The Basic Forces: Nature's Glue

How can complex systems such as nuclei and atoms be assembled from protons, neutrons, electrons, and photons? Before we can begin to answer this question, we must consider the three forces responsible for holding the building blocks of our Universe together—*gravity*, *electromagnetism*, and the *nuclear force*.

Gravity is the familiar attractive force that is responsible for holding us on the Earth, for keeping the moon in orbit about the Earth, and for keeping the planets in orbit about the Sun. It also holds stars together in galaxies. The strength of this force depends upon the *mass* of the bodies concerned and the distance between them. It can be expressed mathematically as

$$F_{\text{(gravitational force)}} = \frac{Gm_1m_2}{r^2} \tag{1}$$

Here G is a constant that characterizes gravity, m_1 and m_2 are the masses of the two bodies, and r is the distance between them. Therefore, the gravitational attraction between two bodies becomes stronger as their masses, m_1 and m_2, increase and as they come closer together.

Electromagnetism is the force that acts between bodies having *electric charge*. Electromagnetism is the fundamental force involved in chemical reactions. For two charged bodies at rest, the electromagnetic force can be expressed mathematically as

$$F_{\text{(electromagnetic force)}} = \frac{kq_1q_2}{r^2} \tag{2}$$

Here k is a constant that describes the electromagnetic force, q_1 and q_2 are the electric charges of the particles, and r is the distance between the charges. Electromagnetic force causes particles with charges of the same sign to repel each other; whereas if the charges are of the opposite sign, the particles attract each other. For example, the hydrogen atom results from the attraction between a positive proton and a negative electron. All atoms and molecules are held together by this force.

The *nuclear force* is the force that holds neutrons and protons together to form atomic nuclei. Despite years of intensive study, it is still not possible to write an exact mathematical equation for the nuclear force. We can, however, express the nuclear force between two particles separated by a distance r approximately as follows.

$$\begin{array}{lclcl} \text{nuclear force} & = & \text{very strong if } r & < & 10^{-12}\text{ cm} \\ \text{nuclear force} & = & 0 \quad \text{if } r & \geq & 10^{-12}\text{ cm} \end{array} \qquad (3)$$

The nuclear force is an on-off sort of attraction that has two components: the "strong" nuclear force, which affects neutrons and protons, and the "weak" nuclear force, which affects electrons and other exotic particles related to the electron. In both cases the force is effective only when the particles are very close together. In this text we will discuss only the "strong" part of the nuclear force.

Now let us briefly summarize the three forces and how they affect particles (Table 3). Gravity depends upon mass and affects protons, neutrons, and electrons. Electromagnetism depends upon electric charge and affects protons and electrons only. The nuclear force involves only neutrons and protons.

The gravitational force is rather weak, but it extends over long distances and may involve many particles. On the other hand, the nuclear force is very strong, but it extends only over short distances and involves few particles. In systems with many particles (such as stars) the total force of gravity can become comparable to the nuclear force. We shall see that this is very important if stars are to synthesize elements.

We have not mentioned photons in this discussion. In general, whenever electromagnetic force acts on electrons and protons, they undergo changes in energy and produce photons.

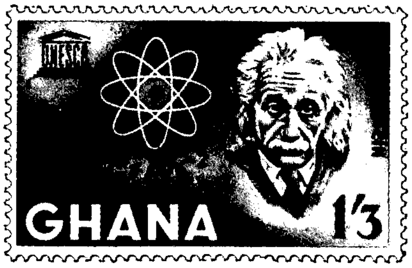
Table 3: Relative Strength of Basic Forces

Force	Strength*	Particles
Gravitational	$\sim 10^{-39}$	n, p, e
Electromagnetic	$\sim 10^{-3}$	$p, e,$
Nuclear	1	n, p

*Nuclear Strength = 1

N-6 Conservation Laws: The Ground Rules

Before we use the fundamental particles and basic forces to play our element-building game, we must first review the ground rules, or *conservation laws.* We call these *laws* because they represent experimental facts for which no exceptions have ever been observed. The conservation laws refer to specific properties of matter that remain constant (are conserved) whenever the basic forces act upon the fundamental particles. For our purpose, the three most important conservation laws are (1) mass-energy, (2) electric charge, and (3) nucleon number. *Nucleon* is a general term used by scientists to describe both neutrons and protons—the particles in the nucleus.



This stamp commemorates Albert Einstein's mathematical expression of the law of conservation of mass and energy, $E = mc^2$.

The conservation of mass and energy is a single law which states that the sum of the mass and the energy in a system does not change when the basic forces act on the fundamental particles. To state this mathematically, we must introduce the idea that mass *(m)* can be converted to energy *(E)*, and vice versa, as stated by the equation

$$E = mc^2 \tag{4}$$

Thus for the reaction

$$\text{system I} \xrightarrow[\text{(basic forces)}]{\text{interaction}} \text{system II}$$

the law of conservation of mass and energy can be written as

$$m(\text{I})c^2 + E(\text{I}) = m(\text{II})c^2 + E(\text{II}) \tag{5}$$

Any change in mass implies a change in energy. The common mass unit for discussing nuclei, the atomic mass unit (u), has already been mentioned. Nuclear energies are usually expressed in millions of electron volts (MeV). For the purpose of comparison, the amount of energy liberated in normal chemical reactions is measured in electron volts (eV). Chemical reactions, such as the burning of gasoline in an automobile engine, are typically one million times *less* energetic than nuclear reactions. The quantity c^2, the velocity of light squared, can be converted for convenience as follows.

$$c^2 = (2.998 \times 10^{10} \text{ cm/s})^2 = 931.5 \text{ MeV/u}$$

PROBLEM

In a certain nuclear reaction the reactants (system I) have a total atomic mass of 13.010 00 u, and the products (system II) have a total atomic mass of 13.000 00 u. If the reactants have zero energy, how much energy is produced in this reaction? From equations (4) and (5) we have

$$\begin{aligned} m(\text{I})c^2 + E(\text{I}) &= m(\text{II})c^2 + E(\text{II}) \\ E(\text{II}) &= [m(\text{I}) - m(\text{II})]\,c^2 + E(\text{I}) \\ E(\text{II}) &= [(13.010\,00 \text{ u} - 13.000\,00 \text{ u})](931.5 \text{ MeV/u}) + 0 \\ &= (0.010\,00 \text{ u})\,(931.5 \text{ MeV/u}) + 0 \\ &= 9.315 \text{ MeV} \end{aligned}$$

Energy is produced because the total mass of system I is greater than that of system II. One mole of nuclei (6.02×10^{23} nuclei) undergoing such a nuclear reaction would have its mass decreased by 0.01 g and would liberate an amount of energy equivalent to the burning of about 30 metric tons of coal. In section *N-17* we will discuss how this equation is used to calculate the energies of nuclear reactions in stars. To make sure you understand this example, calculate the energy produced when the

TIME MACHINE
Atomic Theory and Structure

1885	J. J. Thompson discovers electrons through his studies on cathode rays.
1896	Radioactivity is discovered by Henri Becquerel in France.
1900	Max Planck formulates quantum theory, which dominates atomic physics during early 20th century.
1905	Albert Einstein theorizes that mass and energy are equivalent and formulates the photon theory of light.
1911	Ernest Rutherford proposes theory of the structure of the nuclear atom.
1912	Charles Wilson invents the cloud chamber, which enables atomic particle movement to be photographed.
1913	Niels Bohr develops an atomic theory based on the work of Ernest Rutherford and Max Planck.
1932	James Chadwick discovers the neutron.
1932	C. D. Anderson discovers the positron.
1934	Enrico Fermi theorizes that neutrons and protons are the same fundamental particles in two different quantum states.
1962	The carbon atom, with atomic mass of 12, is adopted by international agreement as the reference value for expressing atomic mass units.

reactants have a mass of 236.100 g and the mass of the products is 235.903 g. Assume the reactants have no kinetic energy (energy of motion).

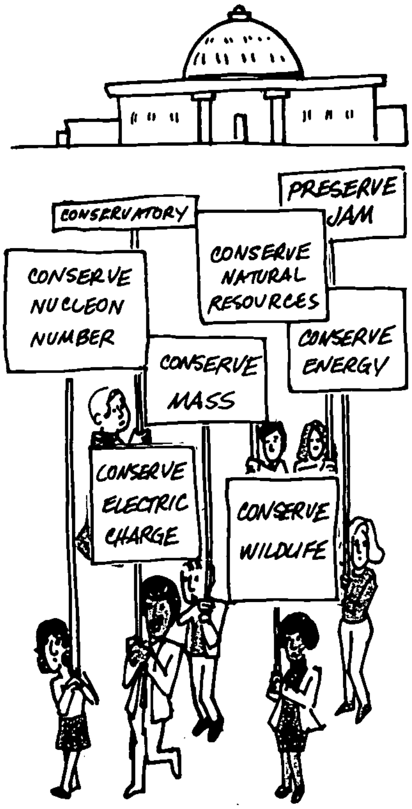
It is important to stress that in all chemical and physical reactions where energy is liberated or absorbed, there is a change of mass between the reactants and the products. Therefore, equations (4) and (5) are always true. It is only for nuclear reactions that this conversion of mass into energy is large enough to be measured directly. Therefore, in chemical reactions, one usually states that mass and energy are conserved independently.

The *conservation of electric charge* means that the total charge of a system does not change when an interaction occurs between particles. This concept is familiar in the balancing of chemical reactions such as

$$Mg^{2+}(aq) \;+\; 2\,OH^-(aq) \longrightarrow Mg(OH)_2(s)$$

Initially there are two positive charges on the Mg^{2+} ion and one negative charge on each of two OH^- ions, for a net charge of zero. The same net charge must be present *after* the chemical reaction. The same rule is valid for the balancing of nuclear reactions and in all other phenomena that involve electric charges.

The *conservation of nucleon number* states that the total number of nucleons involved in a nuclear reaction must always remain the same. Thus, if two protons and two neutrons manage to react with one another, there will be a total of four nucleons after the reaction. We will see in section *N-15* how this conservation law is involved in balancing nuclear reactions.



N-7 Interactions: Getting It Together

The structure of our Universe is the result of interactions involving the fundamental particles and basic forces. Consider the effects of gravity. When only a few particles are involved, this force is extremely weak. But for a large mass, the total gravitational force becomes comparable in strength to the other forces. The mass of the Sun is 2×10^{33} g, which is almost a million times larger than the mass of our Earth. For such a large mass, the gravitational force can become comparable in strength to the electromagnetic and nuclear forces.

During the formation of a star such as our Sun, the gravitational force causes the star's matter to contract. Therefore, its density increases (density = mass/volume). If the density of matter increases, the temperature also increases. You are already familiar with this effect if you have noticed that when you pump up a tire (increasing the density of air), the air inside it becomes hotter. The density of the air decreases when it is released from the tire and the air is cooled. This relationship between temperature and density also exists in stars, but on a much larger scale. For example, the temperature at the center of the Sun is about 15 000 000 K (kelvins) because of the very high density of matter there.

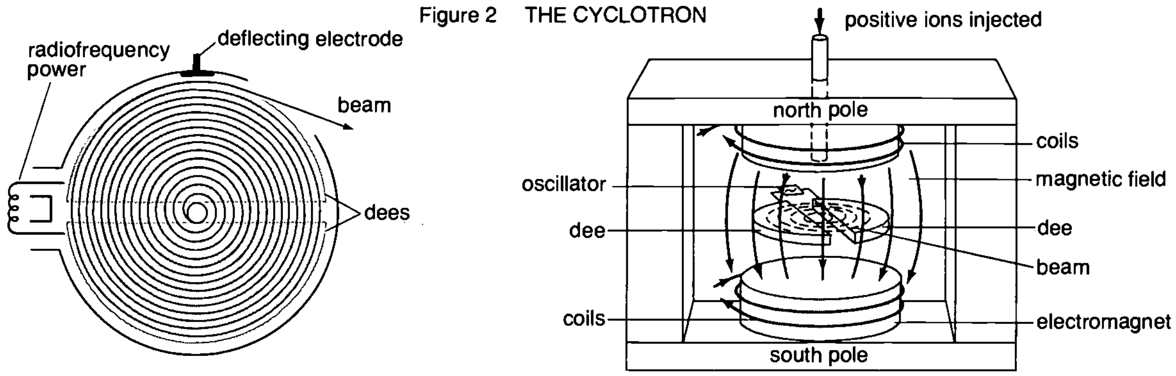
Now let's examine the effects of the nuclear and electromagnetic forces on nucleons. The nuclear force attracts protons and neutrons equally if they are within about 10^{-12} cm of one another. The electromagnetic force has no effect on two neutrons or on a neutron and a proton since the neutron has no charge. On the other hand, it causes protons to repel one another because of their identical positive charge. Therefore, in order to add protons to a nucleus—which is a necessary step in forming heavier elements from the fundamental particles—the protons must usually be accelerated to energies high enough to overcome this repulsion.

In stars, these high energies are reached by means of the high temperatures produced by the forces of gravity. But in the laboratory, scientists are able to increase the energies of protons in another way—by means of particle accelerators.

N-8 Accelerating Particles

Protons and other charged nuclear particles can be accelerated to high energies by means of particle accelerators such as the *cyclotron*. By studying nuclear reactions in particle accelerators, we can learn more about both the nuclear force and the types of nuclear reactions that can occur in stars. In the cyclotron, two hollow D-shaped electrodes (called *dees*) are placed between the poles of a huge electromagnet (Figure 2). Protons or other positively charged particles are injected into the center of the machine (from a high-voltage source of these particles). They are then attracted toward the dee that is negative at that instant, thereby gaining energy. The electromagnet causes the particles to follow a circular path through the

Figure 2 THE CYCLOTRON



dee. Meanwhile, an alternating current applied to the electrodes reverses the electric field between the two dees, causing the opposite dee to be negatively charged. The particles are then attracted to the opposite dee, again gaining energy. The same process is repeated up to more than a million times per second.

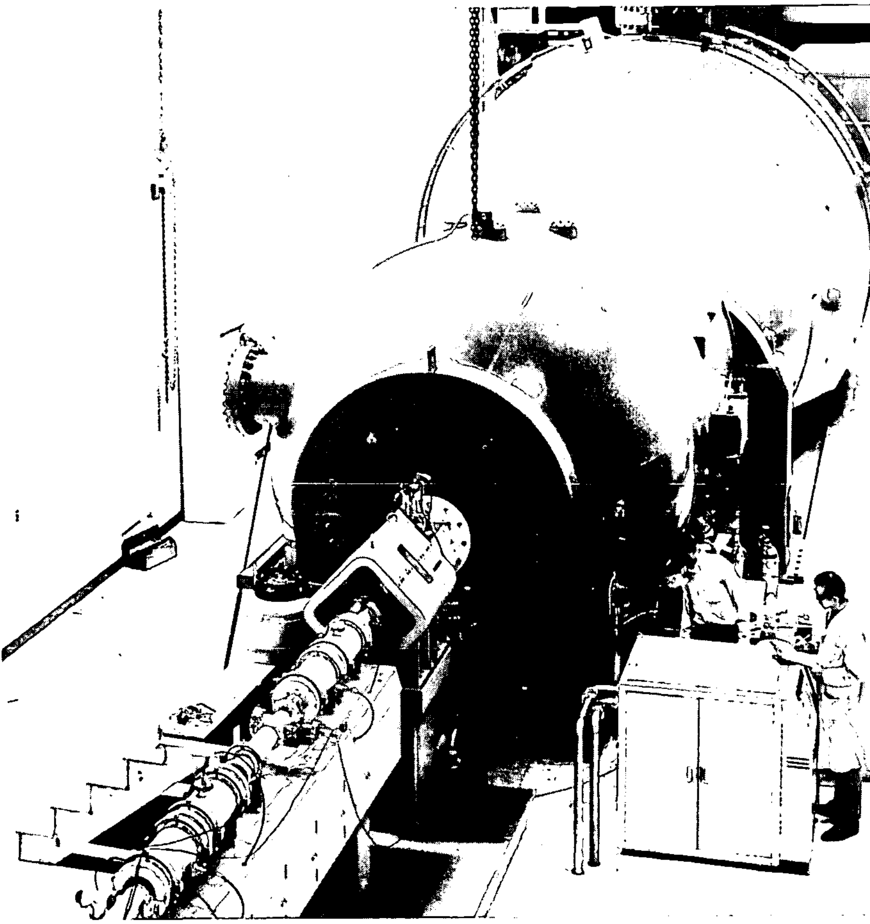
The radius of the circular path in the dee increases with each boost in energy the particles receive, so that they follow a spiral path as they are alternately attracted by the two electrodes. Eventually, the particles can reach energies of the order of 100 MeV. They are removed from the cyclotron by a second electric field (deflecting electrode) outside the machine, which attracts the particles away from their spiral orbit. The particles can then be used in the study of nuclear reactions.

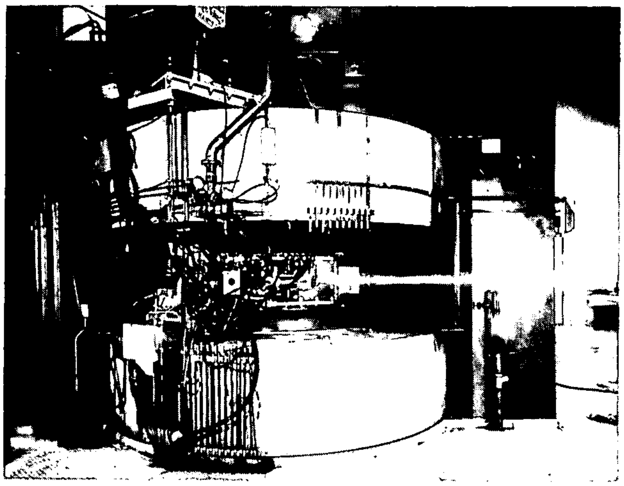
There are other types of nuclear-particle accelerators, such as synchrotrons, synchrocyclotrons, linear accelerators, and Van de Graaff generators. Operating on the principle of attraction between opposite charges or repulsion between like charges, these devices are able to accelerate charged particles to the high energies needed to produce nuclear reactions.

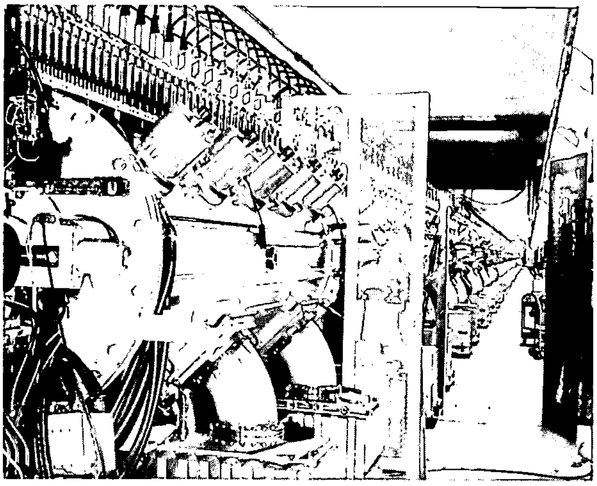
TIME MACHINE

1928	Mickey Mouse makes debut in Walt Disney films.
1929	U.S. stock market crashes.
1930	Grant Wood paints *American Gothic.*
1931	**R. J. Van de Graaff develops first useful electrostatic accelerator.**
1932	**Ernest O. Lawrence and M. S. Livingston report first successful operation of a cyclotron.**
1932	*Brave New World,* by Aldous Huxley, is published.
1933	Eugene O'Neill's only comedy, *Ah, Wilderness!,* opens in New York.

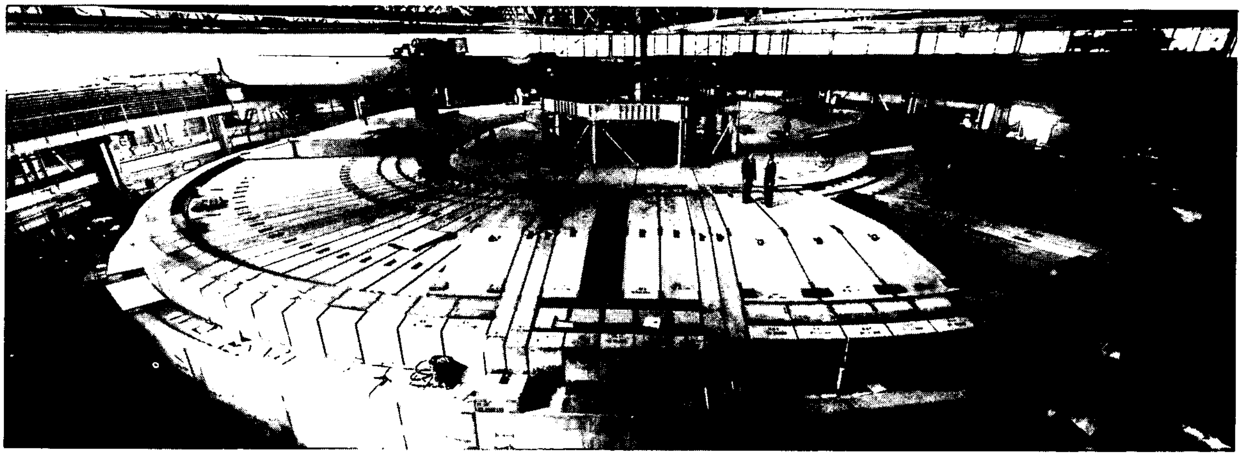
Nuclear reactions have been studied with several different types of particle accelerators, such as the Cockcroft-Walton proton injector *(below left)* and the Van de Graaff accelerator *(below right).*

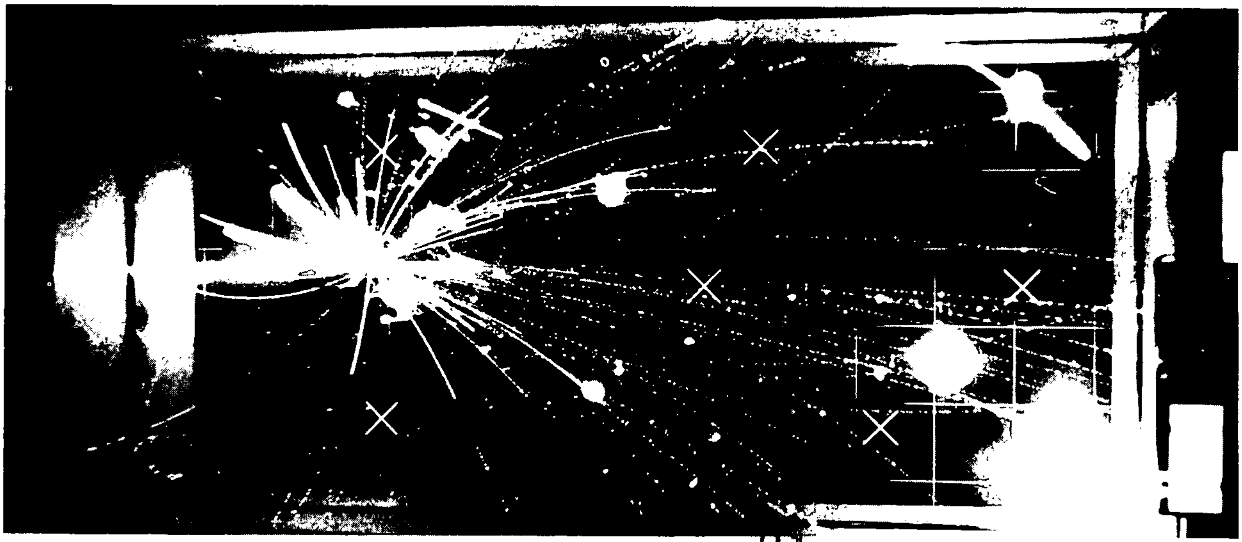






The probe into the nature of matter requires particle beams of high energies. This cyclotron *(above left)* emits deuterons (^{2}H nuclei) at a speed of 45 000 km per second. The linear accelerator *(above right)* and the Bevatron *(below middle)* produce particles with respective energies of millions and billions of electron volts. High-energy particle collisions with target-nuclei can be detected in a bubble chamber *(bottom)*, which makes visible the tracks of particles.





How do we know that nuclear particles are present around us or that they are being produced in nuclear reactions? Interactions between large, *macroscopic* objects can be easily detected. For example, a head-on collision between a "230-pound" fullback and a "260-pound" linebacker is readily observed by visual and audible stimuli, as well as a few shock waves. In contrast, interactions between *microscopic* objects such as nuclear particles are much more difficult to detect because we cannot directly use our senses of sight, hearing, and touch.

In the experiment that follows, you will be introduced to the detection of nuclear radiation being emitted by a source of radioactive nuclei. The radiation you will measure is composed of high-energy photons called *gamma rays* (discussed further in section *N-26*). These gamma rays are emitted from the radioactive nuclei contained in a MINIGENERATOR™.*

The detectors you will use are simple versions of the more sophisticated devices used in the modern-day study of nuclear science. These detectors operate on a basic principle: whenever nuclear radiation strikes anything, it knocks electrons off the atoms that make up the material. In this case the material is a gas contained in the detector (Figure 3). A thin wire with a positive voltage collects the electric charges (negative electrons) that are formed.

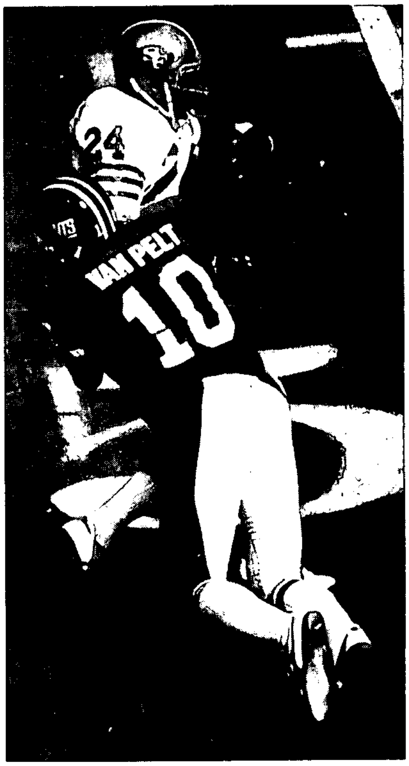
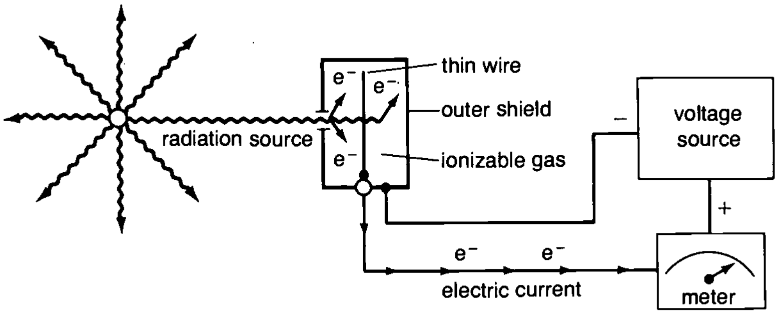
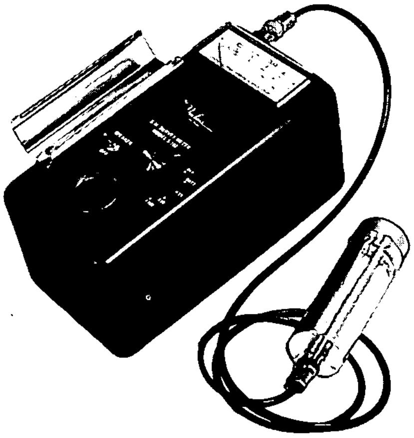


Figure 3 RADIATION DETECTOR



The amount of radiation that is detected is proportional to the current that flows through the electric circuit. Therefore we can determine the presence and relative amount of radioactivity in a given sample with such a device. In performing radiation-detection measurements, consider the radiation as coming from a point source. The radiation is given off in all directions, traveling in straight lines that originate at the center of the source. Clearly, unless the source can be put inside the detector, it will not be possible to collect all the radiation that is emitted. Therefore, as the detector moves farther and farther away from the source, the counting rate should decrease.

Radiation such as gamma rays ionizes the gas in a Geiger-Müller tube. The ionization closes the circuit that activates the rate meter.



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*The term MINIGENERATOR is a registered trademark of Redco Science Inc.

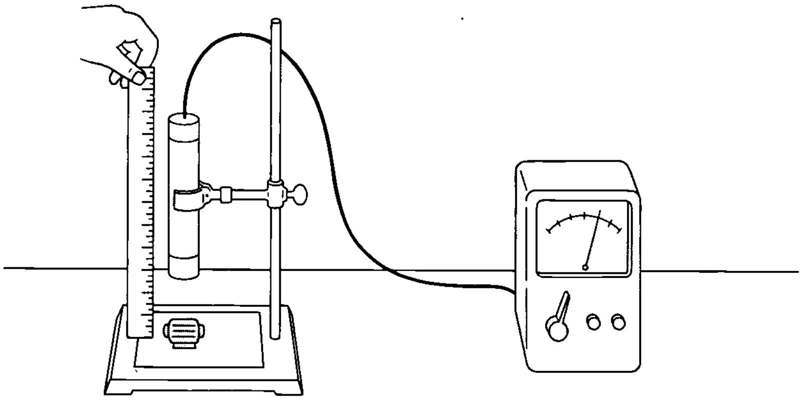
EXPERIMENT

N-9 Radiation Detection

This symbol indicates the presence of radioactive material. It will appear with certain experiments in this module to alert you to the need for special precautions (see *Appendix I: Safety*).

Turn on the detector and allow it to warm up for 5 minutes. Record five readings of *background activity* and average them. The background activity is the reading on your meter when no radiation sources are near; it is a measure of the *natural radiation* always present in our environment. The background activity must always be measured before performing an experiment because it does not come from the MINIGENERATOR and thus is not the radiation you actually wish to measure. Sources of background radiation are discussed in section *N-35*. The value that you determine for the background activity must be subtracted from all subsequent activity readings.

Place the MINIGENERATOR 2 cm from the detector. Then record an activity reading in counts per minute (cpm). In your notebook record your data in a table similar to the one shown in the margin.



Next, place the detector 4 cm from the MINIGENERATOR. Record the activity reading. Keep increasing the distance between the source and the detector by successive steps. Record the activity each time you move the detector. Keep moving the detector until the activity reading is approximately equal to the background activity.

Plot your activity readings (corrected for background) against the distance of separation. Use linear coordinate graph paper. Place the activity readings on the vertical axis of the graph and the distances on the horizontal axis.

SAMPLE WORKSHEET

Background ___ cpm

Distance (cm)	Activity (cpm)	cpm Corrected for Background
2	—	—
4	—	—
6	—	—
8	—	—
10	—	—
12	—	—
14	—	—
16	—	—
18	—	—
20	—	—

Questions:

1. Consult your data regarding the activity measured for distances of 2 cm and 4 cm. When the distance was doubled, was the activity reading reduced fourfold? If not, can you explain why?
2. What happens to the activity readings of gamma radiation when the distance between source and detector is made three times as great?
3. Explain how the distance between you and a radioactive source affects the potential radiation hazards to you.

TIME MACHINE

1906	Pure Food and Drug Act and Meat Inspection Act are passed.
1907	Ivan Pavlov studies conditioned reflexes.
1908	**Hans Geiger and Sir Ernest Rutherford develop a radiation detector.**
1910	Boy Scouts of America is founded.
1911	Richard Strauss's opera *Der Rosenkavalier* opens in Dresden, Germany.

Remote areas of the world are explored for possible sources of uranium and other naturally occurring radioactive substances. Uranium is just one of many radioactive elements that contribute to natural background radiation.

PROBLEMS

1. Which fundamental particles in Table 2 are affected by the gravitational force?
2. What is the *net* electric charge of a system consisting of 5 protons and 2 electrons?
3. How many nucleons are there in a nucleus that contains 7 protons and 8 neutrons?
4. A certain radioactive nucleus decays with a half-life of 1 hour. If a sample contains 4000 of these nuclei at some given time, how many of the original nuclei will remain after 1 hour? after 2 hours? after 4 hours?
5. Suppose a sample contains 800 nuclei of a given radioactive element X. After 40 minutes only 200 nuclei of X remain. What is the half-life of X?
6. In a certain nuclear reaction

$$A + B \longrightarrow C + D$$

the *reactants* ($A + B$) have a total atomic mass of 17.999 876 u and the *products* ($C + D$) have a total atomic mass of 18.000 003 u.

a. Does this reaction violate the conservation of mass-energy?
b. Can energy be obtained from this reaction?
c. Calculate the amount of energy, in millions of electron volts, that must be converted into mass in order to make this reaction proceed as written.

7. Based on the conservation laws in section *N-6* (that is, mass-energy, electric charge, and nucleon number), state whether or not the following nuclear reactions (a–c) and chemical reactions (d–e) can occur as written. In any cases where *no* is the answer, explain your conclusion.

a. $3p + 3n \longrightarrow 5n + 1p$
b. $2p + 4n \longrightarrow 3p + 3n + e$
c. $2p + 2n \longrightarrow 3p + e$
d. $2Li^{+} + O^{2-} \longrightarrow Li_2O$
e. $P + Cl_2 \longrightarrow PCl_3$

The Makeup of Our Solar System

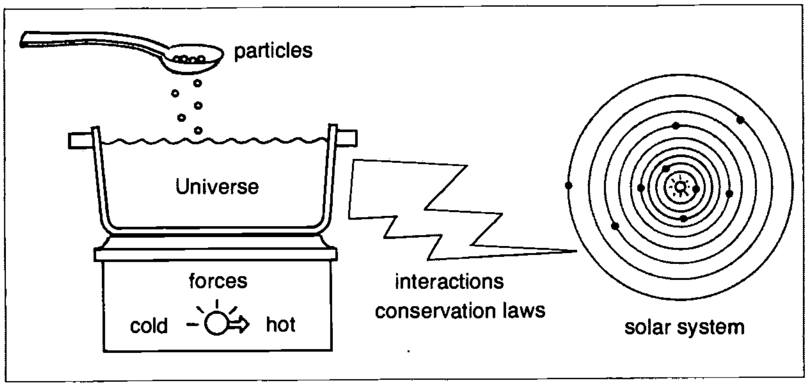
Having reviewed the fundamental properties of matter, it is now possible to ask, What combinations of elementary particles form the nuclei of the elements? This then leads to other questions such as, What elements exist in our solar system? How much of each element is present in nature? Any theory that explains the origin of the elements must provide answers to these questions.

This photograph is a mosaic of different planets taken by NASA spacecraft. The wealth of information that spacecraft transmit back to Earth helps scientists to unravel mysteries about our solar system that have intrigued people for thousands of years.

N-10 Identifying the Nuclides

Let us review from the previous section our "recipe" for making nature's elements.

> Take one Universe as the cooking pot and add the fundamental particles—protons, neutrons, electrons, and photons. Cook vigorously with the basic forces—gravity, electromagnetism, and nuclear force. The resulting interactions yield nature's elements that make up our solar system. Remember that the resulting interactions are regulated by the conservation laws (section *N-6*).



Using this recipe, we find that atomic nuclei are composed of neutrons and protons held together by the nuclear force. The number of protons in a nucleus is the *atomic number (Z)*. The number of neutrons in a nucleus is the *neutron number (N)*. The atomic number represents the total positive electric charge on the nucleus and serves to distinguish each chemical element from all others. The total number of neutrons plus protons, commonly called nucleons, is the *mass number (A)* where

$$A = N + Z$$

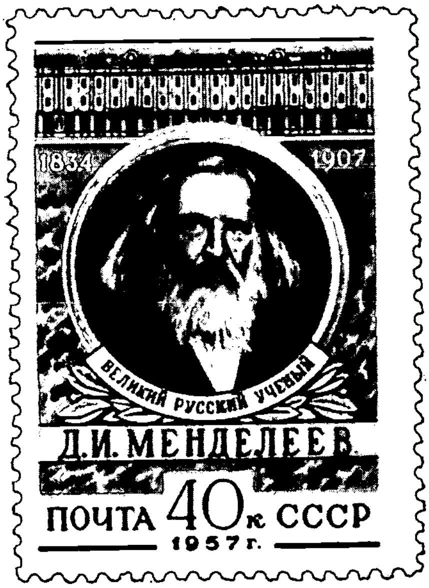
The term *nuclide* is frequently used to describe any atom having a nucleus of mass number A, atomic number Z, and neutron number N. For any nuclide of mass number A, many values of N and Z are possible. Usually, however, only a few of these are sufficiently stable that we can find them in nature or synthesize them in the laboratory.

In general, the following representation is used to describe each possible nuclide.

$$^{A}_{Z}X_{N}$$

Here X is the chemical symbol (such as H for hydrogen, He for helium, and Li for lithium). The N subscript is usually not necessary, since $N = A - Z$. Also, the Z subscript can be omitted if one

Dmitri Mendeleev was one of the first scientists to recognize patterns in the properties of elements. His Periodic Table of the Elements, published in 1869, arranged the elements by atomic "weight."



TIME MACHINE

1918	Influenza epidemic begins and eventually kills 22 million people throughout the world.
1920	Nineteenth Amendment gives American women the right to vote.
1921	**Frederick Soddy wins Nobel Prize for his studies on the occurrence and the nature of isotopes.**
1922	Alexis Carrel discovers white corpuscles.

The discovery of isotopes of oxygen provided further evidence for variations in the mass of atoms of the same element.

knows the atomic number of each symbol. This classification leads to three types of nuclides.

1. *Isotopes:* nuclides for which the atomic number Z is constant but N and A can vary. For example, $^{204}_{82}Pb$, $^{206}_{82}Pb$, $^{207}_{82}Pb$, and $^{208}_{82}Pb$ are all isotopes of the element lead, for which $Z = 82$.
2. *Isotones:* nuclides for which the neutron number N is constant; $^{3}_{1}H_2$ and $^{4}_{2}He_2$ are isotones, each having two neutrons, or $N = 2$.
3. *Isobars:* nuclides having the same mass number A; $^{14}_{6}C$, $^{14}_{7}N$, and $^{14}_{8}O$ are all isobars with a total of 14 nucleons, or $A = 14$.

PROBLEMS

1. Write the complete nuclear representation for the following nuclides.
   a. sodium of mass number 23
   b. sulfur with 15 neutrons
   c. a nuclide of mass number 18 and neutron number 10
2. In the following set of nuclides, which can be classified as isotopes, which as isobars, and which as isotones?
   a. $^{22}_{10}Ne$ c. $^{23}_{12}Mg$
   b. $^{22}_{11}Na$ d. $^{26}_{12}Mg$

N-11 Nuclear Stability

In principle a nucleus can be made up of any combination of neutrons and protons. In practice, however, certain combinations are found to be much more probable than others. To represent this fact visually, we will use a model that we call the "sea of nuclear instability" (Figure 4). This model summarizes much of the information that scientists know about nuclear properties. Study the model carefully, as you will need to refer to it throughout this section.

Figure 4 THE SEA OF NUCLEAR INSTABILITY

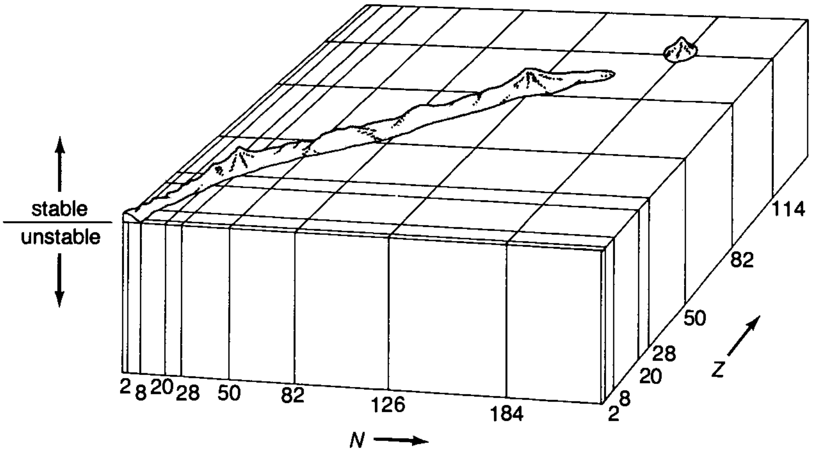
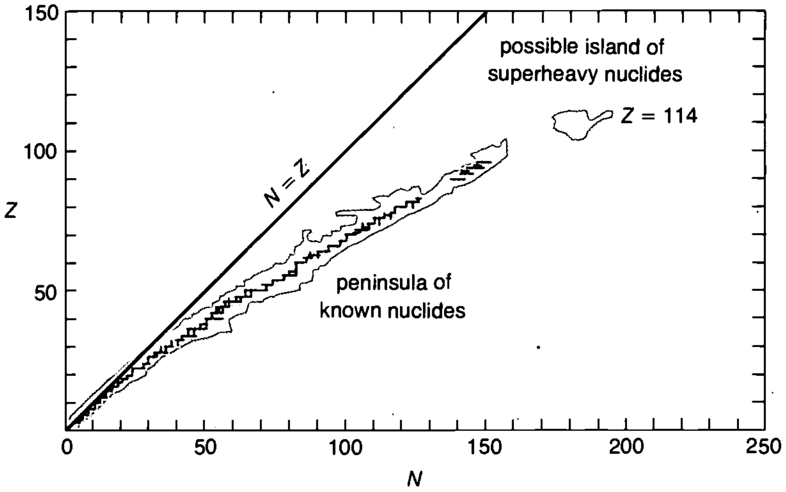


Figure 5 OVERHEAD VIEW OF THE SEA OF INSTABILITY



The dark lines on the peninsula represent naturally occurring nuclides, and the shaded areas represent nuclides with half-lives of greater than 5 minutes.

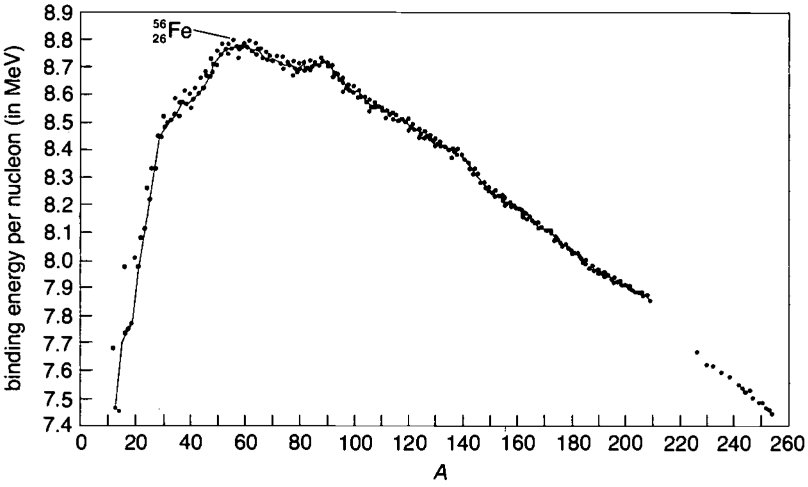
The vertical scale (or elevation) represents a measure of the stability (tendency to remain unchanged) of any nuclide with Z protons and N neutrons. The degree of stability of any nuclide is measured by its half-life for radioactive decay; the longer the half-life, the more stable the nuclide. Nuclides with short half-lives are considered to be unstable. Since most of the possible nuclides have short half-lives, we refer to the model (Figure 4) as the sea of nuclear instability.

In using the model, we have defined sea level as the half-life for radioactive decay of about one second. Nuclides that hang together for less than one second are submerged below sea level. Nuclides that live longer than one second rise out of the sea. These nuclides are represented in our illustration as a mountainous "peninsula of stability" and an "island of stability." The maximum elevation on the model corresponds to nuclides with the longest half-lives; the probability of these occurring in nature is highest. We choose one second as our base simply because this is approximately the shortest half-life a nuclide can have in order to be easily observed experimentally. If we were to choose the age of our solar system (4.5 billion years) as sea level, then much more of the peninsula would be submerged.

The most important feature of our model is the mountainous peninsula that rises up out of the sea of instability. If we were able to fly over the peninsula and look directly down, we would see that the stable nuclides have roughly equal numbers of neutrons and protons *(N = Z)* (Figure 5). The solid line represents equal Z and N values. Note that as the mass number *(N + Z)* of the nuclides increases, the nuclides tend to have more neutrons than protons. This behavior is a result of the repulsive electric charge of the protons in the nucleus. If you return to Figure 4, you will also find the island of stability emerging from the sea just beyond the peninsula of stability. This corresponds to elements with atomic numbers near Z = 114. These are the hypothetical *superheavy elements*, which we will discuss later.

For each mass number there is a maximum elevation on the peninsula that leads to a ridge of maximum stability along the top of the peninsula (Figure 6). The altitude or height of the ridge represents the average energy with which the nucleons in a nucleus are held together. This quantity can be called the *average nuclear binding energy* and is an absolute measure of nuclear stability. In other words, this is the amount of nuclear mass that is converted into energy to bind the neutrons and protons together in the nucleus. The higher the nuclear binding energy, the greater the stability the neutron–proton combinations have against radioactive decay.

Figure 6



Altitude map of the ridge along the peninsula of stability shown in Figure 5.

In Figure 6 you will notice a peak in the binding energy curve for nuclides near $^{56}_{26}$Fe (iron). This peak represents the most stable nuclides and is of considerable importance to our theory of the origin of the elements (section *N-19*). Nuclear reactions favor those processes that produce increased stability—those reactions that increase the average binding energy. Therefore, nuclear reactions that combine light nuclides to form nuclides near $^{56}_{26}$Fe are preferred in nature. These reactions give off energy when they occur. Conversely, nuclides beyond $^{56}_{26}$Fe can gain stability by undergoing *spontaneous radioactive transformations* and nuclear reactions that lead to lighter products near $^{56}_{26}$Fe. On the other hand, nuclear reactions that produce nuclides heavier than $^{56}_{26}$Fe decrease nuclear stability and therefore must absorb energy. This result will enter several of our later discussions.

One last feature of Figure 4 must also be mentioned. The intersecting lines at sea level extend from numbers at the Z-axis and N-axis. The numbers represent what are called the *magic numbers*, or closed-shell configurations, for neutrons and protrons. These occur for $Z = 2, 8, 20, 28, 50$, and 82, and $N = 2, 8, 20, 28, 50, 82$, and 126.

Nuclides that have a magic number of protons or neutrons are relatively stable toward nuclear reactions and radioactive decay. Similar stability occurs in atoms of the chemical elements helium, neon, argon, krypton, xenon, and radon (the inert gases). These atoms have closed electron shells and do not readily take part in chemical reactions.

Because of the existence of closed nuclear shells, local peaks appear along the stability peninsula whenever a magic number of nucleons is encountered. For example, $^{208}_{82}Pb_{126}$ has a closed-shell configuration for both neutrons and protons. Hence it is unusually stable. Beyond $^{208}_{82}Pb$ the peninsula gradually becomes submerged as one gets to heavier and heavier elements. The island of stability that we have previously mentioned exists only because closed nuclear shells are predicted for proton number $Z = 114$ and neutron number $N = 184$. This would make the doubly closed-shell nucleus $^{298}_{114}X$ and its immediate neighbors, the superheavy elements, especially stable.*

In summary, the nuclides that rise out of the sea of instability are those that we expect to observe in nature. Accordingly, the greatest stability results when

1. Z is approximately equal to N (for heavy elements N is somewhat greater than Z);
2. an arrangement nearer $^{56}_{26}Fe$ can be achieved, either by nuclear reactions or by radioactive decay;
3. closed-shell configurations can be reached.

And what about those nuclides that lie submerged in the sea of instability or occupy the lower elevations of the peninsula of Figure 4? These undergo radioactive decay to nuclides with more stable neutron-proton configurations by means of various processes. Nuclides deeply submerged in the sea may spontaneously emit neutrons, protons, or more complex nuclei. The half-lives for such processes are very short ($\sim 10^{-15}$ second). For those nuclides nearer sea level, decay occurs more slowly, and the following types of decay are commonly observed.

1. *Alpha decay:* emission of a $^{4}_{2}He$ nucleus (alpha particle). α is the symbol for an alpha particle.

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*Although there have been reports of the possible observation of these superheavy elements, none has yet been confirmed.

TIME MACHINE

1948	Peter Goldmark invents the LP record.
1950	**Maria Goeppert Mayer and Johannes Jensen propose nuclear shell theory.**
1951	*The Catcher in the Rye*, by J. D. Salinger, is published.
1952	Dwight David Eisenhower is elected 34th president of the United States.
1953	New York Yankees win World Series fifth time in a row.

TIME MACHINE

1898	*The War of the Worlds,* by H. G. Wells, is published.
1899	**Ernest Rutherford discovers alpha and beta rays.**
1901	Marconi transmits telegraphic messages from Cornwall, England, to Newfoundland.
1902	Enrico Caruso makes his first phonograph recording.
1903	Orville and Wilbur Wright fly the first powered airplane.

2. *Beta decay:* in effect, the conversion of a neutron into a proton accompanied by the emission of an electron. $_{-1}^{0}\beta$ is the symbol for this electron. The reverse process occurs when a positron is emitted. $_{1}^{0}\beta$ is the symbol for a positron.
3. *Gamma decay:* emission of an energetic photon (gamma ray) from the nucleus. γ is the symbol for a gamma ray.

The details of these radioactive decay processes, which are important in many nuclear applications, are discussed later in *Radioactive Decay*.

N-12 Transmutation of Elements

We have previously noted that most of the nuclides existing in nature consist of combinations of neutrons and protons that are stable (sections *N-10* and *N-11*). However, there are many nuclides in our environment that have unstable combinations of neutrons and protons. These nuclides *transmute* (transform themselves) spontaneously into more stable forms by means of radioactive decay. Some important examples of natural radioactive nuclides are ^{14}C (carbon), ^{40}K (potassium), ^{232}Th (thorium), and ^{238}U (uranium).

What happens to the nucleus of an atom during radioactive decay? Usually there are two principal products: (1) a light particle called radiation (section *N-11*) and (2) a new nuclide that has a more stable neutron-proton combination. The radiation consists of particles such as electrons, photons, or helium nuclei—the potentially hazardous emissions of radioactive decay. The resultant nuclide, on the other hand, usually represents the formation of a *new element* because its atomic number is changed. It is very important to recognize this latter point. In *chemical reactions* the atomic number of the atoms never changes. In nuclear reactions such as radioactive decay, however, the atomic number can be transmuted to that of another element. For example, in a chemical reaction a carbon atom may be converted into the form of diamond or graphite. It may also combine with oxygen to form carbon dioxide (CO_2), or with hydrogen to form methane (CH_4). The carbon atoms in all of these substances have the atomic number $Z = 6$. But when ^{14}C undergoes radioactive decay, it becomes ^{14}N (nitrogen), a different element with $Z = 7$ (section *N-31*).

In order to demonstrate the change in chemical properties during radioactive transmutation, we will separate in the laboratory radioactive indium, $^{113m}_{49}$In, from radioactive tin, $^{113}_{50}$Sn. (The symbol *m* is placed after the mass number to indicate that a nuclide can emit a gamma ray and has a relatively long half-life.)

In a ^{113}Sn/^{113m}In MINIGENERATOR, a small amount of radioactive ^{113}Sn in the form of Sn^{2+} ions is tightly held by chemical bonds to a substance for which it has a strong attraction (an ion-exchange resin). As the ^{113}Sn changes to ^{113m}In (in the form of In^{3+} ions), this new material is held much less strongly by the ion-exchange resin than is the tin. It is possible to remove (or extract) the newly formed ^{113m}In ions with a solution of hydrochloric acid (HCl) and sodium chloride (NaCl).

This process is called *elution,* and the HCl + NaCl solution is called the *eluant.* In this way the ^{113m}In can be separated from ^{113}Sn in order to study the radioactive decay of ^{113m}In without interference from the radioactivity of ^{113}Sn. As soon as the MINIGENERATOR has been eluted to yield the indium, the activity of the MINIGENERATOR drops to a low level. As additional tin decays to indium, the activity immediately begins to build up again.

One may elute the MINIGENERATOR with any volume of eluant. However, a definite pattern exists in the recovered *eluate* (the indium-plus-eluant solution, which has passed through the MINIGENERATOR). The purpose of the experiment that follows is to chemically separate the elements indium and tin. This will demonstrate the change in atomic number that accompanies this example of radioactive decay.

Before you start this experiment, be sure to review the safety guidelines listed in the appendix of this module. After you have read the experiment, recall the safety guidelines that apply to this activity.

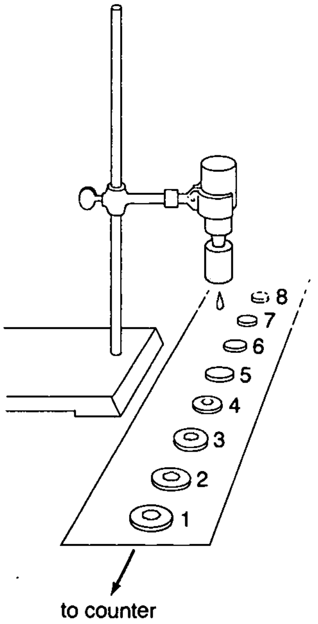
N-13 The Chemistry of Radioactive Nuclides

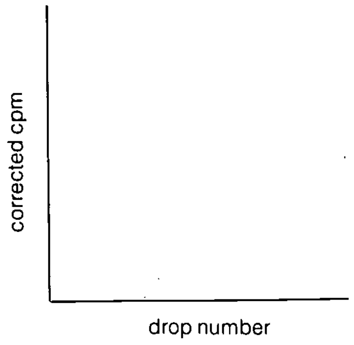
EXPERIMENT

Turn on the ratemeter and allow it to warm up for 5 minutes. Determine and record the background activity. To do so, take *five readings* at 10-second intervals and average these for a reading of the background activity. This reading should be taken in counts per minute (cpm). Hereafter, this background reading must be subtracted from all activity readings. **Note:** *If this is not done, you will be counting the activity of the radioactive source plus the background activity.*

Place a series of 25 disks in a line and number them from 1 to 25. **Note:** *It may be helpful if the disks are arranged on a piece of adding machine tape so that they can be easily managed.* Fill the plastic squeeze bottle with 2 cm^3 of the eluant, a solution of NaCl + HCl, and snap it into the ^{113}Sn/^{113m}In MINIGENERATOR.

Working in groups of at least two, elute the MINIGENERATOR by squeezing one drop of eluate onto each of the 25 disks. Then place the first disk quite close to the detector and take five readings, each spaced 5 seconds apart. Record the five readings, using their average as your counts per minute value. Record this value in a data table. Repeat this process for each of the remaining 24 disks. **Note:** *It is important that each disk be counted in exactly the same way at the same distance from the counter.* Record all counts per minute values for each disk.





Draw a graph on a piece of graph paper using the drop number as the abscissa (x-axis) and the background-corrected activity as the ordinate (y-axis).

Caution: *After completion of the experiment, wash the eluate into a container provided by your instructor. The radioactivity will die away completely after about one day and the eluate can then be discarded during the next laboratory period.*

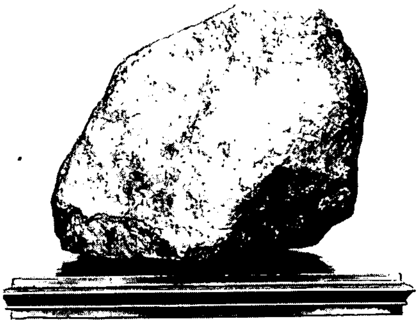
Questions:

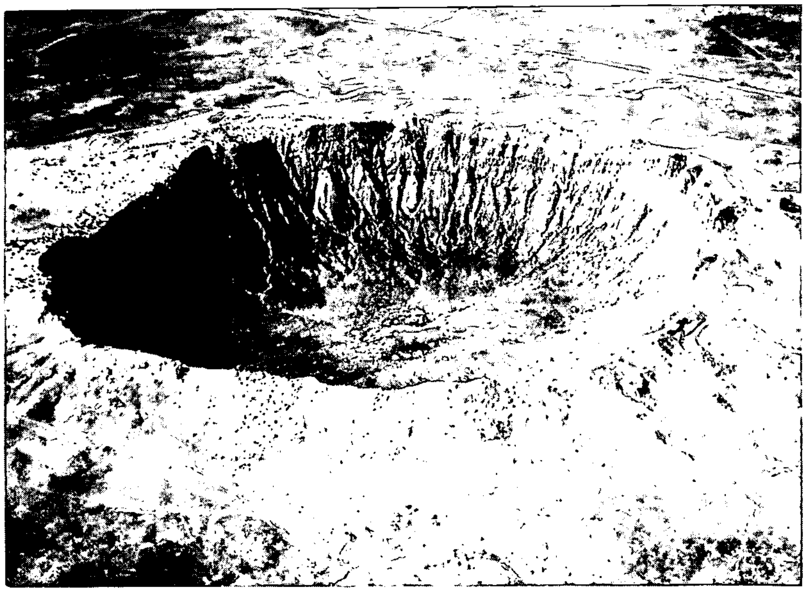
1. Which drop of eluant yields the maximum activity?
2. How many drops of eluant should be used to ensure at least 75 percent of the potential activity for that elution?
3. Why should you wait a day before disposing of the wastes from this experiment?

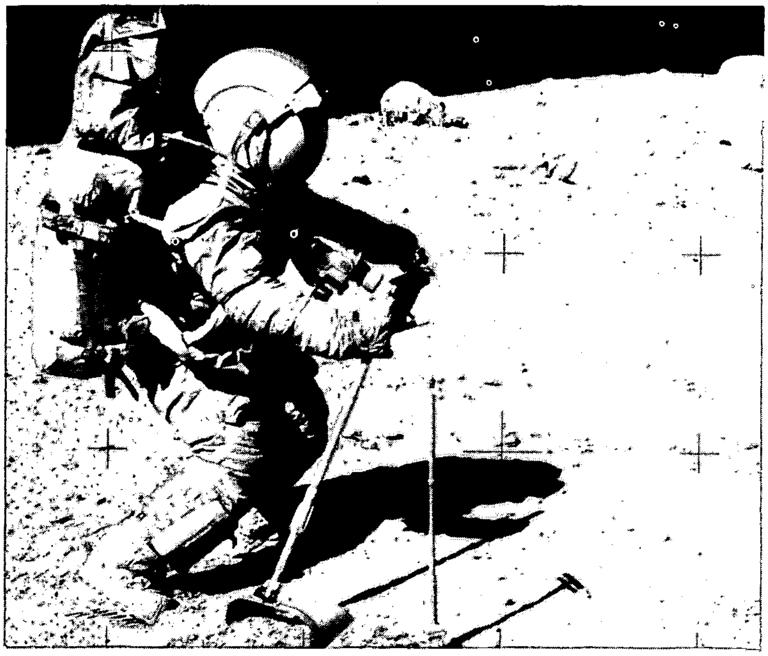
N-14 The Elements in Our Solar System

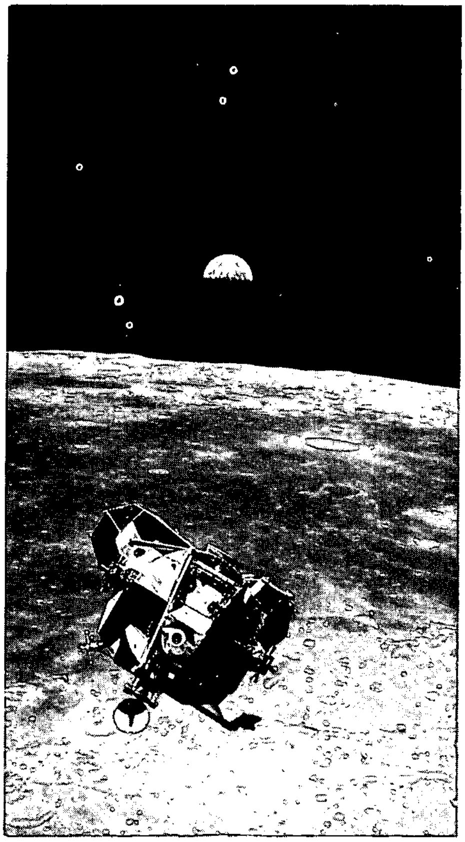
Having discussed the possible neutron-proton combinations, we now turn our attention to the elements that actually exist in our solar system. Scientists have obtained information about these elements by examining meteorites, moon rocks, and samples of material from the Earth. They have also analyzed the different types of radiation that reach us from the Sun and other stars, and from the molecules in interstellar space. From these studies the amounts of the various elements in the solar system have been determined: the *elemental abundances.* The elemental abundances that characterize our entire solar system differ substantially from the abundances of the elements that make up the Earth. This happens because the

Meteorites are a major source of information about matter in space. This meteorite *(below)*, which has a mass of 339 kilograms, fell to Earth in Arkansas. A crater *(below right)*, formed by a meteorite that fell near Winslow, Arizona, is 1265 meters wide and 174 meters deep.









The *Apollo 11* mission to the moon dissolved many previous notions about what the moon is like. As the Earth rises over the moon's horizon *(above right)* the lunar module approaches the orbiting command module for docking. Samples of soil and rock are collected *(above left)* to bring back to Earth to undergo a large array of studies *(below left)*. An electron micrograph *(bottom right)* shows crystals in a lunar-rock sample.

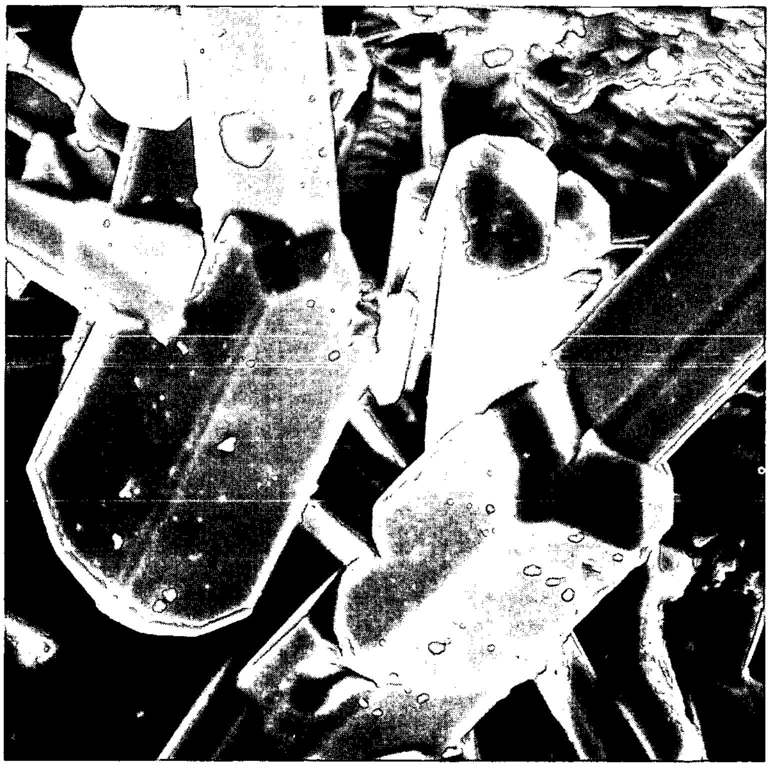


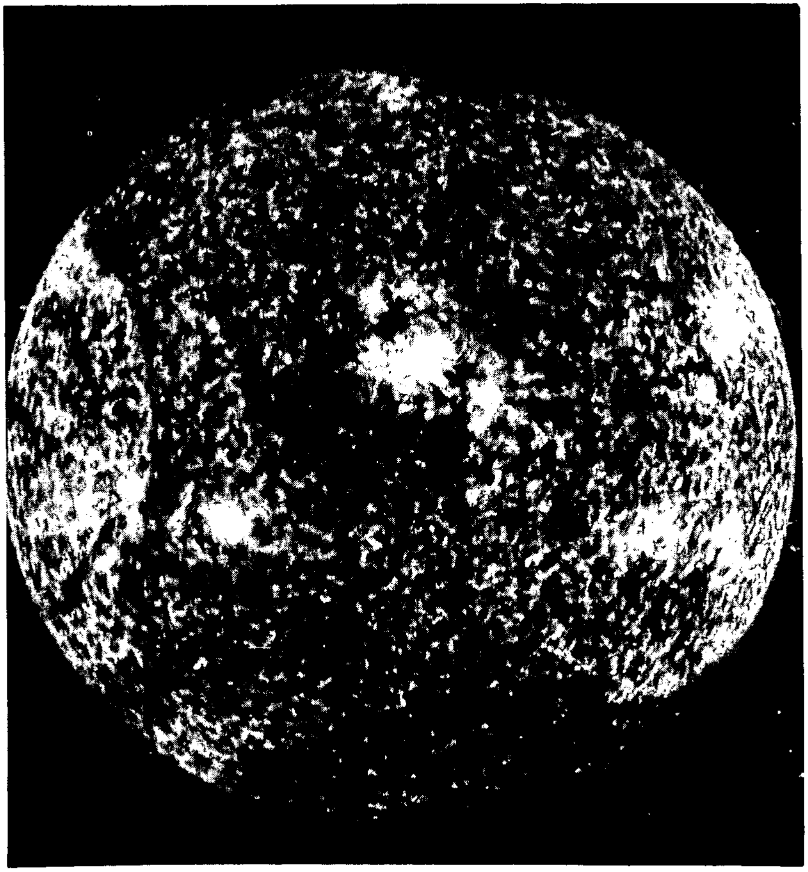
Table 4: Solar System Abundances of the Elements by Mass Percentage

Element	Mass Percentage
Hydrogen: ^1_1H	71
Helium: ^4_2He	27
$A = 5, 8$	0
$_3Li$, $_4Be$, $_5B$	10^{-6}
$_6C$, $_7N$, $_8O$, $_9F$, $_{10}Ne$	1.8
$_{11}Na$–$_{23}V$	0.2
Iron group ($_{24}Cr$–$_{28}Ni$)	0.027
$62 < A < 100$	10^{-4}
$A \geq 100$	10^{-5}

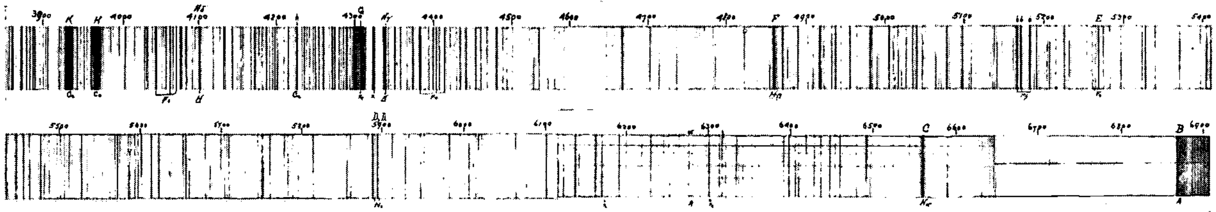
Earth (which has a mass of 6×10^{27} g) makes only a minor contribution to the total amount of material in our solar system. Most of the matter that composes our solar system is contained in the Sun (which has a mass of 2×10^{33} g).

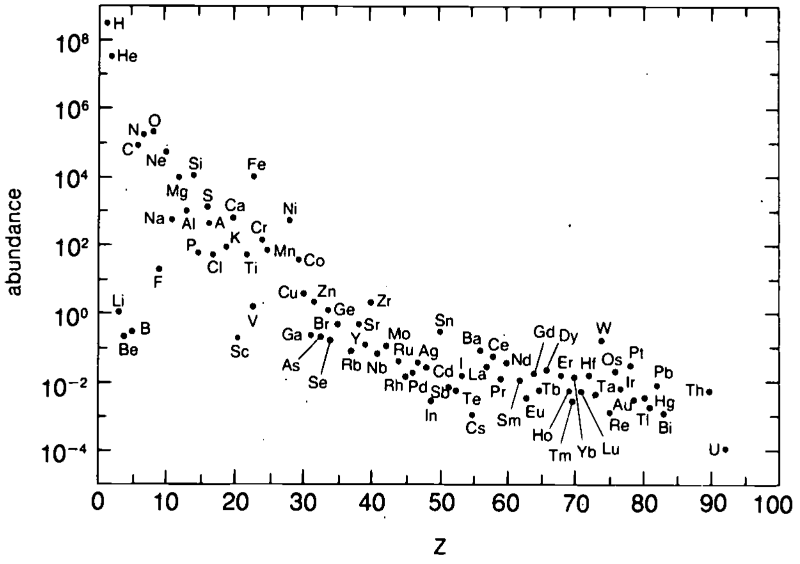
In Table 4 you will find several points of information that are highly significant to theories of how the elements were formed. First, note that our solar system is made up largely of the two lightest elements, hydrogen and helium—the dominant elements in the Sun. This fact is taken as evidence that the elements have been built up from combinations of nucleons.

Another interesting feature is that there are no stable nuclides with mass numbers $A = 5$ and $A = 8$. These nuclides do not exist in nature. In addition, the elements lithium, beryllium, and boron ($Z = 3$ to 5) are present only to a small extent with respect to both



This photograph of the Sun *(right)* was taken with the light emitted by ionized helium. The white regions correspond to the helium. A dark-line spectrum of sunlight *(below)* reveals the presence of many other elements.





Cosmic abundances of the elements. The ordinate for each element is the number of atoms per 10 000 atoms of silicon (Si).

their lighter and heavier neighbors carbon (Z = 6), nitrogen (Z = 7), oxygen (Z = 8), and neon (Z = 10). Thereafter, the elemental abundances decrease fairly regularly with increasing atomic number.

However, the elements iron (Z = 26) and nickel (Z = 28) have unusually high abundances compared to their neighbors. This fact is related to the high stability of the nuclides around iron (Figure 6). The very low abundances of all the elements beyond iron suggest that any process of stellar nucleosynthesis need not be very efficient in order to produce the trends shown in Table 4.

Scientists have confirmed the existence in nature of some 280 different stable nuclides and 67 nuclides that are radioactive. Included in this number are nuclides of all the elements from hydrogen (Z = 1) to bismuth (Z = 83), with the exception of technetium (Z = 43) and promethium (Z = 61). Both of these elements have been synthesized in the laboratory, where it has been found that the longest half-life for a technetium isotope is 2.8×10^6 years and for a promethium isotope, 18 years. Therefore, neither of these elements has an isotope that lives long enough to have survived throughout the age of our solar system (about 4.5 billion years). The radioactive elements thorium (Z = 90) and uranium (Z = 92) are also found in nature, as are the elements with atomic numbers Z = 84 to 89 and Z = 91. These have short half-lives but are produced by the radioactive decay of natural thorium and uranium. A summary of information on the extent of the nuclides in nature is illustrated in Table 5. The remaining elements known to scientists (elements from Z = 93 to Z = 106) do not occur in nature but can be synthesized in the laboratory; they are called *synthetic elements.*

The natural radioactive nuclides on Earth contribute a constant source of energy to our planet. These nuclides are part of the

Table 5: Nuclides Found on Earth

Elements that have existed since the formation of the solar system	Z = 1–42, 44–60, 62–83, 90, 92
Number of natural nuclides	280
Elements that occur as the result of radioactive decay of uranium and thorium	Z = 84–89, 91
Heaviest nuclide in nature	$^{238}_{92}U$

In a volcanic eruption, molten matter from the interior of the Earth escapes to the surface, altering the composition of elements in the Earth's crust and atmosphere.

Earth's rocks and oceans, and they constantly emit nuclear radiation, which is converted into heat. This radiation is thought to be at least partially responsible for keeping the core of the Earth molten and for the existence of volcanoes. Consequently, we live in an environment where we are constantly exposed to small amounts of *natural nuclear radiation*—sometimes referred to as *background radiation*. We will take this into account as we explore nuclear applications in *Uses of Radiation*.

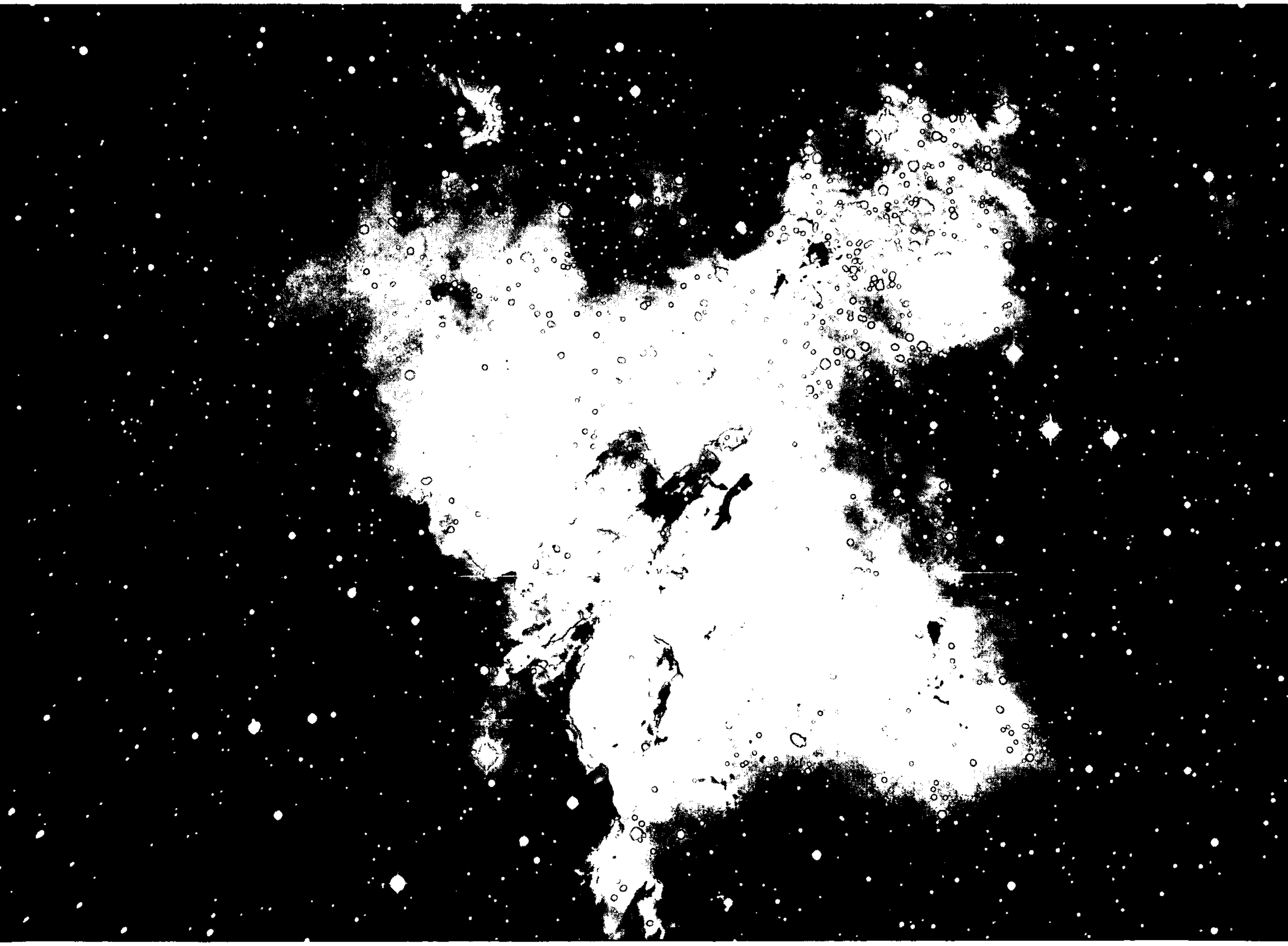
PROBLEMS

1. Consider a neutral atom of the isotope ^{40}K. Give the following information about this isotope.
   a. name of element ______
   b. number of protons in nucleus ______
   c. mass number ______
   d. atomic number ______
   e. chemical atomic mass of the element (listed in periodic chart) ______
   f. neutron number ______
   g. number of electrons in neutral atom ______
   h. number of electrons in ^{40}K^{+} ion ______
   i. The isotope ^{40}K exists in nature. From your answers to parts (c) and (e) above, would you expect this element to possess more than one stable isotope? Why?
2. Write the complete nuclear notation for the following nuclides.
   a. a nuclide with three protons and four neutrons
   b. a nuclide with atomic number 12 and mass number 24
   c. a nuclide with 17 protons and a mass number of 37
3. Based on Figures 5 and 6, and the discussion of nuclide stability summarized at the end of section *N-11*, which of the following nuclides would you expect to be more stable?
   a. ^{18}C or ^{13}C
   b. ^{76}Fe or ^{56}Fe
   c. ^{18}Na or ^{23}Na
   d. ^{56}Fe or ^{238}U
   e. ^{2}H or ^{4}He
4. Which of the following elements would you expect to find in higher abundance in a meteorite? (Refer to Table 4.)
   a. Fe or U
   b. Mg or Au
   c. O or Li
   d. Si or Cu
   e. Cu or Be

Nucleosynthesis and Stellar Evolution

If we assume that element formation began with the fundamental particles, we are then faced with several questions, Where and under what conditions have these processes occurred? Were all the elements made at one time, or are they being synthesized continually? How old are the elements we find on Earth? Although the above questions cannot be fully answered at the present time, the following description of the history of our Universe represents the most generally accepted theory.

Our Earth is a collection of matter—chemical elements—that is just a speck compared with the vast quantities of matter in the Universe. However, the elements found on Earth are the same kinds of elements observed in stars, other planets, and interstellar dust clouds.



N-15 The "Big Bang" Theory

Assuming that the buildup of the Universe began with reactions between simple particles, how do we explain all the events that followed? Scientists believe that the Universe as we now know it must have originated some 15 to 20 billion years ago in the explosion of a dense, high-temperature fireball—a phenomenon referred to as the *big bang*. The first stages of element synthesis were thought to have begun in this explosion, so it is here that we will begin our history of the origin of the elements.

The big bang theory for the origin of the Universe is based upon two important observations of astronomers. First, the stars and galaxies in the sky appear to be moving away from our galaxy; that is, the Universe seems to be expanding. Second, scientists measuring the microwave activity in the Universe have found that there exists a uniform pattern of background radiation. This uniform radiation appears to come from remnants of an ancient cosmological explosion.

If it is assumed that these two phenomena are related, it is possible to reconstruct the Universe that existed billions of years ago. The picture that emerges is one of a very hot, dense gas of neutrons, protons, photons, and electrons—a fireball. These extreme conditions produced an explosion—the *big bang*—which is believed to be responsible for the expansion of the Universe.

In this fireball there existed a supply of both protons and neutrons, the basic building blocks of the elements. During the subsequent expansion and cooling of the fireball, it became possible for nuclear reactions to occur. It is here that the first step in the synthesis of the elements begins with the nuclear reaction

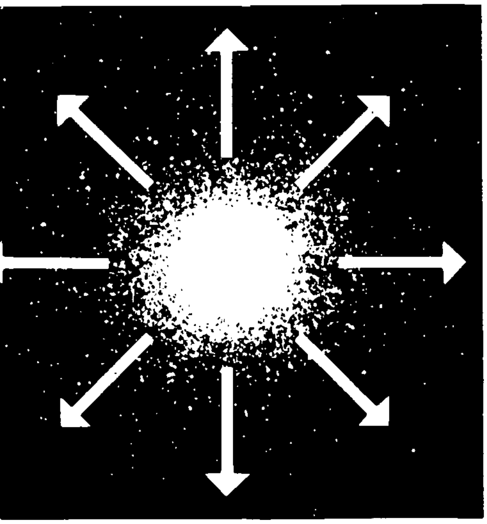
$$^{1}_{1}\mathrm{H} + ^{1}_{0}n \longrightarrow ^{2}_{1}\mathrm{H}$$

This reaction results in the formation of hydrogen of mass number $A = 2$, deuterium.

In balancing such nuclear equations, the conservation laws discussed in section *N-6* are observed. For example, the conservation of nucleons requires that the total mass number (superscript A) must be the same on each side of the equation. The same applies to the conservation of electric charge, which requires that the total charge (subscript Z) be the same on each side of the equation.

$$\begin{array}{lcccc} A & (1 & + & 1 & = & 2) \\ & ^{1}_{1}\mathrm{H} & + & ^{1}_{0}n & \longrightarrow & ^{2}_{1}\mathrm{H} \\ Z & (1 & + & 0 & = & 1) \end{array}$$

We will demonstrate that mass and energy are conserved in this kind of reaction in section *N-17*.



The Big Bang theory explains the origin of the Universe as an explosion of a dense fireball, which brought about the synthesis of elements.

Once $^{2}_{1}H$ nuclei are formed in the expanding gas, it becomes possible for other nuclear reactions to occur. For example, the reactions

$$^{2}_{1}H + ^{1}_{1}H \longrightarrow ^{3}_{2}He$$

$$^{3}_{2}He + ^{1}_{0}n \longrightarrow ^{4}_{2}He$$

lead to production of the isotopes of the element helium ($Z = 2$).

PROBLEMS

If we wish to check to see that the reactions for synthesis of ^{3}He and ^{4}He are correct, we follow the rules for balancing nuclear equations.

Examples:

		left	right	total
^{3}He production: mass number	A =	2 + 1	= 3	= 3
atomic number	Z =	1 + 1	= 2	= 2
^{4}He production: mass number	A =	3 + 1	= 4	= 4
atomic number	Z =	2 + 0	= 2	= 2

Several additional reactions may happen. Based upon the rules for writing nuclear equations, predict the *single* product formed in these reactions.

1. $^{2}_{1}H + ^{1}_{0}n \longrightarrow$ ______
2. $^{4}He + ^{3}He \longrightarrow$ ______
3. $^{4}_{2}He + ^{2}_{1}H \longrightarrow$ ______
4. $^{4}_{2}He + ^{3}_{1}H \longrightarrow$ ______
5. $^{3}_{2}He + ^{3}_{1}H \longrightarrow$ ______

From assumptions concerning the conditions of the big bang and from knowledge of nuclear reactions, scientists have concluded that the ^{2}H, ^{3}He, ^{4}He, and most of the ^{7}Li found in nature were made at that time. The fact that the amount of ^{4}He in the Universe seems to be rather constant (about 27 percent by mass) is another argument scientists use to support the big bang theory.

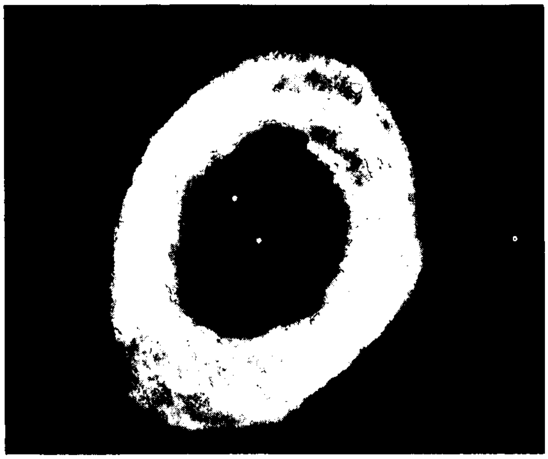
The formation of heavier elements in the big bang is severely restricted by the fact that nuclei with mass numbers $A = 5$ and $A = 8$ are very difficult to form (Table 4, section *N-14*). Thus reactions such as

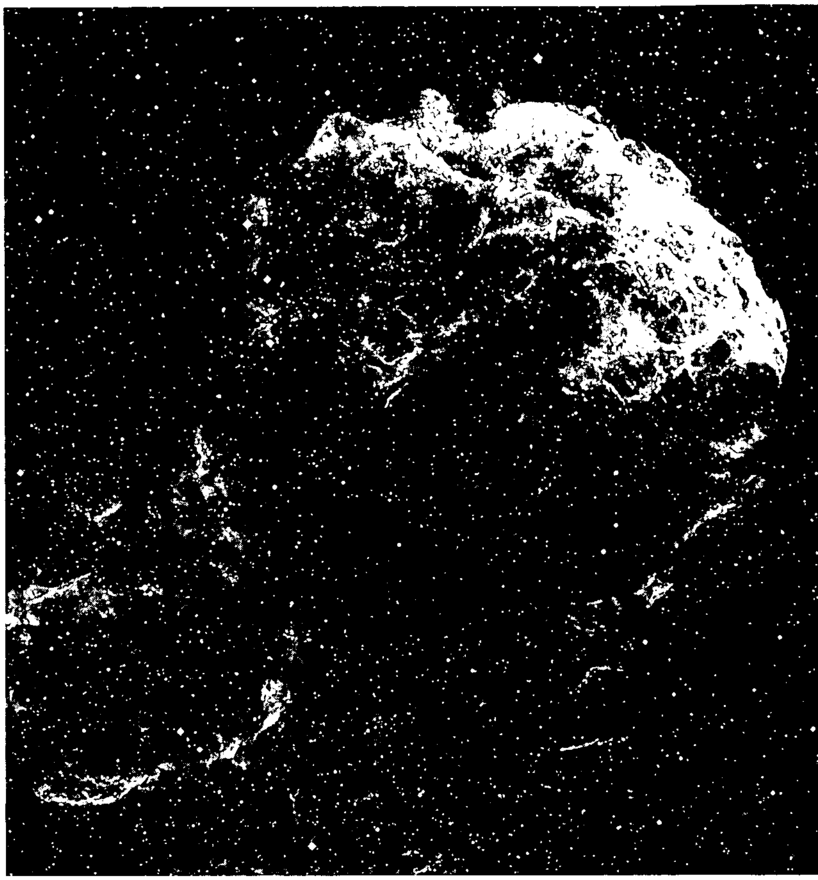
$$^{4}_{2}He + ^{1}_{0}n \longrightarrow ^{5}_{2}He$$

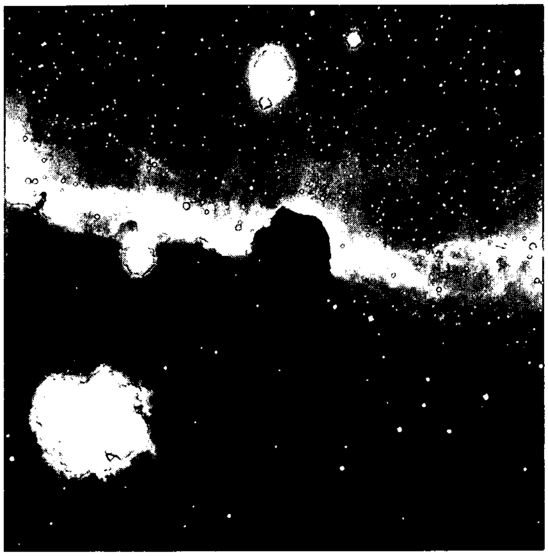
and

$$^{4}_{2}He + ^{4}_{2}He \longrightarrow ^{8}_{4}Be$$

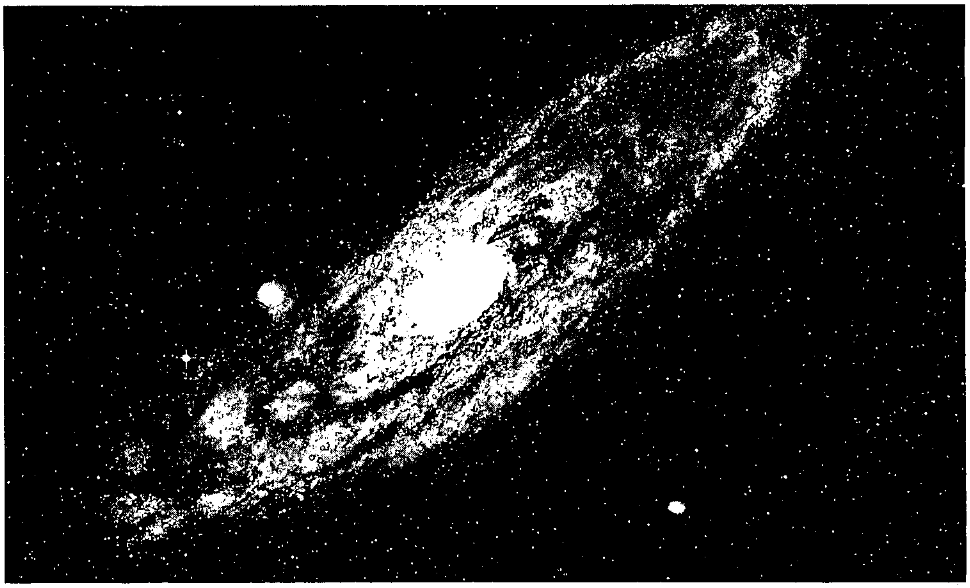
do not occur, thereby blocking the path of the buildup of heavier elements. Furthermore, it seems certain that all of the elements in nature could not have been produced at the beginning of time in a

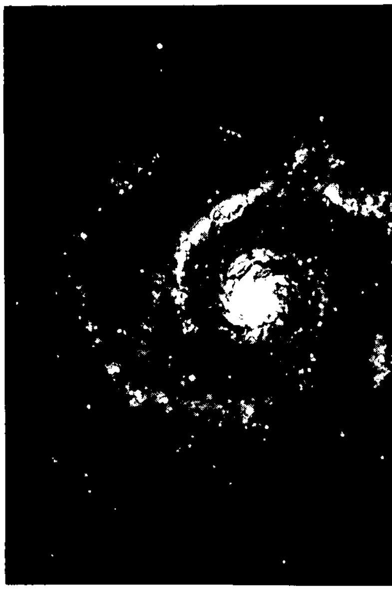






Matter in space creates many beautiful forms. The Ring Nebula in the constellation Lyra *(upper left)*, the wispy, gaseous nebulae in the constellation Gemini *(above)*, and the Horsehead Nebula *(left)* are among the most unusual formations of matter. The Androm Galaxy *(lower left)* and the Spiral Galaxy *(lower right)* are two of the many disk-shaped galaxies in the Universe.





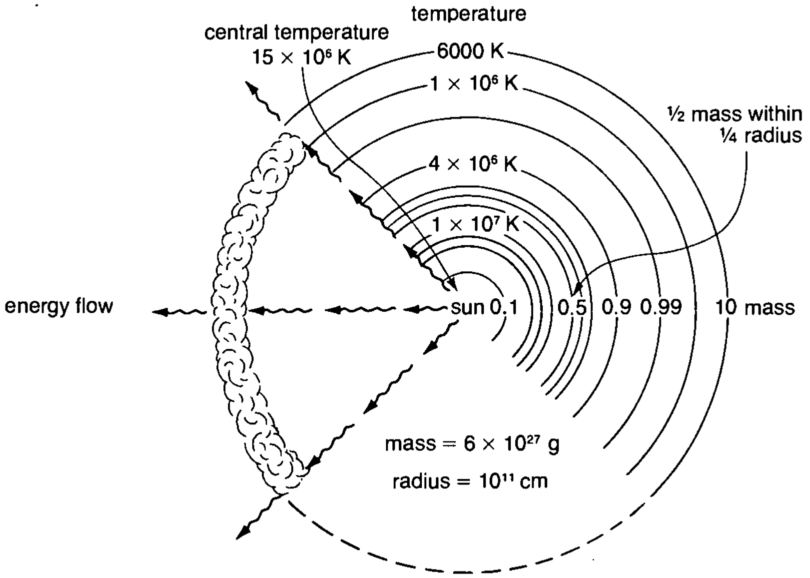
single big bang event. For example, the radioactive element technetium ($^{97}_{43}$Tc) has recently been observed in certain stars. The half-life of this element is about 2 million years—much shorter than the age of the Earth (about 4.5 billion years). This means that some stars have produced elements more recently than others. So we see that although the big bang theory can explain many important features of the Universe, it is unable to account for the origin of the heavy elements.

N-16 Stars from Big Bang Dust

In the aftermath of the big bang, cosmologic dust consisting largely of hydrogen and helium atoms was ejected into space. At the same time this dust cooled to temperatures well below those at which nuclear reactions could occur. If it were not for the force of gravity, this would have been the end of element synthesis. In addition, the elements carbon and oxygen—two of the most important elements for biological systems such as ourselves—would not exist.

However, given enough time, the attractive force of gravity begins to produce lumps of matter that eventually condense into definite objects in space. This process represents the beginning of galaxy and star formation and at the same time provides a new environment for synthesizing elements. As stellar objects condense (over a period of perhaps billions of years), their density increases and they begin to heat up once again. At sufficiently high temperatures (about 10 000 K) the atoms become ionized into nuclei and electrons.

Figure 7 MASS AND TEMPERATURE PROFILE OF THE SUN



TIME MACHINE
Cosmology

1920	Arthur S. Eddington proposes that stars derive their energy from nuclear reactions.
1921	Indian physicist Meghmed N. Saha develops the thermal ionization equation and applies it to the interpretation of stellar spectra.
1938	Hans Bethe and C. von Weisacker attempt to explain the Sun's energy via conversion of hydrogen to helium.
1948	George Gamow proposes "Big Bang" theory of the origin of the Universe.
1949	Mount Palomar Observatory opens with "200-inch" optical telescope, world's largest for next 25 years.
1957	Geoffrey Burbidge, Margaret Burbidge, William Fowler, and Fred Hoyle publish theory of stellar nucleosynthesis.
1974	Russians complete installation of "236-inch" optical telescope in the Caucasus.
1978	Penzias and Wilson win Nobel prize for discovery of microwave background radiation thought to be left over from the "Big Bang."

The electrons are thought to play an important role in stars, but are not related in a simple way to the story of nucleosynthesis presented here. Consequently we will focus on the bare (completely ionized) nuclei. However, after the products of nucleosynthesis cool to sufficiently low temperatures, they pick up electrons to form the neutral atoms and molecules we are familiar with on Earth.

In order for protons to continue developing into a star, two conditions must be present. First, there must be enough protons to enable their mutual gravitational attraction to overpower their electromagnetic repulsion. For bodies with a mass of about one-tenth the mass of our Sun or greater, this condition is met. Second, sufficient time must be available for gravitational attraction to produce a star. The age of the Universe (not our solar system, which is younger) is estimated to be about 15 to 20 billion years. This age appears to leave plenty of time for gravity to condense hydrogen atoms into starlike bodies.

Thus, for sufficiently large masses, the gravitational force continues to attract the protons closer and closer together. As the density increases, the temperature likewise increases. Both quantities reach their maximum at the center, or core, of the star (Figure 7). Eventually a new force comes into play—the nuclear force. At this point the further synthesis of elements begins.

N-17 H-Burning: Main Sequence Stars

As the force of gravity condenses a developing star, the density of the hydrogen nuclei in the core eventually reaches about 100 g/cm^3 (grams per cubic centimeter) with a corresponding temperature of about 15 000 000 K. Such conditions are certainly extreme when compared with those existing for hydrogen on Earth—about 300 K and 0.0001 g/cm^3. In fact, in the core of a star the density of hydrogen is much greater than that of uranium, one of the densest materials on Earth (19.3 g/cm^3). On the other hand, the core of a star is much less dense than a nucleus, which has a density of about 10^{14} g/cm^3. If a nucleus the size of a pencil eraser existed, it would be about as heavy as an oil supertanker!

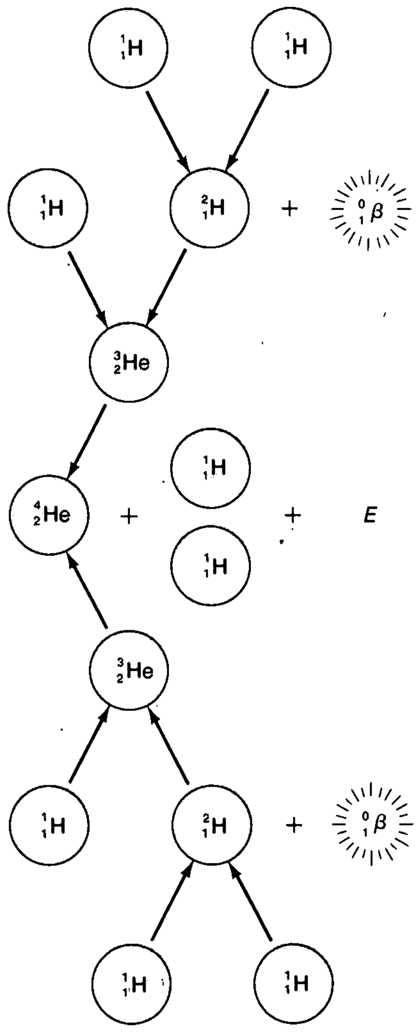
It is important to realize that such high temperatures and pressures are reached only in the core of a star. For example, the temperature at the surface of our Sun is only about 6000 K (Figure 7). At the temperature and pressure of the core, the protons begin to "burn." By "burning" we mean the reaction of two particles or nuclei to form new products with the liberation of energy. For example, the chemical burning of coal (carbon) in oxygen is a common way of obtaining energy.

$$\mathrm{C} + \mathrm{O_2} \longrightarrow \mathrm{CO_2} + \text{energy}$$

For each gram of carbon burned there is a liberation of 7800 calories of energy. Your body needs about three hundred times this much energy every day to keep it going.

The "burning" of nuclei in stars is responsible for producing stellar energy. Without nuclear burning, neither the elements of the Universe nor life itself could exist. About 90 percent of the stars in the Universe derive their energy from the burning of hydrogen into helium. These are called *main sequence stars.* The following series of nuclear reactions illustrates how ${}^{1}_{1}\mathrm{H}$ nuclei (protons) are converted into helium.

Figure 8
THE PROTON-PROTON CYCLE



$$
\begin{array}{lllllllllll}
 & {}^{1}_{1}\mathrm{H} & + & {}^{1}_{1}\mathrm{H} & \longrightarrow & {}^{2}_{1}\mathrm{H} & + & {}^{0}_{1}\beta & + & 1.4\ \mathrm{MeV} & (1) \\
 & {}^{2}_{1}\mathrm{H} & + & {}^{1}_{1}\mathrm{H} & \longrightarrow & {}^{3}_{2}\mathrm{He} & + & 5.5\ \mathrm{MeV} & & & (2) \\
 & {}^{3}_{2}\mathrm{He} & + & {}^{3}_{2}\mathrm{He}^{\dagger} & \longrightarrow & {}^{4}_{2}\mathrm{He} & + & 2\,{}^{1}_{1}\mathrm{H} & + & 12.9\ \mathrm{MeV} & (3) \\
\hline
\text{Net:} & & & 4\,{}^{1}_{1}\mathrm{H} & \longrightarrow & {}^{4}_{2}\mathrm{He} & + & 2\,{}^{0}_{1}\beta & + & 26.7\ \mathrm{MeV} & (4)
\end{array}
$$

†Reactions similar to (1) and (2) produce a second ${}^{3}_{2}\mathrm{He}$.

PROBLEM

From Figure 8, *The Proton-Proton Cycle,* and the accompanying equations, see if you can add equations (1) to (3) to obtain equation (4) for hydrogen burning. Next, try to apply the conservation of mass and energy laws (section *N-6*) to the calculation of the energy released in equation (2). Use the following masses obtained from atomic mass tables in reference books.

$^{1}\mathrm{H} = 1.007\,825\ \mathrm{u}$

$^{2}\mathrm{H} = 2.014\,102\ \mathrm{u}$

$^{3}\mathrm{He} = 3.016\,030\ \mathrm{u}$

The total mass of the reactants minus that of the products can then be expressed in the following way.

$$
\begin{array}{llcl}
\text{reactants:} & {}^{1}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} & = & 3.021\,927\ \mathrm{u} \\
\text{products:} & {}^{3}_{2}\mathrm{He} & = & 3.016\,030\ \mathrm{u} \\
\hline
\text{change in mass:} & & = & 0.005\,897\ \mathrm{u}
\end{array}
$$

This means that the reaction will proceed as written and that 0.005 897 u will be converted to energy. From the equation $E = mc^2$, we can calculate the amount of energy equivalent to the change in mass.

$$E = mc^2 = (0.005\,897\ \mathrm{u})\,(931.5\ \mathrm{MeV/u})^2$$

$$E = 5.493\ \mathrm{MeV} \cong 5.5\ \mathrm{MeV}$$

In general, we can state that for any nuclear reaction, the energy release (E) is

$$E = [(\text{sum of masses of reactants}) - (\text{sum of masses of products})]\,c^2$$

As long as E or m is a positive quantity, the required conservation of mass-energy is fulfilled. Or if we wish to show specifically how much energy is released (E positive) or absorbed (E negative), we should write E on the right-hand side of the equation, as illustrated in equation (2).

Now, from the above data and $m(^4\text{He}) = 4.002\,428$ u, prove that the energy release in equation (3) is correct.

Scientists have done laboratory studies of the hydrogen-burning reactions that synthesize helium. These are called *fusion reactions* because they combine (fuse) two nuclei to form a heavier nucleus. The amount of energy released in the net hydrogen-burning reaction is extremely large. For example, there are 1.5×10^{11} calories liberated per gram of hydrogen "burned" in this reaction. This is more than 20 million times as much energy as is liberated from the chemical burning of a gram of carbon.

The tremendous amount of energy released in hydrogen burning is responsible for stabilizing a condensing star. That is, the energy released during nuclear burning serves as an expansive force that opposes the contraction caused by the force of gravity. When these two effects counterbalance each other, the star appears to be a stable body in space. As long as the nuclear fuel holds out, the star will continue to serve as a constant source of energy.

The mass of a star determines the rate at which it burns nuclear fuel and therefore how long it will live. The heavier the star, the faster it burns. In hydrogen-burning stars, the slowest step is the fusion of two protons to make ^2_1H and a positron. From experimental knowledge of how fast this reaction occurs and how much hydrogen exists in the Sun, it is possible to calculate that our Sun will continue to shine for another 5 billion years or so.

In summary, hydrogen-burning nuclear reactions stabilize a condensing star and generate energy by producing helium from

Underground nuclear explosions provide a unique opportunity to study nuclear reactions. Knowledge obtained from these experiments can help scientists understand the process of nucleosynthesis.

hydrogen. Much of our energy for the future may be obtained by harnessing similar nuclear fusion reactions in the laboratory for the production of *thermonuclear power*. Scientists have already learned to reproduce similar nuclear fusion reactions in an uncontrolled form—the *hydrogen* (or *thermonuclear*) *bomb* (section *N–48*).

PROBLEMS

Balance the following equations for nuclear reactions.

Example: ${}^{7}_{3}\mathrm{Li} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{10}_{5}\mathrm{B} + {}^{1}_{0}n$

1. ${}^{6}_{3}\mathrm{Li} + {}^{1}_{0}n \longrightarrow {}^{4}_{2}\mathrm{He} + \_\_\_\_$

2. ${}^{3}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} \longrightarrow \_\_\_\_ + {}^{1}_{0}n$

3. ${}^{3}_{1}\mathrm{H} + {}^{3}_{1}\mathrm{H} \longrightarrow {}^{4}_{2}\mathrm{He} + \_\_\_\_$

(Reactions 1–3 are similar to those that occur in a thermonuclear reaction.)

A shorthand way of writing the preceding equations is to place the lighter reactant and product inside parentheses separated by a comma, and the heavier reactant and product outside. Write equations 1–3 again in the shorthand form.

Example: ${}^{7}_{3}\mathrm{Li}({}^{4}_{2}\mathrm{He}, {}^{1}_{0}n){}^{10}_{5}\mathrm{B}$

1. ${}^{6}_{3}\mathrm{Li}({}^{1}_{0}n, \_\_\_\_){}^{4}_{2}\mathrm{He}$

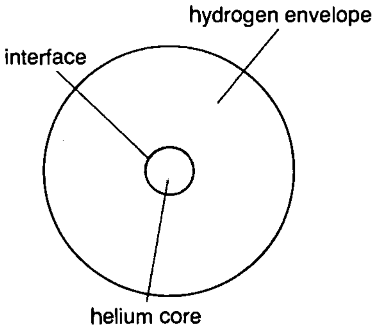
2. ____ (____, ____) ____

3. ____ (____, ____) ____

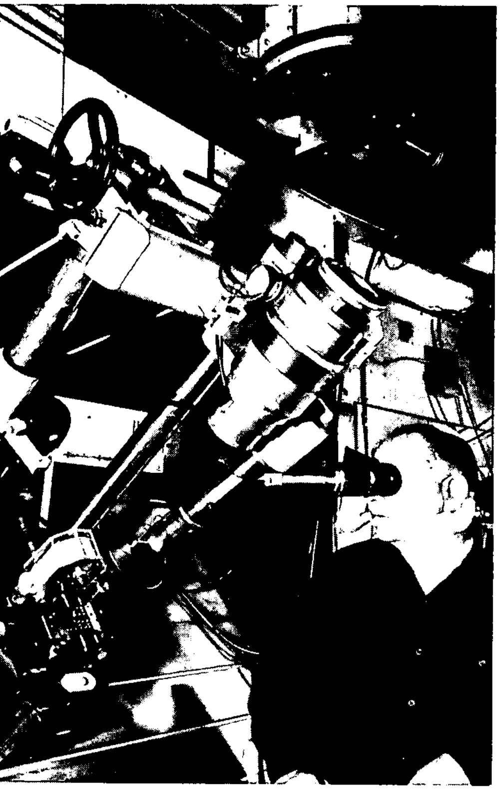
N-18 Helium Burning: Red Giants

As a main sequence star becomes older, it begins to develop two parts: (1) a core composed largely of the helium produced during hydrogen burning and (2) an outer envelope consisting largely of unburned hydrogen (Figure 9). Hydrogen burning continues at the interface between the core and the envelope. At a temperature of 15 000 000 K, the core of a star is not hot enough to permit helium nuclei to react with one another. Can you suggest why? In addition, our knowledge of nuclear science indicates that it is not possible to build up any substantial amount of the elements lithium, beryllium, and boron (Z = 3 to 5) from reactions of protons, ${}^{2}_{1}\mathrm{H}$, or ${}^{3}_{2}\mathrm{He}$ with ${}^{4}_{2}\mathrm{He}$ at such temperatures. Therefore, nuclear burning subsides in the core.

Figure 9



If the mass of the star is sufficiently large, the force of gravity then begins to contract the core once again, until it reaches still higher densities and temperatures. This heating of the core causes



Have you noticed that stars have different colors? The spectroscope, such as this one in use at the Lick Observatory, analyzes light from the stars and enables astronomers to determine what chemical elements are present in other parts of the Universe.

the envelope of the star to expand greatly and gives rise to a new stage in the evolution of the star. This is called the *red giant* stage. During this stage of a star, the gravitational force continues to contract the core. When the temperature reaches about 100 000 000 K (corresponding to a density of 10^4 g/cm^3), a new type of nuclear reaction becomes possible.

Of the several possible nuclear reactions that might conceivably lead to the production of heavier elements (from hydrogen and helium at such temperatures), studies of nuclear reactions have led us to believe that one is most likely to occur. This reaction, called *helium burning*, is represented by the equation

$$3\,{}^{4}_{2}\text{He} \longrightarrow {}^{12}_{6}\text{C} + 7.6\text{ MeV}$$

Therefore, to a large extent, the element-synthesis chain skips over the elements lithium (Li), beryllium (Be), and boron (B) to produce carbon ($Z = 6$). Does this seem consistent with the information presented in Table 4, section *N-14*?

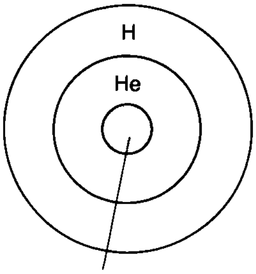
Once helium burning begins, the core of the star is again stabilized—under this new condition, gravitational contraction and expansive nuclear burning offset each other. To produce a helium-burning reaction, three ${}^{4}_{2}$He nuclei must collide at the same time, which is much less probable than two colliding simultaneously (just as the probability of three cars colliding simultaneously at an intersection is less than for two cars colliding). Consequently, the red giant stage of a star can last for millions of years. Another type of reaction that is important in red giants is

$${}^{12}\text{C} + {}^{4}\text{He} \longrightarrow {}^{16}\text{O} + \gamma$$

This reaction enriches the variety of nuclei present in the star, making possible the synthesis of still heavier nuclei in later stages of the star's life cycle.

Stars that are not heavy enough to sustain more advanced stages of nuclear burning gradually burn up their available nuclear fuel and contract into small, hot stars called *white dwarf stars*. These represent the stellar "graveyard," since no further element synthesis can occur—they have reached their final resting place.

Figure 10



N-19 Explosive Nucleosynthesis

As a star passes through the red giant stage, new core conditions eventually develop. For the most part, the core contains ^{12}C, ^{16}O, and ^{20}Ne surrounded by envelopes composed of helium and hydrogen (Figure 10). The large positive charge of the nuclei in the core inhibits nuclear reactions at these temperatures. For sufficiently heavy stars, the core undergoes further gravitational contraction and heating. If the temperature and density reach about 10^9 K and 10^6 g/cm^3, respectively, new types of nuclear reactions become possible. Because nuclear reactions occur quite readily under these conditions, the evolution of the star proceeds rapidly at this stage. For this reason the term *explosive nucleosynthesis* is used to describe element formation in such stars. The first step in this complex sequence of reactions is called *carbon burning*. It involves the fusion of the products of helium burning and is represented by equations of the type

$$ {}^{12}_{6}\mathrm{C} + {}^{12}_{6}\mathrm{C} \longrightarrow {}^{20}_{10}\mathrm{Ne} + {}^{4}_{2}\mathrm{He} + \text{energy} $$

$$ {}^{16}_{8}\mathrm{O} + {}^{16}_{8}\mathrm{O} \longrightarrow {}^{28}_{14}\mathrm{Si} + {}^{4}_{2}\mathrm{He} + \text{energy} $$

As the life cycle of a heavy star continues, a new core composed largely of magnesium (${}^{24}_{12}\mathrm{Mg}$), silicon (${}^{28}_{14}\mathrm{Si}$), and sulfur (${}^{32}_{16}\mathrm{S}$) develops. At this point a star has a fairly varied nuclear composition and a process known as *silicon burning* begins. Reactions of the following type then occur.

$$ {}^{28}_{14}\mathrm{Si} + {}^{4}_{2}\mathrm{He} \rightleftharpoons {}^{32}_{16}\mathrm{S} + \text{energy} $$

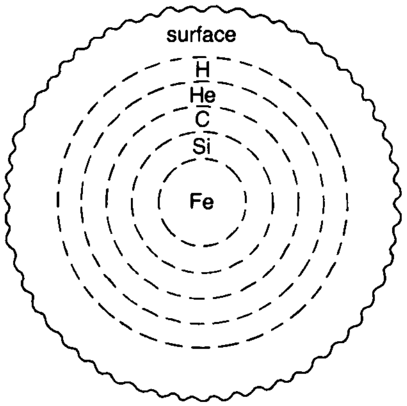
$$ {}^{32}_{16}\mathrm{S} + {}^{4}_{2}\mathrm{He} \rightleftharpoons {}^{36}_{18}\mathrm{Ar} + \text{energy} $$

$$ {}^{36}_{18}\mathrm{Ar} + {}^{4}_{2}\mathrm{He} \rightleftharpoons {}^{40}_{20}\mathrm{Ca} + \text{energy} $$

These reactions can go in either direction ($\rightleftharpoons$), but the reactions going toward the right *always* occur to some extent. This chain of reactions primarily produces nuclei (A = 32, 36, 40, 44, 48, 52, and 56) that turn out to be unusually abundant in nature. Of particular importance is the fact that this chain stops with the production of nuclei with mass number A = 56. Recall that we stated in section *N-11* that ${}^{56}_{26}\mathrm{Fe}$ is nature's most stable nuclide. Fusion reactions cannot successfully produce nuclei heavier than ${}^{56}_{26}\mathrm{Fe}$ in the stellar core because further nuclear reactions will absorb energy rather than release it. At this stage new processes for nucleosynthesis must be sought to explain the existence of the heavy elements beyond iron.

To summarize our theory of stellar evolution so far, we have described a rather complex star. It contains most of the elements up to iron in various layers (Figure 11), including most of those needed to sustain life. The nuclide ${}^{56}_{26}\mathrm{Fe}$ is produced in the core, and the difficulty in producing nuclei beyond iron accounts for the low abundances of the heavier elements. The unusual stability of nuclei in this mass region also means that nuclear reactions can no longer act as a source of energy to stabilize the star against the strong attractive forces of gravity that exist in a massive star.

Figure 11

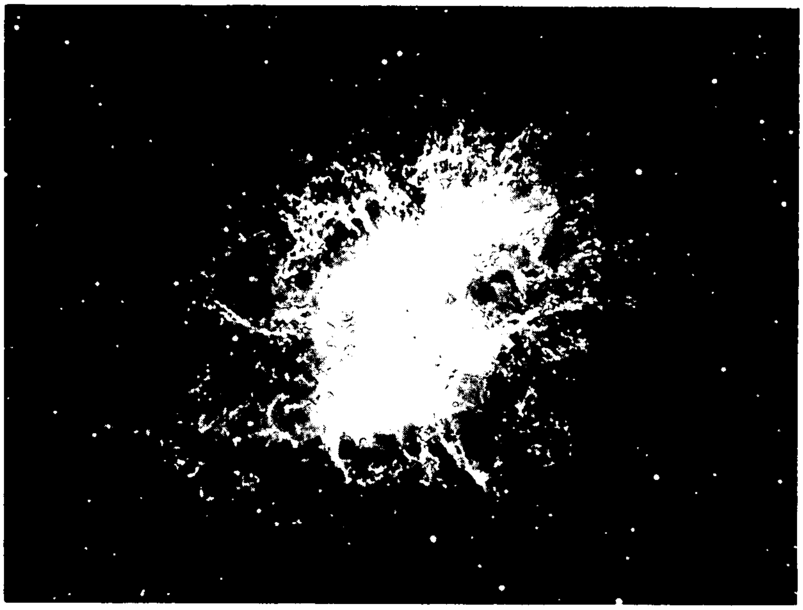


A schematic outline of a star at the end of silicon burning. The temperature at the surface (mostly H) is much lower than that in the core (mostly Fe).

N-20 Heavy Elements: *Zap*, the *r*-Process

The accumulation of the iron-group elements in the core of a star leads to catastrophic conditions. Because nuclear reactions can no longer release energy and provide their stabilizing influence on the star, the gravitational force can cause the star's core to collapse—an *implosion* of the core on itself. An implosion is a rapid contraction, just as an explosion is a rapid expansion. The implosion process occurs on a time scale as short as seconds, during which the density may rise to as high as 10^8 g/cm^3 with a corresponding temperature rise to about 4×10^9 K in the center of the core.

There are two important consequences of this collapse of the core and the rapid heating of the system that follows. First, the rapid increase in stellar temperature triggers all kinds of nuclear reactions throughout the outer envelopes of the star. For a sufficiently massive star, so many reactions result that the entire star may explode with one giant *zap*. It is thought that this process of gravitational collapse, rapid heating, and subsequent explosion of the star occurs in a stellar event known as a *supernova*. This type of star flares up suddenly to an unusually great brightness. Then the light output decreases, rapidly at first but more gradually after the first few days. The Crab Nebula, which Chinese astronomers observed in 1054 A.D., is the remnant of such a supernova.



The Crab Nebula is the remnant of a supernova that exploded in A.D. 1054. A pulsar (perhaps a neutron star) has been observed in the Crab.

A second important consequence of gravitational collapse in an evolving star stems from the conditions in the very center of the stellar core. Here the temperature is highest. At these extreme temperatures, the iron nuclei begin to dissolve. One reaction that can take place is

$$^{56}_{26}\mathrm{Fe} + \text{energy} \longrightarrow 13\,^{4}_{2}\mathrm{He} + 4\,^{1}_{0}n$$

and it may continue with

$$13\,^{4}_{2}\mathrm{He} \longrightarrow 26\,^{1}_{1}\mathrm{H} + 26\,^{1}_{0}n$$

The important feature of these reactions is that they can produce many neutrons in the core region. These neutrons serve as a source of nuclear particles that can interact with previously processed nuclear material in the star and enrich further the variety of nuclei that are produced. Because neutrons have no electric charge, they can be absorbed by nuclei such as ^{56}Fe without the restrictions of the electromagnetic repulsion experienced by charged particles.

This stage of nucleosynthesis is called the *r-process* (*r* stands for *rapid*) and is assumed to be responsible for building up the heavy elements beyond iron according to the following series of reactions.

$$^{56}_{26}Fe \xrightarrow{n} {}^{57}_{26}Fe \xrightarrow{n} {}^{58}_{26}Fe \xrightarrow{n} {}^{59}_{26}Fe \xrightarrow{n} {}^{60}_{26}Fe, \text{ etc.}$$

These reactions continue until some highly unusual nuclei are produced. These nuclei have many extra neutrons and lie well submerged in the sea of instability (section *N-11*). As the process of neutron addition continues, some of the extra neutrons decay into protons, thus producing heavier elements.

$$^{56}_{26}Fe + 23\,{}^{1}_{0}n \longrightarrow {}^{79}_{26}Fe \longrightarrow {}^{79}_{27}Co + {}^{0}_{-1}\beta$$

$$^{79}_{27}Co + 5\,{}^{1}_{0}n \longrightarrow {}^{84}_{27}Co \longrightarrow {}^{84}_{28}Ni + {}^{0}_{-1}\beta$$

This sequence of neutron captures followed by beta decay produces heavier and heavier elements. It is the *r*-process that forms the heaviest elements in nature and must account for the possible existence of any "superheavy" elements ($Z \geq 110$). There is no other nuclear process known by which we can account for the production of the amounts of uranium ($Z = 92$) and thorium ($Z = 90$) we find in nature today.

The upper limit to element synthesis in the *r*-process is imposed by the presence of *nuclear fission* reactions. Suppose $^{269}_{92}U$ is made in the *r*-process by the capture of 213 neutrons in $^{56}_{26}Fe$ accompanied by 66 beta-decay steps. The next possible reaction can be one of two reactions as illustrated in the following equations.

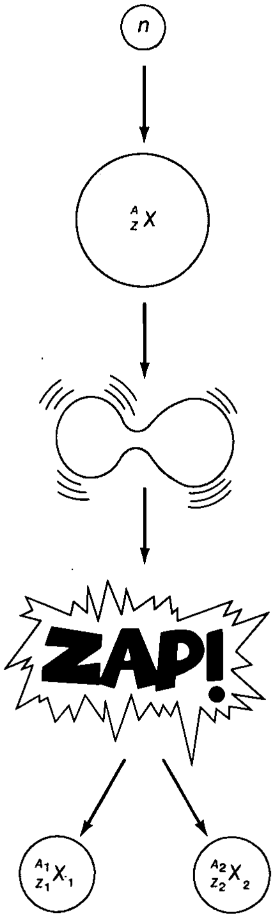
$$^{269}_{92}U + {}^{1}_{0}n \longrightarrow {}^{270}_{92}U \quad \text{(neutron capture)}$$

or

$$^{269}_{92}U + {}^{1}_{0}n \longrightarrow {}^{120}_{40}Zr + {}^{150}_{52}Te \quad \text{(nuclear fission)}$$

The fission reaction involves the division of a heavy nucleus into two nuclei of roughly the same mass number. This process releases a large amount of energy, typically about 200 MeV. In general, a wide variety of products is possible in a fission reaction, including most of the elements between bromine ($Z = 35$) and lanthanum ($Z = 57$). It is not clear at what point fission becomes dominant in the *r*-process chain of mass buildup. Most probably it occurs around mass number $A = 270$, but we cannot be sure of this.

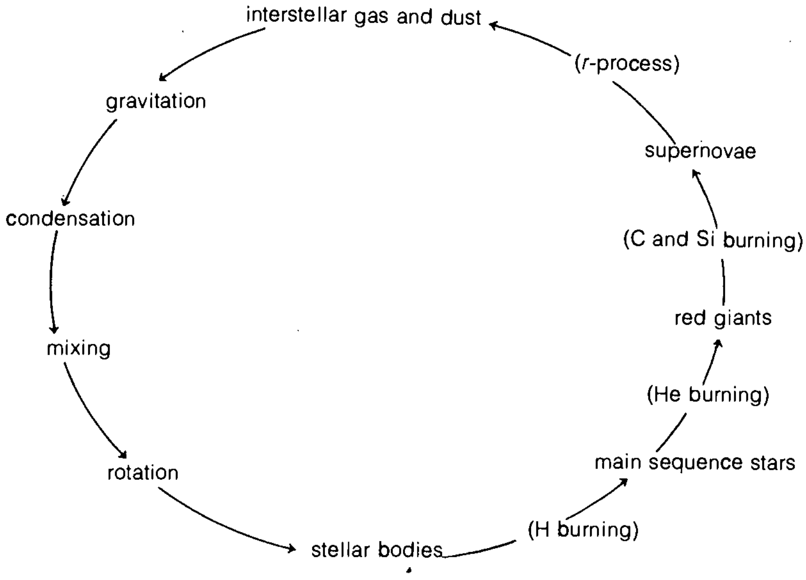
SCHEMATIC DIAGRAM OF NUCLEAR FISSION



$A = A_1 + A_2$
$Z = Z_1 + Z_2$

This diagram illustrates one generation in the life cycle of a star. Later-generation stars go through similar cycles, but they have a richer composition of elements.

LIFE CYCLE OF A STAR
One Generation Per Cycle



Although there are other significant processes responsible for element production, the *r*-process is thought to conclude the life cycle of a first-generation star (a star formed from the original material produced in the big bang). Following gravitational collapse, the explosion of a star blasts processed nuclear material out into space where temperatures and densities are much lower. This material then attracts electrons to form neutral atoms and molecules, and the entire cycle begins anew. That is, the gravitational force once again begins to condense matter to form second-generation stars. Or, in the case of matter with smaller amounts of mass, planets, meteorites, and cosmic dust are formed. Thus, succeeding generations of stars evolve that are richer in nuclear composition. Our Sun must be at least a second-generation star because there is evidence that it contains heavy elements, in addition to hydrogen and helium.

It is clear from the abundances of the elements (Table 4, section *N-14*) that none of the successive stages of element synthesis needs to be very efficient to produce nature's elements. Therefore, even after the complete evolution of a star, 98 percent of the material will still be in the form of hydrogen and helium.

Once again, you are reminded that we have no conclusive proof that such a process has ever occurred. In fact, many pieces of experimental information are still not well understood. Nonetheless, the model scientists have described represents our best current understanding of the origin of the elements.

PROBLEMS

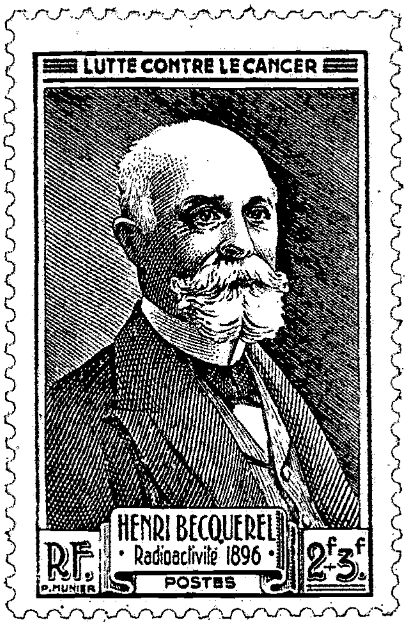
Identify the nucleosynthesis process (such as hydrogen burning) that is illustrated in the following nuclear reactions.

1. ${}^{16}_{8}O + {}^{16}_{8}O \longrightarrow {}^{28}_{14}Si + {}^{4}_{2}He$
2. ${}^{227}_{82}Pb + {}^{1}_{0}n \longrightarrow {}^{228}_{82}Pb$
3. ${}^{1}_{1}H + {}^{1}_{1}H \longrightarrow {}^{2}_{1}H + {}^{0}_{1}\beta$
4. ${}^{36}_{18}Ar + {}^{4}_{2}He \longrightarrow {}^{40}_{20}Ca$
5. ${}^{4}_{2}He + {}^{12}_{6}C \longrightarrow {}^{16}_{8}O$
6. $3\,{}^{4}_{2}He \longrightarrow {}^{12}_{6}C$
7. ${}^{2}_{1}H + {}^{1}_{1}H \longrightarrow {}^{3}_{2}He$
8. ${}^{264}_{100}Fm \longrightarrow 2\,{}^{132}_{50}Sn$
9. ${}^{40}_{20}Ca + {}^{4}_{2}He \longrightarrow {}^{44}_{22}Ti$
10. ${}^{63}_{26}Fe + {}^{1}_{0}n \longrightarrow {}^{64}_{26}Fe$

N-21 Detecting the Remnants

The survival to this day of some of the radioactive remnants of nucleosynthesis provides the key to our understanding of the origin of the elements and the age of the solar system. Two of the *r*-process remnants in particular— the elements thorium and uranium—were the subject of many early investigations that revealed the secrets of atomic and nuclear structure.

Radioactivity was first discovered in 1896 by the French scientist Henri Becquerel. He found that photographic film became exposed when placed near samples of uranium-containing compounds. This happened even when the greatest precautions were taken to avoid exposing the film to light. After careful study of this phenomenon, Becquerel concluded that a form of radiation much more energetic than visible light was penetrating the protective covering of the film and exposing it. We now know that the film was exposed by radiation emitted by radioactive uranium nuclei. This radiation exposes the grains of the film emulsion in the same way that light exposes the film in a camera.



Accidental discoveries in science are made not entirely by luck. Becquerel was alert to what he accidentally observed, and he had the scientific background to appreciate that observation. This sample of uranium ore *(left)*, glowing with radioactivity, was obtained in Greenland.

In the following experiment you will be able to duplicate Becquerel's initial discovery. You can use a MINIGENERATOR as a radioactive source along with photographic film and developing materials.

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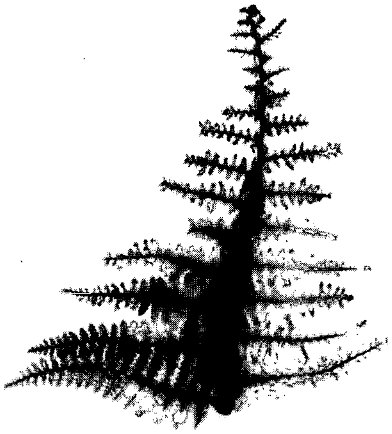
miniexperiment

N-22 Radioautography: Catching the Rays



A radioautograph of a fern frond illustrates the distribution of a radioactive sulfur solution.

There are many forms this experiment can take, depending on the types of materials available. If you are acquainted with the chemistry of photography, you may wish to devise a method of your own.

Part 1: Making the Image

Take a sheet of Polaroid black-and-white sheet film (Type 57) and place a MINIGENERATOR on top of the emulsion side of the film. Allow the MINIGENERATOR to remain there for 48 hours. Arrange this setup so that it will not be disturbed. If the MINIGENERATOR moves, it will cause a blurred image on the film.

Part 2: Developing the Image

Develop the film with either a Polaroid Type 545 holder or any film-roller arrangement that will distribute the developer uniformly across the film. After the development is complete, separate the film from the backing and you should be able to observe the image of the radioautograph.

This is how Becquerel deduced the existence of radioactivity, although he did not have the convenience of modern photographic methods.

N-23 Heavy Elements via the *s*-Process

Up to now our discussion has emphasized the production of new elements in the initial cycle of a star's lifetime. In later-generation stars, the presence of previously processed nuclear material makes it possible to form elements in many new ways. One such mechanism that is important in producing nature's elements is the *s-process* (*s* stands for *slow*). This process, like the *r*-process, involves the capture of neutrons, but it takes place in relatively stable stars where nuclear reactions produce neutrons at a slow, steady rate. For example, neutrons can be produced in red giant stars by means of (^{4}He, n) reactions on ^{13}C and ^{17}O during helium burning.

$$^{13}_{6}\text{C} + {}^{4}_{2}\text{He} \longrightarrow {}^{16}_{8}\text{O} + {}^{1}_{0}n$$

$$^{17}_{8}\text{O} + {}^{4}_{2}\text{He} \longrightarrow {}^{20}_{10}\text{Ne} + {}^{1}_{0}n$$

When sizable amounts of the iron-group elements are present, it is possible to build up heavy elements much the same as in the *r*-process. However, unlike the *r*-process, in which many neutrons are captured in a single nucleus in a matter of minutes, in the *s*-process a single nucleus captures a neutron every few thousand years or so—slowly. Nonetheless, since red giants stay around for millions of years, the *s*-process can exert a strong influence on the production of heavy elements in such stars.

The difference in time scales between the *s*- and *r*-processes results in the formation of different isotopes of the elements. The *r*-process tends to form the heavier isotopes of a given element, whereas the *s*-process forms the lighter isotopes. For example, the stable isotopes of the element selenium, Se (Z = 34, a member of the oxygen family), are produced in the following way.

Table 6: STABLE ISOTOPES OF SELENIUM

Isotope	^{74}Se	^{76}Se	^{77}Se	^{78}Se	^{80}Se	^{82}Se
Percentage of total Se by mass	0.9%	9.0%	7.6%	23.5%	49.8%	9.2%
Nucleosynthesis process	other	*s*-process	*s*-process *r*-process	*s*-process *r*-process	*s*-process *r*-process	*r*-process

Leaded glass and lead-bearing gloves protect a scientist who is working with a "button" of plutonium. The plutonium will be further processed for use in nuclear devices.

Thus, both the *s*- and *r*-processes (as well as another minor process as observed from ^{74}Se) contribute to the formation of the heavy elements. The *s*-process cannot, however, produce nuclides beyond bismuth (^{209}Bi) because the resultant products have very short lifetimes compared with millions of years. For example, ^{209}Bi may absorb a neutron to form polonium (^{210}Po). However, before the polonium isotope can capture another neutron, the ^{210}Po undergoes alpha decay to ^{206}Pb.

The *s*-process, which is thought to be understood fairly well, has been studied extensively in *nuclear reactors*. Nuclear reactors produce neutrons by means of nuclear fission reactions involving either the naturally occurring isotope of uranium, ${}^{235}_{92}U$, or the synthetic plutonium nuclide, ${}^{239}_{94}Pu$. (This plutonium nuclide is made from the capture of a neutron in ${}^{238}_{92}U$, followed by two beta decays.) The total fission reaction can be illustrated by an equation such as

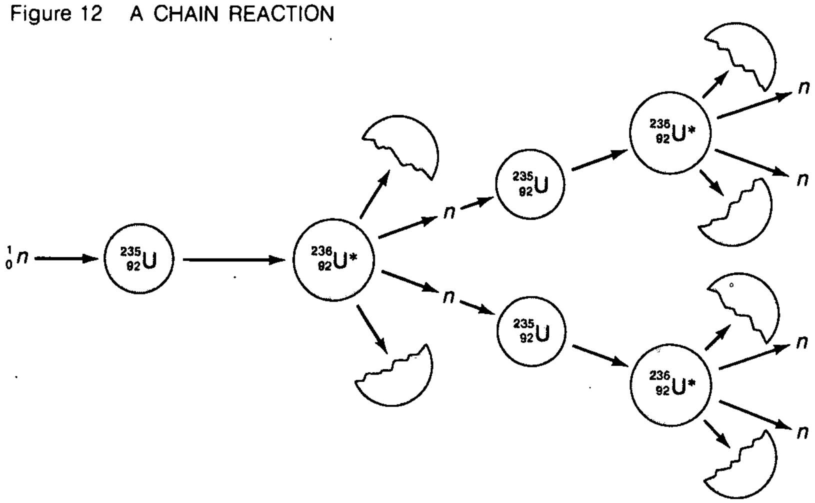
$$ {}^{235}_{92}U + {}^{1}_{0}n \longrightarrow {}^{236}_{92}U^{*\dagger} \longrightarrow {}^{100}_{40}Zr + {}^{134}_{52}Te + 2\,{}^{1}_{0}n + \text{energy} $$

†The asterisk denotes a highly unstable nuclide.

Remember, several products are possible in a fission reaction (section *N-20*). This equation tells us that when ^{235}U captures a neutron, the unstable ^{236}U that is formed then undergoes nuclear fission. In the process two additional neutrons are liberated, along with two heavy nuclides and a large amount of energy. The emission of two to four neutrons is a general feature of nuclear fission reactions. The fact that fission reactions liberate the same particles

that initiate them makes it possible for fission to sustain a *chain reaction* (Figure 12). By this we mean that the reaction can spontaneously multiply itself.

Figure 12 A CHAIN REACTION



This process is self-sustaining and can be used to liberate large amounts of energy, such as for power under the controlled conditions of a nuclear reactor. The energy liberated by the fission reaction per gram of nuclear fuel (^{235}U or ^{239}Pu) is about one-tenth that liberated by thermonuclear fusion reactions. We will discuss nuclear reactors in more detail and mention some of the factors associated with obtaining energy from nuclear power in section *N-45*.

TIME MACHINE

1938	Georg Biro constructs first practical ballpoint pen.
1940	Franklin Roosevelt is first and only U.S. president elected to third term.
1942	**Enrico Fermi develops first self-sustaining nuclear reactor.**
1943	The Aqua-lung is invented.
1944	Quinine is synthesized.

PROBLEMS

1. Balance the following nuclear equations by providing the required single product.
   a. $^2_1H + {}^1_1H \longrightarrow$ ______
   b. $^3_2He + {}^3_1He \longrightarrow {}^4He +$ ______
   c. $^{11}_5B + {}^4_2He \longrightarrow {}^2_1H +$ ______
   d. $^1_1H + {}^{12}_6C \longrightarrow {}^7_4Be +$ ______
   e. $^{12}_6C + {}^{12}_6C \longrightarrow {}^{23}_{11}Na +$ ______
   f. $^4_2He + {}^{27}_{13}Al \longrightarrow {}^{30}_{15}P +$ ______
   g. $^{40}_{19}K\ (p, n)$ ______
   h. $^{56}_{26}Fe\ (^4He,$ ______$)\ {}^{59}_{28}Ni$
   i. $^1_1H\ (p, {}^0_1\beta)$ ______
2. Give an example of a nucleus that could be formed in the following nucleosynthesis processes.
   a. *r*-process
   b. hydrogen burning
   c. silicon burning
   d. helium burning
   e. *s*-process
   f. carbon burning
   g. big bang
3. Identify the nucleosynthesis process that could form the following in nature.
   a. ^{232}Th
   b. ^{208}Pb
   c. ^2_1H
   d. ^{12}C
   e. ^{20}Ne
   f. ^{40}Ca
   g. ^4He
4. If nuclear energy were obtained from the following nuclides, would a fission reaction or a fusion reaction be more useful? You may wish to consult Figure 6, section *N-11*.
   a. ^2H
   b. ^6Li
   c. ^{235}U
   d. ^{239}Pu

Radioactive Decay

So far we have concentrated on the ways in which the nuclides of elements may have been formed in nature. What happens to these elements after nucleosynthesis stops? Since the formation of the solar system and the Earth, the nuclide composition has not remained the same. What changes have occurred? How have these changes taken place?

This stamp commemorates Marie and Pierre Curie, whose discovery of radium helped lay the foundation for the use of radioactive nuclides.

TIME MACHINE

1908	Jack Johnson is first black heavyweight boxing champion of the world.
1910	Rayon first goes into commerical production.
1911	**Marie Curie wins Nobel prize for chemistry, for discovery of radium and polonium and for isolation of pure radium.**
1912	S.S. *Titanic* sinks after hitting an iceberg; 1513 drown.
1913	U.S. federal income tax goes into effect.

N-24 From Stable to Radioactive

Some of the nuclides formed during nucleosynthesis have neutron-proton combinations that correspond to the uppermost ridge of the peninsula of stability (section *N-11*). These *stable nuclides* can be expected to remain unchanged over long periods of time. Other nuclides, such as those formed in the *r*-process, have a nucleon composition that lies lower on the slopes of the peninsula or may even be submerged in the sea of instability. These nuclides are more unstable and undergo spontaneous or natural changes in their neutron-proton ratios in order to become more stable nuclides. The process of nuclear change or transmutation is called *radioactive decay*. All elements have at least one radioactive isotope and most have several. For example, polonium (Z = 84) has 24 known radioactive isotopes. After the elements were formed, transmutations continued to change the element composition of our Universe. This process continues even today.

Some nuclides may be completely stable and never alter their neutron-proton composition. Others may decay rapidly enough to be easily recognized as radioactive. We refer to many other nuclides as stable only because they decay too slowly to be observed in our lifetime. For example, bismuth ($^{209}_{83}$Bi) can undergo alpha decay to thallium ($^{205}_{81}$Tl). However, if you were to observe all the bismuth in the Earth (about 10^{42} atoms) for the remainder of your life, you would probably see only one or two of the bismuth nuclides decay to thallium nuclides. The terms *stable* and *radioactive* (unstable) are relative ones and depend upon the half-life of the nuclides as well as on the length of time a given system is observed.

N-25 Rate of Decay: The Way It Goes

The radioactive decay of all nuclides follows the same mathematical relationship with respect to time. Refer to the results of miniexperiment *N-4, Heads/Tails and Half-life,* which are to be applied to the discussion of radioactive decay presented here. We define radioactivity, *R*, as the number of nuclides that decay per unit time. A formula to calculate radioactivity of any nuclide is

$$R = \frac{\text{(number of nuclides that decay)}}{\text{(unit time)}} = \frac{0.693}{t_{1/2}} \cdot N$$

N refers to the number of atoms in a given sample and can be determined from the mass of the sample. (Remember, one mole contains 6.02×10^{23} atoms.) The quantity $t_{1/2}$ is the half-life. Each radioactive nuclide $^{A}_{Z}X$ has a half-life different from all others. Some fourteen hundred different radioactive nuclides with half-lives ranging from 10^{-9} seconds to 10^{16} years have been measured.

Thus, each radioactive nuclide is, in effect, a nuclear clock, and its half-life determines the time scale over which the clock is useful for recording time.

Mathematically, the radioactive decay law can be written as follows. Suppose we initially have N_0 nuclides. After a time t has gone by, the number N of nuclides that remain is

$$N = N_0\left(\frac{1}{2}\right)^n$$

where n is the ratio of the elapsed time t to the half-life, $t_{1/2}$,

$$n = \frac{t}{t_{1/2}}$$

For our purpose this expression will be used only when n has whole number values ($n = 0, 1, 2, 3,$ etc.), but in principle the equation can be solved for any value of n. Try the following problems to understand better the mathematics of radioactive decay.

PROBLEMS

1. A sample of ^3_1H, tritium (the mass 3 isotope of hydrogen, which is produced by cosmic rays in our atmosphere), contains 24 000 atoms. Its half-life is $t_{1/2} = 12$ years.
   a. What is the radioactivity (in disintegrations per day) of this sample?
   b. How many ^3H atoms will remain 12 years later? 24 years later?
   c. How many atoms will have decayed in these 24 years?
2. Suppose that the length of time for decay in the previous problem had been 48 years.
   a. What would be the radioactivity (in decays per day) of the remaining tritium?
   b. How many atoms would have decayed?
   c. How many atoms would remain?

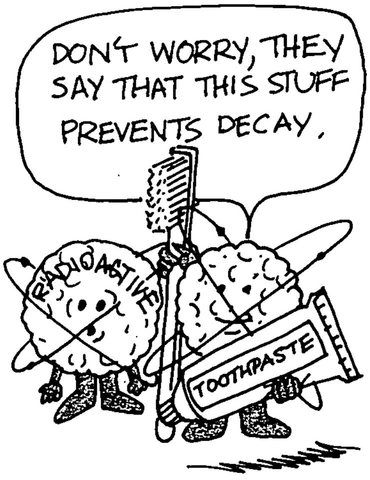
Radioactive decay has made extinct many of the nuclides that originally existed in our solar system. For example, the nuclide $^{244}_{94}Pu$ ($t_{1/2} = 8 \times 10^7$ years) almost certainly existed when the elements in our solar system were formed. However, if the age of our solar system is about 4.5×10^9 years, we can calculate that very little ^{244}Pu is left.

$$n = \frac{4.5 \times 10^9 \text{ years}}{8 \times 10^7 \text{ years}} \cong 56$$

Thus we have

$$\frac{N}{N_0} = \left(\frac{1}{2}\right)^n = \left(\frac{1}{2}\right)^{56} \cong 10^{-16}$$

which indicates that very little of the original ^{244}Pu remains. In general a nuclide must have a half-life greater than about 10^8 years in



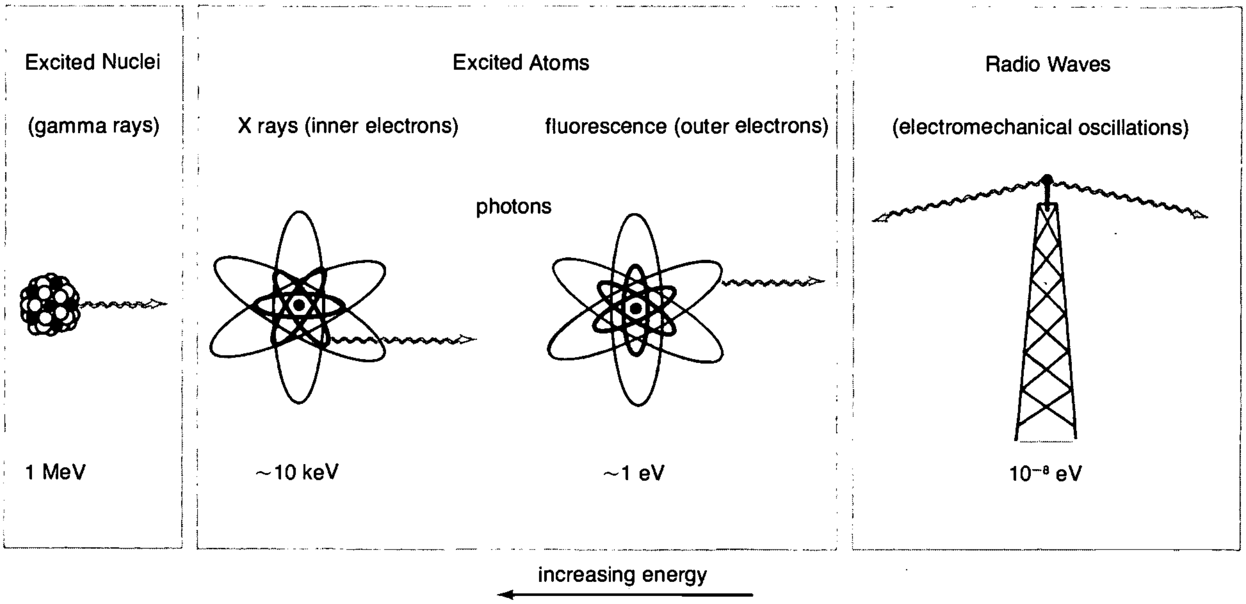
Wilhelm Roentgen discovered X rays, a form of electromagnetic radiation that is similar to gamma rays.

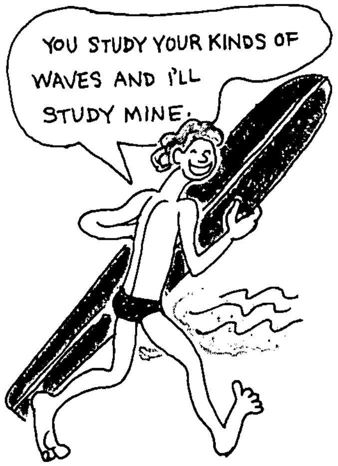
order to be found in measurable quantities in the solar system. We have already briefly mentioned the radioactive decay processes by which such changes have taken place (section *N-11*). We will discuss further each of these decay processes in the sections that follow.

N-26 Gamma Decay

The process of *gamma decay* involves the emission of photons from a nuclide that has extra energy compared with its normal stable state. The term *gamma ray* is used to specify photons that come from nuclei. X rays and visible light are photons that originate in the electron shells of atoms. The relationship between gamma rays and other types of electromagnetic radiation is illustrated in Figure 13.

Figure 13 SOURCES OF ELECTROMAGNETIC RADIATION





In gamma decay the number of neutrons and protons in the nuclide remains constant. Only the energy of the nuclide changes. The symbol *m* is sometimes placed after the mass number of a nuclide to indicate that the nuclide can undergo gamma decay with a relatively long half-life.

$$^{60m}_{27}\text{Co}^{\dagger} \longrightarrow {}^{60}_{27}\text{Co} + \gamma \qquad (t_{1/2} = 10.5 \text{ minutes})$$

†We call $^{60m}_{27}$Co an *isomer* of $^{60}_{27}$Co.

Gamma rays are the most penetrating type of radiation we shall discuss. Sources of gamma rays, such as $^{60m}_{27}$Co, are used in cancer therapy and as radioactive tracer nuclides for a great variety of purposes. But the penetrating quality of gamma radiation means that great care must be taken by persons working with such sources.

N-27 Beta Decay

The process of *beta decay* involves the interconversion of neutrons and protons. Since this does not change the total number of nucleons, the mass number *A* of the nuclide remains unchanged in beta decay. However, the atomic number Z and neutron number *N* each change by one unit. This decay process is common to all the elements. Beta decay is the primary way by which isobars (nuclides with constant mass number *A*) reach the summit along the peninsula of stability.

There are three types of beta decay. One type, *negatron decay*, involves the conversion of a neutron into a proton with the emission of a *negative electron*, or *negatron*, from the nucleus. This decay occurs in nuclides that have an excess of neutrons and produces an increase in the atomic number (Z) of one unit.

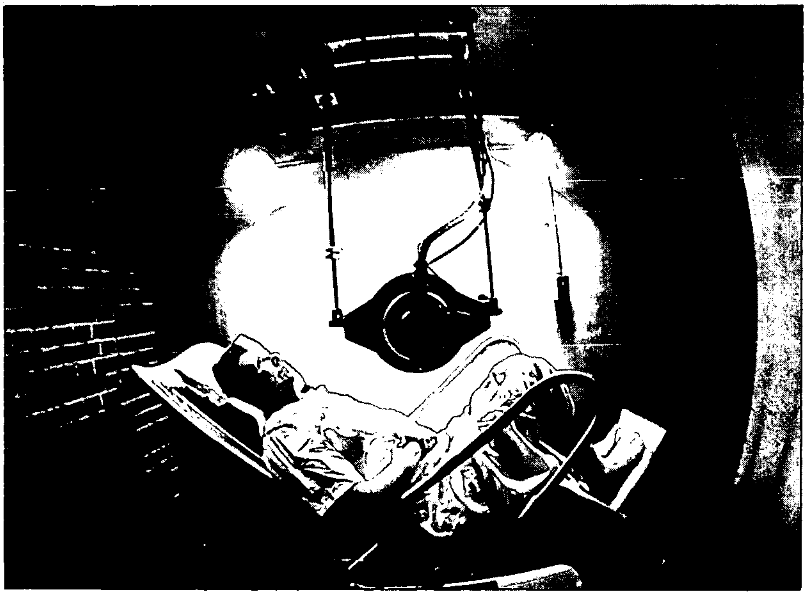
$$^{A}_{Z}X_{N} \xrightarrow[\text{decay}]{\text{negatron}} {}_{Z+1}^{\;\;A}Y_{N-1} + {}^{\;\,0}_{-1}\beta$$

The symbol β means that the electron comes from a nucleus; atomic electrons are represented by *e*. Important examples of this decay process are

$$^{1}_{0}n \longrightarrow {}^{1}_{1}\mathrm{H} + {}^{\;\,0}_{-1}\beta \qquad (t_{1/2} = 12.8 \text{ minutes})$$

$$^{40}_{19}\mathrm{K} \longrightarrow {}^{40}_{20}\mathrm{Ca} + {}^{\;\,0}_{-1}\beta \qquad (t_{1/2} = 1.3 \times 10^{9} \text{ years})$$

The radioactive nuclide of potassium (^{40}K) is important because it has survived since the formation of the solar system. Since potassium, which contains ^{40}K, is an essential ingredient of the human body, all of us are slightly radioactive. Therefore, living things have evolved in the presence of this radiation.



The human body takes in radioactive substances from the environment. The amounts and locations of these substances can be determined by means of special instruments that detect very small quantities of radiation in living tissue.

Two other types of beta decay involve the conversion of protons into neutrons. These are called *positron decay* and *electron-capture decay*. Both produce a decrease in the atomic number by one unit and therefore are common to nuclides that have a surplus of protons over neutrons.

$$^{A}_{Z}X_{N} \xrightarrow[\text{decay}]{\text{positron}} {}_{Z-1}^{\;\;A}Y_{N+1} + {}^{0}_{1}\beta$$

$$^{A}_{Z}X_{N} + {}^{0}_{-1}e \xrightarrow[\text{capture}]{\text{electron}} {}_{Z-1}^{\;\;A}Y_{N+1}$$

The net result is the same in each case, although the processes differ. Positron decay involves the emission of a positron and is common among the lighter elements. Electron capture is more generally found in the heavier elements and involves the reaction of a nucleus with one of its atomic electrons.

Examples of positron decay and electron-capture decay are found in the silicon-burning process by which titanium ($^{44}_{22}$Ti) is formed. $^{44}_{22}$Ti is radioactive and can undergo electron capture according to the equation

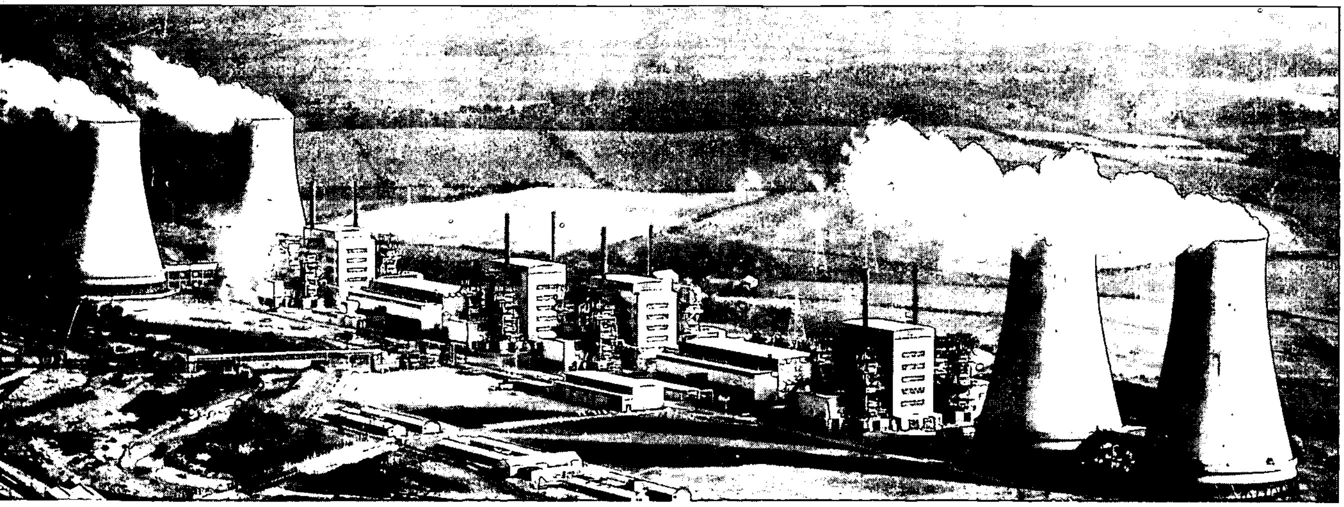
$$^{44}_{22}\text{Ti} + {}^{0}_{-1}e \longrightarrow {}^{44}_{21}\text{Sc} \qquad (t_{1/2} = 47 \text{ years})$$

The nuclide ^{44}Sc (scandium) is also radioactive but undergoes positron decay.

$$^{44}_{21}\text{Sc} \longrightarrow {}^{44}_{20}\text{Ca} + {}^{0}_{1}\beta \qquad (t_{1/2} = 4 \text{ hours})$$

This may be the way that the ^{44}Ca found in nature is produced.

Beta particles ($^{0}_{-1}\beta$ and $^{0}_{1}\beta$) are less penetrating forms of radiation than gamma rays and are not usually so hazardous. However, nuclides that undergo beta decay frequently lead to nuclides that later undergo gamma decay. Therefore, sources of beta radioactivity such as nuclear reactors must be carefully watched to prevent this radiation from escaping into the environment.



Calder Hall, Great Britain's first nuclear-power station and the first in the world to produce electricity on a fully commercial basis, was opened in 1956. Stacks at either end of the plant release excess heat into the environment.

In the following experiment we will measure the half-life of ^{137m}Ba (barium), the radioactive nuclide formed by the beta decay of ^{137}Cs (cesium). The ^{137}Cs is tightly held on the ion-exchange resin in the MINIGENERATOR. The equation for this decay is

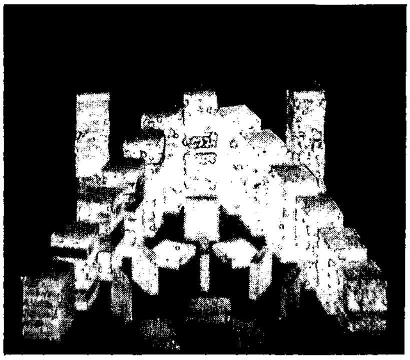
$$^{137}_{55}\text{Cs} \longrightarrow {}^{137m}_{56}\text{Ba} + {}^{0}_{-1}\beta \qquad (t_{1/2} = 30 \text{ years})$$

The $^{137m}_{56}$Ba undergoes gamma decay with a much shorter half-life than that of ^{137}Cs.

$$^{137m}\text{Ba} \longrightarrow {}^{137}\text{Ba} + \gamma \qquad (\text{half-life}^{\dagger})$$

[†] To be determined in this experiment.

The chemistry of ^{137m}Ba does not permit this nuclide to be held tightly by the ion-exchange resin. By washing out the MINIGENERATOR with the proper amount of eluant, you can obtain pure ^{137m}Ba. Its decay is readily observed with radiation detectors.



Fluorescent light emitted by these radioactive ^{137}Cs wafers was enough to take this photograph.

N-28 The Half-life of $^{137m}_{56}$Ba

EXPERIMENT

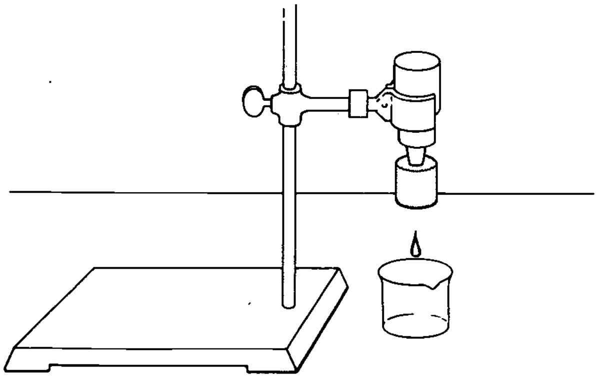
Record the background activity as you have done in past experiments. This value must be subtracted from all subsequent activity readings. Set up the radiation detector as shown in the illustration.

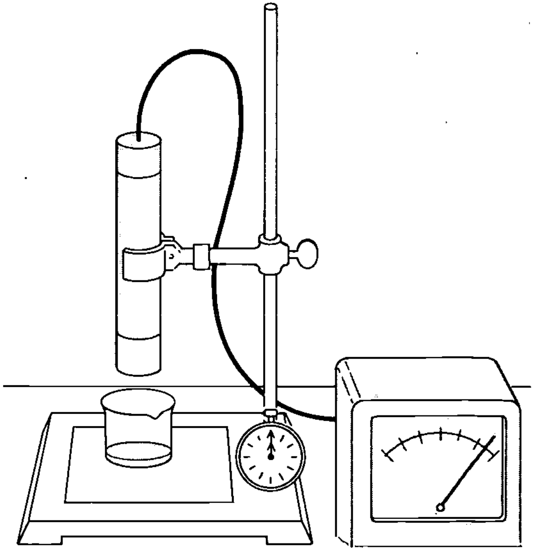
Elute the ^{137}Cs/^{137m}Ba MINIGENERATOR with about 2 cm^3 of the eluant as described in experiment *N-13*. Collect the eluate in a 20-cm^3 beaker and place it beneath the detector. Adjust the source-to-detector distance so that the meter reading is near the maximum, as in the illustration. Wait one minute and then take a reading. This is your zero reading. Take activity readings every 15 seconds for a total of 5 minutes. Record your data in a table similar to the sample. Do not be concerned about fluctuations in the meter reading; these are normal and will average out.

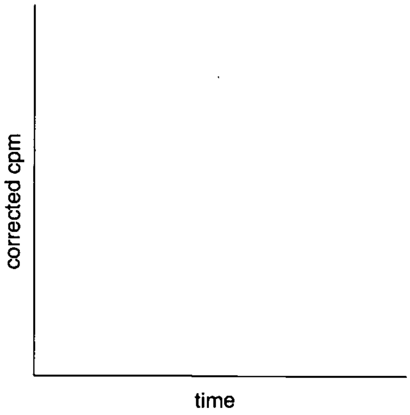
SAMPLE DATA TABLE

Background —— cpm

Time	Activity (cpm)	cpm Corrected for Background
—	—	—
—	—	—
—	—	—
—	—	—
—	—	—
—	—	—







Correct all recorded counts for background. Plot the *corrected counts per minute* versus *time* on graph paper. Draw the best smooth line through these points. Draw a horizontal line to intersect your graph from a point equal to one-half the zero time reading. At the point where this line hits the graph, draw a vertical line to the time axis. The point at which this vertical line intersects the time axis is the half-life of the sample.

Questions:

1. Do all your points fall on the smooth line on the graph? If not, can you suggest reasons for the fluctuations?
2. Using the half-life you measured for ^{137m}Ba, how long will it take for the radioactivity to drop from 20 000 cpm to 5000 cpm?

N-29 Alpha Decay

Alpha decay is a radioactive decay process that is generally observed only among the nuclides beyond barium ($Z = 56$). In alpha decay a heavy nucleus emits a $^{4}_{2}$He nucleus (an alpha particle). The resultant heavy nuclide has an atomic number *(Z)* two units lower and a mass number *(A)* four units lower. This permits a nuclide with a high atomic number to reduce its positive charge and thereby lower the electromagnetic repulsion among the protons in the nucleus. By doing so, a nuclide moves closer in stability to the ^{56}Fe nuclide that is at the peak of the stability peninsula (Figure 6, section *N-11*). An example of this mode of decay is

$$^{210}_{84}\text{Po} \longrightarrow {}^{206}_{82}\text{Pb} + {}^{4}_{2}\text{He} \qquad (t_{1/2} = 138 \text{ days})$$

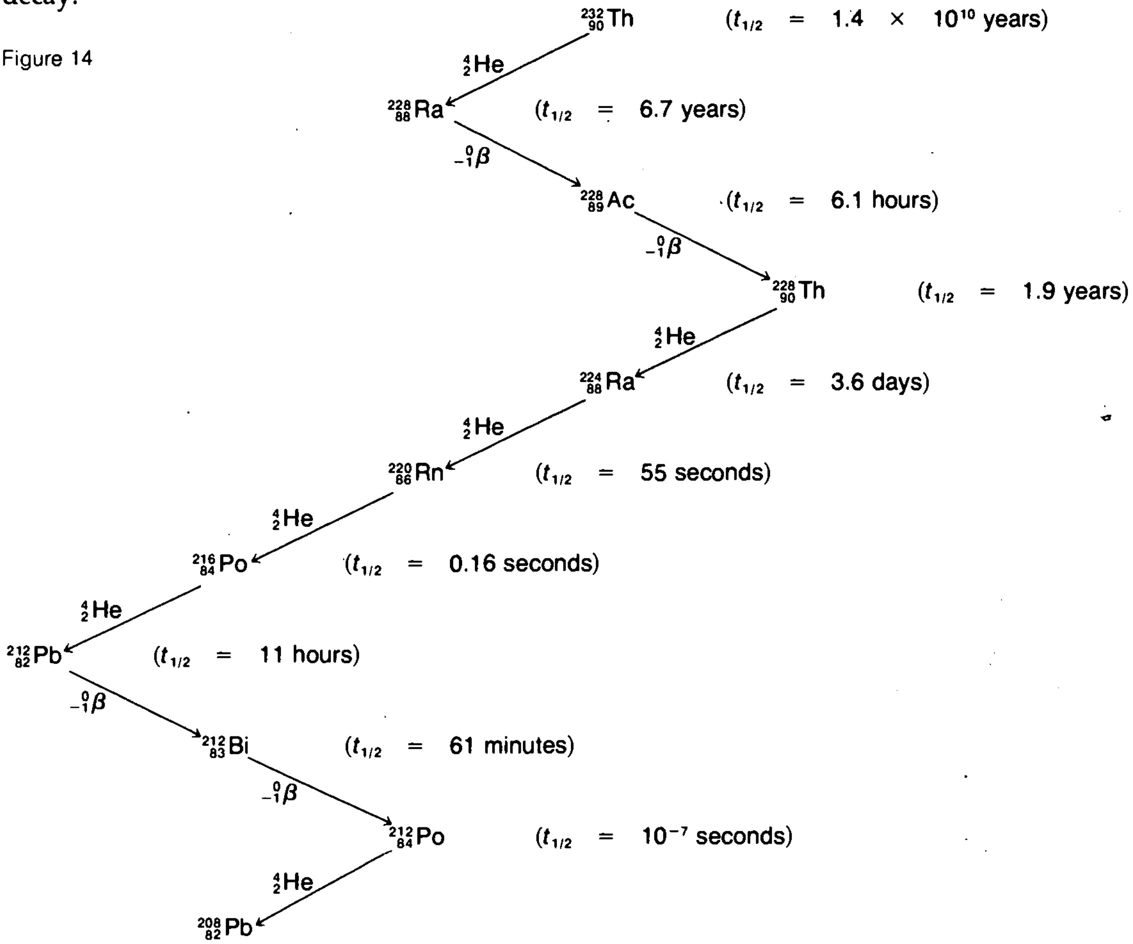
The alpha decay of polonium ($^{210}_{84}$Po) is one reason why the *s*-process (neutron capture at a slow rate, section *N-23*) cannot proceed beyond bismuth ($^{209}_{83}$Bi). Every time $^{210}_{84}$Po is produced from $^{209}_{83}$Bi in the *s*-process, the polonium nuclide decays to lead (^{206}Pb) before it can capture another neutron.

On the other hand, the nuclides beyond $A = 210$ that are formed in the *r*-process (neutron capture at a fast rate, section *N-20*) do not have this problem. The neutrons are captured so quickly in the *r*-process that much larger masses can be reached before decay occurs. Eventually these products undergo alpha decay long after the *r*-process has ended. Only the nuclides $^{238}_{92}$U ($t_{1/2} = 4.5 \times 10^{9}$ years), $^{235}_{92}$U ($t_{1/2} = 7 \times 10^{8}$ years), and $^{232}_{90}$Th ($t_{1/2} = 1.4 \times 10^{10}$ years) have alpha-decay half-lives sufficiently long that they have survived the age of the solar system and can exist in nature. All heavier nuclides that may have existed in the past have now decayed to lighter nuclides. The existence of uranium and thorium in nature means that small amounts of the radioactive decay products of these elements also exist in nature in spite of the fact that their half-lives are too short to have survived the age of our solar system.

The use of a glove box is adequate protection for scientists who handle mildly radioactive materials.

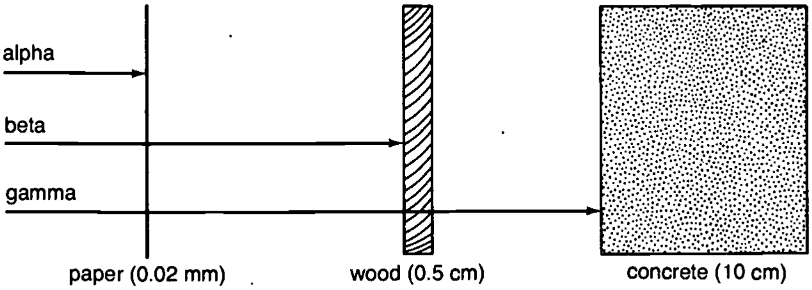
For example, Figure 14 shows the series of decay processes by which $^{232}_{90}Th$ transmutes to stable $^{208}_{82}Pb$, starting with the initial decay.

Figure 14



The penetrating power of alpha particles is quite weak. A few centimeters of air will stop them, leaving only neutral helium atoms. Consequently, alpha-particle emitters are not considered as great a radiation hazard as emitters of gamma and beta radiation. However, if an alpha-radiation source is taken internally, this radiation can be a serious health hazard.

RADIATION PENETRATION ABILITIES



N-30 Spontaneous Fission

We have already described fission reactions that follow nuclear reactions. It is also possible for radioactive decay to occur by means of the fission process. The elements heavier than thorium (Z = 90) undergo this form of decay to some extent. Some of the heaviest elements decay entirely by *spontaneous fission*. The nuclide californium ($^{254}_{98}Cf$) has been produced in thermonuclear explosions and undergoes fission with the release of a large amount of energy to produce a variety of final products.

$$^{254}_{98}\mathrm{Cf} \longrightarrow {}^{108}_{42}\mathrm{Mo} + {}^{142}_{56}\mathrm{Ba} + 4\,{}^{1}_{0}n \qquad (t_{1/2} = 60 \text{ days})$$

It is thought that this nuclide is also produced during nucleosynthesis in the *r*-process. It is interesting to note that the light from some supernovae is found to decrease with a half-life of approximately 50 to 60 days. Hence, we may be indirectly observing the actual decay of $^{254}_{98}Cf$ whenever a supernova explosion occurs. This is an interesting coincidence and not a proven fact. There are other explanations for the light given off by a supernova.

Spontaneous fission, like alpha decay, also occurs after nucleosynthesis in the *r*-process and makes many nuclides extinct. The production of new heavy elements in nuclear reactors is limited by

Highly radioactive materials are confined in sealed areas surrounded by heavy shielding to protect scientists. Mechanical arms enable scientists to manipulate equipment in various experiments.

spontaneous fission. The nuclide fermium (${}^{256}_{100}$Fm) can be produced in a reactor but decays by spontaneous fission with a half-life of 2.6 hours. This half-life is too short to permit the capture of another neutron to form ${}^{257}_{100}$Fm or elements heavier than Z = 100 in any substantial quantities. Spontaneous fission will probably make difficult the discovery of elements near the island of stability. It seems improbable at this time that elements with atomic numbers greater than Z = 115 will be seen experimentally. However, scientists continue to search for the superheavy nuclei, knowing that nature is frequently unpredictable.

PROBLEMS

Write equations for the following decay processes.
1. alpha decay of ${}^{144}_{60}$Nd (neodymium)
2. beta decay of ${}^{40}_{19}$K (negatron emission)
3. positron decay of ${}^{22}_{11}$Na
4. electron-capture decay of ${}^{7}_{4}$Be
5. gamma decay of ${}^{241m}_{95}$Am (americium)
6. spontaneous fission of ${}^{256}_{100}$Fm (fermium) in which two neutrons are emitted from each fragment and the remaining nuclear mass and charge are divided equally between the two fragments

TIME MACHINE

1938	*Rebecca*, by Daphne du Maurier, is published.
1939	**Otto Hahn and Fritz Strassman report splitting the uranium atom; Lise Meitner and Otto Frisch formulate theory of nuclear fission.**
1940	Walt Disney's film *Fantasia* opens.
1941	National Gallery of Art opens in Washington, D.C.

N-31 The Dating Game

Radioactive decay has been an important tool in enabling scientists to determine the age of the solar system and the history of civilization. Several nuclides have been especially useful as "nuclear clocks" for determining the age of our solar system. Their half-lives permit us to date the evolution of our solar system rather well. Among the most important of these are

$${}^{40}_{19}\text{K} + {}^{0}_{-1}\text{e} \longrightarrow {}^{40}_{18}\text{Ar} \qquad \text{(electron capture; } t_{1/2} = 1.3 \times 10^{9} \text{ years)}$$

$${}^{40}_{19}\text{K} \longrightarrow {}^{40}_{20}\text{Ca} + {}^{0}_{-1}\beta \qquad \text{(beta; } t_{1/2} = 1.3 \times 10^{9} \text{ years)}$$

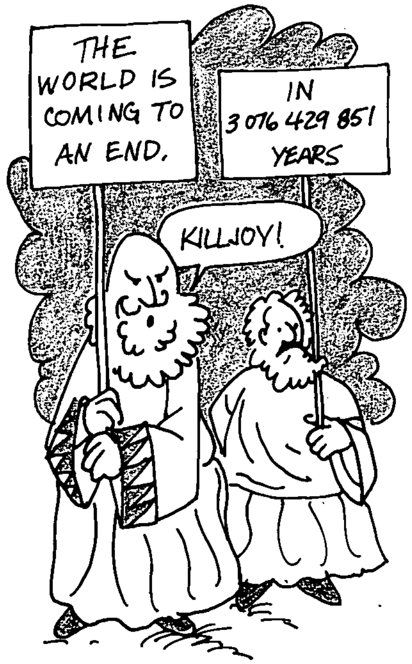
$${}^{87}_{37}\text{Rb} \longrightarrow {}^{87}_{38}\text{Sr} + {}^{0}_{-1}\beta \qquad \text{(beta; } t_{1/2} = 5.7 \times 10^{10} \text{ years)}$$

$${}^{232}_{90}\text{Th} \longrightarrow {}^{228}_{88}\text{Ra} + {}^{4}_{2}\text{He} \qquad \text{(alpha; } t_{1/2} = 1.4 \times 10^{10} \text{ years)}$$

$${}^{238}_{92}\text{U} \longrightarrow {}^{234}_{90}\text{Th} + {}^{4}_{2}\text{He} \qquad \text{(alpha; } t_{1/2} = 4.5 \times 10^{9} \text{ years)}$$

$${}^{235}_{92}\text{U} \longrightarrow {}^{231}_{90}\text{Th} + {}^{4}_{2}\text{He} \qquad \text{(alpha; } t_{1/2} = 7 \times 10^{8} \text{ years)}$$

To use these nuclear clocks, the amount of the radioactive nuclide that exists at the present time and its half-life must be known. The amount of stable product nuclides must also be determined since this is related to the total amount of the radioactive nuclides originally present in a sample. Combining this information in the radioactive decay law, scientists can determine how long decay has been going on.



TIME MACHINE

1957	Bobby Fischer, age 13, wins U.S. chess championship.
1958	Guggenheim Museum opens in New York City—last major building designed by Frank Lloyd Wright.
1959	*The Sound of Music* opens on Broadway.
1960	**Willard Libby receives Nobel prize for radioactive carbon-dating technique.**
1961	Yuri Gagarin of U.S.S.R. is first human to orbit the Earth.

The amount of time that has gone by since the elements condensed into the solar system (the Sun, planets, moons, and meteorites) can be dated from the decay of rubidium ($^{87}_{37}Rb$) and potassium ($^{40}_{19}K$). Meteorites and rocks containing these elements trap the radioactive decay products ^{87}Sr and ^{40}Ar. By measuring the amounts of the Rb and K radioactive nuclides relative to the Sr and Ar stable nuclides, it is possible to determine with considerable confidence that our solar system solidified about 4.5 billion years ago. Using similar techniques, it has been possible to determine many other ages significant to the history of the Earth and the moon. For example, the ages of rocks and geological formations have been determined, as well as the rate at which sediments are deposited on the ocean floor.

Another important dating technique involves the use of the nuclide $^{14}_{6}C$. This nuclide undergoes beta decay with a half-life of 5730 years. Because carbon is an essential element in all living matter and the half-life of $^{14}_{6}C$ closely spans the age of civilization, ^{14}C dating is a highly important tool for archaeologists.

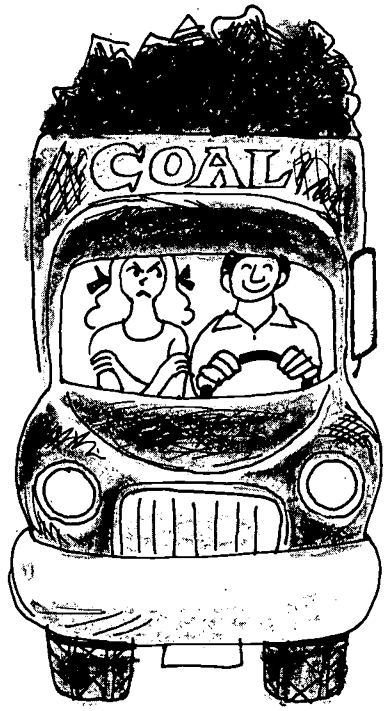
The existence of $^{14}_{6}C$ in nature results from the fact that the Earth is constantly being bombarded with energetic nuclear particles such as protons that come from outer space. These are called *cosmic rays*. When cosmic rays strike nuclides in the upper regions of our atmosphere, they cause a variety of nuclear reactions to occur. Many of these reactions produce neutrons and some short-lived nuclides. These neutrons in turn produce the secondary reaction

$$^{14}_{7}N + ^{1}_{0}n \longrightarrow ^{14}_{6}C + ^{1}_{1}H$$

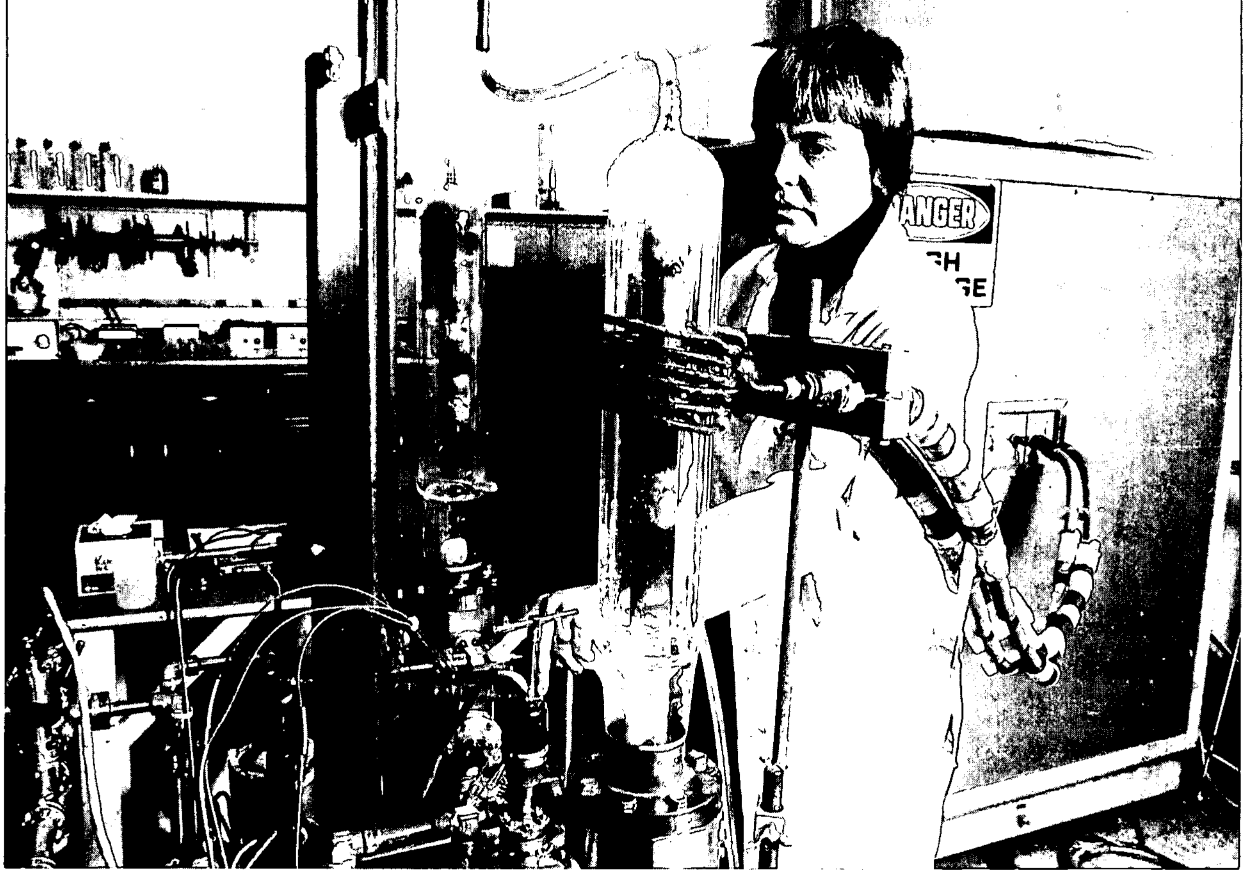
In this way ^{14}C is constantly being produced in our atmosphere and eventually is incorporated into the life cycle as CO_2. Thus, all living organisms, including ourselves, contain radioactive ^{14}C.

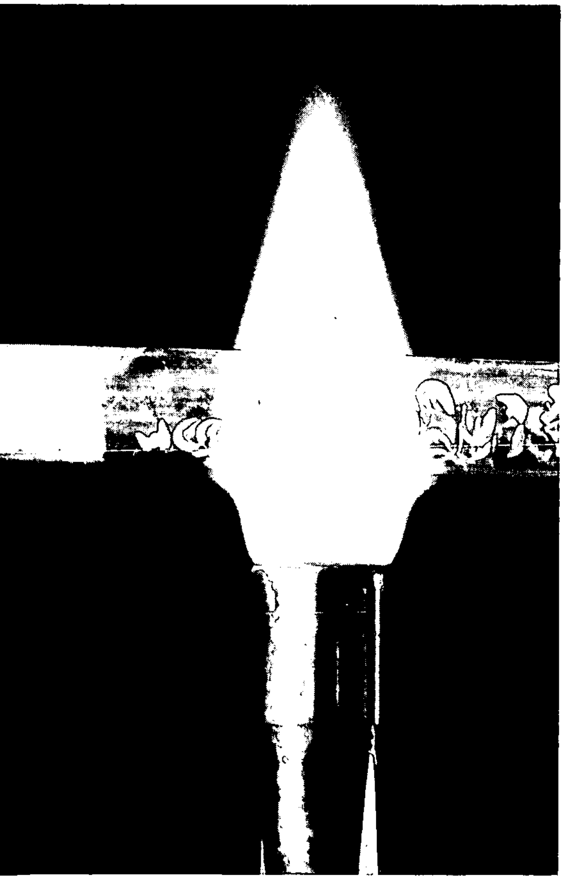
We find that the amount of radioactivity in samples of all living matter is about 15 dpm (disintegrations per minute) per gram of carbon. From measurements of objects of known ages, such as giant redwoods (for which one can also count tree rings), we know that this activity has remained fairly constant during the past few thousand years. The radioactivity level of living organisms remains constant because of the continual flow of carbon dioxide (CO_2) in the life cycle (see *Molecules in Living Systems: A Biochemistry Module*). When an organism dies, however, it does not take in any additional ^{14}C. Thereafter its ^{14}C level begins to decrease. By measuring the radioactivity and mass of carbon in a sample and knowing that it originally contained 15 dpm per gram of carbon, we can calculate the time over which decay has occurred.

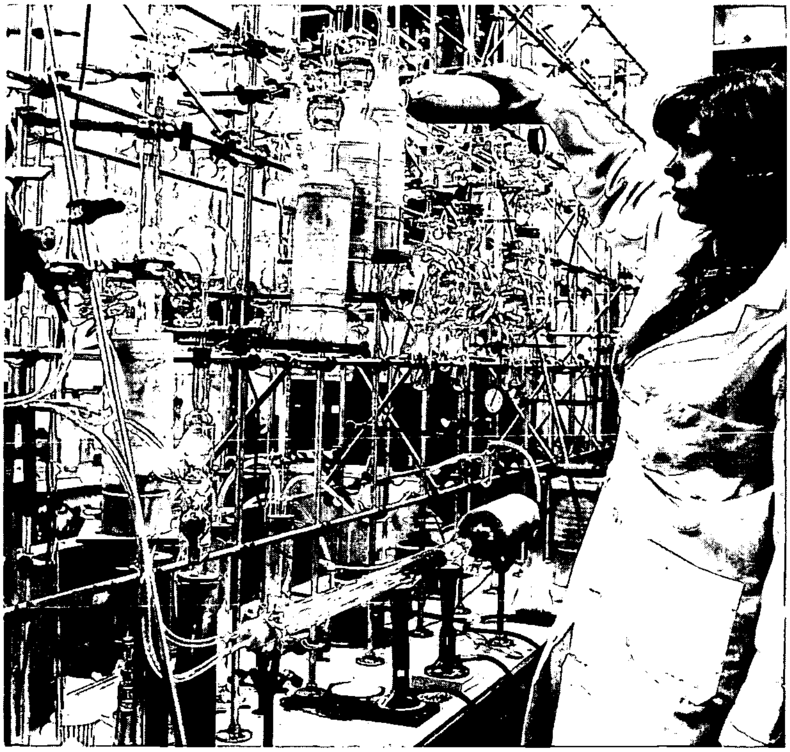
The ^{14}C dating technique has been useful in determining the ages of a wide variety of archaeological samples ranging in age from about two hundred to twenty thousand years. The ages for objects whose history has been recorded generally correspond very well



CARBON DATING







Potassium-argon dating *(top)* involves the melting of rock samples to release the trapped argon that forms when ^{40}K decays. In carbon dating, the sample is burned *(below left)* to allow all the carbon to form CO_2. The collected CO_2 is then trapped for analysis by freezing it with liquid air *(below right)*.

with the historical dates. For example, the Dead Sea Scrolls have been determined to be about 1940 ± 70 years old. The ^{14}C dating technique has proved very valuable in recording the history of the Native American civilization, as well as that of many others.

We have completed our account of the origin and subsequent fate of the elements we find in nature today. Both nuclear reactions and radioactive decay have played an important part in producing our environment as we now know it. These processes in turn have depended upon the behavior of nuclear matter. Before leaving the subject of the atomic nucleus, it is worthwhile to discuss briefly the isotopes of an element that is very common in our environment—potassium ($Z = 19$).

The radioactive nuclides that exist in nature are those that have half-lives of the same order as the age of the solar system (about 4.5 billion years). Natural potassium consists of three isotopes: ^{39}K (93.1 percent), ^{40}K (0.01 percent), and ^{41}K (6.9 percent). Both ^{39}K and ^{41}K are stable, but ^{40}K is radioactive with a half-life of 1.3×10^9 years (section *N*-27).

Potassium is a member of the alkali metal group of elements and is similar to sodium in its chemical properties. Consequently, potassium occurs in nature in the same places that sodium is found—seawater, many kinds of rocks, and all living organisms. The abundance of potassium in the crust of the Earth accounts for a major fraction of the background radiation in nature.

EXPERIMENT

N-32 Radioactive Decay in Our Environment

In this experiment we will estimate the half-life of ^{40}K by measuring the radioactivity of common KCl salt. You will need a sample of reagent-grade KCl, a radiation detector, a MINIGENERATOR, and a watch with a second hand. The procedure involves the measurement of the radioactivity of KCl (*R*, section *N*-25) and determination of the number of ^{40}K atoms *(N)* from the mass and Avogadro's number. The half-life is then calculated from the following equation, rearranged from the first equation in section *N*-25.

$$t_{1/2} = 0.693N/R$$

This stamp commemorates Amedeo Avogadro's discovery that equal volumes of different gases at the same temperature and pressure have an equal number of molecules.

Step 1: Background Measurement

Because the ^{40}K activity in your KCl sample is rather weak, it is important to measure the background activity carefully. The background will represent 20 to 50 percent of the total activity of the KCl sample.

Turn on your radiation counter and allow it to warm up for 5 minutes. Record at least ten background readings at 10-second intervals. Calculate the average of these values and record the results.

average of background readings = background = ______

Step 2: Determination of the Number of ^{40}K Nuclides

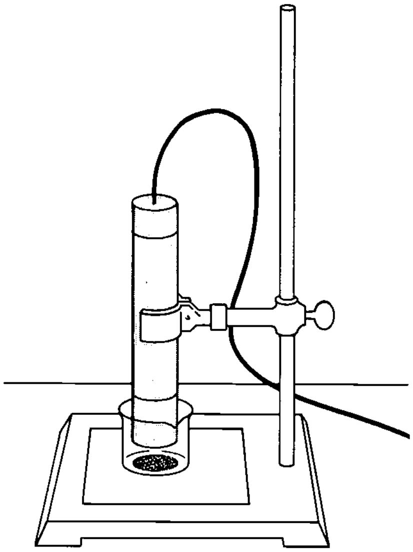
Measure out a 5- to 10-g sample of KCl to an accuracy of three significant figures and record this mass. The number of K^+ ions, $N(\text{K})$, is equal to the number of Cl^- ions, $N(\text{Cl})$, in the sample, which is also equal to the number of KCl units. Therefore, from the mole relationship and Avogadro's number,

$$N(\text{K}) = N(\text{KCl}) = (\text{moles of KCl}) \times (6.02 \times 10^{23} \text{ atoms/mole})$$

Record your result for the total number of K atoms in the sample. _____
However, we must take into account the fact that only 0.01 percent of K is ^{40}K. Hence, we must correct our result by this factor.

$$N(^{40}\text{K}) = N(\text{K}) \times 1.0 \times 10^{-4} = \underline{\hspace{1.5cm}}$$

Step 3: Detection Procedure



Place the KCl sample in a small container into which the counter tube will fit easily. Arrange the KCl salt so that its area coincides with the window area of the counter. Remove any protective shield from the counter and place the counter as close to the KCl sample as possible without actually touching the KCl. Record the counting rate at least 10 times at intervals separated by 10 seconds each. Average your results and record this value. This is the *total activity,* R(total), of the sample plus background.

$$R(\text{total}) = R(^{40}\text{K}) + \text{background} = \underline{\hspace{1.5cm}}$$

To determine the activity of ^{40}K, subtract the background from the total.

$$R(^{40}\text{K}) = R(\text{total}) - \text{background} = \underline{\hspace{1.5cm}} - \underline{\hspace{1.5cm}} = \underline{\hspace{1.5cm}}$$

Step 4: Counter Efficiency

You have now determined the activity of a given mass of KCl in your counter. However, the counting rate that you observed does not include all the radiation emitted by the KCl source. That is, your counter is not 100 percent efficient. Several effects account for this: (1) not all of the KCl radiation strikes the counter (recall section *N-8*); (2) some of the radiation that passes through the detector will not produce an electronic signal or count; and (3) some of the radiation will be stopped by the KCl itself before reaching the counter. In order to estimate the real number of counts from the KCl, your ^{137}Cs MINIGENERATOR can be used to "calibrate" your counter. The ^{137}Cs MINIGENERATOR has an absolute activity of about 3.3×10^4 cps (counts per second). To calibrate the counter, adjust the scale to its least sensitive position and place it next to the MINIGENERATOR. Record this reading remembering to multiply by the scale factor on your counter.

$$\begin{aligned} R(\text{MINIGENERATOR}) &= (\text{counter reading}) \times (\text{scale factor}) \\ &= \underline{\hspace{1.5cm}} \times \underline{\hspace{1.5cm}} = \underline{\hspace{1.5cm}} \end{aligned}$$

The approximate number of real counts from KCl, $R'(^{40}\text{K})$, can now be calculated from this value and $R(^{40}\text{K})$ from step 3:

$$R'(^{40}\text{K}) = \frac{R(^{40}\text{K})}{R(\text{MINIGENERATOR})} \times (3.3 \times 10^4 \text{ cps})$$

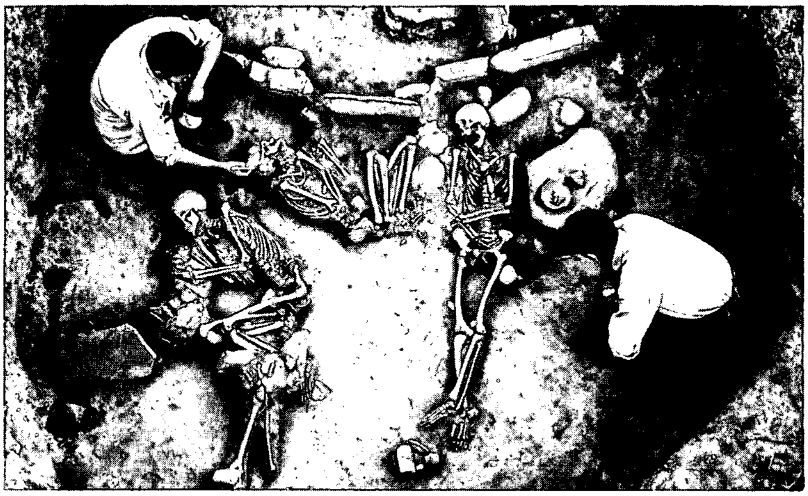
Of course, this is only approximately correct because the radiation from ^{40}K is not the same as that from ^{137}Cs.

Step 5: Half-life for ^{40}K

As we discussed in the introduction, the half-life can be calculated from

$$t_{1/2} = \frac{0.693\ N(^{40}K)}{R'(^{40}K)} = \frac{\qquad\qquad}{3.16 \times 10^{7}\ \text{seconds/year}} = \_\_\_\_\_ \ \text{years}$$

Compare your value with the value given in section *N–31*. Although your answer may be in some error, the procedure demonstrates the way we can determine the half-life of very long-lived nuclides. This method is certainly more practical than waiting for half the ^{40}K nuclides in a sample to decay.



Radioactive dating techniques have been used to date ancient remains such as these at a burial site at Mesa Verde, in Colorado.

PROBLEMS

1. Consider the radioactive decay of ^{11}C ($t_{1/2}$ = 20 minutes), which is produced in the upper atmosphere from cosmic ray reactions.

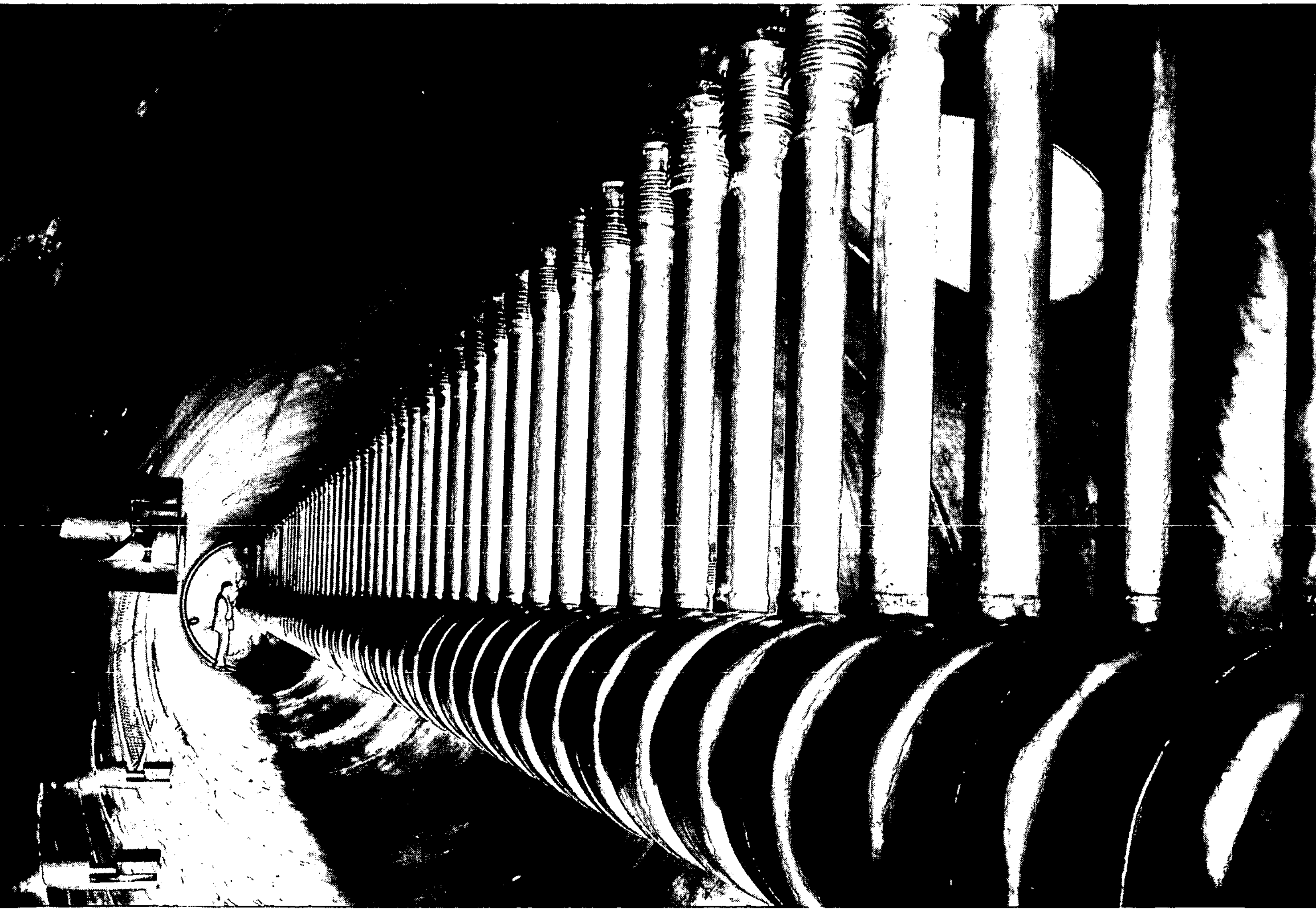
$$^{11}_{6}C \longrightarrow {}^{11}_{5}B + {}^{0}_{1}\beta$$

   Suppose one has a pure sample of ^{11}C at 9:00 A.M. It is found that the sample contains 4.0×10^{5} atoms of ^{11}C at 9:20 A.M.
   a. How many ^{11}C atoms will be present at 9:40 A.M.?
   b. How many ^{11}C atoms will be present at 10:00 A.M.?
   c. How many ^{11}C atoms were present at 9:00 A.M.?
   d. At 10:00 A.M., how many ^{11}B atoms were present in the sample?
   e. How many ^{11}B atoms were present 24 hours later?
2. Calculate the decay rate *R* (number of decays per minute) in 1.0 g of ^{238}U ($t_{1/2} = 4.5 \times 10^{9}$ years).
3. An archaeological sample is found to have a decay rate of 3.8 dpm per gram of carbon (above background) because of its ^{14}C content. If living matter contains 15.1 dpm per gram of carbon, estimate the age of the sample. The half-life of ^{14}C is 5730 years.
4. Write balanced nuclear equations to represent the following nuclear reactions.
   a. alpha decay of $^{240}_{94}Pu$
   b. negatron decay of $^{210}_{83}Bi$
   c. positron decay of $^{52}_{26}Fe$
   d. electron-capture decay of $^{52}_{26}Fe$
   e. gamma decay of $^{242m}_{95}Am$
5. Which of the following types of decay has the greater penetrating effect?
   a. alpha or beta
   b. alpha or gamma
   c. beta or gamma

The Search for New Elements

During our account of how the elements were formed, we mentioned the *transuranium*, or synthetic, elements. These elements with atomic numbers greater than that of uranium ($Z = 92$) do not exist in nature, although it is quite probable that they were present during the early history of the solar system. Scientists have learned how to synthesize transuranium elements through element $Z = 106$. The search for additional new elements continues in many laboratories throughout the world.

This series of ring-shaped tubes was part of the heavy-ion, linear accelerator known as the HILAC. It was used to produce the synthetic elements with atomic numbers 102 through 105. The HILAC was remodeled (becoming the SuperHILAC) to make it capable of accelerating particles as heavy as uranium nuclei.



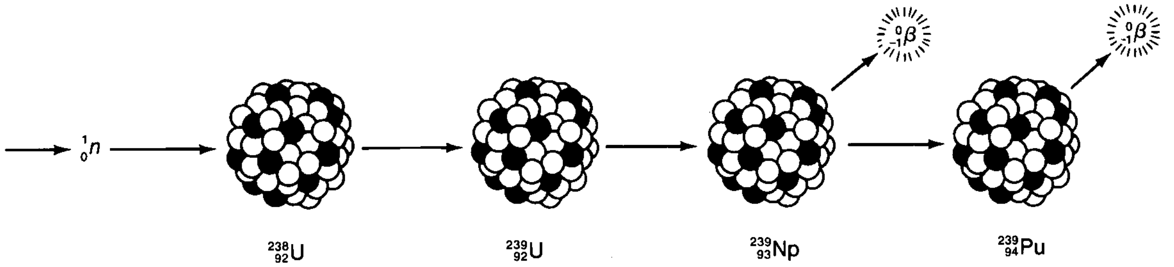
TIME MACHINE

1931	Boris Karloff stars as monster in movie version of 19th-century novel *Frankenstein*.
1932	Vitamin D is discovered.
1933	King Kong makes movie debut.
1934	**Irene and Frederic Joliot-Curie report first laboratory-produced radioactive isotopes.**
1936	Jesse Owens is first American to win four Olympic gold medals in one year.

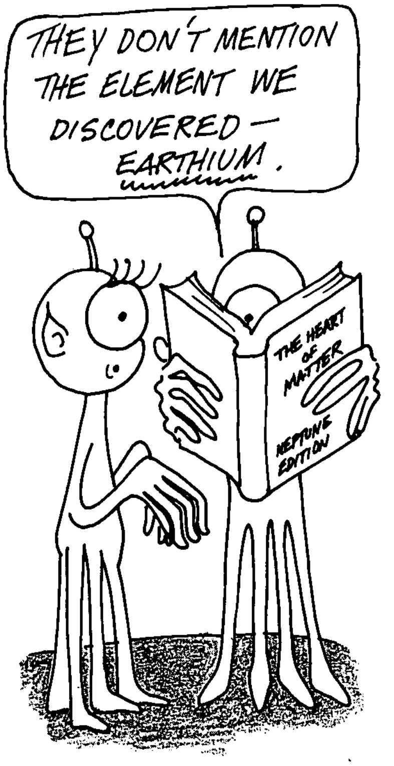
N-33 Modern Alchemy

Detecting new elements is an increasingly difficult problem because of their short half-lives for alpha decay and spontaneous fission. Until the 1940s, uranium (Z = 92) was the heaviest element known. Once scientists learned that they could transmute one element into another by means of nuclear reactions, they quickly realized that new elements could be formed, using uranium as the initial reactant. For example, by adding a neutron to the nuclide ^{238}U, a sequence of nuclear transmutations occurs.

$$\begin{aligned} {}^{238}_{92}\mathrm{U} + {}^{1}_{0}n &\longrightarrow {}^{239}_{92}\mathrm{U} + \gamma \\ {}^{239}_{92}\mathrm{U} &\longrightarrow {}^{239}_{93}\mathrm{Np} + {}^{0}_{-1}\beta \qquad (t_{1/2} = 24 \text{ minutes}) \\ {}^{239}_{93}\mathrm{Np} &\longrightarrow {}^{239}_{94}\mathrm{Pu} + {}^{0}_{-1}\beta \qquad (t_{1/2} = 2.4 \text{ days}) \end{aligned}$$



In this way the previously unknown elements neptunium (Z = 93) and plutonium (Z = 94) were formed. (Since uranium had been named for the planet Uranus, elements 93 and 94 were named after the planets Neptune and Pluto.) The ^{239}Pu produced in the above reaction is also radioactive. But since it undergoes alpha decay with a half-life of 2.4×10^4 years, ^{239}Pu is relatively stable compared with ^{239}U and ^{239}Np. The nuclide ^{239}Pu is now produced in nuclear reactors in large quantities for use as a nuclear fuel.



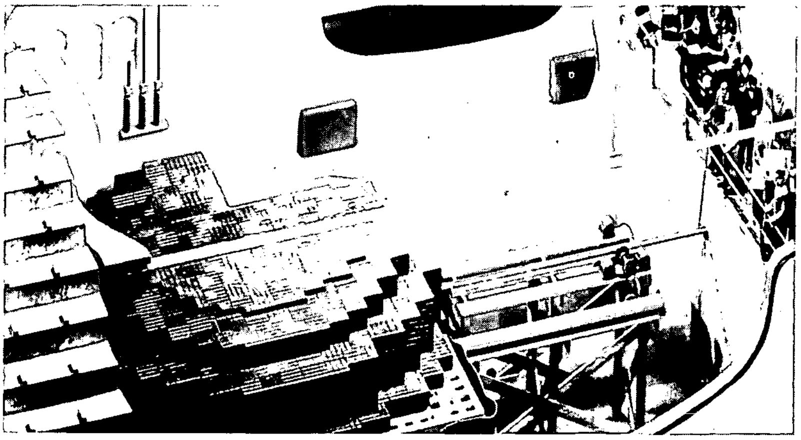
The elements americium (Z = 95) to californium (Z = 98) and mendelevium (Z = 101) were discovered by means of cyclotron bombardments of heavy-element targets with ${}^{2}_{1}$H or ${}^{4}_{2}$He ions, or by the use of nuclear reactors. Much of this work was begun as part of the Manhattan Project, which developed the atomic bomb during World War II. The elements einsteinium (Z = 99) and fermium (Z = 100) were discovered as by-products of the first hydrogen bomb tests in the early 1950s in the South Pacific. These elements were produced by rapid, multiple neutron-capture reactions in the uranium present in the bomb, in very much the same way heavy elements are produced in the *r*-process. The most recent new elements (Z = 102 to 106) have been discovered in special types of accelerators called *heavy-ion accelerators.* These instruments accelerate nuclear projectiles such as carbon and heavier ions. Element 105 was produced by the reaction

$${}^{15}_{7}\mathrm{N} + {}^{249}_{98}\mathrm{Cf} \longrightarrow {}^{260}_{105}\mathrm{Ha} + 4\,{}^{1}_{0}n$$

Table 7: TRANSURANIUM ELEMENTS

Z	Element	Symbol	Chemistry	Most Stable Nuclide
93	Neptunium	Np	inner transition elements; all metals with similar properties to elements 61–71 (promethium to lutetium)	^{237}Np (2.2 × 10^6 yrs; α)
94	Plutonium	Pu		^{244}Pu (8 × 10^7 yrs; α)
95	Americium	Am		^{243}Am (8 × 10^3 yrs; α)
96	Curium	Cm		^{247}Cm (1.6 × 10^7yrs; α)
97	Berkelium	Bk		^{247}Bk (7 × 10^3 yrs; α, β)
98	Californium	Cf		^{251}Cf (800 yrs; α)
99	Einsteinium	Es		^{252}Es (140 days; α, β)
100	Fermium	Fm		^{253}Fm (5 days; α, β)
101	Mendelevium	Md		^{255}Md (30 min; α, β)
102	Nobelium	No		^{259}No (57 min; α)
103	Lawrencium	Lr		^{256}Lr (35 sec; α)
104	Rutherfordium (US) Kurchatovium (USSR)	Rf Ku	transition metal; similar to hafnium (element 72)	^{261}Rf (65 sec; α) ^{260}Ku (0.1 sec; SF*)
105	Hahnium (US) Nielsbohrium (USSR)	Ha Nl	transition metal; similar to tantalum (element 73)	^{260}Ha (2 sec; α) ^{260}Nl (1 sec; SF)
106	No name proposed		transition metal; similar to tungsten (element 74)	(1 sec; α; SF)

*SF is the abbreviation for *spontaneous fission*.



In 1942 Enrico Fermi directed the completion of the first nuclear reactor *(model at left)*. It was built in a squash court at the University of Chicago. The stamp *(below)* commemorates the use of Fermi's reactor to achieve the first controlled nuclear-fission reaction.

The production of the synthetic elements in quantities whose mass is large enough to determine relies primarily on nuclear reactors that use the *s*-process to build heavier nuclides. This method has produced thousands of kilograms of plutonium and smaller amounts of other heavier elements. In fact, sufficient quantities of the element einsteinium and sufficient amounts of the other heavier elements have been produced to permit studies of their chemical properties. Because of the short spontaneous fission half-life of fermium ($^{256}_{100}$Fm), reactor production of *transfermium elements* (elements with Z greater than 100) is not possible. In other words, ^{256}Fm undergoes spontaneous fission as rapidly as it is formed by neutron-capture reactions, thereby preventing the buildup of

TIME MACHINE

1939	The first nylon stockings appear on the market.
1940	**Philip Abelson and Edwin McMillan discover new element, neptunium.**
1941	**Glenn Seaborg, Edwin McMillan, J. W. Kennedy, and A. C. Wall discover new element, plutonium.**
1942	Irving Berlin composes "White Christmas."
1950	**G. Seaborg, S. G. Thompson, K. Street, and A. Ghiorso discover element 98, californium.**

heavier masses. Therefore, the synthesis of large amounts of heavier elements will require the development of new or greatly improved means of production.

There are many ways that transuranium elements are now being used. We have already discussed the highly important application of $^{239}_{94}Pu$ to the production of power for our energy needs (section *N-23*). In addition, nuclides such as $^{238}_{94}Pu$ and $^{242}_{96}Cm$ (curium) serve as highly compact power sources for use in space exploration, for weather satellites, and for medical use in radiotherapy. We will discuss the uses of these and other radioactive nuclides in further detail in *Uses of Radiation*.

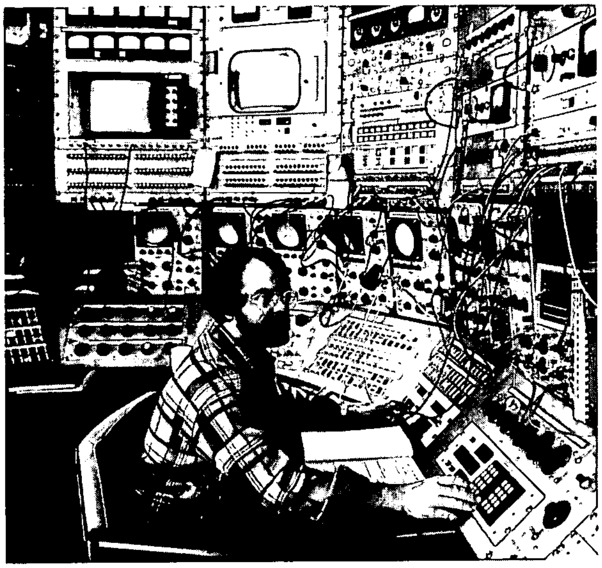
N-34 Superheavy-Element Synthesis

What are the chances that scientists can make elements heavier than those already synthesized in the laboratory? Of special interest in this regard is the possibility of synthesizing the superheavy elements in the vicinity of the nuclide $^{298}_{114}X$. Such a nuclide would contain "magic numbers" of 114 protons and 184 neutrons (section *N-11*).

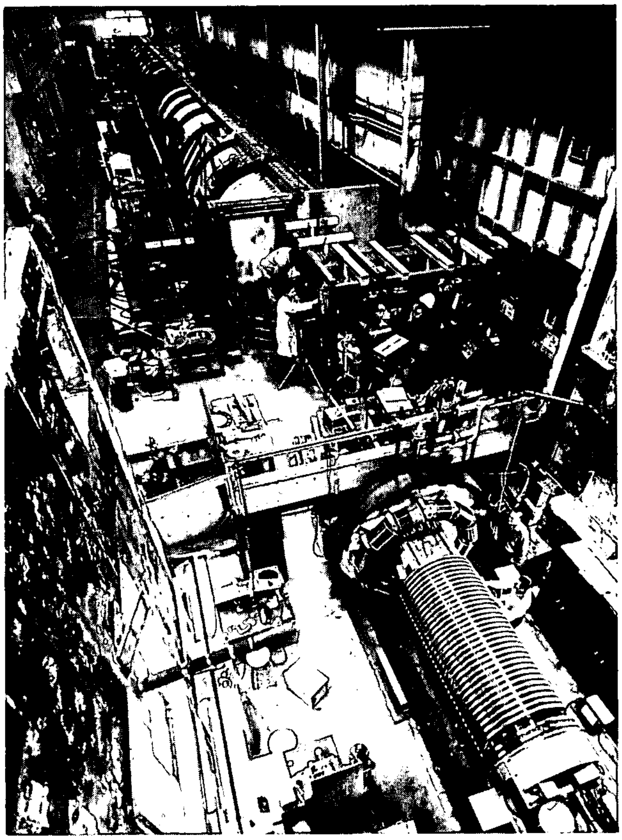
In order to continue the search for elements with higher atomic numbers, it has been necessary to develop special nuclear-particle accelerators (superheavy-ion accelerators) that can accelerate intense beams of nuclei such as argon ($_{18}Ar$), krypton ($_{36}Kr$), xenon ($_{54}Xe$), and even uranium ($_{92}U$) to energies of several hundred million electron volts (MeV). The design of such instruments is highly complicated. They must be able to produce highly charged ions such as $_{36}Kr^{20+}$ or $_{92}U^{30+}$ in order to reach the energies necessary to induce nuclear reactions. In general, atoms do not easily part with large numbers of electrons. Superheavy-ion accelerators have recently been developed in the United States, France, West Germany, and the Soviet Union, and the search for such elements continues.

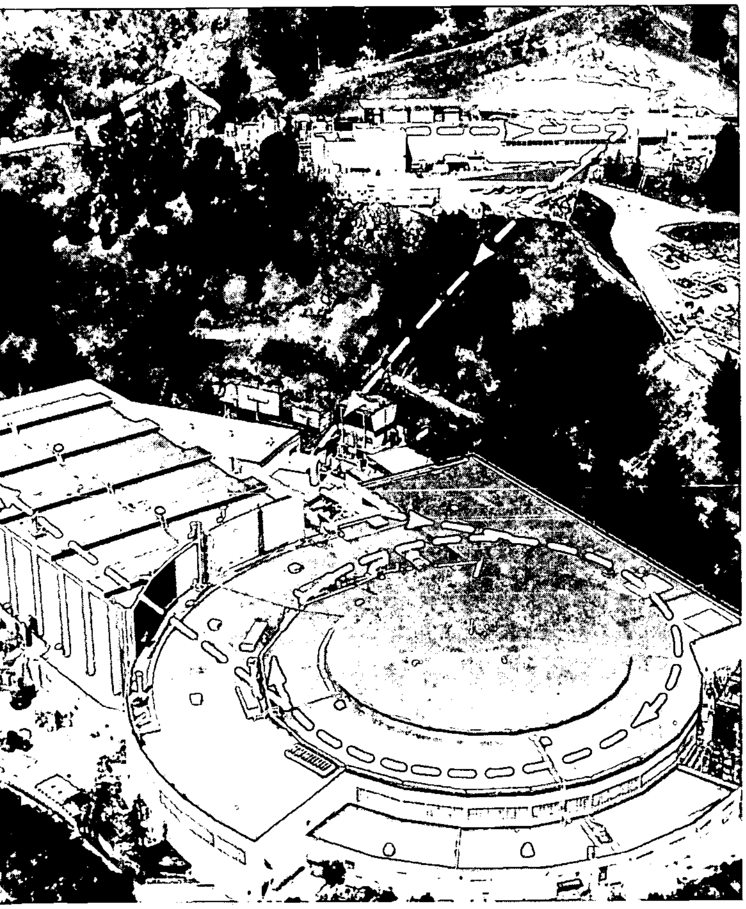
The need for special accelerators arises from the fact that the heaviest nuclide that can be used as a starting point for making heavier elements is californium ($Z = 98$). This nuclide is available in sufficient amounts to be useful as a target material. If atomic number $Z = 114$ is to be reached, nuclear projectiles containing at least 16 protons must be added to a target of californium. For lighter targets, still heavier projectiles must be used so that the target and projectile atomic numbers add up to 114. Several methods have been suggested for producing superheavy elements. One method is to try to add the lightest possible projectile to the heaviest possible target nuclide, such as

$$^{48}_{20}Ca + ^{244}_{94}Pu \longrightarrow ^{288}_{114}X + 4\,^{1}_{0}n$$

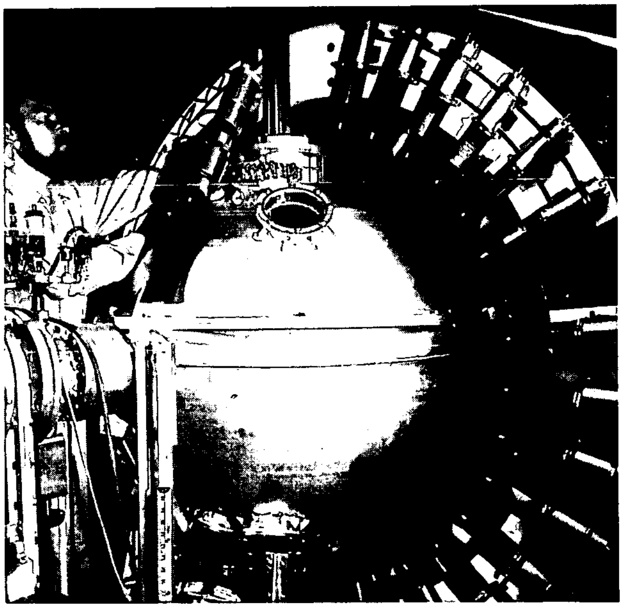


The control room at the Bevalac facility in Berkeley, California *(above)* initiates the acceleration of particles in the SuperHILAC *(right)*.





The Bevalac *(left)* is the combination of SuperHILAC and Bevatron. Particles accelerated by the SuperHILAC, in the background, feed into the Bevatron, in the foreground, for further acceleration. The Bevalac accelerates heavy ions that interact with target material in a detecting chamber *(below)*.



This stamp commemorates the use of uranium for atomic energy.

Another method involves the use of two similar nuclides in an inverse fission process, such as

$$^{136}_{54}\mathrm{Xe} + ^{150}_{60}\mathrm{Nd} \longrightarrow ^{286}_{114}X$$

Note that in both cases it is not possible to reach $^{298}_{114}$X, which is expected to be the most stable isotope of element 114. The lighter isotopes of element 114 are expected to be less stable and thus have shorter half-lives.

One of the more promising production methods is the use of reactions such as

$$^{136}_{54}\mathrm{Xe} + ^{238}_{92}\mathrm{U} \longrightarrow ^{298}_{114}X + ^{76}_{32}\mathrm{Ge}$$

and the ultimate in nuclear reactions,

$$^{238}_{92}\mathrm{U} + ^{238}_{92}\mathrm{U} \longrightarrow ^{298}_{114}X + ^{178}_{70}\mathrm{Yb}$$

The difficulty with these approaches is that the very high electric charges on the colliding nuclei inhibit them from sticking together. And even if they do stick together, the probability for fission of the product is very high. The last reaction—uranium bombarded by uranium—produces nearly every element in the periodic table. Thus, the search for superheavy elements is like searching for a needle in a haystack. However, the clever person looking for the needle in a haystack will use a magnet and hope that the needle will be attracted to it.

Scientists are using this same philosophy to try to find the superheavy elements. Sophisticated electronic and chemical techniques are being developed to serve as "magnets" to sort out the superheavy elements from the large array of product nuclides. Once the nuclear properties of these elements are known, scientists will be able to estimate whether or not the superheavy elements might exist in nature. If the possibility exists, the chemical properties of these elements will indicate where they might be found in the crust of the Earth. At the same time, obtaining knowledge of the properties of superheavy elements will give some idea of their potential usefulness to society.

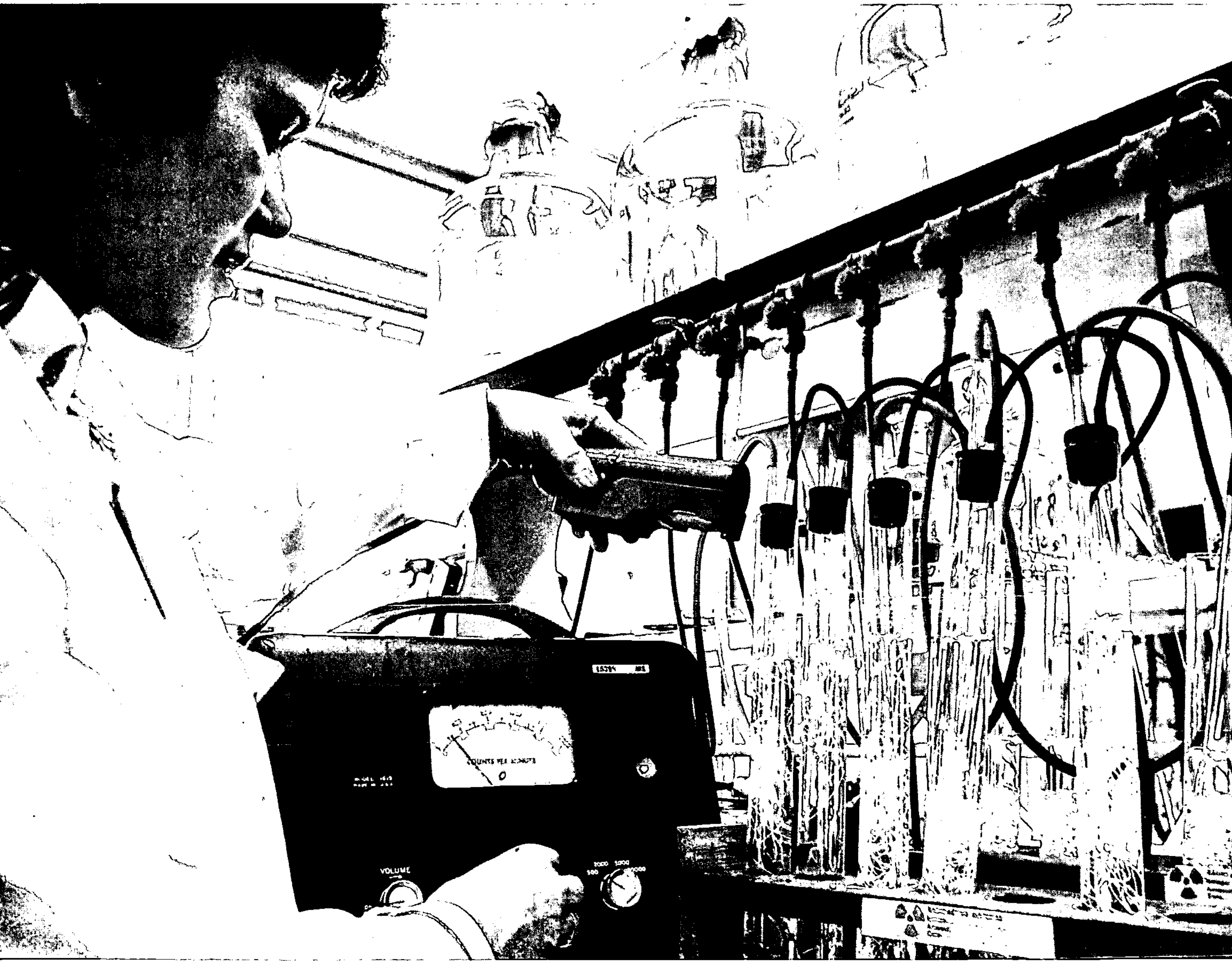
PROBLEMS

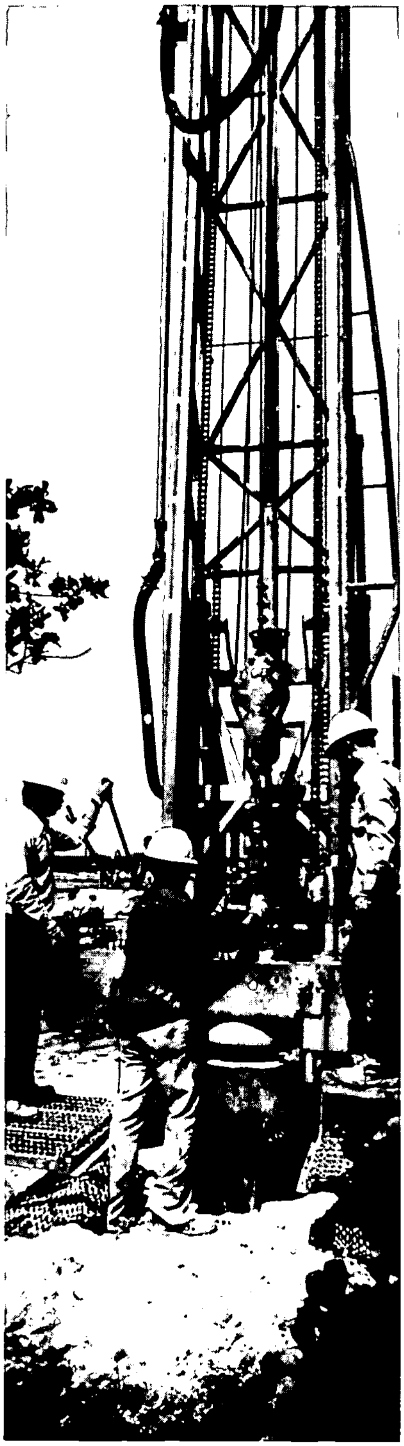
1. Elements 97 and 98 were discovered in the same laboratory. From examination of Table 7, section *N-33*, guess the name of the city and state where this laboratory is located.
2. List three radioactive nuclides that have existed on Earth since its formation.
3. ^{239}Pu has a half-life of 2.4 × 10^4 years. A sample of plutonium has a mass of 0.5 g. After 1.2 × 10^4 years, how much of the sample would remain as plutonium?
4. Discuss why tremendous speeds must be reached in order for two nuclei or a particle and a nucleus to undergo a nuclear reaction.
5. Why must atoms be ionized before they can be accelerated to high speeds?

Uses of Radiation

During the past half-century, nuclear energy and radioactivity have found a constantly increasing number of practical applications in our technological society. Nuclear techniques have become important tools in medicine, agriculture, and industry, and some nuclear processes now benefit us directly. What are these nuclear phenomena and how have they improved our lives?

An agricultural chemist uses a radiation counter to check for radioactive leaks in test tubes containing plant roots. Radioactive isotopes in organic acids are being used to study the absorption characteristics of membranes of root cells.





Environmental disturbance is minimal in uranium solution-mining. A fluid is pumped into the ore bed to dissolve the mineral containing the uranium. Then the solution is pumped from the ground.

N-35 Radiation in Our Environment

Any discussion of the beneficial results of nuclear technology should take into account the potential hazards of nuclear radiation. Because of the ability of nuclear radiation to penetrate deeply into matter and disrupt chemical structures, excessive amounts can be harmful to living organisms.

On the other hand, it must be realized that life has evolved in the presence of "natural," or background, nuclear radiation. This natural radiation has always been part of our environment and comes from two sources: (1) radioactive decay of long-lived nuclides such as ^{40}K, ^{87}Rb, ^{232}Th, ^{235}U, and ^{238}U, which have survived since the synthesis of the elements; and (2) *cosmic radiation* (protons or other high-energy particles from outer space) and its radioactive byproducts such as ^{14}C ($t_{1/2}$ = 5730 years) and ^{3}H ($t_{1/2}$ = 12 years). The radioactive nuclides ^{40}K, ^{14}C, and ^{3}H behave the same chemically as stable K, C, and H isotopes. Since these elements are among the essential ones in all living organisms, this is evidence that life has managed to survive in the presence of natural levels of radiation.

The increase in nuclear technology since the early 1940s has contributed additional radiation to our environment. For example, fallout from the atmospheric testing of nuclear explosives and small radioactivity losses stemming from nuclear reactors have added to the radiation levels to which we are exposed. However, at the present time the amount of this type of radiation is still only a small fraction of the natural radiation in our environment.

A person's annual exposure to background radiation in the United States ranges upward from about 160 mrem (*millirems*). (A millirem is a unit of radiation dosage that expresses the amount of damage that can be caused by radiation.) Medical X rays or other sources contribute further to a person's yearly exposure to radiation. (The various components of natural radiation and radiation caused by human activities are summarized in Table 8.) Although it is generally believed that background radiation levels do not have a significant effect on humans, research continues in order to determine better guidelines for radiation safety and to improve our methods for safely containing the radiation produced by nuclear technology.

PROBLEMS

1. What is your annual radiation dose? To find out, add the radiation doses from Table 8 that apply to you. A potentially fatal exposure is 500 000 mrem.
2. At a distance of 60 cm, the MINIGENERATOR produces a radiation dose of 0.0001 mrem/hour. How long would it take for you to receive a radiation dose equal to what you receive from (a) the annual background radiation? (b) watching color TV three hours a day?

Table 8: SOURCES AND AMOUNTS OF RADIATION PER YEAR*

Source	Amount (mrem)
Cosmic radiation (at sea level) elevation: add 1 for every 100 feet of elevation.	44
House construction (¾ time spent indoors; U.S. average)	
brick	45
stone	50
wood	35
concrete	45
Ground (¼ time spent outdoors; U.S. average)	15
Water, food, air (U.S. average)	25
Weapons test fallout	4
X-ray diagnosis	
chest X ray	9 (each)
gastrointestinal tract X ray	210 (each)
Jet airplane travel, 10 000-kilometer (6000-mile) flights	4 (each)
Television viewing	0.15 × number of hours per day
How close you live to a nuclear power plant	
At site boundary	0.2 } × annual average number of hours you spend there per day
1.6 kilometers (1 mile) away	0.02
8 kilometers (5 miles) away	0.002
over 8 kilometers (5 miles) away	0

*The period of time of exposure is one year unless otherwise stated.

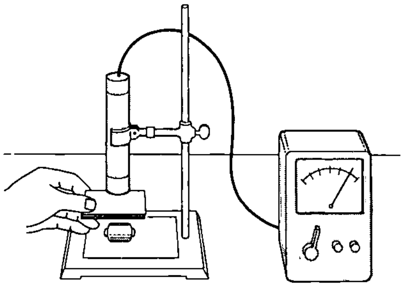
One of the most penetrating types of radiation in our environment is gamma radiation. As gamma rays pass through matter, they interact with the electrons of any atoms that happen to be in their path. Sometimes the gamma rays lose all their energy in a single collision. At other times they bounce off an electron and lose only part of their energy. The net effect is that the number of gamma rays (intensity) coming from a radioactive gamma-ray source is decreased in passing through matter, much the same way that the light from a flashlight is decreased when you place successive pieces of paper in front of the lens. However, since gamma radiation is much more energetic than light, it takes several sheets of metal, rather than paper, to decrease the intensity of these rays. We will investigate the penetrating power of gamma radiation in various materials in the following experiment. Because gamma rays are invisible, we shall need a nuclear-particle detector to observe the radiation.

TIME MACHINE

1909	Louis Bleriot makes first English Channel crossing by plane, in 37 minutes.
1910	Halley's comet comes within 24 million kilometers of Earth during its most recent sighting.
1912	**Victor Hess discovers cosmic radiation by ascending in a balloon to an altitude of 5000 meters.**
1913	*The Rite of Spring*, ballet with music by Stravinsky, causes furor at Paris premiere.
1915	Alexander Graham Bell and Thomas A. Watson hold first transcontinental telephone conversation.

EXPERIMENT

N-36 Gamma-Ray Penetration

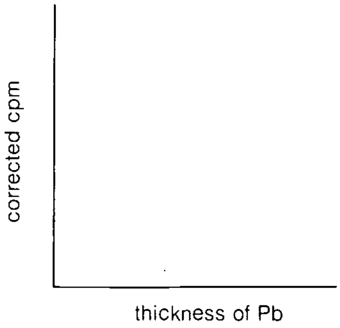


Turn on the detector and allow it to warm up for 5 minutes. Make sure there is no radioactive source near the counter tube. Then compute the average of three readings of the background radiation.

Place a gamma-ray sample (your ^{137}Cs/^{137m}Ba MINIGENERATOR) 2 cm from the detector. Record three one-minute activity readings. (If the dial seems to fluctuate during the one-minute time period, record the best average value that can be determined.)

Next, place three sheets of aluminum of the same thickness between the source and the detector. Take three one-minute readings of the activity. **Note:** *Do not let the detector-to-source distance change.* Record the average value. Repeat the measurement using three sheets of copper, then three sheets of lead. Record your data in your laboratory notebook.

Now measure the thickness of ten sheets of lead. Divide the thickness by 10 for the average thickness of one sheet. Place *one* sheet of lead halfway between the detector and the source. Record the activity. Continue to place additional sheets of lead between the sample and the detector. Record the activity level with each addition. Continue until the activity is reduced to less than one-half of the original rate.



Plot these data on graph paper, using the thickness of sheets of lead as the horizontal axis and the activity count as the vertical axis. Draw the best curve you can through the points. From this graph, select the point at which the activity reading is one-half the reading with no lead sheets present. This distance along the horizontal is called the *half-thickness value*.

Questions:

1. How does the counting rate vary with different shielding metals?
2. How does the counting rate vary with different shielding thicknesses?
3. What thickness of lead reduces the activity count to one-half the initial rate?
4. What effect would changing the source-to-detector distance during the experiment have on your results?

Keeping in mind that radiation is detectable and that radiation can pass through material, let us now examine some of the useful applications of radiation. Our list will be far from complete and must be taken only as an indication of the widespread use of nuclear phenomena in scientific research and technology today.

N-37 Radioactive Tracers in Chemistry

One of the first practical applications of radioactive isotopes was their use as *tracers* for studying the behavior of various elements in specific chemical reactions. Chemical tracers have proved to be one of the most useful and least dangerous of the various applications of nuclear science. A tracer is a small amount of a *radioactive isotope* that is added to the naturally occurring isotopes of that same element. If the experimental results are to be meaningful, the tracer and the stable isotope must be in the same chemical form. If the chemical in the experiment is a compound, the molecules that contain radioactive isotopes are called *tagged molecules*.

In a chemical reaction, the radioactive isotopes of an element behave similarly to the stable isotopes. But, being radioactive, the radioisotopes can be "traced" through the reaction by means of a radiation detector. The characteristic half-life and the emission of unique radiations from a radioactive isotope enable it to be easily identified.

To illustrate the tracer technique more clearly, let us consider a routine problem in inorganic chemistry. Lead nitrate, $Pb(NO_3)_2$, and sodium sulfate, Na_2SO_4, are both soluble in water. However, when they are mixed together a white precipitate forms. By using lead nitrate that contains the radioactive isotope ^{210}Pb, one can confirm that the following reaction occurs.

$$Pb^{2+}(aq) \quad + \quad SO_4^{2-}\,(aq) \quad \longrightarrow \quad PbSO_4(s)$$

The specific proof that lead is contained in the precipitate can be demonstrated by separating the precipitate from the liquid and then detecting radioactivity in the precipitate. This is just a simple example of how chemists use radioactive tracers to study chemical reactions and the nature of chemical bonding.

Research in many fields of science has been advanced by the availability of tagged chemicals. These substances have acted as "eyes" for the scientist studying reactions and are also used in manufacturing and quality-control work.

Tracers are also useful in measuring the amount of a specific substance that is present in a mixture, particularly when good chemical separation techniques are not available. An area of research where tracers have proved especially valuable is that of biochemistry. For example, the functions of the two nucleic acids DNA (*d*eoxyribo*n*ucleic *a*cid) and RNA (*r*ibo*n*ucleic *a*cid) have been studied extensively by means of tracers. These nucleic acids are essential for cell reproduction and are responsible for carrying the genetic code in the manufacture of protein in living cells. Three of the elements that compose RNA and DNA molecules are carbon, hydrogen, and phosphorus, each of which has a radioactive isotope that can be used as a chemical tracer—^{14}C, ^{3}H, and ^{32}P. More detailed information about RNA and DNA and illustrations of the chemical structure of these complex molecules can be found in *Molecules in Living Systems: A Biochemistry Module.*

By studying what happens to molecules of DNA and RNA that contain radioactive atoms, scientists have been able to do research on cell reproduction, on protein synthesis, and even on the uncontrolled cell duplication in cancer.

TIME MACHINE

1944	Tennessee Williams writes *The Glass Menagerie.*
1945	*Animal Farm,* by George Orwell, is published.
1946	**Hermann Joseph Muller receives the Nobel prize for medicine and physiology for his study of mutations induced by X rays.**
1947	Jackie Robinson is first black baseball player to sign with a major league team.
1949	*South Pacific* opens on Broadway.

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miniexperiment

N-38 Tracers

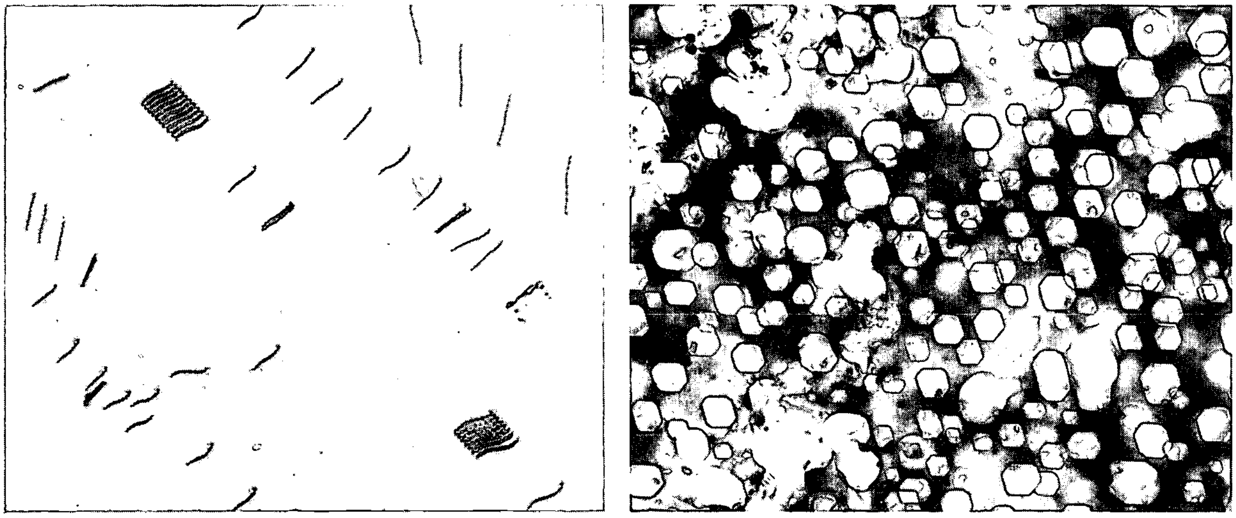
Your instructor will give you a series of compounds that look alike. Using your radiation detector, see if you can determine which of the samples contain radioactivity and which do not. Remember that some compounds have low radioactivity; therefore the tests must be carefully monitored.

N-39 Effects of Radiation Doses

Because of their highly energetic properties, some types of nuclear radiation are capable of penetrating matter to depths of up to several centimeters (see section *N-29* and refer to experiment *N-36*). As radiation passes through matter, it interacts with electrons to disturb or break chemical bonds. A single nuclear radiation event can create a few to thousands of such disturbances, which can lead to the formation of new chemical bonds in a localized region of the irradiated material. The amount of radiation damage depends on many variables, such as the type of radiation, its energy, the exposure time, and the material that is being irradiated.

Irradiation has come into wide usage in recent years to produce significant differences in the properties of irradiated substances. In some cases these changes can lead to more desirable characteristics; in others the effect can be harmful.

Many sources of radiation have been utilized in radiation technology—sources such as neutrons from nuclear reactors, charged



Two pieces of stainless steel magnified 100 000 times are shown above. The sample on the right shows structural damage following exposure to high-energy neutrons. Below, the effect of heavy-ion radiation on living cells is studied as a potential form of radiation therapy for cancer.

particles (protons, alpha particles, electrons, and so on) from accelerators, and gamma rays from intense radioactive sources (^{60m}Co, for example). Different results can be obtained by varying the radiation conditions, such as the type and energy of the radiation. In contrast with tracer techniques, which rely on small amounts of radioactivity, the use of radiation to induce structural changes requires much higher levels of radiation and therefore must be more carefully controlled to produce the desired results.

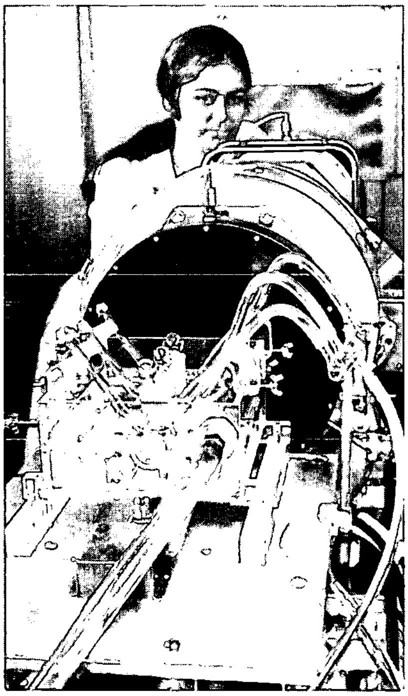
In the field of radiation chemistry, unusual chemical compounds can be studied by exposing them to nuclear radiation. For example, when water is irradiated by an intense gamma ray source, the water molecules can be broken up, as in the following reaction.

$$\overset{\text{WATER}}{\mathrm{H{:}\underset{\cdot\cdot}{\ddot{O}}{:}H}} \xrightarrow{\gamma} \underset{\text{free radicals}}{\mathrm{H\cdot} + \mathrm{\cdot\underset{\cdot\cdot}{\ddot{O}}{:}H}}$$

The process of splitting molecules by radiation is called *radiolysis*. The products of the reaction are called *free radicals* (atoms or groups of atoms having an unpaired electron). The presence of unpaired electrons accounts for the often reactive nature of free radicals. Once the free radicals have been formed, other reactions can then occur.

$$\mathrm{H\cdot} + \mathrm{H\cdot} \longrightarrow H_2 \text{ (hydrogen gas)}$$
$$\mathrm{H{:}\underset{\cdot\cdot}{\ddot{O}}\cdot} + \mathrm{\cdot\underset{\cdot\cdot}{\ddot{O}}{:}H} \longrightarrow H_2O_2 \text{ (hydrogen peroxide)}$$
$$\mathrm{H\cdot} + \mathrm{\cdot\underset{\cdot\cdot}{\ddot{O}}{:}H} \longrightarrow H_2O \text{ (water)}$$

These reactions are a simple illustration of the reactivity of free radicals, but they represent the damage that radiation can do to other molecules. Reactions such as these, when they occur in the human body, are responsible for the harmful biological effects of radiation.

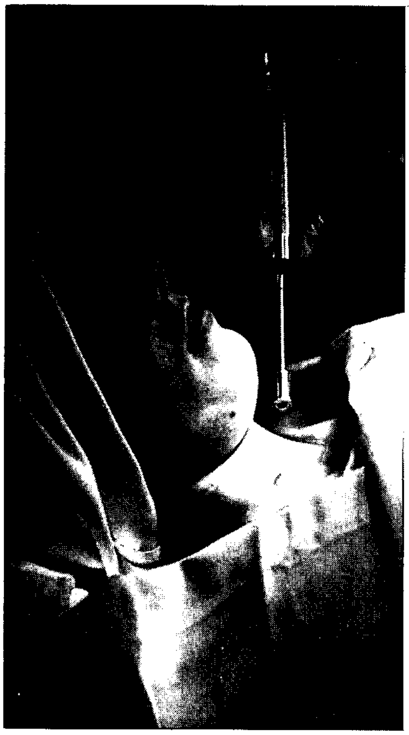


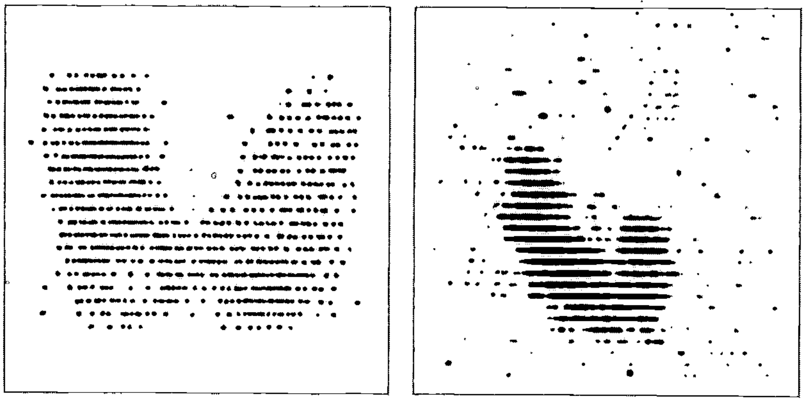
N-40 Nuclear Techniques in Medicine

In medicine, radiation has two primary uses: medical diagnosis and treatment. Using tracers in medicine is similar to using them to study chemical reactions. The only difference is that the chemical reactions in medical applications occur in living organisms. In practice, a radioactive tracer or tagged chemical is given to a patient orally or by injection. A tracer is used that will concentrate in the organ to be examined, and the pattern of the radiation is then observed with a scanning device. Unusual radiation patterns from the organ indicate the presence of a condition that may require medical attention.

Two major advantages of tracer diagnosis are (1) the need for only very small amounts of radioactive material, which reduces both the chemical and radiation hazards to the patient; and (2) the existence of tagged compounds that concentrate in specific areas of the body. This permits the physician to pinpoint an ailment with a high degree of success in many cases and avoid exploratory surgery or extensive X-ray examination.

One of the most common tracers used in medicine is $^{131}I^*$, a radioactive isotope of iodine that decays with a half-life of 8 days. Iodine is necessary for the proper functioning of the *thyroid gland,* which uses this element in the production of *thyroxin.* This chemical controls the rate at which oxygen is used by body cells and is vital to our health. If the thyroid gland is not producing enough thyroxin, the body's ability to use oxygen is decreased. This produces a slowdown in other body processes. The functioning of the thyroid gland can be diagnosed by administering $^{131}I^*$ to the patient. After sufficient time has passed to allow the iodine tracer to concentrate in the thyroid gland, the patient's thyroid is scanned with a radiation detector. The amount of radiation present in the thyroid helps the doctor to determine how well the gland is functioning. Many other radionuclides can be used for diagnosis.





A commemorative stamp *(top)* illustrates the use of radiation to fight cancer, symbolized by the astrological sign the Crab. The radioisotope ^{131}I and a special probe *(above)* refined the technique of thyroid surgery to remove malignant tissue. Radiographs of a healthy thyroid gland *(right)* show uniform distribution of the radioisotope, whereas a malignant thyroid growth *(far right)* concentrates most of the isotope.

- The element chromium in the form of sodium chromate, $Na_2{}^{51}Cr^*O_4$, becomes attached to the hemoglobin in red blood cells. This fact has been used in the diagnosis of anemia and in the detection of ulcers.
- Iron is an essential element of hemoglobin. The tracer $^{59}Fe^*$ can be used to measure the rate of formation of red blood cells in the body and to determine whether or not iron in the diet is being used properly.
- Images of the brain, kidneys, and bones can be produced by using technetium, $^{99m}Tc^*$.

These examples of the use of radionuclides in medical diagnosis are but a small part of an extensive list of applications. Tracers are important tools in medical science, and they may be even more valuable in the future.

Another contribution to medical science is the use of controlled radiation exposures in the form of radiation therapy. Because nuclear radiation is damaging to body cells, as well as to diseased tissue, radiation treatment is generally restricted to cancer patients or to conditions where specific cures are rare.

Radiation therapy for cancer can vary according to the type and location of the diseased tissue. In one type of treatment, the patient is positioned so that the area to be treated is at the center of a circle. Then either the radiation source or the patient is rotated. In this way the desired area is irradiated continuously while surrounding areas receive only limited radiation. This procedure concentrates the radiation in the cancerous region while minimizing the radiation damage to other areas of the body (Figure 15).

The use of radiation to treat cancer does not often result in a cure of the disease. However, radiation therapy can extend the life of a cancer patient by several years, thereby allowing the patient to pursue normal activities.

This instrument uses a particle accelerator to treat certain types of cancer.

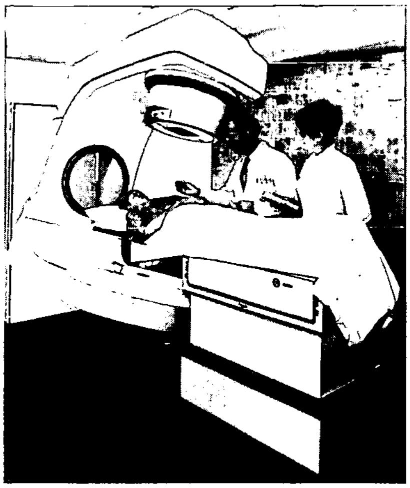


Figure 15

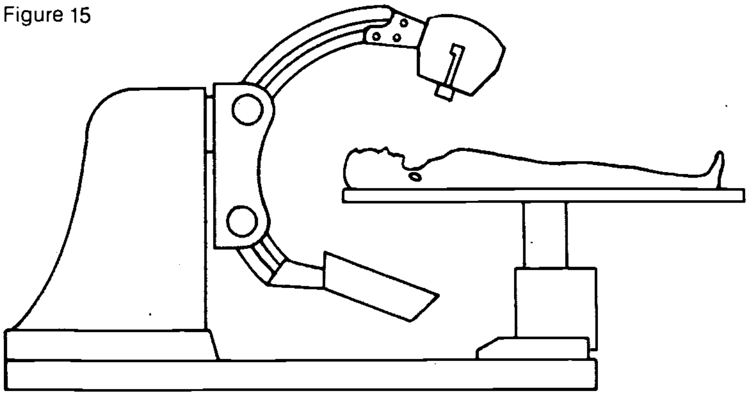
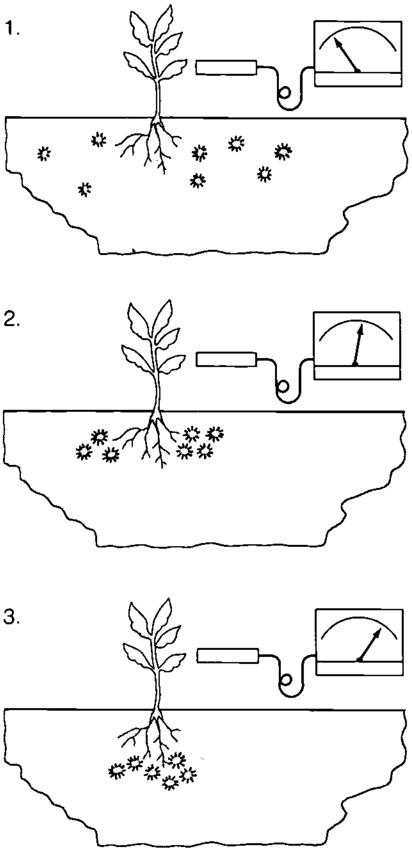


Figure 16



The importance of fertilizer distribution for the growth of plants can be demonstrated with radioactive tracers. Uniform distribution (1) is the least beneficial. Placement below and beside seeds (2) results in high uptake and good root distribution. Placement directly below seeds (3) produces high uptake but poor root distribution.

N-41 Nuclear Techniques in Agriculture

Feeding the world's population is one of the greatest challenges that faces us today. Each year weeds, insects, and disease destroy billions of dollars' worth of crops. In their efforts to reduce such losses and to increase crop yields, agricultural scientists have made extensive use of radioactive tracers. Figure 16 illustrates a simple study that can be performed to learn the effects of variables such as proper fertilization and the optimum conditions for the uptake of nutrients in plant growth.

Tracers are useful in following the paths of chemical weed and insect killers through our environment. For example, suppose a weed killer (herbicide) is applied to a crop growing in a test plot. Naturally, researchers are interested in learning how effective this herbicide is. But other questions must also be answered before the chemical can be put into general use. Most herbicides are toxic in the form in which they are applied. It is necessary to find out if the chemical will eventually show up as a contaminant in the crop itself or if it will concentrate only in the weeds to be killed. From our past experiences with herbicides, scientists would need to know if this chemical is readily broken down into nontoxic forms. Will it be washed away and pollute nearby streams? Is it a hazard to wildlife and humans?

Some of the answers to these questions can be obtained by tagging the molecules of the herbicide with a radioactive tracer. Then, by examining the environment of a test plot with a radiation detector, scientists can check for traces of radiation in streams, animals, and the crop itself.

The application of doses of radiation also plays an important part in developing new products and methods. For example, the irradiation of certain species of insect pests can produce sterile insects. This has helped to control certain insect populations and thereby to curb crop damage. In addition, controlled doses of radiation can successfully destroy many bacteria that ruin seeds and food during storage. This technique, rather than the use of chemical preservatives, is now often used to retard the spoilage of many food items.

Table 9: SOME RADIATION-PRESERVED PRODUCTS

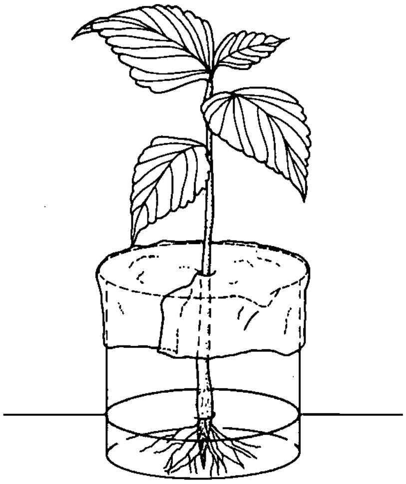
Product	Result	Radiation Source
Bacon	sterilization	^{137}Cs, ^{60}Co, 5-MeV electrons
Wheat flour	insect disinfestation	^{137}Cs, ^{60}Co, 5-MeV electrons
White potatoes	sprout inhibition	^{137}Cs, ^{60}Co
Packaging materials	enhancement of preservation properties	gamma emitters (several)

Other foods such as fruit, fish, chicken, and meats have all been studied after being irradiated. Astronauts consumed irradiated food on their space travels. Some countries and the World Health Organization look favorably on the future of irradiated food for human consumption. It should be emphasized that none of these irradiated foods is actually radioactive. Instead, the radiation induces chemical changes that are beneficial in preserving the food.

The genetic effects of excessive radiation on living matter are usually harmful. It has been found, however, that positive mutations in some plant species can be induced by high doses of radiation. Several improved varieties of beans, peas, and grains have been developed in this way. The genetic change is a result of chemical changes caused by the external source of radiation.

N-42 Plant Absorption of Phosphorus

EXPERIMENT



Obtain some small, healthy potted plants and some radioactive phosphorus (^{32}P) solution prepared in advance by your teacher. Remove the plants from the pots and wash the roots clean.

Take at least three background readings of the plant and a beaker. Record these data. Place the roots of the plant in the bottom of the beaker and pour in enough ^{32}P solution to just cover the roots.

Obtain a piece of plastic wrap large enough to cover the top of the beaker while encircling the stem of the plant. This will help prevent evaporation of the liquid. Place the plant where there is good light and warmth.

After 48 hours, remove the plant from the beaker. Rinse off the roots. Cut the plant to separate its roots, stems, and leaves. Obtain pieces of each part that are no larger than the window on your radiation detector. Set up the detector so that the radiation source-to-detector distance is the same for all measurements. Now measure the maximum radiation in each part of the plant. Record the activity values. Then find the mass of each part and record the data.

Calculate your corrected counts per minute. Determine the counts per minute per gram of each part of the plant. Prepare a chart listing each part examined and the related data.

SAMPLE WORKSHEET

	cpm
Plant	___
Beaker	___

	cpm	mass	cpm/g
Roots	___	___	___
	___	___	___
	___	___	___
Stems	___	___	___
	___	___	___
	___	___	___
Leaves	___	___	___
	___	___	___
	___	___	___

Questions:

1. Which part of the plant had the highest activity per gram?
2. Can you provide an explanation for your observations?
3. Why should you keep the distance between the radiation source and detector the same throughout all measurements?

Extended Activity: Prepare radioautographs of the various parts of the plant. (See experiment *N-22* for a discussion of the procedure.)

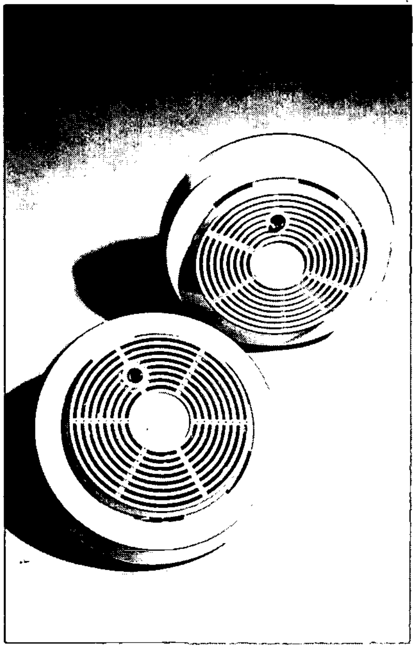
A chemist *(below)* dispenses fertilizer tagged with a radioisotope. Rice plants grown from irradiated seeds *(right)* are examined for improved traits.

A radioisotope is used to trace the distribution of an animal-repelling chemical inside a Douglas-fir seedling *(below left)*. Irradiating the buds of a plant that bears white flowers can produce darker-colored flowers *(middle right)*. Insect pests are sterilized by radiation *(bottom right)* to control their reproduction.

N-43 Radiation and Consumer Products

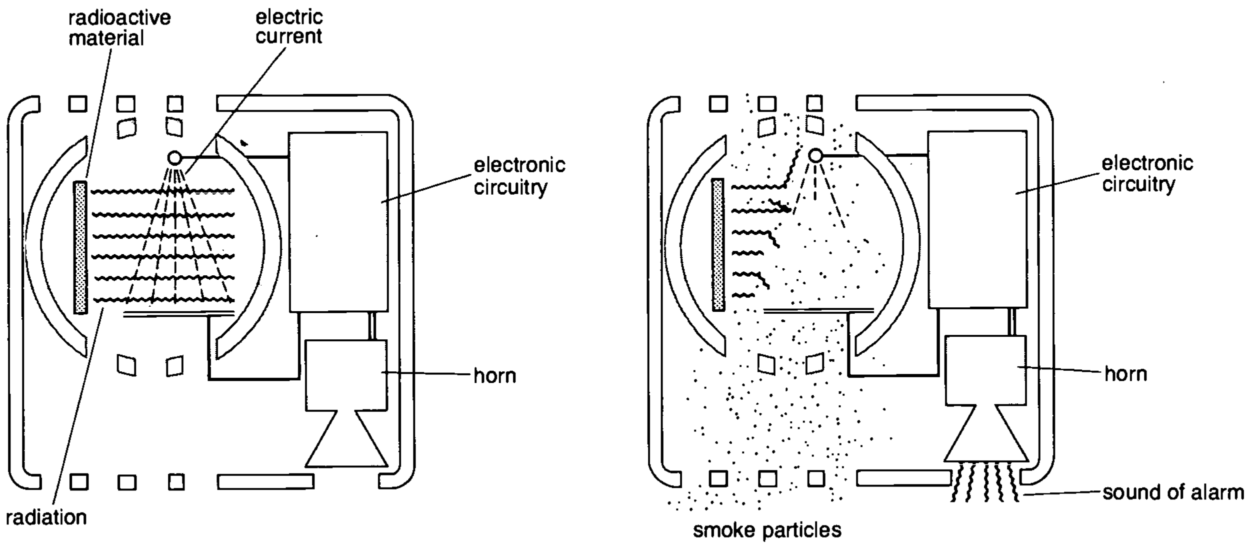
The by-products of nuclear reactors provide a large source of useful radioisotopes. Besides the uses we have already discussed, many of these radioisotopes have important applications in the manufacture of many consumer products. For example, quality-control devices, consisting of a radiation source and detection equipment, are routinely used to check for defects in structural materials. Similar devices provide sensitive thickness control for thin sheets of materials such as metal and plastic. Another use of radioisotopes involves the irradiation of plastics, a process that enhances their strength, flexibility, and/or temperature stability.

Although radioactive materials are primarily used in manufacturing processes, where they can be carefully monitored, one product that incorporates radioactive materials directly has recently found its way into the consumer marketplace. This product is the ionization smoke detector, which contains the transuranium element $^{241}_{95}Am$ (americium). The ^{241}Am is located in the sensing chamber of the smoke detector. This nuclide ($t_{1/2}$ = 450 years) emits alpha particles that enable an electric current to flow through the chamber and through the smoke detector's circuit. The electric current keeps the alarm inactive. Smoke or soot particles that enter the sensing chamber in sufficient amounts reduce the current flowing through the chamber. When the current is reduced below a certain amount, a separate electric circuit for the alarm is activated. The radioactivity from an ionization smoke detector contributes little to the amount of radiation from natural sources to which we are exposed.



The ionization smoke detector *(above)* has become an important protective device for use in the home. Battery-powered models should be checked periodically to make sure that the alarm works properly. The diagrams below illustrate how the device operates before *(left)* and after particles of smoke enter the chamber *(right)*.

IONIZATION SMOKE DETECTOR



TIME MACHINE

1951	Fred Waller invents Cinerama.
1952	**Radioisotopes are used in medicine and industry.**
1953	Queen Elizabeth II is crowned.
1953	**The National Food Irradiation Program is established.**
1954	St. Lawrence Seaway project is approved by President Eisenhower.

N-44 Activation Analysis

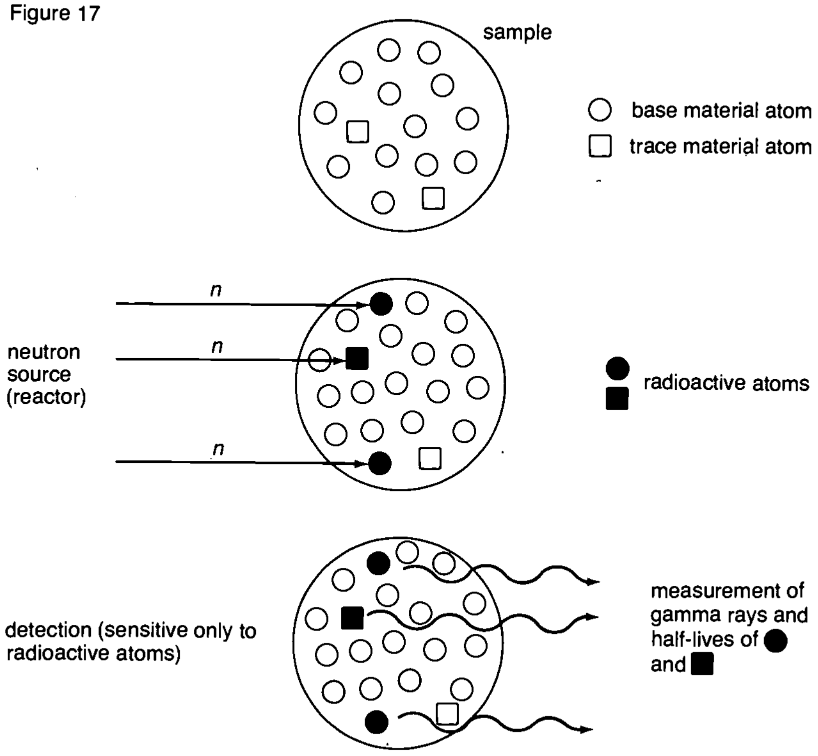
One of the most sensitive techniques scientists have yet devised for the determination of small amounts of a given element in the presence of large quantities of other materials is that of *activation analysis*. This method depends upon nuclear reactions to identify specific elements.

In this technique, an unknown sample is exposed to a source of nuclear particles, usually neutrons. The bombardment of the material by these particles produces nuclear reactions that "activate" nuclei to become radioactive. These radioactive nuclides each have a particular half-life and emit a certain type of radiation (Figure 17). Scientists use these factors to determine the chemical elements in a substance. For example,

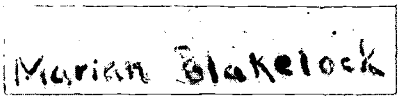
$$^{23}_{11}\mathrm{Na} + {}^{1}_{0}n \longrightarrow {}^{24}_{11}\mathrm{Na} \longrightarrow {}^{24}_{12}\mathrm{Mg} + {}^{0}_{-1}\beta \text{ or } {}^{24}_{12}\mathrm{Mg} + {}^{0}_{-1}\beta + \gamma$$

is a reaction that can help identify the presence of trace amounts of sodium. The radiation given off by the ^{24}Na nucleus consists of beta and gamma rays and can be analyzed with a sensitive radiation detector. The half-life and energy of this radiation serve as sensitive "fingerprints" for the specific element. Identification of the radioactive nucleus produced in the nuclear reactions serves to identify the unknown element that was originally in the sample, since it is known that the reaction was produced by a neutron.

Figure 17

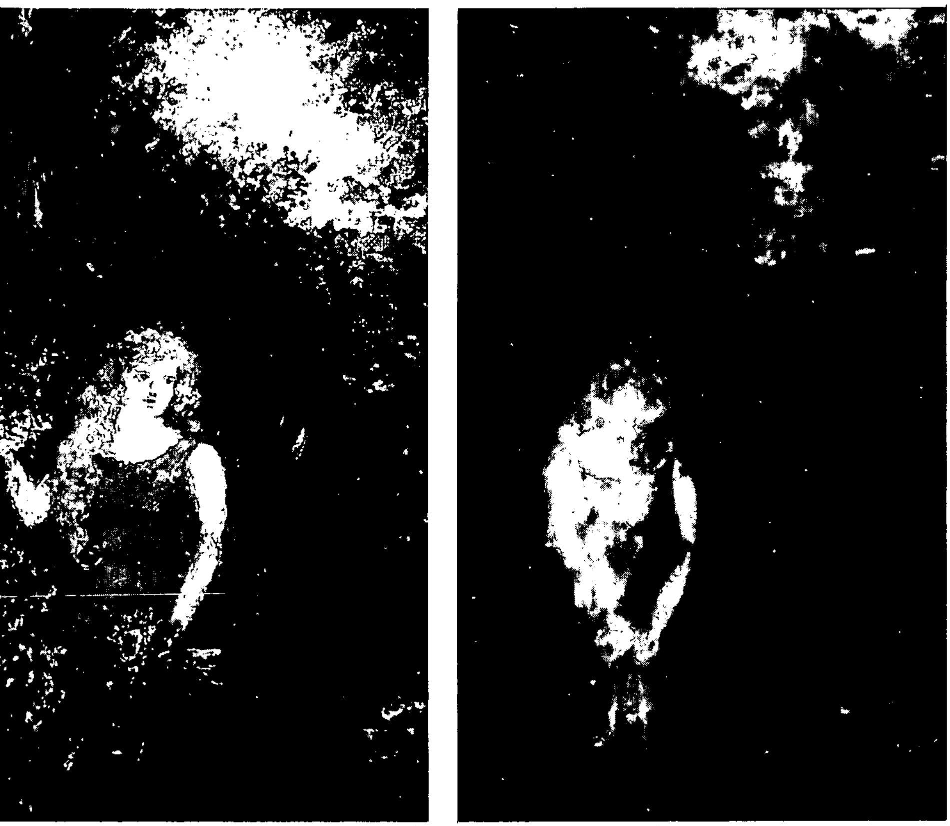


Details of autoradiographs of paintings by Marian Blakelock.



Signature on the surface of a landscape painting from the Sheldon Memorial Art Gallery.

Hidden, partially destroyed signature on *Woman in Red*.



Evidence that the signature on the painting *Woman in Red (far left)* had been changed was provided by the use of neutron-activation autoradiography. This procedure produced an image on film *(left)*, which revealed that the original artist's signature had been tampered with.

Activation analysis is capable of detecting impurities in concentrations as low as 10^{-10} percent, or down to billionths of a gram. As an example of how this technique can be applied to the detection of small amounts of material, let us take a look at the way criminologists currently use activation analysis. Whenever a handgun is fired, gunpowder residues spread over the person holding the gun. Gunpowder contains traces of elements such as antimony, barium, and copper, all of which are sensitive to neutron activation analysis. By taking wipings from a suspect and subjecting them to neutron activation analysis, it is possible to tell whether or not a suspect has fired a gun recently and, if so, in which hand the gun was held and the number of bullets fired. Because of the different materials used in gunpowder by different manufacturers, it is even possible to identify the type and manufacturer of the bullets.

Since nuclear reactors are not very portable, the use of this technique for field studies used to be impossible. However, the transuranium nuclide californium, $^{252}_{98}$Cf, undergoes spontaneous fission with a 2.5-year half-life and liberates neutrons. $^{252}_{98}$Cf can serve as a miniature, portable source of neutrons. This enables neutron activation analysis to be carried out in remote places such as drill shafts and on the ocean bottom.

An investigator prepares to use neutron-activation analysis to reveal traces of gunpowder residue on the hand after a gun has been fired.

There are many other areas where neutron activation analysis is regularly used (as summarized in Table 10), and researchers are developing others.

Table 10: USES OF NEUTRON ACTIVATION ANALYSIS

Petroleum engineering	analysis for vanadium, characteristic of the presence of oil fields
Space science	examination of lunar and planetary surfaces; study of moon rocks
Pollution control	analysis of toxic elements in the air and water; location of their sources
Medicine	discovery of the role of trace elements in metabolism
Geology	analysis of minerals for rare elements; identification of mineral deposits in mine shafts
Electronics	search for impurities in semiconductor materials for transistors
Criminology	comparison of trace elements in evidence associated with suspects
Agriculture	detection of pesticide residue in crops and surrounding environment
Oceanography	studying patterns of ocean currents and sedimentation
Archaeology	determining the chemical composition of ancient artifacts

Although neutron activation analysis is highly specific for elements that are present in trace amounts, it has three important restrictions. First, not all elements have isotopes that are conveniently produced and detected by activation analysis. Second, the technique gives excellent information concerning the elements that are present, but it cannot determine the chemical form of the element. And finally, the method is more expensive than standard chemical techniques. Although activation analysis is a highly valuable tool for scientists, it is most effectively used in conjunction with other forms of chemical analysis.

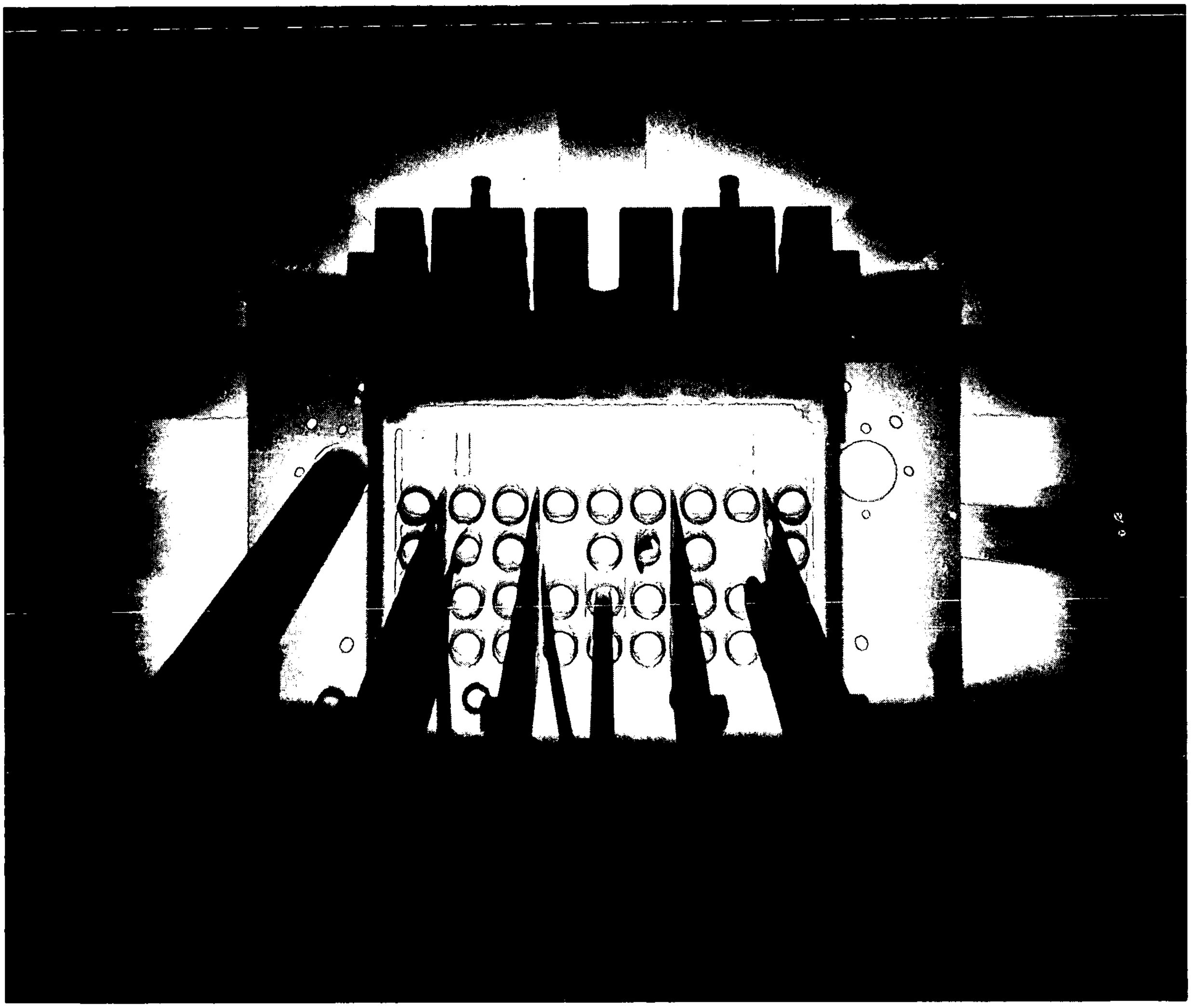
PROBLEMS

1. Discuss other applications of radioisotope use that you may know in addition to those mentioned in this unit.
2. Investigate some specific types of cancer and the most effective type of radiation therapy for each.
3. Compare the hazards of radiation therapy with those of chemotherapy.
4. Discuss what "tagging a compound" means. In the case of photosynthesis, how might you show that glucose is formed from carbon dioxide?

Nuclear Power

As fossil fuel reserves are gradually used up, the need for power from other sources becomes increasingly important. Two major alternative power sources are nuclear fission and nuclear fusion reactors. Fission reactors currently produce about 11 percent of the electricity in the United States. Successful development of a fusion reactor is a major hope for electricity in the twenty-first century. What are the advantages and disadvantages of nuclear power? Do the advantages outweigh the disadvantages?

Unleashing the energy of the atomic nucleus in a controlled manner is a remarkable achievement. The reactor shown in this photograph is a small one designed to provide neutrons for research purposes. The glow, known as Cerenkov radiation, results from the interaction of gamma rays with the surrounding coolant water.



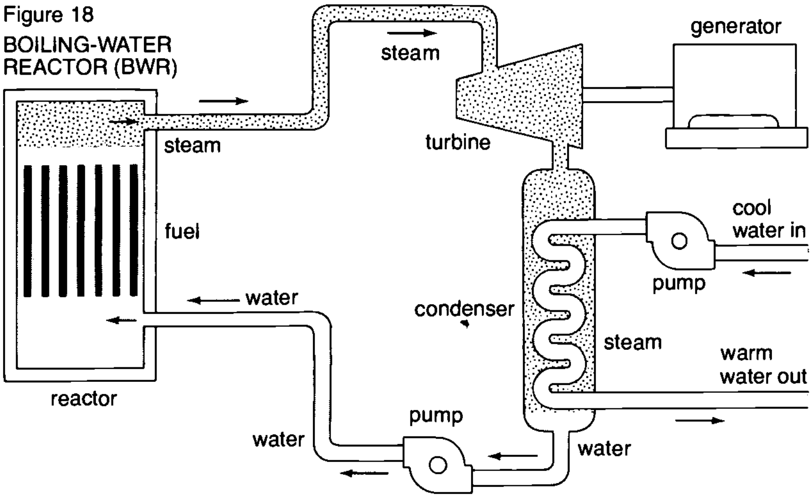
N-45 Nuclear Reactor Operation

Nuclear reactors have been producing useful electrical power for more than twenty years. As pointed out in section *N-23*, the fission of ^{235}U can operate as a chain reaction and provide a self-sustaining source of energy. The control of this chain reaction for useful power generation is accomplished by means of a nuclear reactor (Figure 18). The basic components of a nuclear reactor include the following.

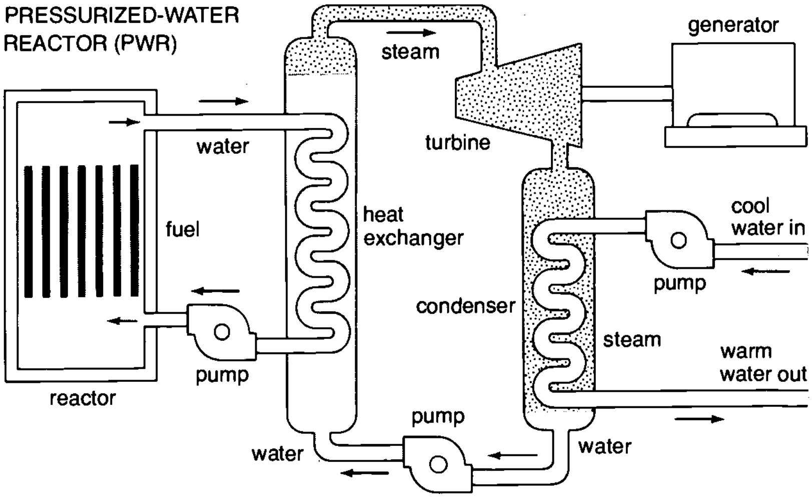
1. **Fuel Rods**—These contain the fissionable material, usually uranium, enriched to about 3 percent ^{235}U. (Natural uranium contains only about 0.7 percent ^{235}U. This concentration is not sufficient to sustain a chain reaction.) The fuel pellets are usually encased in special metal alloy tubes (fuel rods) that can withstand the heat and radiation damage from nuclear fission reactions.

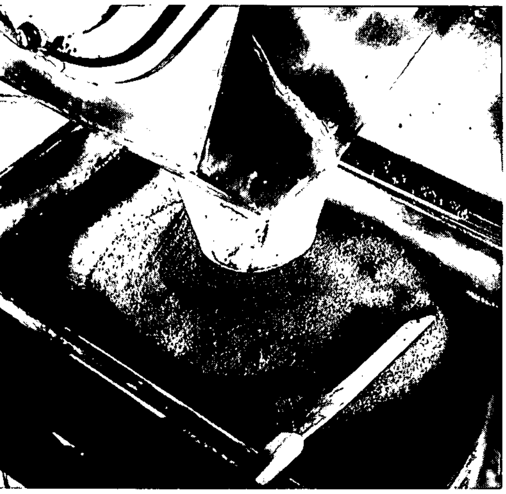
Figure 18

BOILING-WATER REACTOR (BWR)



PRESSURIZED-WATER REACTOR (PWR)





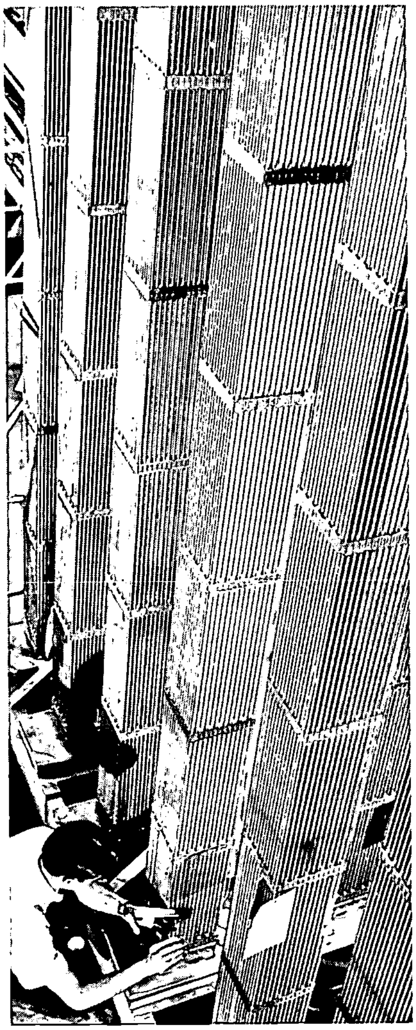
Enriched uranium dioxide fuel.

Nuclear fuel pellets.

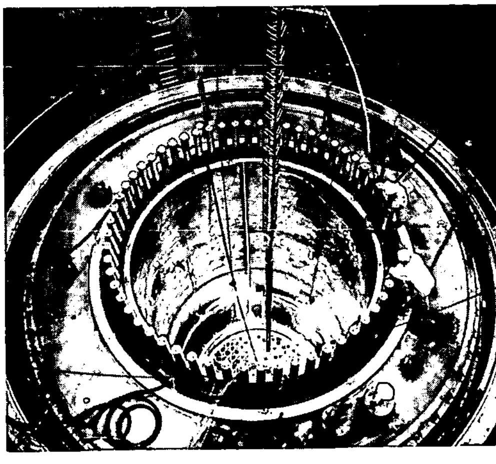
Fuel rod cut open to show pellets.

2. **Control Rods**—These are rods containing elements such as boron or cadmium that do not undergo fission, but are very efficient in absorbing neutrons. In effect, the control rods act as sponges that soak up neutrons when necessary. Moving the control rods into the reactor absorbs more neutrons and slows down the rate of fission reactions. By partially removing the control rods, a more rapid chain reaction can be obtained. In this way the rate of heat energy generation can be maintained at a desired operating level. It is important to note that the design of the reactor and the concentration of ^{235}U in the core are such that a nuclear explosion cannot occur, even if the control rods are removed.
3. **Moderator**—The moderator is a material such as graphite or *deuterated water,* D_2O (D represents ^2_1H, or deuterium), which slows neutrons down and prevents them from escaping the reactor. "Slow" neutrons (those with low energies) are more effective in producing fission reactions with ^{235}U. As a result, the moderator leads to a more efficient use of the ^{235}U fuel and also prevents neutrons from creating a radiation hazard.
4. **Coolant and Heat Exchanger**—In order to transfer heat from the nuclear reactor to the steam-turbine system used to generate electrical energy, an appropriate fluid, or coolant, is used. The coolant can be a liquid or a gas. Depending on the type of reactor involved—*b*oiling-*w*ater *r*eactor (BWR), or *p*ressurized-*w*ater *r*eactor (PWR)—the heat-transfer system will be either a single-stage (BWR) or a two-stage (PWR) system (Figure 18). In a BWR the heat of the reactor changes liquid coolant to steam which drives the turbine. The two-stage, heat-transfer system of a PWR has two coolants. There is a primary coolant that comes into contact with the reactor and a secondary coolant that removes heat from the primary coolant. This transfer of heat takes place in a heat exchanger, a system of coils that provides thermal contact but no mixing of the two coolants. The secondary coolant is used to generate steam-electric power and to carry off the excess heat of the reactor to the environment. In both the BWR and PWR, coolant that comes into contact with the reactor must be contained in a closed system since it can carry considerable radioactivity. The coolant usually acts as a moderator also.

Besides removing heat from the reactor for power generation, the coolant system also serves a vital safety function. It prevents the temperature of the reactor from rising to a point where it would cause structural damage to the reactor components. A loss-of-coolant accident—such as the one that occurred at the Three Mile Island plant in Pennsylvania in 1979—could result in the release of radioactive fission products into the environment



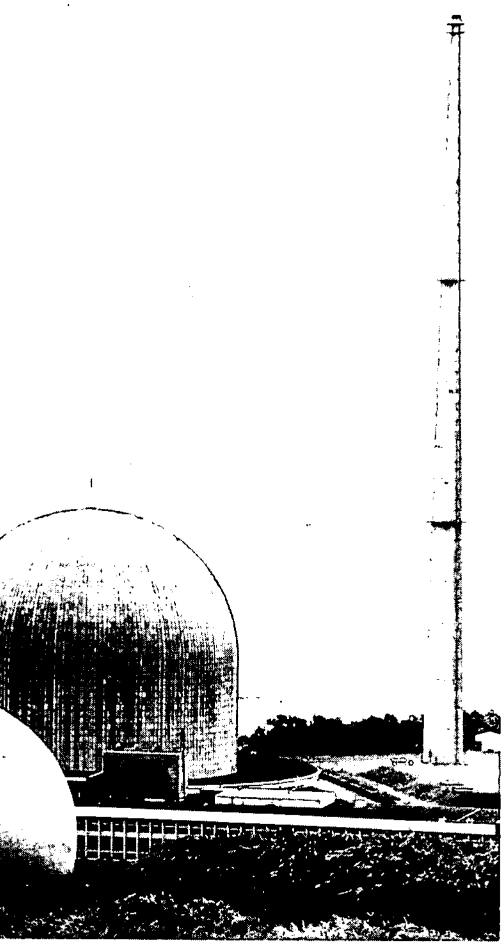
Assembled bundles of fuel rods.



Fuel-rod bundles are loaded into reactor.

and could cause severe damage to the reactor itself. The most serious form such an accident could take would be a "meltdown" of the reactor core. In such a case, the temperature in the reactor would become so high that fuel rods would actually melt, leading to destruction of the reactor and the release of high levels of radiation within the reactor and possibly into the environment.

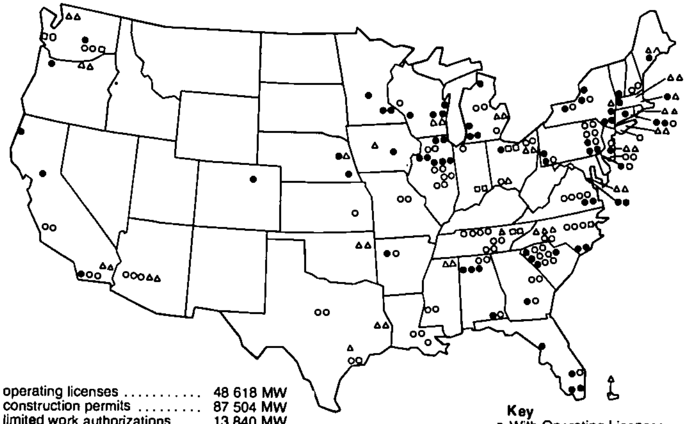
5. **Shielding**—Surrounding the reactor is a thick layer of shielding material designed to protect workers from the radiation produced by the reactor.
6. **Containment Shield**—The entire reactor is encased in a containment shield of highly reinforced concrete. This shield is designed to prevent the escape of radioactive material from the reactor in the event of either a reactor accident, such as a meltdown of the core, or a natural disaster, such as an earthquake.



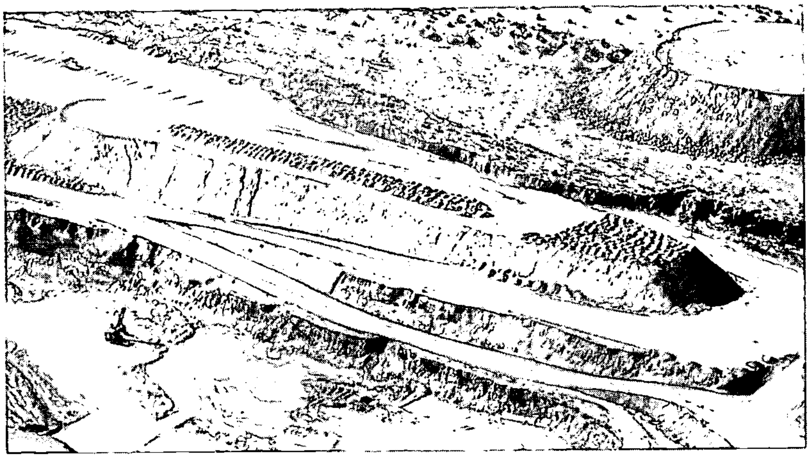
The dome in the middle of this nuclear research center is a containment shield.

The generation of electricity by nuclear power is very similar to that of burning fossil fuels—our conventional source of electricity. Thermal energy released in a nuclear reactor is used to drive a turbine connected to an electric generator. The supplies of nuclear fuel are abundant (relative to fossil fuels) and research in reactor technology continues to improve the safety and efficiency of these devices. One new type of reactor that is being studied very carefully is the *breeder reactor*. The aim of such a reactor is to generate power and form new fissionable materials at the same time. By inserting natural ^{238}U and ^{232}Th into the reactor, it is possible to make ^{239}Pu and ^{233}U, respectively, both of which are excellent nuclear fuels. If successfully developed, this would result in a much slower depletion of our nuclear fuel supplies and provide a better long-term energy source.

CENTRAL STATION NUCLEAR POWER PLANTS IN THE UNITED STATES—1978



68	Reactors with operating licenses	48 618 MW
81	Reactors with construction permits	87 504 MW
13	Reactors with limited work authorizations	13 840 MW
50	Reactors on order (including 8 units not sited on map)	57 217 MW
1	Letters of intent/options	1 150 MW
213	Total	208 329 MW



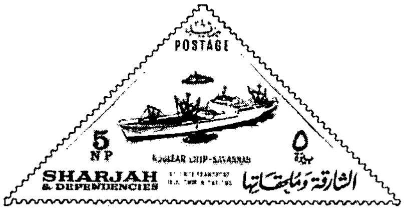
N-46 Nuclear Power and the Environment

Just as with other types of electric power plants, the generation of electric power by means of nuclear reactors can have a significant effect on our environment (see *The Delicate Balance: An Energy and the Environment Chemistry Module*). During the next few decades our society must make critical decisions concerning what trade-offs we wish to make in order to satisfy our desire for cheap, abundant energy and a healthy, unspoiled environment. Some compromises are inevitable.

Nuclear reactor technology has continued to search for improvements in the safety and efficiency of these highly complex devices. The safety record of the nuclear power industry—even when the most serious recorded accidents are considered—is superior to any other major form of electric power generation. Before a reactor is permitted to operate, its design and operating procedures must be approved by several state and federal regulatory agencies. However, in view of the current public concern about the environmental effects of nuclear power, ever-increasing attention is being given to nuclear reactor safety. A single major accident in a nuclear plant has the potential to be much more hazardous than a major accident would be in a fossil-fuel power plant.

Among the major advantages of nuclear power generation are that adequate uranium reserves exist to last well into the twenty-first century and that large deposits of uranium ores are located in the United States. The cost of nuclear power is competitive with the cost of fuel from coal- and oil-fired plants, and the electricity-generating capacity per plant is comparable. Nuclear reactors produce only a negligible amount of air pollution—which is a serious problem for the burning of coal and oil. All three sources of energy—nuclear, coal, and oil—create *thermal pollution* (excess heat), with nuclear power being a slightly greater problem in this regard.

Strip-mining is used to unearth uranium ore at this mine in New Mexico *(top left)*. The mechanical shovel *(above)* helps to speed up the mining process by moving about four and a half cubic meters of earth per load.

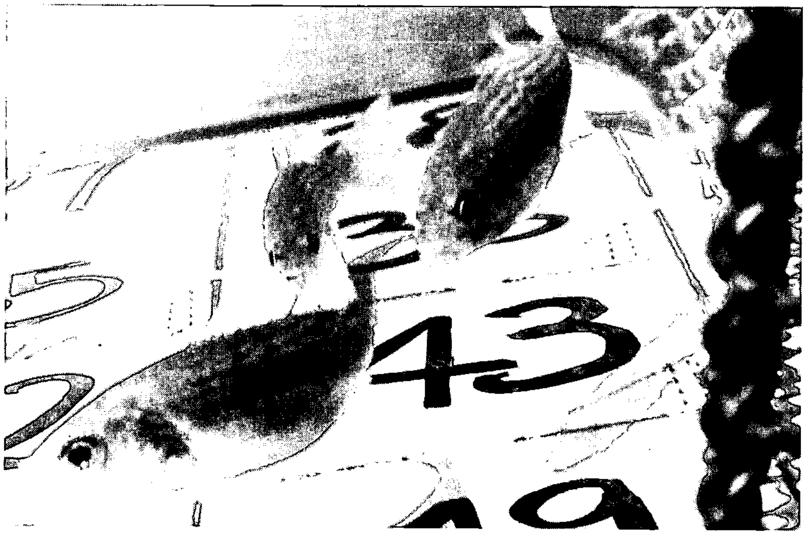


TIME MACHINE

1952	Selman Waksman receives the Nobel prize for his discovery of streptomycin.
1954	**Submarine U.S. *Nautilus* is converted to nuclear power.**
1957	**First commercial nuclear power plant begins operation in Shippingport, Pennsylvania.**
1959	***Savannah*, first U.S. nuclear-powered merchant ship, is launched.**
1960	The bathyscaphe *Trieste* descends to a depth of 10 900 meters (35 800 feet) in the Pacific near Guam.
1961	*Catch-22*, by Joseph Heller, is published.

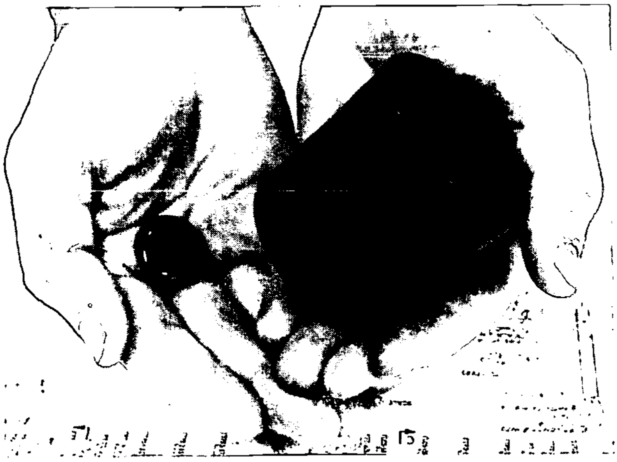
The most serious environmental hazard posed by nuclear power is the possibility of exposure of individuals and the environment to nuclear radiation. The contamination of operating personnel or the release of radioactivity into the atmosphere through a leak in the containment shield must be guarded against. Of greater concern is the possibility of a loss-of-coolant accident or a severe earthquake, which could lead to serious contamination of the environment if safety features fail. Nuclear engineers are studying these problems extensively.

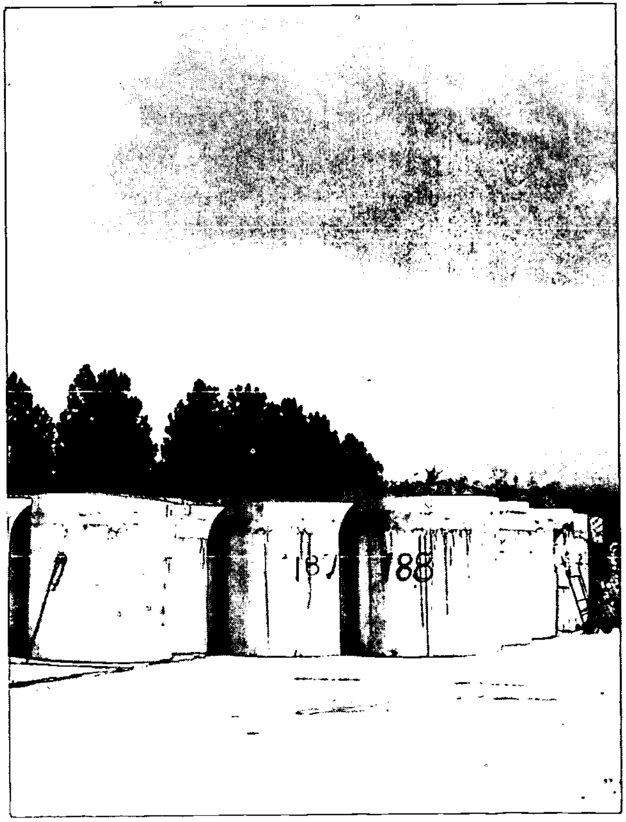
Another area of concern about the safety of nuclear power is that of fuel reprocessing and the storage of nuclear wastes. After a nuclear reactor has been in operation for several months, the ^{235}U fuel begins to be contaminated with fission products. These consist of over a hundred isotopes of about thirty different elements, many of which are radioactive and have half-lives of days to hundreds of years. Eventually the "spent" fuel rods must be removed from the reactor and stored to allow them to cool down, since the radioactive decay of the fission products gives off considerable heat. The fuel rods are shipped to a central storage facility or reprocessing plant, which involves the normal hazards of transportation. At a reprocessing facility the unused ^{235}U is separated from the fission products and made into new fuel pellets. Then the fuel pellets are packed into new fuel rods for shipment back to the reactor. A major problem is encountered with the fission product wastes. Although some of the fission products are useful in industry and research (section *N-44*), for the most part they represent a concentrated residue of highly radioactive nuclei that will not cool down for many decades. This waste disposal problem is one that has received great attention and must be solved before greatly expanded development of nuclear power can become a reality.



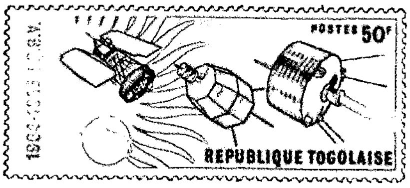
An ecological study tests the ability of fish to stay at a safe distance from a power plant's cooling-water intake screens. The study is part of an effort to prevent this intake of water at power plants from disturbing aquatic life.

Spent fuel-rod bundles must "cool down" *(above left)* before being sent for reprocessing. Vegetation surrounding a reprocessing plant is checked for the presence of radiation *(above right)*. Glass may be used to contain high-level radioactive waste in solid form *(below left)*. Such wastes may also be placed in drums and then sealed inside concrete cylinders *(below right)* for burial underground.





N-47 Miniature Power Sources



This stamp illustrates the use of miniature nuclear-power sources in satellites.

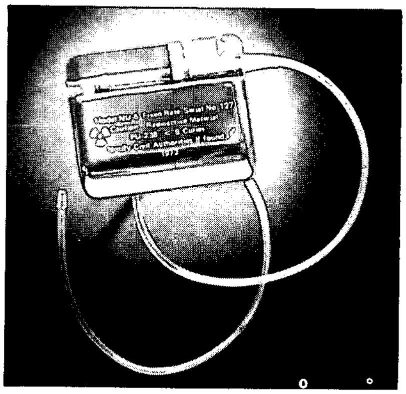
TIME MACHINE

1967	Peggy Fleming becomes world figure-skating champion.
1969	Neil A. Armstrong is first person to set foot on the moon.
1970	**In France and Britain, nuclear-powered heart pacemakers are successfully implanted into three patients to correct a condition called "heart block."**
1971	Choh Hao Li synthesizes hormone that controls human growth.
1974	Henry Aaron hits 715th home run, breaking Babe Ruth's record.

In addition to the use of nuclear reactors for large-scale production of electric power, miniature power sources based on the energy from radioactive nuclei are also used quite extensively. These *radioisotope power generators* operate on the energy liberated by the radioactive decay of a suitable long-lived radionuclide. Some of the common power sources are plutonium, ^{238}Pu ($t_{1/2}$ = 90 years, alpha decay); cerium, ^{144}Ce ($t_{1/2}$ = 290 days, beta decay); curium, ^{242}Cm ($t_{1/2}$ = 162 days, alpha decay); polonium, ^{210}Po ($t_{1/2}$ = 138 days, alpha decay); and strontium, ^{90}Sr ($t_{1/2}$ = 28 years, beta decay). In general, alpha decay is preferred as a radioactive decay process in power sources. Alpha particles can be stopped in a very small amount of material and thus liberate their energy as heat most efficiently. The heat that is produced in radioactive decay can be directly converted to electricity by a *thermoelectric converter*. Generators the size of a grapefruit and having a mass of only a few kilograms have been developed. Some of these have continuously produced 10 to 100 watts of power for as long as five years.

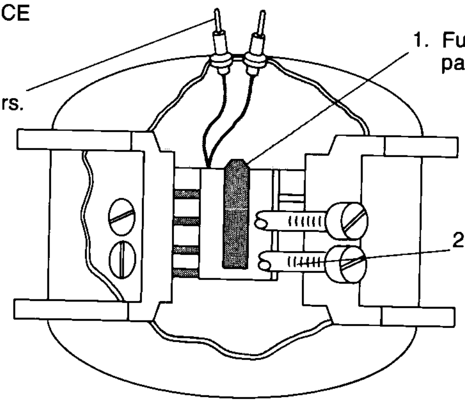
These small, lightweight, and long-lasting devices have proved especially valuable in space exploration, where considerations of size and weight are of prime concern. Many of the lunar surface experimental instrument packages left by astronauts rely in part upon radioactive power generators. These generators have provided power for instruments that record and relay information back to Earth for analysis. Nuclear power sources also sustain the operation of many of our weather satellites and of spacecraft in far-reaching space probes.

On Earth, compact nuclear power sources have many applications, particularly for the operation of equipment in remote places. For example, the instruments in arctic weather stations that supply important information for weather patterns are powered by such sources. Navigational buoys, weather buoys, and lighthouses also are being powered in this way.



Plutonium is the fuel that operates this surgically implanted pacemaker.

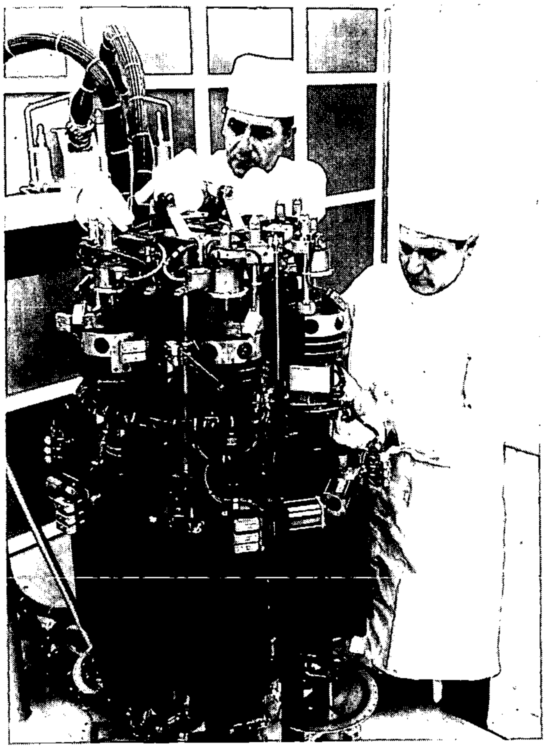
MINIATURE NUCLEAR POWER SOURCE

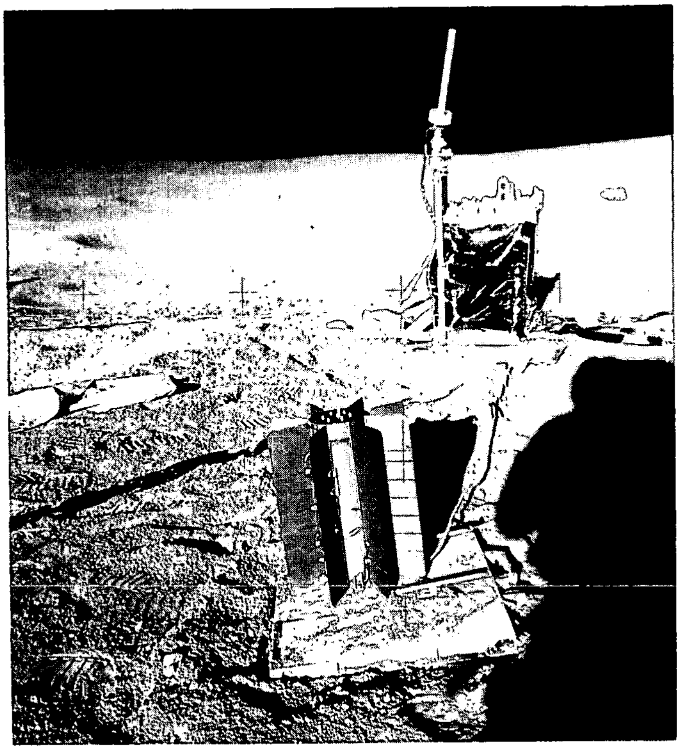


1. Fuel decays spontaneously, emitting particles that produce heat upon absorption.

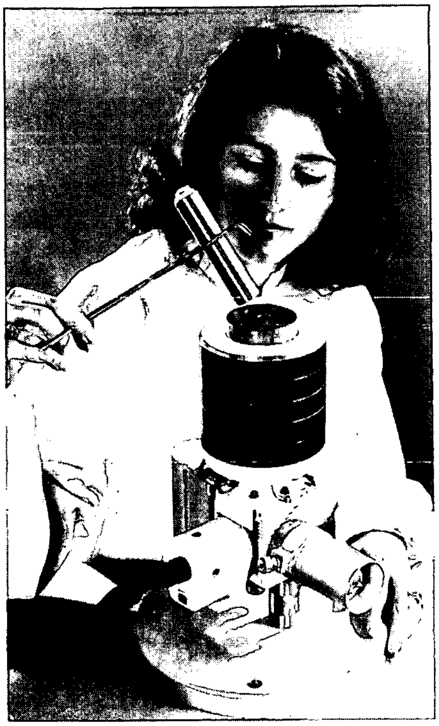
2. Thermoelectric converters convert heat directly into electricity.

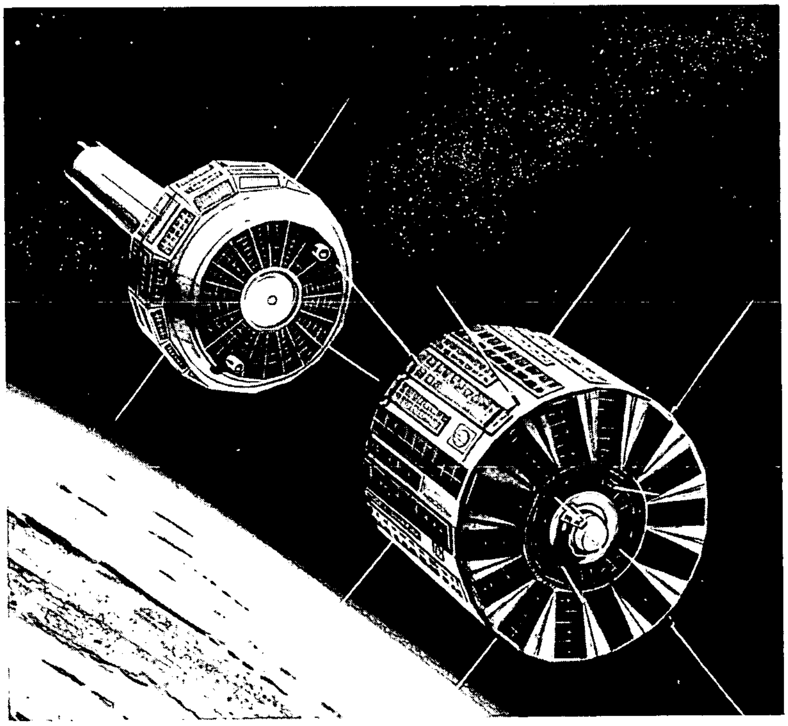
3. Electricity is tapped from terminals connected to thermoelectric converters.





This compact nuclear reactor *(top left)* could be used to power an orbiting space station. A radioisotope thermoelectric generator *(top right,* in the foreground) provided electric power for this experimental equipment used on the moon. A miniature refrigeration unit *(below left)* operates on plutonium fuel cells. Satellites in orbit around the Earth *(below right)* are expected to operate for years on nuclear power. Nuclear-power generators have the advantages of less weight and less complexity over some other power sources.





N-48 Nuclear Fusion: Reach for the Sun

The controlled nuclear fusion process is the subject of intensive research today. By using the same types of reactions that occur in the Sun and in *thermonuclear explosives*, it is hoped that power can be provided on a long-term basis. Examples of nuclear reactions being studied for use in a fusion reactor are

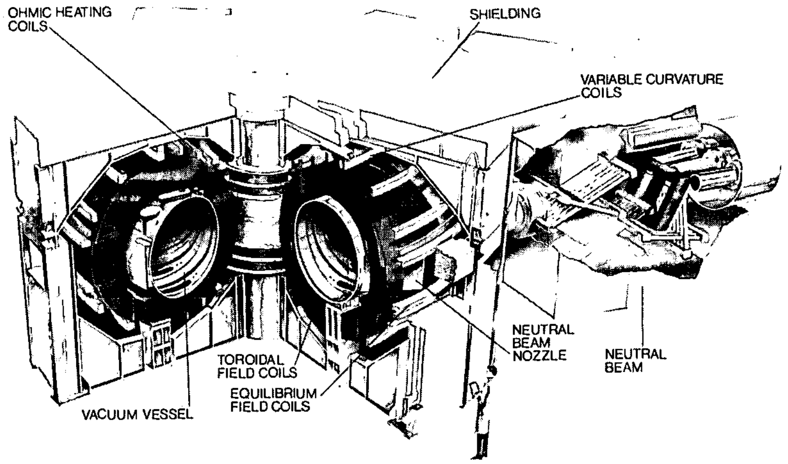
$$
\begin{aligned}
{}^{2}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} &\longrightarrow {}^{3}_{2}\mathrm{He} + {}^{1}_{0}n + \text{energy}\\
{}^{2}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} &\longrightarrow {}^{3}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} + \text{energy}\\
{}^{2}_{1}\mathrm{H} + {}^{3}_{1}\mathrm{H} &\longrightarrow {}^{4}_{2}\mathrm{He} + {}^{1}_{0}n + \text{energy}\\
{}^{2}_{1}\mathrm{H} + {}^{6}_{3}\mathrm{Li} &\longrightarrow 2\,{}^{4}_{2}\mathrm{He} + \text{energy}
\end{aligned}
$$

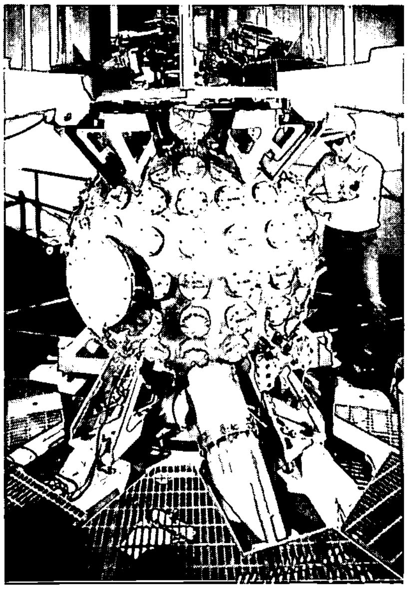
The primary advantages of the nuclear fusion reactor with respect to the nuclear fission reactor are twofold. First, the basic fuel source, deuterium, ${}^{2}_{1}\mathrm{H}$, is abundant and inexpensive to obtain. The ratio of ^{2}H atoms to the most common hydrogen isotope, ^{1}H, in natural seawater is about 1:6500. This means that 1.00 liter of seawater contains about 0.035 g of ^{2}H. Nuclear burning of this amount of ^{2}H is equivalent to burning about 300 liters of gasoline (about 80 gallons). If present energy requirements are maintained in the world, there would be enough energy for about one billion years. The second important consideration concerning nuclear fusion is that the level of production of radioactive wastes is expected to be substantially lower than in nuclear fission reactions.

Many technological problems remain to be solved, however, before fusion power becomes practical. It will probably be at least twenty to thirty years before useful power can be obtained from nuclear fusion reactors. The principal obstacle to the development of fusion energy is that the nuclear reactions require very high temperatures in order to take place. Only at such high temperatures are the nuclei moving fast enough to overcome the electromagnetic repulsion between them. In the core of the Sun, a temperature of about 15×10^{6} K exists. On Earth, all known materials would melt or burn at that temperature.

Scientists have developed several possible ways to contain fusion reactions (Figure 19). One of these is the *magnetic bottle*, in which the high-temperature nuclear fuel is confined within a special doughnut-shaped chamber by specially designed magnetic fields. A second method involves the initiation of the reactions by high-powered *lasers*. A third technique would use heavy-ion accelerators such as those used in the search for superheavy elements (section *N-33*) as a means of producing high temperatures (and therefore high speeds) that would enable nuclei to fuse.

When the technical problems of at least one of these approaches are solved, scientists will be one step closer to developing a long-term source of energy that seems to have minimal impact on the





environment. But other questions arise about nuclear fusion's role as a producer of controllable energy. One problem scientists face is that of efficiently channeling the energy released at the extremely high temperatures of nuclear fusion into other usable forms of energy. Another consideration is that some of the methods of producing fusion require large amounts of input energy. Once controlled fusion has been achieved, the next great challenge will be to sustain it for a long period of time.

In "magnetic-bottle" fusion, the fusion reactants are confined inside the vacuum vessel *(above left)*. In the Shiva laser-fusion test reactor, laser beams focus on a hydrogen-filled fuel target in the center of the target chamber *(above right)*.

PROBLEMS

1. Discuss the relationship of energy needs and our technological civilization.
2. Discuss the following questions.
   a. Should the world's energy needs be allowed to continue to grow at the present rate, or should energy demands be made to remain constant?
   b. What reasons can be given for reducing the amount of energy consumed in our technological world?
3. In addition to miniature nuclear power sources, what other power-generating systems would you include on a spacecraft to supply additional power? on an arctic weather station? on an ocean-navigating buoy?
4. Examine the nuclear fusion reactions and the discussion of fusion. What do you see as the pros and cons of this source of energy?
5. Of the products extracted from spent nuclear fuel, three isotopes are of special importance. They are

   ^{131}I $(t_{1/2} = 8$ days)
   ^{90}Sr $(t_{1/2} = 28$ years)
   ^{239}Pu $(t_{1/2} = 24\,400$ years)

   a. If each radionuclide initially has the same number of nuclei, which will be the most radioactive? Recall the following equation from section *N-25.*

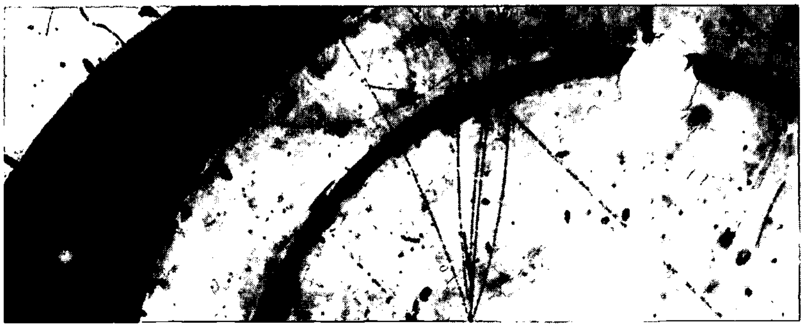
$$R = \frac{\text{(number of nuclei that decay)}}{\text{(unit time)}} = 0.693\ N/t_{1/2}$$

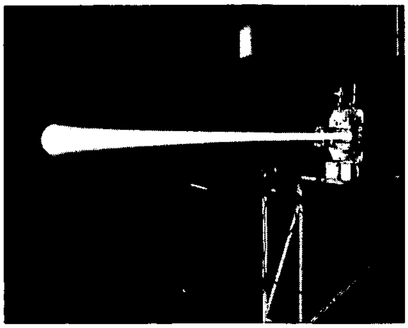
   b. What fraction of the initial radioactive nuclei will still be present after ten half-lives?
   c. The radioactivity of each radionuclide is considered to have reached a "safe level" after the passage of 20 half-lives. What fraction of the original radioactivity will still be present then?
   d. How much time is required for the radioactivity of each of the radionuclides to reach a "safe level"?
6. Write the equation for the alpha decay of ^{238}Pu used in a miniature power source.

Summary

In *The Heart of Matter* we have encountered a broad spectrum of nuclear phenomena that have played vital roles in the history of our Universe. These have ranged from the formation of the simplest nuclei in the big bang to energy production in stars to the fascinating results of modern-day nuclear research and technology. All these subjects continue to be of major scientific interest, and new developments are improving our understanding of them.

An electrical engineer adjusts the mechanism of a pulsed-neutron logging "sonde." This instrument is lowered into a drill hole at an oil exploration site. Using a self-contained source of neutrons and a detecting device, the instrument can measure differences in the reflection of neutrons by oil and fresh water.

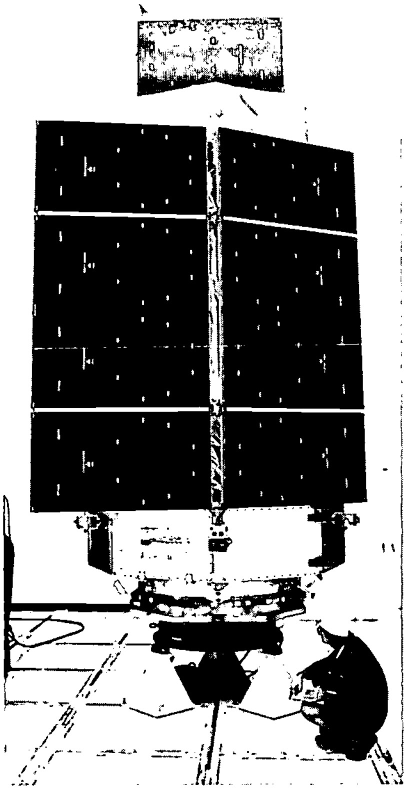


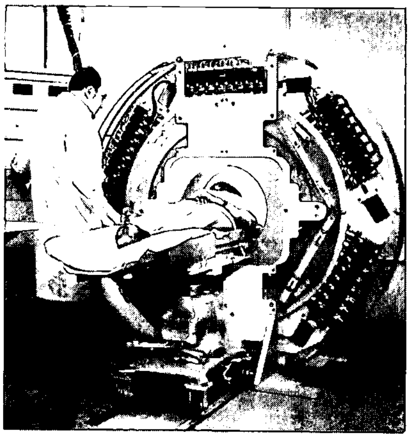


The question of how nuclei are formed is indeed a very basic one and depends on the nature of the fundamental particles and basic forces. The composition and stability of nuclei are pictorialized by the peninsula of stability, which determines the nuclei that exist in nature and the probability of observing them in the laboratory. Nuclear scientists continue to probe the features of the peninsula of stability in more and more detail in search of answers to many intriguing questions: How are the nucleons bound together in the nucleus? Are exotic particles such as pions, quarks, and gluons responsible for this binding? What are the limits of nuclear stability? Can the superheavy elements be synthesized? How does nuclear matter behave under extreme conditions of temperature and density or when it is rotating very rapidly? Studies designed to answer these questions require highly sophisticated equipment such as particle accelerators that can produce beams of any element with very high energies, superconducting magnets, highly sensitive nuclear-particle detectors, and complex electronics and computer systems. In years to come, these efforts promise to produce many exciting new insights into the behavior of nuclei.

After describing the conditions necessary for nuclear stability, we then turned to the question of the origin of nature's elements. The synthesis of nuclei depends on nuclear reactions, and these occur only in environments that have very high temperatures or energies. These requirements have led to the current theory of nucleosynthesis in the Universe, beginning with the big bang and terminating with supernovae as the final step in stellar evolution. Increasingly rigorous tests of our understanding of the origin of the Universe and its elements are being provided by new discoveries from observatories, nuclear science laboratories, and the space program. Space vehicles such as the cosmic- and gamma-ray observatory satellite HEAO-3 are now equipped with devices for measuring many types of nuclear radiation from outer space. These have the ability to detect the elements found in new exploding stars, as well as the composition of cosmic rays and other phenomena. Despite the many remarkable discoveries of the past two decades concerning the nature of our Universe, the future promises to bring even more exciting discoveries.

A photograph *(above left)* records one of the rare times that a neutrino interaction leaves its tracks in a bubble chamber. Particle beams, such as those of heavy hydrogen nuclei *(above right)*, will continue to be used in research and industrial applications. The HEAO satellite *(below)* will help scientists obtain data to study radiation sources in outer space.



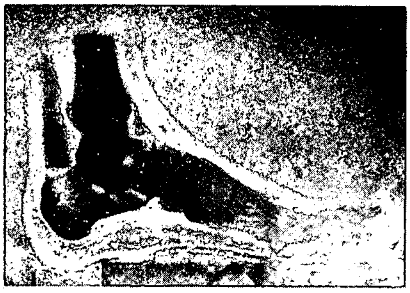


This scanning device *(above)* uses positrons to help diagnose abnormalities deep within the human body.

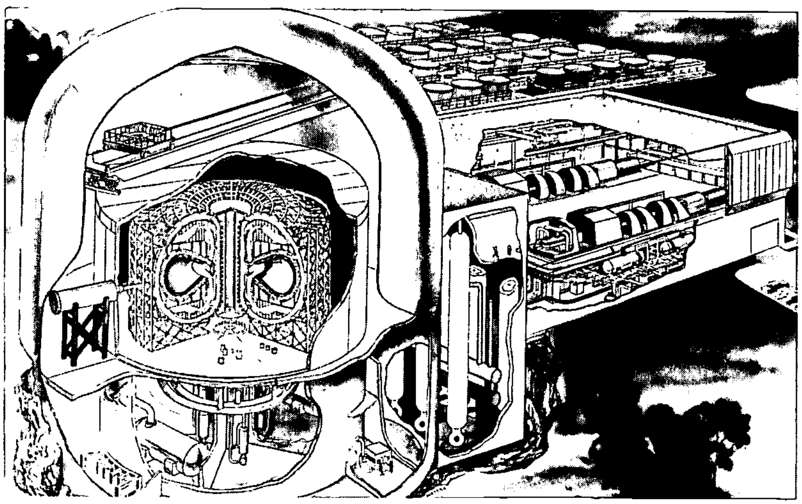
The radioactive decay processes are important both as natural processes and as valuable tools in our technological society. The various types of decay—such as alpha, beta, and gamma decay—all occur naturally as background radiation in our environment. The concepts of half-life and decay rates were discussed, especially the very interesting archaeological applications of the ^{14}C dating technique. Dating with ^{14}C has proved invaluable in tracing the history of our civilization. The many new and dramatic uses of nuclear techniques and the nuclear power industry represent applications of nuclear science that affect our daily lives. The field of nuclear medicine is a rapidly expanding one. Many hospitals now have their own cyclotrons for producing radioactive tracers, as well as sophisticated nuclear scanning devices used for cancer diagnosis and therapy. Radioactive nuclides are also utilized in manufacturing methods and in refined quality-control testing.

Two of the most visible aspects of nuclear technology are nuclear weapons and nuclear power. Much of our current national defense strategy is based on nuclear weaponry. Nuclear power is an essential component of the present energy-generating capacity in the United States. It has many advantages, but like coal and oil, it also has environmental drawbacks. The issue of expanding nuclear power has brought into sharp focus the realization that a balance must be struck between technology, the economy, and the environment. Perhaps nuclear fusion will provide a more satisfactory alternative to the use of nuclear fission for energy production.

It is evident that the power of the nucleus holds a great potential for making Earth a better place in which to live. However, it is our responsibility as a society and as individuals to exercise the intelligence and common sense necessary to exploit this potential. Remember, you are part of our society. The actions you take, both now and in the future, can make a difference.



Heavy-ion radiation can be used to produce more detailed pictures of internal structures than X rays can *(above)*, and at a lower dose of radiation. An artist's portrayal *(right)* shows a workable fusion-power technology that may be developed in the future to add to our energy resources.



Appendix I: Safety

SAFETY IN THE LABORATORY

Proper conduct in a chemistry laboratory is really an extension of safety procedures normally followed each day around your home and in the outside world. Exercising care in a laboratory demands the same caution you apply to driving a car, riding a motorbike or bicycle, or participating in a sport. Athletes consider safety measures a part of playing the game. For example, football players willingly spend a great deal of time putting on equipment such as helmets, hip pads, and shoulder pads to protect themselves from potential injury.

Chemists must also be properly dressed. To protect themselves in the laboratory, they commonly wear a lab apron or a coat and protective glasses. Throughout this course you will use similar items. Hopefully their use will become second nature to you, much as it becomes second nature for a baseball catcher to put on a chest protector and mask before stepping behind home plate.

As you read through a written experimental procedure, you will notice that specific hazards and precautions are called to your attention. Be prepared to discuss these hazards with your teacher and with your fellow students. Always read the entire experimental procedure thoroughly before starting any laboratory work.

A list of general laboratory safety procedures follows. It is not intended that you memorize these safety procedures but rather that you *use* them regularly when performing experiments. You may notice that this list is by no means complete. Your teacher may wish to add safety guidelines that are relevant to your specific classroom situation. It would be impossible to anticipate every hazardous situation that might arise in the chemistry laboratory. However, if you are familiar with these general laboratory safety procedures and if you use common sense, you will be able to handle potentially hazardous situations intelligently and safely. Treat all chemicals with respect, not fear.

GENERAL SAFETY GUIDELINES

1. Work in the laboratory only when the teacher is present or when you have been given permission to do so. In case of accident, notify your teacher immediately.
2. Before starting any laboratory exercise, be sure that the laboratory bench is clean.
3. Put on a laboratory coat or apron and protective glasses or goggles before beginning an experiment.
4. Tie back loose hair to prevent the possibility of its contacting any Bunsen burner flames.
5. Open sandals or bare feet are not permitted in the laboratory. The dangers of broken glass and corrosive liquid spills are always present in a laboratory.
6. Fire is a special hazard in the laboratory because many chemicals are flammable. Learn how to use the fire blanket, fire extinguisher, and shower (if your laboratory has one).
7. For minor skin burns, immediately immerse the burned area in cold water for several minutes. Then consult your teacher for further instructions on possible additional treatment.
8. In case of a chemical splash on your skin, immediately rinse the area with cold water for at least one minute. Consult your teacher for further action.
9. If any liquid material splashes into your eye, wash the eye immediately with water from an eyewash bottle or eyewash fountain.
10. Never look directly down into a test tube—view the contents of the tube from the side. (Why?)
11. Never smell a material by placing your nose directly at the mouth of the tube or flask. Instead, with your hand, "fan" some of the vapor from the container toward your nose. Inhale cautiously.
12. Never taste any material in the laboratory.
13. Never add water to concentrated acid solutions. The heat generated may cause spattering. Instead, as you stir, add the acid slowly to the water or dilute solution.
14. Read the label on a chemical bottle at least *twice* before removing a sample. H_2O_2 is not the same as H_2O.
15. Follow your teacher's instructions or laboratory procedure when disposing of used chemicals.

The following guidelines are of special concern in working with radioactive materials.

16. The radioactive materials that you will be working with in the laboratory consist of only very small quantities of radiation and do not require a special license to use. Nuclear materials are very strictly regulated by state and federal laws. Great care has been exercised to ensure that the materials you will be handling do not constitute any danger to you. Nonetheless, you should treat all samples you handle with the same care required for federally licensed materials. In this way, you will minimize the amount of radiation you are exposed to during the experiment.
17. When handling radioactive materials, always wear rubber or plastic gloves.
18. Do not bring food of any kind into the laboratory when you are working with radioactive materials. Foodstuffs can be easily contaminated during handling, which could result in internal ingestion of radioactive materials.
19. Be sure that no radioactive material comes in contact with your counter. In this way the radiation counter will not become contaminated with radiation, which could lead to high background readings and less accurate results.
20. Never discard liquids down the drain or throw away glassware into the trash receptacle. All used material should be collected in an appropriate storage vessel provided by your instructor and monitored before being discarded.
21. Always check your hands with a radiation monitor before leaving the laboratory.

☢ This symbol indicates the presence of radioactive material. It appears with certain experiments in this module to alert you to the need for special precautions.

Appendix II: Metric Units

PHYSICAL QUANTITY	SI BASE OR DERIVED UNIT		OTHER UNITS	
	NAME	SYMBOL AND DEFINITION	NAME	SYMBOL AND DEFINITION
length	meter*	m	kilometer	1 km = 10^3 m
			centimeter	1 cm = 10^{-2} m
			nanometer	1 nm = 10^{-9} m = 10^{-7} cm
area	square meter	m^2	square centimeter	1 cm^2 = 10^{-4} m^2
volume	cubic meter	m^3	cubic centimeter	1 cm^3 = 10^{-6} m^3
			liter	1 l = 10^3 cm^3
mass	kilogram*	kg	gram	1 g = 10^{-3} kg
time	second*	s		
amount of substance	mole*	mol		
concentration	moles per cubic meter	mol/m^3	moles per liter	1 mol/l = 10^3 mol/m^3
			molar concentration (molarity)	1 M = mol/l
Celsius temperature			degree Celsius	°C
thermodynamic temperature	kelvin*	K		
force	newton	N = kg · m/s^2		
pressure	pascal	Pa = N/m^2 = kg/(m · s^2)	centimeter of mercury	1 cm Hg = 1.333 × 10^3 Pa
			atmosphere	1 atm = 1.013 × 10^5 Pa 1 atm = 76.0 cm Hg
energy	joule	J = N · m = kg · m^2/s^2	calorie	1 cal = 4.184 J

*SI base unit, exactly defined in terms of certain physical measurements.

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In addition, discussion of new developments in chemistry relevant to the topics covered in this module will be found in the following periodicals: *Environment, Environmental Science and Technology, Journal of Chemical Education, Science,* and *SciQuest* (formerly *Chemistry*).

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TABLE OF INTERNATIONAL RELATIVE ATOMIC MASSES*

Element	Symbol	Atomic Number	Atomic Mass
Actinium	Ac	89	227.0
Aluminum	Al	13	27.0
Americium	Am	95	(243)**
Antimony	Sb	51	121.8
Argon	Ar	18	39.9
Arsenic	As	33	74.9
Astatine	At	85	(210)
Barium	Ba	56	137.3
Berkelium	Bk	97	(247)
Beryllium	Be	4	9.01
Bismuth	Bi	83	209.0
Boron	B	5	10.8
Bromine	Br	35	79.9
Cadmium	Cd	48	112.4
Calcium	Ca	20	40.1
Californium	Cf	98	(251)
Carbon	C	6	12.0
Cerium	Ce	58	140.1
Cesium	Cs	55	132.9
Chlorine	Cl	17	35.5
Chromium	Cr	24	52.0
Cobalt	Co	27	58.9
Copper	Cu	29	63.5
Curium	Cm	96	(247)
Dysprosium	Dy	66	162.5
Einsteinium	Es	99	(254)
Erbium	Er	68	167.3
Europium	Eu	63	152.0
Fermium	Fm	100	(257)
Fluorine	F	9	19.0
Francium	Fr	87	(223)
Gadolinium	Gd	64	157.3
Gallium	Ga	31	69.7
Germanium	Ge	32	72.6
Gold	Au	79	197.0
Hafnium	Hf	72	178.5
Helium	He	2	4.00
Holmium	Ho	67	164.9
Hydrogen	H	1	1.008
Indium	In	49	114.8
Iodine	I	53	126.9
Iridium	Ir	77	192.2
Iron	Fe	26	55.8
Krypton	Kr	36	83.8
Lanthanum	La	57	138.9
Lawrencium	Lr	103	(260)
Lead	Pb	82	207.2
Lithium	Li	3	6.94
Lutetium	Lu	71	175.0
Magnesium	Mg	12	24.3
Manganese	Mn	25	54.9
Mendelevium	Md	101	(258)
Mercury	Hg	80	200.6
Molybdenum	Mo	42	95.9
Neodymium	Nd	60	144.2
Neon	Ne	10	20.2
Neptunium	Np	93	237.0
Nickel	Ni	28	58.7
Niobium	Nb	41	92.9
Nitrogen	N	7	14.0
Nobelium	No	102	(259)
Osmium	Os	76	190.2
Oxygen	O	8	16.0
Palladium	Pd	46	106.4
Phosphorus	P	15	31.0
Platinum	Pt	78	195.1
Plutonium	Pu	94	(244)
Polonium	Po	84	(209)
Potassium	K	19	39.1
Praseodymium	Pr	59	140.9
Promethium	Pm	61	(145)
Protactinium	Pa	91	231.0
Radium	Ra	88	226.0
Radon	Rn	86	(222)
Rhenium	Re	75	186.2
Rhodium	Rh	45	102.9
Rubidium	Rb	37	85.5
Ruthenium	Ru	44	101.1
Samarium	Sm	62	150.4
Scandium	Sc	21	45.0
Selenium	Se	34	79.0
Silicon	Si	14	28.1
Silver	Ag	47	107.9
Sodium	Na	11	23.0
Strontium	Sr	38	87.6
Sulfur	S	16	32.1
Tantalum	Ta	73	180.9
Technetium	Tc	43	(97)
Tellurium	Te	52	127.6
Terbium	Tb	65	158.9
Thallium	Tl	81	204.4
Thorium	Th	90	232.0
Thulium	Tm	69	168.9
Tin	Sn	50	118.7
Titanium	Ti	22	47.9
Tungsten	W	74	183.8
Uranium	U	92	238.0
Vanadium	V	23	50.9
Xenon	Xe	54	131.3
Ytterbium	Yb	70	173.0
Yttrium	Y	39	88.9
Zinc	Zn	30	65.4
Zirconium	Zr	40	91.2

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*Based on International Union of Pure and Applied Chemistry (IUPAC) values (1975).

**Numbers in parentheses give the mass numbers of the most stable isotopes.

PERIODIC TABLE OF THE ELEMENTS

1.008
H
Hydrogen
1

200.6 — atomic mass
Hg — symbol
Mercury — name
80 — atomicnumber

IA	IIA	IIIB	IVB	VB	VIB	VIIB	← VIIIB →			IB	IIB	IIIA	IVA	VA	VIA	VIIA	VIIIA
																	4.00 **He** Helium 2
6.94 **Li** Lithium 3	9.01 **Be** Beryllium 4											10.8 **B** Boron 5	12.0 **C** Carbon 6	14.0 **N** Nitrogen 7	16.0 **O** Oxygen 8	19.0 **F** Fluorine 9	20.2 **Ne** Neon 10
23.0 **Na** Sodium 11	24.3 **Mg** Magnesium 12											27.0 **Al** Aluminum 13	28.1 **Si** Silicon 14	31.0 **P** Phosphorus 15	32.1 **S** Sulfur 16	35.5 **Cl** Chlorine 17	39.9 **Ar** Argon 18
39.1 **K** Potassium 19	40.1 **Ca** Calcium 20	45.0 **Sc** Scandium 21	47.9 **Ti** Titanium 22	50.9 **V** Vanadium 23	52.0 **Cr** Chromium 24	54.9 **Mn** Manganese 25	55.8 **Fe** Iron 26	58.9 **Co** Cobalt 27	58.7 **Ni** Nickel 28	63.5 **Cu** Copper 29	65.4 **Zn** Zinc 30	69.7 **Ga** Gallium 31	72.6 **Ge** Germanium 32	74.9 **As** Arsenic 33	79.0 **Se** Selenium 34	79.9 **Br** Bromine 35	83.8 **Kr** Krypton 36
85.5 **Rb** Rubidium 37	87.6 **Sr** Strontium 38	88.9 **Y** Yttrium 39	91.2 **Zr** Zirconium 40	92.9 **Nb** Niobium 41	95.9 **Mo** Molybd'm 42	(97) **Tc** Technetium 43	101.1 **Ru** Ruthenium 44	102.9 **Rh** Rhodium 45	106.4 **Pd** Palladium 46	107.9 **Ag** Silver 47	112.4 **Cd** Cadmium 48	114.8 **In** Indium 49	118.7 **Sn** Tin 50	121.8 **Sb** Antimony 51	127.6 **Te** Tellurium 52	126.9 **I** Iodine 53	131.3 **Xe** Xenon 54
132.9 **Cs** Cesium 55	137.3 **Ba** Barium 56	138.9 **La*** Lanthanum 57	178.5 **Hf** Hafnium 72	180.9 **Ta** Tantalum 73	183.8 **W** Tungsten 74	186.2 **Re** Rhenium 75	190.2 **Os** Osmium 76	192.2 **Ir** Iridium 77	195.1 **Pt** Platinum 78	197.0 **Au** Gold 79	200.6 **Hg** Mercury 80	204.4 **Tl** Thallium 81	207.2 **Pb** Lead 82	209.0 **Bi** Bismuth 83	(209) **Po** Polonium 84	(210) **At** Astatine 85	(222) **Rn** Radon 86
(223) **Fr**† Francium 87	226.0 **Ra** Radium 88	(227) **Ac**** Actinium 89	‡ 104	‡ 105	‡ 106												

*	140.1 **Ce** Cerium 58	140.9 **Pr** Praseody'm 59	144.2 **Nd** Neodymium 60	(145) **Pm** Promethium 61	150.4 **Sm** Samarium 62	152.0 **Eu** Europium 63	157.3 **Gd** Gadolinium 64	158.9 **Tb** Terbium 65	162.5 **Dy** Dysprosium 66	164.9 **Ho** Holmium 67	167.3 **Er** Erbium 68	168.9 **Tm** Thulium 69	173.0 **Yb** Ytterbium 70	175.0 **Lu** Lutetium 71
**	232.0 **Th** Thorium 90	231.0 **Pa** Protactinium 91	238.0 **U** Uranium 92	237.0 **Np** Neptunium 93	(242) **Pu** Plutonium 94	(243) **Am** Americium 95	(245) **Cm** Curium 96	(245) **Bk** Berkelium 97	(251) **Cf** Californium 98	(254) **Es** Einsteinium 99	(254) **Fm** Fermium 100	(256) **Md** Mendel'm 101	(254) **No** Nobelium 102	(257) **Lr** Lawrencium 103

†The most stable known isotopes are shown in parentheses.

‡The discovery of elements 104, 105, and 106 has been claimed by both American and Soviet scientists. The Americans have suggested the name *rutherfordium* and *hahnium* for 104 and 105; the Soviets have suggested the names *kurchatovium* and *nielsbohrium* for these same elements. No name has yet been proposed for element 106.

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