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ABSTRACT

This teacher's guide is designed to provide science teachers with the necessary guidance and suggestions for teaching nuclear chemistry. In this book, the fundamental concepts of nuclear science and the applications of nuclear energy are discussed. The material in this book can be integrated with the other modules in a sequence that helps students see that chemistry is a unified science. 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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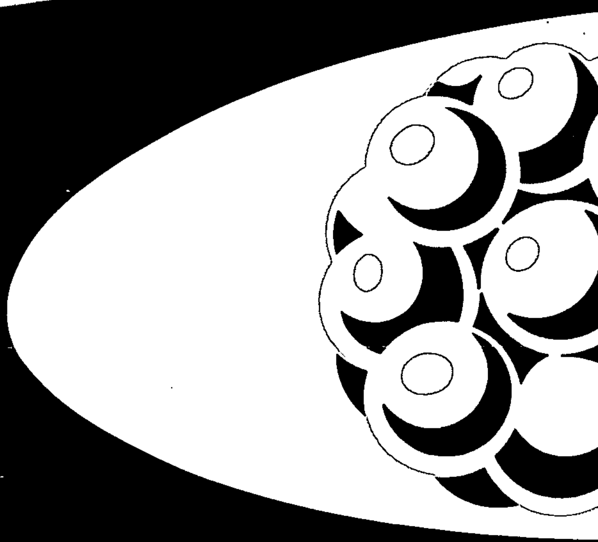
TEACHER'S GUIDE

THE HEART OF MATTER

A NUCLEAR CHEMISTRY MODULE



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TEACHER'S GUIDE

THE HEART OF MATTER

A NUCLEAR CHEMISTRY MODULE

Vic Viola
Robert Hearle

1817

Harper & Row, Publishers
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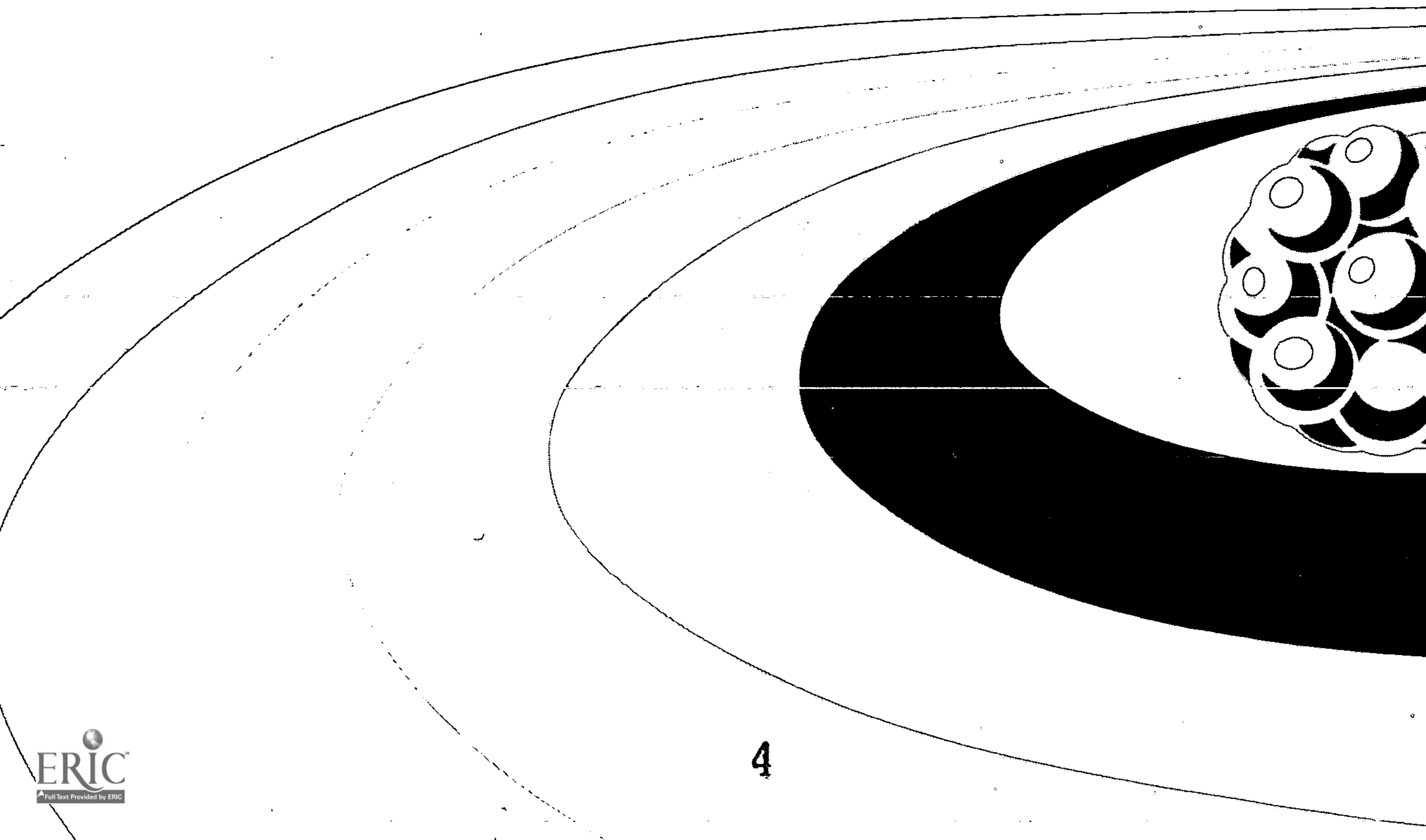

AUTHORS

TEACHER'S GUIDE

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.

ROBERT HEARLE

Robert Hearle came to the University of Maryland in 1970 after working as a research chemist. While at Maryland he taught in the Chemistry and Education Departments, assisted in supervising student teachers in science, and was part of the IAC development team. Bob is now teaching in the Prince George's County, Maryland, school system. His special fields of interest include analytical and organic chemistry and computer-assisted instruction, including the development of a computer-managed independent study program.

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Contents

Introducing The Heart of Matter

In developing this nuclear module, we have tried to fulfill two basic objectives. The first is to present the fundamental concepts of nuclear science—nomenclature, radioactive decay, nuclear reactions—and the applications of nuclear energy. The second objective is to familiarize students with current theories of stellar evolution and nucleosynthesis. By fulfilling these two objectives we are able to treat nucleosynthesis as a story line for the presentation of nuclear phenomena. This approach lends greater continuity to the teaching of nuclear science and does not significantly increase the complexity of the quantitative material introduced to the student. For the many high-school students who do not have access to the apparatus required for a nuclear chemistry program, this approach provides a coherent program that can be implemented without any laboratory work.

Our experience with teaching the subject matter has demonstrated that the average high-school student can successfully master the material at the level presented here. It is expected that *The Heart of Matter* will be taught toward the end of the IAC year and program, perhaps being utilized in advanced high-school courses. With advanced students it may be necessary to provide a more quantitative base: for example, complete presentation of the laws of radioactive decay. Although it is possible to direct interested students toward theory-oriented material, the preference is to direct them toward general topics.

You will note that radioactive decay is discussed rather late in the module. Because of the need to deal with this subject in earlier sections, preliminary discussions are given in sections *N-3 Fundamental Particles: Building Blocks, N-4 Heads/Tails and Half-life*, and *N-12 Transmutation of Elements*. To provide students with an adequate background for the intervening discussions, you should emphasize the subject of half-lives in these sections.

Because stellar nucleosynthesis serves as the basic story line, you need not feel handicapped if your high-school laboratory lacks the equipment required for a nuclear chemistry program. *The Heart of Matter: A Nuclear Chemistry Module* outlines a basic program in nuclear chemistry that can be taught independently of laboratory work, although the laboratory program increases the effectiveness of the module. All that is needed to carry out many of the experiments is a MINIGENERATOR™* and a detector (see *Teaching The Heart of Matter*). The basic laboratory sequence outlined in the student module can be replaced or supplemented by other activities if the basic MINIGENERATOR package is not available to you. Supplementary student readings, films, and class tours of nuclear-particle accelerators or nuclear power reactors are among the options you may wish to include in your classroom program.

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

Special Features in the Student Module

Metric System Le Système International (SI) is used throughout the IAC program. As you work with this module, you may wish to review some points of the metric system as presented in *Reactions and Reason: An Introductory Chemistry Module* (see section *A-8* and Appendix II). There is a metric-units chart in the appendix of *The Heart of Matter* student module that students can easily refer to.

Time Machine A feature we call the *Time Machine* appears in the IAC modules in order to show chemistry in a broader context. For some students this may provide a handle on particular aspects of chemistry by establishing the social-cultural-political framework in which significant progress has been made in chemistry. Students may enjoy suggesting other events in chemistry around which to create *Time Machines* of their own.

Cartoons A popular feature of the IAC program is the use of chemistry cartoons. These cartoons give students a chance to remember specific points of chemistry in another important way—through humor. Suggest that your students create other chemistry cartoons for their classmates to enjoy.

Safety Laboratory safety is a special concern in any chemistry course. In addition to including safety discussions and guidelines in the appendix of each student module and teacher's guide, experiments have been developed in a way designed to eliminate potentially dangerous chemicals and procedures. Moreover, each experiment that might present a hazard—such as fumes, corrosive chemicals, or the use of a flame—has been marked with a safety symbol to alert students and teachers to use added, reasonable caution. Caution statements, in bold type, also appear in experiments to specifically instruct the student on the care required.

Selected Readings Articles and books that tie in with the topics discussed in the IAC program have been listed in the appendix of the student module as well as in the teacher's guide. Encourage your students to use this section. In addition, students should be made aware of the importance of keeping up-to-date with current literature in the ever-changing field of nuclear chemistry. You may wish to suggest other material that you have found interesting and enjoyable.

Illustrations and Photographs The module is extensively illustrated to provide relevant and stimulating visual material to enable students to relate chemistry to everyday life, as well as to provide material for provocative discussion. In using some of these illustrations, it is not the intention of IAC to endorse any particular product or brand, but only to relate chemistry to life outside the classroom. As you proceed through each section, encourage students to collect, display, and discuss photos and illustrations that provoke further discussion.

Problems A number of problems have been interspersed throughout the student module, in addition to the questions that are naturally built into the narratives and the laboratory experiments. You will find some of these problems in specifically marked sections in the student module. These problems can be used in a variety of ways as you see fit. They are not planned as tests; remember, the IAC program is designed so that mastery of the content and skills can be achieved through the repeated reinforcement of ideas and procedures encountered by students as they progress through the various modules. (Also see *Evaluating Student Performance* for additional information on evaluation and evaluation items for this module.)

Managing the Laboratory

In the teacher's guide, hints and suggestions are given for managing each experiment in the laboratory. Share as many of these hints as possible with your students to allow them to participate fully in successful laboratory management. Make sure that you rotate assignments so that each student has a chance to experience this type of participation.

Preparations and Supplies Student aides can be helpful in preparing solutions, labeling and filling bottles, cleaning glassware, and testing experiments. Each experiment has been classroom tested, but you should try each experiment to determine any revisions necessary to meet the needs of your situation or that of your students.

Cleaning Up Involve your students in putting away equipment, washing glassware, and storing material for the next time it is to be used. Taking care of equipment is part of the responsibilities we seek to foster.

Laboratory Reports and Data Processing Recording data and preparing reports on laboratory experimentation are important skills in all science courses and, of course, are part of the IAC program. Although you may have your own methods of student reporting, some of the suggestions that IAC teachers have found successful have been included for your consideration.

It is helpful for students to keep a laboratory notebook. A quadrille-ruled laboratory notebook with a sheet of carbon paper allows a student to produce two data sheets and copies of the report summary. Each page can be permanently retained in the notebook, and the duplicate copy can be submitted for evaluation or tabulation.

You will find it helpful if data summaries, including all written observations, are submitted at the end of the laboratory period, even though the calculations and/or questions are not due until a later date.

You will then be able to assemble a summary of all student results for a particular investigation on the chalkboard or on an overhead transparency. Such data permit useful discussion on determining a "best" value through a median or mean value, a histogram, or through some other visual report of overall student results.

A realistic view of laboratory work suggests that in the most fundamental sense there are no wrong laboratory results. All students obtain results consistent with the particular experimental conditions (either correct or incorrect) they have established. Because careful work will yield more precise results, encourage each student to take personal pride in experimental work. If students disagree on a result, discuss the factors that might account for the difference. A student who provides a thoughtful analysis of why a particular result turned out to be "different" (incomplete drying, a portion of the sample was spilled, etc.) deserves credit for such interpretation.

Laboratory Safety The IAC program introduces many new laboratory procedures and activities to students. To use the IAC program safely you should become thoroughly familiar with all student activities in the laboratory. Do all the experiments and carry out all the demonstrations yourself before presenting them to your class. We have tested each experiment and have suggested the use of chemicals that provide the least chance of causing a safety problem in the laboratory. The teacher's guide has many suggestions to help you provide your students with safe laboratory experiences. Have the students read *Appendix I: Safety*. Then conduct a brief orientation to laboratory safety before the students encounter their first laboratory experience in each module. Review, when necessary, and discuss precautions and safety each time a symbol appears in the student text. In addition, the *Suggested Readings* in the teacher's guide of *Reactions and Reason* lists safety manuals that give detailed instructions on the handling of hazardous chemicals, disposal of chemicals, and general laboratory safety.

Materials for IAC In light of increasing costs for equipment and supplies, as well as decreasing school budgets, we have tried to produce a materials list that reflects only the quantities needed to do the experiments with minimal surplus. Thus, the laboratory preparation sections contain instructions for only a 10 to 20 percent surplus of reagents. Add enough materials for student repeats and preparation errors.

Evaluating Student Performance

There are many ways of evaluating your students' performances. One of the most important forms of evaluation is observing your students as they proceed through the IAC program. IAC has developed skill tests and knowledge tests for use with this module. These test items have been suggested and tested by IAC classroom chemistry teachers. You are encouraged to add these to your own means of student evaluation. The module tests are at the end of the teacher's guide.

In addition to the problems and questions incorporated in the student module text and illustration captions, there are suggested evaluation items at the end of each module section in the teacher's guide. Answers to all of the evaluation items are included to help you in your classroom discussion and evaluation.

For information on evaluating students' attitudes while using this module, see *Reactions and Reason: An Introductory Chemistry Module.*

Module Concepts

BASIC PROPERTIES OF MATTER

- All atoms consist of fundamental particles that are distinguished from one another by their mass, electric charge, and half-life.
- The fundamental particles include the neutron, the proton, and the electron.
- Gravity, electromagnetism, and the nuclear force are three basic forces that may act upon the fundamental particles. These forces are responsible for holding our Universe together.
- In nuclear reactions three entities are conserved: the sum of the mass and energy, the total charge of the system, and the total number of nucleons.
- Interactions between the particles and basic forces in the nucleus determine the stability of the nucleus.

THE MAKEUP OF OUR SOLAR SYSTEM

- The stability of nuclides is related to the ratio of neutrons to protons.
- Nuclear stability is enhanced when protons and neutrons achieve a closed-shell configuration.
- Nuclides may be classified as either stable or radioactive; radioactive nuclides may be either natural or synthetic.
- The relative abundances of the elements give an indication of how they were formed.

NUCLEOSYNTHESIS AND STELLAR EVOLUTION

- Many different star types exist in our Universe.
- Different star types represent different processes of element formation.
- A star is believed to evolve through a sequence beginning with the main sequence stage, continuing through the red giant stage, followed by a supernova stage, destruction, and a new main sequence star.
- Main sequence stars involve fusion of hydrogen to helium.
- Red giants involve helium "burning."
- Successive stages of carbon burning and silicon burning lead to $^{56}_{26}Fe$.
- Nuclei heavier than $^{56}_{26}Fe$ are believed to be formed by a process that involves neutron capture and β-decay. This process is called the *r*-process and is terminated by nuclear fission.
- Heavy elements can be formed also by the *s*-process in a manner similar to that in which they are formed by the *r*-process but at a much slower rate.

RADIOACTIVE DECAY

- Half-life is the time required for one-half of the particles in a radioactive sample to decay.
- Four processes of radioactive decay are gamma decay, beta decay, alpha decay, and spontaneous fission.
- The rate of radioactive decay of naturally occurring nuclides provides a means by which the age of the Earth and archaeological samples can be approximated.
- Radiation is emitted in all directions and its intensity varies with distance, according to the inverse square law.

THE SEARCH FOR NEW ELEMENTS

- The production of synthetic elements relies heavily on the use of nuclear reactors.
- The production of superheavy elements relies on the use of heavy-ion accelerators.

USES OF RADIATION

- Background radiation exists because of the decay of naturally occurring radioactive substances and the presence of cosmic rays.
- Applications of radioactive tracers include the study of the mechanisms of chemical reactions, the nature of chemical bonds, and the diagnosis of illnesses.
- Radiation can be used to split molecules, thus forming free radicals for use in genetic and agricultural research and in the treatment of diseases such as cancer.

NUCLEAR POWER

- Energy is produced in nuclear reactors by means of fission reactions.
- The generation of nuclear power has an effect on the environment.
- Nuclear-fusion reactors are being developed based on fusion reactions that occur in the Sun.
- The components of a nuclear reactor include the fuel rods, control rods, moderator, heat exchanger, shielding, and containment shield.
- ^{235}U is the most common fuel used for nuclear reactors, which derive their energy from nuclear-fission reactions.
- Nuclear power provides a means of making our country independent in terms of its energy needs. However, as with the burning of coal, oil, and gas, there are also tradeoffs for our environment. Among these are the exposure of individuals to radiation, the contamination of the environment with radioactivity in the event of an accident, the reprocessing of nuclear fuel, and the storage of radioactive wastes.

Module Objectives

We have attempted to group module objectives in three broad categories: concept-centered, attitude-centered, and skill-centered. The categories are not mutually exclusive; there is considerable overlap. The conditions for accomplishing each objective are not given, since they can easily be found in the respective section in the module. Note also that concept and skill objectives are more specific than those in the affective domain. It is very difficult to classify objectives in this way, but we have been encouraged to do so by classroom teachers who have helped in this difficult task.

The objectives identified here should provide you with a useful starting point in clarifying your own goals in teaching this module. We encourage you to identify alternate objectives, using this list as a point of departure. Assessment items can be found throughout the text and at the end of major sections in the student module in the form of *Problems*. Other *Evaluation Items* are included after each major section in this guide and in the form of module tests for knowledge and skill objectives, located in the appendix.

Concept-Centered Objectives	*Attitude-Centered Objectives*	*Skill-Centered Objectives*
	BASIC PROPERTIES OF MATTER	
N-1 • Identify the atomic nucleus as the factor that determines whether or not an element can exist in nature and what its chemical characteristics will be. **N-2** • Define the term *stellar nucleosynthesis*. **N-3** • Characterize the fundamental particles of the atom, including their mass, electric charge, and half-life. **N-5** • Name the three basic binding forces in the Universe. Compare the relative strengths of these forces. Describe how these forces affect particles in the atom. **N-6** • Write the mathematical expression for the law of conservation of mass-energy and state the implications of the law. • Explain the meaning of the conservation of electric charge in a reaction. • State the law of conservation of nucleon number.	• Inquire about the possible origins of elements in the Universe. • Recognize the importance of controlling variables in an experiment.	**N-4** • Solve problems that involve the half-lives of radionuclides. • Determine the probability of the occurrence of simple events. **N-6** • Perform calculations based on the law of conservation of mass-energy. **N-9** • Measure amounts of radiation using a radiation detector. • Determine the relationship between the activity of a radioactive source and the distance of that source from a detector.

Concept-Centered Objectives	Attitude-Centered Objectives	Skill-Centered Objectives
N-7 ● Describe the effects that the basic forces have on interactions between the fundamental particles. ● Explain the operation of a radiation detector. **N-8** ● Explain how nuclear particles are accelerated. **N-9** ● State the relationship between the activity of a radioactive source and the distance of that source from a detector.		

THE MAKEUP OF OUR SOLAR SYSTEM

N-10 ● Define and differentiate between *nuclide, nucleon, isotope, isotone,* and *isobar.* **N-11** ● Describe factors that influence the stability of a nucleus. **N-12** ● Explain the meaning of the term *transmutation.* **N-14** ● Compare the abundances of elements in the solar system.	● Become aware of how small the Earth is in relation to the Sun, the solar system, and the Universe.	**N-10** ● Write nuclear representations for nuclides. **N-13** ● Determine the amount of eluant needed to separate a radioactive reactant-product isotope pair.

NUCLEOSYNTHESIS AND STELLAR EVOLUTION

N-15 ● Discuss the big bang theory of element synthesis. **N-16** ● Discuss how stars and galaxies were formed from big bang dust.	● Recognize that a theory may be useful in explaining facts but must be rejected or modified when facts are presented that cannot be explained by the theory.	**N-15** ● Complete nuclear equations for reactions related to the big bang theory.

Concept-Centered Objectives

N-17

- Identify the source of energy in a main sequence star.

N-18

- Explain how helium burning follows hydrogen burning in a star's evolution.

N-19

- Explain how carbon and silicon burning follow helium burning in a star's evolution.

N-20

- Explain the production of heavy elements through the *r*-process.

N-21

- Describe how radioactivity was first discovered.

N-23

- Discuss the production of heavy elements through the *s*-process.
- Compare the ability of the *r*-process and that of the *s*-process to synthesize heavy elements.

Attitude-Centered Objectives

Skill-Centered Objectives

N-17

- Write equations for the hydrogen-burning process.
- Balance nuclear reaction equations using both the longhand and the shorthand methods.
- Perform calculations showing the conversion of matter into energy in nuclear reactions.

N-18

- Write equations that illustrate helium burning.

N-19

- Write equations that illustrate carbon and silicon burning.

N-20

- Write equations that illustrate the *r*-process.

N-22

- Illustrate the effect of radiation on photographic film.

RADIOACTIVE DECAY

N-24

- Explain why the terms *stable* and *radioactive* are relative terms.

N-25

- Define and give an equation for both *radioactivity* and *half-life*.

N-26, 27, 29, 30

- State the four modes of radioactive decay. List the particles given off in each form of radioactive decay.

- Discuss the effects of radioactive decay particles on our environment.

N-25

- Perform calculations based on the rate of radioactive decay.

N-26, 27, 29

- Write equations that illustrate the four basic modes of radioactive decay.

N-28

- Determine experimentally the half-life of a radioactive isotope.

Concept-Centered Objectives	Attitude-Centered Objectives	Skill-Centered Objectives
• Compare the four modes of radioactive decay, including their penetrating powers and their changes in atomic number, atomic mass, and the energy of the reactant nucleus.		**N-31** • Explain the use of radioactive isotopes to determine the age of materials. **N-32** • Measure the half-life of a radioisotope commonly found in the environment.

THE SEARCH FOR NEW ELEMENTS

Concept-Centered Objectives	Attitude-Centered Objectives	Skill-Centered Objectives
N-33, 34 • Compare the number of elements known before 1940 to the number presently known. • Discuss applications of synthetic elements in daily life.	• Discuss the importance of synthesizing new elements.	**N-33, 34** • Write equations that illustrate the synthesis of *transuranium* elements.

USES OF RADIATION

Concept-Centered Objectives	Attitude-Centered Objectives	Skill-Centered Objectives
N-35 • List and discuss the sources of our daily exposure to radiation. **N-37, 40, 41** • Give examples of the use of radioactive tracers in chemistry, medicine, and agriculture. **N-39** • Discuss the effects of nuclear radiation on people and materials. **N-43** • Describe the operation of an ionization smoke detector. **N-44** • Provide examples of how neutron activation analysis is used in different scientific disciplines.	• Discuss the future influence of nuclear chemistry with respect to our society. • Discuss the beneficial uses and the detrimental effects of radiation.	**N-36** • Graph activity vs. shielding thickness data. • Determine half-thickness of a shielding material. **N-38** • Locate radioisotopes using a radiation detector. **N-42** • Demonstrate the uptake of radioactive phosphorus by a plant.

NUCLEAR POWER

N-45

- List the basic components of a nuclear reactor.
- Discuss the operation of a nuclear reactor.

- Discuss the advantages and disadvantages of using nuclear energy as a power source.

N-46

- Discuss the effects of a nuclear power station on the environment.

N-47

- Discuss the application of nuclear power to miniature power sources.

N-48

- Describe the efforts being made to control nuclear fusion reactions for the production of electric power.

Teaching The Heart of Matter

Nuclear chemistry as taught in high school has definite meanings for most of us: the three simple types of radioactive decay, the balancing of nuclear equations, a study of nuclear reactors, and the applications of radioactivity—such as tracers, dating, and radiation therapy.

In *The Heart of Matter: A Nuclear Chemistry Module*, we have developed a new and highly successful approach to the teaching of nuclear chemistry. Although we discuss conventional topics, the major portion of the module is devoted to nontraditional topics, including stellar synthesis of the elements. We have also restructured the approaches to the activities so that concepts such as half-life and half-thickness will acquire definite meanings for the students after they have explored them experimentally.

An excellent laboratory program is available in the form of the package MINIGENERATOR *Nucleonics Kit* and MINIGENERATOR *Nuclear Laboratory for Chemistry and Physics**. Many of the activities in this module have been structured around the MINIGENERATOR program because of its adaptability to many different situations. The kit provides a safe, well-planned, and instructive program.

The heart of the MINIGENERATOR program is the MINIGENERATOR [also see *Journal of Chemical Education* 46(1969): 287], which consists of a long-lived source of radioactivity that is tightly bound on an ion-exchange resin in a self-contained unit. The radioactive decay of the atomic nuclei absorbed on the column produces a new element that is also radioactive but that has a much shorter half-life. The MINIGENERATOR can be used as a constant source of radiation, or the products of decay can be eluted from the resin and used to perform other measurements. Because the radioactive products decay to stable isotopes, there is no danger of radioactive contamination in these experiments.

In the module we suggest a series of experiments that illustrate the principles of nuclear detection, the penetrating power of radiation, ion-exchange elution, half-life measurement, and tracer applications. Depending on the interest level of your class, you can carry out a more extensive program with activities suggested in the MINIGENERATOR program. Three options for conducting the laboratory program follow.

Option I: MINIGENERATOR Program *The* MINIGENERATOR *Nucleonics Kit* contains the complete equipment necessary for an extensive nuclear laboratory program. Its components, which serve up to five students per laboratory, include a radiation detector, two MINIGENERATORS, the required laboratory supplies (solutions, containers, etc.), and a manual, MINIGENERATOR *Experiments in Nucleonics***. There are no problems in using the kits in successive laboratories. Because of the expense involved, kits can be shared by several schools. For the school that makes use of the kit, we have suggested additional experiments at appropriate places in this teacher's guide.

Option II: MINIGENERATORS A less expensive way of operating the laboratory program involves purchasing only the MINIGENERATORS and gathering the remaining materials from local sources. Surplus radiation detectors, for example, can be acquired from your local Civil Defense Authority, as regulations require that these battery-operated devices be replaced every three years. These detectors are usually in good working condition. Ideally, it would be desirable to have two different MINIGENERATORS per group of five students: one ^{137}Cs source, for which the product half-life is 2.6 minutes, and one ^{113}Sn source, for which the product half-life is 100 minutes. If you can purchase only one kind of source, the ^{137}Cs is probably more valuable for the experiments suggested here. The remaining equipment, such as solutions and containers, can easily be prepared or else obtained as common laboratory stock.

*Available from Redco Science Inc., Danbury, CT 06810 and from other distributors.

**Henry H. Kramer and Wayne J. Gemmill, eds., MINIGENERATOR *Experiments in Nucleonics* (New York: Union Carbide Corporation, 1968). Available from Redco Science Inc., Danbury, CT 06810 and from other distributors.

Option III: Demonstration For the even more restricted budget, the purchase of a single MINI-GENERATOR and the acquisition of a surplus detector will make it possible for you to demonstrate the experiments. Instructors who are electronically inclined can add a simple circuit to provide an audio output to the detector, which will result in a more impressive demonstration. Students can record the data as an experiment is done.

Student groups can also work with the MINI-GENERATOR to repeat the experiments that are demonstrated, or you may wish to have student groups provide the demonstrations for the remainder of the students in the class.

To allow for individual preferences, we are leaving the teaching schedule and time plan up to the individual teacher. We would like to advise you, however, that a brisk pace is preferable. Because of the modular structure of the IAC curriculum, many concepts are treated several times from different points of view, and an intensive treatment every time is not necessary. Most teachers allow about six weeks of teaching for *The Heart of Matter*.

Basic Properties of Matter

Discuss with your students the long history of study that has led to the present understanding of the basic properties of matter. Emphasize that these properties have enabled scientists to understand how matter behaves. Using this information, scientists have developed theories concerning the origin of the elements and have continued to acquire new knowledge in this field.

N-1 ELEMENTS: A QUESTION OF BEGINNING

Begin the lesson with a review of the students' understanding of matter. Refer to the key question in the text, "How did the chemical elements in our environment come into existence?" Then point out the *Periodic Table of the Elements* on the inside back cover of the student module. Call on a student to interpret the table. Invite others in the class to add to the student's interpretation and, if necessary, to correct any errors that may have been expressed. What do the students know about the basic properties of matter? What do they know about the structure of an atom?

The term *superheavy elements* refers to the elements near the theoretically predicted, doubly magic nucleus $^{298}114$, discussed in more detail in sections *N-11* and *N-34*.

N-2 FROM THE SMALLEST TO THE LARGEST

Appropriate survey films on astronomy can be useful in giving students a feeling for the size of our solar system and of the Universe itself. A film that can help students gain more insight into relative sizes is *Powers of Ten* (color, 9 minutes. Pyramid Films, Santa Monica, CA 90406).

N-3 FUNDAMENTAL PARTICLES: BUILDING BLOCKS

This section is extremely important because it forms the basis for future discussions. We have purposely avoided listing the complete array of the fundamental particles in the nuclear "zoo." Although many of these particles—such as the neutrino—are highly important to researchers, the students are only required to differentiate between the four particles listed in the student module in order to understand the material presented there or to proceed to higher-level courses. Some emphasis should be given to discussion of the photon, since this particle is important in the laboratory program. The following list of particles has been included for advanced classes or independent study.

Even some of these particles may not be fundamental, since they may consist of smaller particles. For example, the nucleon may actually be

Particle	Symbol	Mass (μ)	Charge	Spin	Half-life
Leptons					
(1) muon	μ	0.10	−1	$\frac{1}{2}$	
(2) electron	$e^-, {}_{-1}^{\ 0}\beta$	0.000 5486	−1	$\frac{1}{2}$	stable
(3) neutrino	ν	0	0	$\frac{1}{2}$	stable
Mesons					
(1) pion	π	0.15	±1, 0	0	10^{-8} s or less
(2) kon	K	0.50	0, −1	0	
Baryons					
(1) nucleon					
(a) neutron	n	1.008 6654	0	$\frac{1}{2}$	12.8 min; stable inside nuclei
(b) proton	p, H	1.007 8252	+1	$\frac{1}{2}$	stable
(2) hyperons	Λ, Σ, Ξ	$>m_n$	±1, 0	$\frac{1}{2}$ $\frac{3}{2}$	less than 10^{-9} s
Graviton (theoretical)		0	0	2	stable

composed of simpler particles called *quarks*, which have been hypothesized to have a one-third integral electric charge. Various combinations of quarks with a total charge of +1 make up the proton, and combinations of quarks with a net neutral charge make up the neutron. Scientists at many high-energy nuclear laboratories are presently searching to confirm the existence of the quark. For further discussion of fundamental particles, see the article by D. B. Cline, A. K. Mann, and C. Rubbia, "The Search for New Families of Elementary Particles," *Scientific American* (January 1976), page 44.

It should also be mentioned that for each of the particles there exists an *antiparticle* with properties exactly the opposite of those listed in the table. For example, the antielectron, or *positron*, has a charge of +1, instead of −1. Antiparticles of all the particles listed, except for the theoretical graviton, have been observed in the laboratory. Although our galaxy is made up of particles, it is conceivable that an antiparticle galaxy exists somewhere in space. If you were to live there, everything would seem very much the same as it does on Earth—unless the antigalaxy were to encounter a normal galaxy, in which case the two would destroy each other instantaneously with one magnificent "zap." This has been observed to happen in the laboratory when particles and antiparticles collide. They annihilate one another and give off more energy than any other known process—that is, an energy equal to the total mass of the particles.

The atomic mass unit has been arbitrarily defined in such a way that the atom ^{12}C has a mass of 12.000 000 . . . u. This definition has been made because of the ease of using carbon as a standard in mass spectrometry measurements. An actual mass measurement of ^{12}C in grams defines the value of the atomic mass unit.

$$1 \text{ u} = 1.660 \times 10^{-24} \text{ g or } 931.48 \text{ MeV}/c^2$$

This value also serves to define the mole.

$$1 \text{ mole} = \text{atoms contained in one gram-atomic mass}$$

$$= \left(\frac{12.000 \text{ g}}{12.000 \text{ u}}/\text{atom}\right)/(1.660 \times 10^{-24} \text{ g/u})$$

$$= 6.023 \times 10^{23} \text{ atoms}$$

The other way of expressing mass, 931.48 MeV/c^2, is an example of the application of Einstein's equation:

$$m = \frac{E}{c^2} = \frac{\text{energy in MeV}}{\text{velocity of light squared}} = \text{mass}$$

Note also that the difference between the mass of 6 protons and 6 neutrons (12.098 944 u) and the mass of the ^{12}C atom (12.000 000 u) is the mass that is converted into the binding energy necessary to hold the ^{12}C nucleus together. This amounts to 92.16 MeV, or an average of 7.68 MeV for each particle in the nucleus. (Average binding energy is discussed in section *N-11*.)

Spin is a fundamental property which we have not discussed in the text. It is a quantum-mechanical property that is classically related to rotation about an axis (as in a spinning top or Earth's daily cycle) and revolution in an orbit (a ball on a string or Earth's yearly cycle around the Sun). Since the qualitative discussions in this text do not depend on spin, this property is best omitted from discussions at the high-school level.

MINIEXPERIMENT N-4 HEADS/TAILS AND HALF-LIFE

The introduction to the concept of half-life in this section is essential to the understanding of later discussions in this module. The miniexperiment should prove helpful in this respect, provided you have an honest class and you do not obtain results of high improbability.

Concepts In performing this miniexperiment, a student will encounter these important ideas*:

- The chances of any random event occurring are determined by the laws of probability.
- Radioactive decay of the neutron can be likened to the tossing of a coin, where one side (tails) represents neutrons that have decayed, and the other side (heads) represents neutrons that have not decayed. Both are random processes.

*This statement appears only with this first miniexperiment, but it applies each time this section appears in an experiment or a miniexperiment, unless otherwise noted.

Objective After completing this miniexperiment, a student should be able to*:

- Determine the half-life of a substance from a knowledge of the number of particles that have decayed or remained after an integral number of half-lives.

Estimated Time One-half period

Student Grouping Students should work individually.

Materials** You will need the following materials for a class of thirty students.
a coin provided by each member of the class
linear graph paper

Advance Preparation None

Prelab Discussion None

Laboratory Tips Appoint a starter to oversee the flips of the coin.

Postlab Discussion The one danger in this experiment is that the students may get the idea that the nuclei wait for one half-life and then suddenly half of them decay and the other half remain intact. Stress that the decay process occurs continuously—but that the *net* result after one half-life is that half of a sample will have decayed. For an advanced class the importance of statistics can be pointed out. The statistical error in this measurement is approximately equal to the square root of the number of events. Thus, in the first flip period (half-life), suppose you obtain a total of 100 tails. The error in this number is ± 10, or 10 percent. In the sixth period, you may have only four tails. The error here is ± 2, or 50 percent. Thus, for small numbers of events, one cannot expect ideal agreement with theory.

There are many variations on the theme of this miniexperiment, and you may wish to develop your own approach.

**The *Materials* list for each experiment or miniexperiment in this module is planned for each group of two to five students, unless otherwise noted.

ANSWER TO PROBLEM

(Student module page 6)

A total of 256 neutrons will remain after 25.6 minutes, and 768 protons will form [$N = (\frac{1}{2})(\frac{1}{2})\ 1024 = 256$].

N-5 THE BASIC FORCES: NATURE'S GLUE

The formulas for the three basic forces given in the text are not intended for quantitative use but rather as a guide to the understanding of the qualitative behavior of the forces. It should be noted also that the formula for the electromagnetic interaction applies to electric charges at rest—that is, the electrostatic force. At this level there is no need for introducing any mathematical formulas for magnetic interactions of charged particles.

The on-off nature of the nuclear force is much more difficult to put into visual form. Despite fifty years of intensive study, nuclear scientists are still unable to write an exact mathematical expression for the nuclear force. Although more sophisticated approximations to the nuclear force are currently used, the formula we give here—the on-off force—is sufficiently close to the best current equations, and we use it because of its mathematical simplicity. A pool table with a single ball is probably as good a classical analog as can be found. That is, you can think of the pool table as being composed of a nucleon (the ball), six centers of the nuclear force (the pockets), and space (the table). As long as the ball is bouncing around from cushion to cushion, it is unaffected by the existence of the pockets. Of course, this wouldn't be true for the gravitational and electromagnetic forces because they exert themselves over long distances. However, once the ball is on the edge of a pocket, it drops in and is bound to the pocket, no longer able to roam freely in space.

A fourth force, the weak nuclear force that accounts for interactions involving leptons, has been omitted from these discussions. Another omission from this section is a review of how photons (which have no mass, charge, or nucleon number) are involved in the forces. Whenever changes in electric or magnetic fields occur—such as when an electron, a proton, or a neutron (which has a small magnetic field but no charge) changes its orbit in an atom or nucleus—a photon is produced or absorbed. Although these subjects are fascinating, they are not essential to our discussion and, therefore, are left to more advanced courses.

All forces are thought to exert themselves on particles by means of the transfer of a fundamental particle. The *graviton* is believed to be the fundamental particle of gravity, the *photon* is the fundamental particle of electromagnetism, and the *pion* is the fundamental particle of the nuclear force.

Miniactivity The objective of this activity is to have the students demonstrate their qualitative understanding of the basic forces. Assuming that pairs of the particles listed in Table 3 (student module page 7) are the same distance apart, students are to arrange them in order from the strongest to the weakest attraction. For example, the gravitational force depends on mass. Consequently, it affects only neutrons, protons, and electrons. The neutron, which is the heaviest of the elementary particles listed, is most strongly attracted by another neutron because of the gravitational force. Two electrons exhibit the weakest gravitational attraction. The nuclear force turns out to be independent of whether the interaction involves neutrons or protons. However, students should not be penalized if they recognize that the total proton–proton interaction may be weaker because of electrostatic repulsion. When both forces are taken into account, the proton–proton force is actually a little weaker.

Present the following problem to your students.

By considering all possible pairs of particles (except photons) in Table 2 (namely, *n-n*, *n-p*, *p-p*, *n*-e, *p*-e, and e-e) to be separated by the same distance *r*, complete the following table for each type of force. As a guide, part of the following table has already been completed. For example, the nuclear force involves only neutrons and protons and is the same for all possible combinations of *n* and *p*. No nuclear attraction occurs for nucleons and electrons. In the case of the electromagnetic force, charge determines the strength of the attraction. Remember that electric charges can (a) attract one another (opposite charges), (b) have no effect (at least one charge neutral), or (c) repel one another (like charges). The gravitational force depends on mass for its strength. Consult Table 2 in the student module for the masses of the particles. Note that the *n-n* pair has the strongest attraction; this is because the neutron is the heaviest particle.

TYPE OF FORCE

	Nuclear					
Particles	*n-n*	___	*p-p*	*n-e*	___	e-e
Strength	(1)	___	(1)	(2)	___	(2)
	Electromagnetic					
Particles	___	*n-n*	*n-p*	*n-e*	___	___
Strength	___	(2)	(2)	(2)	(3)	(3)
	Gravity					
Particles	*n-n*	___	___	___	___	___
Strength	(1)	___	___	___	___	(6)

Note: In this table, a strength of 1 is greater than a strength of 2, 2 is greater than 3, and so on.

Answers:

	Nuclear					
Particles	*n-n*	*n-p*	*p-p*	*n-e*	*p-e*	e-e
Strength	(1)	(1)	(1)	(2)	(2)	(2)

Comment: The nuclear force involves only nucleons; therefore, the force is the same for *n-n*, *n-p*, and *p-p* interactions, and zero nuclear force exists for *n*-e, *p*-e, and e-e interactions.

	Electromagnetic					
Particles	*p*-e	*n-n*	*n-p*	*n*-e	e-e	*p-p*
Strength	(1)	(2)	(2)	(2)	(3)	(3)

Comment: The electromagnetic force involves electric charge; therefore, the *p*-e force is attractive, no net force exists for *n-n*, *n-p*, or *n*-e, and the force is repulsive for e-e and *p-p*.

	Gravity					
Particles	*n-n*	*n-p*	*p-p*	*n*-e	*p*-e	e-e
Strength	(1)	(2)	(3)	(4)	(5)	(6)

Comment: The gravitational force involves mass; therefore, the order is in terms of the product masses. (See Table 2 in the student module.)

N-6 CONSERVATION LAWS: THE GROUND RULES

The rules given here for the conservation laws are the justification for the balancing of chemical reactions as well as of nuclear reactions. The conservation of nucleons simply requires the total mass number on the left-hand side of the equation be equal to that on the right-hand side. The same is true for the conservation of charge. Thus, the justification for the balancing of equations is not that mass must be conserved but rather that nucleons must be conserved. For example, in balancing the chemical equation

$$2\ H_2O_2 \longrightarrow 2\ H_2O + O_2$$

we are, in effect, saying that there are 36 protons (4 from H and 32 from O) and 32 neutrons (all from O) before the reaction and that after the reaction there are still 36 protons and 32 neutrons. They are simply rearranged by the altering of chemical bonds.

The law of conservation of mass and energy implies that in *all* reactions that occur spontaneously—chemical or nuclear—there is a change of mass and energy. In nuclear reactions the mass change as well as the energy change can be measured directly because the mass change is so large. However, in chemical reactions, only the energy change can be directly measured; the mass change is too small to be measured with current experimental techniques. Nonetheless, it still occurs. Thus, it is incorrect to state that mass alone is conserved in chemical reactions. Such a statement would mean that $E = mc^2$ is not valid; but this relationship has proved so accurate in nuclear measurements that there is no basis for challenging it on the chemical scale of energies.

The quantity c^2, the velocity of light squared, can be expressed in many different units. The common units for c are cm/s:

$$c = 2.99 \times 10^{10}\ \text{cm/s}$$

However, if one is interested in converting mass into energy and vice versa in nuclear reactions, it is desirable to express c^2 in more useful units. Thus,

$$c^2 = \frac{\text{cm}^2}{\text{s}^2} = \frac{(\text{mass})\text{cm}^2}{(\text{mass})\text{s}^2} = \frac{\text{energy}}{\text{mass}} = 931.48\ \text{MeV/u}$$

The MeV is the typical unit of energy used in expressing nuclear reactions, just as the eV represents the typical unit of chemical-reaction energy. If you have previously placed emphasis on units such as ergs and calories, a few conversion problems might be in order. *Note:*

$$1\ \text{MeV} = 3.8 \times 10^{-14}\ \text{cal} = 1.6 \times 10^{-6}\ \text{ergs}$$

Remember, this is the energy of a *single* atom, not a mole of atoms. Thus, if a chemical reaction liberates 10 kcal per mole, this energy corresponds to 10 kcal/6 × 10^{23}, or about 5 × 10^{-7} MeV.

ANSWER TO PROBLEM

(Student module page 8)

Mass values from section *N-3*

$$m(\mathrm{I})c^2 + E(\mathrm{I}) = m(\mathrm{II})c^2 + E(\mathrm{II})$$
$$E(\mathrm{II}) = [m(\mathrm{I}) - m(\mathrm{II})]c^2 + E(\mathrm{I})$$
$$E(\mathrm{I}) = 0 \text{ as stated}$$
$$E(\mathrm{II}) = [236.100 \text{ g} - 235.903 \text{ g}]c^2 + 0$$
$$E(\mathrm{II}) = (0.197 \text{ g})\ (931.5 \text{ MeV/u})$$
$$E(\mathrm{II}) = \frac{(0.197 \text{ g})\ (12.000 \text{ u})}{(1.9925 \times 10^{-23} \text{ g})} (931.5 \text{ MeV/u})$$
$$= 1.11 \times 10^{26} \text{ MeV}$$

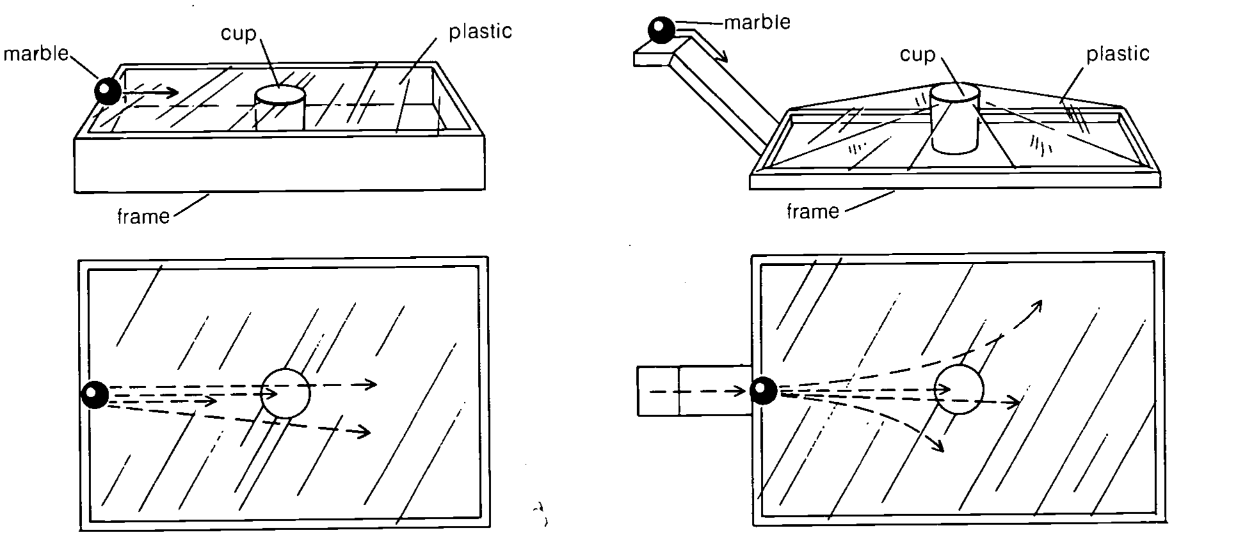
N-7 INTERACTIONS: GETTING IT TOGETHER

This section can be taught in a variety of ways, depending on the facilities available and the interests of the instructor. For example, a discussion of the concept of temperature could come into play here. It is worth remembering that temperature is a measure of the average kinetic energy of the particles in a system. Thus, the temperature of the room you are in right now is a measure of the average energy of the nitrogen and oxygen molecules that are flying around. As a consequence of the high temperatures inside stars, particles have enough energy to initiate nuclear reactions.

Electromagnetism provides many examples of interactions. In preparation for the discussion of a cyclotron, you might find it worthwhile to demonstrate a simple electromagnet. The principles behind them both are the same, but the effects are the opposite. In the electromagnet, electric charges follow a circular path and produce a magnetic field. In the cyclotron a magnetic field induces electric charges to move in a circular path.

The nuclear force can be demonstrated with an overhead projector in the following way. Obtain a small cup (2–3 cm high and 2–3 cm in diameter) and place it in the center of a 22-cm × 28-cm transparent sheet (about 0.01 cm thick). Then stretch plastic wrap over the cup, cut a hole in the wrap over the cup, and tape the wrap to the edges of a frame and the cup.

The apparatus on the right is used to demonstrate the competition between the nuclear force and the electromagnetic force in proton–nucleus interactions. The apparatus on the left is used to demonstrate neutron–nucleus interactions, where only the nuclear force is important. When the apparatus is placed on an overhead projector, marbles rolled across the surface of the plastic wrap can simulate nuclear reactions.



The proton interaction shows that if the marble approaches the cup with sufficient velocity and the proper trajectory, it will be absorbed and will disappear. If the trajectory is not correct or the velocity is too slow, the marble will curve around the cone created by the apparatus and will miss the cup, much like the effect caused by the Coulomb force in normal low-energy nuclear collisions (such as the Rutherford scattering experiment). If the marble is moving too fast, it will jump over the cup and appear to pass through the nucleus. This demonstrates the transparency of nuclear matter that is observed in high-energy reactions. The neutron–nucleus apparatus shows similar results, except that the particle follows a straight path if its trajectory does not intersect the nucleus, illustrating the absence in neutron reactions of effects caused by the electromagnetic force.

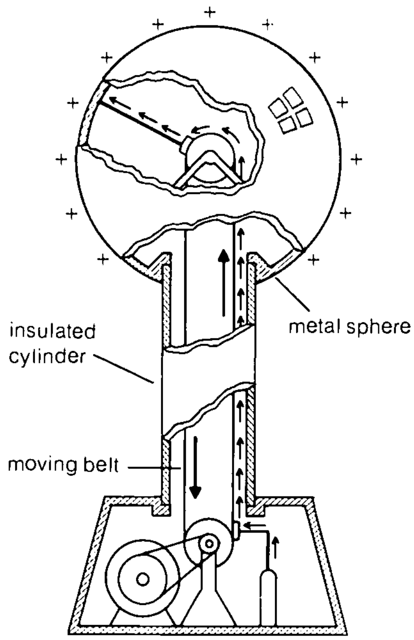
N-8 ACCELERATING PARTICLES

In this section we have described only the cyclotron. If there is a Van de Graaff generator or other accelerator in your area, you might discuss it instead of the cyclotron. A diagram of a simple Van de Graaff generator is shown here. In this device a positive charge is stored on a large hollow sphere by removing electrons from the atoms of the sphere. Positively charged protons are then produced inside the sphere and are subsequently repelled by the charge on the sphere. Therefore, it is electrostatic repulsion that serves to accelerate particles in the Van de Graaff generator, whereas attraction accelerates particles in a cyclotron.

Modern accelerators of this type are called tandem Van de Graaffs. They work on a two-stage (tandem) acceleration principle. In these devices negative ions (-1) are accelerated toward the positively charged sphere (terminal). Then, as they pass through a tube in the terminal, a very thin foil or gas is placed in the path of the beam of particles. In passing through this matter, the -1 ions are stripped of their electrons, thus becoming positively charged ions ($+3$, $+4$, or even higher for some elements). These are then repelled by the positive terminal, thereby increasing the energy of the ions even further.

If there is a nuclear-particle accelerator nearby, a tour of this facility can usually be arranged. The physics department of your local university is a good source of information about tours in your vicinity, or you can write to the U.S. Department of Energy, Division of Technical Information, Box 62, Oak Ridge, TN 37830.

VAN DE GRAAFF GENERATOR



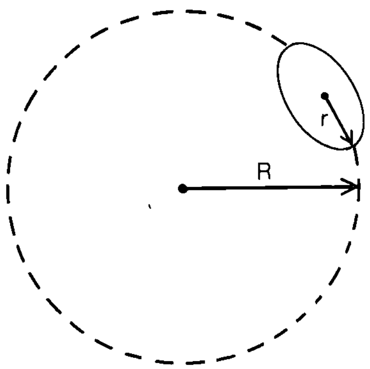
The interaction of gamma rays with gas molecules in the probe of a radiation detector allows for the measurement of the amount of radiation present. The gamma ray ionizes the gas molecules to form electrons and positive ions. The electrons are then collected on the detection wire of the probe. This causes an electric current to flow, which is indicated on the meter. The amount of current is proportional to the amount of radiation present.

The radiation is emitted as if from a point source, so that the radiation detected is related to the distance of the detector from the source. This distance/activity relationship is investigated in experiment *N-9*.

EXPERIMENT
N-9 RADIATION DETECTION

This is Experiment 10 in the MINIGENERATOR *Experiments in Nucleonics* series (Danbury, Conn.: Redco Science Inc., 1968). It is an excellent introduction to the use of radiation detectors and serves to alert the student to the inadvisability of altering the detector-source distance while doing such experiments. The direct measurements are intended to illustrate the inverse square law—that is, the fact that the counting rate of any radioactive source decreases as the square of the distance R from the source. Mathematically, this can be written as

$$\text{activity} \propto \frac{1}{R^2}$$



This derives from simple geometric considerations. If one has a detector of radius r, then it will intercept an area of πr^2 on the surface of a sphere that surrounds a source.

The total area of this sphere, which intercepts the total radiation emitted by the source, is $4\pi R^2$. Thus, the fraction of events collected in the detector is $\pi r^2/4\pi R^2$. Since r is constant for any given detector, the activity gives the $\frac{1}{R^2}$ dependence.

Concepts

- Gamma rays are a form of electromagnetic radiation.
- Radiation is emitted in all directions from a source.
- The intensity of radiation varies with distance from the source according to an inverse square law.

Objectives

- Use a detector to measure the activity of radioactive materials.
- Graph and interpret data from such measurements.
- Explain the relationship between distance and intensity with respect to radiation in either mathematical or narrative terms.
- Suggest safety precautions that might be useful in handling radioactive materials.

Estimated Time One period

Student Grouping Students should work in teams of two, if possible, or in larger groups, depending on the availability of materials.

Materials

radiation detector (usually a Geiger counter)
ruler, centimeter
radioactive source (MINIGENERATOR)
ring stand
2 test-tube clamps for holding the detector tube
radioactive sample tape to hold the radioactive source in place
linear graph paper
pair of rubber gloves for handling the MINIGENERATOR

Advance Preparation The radiation tube should be prechecked, especially if it is battery operated. For practical background, read *Handle Radioisotopes Safely,* a publication in the *"How To"* series published by the National Science Teachers Association.

Prelab Discussion Demonstrate the use of the detector tube and show students how to read the meter, allowing for the fluctuations in the counting rate. Explain the use of different scale factors.

Laboratory Safety Review with your students the standard laboratory safety rules they should be following. Point out the safety section in the Appendix at the end of the student module.

Laboratory Tips The size of the container as well as the radius of the detector tube must be included in the total distance measured. When students take activity readings, the distance between the MINIGENERATOR and the detector must be accurately measured. Although the MINIGENERATOR is not strictly a point source, dimensional effects are minimized by standing the MINIGENERATOR on its end and measuring the distance from the radioactivity symbol on the cylinder to the face of the detector.

Remind your students to subtract the average background radiation from each reading. Statistical fluctuations of the count rate will be important when the detector is at large distances from the source. Consequently, as the counting rate decreases to levels near background, the data will deviate more from the expected curve.

Range of Results Have students put collected data on the chalkboard. Use the average of the data for drawing conclusions.

Postlab Discussion This experiment illustrates the concept of a field of radiation surrounding any source of radioactivity. The gamma rays emitted from the $^{113}Sn/^{113m}In$ MINIGENERATOR effectively demonstrate this principle.

It is useful to describe the field in terms of an absolute number of lines of flux that extend radially outward through concentric spherical shells. The same number of lines of flux pass through each shell (which has a surface area of $4\pi R^2$), but because the lines spread apart, the flux density decreases. We can consider flux density to mean the number of lines of flux that pass perpendicularly through a unit area (1 cm^2) on the surface of any shell.

To illustrate the unity of the properties of all electromagnetic waves, the field description of gamma radiation is compared to light photons emanating from a point source. If any lab study of light propagation has been done by the students, it would be useful to point out the parallels between the two experiments. Also, the principle of distance affecting radiation dosage is fundamental to the safe handling of radioactive materials, as well as the use of microwave ovens, dental and medical X-ray machines, and so on.

Answers to Questions

1. The activity is usually more than the expected ¼. This is in part because the source is not a point in space but has a finite size.
2. The gamma-ray intensity becomes ⅑ as great.
3. The farther you stand from a radioactive source, the safer you are. By doubling the distance, you reduce your exposure fourfold.

Additional Activities

1. Students can check the radiation intensity of other sources, such as an old radium-dial watch or a piece of old orange Fiesta ware.
2. A wide range of experiments that have been tested for high-school use are described in the following paperbacks.
   a. Grafton D. Chase, Stephen Rituper, Jr., and John W. Sulcoski. *Experiments in Nuclear Science*. Minneapolis: Burgess Publishing Company, 1971.
   b. Sr. M. Hermias, and Sr. M. Joecile. *Radioactivity: Fundamentals and Experiments*. New York: Holt, Rinehart & Winston, 1963.

ANSWERS TO PROBLEMS

(Student module page 15)

1. Proton, neutron, and electron; all have mass.
2. $+5 - 2 = +3$
3. $7 + 8 = 15$ nucleons
4. $(\frac{1}{2})$ (4000) = 2000 nuclei remaining after 1 h

   $(\frac{1}{2})(\frac{1}{2})$ (4000) = 1000 nuclei remaining after 2 h

   $(\frac{1}{2})(\frac{1}{2})(\frac{1}{2})(\frac{1}{2})$ (4000) = 250 nuclei remaining after 4 h
5. $\frac{200}{800} = \frac{1}{4} = (\frac{1}{2})(\frac{1}{2})$; therefore, 40 minutes represents two half-lives; $t_{1/2} = 20$ min
6. a. Yes; mass of products is greater than mass of reactants.
   b. No.
   c. $E = mc^2$

   $$E = (m_1 - m_2)c^2$$
   $$= (17.999\,876 \text{ u} - 18.000\,003 \text{ u})c^2$$
   $$= (-0.000\,127 \text{ u})c^2$$
   $$= (-0.000\,127 \text{ u}) = (931.5 \text{ MeV/u})$$
   $$= -0.118 \text{ MeV}$$

   Therefore, 0.118 MeV will be required.
7. We are not concerned here with the conservation of leptons. The leptons include neutrinos, which we do not discuss in this text. For this reason our treatment here is not complete for the weak interaction, which involves leptons.
   a. No; charge is not conserved.
   b. Yes. (*Note:* leptons are not conserved.)
   c. No; nucleons are not conserved.
   d. Yes.
   e. No; nucleons and mass are not conserved (2 Cl on left and 3 on right).

EVALUATION ITEMS

The following are additional evaluation items that you may wish to use with your students at various times during the preceding unit. The correct answer to each question is indicated by shading.

1. Of the three basic forces—gravitational, electromagnetic, and nuclear—which two are able to attract a proton and a neutron to one another?

   nuclear, gravitational

2. Of the three basic forces—gravitational, electromagnetic, and nuclear—which two are able to attract a proton and an electron to one another?

   gravitational, electromagnetic

3. Of the three basic forces—gravitational, electromagnetic, and nuclear—which two are able to attract two neutrons to one another?

   gravitational, nuclear

4. A nucleus is composed of

   A. electrons and protons.
   B. neutrons and protons.
   C. electrons, protons, and neutrons.
   D. electrons and neutrons.

5. Match the following.

D	isobars	A.	nuclides with same number of protons
C	atomic mass (in grams)	B.	total number of protons and neutrons in a nucleus
E	atomic number	C.	mass of a mole of atoms of an element
B	mass number	D.	nuclides with equal mass numbers
A	isotopes	E.	total number of protons in a nucleus

6. The nuclide $^{238}_{92}U$ has all of the following, *except:*

   A. 92 protons C. 238 nucleons
   B. 92 neutrons D. 92 electrons

7. Given the reaction $^{10}_{5}B + n \longrightarrow {}^{4}_{2}He + \_\_$, the missing product is

   A. $^{6}_{4}Be$. B. $^{7}_{3}Li$. C. $^{8}_{4}Be$. D. $^{7}_{3}He$.

8. If a radioactive sample has an activity of 400 cpm at a distance of 2 cm from a Geiger counter, what will be its activity at a distance of 4 cm?

   A. 100 cpm C. 50 cpm
   B. 200 cpm D. 400 cpm

9. Assume that the oxygen atom consists of eight hydrogen atoms and eight neutrons. Calculate the binding energy of oxygen per nucleon, given the following masses.

   mass $^{16}_{8}O$ = 15.99491 u
   mass $^{1}_{1}H$ = 1.007825 u
   mass $^{1}_{0}n$ = 1.008665 u

   7.976 MeV/nucleon

10. One of our greatest hopes for long-range power production is the controlled, nuclear-fusion reaction. If $^{6}_{3}Li$ and $^{2}_{1}H$ are used as reactants in such a device, the reaction that takes place is $^{6}_{3}Li + {}^{2}_{1}H \longrightarrow 2\ {}^{4}_{2}He$. (Remember that $E = mc^2$, where $c^2 = 931$ MeV/u. Use the following atomic masses: $^{6}_{3}Li = 6.0161$ u; $^{2}_{1}H = 2.0141$ u; $^{4}_{2}He = 4.0026$ u.) The number of MeV produced in the reaction is

    A. 3724 MeV. C. 23.3 MeV.
    B. 30.1 MeV. D. 14.896 MeV.

11. In the reaction $^{1}_{1}H \longrightarrow {}^{0}_{1}\beta$ + gamma ray, the conservation law that is violated is

    A. the conservation of charge. C. the conservation of nucleons.
    B. the conservation of energy. D. all of the above

12. Stars and cyclotrons are similar in that they both

    A. undergo nuclear fission.
    B. are particle accelerators.
    C. undergo nuclear fusion.
    D. emit cosmic rays.

13. The neutron has

    A. a positive charge.
    B. a negative charge.
    C. no charge.
    D. approximately the same mass as an electron.

SUGGESTED READINGS

Throughout this teacher's guide we have referred to more detailed writings on specific module topics. Whenever possible, we have referred to articles in *Scientific American* and other journals that provide expanded accounts of present knowledge.

Asimov, Isaac. *Inside the Atom.* New York: Abelard-Schuman, 1966.

Cline, D. B.; Mann, A. K.; and Rubbia, C. "The Search for New Families of Elementary Particles." *Scientific American*, January 1976, p. 44.

Crichton, Michael. *The Andromeda Strain.* New York: Knopf, 1969.

Trower, W. Peter. "Matter and Anti-Matter." *Chemistry*, October 1969, pp. 8–13.

Wilson, R. R. "The Batavia Accelerator." *Scientific American*, February 1974, p. 72.

SUGGESTED FILMS

An Added Sense: The Detection of Nuclear Radiation. Color, 24 minutes. U.S. Department of Energy, Film Library, P.O. Box 62, Oak Ridge, TN 37830.
A presentation of concepts significant to detector technology, such as the design of gas-ionization chambers, forms of nuclear radiation, and the use of proportional and scintillation counters and of thermoluminescence.

A Beginning Without End. Color, 30 minutes. U.S. Department of Energy, P.O. Box 62, Oak Ridge, TN 37830.
Dr. Ernest Lawrence's work on the invention and development of the cyclotron is covered.

Building an Atomic Accelerator. Color, 20 minutes. U.S. Department of Energy, Film Library, P.O. Box 62, Oak Ridge, TN 37830.
Explains the reasons for building an accelerator and describes the basic parts in order to show how the machine works.

Exploring the Atomic Nucleus. Color, 13½ minutes. U.S. Department of Energy, Film Library, P.O. Box 62, Oak Ridge, TN 37830.
A discussion of the use of particle accelerators to explore the atomic nucleus and of processes such as bombardment, particle-interaction detection, and analysis by means of bubble-chamber photographs.

The Heart of the Matter. Color, 16 minutes. U.S. Department of Energy, Film Library, P.O. Box 62, Oak Ridge, TN 37830.
Scientists at the ERDA Fermi National Accelerator Laboratory use atomic particles and the most powerful microscope ever designed to help them search for and analyze some of the ultimate particles of matter.

Powers of Ten. Color, 9 minutes. Pyramid Films, Santa Monica, CA 90406.

Universe. Color, 28 minutes. National Aeronautics and Space Administration. (Please order this film from the NASA Film Library serving the state in which you live.)
Explores almost inconceivable extremes of size (from galaxies to subatomic particles) and time (from cosmic events that occurred billions of years in the past to microcosmic events in the present that endure for only a billionth of a second).

The Makeup of Our Solar System

As an introduction to this unit, you might review briefly with your students their understanding of the solar system. Then refer to the photograph of the planets that is shown on page 16 of the student module and ask: How do the planets differ from one another? What are the special features of Mars and Venus? Of Jupiter? Conclude your introductory comments with a reference to the key questions in the student module: What elements exist in our solar system? How much of each element is present in nature?

N-10 IDENTIFYING THE NUCLIDES

This section provides the basic definitions and nomenclature required to discuss atomic nuclei. One additional point is worth noting. In the nuclear representation

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

the upper right is reserved for the chemical ion state. For example, the complete description of the sodium ion is

$$^{23}_{11}Na^{+}_{12}$$

Point out that the prefix *iso* means "same"; thus, the term *isoelectronic*, as used in inorganic chemistry, means "having the same number of electrons."

ANSWERS TO PROBLEMS

(Student module page 18)

1. a. $^{23}_{11}Na_{12}$
   b. $^{31}_{16}S_{15}$
   c. $^{18}_{8}O_{10}$

2. $^{23}_{12}Mg$ and $^{26}_{12}Mg$ are isotopes
   $^{22}_{10}Ne$ and $^{22}_{11}Na$ are isobars
   $^{22}_{11}Na$ and $^{23}_{12}Mg$ are isotones

N-11 NUCLEAR STABILITY

The "sea of nuclear instability" (Figure 4, student module page 18) is an extremely valuable analogy, if properly utilized. Because it summarizes most of the features of nuclear structure needed for an understanding of the remainder of the module, we urge you to place special emphasis on Figure 4 in your preparation of this section. The key is that the higher the elevation, the more likely it is that a given number of neutrons and protons will stick together to form a stable nucleus. For the nuclear species below sea level, the nuclear force is such that radioactive transformations occur faster than we can observe them. The "island of stability" beyond the "peninsula" is purely theoretical at this time. It may turn out to be below sea level; only future experiments will tell.

A large number of experiments designed to detect the existence of superheavy elements in nature, or to produce them in the laboratory, have been carried out, but none have been successful as of this writing. The greatest hope for our observation of these elements probably lies in specially designed superheavy-ion accelerators recently built in the United States, France, West Germany, and the Soviet Union.

Heavy nuclei tend to be more stable when they have an excess of neutrons over protons, since this eases the competition between the nuclear and electromagnetic forces. As more and more protons are added to a nucleus, the electrostatic repulsion between identical charges acts in opposition to the nuclear attraction. The presence of additional neutrons serves as insulation for the protons against their charge repulsion. This also accounts for the fact that the "peninsula of stability" eventually drops off into the sea; that is, for very heavy nuclei the charge becomes so great that the nuclear force is no longer strong enough to hold the nucleus together. The "island of stability" can exist only because of the special stability afforded by closed nuclear shells that are predicted to exist at $Z = 114$ and $N = 184$.

The elevation of the peninsula in the sea of instability is measured in an absolute sense by the average binding energy of a nucleus. This is the average amount of mass that is converted into energy to bind nucleons together in a nucleus. Figure 6 (student module page 20) is a plot of the average binding energy for those nuclides that run along the uppermost ridge in the sea of stability, or the continental divide, so to speak. Zero binding energy corresponds to the bottom of the ocean, and sea level is about 5–6 MeV/nucleon in most cases. Mathematically, the average binding energy, $\overline{B.E.}$, for any nucleus is computed as

$$\overline{B.E.} = \frac{[Z\,m_{\rm H} + N\,m_n - m(A,Z)]c^2}{A}$$

Here, Z is the number of protons, $m_{\rm H}$ is the mass of the hydrogen atom *(which simultaneously accounts for the mass of the atomic electrons)*, N is the number of neutrons, m_n is the mass of the neutron, $m(A,Z)$ is the mass of a nuclide having A nucleons and Z protons, and A is the number of nucleons. A large value of $\overline{B.E.}$ corresponds to a system that is tightly bound together and, therefore, very stable. Consequently, it rises high out of the sea of instability. Low values, by contrast, are submerged below sea level. As a sample computation, the average binding energy of $^{12}_{6}C$ is calculated here.

$$\begin{aligned}\overline{B.E.}\,(^{12}_{6}C) &= [6m_{\rm H} + 6m_n) - m\,(^{12}_{6}C)]c^2/12\\ &= [6(1.007\,825) + 6(1.008\,665)\\ &\quad - 12.000\,000]u\ (931.48\ \text{MeV/u})/12\\ \overline{B.E.} &= 7.68\ \text{MeV for } ^{12}_{6}C\end{aligned}$$

In relation to the criteria for nuclear stability, it may also be worth mentioning to your students that stable nuclei prefer even numbers of neutrons and protons as compared to odd numbers. This is shown in the following table.

Nuclear Type	*Number of Stable Nuclei*
Z-even, *N*-even	171
Z-even, *N*-odd	55
Z-odd, *N*-even	50
Z-odd, *N*-odd	4

The closed-shell configurations (or magic numbers) for nucleons are derived in the same way as are those for electrons in atoms. That is, a quantum-mechanical problem describing the forces that act on the particles in the system is solved by using the Schrodinger equation. For atoms, the particles consist of electrons and a nucleus; the forces are the electromagnetic attraction between oppositely charged particles and the repulsion between electrons. For nuclei, the particles are neutrons and protons; the forces are the nuclear force of attraction and the electromagnetic repulsion between protons. Because the forces and particles are different in the two cases, it is not surprising that the magic numbers are different. The predictions of closed shells at $Z = 114$ and $N = 184$ are the results of a large number of modern calculations. One final word: The next proton shell beyond 82 is predicted to occur at $Z = 114$ instead of at 126 (as observed for neutrons) because of the influence of the electromagnetic force on protons, a force that doesn't exist for neutrons.

Enlarged versions of the illustrations that appear on pages 18, 19, and 20 of the student module have been included on the following pages. You may reproduce these pages in classroom quantities or make overhead projectuals for use in your classroom discussion.

The effect of isotopes on elemental atomic masses can be demonstrated here. Although we have defined the atomic mass of ^{12}C as 12.000 000 u, the student may note that the tabulated atomic mass for carbon shown on many charts is 12.01u. This is because carbon in nature consists primarily of two isotopes, ^{12}C and ^{13}C. Their relative abundances are 98.892 percent for ^{12}C and 1.108 percent for ^{13}C. Therefore, the element carbon has the following average atomic mass.

$$m(^{12}\mathrm{C}) \times \frac{\%(^{12}\mathrm{C})}{100} = (12.000\,000\ \mathrm{u})\ (0.988\,92)$$
$$= 11.867\ \mathrm{u}$$
$$m(^{13}\mathrm{C}) \times \frac{\%(^{13}\mathrm{C})}{100} = (13.003\,355\ \mathrm{u})\ (0.011\,08)$$
$$= 0.1441\ \mathrm{u}$$
$$(11.867 + 0.1441)\mathrm{u} = 12.011\ \mathrm{u}$$

This is also a useful exercise in significant figures; as you will note, the multiplication products are determined by the significant digits in the percentages of carbon, and the addition sum is limited by the mass times percentage product for ^{12}C. Many exercises such as these can be readily generated.

At this point in the student module, the three basic types of radioactive decay are introduced. Although these will be discussed in detail in *Radioactive Decay*, a qualitative idea of the actual processes that occur in radioactive decay will help students understand both nuclear stability and nucleosynthesis of the elements.

N-12 TRANSMUTATION OF ELEMENTS

This section emphasizes the very important concept that an element can be spontaneously transformed (transmuted) into a new element by radioactive decay. This concept, of course, is not true for chemical reactions in which the identity of the elements always remains unchanged. In addition, section *N-12* serves as an introduction to experiment *N-13*, in which transmutation is illustrated by means of a chemical separation technique. A similar demonstration can be performed with $^{137}Cs/^{137m}Ba$ MINIGENERATORS. Because of the short half-life of ^{137m}Ba, it is necessary to correct the results caused by the radioactive decay of that nuclide. However, if one works quickly (within 5 minutes), a qualitatively correct result can be obtained, even with the uncorrected data.

EXPERIMENT
N-13 THE CHEMISTRY OF RADIOACTIVE NUCLIDES

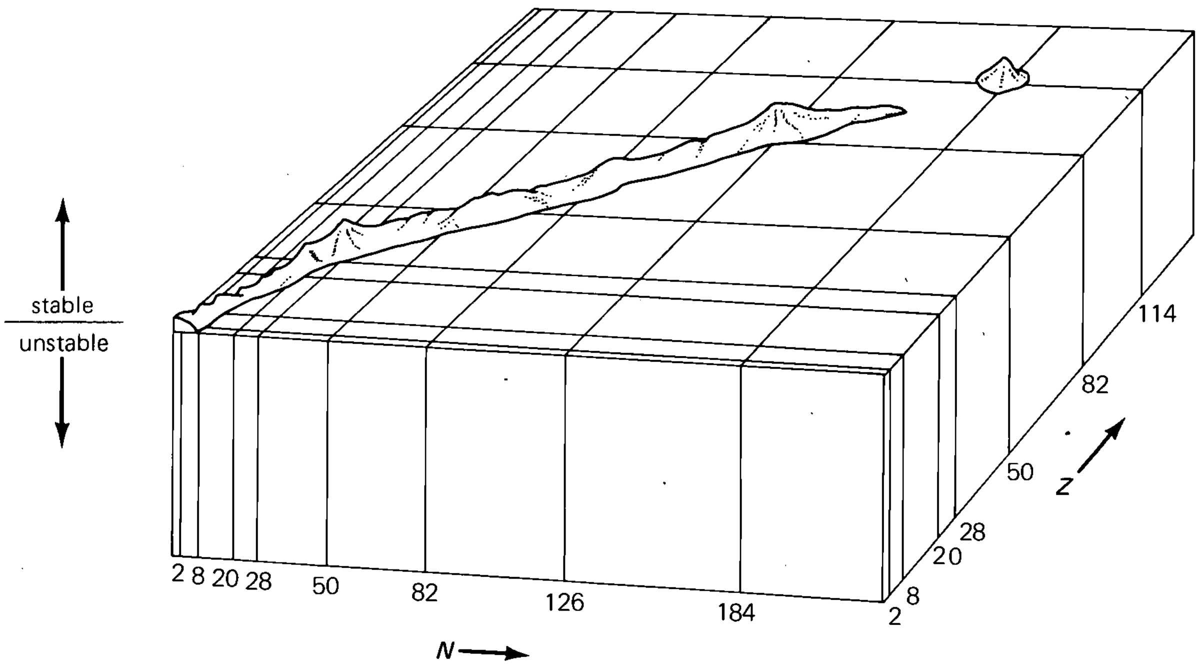
The actual placement of this experiment* is somewhat up to your discretion. Logically, it should precede the measurement of a half-life for nuclear decay in order to give the student experience with the techniques of eluting the MINIGENERATOR. The purpose of the experiment is to introduce the student to the process of eluting the MINIGENERATOR and handling an eluted isotope in liquid form.

Concepts

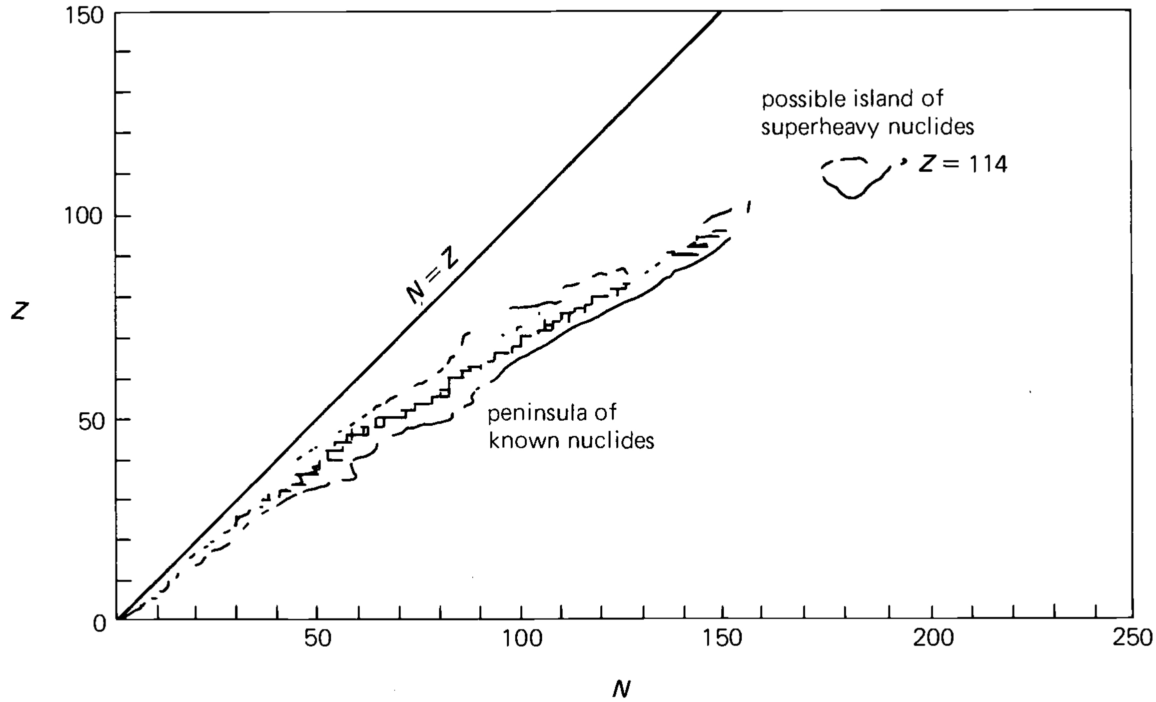
- Radioactive decay transmutes one element into another.
- The concentration of a liquid radioactive source is the ratio of its activity to the volume of solution in which it is found.
- Substances can be separated by differences in their chemical attraction to ion-exchange resins.

*Experiment from MINIGENERATOR *Experiments in Nucleonics* (New York: Union Carbide Corp., 1968). Available from Redco Science Inc., Danbury, CT 06810 and from other distributors.

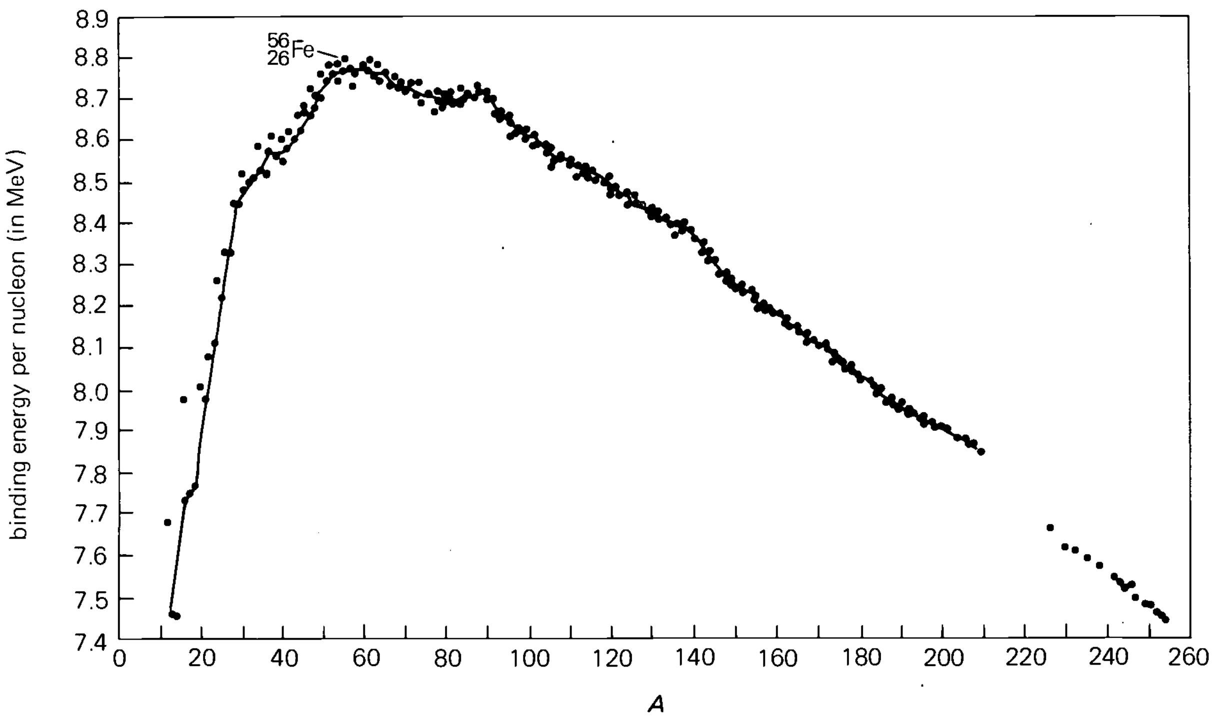
THE SEA OF NUCLEAR INSTABILITY



OVERHEAD VIEW OF THE SEA OF INSTABILITY



ALTITUDE MAP OF THE RIDGE ALONG THE PENINSULA OF STABILITY



Objectives

- Separate two radioactive nuclides by elution from an ion-exchange resin.
- Determine the volume of eluant needed to separate ^{113m}In from ^{113}Sn.
- Measure and record radioactivity in counts per minute.
- Graph data and interpret the graph.

Estimated Time One period

Student Grouping Group size (two to five students) will depend on the equipment available.

Materials

2 cm^3 eluant solution of HCl and NaCl
counter
$^{113}Sn/^{113m}In$ source
25 planchets
plastic squeeze bottle
graph paper
pair of rubber gloves

Advance Preparation To prepare the eluant solution, dilute 3.3 cm^3 12 M HCl (concentrated) to 100 cm^3 and then add 9 g NaCl. You can easily make the planchet by cutting circles of aluminum foil 2.5 cm in diameter. Be sure the rubber caps are replaced on the MINIGENERATORS. If they are not, the ion-exchange resin dries out and future "milkings" are not possible.

Two cubic centimeters of the eluant will yield approximately 35 drops of eluate from the MINIGENERATOR. It is not important that exactly 25 drops be available to the student for 25 planchets. In this experiment the student will deposit one drop on each planchet before taking any activity readings.

Prelab Discussion Describe the principle of a radioisotope generator. Also, discuss what happens in the elution process.

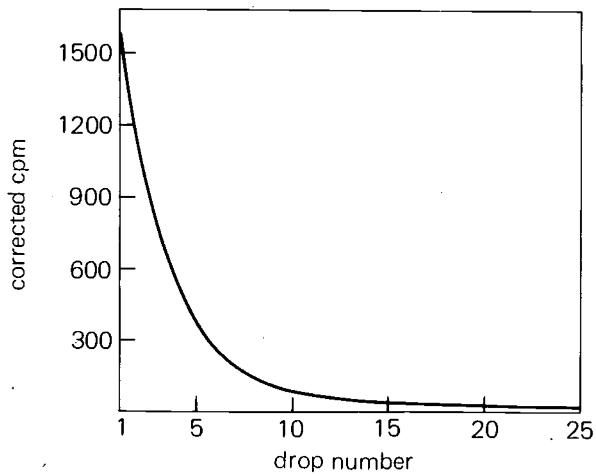
Laboratory Safety Although this experiment has been safety tested, students should learn to handle radioactive materials with caution. Provide brief instructions on the handling and disposing of waste materials. Students handling the radioactive isotopes should wear gloves.

Laboratory Tips You may wish to instruct your students in the use of semilog graph paper. Remind them that it is not necessary to take the logarithm of the number on the ordinate scale—the graph paper does that. Simply plot one number against the other, taking care to read the scales properly.

Range of Results

SAMPLE DATA
Background = 190 cpm

Drop Number	*cpm*	*cpm Corrected for Background*
1	1764	1574
2	1060	870
3	732	542
4	628	438
5	560	370
—	—	—
—	—	—
—	—	—
25	208	18



Postlab Discussion The point to emphasize in this experiment is that radioactive decay transmutes one element into another. This is clearly evident because the tin is tightly held by an ion-exchange column and cannot be washed off easily. On the other hand, the indium product is readily removed from the column. Do not worry about the mechanism of decay in this section. As evidence for the fact that it is indium and not tin that is eluted from the column, note that the last few drops contain almost no activity, and that the MINIGENERATOR still gives evidence of its original activity.

The concentration of a radioactive source is the ratio of its activity to the volume of solution in which it is contained. The concentration is often expressed in microcuries per cubic centimeter. When eluting the MINIGENERATOR, students will find that the greatest amount of activity occurs in the first few drops eluted. As more eluant is used, the sample is diluted and the concentration decreases, although the absolute activity continues to increase slowly. You might point out to the students that the concept of concentration is important in administering radioactive tracers to patients, where the dosage is often defined in volume units rather than in specific activity (the ratio of activity of a radioisotope to the weight of all the isotopes, both stable and radioactive, of that element in the sample).

Answers to Questions

1. The first drop yields the greatest activity.
2. It is suggested that the students figure out for themselves a method to determine how many drops will be needed to elute at least 75 percent of the potential total activity. The students should be asked to explain their reasoning. The number of drops required will be between five and ten. The purpose of this question is to have each student carefully think through the elution process rather than just arrive at a "right" answer.
3. After one day all the ^{113m}In will have decayed to stable ^{113}In. The resultant solution will no longer be radioactive, and the total number of indium atoms ($\sim 10^7$) will be so small that they will not constitute any potential chemical pollution source.

Additional Activity If students wish more experience with the type of activity that experiment *N-13* presents, refer them to Experiment 6 in *Experiments in Nucleonics* (Danbury, Conn.: Redco Science Inc., 1968). This experiment adds the complication that the barium product has a short (2.6 minutes) half-life, so that decay during the experiment must be taken into account. This is not necessary in the Sn/In experiment because little decay occurs during the long (100 minutes) half-life of indium.

N-14 THE ELEMENTS IN OUR SOLAR SYSTEM

A feeling for the relative distribution of the elements in our solar system should result from a study of this section. The data listed in Table 4 (student module page 26) constitute a fundamental piece of information that theories of nucleosynthesis must reproduce. Note that Li, Be, and B are only briefly mentioned and have very low abundances. The mechanisms that generated these elements are still the subject of debate, but it seems highly improbable that they were formed in the same way that most of the other elements were. They probably originated in cosmic-ray-induced nuclear reactions between protons and C, N, and O. The absence of stable nuclides with $A = 5$ and $A = 8$ accounts for the zero percentage of these mass numbers in the solar system. The nuclides ^{5}Li and ^{5}He live only 10^{-21} seconds, at most. All nuclides with mass $A = 8$ decay to ^{8}Be, which has a half-life of only 10^{-16} seconds.

The abundance of information given in this section of the student module has been obtained from various sources. Particularly important are the data from analyses of meteorites and from the radiation spectrum of the Sun. Meteorites are thought to be "primordial" material of the solar system; they condensed into solid bodies soon after their formation and have experienced little chemical change since then. However, this is not true of the Earth, which has a molten core and an active atmosphere. Therefore, the chemical analysis of meteorites is a very important source of information about the solar system. The light emitted by excited atoms on the surface of the Sun and other stars is also of great importance in deducing relative chemical abundances. Because the Sun is the most massive object in the solar system, the distribution of elements in the Sun is an important factor in the overall picture of the solar system. From a knowledge of the spectra of elements on the Earth, we can identify the elements in stars by comparing stellar spectra with known values.

ANSWERS TO PROBLEMS

(Student module page 28)

1. **a.** potassium
   b. 19
   c. 40
   d. 19
   e. 39.1
   f. 21
   g. 19
   h. 18
   i. Yes. If the average mass of all isotopes is 39.1, then at least one stable isotope with mass of less than 40 must be present. The actual abundances of the K isotopes are ^{39}K(93.26%), ^{40}K(0.011%), and ^{41}K(6.73%).
2. **a.** $^{7}_{3}Li_{4}$
   b. $^{24}_{12}Mg_{12}$
   c. $^{37}_{17}Cl_{20}$
3. **a.** ^{13}C; $N \simeq Z$
   b. ^{56}Fe; most stable nucleus; $N \simeq Z$
   c. ^{23}Na; $N \simeq Z$
   d. ^{56}Fe; most stable nucleus; $N \simeq Z$
   e. ^{4}He; nearer ^{56}Fe; closed neutron and proton shells
4. **a.** Fe
   b. Mg
   c. O
   d. Si
   e. Cu

EVALUATION ITEMS

The following are additional evaluation items that you may wish to use with your students at various times during the preceding unit. The correct answer to each question is indicated by shading.

1. In terms of the "sea of instability," which element has the most stable nucleus?

   A. $^{12}_{6}C$ B. $^{28}_{14}Si$ $\boxed{\text{C.}}$ $^{56}_{26}Fe$ D. $^{238}_{92}U$

2. Which nucleus containing the following is likely to be the most stable?

   A. 90 protons and 147 neutrons
   $\boxed{\text{B.}}$ 90 protons and 144 neutrons
   C. 91 protons and 145 neutrons
   D. 90 protons and 144 neutrons

3. Given the atom

   $$^{31}_{16}S_{15}$$

   list the number of protons, neutrons, and nucleons in the nucleus.

   16 protons
   15 neutrons
   31 nucleons

4. Which one of the following nuclear types has the greatest number of stable nuclei?

   A. Z-even, N-even C. Z-odd, N-even
   $\boxed{\text{B.}}$ Z-even, N-odd D. Z-odd, N-odd

5. Which nuclide of each pair is more stable?

   A. $^{25}_{12}X$ or $\boxed{^{26}_{12}X}$

   B. $\boxed{^{32}_{16}X}$ or $^{40}_{16}X$

   C. $\boxed{^{210}_{84}X}$ or $^{212}_{84}X$

SUGGESTED READINGS

Cameron, I. R. "Meteorites and Cosmic Radiation." *Scientific American,* July 1973, pp. 64–73.
Harvey, Bernard. *Nuclear Chemistry.* New Jersey: Prentice-Hall, 1965.
Lewis, J. S. "The Chemistry of the Solar System." *Scientific American,* July 1973, pp. 50–65.
Pasachoff, J. M., and Fowler, W. A. "Deuterium in the Universe." *Scientific American,* May 1974, pp. 108–118.
Scientific American, September 1975. (Entire issue is devoted to the solar system.)
Zafiratos, C. D. "The Texture of the Nuclear Surface." *Scientific American,* October 1972, pp. 100–108.

SUGGESTED FILMS

Satellites of the Sun. Color, 12 minutes. Canadian Consulate General, 1251 Avenue of the Americas, New York, NY 10020.
Through the art of the film, vast distances are overcome and the solar system is presented in amazing detail and perspective.

Nucleosynthesis and Stellar Evolution

The rationale for beginning this discussion with elementary particles and building up to more complex nuclei is that such a process does not have to be very efficient but can still produce the observed elemental abundances. (See Table 4 in the student module.) That is, the solar system has lots of hydrogen and helium but very little of the elements beyond iron. If complex nuclei were the starting material for element synthesis, the nuclear processes necessary to produce the observed abundances would have had to be very efficient.

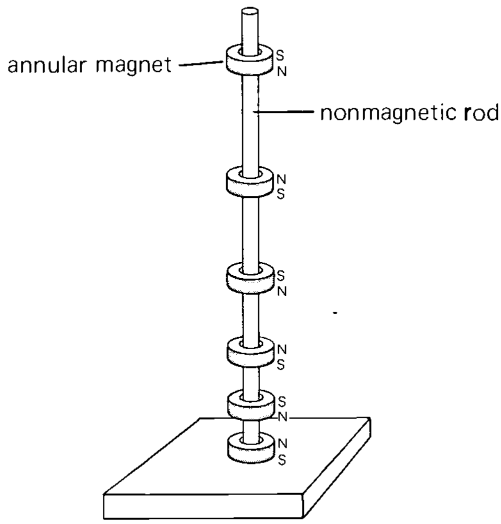
N-15 THE "BIG BANG" THEORY

The *big bang* theory of the Universe has come to be generally accepted during the past decade. Since the studies by Hubble in the early part of the twentieth century, the theory of the expansion of the Universe has become recognized. More recently, in the 1960s, the discovery of the 3-K background radiation in the Universe by Penzias and Wilson (for which they received the Nobel prize in physics in 1978) solidified arguments that the expansion of the Universe originated in the big bang. For an intriguing discussion of the big bang in general terms, refer to S. Weinberg's book *The First Three Minutes* (New York: Basic Books, 1977), which is listed in the *Selected Readings* of the student module. (Weinberg was a corecipient of the Nobel prize in physics in 1979.)

In addition to the reasons stated in the student module, there is further evidence that the big bang probably did not produce the elements beyond lithium. The widely different element compositions of stars implies that the elements were produced by other means as well. This observation, together with the technetium data discussed in the student module, indicates that it is probable that element synthesis is a continuing process in stars rather than something that occurred in only a single big bang event.

Demonstration This is a useful demonstration of the competition between the electromagnetic force and the force of gravity. Its purpose is to show how increasing mass can reduce the effects of electromagnetic repulsion. The same situation is found in stars, although, of course, on a much larger scale. The necessary apparatus consists of the following items.

- a set (4–6) of annular magnets (similar to those used in many kitchen gadgets for attaching hooks to metal surfaces)
- a smooth, nonmagnetic rod mounted vertically (The magnets will be slipped over the rod. Friction losses should be made as small as possible by applying light oil or glycerine to the rod.)



Setup to demonstrate competition between magnetic and gravitational forces.

To demonstrate the desired effect, two magnets are slipped over the rod with like poles facing one another. Measure the equilibrium distance between these two magnets. Now, add a third magnet so that it repels the magnet below it. Again measure the equilibrium distance between the first two magnets. Continue adding magnets in this fashion (similar poles facing each other) and record the distance between the first two magnets each time.

You will observe that as more magnets (mass) are added, the distance between the bottom two magnets becomes smaller. You can point out that this is not an effect of the electromagnetic attraction between the first, third, and fifth magnets because the distance between the highest two magnets on the stack remains about equal to that when only two magnets were on the stack.

The balancing of nuclear reactions is simpler than the balancing of chemical reactions. Simply stated, the sum of the *A* superscripts must be the same on both the right- and left-hand sides of an equation. The same must be true of the *Z* subscripts. In principle, any nucleus can be formed in a nuclear reaction if enough energy is available.

The neutrons that remained at the end of the big bang explosion were unstable and underwent decay to protons.

$$^{1}_{0}n \longrightarrow {}^{1}_{1}\text{H} + {}^{0}_{-1}\beta$$

It would be more precise to write the neutron-decay equation as

$$^{1}_{0}n \longrightarrow {}^{1}_{1}\text{H} + {}^{0}_{-1}\beta + \bar{\nu}$$

An antineutrino is formed in this reaction. Neutrinos commonly accompany the formation of electrons and are associated with the weak nuclear force. We have omitted discussion of neutrinos in the student module in order to simplify the presentation.

In writing the nuclear equation for the neutron decay, one would also be more accurate to write that the hydrogen *ion* (or bare proton) is formed and not the hydrogen *atom*. However, in balancing nuclear equations, one usually does not write ionic states. By always using the mass of a neutral atom (which has its exact complement of electrons), one always obtains the correct answer in nuclear calculations.

ANSWERS TO PROBLEMS

(Student module page 31)

1. $^{2}_{1}\text{H} + {}^{1}_{0}n \longrightarrow {}^{3}_{1}\text{H}$
2. $^{4}_{2}\text{He} + {}^{3}_{2}\text{He} \longrightarrow {}^{7}_{4}\text{Be}$
3. $^{4}_{2}\text{He} + {}^{2}_{1}\text{H} \longrightarrow {}^{6}_{3}\text{Li}$
4. $^{4}_{2}\text{He} + {}^{3}_{1}\text{H} \longrightarrow {}^{7}_{3}\text{Li}$
5. $^{3}_{2}\text{He} + {}^{3}_{1}\text{H} \longrightarrow {}^{6}_{3}\text{Li}$

N-16 STARS FROM BIG BANG DUST

The point to stress in this section is that because of gravity, condensation of the cosmic dust can occur in localized regions of space. This results in an increase in density and subsequent temperature rise for the matter in this region. This process represents the initial stages of star formation and develops the conditions that eventually lead to element synthesis.

It should be noted that at temperatures above about 10 000 K the atoms that constitute the big bang dust are completely ionized into nuclei and electrons. The electrons are present in the core of a star (preserving overall electrical neutrality), but they probably exist in the form of an electron gas rather than being confined to discrete atomic orbitals. Because of the complicated nature of this electron gas, it is not discussed in this module. Once the stellar material cools below about 10 000 K, the electrons that are present attach themselves to the nuclei and thus form neutral atoms.

N-17 H-BURNING: MAIN SEQUENCE STARS

In addition to describing the principles by which the Sun generates energy, this section stresses the concept of mass–energy conversion. The calculation of energy changes in nuclear reactions is introduced in the student module. The nomenclature defines the energy change ΔE in such a way that ΔE is positive when energy is released and negative when it is absorbed. The calculation for the amount of energy released in equation (3) of section *N-17* follows.

ANSWER TO PROBLEM

(Student module page 35)

Equation (3) in *N-17* is

$$^{3}_{2}\text{He} + {}^{3}_{2}\text{He} \longrightarrow {}^{4}_{2}\text{He} + 2\,{}^{1}_{1}\text{H} + 12.9\text{ MeV}$$

To prove that the energy released is 12.9 MeV, we can use the formula $E = mc^2$.

$$\Delta E = [2\,m({}^{3}_{2}\text{He}) - m({}^{4}_{2}\text{He}) - m({}^{1}_{1}\text{H})]c^2$$
$$\Delta E = [2(3.016\ 030)\text{ u} - (4.002\ 603\text{ u}) - 2(1.007\ 825)\text{ u}]c^2$$
$$\Delta E = (0.013\ 807\text{ u})(931.5\text{ MeV/u})$$
$$\Delta E = 12.90\text{ MeV}$$

In addition to the proton-proton cycle, there are other ways in which hydrogen burning can occur. For example, in stars where ^{12}C is present, the following set of reactions, known as the Carbon-Nitrogen-Oxygen cycle, can occur.

$$^{12}_{6}C + ^{1}_{1}H \longrightarrow ^{13}_{7}N;\ ^{13}_{7}N \longrightarrow ^{13}_{6}C + ^{0}_{1}\beta \quad (1)$$
$$^{13}_{6}C + ^{1}_{1}H \longrightarrow ^{14}_{7}N \quad (2)$$
$$^{14}_{7}N + ^{1}_{1}H \longrightarrow ^{15}_{8}O;\ ^{15}_{8}O \longrightarrow ^{15}_{7}N + ^{0}_{1}\beta \quad (3)$$
$$^{15}_{7}N + ^{1}_{1}H \longrightarrow ^{12}_{6}C + ^{4}_{2}He \quad (4)$$

$$\text{Net: } 4\ ^{1}_{1}H \longrightarrow ^{4}_{2}He + 2\ ^{0}_{1}\beta + 26.7 \text{ MeV} \quad (5)$$

Note that the net reaction, equation (5), is the same as that given in equation (4) in the student module.

This reaction was originally proposed by Hans Bethe, one of the pioneers in the field of applying nuclear reactions to stellar processes. It differs from the hydrogen-burning process given in the student module only in that $^{12}_{6}C$ nuclei serve as a catalyst for the reaction. The CNO cycle does occur to a small extent in the Sun. However, the cycle requires a higher temperature than that which we believe exists in the center of the Sun.

Thermonuclear fusion reactions (as in the hydrogen bomb) operate on the same principle. A solid such as $^{6}Li^{2}H$ or $^{6}Li^{3}H$ (which are composed of the less common isotopes of lithium and hydrogen) is used as the energy source. By achieving sufficiently high temperatures, the following self-sustaining set of reactions can occur. A neutron source is needed to trigger the reaction.

$$^{6}_{3}Li + ^{1}_{0}n \longrightarrow ^{4}_{2}He + ^{3}_{1}H + 4.8 \text{ MeV}$$
$$^{3}_{1}H + ^{2}_{1}H \longrightarrow ^{4}_{2}He + ^{1}_{0}n + 17.6 \text{ MeV}$$
$$^{3}_{1}H + ^{3}_{1}H \longrightarrow ^{4}_{2}He + 2\ ^{1}_{0}n + 1.3 \text{ MeV}$$

The energy released is generated very rapidly (the entire reaction is over in about 10^{-6} seconds) and, consequently, is highly explosive. Although the military applications of thermonuclear explosions have received great attention, underground tests have been conducted to investigate the possibility of using such blasts to produce new heavy elements. However, practical applications of such techniques are unlikely to occur except under very unusual conditions.

As can be noted through an examination of these equations, thermonuclear explosions produce a large number of neutrons. This fact is pointed out in the discussion of the *r*-process in section *N-20*.

Some success has been achieved with the controlled-fusion process containing ^{2}H, which is magnetically confined at very high densities in the form of a plasma. As discussed in section *N-48*, however, much work remains to be done before this process will ever provide usable energy.

ANSWERS TO PROBLEMS

(Student module page 37)

1. $^{3}_{1}H$
2. $^{4}_{2}He$
3. $2\ ^{1}_{0}n$

Shorthand notation for the equations is as follows.

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

N-18 HELIUM BURNING: RED GIANTS

The reactions we might expect to occur in a star that has burned much of its hydrogen into helium are

$$\left.\begin{array}{l} ^{4}_{2}He + ^{1}_{1}H \longrightarrow A = 5 \\ ^{4}_{2}He + ^{4}_{2}He \longrightarrow A = 8 \end{array}\right\} \text{not stable}$$

$$\left.\begin{array}{l} ^{4}_{2}He + ^{2,3}_{1}H \longrightarrow ^{6,7}_{3}Li \\ ^{4}_{2}He + ^{3}_{2}He \longrightarrow ^{7}_{4}Be \end{array}\right\} \text{collisions disintegrate products rapidly at } 10^{8}\text{K}$$

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

Only the last of these reactions—helium burning—is thought to be successful in producing heavier elements. Because the probability of forming a $^{8}_{4}Be$ nucleus and then capturing another ^{4}He during the lifetime of the ^{8}Be (10^{-16} seconds) is very small, the rate of nuclear burning is quite slow. This fact accounts for the long lifetimes of red giant stars. Nonetheless, the rate of exothermic nuclear burning is sufficient to balance gravitational contraction. Consequently, the red giants appear to be stable.

The 3 $^{4}He \longrightarrow {}^{12}C$ reaction cannot occur until a temperature of 100 000 000 K has been reached because the electric charge of the He nucleus is twice that of the proton. A much higher temperature is therefore required to make the He-He and He-Be collisions sufficiently energetic to overcome the mutual electric-charge repulsion and permit nuclear attraction to occur. In addition, at such temperatures nuclear reactions between ^{4}He and any Li, Be (except ^{8}Be), and B that might be formed in these reactions disintegrate these latter nuclei very rapidly. For this reason, the element-synthesis chain skips over the elements Li, Be, and B, which accounts for their low abundance in nature. (See Table 4, student module page 26.)

Besides the 3 $^{4}_{2}He$ reaction and the $^{12}C(^{4}He, \gamma)^{16}O$ reaction, small amounts of other nuclei in or near the core of a red giant take part in other types of nuclear reactions. For instance, reactions such as

$$^{16}_{8}O + ^{4}_{2}He \longrightarrow ^{20}_{10}Ne$$
$$^{12}_{6}C + ^{1}_{1}H \longrightarrow ^{13}_{7}N \longrightarrow ^{13}_{6}C + ^{0}_{1}\beta$$
$$^{16}_{8}O + ^{1}_{1}H \longrightarrow ^{17}_{9}F \longrightarrow ^{17}_{8}O + ^{0}_{1}\beta$$

can produce isotopes of Ne, C, O, and others.

Another type of reaction that can occur in red giant stars produces neutrons:

$$^{13}_{6}C + ^{4}_{2}He \longrightarrow ^{16}_{8}O + ^{1}_{0}n$$
$$^{17}_{8}O + ^{4}_{2}He \longrightarrow ^{20}_{10}Ne + ^{1}_{0}n$$

It is thought that these two reactions are the source of neutrons for the *s*-process (section N-23). An important point to remember is that as more new elements are produced in a star, the possibilities for nuclear reactions become greater.

The name *red giant* comes from the fact that these stars are very large and emit light in the red part of the visible spectrum. The increased size comes about because the intense heat of the stellar core expands the envelope of hydrogen gas surrounding it. Since the visible radiation from a star is emitted from its surface, a red giant has the appearance of being very large. However, the actual size of its nuclear furnace is smaller than that in a normal hydrogen-burning star. In about 5 billion years, the Sun is expected to reach the red giant stage and to envelop the Earth.

Miniactivity Have students use the shorthand notation to express the last two nuclear reactions discussed.

Answer: $^{13}C(^{4}He, n)^{16}O$ $^{17}O(^{4}He, n)^{20}Ne$

N-19 EXPLOSIVE NUCLEOSYNTHESIS

Explosive nucleosynthesis is an incompletely understood phase of stellar evolution that is currently the subject of much research. Because of the array of nuclei present in a star at this stage, a complex series of nuclear reactions is possible. Two important experimental facts influence our understanding of this process. First, reactions such as $^{28}Si + ^{28}Si \rightarrow ^{56}Ni$ are not very probable because of the large electrostatic charge between two nuclei with $Z = 14$. The temperature needed to overcome the electric-charge repulsion between two +14 charges is so high that the nuclei would disintegrate first. Second, ^{4}He nuclei are probably important in this stage of a star because nuclei with mass numbers 28, 32, 36, 40, 44, 48, 52, and 56 are unusually abundant in nature, compared with nuclei with mass numbers between these values.

Remember that in all these cycles it is because *nuclear reactions give off energy* that a star is stabilized against gravitational contraction. Therefore, it is essential that at each stage of element synthesis the reactions are exothermic. A star can be stabilized by reactions that build up to ^{56}Fe because the process represents a rise on the binding-energy curve (Figure 6, student module page 20). As more stable nuclei are produced, energy is given off, and the gravitational force that acts to contract the star is opposed. Once ^{56}Fe is reached in the synthesis chain, further nuclear reactions with charged particles can lead only downhill on the binding-energy curve. This absorbs energy from the star, the gravitational force takes over, and the star is no longer in equilibrium.

This section of the student module can be eliminated if you desire to shorten the origin-of-the-elements portion of the module. It is sufficient to state that a complex series of reactions occurs, synthesizing the elements C through Fe, and that the process stops at iron because the reactions no longer give off energy, as described above.

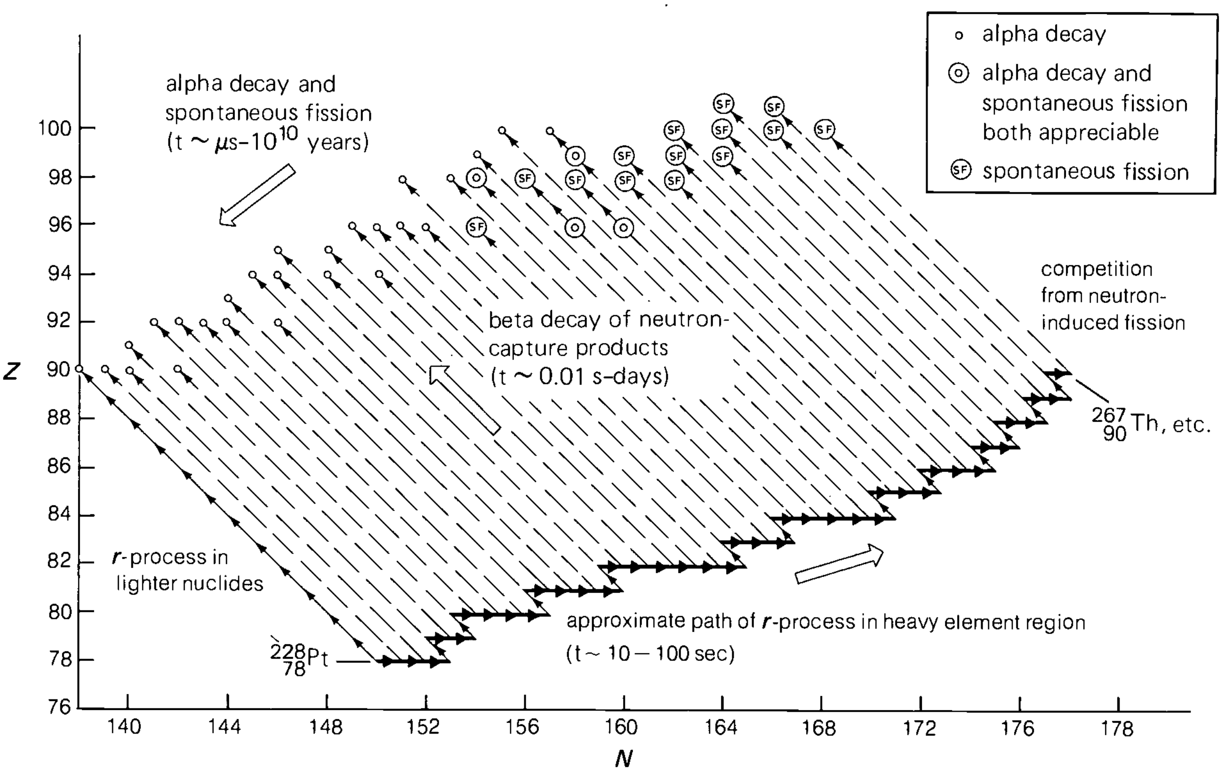
N-20 HEAVY ELEMENTS: *ZAP*, THE *r*-PROCESS

An interesting feature of the *r*-process is that neutron capture must occur within a time span of about 10 to 1000 seconds. The closest experimental analog to this situation is a thermonuclear fusion explosion, or hydrogen-bomb blast. Much information about the *r*-process has been gained in the study of such explosions. The extreme conditions of a short time scale and a large number of neutrons are necessary to satisfy the special requirements of gravitational collapse in the star, as well as to bypass the relative instability of nuclei with mass numbers $A = 210–230$ (which do exist independently in nature).

The residues of the *r*-process are unusual neutron-rich nuclei, which undergo negatron decay after the implosion-explosion stage has ceased to produce neutrons.

$$^{238}_{80}Hg \longrightarrow ^{238}_{92}U + 12\ ^{0}_{1}\beta$$

This series of decays occurs in steps, of course. The following diagram aids understanding of the step-by-step development of the *r*-process. This diagram illustrates the *r*-process path after it has already evolved from $^{56}_{26}Fe$ to $^{228}_{78}Pt$.



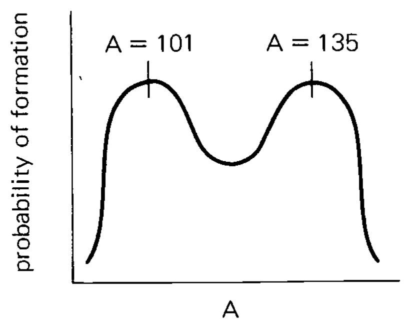
Schematic diagram for average *r*–process path in the heavy element region. Neutron capture occurs along lower path (heavy arrows) starting with $^{228}_{78}$Pt. Equilibrium concentrations of each nuclide along capture path are reached when rate for (n,γ) reaction equals rate of (γ,n) reactions. Reaction path moves to higher Z when beta decay lifetimes become comparable to time required to achieve equilibrium concentrations. At the upper mass limits neutron–induced fission terminates capture path. Nuclides on the *r*–process capture path eventually decay to the line of maximum beta stability, where alpha decay and/or spontaneous fission occur.

It is not clear at what point fission becomes dominant in the *r*-process and terminates the chain of mass-building reactions. It seems most probable that this limit occurs in the vicinity of mass number $A = 270$, in which case nearly all possible products are known. The final excess-neutron products would then undergo radioactive beta decay to form the most stable isobar for each mass number. These subsequently decay to form uranium and other lighter elements. On the other hand, mass numbers as high as $A = 300$ may possibly have been achieved, which would permit synthesis of the "superheavy elements" as well. However, even if the superheavy elements could be formed in the *r*-process, it would be essential that their half-lives for alpha decay and spontaneous fission be as long as the age of the solar system if such elements were to be found in nature. As of yet, no clear evidence has been found to prove the existence of such species in nature.

One question concerning the terminal fate of a star could be discussed. That is, what remains after the implosion-explosion stage? This question is an absorbing one. The observation of unusual stellar objects called *pulsars* has created much excitement among scientists during the past few years. These stars are thought to be giant "nuclei" composed of neutrons, or neutron stars. Their density would be that of nuclear matter (10^{11} grams/cm^3), and they would have a mass nearly that of the Sun but a diameter of only about 16 kilometers. One of these objects is found in the Crab Nebula, where the existence of a supernova has been recorded—a fact that gives further support to the hypothesis that the *r*-process is associated with supernova explosions.

No attempt has been made here to discuss the fission process in detail. The existence of neutron emission in fission (the basis for a chain reaction) is discussed in section *N-23*. It should be pointed out that the nuclear products of fission reactions are nonspecific—that is, a large variety of products can be formed. A typical distribution of the mass numbers of the final products in uranium fission is shown in the following diagram.

The diagram shows that the mass split in fission is usually asymmetric. In balancing fission equations, one can choose a wide variety of products. The only conditions that must be fulfilled are $Z = Z_1 + Z_2$ and $A = A_1 + A_2$ + neutrons.



ANSWERS TO PROBLEMS

(Student module page 43)

1. carbon burning/explosive nucleosynthesis
2. *r*-process
3. hydrogen burning
4. silicon burning/explosive nucleosynthesis
5. helium burning
6. helium burning
7. hydrogen burning
8. *r*-process/fission
9. silicon burning/explosive nucleosynthesis
10. *r*-process

N-21 DETECTING THE REMNANTS

In this section you have an opportunity to discuss one of the important accidental discoveries in science. The depth of presentation will depend on your interest and that of your students. This section introduces *N-22*.

MINIEXPERIMENT
N-22 RADIOAUTOGRAPHY: CATCHING THE RAYS

This experiment duplicates Becquerel's initial discovery of the effect of nuclear radiation on photographic film.

Concepts

- Radioactive elements emit radiation that will expose photographic film.
- The radioactive source can take its own picture.

Objectives

- Expose film, using a radioactive source.
- Relate the white and black areas on exposed film to the location of the radioactive material.

Estimated Time One-half period on each of two days, with one day in between.

Student Grouping Group size will depend on the amount of film and the number of radioactive sources available.

Materials

Polaroid Type 57 black-and-white film (speed 3000)
radioactive sources (such as a ^{137}Cs MINIGENERATOR)
Polaroid Type 545 film holder or a suitable film roller

Advance Preparation Be sure your radiation sources have enough activity to produce satisfactory images.

Prelab Discussion None

Laboratory Safety Review with your students the standard laboratory safety rules they should be following. Note *Appendix I: Safety* at the end of the student module.

Laboratory Tips The experiment as described is designed to make use of the MINIGENERATORS as radiation sources and common Polaroid film as the detector. Other sources of radioactivity can be used, and obviously it is desirable to use as many different sources as possible. The most convenient film-exposure arrangement is that described in the student module—the Polaroid Type 57 black-and-white single-sheet film used with the Polaroid Type 545 holder. The primary problem that may be encountered here is that the Type 57 film size is "4 × 5 inches" and so cannot be developed in ordinary Polaroid cameras. Since the Type 545 holder is not a common item, it may be necessary to find a roller arrangement to develop the film. An alternative to this is to use standard Polaroid Film packs, such as Type 667 black-and-white film, which contains eight sheets to the pack. Unfortunately, none of the standard-size Polaroid Film packs is available in single sheets. With this arrangement, eight exposures can be obtained simultaneously; or, through the insertion of a sheet of lead (~0.16 cm thick) between the uppermost and lower sheets of film in the pack, only the top sheet will receive significant exposure. The top sheet of film can then be developed in any standard Polaroid camera case.

There are many versions of the Becquerel experiment in existence. One of the more sensitive approaches is that described in G. Chase et al., *Experiments in Nuclear Science* (Minneapolis: Burgess Publishing Co., 1971). If you have access to a photographic developing laboratory, you might wish to try this approach, which uses X-ray film and saves time.

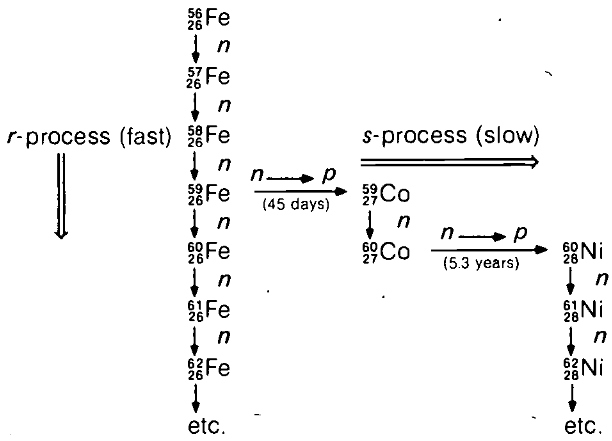
Range of Results In an exposure that uses a ^{137}Cs MINIGENERATOR as a source, the image is approximately circular. This demonstrates that the radiation is not uniformly spread out across the MINIGENERATOR (and consequently, the image is not the same shape as the MINIGENERATOR). The actual location of the radiation is not directly adjacent to the film and therefore the image is spread out.

Postlab Discussion Tracks are left in mineral rocks by radioactive decay. These tracks can be used to determine facts about the history of the Earth. See section *N-31* and J. D. Macdougall, "Fission Track Dating," *Scientific American* (December 1976), pp. 114–122. Also discuss X-ray procedures in medicine and dentistry. The exposure of photographic film is still used in nuclear science today, although the techniques are much more sophisticated than the one we use here.

N-23 HEAVY ELEMENTS VIA THE s-PROCESS

The difference in time scales between the *s*-process and the *r*-process contributes to the formation of different isotopes of the elements. Because the *r*-process involves nuclei with an oversupply of neutrons, it synthesizes the heaviest isotopes of a given element. On the other hand, the long time that elapses between neutron captures in the *s*-process (~5000 years) permits radioactive decay to occur if the nucleus formed is sufficiently unstable. Consequently, the *s*-process, in which the path of nucleosynthesis tends to follow the uppermost ridge along the peninsula of stability (refer to Figures 4, 5, and 6 in the student module), is responsible for forming the most stable isotopes of each heavy element.

To illustrate differences between the two processes, the following diagram indicates the two alternative paths for neutron-capture reactions with ^{56}Fe.



The *s*-process cannot produce the superheavy elements or even uranium or thorium. It must stop at $^{209}_{83}Bi$. This limitation is set by the high instability of nuclei with mass numbers $A = 210$–212, which emit $^{4}_{2}He$ ions to form lighter nuclei (alpha decay) before another neutron can be captured.

One additional mechanism of nucleosynthesis that is not described in the student module is the *p-process*, which is responsible for forming the lightest isotopes of the heavy elements. The *p* stands for either protons or photons. This process involves secondary nuclear reactions that occur at all stages of later-generation stars. It results in slight alterations of the elemental abundances, as follows. Consider the stable nuclide $^{74}_{34}Se$ (selenium), which cannot be produced in either the *s*-process or the *r*-process. However, $^{75}_{33}As$ (arsenic) can be synthesized in both processes, and $^{74}_{34}Se$ is thought to be produced by the following proton- and photon-induced nuclear reactions.

$$^{74}_{32}Ge + ^{1}_{1}H \longrightarrow ^{1}_{0}n + ^{74}_{33}As$$

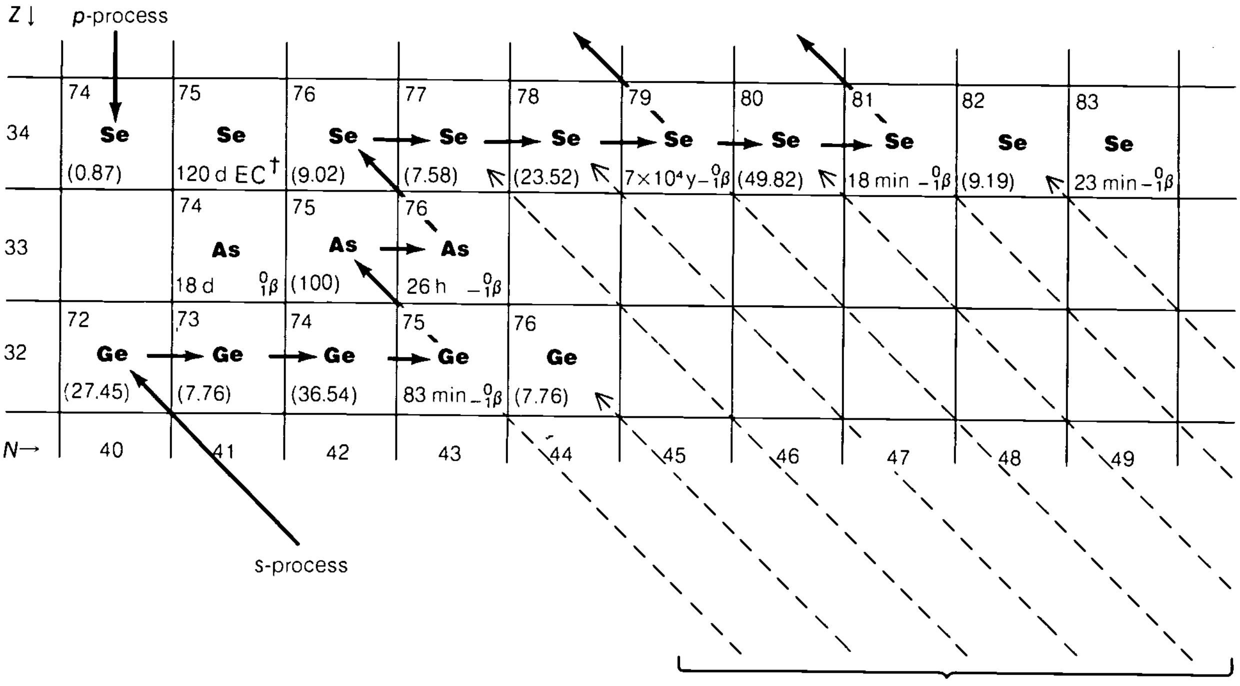
$$^{75}_{33}As + \gamma \longrightarrow ^{1}_{0}n + ^{74}_{33}As$$

$$^{74}_{33}As \xrightarrow{\text{(18 days)}} ^{74}_{34}Se + ^{\ 0}_{-1}\beta$$

That is, $^{74}_{33}As$ is the product of both reactions and undergoes radioactive decay to stable $^{74}_{34}Se$. This process is not very probable, as is evidenced by the fact that the abundance of $^{74}_{34}Se$ is only 0.87 percent of the selenium isotopes in nature. Similarly low abundances for the lightest isotopes of an element are generally found for all the elements beyond iron.

For advanced students only, differences in the *s*-, *r*-, and *p*-processes can be illustrated through a consideration of the stable isotopes of selenium. In the diagram that follows, nuclides in the unshaded boxes are radioactive. The isotope ^{74}Se can be produced only by the *p*-process in the previously described reactions. The *p*-process involves reactions of the type (γ,n) (p,γ), which involve cosmic-ray reactions and are relatively rare. The *r*-process is blocked because ^{74}Ge is stable and beta decay cannot occur; whereas the *s*-process is blocked because ^{74}Ge is stable, and therefore it must capture a neutron rather than undergo beta decay to ^{73}As or ^{74}Se. The isotopes ^{76}Se, ^{77}Se, and ^{78}Se are produced in the *s*-process by slow neutron capture. ^{80}Se may also be produced in the *s*-process; this depends somewhat upon the *s*-process time scale because of the long half-life of ^{79}Se. ^{82}Se cannot be produced by the *s*-process because ^{81}Se has only an 18-minute half-life. The isotopes ^{77}Se, ^{78}Se, ^{80}Se, and ^{82}Se can all be produced in the *r*-process following the beta decay of their lower-*Z* isobars (for instance, Fe or Ni). ^{76}Se is not involved in the *r*-process because ^{76}Ge is stable.

In this section we have included the fact that neutrons are emitted in the fission process. When fission takes place, the two fragments usually have a large amount of extra energy, some of which is dissipated by the emission of neutrons (usually one or two) from each fragment. These neutrons are usually included in any balanced equation for a nuclear fission reaction, but for the beginning student this step can be omitted at the discretion of the teacher. The emission of neutrons in a fission reaction is essential for the propagation of chain reactions in nuclear fission reactors (discussed in section *N-45*). Such chain reactions have apparently occurred in nature as well. For an excellent description of the natural reactor that was discovered in Africa, see G. A. Cowan, "A Natural Fission Reactor," *Scientific American* (July 1976), pp. 36–47.



†electron–capture decay

Nuclides in shaded boxes are stable; the percentage abundance of each isotope of an element is given in parentheses; e g., 9.02% of all selenium is ^{76}Se. Unshaded boxes represent radioactive nuclides. The half-life of each is given along with the decay mode.

Miniactivity Topics that may be suggested for reports are well covered in several *Scientific American* articles listed under *Selected Readings* in the student module. In particular, the following references are pertinent.

Expanding Universe and Black Holes

- Gott, J. R., *Scientific American* (March 1976)
- Pasachoff, J. M., et al., *Scientific American* (May 1974)
- Penrose, R., *Scientific American* (May 1972)
- Thorne, K., *Scientific American* (December 1974)
- Tinsley, B. M., *Physics Today* (June 1977)

Extraterrestrial Life

- Sagan, C., et al., *Scientific American* (May 1975)

ANSWERS TO PROBLEMS

(Student module page 46)

1. **a.** ^{3}He **d.** $^6_3$Li **g.** $^{40}_{20}$Ca
   b. ^{2}H **e.** $^1_1$H **h.** ^1_0n
   c. $^{13}_6$C **f.** ^1_0n **i.** $^2_1$H
2. **a.** ^{238}U, nuclei of Fe and heavier (usually with an excess of neutrons)
   b. ^{2}H, ^{3}He, ^{4}He
   c. primarily ^{32}S, ^{36}Ar, ^{40}Ca, ^{44}Ca, ^{48}Ti, ^{52}Cr, ^{56}Fe; in general, $28 \lesssim A \lesssim 56$
   d. ^{12}C, ^{16}O
   e. Nuclei of Fe and heavier, up to Pb; number of neutrons is usually equal to that of the most stable nucleus for a given A
   f. ^{24}Mg, ^{23}Na, ^{20}Ne, ^{28}Si; in general, $12 \lesssim A \lesssim 28$
   g. ^{2}H, ^{3}He, ^{4}He, ^{7}Li

3. **a.** *r*-process
   b. *s*- or *r*-process
   c. big bang (or hydrogen burning—minor)
   d. helium burning
   e. carbon burning/explosive nucleosynthesis
   f. silicon burning/explosive nucleosynthesis
   g. big bang or hydrogen burning
4. **a.** fusion, **b.** fusion — Combining light nuclei indicates moving up the left-hand part of the binding-energy curve (Figure 6) and releasing energy.
   c. fission, **d.** fission — Splitting heavy nuclei means moving up the right-hand part of the binding-energy curve (Figure 6) and releasing energy.

EVALUATION ITEMS

The following are additional evaluation items that you may wish to use with your students at various times during the preceding unit. The correct answer to each question is indicated by shading.

1. Finding the presence in a star of an element that cannot be found on Earth supports the hypothesis that stars synthesize or produce some of their elements. An element that exists in some stars but that no longer exists on Earth is

   A. $_{92}U$ B. $_{6}C$ C. $_{43}Te$ D. $_{3}Li$

2. Complete the following nuclear reactions.

   A. $^{226}_{88}Ra \longrightarrow {}^{222}_{86}Rn + {}^{4}_{2}He$

   B. $^{234}_{90}Th \longrightarrow {}^{234}_{94}Pa + {}^{\ 0}_{-1}\beta$

   C. $^{210}_{84}Po \longrightarrow {}^{4}_{2}He + {}^{206}_{82}Pb$

3. A nuclear process responsible for limiting the build-up of heavy elements in both stars and the laboratory is

   A. position decay. C. nuclear fission.
   B. electron capture. D. gamma decay.

4. Match the following processes with the appropriate equations.

   C H-burning
   A r-process
   B s-process
   D spontaneous fission

   A. $^{238}_{92}U + 16\,{}^{1}_{0}n \longrightarrow {}^{254}_{92}U$

   B. $^{59}_{27}Co + {}^{1}_{0}n \longrightarrow {}^{60}_{27}Co \longrightarrow {}^{60}_{28}Ni + {}^{\ 0}_{-1}\beta$

   C. $^{2}_{1}H + {}^{1}_{1}H \longrightarrow {}^{2}_{1}H + {}^{0}_{1}\beta$

   D. $^{252}_{98}Cf \longrightarrow {}^{106}_{42}Mo + {}^{142}_{56}Ba + 4\,{}^{1}_{0}n$

5. Match the following:

G	*s*-process	A.	most stable nucleus in the sea of instability
F	*r*-process	B.	most abundant element in solar system
B	$^{1}_{1}H$	C.	used in dating archeological findings
E	$Z = 114$	D.	used as fuel in fission reactors
C	$^{14}_{6}C$	E.	superheavy element
A	$^{56}_{26}Fe$	F.	similar to a thermonuclear explosion
D	$^{235}_{92}U$	G.	similar to formation of elements in nuclear reactors

SUGGESTED READINGS

Bok, B. J. "The Birth of Stars." *Scientific American*, August 1972, pp. 48–61.

Gott, J. R. III; Gunn, J. E.; Schramm, D. N.; and Tinsley, B. M. "Will the Universe Expand Forever?" *Scientific American*, March 1976, pp. 62–79.

Jastrow, Robert. *Red Giants and White Dwarfs*. New York: Harper & Row, 1971. Revised edition.

Lamont, Lawrence. *Day of Trinity*. New York: Atheneum, 1965.

"Man and the Universe." Special issue of *Chemistry*, July–August 1972.

Miller, Jr., Walter M. *Canticle for Liebowitz*. New York: Bantam Books, 1971. Paperback.

Penrose, R. "Black Holes." *Scientific American*, May 1972, pp. 38–46.

Sagan, C., and Drake, F. "The Search for Extraterrestrial Intelligence." *Scientific American*, May 1975, pp. 80–89.

Thorne, K. "The Search for Black Holes." *Scientific American*, December 1974, pp. 32–43.

SUGGESTED FILMS

The Invisible Universe. Color, 14 minutes. National Science Foundation, R. H. R. Filmedia, Inc., 1212 Avenue of the Americas, New York, NY 10036.
An examination of how pulsars, quasars, and objects beyond the range of optical telescopes are being explored by radio telescope.

Persimmon: A Nuclear Physics Experiment. Color, 16 minutes. U.S. Department of Energy, Film Library, P.O. Box 62, Oak Ridge, TN 37830.
Presents and discusses experiments conducted before, during, and after underground detonation of a nuclear explosive.

Radioactive Decay

You can introduce this section by referring once again to the *Periodic Table of the Elements*. Call on a student to identify elements that are radioactive. The term *radioactivity* has long been familiar to high-school chemistry students, and their conceptualization of the phenomenon is probably accurate. The references in the student module to nuclei and to neutron-proton combinations may require a brief review of atomic structure. Refer to the discussion of *stability* in the student module. As the module explains, stability is a relative condition. Clarify this point for your students.

N-24 FROM STABLE TO RADIOACTIVE

You can try the following experiment on your desk top at the beginning of a class to illustrate the dependence of stability on time. Build stacks of soft-drink cans, making each stack successively higher, until you run out of luck. The stack that has one can more than the highest stable stack is stable, but only in the sense of a very short time. If everyone were to leave the room quietly at this point, the students would have to conclude that all the stacks were stable. However, during the course of the lecture the least stable structures should give way, whereas the more stable ones should remain unchanged. If your class is such that the single can falls over, apply for a week of R and R.

N-25 RATE OF DECAY: THE WAY IT GOES

We have not employed natural numbers and logs, and yet we have still provided mathematical exposition of the principles of the first-order decay kinetics. The more advanced student can begin with the first-order decay-rate expression.

$$dN/dt = -\lambda N$$

where N is the number of atoms at any time t and λ is a constant characteristic of the radioactive decay of any given nuclide. Integrating from N_0 atoms initially to N atoms at time t, one obtains

$$\int_{N_0}^{N} \frac{dN}{N} = -\int_0^t \lambda dt$$

which gives

$$N = N_0 e^{-\lambda t}$$

The half-life, $t_{1/2}$, is defined as the time it takes for one half of the nuclei in a sample to decay, so that $t_{1/2}$ is the time at which $N = N_0/2$. Substituting for N in the last equation, one obtains

$$e^{-\lambda t_{1/2}} = 1/2$$

or

$$\lambda t_{1/2} = \ln 2 = 0.693$$

so that

$$t_{1/2} = 0.693/\lambda$$

Thus, if the half-life of a nuclide is known, the number of atoms present after a time t can be determined from $N = N_0 e^{-\lambda t}$.

The nuclide ^{244}Pu, with a half-life of 8×10^7 years, has recently been found in nature, although in extremely small quantities.

Half-life measurements of nuclei cannot detect species with half-lives greater than about 10^{16} years. Consequently, nuclei with half-lives greater than this value are said to be stable in nature. There are 280 of these nuclides, as mentioned in Table 5 (student module page 27). At the other extreme, it is possible to measure half-lives as short as about 10^{-9} seconds. This fact has made it possible to detect a large number of synthetic elements and isotopes. Scientists have managed to synthesize more than 1500 radioactive nuclides that do not exist in nature. Many of these have important applications in chemistry, physics, medicine, and the biological sciences. We will discuss application of radioactive nuclides in *Uses of Radiation*.

ANSWERS TO PROBLEMS

(Student module page 49)

1. **a.** $R = \dfrac{0.693\ (24\,000\ \text{atoms})}{(12\ \text{years})\ (365\ \text{days/year})}$
$= 3.8$ atoms/day

   b. $N = (24\,000)\ (^1\!/_2) = 12\,000$
$N = (24\,000)\ (^1\!/_2)^2 = 6000$

   c. N decayed $= N_0 - N$ remaining
$= 24\,000 - 6000 = 18\,000$

2. **a.** $R = (0.693)(1500)/(12)(365)$
$= 0.24$ atoms/day

   b. 22 500

   c. 1500

N-26 GAMMA DECAY

Note that gamma decay is the type of radiation that is emitted by the MINIGENERATOR. Gamma decay follows nearly every nuclear reaction. Usually it is a very rapid process that occurs with nuclides having half-lives of about 10^{-12} seconds. The gamma ray usually is not included in the equation for a nuclear reaction, although it could be. For example,

$$3\ {}^4He \longrightarrow {}^{12}C + \gamma$$

and

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

are appropriate equations for helium-burning reactions. Because the half-lives are so short, the inclusion of the gamma ray in the equation is arbitrary, depending on whether or not one wishes to emphasize this feature of the process being expressed. As in the case of judging stability, it depends somewhat on the time scale one is considering.

Although gamma decay usually occurs very rapidly, in some nuclei it is slowed down because of nuclear-structure effects. The symbol *m* (for *metastable*) is usually added after the mass number of these nuclei to indicate this factor. A similar process occurs with the fluorescent decay of atomic states, in which the emission of light from atoms is delayed.

N-27 BETA DECAY

In general, for each mass number *A* there are only a few isobars that are stable against beta decay. For all nuclides that have an odd-*A* value, only one stable isobar exists. For even-*A* values, there are frequently two, and sometimes three, isobars that are stable against beta decay.

This situation is a consequence of the tendency for nucleons of the same type to pair with one another—the *pairing effect*. Studies of nuclear structure have shown that nuclei with paired neutrons or paired protons (even *N* and/or even Z) are usually more stable than their immediate neighbors that have odd-*N* or odd-Z values. Evidence to support this statement can be found through an examination of the distribution of even-Z/even-*N*, odd-*A*, and odd-Z/odd-*N* nuclides for the naturally occurring nuclides (which are nature's most stable nuclear species), reviewed in section *N-14* of this guide. An odd-*A* nucleus must always have one odd neutron or proton. There is usually only one stable isobar for odd-*A* nuclides, since all beta-decay chains produce a nuclide with one odd nucleon. Even-*A* isotopes may have as many as three stable isobars because between each successive pair of even-Z/even-*N* isobars there is an odd-Z/odd-*N* isobar, which is usually less stable. Therefore, it is possible for all the even-*N*/even-Z isobars of mass *A* with atomic numbers Z − 2, Z, and Z + 2 to be stable, because the odd-Z/odd-*N* isobars with Z − 3, Z − 1, Z + 1, and Z + 3 are all unstable and undergo beta decay to their neighbors. Beta decay from Z + 2 to Z (double beta decay) has never been observed.

An important example of negatron decay occurs in the *r*-process. In *N-20* we indicated that the nuclide $^{238}_{80}Hg$ (mercury) was probably formed in the *r*-process. After the explosion this decays to ^{238}U by a series of twelve negatron decays:

$$^{238}_{80}\mathrm{Hg} \longrightarrow {}^{238}_{81}\mathrm{Tl} + {}^{\;\,0}_{-1}\beta$$

$$^{238}_{81}\mathrm{Tl} \longrightarrow {}^{238}_{82}\mathrm{Pb} + {}^{\;\,0}_{-1}\beta$$

$$^{238}_{82}\mathrm{Pb} \longrightarrow {}^{238}_{83}\mathrm{Bi} + {}^{\;\,0}_{-1}\beta$$

and so on, to

$$^{238}_{91}\mathrm{Pa} \longrightarrow {}^{238}_{92}\mathrm{U} + {}^{\;\,0}_{-1}\beta$$

Therefore, the maximum stability for $A = 238$ (or ^{238}U) is reached via this process. In order to be rigorously correct in writing equations for beta decay, we should also include the antineutrino, $\bar{\nu}$ (see sections *N-2* and *N-15*), as follows.

$$^{238}_{91}\mathrm{Pa} \longrightarrow {}^{238}_{92}\mathrm{U} + {}^{\;\,0}_{-1}\beta + \bar{\nu}$$

Because of the difficulty in detecting neutrinos and the fact that they are not necessary for the level of presentation in this module, discussion of these particles has been omitted here. Two important conservation laws relating to neutrinos have also been omitted. These are (1) the conservation of leptons (electrons, muons, and neutrinos) and (2) the conservation of spin. (See the table in section *N-3* of this guide.) The creation of an electron in the above example is balanced by the simultaneous creation of an antineutrino; the lepton (electron) and antilepton (antineutrino) cancel each other out to give a net of zero leptons. This conserves leptons, since there were none to begin with. Also, because the electron has spin ½, conservation of spin (a vector quantity, subject to the rules of vector addition) requires another particle with spin ½, which is satisfied by the antineutrino's spin ½.

Positron decay involves the emission of an antiparticle. After the positron leaves the nucleus, it eventually loses its energy through collisions with electrons. Finally, it forms the lightest "element"—positronium—that is, an "atom" composed of a positron and an electron. This "element" lasts only a fraction of a second, and then the pair annihilate one another with the creation of two gamma rays. All the mass of the electron and the positron is converted into the energy of the gamma rays. This conversion is

$$E = mc^2 = (2m_e)c^2 = 2(0.000\,5486\ \mathrm{u})\ 931.48\ \mathrm{MeV/u}$$
$$= 1.02\ \mathrm{MeV,\ or\ } 0.51\ \mathrm{MeV\ per\ gamma\ ray}$$

With regard to the nucleus, the net results of positron decay and of electron-capture decay are identical. However, the electronic configurations of the two products are quite different. The resulting atom of positron emission has an extra electron, which gives the atom a -1 charge state. The resulting atom of electron-capture decay has electrical neutrality, but a vacancy exists in one of its innermost electron orbits. As a result, X-ray emission generally accompanies electron-capture decay.

EXPERIMENT
N-28 THE HALF-LIFE OF $^{137m}_{56}Ba$

The purpose of this experiment* is to determine the half-life of the radioactive nuclide ^{137m}Ba.

Concepts

- The half-life of a radioactive element is the time it takes for the number of atoms in a sample (or its activity) to be reduced by one-half.
- Nuclides are classified as stable or unstable, depending on their half-lives.

Objectives

- Graph sample radioactive-decay activity against time.
- Determine graphically the half-life of a radioactive nuclide.

Estimated Time One period

Student Grouping Group size will depend on the equipment available.

*Experiment 8 in *Experiments in Nucleonics* (Union Carbide Corp., 1968. Available from Redco Science Inc., Danbury, CT 06810.) Experiment 7 is similar to Experiment 8, but it can prove impractical because of the longer half-life of ^{113m}In.

Materials

$^{137}Cs/^{137m}Ba$ MINIGENERATOR
plastic squeeze bottle
small beaker, 20 cm^3
2 cm^3 eluant solution
radiation detector
linear graph paper
rubber gloves (required for person handling the liquid isotope)

Advance Preparation Prepare the eluant solution (see experiment *N-13* in this guide). Be sure students adjust the source-to-detector distance to achieve the maximum meter reading.

Prelab Discussion None, except for a brief safety review.

Laboratory Safety Review with your students the standard laboratory safety rules they should be following. Note *Appendix I: Safety* at the end of the student module.

Laboratory Tips You may wish to use semilog graph paper. Remind your students that it is not necessary to take the logarithm of the number on the ordinate scale; the graph paper does that. They should simply plot one number against the other, taking care to read the scales properly.

Range of Results

SAMPLE DATA (minute intervals only)
Background = 190 cpm

Time (min)	*Activity (cpm)*	*cpm Corrected for Background*
1	1635	1445
2	1300	1110
3	1025	835
4	840	650
5	645	455

The data, when graphed, should yield a half-life of about 2.6 minutes.

Postlab Discussion ^{137m}Ba is a metastable isomer of stable ^{137}Ba. It is formed by the emission of a beta particle from the nucleus of ^{137}Cs. It exists in this radioactive isomeric state until the nucleus achieves a stable ground state by emitting a gamma ray. Most metastable isomers emit their gamma rays in a fraction of a second. Some, however, such as ^{137m}Ba, exhibit delayed gamma-ray emission and have half-lives ranging from seconds to months. The gamma rays emitted have energies measured in thousands of electron volts (keV), and these are attributable to rearrangements of nucleons into lower energy levels. ^{137m}Ba emits a 662-keV gamma ray, which the students will detect.

The students' data should yield a half-life of *approximately* 2.6 minutes. The major sources of error include the fact that the detectors being used are simple devices; statistical fluctuations of the data and background corrections will also lend some uncertainty to the final result.

Answers to Questions

1. All points will not fall on a smooth line because of statistical fluctuations in the decay rate, inaccuracies in reading the counter, and decay during counting.
2. Two times the measured half-life, ideally 5.2 minutes.

N-29 ALPHA DECAY

We have not emphasized alpha decay in the radioactive decay of the products of the *r*-process. After neutron capture produces heavy elements, successive beta decays occur until a beta-stable nuclide is reached. In the heavy-element region ($A \geq 210$), all such nuclides are unstable toward alpha decay and spontaneous fission. As a result, at some time in the distant past, elements that we now synthesize, such as plutonium and curium, were present in the solar system. The half-lives of these species are short compared with the age of the solar system. Therefore, these elements have long since decayed to the only nuclides that are both heavier than bismuth and that have long enough half-lives to have survived until now (^{238}U, ^{235}U, ^{232}Th), or they have decayed to the stable isotopes of lead and bismuth.

The short half-life of $^{210}_{84}Po$ is one reason why the *s*-process

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

(neutron capture on a slow time scale) cannot proceed beyond element 83, bismuth. Every time

$^{210}_{84}Po$ is produced after the ^{209}Bi (n,γ) reaction and the beta decay of ^{210}Bi, it decays back to ^{206}Pb before another neutron can be captured. Therefore, it is not possible to build up more mass. The same limitation prevents the formation of heavy elements in a nuclear reactor; the extreme instability of $^{212}_{84}Po$ is responsible for the limitation in this case ($t_{1/2} = 10^{-7}$ seconds).

Note that $^{208}_{82}Pb$ has both a closed proton shell and a closed neutron shell. Consequently, this nucleus is similar in many respects to a noble gas atom. On the other hand, $^{212}_{84}Po$ is just an alpha particle beyond closed shells for both neutrons and protons. Its unstable behavior is similar to that of metallic elements: it likes to lose its last couple of neutrons and protons.

The reason that alpha decay occurs rather than ^{1}H, ^{2}H, ^{3}H, or ^{3}He decay is that these reactions are not energetically possible; that is, ΔE (section *N-11*) is negative and the occurrence of such decays is prohibited by the law of conservation of mass–energy. Because ^{4}He is a doubly magic nucleus, energy is given off when it is formed. Energetically, it is also possible for ^{12}C and ^{16}O decay to occur. However, because of the large charges on these nuclei, charged particles cannot get out easily. The same electrostatic repulsion barrier that hinders a charged particle's entry into a nucleus when it is on the outside keeps it from getting out when it is on the inside. The net result of all these effects is that the alpha particle is the only light particle that can escape from a nucleus with any appreciable probability.

It is the alpha-decay process—along with spontaneous fission, which is discussed in the next section—that currently limits our ability to make new elements in the laboratory. The heaviest known element, element 106, is highly unstable toward alpha decay. It decays rapidly to lawrencium (element 103) according to the equation

$$^{263}106 \longrightarrow {}^{259}104 + {}^{4}_{2}He \ (t_{1/2} = 0.9 \text{ seconds})$$

Therefore, although element 106 is stable enough so that its momentary existence can be observed, it is too unstable for large amounts of it to accumulate in nuclear-particle accelerators.

It is possible that the superheavy elements corresponding to the island of stability may have alpha-decay half-lives much longer than this, perhaps even as long as the age of the solar system. Scientists are currently pursuing the answer to this problem, but no unambiguous evidence for the existence of such elements has been found as yet. The new superheavy-ion accelerators that are currently being completed at a few laboratories around the world should provide an answer to this compelling question in the near future.

N-30 SPONTANEOUS FISSION

Although instability caused by alpha decay severely limits the production of new heavy elements, it is most likely spontaneous fission that prevents any extension of the *Periodic Table of the Elements*. Spontaneous fission does not occur for elements lighter than thorium ($Z = 90$), but its probability increases rapidly with an increase in atomic number. For example, consider the following list of spontaneous-fission half-lives.

$^{238}_{92}U$ $t_{1/2} = 10^{16}$ years
$^{250}_{96}Cm$ $t_{1/2} = 10^{4}$ years
$^{256}_{100}Fm$ $t_{1/2} = 2.6$ hours

Note how the half-life decreases with increasing Z. Only the special stability of closed nuclear shells can alter this pattern. Therefore, even if elements around $^{298}114$ do exist, it seems highly unlikely because of spontaneous fission that heavier elements could exist.

Fission fragments, because of their high energy and large mass, cause a great deal of radiation damage when they pass through matter. The total distance they travel through air is comparable to that of alpha particles. The radiation damage in crystals from fission fragments has found a useful application in the determination of the ages of deep-sea sediments. The ocean contains a large amount of uranium, which undergoes spontaneous-fission decay in sedimentary rocks. The radiation damage is so great that it leaves a permanent record in the structure of the rock. By appropriate chemical and microscopic analysis, it is possible for scientists to determine the number of fission events that have occurred per number of uranium atoms present in the rock. From knowledge of this quantity and the spontaneous-fission half-life of uranium, it is then possible to determine the age of the rock.

ANSWERS TO PROBLEMS

(Student module page 57)

1. $^{144}_{60}Nd \longrightarrow ^{140}_{58}Ce + ^{4}_{2}He$
2. $^{40}_{19}K \longrightarrow ^{40}_{20}Ca + ^{0}_{-1}\beta$
3. $^{22}_{11}Na \longrightarrow ^{22}_{10}Ne + ^{0}_{1}\beta$
4. $^{7}_{4}Be + ^{0}_{-1}e \longrightarrow ^{7}_{3}Li$
5. $^{241m}Am \longrightarrow ^{241}Am + \gamma$
6. $^{256}_{100}Fm \longrightarrow ^{126}_{50}Sn + ^{126}_{50}Sn + 4\,^{1}_{0}n$

Miniactivity The following additional problems parallel the previous problems. Have students write equations for the following decay processes.

1. Alpha decay of $^{241}_{95}Am$
2. Beta decay of $^{28}_{13}Al$
3. Positron decay of $^{11}_{6}C$
4. Electron-capture decay of $^{52}_{26}Fe$
5. Gamma decay of ^{117m}Sn
6. Spontaneous fission of $^{254}_{98}Cf$, with two neutrons from each of two fragments that have equal mass and charge

Answers:

1. $^{241}_{95}Am \longrightarrow ^{237}_{93}Np + ^{4}_{2}He$
2. $^{28}_{13}Al \longrightarrow ^{28}_{14}Si + ^{0}_{-1}\beta$
3. $^{11}_{6}C \longrightarrow ^{11}_{5}B + ^{0}_{1}\beta$
4. $^{52}_{26}Fe + ^{0}_{-1}e \longrightarrow ^{52}_{25}Mn$
5. $^{117m}Sn \longrightarrow ^{117}Sn + \gamma$
6. $^{254}_{98}Cf \longrightarrow 2\,^{125}_{49}In + 4\,^{1}_{0}n$

N-31 THE DATING GAME

Dating techniques that utilize long-lived radioactive isotopes are widespread. We have touched on only a few of the most important dating techniques in the student module. Determining the average age of element formation (nucleosynthesis in the *r*-process) by measuring the ratio $^{235}U/^{238}U$ in natural ores is an example of some of the other applications. The ratio in this application is found to be 1/139. Assuming that both ^{235}U and ^{238}U were produced in nearly equal amounts during nucleosynthesis, we derive an average age of about 6.5 billion years for the elements of the solar system. We say *average age* here because the elements may have been formed during many stages of stellar evolution. We feel certain the Sun is at least a second-generation star, and it may well be a later-generation star. Consequently, we can speak only of an average age. Note that the elements had to be formed before the Earth and the planets solidified (4.5 billion years ago). Thus, our dating procedures are self-consistent.

The assumption that the radioactivity of ^{14}C in our environment has been at a nearly constant value of about 15.0 disintegrations per minute per gram of carbon throughout time is not quite valid. Studies of the age rings of redwood trees have shown slight variations in the ^{14}C concentration as a function of time. These variations may have resulted from changes in the intensity of the cosmic-ray flux that reached our atmosphere. Another more recent source of variation is the large increase in the use of fossil fuels for energy during the last 150 years, which has enriched the amount of $^{12}CO_2$ in the atmosphere. This has been counterbalanced somewhat during the last twenty-five years by atmospheric testing of nuclear weapons, which has produced additional $^{14}CO_2$.

Miniactivity The following are sample problems for advanced students.

1. A potassium ore is found to contain 2.24×10^{-3} cm^3 of ^{40}Ar gas at STP and 4.0×10^{-6} grams of ^{40}K. How old is the ore if the half-life of ^{40}K is 1.3×10^9 years? Ignore any decay to ^{40}Ca.

Answer:

$$N(^{40}\mathrm{Ar}) = \frac{2.24 \times 10^{-3}\ \mathrm{cm}^3}{22\,400\ \mathrm{cm}^3/\mathrm{mole}}(6.0 \times 10^{23}\ \mathrm{atoms/mole})$$
$$= 6.0 \times 10^{16}\ \mathrm{atoms}$$

$$N(^{40}\mathrm{K}) = \frac{4 \times 10^{-6}}{40} = 10^{-7}\ \mathrm{moles}$$
$$= 6.0 \times 10^{16}\ \mathrm{atoms}$$

$$N_0 = N(\mathrm{Ar}) + N(\mathrm{K}) = 12 \times 10^{16}\ \mathrm{atoms}$$

$$N(\mathrm{K}) = N_0(1/2)^n$$

$$(1/2)^n = \frac{N(K)}{N_0} = \frac{6 \times 10^{16}}{12 \times 10^{16}} = \frac{1}{2}$$

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

$$t = t_{1/2} = 1.3 \times 10^9 \text{ years}$$

2. Suppose that someone reports having found an original record of an ancient ship that shows the crew visited America over 2000 years ago. When the document is subjected to ^{14}C dating, it is found that the activity is 15.0 ± 0.3 disintegrations per minute per gram of carbon. Is the document genuine? What would the activity be if it were genuine?

Answer: It's a fake. The activity would be about 10.7 disintegrations per minute if the document were genuine.

$$A = (1.5 \text{ dpm/g})^{(-0.693)\ (5730\text{ yr})\ (2000\text{ yr})}$$

EXPERIMENT N-32 RADIOACTIVE DECAY IN OUR ENVIRONMENT

This experiment was designed to demonstrate that many common substances in our environment are radioactive, as in the case of ^{40}K. In addition, the experiment shows how the half-life of a very long-lived substance can be measured without actually following its decay through several half-lives. Some approximations are made in the experiment, but surprisingly good results can be obtained for the ^{40}K half-life with the simple method outlined here. It is worth remembering that most important experiments are first carried out by using approximations. The refinements that lead to a definitive experiment usually come well after the initial attempt.

Concepts

- Many common substances in our environment are radioactive.
- The half-life of a very long-lived radioactive nuclide can be determined from its mass and decay rate.
- The accuracy of an experiment's result depends on how carefully the detection instrument is calibrated.

Objectives

- Measure the half-life of ^{40}K that is in a sample of KCl.
- Show that common substances in our environment are radioactive.
- Calibrate a detector relative to an absolute standard, in this case a MINIGENERATOR.
- Emphasize the importance of background radiation in radioactive-decay measurements.

Estimated Time One to two periods.

Student Grouping Groups of two to five, depending on the number of detectors available.

Materials

MINIGENERATOR
radiation detector
10 g of reagent-grade KCl
watch or clock with second hand
balance
20-cm^3 beaker or watch glass

Advance Preparation Since a number of steps are involved in this experiment, it is worthwhile to discuss each step prior to assigning it. Caution students that it is important to observe the fluctuations that may occur in the readings. In particular, have students check to see if the counters go off scale when placed next to the MINIGENERATOR. If so, the counting rate will have to be estimated from the maximum detector reading obtainable.

Prelab Discussion Three important facts need to be stressed prior to taking measurements. First, the equation

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

involves many concepts. Among these are: mass percent; the determination of the number of atoms (N) in a sample; and the decay rate of a sample, as the number of decays observed in a given period of time. The importance of background radiation must also be stressed. Probably one-third of the background observed in these measurements is caused by ^{40}K in the surroundings, apart from the KCl sample itself. The amount of radiation danger posed by synthetic radioactivity must be considered relative to the background radiation. The extent to which radioactive ^{40}K exists in our environment should be emphasized. It is found in rocks, seawater, and our own body fluids.

Laboratory Safety Review with your students the standard laboratory safety rules they should be following. Note *Appendix I: Safety* at the end of the student module.

Range of Results These results were obtained through the use of a ^{137}Cs MINIGENERATOR and a Johnson end-window survey meter.

- **Step I Background, at 10-second intervals**

Counting Period	*Meter Reading (in cpm)*	*Counting Period*	*Meter Reading (in cpm)*	*Counting Period*	*Meter Reading (in cpm)*
1	70	11	50	21	30
2	60	12	35	22	30
3	40	13	35	23	40
4	85	14	25	24	25
5	35	15	45	25	20
6	40	16	15	26	35
7	30	17	20	27	30
8	60	18	35	28	25
9	55	19	30	29	30
10	30	20	25	30	10

Average background = 37 cpm

- **Step 2 Number of ^{40}K atoms**

mass of KCl = 3.96 g

$$N(\text{K}) = \frac{(3.96\text{ g})\ (6.02 \times 10^{23}\text{ atoms/mole})}{(74.6\text{ g/mole}}$$

$$N(\text{K}) = 3.20 \times 10^{22}\text{ atoms}$$

$$N(^{40}\text{K}) = N\ (\text{K}) \times 1.1 \times 10^{-4}$$

$$= (3.20 \times 10^{22})\ (1.1 \times 10^{-4})$$

The factor 1.1×10^{-4} is the fraction of natural K atoms that are in the form of ^{40}K.

$$N(^{40}\text{K}) = 3.5 \times 10^{18}\text{ atoms}$$

- **Step 3 Detection** Results of ten counts with cover removed from detector.

Counting period	*Meter Reading (in cpm)*
1	100
2	120
3	130
4	110
5	120
6	170
7	140
8	65
9	130
10	140

$R(\text{total}) = R(^{40}\text{K}) + \text{background} = 123\text{ cpm}$
$R(^{40}\text{K}) = R(\text{total}) - \text{background}$
$R(^{40}\text{K}) = 123\text{ cpm} - 37\text{ cpm} = 86\text{ cpm}$

- **Step 4 Counter Efficiency**

R(MINIGENERATOR)
$= 450\text{ cpm} \times 100 = 4.5 \times 10^4\text{ cpm}$

$$R'(^{40}\text{K}) = \frac{(86\text{ cpm})\ (3.3. \times 10^4\text{ cps})^*}{(4.5 \times 10^4\text{ cpm})}$$

This step corrects for the detector efficiency (about 2.3%, in this case) and gives

$$R'\ (^{40}\text{K}) = 63\text{ cps}.$$

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

$$t_{1/2} = \frac{(0.693)\ (3.5 \times 10^{18}\text{ atoms})}{(63\text{ atoms decayed/s})}$$

$$t_{1/2} = 3.9 \times 10^{16}\text{ s},$$

or,

$$t_{1/2}\ (\text{years}) = \frac{3.9 \times 10^{16}\text{ s}}{3.16 \times 10^{7}\text{ s/yr}}$$

$$t_{1/2}\ (\text{years}) = 1.2 \times 10^{9}\text{ yr}$$

This compares very well with the accurately determined half-life of 1.3×10^9 years for ^{40}K. However, expect deviations up to a factor of five in your students' results, especially if any difficulties are encountered with measurement of the MINIGENERATOR activity. Ordinarily this will not be a problem.

Postlab Discussion Compare students' results with the accepted value (1.3×10^9 years), and discuss possible errors. Discuss the significance of the background radiation and the use of an absolute standard for obtaining results. Point out the usefulness of this method of half-life determination in contrast to directly observing half the material decay!

ANSWERS TO PROBLEMS

(Student module page 62)

1. **a.** $N = N_0\ (1/2)^n = (4.0 \times 10^5)(1/2)^1$
$= 2.0 \times 10^5$ atoms
   b. 1.0×10^5 (another half-life has passed)
   c. 8.0×10^5
   d. $N(^{11}\text{B}) = N(^{11}\text{C at 9:00}) - N(^{11}\text{C at 10:00})$
$= 8.0 \times 10^5 - 1.0 \times 10^5$
$= 7.0 \times 10^5$
   e. approximately 8.0×10^5

*absolute value of ^{137}Cs MINIGENERATOR

2. From the chemical atomic masses,

$$N(^{238}U) = \frac{1.0\text{ g }(6.02 \times 10^{23}\text{ atoms/mole})}{238.0\text{ g/mole}}$$

$$= 2.5 \times 10^{21}\text{ atoms}$$

$$R = \frac{(0.693)\,(2.5 \times 10^{21}\text{ atoms})}{(4.5 \times 10^{9}\text{ yr})\,(365\text{ d/yr})\,(24\text{ h/d})\,(60\text{ min/h})}$$

$$= 7.3 \times 10^{5}\text{ atoms/min}$$

3. Since R is proportional to N, then

$$R = (1/2)^n R_0$$

$$3.8 = (1/2)^n\, 15.1$$

$$(1/2)^n = \frac{3.8}{15.1}$$

$$n \simeq 2\text{ half-lives}$$

$$\text{age} \simeq 11\,460\text{ yr}$$

4. **a.** $^{240}_{94}Pu \longrightarrow {}^{4}_{2}He + {}^{236}_{92}U$
   b. $^{210}_{83}Bi \longrightarrow {}^{\;0}_{-1}\beta + {}^{210}_{84}Po$
   c. $^{52}_{26}Fe \longrightarrow {}^{0}_{1}\beta + {}^{52}_{25}Mn$
   d. $^{52}_{26}Fe + {}^{\;0}_{-1}e \longrightarrow {}^{52}_{25}Mn$
   e. $^{242m}_{95}Am \longrightarrow {}^{242}_{95}Am + \gamma$

5. **a.** beta
   b. gamma
   c. gamma

EVALUATION ITEMS

The following are additional evaluation items that you may wish to use with your students at various times during the preceding unit. The correct answer to each question is indicated by shading.

1. The reaction that represents positron emission is:

   A. $^{8}_{5}B \longrightarrow {}^{8}_{4}Be + {}^{0}_{1}\beta$
   B. $^{14}_{6}C \longrightarrow {}^{14}_{7}N + {}^{\;0}_{-1}\beta$
   C. $^{137}_{56}Ba \longrightarrow {}^{137}_{56}Ba + \gamma$
   D. $^{235}_{92}U + {}^{1}_{0}n \longrightarrow {}^{137}_{55}Cs + {}^{96}_{37}Rb + 3\,{}^{1}_{0}n$

2. A certain radioactive nuclide has a half-life of 50 minutes. If a sample containing 640 atoms is observed to decay for 100 minutes, how many atoms will remain?

   A. 320 atoms C. 60 atoms
   B. 120 atoms D. 160 atoms

3. Write balanced equations for the following reactions:

   A. the alpha decay of $^{235}_{92}U$
   $^{235}_{92}U \longrightarrow {}^{231}_{90}Th + {}^{4}_{2}He$
   B. the negatron decay of $^{239}_{92}U$
   $^{239}_{92}U \longrightarrow {}^{239}_{93}Np + {}^{\;0}_{-1}\beta$
   C. the fusion of four $^{1}_{1}H$ nuclei to form ^{4}He
   $4\,{}^{1}H \longrightarrow {}^{4}_{2}He + 2\,{}^{0}_{1}\beta$

4. Which of the following is not a mode of radioactive decay?

   A. positron emission C. fission
   B. fusion D. negatron emission

5. If $^{14}_{6}C$ has a half-life of 5730 years, and initially there are 800 carbon atoms, how many carbon atoms will remain after 17 190 years?

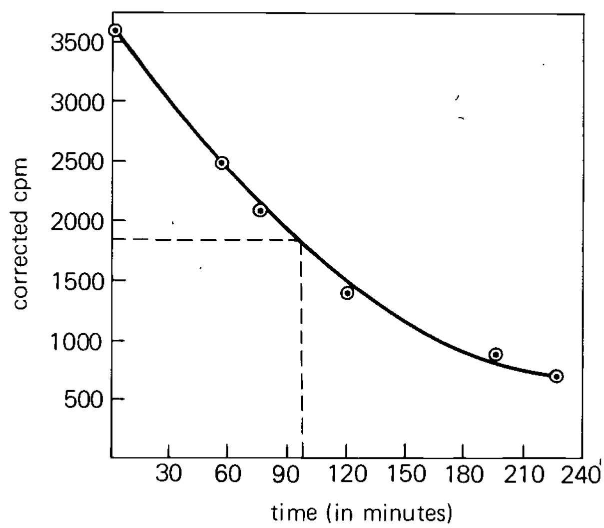
   A. 267 B. 400 C. 100 D. 200

6. Given the following data for a $^{113}Sn/^{113m}In$ experiment, construct a graph of activity versus time in minutes.

Time	*Corrected Activity cpm*
9:45	3700
10:40	2500
11:00	2100
11:45	1400
1:00	900
1:30	700

Using the graph, determine the experimental half-life for ^{113m}In, expressed in minutes.

The dotted line on the graph shows the determination of approximately a 100-minute half-life.



7. Four hours after chemical separation a radioactive nuclide with a half-life of 8 hours has 1000 atoms left. How many atoms were present at the time of separation? 1414

8. $^{241m}_{95}Am \longrightarrow ^{241}_{95}Am + \underline{\gamma}$

9. $^{60m}_{27}Co \longrightarrow \underline{^{60}_{27}Co} + \gamma$

SUGGESTED READINGS

Macdougall, J. D. "Fission-Track Dating." *Scientific American,* December 1976, pp. 114–122.

Peebles, P. J. E., and Wilkinson, D. T. "The Primeval Fireball." *Scientific American,* June 1967, p. 28.

Renfrew, Colin. "Carbon 14 and Pre-history of Europe." *Scientific American,* October 1971, pp. 63–72.

Schramm, D. N. "The Age of the Elements." *Scientific American,* January 1974, pp. 69–77.

SUGGESTED FILMS

Alpha, Beta, and Gamma. Color, 44 minutes. U.S. Department of Energy, Film Library, P.O. Box 62, Oak Ridge, TN 37830.
Explores the origin and nature of alpha, beta, and gamma radiation.

The Atom & Archeology. Color, 25 minutes. U.S. Department of Energy, Film Library, P.O. Box 62, Oak Ridge, TN 37830.
Presents archaeological uses of atomic energy—the atomic clock, the atomic fingerprint, and the atomic X ray.

The Search for New Elements

We recommend that you read G. Seaborg, *Manmade Transuranium Elements* (Englewood Cliffs, N.J.: Prentice-Hall, 1963), which is listed in the *Suggested Reading* of this unit. It presents an excellent, although now somewhat dated, review and history of those elements.

N-33 MODERN ALCHEMY

This section gives a historical account of the nuclear chemists' "alchemy"—the manufacture of elements heavier than uranium. Help your students to grasp the significance of the research that has been conducted during the past forty years by reviewing with them the development of the transuranium elements. Be sure your class understands the use of the cyclotron and other accelerators in the transmutation of elements. Your students may have learned about reactors and accelerators in their previous study of science, but some clarification may be necessary at this point.

Refer to Table 7 (student module page 65). Call on a student to interpret the table. Ask the following questions. "What is the half-life of ^{237}Np (neptunium)? Of ^{224}Pu (plutonium)?" (As the table indicates, the half-life of ^{237}Np is 2.2×10^6 years, and the half-life of ^{224}Pu is 8×10^7 years.) "What kind of decay does plutonium undergo?" (Alpha decay) Ask a student to identify the inner transition elements.

Discuss the equations described in the text for the synthesis of transuranium elements.

It should be noted that scientists in the Soviet Union have reported the discovery of isotopes of elements 104–107 and their decay by spontaneous fission. However, the results of recent work have indicated that many of these discoveries may need further investigation.

N-34 SUPERHEAVY-ELEMENT SYNTHESIS

The chemical properties of the transuranium elements are much like those of their neighbors directly above them in the *Periodic Table of the Elements*. Elements 93–103 complete the inner transition, or actinide, series. Elements 104, 105, and 106 are expected to behave similarly to the transition metals, $_{72}Hf$ (hafnium), $_{73}Ta$ (tantalum), and $_{74}W$ (tungsten), respectively. The superheavy elements will complete the transition metal series with elements 110, 111, and 112 (analogous to Pt, Au, and Hg). These will be followed by a series of normal elements: element 113, belonging to the boron family, element 114, belonging to the carbon family, and element 115, belonging to the nitrogen family. All these elements are expected to be metals, but they will probably have some unusual chemical properties. Note that element 118 is expected to be a "noble gas," but because of its large atomic mass it is most likely to be a "noble liquid."

A number of reports of the observations of superheavy elements have appeared in the scientific literature and the popular press. However, as of this writing, none of the observations reported have been verified. In each case an alternative explanation has been found to discount the reports of evidence for the existence of superheavy elements.

ANSWERS TO PROBLEMS

(Student module page 68)

1. Berkeley, California
2. ^{232}Th, ^{235}U, and ^{238}U (also ^{40}K, ^{87}Rb, ^{50}V)
3. $N \propto m$;

$$(m) = (m_0)\,(1/2)^n = (0.50\ \text{g})\,(1/2)^{1/2} = 0.35\ \text{g}$$

4. Tremendous speeds are required to overcome the electric-charge repulsion between the two positively charged nuclei.
5. Electric and magnetic fields are used to accelerate the particles. These act only on charged particles; therefore, the atoms must be ionized.

EVALUATION ITEMS

The following are additional evaluation items that you may wish to use with your students at various times during the preceding unit. The correct answer to each question is indicated by shading.

1. Place the elements with Z = 110–126 into the periodic table. Predict their chemical properties based on their position in the table.

   Answers determined by teacher.

2. What methods are being used to try to synthesize the superheavy elements?

   heavy-ion reactions and the *r*-process

SUGGESTED READING

Seaborg, Glenn T. *Man-made Transuranium Elements.* Englewood Cliffs, N.J.: Prentice-Hall, 1963. Paperback.

SUGGESTED FILMS

The Alchemist's Dream. Color, 29 minutes. U.S. Department of Energy, Film Library, P.O. Box 62, Oak Ridge, TN 37830. Members of the Argonne Chemistry Division explain the use of the cyclotron in the transmutation of curium to berkelium.

A Journal of Plutonium. Color, 47 minutes. U.S. Department of Energy, Film Library, P.O. Box 62, Oak Ridge, TN 37830. A chronicle of the people and events involved in the discovery, separation, and large-scale production of plutonium.

Uses of Radiation

Suggest to your students that they refer to magazines and newspapers for stories about the uses of radiation. Give the students an opportunity to collect clippings from magazines and newspapers and then make comparisons. Discuss and exchange information. You might also plan a field trip to a hospital in your community. A technician in the radiology department of your local hospital could be asked to give a presentation on the use of radiation in the treatment of patients.

N-35 RADIATION IN OUR ENVIRONMENT

Among the sources of natural radioactivity that we are exposed to daily are radioactive atoms of the inert gas radon, $^{222}_{86}Rn$ and $^{220}_{86}Rn$. These nuclei and their alpha-decay products occur naturally in the air as a result of the decay of ^{232}Th and ^{238}U in the Earth's crust and in the ocean. Although these constitute minimal radiation hazards, they are constant ones and must be considered whenever we discuss the hazards of synthetic radiation, such as that in nuclear reactors.

To give some idea of the extent of radiation in our environment, it is necessary to compare the amount of natural radiation to which we are exposed annually with the standards for the maximum permissible amount of radiation per year. Radiation dosage is measured in terms of the *rem*, which is a measure of the amount of biological damage caused by a given source of radiation. The U.S. Department of Energy has established a maximum safe dosage per year for persons whose work involves the use of radiation. This maximum is 5 rems per year. It should be stressed that this limit has been established to represent an amount of radiation that will not be harmful in any way to the recipient. This limit is based on studies of radiation effects on animals and of radiation accidents involving people.

Natural radiation constitutes about 5 percent of the established safety limit. Several variations should be noted. People living at high altitudes receive more radiation because fewer cosmic rays are attenuated by the atmosphere there. You are better protected from radiation if you live in a log cabin than in a brick house because the latter contains much more ^{40}K. Water supplies that originate in soils rich in potassium, uranium, and thorium are responsible for much more exposure than water that is free of those elements.

Synthetic sources of radiation are medical and dental X rays, radioactive fallout, and industrial sources such as nuclear reactors. The latter two sources together constitute less than 0.5 percent of the maximum safe limit at the present time. In the past, X rays have been our most common source of radiation exposure. Improvements in the design of X-ray devices, however, have greatly reduced their danger. But it is still worthwhile for people to inquire about the safety of X-ray equipment to make sure it is of modern design.

A worksheet to accompany your discussion of the text and illustration on pages 70 and 71 of the student module has been included on the following page. You may reproduce this worksheet in classroom quantities or make an overhead projectual for use in your classroom discussion.

Excellent source material for students that is related to this and the following sections can be found in the Department of Energy's *Understanding the Atom* series. Although the series is out of print, it may still be available in your local library.

Several experiments in *Experiments in Nucleonics* (New York: Union Carbide Corp., 1968. Available from Redco Science Inc., Danbury, CT 06810.) can be added to this section to show how radioactive nuclei can be used as tracers in chemical reactions. These include the following.

Experiment 16 Precipitation of Indium Hydroxide

Experiment 17 Co-precipitation of Indium Hydroxide

Experiment 19 Tracing

Experiment 23 Determination of the Amount of Liquid in a Container

Experiment 25 Diffusion

ANSWERS TO PROBLEMS

(Student module page 70)

1. Answers will vary. Sample answer (not including work-related exposure):

Cosmic radiation	46 mrem
House construction	45 mrem
Ground	15 mrem
Water, food, air	25 mrem
Weapons-test fallout	4 mrem
X-ray diagnosis	9 mrem
Jet airplane travel	36 mrem
Television viewing	0.10 mrem

Annual radiation dose = 180 mrem

2. **a.** Yearly exposure = 180 mrem (from Problem 1);

MINIGENERATOR radiation at 60 cm = 10^{-4} mrem/h

Therefore,

$$\text{time} = \frac{180 \text{ mrem}}{10^{-4} \text{ mrem/h}} = 180 \times 10^4 \text{ h} = 200 \text{ yr}$$

b. Radiation from 3 hours of TV viewing per day = 0.45 mrem

$$\text{time} = \frac{0.45 \text{ mrem}}{10^{-4} \text{ mrem/h}} = 4.5 \times 10^3 \text{ h} = 0.5 \text{ yr}$$

EXPERIMENT N-36 GAMMA-RAY PENETRATION

To compare the penetrating powers of various types of radiation, students will find the diagram on page 55 of the student module to be useful. The thickness of material that is required to stop equal-energy alpha, beta, and gamma rays of a few MeV is shown here.

This experiment is intended to illustrate the high energy of nuclear radiation. It also aims to determine the amounts of material required to absorb nuclear radiation and shows the dependence of absorption on the type of material.

SOURCES OF RADIATION WORKSHEET
(for Student Module, Problem 1, page 70)

SOURCES AND AMOUNTS OF RADIATION PER YEAR*

Source	Amount (mrem)	Your Data
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 (6000-mile flights)	4 (each)	______
Television viewing	0.15 X number of hours per day	______
How close you live to a nuclear power plant		
At site boundary	0.2 X annual average number of hours you spend there per day	______
1 mile away	0.02 X annual average number of hours you spend there per day	______
5 miles away	0.002 X annual average number of hours you spend there per day	______
over 5 miles away	0 X annual average number of hours you spend there per day	______
	Total	______

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

Concepts

- Gamma radiation has great penetrating power.
- Some materials are better able to absorb radiation than others.
- The ability of a given material to absorb radiation depends on its thickness.
- The amount of material necessary to reduce the intensity of radiation to one-half its original value is called the *half-thickness* of the material.

Objectives

- Determine experimentally the half-thicknesses of sheets of aluminum (Al), copper (Cu), and lead (Pb).
- Graph radiation intensity versus sheet thickness and graphically determine half-thickness.
- Compare shielding abilities of various metals and explain the differences.

Estimated Time One period

Student Grouping Groups of two to five, depending on the equipment available.

Materials

radiation detector
MINIGENERATOR or other gamma-ray source
3 sheets of aluminum, 3 sheets of copper, 10 sheets of lead (each sheet approximately 25 cm square and 0.1 cm thick)
linear graph paper
ruler, centimeter
ring stand and ring
pair of rubber gloves

Advance Preparation Check the background radiation yourself before instructing the students to proceed with the experiment. If the students' average readings are questionable, you can have them take more readings to verify their initial findings.

Prelab Discussion This experiment relates directly to the student because it provides a basis for knowledge about shielding individuals from radiation. This knowledge is important for X-ray technicians and their patients, for the nuclear power industry and its employees, for people who work on nuclear-powered ships, and for any other people who work in an area that has radioactive materials.

Laboratory Safety Review with your students the standard laboratory safety rules they should be following. Note *Appendix I: Safety* at the end of the student module.

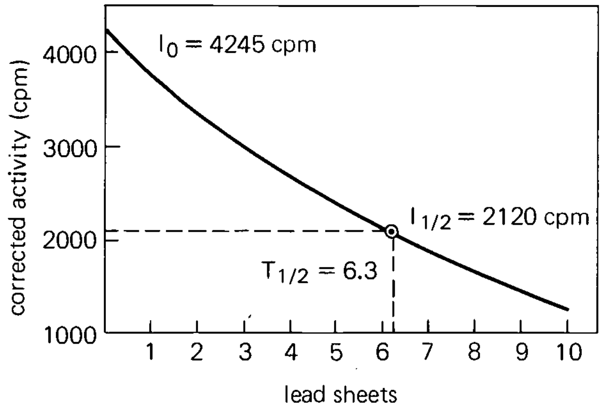
Laboratory Tips Several count-rate readings of each intensity should be taken and averaged to reduce the possibility of statistical errors. This is always good practice if time permits. If the MINIGENERATOR is placed in a counting chamber below the detector, the sheets of lead shielding can be cut into disks that neatly fit on the trays of the counting chamber. Typical lead sheets are about one millimeter thick. The intensity reading will be substantially reduced by the time ten sheets have been placed between the MINIGENERATOR and the detector.

The graph of count rate versus thickness can be plotted on semilogarithmic graph paper. With semilog paper a straight line should result, whereas with linear paper the plot will produce a curved line. The thickness may be plotted in centimeters or merely in units of single sheets of lead, as in the sample data, in which a $^{137}Cs/^{137m}Ba$ MINIGENERATOR and a scintillation detector were used. Remind your students that it is not necessary to take the logarithm of the number on the ordinate scale; the graph paper does that. Have them simply plot one number against the other, taking care in reading the scales.

Range of Results One experimental determination of the half-thickness of lead is illustrated by the sample data and the accompanying graph.

SAMPLE DATA
Background = 1230 cpm

Sheets of Lead	*Activity (cpm)*	*cpm Corrected for Background*
0	5475	4245
1	4940	3710
2	4580	3350
3	4210	2980
4	3870	2640
5	3650	2420
6	3375	2145
7	3090	1860
8	2880	1650
9	2690	1460
10	2480	1250



With these data the curve of the attenuation of gamma-ray intensity caused by shielding indicates a half-thickness of 6.3 sheets of lead. If each sheet is one millimeter thick, the half-thickness is 0.63 cm. The point shown on the graph indicates how the half-thickness of lead was experimentally determined from the sample data.

Postlab Discussion As gamma rays pass through matter they interact with the atoms of that matter. Some of the gamma rays lose all their energy and are absorbed. Other gamma rays lose only some of their energy by colliding with atoms and being deflected. The overall effect of these interactions is a loss of gamma-ray intensity, which can be expressed by Lambert's law.

$$I = I_0 e^{-\mu x}$$

In this equation, I_0 is the original gamma-ray intensity; I is the intensity of gamma rays after they pass through the absorbing material; x is the thickness (cm) of the absorbing material; e is the natural logarithm base; and μ is a linear absorption coefficient (cm^{-1}), which depends on the number of electrons in an atom of the absorbing material and on the energy of the gamma radiation. In general, the higher the atomic number of the absorbing material, the more effective it is in stopping radiation.

The ability of a material to decrease gamma-ray intensity is usually measured by a half-thickness value. This value is the thickness (expressed in centimeters) of a material that decreases the intensity of the gamma ray by one-half. Therefore,

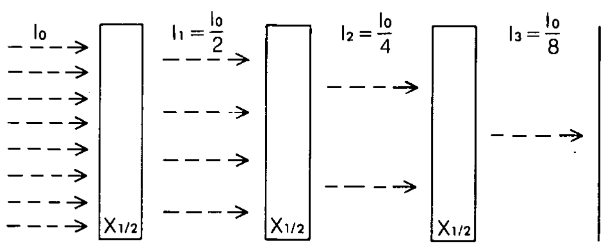
$$I = \frac{1}{2} I_0 e = 2.3$$

$$2.3 \log (I_0 / \frac{1}{2} I_0) = 2.3 \log 2 = \mu x_{\frac{1}{2}}$$

$$x_{\frac{1}{2}} = .693/\mu$$

When gamma rays traverse matter, they give up energy by interacting with the electrostatic field around atomic electrons. Few interactions occur with nuclei because of the very small volume of the nucleus. The nuclear volume is more than 10^{12} times smaller than the volume of the atom. Once a photon undergoes any interaction, it is no longer considered to be part of the primary beam. This experiment investigates the shielding ability of lead without considering the nature of the photon–electron interaction. Refer to Experiment 13 in *Experiments in Nucleonics* (New York: Union Carbide Corp., 1968. Available from Redco Science Inc., Danbury, CT 06810.)

The student has been exposed to several new terms and concepts that might seem bewildering if taken in aggregate. It is not suggested that high-school students be held responsible for the derivation of Lambert's law or geometry effects. Half-thickness can perhaps best be explained by an example of what happens to a quantity of radiation after it passes through several layers of a material, as illustrated in the following diagram. This is basically what the student is doing in identifying half-thickness from a graph of *radiation intensity* versus *thickness of material.* After the students establish a value for the thickness of shielding that will reduce radiation to one half of the previous intensity, they will be asked to consider several implications (Questions 1, 2, 3, and 4).



Schematic representation of the concept of half-thickness ($X_{1/2}$). Gamma rays (eight of them) pass through one half-thickness, and on the average four of them are transmitted; for example, the initial intensity I_0 is cut in half: $I_1 = 1/2\, I_0 = 4$. A second sheet of the same thickness cuts the intensity in half again; for example,

$I_2 = 1/2\, I_1 = 2$ gammas.

Similarly,

$I_3 = 1/2\, I_2 = 1/4\, I_1 = 1/8\, I_0 = 1$ gamma.

Answers to Questions

1. The counting rate decreased from Al to Cu to Pb.
2. The counting rate decreases as the shielding thickness increases.
3. Answers here depend on the MINIGENERATOR source used. For $^{137}Cs/^{137m}Ba$, about 0.6 cm of lead is expected; for $^{113}Sn/^{113m}In$, approximately 0.3 cm of lead. (Gamma-ray energies vary by source.)
4. Increased distance will lead to a lower result and decreased distance to a higher result.

N-37 RADIOACTIVE TRACERS IN CHEMISTRY

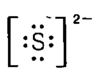
Other examples of radioactive tracing can also be presented. For example, if the labeled solid $Pb^*(NO_3)_2$ is mixed in water with a previously prepared precipitate of $PbSO_4$, it is found that after a while the $PbSO_4$ solid will also contain radioactive lead. This results from the exchange of lead ions between the solution and the solid and demonstrates the ionic nature of $PbSO_4$ and $Pb(NO_3)_2$.

$$Pb^*(NO_3)_2(s) \longrightarrow Pb^{*2+}(aq) + 2\ NO_3^-(aq) \text{ (dissolves completely)}$$

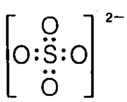
$$PbSO_4(s) \longrightarrow Pb^{2+}(aq) + SO_4^{2-}(aq) \text{ (dissolves very slightly)}$$

$$Pb^{*2+}(aq) + SO_4^{2-}(aq) \longrightarrow Pb^*SO_4(s)$$

On the other hand, if labeled sulfide ions, S^{*2-}, are mixed with unlabeled sulfate ions, SO_4^{2-}, no exchange for the labeled atoms by the latter is observed. This is because of the strong covalent bonds between the sulfur and oxygen atoms in SO_4^{2-}.



sulfide ion



sulfate ion

One important technique that has proved useful for the analysis of complex organic and biochemical compounds is *isotope dilution*. In this method a known mass (or volume) of a labeled compound is added to a mixture (the unknown) that contains the same compound that is unlabeled. The compound is then separated by chemical means. Because the radioactive molecules are chemically the same as those in the unknown mixture, they will behave alike during the separation procedures. Then the total mass (or volume) of the compound (added tracer plus unknown) and its radioactive decay rate are measured. From the ratios of the initial masses and radioactivity to the final masses and radioactivity, the amount of material present in the original unknown sample can then be determined. The equation for this experiment on isotope dilution is

$$\frac{\text{mass of final sample}}{\text{radioactivity of final sample}} = \frac{\text{mass of unknown} + \text{mass of initial tracer}}{\text{radioactivity of initial tracer}}$$

MINIEXPERIMENT N-38 TRACERS

In this experiment the student differentiates between compounds in a group of substances to determine which are radioactive and which are stable. A group of six to eight samples, each having a mass of 10–20 grams, is usually adequate. Easily obtainable radioactive compounds include salts of potassium, rubidium, thorium, and uranium. Old uranium and thorium compounds are most desirable, and if mineral samples of pitchblende or other uranium or thorium ore are available, these will work well. Other possible sources of radioactivity include old radium-dial wristwatches and orange Fiesta cooking ware that is more than fifteen years old. The latter two sources are no longer on the market but can frequently be found in homes as keepsakes. If you have access to the old Fiesta ware, handle it with care. The orange color was obtained through the use of a uranium compound, and the item or items may be very radioactive.

In the group of substances include a number of "blanks," such as NaCl. Also, remember that the activity of the potassium and rubidium compounds is quite low, and so the student must exercise some care in distinguishing between those compounds and other nonradioactive substances. Careful background measurements are essential. In fact, there may be some difficulty in determining the radioactivity of rubidium compounds if the radiation detectors you use are not very sensitive.

N-39 EFFECTS OF RADIATION DOSES

The effects of nuclear radiation on biological systems have been extensively studied. In particular, the survivors of the Hiroshima and Nagasaki nuclear explosions in World War II have been carefully followed. This project continues today. From these and other studies we know that excessive radiation exposure results in an increased incidence of leukemia. For example, if a dose of 500 rems is received by a population sample in a few hours, about 50 percent of those exposed can be expected to die as a direct result of the exposure. However, this dose is 100 times the maximum annual safety limit established for people who work with radiation. It is almost 3000 times the annual background exposure.

Determination of the maximum safe exposure to radiation is the subject of extensive research at the present time. The problem is very complex because of a lack of available data on the effects of low-level radiation on human subjects (although we know what high levels do) and because of the extreme variability in the responses of different individuals. With regard to the latter point, the problem is somewhat like trying to establish a fixed number of minutes one can be exposed to the Sun without getting a sunburn and then applying that limit to the entire population. Various environmental effects add to the problem. For example, the average background radiation in Colorado is more than twice that in Pennsylvania. Yet Pennsylvania ranks about tenth nationally in cancer mortality, whereas Colorado has one of the lowest rates, ranking forty-sixth.

N-40 NUCLEAR TECHNIQUES IN MEDICINE

The application of tracers in medicine is established by the following criteria. A radioactivity-tagged compound that is specific to a given constituent of the body must be available. For example, iodine concentrates in the thyroid gland. Thus, ^{131}I is a good tracer for investigation of the thyroid.

The tracer nucleus should decay by beta- or gamma-ray emission (or both) rather than by alpha decay. This facilitates detection of the radiation, since gamma and beta rays are not absorbed as readily by the human body as are alpha particles. See the illustration on page 55 of the student module for a comparison of the relative penetrating powers of alpha, beta, and gamma rays.

A suitable detection device for the emitted radiation must be available. Modern instrumentation includes scanning devices such as the one shown on page 76 of the student module; these provide a high degree of accuracy in measuring radiation.

You might check with your local hospital to see if radioisotope imaging is performed there as a diagnostic procedure. The field of nuclear medicine has grown very rapidly in the past ten years, and there are now more cyclotrons in hospitals in this country than there are in nuclear research laboratories. Tracer diagnosis has certainly become one of the most effective demonstrations of the benefits of radioactivity. You may want to arrange for a speaker to visit your class to discuss uses of tracers in medicine.

N-41 NUCLEAR TECHNIQUES IN AGRICULTURE

An interesting approach to the constructive use of radiation has been employed in insect control. For example, the screwworm fly is an insect that is common in the southern United States, where it causes considerable damage to livestock. One method of controlling these flies has been to breed them and then to sterilize them with radiation when they reach the adult stage. Large numbers of the sterilized flies are then released in the infested area and allowed to mingle with the normal flies. The mating between sterile flies and the normal population leads to such a high percentage of sterile eggs that very few eggs hatch and, as a result, the next generation of flies is effectively eliminated. This method has proved very successful in the control of the screwworm fly during the past several years.

In applications similar to those discussed in the student module, harmful insects can be labeled in order to track their life cycles and thus gain a better idea of the range of their migration and also to learn what their natural predators are. For example, by using radioactivity-tagged aphids, scientists have learned that these pests are eaten by the praying mantis but not by other large insects. Consequently, the praying mantis can serve as an effective, nontoxic method of aphid control.

Another area of nuclear application is in the study of animal nutrition. Tracers have been found to be valuable in determining the feed that most economically produces the most nutritious meat. They have also been used to test the effects of growth-stimulating hormones and tranquilizers given to cattle. (Cattle are sometimes given tranquilizers during shipment to market—otherwise they get nervous and lose weight.) The tracer technique makes it possible to examine meat processed from such cattle to ensure that these drugs do not appear as contaminants.

EXPERIMENT
N-42 PLANT ABSORPTION OF PHOSPHORUS

This experiment is intended to demonstrate the usefulness of tracers in agriculture. The students will trace the flow of ^{32}P uptake through the roots and stems of a plant to final deposition in the leaves.

Concepts

- Agricultural scientists can use tracers to monitor the flow of materials through plant tissues.
- Plants absorb minerals through their roots, and their stem tissue distributes the minerals to the leaves.

Objectives

- Demonstrate the uptake of ^{32}P by plants.
- Demonstrate the distribution of ^{32}P by the stem tissue to the leaves.

Estimated Time One and one-half periods.

Student Grouping Groups of two to five, depending on the number of radiation detectors available.

Materials

2.5 cm^3 (5 μCi) of ^{32}P solution
potted plant
balance, 0.01 g sensitivity
scissors
plastic wrap
radiation detector
pair of rubber gloves
400-cm^3 beaker

Advance Preparation Dilute 2.5 cm^3 (5 μCi) of ^{32}P solution to 100 cm^3. Prepare enough solution for all the plants. Use 100 cm^3 per plant.

Prelab Discussion Remind the students that this experiment demonstrates a typical use of tracers in agriculture.

Laboratory Safety Review with your students the standard laboratory safety rules they should be following. Note the safety section in *Appendix I* of the student module.

Laboratory Tips Try this experiment yourself beforehand to determine the amount of plant material needed to provide an activity level that your detectors can measure. Each group may need more than one plant, or, if you wish, the groups can pool their different plant tissues.

Range of Results Variable

Postlab Discussion Review the data collected and discuss the relative amounts of ^{32}P in the different types of plant tissues. Perhaps a biology teacher would offer suggestions regarding the use of ^{32}P made by each type of tissue.

Answers to Questions

1. leaf tissue
2. Minerals such as phosphorus are metabolized primarily by the leaves of plants.
3. The distance between the detector and the radiation source should be constant so that the relative amounts of radioactivity among the plant parts can be accurately compared.

N-43 RADIATION AND CONSUMER PRODUCTS

With the exception of the ionization smoke detector, most commercial applications of nuclear techniques are employed in product quality control, where they are very useful in gauging the thickness and uniformity of materials, for locating structural defects, and for similar diagnostic procedures.

N-44 ACTIVATION ANALYSIS

You can evaluate your students' understanding of neutron-activation analysis by asking, "How does a criminologist use neutron activation analysis to determine whether a murder suspect has fired a gun?" A student who understands neutron-activation analysis can readily answer this question. Proceed with your lesson by calling attention to Table 10 (student module page 84).

Miniactivity Many criminology laboratories and environmental studies laboratories use neutron activation analysis as a routine technique. If there is such a laboratory near your school, a guest speaker can be invited to talk about this important analytical technique.

ANSWERS TO PROBLEMS

(Student module page 84)

The answers to the discussion problems will depend on the reading that the students have done. Pursue these problems as time, interest, and information will allow.

Miniactivity Help the students organize a debate on the impact of radiation on society.

EVALUATION ITEMS

The following are additional evaluational items that you may wish to use with your students at various times during the preceding unit. The correct answer to each question is indicated by shading.

1. Give two examples of sources of natural background radiation.

   Sample answers: long-lived, naturally occurring nuclides, such as ^{40}K and ^{238}U; cosmic radiation and its products, such as ^{14}C and ^{3}H.

2. Give two examples of synthetic sources of radiation.

   Sample answers: medical X rays; radioactive fallout.

3. List three uses of radioactive tracers in medicine and agriculture.

   Refer to sections *N-40* and *N-41*.

4. Which nuclide has been used as a tracer in medical diagnosis?

   A. ^{90}Sr C. ^{131}I
   B. ^{235}U D. ^{14}C

5. Which material would have the highest half-thickness value when tested with gamma radiation?

   A. paper C. copper
   B. aluminum D. lead

SUGGESTED READINGS

Basics Books on Atomic Energy. U.S. Department of Energy, Technical Information Center, Oak Ridge, TN 37830.
An excellent source of information on applications of nuclei.

Gordus, Adon A. "Neutron Activation Analysis of Almost Any Old Thing." *Chemistry,* May 1968, pp. 8–15.

Webster, A. "The Cosmic Background Radiation." *Scientific American,* August 1974, pp. 26–33.

SUGGESTED FILMS

Atomic Search. Color, 28 minutes. U.S. Department of Energy, Film Library, P.O. Box 62, Oak Ridge, TN 37830.
The story of some of the achievements scientists made in 1969 in searching for peaceful uses of nuclear energy.

Nuclear Fingerprinting of Ancient Pottery. Color, 20 minutes. U.S. Department of Energy, Film Library, P.O. Box 62, Oak Ridge, TN 37830.
Ancient pottery is analyzed with nuclear techniques to determine its exact chemical composition.

Nuclear Spectrum. Color, 28 minutes. U.S. Department of Energy, Film Library, P.O. Box 62, Oak Ridge, TN 37830.
Scientists directly involved in nuclear research introduce viewers to their laboratories and discuss new investigations and the development of spinoff applications.

Opportunity Unlimited: Friendly Atoms In Industry. Color, 28½ minutes. U.S. Department of Energy, Film Library, P.O. Box 62, Oak Ridge, TN 37830.
Describes how American industry uses radioisotopes to make better products.

This Nuclear Age. Color, 28½ minutes. Canadian Consulate General, 1251 Avenue of the Americas, New York, NY 10020.
An up-to-date account of both pure and applied nuclear research and development in Canada.

Retirement of the Hallam Nuclear Power Facility. Color, 35 minutes. U.S. Department of Energy, Film Library, P.O. Box 62, Oak Ridge, TN 37830.
Documents the decommissioning of a 254-megawatt nuclear power plant located in Nebraska.

A Sea We Cannot See. Color, 28 minutes. U.S. Department of Energy, Film Library, P.O. Box 62, Oak Ridge, TN 37830.
Explains what is meant by low-dose radiation and how it affects life.

Nuclear Power

An understanding of the principles of energy production is becoming increasingly essential for all members of our society. Many of the important decisions we must make as citizens involve energy-related matters that have an important bearing on the future quality of life in our country. Certainly nuclear power falls into this category. Unfortunately, even the conventional means of power production, such as fossil-fuel burning and hydroelectric power, are poorly understood. In order to permit a comparison of principles and problems associated with all forms of energy generation, it would be useful to introduce this unit with a review of sections E-52 and E-62 in *The Delicate Balance: An Energy and the Environment Chemistry Module.*

N-45 NUCLEAR REACTOR OPERATION

Perhaps a utility company in your community operates a nuclear power plant for generating electricity. If so, schedule a field trip to the power plant to give your students an opportunity to observe for themselves how nuclear energy is being used to generate electricity. The list on the following pages can help you identify nearby facilities, many of which will arrange tours for school groups. A university in your area may operate a training reactor, and arranging a tour of it would be an excellent alternative. Refer to and discuss the uses of nuclear power that are mentioned in the student module. Ask and discuss, "Will nuclear power be used increasingly in the years ahead? What about the distant future?" Compare the environmental problems of nuclear-power generation with those of fossil-fuel burning and hydroelectric power. (See *The Delicate Balance: An Energy and the Environment Chemistry Module.*)

The breeder-reactor concept is attractive in that such a reactor produces fuel and power simultaneously. The reactions

$$^{232}_{90}\mathrm{Th} + {}^{1}_{0}n \longrightarrow {}^{233}_{90}\mathrm{Th} \xrightarrow[\text{(22 min)}]{{}^{0}_{-1}\beta} {}^{233}_{91}\mathrm{Pu} \xrightarrow[\text{(27 days)}]{{}^{0}_{-1}\beta} {}^{233}_{92}\mathrm{U}\ (1.6 \times 10^{5}\ \mathrm{yr})$$

$$^{238}_{90}\mathrm{U} + {}^{1}_{0}n \longrightarrow {}^{239}_{92}\mathrm{U} \xrightarrow[\text{(23 min)}]{{}^{0}_{-1}\beta} {}^{239}_{93}\mathrm{Np} \xrightarrow[\text{(2.4 days)}]{{}^{0}_{-1}\beta} {}^{239}_{94}\mathrm{Pu}\ (2.4 \times 10^{4}\ \mathrm{yr})$$

each involve a neutron-capture reaction followed by two successive beta decays. The resultant ^{233}U and ^{239}Pu are both better nuclear fuels than ^{235}U. For a reactor to function in the breeder mode, it must operate at substantially higher temperatures than those of conventional reactors. This means that water cannot be used as the coolant in a breeder reactor, and as a result many complications are introduced into the design. However, the technology has been worked out and plans are being effected for such reactors in Europe. But the fact that ^{233}U and ^{239}Pu are materials that can be used in the creation of nuclear weapons has caused great concern about the proliferation of such weapons.

N-46 NUCLEAR POWER AND THE ENVIRONMENT

Miniactivity Since the controversy concerning nuclear power is a subject that appears frequently in newspapers and magazines, it presents an excellent opportunity to relate classroom work to current affairs. A class debate in which sections of the class are given responsibility for certain topics can be very useful. The following is just a partial list of the topics that can be assigned.

- The Need for Nuclear Power
- Storage of Nuclear Wastes and Fuel Reprocessing
- Environmental Hazards of Nuclear Power
- The Threat of Nuclear Weapons
- Environmental Hazards of Fossil-Fuel Burning and Hydroelectric Power
- The Danger of Theft of Nuclear Material
- Should the United States Export Its Nuclear-Power Technology?

Each of the listed topics has its pros and cons. Besides the daily newspapers, excellent sources include the appropriate *Scientific American* articles listed in the *Selected Readings* of the student module and in the *Suggested Readings* in this guide.

Nuclear Power Reactors

Site	Plant Name	Utility	Commercial Operation
Alabama			
Decatur	Browns Ferry Nuclear Power Station: Unit 1	Tennessee Valley Authority	1974
Decatur	Browns Ferry Nuclear Power Station: Unit 2	Tennessee Valley Authority	1975
Decatur	Browns Ferry Nuclear Power Station: Unit 3	Tennessee Valley Authority	1977
Dothan	Joseph M. Farley Nuclear Plant: Unit 1	Alabama Power Co.	1977
Dothan	Joseph M. Farley Nuclear Plant: Unit 2	Alabama Power Co.	1980
Arkansas			
Russellville	Arkansas Nuclear One: Unit 1	Arkansas Power & Light Co.	1974
California			
Clay Station	Rancho Seco Nuclear Generating Station	Sacramento Municipal Utility District	1975
Eureka	Humbolt Bay Power Plants: Unit 3	Pacific Gas & Electric Co.	1963
San Clemente	San Onofre Nuclear Generating Station: Unit 1	Southern California Edison Co. & San Diego Gas & Electric Co.	1968
Colorado			
Platteville	Ft. St. Vrain Nuclear Generating Station	Public Service Co. of Colorado	1973
Connecticut			
Haddam Neck	Haddam Neck Plant	Connecticut Yankee Atomic Power Co.	1968
Waterford	Millstone Nuclear Power Station: Unit 1	Northeast Nuclear Energy Co.	1971
Waterford	Millstone Nuclear Power Station: Unit 2	Northeast Nuclear Energy Co.	1975
Florida			
Florida City	Turkey Point Plant: Unit 3	Florida Power & Light Co.	1972
Florida City	Turkey Point Plant: Unit 4	Florida Power & Light Co.	1973
Ft. Pierce	St. Lucie Plant: Unit 1	Florida Power & Light Co.	1976
Red Level	Crystal River Nuclear Plant: Unit 3	Florida Power Co.	1977
Georgia			
Baxley	Edwin I. Hatch Nuclear Plant: Unit 1	Georgia Power Co.	1975
Illinois			
Cordova	Quad-Cities Station: Unit 1	Commonwealth Edison & Iowa-Illinois Gas & Electric Co.	1972
Cordova	Quad-Cities Station: Unit 2	Commonwealth Edison & Iowa-Illinois Gas & Electric Co.	1972
Morris	Dresden Nuclear Power Station: Unit 1	Commonwealth Edison Co.	1960

Site	Plant Name	Utility	Commercial Operation
Morris	Dresden Nuclear Power Station: Unit 2	Commonwealth Edison Co.	1970
Morris	Dresden Nuclear Power Station: Unit 3	Commonwealth Edison Co.	1971
Zion	Zion Nuclear Plant: Unit 1	Commonwealth Edison Co.	1973
Zion	Zion Nuclear Plant: Unit 2	Commonwealth Edison Co.	1974
Iowa			
Palo	Duane Arnold Energy Center: Unit 1	Iowa Electric Light & Power Co.	1975
Maine			
Wiscasset	Maine Yankee Atomic Power Plant	Maine Yankee Atomic Power Co.	1972
Maryland			
Lusby	Calvert Cliffs Nuclear Power Plant: Unit 1	Baltimore Gas & Electric Co.	1975
Lusby	Calvert Cliffs Nuclear Power Plant: Unit 2	Baltimore Gas & Electric Co.	1977
Massachusetts			
Plymouth	Pilgrim Nuclear Power Station: Unit 1	Boston Edison Co.	1972
Rowe	Yankee Nuclear Power Station	Yankee Atomic Electric Co.	1961
Michigan			
Big Rock Point	Big Rock Point Nuclear Plant	Consumers Power Co.	1963
Bridgman	Donald C. Cook Nuclear Power Plant: Unit 1	Indiana & Michigan Electric Co.	1975
Bridgman	Donald C. Cook Nuclear Power Plant: Unit 2	Indiana & Michigan Electric Co.	1978
South Haven	Palisades Nuclear Plant	Consumers Power Co.	1971
Minnesota			
Monticello	Monticello Nuclear Generating Plant	Northern States Power Co.	1971
Red Wing	Prairie Island Nuclear Generating Plant: Unit 1	Northern States Power Co.	1973
Red Wing	Prairie Island Nuclear Generating Plant: Unit 2	Northern States Power Co.	1974
Nebraska			
Brownville	Cooper Nuclear Station	Nebraska Public Power District & Iowa Power & Light Co.	1974
Fort Calhoun	Ft. Calhoun Station: Unit 1	Omaha Public Power District	1973
New Jersey			
Salem	Salem Nuclear Generating Station: Unit 1	Public Service Electric & Gas Co.	1977
Toms River	Oyster Creek Nuclear Power Plant: Unit 1	Jersey Central Power & Light Co.	1969
New York			
Buchanan	Indian Point Station: Unit 1	Consolidated Edison Co. of New York, Inc.	1962
Buchanan	Indian Point Station: Unit 2	Consolidated Edison Co. of New York, Inc.	1973

Site	Plant Name	Utility	Commercial Operation
Buchanan	Indian Point Station: Unit 3	Power Authority of State of New York	1976
Ontario	R. E. Ginna Nuclear Power Plant: Unit 1	Rochester Gas & Electric Corp.	1979
Scriba	Nine Mile Point Nuclear Station: Unit 1	Niagara Mohawk Power Corp.	1969
Scriba	James A. FitzPatrick Nuclear Power Plant	Power Authority of State of New York	1975
North Carolina			
Southport	Brunswick Steam Electric Plant: Unit 1	Carolina Power & Light Co.	1977
Southport	Brunswick Steam Electric Plant: Unit 2	Carolina Power & Light Co.	1975
Ohio			
Oak Harbor	Davis-Besse Nuclear Power Station: Unit 1	Toledo Edison Co. & Cleveland Illuminating Co.	1977
Oregon			
Prescott	Trojan Nuclear Plant: Unit 1	Portland General Electric Co.	1976
Pennsylvania			
Middletown	Three Mile Island Nuclear Station: Unit 1	Metropolitan Edison Co.	1974
Peach Bottom	Peach Bottom Atomic Power Station: Unit 2	Philadelphia Electric Co.	1974
Peach Bottom	Peach Bottom Atomic Power Station: Unit 3	Philadelphia Electric Co.	1974
Shippingport	Shippingport Atomic Power Station	Duquesne Light Co.	1957
Shippingport	Beaver Valley Power Station: Unit 1	Duquesne Light Co. & Ohio Edison Co.	1976
South Carolina			
Hartsville	H. B. Robinson Plant: Unit 2	Carolina Power & Light Co.	1971
Seneca	Oconee Nuclear Plant: Unit 1	Duke Power Co.	1973
Seneca	Oconee Nuclear Plant: Unit 2	Duke Power Co.	1974
Seneca	Oconee Nuclear Plant: Unit 3	Duke Power Co.	1974
Vermont			
Vernon	Vermont Yankee Nuclear Power Station	Vermont Yankee Nuclear Power Corp.	1972
Virginia			
Gravel Neck	Surry Power Station: Unit 1	Virginia Electric & Power Co.	1972
Gravel Neck	Surry Power Station: Unit 2	Virginia Electric & Power Co.	1973
Mineral	North Anna Power Station: Unit 1	Virginia Electric & Power Co.	1978
Washington			
Richland	N-Reactor/WPPSS Steam	Department of Energy	1966
Wisconsin			
Carlton	Kewaunee Nuclear Power Plant: Unit 1	Wisconsin Public Service Corp.	1974
La Crosse	Lacrosse (Genoa) Nuclear Generating Station	Dairyland Power Cooperative	1969
Two Creeks	Point Beach Nuclear Plant: Unit 1	Wisconsin Michigan Power Co.	1970
Two Creeks	Point Beach Nuclear Plant: Unit 2	Wisconsin Michigan Power Co.	1973

Undoubtedly the best source of information on the controversial nature of nuclear materials is the *Bulletin of the Atomic Scientists.* This monthly periodical maintains continual debates on questions of nuclear safety and represents the concerns of many of the world's leading experts on the subject. Refer interested students to the article by H. Bethe, "The Necessity of Fission Power," *Scientific American* (January 1976), pp. 21–31.

Remember that scientific objectivity is the goal to strive for in all discussions. Frequently, arguments concerning the use of nuclear materials become based on emotional rather than scientific grounds. There are valid arguments on both sides of the question and, in the author's opinion, anyone who claims to have all the correct answers should be viewed with suspicion. This does not mean that taking a stand should be avoided; eventually decisions must be made.

N–47 MINIATURE POWER SOURCES

The *Understanding the Atom* series produced by the Atomic Energy Commission (now a part of the Department of Energy) contains a useful module on this subject entitled "Power from Radioisotopes." Also, see the article by H. J. Sanders, "Cardiac Pacemakers," *Chemistry* (July 1971), pp. 14–17. For more up-to-date information, you can write to the Technical Information Division, U.S. Department of Energy, Box 62, Oak Ridge, TN 37830.

N–48 NUCLEAR FUSION: REACH FOR THE SUN

A detailed discussion of nuclear-fusion power goes beyond the aims of most high-school courses, and it is probably best discussed at the level presented here. However, students should be made aware of the possibility that this form of energy may someday become available.

ANSWERS TO PROBLEMS

(Student module page 95)

1–4. General discussion items based on the student module.

5. a. ^{131}I; shortest half-life

b. $\frac{1}{2^{10}} = \frac{1}{1024} = 9.8 \times 10^{-4}$

c. 9.5×10^{-7}

d. ^{131}I; 160 days
^{90}Sr; 560 years
^{239}Pu; 4.9×10^{5} years

6. $^{238}_{94}Pu \longrightarrow {}^{234}_{92}U + {}^{4}_{2}He$

7. A good reference here is *The Delicate Balance: An Energy and the Environment Chemistry Module.*

EVALUATION ITEMS

The following are additional evaluation items that you may wish to use with your students at various times during the preceding unit.

1. Discuss the advantages and disadvantages of nuclear-power generation.
2. Discuss the problem of where a nuclear power plant could be built in your area, or discuss why the present site was chosen if there already is one.
3. Compare the impact of nuclear, fossil-fuel burning, and hydroelectric generation of power on the environment.
4. Describe the major components and the operation of a nuclear power plant.

SUGGESTED READINGS

Bebbington, W. P. "The Reprocessing of Nuclear Fuels." *Scientific American*, December 1976, pp. 30–41.

Bethe, H. A. "The Necessity of Fission Power." *Scientific American*, January 1976, pp. 21–31.

Cohen, B. L. "The Disposal of Radioactive Wastes from Fission Reactors." *Scientific American*, June 1977, pp. 21–31.

Cowan, G. A. "A Natural Fission Reactor." *Scientific American*, July 1976, pp. 36–47.

Drell, S. D., and von Hippel, F. "Limited Nuclear War." *Scientific American*, November 1976, p. 27.

Epstein, W. "The Proliferation of Nuclear Weapons." *Scientific American*, April 1975, p. 18.

Gough, W. C., and Eastlund, B. J. "The Prospects of Fusion Power." *Scientific American*, February 1971, pp. 50–64.

Meyers, H. R. "Extending the Nuclear-Test Ban." *Scientific American*, January 1972, p. 13.

Sanders, H. J. "Cardiac Pacemakers." *Chemistry*, July 1971, pp. 14–17.

Seaborg, G. T., and Bloom, J. L. "Fast Breeder Reactors." *Scientific American*, November 1970, pp. 13–21.
York, H. F. "The Debate Over the Hydrogen Bomb." *Scientific American*, October 1975, pp. 106–113.
_____ "The Great Test-Ban Debate." *Scientific American*, November 1972, p. 15.

SUGGESTED FILMS

To Imitate the Sun. Color, 33 minutes. U.S. Department of Energy, Film Library, P.O. Box 62, Oak Ridge, TN 37830. Describes the theoretical challenge of the controlled-fusion concept, the research being done to meet this challenge, and the advantages of fusion power reactors.

Superconducting Magnet for Fusion Research. Color, 22 minutes. U.S. Department of Energy, Film Library, P.O. Box 62, Oak Ridge, TN 37830. Describes the baseball II neutral-beam injection experiment, the winding and installation of this magnet system, and the initial testing of the fusion research facility.

The Ultimate Energy. Color, 28 minutes. U.S. Department of Energy, Film Library, P.O. Box 62, Oak Ridge, TN 37830. A documentary that explores basic theory and current laboratory experiments that are being performed in the investigation of controlled thermonuclear fusion.

Summary

The summary provides you with an opportunity to tie together many of the various nuclear phenomena discussed in this module. It would also be of value to discuss what new discoveries can be expected in the field of nuclear science. Searches will continue for new elements, exotic nuclei with unusual neutron-to-proton ratios, and more fundamental particles, such as quarks. These investigations, along with sophisticated studies of the shape and structure of nuclear matter, promise to provide exciting new insights into the microscopic aspects of the Universe.

At the same time, astronomy and space science continue to provide new clues about the makeup of the Universe. It might be interesting to speculate on how the Universe would be affected if certain basic features of nuclear stability were altered. For example, if lithium, beryllium, and boron nuclei were more stable, the abundances of these elements in the Universe would be greater. These elements would exist at the expense of those elements that we know to be essential to life and that are plentiful in our environment—carbon, nitrogen, and oxygen. The reaction

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

would be supplanted by others as important ones. In addition, beryllium is highly toxic to biological systems as they presently exist. Perhaps life could not exist at all in such an environment, or it might be adapted to the different conditions. One can envision other such modifications that would result from changes in the abundances of the elements in the Universe.

Finally, it is highly probable that the use of nuclear phenomena in technology will continue to expand in the future. Besides the current widespread uses in medicine, industry, and power generation, your students may be able to suggest some new applications. Also, in light of the controversy over nuclear power, a worthwhile exercise would be to imagine a reversal in the historical roles of nuclear- and fossil-fuel generation of power. Assume that nuclear power is the established technology and imagine that coal and oil have just been introduced as power sources during the last twenty-five years. Then discuss the environmental concerns that such a development might pose in relation to strip mining, the price of oil, air pollution, and so on. This exercise will emphasize the difficulties inherent in the introduction of any major advance in technology.

The Heart of Matter conveys to your students some of the exciting ideas and research problems in the realm of nuclear science. The knowledge that your students obtain from studying this module should heighten their awareness and appreciation of their personal relationship to this science.

Appendix : 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.

Metric Units

PHYSICAL QUANTITY	SI BASE OR DERIVED UNIT		OTHER UNITS	
	NAME	SYMBOL AND DEFINITION	NAME	SYMBOL AND DEFINITION
length	meter*	m	kilometer centimeter nanometer	1 km = 10^3 m 1 cm = 10^{-2} m 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 liter	1 cm^3 = 10^{-6} m^3 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.

Module Tests

Two module tests follow, one to test knowledge-centered objectives and the other to test skill-centered objectives. If you choose to use either or both of these module tests as they are presented here, duplicate copies for your students. Or, you may wish to select some questions from these tests that you feel apply to *your* introductory chemistry course and add questions of your own. Either way, make sure that the test you give reflects your emphasis on the chemistry you and your students experienced in this introductory module.

The skill-centered test will require that you set up several laboratory stations containing materials for your students to examine or work with. You may wish to add additional test items to round out the types of skills you and your students have worked on.

Answers to test questions in this section are provided. If you wish to use a standard-type answer sheet with these tests, one is provided in the appendix of the teacher's guide for *Reactions and Reason: An Introductory Chemistry Module*. Duplicate enough copies for each of your students to use, or revise the format to fit your own testing situation.

ANSWERS FOR KNOWLEDGE-CENTERED MODULE TEST

1. B; **2.** D; **3.** C; **4.** A; **5.** B; **6.** A; **7.** B; **8.** B; **9.** C; **10.** C; **11.** C; **12.** B; **13.** D; **14.** D; **15.** A; **16.** A; **17.** C; **18.** A; **19.** C; **20.** C; **21.** D; **22.** C; **23.** A; **24.** B; **25.** B; **26.** C; **27.** D; **28.** D

Skill-Centered Module Test

Using the skill-centered test items will require certain advance preparations on your part. The numerals in the following list indicate the items for which you will have to prepare special laboratory stations. Be sure to test each of the lab stations before allowing students to determine the answers to the skill-centered items. When students are ready to answer these questions, they should go to the numbered station and follow the directions that are given there and in the printed test item. When they finish with the materials at the station, instruct them to leave the materials in proper order for the next student.

1. Provide a plastic centimeter ruler. Tape a strip of masking tape to the desk top with two lines marked in ink. Draw the lines as far apart as desired, but do not make the distance more than one ruler length.

5. Provide a radiation detector and tape the detector tube to the tabletop. Now tape a radioactive source a distance of 5 cm away.

ANSWERS FOR SKILL-CENTERED MODULE TEST

1. *; **2.** C; **3.** B; **4.** B; **5.** *; **6.** C; **7.** B; **8.** A; **9.** D; **10.** A

*Evaluate according to teacher standards.

THE HEART OF MATTER

Knowledge-Centered Module Test

1. The mass number of Al in the reaction $^{27}_{12}Mg \longrightarrow {}_{13}Al + {}_{-1}^{0}\beta$ is:

   A. 26 B. 27 C. 28 D. 29

2. The nuclear process responsible for limiting the buildup of heavy elements in both stars and the laboratory is

   A. positron decay.
   B. gamma decay.
   C. electron capture.
   D. nuclear fission.

3. A student placed thin sheets of an unknown metal between a radioactive source and a Geiger counter and recorded the following data.

Thickness of Metal Sheets	Activity Corrected for Background
0 cm	4200 cpm
1 cm	3700 cpm
2 cm	3350 cpm
3 cm	3000 cpm
4 cm	2600 cpm
5 cm	2400 cpm
6 cm	2100 cpm
7 cm	1900 cpm
8 cm	1600 cpm

   The half-thickness of the metal is

   A. 2 cm. B. 4 cm. C. 6 cm. D. 8 cm.

4. Protons are accelerated in spiral paths in

   A. cyclotrons.
   B. Van de Graaff generators.
   C. nuclear reactors.
   D. linear accelerators.

5. The term *stellar nucleosynthesis* describes the processes responsible for the

   A. condensation of gas clouds in space.
   B. origin of the elements.
   C. formation of the earth.
   D. radioactive decay of elements.

6. The element that has the most stable nucleus is:

   A. $^{56}_{26}Fe$ B. $^{28}_{14}Si$ C. $^{12}_{6}C$ D. $^{238}_{92}U$

7. If a radioactive sample has an activity of 200 cpm at a distance of 20 cm from a Geiger counter, what will its activity be at a distance of 40 cm?

   A. 25 cpm
   B. 50 cpm
   C. 75 cpm
   D. 100 cpm

8. When a star has a core of helium and an outer envelope of hydrogen, it evolves into a

   A. main sequence star.
   B. red giant.
   C. supernova.
   D. white dwarf.

9. Nuclear chemists agree that stars are continuously producing their own elements. If you were a nuclear chemist, which finding would best support the above statement?

   A. There is a greater proportion of lighter elements than heavier ones in a star.
   B. The size of a star grows during part of its lifetime.
   C. An element that no longer exists on Earth has been identified in a star.
   D. The density of a star increases during part of its lifetime.

10. An important medical use of radiation is

A. activation analysis.
B. nuclear power.
C. radiotherapy.
D. all of the above

11. The nuclide $^{252}_{98}\text{Cf}$ has

A. 98 nucleons.
B. 154 electrons.
C. 154 neutrons.
D. 252 protons.

12. A certain radioactive nuclide has a half-life of 100 minutes. If a sample containing 1600 atoms is allowed to decay for 300 minutes, how many atoms of the radioactive nuclide will remain?

A. 100 atoms
B. 200 atoms
C. 400 atoms
D. 800 atoms

13. An isobar of $^{239}_{92}\text{U}$ is

A. $^{235}_{92}\text{U}$.
B. $^{244}_{94}\text{Pu}$.
C. $^{237}_{90}\text{Th}$.
D. $^{239}_{93}\text{Np}$.

14. A proton has

A. no charge.
B. a 12.8-minute half-life.
C. the same charge as an electron.
D. approximately the same mass as a neutron.

15. The *r*-process is represented in which of the following equations?

A. $^{56}_{26}\text{Fe} + 10\,^{1}_{0}n \longrightarrow {}^{66}_{26}\text{Fe}$

B. $^{59}_{27}\text{Co} + {}^{1}_{0}n \longrightarrow {}^{60}_{27}\text{Co} \longrightarrow {}^{60}_{28}\text{Ni} + {}_{-1}^{\;\,0}\beta$

C. $4\,^{1}_{1}\text{H} \longrightarrow {}^{4}_{2}\text{He} + 2\,^{0}_{1}\beta$

D. $3\,^{4}_{2}\text{He} \longrightarrow {}^{12}_{6}\text{C}$

16. The *s*-process is represented in which of the following equations?

A. $^{59}_{27}\text{Co} + {}^{1}_{0}n \longrightarrow {}^{60}_{27}\text{Co} \longrightarrow {}^{60}_{28}\text{Ni} + {}_{-1}^{\;\,0}\beta$

B. $4\,^{1}_{1}\text{H} \longrightarrow {}^{4}_{2}\text{He} + 2\,^{0}_{1}\beta$

C. $^{12}_{6}\text{C} + {}^{12}_{6}\text{C} \longrightarrow {}^{24}_{12}\text{Mg} + \gamma$

D. $3\,^{4}_{2}\text{He} \longrightarrow {}^{12}_{6}\text{C}$

17. Carbon burning is represented in which of the following equations?

A. $^{56}_{26}\text{Fe} + 10\,^{1}_{0}n \longrightarrow {}^{66}_{26}\text{Fe}$

B. $4\,^{1}_{1}\text{H} \longrightarrow {}^{4}_{2}\text{He} + 2\,^{0}_{1}\beta$

C. $^{12}_{6}\text{C} + {}^{12}_{6}\text{C} \longrightarrow {}^{24}_{12}\text{Mg} + \gamma$

D. $3\,^{4}_{2}\text{He} \longrightarrow {}^{12}_{6}\text{C}$

18. The dominant reaction believed to be occurring in main sequence stars is

A. $4\,^{1}_{1}\text{H} \longrightarrow {}^{4}_{2}\text{He} + 2\,^{0}_{1}\beta$ + energy.

B. $2\,^{12}_{6}\text{C} \longrightarrow {}^{24}_{12}\text{Mg}$ + energy.

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

D. $2\,^{3}_{2}\text{He} \longrightarrow {}^{4}_{2}\text{He} + 2\,^{1}_{1}\text{H}$ + energy.

19. In a nuclear reaction, the products are 0.02 u lighter than the reactants. Using the conversion $c^2 = 931$ MeV/u, the amount of energy produced in this reaction is approximately

A. 0.02 MeV.
B. 1 MeV.
C. 20 MeV.
D. 50 000 MeV.

20. The half-life of $^{14}_{6}\text{C}$ is 5730 years, and in living matter it decays at the rate of 15 dpm per gram of carbon. If a sliver of wood from an ancient wheel has a decay rate of 1.875 dpm per gram of carbon, its age is

A. 5730 years.
B. 11 400 years.
C. 17 160 years.
D. 22 880 years.

21. The two most abundant elements in our solar system are

A. hydrogen and nitrogen.
B. hydrogen and oxygen.
C. oxygen and helium.
D. hydrogen and helium.

22. The big bang theory does not account for

A. the red shift.
B. the expanding Universe.
C. the production of elements beyond $^{7}_{3}Li$.
D. the production of $^{4}_{2}He$.

23. Spontaneous fission is represented in which of the following equations?

A. $^{252}_{98}Cf \longrightarrow ^{106}_{42}Mo + ^{142}_{56}Ba + 4\,^{1}_{0}n$

B. $^{238}_{92}U \longrightarrow ^{234}_{90}Th + ^{4}_{2}He$

C. $^{239}_{93}Np \longrightarrow ^{239}_{94}Pu + ^{0}_{-1}\beta$

D. $^{14}_{7}N + ^{4}_{2}He \longrightarrow ^{17}_{8}O + ^{1}_{1}H$

24. Beta decay is represented in which of the following equations?

A. $^{238}_{92}U \longrightarrow ^{234}_{90}Th + ^{4}_{2}He$

B. $^{239}_{93}Np \longrightarrow ^{239}_{94}Pu + ^{0}_{-1}\beta$

C. $^{137m}_{56}Ba \longrightarrow ^{137}_{56}Ba + \gamma$

D. $^{14}_{7}N + ^{4}_{2}He \longrightarrow ^{17}_{8}O + ^{1}_{1}H$

25. Alpha decay is represented in which of the following equations?

A. $^{252}_{98}Cf \longrightarrow ^{106}_{42}Mo + ^{142}_{56}Ba + 4\,^{1}_{0}n$

B. $^{238}_{92}U \longrightarrow ^{234}_{90}Th + ^{4}_{2}He$

C. $^{239}_{93}Np \longrightarrow ^{239}_{94}Pu + ^{0}_{-1}\beta$

D. $^{137m}_{56}Ba \longrightarrow ^{137}_{56}Ba + \gamma$

26. Gamma decay is represented in which of the following equations?

A. $^{238}_{92}U \longrightarrow ^{234}_{90}Th + ^{4}_{2}He$

B. $^{239}_{93}Np \longrightarrow ^{239}_{94}Pu + ^{0}_{-1}\beta$

C. $^{137m}_{56}Ba \longrightarrow ^{137}_{56}Ba + \gamma$

D. $^{14}_{7}N + ^{4}_{2}He \longrightarrow ^{17}_{8}O + ^{1}_{1}H$

27. The attractive forces holding a proton and an electron together are the

A. nuclear and electromagnetic forces.
B. gravitational and nuclear forces.
C. gravitational, electromagnetic, and nuclear forces.
D. electromagnetic and gravitational forces.

28. In the nuclear reaction

$$^{14}_{7}N + ^{4}_{2}He \longrightarrow ^{17}_{8}O + X,$$

the letter X represents

A. $^{3}_{2}He$ B. $^{3}_{1}H$ C. $^{2}_{1}H$ D. $^{1}_{1}H$

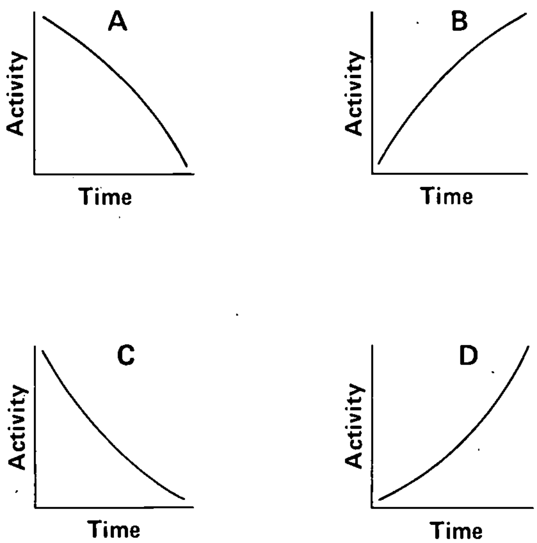
THE HEART OF MATTER

Skill-Centered Module Test

1. Go to station #1 and, using the centimeter ruler provided, determine the distance between the two lines drawn on the piece of masking tape. Record your answer at the bottom of your answer sheet next to #1.

2. Which graph (below) represents the given data for the decay of a radioactive sample?

Activity (cpm)	*Time (h)*
199	0
81	2
66	4
53	6
43	8
35	10
21	15



3. By not subtracting background activity from sample radioactivity readings, the largest error will be in samples where

   A. the sample has high activity.
   B. the sample has low activity readings.
   C. the scale multiplication factor is one.
   D. only half-thickness and half-life values are being determined.

4. By using the following data, determine the distance of the detector from the source if the detector reads 64 cpm. The distance is

   A. 6 cm. C. 10 cm.
   B. 8 cm. D. 12 cm.

Counts/min	*Detector Distance from Source*
1024	2 cm
254	4 cm
16	16 cm

5. Go to station #5 and, using the radiation detector provided, measure the activity of the sample taped to the counter top. Record your answer on the bottom of your answer sheet next to #5. Turn off the radiation detector when finished.

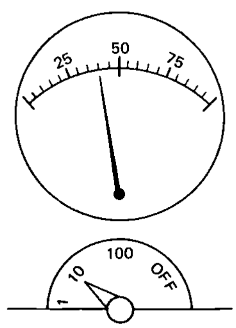
6. If a reading were taken every 15 seconds, how much time elapsed when the following data were collected?

   A. 2.00 min C. 1.50 min
   B. 1.25 min D. 1.75 min

Reading	*cpm*
0	150
1	100
2	80
3	60
4	50
5	40
6	35

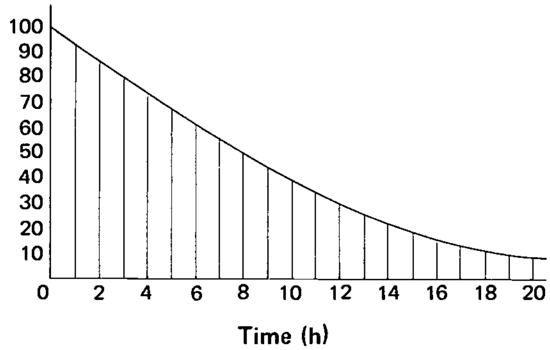
7. The activity shown on the meter pictured below is

   A. 280 cpm. C. 40 cpm.
   B. 400 cpm. D. 28 cpm.



8. Using the graph below, determine the half-life of the sample. The half-life is

A. 6.5 h.
B. 5.5 h.
C. 12.0 h.
D. 5.0 h.

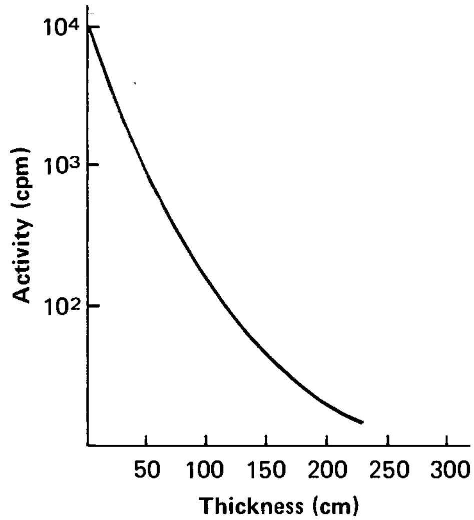


9. When measuring the half-thickness of a sample as you did in this module, which of the following would *not* be a probable source of error?

A. not subtracting background activity from sample activity
B. not having metal plates of uniform thickness
C. not multiplying scale reading by the multiplication factor if the scale is changed
D. not having enough metal plates (thickness) to reduce activity to zero

10. Using the graph (below), determine the half-thickness of lead. The half-thickness is

A. 55 cm.
B. 250 cm.
C. 100 cm.
D. 175 cm.



79

Materials List

*Quantity is based on six teams of five students each. Adjust for other groupings.

NONEXPENDABLE ITEMS

Item	Experiment	Amount
Aluminum sheets (5 cm × 5 cm × 0.1 cm)	36	18 sheets*
Balance	32, 42	1
Beaker, 20-cm^3	28, 32	6*
Beaker, 400-cm^3	42	6*
Bottle, plastic squeeze	13, 28	6*
Clamps, test-tube	9, 36	12*
Copper sheets (5 cm × 5 cm × 0.1 cm)	36	18 sheets*
Lead sheets (5 cm × 5 cm × 0.1 cm)	36	60 sheets*
Planchets (aluminum foil)	13	25 per group
Radiation detector	9, 13, 28, 32, 36, 38, 42	See note
Radioactive sample tape	9	1 roll
Radioactive source (MINIGENERATOR)	9, 13, 22, 28, 32, 36, 38, 42	See note
Ring stands	9, 36	6*
Rubber gloves	9, 13, 28, 36, 42	6 pairs*
Ruler, centimeter	9, 36	6*
Scissors	42	6*
Watch or clock (with second hand)	32	6*

EXPENDABLE ITEMS

Item	Experiment	Amount
Film, Polaroid type 57 (black and white, speed 3000)	22	6 sheets*
Film holder (Polaroid type 545)	22	1
Graph paper, linear	4, 9, 13, 28, 36	1 or 2 pads
Graph paper, semilog (optional)	28, 36	1 pad
Hydrochloric acid, conc.	13, 28	7 cm^3*
Phosphorus solution, ^{32}P (10 μCi/5 cm^3)	42	15 cm^3*
Plants, potted	42	6*
Plastic wrap	42	1 roll
Potassium chloride	32	60 g*
Sodium chloride	13, 28	20 g*
Sources of radioactivity	38	See *N-38*

Note: Quantities required will depend on the number of MINIGENERATORS and/or detectors available to the class. MINIGENERATORS are manufactured by Redco Science Inc., Danbury, CT 06810. Redco also sells a MINIGENERATOR *Nucleonics Kit*, which contains two MINIGERATORS, lead plates, copper plates, and other chemicals for further work with radioactivity.

See *Teaching The Heart of Matter* in this teacher's guide for detailed advice concerning laboratory options. It is assumed in listing quantities here that six MINIGERATORS and six radiation detectors are available for six teams of five students each in a class of thirty.

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Index

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

*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

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
1.008 **H** Hydrogen 1																	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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