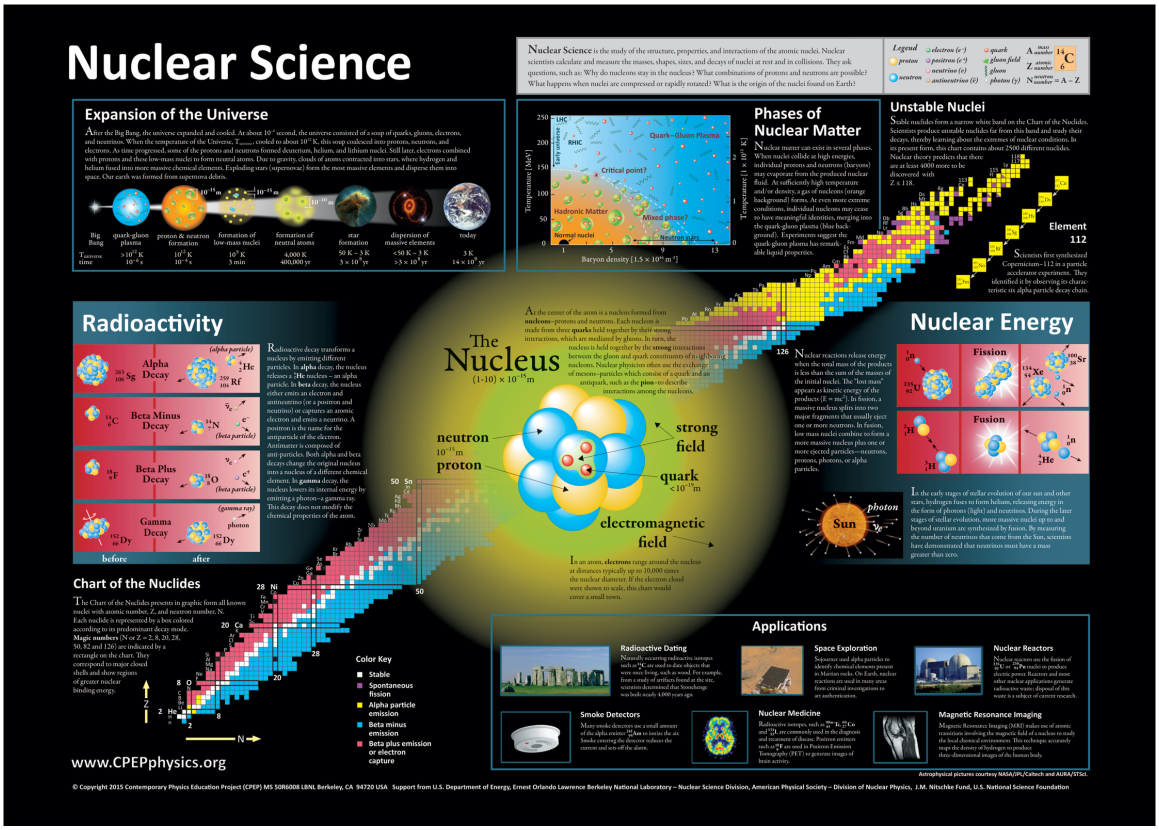
NUCLEAR SCIENCE



A GUIDE

TO THE

NUCLEAR SCIENCE WALL CHART

or

You don't have to be a Nuclear Physicist to Understand Nuclear Science.

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Fifth Edition – October 2019

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First Edition: March 1998

Editor's Note:

In April 1997, we circulated about 300 copies of this booklet throughout the United States and the rest of world. Comments came from teachers who taught all levels and from nuclear scientists throughout the world. From these many excellent comments, we prepared a second version in the summer of 1997. During a week long summer workshop, sponsored by the American Physical Society (APS)—Division of Nuclear Physics, John Cramer, James O'Connell, Ken Krane, Margaret McMahan, Eric Norman, Karen Street and I, completely revised the previous version. Again, we circulated the manuscript and once again, we received many excellent suggestions. We have tried to incorporate as many of these improvements as possible.

This teacher's guide is a work in progress. We welcome your advice and suggestions. We need feedback that describes how useful you have found this guide and what sections you used. We would like success stories as well as discussions of the problems that you have found. We have tried to edit this booklet as carefully as possible. Undoubtedly, there are sections that are too abstract, too abstruse, or perhaps misleading. There are still many typos. Your comments are essential to make the next edition even better. Please send them to

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Many other people besides the authors contributed to the creation of this guide. Because of the large number of contributions, we have only been able to acknowledge a few as authors. We thank the Lawrence Berkeley National Laboratory, U.S. Department of Energy, the American Physical Society—Division of Nuclear Physics, and the J.M. Nitschke Fund for their support and encouragement in preparing this manuscript.

Howard Matis, Berkeley, California, March 1998
For the Nuclear Wall Chart Committee

Notes on the Second Edition

After three printings, we have exhausted the existing booklets. There have been a number of importance advances in our field since the publication of the first editions. For instance, several new elements have been discovered. Most scientists now believe that neutrinos have some very small but unknown mass. The SNO detector and the RHIC accelerator started operation. Because of these changes, we have decided to modify a few chapters and make some typographical changes. In addition, a number of web addresses have been updated. We would like to thank Justin Matis for updating many of the figures and making some corrections to the text.

Howard Matis, Berkeley, California, April 2001

Notes on the Third Edition

Many new advances occurred since the second edition was published. We now know that the neutrino has a non-zero mass and it can transform from one type to another. Several of the previously claimed elements could not be verified and therefore their claim had to be withdrawn. A previous unnamed element now has an official symbol. Experiments at the RHIC accelerator have produced spectacular results. Finally, two physicists were awarded a Nobel Prize for their research on neutrinos. Many scientists consider their work to fall under the field of nuclear physics. We would like to thank Heino Nitsche and Darlene Hoffman for reviewing the chapter on heavy elements.

Howard Matis, Berkeley, California, November 2003

Notes on the Fourth Edition

We have made some small updates trying to keep this as up to date as possible.

Howard Matis, Berkeley, California, June 2018

Notes on the Fifth Edition

We updated the section on Nuclear Chemistry.

Howard Matis, Berkeley, California, October 2019

Contemporary
Physics
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About CPEP

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Chapter 1 Overview

The Nuclear Science Wall Chart has been created to explain to a broad audience the basic concepts of nuclear structure, radioactivity, and nuclear reactions as well as to highlight current areas of research and excitement in the field. This chart follows the example of two very successful wall charts that have been developed earlier by the Contemporary Physics Education Project (CPEP)—one focused on the Standard Model of fundamental particles and another on fusion and plasma physics. New terminology and the physics behind the chart are explained in subsequent chapters and in the glossary.

Nuclear Science is the study of the structure, properties, and interactions of atomic nuclei, which are the hearts of *atom*s. The nucleus is the place where almost all of the mass of ordinary matter resides. Understanding the behavior of nuclear matter under

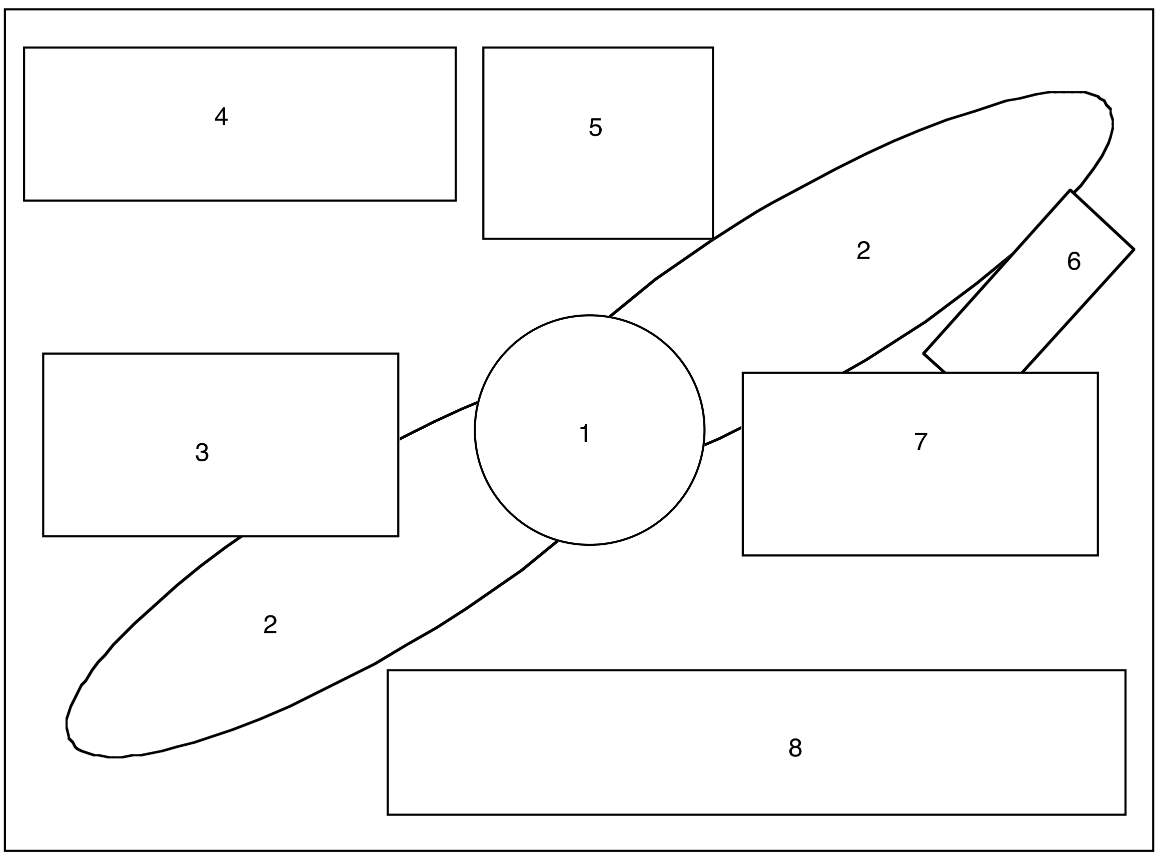

Fig. 1-1. The Nuclear Wall Chart—The sections on the chart are indicated.

both normal conditions and conditions very far from normal is a major challenge. Extreme conditions existed in the early universe, exist now in the cores of stars, and can be created in the laboratory during collisions between nuclei. Nuclear scientists investigate by measuring the properties, shapes, and decays of nuclei at rest and in collisions. They ask questions such as: Why do the *nucleons* stay in the *nucleus*? What combinations of *protons* and *neutrons* are possible? What happens when nuclei are squeezed? What is the origin of the nuclei found on Earth? Nuclear scientists carry out both theoretical and experimental investigations using high-energy *accelerators*, innovative *detectors*, and forefront computing facilities.

A WALK AROUND THE CHART

The Nucleus—1

The atomic nucleus consists of nucleons—protons and neutrons. Protons and neutrons are made of *quarks* and held together by the strong force generated by *gluon* exchange between quarks. In nuclei with many nucleons, the effective strong forces may be described by the exchange of *mesons* (particles composed of quark-antiquark pairs). A proton consists of two up quarks and one down quark along with short-lived constituents of the *strong force* field. A neutron is similar except that it has two down quarks and one up quark. Although scientists are convinced that nucleons are composed of quarks, a single quark has never been isolated experimentally. Energy brought into a nucleus to try to separate quarks increases the force between them. At high enough energy, the addition of energy creates new particles rather than freeing the quarks.

Chart of the Nuclides—2

The Chart of the Nuclides shows the known nuclei in terms of their *atomic number*, Z, and *neutron number*, N. Each box represents a particular nuclide and is color-coded according to its predominant *decay mode*. The so-called "magic numbers," with N or Z equal to 2, 8, 20, 28, 50, 82, and 126 correspond to the closure of major nuclear shells (much like the atomic shells of the electrons) and enhance nuclear stability. Isotopes that have a magic number of both protons and neutrons are called "doubly magic" and are exceptionally stable.

Radioactivity—3

Atoms are *radioactive* if the protons and neutrons in the nucleus are configured in an unstable way. For low numbers of protons (Z), the number of neutrons (N) required to maintain a stable balance is roughly equal to the number of protons. For example, there are 6 protons and 6 neutrons in the nucleus of the most abundant form of carbon. For large numbers of protons in the nucleus, the repulsive electric force between protons leads to stable nuclei that favor neutrons over protons. One stable nucleus of lead contains 126 neutrons and 82 protons. A radioactive atom, lacking a proper balance between the number of protons and the number of neutrons, seeks a more stable arrangement through radioactive decay. These decays occur randomly in time, but large collections of radioactive materials have predictable mean *lifetimes*. The common decay products are named after the first three letters of the Greek alphabet—alpha (α), beta (β), and gamma (γ). In an *alpha decay*, a helium nucleus escapes from a nucleus. Alpha emission reduces the number of protons by two and also the number of neutrons in the nucleus by two. *Beta decay* can proceed either by emission of an *electron* and an *antineutrino* or by emission of their antiparticles, a *positron* and a *neutrino*. Beta decay changes the number of protons and the number of neutrons in the nucleus by converting one into the other. Inverse beta decay involves the capture of an electron by a nucleus. In a *gamma decay* a high energy photon leaves the nucleus and allows the nucleus to achieve a more stable, lower energy configuration. Spontaneous *fission* of a large-mass nucleus into smaller-mass products is also a form of radioactivity.

Expansion of the Universe—4

The universe was created about 15 billion years ago in an event called the *Big Bang*. Around a microsecond after the Big Bang, the universe was populated predominantly by quarks and gluons. As the universe expanded, the temperature dropped. Eventually the universe cooled enough to allow quarks and gluons to condense into nucleons, which subsequently formed hydrogen and helium. Interstellar space is still filled with remnants of this primordial hydrogen and helium. Eventually, density inhomogeneities allowed gravitational interactions to form great clouds of hydrogen. Because the clouds had local inhomogeneities, they gave rise to stars, which collected into galaxies. The universe has continued to expand and cool since the Big Bang, and has a present temperature of only 2.7 Kelvin (K).

After the hydrogen and helium created in the Big Bang condensed into stars, nuclear reactions at the cores of massive stars created more massive nuclei up to iron in a series of nuclear reactions. Higher-mass nuclei were created at the end of the star's life in supernovae explosions. These elements were scattered into space where they later combined with interstellar gas and produced new stars and their planets. Earth and all its occupants, animate and inanimate, are the products of these nuclear astrophysical processes.

Phases of Nuclear Matter—5

One speaks of water existing in three states or phases: solid, liquid, and gas, known to us simply as ice, water, and steam. Temperature and pressure determine the phase of water molecules. Similarly, protons and neutrons exhibit different phases depending on the local nuclear temperature and density. Normal nuclei appear to be in the liquid phase. Different regions of nuclear matter include neutron stars, the early universe, a nucleon gas, or a quark-gluon plasma. Scientists study these phases by colliding beams of accelerated particles to produce extreme conditions. At this time, the quark-gluon plasma has not been identified in any experiment.

Unstable Nuclei—6

Although the Chart of the Nuclides includes about 2500 different nuclides, current models predict that at least 4000 more could be discovered. The proton and neutron "drip lines" define where nuclei with extreme ratios of neutrons-to-protons (N/Z) are expected to become so unstable that the nuclear forces will no longer allow them to form. Scientists are pushing towards making nuclei at both the proton and neutron drip lines as well as new elements at the high mass end of the Chart of the Nuclides. Element 118 (yet to be named) is the most massive element yet made artificially. Products from its alpha decay chain identified the unknown parent nucleus from only a few nuclei.

Nuclear Energy—7

Fission occurs when the nucleus of an atom divides into two smaller nuclei. Fission can occur spontaneously; it may also be induced by the capture of a neutron. For example, an excited state of uranium (created by neutron capture) can split into smaller "*daughter*" nuclei. *Fission products* will often emit neutrons because the N/Z ratio is greater at higher Z. With a proper arrangement of uranium atoms, it is possible to have the neutrons resulting from the first fission event be captured and to cause more uranium nuclei to fission. This "chain reaction" process causes the number of uranium atoms that fission to increase exponentially. When the uranium nucleus fissions, it releases a considerable amount of energy. This process is carried on in a controlled manner in a nuclear reactor, where control rods capture excess neutrons, preventing them from being captured by other uranium nuclei to induce yet another uranium fission. Nuclear reactors are designed so that the release of energy is slow and can be used for practical generation of energy. In an atomic bomb, the chain reaction is explosively rapid.

Fusion occurs when two nuclei combine together to form a larger nucleus. Fusion of low-Z nuclei can release a considerable amount of energy. This is the Sun's energy source. Four hydrogen nuclei (protons) combine in a multistep process to form a helium nucleus. More complicated fusion processes are possible; these involve more massive nuclei. Since the energy required to overcome the mutual electric repulsion of the two nuclei is enormous, fusion occurs only under extreme conditions, such as are found in the cores of stars and nuclear particle accelerators. To fuse higher-Z nuclei together requires even more extreme conditions, such as those generated in novae and supernovae. The stars are ultimately the source of all the elements in the periodic table with $Z \geq 6$ (carbon). Because fusion requires extreme conditions, producing this nuclear reaction on Earth is a difficult technical problem. It is used in thermonuclear weapons, where the fusion reaction proceeds unchecked. Controlled fusion with release of energy has occurred, but no commercially viable method to generate electrical power has yet been constructed.

Applications—8

Basic research in nuclear science has spawned benefits that extend far beyond the original research, often in completely unexpected ways. Nuclear science continues to have a major impact in other areas of science, technology, medicine, energy production and national security. Nuclear diagnostic techniques find many applications in dating archeological objects, in materials research, and in monitoring changes in the environment.

Chapter 2 The Atomic Nucleus

Searching for the ultimate building blocks of the physical world has always been a central theme in the history of scientific research. Many acclaimed ancient philosophers from very different cultures have pondered the consequences of subdividing regular, tangible objects into their smaller and smaller, invisible constituents. Many of them believed that eventually there would exist a final, inseparable fundamental entity of matter, as emphasized by the use of the ancient Greek word, ατο οσ (*atom*), which means "not divisible." Were these atoms really the long sought-after, indivisible, structureless building blocks of the physical world?

The Atom

By the early 20th century, there was rather compelling evidence that matter could be described by an atomic theory. That is, matter is composed of relatively few building blocks that we refer to as atoms. This theory provided a consistent and unified picture for all known chemical processes at that time. However, some mysteries could not be explained by this atomic theory. In 1896, A.H. Becquerel discovered penetrating radiation. In 1897, J.J. Thomson showed that electrons have negative electric charge and come from ordinary matter. For matter to be electrically neutral, there must also be positive charges lurking somewhere. Where are and what carries these positive charges?

A monumental breakthrough came in 1911 when Ernest Rutherford and his coworkers conducted an experiment intended to determine the angles through which a beam of alpha particles (helium nuclei) would scatter after passing through a thin foil of gold.

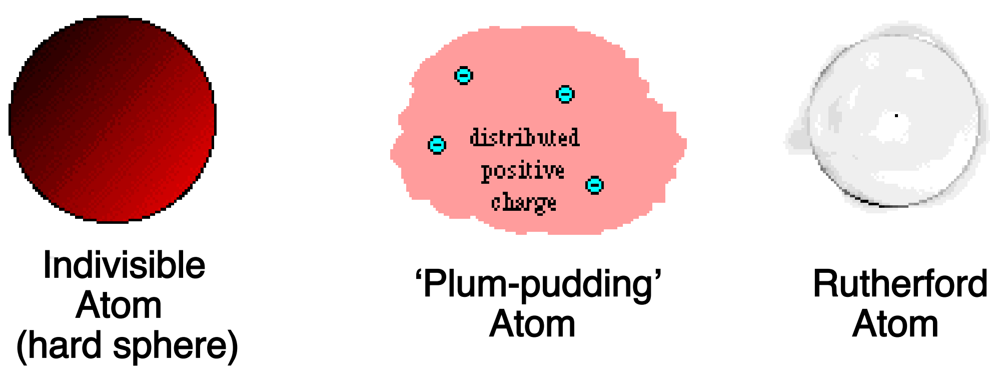

Fig. 2-1. Models of the atom. The dot at the center of the Rutherford atom is the nucleus. The size of the dot is enlarged so that it can be seen in the figure (see Fig. 2-2).

What results would be expected for such an experiment? It depends on how the atom is organized. A prevailing model of the atom at the time (the Thomson, or "plum-pudding," atom) proposed that the negatively charged electrons (the plums) were mixed with smeared-out positive charges (the pudding). This model explained the neutrality of bulk material, yet still allowed the description of the flow of electric charges. In this model, it would be very unlikely for an alpha particle to scatter through an angle greater than a small fraction of a degree, and the vast majority should undergo almost no scattering at all.

The results from Rutherford's experiment were astounding. The vast majority of alpha particles behaved as expected, and hardly scattered at all. But there were alpha particles that scattered through angles greater than 90 degrees, incredible in light of expectations for a "plum-pudding" atom. It was largely the evidence from this type of experiment that led to the model of the atom as having a nucleus. The only model of the atom consistent with this Rutherford experiment is that a small central core (the nucleus) houses the positive charge and most of the mass of the atom, while the majority of the atom's volume contains discrete electrons orbiting about the central nucleus.

Under classical electromagnetic theory, a charge that is moving in a circular path, loses energy. In Rutherford's model, the electrons orbit the nucleus similar to the orbit of planets about the sun. However, under this model, there is nothing to prevent the electrons from losing energy and falling into the nucleus under the influence of its Coulomb attraction. This stability problem was solved by Niels Bohr in 1913 with a new model in which there are particular orbits in which the electrons do not lose energy and therefore do not spiral into the nucleus. This model was the beginning of *quantum mechanics*, which successfully explains many properties of atoms. Bohr's model of the atom is still a convenient description of the energy levels of the hydrogen atom.

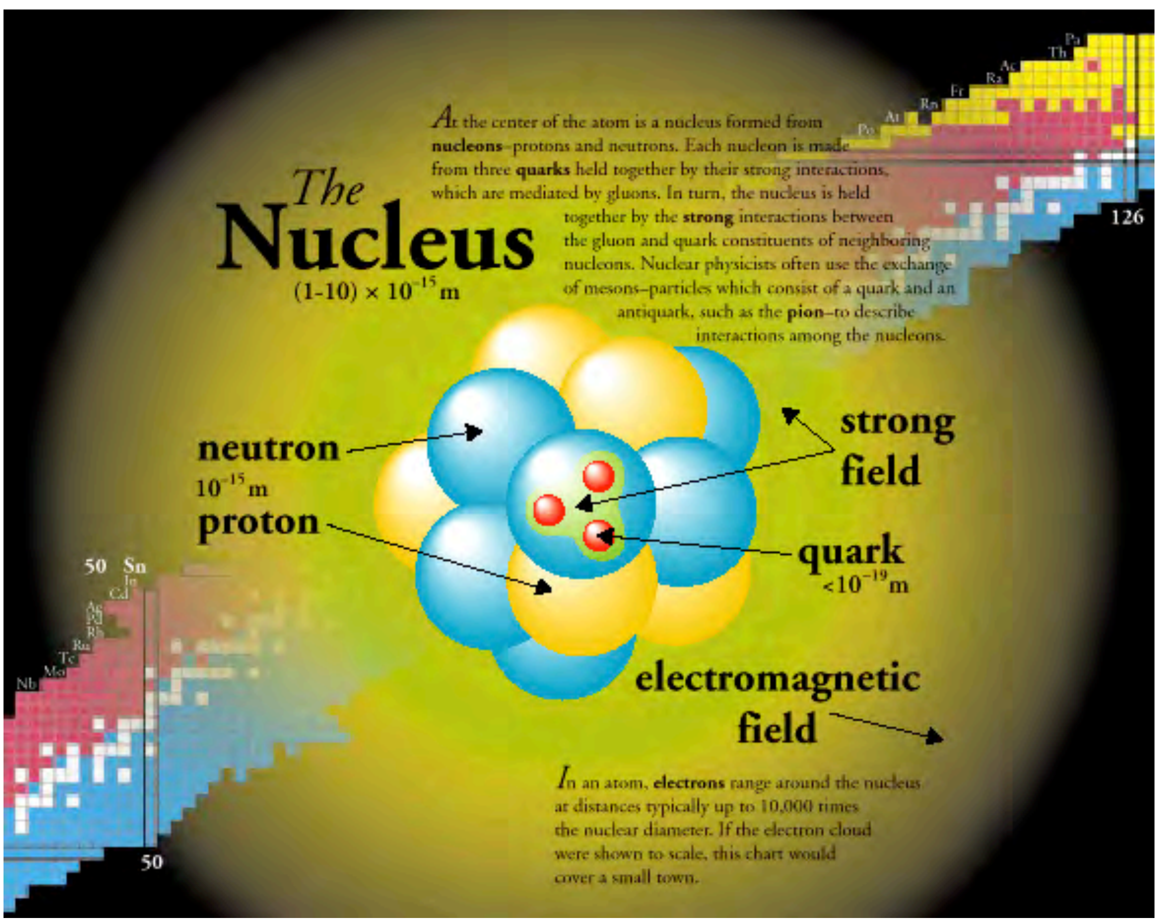

Fig. 2-2. The nucleus.

The Nucleus

The nucleus depicted in Fig. 2-2 is now understood to be a quantum system composed of protons and neutrons, particles of nearly equal mass and the same intrinsic angular momentum (spin) of 1/2. The proton carries one unit of positive electric charge while the neutron has no electric charge. The term *nucleon* is used for either a proton or a neutron. The simplest nucleus is that of hydrogen, which is just a single proton, while the largest nucleus studied has nearly 300 nucleons. A nucleus is identified as in the example of Fig. 2-3 by its *atomic number* Z (*i.e.*, the number of protons), the *neutron number*, N, and the *mass number, A*, where $A = Z + N$.

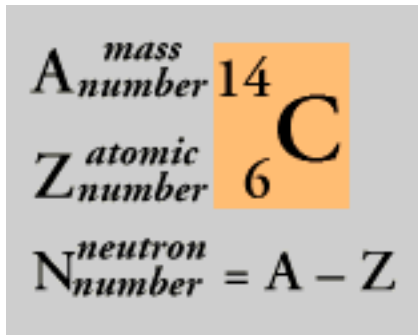

Fig. 2-3. The convention for designating nuclei is by atomic number, Z, and mass number, A, as well as its chemical symbol. The neutron number is given by $N = A - Z$.

What else do we know about the nucleus? In addition to its atomic number and mass number, a nucleus is also characterized by its size, shape, binding energy, angular momentum, and (if it is unstable) *half-life*. One of the best ways to determine the size of a nucleus is to scatter high-energy electrons from it. The angular distribution of the scattered electrons depends on the proton distribution. The proton distribution can be characterized by an average radius. It is found that nuclear radii range from $1\text{-}10 \times 10^{-15}$ m. This radius is much smaller than that of the atom, which is typically 10^{-10} m. Thus, the nucleus occupies an extremely small volume inside the atom. The nuclei of some atoms are spherical, while others are stretched or flattened into deformed shapes.

The binding energy of a nucleus is the energy holding a nucleus together. As shown in Fig. 2-4, this energy varies from nucleus to nucleus and increases as A increases. Because of variations in binding energy, some nuclei are unstable and decay into other ones. The rate of decay is related to the mean lifetime of the decaying nucleus. The time required for half of a population of unstable nuclei to decay is called the half-life. Half-lives vary from tiny fractions of a second to billions of years.

The Isotopes of Hydrogen

It is often useful to study the simplest system. Therefore, hydrogen, the simplest nucleus, has been studied extensively. The *isotopes* of hydrogen show many of the effects found in more complicated nuclei. (The word *isotope* refers to a nucleus with the same Z but different A).

There are three isotopes of the element hydrogen: hydrogen, deuterium, and tritium. How do we distinguish between them? They each have one single proton ($Z = 1$), but differ in the number of their neutrons. Hydrogen has no neutron, deuterium has one, and tritium has two neutrons. The isotopes of hydrogen have, respectively, mass numbers of one, two, and three. Their nuclear symbols are therefore ^{1}H, ^{2}H, and ^{3}H. The atoms of these isotopes have one electron to balance the charge of the one proton. Since chemistry depends on the interactions of protons with electrons, the chemical properties of the isotopes are nearly the same.

Energy may be released as a packet of electromagnetic radiation, a *photon*. Photons created in nuclear processes are labeled *gamma rays* (denoted by the Greek letter gamma, γ). For example, when a proton and neutron combine to form deuterium, the reaction can be written $^{1}n + {}^{1}H \rightarrow {}^{2}H + \gamma$. Energy must balance in this equation. Mass can be written in *atomic mass units* (u) or in the equivalent energy units of million electron-volts divided by the square of the speed of light (MeV)/c^2. (From Einstein's mass-energy equivalence equation, $E = mc^2$, u = 931.5 MeV/c^2.) The mass of the deuterium nucleus (2.01355 u) is less than the sum of the masses of the proton (1.00728 u) and the neutron (1.00866 u), which is 2.01594 u. Where has the missing mass (0.00239 u) gone? The answer is that the attractive nuclear force between the nucleons has created a negative nuclear potential energy—the binding energy E_B—that is related to the missing mass, m (the difference between the two masses). The photon released in forming deuterium has an energy of 2.225 MeV, equivalent to the 0.00239 u required to separate the proton and neutron back into unbound particles. The nuclear decay photons are, in general, higher in energy than photons created in atomic processes.

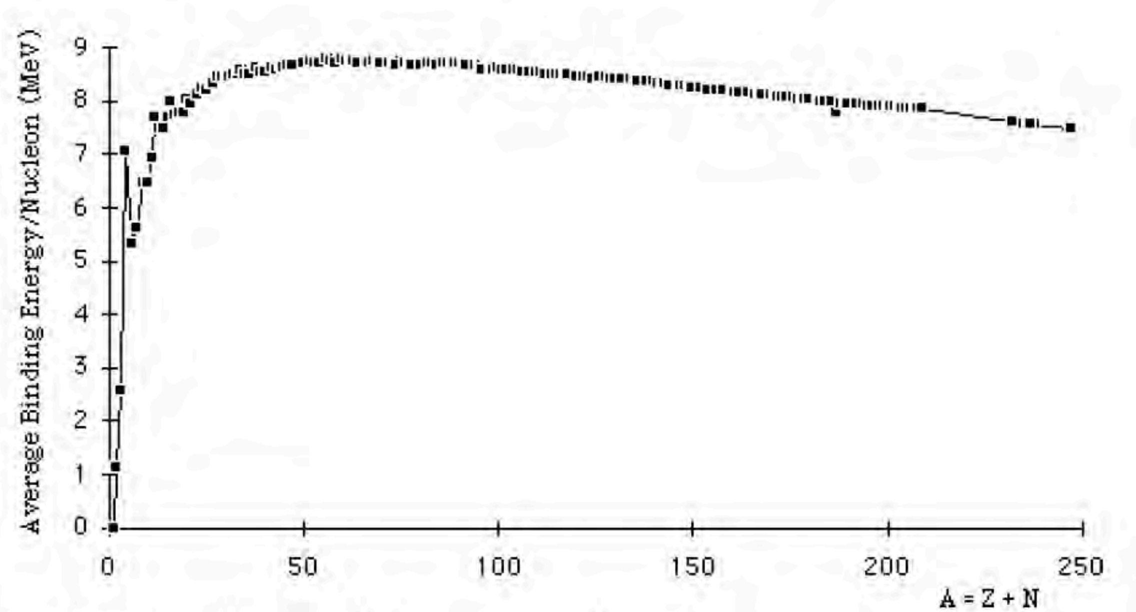

Fig. 2-4. The curve of the average binding energy per nucleon.

When tritium is formed by adding a neutron to deuterium, $^{1}n + {}^{2}H \rightarrow {}^{3}H + \gamma$, a larger amount of energy is released—6.2504 MeV. The greater binding energy of tritium compared to deuterium shows that the nuclear potential energy does not grow in a simple way with the addition of nucleons (the total binding energy is roughly proportional to A). The binding energy per nucleon continues to grow as protons and neutrons are added to construct more massive nuclei until a maximum of about 8 MeV per nucleon is reached around A = 60, past which the average binding energy per nucleon slowly decreases up to the most massive nuclei, for which it is about 7 MeV.

How does a nucleus, which can have up to approximately 100 protons, hold itself together? Why does the electrical repulsion among all those positive charges not cause the nucleus to break up? There must be an attractive force strong enough to be capable of overcoming the repulsive Coulomb forces between protons. Experiment and theory have come to recognize an attractive nuclear interaction that acts between nucleons when they are close enough together (when the range is short enough). The balance between electromagnetic and nuclear forces sets the limit on how large a nucleus can grow.

Theoretical Models

A goal of nuclear physics is to account for the properties of nuclei in terms of mathematical models of their structure and internal motion. Three important nuclear models are the Liquid Drop Model, the Shell Model (developed by Maria Goeppert-Mayer and Hans Jensen), which emphasizes the orbits of individual nucleons in the nucleus, and the *Collective Model* (developed by Aage Bohr and Ben Mottleson), which complements the shell model by including motions of the whole nucleus such as rotations and vibrations.

The Liquid Drop Model treats the nucleus as a liquid. Nuclear properties, such as the binding energy, are described in terms of volume energy, surface energy, compressibility, etc.—parameters that are usually associated with a liquid. This model has been successful in describing how a nucleus can deform and undergo fission.

The Nuclear Shell Model is similar to the atomic model where electrons arrange themselves into shells around the nucleus. The least-tightly-bound electrons (in the incomplete shells) are known as valence electrons because they can participate in exchange or rearrangement, that is, chemical reactions. The shell structure is due to the quantum nature of electrons and the fact that electrons are *fermions*—particles of half-integer spin. Particles with integer spin are *bosons*. A group of bosons all tend to occupy the same state (usually the state with the lowest energy), whereas fermions with the same quantum numbers do just the opposite: they avoid each other. Consequently the fermions in a bound system will gradually fill up the available states: the lowest one first, then the next higher unoccupied state, and so on up to the valence shell. In atoms, for example, the electrons obey the *Pauli Exclusion Principle*, which is responsible for the observed number of electrons in each possible state (at most 2) characterized by quantum numbers n, l, and m. It is the Pauli Principle (based on the fermionic nature of electrons) that gives the periodic structure to both atomic and nuclear properties.

Since protons and neutrons are also fermions, the energy states the nucleons occupy are filled from the lowest to the highest as nucleons are added to the nucleus. In the shell model the nucleons fill each energy state with nucleons in orbitals with definite angular momentum. There are separate energy levels for protons and neutrons. The ground state of a nucleus has each of its protons and neutrons in the lowest possible energy level. Excited states of the nucleus are then described as promotions of nucleons to higher energy levels. This model has been very successful in explaining the basic nuclear properties. As is the case with atoms, many nuclear properties (angular momentum, magnetic moment, shape, etc.) are dominated by the last filled or unfilled valence level.

The Collective Model emphasizes the coherent behavior of all of the nucleons. Among the kinds of collective motion that can occur in nuclei are rotations or vibrations that involve the entire nucleus. In this respect, the nuclear properties can be analyzed using the same description that is used to analyze the properties of a charged drop of liquid suspended in space. The Collective Model can thus be viewed as an extension of the Liquid Drop Model; like the Liquid Drop Model, the Collective Model provides a good starting point for understanding fission.

In addition to fission, the Collective Model has been very successful in describing a variety of nuclear properties, especially energy levels in nuclei with an even number of protons and neutrons. These even nuclei can often be treated as having no valence particles so that the Shell Model does not apply. These energy levels show the characteristics of rotating or vibrating systems expected from the laws of quantum mechanics. Commonly measured properties of these nuclei, including broad systematics of excited state energies, angular momentum, magnetic moments, and nuclear shapes, can be understood using the Collective Model.

The Shell Model and the Collective Model represent the two extremes of the behavior of nucleons in the nucleus. More realistic models, known as unified models, attempt to include both shell and collective behaviors.

Sub-nucleonic Structure and the Modern Picture of a Nucleus

Do protons and neutrons have internal structure? The answer is yes. With the development of higher and higher energy particle accelerators, physicists have found experimentally that the nucleons are complex objects with their own interesting internal structures.

One of the most significant developments in modern physics is the emergence of the *Standard Model* of Fundamental Interactions (Fig. 2-5). This model states that the material world is made up of two categories of particles, *quarks* and *leptons*, together with their antiparticle counterparts. The leptons are either neutral (such as the neutrino) or carry one unit of charge, *e* (such as the electron, muon, and tau). The quarks are pointlike objects with charge 1/3*e* or 2/3 *e*. Quarks are spin-1/2 particles, and therefore are fermions, just as electrons are.

The quarks and leptons can be arranged into three families. The up- and down-quarks with the electron and the electron neutrino form the family that makes up ordinary matter. The other two families produce particles that are very short-lived and do not significantly affect the nucleus. It is a significant fact in the evolution of the universe that only three such families are found in nature—more families would have lead to a quite different world.

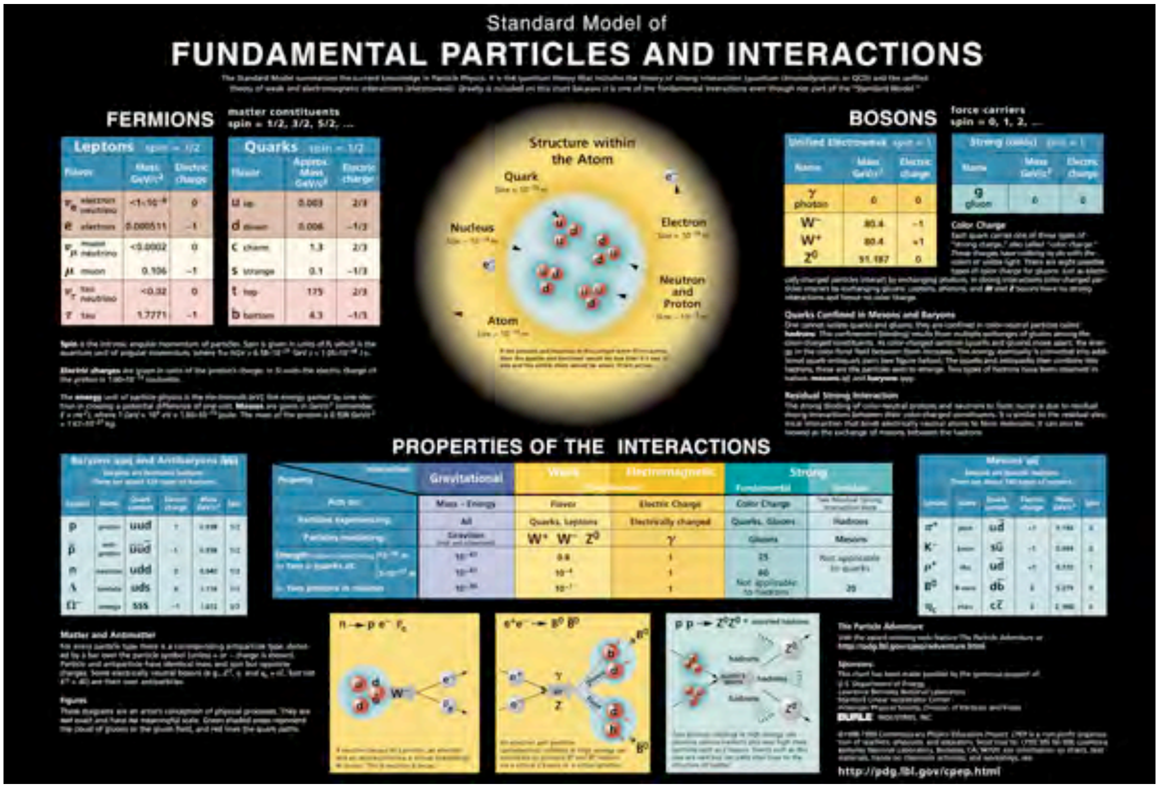

Fig. 2-5. The Standard Model of Particles and Interactions

One could imagine, then, trying to understand the structure of protons and neutrons in terms of the fundamental particles described in the Standard Model. Because the protons and neutrons of ordinary matter are affected by the strong interaction (i.e., the interaction that binds quarks and that ultimately holds nuclei together), they fall into the category of composite particles known as hadrons. Hadrons that fall into the subcategory known as baryons are made of three quarks. Protons, which consist of two up and one down quark, and neutrons (two down and one up quark) are baryons. There are also hadrons called mesons, which are made of quark-antiquark pairs, an example of which is the pion.

Because baryons and mesons have internal quark structure, they can be put into excited states, just as atoms and nuclei can. This requires that energy be deposited in them. One example is the first excited state of the proton, usually referred to as the Delta-1232 (where 1232 MeV/c^2 is the mass of the particle). In the Delta, it is thought that one of the quarks gains energy by flipping its spin with respect to the other two. In an atom, the energy needed to excite an electron to a higher state is on the order of a few to a thousand electron volts. In comparison, in a nucleus, a single nucleon excitation typically costs an MeV (10^6 eV). In a proton, it takes about 300 MeV to flip the spin of a quark. This kind of additional energy is generally only available by bombarding the proton with energetic particles from an accelerator.

Finding a proper theoretical description of the excited states of baryons and mesons is an active area of research in nuclear and particle physics. Because the excited states are generally very short-lived; they are often hard to identify. Research tools at the newly commissioned Jefferson Lab accelerator have been specially designed to look at the spectrum of mesons and baryons. Such research is also being actively pursued at Brookhaven National Laboratory and at many other laboratories. To study the Standard Model, accelerators that produce much higher energy beams are often needed. Such facilities include Fermilab, near Chicago, SLAC at Stanford, and CERN in Geneva. Accelerators for nuclear physics are described in more detail in Chapter 11.

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E. J. Burge, *Atomic Nuclei and Their Particles,* Clarendon Press, Oxford, 1988.

Frank Close, *The Cosmic Onion,* The American Institute of Physics, College Park, 1986.

Steven Weinberg, *The Discovery of Subatomic Particles,* Scientific American Library, New York, 1983.

Yuval Ne'eman and Yoram Kirsh, *The Particle Hunters,* Cambridge University Press, Cambridge, 1996.

Web Sites:

The Particle Adventure

http://www.particleadventure.org — Developed by CPEP to go along with their popular Standard Model Chart (Fig. 2-5). This web site has won numerous awards.

Chapter 3 Radioactivity

In radioactive processes, particles or electromagnetic radiation are emitted from the nucleus. The most common forms of radiation emitted have been traditionally classified as alpha (α), beta (β), and gamma (γ) radiation. Nuclear radiation occurs in other forms, including the emission of protons or neutrons or spontaneous fission of a massive nucleus.

Of the nuclei found on Earth, the vast majority is stable. This is so because almost all short-lived radioactive nuclei have decayed during the history of the Earth. There are approximately 270 stable isotopes and 50 naturally occurring *radioisotopes* (radioactive isotopes). Thousands of other radioisotopes have been made in the laboratory.

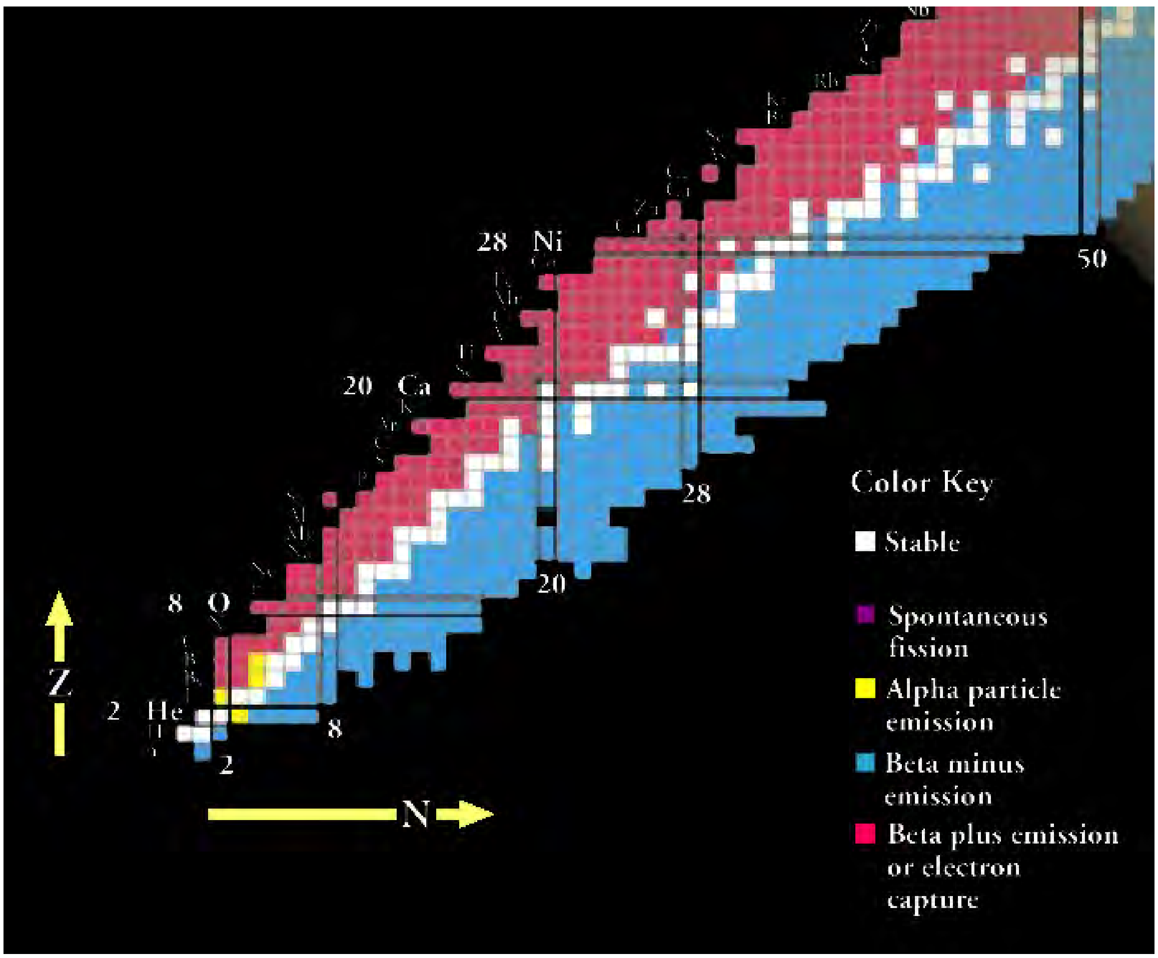


Fig. 3-1. The lower end of the Chart of the Nuclides.

Radioactive decay will change one nucleus to another if the product nucleus has a greater nuclear binding energy than the initial decaying nucleus. The difference in binding energy (comparing the before and after states) determines which decays are energetically possible and which are not. The excess binding energy appears as kinetic energy or rest mass energy of the decay products.

The Chart of the Nuclides, part of which is shown in Fig. 3-1, is a plot of nuclei as a function of proton number, Z, and neutron number, N. All stable nuclei and known radioactive nuclei, both naturally occurring and manmade, are shown on this chart, along with their decay properties. Nuclei with an excess of protons or neutrons in comparison with the stable nuclei will decay toward the stable nuclei by changing protons into neutrons or neutrons into protons, or else by shedding neutrons or protons either singly or in combination. Nuclei are also unstable if they are excited, that is, not in their lowest energy states. In this case the nucleus can decay by getting rid of its excess energy without changing Z or N by emitting a gamma ray.

Nuclear decay processes must satisfy several conservation laws, meaning that the value of the conserved quantity after the decay, taking into account all the decay products, must equal the same quantity evaluated for the nucleus before the decay. Conserved quantities include total energy (including mass), electric charge, linear and angular momentum, number of nucleons, and *lepton number* (sum of the number of electrons, neutrinos, positrons and antineutrinos—with antiparticles counting as -1).

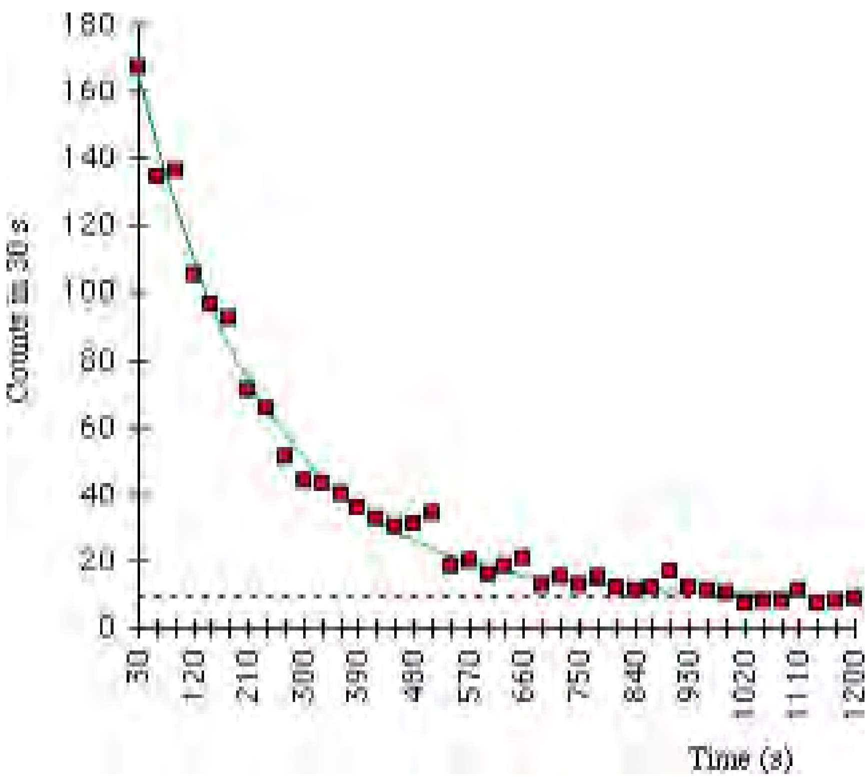


Fig. 3-2. ^{137m}Ba decay data, counting numbers of decays observed in 30-second intervals. The best-fit exponential curve is shown. The points do not fall exactly on the exponential because of statistical counting fluctuations.

The probability that a particular nucleus will undergo radioactive decay during a fixed length of time does not depend on the age of the nucleus or how it was created.

Although the exact lifetime of one particular nucleus cannot be predicted, the mean (or average) lifetime of a sample containing many nuclei of the same isotope can be predicted and measured. A convenient way of determining the lifetime of an isotope is to measure how long it takes for one-half of the nuclei in a sample to decay—this quantity is called the *half-life*, $t_{1/2}$. Of the original nuclei that did not decay, half will decay if we wait another half-life, leaving one-quarter of the original sample after a total time of two half-lives. After three half-lives, one-eighth of the original sample will remain and so on. Measured half-lives vary from tiny fractions of seconds to billions of years, depending on the isotope.

The number of nuclei in a sample that will decay in a given interval of time is proportional to the number of nuclei in the sample. This condition leads to radioactive decay showing itself as an exponential process, as shown in Fig. 3-2. The number, N, of the original nuclei remaining after a time t from an original sample of N_0 nuclei is

$$N = N_0 e^{-(t/T)}$$

where T is the mean lifetime of the parent nuclei. From this relation, it can be shown that

$$t_{1/2} = 0.693T.$$

Alpha Decay

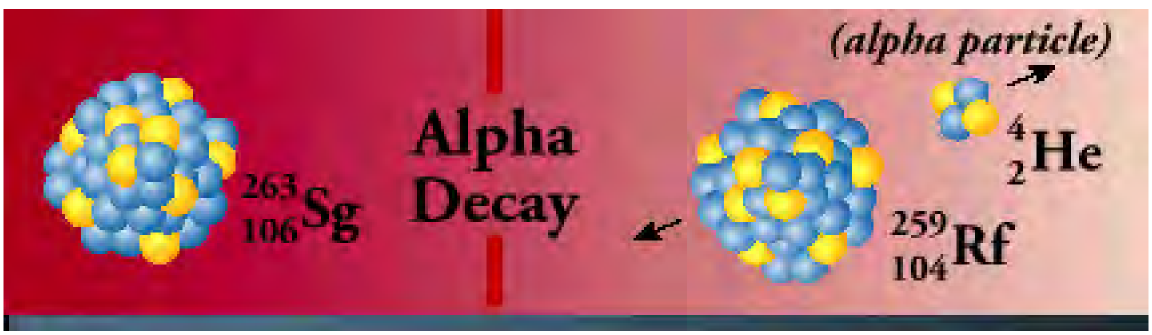


Fig. 3-3. An alpha-particle decay

In alpha decay, shown in Fig. 3-3, the nucleus emits a ^{4}He nucleus, an *alpha particle*. Alpha decay occurs most often in massive nuclei that have too large a proton to neutron ratio. An alpha particle, with its two protons and two neutrons, is a very stable configuration of particles. Alpha radiation reduces the ratio of protons to neutrons in the parent nucleus, bringing it to a more stable configuration. Nuclei, which are more massive than lead, frequently decay by this method.

Consider the example of ^{210}Po decaying by the emission of an alpha particle. The reaction can be written ^{210}Po $\rightarrow$ ^{206}Pb + ^{4}He. This polonium nucleus has 84 protons and 126 neutrons. The ratio of protons to neutrons is Z/N = 84/126, or 0.667. A ^{206}Pb nucleus has 82 protons and 124 neutrons, which gives a ratio of 82/124, or 0.661. This small change in the Z/N ratio is enough to put the nucleus into a more stable state, and as shown in Fig. 3-4, brings the “daughter” nucleus (decay product) into the region of stable nuclei in the Chart of the Nuclides.

In alpha decay, the atomic number changes, so the original (or parent) atoms and the decay-product (or daughter) atoms are different elements and therefore have different chemical properties.

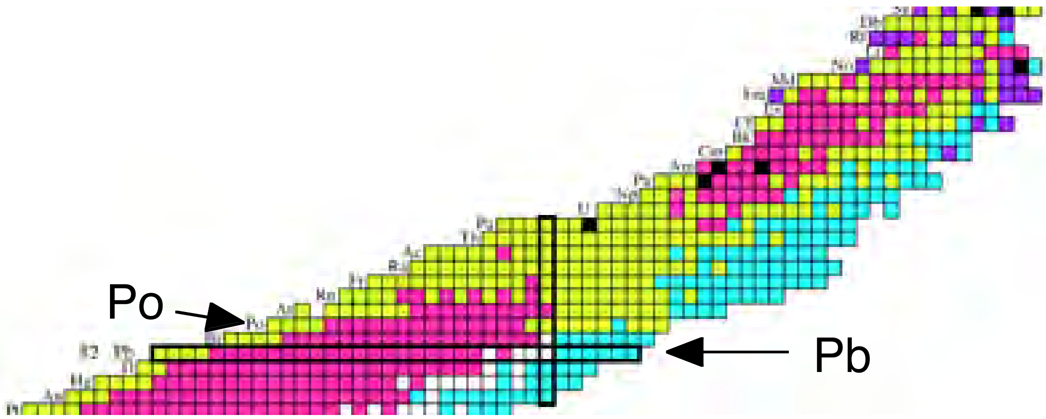
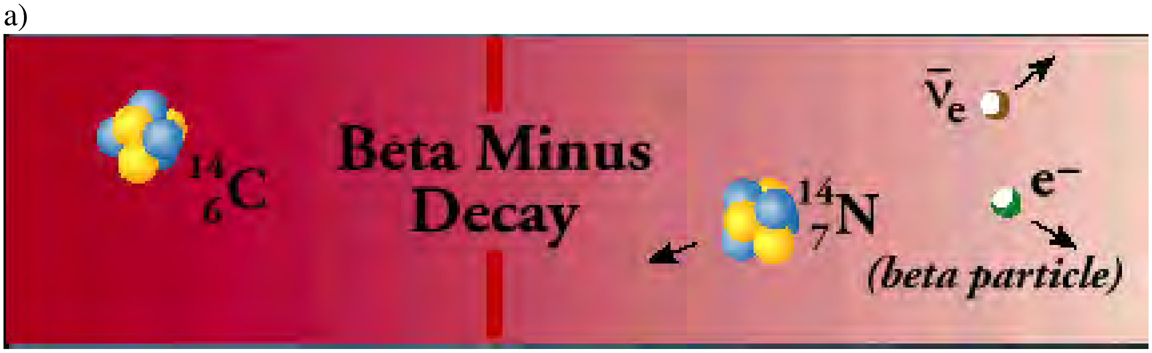


Fig. 3-4. Upper end of the Chart of the Nuclides

In the alpha decay of a nucleus, the change in binding energy appears as the kinetic energy of the alpha particle and the daughter nucleus. Because this energy must be shared between these two particles, and because the alpha particle and daughter nucleus must have equal and opposite momenta, the emitted alpha particle and recoiling nucleus will each have a well-defined energy after the decay. Because of its smaller mass, most of the kinetic energy goes to the alpha particle.

Beta Decay

a)



b)

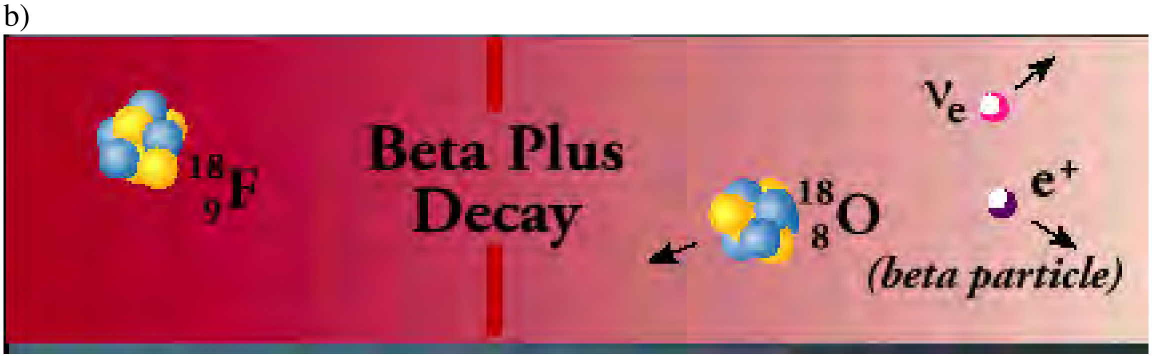


Fig. 3-5. Beta decays. a) Beta-minus decay. b) Beta-plus decay.

Beta particles are electrons or *positron*s (electrons with positive electric charge, or *antielectrons*). Beta decay occurs when, in a nucleus with too many protons or too many neutrons, one of the protons or neutrons is transformed into the other. In beta minus decay, as shown in Fig. 3-5a, a neutron decays into a proton, an electron, and an antineutrino: $n \rightarrow p + e^- + \overline{\nu}$. In beta plus decay, shown in Fig. 3-5b, a proton decays into a neutron, a positron, and a neutrino: $p \rightarrow n + e^+ + \nu$. Both reactions occur because in different regions of the Chart of the Nuclides, one or the other will move the product closer to the region of stability. These particular reactions take place because conservation laws are obeyed. Electric charge conservation requires that if an electrically neutral neutron becomes a positively charged proton, an electrically negative particle (in this case, an electron) must also be produced. Similarly, conservation of lepton number requires that if a neutron (lepton number = 0) decays into a proton (lepton number = 0) and an electron (lepton number = 1), a particle with a lepton number of -1 (in this case an antineutrino) must also be produced. The leptons emitted in beta decay did not exist in the nucleus before the decay—they are created at the instant of the decay.

To the best of our knowledge, an isolated proton, a hydrogen nucleus with or without an electron, does not decay. However within a nucleus, the beta decay process can change a proton to a neutron. An isolated neutron is unstable and will decay with a half-life of 10.5 minutes. A neutron in a nucleus will decay if a more stable nucleus results; the half-life of the decay depends on the isotope. If it leads to a more stable nucleus, a proton in a nucleus may capture an electron from the atom (electron capture), and change into a neutron and a neutrino.

Proton decay, neutron decay, and electron capture are three ways in which protons can be changed into neutrons or vice-versa; in each decay there is a change in the atomic number, so that the parent and daughter atoms are different elements. In all three processes, the number A of nucleons remains the same, while both proton number, Z, and neutron number, N, increase or decrease by 1.

In beta decay the change in binding energy appears as the mass energy and kinetic energy of the beta particle, the energy of the neutrino, and the kinetic energy of the recoiling daughter nucleus. The energy of an emitted beta particle from a particular decay can take on a range of values because the energy can be shared in many ways among the three particles while still obeying energy and momentum conservation.

Gamma Decay

In gamma decay, depicted in Fig. 3-6, a nucleus changes from a higher energy

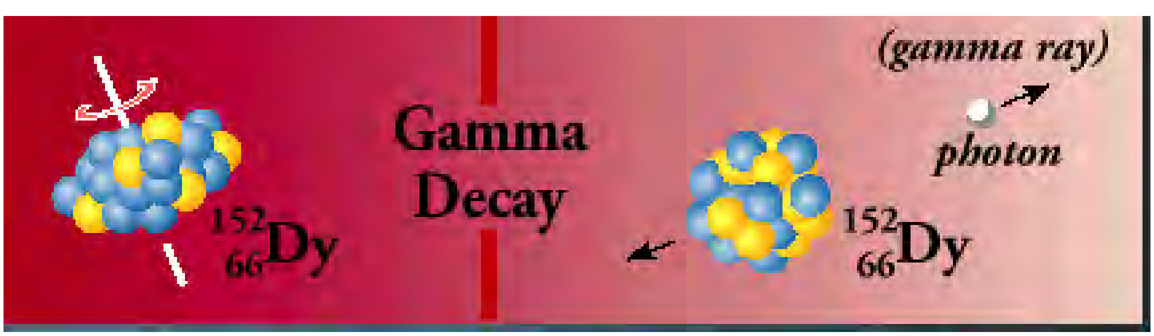


Fig. 3-6. A gamma (γ) decay.

state to a lower energy state through the emission of electromagnetic radiation (*photon*s). The number of protons (and neutrons) in the nucleus does not change in this process, so the *parent* and *daughter* atoms are the same chemical element. In the gamma decay of a nucleus, the emitted photon and recoiling nucleus each have a well-defined energy after the decay. The characteristic energy is divided between only two particles.

The Discovery of Radioactivity

In 1896 Henri Becquerel was using naturally fluorescent minerals to study the properties of x-rays, which had been discovered in 1895 by Wilhelm Roentgen. He exposed potassium uranyl sulfate to sunlight and then placed it on photographic plates wrapped in black paper, believing that the uranium absorbed the sun's energy and then emitted it as x-rays. This hypothesis was disproved on the 26th-27th of February, when his experiment "failed" because it was overcast in Paris. For some reason, Becquerel decided to develop his photographic plates anyway. To his surprise, the images were strong and clear, proving that the uranium emitted radiation without an external source of energy such as the sun. Becquerel had discovered radioactivity.

Becquerel used an apparatus similar to that shown in Fig. 3-7 to show that the radiation he discovered could not be x-rays. X-rays are neutral and cannot be bent in a magnetic field. The new radiation was bent by the magnetic field so that the radiation must be charged and different than x-rays. When different radioactive substances were put in the magnetic field, they deflected in different directions or not at all, showing that there were three classes of radioactivity: negative, positive, and electrically neutral.

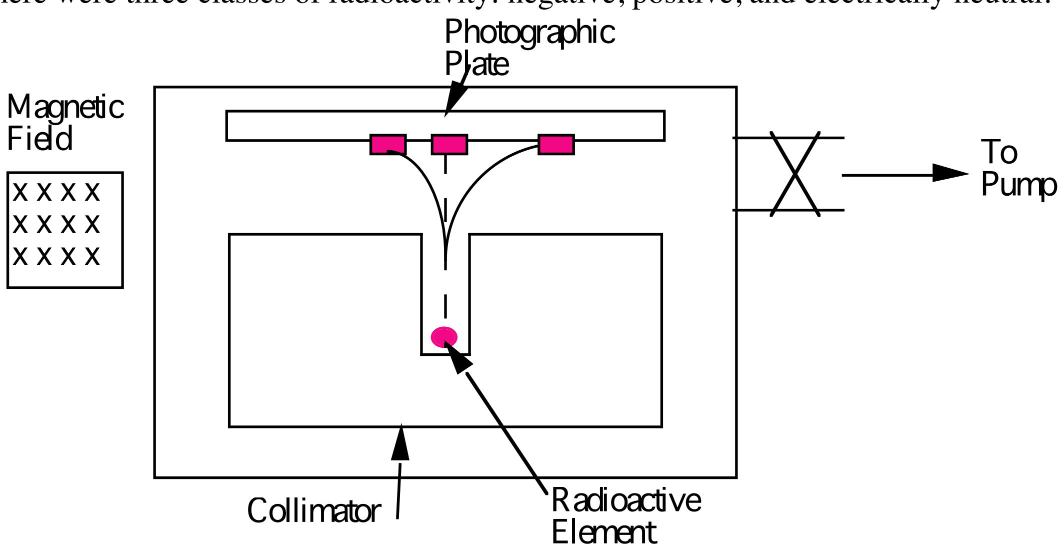


Fig. 3-7. Apparatus similar to that used by Henri Becquerel to determine the magnetic deflection of radioactive decay products. The magnetic field is perpendicular to the direction of motion of the decay products.

The term radioactivity was actually coined by Marie Curie, who together with her husband Pierre, began investigating the phenomenon recently discovered by Becquerel. The Curies extracted uranium from ore and to their surprise, found that the leftover ore showed more activity than the pure uranium. They concluded that the ore contained other radioactive elements. This led to the discoveries of the elements polonium and radium. It took four more years of processing tons of ore to isolate enough of each element to determine their chemical properties.

Ernest Rutherford, who did many experiments studying the properties of radioactive decay, named these alpha, beta, and gamma particles, and classified them by their ability to penetrate matter. Rutherford used an apparatus similar to that depicted in Fig. 3-7. When the air from the chamber was removed, the alpha source made a spot on the photographic plate. When air was added, the spot disappeared. Thus, only a few centimeters of air were enough to stop the alpha radiation.

Because alpha particles carry more electric charge, are more massive, and move slowly compared to beta and gamma particles, they interact much more easily with matter. Beta particles are much less massive and move faster, but are still electrically charged. A sheet of aluminum one-millimeter thick or several meters of air will stop these electrons and positrons. Because gamma rays carry no electric charge, they can penetrate large distances through materials before interacting—several centimeters of lead or a meter of concrete is needed to stop most gamma rays.

Radioactivity in Nature

Radioactivity is a natural part of our environment. Present-day Earth contains all the stable chemical elements from the lowest mass (H) to the highest (Pb and Bi). Every element with higher Z than Bi is radioactive. The earth also contains several primordial long-lived radioisotopes that have survived to the present in significant amounts. ^{40}K, with its 1.3 billion-year half-life, has the lowest mass of these isotopes and beta decays to both ^{40}Ar and ^{40}Ca.

Many isotopes can decay by more than one method. For example, when actinium-226 (Z=89) decays, 83% of the rate is through β^--decay, $^{226}Ac \rightarrow {}^{226}Th + e^- + \overline{\nu}$, 17% is through electron capture, $^{226}Ac + e^- \rightarrow {}^{226}Fr + \nu$, and the remainder, 0.006%, is through α-decay, $^{226}Ac \rightarrow {}^{222}Fr + {}^4He$. Therefore from 100,000 atoms of actinium, one would measure on average 83,000 beta particles and 6 alpha particles (plus 100,000 neutrinos or antineutrinos). These proportions are known as *branching ratios*. The branching ratios are different for the different radioactive nuclei.

Three very massive elements, ^{232}Th (14.1 billion year half-life), ^{235}U (700 million year half-life), and ^{238}U (4.5 billion year half-life) decay through complex "chains" of alpha and beta decays ending at the stable ^{208}Pb, ^{207}Pb, and ^{206}Pb respectively. The *decay chain* for ^{238}U is shown in Fig. 3-8. The ratio of uranium to lead present on Earth today gives us an estimate of its age (4.5 billion years). Given Earth's age, any much shorter-lived radioactive nuclei present at its birth have already decayed into stable elements. One of the intermediate products of the ^{238}U decay chain, ^{222}Rn (radon) with a half-life of 3.8 days, is responsible for higher levels of background radiation in many parts of the world. This is primarily because it is a gas and can easily seep out of the earth into unfinished basements and then into the house.

Some radioactive isotopes, for example ^{14}C and ^{7}Be, are produced continuously through reactions of cosmic rays (high-energy charged particles from outside Earth) with molecules in the upper atmosphere. ^{14}C is useful for radioactive dating (see Chapter 13). Also, the study of radioactivity is very important to understand the structure of the earth because radioactive decay heats the earth's interior to very high temperatures.

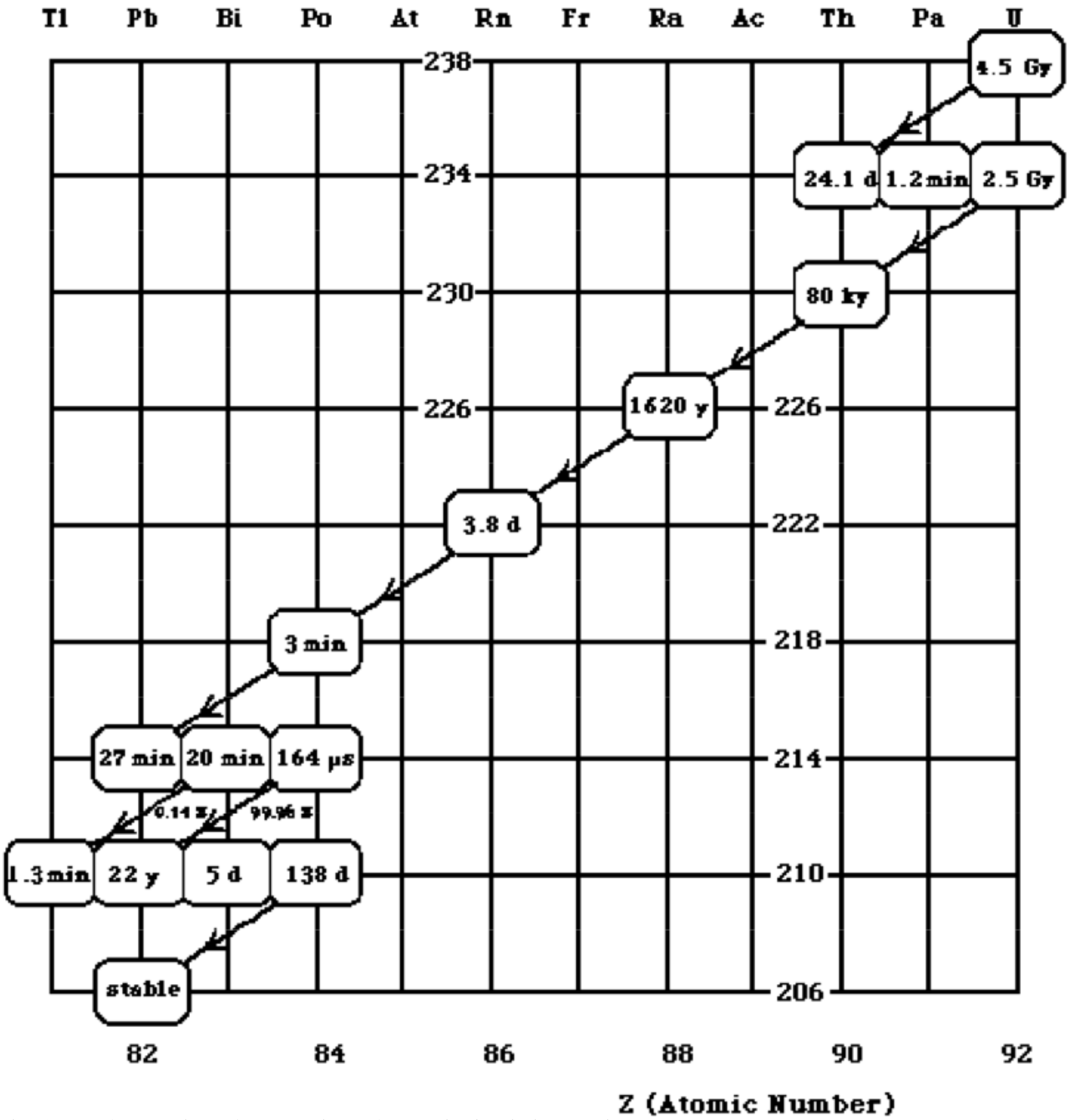


Fig. 3- 8. The uranium decay series. The vertical axis is atomic mass.

Units of Radioactivity

The number of decays per second, or *activity*, from a sample of radioactive nuclei is measured in *becquerel* (Bq), after Henri Becquerel. One decay per second equals one becquerel.

An older unit is the *curie*, named after Pierre and Marie Curie. One curie is approximately the activity of 1 gram of radium and equals (exactly) 3.7×10^{10} becquerel. The activity depends only on the number of decays per second, not on the type of decay, the energy of the decay products, or the biological effects of the radiation (see Chapter 15).

Books and Articles:

Naomi Pacachoff, *Marie Curie and the Science of Radioactivity,* Oxford University Press, 1997.

Bjorn Walhstrom, *Understanding Radiation,* Medical Physics Pub. Corp., 1996.

Web Sites:

The ABCs of Radioactivity
http://abc.lbl.gov A series of experiments on the basic properties of radioactivity. The creators of the Nuclear Science Wall Chart developed this site.

The Discovery of Radioactivity: The Dawn of the Nuclear Age
http://www.gene.com/ae/AE/AEC/CC/radioactivity.html — A description of the key experiments leading to the discovery and characterization of radioactivity and the people who did them. Developed by Genentech.

Table of Nuclides
https://www.nndc.bnl.gov/chart/ — An online table of the nuclides giving information such as branching ratios and half-lives for any isotope.

Chapter 4 Four Fundamental Interactions

The forces of gravity and electromagnetism are familiar in everyday life. Two new forces are introduced when discussing nuclear phenomena: the *strong* and *weak interactions*. When two protons encounter each other, they experience all four of the fundamental forces of nature simultaneously. The weak force governs beta decay and neutrino interactions with nuclei. The strong force, which we generally call the nuclear force, is actually the force that binds quarks together to form baryons (3 quarks) and mesons (a quark and an anti-quark). The nucleons of everyday matter, neutrons and protons consist of the quark combinations *uud* and *udd*, respectively. The symbol *u* represents a single up quark, while the symbol *d* represents a single down quark.

The force that holds nucleons together to form an atomic nucleus can be thought to be a residual interaction between quarks inside each individual nucleon. This is analogous to what happens in a molecule. The electrons in an atom are bound to its nucleus by electromagnetism: when two atoms are relatively near, there is a residual interaction between the electron clouds that can form a covalent bond. The nucleus can thus be thought of as a "strong force molecule."

The force between two objects can be described as the exchange of a particle. The exchange particle transfers momentum and energy between the two objects, and is said to mediate the interaction. A simple analogue of this is a ball being thrown back and forth between two people. The momentum imparted to the ball by one person gets transferred to the other person when she catches the ball.

The potential energy associated with each force acting between two protons is characterized by both the strength of the interaction and the range over which the interaction takes place. In each case the strength is determined by a coupling constant,

Table 4-1. Strength and range of the four fundamental forces between *two protons*. Note that the strong force acts between quarks by an exchange of gluons. The residual strong force between two protons can be described by the exchange of a neutral pion. Note the $W^{\pm}$ is not included as an exchange particle for the weak interaction because it is not exchanged in the simplest proton-proton interaction.

Interaction	**Gravity**	**Weak**	**Electro-magnetism**	**Strong**
				Residual
Exchange particle	Graviton	Z^0	Photon	Pion
Mass ***mc^2 (eV)***	0	91×10^{9}	0	135×10^{6}
Coupling constant ***C^2 (J · m)***	1.87×10^{-64}	3.22×10^{-31}	2.31×10^{-28}	2.5×10^{-27}
Range ***(m)***	∞	2×10^{-18}	∞	1.5×10^{-15}

and the range is characterized by the mass of the exchanged particle. The potential energy, U, between two protons a distance r apart is written as

$$U = \frac{C^2}{r}\exp(-r/R)$$

where R is the range of the interaction, and C^2, is the strength of the interaction. In each case the interaction is due to the exchange of some particle whose mass determined the range of the interaction, $R = h/mc$. The exchanged particle is said to *mediate* the interaction.

Table 4-1 shows a comparison between the coupling constants and ranges of the four forces acting between two protons. Although the graviton has not yet been observed, it is thought that there is an exchange particle associated with gravity and that eventually gravity will be described in a unified theory with the other three forces of nature.

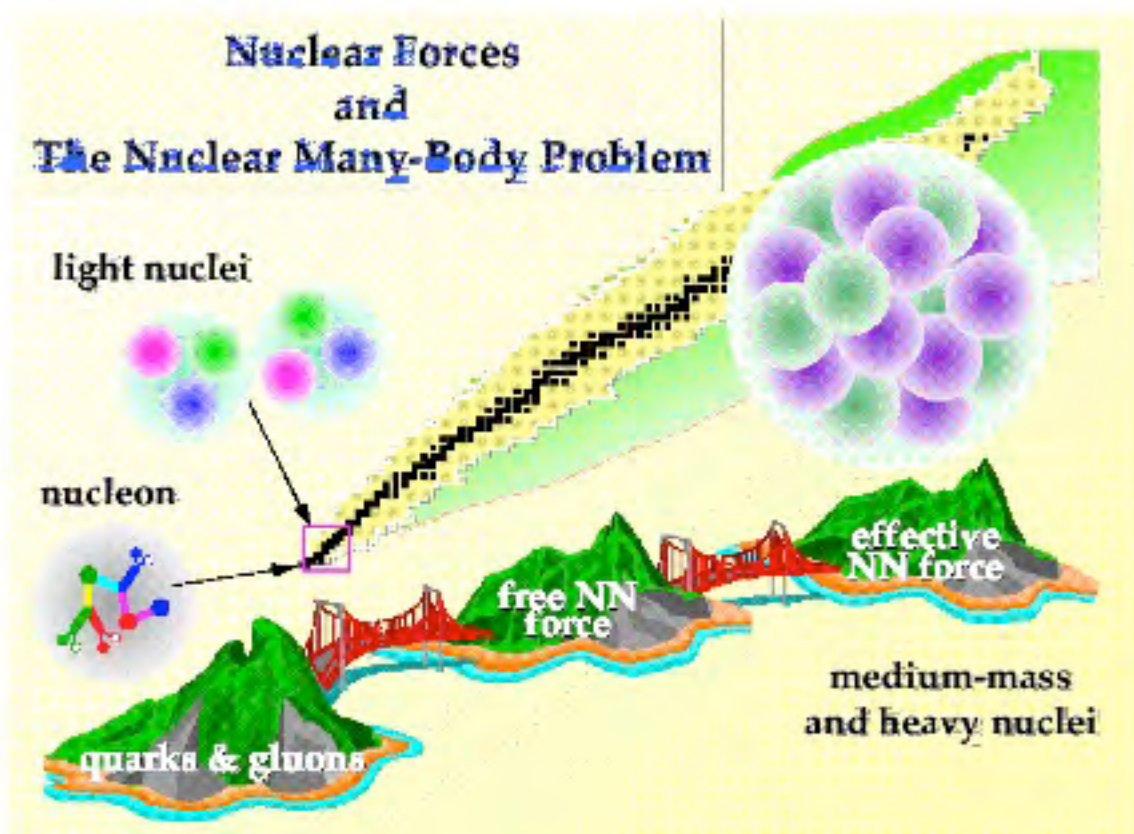


Fig. 4-1. A representation of the strong force. Depending on the complexity of the problem, scientists use different formulations.

The range of the gravitational and electromagnetic forces is infinite, while the ranges of the strong and weak forces are very short. Also, the strength of the interaction depends on the separation between the two protons. Both gravitation and electromagnetism are of infinite range and their strengths decrease as the separation, r, increases—falling off as $1/r^2$. On the other hand, because the exchange particles for the strong and weak forces have a large mass, the force associated with them is zero outside of a short range.

Note that the strong force between two protons is a residual interaction. The quarks inside the nucleons interact through the exchange of gluons that carry a quantum number called "color" (i.e., a "color-neutral" object does not feel the strong force, like an electrically neutral object does not feel electromagnetism). Figure 4-1 shows three different ways that the strong force can be viewed.

The theory of strong interactions among quarks and gluons is *called Quantum Chromodynamics* (QCD). A very successful model of describing this residual force is by the exchange of the π (pi) meson, or pion. This description, dating back to the work of Yukawa in the 1930s, works extremely well except at very short distances, and is generally used to describe most of the properties of complex nuclei. Exactly at what distance inside the nucleus, or correspondingly at what values of momentum transferred between the nucleons, the pion exchange model breaks down is the subject of much current research in nuclear physics. It is presently thought that this transition occurs somewhere around momentum transfers of 1 GeV/c.

Books and Articles:

James O'Connell, *Comparison of the Four Fundamental Interactions of Physics,* The Physics Teacher **36**, 27 (1998).

Richard A. Carrigan and W. Petter Trower (Ed.), *Particles and Forces: At the Heart of Matter: Readings from Scientific American Magazine,* W.H. Freeman Co., 1989.

Chapter 5 Symmetries and Antimatter

Scientists use *symmetry* both to solve problems and to search for new understandings of the world around us. In nuclear science the concept of symmetry plays a key role in gaining an understanding of the physical laws governing the behavior of matter. It provides a shortcut based on geometry for getting at some of Nature's innermost secrets. Because the laws of physics are the same at any time (symmetry in time) and any location (symmetry in position) as another, the laws of conservation of energy and momentum apply.

Symmetry in Rotation

Consider for example the simple idea that when an object is rotated through an angle of 360° it should end in a state no different from its initial state. If we apply this simple symmetry in quantum mechanics, the physics theory of matter and energy at the smallest distances, we find that it imposes the requirement that the angular momentum of rotating objects must be quantized in units of $\hbar$ (Planck's constant, h, divided by 2π). A spinning object, be it a planet, a top, or a nucleus, should only be able to have rotations such that its angular momentum comes out in "chunks" $\hbar$ in size.

Imagine, then the big surprise that swept through the world of physics when it was discovered in the 1930s that this symmetry was "broken" by particles like electrons, protons and neutrons, which were found to have "spin 1/2", or one half an $\hbar$ unit as their "built-in" angular momentum (called "intrinsic angular momentum" or simply "spin"). In nuclear science it has become standard to use $\hbar$ as the measuring stick for angular momentum and to describe the angular momentum of nuclei in units of $\hbar$. Thus, we say that a nucleus has angular momentum 0, or 2, or 7/2, in units of $\hbar$.

One consequence of the half-integer spins of neutrons and protons is that nuclei with an odd number of nucleons must have half-integer angular momentum, while nuclei having an even number of nucleons must have integer angular momentum (in $\hbar$ units). Another consequence is quite bizarre: objects with half-integer spin must be rotated by 720° (not 360°) before they return to their initial state! This peculiar behavior has been demonstrated using very slow (ultracold) spin-oriented neutrons from a reactor, which are split into two beams. In one beam the neutrons are rotated about an axis along their direction of motion through some angle, and then the beams are recombined. It is found that when the rotation angle is 360°, the combined beams are out of phase and cancel, (meaning that they are shifted away from the detector) while after 720° of rotation the beams are in phase and reinforced (meaning that they show a large signal at the detector). A rotation of 720° is needed to put the neutrons back in their original state.

Charge, Parity, and Time Reversal (CPT) Symmetry

Three other symmetry principles important in nuclear science are parity P, time reversal invariance T, and charge conjugation C. They deal with the questions, respectively, of whether a nucleus behaves in a different way if its spatial configuration is reversed (P), if the direction of time is made to run backwards instead of forward (T), or if the matter particles of the nucleus are changed to antimatter (C). All charged particles with spin 1/2 (electrons, quarks, etc.) have antimatter counterparts of opposite charge and of opposite parity. Particle and antiparticle, when they come together, can annihilate, disappearing and releasing their total mass energy in some other form, most often gamma rays.

The changes in symmetry properties can be thought of as "mirrors" in which some property of the nucleus (space, time, or charge) is reflected or reversed. A real mirror reflection provides a concrete example of this because mirror reflection reverses the space direction perpendicular to the plane of the mirror. As a consequence, the mirror image of a right-handed glove is a left-handed glove. This is in effect a parity transformation (although a true P transformation should reverse all three spatial axes instead of only one).

Until 1957 it was believed that the laws of physics were invariant under parity transformations and that no physics experiment could show a preference for left-handedness or right-handedness. Inversion, or mirror, symmetry was expected of nature. It came as some surprise that the radioactive decay beta decay process breaks P symmetry. C. S. Wu and her collaborators found that when a specific nucleus was placed in a magnetic field, electrons from the beta decay were preferentially emitted in the direction opposite that of the aligned angular momentum of the nucleus. When it is possible to distinguish these two cases in a mirror, parity is not conserved. As a result, the world we live in is distinguishable from its mirror image.

Figure 5-1 illustrates this situation. The direction of the emitted electron (arrow)

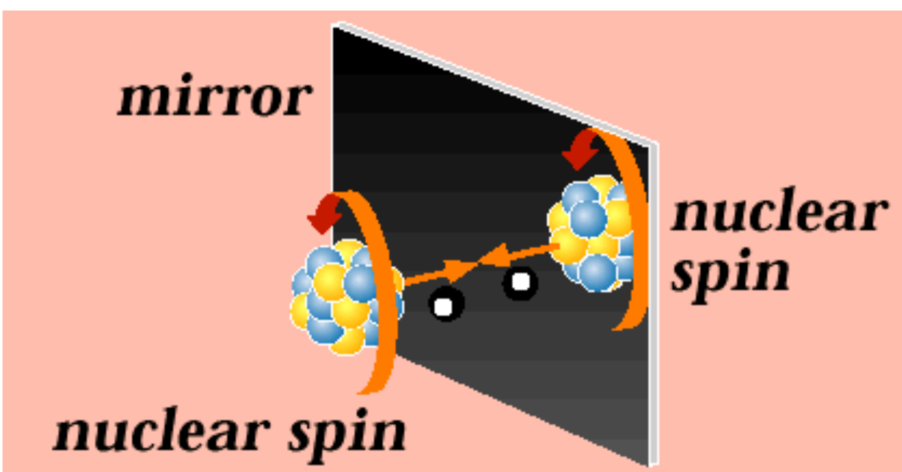


Fig. 5-1. Parity inversion of a nuclear decay

reverses on mirror reflection, but the direction of rotation (angular momentum) is not changed. Thus the nucleus before the mirror represents the actual directional preference, while its mirror reflection represents a directional preference not found in nature. A physics experiment can therefore distinguish between the object and its mirror image.

If we made a nucleus out of antimatter (antiprotons and antineutrons), its beta decay would behave in almost the same way. However the mirror image in Fig. 5-1 would represent the preferred direction of electron emission, while the antinucleus in front of the mirror would represent a directional preference not found in nature.

The great physicist, Richard Feynman, told a story to illustrate this point: suppose you were in two-way contact with some alien species, but only by "telegraph" (*i.e.,* light flashes or radio signals). The well known procedures of SETI (Search for Extraterrestrial Intelligence), starting with prime numbers and progressing to pictures, physics, and chemistry information could be used to develop a common language and arrive at a good level of communication. You could tell the alien how tall you are by expressing your height in mutually understood wavelengths of light. You could tell the alien how old you are as some large number of ticks of a light-frequency clock. Now you want to explain how humans shake hands when they meet, and you describe extending your right hand. "Wait a moment!" says the alien. "What do you mean by 'right'?"

Until 1957, there would have been no way of answering that question. But now you could use the parity experiment shown in Fig. 5-1. You could tell the alien to turn the experiment until the electrons come out in the upward direction (the direction opposite gravity), and the front edge of the rotating nucleus will move from right to left or clockwise to make the angular momentum. This works because the parity violation of the weak interaction allows us, at a fundamental level, to distinguish right from left.

Feynman also had a punch line to this story. Suppose, after lots of communication you finally can go into space and meet your alien counterpart. If, as you approach one another, the alien extends its left hand to shake, watch out! He's made of antimatter! This, of course, is because a parity violation experiment constructed of antimatter would give the opposite result.

If the mirror in Fig. 5-1 not only reversed spatial direction but also changed matter to antimatter, then the experiment in front of the mirror would look just like its mirror image. Changing both C and P preserves the symmetry and we call this CP symmetry. The separate violations of P symmetry and C symmetry cancel to preserve CP symmetry. These symmetry violations arise only from the weak interaction, not from the strong and electromagnetic interactions, and therefore show up strongly only in beta decay.

There are fundamental reasons for expecting that nature at a minimum has CPT symmetry—that no asymmetries will be found after reversing charge, space, and time. Therefore, CP symmetry implies T symmetry (or time-reversal invariance). One can demonstrate this symmetry by asking the following question. Suppose you had a movie of some physical process. If the movie were run backwards through the projector, could you tell from the images on the screen that the movie was running backwards? Clearly in everyday life there would be no problem in telling the difference. A movie of a street scene, an egg hitting the floor, or a dive into a swimming pool has an obvious "time arrow" pointing from the past to the future. But at the atomic level there are no obvious clues to time direction. An electron orbiting an atom or even making a quantum jump to produce a photon looks like a valid physical process in either time direction. The everyday "arrow of time" does not seem to have a counterpart in the microscopic world—a problem for which physics currently has no answer.

Until 1964 it was thought that the combination CP was a valid symmetry of the Universe. That year, Christenson, Cronin, Fitch and Turlay observed the decay of the long-lived neutral K meson, K_L^o, to $\pi^+ + \pi^-$. If CP were a good symmetry, the K_L^o would have CP = -1 and could only decay to three pions, not two. Since the experiment observed the two-pion decay, they showed that the symmetry CP could be violated. If CPT symmetry is to be preserved, the CP violation must be compensated by a violation of time reversal invariance. Indeed later experiments with K^0 systems showed direct T violations, in the sense that certain reaction processes involving K mesons have a different probability in the forward time direction ($A + B \rightarrow C + D$) from that in the reverse time direction ($C + D \rightarrow A + B$). Nuclear physicists have conducted many investigations searching for similar T violations in nuclear decays and reactions, but at this time none have been found.

This may change soon. Time reversal invariance implies that the neutron can have no electric dipole moment, a property implying separation of internal charges and an external electric field with its lines in loops like Earth's magnetic field. Currently ultracold neutrons are being used to make very sensitive tests of the neutron's electric dipole moment, and it is anticipated that a nonzero value may be found within the next few years.

Matter and Antimatter

Time-reversal invariance and the CP violation are connected to another asymmetry of the universe, the imbalance between matter and antimatter. At the microscopic level, matter and antimatter are always created together in 1:1 correspondence. High-energy collisions produce equal numbers of quarks and antiquarks. And yet, our universe has a conspicuous surplus of matter, of which our surroundings and we are made. How did this happen?

A clue to this deep mystery is provided by the CP violation in the K^0 meson, which shows decay modes having a preference for matter over antimatter. The K^0 does not have enough mass for its decay to produce protons. Its decay asymmetry suggests that some more massive particle, perhaps a B^0 meson containing a bottom quark, might in the early universe have decayed preferentially into protons rather than antiprotons, leading to the present day dominance of matter. Current experiments using the B-Factory at the Stanford Linear Accelerator Center (SLAC) are investigating this problem.

Antimatter exists in nature only in the form of antiprotons present in very small numbers in cosmic rays and in *positron*s (antimatter electrons) produced in some radioactive decays. Recently, evidence has also been found for a "fountain" of positrons ejected from some object near the center of our galaxy, presumably a black hole.

However, we are getting better and better at producing and storing antimatter in the laboratory. Antiprotons, antineutrons, and even antideuterons (a nucleus consisting of an antineutron and an antiproton) are routinely produced using high-energy particle accelerators at Fermilab in Illinois and CERN in Geneva, Switzerland. Positrons and antiprotons have been trapped in electric and magnetic fields and held under high vacuum for several months. Recently, "antihydrogen" atoms having a positron orbiting an antiproton have been formed in laboratory experiments. These researchers are looking for any indication that trapped positrons, antiprotons, and antihydrogen atoms show a behavior that differs in any way from that of their normal matter counterparts, because any such difference would represent a violation of CPT symmetry.

Antimatter nuclei are also interesting for other reasons. Special facilities at CERN and Fermilab provide beams of low energy antiprotons and permit nuclear scientists to study the interactions of antiprotons with matter. While a positron and an electron usually annihilate to form a pair of gamma-ray photons traveling in opposite directions, the annihilation of an antiproton with a proton is more complicated. Several π mesons are usually produced. About a third of the mass energy of the proton-antiproton pair becomes inaccessible in the form of energetic neutrinos.

Nevertheless, antimatter can be viewed as an extremely compact form of stored energy that can be released at will by annihilation with matter. The US Air Force has commissioned design studies of antimatter-powered space vehicles that, given a supply of antimatter, look quite feasible. The problem with such schemes is that production of any significant quantity of antimatter would cost far too much right now to be economically feasible.

Other Symmetries

In addition to the symmetries described above, nuclear scientists use a number of other approximate symmetries to describe and predict the behavior of nuclei. Examples of these are charge independence, the expectation that, at the nuclear level, neutron-proton systems should behave the same as proton-proton or neutron-neutron systems; and charge symmetry, the expectation that the interactions between two neutrons should be the same as that between two protons. Charge symmetry can be demonstrated by comparing "mirror nuclei," two low-mass nuclei that have their neutron and proton numbers interchanged and which have very similar nuclear structure, for example ^{13}C (Z=6, N=7) and ^{13}N (Z=7, N=6).

A related symmetry is isospin symmetry, which is related to interchanging the roles of neutrons and protons in certain nuclei. These three symmetries are destroyed when the Coulomb force becomes sufficiently strong, but nevertheless they have proved to be useful approximations in many areas of nuclear science.

Books and Articles:

Martin Gardner, *The New Ambidextrous Universe,* W. H. Freeman & Co., New York, 1990. (Revised edition)

Richard Rhodes, *The Making of the Atomic Bomb,* Simon and Schuster, New York, 1986.

Richard P. Feynman and Stephen Weinberg, *Elementary Particles and the Laws of Physics,* Cambridge University Press, Cambridge, 1987.

Hannes Alven, *Worlds-Antiworlds: Antimatter in Cosmology*.

Web Sites:

Symmetry and Antimatter
https://home.cern/about/experiments/alpha — Description of antihydrogen experiment at CERN and possible applications.

The Antimatter Factory
https://home.cern/about/updates/2018/04/live-inside-cerns-antimatter-factory — The site describes the antiproton decelerator of CERN. This machine produces a copious amount of antiprotons.

Chapter 6 Nuclear Energy Levels

The nucleus, like the atom, has discrete energy levels whose location and properties are governed by the rules of quantum mechanics. The locations of the excited states differ for each nucleus. The excitation energy, E_x, depends on the internal structure of each nucleus. Each excited state is characterized by quantum numbers that describe its angular momentum, parity, and isospin (see chapter 5). Figure 6-1 shows a few of the excited states of the ^{12}C nucleus.

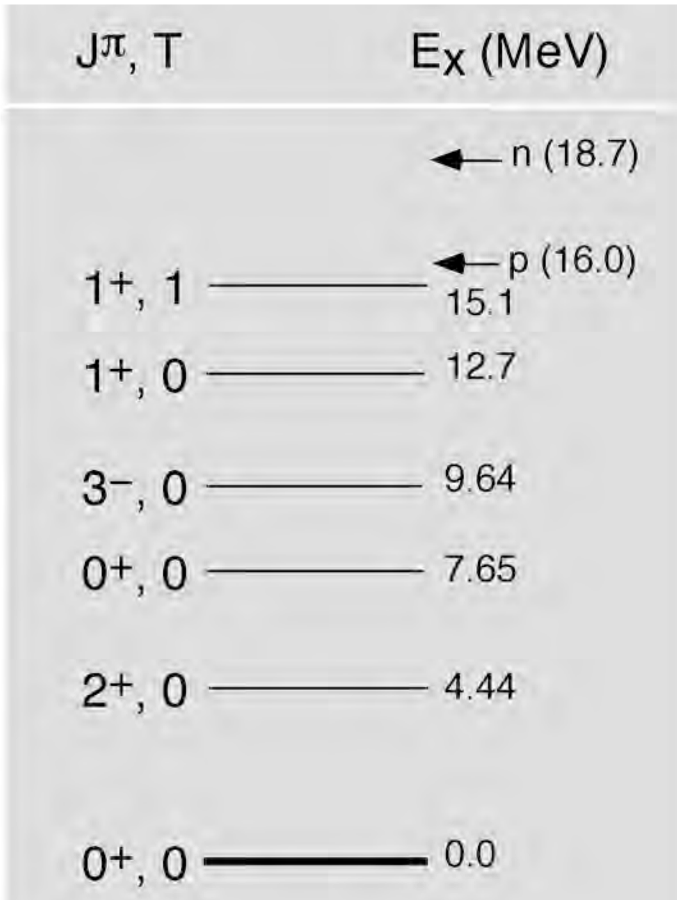


Fig. 6-1. Energy level diagram of some of the excited states of the ^{12}C nucleus. The angular momentum (*J*), parity (*P*), and isospin (*T*) quantum numbers of the states are indicated on the left using the notation J^P. P and n respectively at the top of the diagram indicate the separation energies for a proton and a neutron.

The angular momentum quantum number, *J*, is the integer or half-integer that is the measure of the total angular momentum of the energy state in units of $\hbar$ (Planck's constant *h* divided 2π)

$$\text{angular momentum} = J\ \hbar\ .$$

The parity, *P*, of a nuclear energy level is a statement about what the nuclear structure of the state would look like if the spatial coordinates of all the nucleons were reversed. *P* = + means the reversed state would look the same as the original; *P* = - means the reversed state differs from the original. The isospin (projection) quantum number, *T*, is an integer or half-integer that measures a property that results if neutron and proton coordinates were interchanged. Figure 6-1 shows these quantum numbers for each excited state in the notation J^{P}, T. These quantum numbers are results of the basic symmetries of the underlying force law that governs the binding of nucleons in a nucleus. They determine how an excited state will decay into another state in the same nucleus (gamma decay) or into a specific state in a different nucleus (beta or alpha decay).

Analyzing the interactions among many nucleons to calculate the energy levels and their properties is a complicated mathematical task. Instead, nuclear scientists have developed several nuclear models that simplified the description the nucleus and the mathematical calculations. These simpler models still preserve the main features of nuclear structure.

The Shell Model

One such model is the Shell Model, which accounts for many features of the nuclear energy levels. According to this model, the motion of each nucleon is governed by the average attractive force of all the other nucleons. The resulting orbits form "shells," just as the orbits of electrons in atoms do. As nucleons are added to the nucleus, they drop into the lowest-energy shells permitted by the Pauli Principle, which requires that each nucleon have a unique set of quantum numbers to describe its motion.

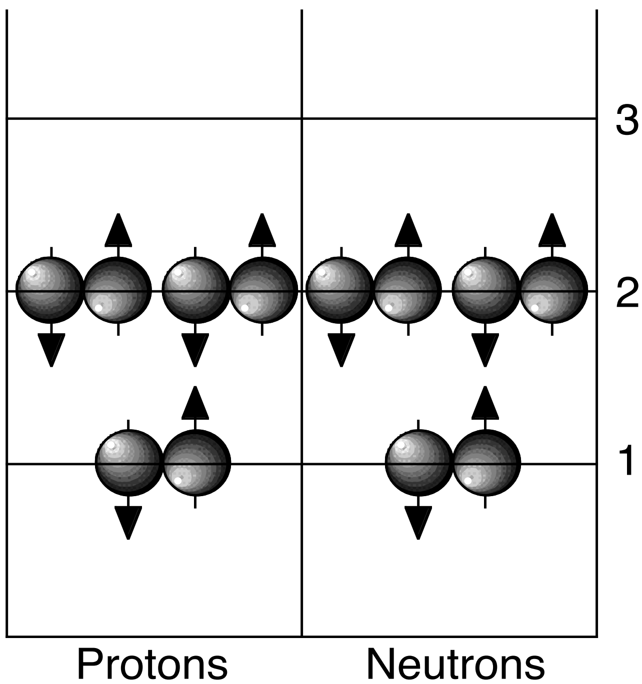


Fig. 6-2. Shell model energy diagram of the orbitals of protons and neutrons in ^{12}C ground state. The arrows on individual nucleons denote its spin state.

When a shell is full (that is, when the nucleons have used up all of the possible sets of quantum number assignments), a nucleus of unusual stability forms. This concept is similar to that found in an atom where a filled set of electron quantum numbers results in an atom with unusual stability—an inert gas. When all the protons or neutrons in a nucleus are in filled shells, the number of protons or neutrons is called a "magic number." Some of the magic numbers are 2, 8, 20, 28, 50, 82, and 126. For example, ^{116}Sn has a magic number of protons (50) and ^{54}Fe has a magic number of neutrons (28). Some nuclei, for example ^{40}Ca and ^{208}Pb, have magic numbers of both protons and neutrons; these nuclei have exceptional stability and are called "doubly magic." Magic numbers are indicated on the chart of the nuclides.

Filled shells have a total angular momentum, J, equal to zero. The next added nucleon (a valence nucleon) determines the J of the new ground state. When nucleons (singly or in pairs) are excited out of the ground state they change the angular momentum of the nucleus as well as its parity and isospin projection quantum numbers. The shell model describes how much energy is required to move nucleons from one orbit to another and how the quantum numbers change. Figure 6-2 shows an energy diagram of the two filled shells of the ground state of ^{12}C. Promotion of a nucleon or a pair of nucleons to an unfilled shell puts the nucleus into one of the excited states shown in Fig. 6-1.

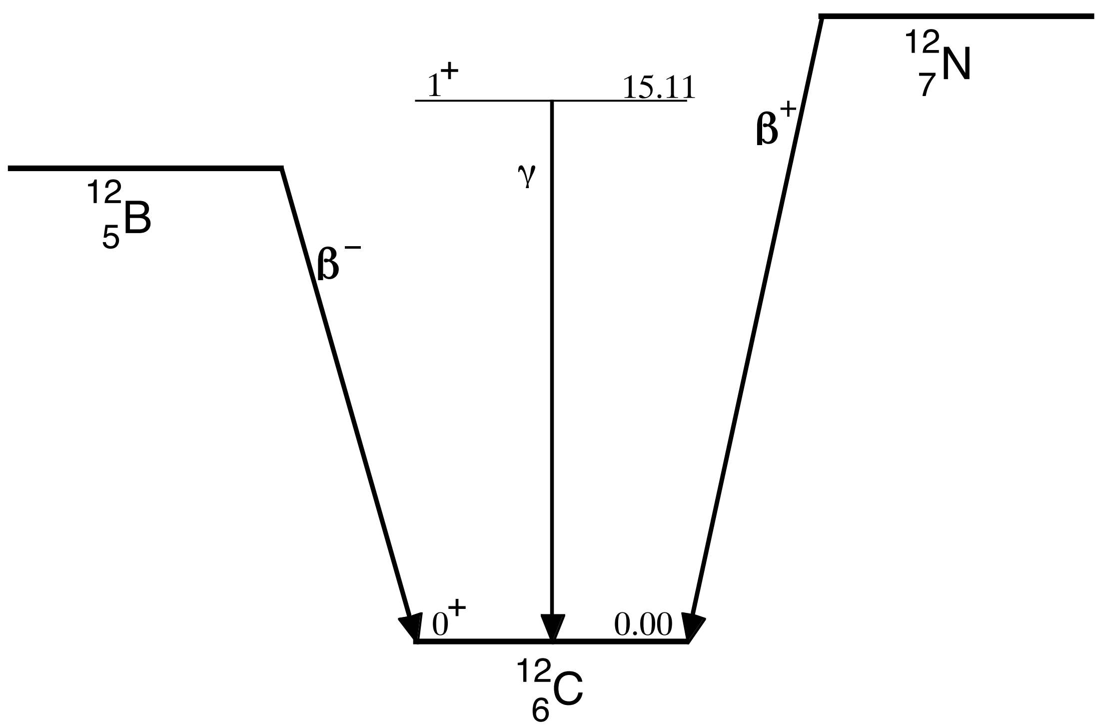


Fig. 6-3. Transitions between discrete energy levels in A = 12 nuclei. The energy is given in MeV.

Excited nuclear states decay to more stable states, *i.e.*, more stable nucleon orbitals. Measuring transition rates between nuclear energy levels requires specialized alpha, beta, and gamma detectors and associated electronic circuitry to precisely determine the energy and half-life of the decay. Quantum mechanics and shell-model theory permit nuclear scientists to compute the transition probability (rate of decay) between nuclear states. For nuclei whose structure can be described by a small number of valence nucleons outside filled shells, the Shell Model calculations agree very well with measured values of spin and parity assignments and transition probabilities.

An example of transitions between a nucleus's energy levels is shown in Fig. 6-3. The ground states of ^{12}B (5 protons, 7 neutrons) and ^{12}N (7 protons, 5 neutrons) are related to each other and to the 15.1 MeV state in ^{12}C. Each has a nucleon in the third energy level shown in Fig. 6-2, each has the quantum number 1^+, 1, and each decays to the ground state of carbon. The boron and nitrogen beta decay emit an e^- and e^+ respectively. The 15.1 MeV state in carbon decays by gamma emission. The shell model calculations of these transition probabilities agree quite well with the measured rates even though different decay mechanisms are at work in each case. Nuclear theorists keep refining the shell model to understand the details of nuclear structure and to make that knowledge available for applications in nuclear technology.

The Collective Model

In addition to individual nucleons changing orbits to create excited states of the nucleus as described by the Shell Model, there are nuclear transitions that involve many (if not all) of the nucleons. Since these nucleons are acting together, their properties are

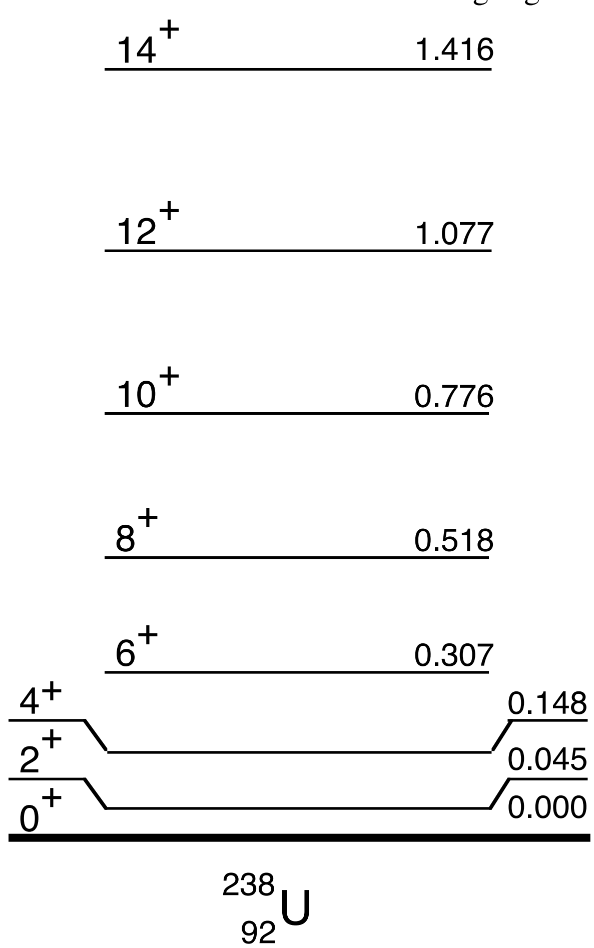


Fig. 6-4. Rotational states of ^{238}U. The energy is given in MeV.

called collective, and their transitions are described by a Collective Model of nuclear structure. High-mass nuclei have low-lying excited states that are described as vibrations or rotations of nonspherical nuclei. Many of these collective properties are similar to those of a rotating or vibrating drop of liquid, and in its early development the Collective Model was called the Liquid-Drop Model. The first important application of the Liquid-Drop model was in the analysis of nuclear fission, in which a massive nucleus splits into two lower-mass fragments. The Liquid Drop Model calculates an energy barrier to fission as a sum of the repulsive Coulomb forces between the protons of the nucleus and the attractive surface tension of the skin of the "liquid drop" nucleus. If the barrier is low enough the nucleus might fission spontaneously. For higher barriers, it takes a nuclear reaction to induce fission.

Figure 6-4 shows the energy levels of ^{238}U. The quantum numbers, level spacings, and gamma ray transition probabilities identify these levels as rotational states of a nonspherical nucleus. Nuclei showing collective properties are usually those with many valence nucleons, that is, those with proton or neutron numbers that are far from filled shells. As with the Shell Model, the Collective Model permits the calculation of spin-parity assignments and transition probabilities that are in good agreement with the measured properties of collective nuclei.

Measuring Energy Levels

Using accelerators to make nuclear reactions (see Chapter 7), scientists can create nuclei which have very high angular momentum. Nuclei respond to this rotation, which can be as fast as a hundred billion billion revolutions per second, in a rich and varied way. These nuclei lose some of their excitation energy and almost all of the initial angular momentum by the emission of gamma rays. The gamma ray flash is finished in less than 10^{-9} seconds, during which 30 or more gamma rays can be emitted.

A number of preferred pathways in the de-excitation process occur. They relate to favorable arrangements of protons and neutrons and can often be associated with specific symmetries or nuclear shapes. If a sufficient fraction of the decay flows down a particular quantized pathway or band, then the associated structure becomes observable and can be studied in detail. Scientists have recently built arrays of over 100 gamma ray detectors to study the details of some of these rare pathways. One such array is Gammasphere, shown in Figure 6-5. Gammasphere was built by groups from Lawrence Berkeley National Laboratory, Argonne National Laboratory, and Oak Ridge National Laboratory. It was used at Berkeley Lab's 88-Inch Cyclotron for two years before being moved to Argonne in 1997. During its tenure in Berkeley, many exciting discoveries were made including:

1. Details of superdeformation in nuclei. Superdeformation occurs when quantum shell effects help stabilize a football shape (2:1 axis ratio) in certain nuclei. Superdeformed nuclei, prevalent in several regions of the chart of the nuclides, have been found to display some amazing properties.

2. *Identical Bands*. Scientists have discovered that sequences of ten or more identical photons are associated with different bands in neighboring nuclei. This comes as a great surprise; it has long been believed that the gamma-ray emission spectrum for a specific nucleus represents a unique fingerprint. Explaining identical bands is now in the hands of shell model theoreticians.

3. *Magnetic Rotation*. Magnetic rotation occurs in nearly spherical nuclei. It is characterized by sequences of gamma rays reminiscent of collective rotational bands but with a quite different character. Namely, each photon carries off only one (rather than two) units of angular momentum and couples to the magnetic rather than electric properties of the nucleons. This is a new form of quantal rotor that is not fully understood at present.

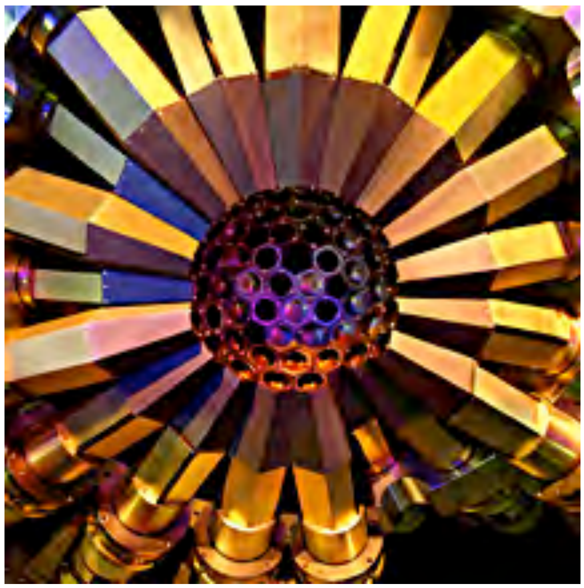


Figure 6-5. One hemisphere of the Gammasphere detector array.

Web Sites:

Gammasphere
https://www.phy.anl.gov/gammasphere— This web site describes the science behind Gammasphere. You can find many pictures of this apparatus.

Chapter 7 Nuclear Reactions

Nuclear reactions and nuclear scattering are used to measure the properties of nuclei. Reactions that exchange energy or nucleons can be used to measure the energies of binding and excitation, quantum numbers of energy levels, and transition rates between levels. A particle accelerator (see Chapter 11), which produces a beam of high-velocity charged particles (electrons, protons, alphas, or "heavy ions"), creates these reactions when they strike a target nucleus. Nuclear reactions can also be produced in nature by high-velocity particles from cosmic rays, for instance in the upper atmosphere or in space. Beams of neutrons can be obtained from nuclear reactors or as secondary products when a charged-particle beam knocks out weakly bound neutrons from a target nucleus. Beams of photons, mesons, muons, and neutrinos can also produce nuclear reactions.

In order for a nuclear reaction to occur, the nucleons in the incident particle, or projectile, must interact with the nucleons in the target. Thus the energy must be high enough to overcome the natural electromagnetic repulsion between the protons. This energy "barrier" is called the Coulomb barrier. If the energy is below the barrier, the nuclei will bounce off each other. Early experiments by Rutherford used low-energy alpha particles from naturally radioactive material to bounce off target atoms and measure the size of the target nuclei.

When a collision occurs between the incident particle and a target nucleus, either the beam particle scatters elastically leaving the target nucleus in its ground state or the target nucleus is internally excited and subsequently decays by emitting radiation or nucleons. A nuclear reaction is described by identifying the incident particle, target nucleus, and reaction products. For example, when a neutron strikes a nitrogen nucleus, ^{14}N, to produce a proton, ^{1}H, and an isotope of carbon, ^{14}C, the reaction is written as

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

Sometimes the reaction is abbreviated as $^{14}N(n,p)^{14}C$. A number of conservation conditions apply to any reaction equation:

1. The mass number A and the charge Z must balance on each side of the reaction arrow. Thus in the example the sum of superscripts 1 + 14 on the left equals the 14 + 1 on the right to balance the *A's*. The 0 + 7 subscripts on the left equals the 6 + 1 on the right to balance the *Z's*.
2. The total energy before the reaction must equal the total energy after the reaction. The total energy includes the particle kinetic energies plus the energy equivalent of the particle rest masses, $E = mc^2$.
3. Linear momenta before and after the reaction must be equal. For two-particle final states this means that a measurement of one particle's momentum determines the other particle's momentum.
4. Quantum rules govern the balancing of the angular momentum, parity, and isospin of the nuclear levels.

A specific reaction is studied by measuring the angles and kinetic energies of the reaction products (the kinematic variables). Particle and radiation detectors designed for the expected charge and energy of each product are arranged around the target. (See Chapter 12 for a discussion of detector types.)

The most important quantity of interest for a specific set of kinematic variables is the reaction cross section. The cross section is a measure of the probability for a particular reaction to occur. This quantity, σ, which has the dimension of area, is measured by the experimental ratio

$$\sigma = \frac{\text{number of reaction particles emitted}}{\text{(number of beam particles per unit area)(number of target nuclei within the beam)}} \cdot$$

The cross section can also be calculated from a mathematical model of the nucleus by applying the rules of quantum mechanics. Comparing the measured and calculated values of the cross sections for many reactions validates the assumptions of the nuclear model.

Table 7-1 shows some of the many types of nuclear reactions and what they teach us about nuclei and nuclear energy.

Table 7-1. Nuclear Reaction Types

Reaction	What is Learned
Nucleon - nucleon scattering	Fundamental nuclear force
Elastic scattering of nuclei	Nuclear size and interaction potential
Inelastic scattering to excited states	Energy level location and quantum numbers
Inelastic scattering to the continuum	Giant resonances (vibrational modes)
Transfer and knockout reactions	Details of the Shell Model
Fusion reactions	Astrophysical processes
Fission reactions	Properties of Liquid-drop Model
Compound nucleus formation	Statistical properties of the nucleus
Multifragmentation	Phases of nuclear matter, Collective Model
Pion reactions	Investigation of the nuclear "glue"
Electron scattering	Quark structure of nuclei

The elastic scattering cross sections of protons and neutrons on a proton target give the essential data to reconstruct the nucleon-nucleon. A complete theory of nuclear structure and dynamics must start with this elemental interaction.

The systematics of nuclear sizes, shapes, binding energies, and other nuclear properties are the data that nuclear models are challenged to explain. The Shell Model that has been mentioned in Chapters 2 and 6 has combined the large body of nuclear data into a coherent theory of nuclear structure. Most of this data was the result of elastic and inelastic scattering of electrons, protons, and neutrons from nuclei found in the chart of the nuclides.

At high enough excitation energies, a nucleus can undergo a series of normal modes of collective oscillations called giant resonances. The nucleus rings like a bell at distinct frequencies with all the nucleons participating and sharing the excitation energy.

Fusion reactions are the combining of two nuclei to form a more massive nucleus. Many fusion reactions release large amounts of energy. An example is the combining of two isotopes of hydrogen (tritium and deuterium) to form helium and a neutron plus a large amount of kinetic energy in the reaction products:

$$^{3}H + ^{2}H \rightarrow ^{4}He + n + 17.6 \text{ MeV}.$$

This reaction as a potential electric power source is discussed in Chapter 14. Another example of fusion is the reaction set that powers the Sun and other low-mass stars:

$$^{1}H + ^{1}H \rightarrow ^{2}H + e^{+} + \nu_{e},$$
$$^{2}H + ^{1}H \rightarrow ^{3}He + \gamma,$$
$$^{3}He + ^{3}He \rightarrow ^{4}He + ^{1}H + ^{1}H.$$

The net energy output from this chain is 26.7 MeV for each helium-4 nucleus formed.

Neutron-induced fission of massive nuclei into two lower-mass nuclei plus neutrons is also an energy source for power generation. This topic is discussed in Chapter 14.

Compound nucleus formation is a reaction in which two nuclei combine into a single excited nucleus; the excited nucleus lives for a relatively long time and “forgets” how it was formed. The decay from this state of excitation is by “evaporation” of nucleons from the heated liquid drop of the compound nucleus, by gamma decay, or by fission of the compound nucleus. The statistical nature of this process teaches us about the average properties of excited states of complex nuclei.

Multifragmentation reactions, in which high-energy nuclei collide with other nuclei, are a method of creating nuclear matter in unusual conditions of density and excitation energy. These states may be in a different phase from normal nuclei and be characteristic of the matter in the early universe.

The fundamental force between nucleons in nuclei is dominated by the exchange of π mesons (pions). When these particles are created in high-energy proton reactions, they can be used to bombard nuclear targets. When the pion interacts with a nucleus, it forms a resonance with one of the bound nucleons. The resonance is shifted and broadened compared to the reaction on a free nucleon. These changes reflect the influence of the neighboring nucleons.

When nucleons are flung at one another, they can mesh briefly. During the time they are one nucleus, the quarks in the nucleons can interact with one another as if they were free particles. As with Rutherford scattering, an investigation of the angle that a particle is scattered gives information about the conditions inside the nucleons.

Nuclear reactions and their interpretation are the main activity of most nuclear scientists. The continuing development of accelerators and detectors (see Chapters 11 and 12) permit the refinement of nuclear data and models to benefit basic science and nuclear applications.

Books and Articles:

Robin Herman, *Fusion*, Cambridge University Press, Cambridge 1990.

Robert Serber, *The Los Alamos Primer*, University of California Press, Berkeley, 1992.

Chapter 8 The Search for "Heavy" Elements

The known chemical elements are arranged (Fig. 8-1) in a pattern that relates their chemical properties. That arrangement is called the "Periodic Table", and is the fundamental tool for physicists and chemists. The elements are arranged in groups (columns) indicative of similar chemical properties and periods (rows) indicative of electronic shell occupation. To a person who understands how to read the periodic table, an enormous amount of elementary properties can be discerned – for example, which element might bond with which other elements and in what ratios to form chemical compounds, which elements are metallic and which are not. The first periodic table was constructed in 1869 by Dmitri Mendeleev. Other scientists had noticed repeating patterns or periodicity in the various known elements (at that time only 63 elements were known), but Mendeleev was the first to boldly use his table to predict the existence of as yet unknown elements and actually leave spaces in his chart for them. Several elements (Ga and Ge for example) where found in subsequent years, based on his predictions of their expected masses and chemical properties, cementing the form and usefulness of the periodic table. UNESCO declared 2019 the International Year of the Periodic Table in honor of the 150th anniversary of the first periodic table.

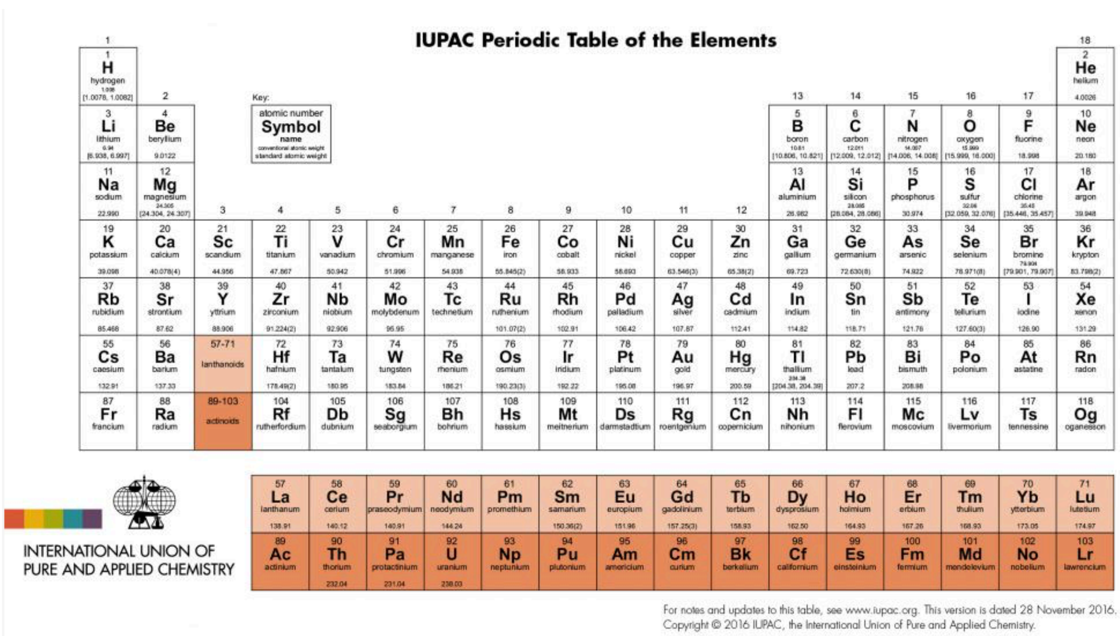


Fig. 8-1. The Periodic Table. Reference https://iupac.org/what-we-do/periodic-table-of-elements/

Each element is uniquely defined by proton number, Z. Changing the number of neutrons, N, does not changes the chemical properties significantly, but can make a **major** difference in the nuclear properties. This arrangement showing the number of neutrons and protons can be displayed in a chart of nuclides, which also conveys important nuclear properties such as half-life and decay modes. The uppermost end of the chart of nuclides as known in 2019 is shown in Fig. 8-2. Elements through oganesson (Og, Z = 118) have been discovered, confirmed[1], and named (see Table 8-1).

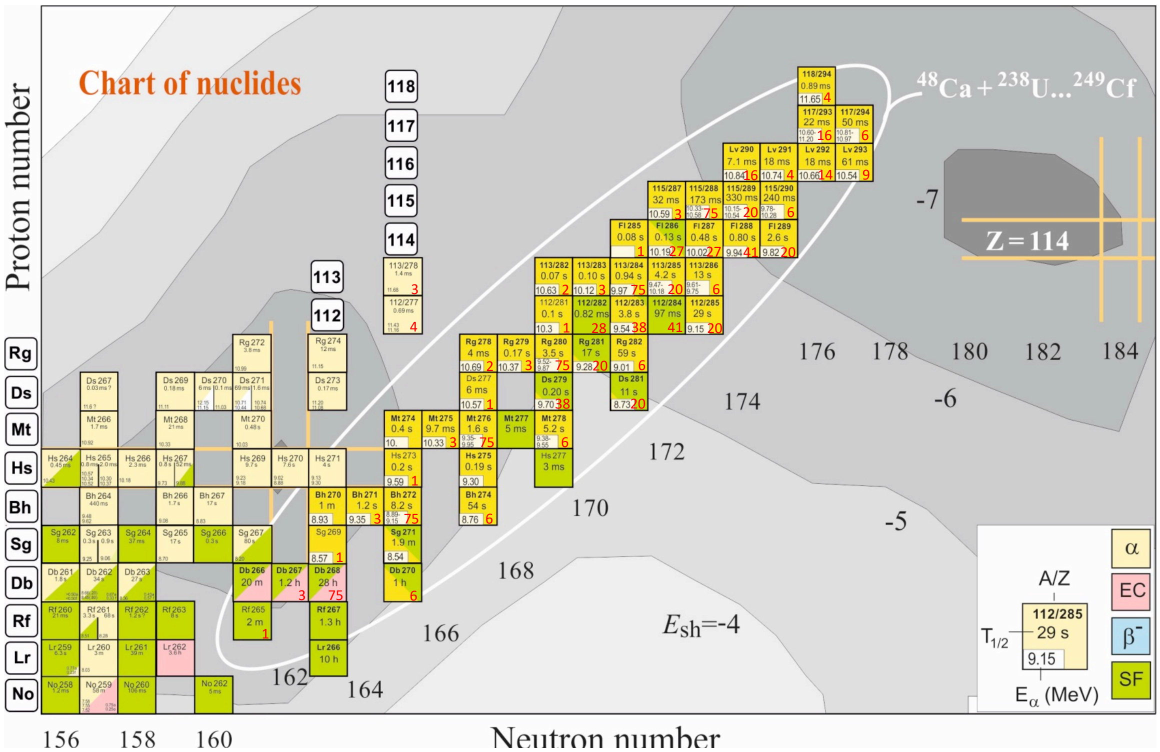


Fig. 8-2. The uppermost part of the chart of nuclides in June 2018. The color of the boxes indicates decay mode and text in the boxes indicate half-life and decay energies, The red numbers are the total number of atoms of that particular isotope that have been produced worldwide by June 2018. The grey shaded background is the magnitude of the shell corrections in a nuclear model and indicate one possible location for the next doubly magic "Island of Stability" or region of enhanced stablility near Z = 114 and N = 184.

When a nucleus captures a neutron, it often tries to correct for its neutron excess by beta decay, turning a neutron into a proton and thus creating an atom with atomic number *Z* increased by one unit. This commonly observed phenomenon suggests a way to create new elements of increased atomic number and thus to create ever more massive elements that are not found on Earth. Most of these elements are radioactive, with very short half-lives. However, theories of nuclear structure predict that at a certain atomic number, which is currently beyond present experimental limits, new long-lived nuclei can be created.

The most massive naturally occurring element on Earth is uranium (U), with a nucleus of 92 protons. In 1934, scientists started the search for more massive elements with 93 or more protons. They succeeded in 1940 when neptunium (Np, Z = 93) was synthesized at the University of California, Berkeley. Edwin McMillan and Philip Abelson observed Np while studying fission products produced in the bombardment of

[1] Oganesson has only been produced at the Flerov Laboratory of Nuclear Reactions in Dubna, Russia.

^{238}U with thermal neutrons. They found a radioactive reaction product that was not a fission product. This product was formed by the capture of a neutron to produce ^{239}U, which subsequently β^- decayed to ^{239}Np via the reaction

$$^{239}U + {}^{1}n \rightarrow {}^{239}U\ (23.5\ \text{min}) \rightarrow {}^{239}Np\ (2.36\ \text{d}),$$

where the half life of the nucleus is indicated in the parenthesis. McMillan and Abelson chemically separated this new element, Np, from the interfering fission products and chemically identified it as neptunium. Since this breakthrough discovery, scientists from all over the world have been trying to discover ever more massive artificially produced elements.

Plutonium (Pu, Z = 94) was discovered in 1941 by bombarding a uranium target with deuterons (a hydrogen nucleus with one proton and one neutron) in the 60-Inch Cyclotron at Berkeley. Glenn Seaborg, Arthur Wahl and Joseph Kennedy chemically separated neptunium from the target and detected alpha particles from the plutonium daughter nuclei, as:

$$^{238}U + {}^{2}H \rightarrow 2\ {}^{1}n + {}^{238}Np\ (2.1\ \text{d}) \rightarrow {}^{238}Pu\ (88\ \text{yr})$$

They chemically identified the isotope ^{238}Pu. Then, joined by Emilio Segre, they identified ^{239}Pu and showed that it was fissionable with thermal neutrons.

Once ^{239}Pu was discovered, there was the potential for using it as a new target to produce more massive elements because of its long half-life of 24,100 years. Because its half life is so long, scientists can keep the target for a long number of years.

In 1944 a ^{239}Pu target was bombarded with alpha particles at the 60-Inch Cyclotron to produce curium (Cm, Z = 96) through the following nuclear reaction

$$^{239}Pu\ (24{,}110\ \text{yr}) + {}^{4}He \rightarrow {}^{242}Cm\ (162.8\ \text{d}) + {}^{1}n.$$

After bombardment the material was sent to the Metallurgical Laboratory at The University of Chicago for chemical separation and identification of the new element. The element ^{242}Cm decays to ^{238}Pu by emitting alpha particles. The identification of curium was possible because the alpha decay of the daughter nucleus, ^{238}Pu, was already known and could be used as a signature for the identification of the curium precursor.

The discovery of americium (Am, Z = 95) soon followed when a ^{239}Pu target was bombarded with thermal neutrons in a nuclear reactor. Plutonium captured several neutrons and ultimately became americium (^{241}Am):

$$^{239}Pu\ (24{,}110\ \text{yr}) + {}^{1}n \rightarrow {}^{240}Pu\ (6{,}564\ \text{yr}) + {}^{1}n \rightarrow {}^{241}Pu\ (14.4\ \text{yr})$$

and

$$^{241}Pu\ (14.4\ \text{yr}) \rightarrow {}^{241}Am\ (432.7\ \text{yr}) + {}^{1}n \rightarrow {}^{242}Am\ (16.0\ \text{h}) \rightarrow {}^{242}Cm\ (162.8\ \text{d}).$$

Americium was chemically separated from plutonium and further identified by observing its beta decay to the known ^{242}Cm isotope.

Once americium and curium were found and isolated in macroscopic amounts, they were used as targets to produce more massive elements through particle bombardments. Berkelium (Bk, Z = 97) was produced by bombarding milligram quantities of americium with helium ions,

$$^{241}\text{Am (432.7 yr)} + {}^{4}\text{He} \rightarrow {}^{243}\text{Bk (4.5 h)} + 2\,{}^{1}\text{n}.$$

Rapid chemical techniques were developed in order to separate and identify this new short-lived element. Likewise, californium (Cf, Z = 98) was produced in a helium bombardment of a target made of microgram amounts of curium by

$$^{242}\text{Cm (162.8 d)} + {}^{4}\text{He} \rightarrow {}^{245}\text{Cf (45 min)} + {}^{1}\text{n}.$$

The identification of this element was accomplished with only the 5000 atoms produced in this experiment. The next two elements, einsteinium (Es, Z = 99) and fermium (Fm, Z = 100), were unexpectedly found in the debris from the "Mike" thermonuclear explosion that took place in the Pacific Ocean in 1952. Debris from the explosion was collected and analyzed at several laboratories, and the new elements were discovered in chemical separations of the material. Scientists explained the production of einsteinium and fermium through multiple neutron captures by the uranium used in the thermonuclear device followed by several successive beta decays, which ultimately resulted in atoms with atomic numbers 99 and 100.

The last three elements in the actinide series are mendelevium (Md, Z = 101), nobelium (No, Z = 102) and lawrencium (Lr, Z = 103). Mendelevium was truly a unique discovery because the new element was produced and identified virtually one atom at a time. Einsteinium was bombarded with helium ions to produce mendelevium through:

$$^{253}\text{Es (20.5 d)} + {}^{4}\text{He} \rightarrow {}^{256}\text{Md (78.1 min)} + {}^{1}\text{n}.$$

The production of mendelevium was estimated to be only a few atoms per experiment. The reaction products from the bombardment were collected on thin gold foils that were dissolved in an acid solution, and then chemically treated in order to separate and identify the Md atoms. This is commonly called the recoil method, and is used when small numbers of atoms are produced.

The discovery of nobelium was controversial. A team of scientists from several different laboratories claimed discovery in 1957. However, scientists from the United States and the Soviet Union could not confirm their findings. The original claim was proven to be false; the product that was thought to be nobelium was actually something completely different. Nobelium was finally produced and positively identified in 1958 through the following reaction:

$$^{246}\text{Cm (4730 yr)} + {}^{12}\text{C} \rightarrow {}^{254}\text{No (55 s)} + 4\,{}^{1}\text{n}.$$

The first identification of lawrencium was made at the Berkeley Laboratory's Heavy Ion Linear Accelerator (HILAC) in 1961. Several targets of californium isotopes were bombarded with beams of boron. The reaction products were collected on a Mylar tape and moved past a series of alpha detectors. The element lawrencium was identified on the basis of the known alpha decays of its descendant nuclei.

By observing the decay chain of their descendant nuclei, scientists discovered elements 104 through 118. Only a few atoms of these new elements were produced in each experiment. The atoms were isolated from the target and beam material by using a particle separator, which separates atoms, based on their different masses. The atoms were then allowed to decay and the subsequent alpha particle decay products from the descendant nuclei were correlated to identify the unknown parent nucleus. The heaviest The decay chains used to identify Og and Sg are shown in Fig. 8-3. Different combinations of targets and projectiles were used in accelerators to produce these elements (see Table 8-2).

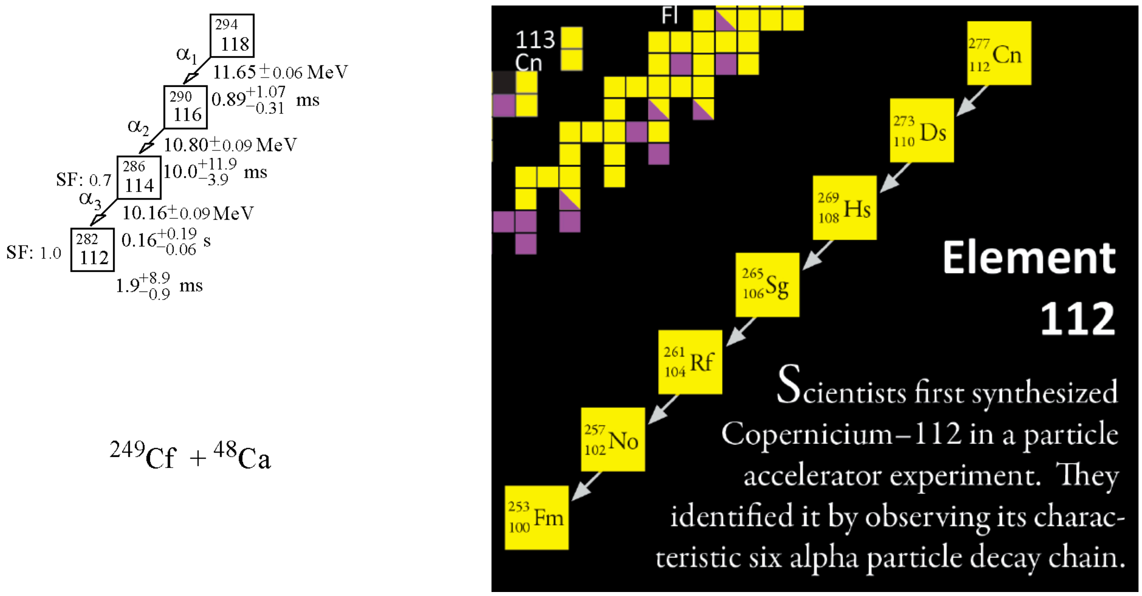


Fig. 8-3. The decay chain for identifying Og(118) and the decay chain for Sg(112) from the Nuclear Wall Chart.

There are two methods for producing new elements. First, cold-fusion reactions typically use more symmetric beam and target nuclei to produce a compound nucleus. Secondly, hot-fusion reactions use a more asymmetric beam and target nuclei to produce a compound nucleus with generally higher excitation energy. Both of these types of reactions utilize doubly magic nuclei, as either target or projectile in anattempt to increase the stability of the compound nucleus. Cold-fusion reactions have produced elements 104-112 and hot-fusion reactions have produced elements 113-118. Element 113 has also been produced with a cold-fusion reaction.

Rutherfordium (104), dubnium (105), and seaborgium (106) were synthesized and identified at Berkeley. Bohrium (107), hassium (108), and meitnerium (109) were synthesized and identified in the early 1980s at the Gesellschaft für Schwerionenforschung (GSI) laboratory near Darmstadt, Germany via cold-fusion nuclear reactions.

The decade of the 1990's brought three more new elements to the periodic table, elements named darmstadtium (110), roentgenium (111) and copernicium (112), all produced first via cold-fusion reactions at GSI (see Table 8-2). The half-lives of the produced isotopes were all in the milliseconds to microseconds range, and the production rates continued to plummet.

In 1998, the Dubna/LLNL collaboration began to investigate superheavy element production using the hot-fusion reaction of beams of ^{48}Ca with various actinide targets, in an attempt to reach the Island of Stability long predicted to be at Z = 114 and N = 184. The first reaction was ^{48}Ca + ^{244}Pu → ^{292}114* and yielded element 114, now named flerovium. While the cross-sections for production of superheavy elements via cold-fusion reactions continued to plummet, those for hot-fusion reactions were unusually high, around a picobarn (see Fig. 8-4).

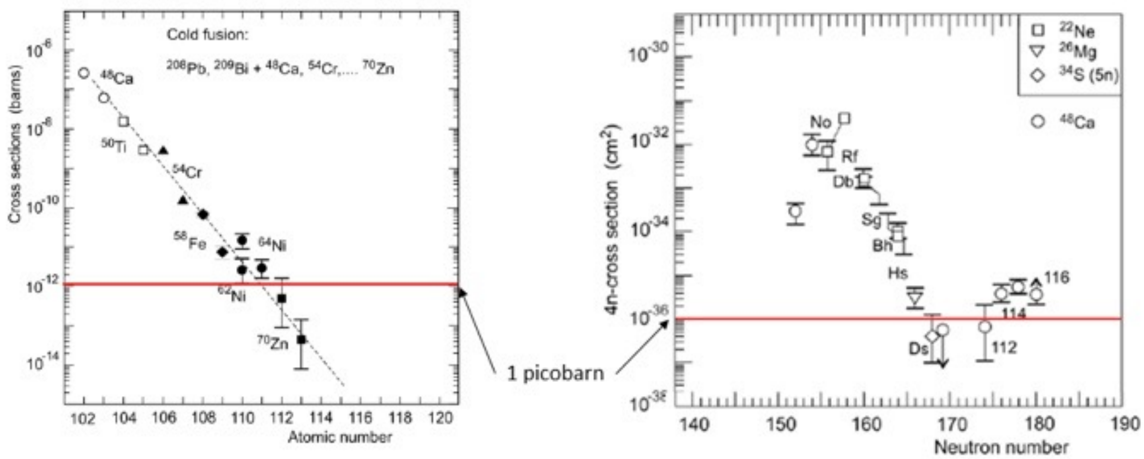


Fig. 8-4. Comparison of production rates of nuclei between cold-fusion reactions (left) and hot-fusion reactions (right). Red lines indicate one picobarn cross-sections.

During the decade of 2000-2010, six new chemical elements were produced by the Dubna/LLNL collaboration (and later collaborators from ORNL and Vanderbilt University), and one element, element 113 (nihonium), was also produced via heroic experiments at RIKEN laboratory in Japan using the cold-fusion reaction ^{70}Zn + ^{209}Bi. Hot-fusion reactions produced flerovium (114), livermorium (116), moscovium (115) and nihonium (113), oganesson (118) and finally tennessine (117). These elements were confirmed by other laboratories and accepted by the IUPAC, thus completing the seventh row or period of the periodic table.

It should be noted that the half-lives of some isotopes produced via these reactions are significantly longer than those of prior isotopes produced via cold-fusion reactions. Using Cn isotopes as an example, ^{285}Cn ($t_{1/2}$ = 29 s) lives nearly 5 orders of magnitude longer than ^{277}Cn ($t_{1/2}$ = 0.69 ms). This, combined with increased production rates, provides strong evidence that the newly produced isotopes exist on the shores of the Island of Stability, near the N = 184 and Z = 114 closed shells. Theorists now predict a region of enhanced stability centered around Z = 114, 120, 124 or 126, perhaps a broader region of isotopes with longer half-lives. The heaviest produced isotopes are still 7 neutrons short of N = 184.

There have been multiple attempts, by multiple laboratories, to produce elements 119 and 120 using different hot-fusion reactions. Because targets of Es and Fm cannot be made due to small amounts of target material exisiting on the planet at any given time, beams of ^{48}Ca cannot be used, and any advantage obtained using a doubly magic nucleus as beam is lost. Nevertheless, attempts to produce the next elements have been made, and have even captured the imagination of the public at large.

The popular TV show, "The Big Bang Theory" even had several story lines where the genius character, Sheldon Cooper, postulated the production of element 120 using various reactions (see Fig. 8-5). All of the reactions on the whiteboard have been tried, with no success so far, except for the reaction containing Md as a target because a target of Md cannot be made due to scarcity of the material.

Weare in a time period where development of better equipment is occuring to continue the searches for new superheavy elements. The Super Heavy Element Factory (SHEF) in Dubna, Russia is currently nearing completion and will be dedicated to super heavy element research.

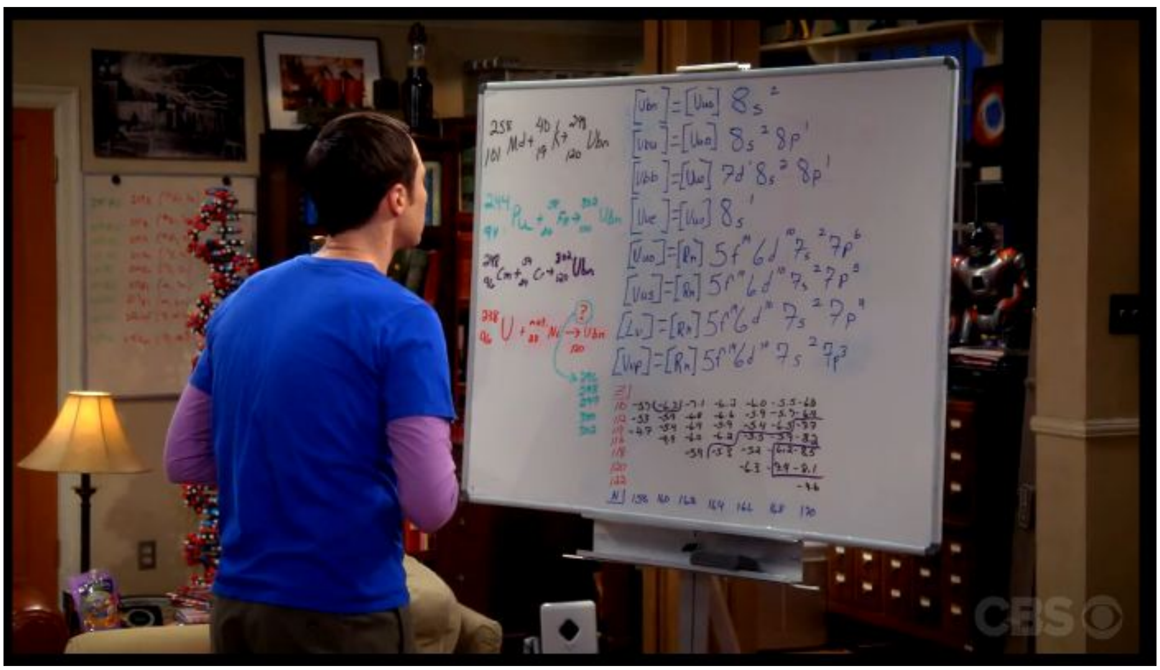


Figure 8-5. Season 7 (2013) – "The Romance Resonance" of the popular TV series "The Big Bang Theory" in which various nuclear reactions are suggested to produce element 120. From top to bottom, the reactions ^{258}Md + ^{40}K, ^{244}Pu + ^{58}Fe, ^{248}Cm + ^{54}Cr and ^{238}U + Ni are suggested. All of these reactions have been attempted, except for the ^{258}Md reaction because a target cannot be constructed of this scarce material.

Traditionally, the discoverers of a new element chose its name, and then the International Union of Pure and Applied Chemistry (IUPAC) officially approves it. Table 8-1 lists the currently approved IUPAC names.

Table 8-1. "Heavy" element names that are approved by IUPAC.

Element Number	IUPAC Proposal	Symbol
101	Mendelevium	Md
102	Nobelium	No
103	Lawrencium	Lr
104	Rutherfordium	Rf
105	Dubnium	Db
106	Seaborgium	Sg
107	Bohrium	Bh
108	Hassium	Hs
109	Meitnerium	Mt
110	Darmstadtium	Ds
111	Roentgenium	Rg
112	Copernicium	Cn
113	Nihonium	Nh
114	Flerovium	Fl
115	Moscovium	Mc
116	Livermorium	Lv
117	Tennessine	Ts
118	Oganesson	Og

New experimental techniques and apparatus have been developed for scientists to extend the periodic table to even more massive elements. A more efficient particle separator uses magnetic fields to separate atoms based on their mass and charge. This equipment can detect nuclides with low production rates and extremely short half-lives. The present limits for discovering new elements are based on the low production rates and short half-lives. The hope is that new development in detection equipment will increase the sensitivity for detecting fewer atoms (or even a single atom) with very short half-lives.

As can be seen from the prior discussion, a variety of techniques have been used to synthesize new chemical elements. Modern "nuclear alchemists" working on the synthesis of superheavy elements "transmute" one element into another by using particle accelerators to smash one element into another. The currently preferred method of producing new elements is fusion-evaporation reactions. This process uses the fusion of two nuclei to form a compound nucleus which then emits few or several neutrons and produces the brand new element.

It has been possible to study the chemical properties on the macroscopic scale for elements as massive as einsteinium (99) and on the tracer scale for elements as massive as seaborgium (106). The elements beyond the actinides in the Periodic Table are termed the "transactinides" and are shown in a Modern Periodic Table, Fig. 8-1, in their expected places. The yields of the most massive elements produced in bombardments of target nuclei with "heavy" ions become extremely small with increasing atomic number, dropping to as little as one atom per week of bombardment for elements as massive as atomic number 112. The production of one isotope of element 113 with cold fusion reactions was at a production rate of about one atom per half-year. The half-lives decrease into the millisecond and the microsecond range so that identification of the new nuclei becomes increasingly difficult. Their half-lives would be impossibly short were it not for the presence of closed shells of nucleons to increase the nuclear stability.

Table 8-2. Summary of the reactions and methods used in the discovery of the actinide and transactinide elements. See Chapter 7 for an explanation of the reaction notation.

Element	Production Reaction(s)[1]	Method of Discovery	Year
neptunium (Np)	$^{238}U(n,\beta^-)^{239}Np$	Chemical Separation	1940
plutonium (Pu)	$^{238}U(^{2}H,2n)^{238}Np$ $^{238}Np(\beta^-)^{238}Pu$	Chemical Separation	1941
curium (Cm)	$^{239}Pu(^{4}He,n)^{242}Cm$	Chemical Separation	1944
americium (Am)	$^{239}Pu(n,\gamma)^{240}Pu$ $^{240}Pu(n,\gamma)^{241}Pu$ $^{241}Pu(\beta^-)^{241}Am$	Chemical Separation	1945
berkelium (Bk)	$^{241}Am(^{4}He,2n)^{243}Bk$	Chemical Separation	1949
californium (Cf)	$^{242}Cm(^{4}He,n)^{245}Cf$	Chemical Separation	1950
einsteinium (Es)	$^{238}U(15n,7\beta^-)^{253}Es$	Chemical Separation[2]	1952
fermium (Fm)	$^{238}U(17n,8\beta^-)^{255}Fm$	Chemical Separation[2]	1953
mendelevium (Md)	$^{253}Es(^{4}He,n)^{256}Md$	Recoil Method, Chemical Separation	1955
nobelium (No)	$^{246}Cm(^{12}C,4n)^{254}No$	Recoil Method, Chemical Separation	1958
lawrencium (Lr)	$^{249/250/251/252}Cf(^{10/11}B,xn)^{258}Lr$	Direct α Counting[3]	1961
rutherfordium (Rf)	$^{249}Cf(^{12}C,4n)^{257}Rf$ $^{249}Cf(^{13}C,3n)^{259}Rf$	Parent-Daughter α Correlation	1969
dubnium (Db)	$^{249}Cf(^{15}N,4n)^{260}Db$	Parent-Daughter α Correlation	1970
seaborgium (Sg)	$^{249}Cf(^{18}O,4n)^{263}Sg$	Parent-Daughter- Granddaughter α Correlation	1974
bohrium (Bh)	$^{209}Bi(^{54}Cr,n)^{262}Bh$	Velocity Separator[4]	1981
hassium (Hs)	$^{208}Pb(^{58}Fe,n)^{265}Hs$	Velocity Separator[4]	1984
meitnerium (Mt)	$^{209}Bi(^{58}Fe,n)^{266}Mt$	Velocity Separator[4]	1982
darmstadtium (Ds)	$^{209}Bi(^{59}Co,n)^{267}Ds$ $^{208}Pb(^{62,64}Ni,n)^{269,271}Ds$ $^{244}Pu(^{34}S,5n)^{273}Ds$	Mass Separator Velocity Separator[4,5] Recoil Separator	1991 1994 1995
Roentgenium (Rg)	$^{209}Bi(^{64}Ni,n)^{272}Rg$	Velocity Separator[4]	1994
Copernicium (Cn)	$^{208}Pb(^{70}Zn,n)^{277}Cn$	Velocity Separator	1996
Nihonium (Nh)	$^{243}Am(^{48}Ca,3n)^{288}Mc$ $^{237}Np(^{48}Ca,3n)^{282}Nh$ $^{209}Bi(^{70}Zn,n)^{278}Nh$	Gas-filled Separator[6]	2003
Flerovium (Fl)	$^{244}Pu(^{48}Ca,3n)^{289}Fl$	Gas-filled Separator[7]	1999
Moscovium (Mc)	$^{243}Am(^{48}Ca,3n)^{288}Mc$	Gas-filled Separator[7]	2003
Livermorium (Lv)	$^{248}Cm(^{48}Ca,3n)^{293}Lv$	Gas-filled Separator[7]	2000
Tennessine (Ts)	$^{249}Bk(^{48}Ca,3n)^{294}Ts$	Gas-filled Separator[7]	2010
Oganesson (Og)	$^{249}Cf(^{48}Ca,3n)^{294}Og$	Gas-filled Separator[7]	2002

[1]When more than one reaction is given, it means that a sequence of reactions was necessary to discover the element, or multiple reactions were used to produce different isotopes.
[2]The Es and Fm reactions were not done in a laboratory setting; multiple neutron captures, followed by successive beta decays were the result of a thermonuclear explosion.
[3]A mixture of four Cf isotopes was bombarded simultaneously with a beam containing ^{10}B and ^{11}B. The symbol "xn" means that different numbers of neutrons were emitted, depending on the actual combination of target and beam used to produce Lr.
[4]A velocity separator is used to separate reaction products based on the fact that reaction products of different masses will be emitted with different velocities.
[5]At GSI two different reactions were used to produce two different isotopes of element Ds.
[6]Nh was first produced with the ^{48}Ca + ^{243}Am reaction as a decay product of element 115, and then also with the ^{70}Zn reaction over the course of many years of beam time.
[7]Production of these elements was by a variety of cross-bombardment reactions and at various beam energies so excitation functions could be determined. Lighter elements are also decay products of heavier elements.

It has been possible to study the chemical properties of rutherfordium, hahnium and seaborgium using the advanced techniques of one-atom-at-a-time chemistry. These experiments show that these properties generally are consistent with those expected on the basis of extrapolation from those of their lower-mass *homologues* in the Periodic Table, hafnium, tantalum, and tungsten. Recent studies have shown that the properties of bohrium (107) and hassium (108) are the homologues of rhenium and osmium. Some initial chemical studies of Cn (Z = 112) and Fl (Z = 114) have been performed which indicate that Cn is likely a homologue of Hg. So far the studies have been inconclusive on Fl. However, the chemical properties cannot be determined reliably in detail from trends exhibited by the lighter homologues, because of the important role played by relativistic effects (the fact that some electrons are moving at velocities near the speed of light) in these more massive elements. Elements higher than hassium are placed in their expected place in the Periodic Table.

Just how many elements are there? Eventually, it will not be possible to add another proton to the nucleus even with the addition of many neutrons The repulsion of the protons will be so high, that no number of neutrons could keep the nucleus together. Because of the complex interplay between the nucleons, via the short-range attractive strong nuclear force and the longer range repulsive Coulomb force, forces that are poorly understood, it is extremely difficult to predict at what proton number the nucleus will rapidly fall apart. Additionally, as the nucleus becomes more massive, the orbiting electrons become more relatavistic, and at some point the innermost electrons will actually spend the majority of the time inside the nucleus. This will increase the probability of "forced" beta-decay, where a proton is converted into a neutron, and will also preclude any increase in the number of protons in the nucleus. This effect has been estimated with the best relatavistic calculations, by P. Pyykkö, to occur at Z = 172, and the resultant periodic table is shown in Fig. 8-6. It is exciting to consider that perhaps a third of the elements in the periodic table have yet to be discovered.

Periodic Table 1-172

Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Orbitals
1	1 H																	2 He	1s
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne	2s2p
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar	3s3p
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr	4s3d4p
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe	5s4d5p
6	55 Cs	56 Ba	57-71	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn	6s5d6p
7	87 Fr	88 Ra	89-103	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113	114	115	116	117	118	7s6d7p
8	119	120	121-	156	157	158	159	160	161	162	163	164	139	140	169	170	171	172	8s7d8p
9	165	166											167	168					9s9p

6	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	4f
7	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	5f
8	141	142	143	144	145	146	147	148	149	150	151	152	153	154	155	6f

8	121	122	123	124	125	126	127	128	129	130	131	132	133	134	135	136	137	138	5g

Figure 8-6. Periodic table extrapolated to element 172 using the best relatavistic calculations to predict chemical behavior beyond the known 118 elements.

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Chapter 9 Phases of Nuclear Matter

As we know, water (H_2O) can exist as ice, liquid, or steam. At atmospheric pressure and at temperatures below the 0˚C freezing point, water takes the form of ice. Between 0˚C and 100˚C at atmospheric pressure, water is a liquid. Above the boiling point of 100˚C at atmospheric pressure, water becomes the gas that we call steam. We also know that we can raise the temperature of water by heating it— that is to say by adding energy.

However, when water reaches its melting or boiling points, additional heating does not immediately lead to a temperature increase. Instead, we must overcome water's latent heats of fusion (80 kcal/kg, at the melting point) or vaporization (540 kcal/kg, at the boiling point). During the boiling process, as we add more heat more of the liquid water turns into steam. Even though heat is being added, the temperature stays at 100˚C. As long as some liquid water remains, the gas and liquid phases coexist at 100˚C. The temperature cannot rise until all of the liquid is converted to steam. This type of transition between two phases with latent heat and phase coexistence is called a “first order phase transition.”

As we raise the pressure, the boiling temperature of water increases until it reaches a critical point at a pressure 218 times atmospheric pressure (22.1 Mpa) and a temperature of 374˚C is reached. There the phase coexistence stops and the phase transition becomes continuous or “second order.” We can make a diagram, Fig. 9-1 that shows the states of water depending on pressure and temperature.

This diagram indicates that even at temperatures below 0 C, as the pressure increases, ice can turn into water. The diagram can be used to predict the state of H_2O at any temperature and pressure. We call the mathematical relations inferred by the chart the “equation of state” of water.

Just as the state of a collection of atoms or molecules depends on temperature and pressure, we find that the state of a nucleus depends on temperature and on the density of the nucleons. Thus we may ask what is the equation of state for nuclear matter? In their normal states of lowest energy, nuclei show liquid-like characteristics and have a density of 0.17 nucleons/fm^3. In more conventional units, this corresponds to 2.7×10^{17}kg/m^3, or 270 trillion times the density of liquid water.

In a laboratory, the only possible way to heat nuclei to significant temperatures is by colliding them with other nuclei. The temperatures reached during these collisions are astounding. In atomic physics, the electron volt (1.6×10^{-19}joules) is used as a convenient unit because it is roughly the energy scale of atomic and chemical processes. Similarly, nuclear scientists use millions of electron volts or MeV (1.6×10^{-13}joules) as a convenient energy unit because it is roughly the energy scale of nuclear processes. An average energy of 1 MeV corresponds to a temperature of 1.2×10^{10}K. The temperatures we can reach in nuclear collisions range up to 100 MeV and above— more than 200 million times the temperature at the surface of the Sun (~5,500 K)!

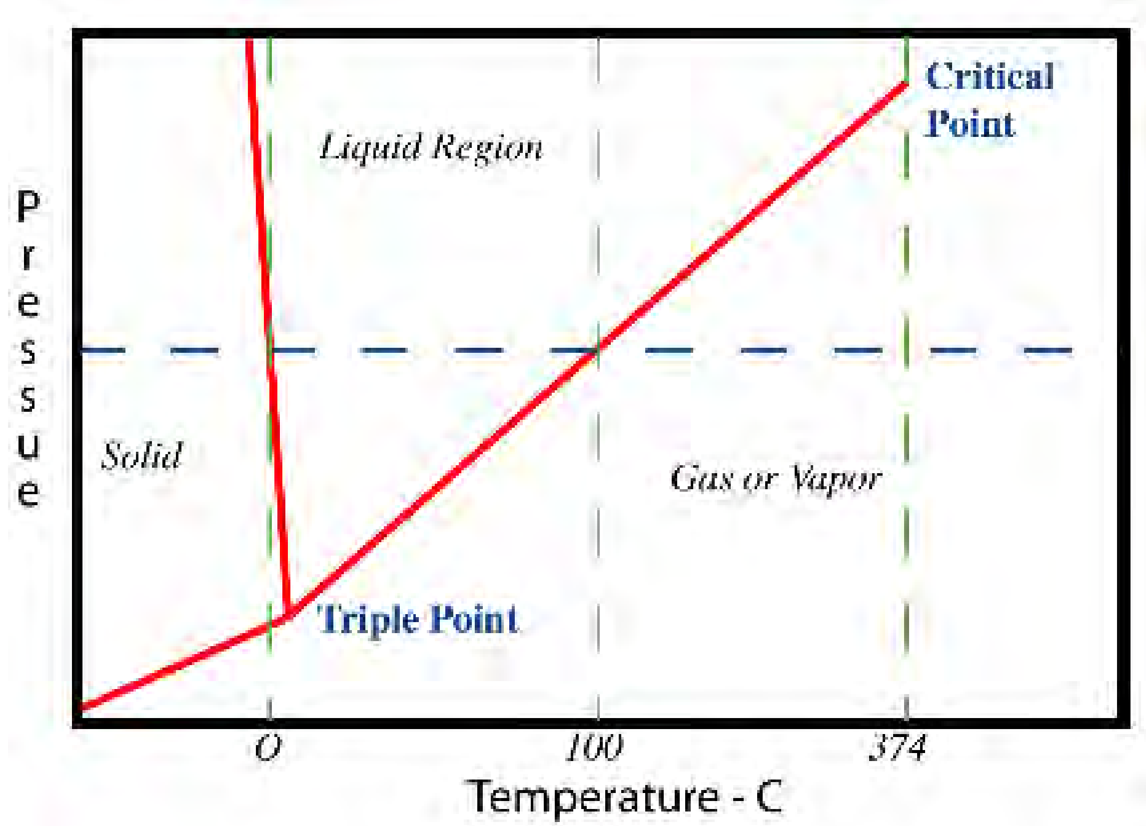

Fig. 9-1. The Phase Diagram for "water." The location of the "Triple Point" is displaced to the right to make it visible. The triple point of water is at a temperature of 0.0098 C and a pressure of 4.579 mm of mercury. The dashed horizontal line is at one atmosphere.

If we heat a nucleus to a temperature of a few MeV, some of its nuclear "liquid" will evaporate. From knowing the general form of the interactions between nucleons, we know that, just like water, the nuclear liquid also has a latent heat of vaporization, and that nuclei should undergo a first-order phase transition. This liquid-gas coexistence is also expected to terminate at a critical point, the critical point of nuclear matter. One of the major thrusts of heavy ion research at laboratories such as Michigan State University's National Superconducting Cyclotron Laboratory is to find out if these theoretical expectations are correct. Experiments try to determine at what temperature and density the critical point of nuclear matter is located.

Nuclear physicists face major challenges in their efforts to explore the nuclear equation of state and these nuclear phase transitions. We can only establish the hot and dense conditions needed for this process during heavy ion collisions. Thus we do not have the luxury of carefully preparing our sample at a given pressure, temperature and density, as is done when studying the phase diagram of water. Instead, we have only a time interval of about 10^{-21} seconds during which to conduct our experiment. To complicate things further, our sample does not stay at a given density and temperature, but rapidly expands and cools during our experiment. We also do not have any direct way of measuring the state variables (temperature, pressure, and density). We need to determine them from observables such as:

1. the abundance of isotopes,
2. the population of excited nuclear states,
3. the shapes of the energy spectra from nuclear collision remnants,
4. the production of particles such as pions.

It is also not obvious that thermal equilibrium can be established during these short time scales. Finally, there is the problem of finite particle number. When studying the phases of water, the sample usually contains very large numbers of molecules. This, again, is a luxury not enjoyed in heavy ion collisions, where the number of nucleons is at best only a few hundred. We then have to establish what signatures of a phase transition remain when so few elementary constituents are present.

Despite these challenges, progress in this field has been significant. We now have deep insights into how the thermodynamic state variables can be measured during heavy ion collisions. We are confident that thermal equilibrium can be established, have found evidence for phase coexistence, and we are beginning to pin down the critical point of the nuclear liquid-vapor phase diagram. Information about the size of fragments produced when nuclear matter is near its critical point gives essential information about the nuclear equation of state. Recent experiments on nuclear breakup are leading to improved understanding of this important question.

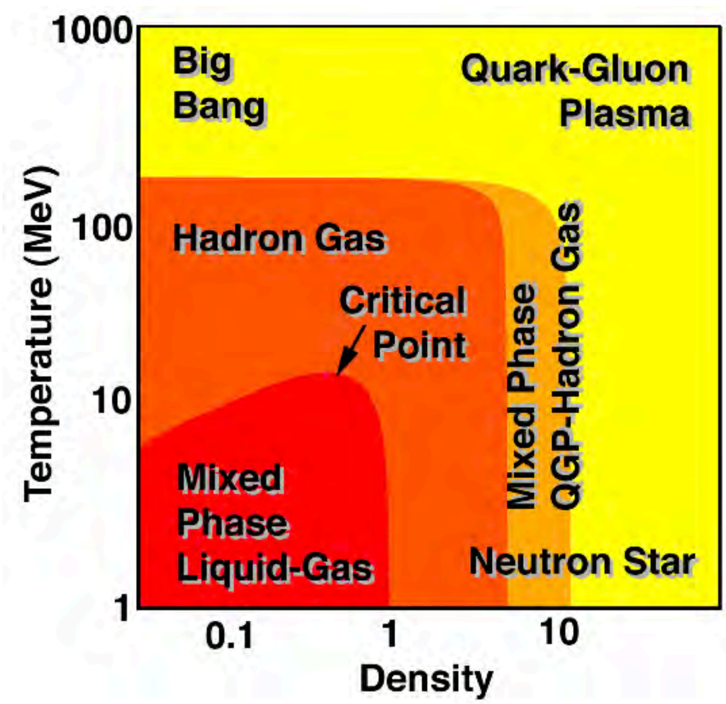

Fig. 9-2. The phase diagram for nuclear matter, as predicted theoretically. The horizontal axis shows the matter density, and the vertical axis shows the temperature. Both axes are shown in logarithmic scale, and the density is given in multiples of normal nuclear matter density. Please note that the temperature axis is the vertical one, as opposed to Fig. 9-1.

The yellow part of Figure 9-2 shows that the phase transition between the nuclear liquid and a gas of nucleons is not the only phase transition that heavy ion scientists are studying. At even higher temperatures and densities, the nucleons themselves can undergo a phase transition.

We can view each nucleon as a "bag" containing quarks and gluons. These can move relatively freely inside their own bag, but the theory says that they cannot escape from the bag— they are "confined." For this reason, we have never been able to detect individual free quarks or gluons. However, if we are able to produce an extremely dense gas of hadrons (mainly pions and nucleons), then their bags can overlap. This overlap lets the quarks and gluons from different bags mix freely and travel across the entire nuclear volume. We call this state a "quark-gluon plasma," in analogy with an atomic plasma in which electrons become unbound from atoms. From theoretical calculations, we also expect the phase transition to a quark-gluon plasma to be of first order, with a phase coexistence region.

Major research efforts at BNL (Brookhaven National Laboratory) in New York and at CERN (Conseil Europeen pour la Recherché Nucleaire) in Switzerland are directed toward establishing the conditions for creating this phase transition and observing its signatures. The Relativistic Heavy Ion Collider (RHIC), which began operation in the year 2000, has as its main mission the study of this exotic and unique phase transition in the nuclear equation of state. It accelerates two counter-circulating beams of gold nuclei, each at speeds extremely close to the speed of light. The machine then steers the gold nuclei so that they collide inside the experimental detectors.

All of the theoretical and experimental challenges described above are also present when studying the transition to the quark-gluon plasma. In addition, there is another, possibly even more severe obstacle to overcome— the quark-gluon plasma cannot survive longer than a few times 10^{-22} seconds. After that, the density and temperature reached during a heavy ion collision fall to values that force quarks and gluons to recombine into hadrons (strongly interaction particles, particularly p mesons) again. The number of hadrons produced in relativistic heavy ion collisions is staggering. For every nucleon that was initially contained in the two colliding gold nuclei, there can be more than 50 pions produced during each RHIC collision. This amounts to several thousands of hadrons emerging from each relativistic heavy ion collision, as shown in Fig. 9-4. The essential problem for the nuclear scientist is then to distinguish between those hadrons that were created from the ashes of the quark-gluon plasma and those that might be created in a dense gas composed only of hadrons.

Figure 9-4 shows a single collision of one of the new detectors (STAR) at RHIC. Each line represents a particle that is tracked and measured in the magnetic field of the detector, with the colors indicating different particle momenta. The detector measures the thousands of particles produced by the collision. Analysis of these data is like an attempt to "put Humpty-Dumpty together again"— to see if the collision showed any evidence that a quark-gluon plasma had been formed. Message carried by energetic particles produced in the early stages of the collision and by later particles produced in the evolving fireball must be carefully interpreted to understand the physics of the collision process.

What is the purpose of studying the nuclear matter phase diagram? The answer is that we need this information to understand the early history of our universe, and to understand high-density objects, called "neutron stars" in our present-day universe.

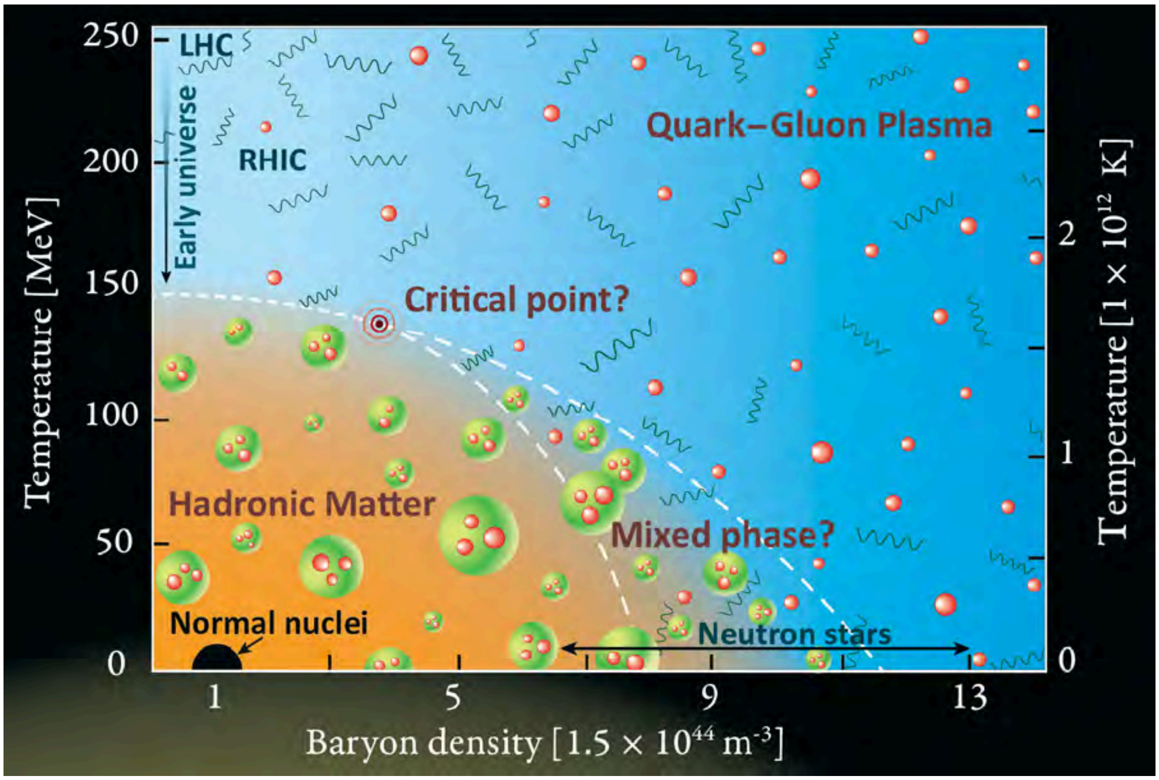

Fig. 9-3. This is a similar phase diagram as drawn in Fig. 9-2. A representation of the quarks is shown in the hadron gas area. The mixed phased region shows the existence of both hadrons and quarks and gluons. The quark-gluon plasma region shows the existence of quarks and gluons.

In the upper left corner of Figs. 9-2 and 9-3 is a region labeled "Early Universe". In the first microsecond after the Big Bang, the entire universe should have been in the state indicated there. Heavy ion collisions at Brookhaven National Laboratory at the RHIC facility, which recently began operation, and at the Large Hadron Collider (LHC) facility currently being constructed at CERN in Geneva, Switzerland will create dense matter and antimatter in about equal quantities. These accelerators can produce conditions similar to those of our early universe.

Figures 9-2 and 9-3 also show a region labeled "neutron star". When a massive star undergoes a supernova explosion, a core of iron nuclei remains. Gravity brings the nuclei together. The short-range nuclear repulsive force is not strong enough to keep the nuclei apart. As the core collapses, the individual nucleons separate from the nucleus. The protons become neutrons by inverse beta decay. Therefore, the neutron star is very large collection of neutrons, typically a few kilometers in diameter, which is held together by gravity. Some theorists predict that a neutron star of a large enough mass could be of high enough density to produce a quark-gluon plasma. The high-density end of the neutron star region indicates this region.

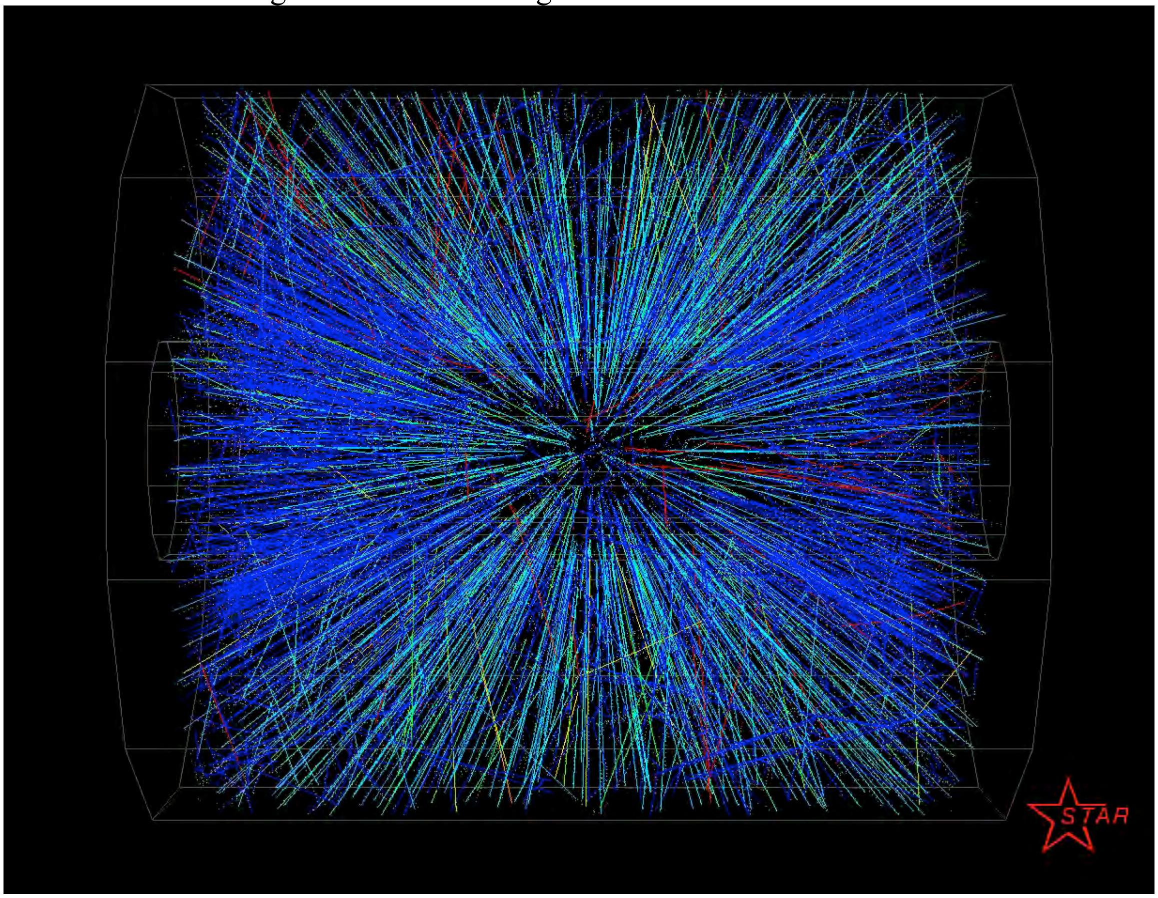

Fig. 9-4. This picture shows a collision between two gold nuclei in the STAR detector at the RHIC accelerator. Each line represents the path of a particle produced in the collision. It is recorded electronically, and the mass and momentum of each particle corresponding to each track is assigned by sophisticated computer software.

Thus, the study of the nuclear equation of state is connected to the initial phases of the early Universe, to ultra-violent stellar explosions, and to experiments around the world. These laboratories bring nuclei, which are traveling almost at the speed of light, into violent collisions to perhaps produce a state of matter in which quarks and gluons, if only briefly, become free particles. Exciting and surprising results have already began to emerge from RHIC. When the higher energy LHC facility comes into operation around 2007, we can expect even more unanticipated discoveries. These accelerators can produce states of matter in the laboratory that have not existed since the first microsecond of the Big Bang.

Web Sites:

RHIC- The Relativistic Heavy Ion Collider
https://www.bnl.gov/rhic/ — From this site you can find information about RHIC and the four experiments that are being done there.

ALICE – A Large Ion Collider Experiment
https://home.cern/about/experiments/alice — ALICE is the only dedicated heavy ion experiment at the LHC facility at CERN. It is scheduled to go into operation around 2007.

Chapter 10 Origin of the Elements

Approximately 73% of the mass of the visible universe is in the form of hydrogen. Helium makes up about 25% of the mass, and everything else represents only 2%. While the abundance of these more massive ("heavy", $A > 4$) elements seems quite low, it is important to remember that most of the matter in our bodies and in the Earth are a part of this small portion of the matter of the universe. The low-mass elements, hydrogen and helium, were produced in the hot, dense conditions of the birth of the universe itself. The birth, life, and death of a star are described in terms of nuclear reactions. The chemical elements that make up the matter we observe throughout the universe were created in these reactions.

Approximately 15 billion years ago the universe began as an extremely hot and dense environment, the Big Bang. Immediately after its formation, it began to expand and cool. The high energy density produced quark-antiquark electron-positron, and other particle-antiparticle pairs. However, as the particles and antiparticles collided with each other, they would annihilate. As the universe expanded, the average energy of the radiation became smaller. Particle creation and annihilation continued until the temperature cooled enough so that pair creation became no longer energetically possible.

One of the signatures of the Big Bang that persists today is the long-wavelength electromagnetic radiation that fills the universe. This is radiation left over from the original fireball. The present temperature of this "background" radiation is 2.7 K. (The temperature, T, of a gas or plasma and average particle kinetic energy, E, are related by the Boltzmann constant, $k = 1.38 \times 10^{-23}$ J/K, in the equation $E = kT$.) Figure 1 shows the temperature at various stages in the time evolution of the universe from the era of the quark-gluon plasma to the present time.

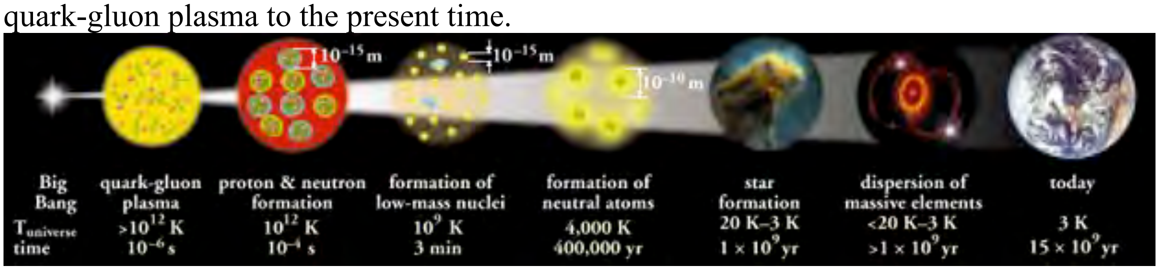

Fig. 10-1. The evolution of the universe

At first quarks and electrons had only a fleeting existence as a plasma because annihilation removed them as fast as they were created. As the universe cooled, the quarks condensed into nucleons. This process was similar to the way steam condenses to liquid droplets as water vapor cools. Further expansion and cooling allowed the neutrons and some of the protons to fuse to helium nuclei. The 73% hydrogen and 25% helium abundances that exists throughout the universe today come from that condensation period during the first three minutes in the history of the universe. The 2% of nuclei more massive than helium present in the universe today were created later in stars.

The nuclear reactions that formed ^{4}He from neutrons and protons were radiative capture reactions. Free neutrons and protons fused to deuterium (d or ^{2}H) with the excess energy emitted as a 2.2 MeV gamma ray,

$$n + p \rightarrow d + \gamma.$$

These deuterons could capture another neutron or free proton to form tritium (^{3}H) or ^{3}He,

$$d + n \rightarrow {}^3H + \gamma \text{ and } \quad d + p \rightarrow {}^3He + \gamma.$$

Finally, ^{4}He was produced by the reactions:

$$d + d \rightarrow {}^4He + \gamma, \qquad {}^3He + n \rightarrow {}^4He + \gamma \qquad \text{and} \qquad {}^3H + p \rightarrow {}^4He + \gamma.$$

Substantial quantities of nuclei more massive than ^{4}He were not made in the Big Bang because the densities and energies of the particles were not great enough to initiate further nuclear reactions.

It took hundreds of thousands of years of further cooling until the average energies of nuclei and electrons were low enough to form electrically neutral hydrogen and helium atoms. After about a billion years, clouds of cold atomic hydrogen and helium gas began to be drawn together under the influence of their mutual gravitational forces. The clouds warmed as they contracted to higher densities. When the temperature of the hydrogen gas reached a few million Kelvin, nuclear reactions began in the cores of these protostars. Now more massive elements began to be formed in the cores of stars.

The Sun

The Sun produces 4×10^{26} joules per second of electromagnetic radiation — a fraction of this energy is intercepted by Earth. The source of this energy is a series of reactions that convert four protons into one helium nucleus plus 26.7 MeV of energy that appears as energy in the reaction products. Since 1 MeV is equivalent to 1.6×10^{-13} J, there must be

$$\frac{4\times10^{26}\ J/s}{\left(267\frac{MeV}{reaction}\right)\times\left(1.6\times10^{13}\frac{J}{MeV}\right)} = 9.4 \times 10^{38} \text{ reactions/s}$$

occurring in the sun to maintain its energy flow. The basic reaction chain (86% of the time) is the fusion sequence:

$$^1H + {}^1H \rightarrow {}^2H + e^+ + n_e,$$
$$^2H + {}^1H \rightarrow {}^3He + \gamma,$$
$$^3He + {}^3He \rightarrow {}^4He + {}^1H + {}^1H.$$

These fusion reactions occur only at the center of the Sun where the high temperature (~10^7 K) gives the hydrogen and helium isotopes enough kinetic energy to overcome the long-range repulsive Coulomb force and come within the short-range of the attractive strong nuclear force. The reaction energy slowly percolates to the surface of the Sun where it is radiated mainly in the visible region of the electromagnetic spectrum (Fig. 10-2). Only the neutrinos escape from the Sun without losing energy.

A detailed mathematical model of the temperature and density profile of the Sun powered by nuclear reactions also serves as a model of other stars. We cannot observe the nuclear reactions directly for confirmation of the nuclear processes. Therefore, astrophysicists look to the neutrinos produced in the fusion of two protons to form deuterium and in the less common (14%) branch of the reaction chain where the fusion of ^{3}He with ^{4}He leads to radioactive isotopes of beryllium and boron that emit neutrinos. For many years, massive underground neutrino detectors observed electron-type neutrinos coming from the Sun, but found fewer neutrinos than expected from the model calculations. One speculation about the missing neutrinos was that they might have converted from neutrinos associated with electrons to those associated with muons or taus as they transit from the interior of the Sun to Earth. Such a conversion could only occur if at least one of the neutrino species has a non-zero mass. The Sudbury Neutrino Observatory, with its sensitivity to all types of neutrinos, has recently demonstrated that this kind of conversion does in fact occur and that two thirds of the neutrinos reaching us from the Sun are actually mu or tau neutrinos. These results also provide a measurement of the difference in masses between the types of neutrinos involved in the conversion process.

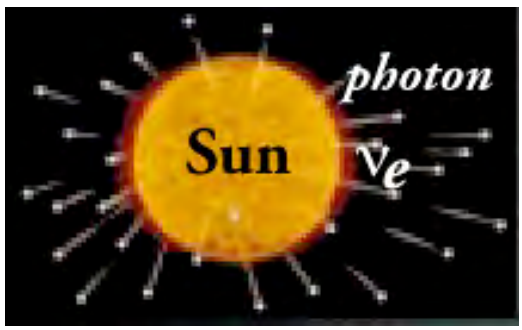

Fig. 10-2. The solar energy reactions emit photons and neutrinos.

Other Stars

A star the size of the Sun will burn hydrogen into helium until the hydrogen in the core is exhausted. At this point, the core of the star contracts and heats up until the fusion of three ^{4}He nuclei into ^{12}C can begin. Stars in this stage of evolution are known as red giants. Low mass stars such as our Sun will then evolve into a compact object called a white dwarf. All nuclear reactions in a white dwarf have stopped. Higher mass stars have internal temperatures (10^{8} K) that allow the fusion of carbon with helium to produce oxygen nuclei and energy. For very massive stars, the exothermic fusion of low-mass nuclei into successively more massive nuclei can proceed all the way up to nuclei in the iron region (A ~ 60). Table 10-1 shows the temperature (1 keV is equivalent to 1.16×10^{7} K), interior density, and process lifetime that occur in stellar evolution of a star 25 times more massive that the Sun. Note the accelerating time-scale as higher mass nuclei are burned.

Once the core of the star is converted into iron-region nuclei, the star has nearly reached the end of its life. Because the average binding energy per nucleon reaches a maximum at this point (see Fig. 2-3), there are no further energy-generating reactions possible and the core of the star collapses because the gravitational force cannot be counter-balanced by the high-temperature, high-pressure interior.

As the collapse of the core occurs, the density grows to the point where it becomes energetically favorable for electrons to be captured by protons via the weak interaction, producing neutrons and neutrinos. This process turns the core of the star into neutrons and produces a huge burst of neutrinos. When the core reaches nuclear density, it rebounds explosively, throwing off much of the mass of the surrounding star. This explosive expansion is called a supernova, one of the most spectacular events in astronomy. If the mass of the remnant core is less than two to three times the mass of the Sun, the core will settle down as a compact neutron star with no further nuclear reactions. More massive cores continue to contract due to the intense gravitational force until the size of the core diminishes to a point — a singularity called a black hole. The object is called "black" because the gravitational force is so strong nothing, not even light, can escape from it.

Table 10-1. The major stages in the evolution of a massive star.

Burning Stage	**Temperature (keV)**	**Density (kg/m^3)**	**Time-scale**
Hydrogen	5	5×10^6	7×10^6 yr
Helium	20	7×10^8	5×10^5 yr
Carbon	80	2×10^{11}	600 yr
Neon	150	4×10^{12}	1 yr
Oxygen	200	10^{13}	6 months
Silicon	350	3×10^{13}	1 day
Collapse	600	3×10^{15}	seconds
Bounce	3000	10^{17}	milliseconds
Explosive	100-600	varies	0.1-10 seconds

In February of 1987 a supernova in a companion to our galaxy, known as the Large Magellenic Cloud, was observed. Underground neutrino detectors saw the neutrinos emitted during the few seconds of the collapse and the birth of either a neutron star or a black hole. The supernova continued to glow for months in the night sky due to the decay of radioactive isotopes that were produced in the explosion. Balloon- and satellite-based detectors observed characteristic nuclear gamma rays from the decays of radioactive Ni and Co isotopes in the supernova debris. Neutron-capture reactions on iron-region nuclei during the few moments of the explosion are believed to have produced nuclei more massive than A = 60. A sequence of neutron capture reactions and beta decays can produce elements all the way up to uranium, and perhaps on further to the region of the superheavy elements.

Books and Articles:

Steven Weinberg, *The First Three Minutes*, Basic Books, New York, 1993.

David Lindley, *The End of Physics,* Basic Books, New York, 1993.

Michael W. Friedlander, *Cosmic Rays,* Harvard University Press, Cambridge, 1989

Nickolas Solomey, *The Elusive Neutrino: A Subatomic Detective Story (Scientific American Library),* W.H. Freeman Co., 1997.

Chapter 11 Accelerators

One of the most important tools of nuclear science is the particle accelerator. Prior to its invention in 1932, the only known sources of particles that could induce nuclear reactions were the natural alpha particle emitters, for example radium. In fact, the only type of nuclear reaction known during that period was that of an alpha particle interacting with a nucleus and producing a proton. Today the use of natural alpha emitters to induce nuclear reactions is largely of historical interest because accelerators produce higher intensities and higher energies of not only alpha particles, but of most elements between hydrogen and uranium.

Cockroft-Walton

Common to all accelerators is the use of electric fields for the acceleration of charged particles; however, the manner in which the fields are applied varies widely. The most straightforward type of accelerator results from the application of a potential difference between two terminals. To obtain more than about 200 kV of accelerating voltage, it is necessary to use one or more stages of voltage-doubling circuits. The first such device was built by J. D. Cockcroft and E. T. S. Walton in 1932 and was used for

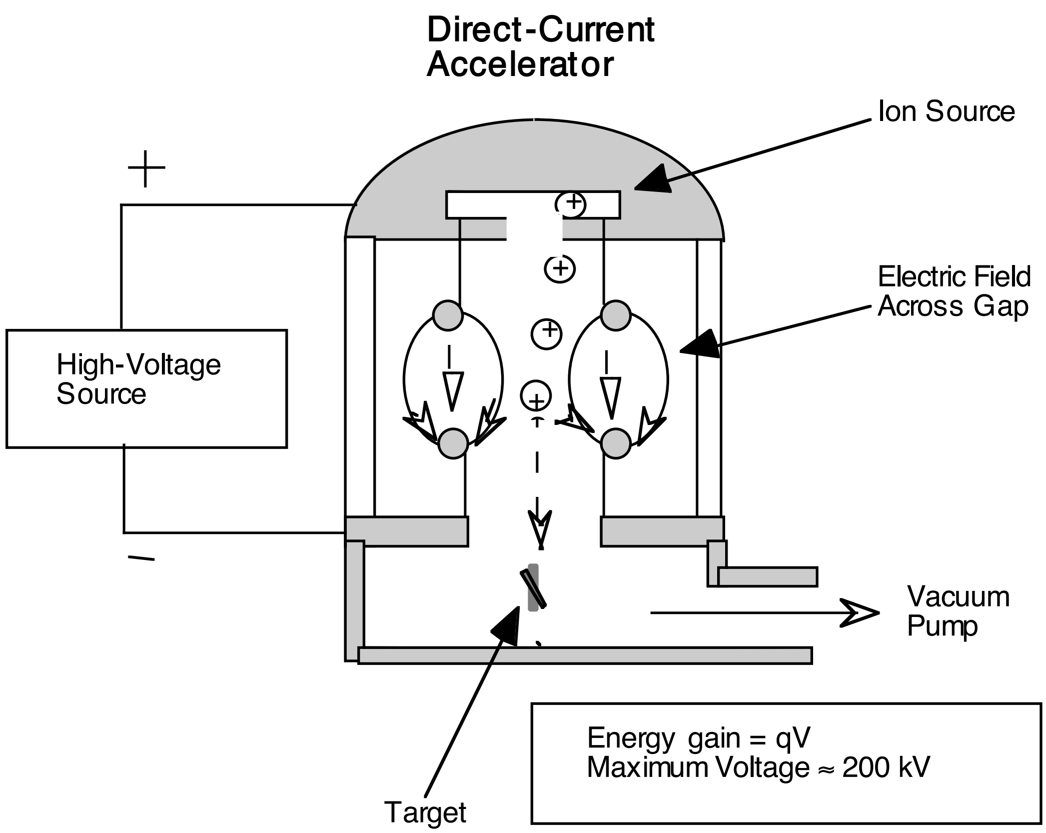

Fig. 11-1. A Cockroft-Walton accelerator. The symbol q in the formula refers to the charge of the particle.

the first transmutation experiments with artificially accelerated particles (protons). Cockcroft-Walton accelerators are still widely used today, sometimes as injectors to much larger accelerators.

Van de Graaff

Beginning in 1929, R. J. Van de Graaff pioneered the Van de Graaff accelerator, in which a high potential difference is built up and maintained on a smooth conducting surface by the continuous transfer of positive static charges from a moving belt to the surface. When used as a particle accelerator, an ion source is located inside the high-voltage terminal. Ions are accelerated from the source to the target by the electric voltage between the high-voltage supply and ground.

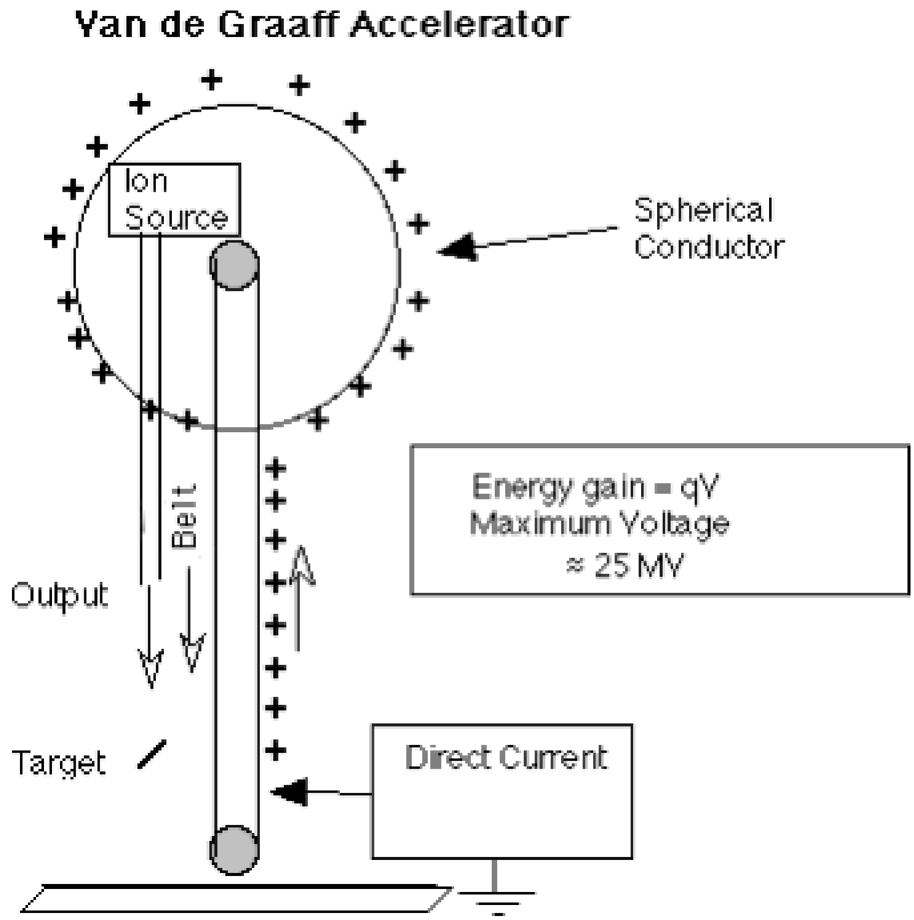

Fig. 11-2. A Van de Graaff accelerator.

The maximum energy obtainable from an electrostatic accelerator such as the Van de Graaff can be greatly increased by the application of the "tandem" principle. In a tandem Van de Graaff accelerator, first built in the 1950s, negative ions are first accelerated towards a positive high-voltage terminal in the center of a pressure tank. Inside the terminal the negative ions, which now have an energy in MeV equal to the terminal potential difference in megavolts (10^6 V) times the charge of the ion, pass through either a foil or gas "stripper" and are stripped of electrons, producing a positive-ion beam. This beam is then accelerated a second time away from the high-voltage terminal. Many tandem Van de Graaff accelerators are in operation throughout the world, including the 25-MV Holifield facility at Oak Ridge National Laboratory in Tennessee.

The limitation of these types of accelerators arises from the maximum practical potential difference that can be held by the charged surfaces. An additional problem in the tandem accelerator is the need to start with negative ions, which can be hard or impossible to obtain for some elements. Positive ion sources are available for a wider variety of elemental species. Positive ion sources can also produce ions of charge higher than one, which is all that is obtainable in negative ion sources.

Linear

The radio frequency (RF) linear accelerator avoids these problems by the repeated acceleration of ions through relatively small potential differences. In a linear accelerator, an ion is injected into an accelerating tube containing a number of electrodes. A high-frequency alternating voltage from an oscillator is applied between groups of electrodes. An ion traveling down the tube will be accelerated in the gap between the electrodes if the voltage is in the proper phase. The distance between electrodes increases along the length of the tube so that the particle stays in phase with the voltage.

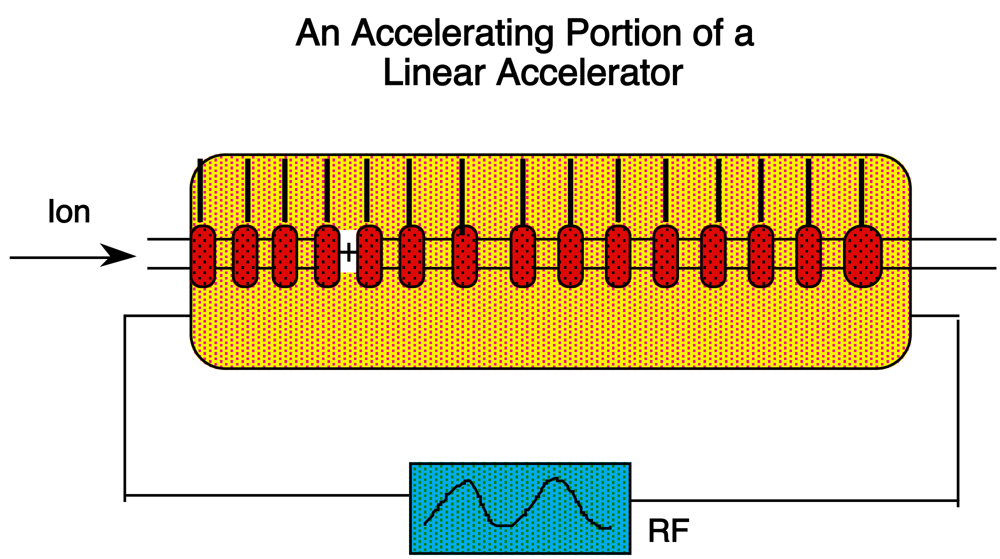

Fig. 11-3. Side view of a linear accelerator. (This figure does not show the increasing spacing between cavities as discussed in the text.)

R. Wideroe built the first linear accelerator in 1928. This device produced positive ions with energy of about 50 keV. Intensive work on linear accelerators was carried out in many laboratories in the early 1930s. The linear accelerator did not receive much further attention until after World War II, when the availability of high-power microwave oscillators made possible acceleration to high energies in relatively small linear accelerators. Since that time, a sizable number of linear accelerators, also called linacs, have come into operation, both for electron and proton acceleration, as well as several heavy-ion linacs. SLAC, a 3-km electron linac at Stanford University, is the longest linac presently operating. It accelerates electrons and positrons to energies of 50 GeV.

Cyclotron

The best known and one of the most successful devices for acceleration of ions to millions of electron volts is the cyclotron, which was invented by E. O. Lawrence in 1929. The first working model produced 80-keV protons in 1930. A cyclotron, as well as a linac, uses multiple acceleration by a radio frequency electrical field. However, the ions in a cyclotron are constrained by a magnetic field to move in a spiral path. The ions are injected at the center of the magnet between two semicircular electrodes called “Dees”. As the particle spirals outward it gets accelerated each time it crosses the gap between the Dees. The time it takes a particle to complete an orbit is constant, since the distance it travels increases at the same rate as its velocity, allowing it to stay in phase with the RF. As relativistic energies are approached, this condition breaks down, limiting cyclotrons in energy. However, cyclotrons are still in use all over the world for nuclear science studies, radioisotope production, and medical therapy.

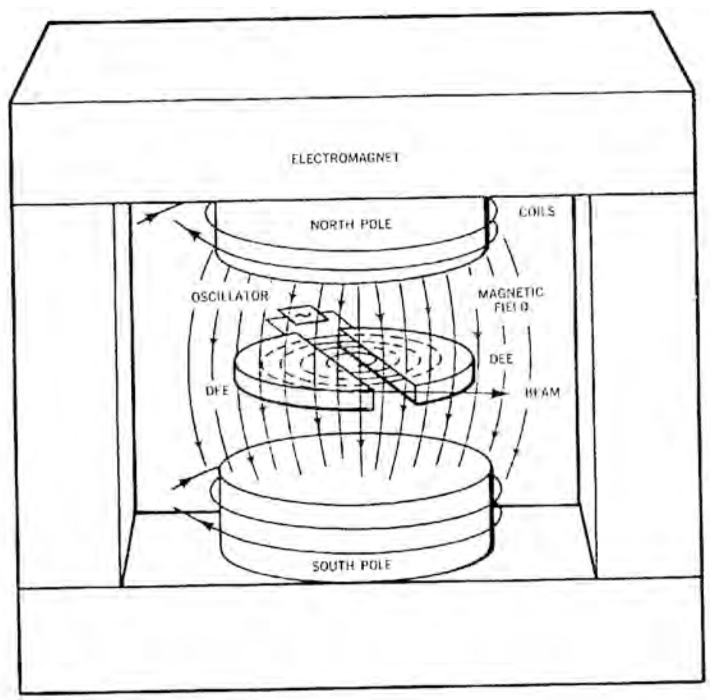

Fig. 11-4. A schematic of a cyclotron.

Synchrotron

The synchrotron was developed to overcome the energy limitations of cyclotrons imposed by special relativity. In a synchrotron, the radius of the orbit is kept constant by a magnetic field that increases with time as the momentum of a particle increases. The acceleration is provided, as in a cyclotron, by a RF oscillator that supplies an energy increment every time a particle crosses an accelerating gap. The Relativistic Heavy Ion

Collider (RHIC), which is located at Brookhaven National Laboratory in New York, collides two beams of ions ranging from protons to gold at energies up to 100 GeV per nucleon. Nuclear scientists expect that such collisions will create nuclear temperatures and densities high enough to reach the quark-gluon plasma phase of nuclear matter.

Continuous Electron Beam

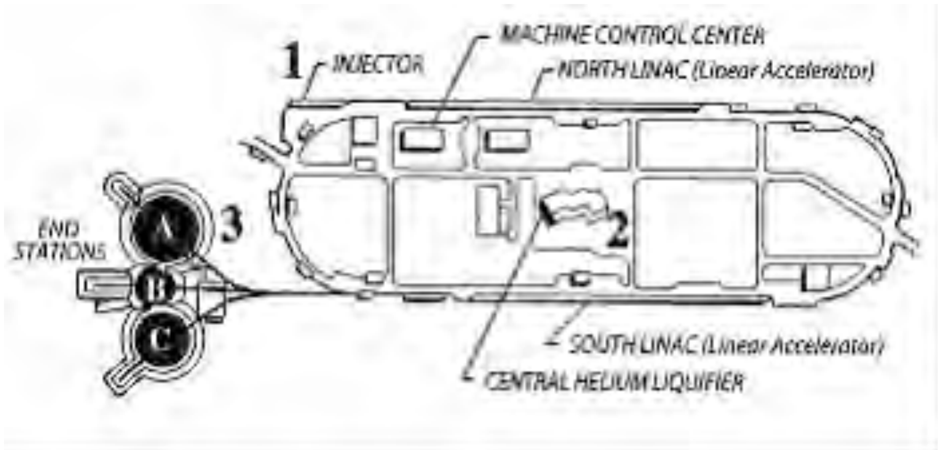

Fig. 11-5. The electron accelerator at Thomas Jefferson Laboratory.

The Thomas Jefferson National Accelerator Facility in Newport News, Virginia is an electron accelerator. A diagram of this machine is shown in Fig. 11-5. At this accelerator, an electron beam travels through several linacs. The accelerator uses superconducting radio-frequency technology to drive electrons to higher and higher energies with a minimum of electrical power. This accelerator produces a continuous electron beam to ensure that each electron interaction with a nucleus is separated enough in time so that the whole reaction can be measured.

Web Sites:

RHIC- The Relativistic Heavy Ion Collider
https://www.bnl.gov/rhic/ — From this site you can find information about RHIC and the four experiments that are being done there.

Jefferson Lab
https://www.jlab.org/ —Jefferson Lab is a basic research laboratory built to probe the nucleus of the atom to learn more about the quark structure of matter.

DOE Nuclear Physics
https://science.energy.gov/np/ —This page provides links to the Department of Energy's Nuclear Physics facilities.

Chapter 12 Tools of Nuclear Science

Presently, the most commonly used tools of nuclear science are accelerators (see Chapter 11), reactors, detectors, and computers. The technological development of these devices has gone hand in hand with advances in nuclear science, sometimes leading and sometimes following closely behind.

Nuclear Reactors

Nuclear reactors created not only large amounts of plutonium needed for the weapons programs, but a variety of other interesting and useful radioisotopes. They produced ^{60}Co, in which the non-conservation of parity was first discovered, and a number of transuranic isotopes that are used to study the limits of the periodic table. Reactors also produce isotopes for commercial and medical purposes:

1. ^{241}Am—used in smoke detectors,
2. ^{60}Co—used in industry to inspect weld quality, also used in cancer therapy,
3. ^{99m}Tc—used for medical diagnosis, and
4. ^{137}Cs—also used for medical therapy.

Reactor neutrons have been used for material studies that involve their scattering from the crystal planes.

Detectors

The interactions of alpha, beta, and gamma radiations with matter produce positively charged ions and electrons. Radiation detectors are devices that measure this ionization and produce an observable output. Early detectors used photographic plates to detect "tracks" left by nuclear interactions. The cloud chambers, used to discover sub-nuclear particles, needed photographic recording and a tedious measurement of tracks from the photographs. Advances in electronics, particularly the invention of the transistor, allowed the development of electronic detectors. Scintillator-type detectors use vacuum tubes to perform the initial conversion of light to electrical pulses. The amplification and storing these data follow the advances in transistor electronics. Miniaturization in electronics has revitalized types of gas-filled detectors. These detectors were developed as "single element" detectors and now have been revived into "multiple element" detectors with more than one thousand elements. Advances in materials, particularly ultra-pure materials, and methods of fabrication have been critical to the creation of new and better detectors.

As the requirements for greater accuracy, efficiency, or sensitivity increases, so does the complexity of the detector and its operation. The following list presents some types of commonly used detectors and includes comments on each of them:

Geiger Counter: The detector most common to the public is the Geiger-Mueller counter, commonly called the Geiger counter. It uses a gas-filled tube with a central wire at high voltage to collect the ionization produced by incident radiation. It can detect alpha, beta, and gamma radiation although it cannot distinguish between them. Because of this and other limitations, it is best used for demonstrations or for radiation environments where only a rough estimate of the amount of radioactivity is needed.

Scintillation detectors: Scintillators are usually solids (although liquids or gases can be used) that give off light when radiation interacts with them. The light is converted to electrical pulses that are processed by electronics and computers. Examples are sodium iodide (NaI) and bismuth germanate (BGO). These materials are used for radiation monitoring, in research, and in medical imaging equipment.

Solid state X-ray and gamma-ray detectors: Silicon and germanium detectors, cooled to temperatures slightly above that of liquid nitrogen (77 K), are used for precise measurements of X-ray and gamma-ray energies and intensities. Silicon detectors are good for X-rays up to about 20 keV in energy. Germanium detectors can be used to measure energy over the range of >10 keV to a few MeV. Such detectors have applications in environmental radiation and trace element measurements. Germanium gamma ray detectors play the central role in nuclear high-spin physics, where gamma rays are used to measure the rotation of nuclei. Large gamma-ray detection systems, such as Gammasphere and Eurogam are made of these detectors.

Low-energy charged particle detectors: Silicon detectors, normally operated at room temperature, play a major role in the detection of low-energy charged particles. Singly, they can determine the energy of incident particles. Telescopes (combinations of two or more Si detectors) can be used to determine the charge (Z) and mass (A) of the particle. This type of detector is used in environmental applications to look for alpha-particle emitters (such as radium) in the environment.

Neutron detectors: Neutrons are much harder to detect because they are not charged. They are detected by nuclear interactions that produce secondary charged particles. For example, boron trifluoride (BF_3) counters make use of the $^{10}B(n,\alpha)^{7}Li$ reaction to detect neutrons. Often one uses a moderator, such as paraffin, to slow the neutrons and thus increase the detection efficiency. These detectors are used to monitor the neutron fluxes in the vicinity of a reactor or accelerator. Liquid scintillators can measure both neutrons and gamma rays. By carefully measuring the shape of the electronic signal, scientists can and distinguish between these two types of particles.

Neutrino Detectors: Neutrinos interact very weakly with matter and are therefore very hard to detect. Thus, neutrino detectors must be very large. The Sudbury Neutrino Observatory in Canada, was developed to understand the solar neutrino problem (too few neutrinos come out of the Sun than expected) and contains an active volume of 1000 tonnes (metric tons) of deuterium oxide (heavy water). This is a Cherenkov counter in which the interaction of the neutrino with the heavy water produces an electron moving faster than the speed of light in the water. The moving electron generates a cone of light that can be observed with photomultiplier tubes. Information from these tubes provide the information to determine the energy and direction of the incident neutrino.

<u>*High-energy charged particle detectors:*</u> As the energy increases, large and even more complex detection systems are needed, some involving thousands of individual detectors. These detectors typically involve the "tracking" of large numbers of particles as they pass through the detector. Large magnets are required to bend the paths of the charged particles. Multi-wire detection systems with nearly a quarter of a million channels of electronics provide information on these tracks. High-speed computer systems process and store the data from these detectors. Similarly, powerful computer systems are needed to analyze these data so that a scientific discovery can be made.

Table 12-1. A partial list of detectors used in Nuclear Science. Some detectors can be used only in a limited energy range.

Particle Type	**Detector Type**	**Features**
Charged		
protons, nuclei, electrons, or pions	Geiger-Müller counters	portable radioactivity detector
	gas ionization counters	gas-filled chamber in an electric field
	multiwire chambers	good position resolution
	semiconductor detectors	good energy resolution
	magnetic spectrometers	good momentum resolution
	scintillators and photomultipliers	good timing resolution
	Cherenkov detectors	good particle identification
Neutral		
photons	scintillators and photomultipliers	good timing, moderate energy resolution
	germanium semiconductor crystals	good energy resolution
neutrons	liquid scintillator or BF_3 tubes	via fission, capture gamma rays, or proton collisions
neutrinos	Cherenkov detectors	via neutrino-electron interactions
	nuclear reactions	detect resultant radiation

Table 12-1 summarizes the information that is presented in this section. It shows the different types of detectors that are suitable for measuring specific particles. When an experiment is designed, first a scientist chooses a particular detector based on the particles and their properties (such as energy, position, or time) that must be measured. Some detectors, such as scintillators, can make accurate time measurements but only a fair position determination. A scientist designs an experiment using an optimum choice of detector system. Cost is a major factor in modern detector design, especially for large systems consisting of a multitude of detectors and associated electronics.

Computers

Beginning in the 1970s, computers played a role in nuclear science that developed from relatively minor to significant. Before this time, computers were used for calculations to develop and refine theories in nuclear science. As computers moved to being interfaced with detectors and accelerators, they became inseparable from the experiment. Indeed, the design of detectors for large experiments includes the integration of computer systems into each detector element. Computers are still used to calculate predictions of experiments based on various theories. Only the most powerful computer systems can generate simulations of the expected data from today's giant experiments. Similarly, only the most powerful computers can process the data that come from these experiments.

Other Sciences and Technologies

While technology has been a driving force for nuclear science research, this field has similarly pushed the limits of technology. Likewise, advances in other scientific disciplines have been important to the progress in nuclear science. Development and advances in chemistry were essential to the discovery of most of the transuranic elements. This technology is still used to separate chemical species and allows studies of nuclei produced in accelerator or reactor experiments. Advances in solid state physics have produced larger and better silicon and germanium detectors for use in x-ray, gamma ray, and particle spectroscopy. Advances in ultralow-temperature physics have produced superconducting magnets. They are used by the Michigan State University Cyclotron, by the superconducting radio frequency acceleration cavities at the Argonne National Laboratory's ATLAS accelerator, at the Jefferson Laboratory, and at the RHIC collider.

Chapter 13 "... but What is it Good for?"

As in other scientific fields, nuclear scientists generally work with a great interest and excitement for the science. Understanding the building blocks of nature and the physical laws that govern them is the ultimate goal. On the other hand, members of the public are the taxpayers who finance most research in basic science and, understandably, often want to see something more concrete emerge from their investments, some further benefit to society. In the century since Rutherford discovered the nucleus, numerous applications take advantage of one or more of the following: 1) the properties of nuclei, 2) measurement techniques developed in nuclear physics, 3) particle accelerators, and 4) other tools of nuclear science such as detectors.

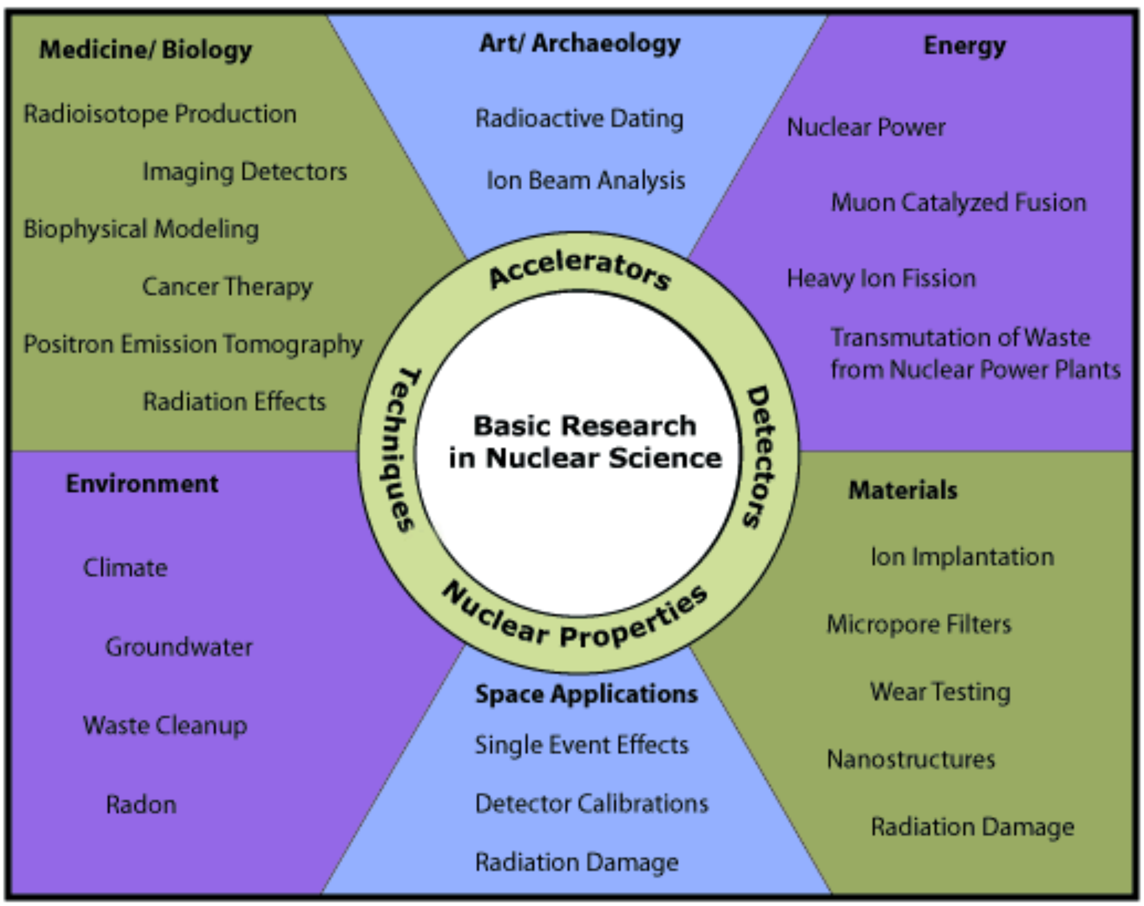

Fig. 13-1. Applications of nuclear science.

These applications benefit disciplines as diverse as medicine, biology, art, archaeology, energy, materials science, space exploration, and the environment. Many of these applications are detailed in Fig. 13-1. Only, a sample of them will be described in this chapter. The energy applications of nuclear science are described separately in Chapter 14.

The following examples are illustrative of the wide variety of applications of nuclear science. While some of these applications are very specific and have little effect on our daily lives, many of these applications are all pervasive. We probably use some electricity generated by nuclear reactors, protect our homes with smoke alarms, and have all been affected by the geopolitics of nuclear weapons.

Smoke Detectors

Most common smoke detectors (Fig. 13-2) contain a small amount of ^{241}Am, a radioactive isotope. ^{241}Am is produced and recovered from nuclear reactors. Alpha particles emitted by the decays of ^{241}Am ionize the air (split the air molecules into electrons and positive ions) and generate a small current of electricity that is measured by a current-sensitive circuit. When smoke enters the detector, ions become attached to the smoke particles, which causes a decrease in the detector current. When this happens, an alarm sounds. These detectors provide warning for people to leave burning homes safely. Many lives have been saved by the their use.


Fig. 13-2. A common smoke detector.

Because the distance alpha particles travel in air is so short, there is no risk of being exposed to radiation by having a smoke detector in the house. Since ionization-type smoke detectors contain radioactive materials, they should be recycled or disposed of as radioactive waste. It is important to follow the instructions that come with the smoke alarm when they need to be discarded.

Nuclear Medicine

Radioisotopes for diagnosis and treatment

One major use of radioisotopes is in nuclear medicine. Of the 30 million people who are hospitalized each year in the United States, 1/3 are treated with nuclear medicine. More than 10 million nuclear-medicine procedures are performed on patients and more than 100 million nuclear-medicine tests are performed each year in the United States alone. A comparable number of such procedures are performed in the rest of the world.

There are nearly one hundred radioisotopes whose beta and/or gamma radiation is used in diagnosis, therapy, or investigations in nuclear medicine. The most used radioisotopes were discovered before World War II using the early cyclotrons of Ernest Lawrence, with the initial applications to medicine being developed by his brother John Lawrence. Some of the most well known radioisotopes, discovered by Glenn Seaborg and his coworkers, are ^{131}I (discovered in 1938), ^{60}Co (1937), ^{99m}Tc (1938), and ^{137}Cs (1941). By 1970, 90 percent of the 8 million administrations per year of radioisotopes in the United States utilized either ^{131}I, ^{60}Co, or ^{99m}Tc. Today, ^{99m}Tc, with a half-life of 6 hours, is the workhorse of nuclear medicine. It accounts for more than 10 million diagnostic procedures a year in the United States. It is used for brain, bone, liver, spleen, kidney, lung and thyroid imaging as well as for blood-flow studies.

^{131}I, with a half-life of 8 days, is used to diagnose and treat thyroid disorders. Seaborg's mother was one of the first to benefit from the use of this radioisotope that her son had discovered. Fatally ill from hyperthyroidism, (a related condition from which her sister died), diagnosis and treatment with ^{131}I led to her complete recovery and a long life. Former President George Bush and First Lady Barbara Bush are some notable people who were successfully treated for Graves' disease, a thyroid disease, with ^{131}I. Radioactive iodine treatment is so successful that it has virtually replaced thyroid surgery.

a) b)

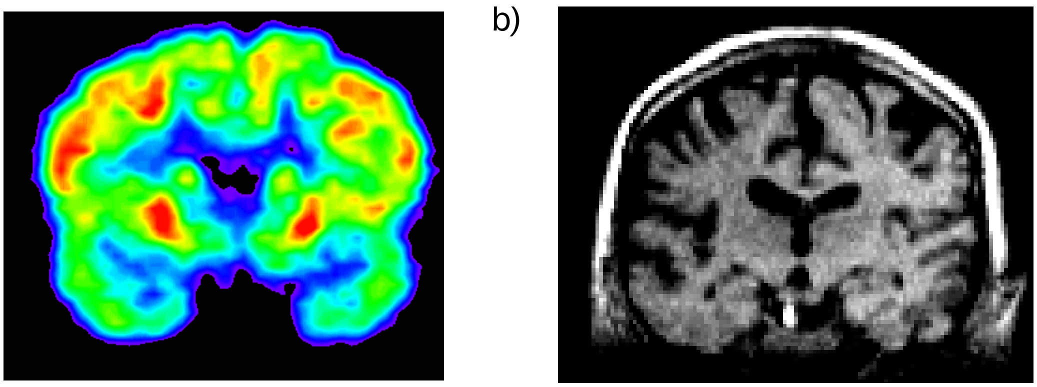

Fig. 13-3. a) PET image of the human brain. b) MRI image of the human brain.

A very effective role for radioisotopes in nuclear medicine is the use of short-lived positron emitters such as ^{11}C, ^{13}N, ^{15}O, or ^{18}F in a process known as Positron Emission Tomography (PET). Incorporated in chemical compounds that selectively migrate to specific organs in the body, diagnosis is effected by detecting annihilation gamma rays—two gamma rays of identical energy emitted when a positron and an electron annihilate each other. These gamma rays have the very useful property that they are emitted in exactly opposite directions. When both are detected, a computer system may be used to reconstruct where the annihilation occurred. By attaching a positron emitter to a protein or a glucose molecule, and allowing the body to metabolize it, we can study the functional aspect of an organ such as the human brain. The PET image shows where the glucose has been absorbed (Fig. 13-3a).

PET imaging becomes even more valuable when we can observe the functional image compared to the anatomical image. Magnetic Resonance Imaging (MRI)—originally known as Nuclear Magnetic Resonance Imaging—can provide very detailed images of the anatomy as shown in the second image shown in Fig. 13-3b. These techniques provide researchers a better understanding of what is healthy tissue versus what is diseased.

Cancer therapy

The radioisotope ^{60}Co emits gamma rays that are used to destroy cancer cells. Hundreds of thousands of Americans who suffer from cancer have been treated in this way. Every year millions of cubic meters of medical products and equipment are sterilized by irradiation worldwide. The isotope ^{137}Cs has found substantial applications as a gamma-ray source in medical therapy, similar in its use to that of ^{60}Co.

Cancer treatment with beams of massive ions directly from an accelerator has gained increasing utilization in the last decade. Unlike gamma rays, which distribute their energy equally in healthy as well as cancerous cells, massive particles such as protons or alpha particles will deposit the bulk of their energy just before they stop. If the energy is well chosen, most of the energy will be dumped into the tumor and not into the surrounding healthy tissue. Using three dimensional water degrader columns, the shape of the tumor can be mapped out and selectively irradiated. Dedicated accelerators are now being built to continue this work at medical centers. In the United States, the Loma Linda Medical Center in California is now operating a proton synchrotron for therapy, and a second facility is being built at Massachusetts General in Boston.

Boron Neutron Capture Therapy (BNCT) is under development for the treatment of glioblastoma multiforma, a brain cancer which afflicts some 12,500 people a year in the US alone and is almost impossible to treat by currently available means. In BNCT, boron is synthesized into compounds that are selectively taken up by cancerous cells in the brain and not by healthy ones. In subsequent irradiation by low-energy neutrons (from a reactor or accelerator), the following neutron-capture reaction occurs:

$$^{10}B + n \rightarrow {}^{11}B \rightarrow {}^{7}Li + {}^{4}He.$$

The recoiling lithium and helium nuclei have short ranges and large energy losses. These particles destroy the cancerous cells and spare the surrounding healthy tissue.

Radioactive Dating

The technique of comparing the abundance ratio of a radioactive isotope to a reference isotope to determine the age of a material is called radioactive dating. Many isotopes have been studied, probing a wide range of time scales.

The isotope ^{14}C, a radioactive form of carbon, is produced in the upper atmosphere by neutrons striking ^{14}N nuclei. The neutron is captured by the ^{14}N nucleus and knocks out a proton. Thus, we have a different element, ^{14}C. The isotope, ^{14}C, is transported as $^{14}CO_2$, absorbed by plants, and eaten by animals. If we were to measure the ratio of ^{14}C to ^{12}C today, we would find a value of about one ^{14}C atom for each one trillion ^{12}C atoms. This ratio is the same for all living things—the same for humans as for trees or algae.

Once living things die, they no longer can exchange carbon with the environment. The isotope ^{14}C is radioactive, and beta-decays with a half-life of 5,730 years. This means that in 5,730 years, only half of the ^{14}C will remain, and after 11,460 years, only one quarter of the ^{14}C remains. Thus, the ratio of ^{14}C to ^{12}C will change from one in one trillion at the time of death to one in two trillion 5,730 years later and one in four trillion 11,460 years later. Very accurate measurements of the amount of ^{14}C remaining, either by observing the beta decay of ^{14}C or by accelerator mass spectroscopy (using a particle accelerator to separate ^{12}C from ^{14}C and counting the amount of each) allows one to date the death of the once-living things.

Perhaps you have heard of Iceman, a man living in the Alps who died and was entombed in glacial ice until recently when the ice moved and melted. The man's body was recovered and pieces of tissue were studied for their ^{14}C content by accelerator mass spectroscopy. The best estimate from this dating technique says the man lived between 3350 and 3300 BC.

The boat of a pharaoh was discovered in a sealed crypt and reassembled in a museum near the pyramids (see Fig. 13-4). Its wood was dated using ^{14}C to be about 4,500 years old.

Fig. 13-4. The pharaoh's funerary boat. © National Geographic Society

Other methods of dating are used for non-living things. ^{40}K decays with a half-life of 1.3×10^9 years to ^{40}Ar, which can be trapped in rocks. A potassium-argon method of dating, developed in 1966, measures the amount of ^{40}Ar arising from the ^{40}K decay and is compared to the amount of ^{40}K remaining in the rock. From the ratio, the time since the formation of the rock can be calculated.

The age of our galaxy and earth also can be estimated using radioactive dating. Using the decays of uranium and thorium, our galaxy has been found to be between 10 and 20 billion years old and the earth has been found to be 4.6 billion years old. The Universe must be older than our galaxy. Within experimental error, this estimate agrees with the 15 billion-year estimate of the age of the Universe.

Neutron Activation Analysis

There are at least 50 elements occurring in nature that have radioactive isotopes with one neutron more than their stable isotopes. This means that the radioactive species can be made by neutron bombardment. This procedure is typically done in a nuclear reactor, although other neutron sources can sometimes be used. The stable nucleus absorbs one neutron and becomes a radioactive nucleus. By detecting the decay of these nuclei, which can be done with great sensitivity, one can measure the concentration of the stable element of interest in the sample.

A simple example of neutron activation analysis involves the measurement of iridium in soils. This is the measurement that led to the theory that the extinction of the dinosaurs, 65 million years ago, was caused by the impact of an asteroid or comet somewhere on Earth. An impact would produce so much debris in the air that earth would receive a large reduction in sunlight and thus fewer plants would grow. With less food available, there would be a devastating reduction in number of animals. This reduction was so severe that most species, including the dinosaurs, became extinct.

In 1979, a group of scientists reported that neutron activation analysis had shown unusual amounts of the element iridium in Italian Cretaceous-Tertiary boundary sediments. Since iridium is a metal, which has very low abundance on earth, they attributed the excess iridium to an impact of a 10-kilometer diameter asteroid. This work, which melded the disciplines of physics (Nobel Laureate Luis Alvarez), geology (his son, Walter Alvarez) and nuclear chemistry (Isadore Perlman, Frank Asaro and Helen Michel), galvanized the scientific world because the concepts presented could be tested by many diverse techniques.

Since the initial report, anomalous amounts of iridium have been found at the Cretaceous-Tertiary boundary in over 100 sites worldwide. Many experiments have confirmed its impact origin.

Industrial Applications

The applications of radioisotopes in industry are numerous. Many types of thickness gauges exploit the fact that gamma rays are attenuated when they pass through material. By measuring the number of gamma rays, the thickness can be determined. This process is used in common industrial applications such as:

1. the automobile industry—to test steel quality in the manufacture of cars and to obtain the proper thickness of tin and aluminum
2. the aircraft industry—to check for flaws in jet engines
3. construction—to gauge the density of road surfaces and subsurfaces
4. pipeline companies—to test the strength of welds
5. oil, gas, and mining companies—to map the contours of test wells and mine bores, and
6. cable manufacturers—to check ski lift cables for cracks.

The isotope ^{241}Am is used in many smoke detectors for homes and businesses (as mentioned previously), in thickness gauges designed to measure and control metal foil thickness during manufacturing processes, to measure levels of toxic lead in dried paint samples, and to help determine where oil wells should be drilled.

The isotope ^{252}Cf (a neutron emitter) is used for neutron activation analysis, to inspect airline luggage for hidden explosives, to gauge the moisture content of soil and other materials, in bore hole logging in geology, and in human cervix-cancer therapy.

In addition, there are manifold uses in agriculture. In plant research, radiation is used to develop new plant types to speed up the process of developing superior agricultural products. Insect control is another important application; pest populations are drastically reduced and, in some cases, eliminated by exposing male insects to sterilizing doses of radiation. Fertilizer consumption has been reduced through research with radioactive tracers. Radiation pellets are used in grain elevators to kill insects and rodents. Irradiation prolongs the shelf life of foods by destroying bacteria, viruses, and molds.

The useful application of radioisotopes extends to the arts and humanities. Neutron activation analysis is extremely useful in identifying the chemical elements present in coins, pottery, and other artifacts from the past. A tiny unnoticeable fleck of paint from an art treasure or a microscopic grain of pottery suffices to reveal its chemical makeup. Thus the works of famous painters can be "fingerprinted" so as to detect the work of forgers.

Neutron scattering has proved to be a valuable tool for studying the molecular structure and motion of molecules of interest to manufacturing and life processes. Accelerators and reactors produce low-speed neutrons with wavelength appropriate to "see" structures of the size of magnetic microstructures and DNA molecules. Neutrons can penetrate deeply into bulk materials and use their magnetic moment or strong interaction forces to preferentially scatter from magnetic domains or hydrogen atoms in long chain nucleosomes. Neutrons are also used in materials surface and interface studies taking advantage of their reflectivity properties. Intense sources of neutrons include: the IPNS at Argonne National Laboratory in Illinois and LANSCE at Los Alamos National Laboratory in New Mexico.

Removal of Land Mines

Wars have been fought around the globe, and land mines were used extensively by the battling parties. There may be up to 100 million abandoned mines just waiting to maim and kill unsuspecting civilians. Techniques similar to airport weapons detectors have been considered for finding and neutralizing these mines without loss of life.

A promising technology involves nuclear quadrupole resonance. Nitrogen, a common component in explosives, has a nucleus with an ellipsoidal shape. Depending on what kind of crystalline structure the nitrogen nuclei find themselves in, their non-sphericity produces a unique set of very narrowly spaced energy levels that is characteristic of the crystalline solid itself. An explosive compound can therefore be identified by the subtle effect of its constituent nitrogen atoms. This technique could also differentiate explosives from scrap metals in the ground. More details may be found in the reference at the end of this chapter.

Radioisotope Power Generation

Long-lived power sources are needed for equipment that is too remote or inaccessible for replacement. By choosing a radioactive element with a long half-life, we can create a long-lived power source. The appropriate element should:

1. produce weakly penetrating radiation that can be easily shielded,
2. a specific power of at least 0.2 kW/kg,
3. have good corrosion resistance,
4. be insoluble in water, and
5. be made of reasonably available material.

Among the transuranium elements, oxides of the alpha-emitting nuclides ^{238}Pu ($t_{1/2}$ = 87.7 years) and ^{244}Cm ($t_{1/2}$ = 18.1 years) are useful fuels. A few grams to kilograms of such nuclides, in appropriately shielded containers, provide intense sources of heat with power levels up to hundreds of watts, since the alpha particles are stopped very easily and their decay energy converted into thermal energy. Using thermoelectric devices without moving parts, it is possible to convert the resultant heat flow into usable electricity.

Such power sources are small, lightweight, and rugged. One of their uses is in the SNAP (Space Nuclear Auxiliary Power) units used to power satellites, or more importantly, to power remote sensing instrument packages. A satellite that used a SNAP source is shown in Fig. 13-5. SNAP sources (fueled by ^{238}Pu) served as the power sources for instrument packages on the five Apollo missions, the Viking unmanned Mars lander, and the Pioneer, Voyager and Cassini probes to Jupiter, Saturn, Uranus, Neptune, Pluto, and beyond.

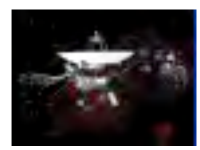

Fig. 13-5. A picture of a satellite that was powered by nuclear energy.

In addition to space applications, radionuclide power sources have been used as terrestrial sources of energy wherever compact and long-lived sources, not requiring maintenance, are needed. In the early 1970s, ^{238}Pu batteries were used as the power sources for cardiac pacemakers. Over 3,500 units were implanted and most remain functioning. Due to a lower cost and easier construction, lithium batteries have largely supplanted the plutonium.

Nuclear Weapons

Without a doubt, the development of nuclear weapons is one application of nuclear science that has had a significant global influence. Following the observation of fission products of uranium by Hahn and Strassmann in 1938, a uranium fission weapon became possible in the eyes of a number of nuclear scientists. It was Albert Einstein who signed a letter to Franklin Roosevelt, President of the United States, and alerted him to the potential development of a nuclear weapon. Thus began the Manhattan Project, resulting in production of the first nuclear weapons.

In 1945, a bomb using the fission of ^{235}U was dropped on Hiroshima, while a bomb using the fission of ^{239}Pu was dropped on Nagasaki. The awesome destruction that was produced by two nuclear devices changed the face of warfare forever. Not only did these two explosions end the most destructive war in history, but also the possessor of these weapons of mass destruction seemed invincible to any adversary.

The legacy of nuclear weapons remains in the soil around us, where we can still measure minute amounts of fallout from the atmospheric nuclear tests of the 1950s and 1960s. The weapons need constant maintenance because radiation damage affects the materials and triggering devices that must act together to make the weapon work. Furthermore, the isotope tritium, which is used in weapons, naturally decays. Storage and disposal of the weapons is technically difficult but probably a manageable problem. However, it is a daunting political and social problem. It is a challenge to maintain these weapons, to significantly reduce their numbers, to clean up the waste, and to insure that these weapons never will be used again.

Nuclear weapons are with us to this day and could be with us in the future. Even if all conflicts among nations end, some nuclear weapons might be retained. Earth is vulnerable to impacts from comets and asteroids. Some scientists have proposed that nuclear weapons could possibly be used to deflect them from hitting our planet.

Space Applications: Radiation-Induced Effects

Radiation-induced spacecraft anomalies have been known since the Explorer I launch on January 31, 1958, when a Geiger counter put aboard by J. A. Van Allen suddenly stopped counting. It turned out that the counter was in fact saturated by an extremely high-count rate. This led to the discovery of the Van Allen belts.

The inner belt, beginning at about 1,000 km above the surface of the Earth, contains primarily protons with energies between 10-100 MeV. The offset between Earth's geographical and magnetic axes causes an asymmetry in the radiation belt above the Atlantic Ocean off the Brazilian coast, allowing the inner belt to reach a minimum altitude of 250 km. This "South Atlantic Anomaly" is important because it occupies a region through which low-orbiting satellites spend as much as 30% of their time. During a solar flare, which can happen anytime, the number of protons suddenly increases by more than a million.

The first spacecraft loss due to total radiation dose effects occurred unexpectedly in 1962. A satellite, Telstar, was launched just one day after a high altitude nuclear weapons test. This weapons test produced a large number of beta particles, which caused a new and very intense radiation belt that lasted until the early 1970s. Telstar and six other satellites were lost within a seven-month period after this weapons test. Telstar was well studied and the loss was traced directly to breakdown of diodes in the command decoder due to the total radiation dose.

Radiation effects studies done at accelerators measure total-dose effects, displacement damage, or single event effects (SEE). A SEE occurs when one ion passing through a semiconductor causes enough damage to upset the circuit in some way. In 1978, the first SEEs were observed at ground level when Intel Corporation discovered that anomalous upsets occurring in dynamic random access computer memories were being caused by alpha particles emitted from trace amounts of thorium and uranium in the materials from which the device's packages were made. It was quickly found that massive ions, protons, and neutrons could all induce SEEs.

SEEs can result in the flip of a memory bit. This change can produce upsets with little other effect on the circuit. On the other hand, the effect can be more catastrophic causing and the chip could stop latchup and stop working. Sometimes powering down the chip will return it to life; for other times, it might burn out altogether or rupture a gate.

Biology Studies

Radiation biologists study the effect of radiation on living tissue. This field, that has direct analogies to the SEEs, examines the damage sustained by cells in the cosmic ray environment of space, a single event effect. These studies are necessary before we send astronauts to Mars.

Materials Studies

In 1959, it was discovered that mica that was exposed to fission fragments showed "nuclear tracks" when viewed under an ordinary microscope. This discovery led to a new class of nuclear physics detectors as well as a wide range of practical applications in earth science, oceanography, biology, medicine, archaeology, and space science.

By exposing thin sheets of plastic or other material to massive ions, tracks can be made through the material and then etched to make very fine "micropore" filters (30 nm to 8 mm hole size). These have been made at reactors since about 1970 and are used primarily in the biomedical field, with other applications in geophysics, meteorology, and brewing.

Another use for these sheets of plastic is to measure radon levels. By counting the number of ion tracks left in the plastic, one can measure the radon concentration.

Books and Articles:

P. Morrison and K. Tsipis, "New Hope in the Minefields," *Tech. Rev.*, **100** (7), 38 (1997).

Chapter 14 Energy from Nuclear Science

The isotope ^{235}U, with an abundance of only 0.7% in natural uranium, is commonly used to produce electricity in nuclear fission reactors**.** This isotope has the distinctive and useful property of undergoing nuclear fission through interaction with thermal-energy neutrons (neutrons with average speeds of only a few km/s). The other main isotope of uranium, ^{238}U, does not undergo nuclear fission with thermal neutrons, but it does capture neutrons to form the isotope ^{239}Np that then decays to ^{239}Pu. This isotope of plutonium undergoes nuclear fission with thermal neutrons with a higher probability than that of ^{235}U. The energy released in the fission of ^{235}U and ^{239}Pu, mainly in the form of kinetic energy of the fission fragments, provides the heat to run the turbines that generate electricity at a nuclear fission power plant.

Nuclear Fission Energy

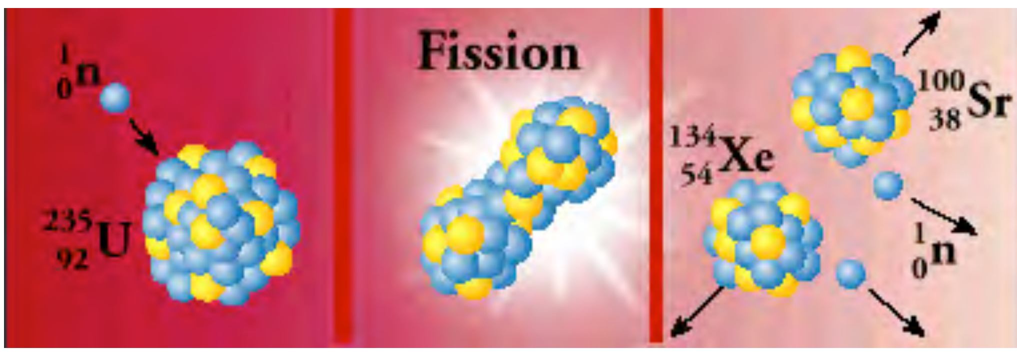

Fig. 14-1. Fission of ^{235}U after absorption of a thermal neutron.

The relevant nuclear reactions can be written as follows:

$$^{235}U + {}^{1}n \rightarrow \text{fission products + neutrons + energy (\sim200 MeV)} \qquad (1)$$

$$^{238}U + {}^{1}n \rightarrow {}^{239}U + \text{gamma rays} \qquad (2)$$

$$^{239}U \rightarrow {}^{239}Np \rightarrow {}^{239}Pu \qquad \text{(a series of beta decays).} \qquad (3)$$

An integer number of neutrons, for example, either two, three or four, are emitted in the reactions leading to different pairs of fission products described in reaction (1). The average number is 2.43. Some of the neutrons in reaction (1) can be used to induce fission in another ^{235}U nucleus, thus continuing a controlled, self-perpetuating nuclear chain reaction. Some fraction of the remaining neutrons from reaction (1) is utilized in reaction (2) to produce ^{239}Pu. The rest are absorbed in other nuclei without further effect.

The isotope ^{232}Th, although not fissionable with thermal neutrons, is a possible energy source because it absorbs thermal neutrons to produce long-lived ^{233}U, which also undergoes thermal neutron fission with a high probability. Thus the "big three" readily fissionable nuclei are ^{235}U, ^{239}Pu, and ^{233}U.

Fig. 14-2. The reactor vessel of a commercial reactor is inside this containment building.

A typical pressurized (or boiling) water nuclear reactor consists of a core of fissionable material (UO_2, enriched to 3.3% to 4% in ^{235}U) in which the chain reaction takes place. A picture of a reactor is shown in Fig. 14-2. The energy released in the fission process, which is primarily in the form of the kinetic energy of the fission fragments, heats the water. The water serves both as a neutron moderator (it slows down the fission neutrons to thermal energies), and as a heat transfer fluid. Rods of neutron-absorbing material inserted into the core control the chain reaction. The thermal energy is removed from the core by the water to an external thermal-energy converter. In the pressurized water reactor (PWR), the thermal energy produces steam for the turbine through the use of a heat exchanger, whereas in a boiling water reactor (BWR), the steam is produced for direct use in the turbine.

Nuclear reactions liberate a large amount of energy compared to chemical reactions. One fission event results in the release of about 200 MeV of energy, or about 3.2×10^{-11} watt-seconds. Thus, 3.1×10^{10} fissions per second produce 1 W of thermal power. The fission of 1 g of uranium or plutonium per day liberates about 1 MW. This is the energy equivalent of 3 tons of coal or about 600 gallons of fuel oil per day, which when burned produces approximately 1/4 tonne of carbon dioxide. (A tonne, or metric ton, is 1000 kg.)

Nuclear reactors manufacture their own fuel, since they produce ^{239}Pu from ^{238}U. With the total worldwide installed nuclear capacity of 3.4×10^5 MW_e (megawatt electrical), one can estimate that more than 100 tonnes of ^{239}Pu are produced each year in reactors whose primary energy source is the fission of ^{235}U. This ^{239}Pu can be reprocessed from used fuel rods and used to power other reactors.

It is actually possible to generate more ^{239}Pu than is used up in the reactor by surrounding the core with a uranium blanket and generating ^{239}Pu in this blanket. This is called a breeder reactor. A breeder reactor needs to be operated with fast neutrons, a so-called "fast breeder" reactor. In a fast-breeder reactor, water cannot be used as a coolant because it would moderate the neutrons. The smaller fission cross sections associated with the fast neutrons (as compared with thermal neutrons) leads to higher fuel concentrations in the core and higher power densities, which, in turn, create significant heat transfer problems. Liquid sodium metal may be used here as a coolant and heat-transfer fluid. Research on breeder reactors has essentially stopped in the United States because of concerns over nuclear proliferation since the plutonium bred in the reactor might be used for making weapons. Due to such concerns and the complexities of construction and operation, it is unlikely that breeder reactors will ever come into general operation within the next several decades, if ever.

In a yearly operating cycle of a typical (1000 MW_e) pressurized water reactor, the spent fuel contains about 25 tonnes of uranium and about 250 kg of ^{239}Pu. Some 40% of the energy produced in the course of a nuclear fuel cycle comes from ^{239}Pu. Since about 20% of the electricity generated in the United States comes from nuclear power plants, about twice as much electricity is generated from ^{239}Pu as is generated from oil-fired electrical generating plants.

Some 435 nuclear power plants operating around the world generate about 345,000 MW_e of electricity in 32 countries, about one-sixth the world's electricity supply. Some countries depend vitally on the electricity generated by nuclear energy. France generates 76% of its electricity from nuclear power plants; Belgium—56%, South Korea—36%, Switzerland—40%, Sweden—47%, Finland—30%, Japan—33%, and the United Kingdom—25%. Bulgaria generates 46% of its electricity from nuclear power, Hungary—42%, and the Czech Republic and Slovakia combined—20%. Although the United States is not a leader in percentage, it has the largest total electric output from nuclear power: 98,000 MW_e from 105 plants, generating around 20% of US electric power.

However, the United States, which led the world in early nuclear electric power development, was also first to be affected by its decline. Over the past two decades the US nuclear electric power industry has received no new domestic orders due to concerns over reactor safety, waste disposal, regulatory uncertainty, increased costs, and decreased electrical demand growth. These same pressures are now affecting nuclear power worldwide, although countries such as France and South Korea still have vigorous programs.

A rebirth or nuclear power might be imminent. There is research on how to solve these problems. Furthermore, there is worldwide problem of global warming due to the release of greenhouse gases. Nuclear power does not produce greenhouse gasses, so it could be used instead of fossil fuels.

The public has become suspicious of nuclear energy partly because of the elaborate methods used to address safety concerns. Most worrisome is the need for external electrical power to supply the pumps used in emergency core cooling systems in the types of reactors now used in the United States. In an accident, this external supply could possibly be disrupted leading to a release of radioactivity. New reactor designs use passive safety to address this problem. Passive safety features can be thought of as characteristics of a reactor that, without operator intervention, will tend to shut or cool a reactor down, keep it in a safe configuration, and prevent release of radioactivity. These features fall into two broad categories—features that are designed to prevent accidents and those that mitigate the effects of accidents. Many current problems arise from the huge scale of reactor construction projects. Typically, 1000 MW reactors have been constructed on site. The new types of reactors are smaller (e.g. 600 MW) and may be constructed in factories where uniformity and quality control can produce reactors and operating procedures less prone to failure. Examples of these new designs are two types of Advanced Passive Light Water Reactors (APLWRs), the Liquid Metal Reactor (LMR), and the Modular High Temperature Gas-cooled Reactor (MHTGR). The APLWR is the most developed of these new reactors. The AP-600 (Advanced Passive 600 MW_e) is a pressurized water reactor. It runs at lower temperatures and with larger water inventories than current light water reactors, and has a passive emergency core-cooling system that utilizes gravity. It uses passive natural circulation for the removal of heat from the core.

Nuclear fission reactors, usually pressurized water reactors with energy conversion based on a steam-turbine cycle, have been used extensively to power ships. The United States has built and launched an impressive number of nuclear powered ships—a total of 155 attack and missile submarines, 9 guided missile cruisers (18 reactors), and 5 aircraft carriers (with a total of 24 reactors) and has operated 9 prototype reactors on land. Of this total, 22 submarines have been decommissioned or are non-operational. Shipboard reactors are constructed smaller than similar installations ashore, with special attention given to maintenance, protection from collision, and leakage. Although the primary use of nuclear power has been in submarines and other military vessels, a few non-military marine installations have been demonstrated. Examples include the Russian icebreaker Lenin and the United States demonstration merchant ship NS Savannah.

Nuclear Fusion Power

Nuclear fusion reactors, if they can be made to work, promise virtually unlimited power for the indefinite future. This is because the fuel, isotopes of hydrogen, is essentially unlimited on Earth. Efforts to control the fusion process and harness it to produce power have been underway in the United States and abroad for more than forty years.

Fig. 14-3. A diagram showing a typical fusion reaction.

Nuclear fusion is the source of energy in the sun and stars where high temperatures and densities allow the positively charged nuclei to get close enough to each other for the (attractive) nuclear force to overcome the (repulsive) electrical force and allow fusion to occur. Fig. 3 shows one fusion reaction. The most promising fusion reaction,

$$^{3}H + ^{2}H \rightarrow ^{4}He + n + 17.6\ MeV$$

involves the radioactive nuclide tritium (^{3}H), available from the nuclear production reaction

$$^{6}Li + n \rightarrow ^{3}H + ^{4}He.$$

To produce energy using this reaction, both the magnetic confinement reactor with a high-temperature plasma (a gas that has been completely ionized) and the inertial confinement reactor (which utilizes laser implosion technologies) have been investigated. Extremely high plasma temperatures are required in the magnetic confinement reactor and difficult laser implosion techniques are required for the inertial confinement reactor. Although significant progress has been made in these investigations, no working reactor that produces more energy than it consumes has been built. Unfortunately, the funding for continuing this work has declined, and the work is proceeding at a slower pace.

Although these types of reactors would not have the fission product waste disposal problem of fission reactors, fusion reactors generate large number of fast neutrons, leading to large quantities of radioactive byproducts.

Another approach to nuclear fusion—an approach that could lead to aneutronic power (power without neutrons) and non-radioactive nuclear energy—uses the concept of colliding-beam fusion (CBF). One aneutronic method features the ^{2}H + ^{3}He reaction leading to the products ^{1}H + ^{4}He. However, this requires ^{3}He, which only has limited availability on the Earth. The Moon is a potential source of ^{3}He produced by cosmic-ray protons hitting the Moon directly and not being absorbed by an atmosphere as on Earth. Another potential approach for colliding beam fusion is the ^{11}B + ^{1}H reaction leading to the three ^{4}He nuclei. The energy release is in the form of charged particles whose kinetic energy can be converted to electricity with a very high efficiency. Current research predicts that this energy source has an extremely high degree of cleanness and efficiency. In all current energy sources, approximately two-thirds of the energy is lost in the form of waste heat or thermal pollution. In the CBF approach, there is virtually no waste. This design favors small size for the greatest efficiency (100 MW_e or less), and would lead to either power plants with several reactors or decentralization of energy production.

Chapter 15 Radiation in the Environment[i]

Many forms of "radiation" are encountered in the natural environment and are produced by modern technology. Most of them have the potential for both beneficial and harmful effects. Even sunlight, the most essential radiation of all, can be harmful in excessive amounts. Most public attention is given to the category of radiation known as "ionizing radiation." This radiation can disrupt atoms, creating positive ions and negative electrons, and cause biological harm. Ionizing radiation includes x-rays, gamma rays, alpha particles, beta particles, neutrons, and the varieties of cosmic rays.

Radiation Damage and its Study

All ionizing radiations, at sufficiently large exposures, can cause cancer. Many, in carefully controlled exposures, are also used for cancer therapy. Whether harmful or beneficial, exposures to ionizing radiation have been an inevitable part of the environment throughout the Earth's history. The nucleosynthesis processes that produced the elements created both stable and unstable nuclides. The unstable nuclides with very long half-lives, together with their radioactive progeny, constitute the natural radioactivity on Earth today. In addition, violent processes in the sun and elsewhere lead to the bombardment of the Earth by cosmic rays. Thus, radiation is an old and familiar, if unrecognized, pollutant.

However, human awareness of radioactivity and ionizing radiation has only a 100-year history starting with the discovery of x-rays and radioactivity. The first evidence that ionizing radiation could do harm came within months after the discovery of x-rays, when an early x-ray worker developed injuries to his skin. Serious efforts[ii] to understand and control radiation exposures started in the 1920s and greatly expanded during and after World War II.

Information on the effects of radiation comes from studies of exposed groups and individuals, from animal experiments, and from studies at the cellular and molecular level. It is now well established that ionizing radiation has both prompt and delayed effects. At very high radiation exposures, death will occur within several months or less. At moderate levels, radiation exposure increases the chance that an individual will develop cancer, with a time delay of ten or more years for most cancers. At low levels, the cancer risk decreases, but the relationship between cancer risk and the magnitude of the exposure is uncertain.

Other effects of radiation, in part inferred from animal experiments, include an increased risk of genetic defects and, for exposures of the fetus before birth, of mental retardation. In terms of frequency of occurrence and severity of effects, cancer is the most serious consequence and receives the greatest attention.

The importance of genetic effects has turned out to be much less than was originally expected. In the words of a 1993 NCRP report: "... the genetic risks have been found to be smaller and the cancer risks larger than were thought (in the 1950s)." Strikingly, no statistically significant genetic effects have been found among the extensively studied children of survivors of the Hiroshima-Nagasaki bombings. On the basis of animal experiments, however, one expects some genetic effects—even if so far not observable above the large background of "natural" defects. In addition, the Hiroshima-Nagasaki studies have shown an increased incidence of mental retardation among children who received large prenatal radiation doses, especially for exposures 8 to 15 weeks after conception.

Units of Radioactivity and Dose

The original unit for measuring the amount of radioactivity was the *curie* (Ci)—first defined to correspond to one gram of radium-226 and more recently defined as:

1 curie $= 3.7 \times 10^{10}$ *radioactive decays per second* [exactly].

In the International System of Units (SI) the becquerel (Bq) has replaced the curie, where
1 becquerel = 1 radioactive decay per second $= 2.703 \times 10^{-11}$ *Ci*.

The magnitude of radiation exposures is specified in terms of the *radiation dose*. There are two important categories of dose:

1. The *absorbed dose*, sometimes also known as the *physical dose*, defined by the amount of energy deposited in a unit mass in human tissue or other media. The original unit is the *rad* [100 erg/g]; it is now being widely replaced by the SI unit, the *gray* (Gy) [1 J/kg], where 1 gray = 100 rad.
2. The *biological* dose, sometimes also known as the *dose equivalent,* expressed in units of *rem* or, in the SI system, *sievert* (Sv). This dose reflects the fact that the biological damage caused by a particle depends not only on the total energy deposited but also on the rate of energy loss per unit distance traversed by the particle (or "linear energy transfer"). For example, alpha particles do much more damage per unit energy deposited than do electrons. This effect can be represented, in rough overall terms, by a *quality factor,* Q. Over a wide range of incident energies, Q is taken to be 1.0 for electrons (and for x-rays and gamma rays, both of which produce electrons) and 20 for alpha particles. For neutrons, the adopted quality factor varies from 5 to 20, depending on neutron energy.

The biological impact is specified by the *dose equivalent* H, which is the product of the absorbed dose D and the quality factor Q: $H = Q D$.

The unit for the dose equivalent is the rem if the absorbed dose is in rads and the sievert (Sv) if the absorbed dose is in grays. Thus, 1 Sv = 100 rem. As discussed below, 1 rem is roughly the average dose received in 3 years of exposure to natural radiation. 1 Sv is at the bottom of the range of doses that, if received over a short period of time, are likely to cause noticeable symptoms of radiation sickness.

The dose equivalent is still not the whole story. If only part of the body is irradiated, the dose must be discounted with an appropriate weighting factor if it is to reflect overall risk. The discounted dose is termed the *effective dose equivalent* or just the *effective dose*, expressed in rems or sieverts.

Radioactivity in the Natural Environment

The radioactive nuclei, or *radionuclides*, found naturally on Earth can be grouped into three series—headed by uranium-238, uranium-235, and thorium-232—plus several isolated beta-particle emitting nuclei, most prominently potassium-40 and rubidium-87. Average abundances of these nuclides are listed in Table 15-1.

Table 15-1. Half-lives and average abundances of natural radionuclides.

	^{40}K	^{87}Rb	^{232}Th	^{238}U
Half-life (billion years)	1.277	47.5	14.05	4.468
Upper continental crust				
Elemental abundance (ppm)	28000	112	10.7	2.8
Activity (Bq/kg)	870	102	43	35
Activity (nCi/kg)	23	2.7	1.2	0.9
Activity (kCi/km^3)	66	8	3.3	2.6
Oceans				
Elemental concentration (mg/liter)	399	0.12	1×10^{-7}	0.0032
Activity (Bq/liter)	12	0.11	4×10^{-7}	0.040
Activity (nCi/liter)	0.33	0.003	1×10^{-8}	0.0011
Ocean sediments				
Elemental abundance (ppm)	17000		5.0	1.0
Activity (Bq/kg)	500		20	12
Activity (nCi/kg)	14		0.5	0.3
Human body				
Total activity (Bq)	4000	600	0.08	0.4[a]
Total activity (nCi)	100	16	0.002	0.01

a. In the human body the activity of ^{210}Pb and ^{210}Po, both progeny of ^{238}U, is much greater than that of ^{238}U itself.

The most interesting of the series is the uranium-238 series which decays via a chain containing 8 alpha decays and 6 beta decays to lead-206. This chain includes the longest-lived isotopes of radium and radon: radium-226 and radon-222, respectively. In each of the three chains the parent nucleus has a much greater lifetime than does any of the progeny. Therefore, a steady-state is established in which, for a given sample of material, each member of the series has the same activity—aside from deviations due to differences in chemical properties, which cause different elements to be transferred at different rates into or out of a given sample of material.

Including all the succeeding decays, the total activity in the thorium-232 and uranium-238 series is, very roughly, ten times the activity indicated for thorium-232 and uranium-238 alone. Thus, for each of the series, the total activity in the Earth's crust averages roughly 30,000 Ci/km^3. For both series together and including the contributions of potassium-40 and rubidium-87, the total activity in the crust averages about 100,000 Ci/km^3. There is also a considerable amount of radioactivity in the oceans, with potassium-40 dominant in the ocean itself and thorium-232 relatively more important in the ocean sediments. For the oceans as a whole (1.4×10^{21} liters), the total activity is about 4×10^{11} Ci for potassium-40 and 1×10^9 Ci for uranium-238. Potassium-40 is also present in significant amounts in the human body, especially in muscle tissue.

In addition to these ancient radionuclides and their progeny, some radionuclides are being continually produced by cosmic rays. The most prominent of these is carbon-14, produced in the interaction of cosmic ray neutrons with nitrogen in the atmosphere.

Table 15-2. Average radiation doses in the United States, 1980-1982 (effective dose per year).*

Radiation source	Comments	Effective dose mSv/yr	mrem/yr
Natural sources			
indoor radon	due to seepage of ^{222}Rn from ground	2.0	200
radionuclides in body	primarily ^{40}K and ^{238}U progeny	0.39	39
terrestrial radiation	due to gamma-ray emitters in ground	0.28	28
cosmic rays	roughly doubles for 2000 m gain in elevation	0.27	27
cosmogenic	especially ^{14}C	0.01	1
total (rounded)		3.0	300
Medical sources			
Diagnostic x-rays	excludes dental examinations	0.39	39
Medical treatments	radionuclides used in diagnosis (only)	0.14	14
total		0.53	53
Other			
consumer products	primarily drinking water, building materials	0.1	≈10
occupational	averaged over entire US population	0.01	1
nuclear fuel cycle	does not include potential reactor accidents	0.0005	0.05
TOTAL (rounded)		3.6	360

*From *Ionizing Radiation Exposure of the Population of the United States,* NCRP Report No. 93 (National Council on Radiation Protection and Measurements, Washington DC, 1987).

Typical Radiation Doses

The chief sources of radiation exposure in the United States, as tabulated by the NCRP, are indicated in Table 15-2. The largest single source of exposure is from radon, which is produced in the decay of radium-226 in the soil and enters a house through openings at the base. The "radon" dose arises mostly from the inhalation of the progeny of radon-222, and varies widely from house-to-house depending upon the radium content of the underlying soil, its porosity, and the house construction. The average effective dose of 2.0 mSv/yr (200 mrem/yr) corresponds to the average radon concentration, but there are more than one million homes with radon levels that are more than five times as great. Appendix D has more information on the average annual radiation exposure and its sources that are received by the U.S. population.

Effects of Low Doses

Most of the radiation doses that are received by members of the public and by radiation workers—both routinely and in accidents—are what are commonly referred to as "low doses." There is no precise definition of "low" but it would include doses below, for example, 10 mSv per year. As seen from Table 15-2, the average radiation doses received by people in the U.S. are in the "low dose" region. It is obviously important to determine the effects of low radiation doses—or, more precisely, the effects of small additions to the unavoidable natural background dose.

However, despite much study, these effects are not known, being too small to see unambiguously. The most prominent assumption, accepted by most official bodies, is the so-called *linearity hypothesis,* according to which the cancer risk is directly proportional to the magnitude of the dose, down to zero dose. In applying this assumption a consensus estimate is that the risk to a "typical" individual of an eventual fatal cancer is 0.00005 per mSv (or 0.05 per Sv). Thus, if 100,000 people each receive an added dose of 1 mSv, then 5 additional cancer deaths are to be expected. At the same time, while adopting the linearity hypothesis as a prudent working assumption, many of the leading studies have also indicated the possibility that small increases in radiation dose do not create any additional cancer risk. This reflects the considerable disagreement that exists within the scientific community as to the validity of the linearity hypothesis (see Appendix F).

Effects of Large Doses

Radiation doses above 3 Gy (300 rad) can be fatal and doses above 6 Gy (600 rad) are almost certain to be fatal, with death occurring within several months (in shorter times at higher doses). [Note: Very high doses are commonly expressed in grays, because the standard quality factor is not appropriate. For gamma rays and electrons, 1 Gy corresponds to 1 Sv.] Above 1 Gy, radiation causes a complex of symptoms, including nausea and blood changes, known as radiation sickness. For doses below 1 Sv (100 rem), there is little likelihood of radiation sickness, and the main danger is an increased cancer risk. The most important data base and analyses are from the RERF studies of the Hiroshima and Nagasaki survivors. In these studies, the exposure and medical histories are analyzed for an exposed group (50,113 people) and an unexposed, or minimally exposed, group (36,459 people). Through 1990, there have been 4,741 cancer fatalities in the exposed group, of which 454 are attributed to radiation exposure. There is a statistically significant excess for both solid cancer tumors and leukemia for doses above 0.2 Sv (20 rem). These data, in a succession of updated versions, have provided much of the information used in comprehensive studies of radiation effects.

Nuclear Reactor Accidents

The accidents at the Three Mile Island (TMI) and Chernobyl nuclear reactors have triggered particularly intense concern about radiation hazards. The TMI accident, in Pennsylvania in 1979, resulted from a combination of deficient equipment and operator errors. Even though there was severe damage to the nuclear fuel within the reactor, very little radioactivity escaped into the outside environment. The effectiveness of the large concrete containment building that surrounded the reactor contributed to this relatively small release. Subsequent studies concluded that the maximum dose received by any member of the public was less than 1 mSv (100 mrem). The collective off-site dose is estimated to have been about 20 person-Sv. Under the standard low-dose assumption, this corresponds to one eventual cancer fatality in the neighboring population of 2 million people. (This population receives an annual collective dose of about 6000 person-Sv from natural sources.)

The 1986 Chernobyl accident was far more serious. It occurred in a reactor with an unsafe reactor design unique to the Soviet Union. The reactor had no effective containment, and there was a very large release of radionuclides to the environment. The accident led to the death within several months of 31 reactor personnel and firefighters—28 from a combination of radiation effects and burns from fire, 2 from other injuries, and one from a heart attack. A total of 237 workers were hospitalized for symptoms of radiation sickness, including the 28 who died. A 1996 summary reported additional 14 deaths among the more severely exposed workers, but it is not clear that these deaths were all due to the prior exposure.

There is strong evidence of a substantial increase in thyroid cancers among children living in the vicinity. No other health effects from Chernobyl have been convincing established. However, it is too soon for them to have been fully manifested. Standard calculations of radiation effects predict that there will be a large number of excess cancer deaths among the so-called “liquidators,” who were engaged in cleanup operations after the accident, as well as in the neighboring population.

Considering impacts at greater distances, one early study estimated that the collective dose in the Northern Hemisphere over a 50-year period would be about 930,000 person-Sv. While there is substantial uncertainty in the dose estimate, there is even greater uncertainty as to the impact. If one accepts the linearity hypothesis and assumes 0.05 fatalities per Sv, this dose corresponds to 47,000 eventual cancer fatalities. About 29,000 of these fatalities would occur in Europe (outside the former Soviet Union) due to a cumulative collective dose of 580,000 Sv—an average individual *lifetime* dose of 1.2 mSv for 490 million people. Given these low average doses, any estimate of predicted deaths from Chernobyl is highly speculative. The deaths will not be identifiable, being masked by the 88,000,000 “normal” cancer fatalities expected in this region during the 50-year period.

Criteria for Radiation Protection

The responsibility in the United States for regulation of radiation exposures rests with the Environmental Protection Agency (EPA) and the Nuclear Regulatory Commission (NRC). There has been a gradual worldwide tightening of the standards for radiation protection. This principle is driven, in part, by the view that it is better to "err on the side of caution" and somewhat more formally by the ALARA principle. As expressed by the ICRP in 1977, the ALARA principle states that "all exposures shall be kept as low as reasonably achievable, economic and social factors being taken into account." Current EPA and NRC limits and other recommendations are summarized in Table 15-3.

Table 15-3. Dose standards for radiation exposure in the United States, expressed in terms of annual effective dose.

	Dose limit (mSv/yr)	**Dose limit (mrem /yr)**
Occupational limit	50	5000
General public		
limit for any licensed facility (excluding medical)	1	100
limit for nuclear power facility	0.25	25
limit for waste repository (excluding Yucca Mountain)	0.15	15
NAS recommendation for Yucca Mountain[a]	0.02 - 0.2	2 - 20
EPA recommended "action level" for indoor radon	≈ 8	≈ 800

[a]Converted from the recommendation on risk, assuming risk of 0.05 per Sv.

The NRC imposes a limit of 1 mSv/yr on the effective dose that can be received by any member of the public from a NRC-licensed facility (exempting medical treatments). EPA regulations impose a limit of 0.25 mSv/yr on the effective dose from nuclear power facilities, including nuclear reactors. They provide a still more stringent 0.15 mSv/yr for waste disposal sites under the EPA's authority.

Actual exposures to the public from nuclear power operations are lower than the regulatory limit of 0.25 mSv/yr, and the limit is not presently constraining. It is unlikely to be approached except in the case of an accident, in which case the existence of regulations might be moot. The regulatory limits may, however, provide a spur to careful operation.

Permitted occupational exposures, for nuclear workers and others, are considerably higher than those for the general public—the present US limit is 50 mSv/yr. However, the ALARA principle also applies, and the average dose for nuclear workers is much below this limit.

The EPA has taken only an advisory, but not regulatory, position on indoor radon exposures, because it has no authority over air in private residences. For radon, the EPA suggests that remedial action be taken if the indoor concentration exceeds a level of 4 pCi/liter, corresponding roughly to an effective dose of 8 mSv/yr.

Standards for the proposed Yucca Mountain nuclear waste repository have not yet been established. However, recommendations on the nature of these standards have been made by a congressionally mandated committee working under the auspices of the National Research Council, an agency of the National Academy of Sciences. This committee recommended a limiting risk factor of 10^{-5} to 10^{-6} per year. If one assumes the present conventional risk factor of 0.05 per Sv, this translates to effective doses of 0.2 mSv/yr to 0.02 mSv/yr. This limit is to be applied to the average member of a small "critical group" (probably numbering under 100 people) that is particularly dependent on water contaminated by radionuclide releases from the repository. In the NAS recommendation, this limit would apply for up to 1 million years. Some observers believe that it unreasonable to require this level of protection for a small group of people so far into an unpredictable future.

Perspectives on Radiation Risks

The recommended standards for Yucca Mountain are illustrative of the unusual attention and concern surrounding risks from man-made ionizing radiation. Many reasons have been advanced for this concern, including the connection between radiation and nuclear weapons and the fact that human senses cannot detect radiation.

Ironically, however, it has also been very difficult to detect adverse effects from low-level radiation. The search for radiation effects among populations exposed to moderately elevated radiation levels—inhabitants of regions with high natural levels of radiation, nuclear industry workers (excluding miners), and residents of houses with high radon levels—has not provided any conclusive evidence of excess cancer rates. In a push of the pendulum far to the skeptical side, this creates a temptation to dismiss entirely the hazards of low doses.

It is difficult to find a firmly based middle ground. The available information, taken as a whole, provides no conclusive evidence as to the nature of the consequences at low doses and low dose rates. However, proponents of the linearity hypothesis and of hormesis —as well as believers in a near-zero effect—can find support from individual studies (see Appendix F). Under these circumstances, adopting the linearity hypothesis for purposes of setting radiation limits may be a prudent regulatory expedient. However, it should be recognized that the scientific validity of the hypothesis is not well established.

The current uncertainties highlight the importance of continued studies of the effects of low-level radiation. A better scientific understanding of radiation risks is crucial to the formulation of appropriate protective standards and, more broadly, to the achievement of a responsible balance in assessing the use of nuclear technologies in industry, medicine, and energy production.

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[i] Parts of this chapter and of Appendix F draw upon: David Bodansky, *Nuclear Energy: Principles, Practices, and Prospects* (AIP/Springer-Verlag, New York, 1996).

[ii] There are now a many official and semi-official bodies that are concerned with radiation protection. These bodies provide important summary reports and advice. These include the International Commission on Radiological Protection (ICRP), the (US) National Council on Radiation Protection and Measurements (NCRP), the Committee on the Biological Effects of Ionizing Radiations of the National Research Council (BEIR), the United Nations Committee on the Effects of Atomic Radiation (UNSCEAR), and the Radiation Effects Research Foundation (RERF), a joint United States-Japan organization studying the effects of the atomic bombs at Hiroshima and Nagasaki.

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Appendix A Glossary of Nuclear Terms

absorber: Any material that stops ionizing radiation. Lead, concrete, and steel attenuate gamma rays. A thin sheet of paper or metal will stop or absorb alpha particles and most beta particles.

accelerator: Device used to increase the energy of particles, which then collide with other particles. Major types are linear accelerators and circular accelerators. The name refers to the path taken by the accelerated particle.

activity: The rate of radioactive decay.

alpha particle (alpha radiation, alpha ray): A ^{4}He nucleus. It is made up of two neutrons and two protons. It is the least penetrating of the three common forms of radiation, being stopped by a thin sheet of paper. It is not dangerous to living things unless the alpha-emitting substance is inhaled or ingested or comes into contact with the lens of the eye.

annihilation: Annihilation of particles is the disappearance of the mass energy of a particle and its corresponding antiparticle, and its appearance as another sort of energy (possibly including a spray of particles of total quantum number zero for each of the additive quantum numbers).

antineutrino: Antiparticle to the neutrino. See antiparticles.

antiparticle: Particle having the same mass, spin, isospin as a particle, but having all additive quantum numbers opposite to those of its respective particle. Antiparticles have the opposite charge of its corresponding particle. Antibaryons are antiparticles to baryons, antileptons are antiparticles to leptons, and antiquarks are antiparticles to quarks. The antiparticle for a particular particle, for example a neutrino, is denoted an antineutrino.

asymptotic freedom: Quark-quark interactions weaken as the energy gets higher, or, equivalently, as the quarks approach one another.

atom: A particle of matter indivisible by chemical means. It is the fundamental building block of molecules. It consists of a positively charged nucleus and orbiting electrons. The number of electrons is the same as the number of protons in the nucleus.

atomic mass (sometimes mistakenly called atomic weight): The mass of a neutral atom. Its value in atomic mass units (u) is approximately equal to the sum of the number of protons and neutrons in the nucleus of the atom.

atomic mass number: *A*, the total number of nucleons (protons and neutrons) found in a nucleus.

atomic number: *Z*, the total number of protons found in a nucleus.

atomic mass unit (amu or u): Unit of mass defined by the convention that the atom ^{12}C has a mass of exactly 12 u; the mass of 1 u is 1.67×10^{-27} kg.

background radiation: The radiation found in the natural environment originating primarily from the naturally radioactive elements of Earth and from cosmic rays. The term may also mean radiation extraneous to an experiment.

baryon: A massive composite hadron (made of three quarks) such as the proton or the neutron.

baryon number: Quantum number characteristic of baryons. Each baryon has a value of +1, while each anti-baryon has a value of -1.

becquerel (Bq): Unit of activity in the International System—one disintegration per second; 1 Bq = 27 pCi.

beta particle (beta radiation, beta ray): An electron of either positive charge (e^+ or β^+) or negative charge (e, e^- or β^-) emitted by an atomic nucleus or neutron in the process of a transformation. Beta particles are more penetrating than alpha particles but less than gamma rays or x-rays. Electron capture is a form of beta decay.

Big Bang: Beginning of the universe; a transition from conditions of unimaginable density and temperature to conditions of lower density and temperature.

blackbody: An object that is a perfect emitter and absorber of radiation.

blackbody radiation: Radiation emitted by a blackbody (the intensity depends on temperature).

black hole: An object so dense that light cannot escape from it.

boson: A particle having spin that is an integer multiple of $\hbar$.

Cherenkov radiation: Light emitted by particles that move through a medium in which the speed of light is slower than the speed of the particles.

conservation law: A relation asserting that a specific quantity is conserved. For example, conservation of energy, conservation of momentum, conservation of electron number. Conservation laws are connected to symmetries through Noether's theorem.

cyclotron: Circular accelerator in which the particle is bent in traveling through a magnetic field, and an oscillating potential difference causes the particles to gain energy.

cyclotron frequency: Frequency at which the electric field is switched in order to accelerate the particles in the cyclotron. The frequency is related to the mass and charge of the particle to be accelerated.

curie (Ci): The original unit used to describe the intensity of radioactivity in a sample of material. One curie equals thirty-seven billion disintegrations per second, or approximately the radioactivity of one gram of radium. This unit is no longer recognized as part of the International System of units. The becquerel has replaced it.

daughter: A nuclide formed by the radioactive decay of a different (parent) nuclide.

decay (radioactive): The change of one radioactive nuclide into a different nuclide by the spontaneous emission of radiation such as alpha, beta, or gamma rays, or by electron capture. The end product is a less energetic, more stable nucleus. Each decay process has a definite half-life.

decay rate: The ratio of activity to the number of radioactive atoms of a particular species.

decay time: The time required for a quantity to fall to $1/e$ times the original value.

dees: Regions of space in a cyclotron shielded from electric field in which the magnetic field causes the particles to bend in a semicircle.

density: The ratio of an object's mass to its volume.

detector: A device or series of devices used to measure nuclear particles and radiations.

dose: A general term denoting the effect of absorption of a quantity of radiation or energy absorbed.

electric dipole moment: The product of charge and distance of separation for an electric dipole.

electromagnetic radiation: Radiation consisting of electric and magnetic fields that travel at the speed of light. Examples**:** light, radio waves, gamma rays, x-rays.

electron: An elementary particle with a unit electrical charge and a mass 1/1837 that of the proton. Electrons surround an atom's positively charged nucleus and determine that atom's chemical properties.

electron-volt (eV): Energy unit used as the basis of measurement for atomic (eV), electronic (keV), nuclear (MeV), and subnuclear processes (GeV or TeV). One electron-volt is equal to the amount of energy gained by an electron dropping through a potential difference of one volt, which is 1.6×10^{-19} joules.

electron capture: A radioactive decay process in which an orbital electron is captured by and merges with the nucleus. The mass number is unchanged, but the atomic number is decreased by one.

electroweak interaction: A theory that unifies the electromagnetic and weak interactions.

excited state: The state of an atom or nucleus when it possesses more than its normal energy. Typically, the excess energy is released as a gamma ray.

fermion: A particle having a spin that is an odd integer multiple of $\hbar/2$.

fissile nucleus: A nucleus that may fission after collision with a thermal (slow) neutron or that fissions spontaneously (by itself).

fission: The splitting of a heavy nucleus into two roughly equal parts (which are nuclei of lower-mass elements), accompanied by the release of a relatively large amount of energy in the form of kinetic energy of the two parts and in the form of emission of neutrons and gamma rays.

fission products: Nuclei formed by the fission of higher mass elements. They are of medium atomic mass and almost all are radioactive. Examples: ^{90}Sr, ^{137}Ce.

fusion: A process whereby low mass nuclei combine to form a more massive nucleus plus one or move massive particles.

gamma ray: A highly penetrating type of nuclear radiation, similar to x-radiation, except that it comes from within the nucleus of an atom, and, in general, has a shorter wavelength.

gauge boson: Particle mediating an interaction. By exchange of the gauge particle, the interaction between two particles is accomplished.

Geiger counter: A Geiger-Müller detector and measuring instrument. It consists of a gas-filled tube that discharges electrically when ionizing radiation passes through it and a device that records the events.

gluon: A gauge particle mediating the color strong interaction.

gray (Gy): Unit of absorbed dose due to any type of radiation. An exposure to 1 gray results from radiation depositing one joule per kilogram of animal tissue or any other material.

hadron: A strongly interacting particle.

half-life: The time in which half the (large number of) atoms of a particular radioactive nuclide disintegrate. The half-life is a characteristic property of each radioactive isotope.

homolog (or homologs): Elements in the same periodic table group that tend to exhibit similar, but not identical, chemical properties.

hormesis: Controversial theory that argues that there is a benefit to health, or decrease in biological damage from radiation as dose in increased (valid only for very small doses).

Hubble Constant: Ratio of outward speed of galaxies to their distances from Earth.

induced radioactivity: Radioactivity that is created by bombarding a substance with neutrons in a reactor or with charged particles produced by particle accelerators.

infrared radiation: Electromagnetic radiation of longer wavelength than visible light.

ion: An atomic particle that is electrically charged, either negatively or positively.

ionizing radiation: Radiation that is capable of producing ions either directly or indirectly.

irradiate: To expose to some form of radiation.

isomer: Nuclides with the same number of neutrons and protons in different states of excitation.

isomeric transition: A relatively long-lived radioactive decay in which a nucleus goes from a higher to a lower energy state. The mass number and the atomic number are unchanged.

isotope: Isotopes of a given element have the same atomic number (same number of protons in their nuclei) but different mass numbers (different number of neutrons in their nuclei). ^{238}U and ^{235}U are isotopes of uranium.

joule (J): Unit of energy, equivalent to the work done in lifting a one-newton weight a distance of one meter.

K-capture: The capture by an atom's nucleus of an electron from the innermost electron orbital (K-shell) surrounding the nucleus.

kelvin (K): Unit of temperature equal in size to the Celsius degree, but with the zero set by the absolute zero of temperature, -273.15°C. Ice freezes at 273 K, room temperature is about 293 K, and water boils at 373 K, at sea level. human body temperature is 310 K.

keV: One thousand electron volts.

lepton: A particle (such as the electron or neutrino) that is not subject to strong interactions.

lepton number: Additive quantum number defining leptons; the three lepton numbers are electron number, muon number, and tau number. These numbers remain the same in all reactions.

lifetime: The mean life of a particle or radioactive nucleus. This is equivalent to the decay time.

linac: Another name for a linear accelerator.

linear accelerator: A particle accelerator that follows a straight line.

mass energy: Energy a particle has by virtue of its mass (given by m times c^2).

mass number: The total number of protons and neutrons in the nucleus**:** $A=Z+N$. This is also the total nucleon number of the nucleus.

meson: A particle (such as the pion) made of quark-antiquark pairs.

MeV: One million electron volts.

microwaves: Electromagnetic radiation with wavelength intermediate between radio wave and infrared radiation.

multiwire proportional counter: Particle detector using changes in the current in wires due to the passage of ionizing particles nearby.

muon: A charged lepton about 200 times more massive than an electron.

muon number: Additive quantum number characterizing muons and muon neutrinos.

neutrino: An electrically neutral particle with negligible mass. It is produced in processes such as beta decay and reactions that involve the weak force.

neutron: One of the basic particles that make up a nucleus. A neutron and a proton have about the same mass, but the neutron has no electrical charge.

neutron number: The total number of neutrons in the nucleus, N.

nuclear binding energy: The energy that free nucleons give up in order to be bound inside a nucleus.

nuclear reactor: A device in which a fission chain reaction can be initiated, maintained, and controlled. Its essential components are fissionable fuel, moderator, shielding, control rods, and coolant.

nucleon: A constituent of the nucleus; that is, a proton or a neutron.

nucleus: The core of the atom, where most of its mass and all of its positive charge is concentrated. Except for ^{1}H, the nucleus consists of a combination of protons and neutrons.

nuclide: Any species of atom that exists for a measurable length of time. Its atomic mass, atomic number, and energy state can distinguish a nuclide.

parent: A radionuclide that decays to another nuclide.

photon: A packet of electromagnetic energy. Photons have momentum and energy, but no rest mass or electrical charge.

photomultiplier: Commonly used device for detecting photons by converting them to an electrical signal.

pion: The least massive known spin-0 meson. The three charge states of the pion (negative, neutral and positive) are involved in the long-range force between the nucleons.

proton: One of the basic particles that makes up an atom. The proton is found in the nucleus and has a positive electrical charge equal to the negative charge of an electron and a mass similar to that of a neutron**:** a hydrogen nucleus.

proton number: The total number of protons in the nucleus, Z.

QCD: Quantum chromodynamics, the gauge theory describing the color strong interaction.

QED: Quantum electrodynamics, the gauge theory describing electromagnetism.

quark: A strongly interacting fermion that is a building block of hadronic matter. Quarks come in six flavors: up, down, charm, strange, top, and bottom.

rad (Radiation Absorbed Dose): A former unit of an absorbed dose of ionizing radiation. One rad is equal to the absorption of radiation energy per gram of matter. It has been replaced by the gray (see above).

radioactive dating: A technique for estimating the age of an object by measuring the amounts of various radioisotopes in it.

radioactive waste: Materials that are radioactive and for which there is no further use.

radioactivity: The spontaneous decay or disintegration of an unstable atomic nucleus accompanied by the emission of radiation.

radioisotope: A radioactive isotope. A common term for a radionuclide.

radionuclide: A radioactive nuclide. An unstable isotope of an element that decays or disintegrates spontaneously, emitting radiation.

rem (röntgen equivalent, man): A measure of dose deposited in body tissue, averaged over the body. One rem is approximately the dose from any radiation corresponding to exposure to one röntgen of γ radiation. The rem is no longer accepted for use with the International System. One rem is equivalent to 0.01 sievert.

residual strong force: Force between composite objects (made of quarks) due to the remaining effect of the color force on colorless objects. These forces are much weaker than the strong color force.

röntgen or **roentgen (R):** Unit of exposure measuring the ionizing ability of γ radiation; one röntgen produces one electric charge (1.6×10^{-19} C) per 10^6 m^3 of dry air at 0°C and atmospheric pressure. This corresponds to an energy loss of 0.0877 joule per kilogram in air. The röntgen is no longer accepted for use with the International System.

scaler: An electronic instrument for counting radiation induced pulses from radiation detectors such as a Geiger-Müller tube.

scintillation counter: An instrument that detects and measures gamma radiation by counting the light flashes (scintillations) induced by the radiation.

scintillator: Material that emits light when particles traverse it.

secular equilibrium: A state of parent-daughter equilibrium that is achieved when the half-life of the parent is much longer than the half-life of the daughter. In this case, if the two are not separated, the daughter will eventually decay at the same rate at which it is being produced. At this point, both parent and daughter will decay at the same rate until the parent is essentially exhausted.

shielding: A protective barrier, usually a dense material that reduces the passage of radiation from radioactive materials to the surroundings by absorbing it.

sievert (Sv): A measure of dose (technically, dose equivalent) deposited in body tissue, averaged over the body. Such a dose would be caused by an exposure imparted by ionizing x-ray or gamma radiation undergoing an energy loss of 1 joule per kilogram of body tissue (l gray). One sievert is equivalent to 100 rem.

source: A radioactive material that produces radiation for experimental or industrial use.

stable: Non-radioactive.

Standard Model: Gauge theory encompassing the electroweak and strong interactions.

strong interaction: The interaction due to exchange of color. Also called strong force.

symmetry: Invariance of equations of motion under changes in condition.

thermal energy: Random kinetic energy possessed by objects in a material at finite temperature.

tracer: A small amount of radioactive isotope introduced into a system in order to follow the behavior of some component of that system.

transmutation: The transformation of one element into another by a nuclear reaction.

ultraviolet radiation: Electromagnetic radiation having wavelengths between the visible part of the spectrum and x-rays.

Van de Graaff accelerator: Device using a high voltage terminal to accelerate charged particles.

weak interaction: The interaction responsible for weak decays of particles, mediated by the exchange of $W^{\pm}$ and Z^{0} gauge bosons.

x-radiation: Electromagnetic radiation usually produced in transitions of the inner electrons of atoms. The wavelength is between ultraviolet and gamma rays.

x-ray: Electromagnetic radiation with wavelengths between ultraviolet and gamma rays.

Appendix B Classroom Topics

Topics for discussion or for written reports

1. Describe the three modes of radioactivity decay; explain the changes in atomic number and mass number for each; and diagram an example of each.
2. Describe how radioactive decay is related to energy states in the nucleus.
3. Describe nuclear stability in terms of the neutron to proton ratio.
4. Explain the shape of the chart of the nuclides.
5. Describe the distinction between fission and fusion reactions.
6. Describe the role of neutrons in causing and sustaining nuclear fission.
7. Give several examples of radioactive isotopes; predict how much will remain at the end of their third half-life.
8. Give examples of reactions producing transuranic elements.
9. Define the purpose of accelerators; compare and contrast linear accelerator, cyclotron and synchrotron.
10. List and define the four basic interactions between particles.
11. Demonstrate parity symmetry using a plane mirror as a prop.
12. Describe the nuclear evolution of the Universe in terms of time and temperature.
13. Use the World Wide Web to find a nuclear laboratory and learn about the research being done there. Report your findings to your class.

Topics about Nuclear Science related to societal issues

1. How does the application of radioactivity benefit and hurt us?
2. Is radioactivity unnatural?
3. In the future, what role should nuclear power plants act in supplying power for the world? How will new technologies such as solar effect this?
4. Compare and contrast the effects that nuclear, coal, hydroelectric and solar power have on the environment. How do they effect the Earth's $C0_2$ level? Do they contribute to global warming? What are the economic advantages and disadvantages of each?
5. Should we pursue the development of fusion power?
6. What should be done about the radioactive waste from medical applications? From nuclear power.
7. Do we have no more need for nuclear weapons? What can be done with dismantled nuclear weapons?

Possible Misconceptions

1. *Radioactivity first appeared during World War II.* Radioactivity has been around since the Big Bang. Humans have known about radioactivity and used it since the end of the 19th century.
2. *Atoms cannot be changed from one element to another.* Atoms can be changed to from one element to another with the addition or subtraction of protons. We see elements change in alpha decay, beta decay, fission, and fusion reactions.
3. *Fission and fusion are the same; fission is more powerful than fusion.* Fission is the splitting of heavier nuclei into lighter ones and fusion is the combining of lighter nuclei to form heavier ones.
4. *Neutrons and protons have no internal structure.* Neutrons and protons are composed of quarks and gluons.
5. Nuclear power plants produce harmful radioactive waste while other forms of electrical generation do not. Mining for coal brings uranium to the surface of earth and the uranium is distributed into the atmosphere when the coal is burned.
6. *Radiation causes cancer. Thus, it cannot be used to cure cancer.* Excessive radiation can cause cancer. The destructive power of radiation on cancerous cells can cure cancer.
7. *Once a material is radioactive it is radioactive forever.* One can physically or chemically remove the radioactive particles from the material or wait for it to decay. Some radioactive nuclei decay in a short time while other nuclei might last longer 10,000 years or even longer.

Appendix C Useful Quantities in Nuclear Science

atomic mass unit (u)	$\frac{1}{12}$ mass ^{12}C	$1.6605402 \times 10^{-27}$ kg
electric charge (coulomb)	e	$1.60217733 \times 10^{-19}$ C
speed of light (vacuum)	c	299792458 m/s (exact)

Particle	**Mass** (in *u*)	**Charge** (in electron charge, *e*)	**Half-life** (in seconds)
proton, p	1.007276	+1	stable
neutron, n	1.008665	0	624
electron, e or e^-	0.000549	-1	stable
neutrino, ν	> 0	0	stable
antiproton, $\bar{\nu}$	1.007276	-1	stable†
antineutron, $\bar{n}$	1.008665	0	624†
positron, e^+	0.000549	+1	stable
antineutrino, $\bar{\nu}$	> 0	0	stable†
muon, $\mu^{\pm}$	0.10565	+1, -1	3.17×10^{-6}
pion, $\pi^{\pm}$	0.14	+1, -1	3.76×10^{-8}
pion, π^0	0.14	0	6.63×10^{-17}
photon, γ	0	0	stable
gluon, g	0	0	
up quark, u	approximately 0.005	+2/3	
down quark, d	approximately 0.01	-1/3	
strange quark, s	0.1 to 0.3	-1/3	
charm quark, c	1.0 to 1.6	+2/3	
bottom quark, b	4.1 to 4.5	-1/3	
top quark, t	180 ± 12	+2/3	
^1H atom	1.007825	0	stable
^2H nucleus	2.013553	+1	stable
^2H atom	2.014102	0	stable
^3H nucleus	3.015500	+1	3.88×10^8
^3H atom	3.016049	0	3.88×10^8
^3He nucleus	3.014932	+2	stable
^3He atom	3.016029	0	stable
^4He nucleus	4.001506	+2	stable
^4He atom	4.002603	0	stable
^{12}C atom	12.000000	0	stable
^{238}U atom	238.050785	0	1.41×10^{17}

† Antiparticles are assumed to have same half-life as particles.
From the Review of Particle Properties, R. M. Barnett *et al*., Physical Review **D54**, 1 (1996).

International System of Units (SI)—SI prefixes

value	name	symbol
10^{-24}	yocto	y
10^{-21}	zepto	z
10^{-18}	atto	a
10^{-15}	femto	f
10^{-12}	pico	p
10^{-9}	nano	n
10^{-6}	micro	µ
10^{-3}	milli	m
10^{-2}	centi	c
10^{-1}	deci	d
10	deca	da
10^{2}	hecto	h
10^{3}	kilo	k
10^{6}	mega	M
10^{9}	giga	G
10^{12}	tera	T
10^{15}	peta	P
10^{18}	exa	E
10^{21}	zetta	Z
10^{24}	yotta	Y

Example of a Branching Ratio

Examples of three ways that ^{226}Ac decays. The quantity to the right is the fraction of times that a particular decay occurs. The sum is not 100% because the numbers are rounded.

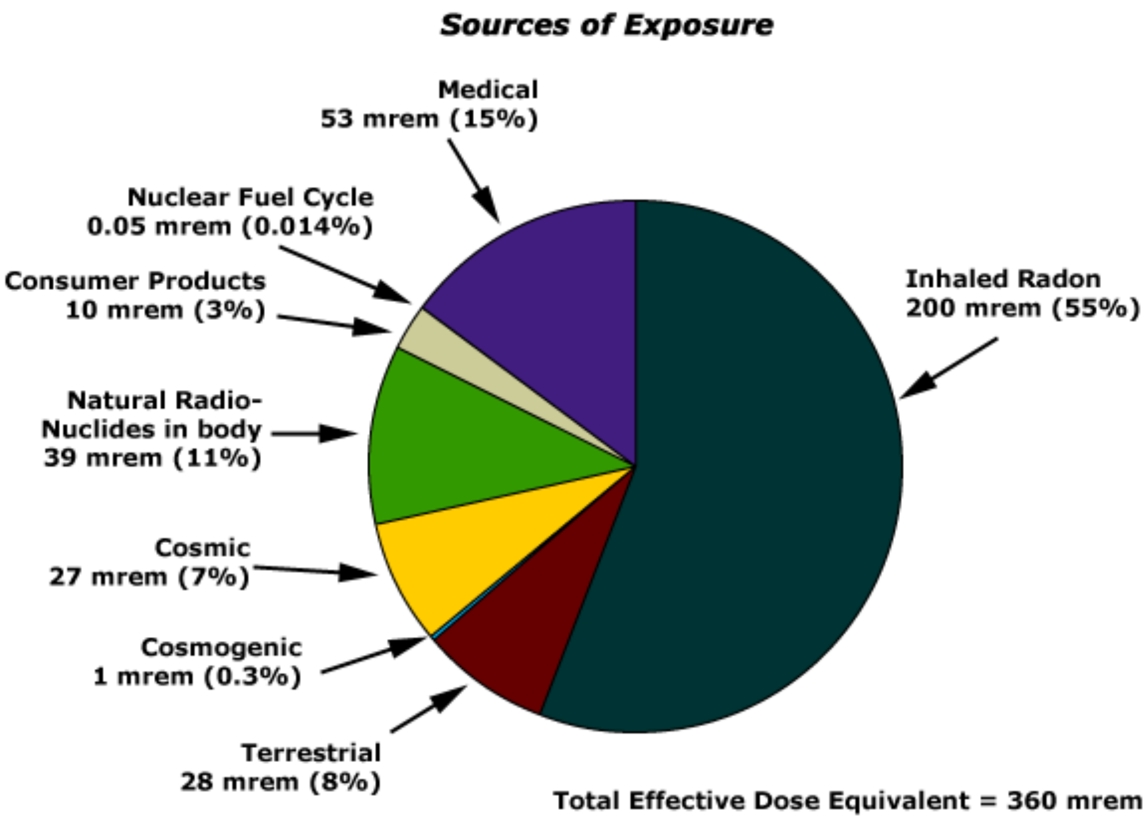
$^{226}Ac \rightarrow {}^{226}Th + e^{-} + \bar{\nu}$ 83%

$^{226}Ac + e^{-} \rightarrow {}^{226}Fr + \nu$ 17%

$^{226}Ac \rightarrow {}^{222}Fr + {}^{4}He$ 0.006%

Appendix D Average Annual Radiation Exposure

Reference: NCRP Report #93
Ionizing Radiation Exposure of the Population of the United States (1987)



Natural Background Radiation = 295 mrem (82%)
Manmade Radiation = medical + consumer products = 63 mrem (18%)

Appendix E Nobel Prizes in Nuclear Science

Many Nobel Prizes have been awarded for nuclear research and instrumentation. The field has spun off: particle physics, nuclear astrophysics, nuclear power reactors, nuclear medicine, and nuclear weapons. Understanding how the nucleus works and applying that knowledge to technology has been one of the most significant accomplishments of twentieth century scientific research. Each prize was awarded for physics unless otherwise noted.

Name(s)	**Discovery**	**Year**
Henri Becquerel, Pierre Curie, and Marie Curie	Discovered spontaneous radioactivity	1903
Ernest Rutherford	Work on the disintegration of the elements and chemistry of radioactive elements	1908 (chem)
Marie Curie	Discovery of radium and polonium	1911 (chem)
Frederick Soddy	Work on chemistry of radioactive substances including the origin and nature of radioactive isotopes	1921 (chem)
Francis Aston	Discovery of isotopes in many non-radioactive elements, also enunciated the whole-number rule of atomic masses	1922 (chem)
Charles Wilson	Development of the cloud chamber for detecting charged particles	1927
Harold Urey	Discovery of heavy hydrogen (deuterium)	1934 (chem)
Frederic Joliot and Irene Joliot-Curie	Synthesis of several new radioactive elements	1935 (chem)
James Chadwick	Discovery of the neutron	1935
Carl David Anderson	Discovery of the positron	1936
Enrico Fermi	New radioactive elements produced by neutron irradiation	1938
Ernest Lawrence	Invented the cyclotron	1939
George De Hevesy	Use of isotopes as tracers in the study of chemical processes	1943 (chem)
Otto Hahn	Discovered fission of massive nuclei	1944 (chem)
Patrick Blackett	Improved cloud chamber and discoveries in nuclear physics and cosmic rays	1948
Hideki Yukawa	Predicted the existence of mesons as the basis of the nuclear force	1949
Cecil Powell	Developed the photographic method of studying nuclear processes	1950
Edwin McMillan and Glenn Seaborg	Discoveries in the chemistries of the transuranium elements	1951 (chem)
John Cockcroft and Ernest Walton	Transmutation of nuclei by accelerated particles	1951

Felix Bloch and Edward Purcell	Measured magnetic fields in atomic nuclei (NMR)	1952
Walther Bothe	Analysis of cosmic radiation using the coincidence method	1954
Willard Libby	For his method to use ^{14}C for age determination	1960 (chem)
Robert Hofstadter	Studied nuclear structure with electron scattering	1961
Rudolf Mössbauer	Discovery of recoilless resonance absorption of gamma rays in nuclei	1961
Eugene Wigner	Application of symmetry principles to the nucleus	1963
Maria Goeppert-Mayer and Hans Jensen	Developed the nuclear shell model	1963
Hans Bethe	Developed the theory of nuclear reactions in stars	1967
Aage Bohr, Ben Mottelson, and James Rainwater	Developed the theory of collective states in nuclei	1975
Rosalind Yalow	Study of insulin using radioactive tracers	1977 (bio)
William Fowler	Studies on the formation of nuclear reactions which produce chemical elements in astrophysical processes	1983
Raymond Davis and Mastoshi Koshiba	Contributions to the understanding of cosmic neutrinos	2002
Takaaki Kajita and Arthur B. McDonald	For the discovery of neutrino oscillations, which shows that neutrinos have mass	2015

Appendix F Radiation Effects at Low Doses

For the Hiroshima and Nagasaki bombs, the exposure of the population was primarily from gamma rays and neutrons emitted almost simultaneously with the bomb explosion. The observational evidence for radiation-induced cancer in humans comes largely from these exposures and others in which large doses were received over short periods of time. However, for the setting of environmental standards and for gauging the consequences of exposures routinely received by the general public, the most important doses are relatively small doses received over long periods of time.

Conventional Assumption for Low Doses: the Linearity Hypothesis

In the absence of directly applicable observational evidence, the rate of cancer induction at low doses and dose rates is estimated by extrapolation from observations at high doses. A particularly simple extrapolation estimate is provided by the widely adopted *linearity hypothesis*, according to which the increased risk is proportional to the excess radiation dose.

The major advisory bodies in their recent publications have adopted this hypothesis. There are some differences in details. Several of these groups (ICRP, NCRP and UNSCEAR, but not BEIR V) have included a dose and dose rate effectiveness factor (variously, DDREF or DREF) of about 2, which halves the risk per unit dose at low doses or low dose rates (or both) compared to the risk given by a linear extrapolation from the high dose region. [See end note at the end of Chapter 15 for identification of these groups.]

Taking the DDREF into account, as well as other minor differences in the estimates, an overall consensus estimate for low doses and low dose rates is:

risk of eventual fatal cancer: 0.05 per Sv (0.0005 per rem).

This risk factor can be taken to apply to an "average person" but in its most precise form applies to a general population. Consider a population of 100,000, with a representative distribution by age and sex. Then, for example, if each person receives a 20 mSv dose, the collective exposure is 2000 person-Sv and the calculated number of excess eventual cancer deaths is 100.

Despite being widely accepted as a guideline in setting standards for protecting public health, the linearity hypothesis is not firmly established as an expression of scientific knowledge. Thus, the BEIR V report expresses the following major reservation:

> ... departure from linearity cannot be excluded at low doses below the range of observation. Such departures could be in the direction of either an increased or decreased risk. Moreover, epidemiological data cannot rigorously exclude the existence of a threshold in the millisievert dose range. Thus the possibility that there may be no risks from exposures comparable to natural background radiation cannot be ruled out. At such

low doses and dose rates, it must be acknowledged that the lower limit of the range of uncertainty in the risk estimates extends to zero.

Reflecting the uncertainties, many alternative forms have been proposed for the shape of the curve relating cancer risk and radiation dose (see Figure F-1). These include:

1. The linearity assumption [curve B].
2. Greater risk at low doses than implied by linearity ("supra-linearity") [curve A].
3. A linear-quadratic curve in which the low-dose risk is depressed [curve C].
4. A negative region at very low doses, corresponding to a beneficial effect (this is termed hormesis) [curve D].
5. A threshold, below which there is no appreciable cancer induction [not shown].
6. A DDREF which reduces the risk below that calculated for linearity [not shown].

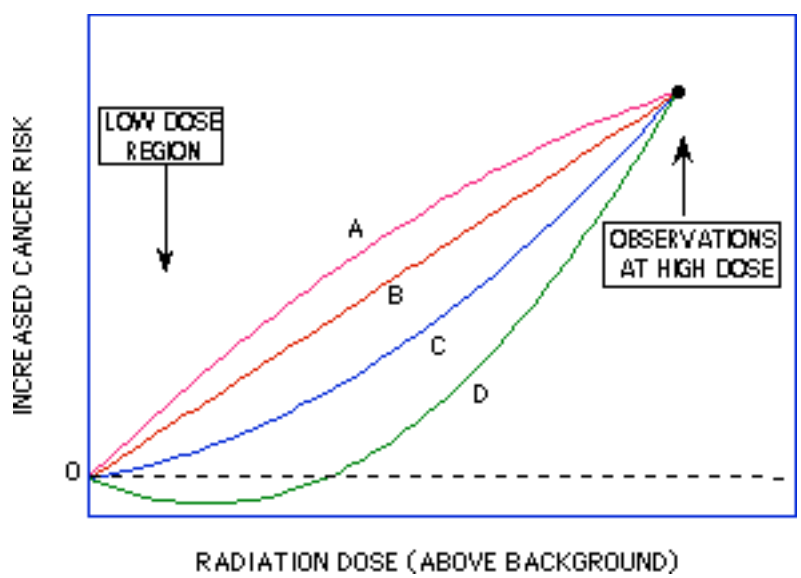


Figure F-1. Alternative assumptions for the extrapolation of the cancer risk vs. radiation dose to low-dose levels, given a known risk at a high dose: supra-linearity (A), linear (B), linear-quadratic (C) and hormesis (D).

The conventional wisdom, as reflected by the chief advisory bodies, is to accept linearity (1), usually with inclusion of a DDREF (6). Alternative (2) and (4) are outside the mainstream of standard assessments, and can be considered to be maverick opinions, although of late more serious attention has been given to hormesis (4) and to the possibility of adaptive mechanisms that might explain it.[i]

The most substantial dissent from the conventional wisdom is the contention that at low doses the effects are much lower than implied by linearity. This view is reflected in a position statement issued in early 1996 by the *Health Physics Society,* a leading US professional organization. According to this statement, for doses below 100 mSv (10 rem) "risks of health effects are either too small to be observed or are non-existent." This statement reflects the very controversial status of the assessment of the radiation risks at low doses.

Evidence on Radiation Effects at Low Doses and Low Dose Rates

In principle, the uncertainties surrounding low-dose/low-dose-rate effects could be settled by the study of populations that have been exposed to slightly above-average radiation doses. Such populations exist in many countries, including China, India, Brazil and the United States.[ii] However, due to statistical uncertainties, the difficulties of establishing appropriate comparison groups, and lack of consistency among studies, these studies have not provided convincing evidence either to support or refute the linearity hypothesis.

A second possibility is to look at the experience of workers in the nuclear industry. The results of individual studies have been inconclusive, and to investigate the matter further a combined analysis has been carried out of seven studies—three for sites in the United States (Hanford, Oak Ridge, and Rocky Flats), three for sites in the United Kingdom, and one for Canada. A total of 95,673 workers was included, of whom 60% received effective doses above 10 mSv (1 rem). In the entire population, there were 15,825 deaths, of which 3976 were from cancer. The comprehensive results for all cancers taken together showed a very slight decrease in cancer rate with increasing dose. However, this result had no statistical significance. Of possible greater statistical significance is a slight increase with radiation dose for some types of leukemia. Overall, the statistical uncertainties were large enough that the analysis did not rule out linearity or any of the other alternative dose-response curves indicated in Figure 15-1—although it does set an upper limit on the possible magnitude of a hypothesized supra-linearity effect.

There is one group of nuclear industry workers for, which there has been well-established harm, namely uranium miners who received large doses from radon and clearly have elevated lung cancer rates. The radon in mines originates from the decay of radium and the seepage of the resulting radon into the mine. There is similar seepage of radon into houses, causing a buildup of indoor radon, although usually at levels far below those experienced by the early uranium miners. The EPA estimates that indoor radon now leads to 7000 to 30,000 lung cancer fatalities per year in the United States.

Efforts to confirm directly the effects of indoor radon have led to mixed and highly controversial conclusions. One class of studies, termed ecological studies, looks for correlations between the average radon level in a region and the lung cancer fatality rate. In the largest and best known of these studies, covering 1,729 counties in the United States, Bernard Cohen finds the county-by-county lung cancer rates to be inversely correlated with average radon levels. Although many readers have interpreted this study as suggesting hormesis, Cohen limits his conclusions to saying that the results refute the linearity hypothesis. This study covered most of the US population, and therefore the statistical uncertainties are small.

However, those who contend that ecological studies are inherently flawed hotly dispute these conclusions. They call instead for reliance on epidemiological studies in which comparisons are made between groups of individuals, where the radon exposure and health history is determined for each person. In *case-control* studies, a group of lung cancer victims is matched against a non-diseased control group and the history of past radon exposure is compared. In an analysis published in early 1997, Jay Lubin and John Boice carried out a combined analysis of the eight largest case-control studies. From this combined data, they find a positive correlation between risk and dose, consistent with a linear extrapolation from the data on miners. The contradiction between this result and that of Cohen will probably not be resolved without additional studies.

In summary, none of these approaches has provided unambiguous evidence of cancer induction at low dose levels, and the issue remains highly controversial. In a 1990 report, the ICRP concluded that: "Overall, studies at low dose, while potentially relevant to the radiation protection problem, have contributed little to quantitative estimates of risk." Progress since 1990 does not appear to have decisively changed the situation. It is not obvious that epidemiological or ecological studies of any sort will be able to resolve the question of the effects of low-level radiation, although it should be possible to set upper limits on the magnitude of any effects.

In the end, the answers may have to come from a better understanding of damage and repair mechanisms at the cellular or molecular level. Here as well, however, the fundamental issues are still unsettled. For example, in a 1994 UNSCEAR report on adaptive responses to radiation, the state of knowledge was summarized in the following cautious manner:

> It is to be hoped that better understanding of mechanisms of radiation effects obtained in molecular studies might provide a basis upon which to judge the role of adaptive response in the organism. In the meantime, it would be premature to conclude that cellular adaptive responses could convey possible beneficial effects to the organism that would outweigh the detrimental effects of exposure to low doses...

It is these uncertainties, on biological as well as epidemiological questions, that keep the controversies alive.

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[i] The term *adaptive* refers to processes that, in the words of the 1994 UNSCEAR Report, "... may condition cells so as to induce processes that reduce either the natural incidence of cancer in its various forms or the likelihood of excess cancers being caused by further ionizing radiation."

[ii] For example, it has been pointed out that cancer rates are lower in Colorado than in Louisiana, although the doses from terrestrial radiation and cosmic rays are roughly 1 mSv/yr greater in Colorado due to the mineral content of the ground and the higher altitude. But this comparison carries little significance without extensive comparisons of other factors that might influence the cancer rates in the two populations.