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BASIC RESEARCH SERVING SOCIETY

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Foreword

The Department of Energy, The National Science Foundation and the Division of Nuclear Physics of the American Physical Society have recognized a need to communicate the opportunities, the achievements, and the benefits to society arising from basic research in nuclear science. Research at the forefront of science is a hallmark of our advanced society, and the fruits of this research should be known to the members of the society which supports it. The Division of Nuclear Physics asked Professor Steven Koonin of the California Institute of Technology to author a short article with the above goal in mind. This pamphlet is the result. The organizations and individuals associated with the inception and production of the article, and the members of the nuclear science community, express their gratitude to Dr. Koonin.

Nuclear Science

Nuclear science is part of the frontier of basic science. Its subject is the atomic nucleus, a tiny but complex bit of matter that lies within every atom of the universe. The study of nuclei and the particles of which they are constructed contributes to man's understanding of the world around him; nuclear properties provide unique examples of the strange natural laws which operate at the submicroscopic level.

Nuclear science also has a long tradition as an applied science, using the properties of nuclei and the methods by which they are studied to improve the quality of life and to address some of the problems faced by modern society. It has furthered man's understanding of nature and has placed powerful forces and vast energy supplies at his disposal.

Nuclear science has made, and continues to make, invaluable contributions to other scientific fields. Its tools, working methods, and products are found throughout modern science and technology. The study of elementary particles (now high-energy physics) was begun by nuclear scientists using the methods and equipment of nuclear science. Radioactive isotopes, discovered and studied by nuclear scientists, are widely used in medicine, biology, chemistry, archaeology, space science, and numerous other disciplines.

This booklet describes nuclear science—its past accomplishments and future directions- and gives just a few examples of the importance of nuclear science to other sciences, to technology, and to education.

The Heart of the Atom

The discovery of the atomic nucleus was a major landmark in our investigation into the nature of matter. This subject has fascinated us since the 5th Century BC, when the Greek philosopher Democritus hypothesized the existence of atoms, which he believed to be the smallest units of matter. By the 19th Century, chemical studies had demonstrated that ordinary matter was composed of atoms and molecules whose size was roughly 10^{-8} cm (about ten billionths of a centimeter). Although many of the laws of chemistry had been deduced, atoms were still believed to be the basic, indivisible building blocks of the universe.

The first hint that atoms might consist of yet smaller entities came in 1897, when Thomson showed that atoms contain electrons, light particles with negative electric charge. Since it was known that atoms are electrically neutral, this naturally raised the question of where in the atom did the compensating positive electric charge lie; that is, "What was the structure of the atom?" The answer was provided in 1910 by Rutherford, who performed a classic experiment demonstrating the existence of the atomic nucleus.

To understand how Rutherford studied an object far too small to be seen directly (even through a microscope), consider a hypothetical analogy: Imagine a blindfolded person who seeks to determine the character of an object some distance from him. To do this, he employs an air rifle

and some assistants, arrayed around the object. By firing pellets in different directions and asking which of his assistants detects the ricocheting pellet from each shot, he can gradually gain a picture of the size of the object and which portions of it can stop his projectiles.

Rutherford's principle was the same as the rifleman's, but his "rifle" was the naturally radioactive substance radium, his pellets were alpha-particles (helium nuclei), his "object" was a gold atom in a thin gold foil, and his "assistants" were detectors which emitted a flash of light when struck by an alpha particle. A schematic drawing of Rutherford's experiment is shown in Figure 1. His results demonstrated that the positive atomic charge was condensed in a small region at the atom's center and that this atomic "nucleus" contained nearly the entire mass of the whole atom. Thus, an atom consists of very light negative electrons attracted to and orbiting about a heavy positive nucleus. The atom's behavior, such as its chemical properties, depends on the number and motion of the electrons. The quantitative understanding of this simple atomic picture in the 1920's was one of the early triumphs of quantum mechanics, the rules which govern all atomic and sub-atomic phenomena.

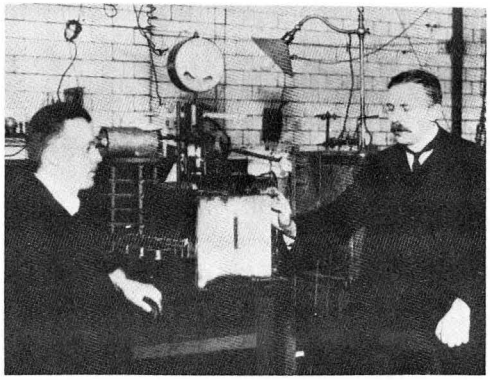


Figure 2. Geiger and Rutherford in Schuster Laboratory, Manchester. Photograph courtesy of The American Institute of Physics.

Nuclear science, which is concerned with the structure of the nucleus, can be said to date from 1932, when Chadwick discovered that nuclei contain *neutrons,* particles with no electrical charge.

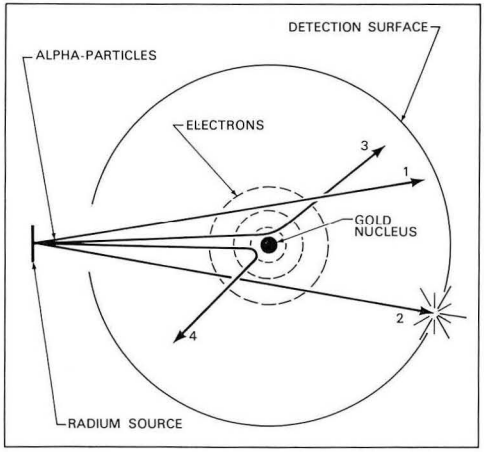


Figure 1. A sketch of Rutherford's experiment. Alpha-particles (*helium nuclei*) from the radioactive radium source pass almost undeflected (*1 and 2*) through the cloud of electrons surrounding an atomic nucleus (*shown highly magnified*). Particle 3 is appreciably deflected and particle 4 is almost completely turned around. These observations showed that almost the entire weight of the atom is concentrated into a small region - the nucleus - rather than being spread out over the whole atomic volume.

Today, we understand that nuclei are composed of different numbers of two types of almost equally massive particles: the electrically neutral neutrons and the positively charged protons, collectively called nucleons. A given type of nucleus is therefore specified by its neutron number and proton number. The simplest nucleus, that of the hydrogen atom, consists of a single proton. In small nuclei, the numbers of neutrons and protons are roughly equal, but in larger nuclei an excess of neutrons is required to provide the additional attractive force needed to overcome the mutual electrical repulsion of the protons.

Since atoms are ordinarily neutral, the number of electrons in an atom is equal to the number of protons in its nucleus. The number of electrons determines the chemical properties of the atom. Atoms whose nuclei have equal numbers of protons but different numbers of neutrons are called isotopes and are nearly identical in all chemical aspects, although their nuclei may have very different properties. At the present time, over 2600 different nuclear species are known (Figure 3) ranging in proton number from 1 to 109 and in mass number (total number of nucleons) from 1 to 263.

Nuclei are incredibly small. Their diameters are typically 10^{-12} cm, or about one trillionth of a centimeter. Nuclei are very much smaller than the atoms at whose centers they lie and are quite separated from each other in ordinary matter. Indeed, if a typical atom were expanded so that its nucleus were the size of a baseball, its electrons would orbit at an average distance of several miles. The combination of small size and great mass makes nuclei the densest form of matter known; a piece of nuclear material the size of a sugar cube would weigh about 200 million tons and would promptly be pulled by gravity to the center of the earth.

The nucleons in a nucleus are not at rest. Due to their mutual interaction, they are in a state of constant motion governed by the laws of quantum mechanics. In addition to the ordinary "ground" state of motion that the nucleons may have, they can also be made to move about in more energetic patterns, giving rise to excited nuclear states. Many such states are known for each species of nucleus and can be classified by both their energy and the particular characteristics of the motion of the nucleons.

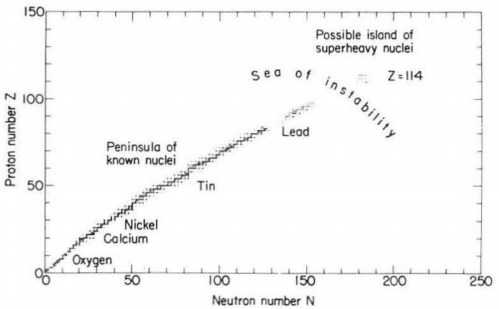


Figure 3. Chart of nuclear species. A heavy dot at a particular proton and neutron number indicates a nucleus which is naturally occurring. Light dots indicate nuclei which have been produced artificially in the laboratory. The position of some familiar elements is shown. Also shown is an "island" of superheavy nuclei which is predicted to exist by some theories but has not yet been discovered.

The state of a nucleus can be changed by the emission or absorption of various types of radiation, including electrons, neutrinos (electrically neutral particles of small or vanishing mass), and photons, the "particles" of light. Nuclear states can also be changed by collisions with other nuclei.

Nuclei are truly unique and important forms of matter. They are the only readily accessible example of the effects of nature's most powerful force, which is called the "strong" force. Most of the material in the universe is in the form of nucleons or nuclei, and nuclei are the ultimate source of energy, since the sun and stars shine by energy gained from the transformation of one nuclear species into another. Even if practical benefits did not accrue, these facts alone would be sufficient motivation for a detailed and thorough study of nuclei and their properties.

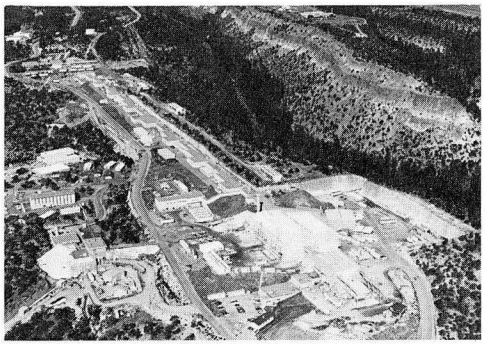


Figure 4. An aerial view of the Clinton P. Anderson Meson Physics Facility (*LAMPF*) at the Los Alamos National Laboratory. This accelerator, extending over one-half of a mile from background to foreground, produces intense beams of high-energy protons and mesons. Visible in the foreground are the main experimental buildings housing detectors for basic nuclear science research and a facility for bio-medical research with particle beams.

Seeing Into the Sub-Atomic World

Most of our knowledge of nuclei has been obtained from experiments very much in the spirit of Rutherford's. To illustrate how this has been accomplished, it is useful to return to the blindfolded rifleman. Once he has determined the size of the object, he might choose to shoot at its edge, knocking off fragments for his assistants to analyze. Alternatively, he could vary the speed of his pellets and determine the strength of the object by seeing which ones are stopped in it. In the same way, nuclei are studied by firing nuclear projectiles at them and analyzing the products of the ensuing collisions.

Experience has shown that nuclei are best studied by using projectiles whose energy is known precisely. High-speed projectiles are also often desirable, since the properties of particles imply that the greater their speed, the more detail they can reveal about the target. Thus, we no longer use natural radioactivity as our "rifle", but instead employ accelerators, machines which produce precise beams of high-speed particles (Figure 4). Our "assistants" have also changed since Rutherford's time, although they operate on similar principles. Detectors are often major pieces of apparatus in their own right, employing magnets, state-of-the-art electronics, and other devices to determine the character and velocity of each of the many products of a nuclear collision. One of these detectors is shown in Figure 5.

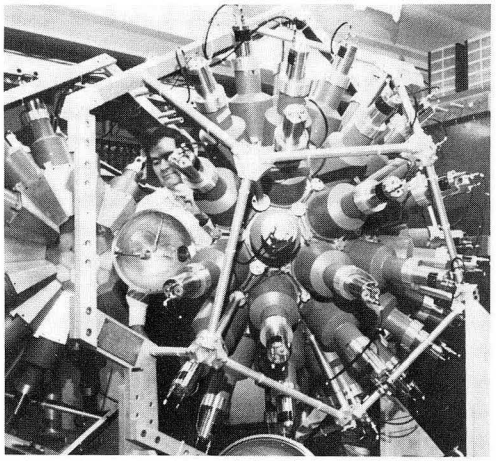


Figure 5. The "spin spectrometer" at the Oak Ridge National Laboratory. Some 72 individual detectors almost completely surround the target to record nearly all of the photons emitted during a nuclear collision. By analyzing the photons, nuclear scientists study the properties of rapidly spinning nuclei.

Nuclei exhibit an extraordinary range of properties. At one extreme, the behavior of a nucleus is determined by the motion of a single one of its constituent nucleons; at the other extreme, a nucleus behaves like a small drop of honey. Many nuclei are spherical, while others are shaped like footballs. Some nuclei have complicated bumps and hollows on their surfaces. Many of them are in a permanent state of rotation, while others are stationary. To study all of these properties, and many others that have been discovered, nuclear scientists need a wide variety of projectiles. Each of them is best suited to study a particular aspect of the nucleus, each is produced by a different type of accelerator, and each is best observed by a different type of detector.

There are four fundamental forces in Nature: the "strong", "weak", electromagnetic, and gravitational forces. One of the most important tasks of basic science is to study these forces and to try to establish their inter-relationships. The properties of nuclei are determined by three of the four fundamental forces—all but gravity. Studies of nuclei led to the discovery of two of these forces, the "strong" and the "weak", and have revealed much about their basic character. For example, we know that the "strong" force between nucleons holds a nucleus together. We understand something, but not everything, about how the "strong" force between two nucleons depends upon the distance between them. But we do not know for certain how this force changes when other nucleons are present. New theories have recently been developed which relate the seemingly varied forces of Nature. Nuclear scientists are using nuclear properties to test these relations in experiments which complement those undertaken by elementary particle physicists.

Projectiles for the study of nuclei can be chosen to emphasize the role of each kind of force. Their character ranges from the almost surgical precision and delicacy of high-speed electrons to the violent and dramatic collisions of large nuclei moving at nearly the speed of light (Figure 6). Only the gravitational force, which is far too weak to be effective in ordinary nuclei, has not been employed in the nuclear science laboratory. However, it does play an important role in the very largest of nuclei, the neutron stars.

The electromagnetic interaction of high-energy light rays (photons) with nuclei provides a vast body of information about the structure of the nucleus. High-speed

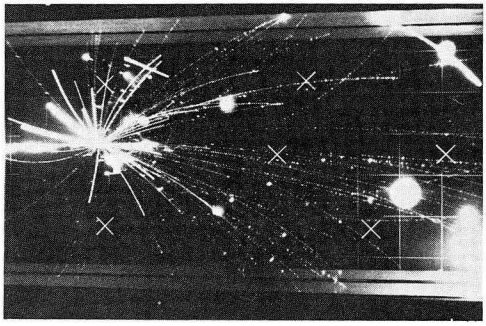


Figure 6. The head-on collision of a high-energy Argon nucleus (*40 nucleons, entering from the left*) with a Lead target nucleus (*208 nucleons*) as recorded at the Bevalac accelerator operated by the Lawrence Berkeley Laboratory. A device called a streamer chamber is used to make visible the more than 50 small nuclei and mesons emerging from this collision. Computer analyses of pictures such as this one permit the properties of the collision to be determined, including the very high temperatures reached.

electrons, obtained from an accelerator, also interact with nuclei through the electromagnetic force. By using electron accelerators and detectors much as giant microscopes, scientists have been able to "see" in unprecedented detail how the electrical charge and currents are distributed in nuclei (Figure 7). The faster the electrons, the finer the detail that they can reveal. For this reason, nuclear scientists are planning to build an electron accelerator more powerful than any of those that exist presently.

The "weak" force can transform an isolated neutron into a proton, an electron, and an uncharged anti-neutrino. Neutrons within nuclei can also undergo this same transformation. Protons within a nucleus (but not in free space) can be similarly transformed, resulting in a neutron, a positively charged electron, and a neutrino. Thus, the weak force provides a way for a nucleus to reach a lower level of energy by changing its relative number of neutrons and protons. Because many nuclear properties are so well known, they can be used to study the weak force itself. Basic features of the weak force have been revealed by experiments that use the nucleus as a controlled but selectively variable environment for its action. The "weak" force is so feeble that its action takes place very slowly on the nuclear time scale; the transformations it causes may take seconds, days, or even years to occur. It is this force which is responsible for most of the radioactivity of waste products from nuclear power plants.

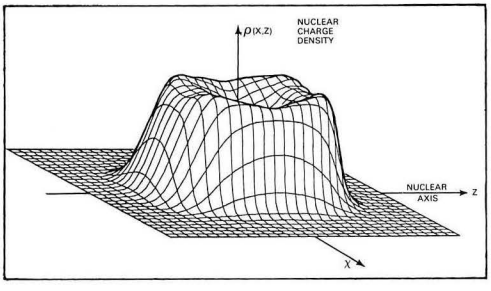


Figure 7. A perspective view of the distribution of electrical charge in a nucleus of the element Ytterbium with 174 nucleons (*70 protons and 104 neutrons*) as determined by electron-scattering experiments at the MIT-Bates Electron Accelerator. This nucleus is seen to be elongated and to have its highest density in regions away from its center.

The strong interaction governs collisions caused by many different types of projectiles. Among these are the nuclei themselves, both small and large (the latter are known as heavy ions). Other important projectiles that play a role in the nuclear interaction are mesons. Particle beams may be created of pions and kaons whose masses are between those of the

electron and the nucleon. All of these projectiles interact with a target nucleus with the same "strong" force that binds nucleons together. They therefore cause far more dramatic collisions than do electromagnetic or "weak" projectiles, such as neutrinos. Light nuclei can be used to cleanly add or remove one or several nucleons from a target nucleus. This technique has taught us much of what is known about how nucleons move within the nucleus. Pions affect the nucleus in unique ways, since they are a major carrier of the strong force between nucleons. Together with kaons, they offer the opportunity to introduce "impurities" into the nucleus by changing the state of the nucleons themselves, rather than the nucleus as a whole. Heavy ions extend our knowledge of nuclear behavior in yet another dimension. Unlike other projectiles, they can be comparable in size to the target nucleus itself and so can significantly change its shape, temperature, spin, and neutron or proton number; in short, severely stress the target nuclear material. Collisions between high-speed heavy ions and target nuclei are the best hope for producing and studying in the laboratory the hot dense matter important in such astrophysical objects as supernovae and neutron stars. In this way, nuclei have been heated to temperatures of one trillion degrees, far hotter than the sun and stars.

The thorough exploration of all nuclear properties requires vigorous and active research programs using the full spectrum of accelerators and projectiles available. These techniques are now the standard tools of nuclear research and therefore play a central role. However, of greater importance are new accelerators producing intense beams of electrons, neutrinos, kaons, antiprotons, and high-speed heavy ions. All of these have become feasible because of recent advances in accelerator design, but most of them await construction.

The Diversity of Nuclear Properties

A common feature in many branches of modern science is the study of many-body systems. These contain a large number of particles that interact with each other through one or more of the four fundamental forces. Many-body systems of all types and sizes are found throughout the natural world. They include the planets in the solar system, the electrons in an atom, and the nucleons in a nucleus. Nearly all many-body systems are so complicated that their properties are very difficult to predict exactly, even when the fundamental forces governing them are well understood. Nevertheless, approximate calculations can often be made with great accuracy. For example, because gravity is so weak and the solar system is so large, it has been possible for centuries to predict accurately the motions of the planets in the sky, the tides of the oceans, and the times of eclipses.

The electromagnetic force that holds electrons within atoms is far stronger than gravity, and atoms are much more compact than is the solar system. As a result, the approximations used in describing the motions of the planets must be substantially modified to calculate the motions of many electrons around an atomic nucleus. Nevertheless, because of recent advances

in computational chemistry and computer technology, many atomic properties can now be investigated more easily by calculations on a computer than by experiments in a laboratory.

The "strong" force between nucleons is even stronger and more complicated than the electromagnetic force between electrons, and nuclei are far denser than atoms. Exact predictions of the properties of nuclei, which may contain more than two-hundred nucleons, are therefore impossible at present, even with the largest computers. Moreover, our experience with other many-body systems in physics has taught us that they exhibit a surprising diversity of phenomena. This is indeed the case with nuclei. We therefore understand the nucleus not as a system whose features follow directly from a few simple equations (although these may indeed exist), but rather through a set of overlapping and occasionally contradictory models which describe different aspects of the nuclear world. One of the great challenges of nuclear science is to reconcile very different yet equally valid pictures of the same nucleus. Here are some broad themes which summarize our current knowledge of nuclei.

The Strong Force: The force between nucleons is the "strong" force. It is fundamental to nuclear science, for it determines nearly all nuclear properties. Experiments have shown that there is no strong force between two nucleons when they are far apart. The strong force begins to attract the nucleons toward one another when they come closer together, as in an ordinary nucleus, but becomes strongly repulsive when they are separated by distances smaller than about one-tenth of the radius of a nucleus. The strength of the "strong" force also depends in a very complicated way on the spins and relative motion of the two interacting nucleons. For larger separations, this force arises from the exchange of pions and other mesons between the nucleons, although there are as yet but a few experiments which conclusively reveal the presence of mesons in nuclei. This situation is changing rapidly and we hope to gain a rather complete characterization of the role of mesons in nuclei.

Nucleons themselves are believed to be complex structures, very likely consisting of smaller particles called quarks and gluons. It is believed that the repulsion between nucleons when they are a very short distance apart is somehow due to the quarks, although we do not yet know precisely how. This is one of the most interesting problems in all of physics and is currently under active study. Since nuclei are the only stable systems of strongly interacting particles, they offer a unique opportunity for exploring the consequences of this quark structure. Are there nuclear properties which are substantially affected by such "exotic" constituents? How might we best observe them? Are there circumstances in which nuclear systems behave like a collection of quarks rather than like a collection of nucleons? The role of quarks and mesons in nuclei is one of the fundamental questions of modern nuclear science. Its elucidation will have an impact on how we understand both nuclei and the nucleons of which they are composed.

The Shell and Liquid Drop Models: Despite the strong interaction between each pair of nucleons, many nuclear properties can be understood in terms of a simple picture known as the "shell" model. In the shell model, each nucleon moves almost independently under the average influence of the others, much as the planets orbit the sun or atomic electrons orbit a nucleus. This extraordinary simplicity is very surprising, but can be explained on the basis of the force between the nucleons and the laws of quantum mechanics governing their motion. Thus, very much in analogy with our understanding of atoms, certain features of an entire nucleus, which may contain more than two hundred nucleons, are determined by the motion of only one or a few almost independent nucleons near the nuclear surface. The shapes, spins, and other properties of weakly excited nuclei can be predicted with some confidence by this model, as can the average characteristics of the myriad of strongly excited states of a given nucleus.

In the shell model, nuclear properties rest on the nearly independent motion of a few nucleons near the nuclear surface and hence vary dramatically from nucleus to nucleus. However, other aspects of nuclear behavior imply that nucleons can also behave cooperatively; so that the nucleus appears as a small electrically charged droplet of nuclear matter. There is no real inconsistency here, however, as can be seen through the following analogy. In studying people, a psychologist might try to understand individuals one by one. But no matter how clever he is, he could not predict with confidence the result of many people voting in a national election from his knowledge of people taken one at a time. People live in a society; they influence it and are influenced by it. Similarly, a nuclear scientist may use the shell model when studying the behavior of an individual nucleon within its "society", the nucleus. But when he turns his attention to the much larger "society" of nucleons and tries to understand how it behaves as a whole, he uses a different model, the liquid drop model.

Nuclear liquid drops are endowed with such familiar properties as density, pressure, surface tension, and temperature. These properties arise from a cooperative motion of many nucleons and vary smoothly from one nucleus to another. They include the amount of energy needed to break the nucleus apart into separate nucleons, the vibrations and rotations of the nucleus as a whole, and the very important process of fission, in which a large nucleus divides into two smaller nuclei of comparable size (Figure 8). Such cooperative behavior can be explained qualitatively in terms of the general features of the strong and electromagnetic interactions between nucleons, but any attempt at a precise description nearly always exhausts our ability to treat the nuclear many-body system. Thus, for example, we understand that larger nuclei are more prone to fission, but to predict the detailed fission properties of a given nucleus requires a synthesis of both the liquid drop and the independent-particle shell model pictures. Considerable progress has been made on this problem in the past decade.

Nuclear Symmetries: The concept of symmetry is fundamental to all of modern science. It has been applied with great success to understand elementary particles, atoms, and solid materials. Nuclei are no exception; symmetries play a major role in our modern understanding of nuclear structure. Figure 9 may help in understanding exactly what symmetries are. Two hypothetical nuclear shapes are shown. The upper one appears identical

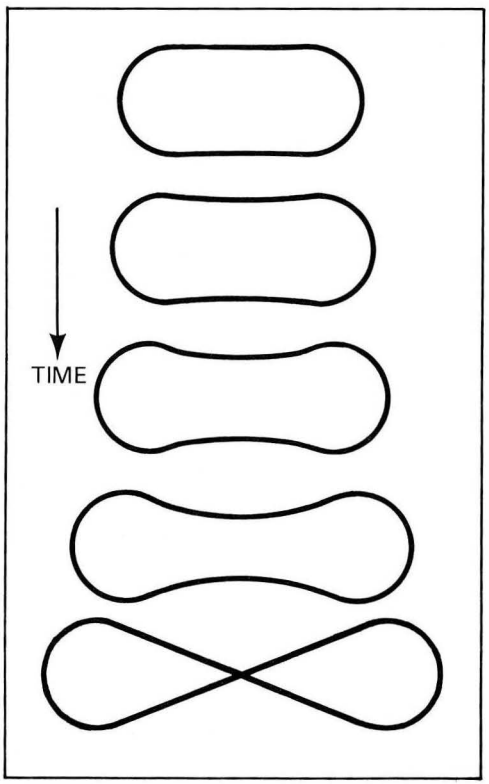


Figure 8. Successive stages in a model of the fission of a Uranium nucleus with 236 nucleons (*92 protons and 144 neutrons*). In these calculations, the nucleus is assumed to behave like an electrically charged, viscous liquid drop. The time between successive pictures is a billionth of a trillionth of a second.

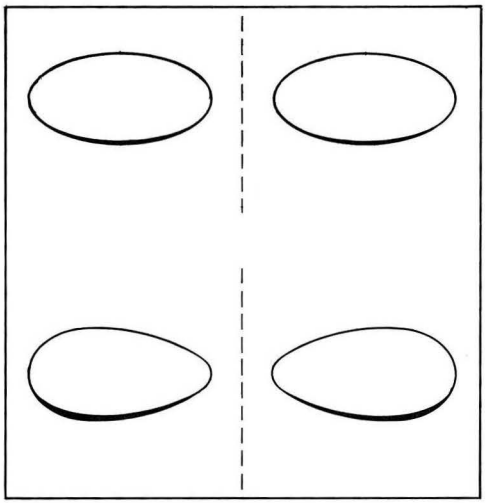


Figure 9. An illustration of the concept of nuclear symmetries.

to its "reflection" across the dashed line, while the lower shape appears to "reverse" when reflected. Thus, these shapes can be characterized by saying that the upper one is symmetric while the lower one is not. In an analogous manner, all nuclear states can be classified by their behavior under a host of transformations similar to the "reflection" described above. These include rotating the nucleus, reflecting it in a hypothetical mirror (termed parity), and the reversing the sense of time. Such classifications result in surprising relations between the properties of apparently unrelated nuclear states.

A nuclear symmetry which follows from the most fundamental properties of the strong interaction is that associated with the interchange of neutrons and protons in a nucleus, termed isospin. Thus, the behavior of a Carbon nucleus with 6 protons and 7 neutrons can be related to that

of a Nitrogen nucleus with 7 protons and 6 neutrons. Isospin is particularly evident in light nuclei, which have nearly equal numbers of neutrons and protons. It is the simplest example of the more complex symmetries central to modern elementary particle physics. The motion of the nucleons in excited nuclear states also appears to exhibit certain symmetries. These are not yet well understood, but are thought to arise from the special properties of the interactions among the surface nucleons. Symmetries of all types impose order and regularity on seemingly chaotic patterns of nuclear behavior. However, they are often not evident in a superficial study and are revealed only by a careful and systematic investigation of many individual nuclear properties.

Nuclear Reactions: One reason for studying nuclear collisions is to understand the structure of the target and projectile nuclei involved. However, the processes by which nuclei interact with each other form a major field of study in its own right which offers important insights into dynamic nuclear properties. For example, heavy ion collisions have shown that large nuclei under stress are extremely viscous and behave in collisions much like small drops of honey (Figure 10). The character of nuclear reactions ranges from the fast, "direct" type which occur when the target and projectile just graze each other and involve only a few nucleons of the system to the slow "compound nucleus" type in which the collision energy is shared among many nucleons and is eventually removed by the "boiling off" of small nuclear fragments. Recently discovered collisions of an intermediate character, in which there is only a partial sharing of energy, promise to reveal much about highly-excited quantum-mechanical systems.

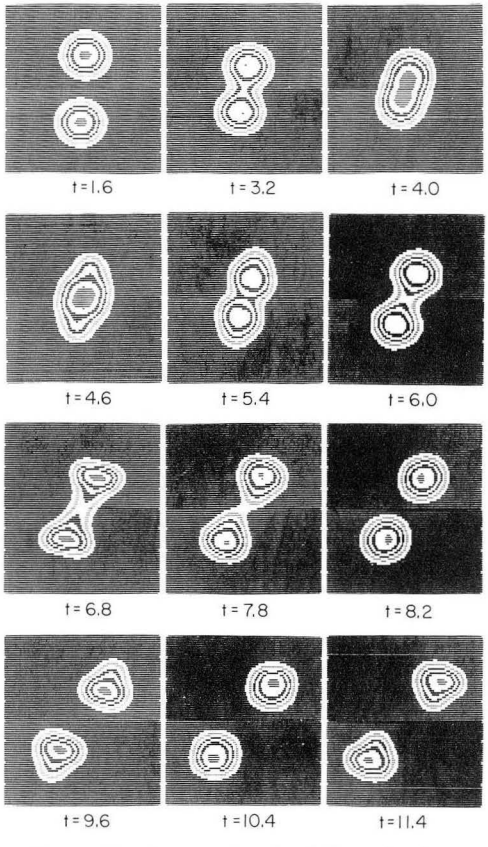


Figure 10. A computer simulation of a low-energy, nearly head-on collision of two Oxygen nuclei (*composed of 16 nucleons each*) carried out with the Time-Dependent Hartree-Fock method. (The number t indicates the time.) The two nuclei approach each other, interact, and then separate, vibrating as they recede. Comparisons of calculations such as these with experimental results can be used to test our understanding of how nuclei behave in such exotic circumstances.

Outstanding Questions: Many aspects of nuclei are well understood, but there remain substantial gaps in our knowledge. Some of these have been mentioned above; among other outstanding questions, one can list the following.

The neutrons in nuclei have no electrical charge and are therefore difficult to detect with probes that interact via the electromagnetic force. Hence, the distribution of neutrons in nuclei, one of the major nuclear components, has not yet been mapped out accurately by experiments; however, it can be measured with proton or meson beams. The coordinated motion of two or more nucleons within a larger nucleus is an effect not predicted in the simple shell model, but is nevertheless expected to be revealed by experiments using high-energy projectiles.

New forms of cooperative nuclear motion, the properties of nuclei with very different numbers of protons and neutrons or with unusual shapes, and unexpected symmetries are other topics which stretch the limits of our present knowledge but can be studied thoroughly in future experiments. The extreme conditions encountered in heavy ion collisions promise to provide the answers to an entirely different set of questions about nuclear behavior. What are the properties of rapidly spinning nuclei and how fast can they spin before flying apart? Are there "superheavy" nuclei containing more than 300 nucleons, as has been predicted by some theories (see Figure 2)? How do such quantities as energy, spin and even matter itself flow through a single nucleus or between two nuclei during the fleeting moment of a collision? How are these properties related to the interaction between nucleons? How do nuclei behave when greatly heated or compressed? Are there new forms of nuclear matter in which the nucleons dissolve to release their quarks or the pions condense into a fluid around the nucleons?

The long tradition of using nuclei as microscopic laboratories to study the strong, weak, and electromagnetic interactions will continue to produce invaluable insights into Nature's fundamental forces. How do nuclei behave under isospin and time-reversal transformations? What is the nature of the weak interaction between nucleons? What is the mass of the neutrino, an electrically neutral particle whose mass might serve to stem the outward rush of the universe caused by the big bang?

Theoretical research is intimately tied to all of the investigations described above. Although the nucleus shares some attributes of the other many-particle systems of physics, it is unique in that it is composed of a relatively small number of strongly interacting particles and can be highly excited. Its correct theoretical description will continue to require a broad approach using many different mathematical techniques and the speed and power of modern computers to definitively confront theoretical predictions with experimental observations.

Nuclear Tools in Other Sciences

Basic nuclear science has had a profound impact on other scientific fields. Nuclei

are basic components of matter and efficient techniques for their manipulation and detection are readily available. Nuclear methods have therefore become an integral part of scientific investigations ranging from atomic physics and cosmology to biochemistry and archaeology. The following paragraphs are only a very small sampling of the myriad of ways in which nuclear science has helped to further our understanding of the natural world.

Astrophysics and Planetary Science: Nuclei and their reactions play a central role in the Cosmos. Virtually all of the matter in the universe emerged from the initial stages of the "Big Bang" as protons, the simplest nuclei. Later processes in the Big Bang built up a few of the lightest elements. From their abundances, one can deduce the number of nucleons in the universe; it appears that the total mass of the nucleons is not sufficient to stop the present expansion of the universe. All of the larger nuclei had to be built up by a series of nuclear reactions in stars. This process of nucleosynthesis releases the energy which powers the stars and leaves its traces in the nuclear properties of the elements it produces. During much of their lifetime, stars such as the sun convert protons into helium nuclei by the fusion process; indeed, the detection of the neutrinos emitted during this process is our most direct glimpse into the solar interior. At the end of its life, a star may erupt in a dramatic supernova (Fig. 11), a tremendous explosion of nucleosynthesis in which many of the nuclei produced are blown out into space. The explosion often leaves behind a small neutron star, a giant nucleus whose structure is determined by nuclear properties. Studies of the nuclear composition of such cosmic material as meteorites offer valuable insights into the evolution of matter, which is the fabric of the early history of the universe and the solar system. Necessary adjuncts to these studies are experiments in the laboratory to measure the nuclear reactions which occur in stars and theoretical work to estimate those aspects which cannot be measured directly. Comparing such predictions, with astronomical observations makes it possible to determine the temperatures and densities present in such cosmic phenomena as supernova explosions.

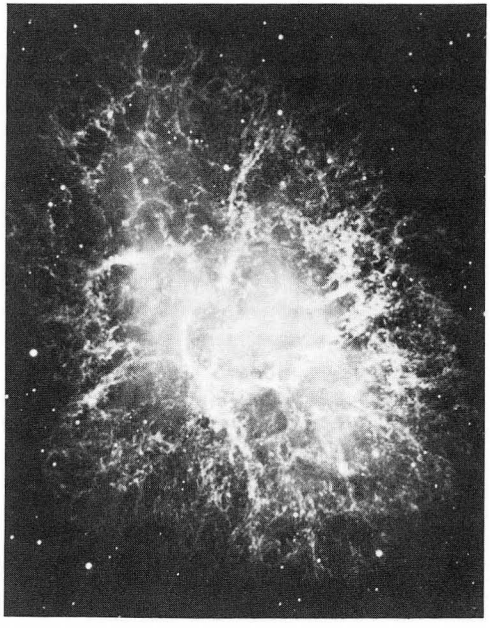


Figure 11. A supernova — the Crab nebula.

Recent planetary exploration has also employed nuclear science, for example using fission to power unmanned spacecraft or using nuclear detector techniques to map the distribution of chemical elements on the moon.

Atomic Physics: When high-energy beams of atoms produced from nuclear accelerators pass through solids or gases, the nuclei are stripped of a large number of their surrounding electrons. The resulting atoms consist of a highly charged nucleus surrounded by only one or a few electrons. Their properties provide a stringent test of quantum electrodynamics, the basic theory of electrons and their interaction with photons. Two colliding heavy ions can fleetingly simulate the nucleus of an element far beyond the borders of the known Periodic Table where anti-matter may be created spontaneously by the very strong electrical forces present.

Chemistry and Biology: The use of radioactive isotopes to trace the course of chemical reactions and biological processes is a well-known technique now more than thirty years old. Less well-known are a group of methods for mapping molecules using the response of nuclei to magnetic fields or the way in which neutrons and photons are scattered by the molecules being studied. Recently, mesonic atoms, in which a negatively charged meson orbits a nucleus, have promised to shed new light on the nature of chemical bonds. A technique using fission fragments to release large biological molecules from surfaces in a relatively intact form, may allow biochemists to study these molecules directly.

Condensed-Matter Physics: A host of nuclear methods are routinely used to characterize the properties of solids and liquids. Among the more prominent of these are neutron scattering and the Mössbauer effect. This latter involves photons emitted by a nucleus and was only a scientific curiosity when it was first discovered in 1958; it is now used for some of the most precise measurements of an atom's environment. The motion of electrons in solid matter can be simply studied by observing their interaction with positrons, a form of nuclear radiation emitted in transformations caused by the weak force, while recent experiments with muons furnish invaluable data on the magnetic fields in solids.

Archaeology and Paleontology: The use of the naturally radioactive isotope of Carbon with mass number 14 as a "clock" with which to date organic material began nearly thirty years ago. Recently, nuclear scientists have dramatically broadened the applicability of this technique by showing that it is possible to use accelerators to detect the Carbon nucleus directly, rather than by its radiation. This means that much smaller samples can be used (the entire object being dated often had to be destroyed in previous methods) and objects as old as 50,000 years can be dated accurately. Accelerator dating using the isotopes of other elements can also provide "clocks" for measuring shorter and longer periods of time. Other nuclear techniques for the

rapid measurement of a material's chemical composition have been used to trace everything from ancient trade routes (Fig. 12) to the migration of fish in the ocean. One of these methods, neutron activation, was recently used to show that the extinction of the dinosaurs may have been due to the dust from a giant meteorite, which dimmed the sunlight for a period sufficient to reduce the supply of edible plants.

Figure 12. High-precision neutron activation analysis was used to enable archaeologists to trace a pattern of trade among the Indians of ancient Peru. Obsidian from different sources has characteristic abundances of trace elements which provide distinctive geochemical "fingerprints". This enables obsidian from archaeological sites to be matched with the sources and enables researchers to infer the trade routes and social and economic contacts among ancient peoples from the movement of this important commodity, which was highly valued for its use in tools and weapons.

The Application of Nuclear Science to Society's Problems

Modern society faces a broad spectrum of problems with often dwindling resources available for their solution. While there are no magic answers for any of them, nuclear science has a remarkable history of producing spin-offs directly applicable to their solution and also to improving the overall quality of life. Because the number of such applications reaches into the hundreds, only a few of the more outstanding examples can be presented here.

The treatment of cancer by nuclear radiation is a widespread and accepted clinical practice. Approximately one out of every four Americans will have to cope with this disease; over half of these will be treated with radiation. The most common therapy uses photons, either emitted by artificially produced nuclei or generated by electron accelerators directly adapted from basic research. More effective methods of treatment are constantly being sought, often using particle beams developed primarily for basic studies of nuclei. Pion, neutron, and heavy ion therapies seem particularly promising, and clinical studies using these particles are underway at several nuclear laboratories.

Radioactive isotopes play an important role in many other diagnostic and therapeutic medical procedures; in the U.S. these procedures were used on patients some 12 million times in 1975. The detection and location of tumors using radioactive nuclei has become routine.

Currently of high interest is the technique of Positron Emission Tomography (PET) (Fig. 13), which uses nuclear radiation to construct 3-dimensional images of regions of the body. The accelerator production of isotopes needed for PET and the design of the sophisticated detection systems it employs rely heavily on experience gained in basic nuclear science.

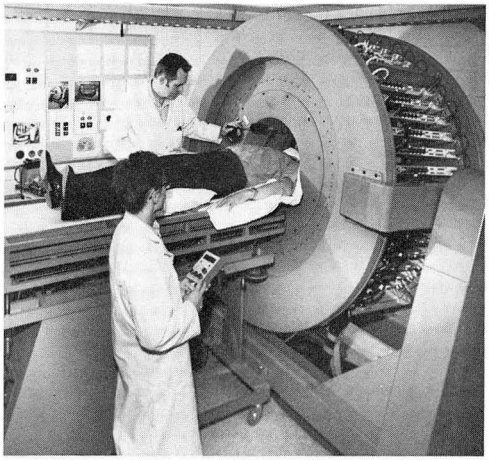
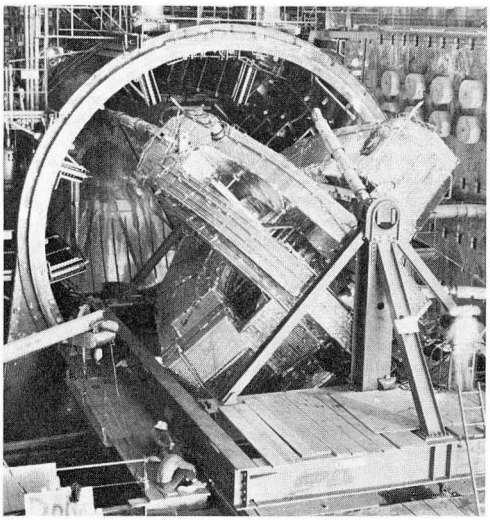


Figure 13. The Positron Emission Tomograph provides high-resolution images of labeled compounds in the body. A ring of 280 gamma-ray detectors (*sodium iodide and bismuth germanate crystals*) completely encircles the patient and makes 14,700 simultaneous measurements of internal activity.

Energy is a basic necessity of our developed society, and the search for new energy sources is one of its most urgent tasks. Nuclear science and technology are involved in almost every phase of this activity, most visibly in the several dozen commercial power plants based on nuclear fission. The safe and efficient operation of these reactors rests on literally thousands of pieces of nuclear data acquired in the course of basic research. The same nuclear fusion reactions which build helium from hydrogen in the sun may soon provide a virtually inexhaustible energy supply on earth (Fig. 14). The pressure of particle beams from accelerators might be used to squeeze microscopic targets to the temperatures and densities required to initiate the fusion reactions.

Figure 14. A workman prepares the 375-ton yin-yang superconducting magnet pair of the Mirror Fusion Test Facility (*MFTF*) at the University of California's Lawrence Livermore National Laboratory for a move into the experiment's building. The MFTF is a research facility to determine the stability of superhot fuel plasmas maintained at near reactor conditions in a "tandem mirror" configuration.



Energy related applications of nuclear science which are less well-known involve fossil fuels, conservation, pollution monitoring, and the conversion of solar power to electrical power. For example, a small device which can be lowered down a drill hole uses neutron activation to analyze the chemical composition of the walls and so help to locate the oil-bearing strata quickly (Fig. 15). New materials better able to withstand the intense conditions in fission or fusion power plants are being tested using neutron and heavy ion beams to simulate the damage caused by radiation. A widely used nuclear technique to introduce impurity atoms into silicon has resulted in a four-fold increase in the capacity of certain solid-state power devices; when sufficiently improved, this same method might be used to produce more efficient solar cells.

There are scores of other practical applications of nuclear science. For example, nuclear detectors which monitor radioactive gases released naturally by rocks may substantially improve our understanding of the stresses leading up to earthquakes and might one day lead to reliable predictions of tremors. In a very different application, electronic circuits originally developed for nuclear detection systems were the forerunners of many of those now used in modern computers. Applications of nuclear science to electronics continue today, for example in the use of accelerator beams to simulate the damaging effects of cosmic ray particles on the delicate integrated circuits used in satellites, or in the tiny bit of radioactive material contained in most residential smoke detectors.

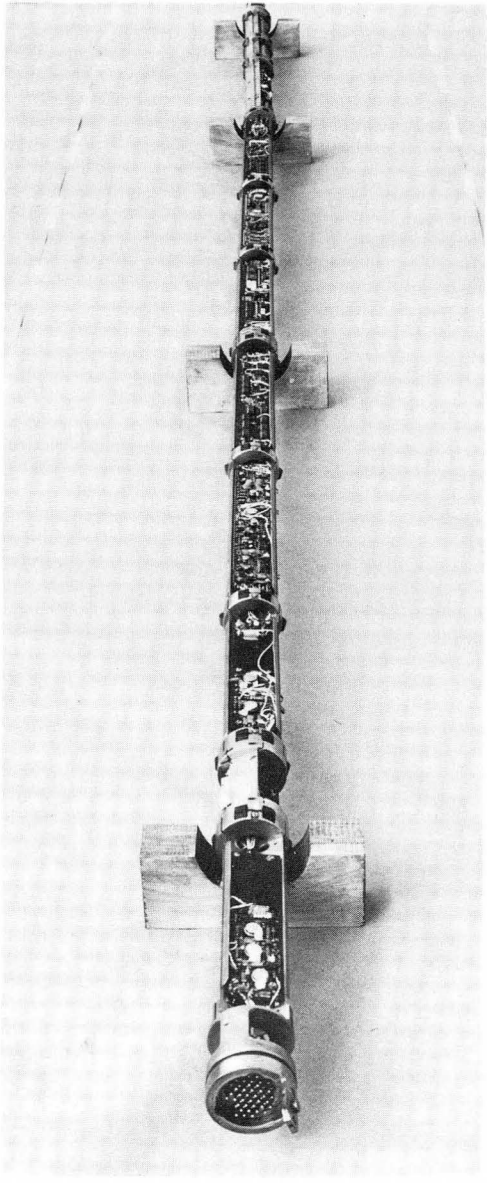


Figure 15. Gamma Spectrometer Tool™ for oil reservoir analysis uses gamma radiation induced by neutrons from a pulsed-neutron generator to determine relative concentrations of various elements in the formation. Photo courtesy of Schlumberger Well Services, Houston, Texas.

Nuclear Science and Education

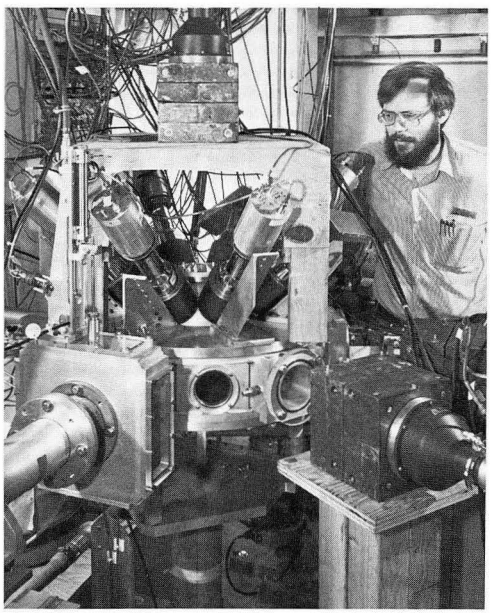
The education of students in all branches of basic and applied science is essential to the well being of our increasingly complex technological society. Education and training of young minds in nuclear science is no exception.

Research in nuclear science at the graduate and postgraduate levels provides an unequaled opportunity for the student. The theoretical concepts involved are broad and general. Many of the ideas and mathematical techniques that are used in the study of the microscopic nucleus can be applied directly in diverse branches of science ranging from the chemical behavior of colliding atoms and molecules to the structure of giant stars.

The scale of experimental research in nuclear science is sufficiently large to provide the student with wide experience in the use of such modern tools as high vacuum systems, modern electronics, and both large and small computers (Fig. 16). But the scale is not so large that the student is just a junior partner in a large research team. Nuclear science has excellent opportunities for the graduate student to plan and carry out experiments of his or her own choosing. The student can design and build special equipment, assemble complex electronic systems, and write programs for computers that will analyze and record tens of thousands of pieces of information per second during the experiment.

Students with training in nuclear science find employment in many diverse fields. Historically, only about one third of nuclear science Ph.D. graduates make permanent careers in basic nuclear research and teaching. The majority spread out to enrich other fields of science and technology. They are employed in nuclear medicine, national defense, nuclear power and waste disposal management, and in the instrumentation and computer industries. The support and vitality of the laboratories that provide this invaluable training in nuclear science is therefore a matter of urgent national concern.

Figure 16. Apparatus used to study how nuclei react in heavy ion collisions in the 88-inch cyclotron at the University of California's Lawrence Berkeley Laboratory. The external detectors record gamma rays. Internal detectors record particles emitted in the reaction.



Afterword

This pamphlet has tried to portray nuclear science as the many-faceted and far-reaching enterprise it is. Its subject matter ranges from the fundamental considerations of elementary particles and many-body systems to the practical problems of constructing accelerators and detectors which promise better understanding of sub-atomic phenomena to the application of such basic knowledge for Society's benefit. The understanding of nuclei and their applications is an activity on an international scale, in which both the competition and cooperation of scientists from many nations serves to advance man's knowledge. In the United States, nuclear scientists range from dedicated professionals at national laboratories to university faculty, whose research also trains students in a wide range of technological areas. Their work is a vigorous and healthy enterprise whose continued success is of clear importance to the Nation's intellectual life and material well-being.

Acknowledgments

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Glossary

Accelerator — A device which increases the speed, and thus the energy, of nuclear particles. Particle accelerators serve as artificial sources of well-defined beams of radiation for studies in nuclear science.

Antimatter — Matter composed of antiparticles, i.e., antiprotons, antielectrons, antineutrons, etc., instead of ordinary protons, electrons, neutrons, etc.

Antiparticles — Each particle has a partner, called an antiparticle, which is identical except that all charge-like properties are opposite to those of the particle. When a particle and its antiparticle meet, these properties cancel out in an explosive process called annihilation.

Atom — The smallest unit of a chemical element, consisting of a nucleus surrounded by electrons.

Baryon — A type of strongly interacting particle which includes the proton, neutron and all heavier particles whose decay products include the proton. Baryons are composed of quarks in combinations of three.

Electromagnetic Force — A long-range force associated with the electric and magnetic properties of particles. This force is intermediate in strength between the weak and strong force. The carrier of the electromagnetic force is the photon.

Electron — An elementary particle with a unit negative electrical charge and a mass 1/1840 that of the proton. Electrons surround an atom's positively charged nucleus and determine the atom's chemical properties.

Excited State — The addition of energy to a system transfers it from its ground state to a higher energy state called an excited state.

Fission — A process in which the nucleus of a heavy atom such as uranium splits into two smaller nuclei and releases energy.

Fusion — A process in which two light nuclei are joined or fused together to make a heavier nucleus with the release of energy.

Gamma Rays — A term used for the energetic photons that are emitted in the decay of atomic nuclei and other unstable particles.

Gluon — A particle which is hypothesized to mediate or carry the force between quarks. Like the quarks, the gluon is predicted to be unobservable as an isolated particle.

Gravity — The weakest of the four basic forces and the one responsible for the weight of matter and the motion of the stars and planets.

Ground State — The state of a nucleus, an atom, or a molecule at its lowest (normal) energy level.

Heavy Ion — A sub-atomic projectile which is a large nucleus moving at high speed.

Isospin — A nuclear symmetry associated with the interchange of neutrons and protons in a nucleus.

Isotopes — Nuclei having the same proton number but different neutron number. Isotopes have very similar chemical properties but very different nuclear properties.

Kaon — A meson with a mass intermediate between the pion and the nucleon. Kaons can have positive, negative or zero electric charge. The kaon is the lightest member of the family of strange particles, which are subject to special rules in both their formation and decay processes.

Liquid Drop Model — A model for predicting nuclear properties in which the nucleus is assumed to behave as a small, electrically charged drop of nuclear matter.

Meson — Any strongly interacting particle which is not a baryon. Mesons are composed of quark-antiquark combinations.

Muon — A particle in the lepton family (a family of weakly interacting particles) with a mass 207 times that of the electron and having other properties very similar to those of the electron. Muons may have positive or negative charge.

Neutrino — A particle with no electric charge and very little or no mass. Neutrinos accompany the emission of positrons and muons in radioactive decay and nuclear reactions, respectively. Neutrinos interact with other particles only through the weak force and are therefore difficult to detect.

Neutron — An uncharged baryon with a mass slightly greater than that of the proton. The neutron is a strongly interacting particle and a constituent of all atomic nuclei except hydrogen.

Nucleon — A proton or a neutron.

Nucleus — The central core of an atom, made up of neutrons and protons held together by the strong force.

Parity — A property of nuclear particles and nuclear reactions which refers to a right-left or mirror symmetry. The strong and electromagnetic forces conserve parity, which means these forces cannot be used to detect a preference in nature for a right-handed or left-handed symmetry. However, the weak force interaction, responsible for radioactive decay, does not conserve parity.

Photon — A quantum or pulse of electromagnetic energy. A unique massless particle that carries the electromagnetic force.

Pion — One of the mesons. It is the main mediator of the strong force. Pions can be electrically charged (positive or negative) or neutral, and have a mass about 270 times that of the electron.

Positron — The antiparticle of the electron.

Proton — A baryon with a single positive unit of electric charge and a mass approximately 1840 times that of the electron. It is the nucleus of the hydrogen atom and a constituent of all atomic nuclei.

Quantum Mechanics — The mathematical framework for describing the behavior of photons, molecules, atoms and subatomic particles. According to quantum mechanics, the forces between these particles act through the exchange of discrete units or bundles of energy called quanta.

Quark — One of a small family of particles which may be truly elementary. All nucleons and mesons are believed to consist of combinations of quarks or quarks and antiquarks.

Shell Model — A model of the nucleus in which each nucleon is assumed to move almost independently under the average influence of the others.

Strong Force — A short-range force which dominates the behavior of interacting mesons and baryons and accounts for the strong binding among nucleons.

Symmetries — Patterns of sub-atomic behavior which can be used to classify and predict nuclear properties.

Weak Force — A short-range force which governs the production and decay of many nuclear and subnuclear particles. It is much weaker than the strong force, but stronger than gravity.

*Some of these definitions come from the glossary in the booklet *HIGH ENERGY PHYSICS, The Ultimate Structure of Matter and Energy* (DOE/ER-0027) published by the U.S. Department of Energy, Office of Energy Research, Division of High Energy Physics.

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