Optional Reading: Unleashing the Energy of the Atom

The word "atom" has been passed on to us from the ancient Greeks. Democritus, a philosopher of the fifth century B.C., is usually credited with the idea that matter was made up of tiny units that could not be further subdivided. Democritus called these units atomos. Until the end of the nineteenth century, the indivisibility of the atom was a fundamental assumption of science.

Advances in chemistry in the nineteenth century, however, gradually revealed the structure and function of atoms. Scientists learned that elements could be classified according to the mass of their atoms. They also recognized that atoms of different elements could combine to form molecules possessing properties not shared by their atomic components.

The Birth of Atomic Physics

Around the turn of the century, physicists determined that the atom was made up of smaller units. Experiments revealed that each atom contained tiny particles, eventually known as electrons, and a dense core, which was to be called the **nucleus**. Physicists suspected that the energy binding the nucleus, if released, would dwarf the energy released by chemical reactions. (Chemical reactions were the basis for the explosive power of dynamite, discovered by Alfred Nobel in 1866, and trinitrotoluene, known as TNT.) The occasional spontaneous breaking up of a nucleus, known as **radioactive decay** or radioactivity, gave physicists a hint of the scale and potential of nuclear energy. Nonetheless, there seemed to be no practical way of cracking the nucleus.

Albert Einstein, a German physicist, was among the first scientists to grasp the power of the atom. In 1907, Einstein expressed the relationship between energy and matter in the formula, $E=mc^2$ (energy equals mass multiplied by the speed of light, squared). An implication of Einstein's formula was that mass could be transformed, under the proper conditions, into powerful packets of energy.

Note: Bold terms are defined in the glossary on pages 8-10. Concepts marked with (*) are explained in greater depth in the optional lesson, "The Physics of the Atomic Bomb."

Careful measurements of the products of radioactive decay confirmed Einstein's hypothesis. Scientists found that after radioactive decay the total mass of a nucleus and its by-products weighed less than the mass of a nucleus not affected by radioactive decay. They concluded that energy released in the process of radioactive decay was caused by the transformation of the missing mass.*

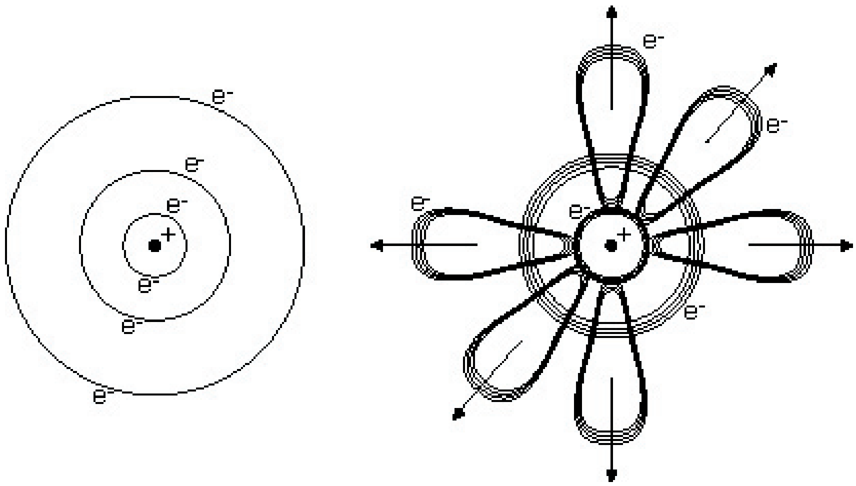
How did scientists determine the structure of the atom?

In the first decades of the twentieth century, British physicists J.J. Thomson and Ernest Rutherford, Danish physicist Niels Bohr, and others made important strides in determining the structure of the atom. In what is now familiar to students of physics, scientists established that each atom consists of a small, dense nucleus surrounded by light electrons, spinning in orbitals, which fill most of the space occupied by an atom.* **Electrons** were shown to have a single negative charge. Scientists also recognized that the nucleus of an atom is made up of **protons**, particles carrying a single positive charge that possess 1,836 times the mass of electrons.

The picture of the atom was completed in 1932 by James Chadwick, a British physicist. Chadwick discovered that the nucleus of an atom includes **neutrons** as well as protons. Neutrons are heavy particles with slightly more mass than protons, but possessing no electrical charge.

What is radioactive decay?

Soon after Chadwick's discovery, research in France and Britain helped shed light on the process of radioactive decay and nuclear transformation. Scientists identified **alpha particles**, a common product of radioactive decay, as small charged masses consisting of



The diagram on the left represents Niels Bohr's first effort to draw a model of the atom. The model on the right, which was developed later, includes orbitals of electrons.

two protons and two neutrons. **Beta particles**, another product of radioactive decay, were identified as high-speed electrons. The third important set of products of radioactive decay, **gamma rays**, was recognized as massless packets of energy traveling at the speed of light, much like the energy packets that constitute X-rays and visible light.

By the mid-1930s, the secrets of the atom were yielding to the accelerating pace of research in Europe and the United States. Nonetheless, even many of the most prominent atomic physicists underestimated the potential of their work. Ernest Rutherford, for example, in a 1933 interview dismissed the possibility of nuclear energy.

> ***"With thirty thousand or seventy thousand volts, [I] believe that we should be able to transform all the elements ultimately. We might in these processes obtain very much more energy than the proton supplied, but on the average we could not expect to obtain energy in this way. It is a very poor and inefficient way of producing energy, and anyone who looked for a source of power in the transformation of the atoms is talking moonshine."***
>
> —Ernest Rutherford, 1933

How did the concept of a chain reaction help scientists to think about an atomic bomb?

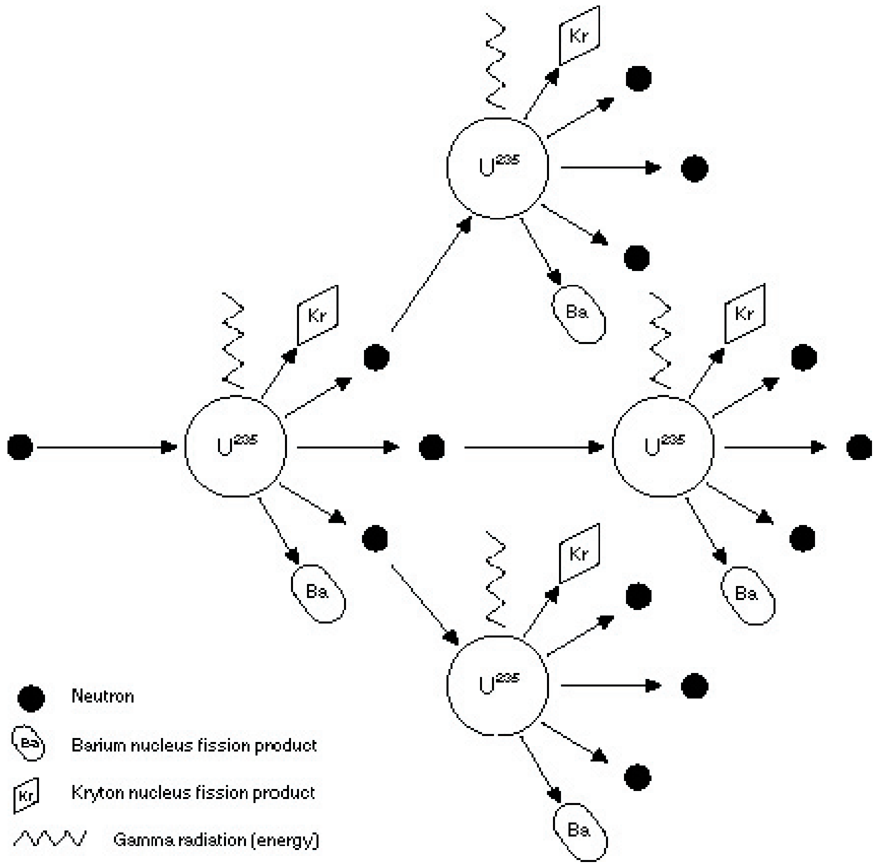
Rutherford's conclusion, as well as many of his assumptions, was soon to be proven wrong. The main challenge was to come from Leo Szilard, a Hungarian physicist who had been a student of Einstein and Max Planck. Rutherford had assumed that only positively charged particles, either protons or alpha particles, could be used to split the nucleus of an atom. Since the nucleus is also positively charged, it naturally repels protons and alpha particles. Szilard, however, felt that Chadwick's discovery of the neutron had opened up other possibilities. He believed that the use of the non-charged neutron to split the nucleus would require much less energy than the approach Rutherford imagined.

Moreover, Szilard realized that the splitting of the nucleus would release additional neutrons, which, in turn, could split other nuclei. According to Szilard's view, the splitting of a single nucleus could trigger a **chain reaction** that would split all available nuclei. The energy released by such a chain reaction would far exceed the energy required to start the process.

Szilard's elegantly simple concept would make the Hungarian scientist, in the eyes of many historians, the "father" of the atomic bomb. But while Szilard laid down the theoretical foundations of the bomb in the mid-1930s, his ideas were not widely publicized within the scientific community. In the years that followed, hundreds of other scientists were to contribute to the expanding field of atomic physics.

How did Nazi Germany's policies contribute to the development of the bomb?

Ironically, Adolf Hitler played a critical



A drawing of a nuclear fisson chain reaction.

Jewish grandparents, even if the person in question had converted to Christianity.) Nazi policies also threatened non-Jewish scientists who were married to Jews.

In response to Hitler's persecution of the Jews, hundreds of Germany's top scientists and intellectuals immigrated to the United States and Britain. The immigrants included some of the world's leading minds in atomic physics. As Nazi power grew, dozens of scientists from Austria, Hungary, and other central European states, including Leo Szilard, followed their German-born counterparts.

Benito Mussolini, Italy's fascist dictator, added to the flow of refugees in 1938 when he stripped Italian Jews of their civil rights and professional status. While Italy was home to only a few thousand Jews, one of them was married to Enrico Fermi, a Nobel prize winning physicist. Fermi immigrated to the United States in 1939. By 1941, nearly one hundred European physicists had found refuge in the United States.

role in supplying the United States with the intellectual resources necessary to develop an atomic bomb. The ideology of Hitler's Nationalist Socialist Democratic Workers' Party, known as the Nazis, revolved around hatred. Hitler blamed Germany's problems on communists, liberal democrats, and, above all, Jews. He held that the Germans were the "master race," entitled to rule the world.

When Hitler came to power in 1933, he acted decisively to end democracy and establish a Nazi dictatorship. Germany's Jews were a principal target of Hitler's policies. Jews within Germany's civil service system, which included the universities, lost their jobs. Although Jews represented only 1 percent of Germany's population, in some universities more than one-third of the professors of physics, chemistry, mathematics, and biology were Jewish or Christians of Jewish descent. (Nazi law defined a Jew as anyone with at least three

The Race for the Bomb

By the time Fermi arrived in the United States, scientists on both sides of the Atlantic had made major breakthroughs in unlocking the secrets of the atom. A German physicist, Otto Hahn, was the first to discover that bombarding natural uranium with neutrons produced two very different types of nuclear reactions. Bombardment by high-energy neutrons caused fragments of the nucleus—usually alpha particles—to break off. At the same time, and more difficult to detect, bombardment by low-energy neutrons caused some uranium atoms to break into two smaller, nearly equal, parts.

The splitting of the nucleus into two smaller nuclei, a process called **fission**, would bring Szilard's concept closer to reality.* Because of their instability, the smaller nuclei emitted additional neutrons—two or more for every primary neutron used to begin the process. The mechanism for setting off a nuclear chain reaction, marked by a tremendous release of energy, was now clear.

In early 1939, physicists were openly discussing the prospect of unleashing a self-sustaining nuclear chain reaction to spark an atomic explosion. *The New York Times* even published an article on the subject on April 30, 1939. That same month, the German government undertook limited research into the military uses of atomic energy. Both policymakers and scientists in the United States and Britain watched Germany's advances in nuclear research with growing anxiety.

What did scientists learn about uranium and thorium?

Before progress toward a nuclear chain reaction could proceed further, several theoretical issues had to be resolved. Nuclear physicists were working to determine which material should be used to set off a self-sustaining nuclear chain reaction, or even to construct an atomic bomb. While in theory the nucleus of any material could be split under ideal laboratory conditions, the heavier elements, particularly uranium and thorium, seemed the most promising for fission. (Uranium and thorium are classified as heavy elements because their atoms contain a comparatively high number of protons in their nuclei.)

Uranium is slightly radioactive—meaning that the nucleus of a uranium atom may spontaneously emit pieces of itself. In its natural state, a mass of uranium would have half of its atoms transformed through radioactive decay in 4.5 billion years. (In scientific terms, uranium is said to have a **half life** of 4.5 billion years.) In the late 1930s, deposits of uranium ore were found mainly in Canada, Congo, the Czech Republic, and Slovakia.

Uranium exists naturally in two **isotopes**, U^{238} and U^{235}. Natural uranium is more than 99 percent U^{238}. The isotope U^{235}, which has three fewer neutrons in its nucleus than U^{238}, was identified by physicists as the source of the fission phenomenon. Thorium, another heavy element, exists in one stable isotope, Th^{232}.

Small-scale fission experiments in early 1939 with uranium and thorium atoms suggested to Niels Bohr that U^{235} was the best candidate for producing a self-sustaining nuclear chain reaction. Other physicists, including Enrico Fermi, continued to explore the possibility that a self-sustaining nuclear chain reaction could be set off using natural uranium.

Why did Einstein write to President Roosevelt?

Research in atomic physics on the eve of World War II was becoming increasingly costly. The small group of atomic physicists in the United States wanted access to large amounts of refined uranium and pure graphite to construct an experimental nuclear **reactor**. To get their project off the ground they needed government funding. However, when the scientists presented their case to U.S. army and naval officers in early 1939, they received a cool reception.

Frustrated by the response of the military, the scientists decided to approach high-level officials in the U.S. government to warn them of the threat posed by Germany's efforts to build an atomic bomb. Leo Szilard hoped to enlist the help of his former teacher, Albert Einstein, in his campaign to win government support. Einstein, who had taken up residence in Princeton, New Jersey, soon after immigrating to the United States in 1930, was widely recognized at the time as the world's leading theoretical physicist.

Like his British counterpart, Ernest Rutherford, Einstein initially doubted that the atom could be harnessed to produce energy. He had not closely followed the theoretical research on nuclear chain reactions in the late 1930s. Nonetheless, when Szilard explained the purpose of his research at a meeting between the two men in July 1939, Einstein immediately grasped its significance.

Einstein agreed to write to the Belgian ambassador in Washington to convince the Belgians to bar Nazi Germany from importing the uranium ore being mined in what was then known as the Belgian Congo. The following week, at the suggestion of Alexander Sachs, a prominent biologist, Einstein decided to approach President Roosevelt. Together with Szilard, Einstein wrote a brief letter and an accompanying memorandum to the president. The letter and the memorandum were personally delivered to Roosevelt by Sachs in October 1939.

How did Roosevelt respond to Einstein's letter?

Roosevelt quickly understood the potential danger. "What you are after," he said to his friend Sachs, "is to see that the Nazis don't blow us up." After meeting with Sachs, Roosevelt established the Advisory Committee on Uranium. Although the two military representatives on the advisory committee remained wary, government funding for nuclear research was granted.

In June 1940, as Nazi armies overran France, the advisory committee was disbanded and responsibility for atomic weapon research was given to the newly created National Defense Research Committee, with Vannevar Bush, former vice-president of the Massachusetts Institute of Technology, as chairman. The committee, consisting of top scientists and administrators, reported directly to the president. Committee members, however, were skeptical

F.D. Roosevelt
President of the United States
White House
Washington, D.C.

Sir:

Some recent work by E. Fermi and L. Szilard, which has been communicated to me in manuscript, leads me to expect that the element uranium may be turned into a new and important source of energy in the immediate future. Certain aspects of the situation which has arisen seem to call for watchfulness and, if necessary, quick action on the part of the Administration.... [I]t may become possible to set up a nuclear chain reaction in a large mass of uranium, by which vast amounts of power and large quantities of new radium-like elements would be generated....

This new phenomenon would also lead to the construction of bombs...extremely powerful bombs of a new type.... A single bomb of this type, carried by boat and exploded in a port, might very well destroy the whole port together with some of the surrounding territory.... In view of this you may think it desirable to have some permanent contact maintained between the Administration and the group of physicists working on chain reactions in America...[and] to speed up the experimental work, which is at present being carried on within the limits of the budgets of University laboratories....

I understand that Germany has actually stopped the sale of uranium from the Czechoslovakian mines which she has taken over....

Yours very truly,
A. Einstein

of the project proposed by Szilard and Fermi, and awarded the scientists less funding than they had requested.

Overcoming Scientific Obstacles

With government support, the scientists under the guidance of Szilard and Fermi focused their research on the theoretical, experimental, and technological problems involved in constructing an atomic bomb.

First, a larger experimental atomic reactor was necessary to study chain reactions of natural uranium atoms under controlled conditions. Early work on atomic reactors had demonstrated the need for a moderating substance to achieve a self-sustaining nuclear chain reaction. Scientists calculated that a **moderator** would act to slow down the neutrons being produced by fission so they would react with other uranium nuclei to produce a nuclear chain reaction, rather than knock off alpha particles.

How did scientists deal with the problem of developing a moderator?

Scientists soon pinned their hopes on two substances—graphite (pure carbon) and **heavy water**—to work as moderators. Each presented problems. Impurities in graphite, even minute amounts, would "capture" the neutrons produced by fission and prevent them from contributing to a nuclear chain reaction. Tons of very pure graphite would be required.

Heavy water presented another set of problems, mainly in terms of production. In ordinary water, or H_2O, the nuclei of hydrogen atoms consist of one proton. In heavy water, the hydrogen atoms are the isotope deuterium, which has one neutron and one proton in the nucleus. Deuterium has twice the mass of hydrogen, hence the name heavy water. In 1940, heavy water was very expensive to separate from H_2O. Moreover, the world's largest plant capable of producing heavy water was located in German-occupied Norway. Thus, wartime atomic research programs in both the United States and Britain focused their attention on using graphite as a moderating substance, while German scientists concentrated on heavy water.

In April 1940, the British government helped prod the American atomic effort into high gear. The British formed a small committee of scientists to advise the government on atomic research. Code-named the "Maud Committee," the British scientists answered one of the key theoretical questions involved in the development of an atomic bomb. Until the British findings, scientists in the United States had been unable to determine how much U^{238}, U^{235}, or Th^{232} was necessary to produce a self-sustaining nuclear chain reaction. (The minimum amount of material necessary for a chain reaction is known in scientific terms as a **critical mass**.)

How did the Maud Committee assist in the development of the bomb?

While the British estimated that many tons of U^{238} were necessary to reach a critical mass, they calculated that a self-sustaining nuclear chain reaction could be set off with as little as ten pounds of U^{235}. In addition, these scientists proved that only fast neutron "bullets" could produce full fission within a time span short enough (0.000004 seconds) to achieve maximum explosive power. In its final report on July 15, 1940, the Maud Committee recommended that the United States and Britain work together to build an atomic bomb as quickly as possible.

> ***"The committee considers that the scheme for a uranium bomb is practicable and likely to lead to decisive results in the war.***
> ***It recommends that this work continue on the highest priority and on the increasing scale necessary to obtain the weapon in the shortest possible time.***
> ***"That the present collaboration with America should be continued and extended especially in the region of experimental work."***
> —Final Report of the Maud Committee

The British position encouraged the National Academy of Sciences Review Panel, which had been established to advise the National Defense Research Committee, to observe in November 1940 that, "A fission bomb of superlative destructive power will result from bringing quickly together a sufficient mass of element U^{235}." Vannevar Bush, the committee's chairman, passed along the panel's conclusion to President Roosevelt, along with his recommendation that the atomic bomb project receive the highest priority. Roosevelt agreed, recording his approval with a simple handwritten "O.K." on a sheet of White House stationary. Over the next five years, the United States would spend more than $2 billion, without explicit Congressional authorization, to build an atomic bomb.

Glossary of Scientific Terms

Alpha Particle:

The nucleus of a helium atom that has been stripped of its two electrons, thus consisting of two protons and two neutrons. Alpha particles are a common product of natural radioactive decay and nuclear fission. They have a double positive charge and a short range (several centimeters) in air. Because of their charge, alpha particles may be accelerated in a magnetic field and used to bombard other nuclei.

Beta Particle:

A product of nuclear decay or induced fission. In their most common form, beta particles have the mass and charge of an electron. They are normally stopped by one centimeter of solid material. Short-lived beta particles with a positive charge, called positrons, have been observed.

Chain Reaction:

The process used in nuclear reactors and nuclear weapons by which neutrons emitted from nuclei being split (see "Fission") in turn cause other nuclei to split, thus continuing the reaction. The rate of the reaction depends on the supply of released neutrons and the concentration of fissionable nuclei.

Critical Mass:

The minimum mass, or weight, of fissionable material necessary to sustain a nuclear chain reaction once the process has been started. The size of a critical mass depends on the type of nuclei present, the concentration of non-fissionable nuclei present, the shape of the mass, and the pressure.

Cross Section:

A way of measuring the likelihood that a type of nucleus will react with a neutron passing near it. A large cross section means that a neutron does not have to pass as close to a nucleus for it to cause a nuclear reaction (usually fission or capture) as a small cross section would require. Measuring capture and fission cross sections using experimental reactors played a critical part in developing the atomic bomb and in designing more effective reactors.

Cyclotron:

A machine which accelerates subatomic charged particles, such as alpha particles, using strong magnetic fields. Cyclotrons are usually built in a racetrack-like oval shape. Linear accelerators are another type of machine used to produce high-energy charged particles.

Deuterium:

An isotope of hydrogen having a neutron as well as a proton in the nucleus. Deuterium has a mass twice that of common hydrogen. When chemically combined with oxygen, deuterium forms "heavy water." One part in 6,700 parts of naturally occurring hydrogen is deuterium.

Fission:

The process by which a nucleus, usually of a heavy element, splits into two nuclei of nearly equal mass, generally releasing large amounts of energy and subatomic particles such as neutrons, alpha particles, beta particles, and gamma radiation. Fission may occur in a nucleus spontaneously or may be induced, usually by bombarding it with a neutron.

Fusion:

The process by which two small nuclei combine under extreme temperature and pressure to form a larger nucleus. A small amount of mass is lost in fusion and transformed into energy. Under proper conditions, two deuterium nuclei may undergo fusion and produce a helium nucleus.

Gamma Radiation:

High-energy bundles of electromagnetic radiation released by a nucleus undergoing a nuclear reaction. Although similar to visible light, these photons, because of their high energy, penetrate solids and travel long distances. The existence of gamma radiation is the most common test for the presence of radioactive materials.

Gaseous Diffusion:

The process by which gas molecules pass through materials which, because of the presence of microscopic holes, are porous to the gas. The rate of diffusion depends on the size and speed of the molecules.

Half Life:

The time required for 50 percent of the nuclei of a particular isotope to undergo spontaneous nuclear transformation. For example, C^{14} has a half life of 5,700 years. Eight kilograms of pure C^{14} today will contain only four kilograms of C^{14} in 5,700 years. The rest will have been transformed into nitrogen. After another 5,700 years, only two kilograms of the mass will be C^{14}.

Heavy Water:

Water in which the hydrogen atoms are deuterium, or D_2O. Since deuterium nuclei work very well to slow down neutrons without capturing them (see "Moderator"), heavy water is used in some nuclear reactors to promote a nuclear chain reaction by keeping the neutrons "bouncing around" at the proper energies until they can strike another nucleus to cause fission.

Implosion:

The technique used to assemble a critical mass of fissionable material by using high-explosive charges to propel subcritical masses toward one another in a spherical arrangement. While this is the most efficient design for a nuclear fission explosion, the shape of the high-explosive charges and the timing of their detonation demands exact precision.

Initiator:

The trigger which produces free neutrons to begin a nuclear chain reaction explosion. A combination of berylium and polonium is frequently employed in the initiator.

Isotopes:

Two or more atomic forms of the same element which differ in the number of neutrons in their nuclei. For example, a U^{238} atom has 146 neutrons in its nucleus while a U^{235} atom has 143 neutrons in its nucleus. Although these atoms differ in mass, they behave the same chemically and cannot be separated using normal chemical means. Because of their different nuclear structures, isotopes commonly have different half lives.

Moderator:

A substance used to slow down but not capture neutrons produced in a controlled nuclear chain reaction. By bouncing the neutrons toward other nuclei at speeds that promote fission, the moderator plays an important role in continuing the process of a nuclear chain reaction. Heavy water and pure graphite (carbon) are ideal moderators. Small amounts of impurities in the moderator tend to soak up the free neutrons and thus slow down a nuclear chain reaction.

Nucleus:

The small, heavy center of an atom. The nucleus contains protons, which carry a positive charge, and neutrons, which have no charge. More than 99 percent of the mass of an atom is in the nucleus. The "size" of an atom is determined by the orbital patterns of the very light, negatively charged electrons spinning around the nucleus. In an uncharged atom, the number of electrons equals the number of protons.

Neutron:

An uncharged particle usually found in the nuclei of atoms. Having about the same mass as a proton, neutrons may be freed in a nuclear reaction and may, in turn, cause other nuclear reactions if they pass close enough to other nuclei. The energy of the neutron and the cross section of other nuclei determine the likelihood of another reaction (see “Cross Section).

Periodic Table:

An arrangement of the known elements. The periodic table is arranged according to the number of protons within the atomic nuclei of each element. The atomic mass of an element is a measure of the relative mass of its atoms.

Pile:

The descriptive name given by Enrico Fermi for the reactor built at the University of Chicago which achieved the first self-sustaining nuclear chain reaction in December 1942. The term pile is used now to refer to any atomic reactor.

Predetonation:

The beginning of an explosive nuclear chain reaction before the components of a bomb are in the proper position. Predetonation greatly reduces the power produced by an explosion. The tendency of Pu^{239} to begin spontaneous fission as subcritical masses approach one another forced the scientists of the Manhattan Project to find an alternative to the cannon design for the plutonium bomb. The implosion design solved this problem by uniting the subcritical mass components of the plutonium bomb much more rapidly.

Proton:

Heavy, positively charged particles that, with neutrons, make up the nucleus of an atom. The number of protons in a nucleus determines what element is formed. The atomic number of an element represents the number of protons in the nucleus.

Reactor:

An arrangement of fissionable isotopes (such as U^{235}), non-fissionable isotopes (such as U^{238}), control rods, and a moderator substance designed to produce a controllable nuclear chain reaction. The control rods, made of neutron-absorbing material, may be withdrawn or inserted to regulate the speed of the reaction. During the operation of a reactor, some U^{238} atoms will be converted into Pu^{239} as a result of neutron bombardment. Reactors are also called atomic piles.

Radioactive Decay:

The process, also known as nuclear decay, by which a nucleus spontaneously emits small pieces of itself, usually in the form of alpha particles or beta particles, with a corresponding release of energy. Radioactive decay eventually changes the nucleus of one element into the nucleus of a different element, usually within several places on the periodic table of the original element. For example:

$$C^{14} \rightarrow N^{14} + \text{beta particle}$$

Spontaneous Fission:

The process by which nuclei split into two approximately equal smaller nuclei without having been bombarded by free neutrons. Spontaneous fission generally results in the release of free neutrons.