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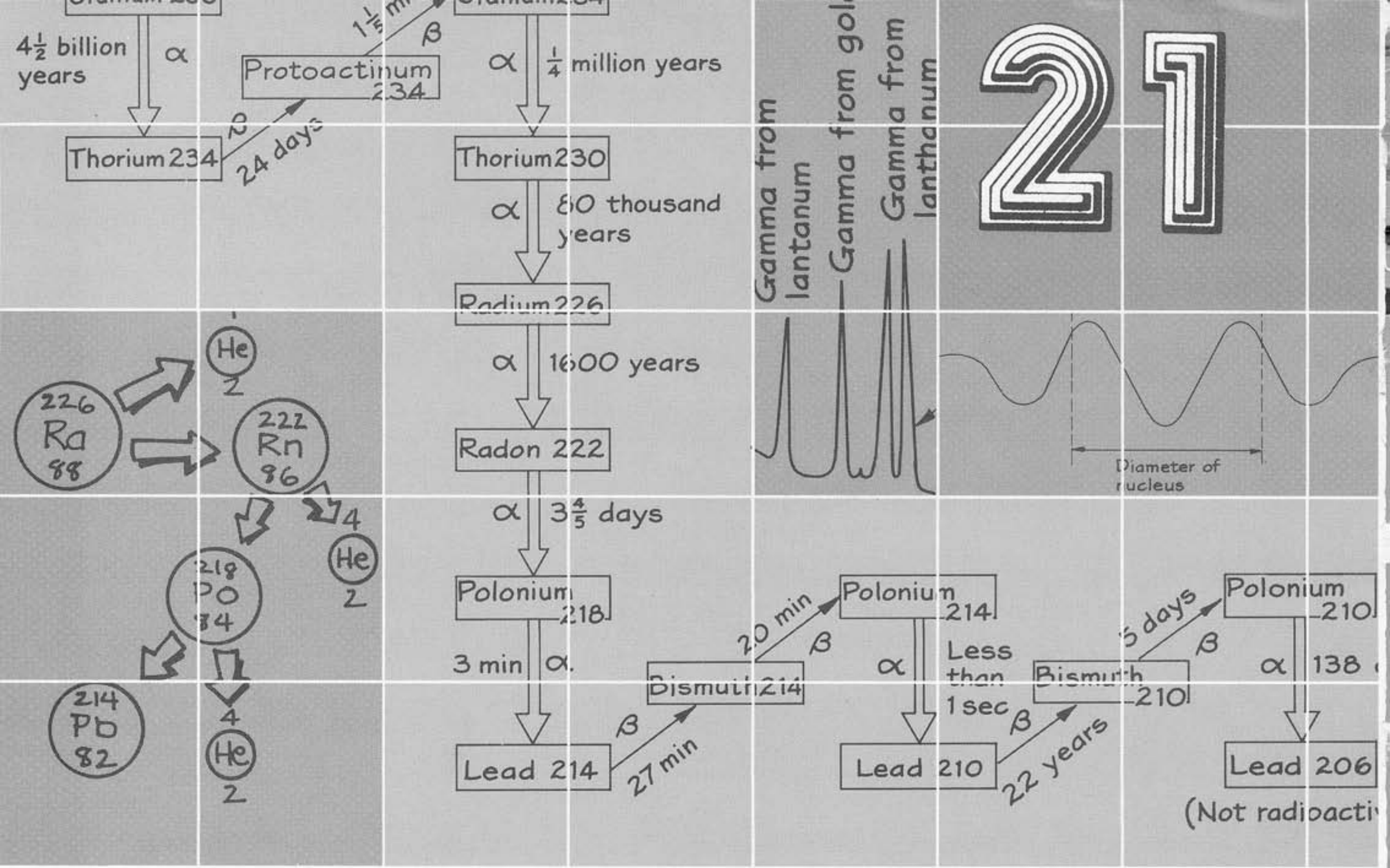


Radioactivity

Nuclear physics—a threat or a remedy? Does it reveal people's remarkable intellect or the stupidity with which people use their knowledge? Is it a means of vast destruction or a valuable diagnostic and research tool? Is it a vast source of energy or the most dangerous pollutant yet unleashed? The story of nuclear physics lies hopelessly entangled in the joys and sorrows of the twentieth century. It is with this topic that we close our book.

In 1896, Henri Becquerel noticed the radiation emitted by uranium salts. This radiation, which had much higher energy than any previously known, was named *radioactivity*. The emissions provided clues to the structure of the nucleus just as light spectra were providing clues to the structure of the atom. *Nuclear transformations* are the causes of the reactions that occur as the nuclear radiation is released. Nuclear radiation occurs in three major types, called *alpha, beta,* and *gamma* radiation. In alpha and beta radiation, one element is transformed into another. The *half-life* of a radioactive substance describes the rate at which these transformations occur.

THE NATURE OF THE NUCLEUS

Because the nucleus is so small (about 10^{-15} meters (m) in diameter), we cannot observe it directly. Like our knowledge of atoms, our knowledge of the nucleus comes from indirect evidence. Rutherford's scattering experiment, in which he fired alpha particles at thin gold foil, provided clues to both the size and the mass of the nucleus. Radioactivity, the energy and particles emitted by materials such as uranium, provides clues to the types of particles that would be found in the nucleus. The periodic table, Figure 21-1, organizes the various chemical elements according to several properties, some of which could be explained only in terms of nuclear structure. Before looking at the details of nuclear transformations, we briefly review the evidence that supports our present model of the nucleus.

Clues to the Structure of the Nucleus

In some respects understanding the nucleus means understanding the periodic table of elements. By the turn of the twentieth century, chemists had isolated and identified the physical and chemical properties of the seventy or so elements that are shaded in Figure 21-1. Elements with similar properties are grouped into families and listed vertically. For example, fluorine (F) and chlorine (Cl) have similar properties and are listed in the same vertical column. From upper left to lower right, the elements are placed in order of increasing

Figure 21-1

Modern version of the periodic table. The elements that are shaded were known at the turn of the twentieth century, when radioactivity was discovered.

Periodic Table of the Elements

1 **H** 1.0079																1 **H** 1.0079	2 **He** 4.00260
3 **Li** 6.941	4 **Be** 9.01218											5 **B** 10.81	6 **C** 12.011	7 **N** 14.0067	8 **O** 15.9994	9 **F** 18.99840	10 **Ne** 20.179
11 **Na** 22.98977	12 **Mg** 24.305											13 **Al** 26.98154	14 **Si** 28.086	15 **P** 30.97376	16 **S** 32.06	17 **Cl** 35.453	18 **Ar** 39.948
19 **K** 39.098	20 **Ca** 40.08	21 **Sc** 44.9559	22 **Ti** 47.90	23 **V** 50.9414	24 **Cr** 51.996	25 **Mn** 54.9380	26 **Fe** 55.847	27 **Co** 58.9332	28 **Ni** 58.70	29 **Cu** 63.546	30 **Zn** 65.38	31 **Ga** 69.72	32 **Ge** 72.59	33 **As** 74.9216	34 **Se** 78.96	35 **Br** 79.904	36 **Kr** 83.80
37 **Rb** 85.4678	38 **Sr** 87.62	39 **Y** 88.9059	40 **Zr** 91.22	41 **Nb** 92.9064	42 **Mo** 95.94	43 **Tc** 98.9062	44 **Ru** 101.07	45 **Rh** 102.9055	46 **Pd** 106.4	47 **Ag** 107.868	48 **Cd** 112.40	49 **In** 114.82	50 **Sn** 118.69	51 **Sb** 121.75	52 **Te** 127.60	53 **I** 126.9045	54 **Xe** 131.30
55 **Cs** 132.9054	56 **Ba** 137.34	57 ***La** 138.9055	72 **Hf** 178.49	73 **Ta** 180.9479	74 **W** 183.85	75 **Re** 186.207	76 **Os** 190.2	77 **Ir** 192.22	78 **Pt** 195.09	79 **Au** 196.9665	80 **Hg** 200.59	81 **Tl** 204.37	82 **Pb** 207.2	83 **Bi** 208.9804	84 **Po** (210)	85 **At** (210)	86 **Rn** (222)
87 **Fr** (223)	88 **Ra** 226.0254	89 **†Ac** (227)															

* Lanthanide series	58 **Ce** 140.12	59 **Pr** 140.9077	60 **Nd** 144.24	61 **Pm** (147)	62 **Sm** 150.4	63 **Eu** 151.96	64 **Gd** 157.25	65 **Tb** 158.9254	66 **Dy** 162.50	67 **Ho** 164.9304	68 **Er** 167.26	69 **Tm** 168.9342	70 **Yb** 173.04	71 **Lu** 174.97
† Actinide series	90 **Th** 232.0381	91 **Pa** 231.0359	92 **U** 238.029	93 **Np** 237.0482	94 **Pu** (244)	95 **Am** (243)	96 **Cm** (247)	97 **Bk** (247)	98 **Cf** (251)	99 **Es** (254)	100 **Fm** (257)	101 **Md** (258)	102 **No** (255)	103 **Lr** (256)

atomic mass. The resulting periodic table shows a relationship among the collection of known chemical elements. At first, however, no one understood why elements could be grouped in this way.

Rutherford's scattering experiment provided clues to the ordering of the elements. As you saw in Chapters 8 and 18, Rutherford showed that atoms consist of positively charged, massive nuclei that are surrounded by much less massive, negatively charged electrons. When the magnitude of the electrical charge of the nucleus is compared to the magnitude of the charge of a single electron, a pattern emerges. Carbon, the 6th element in the periodic table, has a nucleus with a charge 6 times the magnitude of the charge of an individual electron. Gold, the 79th element in the table, has a nucleus with a charge 79 times the magnitude of that of a single electron. The horizontal arrangement of elements in the periodic table is related to the amount of electric charge present in the nucleus. Since atoms have zero net charge, the number of electrons must be equal to the magnitude of the charge on the nucleus. Thus, the horizontal arrangement also describes the number of electrons present in each atom. Carbon atoms have 6 electrons; gold atoms have 79 electrons; and so forth.

The quantum mechanical model of the atom (Chapter 18) creates an image of a relatively stationary nucleus surrounded by electron clouds. While electrons change their average distances from the nucleus as atoms release or absorb energy, the nucleus never seems to change. Elements combine chemically as electrons of their atoms interact with those of neighboring nuclei. For example, the atoms of hydrogen gas can combine with those of oxygen to form molecules of water. The atoms that form water share electrons with each other. The nucleus, however, remains uninvolved in such interactions. An element's physical properties (how it is affected by conditions such as light and temperature) as well as its chemical properties (how it combines with other elements) depend on the number and energy levels of the electrons surrounding the nucleus. But the number of electrons in an atom depends on the charge of the nucleus. Ultimately, then, the structure of the nucleus determines the unique properties of every element.

Inside the Nucleus

The nucleus contains two particles, the proton and the neutron. Together these particles explain both the mass and electric charge associated with each nucleus. Protons have an electric charge of $+1.6 \times 10^{-19}$ coulombs (C), equal in magnitude but opposite in sign to the charge on the electron. They have a mass of 1.672×10^{-27} kilograms (kg). Neutrons have no electrical charge. Their mass, 1.675×10^{-27} kg, is approximately equal to the mass of the proton. As predicted by Rutherford's scattering experiment, the masses of the particles found in the nucleus are enormous compared to the mass of the electron. Protons and neutrons are each about 1850 times more massive than an electron. Because of their presence in the nucleus and their similar characteristics, protons and neutrons are collectively called **nucleons.**

The mass and electric charge of different atomic nuclei can be explained in terms of their nucleons. Protons establish the electric charge associated with the nucleus. The horizontal order of elements in the periodic table reflects the number of protons present in each nucleus. Hydrogen has one proton; helium has two; lithium has three; and so forth. Thus the characteristics of an element reflect the number of protons in its nucleus. Neutrons add mass to the nucleus without affecting its charge. Helium has only two protons, but its mass is about four times that of hydrogen. Lithium, with three protons, has a mass nearly seven times that of hydrogen. We explain these masses by assuming that the helium nucleus consists of two protons and two neutrons, while the lithium nucleus consists of three protons and four neutrons.

Since neutrons carry no electrical charge, they can be added to the nucleus without affecting its chemical identity. For example, a typical hydrogen atom has one proton and no neutrons in its nucleus. If we add a neutron, the nucleus is more massive but still has one proton. It is still a hydrogen nucleus. Careful measurements of atomic masses show that such variations do occur. Hydrogen nuclei commonly exist in three variations: nuclei with one proton and no neutrons, with one proton and one neutron, and with one proton and two neutrons. Nuclei of a single element that have different numbers of neutrons (and, therefore, different masses) are called **isotopes** of the element. The atomic masses listed in the periodic table are the average masses of the mixtures of isotopes commonly found for each element.

Investigators have now identified over 100 elements, each of which has several isotopes. This means that a lot of different kinds of nuclei exist. To identify a specific nucleus we use the shorthand notation shown in Figure 21-2. A one- or two-letter symbol (*X* in the figure) identifies the chemical element. For example, hydrogen is identified as H; helium, as He. A subscript (*Z*), called the **atomic number,** identifies the number of protons in the nucleus and is the number given to each element in the periodic table. A superscript (*A*), called the **mass number,** describes the total number of nucleons found in the nucleus. Thus the atomic number identifies the chemical element, while the mass number identifies the specific isotope of that element. The number of neutrons in a particular nucleus can always be determined by subtracting the atomic number from the mass number (number of neutrons = $A - Z$). Several examples are:

Hydrogen	one proton, no neutrons	${}^{1}_{1}\mathrm{H}$
Helium	two protons, two neutrons	${}^{4}_{2}\mathrm{He}$
Oxygen	eight protons, eight neutrons	${}^{16}_{8}\mathrm{O}$

We sometimes refer to an isotope by giving its chemical name and its mass number. For example, the isotopes listed above are called hydrogen 1, helium 4, and oxygen 16.

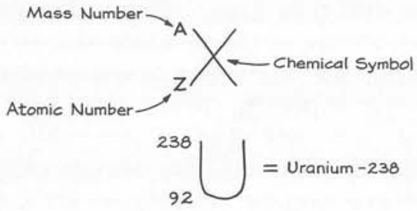


Figure 21-2
Shorthand notation used to describe nuclei.

We use a similar scheme for the electron. The symbol ${}_{-1}^{0}e$ identifies the electron as having a charge ("atomic number") of −1 and a mass of essentially zero when compared to the mass of the nucleons.

When expressed in kilograms, the masses of the nuclei are extremely small and somewhat cumbersome to use. So, we use a different unit of mass, the *atomic mass unit.* One **atomic mass unit** (amu) is 1.660565×10^{-27} kg, approximately equal to the mass of a nucleon. A proton has a mass of 1.006 amu, while the mass of a neutron is 1.0087 amu.

SELF-CHECK 21A

How many protons and neutrons are present in each of the following isotopes of uranium?

${}_{92}^{234}U \quad {}_{92}^{235}U \quad {}_{92}^{238}U$

NUCLEAR TRANSFORMATIONS

The light emitted by matter provides us with a brilliant display of information for building a model of atomic structure. As electrons jump from one orbit to another, atoms emit or absorb photons of electromagnetic radiation, including visible light. But photons are not the only radiation emitted by matter. In 1896 Henri Becquerel conducted a series of experiments with uranium and uranium salts that led to the discovery of new radiations that were far more intense than any yet known. Unlike the radiation associated with light spectra, these emissions included particles with mass and charge. Such radiation could be understood only in terms of nuclear changes. Ultimately, they provided the information for building a model of the nucleus.

Radioactivity

Figure 21-3 describes Becquerel's initial observations. He had wrapped a photographic plate with several pieces of thick black paper to keep it from being exposed to ordinary light. He then placed a chunk of uranium salt on top of the paper and put the plate in a dark drawer for several days. Since the photographic plate was well protected from light, we would expect the developed plate to be uniformly gray. Instead, Becquerel found an intense silhouette beneath the location of the uranium salt. After a series of careful experiments he concluded that uranium emits some sort of radiation that can penetrate paper and expose photographic plates.

Marie and Pierre Curie undertook a systematic study of Becquerel's rays, which they named *radioactivity.* They demonstrated that certain known elements in addition to uranium are radioactive, and they isolated previously

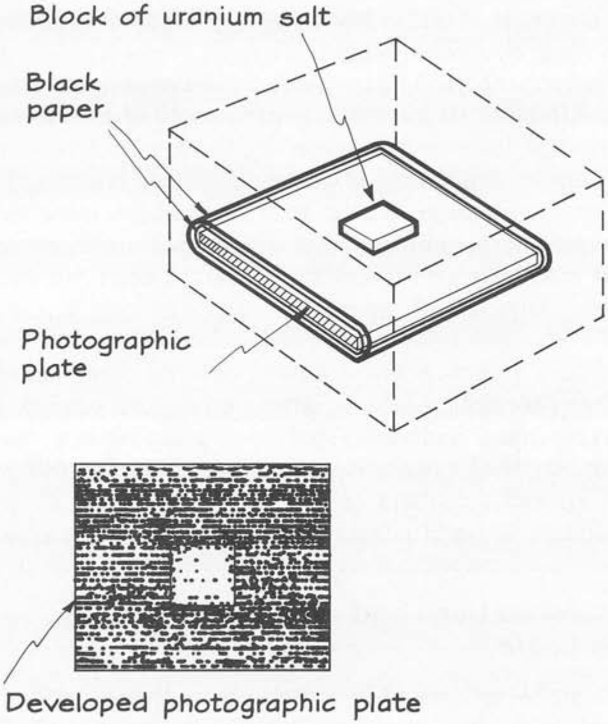


Figure 21-3
Uranium salts emitted radiation intense enough to expose a photographic plate that had been well protected from light.

unknown elements that are also radioactive. Rutherford and others concluded that the emissions are mixtures of three distinct types of radiations, which they called alpha, beta, and gamma.

The three kinds of radiation are distinguished by how hard they are to stop in matter and by their behavior when subjected to magnetic and electric forces. **Alpha radiation** is easily stopped by placing a few sheets of paper in its path. In the presence of a magnetic or electric force, alpha radiation is deflected. **Beta radiation** is not stopped by matter as easily as alpha, but it can be blocked by a rather thin sheet of aluminum. When magnetic or electric forces are present, beta radiation deflects in the opposite way from alpha. **Gamma radiation** is very difficult to stop; it can be stopped only by thick blocks of lead. It is not affected by either electric or magnetic forces. Subsequent experimentation revealed that all three radiations had already been known. Alpha radiation consists of helium nuclei ($^{4}_{2}He$) and beta of electrons ($_{-1}^{0}e$). Gamma radiation (γ) is electromagnetic radiation but with a much shorter wavelength than any previously known.

The positively charged helium nuclei that form the alpha radiation interact electrically with the atoms in matter. Because of their relatively large mass and charge, they lose energy quickly during these interactions. So, alpha radiation can be stopped by a rather small amount of matter. The electrons that make up beta radiation have a smaller mass and electrical charge than alpha particles. Thus they lose energy at a slower rate and travel further before stopping. Because alpha and beta particles have opposite electric charges, they move in opposite directions in the presence of magnetic and electric forces. Because gamma radiation is electromagnetic energy, it has neither charge nor mass. Thus it interacts very little with matter and is not affected by magnetic or electric forces.

Of the three phenomena, gamma radiation seems at first glance the least surprising. After all, atoms emit a great variety of electromagnetic radiations as they change their energy states. But, when compared with the energy emitted by atoms, the energy of gamma radiation is astounding. Gamma photons carry, on the average, 6.6×10^{-13} joules (J)—more than a million times the maximum energy an electron in a hydrogen atom can emit. Clearly, the energy must come from an interaction different from the electron transitions in the atom. Gamma radiations must originate from interactions inside the nucleus.

Alpha and beta radiation are distinct from any other energy forms. In burning and other chemical reactions, atoms emit pure energy. Electromagnetic energy has no mass. Radiations that carry away mass as well as energy are clearly different. They raise a new question: If radium (88 protons, 138 neutrons) emits an alpha particle (2 protons, 2 neutrons), do we still have radium? Our intuitive sense of conservation tells us that the answer is no.

Nuclear Transformations and Conservation Logic

The emission of alpha or beta radiation causes a change, called a **nuclear transformation,** in the nucleus from which it was emitted. Both alpha and beta emissions result from nuclear transformations. A radium nucleus that emits alpha radiation, for example, is no longer radium. It has been transformed into the nucleus of a different chemical element and an alpha particle, which is separated from the nucleus. We write

$$\text{Old element} \longrightarrow \text{new element} + \text{alpha particle } ({}^{4}_{2}\text{He})$$

where the arrow indicates *changed into*.

When radium emits an alpha particle, it is changed into radon gas. This transformation can be expressed as:

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

We say that radium has decayed into radon.

Nuclear transformations occur within the boundaries of the conservation laws of physics. Conservation of electric charge can be verified directly from the notation describing the interaction. For example, the charge carried by the radium nucleus (+88) equals the sum of the electric charges of the radon nucleus (+86) and the alpha particle (+2). Electric charge is conserved in nuclear interactions as it is in all other interactions.

A new conservation principle involves the total **number of nucleons** in the interaction. This number does not change during a nuclear transformation. In the present example radium has 226 nucleons, which equals the sum of the nucleons in radon (222) and helium (4) nuclei. For an alpha decay, the nucleons do not change from one type to another; protons do not change into neutrons. However, beta transitions require that a neutron change to a proton. Even in this case, however, the total number of nucleons (protons + neutrons) is conserved.

In nuclear transformations, conservation of energy takes a slightly different form from most of our previous uses. Here, energy must include Albert Einstein's statement that mass is a form of energy and that the mass-energy equivalence is given by

$$\text{Energy} = \text{mass} \times (\text{speed of light})^2$$

(See Chapter 9). In the radium → radon + alpha decay, the mass of the radium (226.025406 amu) is greater than the sum of the masses of radon (222.017574 amu) and helium (4.002604 amu). Conservation of energy requires that this mass difference (0.005228 amu $= 8.7 \times 10^{-30}$ kg) result in 7.8×10^{-13} J of energy. If the radium nucleus was not moving initially, the radon and helium nuclei will move away from each other with kinetic energies that total 7.8×10^{-13} J. This energy is what we commonly refer to as *nuclear energy.*

Conservation of momentum places a restriction on the relative motions of the products in a nuclear transformation. If the initial nucleus was not moving, then the products must move away from each other in such a way that the vector sum of their momenta is zero. For the radium decay, this restriction means that the alpha particle, with a much smaller mass, must have a much higher speed than the more massive radon. Only then will their momenta add to zero.

Alpha, beta, and gamma emissions are the processes by which most naturally radioactive nuclei decay. As we shall see, alpha and beta transformations both lead to the formation of new nuclei. Gamma transformations involve a rearrangement of the nucleons within the same nucleus. While other radioactive processes have been discovered, alpha, beta, and gamma decay remain common to many nuclear reactions. We examine each process in more detail.

SELF-CHECK 21B

A nuclear transformation can occur only if no conservation laws are violated. Using conservation of nucleons and charge, determine whether the nuclear transformations listed below are possible. Explain your conclusions.

$$^{14}_{6}\text{C} \rightarrow {}^{14}_{7}\text{N} + {}^{0}_{-1}e$$
$$^{19}_{9}\text{F} \rightarrow {}^{3}_{2}\text{He} + {}^{16}_{8}\text{O}$$

ALPHA DECAY

As we discussed in Chapter 8, the struggle between the attraction of the strong nuclear interaction among all nucleons and the repulsion of the electrical interactions among protons can cause some nuclei to decay. Nuclei that decay are called *unstable,* while those that do not are *stable*. Alpha decay is a common nuclear transformation by which heavy, unstable nuclei decay to lighter, more stable nuclei. In alpha decay a nucleus splits into an alpha particle and a nucleus of an element two places to the left in the periodic table. Energy is released in the form of kinetic energy of the two products. Polonium 210, for example, changes into lead 206 by emitting an alpha particle. This transformation is written

$$^{210}_{84}\mathrm{Po} \rightarrow {}^{206}_{82}\mathrm{Pb} + {}^{4}_{2}\mathrm{He}$$

Lead is two places to the left of polonium in the periodic table. Mass in the polonium nucleus is converted into the energy needed to force the lead nucleus and the alpha particle apart.

Among unstable nuclei, alpha decay is somewhat common. To understand the reasons for alpha decay, we must turn to the wave nature of matter and consider the matter waves of the alpha particle as it exists in the nucleus. Alpha decay occurs so frequently that physicists speculate that the alpha particle somehow retains an identity within the nucleus. While we are not certain that such an assumption is valid, it does provide us with a useful model to consider.

The matter wave associated with the alpha particle within the nucleus provides us with one way of understanding the conditions in which alpha decay occurs. As illustrated in Figure 21-4, a matter wave can be associated with the alpha particle in the nucleus. When compared to the size of the nucleus, the length of this wave describes the conditions under which alpha decay will occur. In all cases most of the wave exists within the boundary of the nucleus. Nuclei that decay by alpha particle emission, however, have significant fractions of the alpha particle matter wave extending beyond the nucleus. (Recall that the amplitude of the wave packet at any point is related to the probability that the particle will exist at that point.) Because of this wave extension, the alpha particle can exist outside and inside the nucleus.

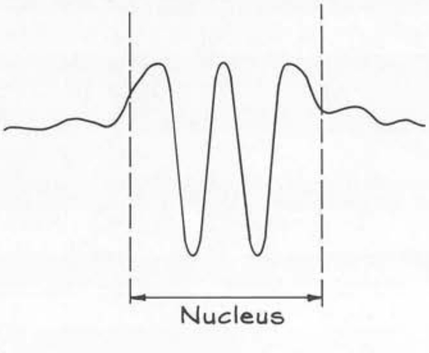


Figure 21-4

A wave packet can be associated with the alpha particle. If the wave packet spills out beyond the boundary of the nucleus, there is a finite probability that the alpha particle will move outside the nucleus briefly.

Inside the nucleus, the strong nuclear force of attraction exceeds the electric force of repulsion, and the alpha particle remains part of the nucleus. Once it wanders outside the nucleus, however, the strong nuclear force, which has a very short range, has less effect on the alpha particle. At some point, the electric repulsion takes over, and the alpha particle is permanently ejected from the nucleus. An alpha decay occurs, with a new nucleus being left behind.

BETA DECAY

Beta decay describes the process by which one element can be transformed into the next element to the right in the periodic table. For example, a nucleus of carbon, element 6, can be transformed into a nucleus of nitrogen, element 7. A beta particle (electron) and another particle called an antineutrino ($\bar{\nu}_e$) are released in this process.

$$^{14}_{6}\mathrm{C} \longrightarrow {}^{14}_{7}\mathrm{N} + {}^{0}_{-1}e + \bar{\nu}_e$$

In some respects, beta decay is more of an enigma than alpha decay. While the assumption that the alpha particle somehow retains its identity within a nucleus is not well justified, it is not impossible to believe. A beta particle, on the other hand, is an electron. Electrons do not exist in the nucleus. Were it not for the observable transformation of a nucleus, as from carbon to nitrogen, we might suppose that the electron is released from the atom and not the nucleus. However, the nuclear transformation is unmistakable.

The Transformation of the Neutron

Observation of neutrons outside the nucleus provides some insight into the process of beta decay. Neutrons that are free from a nucleus are relatively unstable and decay fairly quickly into a proton, an electron, and an antineutrino.

$$^{1}_{0}n \longrightarrow {}^{1}_{1}p + {}^{0}_{-1}e + \bar{\nu}_e$$

This decay led many people to speculate that a neutron consists of a proton, an electron, and an antineutrino bound together by some force. Through a series of careful experiments, physicists have tried to identify protons and electrons within the neutron. To date, these experiments have been unsuccessful. As far as we can tell, the proton, electron, and antineutrino do not exist inside the neutron. They appear to be created at the moment the neutron decays.

In general, beta decay shows many of the characteristics of neutron decay. As carbon decays into nitrogen, a neutron disappears. The number of protons increases by one and an electron and an antineutrino are ejected. However, neither the electron nor the antineutrino exist inside the nucleus before the time that the decay occurs.

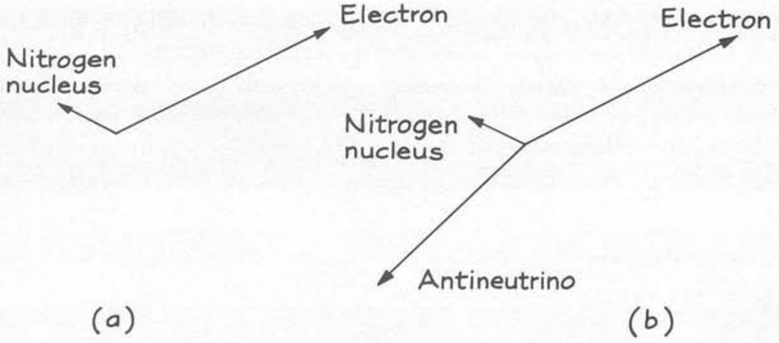


Figure 21-5
Momentum is conserved in beta decay processes. **(a)** Measurements showed that the nitrogen nucleus and the electron did not move off in opposite directions. **(b)** Momentum would be conserved only if a third particle were released in beta decay.

While alpha decay is characterized by the ejection of nucleons that are in the nucleus, beta decay involves the transformation of one type of nucleon into another by emitting particles that were not present until the transformation occurred. This difference, along with other more complex reasons, led physicists to conclude that a fundamental interaction different from the strong nuclear interaction was responsible for beta decay. It was clearly occurring in the nucleus. Further, careful measurements showed that the strength of the interaction was weaker than the strong nuclear force. Thus the interaction responsible for beta decay was named the *weak nuclear interaction.*

Antineutrinos and Conservation Logic

We have listed an antineutrino as a product of beta decay without explaining what the antineutrino is and why it is always included in these interactions. The story of its discovery illustrates the extent to which modern science relies on conservation logic.

When physicists first studied beta decay in detail, they detected the emitted electrons and the transformation of the nucleus. The carbon 14 reaction, for example, was first thought to be carbon transforming into a nitrogen nucleus and an electron only. Measurements of beta decay yielded two startling results. First, the beta particle had too little kinetic energy. The difference between the mass of the carbon 14 and the combined masses of the nitrogen 14 and the electron is 0.0002 amu. If all of this mass difference is converted into kinetic energy of the products, then the electron should have a kinetic energy of about 3×10^{-14} J. However, the kinetic energy of the electron ranged from zero to all the energy available, with the majority of the electrons being emitted with an energy of about 1.5×10^{-14} J. The second surprise was that when the carbon nucleus was initially not moving, the nitrogen nucleus and the electron did not move off in exactly opposite directions, as conservation of momentum requires (Figure 21-5(a)). Neither momentum nor energy appeared to be conserved in beta decay.

Rather than abandon the conservation principles, physicists suggested that yet another particle must be present in the products of beta decay. Conservation laws dictated that this new particle could have no electric charge (electric charge was already conserved), must have a very small mass, and must move off with a speed and a direction that would conserve momentum

Beta Decay in the Study of Art

Beta decay occurs in many naturally radioactive nuclei. In addition, stable nuclei can be turned into isotopes that emit electrons and antineutrinos by placing them in a beam of neutrons. The neutron is absorbed by a nucleus and a new, radioactive nucleus is created. A transformation that illustrates this process is

$$ {}_{0}^{1}n + {}_{11}^{23}\mathrm{Na} \rightarrow {}_{11}^{24}\mathrm{Na} \rightarrow {}_{12}^{24}\mathrm{Mg} + {}_{-1}^{0}e + \bar{\nu}_e $$

A neutron transforms the stable sodium 23 nucleus into an unstable isotope, sodium 24, which then emits an electron and antineutrino and becomes magnesium 24, another stable isotope. Hundreds of isotopes can be converted into beta emitters by this process.

The large number of nuclei that can be changed into beta emitters when they absorb a neutron has made beta decay an important tool for art historians. Typically, a painting is placed in front of a beam of neutrons. Nuclei of elements found in paint and charcoal are changed into unstable nuclei, which then transform into new stable nuclei by beta emission. A photographic plate placed over the painting reveals the location of these unstable nuclei as each emitted electron interacts with the photographic emulsion. The result is a "picture" of the locations of these unstable nuclei.

Moonlight by R.A. Blakelock (Figure A) was treated in this manner. One of the beta decay photographs showed the presence of a painting beneath the top painting (Figure B). Pigments used to paint the original figure of a woman included arsenic 76, antimony 12, and chromium 51. All these isotopes become beta emitters when they absorb a neutron.

Analyses such as these are important for two reasons. First of all, they provide information about the artist's style, techniques, and use of materials. Such information is valuable to art historians and collectors who want to identify forgeries. (Blakelock's work was often copied, but the forgers generally used slightly different pigment preparations.) Secondly, the analysis can be conducted without destroying the painting. Neutrons are absorbed by only a few of the many nuclei in the painting. So few nuclei change to different nuclei that the procedure produces no noticeable change in the original work.

Figure A

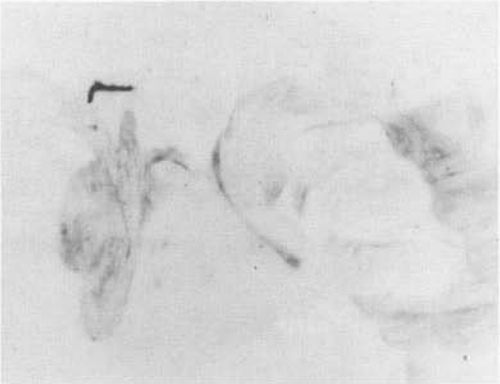


Figure B

© 1977 by Sidney Harris.

"THE QUESTION NOW IS, 'HOW MANY NEUTRINOS CAN DANCE ON THE HEAD OF A PIN?'"

(Figure 21-5(b)). Italian physicist Enrico Fermi named the yet-to-be-discovered particle the *neutrino*—little neutral one. For more than 20 years the neutrino hypothesis remained unproved, though generally accepted. Finally, in the mid-1950s physicists detected a particle with properties identical to those predicted for the neutrino. Either a neutrino or its close relative, the antineutrino, is a part of every beta decay.

GAMMA DECAY

The third common form of nuclear radiation is gamma radiation. Having neither mass nor electric charge, this radiation is electromagnetic radiation of very high energy. Gamma decay releases energy from the nucleus but does not transform one isotope into another.

Gamma Decay Releases Electromagnetic Energy

Just as the electromagnetic energy emitted by atoms moves the atom from one energy state to another, gamma emission from nuclei moves the nucleus from one nuclear energy state to another. The nucleus just before a gamma transformation is in an excited, or high-energy, state. After the emission of

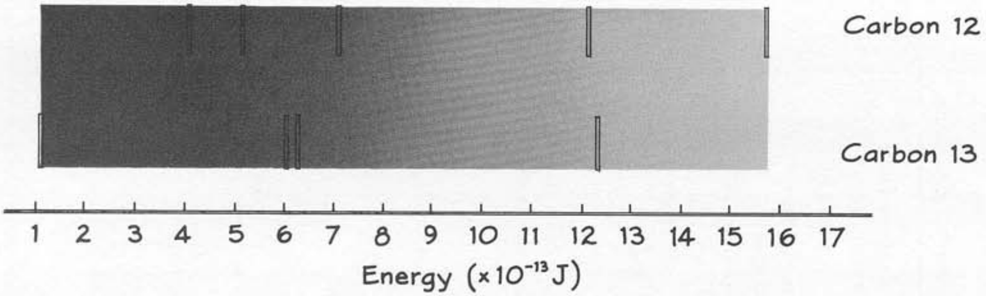


Figure 21-6
The energy spectrum of gamma radiation emitted by carbon 12 is distinctly different from that for carbon 13.

gamma radiation, the nucleus is in a lower-energy state. The difference in the nuclear energy states is the energy of the gamma radiation.

We represent the gamma transformation by a notation similar to that used for alpha and beta decay. However, we add an asterisk to identify a nucleus that is in an excited state. One gamma transformation is

$$^{12}_{6}\mathrm{C}^{*} \rightarrow {}^{12}_{6}\mathrm{C} + {}^{0}_{0}\gamma$$

The zeros as subscript and superscript on the gamma indicate that the gamma radiation carries no charge and no mass away from the transformation.

Gamma radiations that are emitted by the excited states of a nucleus have a unique spectrum associated with each isotope of an element. As illustrated in Figure 21-6, the gamma spectrum for carbon 12 is distinctly different from that for carbon 13. Just as we can identify atoms from their light spectrum, we can identify specific isotopes from the gamma radiation spectrum that they emit.

SELF-CHECK 21C

The difference between one of the excited states and the lowest energy state of nickel 60 is 2.1×10^{-13} J. What is the energy of the gamma radiation when nickel 60 undergoes a gamma transformation from the excited state to the ground state?

Gamma Spectra and Criminal Investigations

The uniqueness of the gamma spectrum emitted from a particular isotope has become a valuable tool to criminal investigators. One common application involves the use of gamma spectra to identify paint samples from automobiles.

Each time a batch of paint is mixed, the mixture is slightly different from other batches. While the colors may look identical, small differences in the mixing procedure or the cleanliness of the equipment can introduce slight impurities into the batch. These impurities, generally unique to each batch, can be used to link paint samples to a vehicle suspected in a hit-and-run accident.

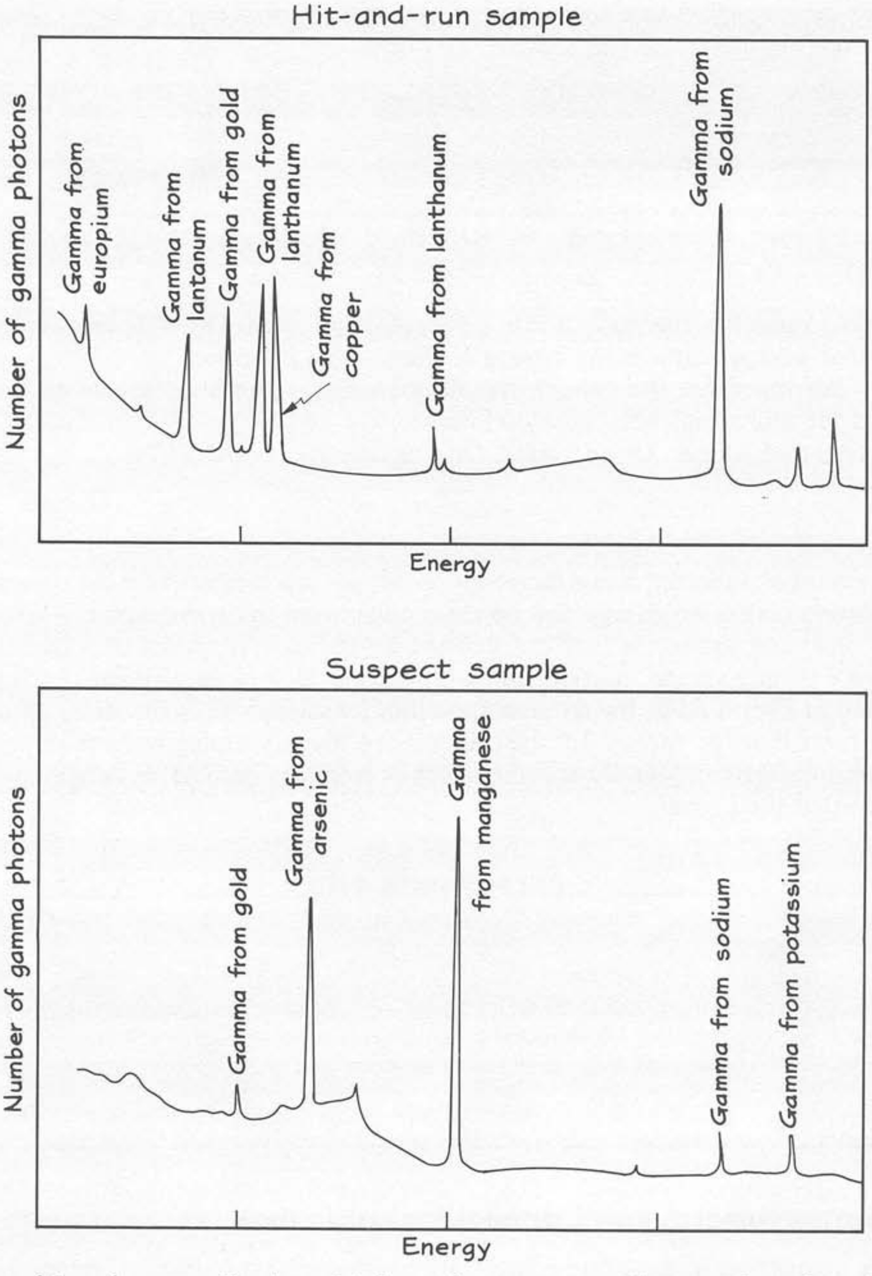


Figure 21-7
Differences in the gamma spectra of paint samples led detectives to conclude that the two could not be from the same vehicle.

In a hit-and-run accident, paint from the car is usually transferred to the object struck. Using gamma spectra, detectives can compare a sample of this rubbed-off paint with a sample of paint from the suspect vehicle. Even if the two paint samples are the same color, they might not be from the same vehicle. The probability that they came from the same vehicle increases greatly if the detectives can show that the paint came from the same batch.

To determine if the paint samples were mixed in the same batch, scientists place the two samples in front of a beam of moving neutrons. These neutrons are absorbed by nuclei in the paint, changing them to excited states of different isotopes. These new isotopes move to their lowest energy state by the emission of gamma radiation. For example,

$$^{1}_{0}n + ^{55}_{25}\mathrm{Mn} \rightarrow ^{56}_{25}\mathrm{Mn}^{*} \rightarrow ^{56}_{25}\mathrm{Mn} + ^{0}_{0}\gamma$$

By comparing the gamma spectra of the two samples, detectives can determine whether both samples came from the same batch of paint. If they did not, the suspected vehicle was not involved in the accident. Figure 21-7 illustrates two spectra obtained from samples suspected to be from the same car. The spectra clearly reveal that the two samples come from different batches. The suspected vehicle was not involved in the accident from which the other sample was taken even though both samples are the same color.

HALF-LIFE

In extending Becquerel's early work with uranium and uranium compounds, Marie Curie attempted to identify systematically other radioactive elements. Her measurements with uranium and thorium compounds allowed her to link the intensity of radioactive emissions to the amount of radioactive materials present. Curie found that the radioactivity emitted by pitchblende, an ore that is roughly 80% uranium oxide, was nearly five times that expected from the amount of uranium present. This result caused her to undertake an extensive chemical analysis of pitchblende, which turned out to contain three new radioactive elements—polonium, radium, and radon. A single ore, then, was found to have at least four radioactive elements.

As more radioactive isotopes were isolated, physicists realized that spontaneous transformations often lead to a sequence of reactions, as shown in Figure 21-8. Radium spontaneously emits an alpha particle and decays into radon. Radon decays into polonium; polonium decays into lead. Viewed in terms of such a sequence, Curie's results were hardly surprising. What was surprising was how relatively few radon and polonium atoms were present. Clearly, isotopes decay at different rates.

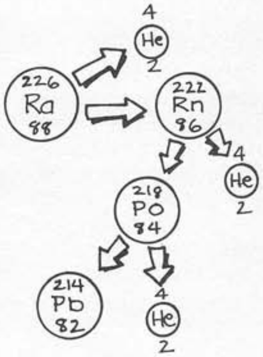


Figure 21-8

Spontaneous transformations often lead to a sequence of nuclear reactions.

Half-Life Describes the Rate of Decay

We can measure, theoretically, the rate at which a radioactive isotope decays by starting with a sample of a known number of nuclei and periodically counting the number of undecayed nuclei left. In practice, this turns out to be difficult. Instead, we count the number of radiations emitted. Each time one is detected, we know that one nucleus has decayed. Sample data for the decay of polonium are presented in Table 21-1. The same information is shown graphically in Figure 21-9.

The decay of an individual nucleus is random. We cannot know when any particular nucleus will decay, but we can look at collections of nuclei and describe them as an entity. Then, we describe the decay rate in terms of the time required for half of the remaining nuclei to decay. As you can see from Table 21-1, the half-life of polonium is a little more than 3 minutes (min).

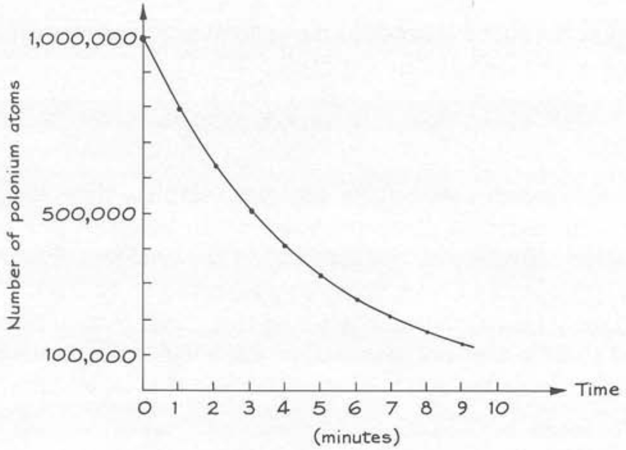


Figure 21-9

Graph showing the number of polonium atoms left as a function of time. Most of the polonium nuclei decay during the first few minutes.

Table 21-1 Decay of Polonium into Lead

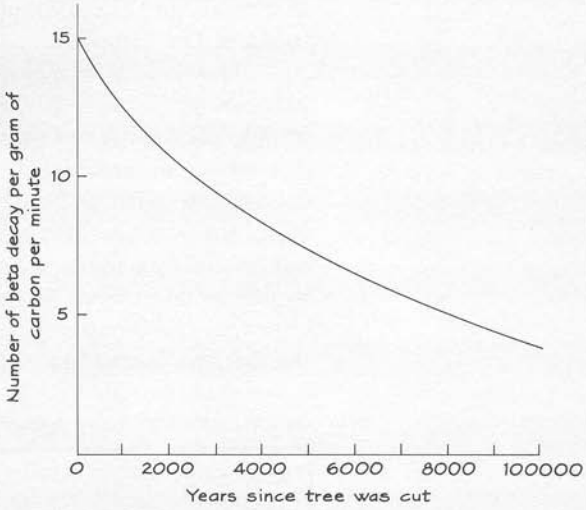
$^{218}_{84}Po \rightarrow ^{214}_{82}Pb + ^{4}_{2}He$

Time (min)	Number of Polonium Atoms	Number of Lead Atoms
0	1,000,000	0
1	796,751	203,249
2	634,812	365,188
3	505,787	494,213
4	402,986	597,014
5	321,080	678,920
6	255,821	744,179
7	203,825	796,175
8	162,398	837,602
9	129,391	870,609

Slightly more than half our initial sample (505,787) is left at the end of 3 min. After 3 min more, approximately half this number (255,281) remain, and so forth. During a time equal to one half-life, one-half of the remaining nuclei decay.

Each nucleus that undergoes a nuclear transformation has a well-defined half-life. Half-lives can range from a fraction of a second to thousands of years. The half-life of radium 226, for example, is 1620 years. Its decay product, radon 222, has a much shorter half-life of 3.82 days. As we just mentioned,

Half-Lives in Archeological Dating



The constancy of the half-life of a particular isotope has proven invaluable to archeologists. Because carbon is the primary building block of living tissue, many archeological studies concentrate on this element. Carbon exists in seven different isotopes, two of which (carbon 12 and carbon 13) are stable. The other isotopes are radioactive and have half-lives that range from 2.3 seconds to 5568 years. The 5568-year half-life of carbon 14 has made it useful to archeologists in dating artifacts.

Carbon 14 transforms to nitrogen 14 by beta decay,

$$ {}^{14}_{6}\mathrm{C} \rightarrow {}^{14}_{7}\mathrm{N} + {}^{0}_{-1}e + \bar{\nu}_e $$

However, the percentage of carbon 14 found in the atomsphere has remained rather constant because it is continuously being replenished by neutron collisions in the upper atmosphere. Neutrons from space strike nitrogen 14 to produce carbon 14 and a proton. Consequently, decays of carbon 14 are balanced by its creation.

All living things continuously take up carbon from the environment. A tree, for example, takes in carbon dioxide in the process of photosynthesis and incorporates the carbon in its tissue. A known fraction of the carbon dioxide molecules contains carbon 14. Since the proportion of carbon 14 in the atmosphere remains constant, so should the proportion of carbon 14 in the tree. As long as the tree continues to take in carbon from the atmosphere, we should be able to detect about 15 beta emissions per minute for each gram of carbon in the tree.

When a tree is cut to provide wood for a house or a boat, for instance, it stops taking in carbon from the atmosphere. No more carbon 14 will enter the wood. However, the nuclei of carbon 14 already there will continue to decay with a half-life of 5568 years. If we measure 15 beta emissions per minute per gram of carbon at the time of cutting, then 5568 years later we should measure about 7 to 8 beta particles per minute per gram of carbon in the wood. By comparing the emissions of the cut sample with emissions of a living sample, we can infer the length of time that has elapsed since the tree was cut. The graph presents a rough estimate of the beta emissions found at various time intervals.

Archeologists use this technique extensively to date wooden artifacts and animal skeletons. The method does have limitations, however. First of all, the investigator must separate the beta particles emitted by carbon 14 from those emitted by other nuclei. This procedure is not simple. Secondly, we do not know the half-life of carbon 14 exactly. Finally, the number of beta particles emitted per gram of carbon is very small. The archeologist must use enough material to obtain a valid measurement and yet not destroy the artifact. These problems combine to give an uncertainty of about 15% in dates obtained by use of carbon 14 decays. A boat that is measured by carbon dating to be 500 years old may be as little as 425 years old or as old as 575 years. For some purposes this level of uncertainty is acceptable; for others, it is not.

polonium 218 has a half-life of only 3 min. The short half-lives of radon 222 and polonium 218 explain why Curie found such small amounts of these isotopes in her samples.

The half-life of a nucleus is remarkably constant for a given isotope. It is independent of any physical or chemical conditions in which the nucleus is found. The half-life of uranium 238 is 4.15×10^9 years regardless of whether it is combined chemically with other elements, whether it is found at the surface of the earth or 2 miles below, and whether the climate changes over the life of the isotope. This independence of the half-life from the surrounding conditions reflects the small range of the nuclear force. The very small nucleus is well isolated from its surroundings. Conditions affecting the atom, such as chemical combinations, primarily involve the electrons. Interactions involving the nuclear forces are not affected by these distant conditions.

SELF-CHECK 21D

Suppose you start with 256 nuclei of polonium 218, which has a half-life of 3 min. How many nuclei remain after 3 min? 6 min? 9 min?

Radioactive Decay Series and the Age of the Earth

The presence of so many radioactive nuclei in pitchblende led physicists to suggest that uranium, radium, radon, and polonium are linked by a series of radioactive transformations. A **radioactive-decay series** is a sequence of decay processes that leads from an unstable nucleus to a stable one through several nuclear transformations. Experiments identified the parent of this particular series as uranium 238. The stable nucleus that concluded the series was lead 206. As illustrated in Figure 21-10, the series transforms uranium 238 into lead 206 through eight alpha decays and six beta decays.

Many of the nuclei in the uranium 238 series have extremely short half-lives. Polonium 218 has a half-life of 3.05 min; that of lead 210 is 22 years. If we started with a small amount of either isotope, we could expect to have none of either after a few hundred years. However, the supply of polonium 218 and lead 210 is constantly being replenished by the decay of the parent element. Uranium 238 has such a long half-life (4.5 billion years) that we expect the decay series to be fed for billions of years to come.

The uranium 238 transformation series is one of four such series that have been identified. The parent of one series, neptunium 237, has a relatively short half-life (2.25 million years) and, thus, no longer occurs naturally. However, the series is produced artificially by creating neptunium 237 in the laboratory. All naturally occurring decay series end with an isotope of lead, while the neptunium series terminates with bismuth.

Because of the exceptionally long half-lives of the parent elements, radioactive-decay series provide a technique for estimating the ages of rocks

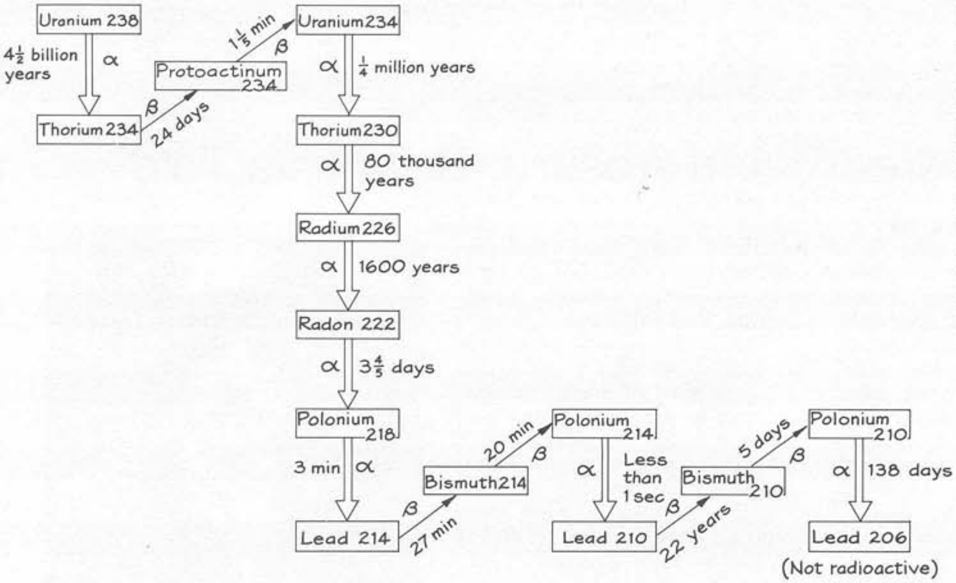


Figure 21-10

The uranium transformation shows a sequence of reactions leading from the uranium 238 nucleus to the lead 206 nucleus. Eight alpha decays and six beta decays are required to complete the process from unstable to stable nuclei.

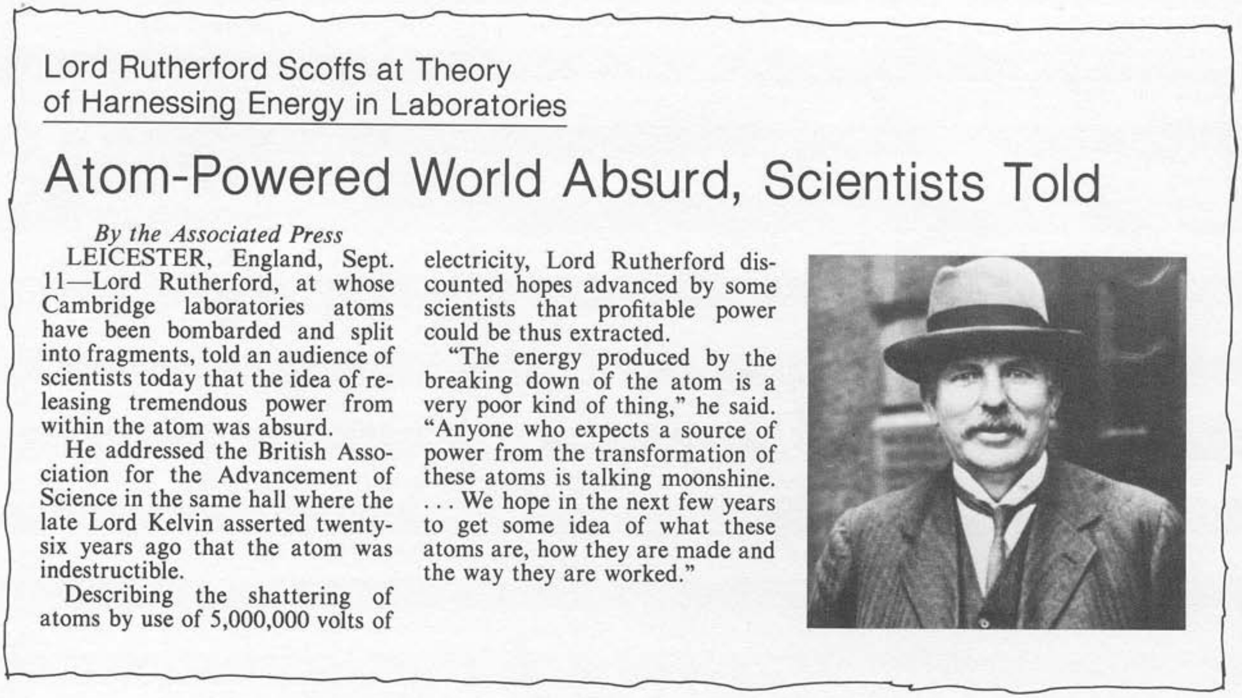
on the earth and, to some extent, the age of the earth itself. The absence of neptunium 237 in natural rock implies that the earth is at least as old as the half-life of that element, 2.25×10^6 years. How much older? We can get some idea by comparing the ratio of the parent to the final product in each of the naturally occurring decay series. These and similar comparisons suggest that the earth is about 4.5 billion years old.

Tiny particles, bound in an uneasy truce within the incredibly small space of the nucleus, can in some cases fly apart, spontaneously releasing a small amount of energy. In the early years of this century, this energy was extremely useful for learning more about the structure of the nucleus. However, some of the early investigators saw no practical use for it (Figure 21-11). Only later did they discover and understand the enormous energies released and available for use in nuclear fusion and nuclear fission, the subjects of our final chapter.

CHAPTER SUMMARY

Chemical elements can be identified uniquely by the masses and electric charges carried by their nuclei. Both characteristics can be described by the presence of protons and neutrons in the nucleus. Protons have an electric charge equal in magnitude but opposite in sign to the charge on an electron. The proton mass is about 1850 times greater than the mass of the electron. A neutron carries no electric charge and has a mass approximately equal to that of the proton. Atoms with the same number of protons but different numbers of neutrons are called *isotopes*.

Some nuclei spontaneously emit radiations more intense than that seen in the spectra of atoms. Called *radioactivity,* this radiation was found to consist



Lord Rutherford Scoffs at Theory of Harnessing Energy in Laboratories

Atom-Powered World Absurd, Scientists Told

By the Associated Press

LEICESTER, England, Sept. 11—Lord Rutherford, at whose Cambridge laboratories atoms have been bombarded and split into fragments, told an audience of scientists today that the idea of releasing tremendous power from within the atom was absurd.

He addressed the British Association for the Advancement of Science in the same hall where the late Lord Kelvin asserted twenty-six years ago that the atom was indestructible.

Describing the shattering of atoms by use of 5,000,000 volts of electricity, Lord Rutherford discounted hopes advanced by some scientists that profitable power could be thus extracted.

"The energy produced by the breaking down of the atom is a very poor kind of thing," he said. "Anyone who expects a source of power from the transformation of these atoms is talking moonshine. . . . We hope in the next few years to get some idea of what these atoms are, how they are made and the way they are worked."

Figure 21-11

Ernest Rutherford's crystal ball was slightly cloudy when he discussed practical applications of nuclear energy.

of alpha, beta, and gamma radiation. *Alpha radiation* consists of particles made up of two protons and two neutrons (that is, helium nuclei). The alpha decay of a nucleus can be explained in terms of a wave packet that extends beyond the nucleus. Once the alpha particle moves outside the nucleus, the electrical forces of repulsion exceed the nuclear forces of attraction and the alpha particle is ejected. *Beta particles* are electrons. Electrons and antineutrinos are ejected from the nucleus at the time of the transformation. *Gamma radiation* is electromagnetic radiation that is a million times more energetic than that emitted in atomic spectra. It occurs when a nucleus in an excited state moves to a lower energy state and emits energy.

Alpha and beta radiation arise because the nuclei undergo nuclear transformations in which a nucleus of one element changes into a nucleus of a different element. Such transformations proceed under the constraints of the conservation laws. The energy released in nuclear transformations comes from mass that has been transformed into energy in accordance with Einstein's principle of mass-energy equivalence.

Radioactive isotopes decay at a rate characteristic of each isotope. These rates are described by the *half-life,* the time required for half of the undecayed nuclei to decay. Half-lives can range from a fraction of a second to millions of years. The half-life is independent of any physical or chemical change the atom undergoes.

ANSWERS TO SELF-CHECKS

21A. ${}^{234}_{92}U$ contains 92 protons and $(234 - 92) = 142$ neutrons.

$^{235}_{92}U$ contains 92 protons and $(235 - 92) = 143$ neutrons.

$^{238}_{92}U$ contains 92 protons and $(238 - 92) = 146$ neutrons.

21B. The first transformation is possible. Both nucleon number and electric charge are conserved. The second transformation is not possible. Electric charge is not conserved, although nucleon number is.

21C. Gamma radiation is emitted from the nucleus in much the same way that radiation is emitted by atoms undergoing electron transitions. The energy released is equal to the difference in energy of the excited and the ground state. The energy released is 2.1×10^{-13} J.

21D. Three minutes is one half-life. We will have $(\frac{1}{2}) \times 256 = 128$ polonium atoms left. Six minutes is two half-lives. We will have $(\frac{1}{2}) \times 128 = 64$ polonium nuclei left. Nine minutes is three half-lives. We will have $(\frac{1}{2}) \times 64 = 32$ polonium nuclei left.

PROBLEMS AND QUESTIONS

A. Review of Chapter Material

A1. Define each of the following terms:
Nucleon
Isotope
Atomic number
Mass number
Radioactivity
Nuclear transformation
Alpha decay
Beta decay
Gamma decay
Half-life
Radioactive-decay series
Atomic mass unit

A2. Describe the role of the proton and neutron in determining the mass and electric charge of a nucleus.

A3. How does the nucleus change if a proton is added? If a neutron is added? Which determines the chemical element?

A4. What observations allow us to conclude that the radiation emitted by uranium and radium consists of three distinct forms?

A5. What conservation laws govern nuclear transformations?

A6. From where does the energy that people refer to as *nuclear energy* come in a nuclear transformation?

A7. Under what conditions will alpha decay occur?

A8. In what ways are beta decay and the decay of a free neutron similar?

A9. Why is the third particle, the antineutrino, required to explain the results of beta decay?

A10. How is gamma decay different from alpha and beta decay?

A11. How do we describe the rate at which an isotope decays?

A12. With the help of Figure 21-10, describe the radioactive decay series in which uranium 238 is the parent nucleus and lead 206 is the stable end product.

B. Using the Chapter Material

B1. How many protons and neutrons are in each of the isotopes listed below?

$$^{198}_{79}Au \qquad ^{45}_{20}Ca \qquad ^{36}_{17}Cl \qquad ^{59}_{26}Fe$$

In a neutral atom, how many electrons will surround each of these nuclei?

B2. Show that electric charge and nucleon number are conserved in the reactions shown below.

$$^{90}_{39}Y \rightarrow {}^{90}_{40}Zr + {}^{0}_{-1}e + \bar{\nu}_e$$

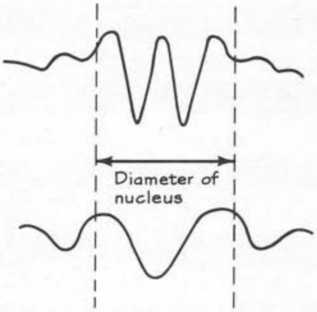
$$^{239}_{94}Pu \rightarrow {}^{235}_{92}U + {}^{4}_{2}He$$

B3. Can each of the reactions listed below occur? If the answer is no, explain how you reached your conclusion.

$$^{24}_{11}\text{Na} \rightarrow ^{24}_{12}\text{Mg} + ^{4}_{2}\text{He}$$

$$^{42}_{19}\text{K} \rightarrow ^{42}_{20}\text{Ca} + ^{0}_{-1}e + \bar{\nu}_e$$

B4. The figure below shows the wave packets for alpha particles in two different nuclei. The size of the nucleus has been superimposed over the wave packet. Which is more likely to undergo alpha decay? Explain how you reached your answer.



B5. When iodine 131 undergoes beta transformation, it emits electrons with energies ranging from 0 to 10×10^{-14} J. If an electron leaves the iodine with 4×10^{-14} J, how much energy does the accompanying antineutrino have? (Assume the antineutrino has zero mass.)

B6. Conservation of electric charge and conservation of nucleon number allow a free proton to undergo beta decay, releasing a neutron, a beta particle, and whatever other particles are required. Such a reaction never occurs, however. Use conservation of mass-energy to explain why.

B7. Oxygen 20 has an excited state that is 1.6×10^{-13} J above the ground state. What is the energy of the gamma radiation when this state transforms into the ground state?

B8. The half-life of strontium 90 is 29 years. Suppose you start with 1,000,000,000 nuclei of strontium 90. How many strontium 90 nuclei will remain after 29 years? After 58 years? After 116 years?

B9. Suppose you begin with a sample of 400,000 bismuth 210 nuclei. Fifteen days later you measure the number of bismuth 210 nuclei still present and find 50,000. What is the half-life of bismuth 210?

B10. A part of a tree is broken off. At the time of the break, the part had 2×10^5 nuclei of carbon 14 in it. Approximately 11,000 years later, how many carbon 14 nuclei are in the branch?

B11. For each of the reactions below, fill in the missing particles or nuclei.

$$^{35}_{16}\text{S} \rightarrow ^{35}_{17}\text{Cl} + ?$$

$$^{210}_{84}\text{Po} \rightarrow ? + ^{4}_{2}\text{He}$$

$$^{131}_{54}\text{Xe}^* \rightarrow ^{131}_{54}\text{Xe} + ?$$

$$^{32}_{15}\text{P} \rightarrow ^{32}_{16}\text{S} + ?$$

$$^{1}_{0}n + ^{208}_{83}\text{Bi} \rightarrow ? + \gamma$$

$$^{19}_{9}\text{F} + ? \rightarrow ^{22}_{11}\text{Na} + ^{1}_{0}n$$

C. Extensions to New Situations

C1. Watch dials with radium in them will glow in the dark.

a. Radium ($^{226}_{88}\text{Ra}$) transforms to radon ($^{222}_{86}\text{Rn}$). What particle is emitted in the transformation?

b. Through what force can this particle interact with the electrons in the paint?

c. During this interaction, what type of particle is exchanged between the alpha particle and the atomic electron? (You may wish to refer to the discussion of exchange particles in Chapter 8.)

d. If an electron in an atom absorbs a photon, what will happen to it?

e. How will the energy of the electron show up when it returns to the ground state?

f. Why does radium in the dial paint make the dial glow in the dark?

g. Some liquid crystal watches contain hydrogen 3, which undergoes beta transformation. Describe why they will glow in the dark.

C2. In the next chapter, we discuss the use of nuclear energy to generate electricity. One of the problems with nuclear energy is the radioactive waste products produced. An important component of this waste is cesium 137, which has a half-life of 30 years. Even though cesium has this relatively short half-life, it must be stored for thousands of years.

a. Suppose you have a sample with 10^{10} nuclei. After 10 half-lives, how many nuclei are left to transform later?

b. How many nuclei will decay between 300 years and 330 years?

c. If 10^5 radiations per year were considered dangerous, would you need to store the material longer than 330 years?

d. Why do you suppose that cesium 137 waste from reactors must be stored for such a long time?

(*Note:* The numbers in this problem were used to illustrate the difficulty and do not represent real situations.)

C3. The material at the center of the earth is very hot. The present theory is that this heat is the result of radioactive transformations in the earth. How do you think that such transformations could generate heat?

C4. One type of smoke detector contains a very small sample of americium 243 ($^{243}_{95}Am$).

a. The $^{243}_{95}Am$ transforms to neptunium 239 ($^{239}_{93}Np$). What particle is emitted in the process?

b. The particles are emitted into a space that is in an electric field. If a large number of charged particles are there, a current will flow and the alarm will sound. The transformation products by themselves are not sufficient to cause the necessary current. Why do the smoke particles, which are not radioactive, cause the current to exist?

c. The smoke particles interact with the charged alpha particles. How can this interaction increase the number of electrically charged smoke particles?

d. The neptunium undergoes beta transformation. Into what does it transform?

C5. A sample of material containing nuclei that transform by all three processes is placed between two electrically charged plates. Plate A has a positive charge; plate B is negative. Describe the motion of each form of radiation in this situation.

C6. Persons who work around radioactivity or X rays must be sure that they do not receive too much radiation. To monitor the amount that reaches their bodies, they wear film badges. These contain small pieces of photographic film enclosed in paper wrappers. How can these devices determine the amount of radiation to which they are exposed?

C7. The uranium 235 decay series undergoes a series of transformations until it reaches the stable lead 207 isotope. The order in which the decay processes occur is listed below. Use this order and the periodic table in Figure 21-1 to construct a diagram similar to that shown for uranium 238 in Figure 21-10: alpha-beta-alpha-beta-alpha-alpha-alpha-alpha-beta-alpha-beta.

C8. Listed are the stable isotopes of lead, their relative abundances, and their masses. We could determine the average mass of lead by assuming that we had 100 atoms distributed as shown by their relative abundances. Calculate this value by:

a. multiplying the relative abundance of each isotope by its mass

b. adding the four values

c. dividing by the number of atoms in our sample, 100.

How does this value compare with the atomic mass given in the periodic table in Figure 21-1?

Isotope	*Relative Abundance (%)*	*Mass (amu)*
$^{204}_{82}Pb$	1.50	203.9731
$^{206}_{82}Pb$	23.60	205.9745
$^{207}_{82}Pb$	22.60	206.9759
$^{208}_{82}Pb$	52.30	207.9766

C9. Paintings can be dated using the analysis of the level of radioactivity emitted by lead-white paint, a common material used by artists for several hundred years. Lead-white, as the name implies, is made with lead removed from lead ore. Since most lead ores contain small quantities of uranium 238, isotopes within the uranium series are present in the ore. While the chemical separation of lead from the ore eliminates most of these radioactive isotopes, a small amount of radium remains. Consequently, the paint sample has some radioactivity present.

a. What radioactive isotopes can be present in lead-white paint?

- b. When the paint is first made, some lead 210 is present naturally. What happens to this lead 210 over a few hundred years?
- c. After the lead 210 mentioned in part (b) has decayed, some lead 210 will still be in the paint. From where will it come?
- d. When will paint have greater amounts of lead 210, when it is first created or a few hundred years later?
- e. How can the answers to parts (a)-(d) be used to detect art forgeries?

C10. As stated in the chapter, alpha particles can be stopped by paper and beta particles by a few centimeters of metal, but gamma particles can travel through many centimeters of material. Suppose you had a sample that emitted some type of nuclear radiation. How could you use the interactions with matter, stated above, to determine which type of radiation is present?

D. Activities

D1. If you can borrow a Geiger counter, see if you can find sources of radioactivity.

D2. Many science fiction stories contain references to radioactive transformations. Read such a story and see if the discussion contains correct physics.