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Physics, Chapter 45: Natural Radioactivity

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45

# Natural Radioactivity

45-1   The Discovery of Radioactivity: Evidence from the Nucleus

The discovery of an important phenomenon usually leads to other important discoveries. The discovery of x-rays by Roentgen in 1895 led to the discovery of radioactivity by Becquerel in 1896. In the gas type of x-ray tube used by Roentgen, the glass walls of the tube were observed to fluoresce. Becquerel was interested in determining whether there was any relationship between the fluorescence of the glass of an x-ray tube and the phosphorescence of certain salts which were irradiated by ordinary light. One of the salts used by Becquerel was the double sulphate of uranium and potassium. He wrapped a photographic plate in very thick black paper, placed a crystal of the uranium salt on it, and exposed the whole thing to sunlight. Later, on developing the plate, he found the silhouette of the crystals on the negative; he interpreted this as produced by radiations coming from the crystal. He also performed other experiments in which he placed various absorbing materials between the uranium salt and the photographic plate; in each case, upon developing the plate, he found the shadow of the absorbing material imaged on the plate; he interpreted this as being due to the absorption of the radiation by the substance which had been placed between the uranium salt and the photographic plate. The crowning experiment was the one in which he decided not to irradiate the salt with light from an external source but to determine whether the salt was itself the source of these radiations. For these experiments he built a light tight box that would hold a photographic plate at the bottom. In one experiment some uranium salt crystals were placed on the photographic plate; later, on developing this plate, Becquerel obtained the silhouettes of the individual crystals. In another experiment he put a piece of aluminum between the uranium crystals and the photographic plate, and, on developing the plate, he again found the silhouettes of the crystals, but they were of decreased intensity due to the absorption of some of the radiations by the aluminum. From these experiments Becquerel concluded

that the radiations came from the uranium salt, and that the external light had no influence on them.

Becquerel then proceeded with a series of experiments to determine the origin of these radiations. He used a variety of compounds of uranium in these experiments and came to the conclusion that the radiations were emitted by the uranium in the compounds. Some of the compounds used were phosphorescent; others were not. Becquerel also discovered a most important property of these radiations; namely, they could cause the dis-
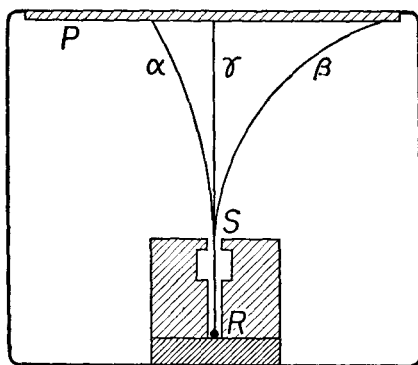
Fig. 45-1   Paths of the rays from a radioactive substance R in a magnetic field. The magnetic field is perpendicular to the plane of the paper and directed into the paper.

charge of electrically charged bodies. This made it possible to investigate the phenomenon quantitatively with the aid of ionization chambers and electroscopes or electrometers.

Using an ionization method, Mme. Curie made quantitative measurements on the activity of uranium salt and demonstrated that this activity was directly proportional to the mass of uranium, showing that radioactivity was an atomic rather than a molecular phenomenon. In 1898 M. and Mme. Curie discovered two new radioactive elements, polonium and radium, in a systematic chemical analysis of uranium pitchblende. The activity of radium was found to be more than a million times that of an equal mass of uranium. Many more radioactive substances have been discovered since then.

Early work by Rutherford on the penetrating power of the radiation from uranium salt showed that the radiation consisted of two components: a very soft radiation easily absorbed in matter, which he called *alpha rays*, and a more penetrating type called *beta rays*. Subsequent work showed that radioactive substances emitted a third type of radiation called *gamma rays*. When a radioactive source is placed in an evacuated chamber provided with a photographic plate, as shown in Figure 45-1, and a strong magnetic field is applied at right angles to the plane of the paper, three distinct lines are found on the photographic plate. The line deflected to

the left in the figure is produced by positively charged alpha rays. The line deflected to the right is produced by negatively charged beta rays. The undeviated line is produced by gamma rays, which are undeflected by the magnetic field. Experiments on interference and diffraction of the gamma rays, similar to those performed with x-rays, show that gamma rays are electromagnetic radiations of very short wavelengths of the order of 0.1 A or less. The alpha particles making up the alpha rays are known to be helium nuclei, and the beta rays are known to consist of electrons. These radiations are spontaneously emitted by radioactive nuclei; that is, radioactivity is a nuclear rather than an atomic process.

45-2 Radioactive Transformations. Half Life

The rate at which a particular radioactive material disintegrates is, with only minor exceptions, independent of physical and chemical conditions. In general, we find that it is impossible to predict which of the atoms in a given collection will disintegrate at a particular time, but that it is possible to make statistical predictions that a certain number of atoms will disintegrate in a given time interval. This implies that each atom has equal probability λ of disintegrating in a unit time, and that the probability that this atom will disintegrate in a time interval dt is given by $\lambda\,dt$. If there are N atoms of a particular species present in a given sample, the total number of atoms we would expect to disintegrate in the time interval dt is the product of the number of atoms present by the probability that each one will disintegrate, or

$$dN = -\lambda N\,dt, \qquad\qquad \textbf{(45-1)}$$

where dN is the number of disintegrating atoms, or the number whose species is changed, in the time interval dt. Integrating this expression, we find

$$\boxed{N = N_0 e^{-\lambda t},} \qquad\qquad \textbf{(45-2)}$$

where N_0 represents the number of atoms present at time $t = 0$, N is the number remaining at time t, and λ is a constant for the particular process called the *disintegration constant*. Equation (45-2) shows that the number of atoms of a given radioactive substance decreases exponentially with time. Half of the material will have disintegrated at the end of a time T, called the *half life*, which can be determined by setting $N = N_0/2$, and $t = T$ in Equation (45-2), yielding

$$\lambda T = \log_e 2 = 0.693. \qquad\qquad \textbf{(45-3)}$$

At the end of one half life, one half of the original material remains in the

sample; at the end of two half lives, one quarter of the original material will still be in existence, and so on.

The half lives vary considerably among the radioactive elements. Radium, for example has a half life of 1,620 years, while that of radon is 3.82 days. In general, we find that the process of alpha emission exhibits the longest half lives, ranging up to billions of years. The process of beta emission is of intermediate lifetime, while the process of gamma-ray emission has half lives ranging from months to intervals of 10^{-10} sec. The half life of a radioactive substance may be determined by measuring its *disintegration rate dN/dt*. This may be measured with an ion chamber and an electrometer by measuring the ion currents generated by the emitted radiations, or by means of a *Geiger counter*.

One interesting application of the concept of radioactive disintegration lies in the field of *radiocarbon dating*. Carbon 14 is a radioactive isotope of carbon with a half life of 5,580 years. In terms of the earth's age of several billions of years, the half life of carbon 14 is very small, and any of this isotope originally present would be very much depleted. It is believed that cosmic radiation incident upon the earth's atmosphere continually replenishes the supply of carbon 14, by the interaction of neutrons liberated in the atmosphere by cosmic rays, with atmospheric nitrogen. Carbon is a constituent of all living matter. When a living organism dies, its intake of carbon 14 from the atmosphere ceases, and the percentage of this isotope in the carbon constituent of organic matter diminishes exponentially after death. It is thus possible to determine the age of archaeological and geological samples containing carbon by determining the percentage of carbon 14 in them and by assuming that the rate of production of this isotope has remained reasonably constant. Wherever possible, age determinations by radiocarbon dating are compared with other reliable methods as a check, and it has been found that carbon dating has been very satisfactory. It is now possible to use carbon dating with reasonable accuracy for age determinations up to about 30,000 years.

45-3   Radioactive Series

In the years following the discovery of radioactivity of uranium by Becquerel in 1896, many elements and isotopes of elements were found to be radioactive. Most of the naturally radioactive isotopes were found to be genetically related and fitted into one of three *radioactive series*. These are known as the *uranium series*, the *thorium series*, and the *actinium series*. Radium, for example, is a member of the uranium series. This series starts with the isotope of uranium, $_{92}U^{238}$, which has a half life of 4.50×10^9 years. The other members of the series are formed through a succession of alpha-particle and/or beta-particle emissions, as shown in Figure 45-2.

The emission of an alpha particle by an isotope having given values of Z and A results in the production of a new isotope of atomic number $Z - 2$ and mass number $A - 4$. The emission of a beta particle leaves the mass number unchanged but increases the atomic number of the product nucleus to $Z + 1$.
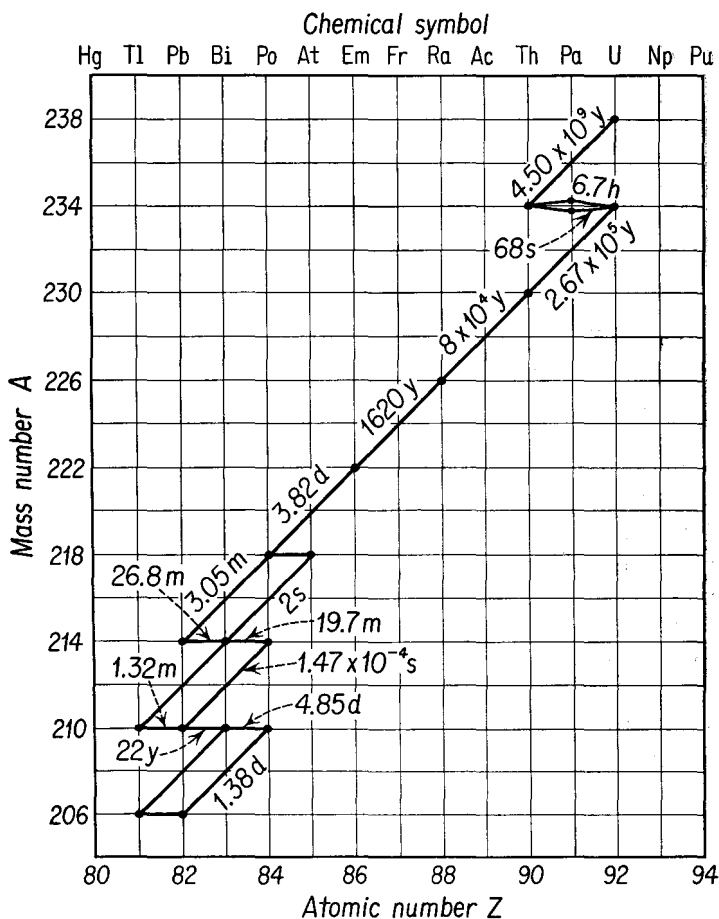
Fig. 45-2 The naturally radioactive uranium series. The half lives of the disintegrations are expressed in either years (y), days (d), hours (h), minutes (m), or seconds (s).

Each of the three naturally radioactive series terminates with a non-radioactive isotope of lead. In the uranium series this isotope has a mass number of 208, in the actinium series its mass number is 207, and in the thorium series its mass number is 208.

The half lives of the radioactive isotopes of the uranium series are

indicated in Figure 45-2. If a sample of ore containing uranium is analyzed chemically, and the percentage of uranium and lead is measured, it is possible to calculate from the ratio of uranium to lead how long a time must have elapsed for the radioactive production of this amount of lead. This value can be used as an indication of the age of the earth. From such measurements the age of the earth is known to lie between 3 and 6 billion years.

In our discussion of radioactive decay, it was tacitly assumed that a given isotope will have only one mode of disintegration. However, a glance at Figure 45-2 will show many interesting cases of *branching*. For example, the isotope of polonium with $Z = 84$ and $A = 218$, also known as radium A, will decay most often (in 99.96 per cent of the cases) with the emission of an alpha particle forming the product nucleus $_{82}Pb^{214}$. However, in a few cases (0.04 per cent) the nuclei will emit beta particles, forming the product nucleus $Z = 85$ and $A = 218$, an isotope of astatine. We interpret branching as indicating that a given nucleus may decay in two ways with different probabilities; the probability for disintegration by the first mode is λ_1, and the probability for disintegration in the second mode is λ_2. In this case the total probability for disintegration by any mode is $\lambda = \lambda_1 + \lambda_2$. The isotope disintegrates according to the disintegration constant λ, but the branching ratios or the percentage of the disintegrations which take place in a particular branch is determined by the constants, λ_1 and λ_2.

When a radioactive decay chain is in equilibrium, the number of atoms of any particular isotope remains substantially constant. Thus if the chain or series consists of isotopes A, B, C, and so on, which are formed by successive disintegrations, the number of atoms of isotope B remains constant, implying that the number of B atoms formed from A is equal to the number of disintegrating B atoms, in any time interval. From Equation (45-1) this implies

$$\lambda_A N_A = \lambda_B N_B = \lambda_C N_C, \tag{45-4}$$

and we may determine the disintegration constant of a long-lived member of the chain by chemically isolating one of the shorter-lived members C. The disintegration constant λ_C may be measured by means of an ion chamber, and N_C may be determined with an analytical balance and a knowledge of the atomic weight of this isotope. If, then, element A is separated chemically and weighed, the number N_A of A atoms present may be determined, and λ_A may then be calculated from Equation (45-4).

45-4 Radioactive Disintegration by Alpha-Particle Emission

The alpha particle is the nucleus of the helium atom. This was suggested by experimental determinations of the ratio of charge to mass determined

by Rutherford and co-workers in an apparatus similar to a mass spectrograph. To make the identification certain Rutherford and Royds, in 1909, carried out a spectrographic analysis by collecting the alpha particles emitted by the radioactive element radon into a spectroscopic tube which had previously been thoroughly evacuated. Using a spectroscope, they examined the light emitted by this tube under electrical excitation, and observed the spectrum of helium. This spectroscopic evidence proves conclusively that alpha particles are helium nuclei. The alpha particles became helium atoms by the capture of electrons from the glass walls of the tube.
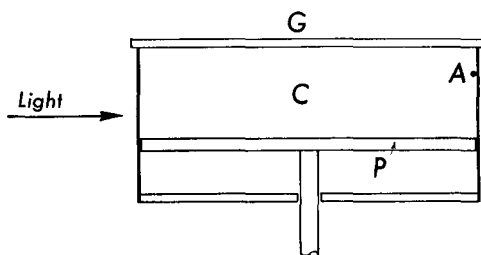

**Fig. 45-3**   Schematic diagram of a Wilson cloud chamber.

The energy of the alpha particles emitted from a particular isotope may be determined by measuring the radius of the circular orbit which the particles follow when they pass into a transverse magnetic field. When this is done, it is found that the alpha particles are emitted in a *line spectrum;* that is, the alpha particles are emitted with characteristic energies. This is interpreted as meaning that each alpha particle is emitted in a transition from a discrete state of the parent nucleus to a discrete state of the product nucleus. The energy of alpha particles may also be determined by measuring the *range* of the particle in a gas, such as air, using a *Wilson cloud chamber*, as shown in Figure 45-3. This apparatus consists essentially of a cylinder C containing a gas saturated with water vapor, and a piston P which may be lowered very rapidly to produce a sudden expansion of the gas in the chamber. As a result of this expansion, the gas is cooled and becomes supersaturated with water vapor. If there are any ions present in the gas, the water vapor will condense on these ions, forming small droplets. If a source of alpha particles is placed inside the chamber at A, then, in their passage through the gas in the chamber, the alpha particles will ionize gas molecules along their paths. During each expansion of the gas, water droplets form on the ions, showing the path of each individual alpha particle. Typical alpha-ray tracks are shown in Figure 45-4. These tracks are, in general, straight lines almost up to the end of the range. Occasionally, a track is bent sharply, or else it branches off into two tracks. These are usually ascribed to collisions with nuclei of the gas.

An important relationship exists between the range of alpha particles and the disintegration constant of the emitter, known as the *Geiger-Nuttall law*, which is usually written in the form

$$\log R = A \log \lambda + B, \qquad (45\text{-}5)$$

where A is a constant which has practically the same value for each of the three radioactive series, and B is a constant which has a different value for each series.
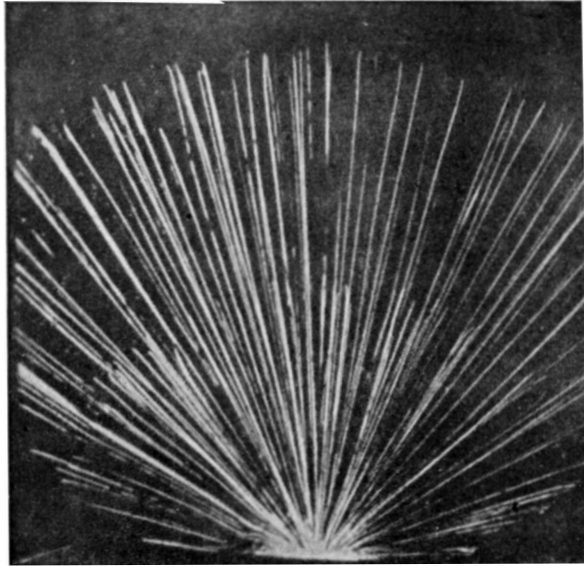

Fig. 45-4   Tracks of α particles from thorium $(C + C')$ in a Wilson cloud chamber, showing two distinct ranges. (From Rutherford, Chadwick and Ellis, *Radiations from Radioactive Substances*. By permission of The Macmillan Company, publishers.)

The radioactive disintegration of a nucleus by alpha-particle emission was first successfully explained, in terms of the penetration of a potential barrier, by Gamow, Condon, and Gurney in 1928.   The alpha particle emitted from a nucleus in a given transition comes out of each nucleus with the same kinetic energy, but this energy is much smaller than the height of the barrier.   The barrier arises from the Coulomb repulsive force upon an alpha particle.   At the radius of the nucleus, given by

$$R = r_0 A^{1/3}, \qquad (45\text{-}6)$$

where R is the nuclear radius, and the radius parameter $r_0 = 1.4 \times 10^{-13}$ cm, the potential energy of an alpha particle would be about 30 Mev in U238, while the kinetic energy of the emitted alpha particles is only 4.2

Mev. From a classical point of view, the alpha particle should never leave the nucleus, for it is surrounded by high potential walls which it cannot surmount, as shown in Figure 45-5. Thus, classically, there should be no such thing as alpha particle emission. When the alpha particle is considered as a wave, incident upon the barrier in one of its reflections back and forth within the nucleus, its passage through the barrier is determined by considerations similar to the transmission of light through a film. The thickness of the film seen by the alpha particle depends upon its energy $\mathcal{E}_\alpha$.
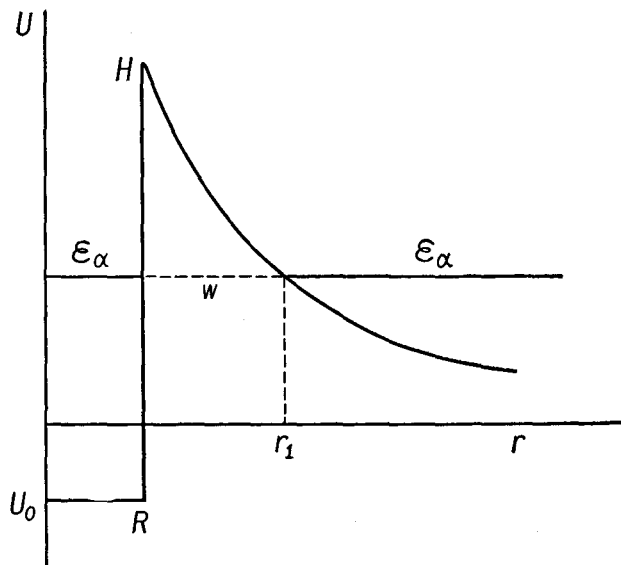

Fig. 45-5 Potential barrier presented by the nuclear charge and nuclear forces to an alpha particle. An alpha particle of energy $\mathcal{E}_\alpha$ sees a barrier of width w and height H

Particles of high energy see a thin film which they pass through quite readily, while particles of low energy see a thick film, for which the probability of penetration is small. Using these wave mechanical ideas and the appropriate equations, Gamow, Condon, and Gurney were able to account quantitatively for the Geiger-Nuttall law.

The transmission of alpha particles through a nuclear barrier is analogous to the transmission of light through a thin air film. Let us suppose that light is incident upon the face of a totally reflecting prism, as shown in Figure 45-6. When the hypotenuse of the prism is placed in contact with a second prism whose hypotenuse is slightly curved, we would expect light to be transmitted through the region of contact, but the question arises as to whether there should be any light passing through the thin air film because of the total internal reflection expected in the prism I. When the

light passing through both prisms is examined, we see a spot of light sur-
rounded by interference maxima, indicating that there has been trans-
mission of light through the air film, just as there is penetration of alpha
particles through a potential barrier. We must understand that the
concept of total internal reflection of light is a ray concept, analogous to
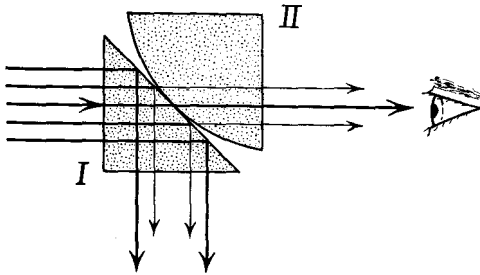
Fig. 45-6 Light partially trans-
mitted through a thin film, though
incident upon the face of a "totally
reflecting" prism, *I*.

the particle concept of an alpha particle. When the problem of total in-
ternal reflection is examined from the wave point of view, the wave ampli-
tude does not diminish to very small intensity for a distance of several
wavelengths outside the total reflecting surface, and if a second glass surface
is interposed, as in the case of prism II, some of the light is transmitted.

## 45-5   Scattering of Alpha Particles by Nuclei

An alpha particle is a comparatively massive particle possessing a consider-
able amount of kinetic energy. Its mass is about 7,500 times that of an
electron, and its kinetic energy may be of the order of several million elec-
tron volts. It thus forms an ideal projectile for investigating the properties
of atoms. Beginning in 1910, Rutherford and his co-workers, Geiger and
Marsden, undertook a series of experiments in which alpha particles of
known energy were fired at thin metallic foils, as shown in Figure 45-7.
Most of the alpha particles went straight through the foils without devia-
tion, many others were deviated, or scattered through small angles, but a
few were deviated through angles greater than 90°; that is, they were
scattered backward toward the side facing the incident beam.

Alpha particles carry a positive charge equivalent to twice the charge
of an electron. Because of their large energy and great mass, the only way
to account for the backward scattering of the alpha particles was to assume
that they came very close to another massive charged particle. Further-
more, since most of the alpha particles incident on the foil went through it
with little or no deviation, the massive charged particles must be very small
in comparison with the distance between them, as indicated in Figure 45-8.
On the basis of these experiments, Rutherford, in 1911, proposed his

nuclear theory of the atom.   These experiments were then extended to
determine the nuclear charge and the nuclear radius, and to produce nuclear
disintegrations artificially by bombarding the nuclei with alpha particles.
It must be emphasized that Rutherford's alpha-particle-scattering experi-
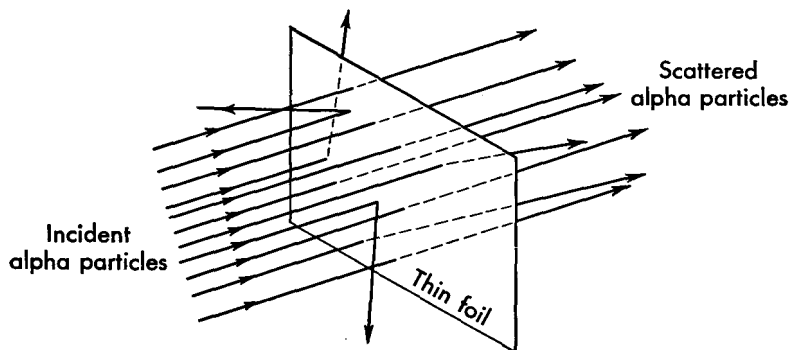
Fig. 45-7 Alpha particles directed against a thin foil. Most of them go through the
foil either without any deviation or with very slight deviations from the original direction.
A few alpha particles, however, are deviated through very large angles.
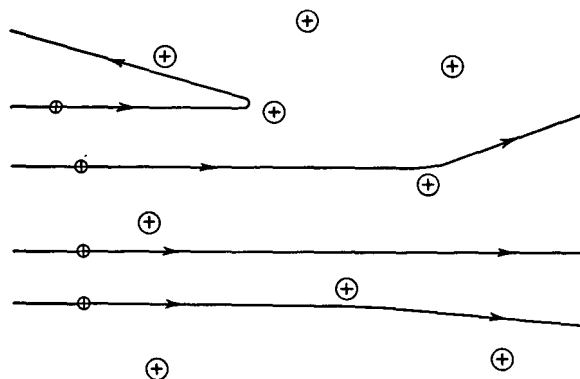
Fig. 45-8 Schematic diagram showing the paths of some alpha particles through a thin
foil. The distances between nuclei (larger circles) are much greater than those shown
here. A close approach of an alpha particle to a nucleus will therefore be a very rare
event.

ment represented the beginning of nuclear physics and the nuclear theory of
the atom.   It was upon this foundation that the Bohr theory of the atom
was laid.   The technique of bombarding the nucleus with particles of high
energy to explore its properties was introduced by Rutherford and forms
the basis of the present-day methods for exploring nuclear forces and other
nuclear properties.   The higher the energy of the bombarding particle, the

farther into the nucleus the particle can penetrate, so that we may obtain greater knowledge of the nuclear structure.   It is for this reason that physicists are continually engaged in the construction of accelerators capable of producing particles of higher and higher energies.

45-6   Beta-Ray Spectra

The beta particles, or electrons, emitted in the radioactive disintegration of a nucleus are most commonly investigated by measurement of the radii of curvature of their paths in a magnetic field of known induction B.   One such arrangement is shown in Figure 45-9.   In this arrangement beta rays from the source C are bent around by the magnetic field and are focused on the aperture O.   The number of particles entering the aperture O is counted
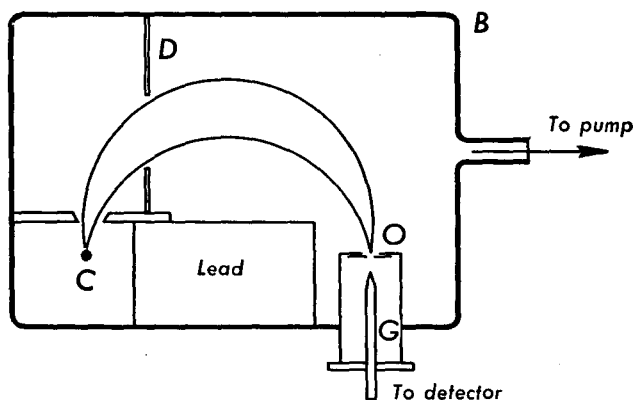

Fig. 45-9   Variable field magnetic spectrometer.

at a given value of the magnetic induction B.   By repeating this determination at a number of different values of B, the number of particles in a given momentum interval can be determined as a function of the momentum.

The results of these experiments show that there are apparently two distinct types of beta-ray spectra, one a sharp line spectrum, and the other a continuous spectrum.   The sharp line spectrum has been shown to consist of *internal conversion* electrons.   A nucleus in an excited state may descend to the ground state either by the emission of a gamma ray, as we will see in the next section, or by a radiationless transfer of its energy to an atomic electron.   The latter process is called internal conversion and takes place by the emission of a K, L, M, or N electron from the electronic shells of the atom.   The continuous spectrum is that produced by the electrons emitted by the nucleus in the process of beta decay.   A typical beta spectrum is shown in Figure 45-10, where the number of beta particles having a

given energy is plotted as the ordinate, and the energy of these particles, expressed in million electron volts, is plotted as abscissa. The beta-ray spectrum of an isotope differs remarkably from the other spectra characteristic of the same element in that all other characteristic spectra are line spectra, while the beta-ray spectrum is a continuous spectrum. Since the spectrum is presumably emitted in the transition of a nucleus of atomic number Z and mass number A in a definite energy state to a definite energy
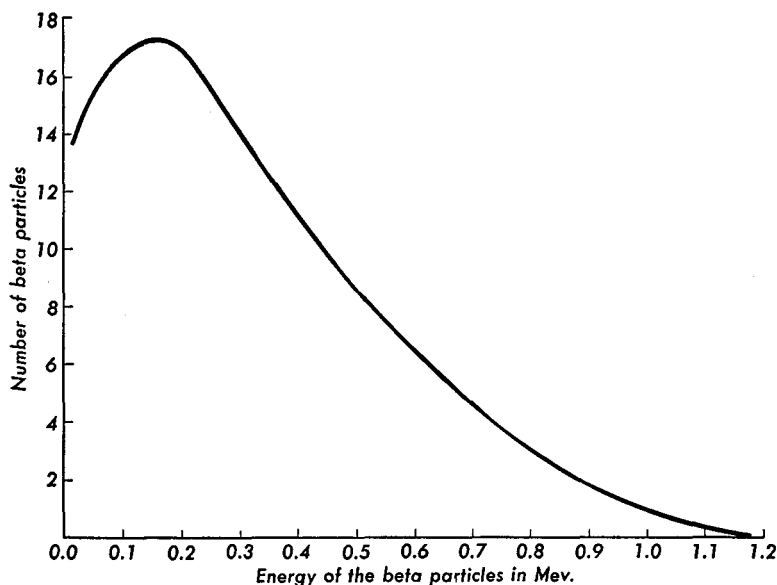

Fig. 45-10 Distribution of energy among beta particles emitted in the beta decay of bismuth, $A = 210$ (radium E).

state of a nucleus of atomic number $Z + 1$ and mass number A, it was difficult to understand why the spectrum was a continuous one.

It was originally believed that the beta particles were emitted with discrete energy, and that these particles lost energy on passing out of the sample by collision with the atoms of the sample. Calorimetric measurements showed that this was not so, and that the mean energy per disintegration corresponded to the mean energy of the spectrum rather than its end-point energy. A way out of the dilemma was suggested by Pauli in 1931. Pauli proposed that the actual disintegration energy corresponded to the end-point energy in the beta-ray spectrum, and that a second particle was emitted simultaneously, along with the beta particle. This particle, called the *neutrino*, was assumed to be an electrically neutral particle of very small mass. The disintegration energy of the nucleus is then shared among

the electron, the neutrino, and the product nucleus in such a way as to conserve energy and momentum. This implies that the spectrum is continuous, and the total energy of the particles involved in the process may be shared in any way consistent with the conservation laws.

When it was first proposed, the neutrino seemed an interesting fiction, invented to account for the missing energy in beta decay. As time passed, evidence accumulated to lend substance to the neutrino concept. In 1934 Fermi developed a theory of beta decay based on the neutrino which accounted for the shape of the beta-ray spectrum. Recently, Reines and Cowan (1953) have detected the neutrino in a very elaborate experiment utilizing the copious supply of neutrinos produced during the operation of a nuclear reactor. Very little detailed information is known about the neutrino. For example, its mass is known to be less than 0.05 per cent of the mass of the electron. At the present time the neutrino is required in order to obtain consistent explanations of many nuclear processes classed as weak interactions, and there seems to be little doubt that such a particle really exists. Our present theory of beta decay can be represented by the equation

$$n \text{ (in nucleus)} \rightarrow p \text{ (in nucleus)} + \beta + \nu;$$
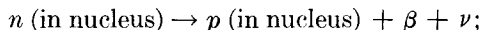
that is, a neutron n in the nucleus decomposes into a proton p in the nucleus, and in the process an electron β and a neutrino ν are ejected from the nucleus. Although electrons are emitted by the nucleus in beta decay, there are no electrons in the nucleus.

In addition to the emission of an electron, there are two other processes involving neutrino's which may take place when a nucleus disintegrates; these are also classed as beta-decay processes. In one of these processes a positively charged particle, called a *positron*, is emitted from the nucleus. The positron has the same mass and the same numerical value of charge as the electron. Like the electron, the positron is emitted as a continuous spectrum along with a neutrino. Positrons are emitted by those isotopes whose nuclear charge is too great for their mass, in the nuclear stability diagram of Figure 44-5. A second mode of reduction of the nuclear charge by an unstable isotope is the process of *electron capture*. Here a nucleus absorbs one of its atomic electrons and ejects a neutrino. When the absorbed electron is in the K shell, the process is called K capture. We may visualize the processes of positron emission and electron capture as being incidental to the transformation of a proton in the nucleus into a neutron.

45-7 Gamma-Ray Emission. Isomerism

We have previously noted that the line spectra found in a beta-ray spectrometer may be attributed to the process of internal conversion, in which a

nucleus in an excited state makes a transition to a state of lower energy by ejecting an atomic electron.   Accompanying these internal conversion electrons, it is found that gamma rays are emitted from the radioactive source; that is to say, some nuclei alter their states by the emission of conversion electrons, while in other cases the transition is effected by the emission of gamma rays.   If the emitted gamma ray is of frequency f, the kinetic energy of the conversion electron is $\mathcal{E}$, and the K shell excitation energy as measured in x-ray absorption is $\mathcal{E}_K$, it is found that K conversion electrons obey the relationship

$$\mathcal{E} = hf - \mathcal{E}_K, \tag{45-7}$$

and similarly for the L, M, and N conversion electrons.   By a study of the conversion electrons emitted from a radioactive source, we may determine both the gamma-ray energy associated with a particular transition and the element responsible for the transition, from the characteristic K-L and L-M shell energy differences.

Many gamma-ray transitions have measurable lifetimes, ranging from 10^{-10} sec to several months.   Excited states which have measurable lifetimes are called *isomeric states*.   One of the strong evidences for a nuclear shell structure is the existence of "islands of isomerism" in the N-P diagram of the radioactive isotopes just prior to the closure of a shell at one of the magic numbers.   For example, there are 29 known cases of isomerism in odd A nuclei where either the odd proton number or the odd neutron number, as the case may be, lies between 39 and 49.   As the magic number 50 is crossed, there are no cases of isomerism until we begin to approach the next magic number 82.

The nucleus must be in an excited state in order to emit gamma rays. This excitation may be accomplished in several ways.   When a sample of a substance is placed in a nuclear reactor and bombarded with neutrons, some of the nuclei of the sample may capture neutrons.   Some of the binding energy of a neutron to the nucleus is promptly emitted in the form of gamma radiation and is known as "capture gamma rays"; if the product nucleus has an isomeric state, the sample will contain some nuclei in this state for an appreciable time, and these may be subsequently studied.   In a similar way it is possible to raise a nucleus to an excited state by irradiating a sample with high-energy x-rays.   Nuclei may also be excited by collision with charged particles of sufficient energy, by a process known as *Coulomb excitation*.   When a parent nucleus disintegrates by alpha or beta emission, these transitions may take place to an excited state of the product nucleus, with the subsequent emission of gamma rays and conversion electrons.

When all available information about the radiation emitted from a particular source is in hand, it is the problem of the nuclear spectroscopist

to attempt to assemble this information into an energy-level diagram which accounts for all the observed transitions. One such case is shown in Figure 45-11 for thorium C ($_{83}Bi^{212}$), a member of the thorium family of
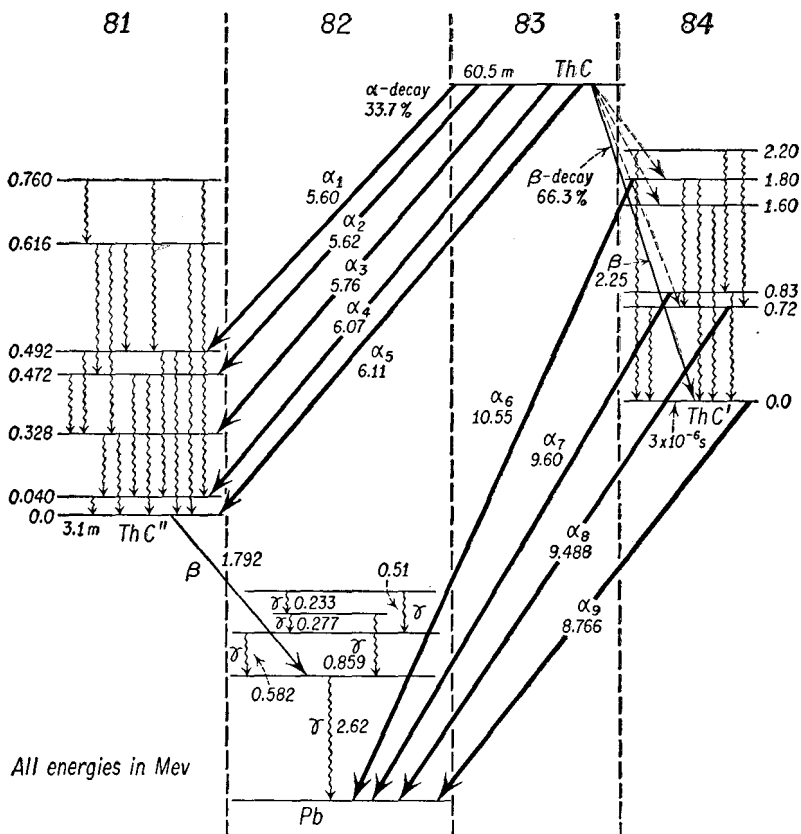
Fig. 45-11 Nuclear energy-level diagram for the disintegration of Th C. (After *Nuclear Data*, National Bureau of Standards, Circular 499.)

naturally radioactive elements. At the present state in the study of the nucleus, such diagrams are still being assembled, and no theory of nuclear structure comparable in scope to the Bohr theory of the atom has yet been devised.

45-8 Interaction of Radiation with Matter

We have studied some of the processes by which electromagnetic radiation interacts with matter. Thus light may be scattered by the free electrons

of a substance, generating the blue of the sky. In the limit of low energies of the incident photon, the scattering process may be treated as a wave phenomenon, in which the electric vector of the incident wave is thought to accelerate the electrons of a system and cause them to reradiate at the frequency of the incident radiation. When the wavelength gets sufficiently short, as in the case of x-rays, we note that the particlelike characteristics of electromagnetic radiation predominate, and it is necessary to supplement

Fig. 45-12 Cloud-chamber photograph of the paths of a pair of oppositely charged particles, an electron and a positron, formed by the disintegration of a 5.7 Mev gamma-ray photon in its passage through a sheet of lead 0.002 inch thick. Magnetic field of 1,680 gausses is directed into the paper. (Photograph by H. R. Crane.)

the wave picture with a quantum picture, as in the Compton effect, in which the scattering process is treated as an elastic collision between a photon and a free electron. Looking toward the problem of low-energy scattering from the vantage point of the Compton effect, we see that these are two complementary views of the same scattering process, involving the scattering of electromagnetic waves by free electrons, in an elastic collision.

Electromagnetic waves interact with matter inelastically in the photo-electric effect, in that some of the incident energy of the radiation is absorbed by the atom or nucleus in the process of freeing the emitted particle. At low energies of the order of a few electron volts, electrons are

liberated from the outer shell of an atom or from the free electrons of a metal; at higher energies of the order of thousands of electron volts, as in x-rays, the electrons from the inner shells of an atom may be liberated; at extremely high energies of the order of millions of electron volts, the radiation may interact with nuclei, producing the nuclear photoeffects, involving the emission of protons or neutrons, or simply the excitation of a nucleus to a state of higher energy.

Another process of importance at high energies is *pair production*, in which a gamma-ray photon of energy greater than 1.02 Mev interacts with matter to form an electron-positron pair. A cloud-chamber photograph of such an interaction is shown in Figure 45-12. The determination of this threshold energy in itself constitutes a verification of the mass-energy equation, for mc^2 for the electron is 5.11×10^5 ev, according to this equation, so that we must not expect to find an electron-positron pair materialized from a photon unless the energy of the incident photon is greater than $2mc^2$, or 1.02 Mev. The process is also a verification of the law of conservation of charge, which we discussed in connection with electric currents. Since the electric charge of an incident photon is zero, the net charge of the materialized matter must also be zero. In the process of pair production, an electron and positron of equal and opposite charge are produced. When the incident photon has energy greater than 1.02 Mev, the excess energy is shared by the electron and positron as kinetic energy.

The relative importance of each of these processes varies with energy and with the atomic number of the material being irradiated. At low photon energies the photoelectric effect contributes most to the absorption coefficient, at intermediate energies the Compton effect predominates, while at high energies pair production is most important.

Problems

45-1. The half life of U238 is 4.50×10^9 years. (a) Compute the disintegration constant in $\sec^{-1}$. (b) Calculate the number of alpha particles per second emitted by 1 gm of this isotope.

45-2. The half life of radon is 3.82 days. (a) Compute its disintegration constant in $\sec^{-1}$. (b) Calculate the number of alpha particles emitted per second by 1 cm^3 of radon gas at 1 atm pressure and 0°C. Neglect the radiations from the product nuclei.

45-3. A *curie* is defined as the quantity of any radioactive isotope in which the number of disintegrations per second is 3.700×10^{10}. Using the data of Problem 45-1, how many curies are present in 1 gm of U238?

45-4. A hospital has 1 gm of radium $_{88}Ra^{226}$ which has a half life of 1,620 years in equilibrium with its decay products. Radium is a member of the uranium series, illustrated in Figure 45-2. What is the mass of radon $_{86}Rn^{222}$ present in the container?

45-5. A 1-millicurie source of radon is measured again after a period of 2 days. The half life of radon is 3.82 days. What is the activity of this source, in curies, at the time of the measurement?

45-6. What is the height of the Coulomb barrier experienced by an alpha particle in $_{92}U^{238}$?

45-7. When an alpha particle is emitted from a nucleus, the law of conservation of momentum requires that the nucleus must recoil. Not all of the available energy is delivered to the alpha particle as kinetic energy, for the nucleus acquires kinetic energy as well. The mass of radium is 226.10309 amu, the mass of radon is 222.09397 amu, and the mass of helium is 4.00388 amu. In the disintegration of radium into radon plus an alpha particle (a) what is the mass difference, in atomic mass units, between radium and its products? (b) The emitted alpha particle has a kinetic energy of 4.80 Mev. What is the kinetic energy, in million electron volts, of the recoil nucleus?

45-8. A gamma ray is emitted from Cs^{137} of energy 661.77 kev. In x-ray investigations it is found that K photoelectrons are emitted from cesium when irradiated with x-rays of wavelength 0.34473 A, and L photoelectrons are emitted when the wavelength is 2.17245 A or shorter. What are the energies of K and L internal conversion electrons emitted in the above transition in cesium?