Chapter 3 Radioactivity

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

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

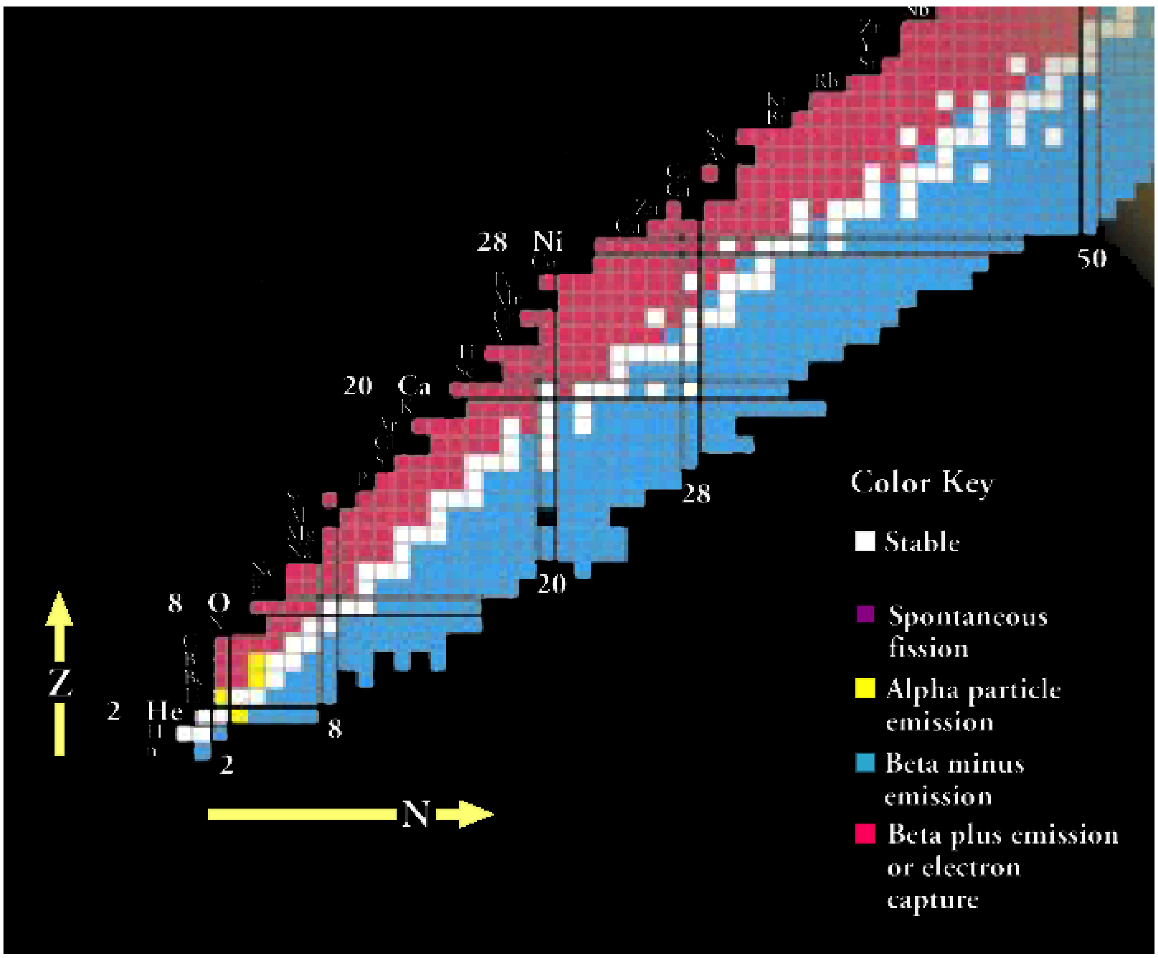

Fig. 3-1. The lower end of the Chart of the Nuclides.

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

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

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

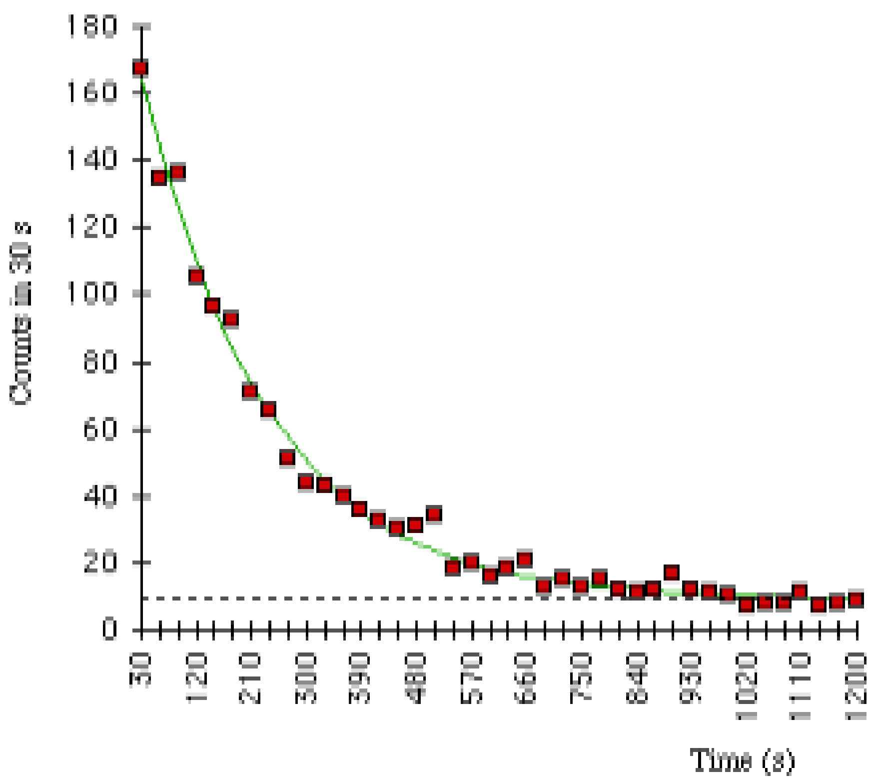

Fig. 3-2. ^{137m}Ba decay data, counting numbers of decays observed in 30-second intervals. The best-fit exponential curve is shown. The points do not fall exactly on the exponential because of statistical counting fluctuations.

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

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

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

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

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

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

Alpha Decay

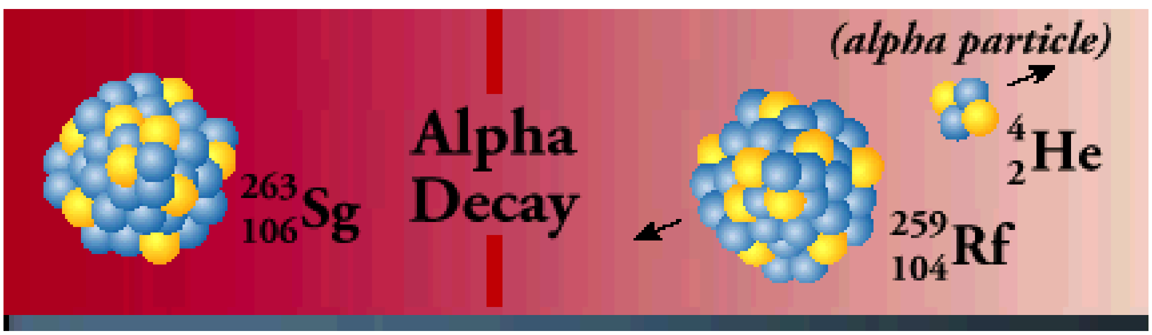

Fig. 3-3. An alpha-particle decay

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

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

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

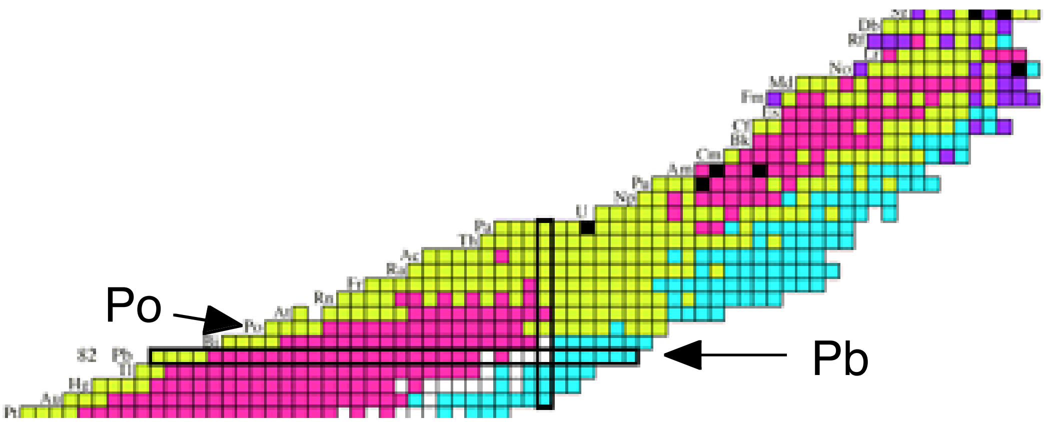

Fig. 3-4. Upper end of the Chart of the Nuclides

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

Beta Decay

a)
b)

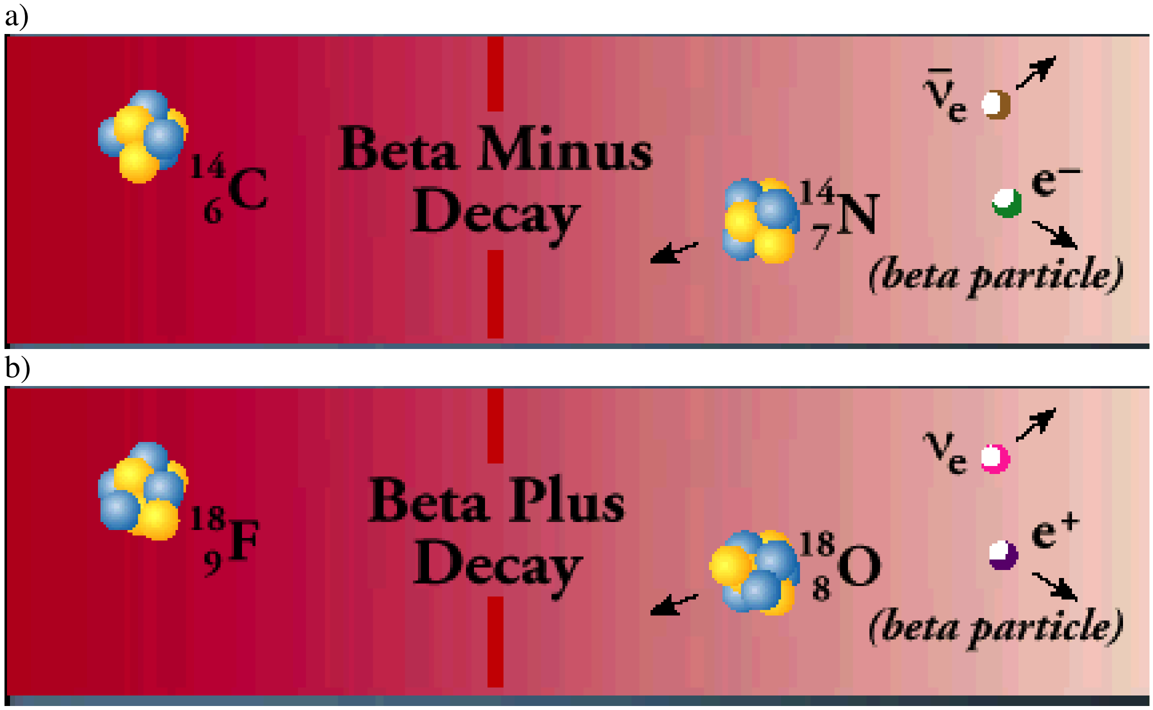

Fig. 3-5. Beta decays. a) Beta-minus decay. b) Beta-plus decay.

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

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

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

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

Gamma Decay

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

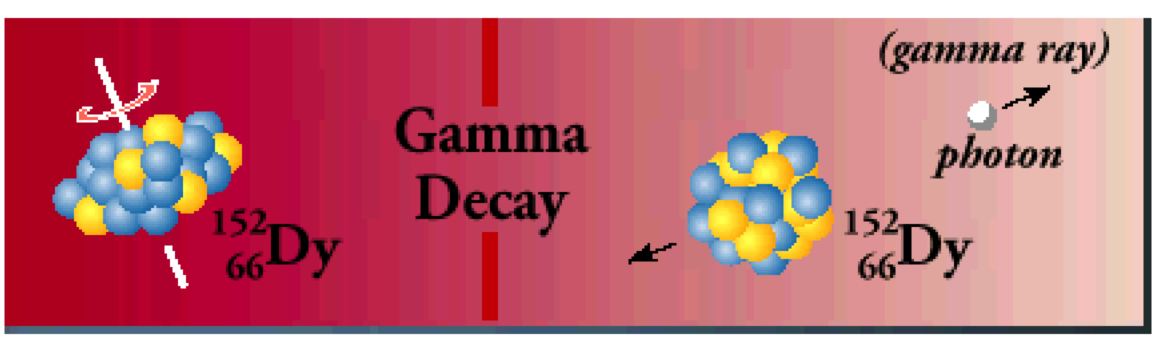

Fig. 3-6. A gamma (γ) decay.

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

The Discovery of Radioactivity

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

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

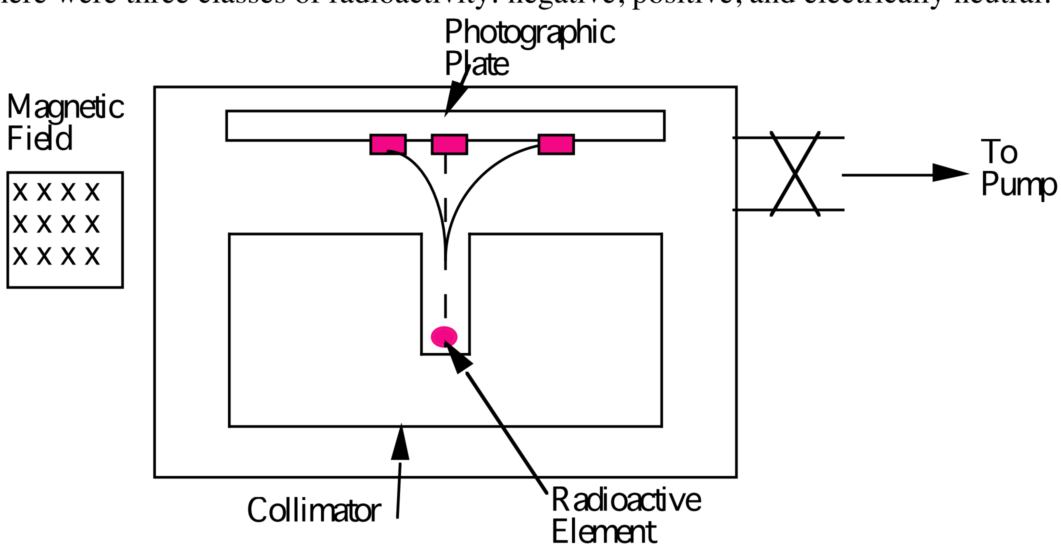

Fig. 3-7. Apparatus similar to that used by Henri Becquerel to determine the magnetic deflection of radioactive decay products. The magnetic field is perpendicular to the direction of motion of the decay products.

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

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

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

Radioactivity in Nature

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

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

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

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

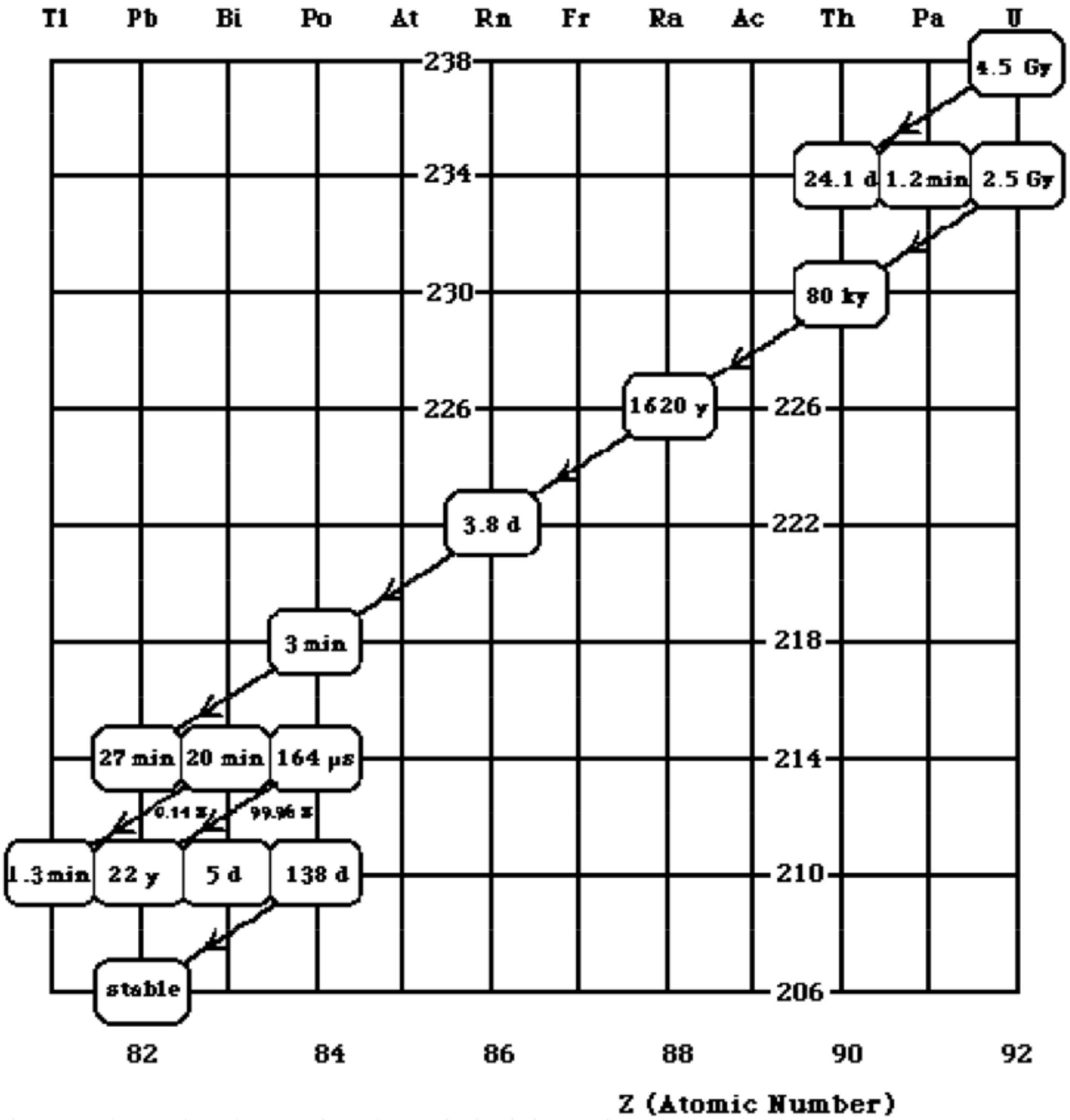

Fig. 3- 8. The uranium decay series. The vertical axis is atomic mass.

Units of Radioactivity

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

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

Books and Articles:

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

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

Web Sites:

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

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

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