Radioactivity

In 1896, Becquerel accidentally discovered that crystal of uranium salt emitted rays that were similar to x-ray in that they were highly penetrating, could effect and darken a photographic plate and ionize gases even though the plate is covered to exclude light. This process of spontaneous emission of radiation by uranium was soon to be called **radioactivity.**

Subsequent experiments by other scientists showed that other substances were more powerfully radioactive. The most significant early investigations of this type were conducted by Marie and Pierre Curie (1859–1906). After several years of careful and laborious chemical separation processes, the Curies reported the discovery of two previously unknown elements, both radioactive, named polonium and radium. Additional experiments, including Rutherford's famous work on alpha-particle scattering, suggested that radioactivity is the result of the ***decay,*** or disintegration, of unstable nuclei.

Three types of radioactive decay occur in radioactive substances: *alpha* (α) decay, in which the emitted particles are ^{4}He nuclei; **beta** (β) decay, in which the emitted particles are either **electrons or positrons**; and gamma (γ) decay, in which the emitted particles are high-energy photons.

A **positron** is a particle like the electron in all respects except that the positron has a charge of +*e*. (The positron is the *antiparticle* of the electron). The symbol e^- is used to designate an electron, and e^+ designates a positron.

We can distinguish among these three forms of radiation by using the scheme described in *Figure 8*. The radiation from radioactive samples that emit all three types of particles is directed into a region in which there is a magnetic field.

The radiation beam splits into three components, two bending in opposite directions and the third experiencing no change in direction. This simple observation shows that the radiation of the undeflected beam carries no charge (the gamma ray), the component deflected upward corresponds to positively charged particles (alpha particles), and the component deflected downward corresponds to negatively charged particles (e^-). If the beam includes a positron (e^+), it is deflected upward like the alpha particle, but it follows a different trajectory due to its smaller mass.

The three types of radiation have quite different penetrating powers. Alpha particles barely penetrate a sheet of paper, beta particles can penetrate a few millimeters of aluminum, and gamma rays can penetrate several centimeters of lead. The decay process is probabilistic in nature and can be described with statistical calculations for a radioactive substance of macroscopic size containing a large number of radioactive nuclei. For such large numbers, the rate at which a particular decay process occurs in a sample is proportional to the number of radioactive nuclei present (that is, the number of nuclei that have not yet decayed). If *N* is the number of undecayed radioactive nuclei present at some instant, the rate of change of *N* with time is

$$\frac{dN}{dt} = -\lambda N \qquad \text{eq. 44.5}$$

Where λ, called the **decay constant,** is the probability of decay per nucleus per second.

The negative sign indicates that dN / dt is negative; that is, *N* decreases in time. Equation 44.5 can be written in the form

$$\frac{dN}{N} = -\lambda \, dt$$

Which, upon integration, gives

$$\mathbf{N = N_0 \exp^{-\lambda t}}$$ eq. 44-6 (*Exponential behavior of the number of undecayed nuclei)*

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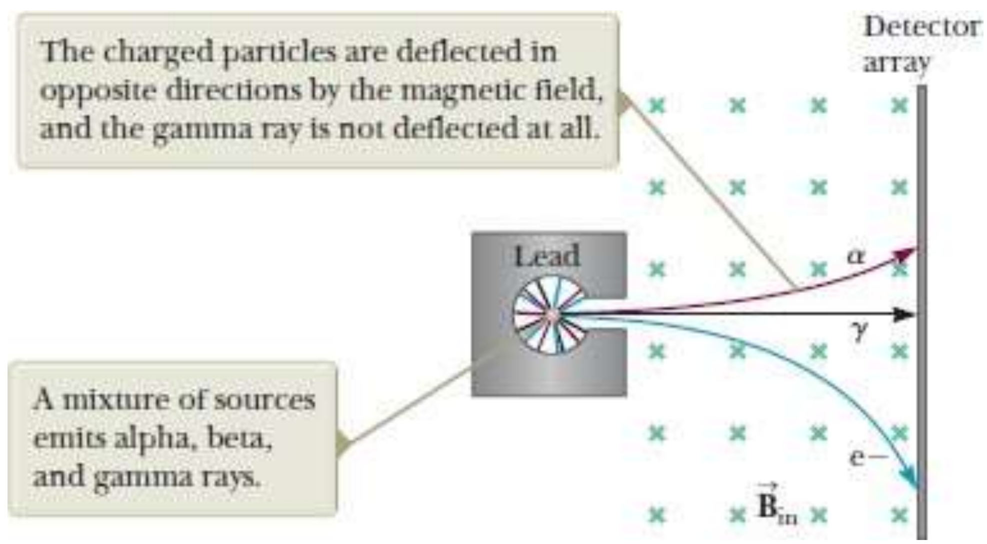

Figure 8 The radiation from radioactive sources can be separated into three components by using a magnetic field to deflect the charged particles. The detector array at the right records the events.

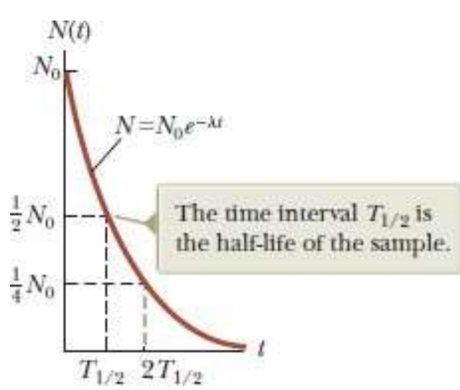

Figure 9 Plot of the exponential decay of radioactive nuclei. The vertical axis represents the number of undecayed radioactive nuclei present at any time t, and the horizontal axis is time.

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where the constant N_0 represents the number of undecayed radioactive nuclei at t = 0. Equation 44.6 shows that the number of undecayed radioactive nuclei in a sample decreases exponentially with time. The plot of **N** versus **t** shown in figure **9** illustrates the exponential nature of the decay. The decay rate R, which is the number of decays per second, can be obtained by combining Equations 44.5 and 44.6:

$$R = \left|\frac{dN}{dt}\right| = \lambda N = \lambda N_0 e^{-\lambda t} = R_0 e^{-\lambda t}$$ (eq. 44.7) Exponential behavior of the decay rate.

where $R_0 = \lambda N_0$ is the decay rate at t= 0. The decay rate R of a sample is often referred to as its activity. Note that both N and R decrease exponentially with time.

Another parameter useful in characterizing nuclear decay is the half-life $T_{1/2}$:

The half-life of a radioactive substance is the ***time interval during which half of a given number of radioactive nuclei decay.***

To find an expression for the half-life, we first set $N = N_0/2$ and $t = T_{1/2}$ in Equation 44.6 to give

$$\frac{N_0}{2} = N_0 e^{-\lambda T_{1/2}}$$

Canceling the N_0 factors and then taking the reciprocal of both sides, we obtain

$e^{\lambda T_{1/2}} = 2$. Taking the natural logarithm of both sides gives

$$T_{1/2} = \frac{\ln 2}{\lambda} = \frac{0.693}{\lambda}$$ eq. (44.8) half life time

After a time interval equal to one half-life, there are $N_0/2$ radioactive nuclei remaining (by definition); after two half-lives, half of these remaining nuclei have decayed and $N_0/4$ radioactive nuclei are left; after three half-lives, $N_0/8$ are and so on. In general, after n half-lives, the number of undecayed radioactive nuclei remaining is

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$$N = N_0\left(\tfrac{1}{2}\right)^n \qquad \text{eq. (44.9)}$$

where **n** can be an integer or a noninteger.

A frequently used unit of activity is the curie (Ci), defined as

1 Ci ≡ 3.7 * 10^{10} decays/s (The Curie)

This value was originally selected because it is the approximate activity of 1 g of radium. The SI unit of activity is the becquerel (Bq):

1 Bq ≡1 decay/s (The Becquerel)

Therefore, 1 Ci =3.7 * 10^{10} Bq. The curie is a rather large unit, and the more frequently used activity units are the millicurie and the microcurie.

Example:

The isotope carbon-14, ${}^{14}_{6}C$, is radioactive and has a half-life of 5730 years. If you start with a sample of 1000 carbon-14 nuclei, how many nuclei will still be undecayed in 25000 years?

Solution:

Divide the time interval by the half-life to determine the number of half-lives (n)

$$n = \frac{25\,000 \text{ yr}}{5\,730 \text{ yr}} = 4.363$$

Determine how many undecayed nuclei are left after this many half-lives using Equation 44.9

$$N = N_0\left(\tfrac{1}{2}\right)^n = 1\,000\left(\tfrac{1}{2}\right)^{4.363} = 49$$

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