Reese Ch. 26, Part A3
(Sects. 11-13 = pp. 1225-1231)

- Types of Spontaneous Nuclear Decay
- The Exponential Law of Decay
- Applications of Radioactivity
- Radiation Units, Dose, and Exposure

Spontaneous Nuclear Decay I: Types of Decay

- Emission of Alpha Particle (α)
- Emission of High-Speed Electron (β^-)
- Emission of High-Speed Positron (β^+)
- Electron Capture (competes with β^+)
- Spontaneous Fission (competes with α)
- Emission of High-Energy Photon (γ "decay")

Note: For some unstable nuclides, there is competition among several modes of decay.

Spontaneous Nuclear Decay II: Alpha (α) Radioactivity

- Parent nuclei are heavier than lead (Z =82).
- Daughter nucleus: Z′ = Z - 2 ; A′ = A – 4
- The alpha particle carries almost all of decay energy (Q), which is in the range 3 - 9 MeV.
- Half-life is VERY strongly dependent on Q.
- Alpha particles lose energy by ionizing atoms of the material through which they are passing. They are NOT very penetrating.

Spontaneous Nuclear Decay III: Beta-minus Radioactivity

- Parent nuclei are typically neutron-rich.
- Daughter nucleus: Z′ = Z +1 ; A′ = A.
- Decay energy is typically somewhat less than that for alpha decays.
- Decay energy (Q) is divided between the β^- and an electron antineutrino $(\bar{\nu}_e)$, so there's a continuous "spectum" of KE for the β^-.
- Beta particles do not ionize atoms as efficiently as alphas, so they are somewhat more penetrating.

Spontaneous Nuclear Decay IV: Beta-plus Radioactivity

- Parent nuclei are typically proton-rich.
- Daughter nucleus: Z′ = Z -1 ; A′ = A.
- Decay energy is typically somewhat less than that for alpha decays.
- Decay energy (Q) is divided between the β^+ and an electron neutrino (ν_e), so there's a continuous "spectum" of KE for the β^+.
- The β^+ and β^- particles are equivalent in their ability to ionize atoms, but β^+ particles can also participate in "pair annihilation" with an atomic electron.

Spontaneous Nuclear Decay V: Electron Capture (EC)

- Parent nuclei are typically proton-rich.
- Daughter nucleus: Z′ = Z -1 ; A′ = A.
- Decay energy is typically somewhat less than that for alpha decays.
- Decay energy (Q) is carried away by an electron neutrino (ν_e).
- A vacancy is produced in a previously full inner electron shell (usually the innermost shell), so there will be atomic de-excitation after an electron capture.
- For reasons that we won't pursue here, in some cases the decay energy is too small to allow for beta-plus decay. Then electron capture might be the only available decay route.

Spontaneous Nuclear Decay VI: Spontaneous Fission

- There are just a few very heavy nuclei which undergo spontaneous fission as a not-very-likely alternative to alpha decay (and in some cases beta decay as well).
- The fission results in two medium-weight nuclides, plus one or more neutrons. The energy release is typically about 200 MeV, and the neutrons carry away much of that energy.
- The fission fragments do not travel far, but they are often radioactive themselves.
- The neutrons are much more penetrating, but one way in which they are "stopped" is by being absorbed by some other nuclei. Among the possible results is induced fission, which will be discussed in PHYS 270.

Spontaneous Nuclear Decay VII: Gamma Emission

- Just as atoms have a ground state and excited states, so do nuclei.
- Often the decay of an unstable nucleus leaves the daughter nucleus highly excited.
- One way for an excited nucleus to return to its ground state is via decay of a high-energy photon (or "gamma ray") or perhaps several of them in succession.
- Gamma rays are highly penetrating; several centimeters of lead may be required to destroy or degrade them (via photoionization, pair production, or Compton scattering.)

The Exponential Law of Decay: I

Many experiments have confirmed that if at t = 0 there is a very large number N_o of radioactive nuclei (of a given nuclide, or nuclear species), then the number N(t) of parents remaining at time t is given by:

$$\boxed{N(t) = N_o e^{-\lambda t}}$$

The constant λ is called the disinstegration constant; its SI units are sec^{-1}.

The Exponential Law of Decay: II

The number of decays per unit time is called the activity of the sample. Notice that the activity is also described by a decreasing exponential with the same time constant λ:

$$\boxed{\text{Activity} = -\frac{\mathrm{d}N(t)}{dt} = \lambda N(t) = \lambda N_o e^{-\lambda t}}$$

The Exponential Law of Decay: III

- Under the exponential law of decay, during a time interval of fixed length Δt, the same fraction of the parent population survives as during any other interval of that same length:

$$\boxed{\frac{N(t+\Delta t)}{N(t)} = \frac{N_o e^{-\lambda(t+\Delta t)}}{N_o e^{-\lambda t}} = e^{-\lambda \Delta t}}$$

- The **half-life** of a radioactive nuclide is the interval for which the survival probability is one-half:

$$\frac{1}{2} = e^{-\lambda \tau_{1/2}} \Rightarrow \boxed{\tau_{1/2} = \frac{\ln 2}{\lambda} \approx \frac{0.6931}{\lambda}}$$

The Exponential Law of Decay: IV

- The **mean life** of a radioactive nuclide is the average age at which a parent nucleus decays:

$$\boxed{\overline{\tau} \equiv \frac{\int_0^\infty t\left[-\frac{dN}{dt}\right]dt}{\int_0^\infty \left[-\frac{dN}{dt}\right]dt}}$$

- It is not difficult to show that $\overline{\tau} = \frac{1}{\lambda} \approx 1.442\tau_{1/2}$.
- The fraction that survive one mean life is $e^{-1} \approx 0.3679$

Applications of Radioactivity

- Radioactive dating: The relative numbers of parent and daughter nuclei can serve as an indicator of the age of an object.
- Tracking nuclear materials: Radioactivity is an important means of detecting the presence of materials that could be used to make a nuclear weapon or a “dirty” conventional bomb.
- Medicine: Radioactive nuclides can be used as tracers in medical testing and can also be used to provide targeted radiation therapy.

Radiation Units: Activity

- The SI unit of activity is called the becquerel and is equal to 1 disintegration per second. A much more commonly used unit is the curie (abbreviated Ci), which is much larger than the becquerel:

  $$\boxed{1\ \text{Ci} = 3.6 \times 10^{10}\ \text{Bq}}$$

  A typical activity for a source that is both portable and fairly radioactive might be a few microcuries.

Radiation Units: Dose

One important measure of the dose of radiation absorbed by a person is the energy absorbed per kilogram. An old unit for this is the rad (*radiation absorbed dose)*, which equals 0.01 J/kg absorbed. The modern SI unit for dose is the gray (abrreviated Gy):

$$\boxed{1\ \text{Gy} = 100\ \text{rad} = 1.00\ \text{J/kg absorbed}}$$

Radiation Units: Exposure

Different types of radiation have greatly different biological effects. To quantify this, radiation scientists use a “quality factor” (QF), which ranges from 1 to 20. The dose-equivalent exposure is given by

$$\boxed{\text{exposure} = \text{dose} \times \text{QF}}$$

The unit used for expressing exposure is the sievert (abbreviated Sv). The exposure in sieverts equals the dose in grays times the quality factor.