Chapter 31
Nuclear Energy; Effects and Uses of Radiation

31-4 Passage of Radiation Through Matter; Radiation Damage

Radiation includes alpha, beta, and gamma rays; X rays; and protons, neutrons, pions, and other particles.

All these forms of radiation are called ionizing radiation, because they ionize material that they go through.

This ionization can cause damage to materials, including biological tissue.

31-5 Measurement of Radiation—Dosimetry

Radiation damages biological tissue, but it can also be used to treat cancer and other diseases.

It is important to be able to measure the amount, or dose, of radiation received. The source activity is the number of disintegrations per second, often measured in curies, Ci.

$$1\ \text{Ci} = 3.70 \times 10^{10}\ \text{disintegrations per second}$$

or decays per second

The SI unit for source activity is the becquerel (Bq):

1 Bq = 1 disintegration/s

The magnitude of the source activity, $\Delta N/\Delta t$, is related to the number of radioactive nuclei present, N, and to the half-life, $T_{\frac{1}{2}}$, by (see Section 30–8):

$$\frac{\Delta N}{\Delta t} = \lambda N = \frac{0.693}{T_{\frac{1}{2}}} N.$$

31-5 Measurement of Radiation—Dosimetry

Another type of measurement is the **exposure**. *The earliest unit of dosage was* the **roentgen (R), defined in terms of the amount of ionization produced by the** radiation (1R = 1.6 x 10^{12} ion pairs per gram of dry air at standard conditions). Today, 1 R is defined as the amount of X-ray or radiation that deposits 0.878 x 10^{-2} J of energy per kilogram of air.

Another measurement is the absorbed dose—the effect the radiation has on the absorbing material.

The rad, a unit of dosage, is the amount of radiation that deposits energy at a rate of 1.00×10^{-2} J/kg in any material.

The SI unit for dose is the gray, Gy:

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

- The gray and the rad are physical units of dose—the energy deposited per unit mass of material.

31-5 Measurement of Radiation—Dosimetry

TABLE 31–1 Relative Biological Effectiveness (RBE)	
Type	**RBE**
X- and γ rays	1
β (electrons)	1
Protons	2
Slow neutrons	5
Fast neutrons	≈ 10
α particles and heavy ions	≈ 20

The effect on tissue of different types of radiation varies, alpha rays being the most damaging. To get the effective dose, the dose is multiplied by the relative biological effectiveness.

The relative biological effectiveness (RBE) of a given type of radiation is defined as the number of rads of X-ray or gamma radiation that produces the same biological damage as 1 rad of the given radiation.

31-5 Measurement of Radiation—Dosimetry

The **effective dose** can be given as the product of the dose in rads and the RBE, and this unit is known as the **rem** (which stands for *rad equivalent man*):

$$\text{effective dose (in rem)} = \text{dose (in rad)} \times \text{RBE}. \qquad \textbf{(31–10a)}$$

This unit is being replaced by the SI unit for "effective dose," the **sievert** (Sv):

$$\text{effective dose (Sv)} = \text{dose (Gy)} \times \text{RBE} \qquad \textbf{(31–10b)}$$

so

$$1\ \text{Sv} = 100\ \text{rem} \qquad \text{or} \qquad 1\ \text{rem} = 10\ \text{mSv}.$$

If the dose is measured in rad, the effective dose is in rem; if the dose is grays, the effective dose is in sieverts, Sv.

Natural background radiation is about 0.3 rem per year. The maximum for radiation workers is 5 rem in any one year, and below 2 rem per year averaged over 5 years.

A short dose of 1000 rem is almost always fatal; a short dose of 400 rem has about a 50% fatality rate.

EXAMPLE 31–13 **Radon exposure.** In the U.S., yearly deaths from radon exposure (the second leading cause of lung cancer) are estimated to be on the order of 20,000 and maybe much more. The Environmental Protection Agency recommends taking action to reduce the radon concentration in living areas if it exceeds 4 pCi/L of air. In some areas 50% of houses exceed this level from naturally occurring radon in the soil. Estimate (*a*) the number of decays/s in $1.0\,\text{m}^3$ of air and (*b*) the mass of radon that emits 4.0 pCi of $^{222}_{86}\text{Rn}$ radiation.

SOLUTION (*a*) We saw at the start of this Section that $1\,\text{Ci} = 3.70 \times 10^{10}$ decays/s. Thus

$$\frac{\Delta N}{\Delta t} = 4.0\,\text{pCi} = \left(4.0 \times 10^{-12}\,\text{Ci}\right)\left(3.70 \times 10^{10}\,\text{decays/s/Ci}\right)$$
$$= 0.148\,\text{s}^{-1}$$

per liter of air. In $1\,\text{m}^3$ of air $\left(1\,\text{m}^3 = 10^6\,\text{cm}^3 = 10^3\,\text{L}\right)$ there would be $\left(0.148\,\text{s}^{-1}\right)(1000) = 150\,\text{decays/s}$.

(b) From Eqs. 30–3b and 30–6

$$\frac{\Delta N}{\Delta t} = \lambda N = \frac{0.693}{T_{\frac{1}{2}}} N.$$

Appendix B tells us $T_{\frac{1}{2}} = 3.8235 \text{ days}$ for radon, so

$$\begin{aligned} N &= \left(\frac{\Delta N}{\Delta t}\right) \frac{T_{\frac{1}{2}}}{0.693} \\ &= \left(0.148 \text{ s}^{-1}\right) \frac{(3.8235 \text{ days})(8.64 \times 10^4 \text{ s/day})}{0.693} \\ &= 7.06 \times 10^4 \text{ atoms of radon-222.} \end{aligned}$$

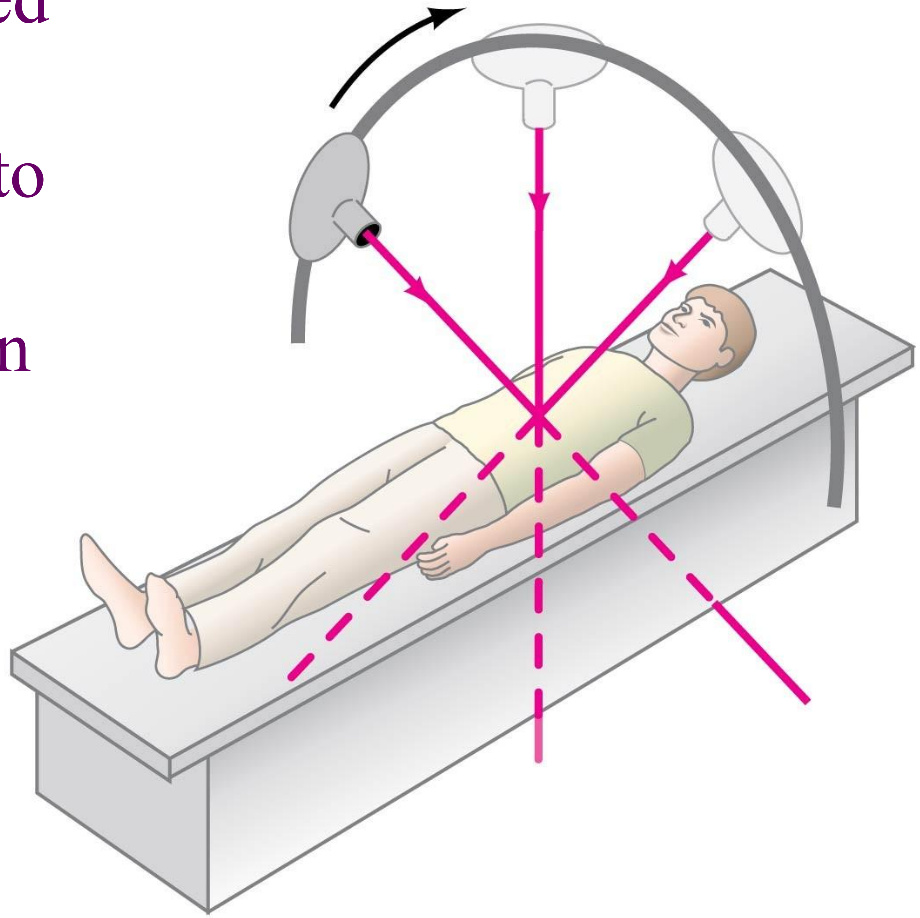
The molar mass (222 u) and Avogadro's number are used to find the mass:

$$m = \frac{(7.06 \times 10^4 \text{ atoms})(222 \text{ g/mol})}{6.02 \times 10^{23} \text{ atoms/mol}} = 2.6 \times 10^{-17} \text{ g}$$

or 26 attograms in 1 L of air at the limit of 4 pCi/L. This 2.6×10^{-17} g/L is 2.6×10^{-14} grams of radon per m^3 of air.

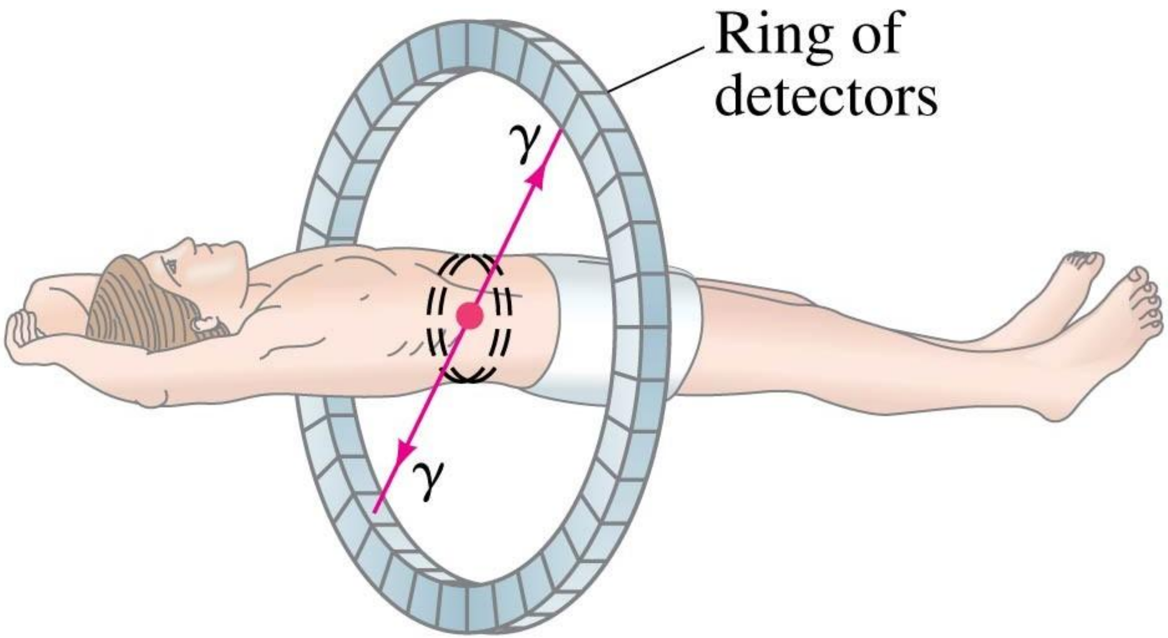
31-6 Radiation Therapy

Cancer is sometimes treated with radiation therapy to destroy the cells. In order to minimize the damage to healthy tissue, the radiation source is often rotated so it goes through different parts of the body on its way to the tumor.



31-8 Emission Tomography: PET and SPECT

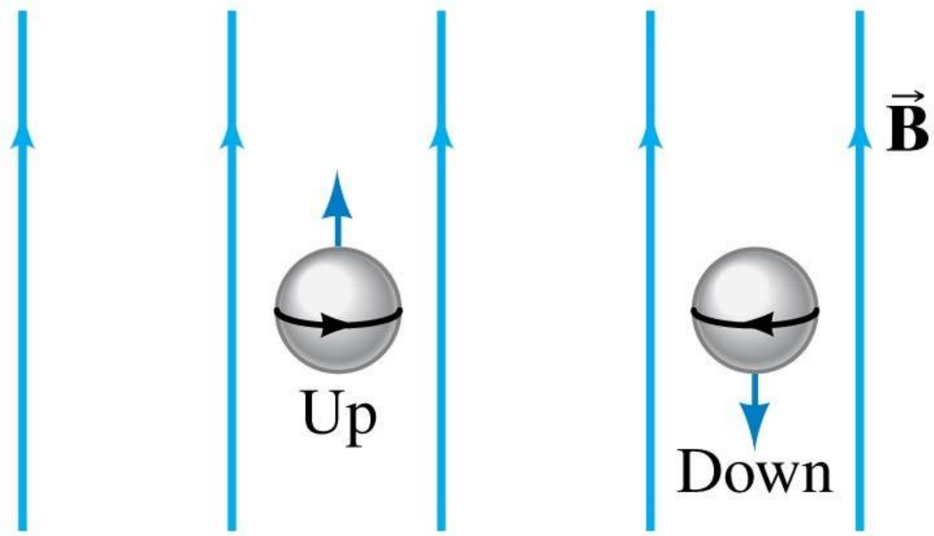
Radioactive tracers can also be detected using tomographic techniques, where a three-dimensional image is gradually built up through successive scans.



31-9 Nuclear Magnetic Resonance (NMR) and Magnetic Resonance Imaging (MRI)

A proton in a magnetic field can have its spin either parallel or antiparallel to the field.

The field splits the energy levels slightly; the energy difference is proportional to the field magnitude.



31-9 Nuclear Magnetic Resonance (NMR) and Magnetic Resonance Imaging (MRI)

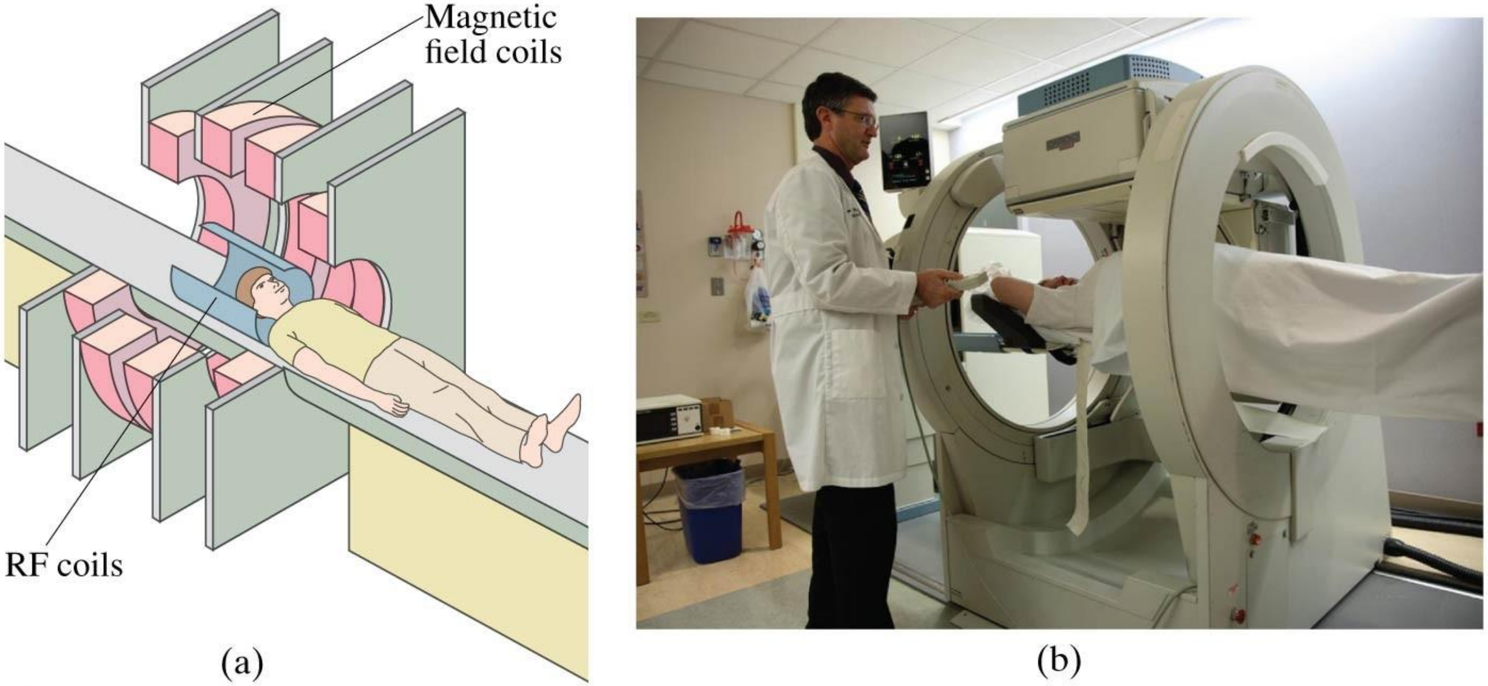
The object to be examined is placed in a static magnetic field, and radio frequency (RF) electromagnetic radiation is applied.

When the radiation has the right energy to excite the spin-flip transition, many photons will be absorbed. This is nuclear magnetic resonance.

The value of the field depends somewhat on the local molecular neighborhood; this allows information about the structure of the molecules to be determined.

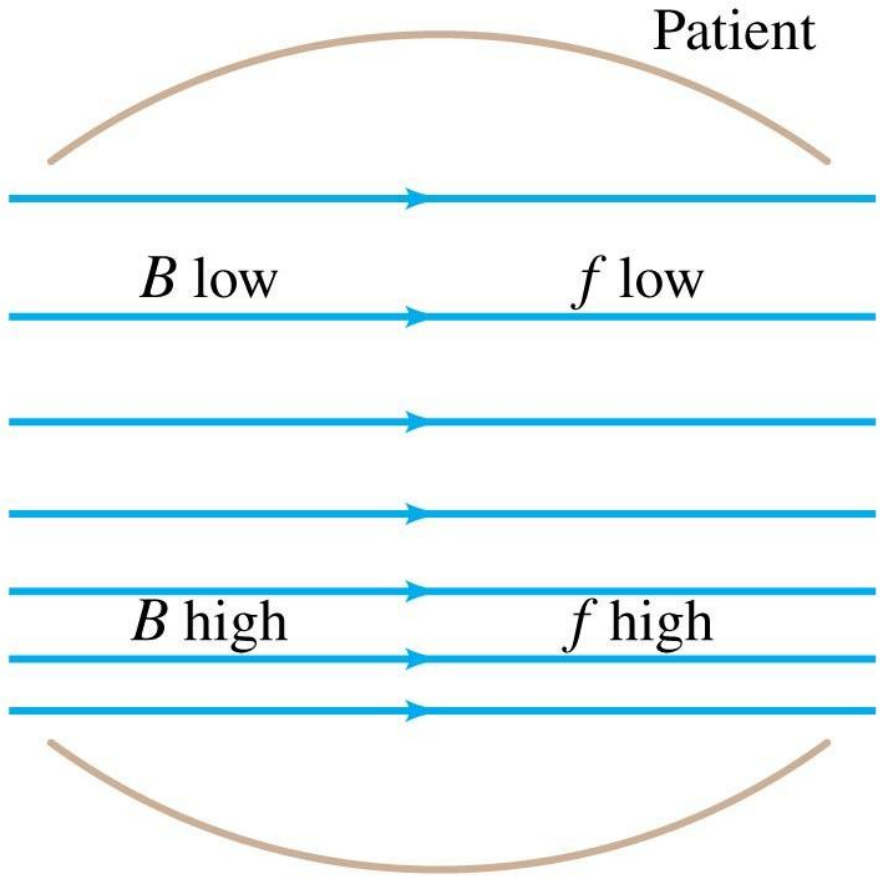
31-9 Nuclear Magnetic Resonance (NMR) and Magnetic Resonance Imaging (MRI)

Magnetic resonance imaging works the same way; the transition is excited in hydrogen atoms, which are the commonest in the human body.



31-9 Nuclear Magnetic Resonance (NMR) and Magnetic Resonance Imaging (MRI)

Giving the field a gradient can contribute to image accuracy, as it allows determining the origin of a particular signal.



31-9 Nuclear Magnetic Resonance (NMR) and Magnetic Resonance Imaging (MRI)

Here is a summary of the medical imaging techniques we have discussed.

TABLE 31–2 Medical Imaging Techniques

Technique	Where Discussed in This Book	Optimal Resolution
Conventional X-ray	Section 25–12	$\frac{1}{2}$ mm
CT scan, X-ray	Section 25–12	$\frac{1}{2}$ mm
Nuclear medicine (tracers)	Section 31–7	1 cm
SPECT (single photon emission)	Section 31–8	1 cm
PET (positron emission)	Section 31–8	2–5 mm
MRI (NMR)	Section 31–9	$\frac{1}{2}$–1 mm
Ultrasound	Section 12–9	0.3–2 mm

Problem 38

(I) 350 rads of α-particle radiation is equivalent to how many rads of X-rays in terms of biological damage?

Solution:

Because the RBE of alpha particles is up to 20 and the RBE of X-rays is 1, it takes 20 times as many rads of X-rays to cause the same biological damage as alpha particles. Thus the 350 rads of alpha particles is equivalent to $350\text{ rads}\times 20 = \boxed{7000\text{ rads}}$ of X-rays.

Problem 42

(II) A 0.035-μCi sample of $^{32}_{15}P$ is injected into an animal for tracer studies. If a Geiger counter intercepts 35% of the emitted β particles, what will be the counting rate, assumed 85% efficient?

Solution:

The counting rate will be 85% of 35% of the activity.

$$(0.035\times10^{-6}\text{ Ci})\left(\frac{3.7\times10^{10}\text{ decays/s}}{1\text{ Ci}}\right)\left(\frac{1\,\beta}{1\text{ decay}}\right)(0.35)(0.85) = 385.3\text{ counts/s} \approx \boxed{390\text{ counts/s}}$$

Problem 44

(II) A 1.6-mCi source of ${}^{32}_{15}P$ (in $NaHPO_4$), a β emitter, is implanted in a tumor where it is to administer 32 Gy. The half-life of ${}^{32}_{15}P$ is 14.3 days, and 1.0 mCi delivers about 10 mGy/min. Approximately how long should the source remain implanted?

Solution:

We approximate the decay rate as constant and find the time to administer 32 Gy. If that calculated time is significantly shorter than the half-life of the isotope, then the approximation is reasonable. If 1.0 mCi delivers about 10 mGy/min, then 1.6 mCi would deliver 16 mGy/min.

$$\text{dose} = \text{rate} \times \text{time} \quad \rightarrow \quad \text{time} = \frac{\text{dose}}{\text{rate}} = \frac{32\text{ Gy}}{16\times10^{-3}\text{ Gy/min}}\left(\frac{1\text{ day}}{1440\text{ min}}\right) = 1.39\text{ days} \approx \boxed{1.4\text{ days}}$$

This is only about 10% of a half-life, so our approximation is reasonable.

Problem 45:

What is the mass of a 2.50-μCi ${}^{14}_{6}\mathrm{C}$ source?

Solution:

Since the half-life is long (5730 yr), we can consider the activity as constant over a short period of time. Use the definition of the curie from Section 31–5.

$$(2.50\times10^{-6}\ \mathrm{Ci})\left(\frac{3.70\times10^{10}\ \mathrm{decays/s}}{1\ \mathrm{Ci}}\right)=9.25\times10^{4}\ \mathrm{decays/s}=\frac{\Delta N}{\Delta t}=\frac{0.693}{T_{\frac{1}{2}}}N\ \rightarrow$$

$$N=\frac{\Delta N}{\Delta t}\frac{T_{\frac{1}{2}}}{0.693}=(9.25\times10^{4}\ \mathrm{decays/s})\frac{5730\ \mathrm{yr}}{0.693}(3.156\times10^{7}\ \mathrm{s/yr})=2.414\times10^{16}\ \mathrm{nuclei}$$

$$2.414\times10^{16}\ \mathrm{nuclei}\left(\frac{0.0140\ \mathrm{kg}}{6.02\times10^{23}\ \mathrm{nuclei}}\right)=\boxed{5.61\times10^{-10}\ \mathrm{kg}}=0.561\ \mu\mathrm{g}$$

Problem 40:

How much energy is deposited in the body of a 65-kg adult exposed to a 2.5-Gy dose?

Solution:

A gray is 1 joule per kilogram, according to Eq. 31–9.

$$(2.5\ \text{J/kg}) \times 65\ \text{kg} = 162.5\ \text{J} \approx \boxed{160\ \text{J}}$$