Chapter 21
Nuclear Chemistry

- Nuclear chemistry involves changes in the nuclear composition of atoms that are radioactive.
- Nuclear changes provide a source of energy.
- Nuclear changes can be used for medical diagnosis and treatment.

21.1 Radioactivity

- Why do the elements occur in widely different amounts in the universe?

Radioactivity

- The elements have different stabilities. Of the natural elements, 81 elements ($_1$H – $_{83}$Bi, with the exception of Tc and Pm) have at least one stable isotope that is not radioactive.
- Of the natural elements, 9 elements (Po–U) are radioactive.
- The heavier elements (Np –) are synthetic and radioactive. Elements with their molar mass in parentheses ( ) on the periodic table are radioactive. Why don't these have a more precise molar mass?
- Not all elements are equally stable — the radioactive ones undergo nuclear decay to form other elements.
- When discussing nuclear reactions, we are interested in specific nucleons (nuclear particles) — protons and neutrons — which provide the majority of the mass of the nucleus.
- Z = atomic number = number of protons
- N = neutron number = number of neutrons
- A = Z + N = mass number = number of nucleons
- nuclides = nuclei of isotopes
- symbol: ${}^{A}_{Z}E$
- Only 264 of the 1700 known nuclides are stable; the others decompose at some characteristic rate, emitting some type of radiation.

Nuclear Equations

- Radiation arises from nuclear reactions:
- parent nuclide → daughter nuclide + radiation
- To balance, two conditions must be met:
  - Conserve mass number (A)
  - Conserve nuclear charge (Z)
- If we know two of the nuclear particles, we can use these rules to identify the third particle.

Nuclear Reactions

- Emission of alpha particles:
- ${}^{226}_{88}\text{Ra} \rightarrow {}^{222}_{86}\text{Rn} + {}^{4}_{2}\text{He}$
- Used in radiation therapy

- Conserve A: 226 = 222 + 4
- Conserve Z: 88 = 86 + 2
- Group Work:
- What is the product of the following reaction?
- ${}^{232}_{90}\text{Th} \rightarrow ? + {}^{4}_{2}\text{He}$

Nuclear Reactions

- Emission of beta particles (electrons):
- ${}^{131}_{53}\text{I} \rightarrow {}^{131}_{54}\text{Xe} + {}^{0}_{-1}\text{e}^{-}$
- Used to diagnose thyroid disorders
- Conserve A: 131 = 131 + 0
- Conserve Z: 53 = 54 + –1
- Group Work:
- What is the product of the following reaction?
- ${}^{60}_{27}\text{Co} \rightarrow ? + {}^{0}_{-1}\text{e}^{-}$

Nuclear Reactions

- Emission of beta+ particles (positrons):
- ${}^{18}_{9}\text{F} \rightarrow {}^{18}_{8}\text{O} + {}^{0}_{+1}\text{e}^{+}$
- Conserve A: 18 = 18 + 0
- Conserve Z: 9 = 8 + 1
- Group Work:
- What is the product of the following reaction?
- ${}^{23}_{12}\text{Mg} \rightarrow ? + {}^{0}_{+1}\text{e}^{+}$

Nuclear Reactions

- Emission of gamma rays:
- ${}^{224}_{88}\text{Ra}^{*} \rightarrow {}^{224}_{88}\text{Ra} + \gamma$
- Conserve A: 224 = 224 + 0
- Conserve Z: 88 = 88 + 0
- Accompanies nuclear transformations which leave excited (high energy) nuclei; no nuclear change is associated with gamma rays since A = 0 and Z = 0 for γ rays

Types of Radiation

- Three types of radiation are commonly detected: alpha, beta or gamma
- Alpha
  - $\alpha = {}^{4}_{2}\text{He}^{2+}$ or ${}^{4}_{2}\text{He}$ or ${}^{4}_{2}\alpha$
  - least penetrating
  - can be stopped by aluminum foil > 10^{-3} cm, paper, skin
  - least harmful
  - most massive
- Beta
  - $\beta = {}^{0}_{-1}\text{e}^{-}$
  - high energy electrons (e^{-}) or positrons (e^{+})

  - more penetrating
  - stopped by 0.05 – 0.1 cm of aluminum
  - travel 10 ft through air
  - commonly emitted by TV sets
  - electron: ${}^{0}_{-1}\beta^{-}$ or ${}^{0}_{-1}e^{-}$ or e^{-}
  - positron: ${}^{0}_{+1}\beta^{+}$ or ${}^{0}_{+1}e^{+}$ or e^{+}
- Gamma
  - γ = energy with no mass or charge
  - Most penetrating radiation
  - Stopped by 5 – 11 cm of aluminum or thick layer of concrete or lead
  - Lead is commonly used to enclose radioactive materials because radiation does not penetrate readily
  - In the 1950s, it was common to build thick concrete bomb shelters
- Other particles:
  - proton (p^{+} or ${}^{1}_{1}p$ or ${}^{1}_{1}H$)
  - neutron (n or ${}^{1}_{0}n$)
  - neutrino (${}^{0}_{0}\nu$) and antineutrino (${}^{0}_{0}\nu$), which have no mass or charge and accompany emission of beta particles; these are generally ignored by chemists

21.2 Patterns of Nuclear Stability

- The stable nuclides occur in a narrow band of Z and N values — an “island of stability”.
- For $Z = 1–20$, $N = Z$ ($N/Z = 1$)
- For $Z > 20$, $N > Z$ ($N/Z \leq 1.6$)
- The stable isotopes form a zig–zag pattern within the island of stability.
- Even Z, even N: most stable
- Even N & even Z for 60% of the stable nuclides (157)
- Even N or even Z for most of the rest (102)
- Only 5 stable nuclides have both odd N and odd Z, one of which is hydrogen, ${}^{1}_{1}H$
- This is reflected in the abundances shown in slide 2

- Which of the following two nuclides is most likely to be stable and which is most likely to be radioactive?
  - ${}^{10}_{5}B$ and ${}^{12}_{5}B$
  - ${}^{10}_{5}B$ and ${}^{13}_{5}B$
  - ${}^{10}_{5}B$ and ${}^{9}_{5}B$
  - ${}^{11}_{5}B$ and ${}^{8}_{5}B$
- ${}^{10}_{5}B$ and ${}^{11}_{5}B$ are stable; the other isotopes of B are radioactive. Consider both even N and Z = N.

- Which of each pair of nuclides is most likely to be radioactive?
  - ${}^{16}_{8}O$ and ${}^{17}_{8}O$
  - ${}^{16}_{8}O$ and ${}^{18}_{8}O$
  - ${}^{28}_{14}Si$ and ${}^{29}_{14}Si$

  - $^{28}_{14}Si$ and $^{30}_{14}Si$
  - $^{12}_{6}C$ and $^{13}_{6}C$

Radioactivity

- There is a shell model of the nucleus (similar to electronic shells) which ascribes special stability to nuclides with "magic numbers" or filled shells: 2, 8, 20, 28, 50, 82, 126
- Nuclides with these numbers of protons and neutrons are especially stable (note that these are all even numbers).
- Stable nuclides: $^{4}_{2}He$, $^{16}_{8}O$, $^{40}_{20}Ca$

Spontaneous Nuclear Decay Reactions

- Unstable nuclides decay spontaneously to try to reach a more stable N/Z ratio, while emitting radiation at a characteristic rate.
- Nuclides outside the island of stability change to reach the stable N/Z region

Types of Decay Processes

- If $Z > 83$, α decay gets rid of excess mass, with a slight decrease in N/Z.
- If N/Z is too high, β decay converts a neutron to a proton plus an electron, decreasing N/Z.
- If N/Z is too low, $\beta+$ decay converts a proton to a neutron and a positron, increasing N/Z.
- If N/Z is too low, electron capture (EC) results in a proton capturing an inner electron and becoming a neutron, increasing N/Z.
- If the nuclide has too much energy, γ decay gets rid of it.

What type of decay?

- $^{14}_{6}C$ $N/Z = 8/6 = 1.33$
- Stable N/Z for light element is 1.00
- β decay gives smaller N/Z
- $^{14}_{6}C \rightarrow {}^{14}_{7}N + {}^{0}_{-1}e^{-}$
- $^{14}_{7}N$ $N/Z = 7/7 = 1.00$

What type of decay?

- $^{13}_{7}N$ $N/Z = 6/7 = 0.86$ (too small)
- Stable N/Z for light element is 1.00
- Increase ratio by positron emission or electron capture
- $^{13}_{7}N \rightarrow {}^{13}_{6}C + {}^{0}_{+1}\beta^{+}$
- $^{13}_{6}C$ $N/Z = 7/6 = 1.17$
- Can't get closer than this; nuclides prefer to be greater than 1 rather than less than 1

What type of decay?

- Sometimes uses electron capture instead. Can't tell which will occur; the result is the same.
- ${}^{0}_{-1}e^{-} + {}^{22}_{11}Na \rightarrow {}^{22}_{10}Ne$
- Stable nuclides in this region have N/Z slightly greater than 1.0

- ${}^{22}_{11}Na$ N/Z = 1.0
- ${}^{22}_{10}Ne$ N/Z = 1.2

What type of decay?

- Heavy elements decay by a combination of α and β decay. See the uranium series (Figure 21.4). Ultimately a heavy radioactive element will decay through a series of radioactive elements until it gets to a stable isotope of lead or bismuth.
- Four such series of decays are known:
    - U
    - Th
    - Ac
    - Np

Other Reactions

- Fission: nucleus splits into two lighter nuclei and neutrons
- Fusion: two light nuclei combine into a heavier nucleus
- Nuclear Bombardment: nuclei collide with high energy (accelerated) particles, possibly followed by decay

21.3 Nuclear Transmutations

- Bombardment reactions: Used to create new elements
- December 1994 in Darmstadt, Germany:
  ${}^{64}_{28}Ni + {}^{209}_{83}Bi \rightarrow {}^{272}_{111}? + {}^{1}_{0}n$
- Conserve A: 64 + 209 = 273 = 272 + 1
- Conserve Z: 28 + 83 = 111 = 111 + 0
- These reactions usually emit one or more particles, such as neutrons.
- This new nuclide survives for only 0.002 seconds

- What is the product of the following reaction?
  ${}^{97}_{42}Mo + {}^{2}_{1}H \rightarrow ? + 2{}^{1}_{0}n$

Particle Accelerators

- Bombardment reactions require a stream of particles directed onto a target element. Thus, new elements, or useful isotopes can be produced with various particle accelerators.
- For bombardment reactions, we usually need to accelerate particles to overcome nuclear–nuclear repulsions. (Neutrons usually have to be slowed down.)
- Linear Accelerator
    - A beam of charged particles is accelerated by passing it through a series of tubes having alternating electrical charge.
    - The tubes get successively longer because the particles are moving faster.
- Circular accelerator (cyclotron)
    - A magnetic field is used to keep the particles in a circular pathway.
    - Alternating current on the “D”s is used to accelerate the particles.
    - Some cyclotrons have a radius of 1 km.
    - The canceled supercollider in Texas would have been much larger.

Bombardment Reactions

- Reaction in a nuclear reactor:
  ${}^{238}_{92}U + {}^{1}_{0}n \rightarrow {}^{239}_{93}Np + {}^{0}_{-1}e^{-}$
- Preparation of Tc for medical imaging:
  ${}^{97}_{42}Mo + {}^{2}_{1}H \rightarrow {}^{97}_{43}Tc + 2{}^{1}_{0}n$
- Synthesis of transuranium elements:
  ${}^{238}_{92}U + {}^{4}_{2}He \rightarrow {}^{239}_{94}Pu + 3{}^{1}_{0}n$
  ${}^{238}_{92}U + {}^{12}_{6}C \rightarrow {}^{246}_{98}Cf + 4{}^{1}_{0}n$
  ${}^{238}_{92}U + {}^{14}_{7}N \rightarrow {}^{247}_{99}Es + 5{}^{1}_{0}n$
- In September 1982, two new elements were formed by bombardment with heavy nuclides:
  ${}^{58}_{26}Fe + {}^{206}_{82}Pb \rightarrow {}^{265}_{108}Hn + {}^{1}_{0}n$
  ${}^{58}_{26}Fe + {}^{209}_{83}Bi \rightarrow {}^{266}_{109}Mt + {}^{1}_{0}n$
  Prepared only a few atoms of each
- The interest in preparing new elements is generated in part by the prediction that there will be another island of stability among elements with Z~114 or 126, N~184

21.4 Rates of Radioactive Decay

- The rate of decay, as well as the type and energy of the radiation, determines the damage caused by radiation.
- Nuclear decay follows first–order kinetics, which gives a constant $t_{1/2}$ over the course of the decay. Nuclear decay rates are also independent of temperature. Usually we cite $t_{1/2}$ instead of a rate constant.
- Note that successive half–lives have the same value.
- The radiation intensity and the number of radioactive nuclei decrease by a factor of 2 during each half–life.

Kinetics

- N = number of atoms of a nuclide
- $N = N^{o}e^{-kt}$
- $N = 1/2\ N^{o}$ at $t = t_{1/2}$
- $\ln N = \ln N^{o} - 0.693\ t/t_{1/2}$

Kinetics

- Can use kinetics, just like in Chapter 14, to do various calculations.
- How much nuclide is left after ___ time?
- How long do we have to store nuclear waste?
  (Usually 10 $t_{1/2}$: $2^{-10} = 0.000977$, so 99.9023% has decayed)
  ${}^{51}Cr$ ($t_{1/2} = 27.8$ days) is stored for $\geq$ 10 months
- How much time has elapsed if conversion is ___% complete?
  Use $\ln(N/N^{o}) = -0.693t/t_{1/2}$

- Gold–128 undergoes beta decay to give mercury–128 with a half–life of 2.7 days. What fraction of gold–128 is left after 14 days?
- $\ln(N/N^{o}) = -0.693t/t_{1/2}$

- $\ln(N/N^o) = –0.693 \times 14 \text{ days}/2.7 \text{ days} = –3.593$
- $N/N^o = e^{–3.593} = 0.0275$

Archeological Dating

- Radiocarbon dating uses ^{14}C content
- ^{14}C is produced by bombardment of ^{14}N with neutrons (in cosmic rays)
  $^{14}_{7}N + ^{1}_{0}n \rightarrow ^{14}_{6}C + ^{1}_{1}H$
- ^{14}C is incorporated into living system, but undergoes radioactive decay with a half–life of 5730 years:
  $^{14}_{6}C \rightarrow ^{14}_{7}N + ^{0}_{-1}e^{-}$
- When a plant or animal dies, it no longer incorporates new ^{14}C, and the ^{14}C begins to decay, causing the ^{14}C content to become less than that in the atmosphere
- Have to calibrate in some way to take into account variations in the atmospheric content of ^{14}C
- Count bristle–cone pine tree rings to date the rings; correlate with a measurement of their ^{14}C content (University of Arizona)
- Living tissue has 15.3 disintegrations per minute per g C
- Can measure $\geq$0.03 dis/min/g
- 15.3 → 0.03 in about 9 $t_{1/2}$
- Thus, the effective time range is $\leq 9 \times 5730 \simeq 50{,}000$ years

Geological Dating

- Geological dating is similar to archeological dating, but uses longer–lived nuclides
- Measure ratio of ^{40}K to ^{40}Ar in rocks
  $^{40}_{19}K + ^{0}_{-1}e^{-} \rightarrow ^{40}_{18}Ar$ 89%
  $^{40}_{19}K \rightarrow ^{40}_{20}Ca + ^{0}_{-1}e^{-}$ 11%
  Combined half–life is 1.27×10^9 years
- Measure ratio of ^{238}U to ^{206}Pb in rocks
  $^{238}U \rightarrow \rightarrow \ldots \rightarrow ^{206}Pb$
  $t_{1/2} = 4.5 \times 10^9$ years
- terrestrial rocks: $t \leq 2 \times 10^9$ years
- terrestrial rocks: $t = 2–3 \times 10^9$ years
- meteorites: $t \leq 4.5 \times 10^9$ years

21.5 Detection of Radioactivity

- Study nuclear properties by studying the radiation emitted.
- Detection:
  - film badge for personal exposure
  - Geiger–Muller counter
    - radiation causes ionization of Ar(g), which gives a pulse of electric current that is sent to a counter
    - detects α, β, or γ
  - scintillation counter
    - ZnS or NaI fluoresces (light flash) when irradiated; light is passed through a photomultiplier tube and recorded on a counter

Quantity of Radiation

- activity = number of nuclei disintegrating per unit time
- units = Curie (Ci)
- 1 Ci = 3.7 x 10^{10} disintegrations/sec = amount for 1 g of ^{226}Ra

21.6 Energy Changes in Nuclear Reactions

- Chemical reactions have energy changes of 100–1000 kJ/mol
- Nuclear reactions are of interest because of their large energy output
- The mass of an atom is less than the separate masses of the component subatomic particles — this discrepancy is called the mass defect.

Mass Defect

- $^{20}_{10}$Ne 19.9924 amu
- Assume $10p^+ + 10n + 10e^- \rightarrow {}^{20}_{10}\text{Ne}$
- mass of p^+ = 1.00728 amu
- mass of n = 1.00867 amu
- mass of e^- = 0.0005486 amu
- sum of particle masses = 20.1650 amu
- mass defect = 20.1650 amu – 19.9924 amu = 0.1726 amu
-
- What is the mass defect for $^{40}_{20}$Ca, which has a mass of 39.9626 amu?
- mass of p^+ = 1.00728 amu
- mass of n = 1.00867 amu
- mass of e^- = 0.0005486 amu

Mass Defect

- The mass defect corresponds to the atom having a lower energy than its component particles
- The energy corresponding to the mass defect is called the nuclear binding energy
- The Einstein equation is used to determine the mass–energy equivalence:
- $E = mc^2$
  1 amu = 1.66056 x 10^{-27} kg
  c = 2.9979 x 10^8 m/s
  joule = kg m^2/s^2

Nuclear Binding Energy

- For $^{20}_{10}$Ne, E = 0.1726 amu x 1.66056 x 10^{-27} kg/amu x (2.9979 x 10^8 m/s)^2
- E = 2.576 x 10^{-11} J for one atom
- For 1 mole of atoms (6.022 x 10^{23} atoms): E = 1.551 x 10^{13} J/mol
- It is common to use MeV as a unit to get convenient numbers for single atoms:
  1 MeV = 1.6602 x 10^{-13} J
- E = 2.576 x 10^{-11} J x 1 MeV/1.6602 x 10^{-13} J = 160.8 MeV for one atom
- For the overall conversion, we can use the equivalence: 1 amu = 931.5 MeV
- For $^{20}_{10}$Ne, the binding energy per nucleon is E = 160.8 MeV/20 nucleons = 8.040 MeV/nucleon

- Examine a graph of nuclear binding energy (per nucleon) against mass number
- The curve is smooth, with spikes for very stable nuclides: ${}^{4}_{2}He$, ${}^{12}_{6}C$, ${}^{16}_{8}O$ (N = Z = even)
- Maximum value at ${}^{56}_{26}Fe$, which is prevalent in Earth's crust
- Elements with Z = 20–30 are prevalent in the crust, as are ${}^{16}O$, ${}^{12}C$, and ${}^{14}N$
- No elements heavier than the region of the maximum in the curve are present in amounts >1% in the crust
- Light nuclides undergo fusion or bombardment to convert to other nuclides closer to the maximum value
- Heavy nuclides undergo fission to give nuclides closer to the maximum value
- If a nuclear reaction gives products with a higher nuclear binding energy, then energy is released by the reaction.
- To calculate the energy released, calculate the mass defect, then multiply by 931.5 MeV/amu

21.7 Nuclear Fission

- Some nuclides undergo spontaneous fission; others undergo fission when bombarded with another nuclide or with a nucleon
- ${}^{235}U$ is used in nuclear power plants
  ${}^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{236}_{92}U \rightarrow$ mixture of products
  ${}^{236}_{92}U \rightarrow {}^{92}_{36}Kr + {}^{141}_{56}Ba + 3{}^{1}_{0}n + \gamma$
  ${}^{236}_{92}U \rightarrow {}^{90}_{38}Sr + {}^{143}_{54}Xe + 3{}^{1}_{0}n + \gamma$
  ${}^{236}_{92}U \rightarrow {}^{94}_{40}Zr + {}^{140}_{58}Ce + 2{}^{1}_{0}n + \gamma$
  and others
- Average of 1 n is consumed, but an average of 2.4 n are produced, so more reaction occurs with the new neutrons and the reaction speeds up.
- This is called a chain reaction.
- One step in a chain reaction produces more neutrons than it consumes.
- Successive steps get faster and faster

Nuclear Reactor

- The size and shape of the uranium fuel determines how many neutrons escape and how many react.
- If we exceed some critical mass, the reaction becomes increasingly faster and results in a nuclear explosion.
- To control the process, we must remove some neutrons and slow down fast neutrons so they will react.

Reactor Core

- We use B or Cd control rods.
- ${}^{10}_{5}B + {}^{1}_{0}n \rightarrow {}^{7}_{3}Li + {}^{4}_{2}He$

Nuclear Reactor

- Fuel is not pure ${}^{235}U$.
- Usually use U_3O_8 enriched from a natural 0.7% ${}^{235}U$ to 2–3% ${}^{235}U$.

- Use a moderator to slow down neutrons: H_2O or D_2O or graphite.
- Get an energy output of 200 MeV/atom or 2×10^{10} kJ/mol as the kinetic energy of the products.
- Use this kinetic energy to heat water (the coolant) to 310–350°C (under pressure to prevent boiling).
- The hot water is then used to heat water contained in a secondary loop (to prevent any possible radiation loss) to make steam that drives a turbine in a generator.
- The steam is condensed and cooled in a cooling tower.
- The reactor core is enclosed in a containment building (the usual dome shape seen at nuclear power plants.
- Chernobyl used no containment, so the radiation leak was worse than from Three Mile Island.
- Storage of fission products is a major challenge.

21.8 Nuclear Fusion

- Fusion is already a source of energy; this is the process that produces sunlight.
- However, we have not yet carried out fusion in a reactor under control to produced energy.
- Sun: $4\,{}^{1}_{1}H \rightarrow {}^{4}_{2}He + 2\,{}^{0}_{+1}\beta^{+}$ + 25 MeV energy
- Need energy to initiate fusion (to overcome internuclear repulsions). In the sun, the temperature is about 10^7 K
- In a fusion bomb (hydrogen bomb), high temperature and pressure are provided by a fission explosion.
- The temperature needed to initiate fusion is called the ignition temperature.
- Fusion reactors are of interest because we have a greater supply of fuel and because they would produce fewer radioactive waste products, compared to a fission reactor.
- To date, it has been possible to carry out controlled fusion, but the input energy still exceeds the output energy.
- The most likely candidate for a fusion reaction is:
  ${}^{2}_{1}H + {}^{3}_{1}H \rightarrow {}^{4}_{2}He + {}^{1}_{0}n$
  $\Delta E = 17.6$ MeV, T(ignition) = 10^8 K (or 10 keV)
  Energy gain = 1760
- ${}^{2}_{1}H$ is deuterium (D), available from water (heavy water)
- ${}^{3}_{1}H$ is tritium (T), available from the bombardment of Li with neutrons. We currently have about a thousand–year supply of lithium.
- Layout of fusion reactor:
  - Li blanket around a plasma core
  - Li absorbs n and produces more tritium than is used (called a breeder reactor)
- Problems:
  - achieving high temperature and pressure
  - holding an ionized gas (plasma) at high T & P (any container melts)
- Possible solutions:
  - use magnetic field from a donut–shaped machine called a tokamak
  - or use fuel in the form of beads and irradiate with a laser beam

21.9 Biological Effects of Radiation

- Can damage tissue cells
- Radiation comes continuously from many sources besides nuclear power plants and applications of isotopes
- Natural radiation sources:
    - granite
    - soil
    - water
    - food
    - air
    - brick
    - concrete
    - cosmic rays (airplane flights)
    - radon in houses

- Amount of radiation exposure measured in rem
- rem = roentgen equivalent for man
- rad = radiation absorbed dose (10^{-2} J/kg tissue)
- RBE = relative biological effectiveness
    - RBE = 1 for x–ray, γ, β
    - RBE = 2.5 for slow neutrons
    - RBE = 10 for α, protons, fast neutrons
    - RBE = 20 for heavy ions
- 1 rem = 1 rad x 1 RBE
- Normal exposure = 200 mrem (0.2 rem) per year, which produces no observable effects
- Single dose of 0–25 rem: no effect
- 25–100 rem: temporary blood cell changes
- 100–300 rem: radiation sickness; decrease in white blood cells
- 400–600 rem: 50% chance of death
- $\geq$ 1000 rem: 100% chance of death

- Calculate your radiation exposure:

Cosmic radiation at sea level	27 mrem/year
Add 1 for every 250 ft elevation	4 for Phoenix
Radiation from earth	28
Building materials in houses	4
Radon gas from the ground	200
Radiation from food and water	39
Jet plane travel (9.5 mrem/hr)	___
If you smoke (~1300 mrem/yr)	___
Average medical exposure	25–55 mrem/yr
Add 6 for each chest x–ray	____
Add 245 for intestinal x–ray	____
Smoke detectors	10
Power plants	1
Your total exposure this year:	_____ mrem

- Applications of Isotopes

- Warfare
- Archeological/geological dating
- Small power generators for space vehicles and pacemakers
- Smoke alarms
- Radioactive tracers (e.g., ^{51}Cr):
  $CrNC^{2+} + {}^{*}Cr^{2+} \rightarrow {}^{*}CrCN^{2+} + Cr^{2+}$
- Medical diagnoses
  - ^{99}Tc for tumors in spleen, liver, brain, thyroid
  - tracer put into a metabolite that concentrates in cancerous cells
  - ^{131}I or ^{123}I in thyroid
- Cancer therapy — destroy cells with γ rays
  - ^{131}I for thyroid cancers
  - ^{198}Au for lung cancer
  - ^{32}P for eye tumors
- Positron Emission Transaxial Tomography (PET or PETT Scan)
  - images slices of tissue
  - ^{11}C, ^{18}F, ^{15}O, or ^{13}N are used as positron emitters
  - detect gamma rays formed when a positron annihilates an electron
  - the gamma rays emanate from the annihilation site
  - the location and number of gamma ray production events is used by computer to construct an image of the concentration of positron–emitting nuclides
- Chemical analysis
  - neutron activation analysis used to authenticate antiques and art
- Food preservation by killing bacteria and molds