Ch. 20: Nuclear Chemistry

Ch 20 Bonus: 31, 35, 41, 47, 51, 53, 57, 61, 67, 69, 75, 89, 105

Check MasteringChemistry deadlines

Chemical Reactions - outer shell electrons are involved and the nuclei are unaffected.

Nuclear Reactions - changes occur in the nucleus. Atoms change.

An atom is characterized by its atomic number, $Z$, its mass number, $A$, and the nuclide symbol, $^AX$. Isotopes are atoms with the same atomic number, but different mass/neutron numbers.

The chemical environment, what an element it is bonded to and solutions it may be in, has no affect on nuclear processes.

Nuclear Reactions include the nuclide symbols and radiation involved. The outer electrons are ignored and not written.

An alpha particle (nucleus of a helium atom, $^4_2\text{He}^{+2}$) is $^2\text{He}$, the charge is absent.

In nuclear equations, mass numbers and atomic numbers add up to the same values on each side of the reaction.

Radioactive decay of carbon-14: Notice that mass numbers add to 14 and atomic numbers add up to 6.

$$^{14}_6\text{C} \rightarrow ^{14}_7\text{N} + ^0_{-1}\beta$$

(β, beta particles are electrons)

Characteristics of Nuclear Reactions:

1. Changes occur in the atom’s nucleus
2. Different isotopes have the same behavior for chemical reactions, but react differently in nuclear reactions.
3. Rates of nuclear reactions are unaffected by temperature, pressure, catalyst or chemical environment.
4. Energy changes in nuclear reactions are million times more than chemical reactions. Example: 1.0 gram of CH$_4$ combusting with oxygen releases 56 kJ while 1.0 gram of $^{235}_{92}\text{U}$ releases $8.7 \times 10^7$ kJ during its nuclear transformation.
**Radioactive Decay** is a process in which a nucleus spontaneously disintegrates into smaller pieces and gives off radiation. Radioactive nuclei decay by emission of alpha, beta, and gamma radiation, as well as by positron emission and electron capture. Radiations emitted in nuclear reactions have the potential to cause cell damage that can lead to cancer and other illnesses.

**Nuclear Transmutations** are nuclear reactions that are induced by bombardment of a nucleus by another nucleus or particle.

- **Nuclear fusion**: light nuclei rearrange to form a new larger stable nucleus.
- **Nuclear fission**: reaction splits a heavy nucleus under nuclear bombardment to form two or more product nuclei.

**Radioisotope Decays**: first order kinetic processes with characteristic half-lives, useful in determining the age of ancient artifacts and geologic formations.

**Energy changes**: related to mass changes via Einstein’s equation: \( E = mc^2 \)

**History:**

**Antoine-Henry Becquerel (1896)** discovered nuclear radiation in Paris while studying X-rays and photographic plates using uranium salt crystals. He designed an experiment to test if phosphorescent minerals gave off X-rays. X-rays are detected by their ability to penetrate matter and expose a photographic plate. Becquerel discovered that certain minerals were constantly producing energy rays that could penetrate matter even in the dark without phosphorescence. Phosphorescence is the long-lived emission of light by atoms or molecules that sometimes occurs after they absorb light.

Becquerel determined

1. All the minerals that produced these rays contained uranium. He called them *uranic rays* because the minerals contained uranium. These rays are similar to X-rays, but not related to phosphorescence
2. The rays were produced even though the mineral was not exposed to outside energy. *Energy was apparently produced without energy input.*

**Marie Curie** continued the study of uranic rays (*later changed to ray activity, then to radioactivity*) as a doctoral dissertation topic. Madam Curie proposed the term radioactivity to describe the emission of ionizing radiation by some heavy elements. Marie and her husband Pierre Curie discovered new elements by detecting their rays, Polonium- named after her native Poland- and Radium- an extremely radioactive element.
that spontaneously glows green phosphorescence and is 900x more radioactive than Uranium. Marie Curie broke down minerals and used an electroscope to detect where the uranic rays were coming from.

**Ernest Rutherford (1897)** a New Zealand physicist, studied radionuclides and identified and named three common types of radiation: **alpha, beta,** and **gamma** radiation.

---

Rutherford discovered that during the radioactive process, atoms of one element are changed into atoms of a different element (**transmutation**) showing that Dalton’s Atomic Theory is valid only for **chemical** reactions. For one element to change into another, the number of protons in the nucleus must change!

The first new **element manmade** and produced in a laboratory in 1937 is Technetium, $^{98}_{43}$ Tc, from the Greek tekhnétos-meaning artificial. The fusion reaction is below.

$$^{96}_{42}\text{Mo} + ^2_1\text{H} \rightarrow ^{98}_{43}\text{Tc}$$

Later Tc was made as a fission product of Uranium. Technetium has no stable isotopes and is used today in radioactive medical diagnostics.

July 16, 1945 the first **Atomic Bomb** was tested in Alamogordo, New Mexico.

June 26, 1954, at Obninsk, Russia, the world's first **nuclear power plant** that generated electricity for commercial use producing a net electrical output of 5 MW was connected to the power grid.

March 28, 1979, at Three Mile Island Nuclear Power Station, Pennsylvania; Unit 2 experienced a **partial reactor meltdown**, uranium fuel rods started to liquefy, but they did not fall through the reactor floor and breach the containment systems. Considered the worst nuclear disaster in US history, it was caused by human error and the failure of a rather minor valve in the reactor. No deaths.
1:24 am April 26, 1986 Chernobyl, USSR, the nuclear reactor blew a hole through the roof of the reactor after the core spiraled 120x normal levels and contaminated a large area. Unsafe areas were evacuated for decades, 31 died, 230 hospitalized, countless others exposed. Safety features were temporarily turned off while testing cheaper maintenance methods.

March 11, 2011, the Tōhoku 9.0 earthquake near the island of Honshu and following (43–49 ft) tsunami led to multiple meltdowns at Fukushima I nuclear power facility. Reactors on Units 1, 2, and 3 were operating and underwent an automatic shutdown when the earthquake struck. Stopping the normal source of power, on-site emergency diesel generators began powering the plant's cooling and control systems. The tsunami topped the plant's (19 ft) seawall, flooding the basement of the Turbine Buildings and disabling the emergency diesel generators located there. Alternative power from the grid was available by midnight. However, switching stations that sent power from backup generators to the reactors' cooling systems for Units 1 through 5 were in the poorly protected turbine buildings. If the switching stations had been moved to inside the reactor buildings or to other flood-proof locations, power would have been provided by these generators to the reactors' cooling systems. The Japan government announced in December, 2011 that the three melted reactors at the plant had basically stabilized and that radiation releases had dropped. It still will take decades to fully decommission the plant, and it must be kept stable until then.

Radioactive Decay:

1. Alpha (α) Decay- Alpha particles are the nuclei of helium-4 atoms, $^4_2$He (the +2 is understood and absent). Alpha particles are deflected by electric and magnetic fields due to their positive charge. Think of alpha particle emission as a process in which a bundle of two protons and two neutrons is emitted by a radioactive nucleus. They produce large numbers of ions as they travel through matter, but their penetrating power is low, a sheet of paper can stop them.

Most ionizing, but least penetrating of the types of radioactivity

\[ ^{226}_{88}\text{Ra} \rightarrow ^{222}_{86}\text{Rn} + ^4_2\text{He} \]

\text{Alpha Decay}

$\alpha$ particle $= ^2_4\text{He}$
2. **Beta (β⁻) Decay** - Beta particles are electrons that are not one of the original electrons in the atom; they come from the decay of a neutron into a proton.

\[
^0_1n \rightarrow ^1_1p + ^0_{-1}\beta + \nu \quad (\nu \text{ is an antineutrino})
\]

Beta particles are deflected by electric and magnetic fields in the opposite direction from alpha particles due to their negative charge. The neutrino and antineutrino, \(\nu\), were first postulated in the 1930's and finally detected in the 1950's. Even today little is known of the neutrinos properties. Neutrinos accompany positron emission and electron capture; antineutrinos are associated with beta emission. The elusive neutrino is generally not included in the nuclear equation an example follows. A \(\beta\) particle is like an electron

- moving much faster
- produced from the nucleus

About 10 times more penetrating than \(\alpha\), but half the ionizing ability

\[
^{234}_{90}\text{Th} \rightarrow ^{234}_{91}\text{Pa} + ^0_{-1}\beta
\]

3. **Positron (β⁺) Emission** - A proton within the nucleus is converted to a neutron, and a positron particle and a neutrino are emitted.

\[
^1_0p \rightarrow ^0_1n + ^0_{+1}\beta + \nu
\]

The positron has similar properties to the beta particle, except it has a positive charge. Positrons are known as antimatter; it destroys matter when reacting with an electron you have only energy left.

- anti-electron

Similar to beta particles in their ionizing and penetrating ability

\[
^{95}_{43}\text{Tc} \rightarrow ^{95}_{42}\text{Mo} + ^0_{+1}\beta
\]

4. **Electron Capture (EC)** - Achieves the same effect as a positron emission. In this case an inner core electron in the atom is absorbed by the nucleus and converts a proton to a neutron. When an electron from a higher quantum level drops to replace the electron, X-radiation is emitted.

- No particle emission, but atom changes
- same result as positron emission
- Proton combines with the electron to make a neutron

\[
^{40}_{19}\text{K} + ^0_{-1}\text{e} \rightarrow ^{40}_{18}\text{Ar} \quad (\text{followed by X radiation})
\]
5. **Gamma (γ) Radiation** - When the decay process leaves a nucleus in an excited state it will jump down to a lower state and emit gamma radiation that has no mass and no charge. An excited state is sometimes indicated by m for metastable. Gamma (g) rays are high energy photons of light.

No loss of particles from the nucleus
No change in the composition of the nucleus
Same atomic number and mass number
Least ionizing, but most penetrating
Generally occurs after the nucleus undergoes some other type of decay and the remaining particles rearrange

\[ {^{99}_{43} \text{Tc}} \rightarrow {^{99}_{43} \text{Tc}} + {^{0}_{0} \gamma} \]

**TABLE 19.1 Modes of Radioactive Decay**

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Process</th>
<th>Change in:</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha )</td>
<td>Parent nuclide</td>
<td>Daughter nuclide</td>
<td>( \alpha ) particle</td>
</tr>
<tr>
<td>( \beta )</td>
<td>Parent nuclide</td>
<td>Daughter nuclide</td>
<td>( \beta ) particle</td>
</tr>
<tr>
<td>( \gamma )</td>
<td>Excited nuclide</td>
<td>Stable nuclide</td>
<td>Photon</td>
</tr>
<tr>
<td>Positron emission</td>
<td>Parent nuclide</td>
<td>Daughter nuclide</td>
<td>Positron</td>
</tr>
<tr>
<td>Electron capture</td>
<td>Parent nuclide</td>
<td>Daughter nuclide</td>
<td>Positron</td>
</tr>
</tbody>
</table>
Predicting Radioactive Decay

- The particles in the nucleus are held together by a very strong attractive force only found in the nucleus called the strong force which acts only over very short distances.
- The neutrons play an important role in stabilizing the nucleus, as they add to the strong force, but don’t repel each other like the protons do.

Compare N/Z ratio with periodic table

<table>
<thead>
<tr>
<th>Type of decay</th>
<th>Usual condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>α</td>
<td>Z &gt; 83</td>
</tr>
<tr>
<td>β−</td>
<td>N/Z too large</td>
</tr>
<tr>
<td>β+</td>
<td>N/Z too small</td>
</tr>
<tr>
<td>EC</td>
<td>N/Z too small</td>
</tr>
<tr>
<td>γ</td>
<td>Excited nucleus</td>
</tr>
</tbody>
</table>

Practice Radioactive Decay Equations

Predict the type of radioactive decay process that is likely for each of the following nuclides and write out the reaction. (There may be 2 choices)

a) $^{228}_{92}U$

b) $^{68}_{29}Cu$

c) $^{8}_{5}B$

d) $^{11}_{6}C$

e) $^{214}_{83}Bi$

f) $^{38}_{19}K$

g) Some reactions do not stop after a single decay. An example is the decay of uranium-238, which is a 14 step process involving alpha, beta and gamma emissions before it becomes a stable lead-206 isotope. Write out the first five steps knowing that the daughters of the reaction are in order as follows, $^{234}_{90}Th$, $^{234}_{91}Pa$, $^{234}_{92}U$, $^{230}_{90}Th$, $^{226}_{88}Ra$.
**Rate of Radioactive Decay** - The change in the amount of radioactivity of a particular radionuclide is predictable and not affected by environmental factors. It does not change with temperature, pressure or chemical environment. Individual nuclei may decay in an instant or several million years. We measure rates of decay by a *first order rate law* that depends on the overall number of radioactive isotope nuclei in a sample.

\[
\text{Decay Rate} = k[N_t]
\]

\[
t_{\frac{1}{2}} = \frac{\ln 2}{k}
\]

\[
\ln N_t = -kt + \ln N_0
\]

or

\[
\ln (N_t/N_0) = -kt
\]

$N_t =$ number of individual (not moles) radioactive nuclei at a given time, $t$.

The unit Becquerel (Bq) is an SI unit for measuring radioactivity, equal to the activity resulting from the decay of one nucleus per second.

The unit of a Curie (Ci) = $3.7 \times 10^{10}$ nuclei disintegrations/second, which is equivalent to the rate of decay of one gram of radium-226 that Marie Curie isolated.

**Some half-life values**

<table>
<thead>
<tr>
<th>$^4_1$K</th>
<th>$1.28 \times 10^9$ years</th>
<th>Beta decay</th>
<th>Geological dating</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{14}_{6}$C</td>
<td>5730 years</td>
<td>Beta decay</td>
<td>Archeological dating</td>
</tr>
<tr>
<td>$^{131}_{53}$I</td>
<td>8.02 days</td>
<td>Beta decay</td>
<td></td>
</tr>
<tr>
<td>$^{238}_{92}$U</td>
<td>$4.51 \times 10^9$ years</td>
<td>Alpha decay</td>
<td></td>
</tr>
<tr>
<td>$^{235}_{92}$U</td>
<td>$7.04 \times 10^8$ years</td>
<td>Alpha, gamma decay</td>
<td>Nuclear reactors</td>
</tr>
<tr>
<td>$^{32}_{15}$P</td>
<td>14.26 days</td>
<td>Beta decay</td>
<td>Leukemia therapy</td>
</tr>
<tr>
<td>$^{13}_{8}$O</td>
<td>$8.7 \times 10^{-3}$ seconds</td>
<td>Electron capture or positron decay</td>
<td></td>
</tr>
</tbody>
</table>
Carbon-14 Dating- In the upper atmosphere nitrogen-14 can be changed to carbon-14 by the reaction $^{14}_7\text{N} \ (\text{n}, \ p) \ ^{14}_6\text{C}$. A small constant fractional abundance of carbon-14 (about one $^{14}_6\text{C}$ nuclei for each $10^{12}$ total carbon nuclei) is maintained in the atmosphere at all times. Living plants take in CO$_2$ and maintain a constant fraction of carbon-14. Once the plant dies the half-life of carbon-14 makes the fraction of the isotope decrease. From this knowledge it is possible to measure beta emissions and date old organic matter.

$$^{14}_6\text{C} \rightarrow ^{14}_7\text{N} + ^0_1\beta$$

Practice Rate of Radioactive Decay Problems-

1. For 1.00 milligram of iodine-131…
   a) Solve for k in units of inverse days and then in inverse seconds.
   b) What is the initial rate of decay in nuclei disintegrations/s?
   c) What percentage of the original iodine-131 remains after 30 days?

2. Wood from a cypress tree beam that was found in the tomb of the Egyptian King Sneferu gave 8.1 disintegrations/minute for each gram. Living material of the same type gives 15.3 dis min$^{-1}$ g$^{-1}$.
   a) How old is the beam?
   b) What approximate year was the cypress tree cut down?

Nuclear Stability- Nuclear stability is determined to a large extent by the neutron to proton ratio. For stable nuclei, this ratio increases with increasing atomic number (1:1 for lighter atoms increasing to 1:1.5 for heavier atoms). All nuclei with 84 or more protons are radioactive.

Nuclear Force- Why don't the protons in the same nucleus repel? Attraction between nucleons acting at short distance ($1 \times 10^{-15}$ m) compensates for repulsion of electric charges. This attraction is called the strong nuclear force. Neutrons are closely involved in this force. As the number of protons increase, there is a greater need for neutrons to counteract the proton to proton repulsions.

Magic Numbers- A model in which Z (protons) and N (neutrons) exist in levels is called the shell model of the nucleus. Certain numbers of protons and neutrons are very stable (similar to the electron core in noble gases). These “magic numbers” for a completed shell are for Z (protons) 2, 8, 20, 28, 50, 82, 114 and for N (neutrons) 2, 8, 20, 28, 50, 82, 126, 184.
The distribution of naturally occurring stable nuclides fall in the following combinations: \( Z \text{ even} - N \text{ even} = 163 \); \( Z \text{ even} - N \text{ odd} = 55 \); \( Z \text{ odd} - N \text{ even} = 50 \) and \( Z \text{ odd} - N \text{ odd} = 4 \). There are no stable nuclides with an atomic number greater than 83.

All but two (\(^{43}\text{Tc}\) and \(^{61}\text{Pm}\)) under 83 have at least one stable isotope.

A band of stability naturally occurs if you chart the number neutrons, \( N \), (y axis) versus the number of protons, \( Z \), (x axis). The result has an \( N/Z \) ratio initially about one to one and slowly increasing to about 1.5 to 1. The easiest way to figure the stable ratio is to look on the periodic table and compare to the weighted average atomic mass listed, this generally corresponds to the appropriate stable ratio. As an example, nitrogen (\( \text{N} \)) has a weighted average mass of 14.0, this tells us that for 7 protons we generally will have 7 neutrons therefore the stable ratio is \( 1:1 \). Lead (\( \text{Pb} \)) has a weighted average mass of 207.2, this indicates we have about 125 neutrons with 82 protons therefore the stable ratio is approximately \( 1.5:1 \).

**Energetics of Nuclear Reactions**— use Einstein's equation, \( E = mc^2 \), for nuclear mass-energy calculations. \( E \) is energy in Joules, \( m \) is mass in kg, \( c \) is speed of light \( 3.0 \times 10^8 \text{ m/s} \). All reactions that gain or lose energy also change slightly in mass, but much too small to be noticed for chemical reactions. In nuclear reactions the changes in mass and energy are millions more than any chemical reaction. Just because the reaction may be energetically favorable, does not mean the rate is fast.

\[
E = mc^2 \\
1 \text{MeV} = 1.6022 \times 10^{-13} \text{ J} \\
1 \text{amu} = 931.5 \text{ MeV}
\]

- A few nuclei are so unstable that if their nucleus is hit just right by a neutron, the large nucleus splits into two smaller nuclei — this is called fission.
- Small nuclei can be accelerated to such a degree that they overcome their charge repulsion and smash together to make a larger nucleus - this is called fusion.

Lise Meitner first worked on calculations involving energetics of nuclear reactions.

Both fission and fusion release enormous amounts of energy — fusion releases more energy per gram than fission.

**Nuclear Binding Energy**— the energy to break a nucleus into individual protons and neutrons. For \( \text{He} \) this would separate into 2 protons and 2 neutrons.

**Mass defect** is the difference between the total nucleon mass of the \( p \) and \( n \) particles minus the nuclear mass of the isotope.
**Practice Energy Problems**

1. Solve for the mass difference of an alpha particle, the energy involved in breaking a single alpha particle into 2 protons and 2 neutrons, and the energy in kJ/mol.

\[
\frac{4}{2}\text{He} \rightarrow 2\frac{1}{1}\text{p} + 2\frac{0}{0}\text{n}
\]

\[
4.00150\text{ amu} = 2(1.00728\text{ amu}) + 2(1.00867\text{ amu})
\]

2. What is the energy associated with the α decay of \(^{146}_{62}\text{Sm}\) (145.913053 u) to \(^{142}_{60}\text{Nd}\) (141.907719 u)? Use the mass of the alpha particle as, \(^{4}_{2}\text{He}\) (4.0015058 u).

3. The decay of \(^{222}_{88}\text{Rn}\) by alpha particle emission is accompanied by a loss of 5.590 MeV of energy. What quantity of mass, in amu, is converted to energy in this process?

**Nuclear Transmutation Reactions**

The origin of all elements is the stars. Nuclear fusion creates heavier elements from lighter ones. **Ernest Rutherford** in 1919 was the first to artificially bombard 2 nuclei and different nuclei.

\[
\frac{14}{7}\text{N} + \frac{4}{2}\text{He} \rightarrow \frac{17}{8}\text{O} + \frac{1}{1}\text{H}
\]

**James Chadwick** in 1932 finally isolated the elusive neutron after years of theory describing it by the fusion reaction,

\[
\frac{9}{4}\text{Be} + \frac{4}{2}\text{He} \rightarrow \frac{12}{6}\text{C} + \frac{1}{0}\text{n}
\]

**Irene and Frederic Joliot-Curie** in 1934 made the first manmade radioactive material, phosphorus-30, and won the 1935 Nobel Prize in chemistry for the reaction,

\[
\frac{27}{13}\text{Al} + \frac{4}{2}\text{He} \rightarrow \frac{30}{15}\text{P} + \frac{1}{0}\text{n}
\]

\[
\frac{30}{15}\text{P} \rightarrow \frac{30}{14}\text{Si} + 0+1\beta
\]

These three significant experiments led to the results that (1) all nuclei contain protons, and (2) it is possible to change an element in a lab setting.
**Particle Accelerator:** High energy particles can be smashed into target nuclei, resulting in the production of new nuclei. The particles may be radiation from another radionuclide, or charged particles that are accelerated.

Particles from natural sources travel too slow to penetrate large nuclei. By accelerating charged particles in a cyclotron, synchrotron, or particle accelerator, more lab elements can be created by nuclear bombardment. Projectile particles are introduced into a vacuum chamber and are accelerated to very high energies by circulating them through magnets in a ring that has a large circumference of a few miles until they are finally deflected out to strike a target substance.

Cf–244 is made by bombarding U–238 with C–12 in a particle accelerator:

\[
\frac{238}{92}U + \frac{12}{6}C \rightarrow \frac{244}{98}O + 6 \frac{1}{0}n
\]

**Cyclotron:**

![Cyclotron Diagram](image)

Tc-97 is made by bombarding Mo-96 with deuterium, releasing a neutron:

\[
\frac{96}{42}Mo + \frac{2}{1}H \rightarrow \frac{97}{43}Tc + \frac{1}{0}n
\]

**Symbols of Particles**

<table>
<thead>
<tr>
<th>Particle</th>
<th>Symbol</th>
<th>Abbreviated form</th>
</tr>
</thead>
<tbody>
<tr>
<td>neutron</td>
<td>( \frac{1}{0}n )</td>
<td>n</td>
</tr>
<tr>
<td>proton</td>
<td>( \frac{1}{1}H ) or ( \frac{1}{1}p )</td>
<td>p</td>
</tr>
<tr>
<td>deuteron</td>
<td>( \frac{2}{1}H )</td>
<td>d</td>
</tr>
<tr>
<td>trition</td>
<td>( \frac{3}{1}H )</td>
<td>t</td>
</tr>
<tr>
<td>alpha particle</td>
<td>( \frac{4}{2}He )</td>
<td>( \alpha )</td>
</tr>
</tbody>
</table>
**Abbreviated notation**-Bombardment reactions may be written in an abbreviated form using the form, \( X (x, y) Y \), where the large \( X \) represents the isotope that is bombarded, small \( x \) hits the target \( X \), \( y \) is the small particle formed and \( Y \) is the larger isotope formed. For example,

\[
\frac{14}{7}N + \frac{4}{2}He \rightarrow \frac{17}{8}O + \frac{1}{1}H \quad \text{is abbreviated} \quad \frac{14}{7}N (\alpha, p) \frac{17}{8}O
\]

**Practice Nuclear Bombardment Equations**

Write out both the entire nuclear equation and the abbreviated form while filling in the missing pieces for the following nuclear bombardment reactions.

<table>
<thead>
<tr>
<th>Entire reaction</th>
<th>Abbreviated form</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) ( \frac{63}{29}Cu + \frac{4}{2}He \rightarrow \frac{1}{0}n + )</td>
<td>( \frac{45}{21}Sc (n, \alpha) )</td>
</tr>
<tr>
<td>b)</td>
<td></td>
</tr>
<tr>
<td>c) ( \frac{12}{6}C + \frac{3}{1}H \rightarrow )</td>
<td>( )</td>
</tr>
<tr>
<td>d)</td>
<td>( )</td>
</tr>
</tbody>
</table>

**Detecting Radioactivity:**

To detect something, you need to identify what it does

- Radioactive rays can expose light-protected photographic film, so photographic film detects the presence of radioactive rays – film badge dosimeters
- Radioactive rays cause air to become ionized, so an electroscope detects radiation by its ability to penetrate the flask and ionize the air inside.
- A Geiger-Müller counter works by counting electrons generated when Ar gas atoms are ionized by radioactive rays
Radioactive rays cause certain chemicals to give off a flash of light when they strike the chemical. A scintillation counter is able to count the number of flashes per minute.

**Measuring Radioactivity**

<table>
<thead>
<tr>
<th>Unit</th>
<th>Definition</th>
<th>Conversion to Rems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Becquerel (Bq)</td>
<td>1 disintegration/second</td>
<td></td>
</tr>
<tr>
<td>Curie (Ci)</td>
<td>$3.7 \times 10^{10}$ disintegrations/s</td>
<td>No matter the kind of radiation</td>
</tr>
<tr>
<td>Gray (Gy)</td>
<td>1 J/kg tissue</td>
<td>Energy absorbed</td>
</tr>
<tr>
<td>Rad</td>
<td>0.01 Gy</td>
<td>Radiation absorbed dose</td>
</tr>
<tr>
<td>Sievert (Sv)</td>
<td>1 J/kg</td>
<td>Tissue damage</td>
</tr>
<tr>
<td>Rem</td>
<td>0.01 Sv</td>
<td>Roentgen equivalent for man</td>
</tr>
</tbody>
</table>

**Biological Effects of Radiation:**

The average radiation **dose annually** is about 120 mrem for people; 70% from natural sources and 30% from medical procedures.

**High levels** of radiation over a short period of time kill large numbers of cells. This weakens the immune system and lowers ability to absorb nutrients from food which may result in death, usually from infection.

**Low doses** of radiation over a period of time show an increased risk for the development of cancer as radiation damages DNA that may not get repaired properly. Low doses over time may damage reproductive organs, which may lead to sterilization or damage to reproductive cells leading to genetic defects in offspring.

A correction factor is used to account for a number of factors that affect the result of the exposure. This biological effectiveness factor is the **RBE**, and the result is the dose in rem.

$$\text{rads} \times \text{RBE} = \text{rems}$$

The more energy the radiation has, the larger its effect.

The better the radiation penetrates human tissue, the deeper the effect:  
Gamma >>> Beta > Alpha

*Penetrating Ability of Radioactive Rays*
The more ionizing the radiation, the larger the effect of the radiation:

Alpha > Beta > Gamma

Radioactive half-life of the radionuclide

Biological half-life of the element

Physical state of the radioactive material

**Effects of Short term Radiation on Humans**

<table>
<thead>
<tr>
<th>Dose Range (rem)</th>
<th>Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-25</td>
<td>No detectable effects</td>
</tr>
<tr>
<td>25-100</td>
<td>Temporary decrease in white blood cells</td>
</tr>
<tr>
<td>100-200</td>
<td>Nausea, vomiting, decrease in white blood cells</td>
</tr>
<tr>
<td>200-300</td>
<td>Vomiting, diarrhea, listlessness</td>
</tr>
<tr>
<td>300-600</td>
<td>All above plus hemorrhaging, death in some cases</td>
</tr>
<tr>
<td>Above 600</td>
<td>Eventual death in most cases</td>
</tr>
</tbody>
</table>

**TABLE 19.4 Exposure by Source for Persons Living in the United States**

<table>
<thead>
<tr>
<th>Source</th>
<th>Dose</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Natural Radiation</strong></td>
<td></td>
</tr>
<tr>
<td>A 5-hour jet airplane ride</td>
<td>2.5 mrem/trip (0.5 mrem/hr at 39,000 feet) (whole body dose)</td>
</tr>
<tr>
<td>Cosmic radiation from outer space</td>
<td>27 mrem/yr (whole body dose)</td>
</tr>
<tr>
<td>Terrestrial radiation</td>
<td>28 mrem/yr (whole body dose)</td>
</tr>
<tr>
<td>Natural radionuclides in the body</td>
<td>35 mrem/yr (whole body dose)</td>
</tr>
<tr>
<td>Radon gas</td>
<td>200 mrem/yr (lungs dose)</td>
</tr>
<tr>
<td><strong>Diagnostic Medical Procedures</strong></td>
<td></td>
</tr>
<tr>
<td>Chest X-ray</td>
<td>8 mrem (whole body dose)</td>
</tr>
<tr>
<td>Dental X-rays (panoramic)</td>
<td>30 mrem (skin dose)</td>
</tr>
<tr>
<td>Dental X-rays (two bitewings)</td>
<td>80 mrem (skin dose)</td>
</tr>
<tr>
<td>Mammogram</td>
<td>138 mrem per image</td>
</tr>
<tr>
<td>Barium enema (X-ray portion only)</td>
<td>406 mrem (bone marrow dose)</td>
</tr>
<tr>
<td>Upper gastrointestinal tract test</td>
<td>244 mrem (X-ray portion only) (bone marrow dose)</td>
</tr>
<tr>
<td>Thallium heart scan</td>
<td>500 mrem (whole body dose)</td>
</tr>
<tr>
<td><strong>Consumer Products</strong></td>
<td></td>
</tr>
<tr>
<td>Building materials</td>
<td>3.5 mrem/year (whole body dose)</td>
</tr>
<tr>
<td>Luminous watches (H-3 and Pm-147)</td>
<td>0.04–0.1 mrem/year (whole body dose)</td>
</tr>
<tr>
<td>Tobacco products (to smokers of 30 cigarettes per day)</td>
<td>16,000 mrem/year (bronchial epithelial dose)</td>
</tr>
</tbody>
</table>

*Source: Department of Health and Human Services, National Institutes of Health.*

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Applications of Radioactive Isotopes

1) Energy (Power Plants and Bombs)

Nuclear fission:
Nuclei such as $^{235}\text{U}$, break into fragments when struck by a neutron…

\[
^{235}\text{U} + ^1\text{n} \longrightarrow ^{140}\text{Ba} + ^{93}\text{Kr} + 3^1\text{n} + \text{energy}
\]

This reaction will not occur the same way each time, more than 400 fission pathways for Uranium-235 have been identified.

The three neutrons as products may continue the reaction resulting in a chain reaction. If the amount of reactant has a critical mass the chain reaction is self-sustaining.

The same fission process that can generate a Nuclear Bomb can be controlled in Nuclear Power Plants to generate electricity. Control rods absorb and regulate the flow of the neutrons.

31 countries have about 440 nuclear power plant units with an electric net capacity of about 370 GW (21% of the World’s electrical power). The US produces the most nuclear power (98,000 MWatts) from 103 commercial generators, while France produces the highest percentage of power (78%) from nuclear reactors.

To produce fissionable uranium, the natural uranium must be enriched in U–235 to about 7% for “weapons grade” and about 3% for reactor grade.

Power Plant:

The fissionable material is stored in long tubes, called fuel rods, arranged in a subcritical matrix. Between the fuel rods are control rods made of neutron-absorbing material (B and/or Cd). Control rods are placed in a material (often heavy water) to slow down the ejected neutrons, called a moderator. This allows
the chain reaction to occur below critical mass. Neutrons are needed to sustain the moderated reaction, but not too many to spiral out of control.

**Concerns over Nuclear Power:**

Core melt-down  
Waste disposal  
Transporting waste  
How do we deal with nuclear power plants that are no longer safe to operate?

**2) Chemical Analysis**

- Radioactive tracers follow the progress of a “tagged” atom in a reaction.
- Authenticating art object, many older pigments and ceramics were made from minerals with small amounts of radioisotopes
- Crime scene investigation
3) **Radioactive Dating:**

By measuring and comparing the amount of a parent radioactive isotope and its stable daughter we can determine the age of the object using the half-life

- **Mineral (geological) dating**
  
  Comparing the amount of U-238 to Pb-206 in volcanic rocks and meteorites dates the Earth to between 4.0 and 4.5 billion yrs. old
  
  One can also compare amount of K-40 to Ar-40

- **All things that are alive or were once alive contain carbon**
  
  Three isotopes of C exist in nature, $^{14}$C, is radioactive, half-life = 5730 yrs
  
  We expect a radioisotope with this relatively short half-life to have disappeared long ago, but Cosmic rays (protons and alpha particle) constantly bombard the atmosphere and atmospheric chemistry keeps producing $^{14}$C at nearly the same rate it decays. While living, $\text{C–14}/\text{C–12}$ ratio is constant because the organism replenishes its supply of carbon. Once the organism dies the $\text{C–14}/\text{C–12}$ ratio decreases
  
  The limit for this technique is 50,000 years old or about 9 half-lives, after which radioactivity from $\text{C–14}$ will be below the background radiation

4) **Medical Therapy and Diagnosis**

Changes in the structure of the nucleus are used in many ways in medicine.

Nuclear radiation can be used to visualize or test structures in your body to see if they are operating properly. It is possible to label atoms so their intake and output can be monitored.

Nuclear radiation can also be used to treat diseases because the radiation is ionizing, allowing it to attack unhealthy tissue

Cancer cells are more sensitive to radiation than healthy cells – use radiation to kill cancer cells without doing significant damage.

- **brachytherapy:** place radioisotope directly at site of cancer
- **teletherapy:** gamma radiation from Co–60 outside to penetrate inside
- **radiopharmaceutical therapy:** radioisotopes that concentrate in one area of the body
- **PET scan:** positron emission tomography
  
  uses F–18 tagged glucose.
  
  F–18 is a positron emitter
  
  brain scan and function

![PET scan of a brain](https://example.com/pet-scan.jpg)
5) Preparing manmade elements that do not naturally occur

6) Others:

- Agribusiness: develop disease-resistant crops or trace fertilizer use
- Treat computer disks to enhance data integrity
- Initiate polymerization on nonstick pan coatings
- Sterilize cosmetics, hair products and contact lens solutions and other personal hygiene products
- Smoke detectors use Am–24. The smoke blocks ionized air, breaks circuit and then initiates an alarm
- Insect control
- Food preservation

Rate Answers from notes:

1a) $k = 0.0859 \text{ day}^{-1}$, $k = 1.2 \times 10^{-6} \text{ s}^{-1}$  
1b) $5.5 \times 10^{12} \text{ dis/s}$  
1c) 7.6% remains

2a) 5260 yrs old  
2b) 3250 BC

Energy Answers:

1) 0.0304 amu, 28.3 MeV, $4.54 \times 10^{-12} \text{ J/particle}$, $2.73 \times 10^9 \text{ kJ/mol}$

2) 3.566 MeV

3) $6.001 \times 10^{-3} \text{ amu}$

Practice problems

1. The most abundant isotope of boron is $^{11}_5\text{B}$, which has a natural abundance of 80.2%. The nucleonic mass of $^{11}_5\text{B}$ is 11.006562 amu. Masses of a proton = 1.007276 amu and a neutron = 1.008665 amu. $1 \text{ MeV} = 1.6022 \times 10^{-13} \text{ J}$; $1 \text{ amu} = 931.5 \text{ MeV}$

   a) Write out the balanced nuclear equation with boron-11 as the reactant and the products are only protons and neutrons.

   b) Solve for the mass defect of $^{11}_5\text{B}$ in units of amu/boron-11

   c) Solve for the nuclear binding energy of the dissociation of $^{11}_5\text{B}$ in units of
      a) MeV/boron-11, b) J/boron-11, and c) kJ/mol boron-11 broken into protons and neutrons.

2. Write the balanced nuclear equation for the following

   a) electron capture of $^{25}_{13}\text{Al}$

   b) beta emission of $^{65}_{29}\text{Cu}$
3. Describe nuclear fusion and include an example.

4. Describe nuclear fission and include an example.

5. Predict the type of radioactive decay process that is likely for each of the following nuclides and write out the reaction.
   a) $^{214}_{82}$Pb $\rightarrow$
   b) $^{232}_{90}$Th $\rightarrow$
   c) $^{40m}_{18}$Ar $\rightarrow$

6. Fill in the missing piece and write the abbreviated form of the following nuclear bombardment reactions.
   a) $^{109}_{47}$Ag + _____ $\rightarrow$ $^{112}_{49}$In + $^1_0$n
      abbrev.
   b) $^{98}_{42}$Mo + _____ $\rightarrow$ $^0_0$$\gamma$ + $^{99}_{42}$Mo
      abbrev.

7. A sample of moon rock was analyzed by mass spectroscopy. Only 11.47% of the original $^{40}_{19}$K remained the rest had decayed to $^{40}_{18}$Ar. The initial amount, $N_0$ would be 100%. Half-life of potassium-40, $t_{1/2} = 1.28 \times 10^9$ yrs.
   a) Solve for the rate constant, $k$.
   b) Approximately, how old is the moon rock?

8. There are no stable nuclides with an atomic number greater than ________.

9. Rate of Radioactive Decay—does not change with __________, __________
    or _________________.

10. List several applications of nuclear chemistry.

11. Of the 2 isotopes, iodine-136 and iodine-122, one decays by beta emission and the other by positron emission. Identify which is which and write out the expected radioactive decay reactions.