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21.1: Radioactivity

- nucleons – neutron and proton
- all atoms of a given element have the same number of protons, atomic number
- isotopes – atoms with the same atomic number but different mass numbers
- three isotopes of uranium: uranium-233, uranium-235, uranium-238
  \[^{233}\text{U}, \ ^{235}\text{U}, \ ^{238}\text{U}\]
- (superscript is mass number, subscript atomic number)
- radionuclides – nuclei that are radioactive
- radioisotopes – atoms containing radionuclides

21.1.1 Nuclear Equations

- alpha particles – helium-4 particles
- alpha radiation – stream of alpha particles
- emission of radiation is one way that an unstable nucleus is transformed into a more stable one
  \[^{238}\text{U} \rightarrow ^{234}\text{Th} + ^4\text{He}\]
- superscript = mass number
- subscript = atomic number
- radioactive decay – when a nucleus spontaneously decomposes
sum of the mass numbers is the same on both sides of the equation
sum of the atomic numbers same on both sides of the equation
radioactive properties of the nucleus are independent of the state of chemical combination of the atom
chemical form does not matter when writing nuclear equations

21.1.2 Types of Radioactive Decay

• three most common type of radioactive decay: alpha(α), beta(β), and gamma(γ) radiation

<table>
<thead>
<tr>
<th>Property</th>
<th>α</th>
<th>β</th>
<th>γ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge</td>
<td>2+</td>
<td>1-</td>
<td>0</td>
</tr>
<tr>
<td>Mass</td>
<td>6.64x10^{-24} g</td>
<td>9.11x10^{-28} g</td>
<td>0</td>
</tr>
<tr>
<td>Relative penetrating power</td>
<td>1</td>
<td>100</td>
<td>10,000</td>
</tr>
</tbody>
</table>

Nature of radiation

- **α** (alpha) – high speed electrons emitted by an unstable nucleus
- **β** (beta) – high-speed electrons emitted by an unstable nucleus
- **γ** (gamma) – high-energy protons

- **β** - beta decay results in increasing the atomic number
- **γ** - gamma radiation does not change atomic number or mass number or a nucleus
- **γ** - gamma radiation does not change atomic number or mass number or a nucleus
- **γ** - represents the energy lost when the remaining nucleons reorganize into more stable arrangements

- **positron** – particle that has same mass as an electron but opposite charge
- **positron** – particle that has same mass as an electron but opposite charge

- **positron** – represented by

\[ 0_e \]

- **positron** – emission of a positron has effect of converting a proton to a neutron + decreasing atomic number of nucleus by 1

- **electron capture** – the capture by the nucleus of an inner-shell electron from the electron cloud surrounding the nucleus
- **electron capture** – the capture by the nucleus of an inner-shell electron from the electron cloud surrounding the nucleus

- **electron capture** – has effect of converting a proton to neutron

\[ 1_p + 0_e \rightarrow 0_n \]
Particle & Symbol \\
Neutron & \( ^{0}_{1}n \) \\
Proton & \( ^{1}_{1}H \) or \( ^{1}_{1}p \) \\
Electron & \( ^{-1}_{0}e \) \\
Alpha Particle & \( ^{4}_{2}He \) or \( ^{4}_{2}\alpha \) \\
Beta Particle & \( ^{0}_{-1}e \) or \( ^{0}_{-1}\beta \) \\
Positron & \( ^{0}_{1}e \) \\

21.2: Patterns of Nuclear Stability

21.2.1 Neutron-to-Proton Ratio

- **strong nuclear force** – a strong force of attraction between a large number of protons in the small volume of the nucleus
  - stable nuclei with low atomic numbers up to 20 have nearly equal number of neutrons and protons
  - for higher atomic numbers, the number of neutrons are greater than the number of protons
  - the neutron-to-proton ratio of stable nuclei increase with increasing atomic number

- **belt of stability** – area where all stable nuclei are found
  - ends at bismuth
  - all nuclei with 84 or more protons are radioactive
  - an even number of protons and neutrons is more stable than an odd number

- determining type of radioactive decay
  - 1) nuclei above the belt of stability
    - high neutron-to-proton ratios
    - move toward belt of stability by emitting a beta particle
    - decreases the number of neutrons and increases the number of protons in a nucleus
  - 2) nuclei below the belt of stability
    - low neutron-to-proton ratios
    - move toward belt of stability by positron emission or electron capture
    - increase number of neutrons and decrease the number of protons
• positron emission more common with lower nuclear charges
• electron capture becomes more common with increasing nuclear charge
• 3) nuclei with atomic numbers
  \[ Z > 84 \]
  • alpha emission
  • decreases both number of neutrons and protons by 2

21.2.2 Radioactive Series
• ◦ some nuclei cannot gain stability by a single emission
  ◦ radioactive series or nuclear disintegration series – series of nuclear reactions that begin with an unstable
    nucleus to a stable one
  ◦ three types of radioactive series found in nature
    • uranium-238 to lead-206, uranium-235 to lead-207, and thorium-232 to lead-208

21.2.3 Further Observations
• ◦ nuclei with 2, 8, 20, 28, 50, or 82 protons or 2, 8, 20, 28, 50, 82, or 126 neutrons are more stable than with
  nuclei without these numbers
  ◦ numbers called magic numbers
  ◦ nuclei with even number of protons and neutrons more stable than with odd number of protons and neutrons
  ◦ observations made in terms of the shell model of the nucleus
    • nucleons reside in shells
  ◦ magic numbers represent closed shells in nuclei

21.3: Nuclear Transmutations
• ◦ nuclear transmutations – nuclear reactions caused by the collision of one nucleus with a neutron or by
  another nucleus
  ◦ first conversion of one nucleus into another performed by Ernest Rutherford in 1919
  ◦ converted nitrogen-14 to oxygen-17
  \[ _{7}^{14} \text{N} + _{2}^{4} \text{He} \rightarrow _{8}^{17} \text{O} + _{1}^{1} \text{H} \]
  \[ _{7}^{14} \text{N}(\gamma, p)_{8}^{17} \text{O} \]

21.3.1 Using Charged Particles
• ◦ particle accelerators – used to accelerate particles at very high speeds
  ◦ cyclotron, and synchrotron

21.3.2 Using Neutrons
• neutrons do not need to be accelerated
21.3.4 Transuranium Elements

- transuranium elements – elements with atomic numbers above 92 that are produced by artificial transmutations

21.4: Rates of Radioactive Decay

- radioactive decay is a first-order process
  - has characteristic of half life, which is the time required for half of any given quantity of a substance to react
  - half-life unaffected by external conditions

21.4.1 Dating

- radiocarbon dating assumes that the ratio of carbon-14 to carbon-12 in the atmosphere has been constant for at least 50,000 years
- age of rocks can be determined by ratio of uranium-238 to lead-206

21.4.2 Calculations Based on Half-life

- rate = kN
  - k = decay constant, N = nuclei
  - \( \ln \frac{N_t}{N_0} = -kt \)
  - t = time interval of decay, k = decay constant, \( N_0 \) = initial number of nuclei at time zero, \( N_t \) = number remaining after time interval
  - \( k = \frac{0.693}{t_{\frac{1}{2}}} \)

21.5 Detection of Radioactivity

- Geiger counter – device used to measure and detect radioactivity
  - Based on ionization of matter caused by radiation
  - Phosphors – substances that give off light when exposed to radiation
  - Scintillation counter – used to detect and measure radiation based on tiny flashes of light produced when radiation strikes a suitable phosphor

21.5.1 Radiotracers

- radioisotopes can be used to follow an element through its chemical reactions
  - isotopes of same element have same properties
  - radiotracer – radioisotopes used to trace an element

21.6: Energy Changes in Nuclear Reactions

- \( E = mc^2 \)
21.6.1 Nuclear Binding Energies

- masses of nuclei always less than masses of individual nucleons
- **mass defect** – mass difference between a nucleus and its constituent nucleons
- energy is needed to break nucleus into separated protons and neutrons, addition of energy must also have an increase in mass
- nuclear binding energy – energy required to separate a nucleus into its individual nucleons
  - the larger to nuclear binding energy the more stable the nucleus toward decomposition
- **fission** – energy produced when heavy nuclei split
- **fusion** – energy produced when light nuclei fuse

21.7: Nuclear Fission

- fission and fusion both exothermic
- chain reaction – reaction in which the neutrons produced in one fission cause further fission reactions
- in order for a fission chain reaction to occur, the sample of fissionable material must have a certain minimum mass
- **critical mass** – amount of fissionable material large enough to maintain the chain reaction with a constant rate of fission
- **supercritical mass** – mass in excess of a critical mass

21.7.1 Nuclear Reactors

- nuclear reactors the fission is controlled to generate a constant power
- reactor core consists of fissionable fuel, control rods, a moderator, and cooling fluid
- fission products are extremely radioactive and are thus hard to store
- about 20 half-lives needed for products to react acceptable levels for biological exposure

21.8: Nuclear Fusion

- fusion is appealing because of availability of light isotopes and fusion products are not radioactive
- high energies needed to overcome attraction of nuclei
- **thermonuclear reactions** – fusion reactions
- lowest temperature required is about 40,000,000 K

21.9: Biological Effects of Radiation

- when matter absorbs radiation, the energy of the radiation can cause either excitation or ionization
- ionization radiation more harmful than nonionization radiation
- most of energy of radiation absorbed by water molecules
• **free radical** – a substance with one or more unpaired electrons
• can attack other biomolecules to produce more free radicals
• gamma rays most dangerous
• tissues that take most damage are the ones that reproduce at a rapid rate
• bone marrow, blood forming tissues, lymph nodes

21.9.1 Radiation Doses

• becquerel (Bq) – SI unit for activity of the radiation source; rate at which nuclear disintegrations are occurring
  • 1 (Bq) = 1 nuclear disintegration/s
• curie (Ci) = \(3.7 \times 10^{10}\) disintegrations/s = rate of decay of 1g of radium
• two units used to measure amount of exposure to radiation: gray (Gy) and rad
• gray – SI unit of absorbed dose = absorption of 1 J of energy per kilogram of tissue
• rad (radiation absorbed dose) – absorption of \(1 \times 10^{-2}\) J of energy per kilogram of tissue
• 1 Gy = 100 rads
• relative biological effectiveness – RBE
  • 1 for gamma and beta radiation, 10 for alpha radiation
  • exact value varies with dose rate, total dose, and type of tissue affected
  • rem (roentgen equivalent for man) – product of the radiation dose in rads and the RBE of the radiation
gives the effective dosage
  • rem is unit of radiation damage that is usually used in medicine
  • number of rems = (number of rads)(RBE)
• Sievert (Sv) – SI unit for dosage
  • 1 Sv = 100 rem
  • annual exposure = 360mrem

21.9.2 Radon

• radon exposure estimated to account for more than half annual exposure
• half-life of radon is 3.82 days
• decays into radioisotope polonium
• atoms of polonium can be trapped in lungs giving out alpha radiation causing lung cancer
• recommended levels of radon-222 in homes is to be less than 4 pCi per liter of air