CHAPTER EIGHTEEN

THE NUCLEUS: A CHEMIST'S VIEW

For Review

1. a. Thermodynamic stability: the potential energy of a particular nucleus as compared to the sum of the potential energies of its component protons and neutrons.

   b. Kinetic stability: the probability that a nucleus will undergo decomposition to form a different nucleus.

   c. Radioactive decay: a spontaneous decomposition of a nucleus to form a different nucleus.

   d. Beta-particle production: a decay process for radioactive nuclides where an electron is produced; the mass number remains constant and the atomic number changes.

   e. Alpha-particle production: a common mode of decay for heavy radioactive nuclides where a helium nucleus is produced causing the mass number to change.

   f. Positron production: a mode of nuclear decay in which a particle is formed having the same mass as an electron but opposite in charge.

   g. Electron capture: a process in which one of the inner-orbital electrons in an atom is captured by the nucleus.

   h. Gamma-ray emissions; the production of high-energy photons called gamma rays that frequently accompany nuclear decays and particle reactions.

A is the mass number and is equal to the number of protons plus neutrons in a nuclei; the sum of all the mass number values must be the same on both sides of the equation (A is conserved). Z is the atomic number and is equal to the number of protons in a nucleus; the sum of the atomic number values must also be the same on both sides of the equation (Z is conserved).

2. The zone of stability is the area encompassing the stable nuclides on a plot of their positions as a function of the number of protons and the number of neutrons in the nucleus. The neutron/proton ratio increases to a number greater than one as elements become heavier. Nuclides with too many neutrons undergo beta-particle production in order to decrease the neutron/proton ratio to a more stable value. Position production, electron capture and alpha-particle production all increase the neutron/proton ratio, so these occur for nuclides having too many protons.

3. First-order kinetics is where there is a direct relationship between the rate of decay and the number of nuclides in a given sample. The rate law for all radioactive decay is rate = kN. Because of the direct relationship between rate and N, as the number of nuclides is halved, the rate is also halved. The first-order rate law and the integrated first-order rate law are:
rate = kN and ln \left( \frac{N}{N_o} \right) = kt

k is the first-order rate constant, N is the number of nuclides present at some time t, \(N_o\) is the initial number of nuclides present at \(t = 0\), and \(t\) is the time the decay process has been occurring.

The half-life equation is: \(t_{1/2} = \ln 2/k\). The half-life for all radioactive decay is independent of the number of nuclides present; it is a constant. From the half-life equation, \(t_{1/2}\) is inversely related to the rate constant, k. As k increases, \(t_{1/2}\) decreases and vice versa.

4. Nuclear transformation: the change of one element into another. Like all nuclear processes, the reaction must be mass number balanced and atomic number balanced. Particle accelerators are devices used to accelerate nuclear particles to very high speeds. Because of the electrostatic repulsion between the target nucleus and a positive ion, accelerators are needed for bombardment of like charged ions in order to overcome the electrostatic repulsion.

5. Geiger counter: an instrument that measures the rate of radioactive decay based on the ions and electrons produced as a radioactive particle passes through a gas-filled chamber. The instrument takes advantage of the fact that the high-energy particles from radioactive decay processes produce ions when they travel through matter. The formation of ions and electrons by the passage of high-energy particles allows a momentary current to flow. Electronic devices detect the current flow and the number of these events can be counted. This gives the decay rate of the radioactive sample.

Scintillation counter: an instrument that measures radioactive decay by sensing flashes of light produced in a substance by the radiation. Certain substances, such as zinc sulfide, give off light when they are struck by high energy radiation. A photocell senses the flashes of light which is a measure of the number of decay events per unit of time.

Radiotracer: a radioactive nuclide, introduced into an organism for diagnostic purposes, whose pathway can be traced by monitoring its radioactivity. \(^{14}\text{C}\) and \(^{31}\text{P}\) work well as radiotracers because the molecules in the body contain carbon and/or phosphorus; they will be incorporated into the worker molecules of the body easily, which allows monitoring of the pathways of these worker molecules. \(^{131}\text{I}\) works well for thyroid problems because iodine concentrates in the thyroid.

To study chemical equilibrium, a nonradioactive substance can be put in equilibrium with a radioactive substance. The two materials can then be checked to see if all the radioactivity remains in the original material or if it has been scrambled by the equilibrium. The scrambling of the radioactive substance is proof that equilibrium is dynamic.

6. Plants take in \(\text{CO}_2\) in the photosynthesis process, which incorporates carbon, including \(^{14}\text{C}\), into its molecules. As long as the plant is alive, the \(^{14}\text{C}/^{12}\text{C}\) ratio in the plant will equal the ratio in the atmosphere. When the plant dies, \(^{14}\text{C}\) is not replenished as \(^{14}\text{C}\) decays by beta-particle production. By measuring the \(^{14}\text{C}\) activity today in the artifact and comparing this to the assumed \(^{14}\text{C}\) activity when the plant died to make the artifact, an age can be determined for the artifact. The assumptions are that the \(^{14}\text{C}\) level in the atmosphere is constant or that the \(^{14}\text{C}\) level at the time the plant died can be calculated. A constant \(^{14}\text{C}\) level is a pure
assumption, and accounting for variation is complicated. Another problem is that some of the material must be destroyed to determine the $^{14}$C level.

$^{238}$U has a half-life of $4.5 \times 10^9$ years. In order to be useful, we need a significant number of decay events by $^{238}$U to have occurred. With the extremely long half-life of $^{238}$U, the period of time required for a significant number of decay events is on the order of $10^8$ years. This is the time frame of when the earth was formed. $^{238}$U is worthless for aging 10,000 year-old objects or less because a measurable quantity of decay events has not occurred in 10,000 years or less. $^{14}$C is good at dating these objects because $^{14}$C has a half-life on the order of $10^3$ years. $^{14}$C is worthless for dating ancient objects because of the relatively short half-life; no discernable amount of $^{14}$C will remain after $10^8$ years.

7. Mass defect: the change in mass occurring when a nucleus is formed from its component nucleons.

Binding energy: the energy required to decompose a nucleus into its component nucleons.

The mass defect is determined by summing the masses of the individual neutrons and protons that make up a nuclide and comparing this to the actual mass of the nuclide. The difference in mass is the mass defect. This quantity of mass determines the energy released when a nuclide is formed from its protons and neutrons. This energy is called the binding energy. The equation $\Delta E = \Delta mc^2$ allows conversion of the mass defect into the binding energy. $^{56}$Fe, with the largest binding energy per nucleon of any nuclide, is the most stable nuclide. This is because when $^{56}$Fe is formed from its protons and neutrons, it has the largest relative mass defect. Therefore, $^{56}$Fe is the most stable nuclei because it would require the largest amount of energy per nucleon to decompose the nucleus.

8. Fission: splitting of a heavy nucleus into two (or more) lighter nuclei.

Fusion: Combining two light nuclei to form a heavier nucleus.

The energy changes for these nuclear processes are typically millions of times larger than those associated with chemical reactions. The fusion of $^{235}$U produces about 26 million times more energy than the combustion of methane.

The maximum binding energy per nucleon occurs at Fe. Nuclei smaller than Fe become more stable by fusing to form heavier nuclei closer in mass to Fe. Nuclei larger than Fe form more stable nuclei by splitting to form lighter nuclei closer in mass to Fe. In each process, more stable nuclei are formed. The difference in stability is released as energy.

For fusion reactions, a collision of sufficient energy must occur between two positively charged particles to initiate the reaction. This requires high temperatures. In fission, an electrically neutral neutron collides with the positively charged nucleus. This has a much lower activation energy.

9. $^{235}$U splits into lighter elements when it absorbs a neutron; neutrons are also produced in the fission reaction. These neutrons produced can go on to react with other $^{235}$U nuclides, thus continuing the reaction. This self-sustaining fission process is called a chain reaction.
In order for a fission process to be self-sustaining, at least one neutron from each fission event must go on to split another nucleus. If, on average, less than one neutron causes another fission event, the process dies out and the reaction is said to be subcritical. A reaction is critical when exactly one neutron from each fission event causes another event to occur. For supercritical reactions, more than one neutron produced causes another fission event to occur. Here, the process escalates rapidly and the heat build up causes a violent explosion. The critical mass is the mass of fissionable material required to produce a self-sustaining chain reaction, not too small and not too large.

Reference Figure 18.14 for a schematic of a nuclear power plant. The energy produced from controlled fission reactions is used to heat water to produce steam to run turbine engines. This is how coal-burning power plants generate energy.

Moderator: slows the neutrons to increase the efficiency of the fission reaction.

Control rods: absorbs neutrons to slow or halt the fission reaction.

Some problems associated with nuclear reactors are radiation exposure to workers, disposal of wastes, nuclear accidents including a meltdown, and potential terrorist targets. Another problem is the supply of $^{235}$U, which is not endless. There may not be enough $^{235}$U on earth to make fission economically feasible in the long run.

Breeder reactors produce fissionable fuel as the reactor runs. The current breeder reactors convert the abundant $^{238}$U isotope (which is nonfissionable) into fissionable plutonium. The reaction involves absorption of a neutron. Breeder reactors, however, have the additional hazard of handling plutonium which flames on contact with air and is very toxic.

10. Some factors for the biological effects of radiation exposure are:

a. The energy of the radiation. The higher the energy, the more damage it can cause.

b. The penetrating ability of radiation. The ability of specific radiation to penetrate human tissue where it can do damage must be considered.

c. The ionizing ability of the radiation. When biomolecules are ionized, there function is usually disturbed.

d. The chemical properties of the radiation source. Specifically, can the radioactive substance be readily incorporated into the body, or is the radiation source inert chemically so it passes through the body relatively quickly.

$^{90}$Sr will be incorporated into the body by replacing calcium in the bones. Once incorporated, $^{90}$Sr can cause leukemia and bone cancer. Krypton is chemically inert so it will not be incorporated into the body.

Even though gamma rays penetrate human tissue very deeply, they are very small and cause only occasional ionization of biomolecules. Alpha particles, because they are much more massive, are very effective at causing ionization of biomolecules; these produce a dense trail of damage once they get inside an organism.