Chapter 21

Nuclear Chemistry

Chapter 21 suggested problems
7th Ed.: 27, 29, 55, 63, 65, 87
8th Ed.: 29, 31, 57, 65, 67, 89

Interesting links:
Interactive Chart of Nuclei at http://www.nndc.bnl.gov/nudat2/index.jsp
Wikipedia Isotope Table at http://en.wikipedia.org/wiki/Isotope_table_%28divided%29
Exploring the Table of Isotopes at http://ie.lbl.gov/education/isotopes.htm
The Isotopes Project Home Page at http://ie.lbl.gov/ip.html
Historical Chart of the Nuclides (PDF, 241 kb) at http://ie.lbl.gov/toipdf/history.pdf

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Class Notes

I. Radioactivity

  A. Two types of radiation - electromagnetic and ionizing

  B. Electromagnetic radiation: a consequence of the disturbance of electromagnetic fields, with the resulting emission of photons of varying energies which in turn form the electromagnetic spectrum

  C. Ionizing radiation: generally the result of events within the nuclei of atoms which result in the emission of particles, often charged particles, which collide with neutral particles as they travel which are ionized as a consequence of the collisions

  D. Nucleons: particles within the nucleus (protons and neutrons)

  E. Nuclei that are radioactive are called radionuclides, and the atoms containing radionuclides are called radioisotopes

II. Radioactive emissions: an unstable nucleus emits one or more particles and is converted into a more stable isotope of a different element

  A. Alpha decay

    1. A nuclear event that results in the ejection of an alpha particle (a-particles)

2. a-particles: two protons, two neutrons

3. a-particles are heavy but lack penetrating power: can be stopped by several sheets of paper

4. Alpha decay result in the conversion of the parent element into a new element (*transmutation*) with an atomic number lessened by two (i.e. two fewer protons) and with an atomic mass lessened by four (i.e. two fewer protons and two fewer neutrons, or four fewer *nucleons*)

5. Nuclear equation: $^{226}_{88}Ra \rightarrow {}^{4}_{2}a + {}^{222}_{86}Rn$

B. Beta decay

1. A nuclear event that results in the decay of a neutron into a proton and a high energy electron (b-particle) which is ejected from the nucleus

2. The force responsible for holding protons and electrons together in a neutron is called the Weak Force

3. b-particles are less massive than a-particles but have much higher energy and are more penetrating (e.g., 0.3 cm thickness of Al)

4. The atomic mass of the element stays the same but the atomic number increases by one

5. Nuclear equation: $^{234}_{90}Th \rightarrow {}^{0}_{-1}b + {}^{234}_{91}Pa$

C. Positron emission

1. A nuclear event that results in the decay of a proton into a neutron and a high energy anti-electron (positron) which is ejected from the nucleus

2. Positrons are the anti-matter equivalent of electrons, i.e., have the same mass as an electrons but have a +1 charge

3. Penetration???

4. The atomic mass of the element stays the same but the atomic number decreases by one

5. Nuclear equation: $^{207}_{84}Po \rightarrow {}^{0}_{+1}b + {}^{207}_{83}Bi$

D. Electron capture

1. A nuclear event in which an inner shell electron is captured by the nucleus, which results in the conversion of a proton into a neutron and a high energy anti-electron (positron) which is ejected from the nucleus

2. The atomic mass of the element stays the same but the atomic number decreases by one

3. Nuclear equation: $^{7}_{4}Be + {}^{0}_{-1}b \rightarrow {}^{7}_{3}Li$

E. Gamma ray emission

1. Gamma radiation is made of high energy photons
2. Almost always accompanies other radioactive events and is equal to the energy lost when unstable nuclei rearrange themselves into more stable configurations
3. Extremely high energy, requires several mm of Pb, a foot or more of concrete, etc. to stop
4. Since photons are without mass or charge, photon emission does not change either the atomic number or the atomic mass
5. As a consequence, the emission of gamma particles is not shown when writing nuclear equations

III. Radioactive decay

A. Nucleons are held together by the Strong Force, independent of which neutrons seem to act as buffers between the protons

B. Just as electrons arrange themselves into shells based on their energy, so do nucleons into groups following similar rules ("Particle Explosion:" 58)

C. Stability rules (BLB: 810ff)

1. Magic numbers: nuclei with 2, 8, 20, 28, 50, or 82 protons - or - with 2, 8, 20, 28, 50, 82, or 126 neutrons are more stable than those that do not contain one or the other of the number of nucleons
2. In the lighter elements the n:p ratio is roughly 1:1, but this ratio is about 1.25:1 in elements with A.N. of 25-45, about 1.4:1 in elements with A.N. of 45-65, and about 1.5:1 in elements with A.N. of 65-84
3. Nuclei above the stable ratio tend to lower the ratio through beta decay and increasing the number of protons while decreasing the number of neutrons
4. Nuclei below the stable ratio tend to increase the ratio through positron emission and increasing the number of neutrons while decreasing the number of protons
5. Above A.N. = 84 no nucleus is stable and all nuclei are radioactive and decay to more stable nuclei, especially through alpha decay

D. Decay is generally a series of events from radioactive and unstable toward stable isotopes

E. Radioactive series: the transmutation of ${}^{238}_{92}U$ to Pb is a 14 step process involving 8 alpha decays and 6 beta decays (Wertz: 1093)

1. ${}^{238}_{92}U \rightarrow {}^{4}_{2}a + {}^{234}_{90}Th$
2. ${}^{234}_{90}Th \rightarrow {}^{0}_{-1}b + {}^{234}_{91}Pa$
3. ${}^{234}_{91}Pa \rightarrow {}^{0}_{-1}b + {}^{234}_{92}U$

4. $^{234}_{92}U$ -> $^{4}_{2}a$ + $^{230}_{90}Th$
5. $^{230}_{90}Th$ -> $^{4}_{2}a$ + $^{226}_{88}Ra$
6. $^{226}_{88}Ra$ -> $^{4}_{2}a$ + $^{222}_{86}Rn$
7. $^{222}_{86}Rn$ -> $^{4}_{2}a$ + $^{218}_{84}Po$
8. Etc.

IV. Half-lives ($t_{1/2}$)

A. The amount of time it takes for an amount "X" of a radioactive element to decay to 1/2X

1. $^{238}_{92}U$ (10^9 years) -> $^{4}_{2}a$ + $^{234}_{90}Th$ (24 days)
2. $^{234}_{90}Th$ -> $^{0}_{-1}b$ + $^{234}_{91}Pa$ (1.2 minutes)
3. $^{234}_{91}Pa$ -> $^{0}_{-1}b$ + $^{234}_{92}U$ (10^5 years)
4. $^{234}_{92}U$ -> $^{4}_{2}a$ + $^{230}_{90}Th$ (10^4 years)
5. $^{230}_{90}Th$ -> $^{4}_{2}a$ + $^{226}_{88}Ra$ (1662 years)
6. $^{226}_{88}Ra$ -> $^{4}_{2}a$ + $^{222}_{86}Rn$ (3.8 days)
7. $^{222}_{86}Rn$ -> $^{4}_{2}a$ + $^{218}_{84}Po$ (3.0 minutes)
8. Etc.

B. Every radioisotope has its own individual decay constant "k" that describes how rapidly or slowly the element decays

C. $\ln (N_t / N_o) = -kt$

D. $t_{1/2} = 0.693/k$

E. Examples

1. The half-life of cobalt-60 is 5.3 years. How much of a 1.000 g sample of cobalt-60 is left after a 15.9 year period?
   Since 15.9 is three half-lives, the sample has decreased to (1/2) x (1/2) x (1/2) x 1.000 g = 0.250 g

2. A wooden artifact from a Chinese temple has a ^{14}C activity of 24.9 counts per minute as compared with an activity of 32.5 counts per minute for a standard of zero age. Given that the half-life of ^{14}C is 5715 years, calculate the age of the artifact.
   $t_{1/2} = 0.693/k \Rightarrow k = 0.693/t_{1/2} = 1.213 \times 10^{-4}\ yr^{-1}$
   $\ln (N_t / N_o) = -kt \Rightarrow [\ln (N_t / N_o)/-k] = t = [\ln (24.9/32.5)/-1.213 \times 10^{-4}\ yr^{-1}] = 2196$ years

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