NUCLEAR CHEMISTRY

PART ONE: THE PRINCIPLES OF NUCLEAR CHEMISTRY

Chemical reactions involve electrons in the outer parts of atoms, whereas nuclear reactions involve protons and neutrons in the nucleus.

1.1 RADIOACTIVITY

Radioactivity was discovered by the French physicist Henri Becquerel in 1896. When studying metals that fluoresce, he found that exposure to a uranium ore a covered photographic plate to become fogged. He also found that even when the photographic plate was wrapped in other metals it became fogged. Becquerel decided that uranium salts emit rays which are capable of penetrating black paper and thin sheets of metal. The elements which give off these invisible rays are said to be **radioactive**. The property of giving off these rays is called **radioactivity**.

Marie and Pierre Curie continued Becquerel's research and found that pitchblende was even more radioactive than uranium. They believed that this ore contained a new element which was more radioactive than uranium. After two years of work and exposure to radioactive material they were able to concentrate *polonium*. After this discovery they continued their work and later discovered a new metal which resembled elements of Group 2, but was also very radioactive. They called it *radium*.

1.2 PROPERTIES OF A RADIOACTIVE ELEMENT – RADIUM

The invisible rays given off from radioactive elements affect the light-sensitive emulsion on a photographic plate in the same way ordinary light does. These rays are also able to penetrate many different materials.

The invisible rays from radioactive elements will also discharge a charged electroscope. When an electroscope becomes charged so do the two pieces of metals foil. This causes them to separate, since like charges repel. The rays from radioactive elements ionize the air molecules around the electroscope which allows them to conduct electricity; thus removing the charge from the foil pieces.

The invisible rays can be measured in a Geiger-Müller tube. The rays enter the tube through a thin glass envelope and ionize the gas molecules inside the tube. The electrons and positive ions are attracted to charged electrodes causing a pulse of current. These pulses are then measured by a Geiger counter.

Radium compounds mixed with another compound cause the latter to glow in the dark. Radium salts are constantly emitting energy. Part of this energy is in the form of light and part of it is in the form of heat. The amount of light given off by radium is only enough to be seen in the dark.

1.3 THE LEAD BLOCK EXPERIMENT

The British scientist Lord Rutherford experimented with radium salts in the bottom of a hole in a block of lead. He found that a screen of zinc sulfide flashed when it was bombarded with radiation. Rutherford also found that if he place a magnet in the path of the radioactive rays three patches of light were produced in the screen. Some rays were bent in one direction, others in the opposite direction, and some were not bent at all. To account for this Rutherford concluded that some particles were positively charged, some were negatively charged, and other were uncharged. He name these particles *alpha*, *beta*, and *gamma rays*, respectively.

Alpha particles were found to be helium nuclei (having two protons and two neutrons, +2 charge, and mass of 4 u). They travel at high speeds but have weak penetrating power. They have a small range in air and are stopped by thin sheets of aluminium and even paper. However, they do ionize the molecules of any gas they pass through.

Beta particles are high-energy electrons (have a –ve charge). They travel at speeds approaching that of light and have a penetrating power greater than alpha particles. However, they don't ionize gas particles as well.

Gamma rays are not charged (they aren't particles). They are high-energy and frequency electromagnetic radiations, similar to X-rays. They travel at the speed of light and are very penetrating. They have little ionizing effect on gases.

1.4 STABILITY OF THE NUCLEUS

In order for an atom to be radioactive, its nucleus must be unstable. Thus, certain unstable nuclei spontaneously break down into more stable nuclei, emitting particles and rays as they do so. Three factors must be considered when trying to decide whether or not a nucleus is stable.

- MASS

When a nucleus is made from its components some of the mass is lost. The mass of a nucleus is slightly less than the sum of the masses of the protons and neutrons of which it is composed. This is called the mass defect. The **mass defect** is the mass converted into energy when a nucleus is made from its components. This energy is called **binding energy** of the nucleus. The connection between mass and energy is given in Einstein's equation:

$$E = mc^2$$

where E = energy released, m = loss in mass, and c = velocity of light. This is the origin of the substantial quantity of energy released in the fission of atomic nuclei.

Whenever the binding energy is large, the nucleus will be stable. However, it has been found that the binding energy is smaller for very heavy and very light nuclei than it is for nuclei of intermediate mass. Therefore, nuclei of very light and very heavy atoms are least stable because they have the smallest binding energies. An isotope of iron, $^{56}_{26}\mathrm{Fe}$, is the most stable nucleus in nature.

- P/N RATIO

The stability of a nucleus also depends on the proton to neutron ratio. For any given number of protons, there is a small range of number of neutrons that permit a stable nucleus. For the first 20 elements the preferred ratio is 1:1. Beyond the first 20 element nuclei must have more neutrons than electrons.

There is a favourable "belt" of p/n ratios for nuclear stability, called "the band of stability".

If the p/n ratio of the nucleus lies outside this belt, the nucleus is radioactive.

If the p/n ratio is too large alpha particle are emitted in order to achieve stability (favourable p/n ratio by decreasing the p/n ratio), and if the p/n ratio is too small beta particles are emitted to increase the p/n ratio.

- EVEN-ODD RULE

The stability of a nucleus can also be predicted by looking at its number of protons and neutrons. Nuclei with an even number of p and n is likely more stable than nuclei with an odd number of p and an even number of n or vice-versa (even p, odd n). There are only four stable nuclei that have an odd number of protons and neutrons.

Although these three factors can be used to predict the stability of a nucleus, sometimes they contradict. Some examples are: N has a p/n ration of 1:1, but the nucleus has an odd number of protons and neutrons; B has a p/n ratio of 1:1, but it has an odd number of protons and an even number of neutrons; C satisfies both rules.

It has been found that nuclei with certain numbers of protons and neutrons are unusually stable. These magic numbers are: 2, 8, 20, 28, 50, and 82 for protons and 2, 8, 20, 28, 50, 82, and 126 for neutrons. Nuclei with these magic numbers of either protons or neutrons tend not to take part in nuclear reaction in the same manner noble gases tend not to take part in chemical reactions.

To explain this kind of behaviour the shell model has been developed. This model uses the principles of quantum mechanics to describe the arrangement of nucleons in the nucleus in a manner similar to the arrangement of electrons in the orbitals. Each energy level can accommodate a fixed number of nucleons.

1.5 BALANCING NUCLEAR EQUATIONS

Some concepts must be learnt so one can balance a nuclear equation.

First, only the nuclei are represented. The carbon isotope, with 6 p and 6 n, is represented by $^{12}_{6}\mathrm{C}$ (atomic number = 6 (# of protons), and mass number = 12 (protons + neutrons)). The symbol of some important particles are shown on the left. Deuterium is an isotope of hydrogen. It has one proton and one neutron, and its mass number is two. It is also called a heavy hydrogen.

When balancing a nuclear equation, we must remember that the sum of the superscripts on the left equals the sum of the superscripts on the right (conservation of mass). The same goes for the subscripts (conservation of charge). For example,

$^{238}_{92}\mathrm{U} \rightarrow {}^{234}_{90}\mathrm{Th} + {}^{4}_{2}\mathrm{He}$

238 = 234 + 4
92 = 90 + 2

$^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{90}_{38}\mathrm{Sr} + {}^{143}_{54}\mathrm{Xe} + 3\ {}^{1}_{0}\mathrm{n}$

235 + 1 = 236 = 90 + 143 + (3 x 1)
92 + 1 = 92 = 38 + 54 + (3 x 0)

W

1.6 TYPES OF NUCLEAR REACTIONS

There are four types of nuclear reactions. The first type is radioactive decomposition. If a nucleus is altered by the loss of an alpha particle or a beta particle, the reaction is a **radioactive decomposition**.

If a nucleus is bombarded by alpha particles, protons, or neutrons, an unstable nucleus may result. The unstable nucleus can emit a proton or a neutron in order to gain stability. This process is called **artificial transmutation**.

If a heavy nucleus splits to form nuclei of intermediate mass, the process is called **fission**. If two light nuclei combine to form a heavier, more stable nucleus, the process is called **fusion**. We will talk about each type of nuclear reaction later.

1.7 RADIOACTIVE DECOMPOSITION

- ALPHA DECAY

Certain heavy nuclei spontaneously break down into lighter nuclei. Alpha particle (helium nuclei) are emitted.

This process is known as alpha decay: $^{238}_{92}\mathrm{U} \rightarrow {}^{234}_{+0}\mathrm{Th} + {}^{4}_{2}\mathrm{He}$

The uranium nucleus has been changed to a thorium nucleus because two protons have left the uranium nucleus. A **transmutation** is a change in the identity of a nucleus because of a change in the number of protons in the nucleus. Uranium has been transmuted to thorium.

$^{234}_{90}\mathrm{Th}\ * \rightarrow {}^{234}_{90}\mathrm{Th} + \text{Gamma Rays}$

The equation below describes the transmutation of uranium to thorium better than the equation above:

$^{238}\mathrm{U} \quad {}^{234}\mathrm{Th}\ * \quad {}^{4}\mathrm{He}$

The $^{234}_{90}\mathrm{Th}\ *$ is an excited thorium nucleus which loses its extra energy by giving off gamma rays.

During alpha-decay, the mass number falls by four units and the atomic number falls by two units.

If a sample initially contained a certain number of nuclei, then after a period of time called the **half-life** ($t_{1/2}$), only half of the original number of nuclei will remain. The half-life for uranium-238 is 4.6×10^9 years. The half -life of a radioactive isotope is the time taken for the mass or concentration of the isotope to fall to half its initial value. The half-life of a radioactive isotope is unaffected by external conditions. It can be used as a relative stability of an isotope.

- BETA DECAY

The emission of a negatively charged electron (beta particle) from a nucleus causes the positive nuclear charge to increase by 1. Since the electron is very small, loss of one electron causes no change in the mass number. The throrium-234 nucleus formed during alpha decay of uranium-238 is itself unstable and is transmuted to a protactinium-234 nucleus by beta decay: $^{234}_{90}\mathrm{Th} \rightarrow {}^{234}_{91}\mathrm{Pa} + {}^{0}_{-1}\mathrm{e}$.

Since nuclei are supposed to contain only protons and neutrons, we might wonder where the electron (beta particle) originated. The Italian nuclear scientist Enrico Fermi suggested that an electron is created at the moment of beta decay. It is believed that a neutron transforms into a proton and an electron at decay: $^{1}_{0}\mathrm{n} \rightarrow {}^{1}_{1}\mathrm{H} + {}^{0}_{-1}\mathrm{e}$.

Just as in alpha decay, some beta decays produce an excited state of protactinium-234. Gamma rays are produced as the excited protactinium decays. The half-life of thorium-234 is 24 days. Thus, as the uranium-238 decays to thorium by alpha decay, the thorium more rapidly decays to protactinium by beta decay. This radioactive decay series began with urainum-238, decaying to thorium-234, which in turn decayed to protactinium-234. The protactinium-234 decays by beta decay: $^{234}_{91}\mathrm{Pa} \rightarrow {}^{234}_{+3}\mathrm{U} + {}^{0}_{-1}\mathrm{e}$. The uranium-234 then decays by five alpha in a row to $^{214}_{82}\mathrm{Pb}$. The lead-214 decays by two beta, then one alpha, then two more beta, and finally one alpha decay to $^{206}_{82}\mathrm{Pb}$. Lead-206 is stable and the series ends. This is one of three naturally occurring radioactive decay series.

Alpha decays produce more stable nuclei by decreasing the mass of a heavy nucleus. The loss of an alpha particle lowers the mass of a heavy nucleus by four mass units. Recall that an intermediate mass nucleus is more stable than a heavy nucleus.

During beta-decay, the mass number remains constant, but the atomic number rises by one unit. Beta decays produce more stable nuclei by converting a neutron into a proton. Since many nuclei have more neutrons than protons, the conversion brings the p/n ratio closer to one to one.

1.8 APPLICATIONS OF NATURAL RADIOACTIVITY

A reliable method of determining the age of an old object depends on the presence of natural radioactivity. For example, to find the age of an old crystal of pitchblende (U_3O_8), which is found to contain some lead, we assume that the lead came from natural radioactive decay. The amount of lead is proportional to the length of time of formation to the present. Since the rate of uranium decay is known the age can be calculated.

The age of minerals can also be determined by using the decay of $^{40}_{19}\mathrm{K}$ to form $^{40}_{18}\mathrm{Ar}$. By determining the amount of the two nuclei, it is possible to determine the age of the mineral.

Another type of dating is called **carbon-dating**. Radioactive carbon-14 is produced from the bombardment of atmospheric nitrogen by neutrons from cosmic rays: $^{14}_{7}\mathrm{N} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{14}_{6}\mathrm{C} + {}^{1}_{1}\mathrm{H}$. The concentration of $^{14}CO_2$ in the atmosphere is kept in balance. Living plants and animals establish a balance with the atmospheric $^{14}CO_2$ and thus contain a constant amount of carbon-14. When plants and animals die, the balance is upset as carbon-14 decays without being replaced. Since the half-life of carbon-14 is known, the date of death can be calculated by the amount of carbon-14 radioactivity in the specimen.

Part Two: Splitting the Atom

Not all radioactive elements occur naturally. Many elements undergo artificially induced nuclear reaction with the formation of unstable nuclei, which then undergo radioactive disintegration. The process can be used to generate isotopes which are useful and to generate huge amounts of energy, as we shall see next.

1.9 Artificial Transmutation

Lord Rutherford produced the first artificial transmutation in 1919 by allowing alpha particles from a radium source to bombard nitrogen atoms. Protons and an isotope of oxygen were produced: ${}^{14}_{7}\mathrm{N} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{17}_{9}\mathrm{O} + {}^{1}_{1}\mathrm{H}$. Rutherford repeated this experiment with other elements, but was unable to do it with elements heavier than potassium. This was because alpha particle have a +2 charge. Since the nuclear charge of heavier elements was greater than the speed of the alpha particle was able to overcome the particle was repelled. A solution to this is to use protons which have half the charge of an alpha particle. The neutron was discovered when James Chadwick bombarded beryllium with alpha particles to produce carbon and an uncharged particle.

1.10 Particle Accelerators

The energy required for a transmutation reaction is usually provided as kinetic energy by one of the reactants. Generally, the charged particles used to produce transmutation reactions are accelerated to the necessary kinetic energies by accelerators that use magnetic and electric fields to accelerate the particles. Examples of these machines are cyclotrons and linear accelerators. Cyclotrons accelerate particle in a spiral path. In linear accelerators, particles pass down a series of charged cylinders so that they are continuously accelerated. In all accelerators, the particles move in a vacuum so as to avoid collisions with gas molecules.

1.11 Neutrons Are Better Bullets

Before the discovery of neutrons, alpha particles, deuterons, and protons were used for studying atomic nuclei. Since its discovery the neutrons has been used instead since it is not repelled by the nucleus. Usually neutrons produced by nuclear reactions must be slowed down before they can be absorbed by other atoms. Fast neutrons lose their kinetic energy when they collide with the atoms, which are able to slow the neutrons without absorbing or reacting with them. Neutrons can be obtained by bombarding beryllium with alpha particles.

Artificial elements can be produced by neutron bombardment. When slow neutrons strike uranium-238, they produce uranium-239, which beta decays into neptunium-239, which consequently beta decays into plutonium-239.

Neptunium and plutonium are two **transuranium elements**: that is, they have more than 92 protons. Transuranium elements can be prepared by bombardment by different particles.

Stable nuclei can be made artificially radioactive by neutron bombardment. For example, Cobalt-59 can be converted into radioactive cobalt-60; sulfur-32 can be converted into radioactive phosphorus-32. There radioisotopes are useful in many different areas.

1.12 Fission

At the time that Enrico Fermi was demonstrating that uranium-238 could be transmuted to neptunium and plutonium, a number of unexplained results indicated that occasionally large amounts of energy were released. Otto Hahn and Fritz Strassmann proved that whenever this large energy release occurred, atoms of intermediate atomic number were produced. Later Lise Meitner suggested that uranium nucleus absorbed neutrons and split into two roughly equal particles, which because of their smaller masses released great amounts of energy.

The splitting of a uranium nucleus into two smaller nuclei was called fission. It was found that uranium-235 was responsible for most of the fission and that, in the process, two or three neutrons were set free. These neutrons could then cause additional fissions in other uranium-235 nuclei. This would set a rapidly growing, fast chain reaction which would release huge amounts of energy almost instantaneously.

Seeing the potential to produce a weapon of massive destruction the US government, urged by Albert Einstein, started the Manhattan Project which lead to the development of the atomic bomb.

1.13 The Atomic Bomb

Uranium-235 and plutonium undergo rapid fission in a chain reaction; however, uranium-235 makes up only 0.7% of natural uranium which makes it difficult to make atomic bombs.

In order for it to explode, the bomb must contain a certain minimum amount of fissionable material. This is called the **critical mass**. The bomb, in the safety position consists of two or more separate quantities of fissionable material that contain less than the critical mass. If these masses are jammed together to form a larger mass which has less surface area per unit volume, the critical mass is exceeded and an explosive chain reaction results.

An atomic bomb (containing uranium-235) was first used in war on August 6, 1945 on Hiroshima. A second bomb (containing plutonium-239) was used on Nagasaki two days later. The explosion of an atomic bomb produces extremely high temperatures, a severe shock wave, and gamma rays which cause radiation sickness and genetic damage.

Part Three: Canada's Nuclear Industry

1.14 Nuclear Reactors

The first **nuclear reactor**, a device that controls a chain reaction, was developed by a group of scientist led by Fermi in 1942.
Their reactor was called an atomic pile and consisted of layers of uranium oxide and uranium metal separated by graphite bricks.

Graphite is a **moderator;** in other words, it slows down neutrons. Neutrons released during fission travel at very high speeds; however, they need to be slowed down in order to be captured by scarce uranium-235 nuclei. The carbon atoms in the graphite bricks served this purpose.

The reactor also contained control rods of cadmium metal which slowed down the chain reaction. When the control rods were removed fissions were able to occur. At the critical point the pile operated on its own. The control rods could shut down the pile by being placed back into it. Fermi's pile was cooled by allowing air to flow between the graphite blocks. All reactors have a **fuel, a moderator, a control, and a cooling system**. Reactors have three main functions: (1) produce radioactive isotopes; (2) release of vast amounts of energy in the form of heat from fissions; and (3) produce new nuclear fuels.

1.15 Canada and Nuclear Chemistry

Much of the fundamental research on radioactivity has been done in Canada; therefore, Canadians are very interested in peaceful uses of nuclear energy. The Atomic Energy Research Laboratories at Chalk River, Ontario, began operation in 1944. It was then taken over by the NRC in 1952, and finally it became part of Atomic Energy Canada Ltd. (AECL). Today AECL also has a reactor design group in Toronto, a group with a reactor in Manitoba, and a commercial products group in Ottawa.

Canadian scientist are experts at using natural uranium as fuel and heavy water as moderator in nuclear reactor. Canadians made the first reactor outside the US. The ZEEP (Zero Energy Experimental Pile), as it was called, consisted of an aluminum tank filled with heavy water and surrounded by a graphite layer. Movable rods of uranium cased in aluminum were hung in the heavy water. The ZEEP was used to find the best distances between fuel rods for different types of fuel. This is important because it the rods are too close the neutrons will still be travelling too fast to cause fission in a nearby rod; if the rods are too far apart the neutrons scatter without causing fission.

The heavy water, 42 MW NRX reactor began operation in 1947. It has automatic means of irradiating material to produce radioactive isotopes, and it produces large amount of neutrons from fission of uranium-235. The NRX was essential for research until the 200MW NRU began operation in 1957. The only differences between the NRX and the NRU are that the NRU uses heavy water as a moderator and coolant, and it is fuelled by natural uranium.

1.16 AECL Power Projects

The AECL Power Projects group is responsible for the design of nuclear power plants and for the project management of nuclear power stations built by AECL. Scientist are very interested in fission as a source of power because 1 kg of nuclear fuel (like uranium-235) produces as much heat as 2 700 000 kg of coal.

The Canadian nuclear power program is based on experience with heavy water-moderated, natural uranium type of reactors. Southern Ontario requires more energy that its hydro facilities can produce so it is natural the they invest money in efficient nuclear power plants. A 20 MW nuclear power demonstration plant (NPD) was built in 1962 and it was so successful that a full-sized plant was ordered. The Douglas Point Power Reactor is similar to the NPD but produces 200 MW. It was built by AECL and is a CANDU (Canada Deuterium Uranium) reactor.

1.17 CANDU Reactors

The CANDU reactor has proven to be one of the most efficient types of nuclear reactors in the world. CANDU reactors have been built in Douglas Point, Darlington, and Pickering, Ontario, in Gentilly, Quebec, and in Point Lepreau, New Brunswick.

- Fuel

The fuel of a CANDU reactor is UO_2 pellets which are converted from uranium ore. These pellets are placed in zircaloy tubes whose ends are shut, and these tube in turn are assembled to form a fuel bundle containing 22.2 kg of UO_2. The fuel bundles are then placed in fuel channels in the reactor vessel, called a calandria. A fuel charge of one reactor has a total mass of 105 t. The natural uranium in the UO_2 pellets consists of 99.3% uranium-238 and 0.7% uranium-235. Only the uranium-235 can undergo fission and produce energy in the reactor.

The are two types of reactions in a reactor which is fueled with natural uranium: the fission and the neutron capture reaction. The fission reaction consists of the splitting of uranium-235 as follows:

$$^{135}_{92}\mathrm{U} + \underset{\text{slow}}{^{1}_{0}\mathrm{n}} \rightarrow {}^{90}_{38}\mathrm{Sr} + {}^{143}_{54}\mathrm{Xe} + \underset{\text{fast}}{^{1}_{0}\mathrm{n}} + \text{Energy}$$

Most of the neutrons produced in the fission are slowed down by the moderator and hit other uranium-235 nuclei; however, some fast moving neutrons hit uranium-238 nuclei before being slowed down causing the uranium-238 to be converted into plutonium-239: ${}^{238}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{239}_{92}\text{U} \rightarrow {}^{239}_{92}\text{Np} + {}^{0}_{-1}\text{e}$ **then** ${}^{239}_{93}\text{Np} \rightarrow {}^{239}_{94}\text{Pu} + {}^{0}_{-1}\text{e}$

About half of the plutonium-239 produced by neutron capture also undergoes fission and contributes to one-third of all the heat produced by a fuel bundle.

As the fuel is used up, the spent fuel is removed from one end and new fuel is added on the other end by a computer while the reactor is in full operation. A 600Mw CANDU plant consumes 95t of UO_2 fuel in17 months.

- MODERATOR

For the uranium-235 to undergo fission its nuclei must absorb slow-moving neutrons. Since the neutrons released as a result of fission are moving too fast, they must be slowed down. This is done by colliding them with particles of the same mass. CANDU reactors use heavy water (D_2O) as a moderator. Heavy water is the best moderating material because its deuterium atoms have a smaller probability of absorbing the neutron than hydrogen in water and carbon in graphite; as a result, heavy water does not interfere with fission allowing natural uranium to be used as fuel. Heavy water also allows for a high burn-up (amount of energy extracted from fuel); thus, the reactors have a higher power output. The disadvantage of heavy water is its high cost.

- CONTROLS

The energy output of a reactor can be controlled by adjusting the level of ordinary water in one or more compartments called liquid zone control units. When the water is raised in one of these units the water absorbs the neutrons reducing fission. Water levels can be raised in all 14 units to completely stop the chain reaction.

There are also three methods of shutting down a reactor. The first method consists of shut-off rods made of neutron absorbing material. When dropped into the core of the reactor they stop the chain reaction. The second method consists of injecting a liquid “poison” into the moderator. This “poison” is a neutron absorber, which also stops the chain reaction. The third method involved dumping the heavy water moderator into a dump tank below the calandria so that the neutrons are slowed down enough not to be able to cause fission.

- COOLANT

The products of fission move apart with such energy that they cause the fuel to heat up. CANDU reactors use heavy water under pressure as a coolant flowing through tubes enclosing the fuel bundles. The coolant is then passed through a stem generator where it causes ordinary water to boil. The steam produced is fed through turbines that generate energy as the heavy water is pumped back into the core. CANDU reactors use 143t of heavy water as coolant.

- USED FUEL

A used fuel bundle contains uranium-238, uranium-235, and plutonium, among other isotopes. After they are removed from the reactor the fuel bundles are temporarily stored in reinforced concrete pools at nuclear power stations where the water prevents radiation from causing harm. Most of that radiation is eliminated by natural decay in 10 years; however, plutonium, which has a half-life of 24 000 years, is still radioactive. As a result there must be a method for permanent disposal. Two suggestions are plausible.

The first is to seal the fuel bundles in corrosion-proof containers to be disposed of. The second is to remove the useful material such as plutonium and chemically react the remaining waste with glass-forming substances to form insoluble solids for disposal.

In both cases the disposable materials would be placed in a deep vault carved in the Canadian Shield which is known for its geological stability. The vault, which would be able to store all the nuclear fuel wastes produced in Canada in the next fifty years, would be monitored for a period of time and then would be sealed.

1.18 Production of Heavy Water

Heavy water is present in minute amounts in ordinary water; as a result, it must be extracted for use in the nuclear industry. The extraction process consists of exchanging deuterium between liquid water and hydrogen sulfide at 128 ºC then dissolving the D_2S in water at 32ºC. The deuterium moves to the water, increasing its content of D_2O. This process is repeated until the concentration of D_2O is approximately 30%. Since Heavy water has a higher boiling point than water, D_2O that is 99.75% pure can be obtained.

1.19 AECL Commercial Products – Uses of Radioactive Isotopes

The Commercial Products group of AECL is responsible for the processing and distribution of radioactive isotopes and for the design and manufacture of associated equipment. Radioactive isotopes can be used in medical therapy; in sterilization of vegetables, fruits, and grain, as well as medical supplies and wool; and in the study of wearing of machine parts. Cobalt-60 isotopes in cobalt bombs are used to treat malignant cancer tumours. Cobalt-60 is also used to sterilized certain food so they have a longer shelf life, as well as packed medical instruments. Radioisotopes can also be added to metal surfaces to test the efficiency of lubricants. Even the slightest wear causes radioactive atoms to be detected in the lubricants.

Part Four: The Nuclear Age

As in any other industry, there have been some improvements in the nuclear industry; however, there are still risks associated the with use of nuclear energy. Some improvements to reactor design and some concerns surround the use of nuclear energy to generate energy will be discussed in the following chapters.

1.20 Breeder Reactors

When uranium-235 undergoes fission, a second reaction (the conversion of uranium-238 into plutonium-239) also takes place. Since an average of 2.5 neutrons are released during each fission and plutonium-239 is fissionable, a reactor can be made so that more fissionable fuel is produced than consumed.

Breeder reactors have a reduced amount of moderator so that more of the uranium-238 is converted into plutonium-239. *Fast breeders* are breeder reactors that have almost no moderators in order to maximize plutonium-239 production. This plutonium can then be used to produce fuel cores for other reactors.

1.21 Fusion

As we have seen before fusion is a reaction in which energy is released when light atoms combine to form a heavier atom. The simplest fusion is the combination of hydrogen nuclei to form helium nuclei. In this reaction some mass was converted into a large amount of energy. Fusion produces more energy that fission; however, it can only occur at high temperatures since the nuclei must be moving at very large speeds in order to combine. Research is being conducted in fusion in order to produced fusion reactors.

1.22 The Hydrogen Bomb

Deuterium and tritium isotopes fuse more rapidly than ordinary hydrogen so they can be used to construct what are called hydrogen bombs. The main reaction in a hydrogen bomb is the fusion of deuterium and tritium. An atomic bomb is the detonator for a hydrogen bomb because it produces the high temperature for fusion to take place.

There are three reactions in the hydrogen bomb. The first is the detonation of the atomic bomb. The second is the splitting of the lithium nuclei by neutrons from the atomic bomb to form tritium and helium and release energy. The third reaction is the fusion of deuterium and tritium to form helium and release a neutron and energy. The total energy released from a hydrogen bomb is greater than that release by an atomic bomb.

1.23 Ionizing Radiation

Ionizing radiation is radiation which is capable of interacting with atoms or molecules to form ions. This type of radiation can be very harmful to humans since it can cause chemical reactions in cells.

The SI unit for ionizing radiation is the **sievert**; however, the **rem** (radiation equivalent man) is more commonly used. The rem doesn't correspond to a fixed amount; rather, it takes in account the different effects of different types of radiation on biological matter. Ionizing radiation can be natural (cosmic rays, radioactive elements in the earth and human body) or resultant of human activity (X-rays, radiation therapy, nuclear power plants). The safe maximum dose of radiation is 500 mrem /year; however doses of up to 25 000 mrem /year produce no detectable physiological change. A dose of 500 000 mrem /year kills half of the people exposed in 30 days.

1.24 Problems of the Nuclear Age

The first problem of the nuclear age is what to do with radioactive wastes such as that from a reactor. A nuclear reactor produces two types of waste:

1. Low level waste (stuff that has come in contact with nuclear material, mops, plastic sheets, protective clothing). This is stored:

2. High level spent fuel. This stuff is really hot as it contains all the fission products which are in turn radioactive. Initially this is stored under water in a large pool, onsite. Its radioactivity decreases with time:

   After 1 year <100 times the radioactivity
   After 5 years < 1000 times the radioactivity
   After 500 years <little radioactivity left

   After ~ 5 years in the pool the material can be stored in reinforced concrete canisters. Research is being conducted for safer storage alternatives. Can you think of any?

Some of the wastes decays to safe levels rapidly but some like cesium-137 can take as much as 600 years to be safe. As a result permanent storage must be safe for up to a thousand years. Waste disposal also includes water or even trash from nuclear power plants which are likely contaminated.

The second problem involves dangers with mining uranium. Mining uranium can cause contamination to spread, and can kill miners which can have radioactive dust lodged in their lungs.

The third problem is the possibility of radiation being released into the atmosphere by accidents in nuclear power plant (*e.g.* Chernobyl).

The fourth problem is the fallout from the explosion of atomic and hydrogen bombs which after it ascends into the atmosphere comes down and contaminates and accumulates in plants and animals.

The last problem is the huge amount of atomic and hydrogen bombs in the hands of numerous countries which may use them at any time.

QUESTIONS: CHEMISTRY TODAY I, WHITMAN, ZINCK & NALEPA

p. 596: Part One Review Questions

1. Lord Rutherford experimented with radium salts in the bottom of a hole in a block of lead. Rutherford placed a zinc sulfide screen in from of the hole and found that it flashed when bombarded with radiation. He then placed a magnet in the path of the radioactive rays three patched of light were produced. Some rays were bent to the right, some to the left, and some were not bent. He concluded that some particles were positively charged, some were negatively charged, and some were uncharged. He called them alpha, beta, and gamma rays respectively.

2. Binding energy is the amount of energy converted from mass when a nucleus is made from its components. p/n ratio is the ratio of protons to neutrons in the nucleus of an atom. Even-odd rule is the rule that predicts the stability of nuclei by their number of protons and neutrons. The binding energy is used to predict the stability of a nuclei because it is known that nuclei with a large biding energy are more stable. The p/n ratio is used to predict the stability of nuclei because it is known that nuclei are only stable for a certain range of p/n ratios. Finally, the even-odd rule is used to predict the stability of nuclei because it is known that nuclei with an even number of p and n is likely more stable than nuclei with an odd number of p and an even number of n or vice-versa (even p, odd n), or more stable than nuclei with and odd number of p and n.

3. a) ${}^{27}_{13}\text{Al} + {}^{2}_{1}\text{H} \rightarrow {}^{4}_{2}\text{He} + {}^{25}_{12}\text{Mg}$ b) ${}^{7}_{3}\text{Li} + {}^{1}_{1}\text{H} \rightarrow 2\,{}^{4}_{2}\text{He}$

4. Nuclear fusion is the combination of two light nuclei to form a heavier, more stable nucleus, while nuclear fission is the splitting of a heavy nucleus to form nuclei of intermediate mass.

5. Half-life of a radioactive substance is the period of time it takes for mass of the substance to half. If the half-life of the substance is know one can calculate the age of the material by using the half-life and the amount of the radioactive substance and the substance formed by natural decay.

p. 603: Part Two Review Questions

1. ${}^{9}_{4}\text{Be} + {}^{4}_{2}\text{He} \rightarrow {}^{12}_{6}\text{C} + {}^{1}_{0}\text{n}$

2. Neutrons are better bullets for studying atomic nuclei than alpha particles or protons because it does not have a charge; therefore, it will not be repelled by the nucleus of an atom.

3. When a uranium-235 nucleus absorbs a slow moving neutron it splits into barium-141, krypton-92 and releases three neutrons and a vast amount of energy. These three neutrons, if slowed down, can then hit three other uranium-235 nuclei; thus, starting a chain reaction.

4. Critical mass is the minimum amount of fissionable material necessary to sustain a chain reaction. The critical mass is so important because if the amount of fissionable material is too small not enough nuclei will split and if the amount of fissionable material is too large a explosive chain reaction results.

p. 612: Part Three Review Questions

1. The three main functions of a nuclear reactor are to produce radioactive isotopes, release vast amounts of energy, and produce new nuclear fuels.

2. A CANDU reactor uses natural uranium as fuel.

3. $^{235}_{92}\text{U} + \underset{\text{slow}}{^{1}_{0}\text{n}} \rightarrow {}^{90}_{38}\text{Sr} + {}^{143}_{54}\text{Xe} + \underset{\text{fast}}{^{1}_{0}\text{n}} + \text{Energy}$ → fission of uranium-235

$^{238}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{239}_{92}\text{U} \rightarrow {}^{239}_{92}\text{Np} + {}^{0}_{-1}\text{e}$ **then** $^{239}_{93}\text{Np} \rightarrow {}^{239}_{94}\text{Pu} + {}^{0}_{-1}\text{e}$ → neutron capture of uranium-238

4. The moderator's function is to slow down the fast moving neutrons released during fission of uranium-235 so they can hit other uranium-235 nuclei; thus, maintaining the chain reaction. The moderator used in CANDU reactors is heavy water (D_2O).

5. The three types of shut-down methods of a CANDU reactor consist of the use of shut-off rods, injection of "poison" into the core, or heavy water dump. The first method consists of dropping neutron absorbing rods, shut-off rods, into the core of the reactor to stop the chain reaction. The second methods consists of injecting a neutron absorbing liquid, liquid "poison", into the core of the reactor once again to stop the chain reaction. The third method consists of dumping the heavy water into a dump tank under the calandria so that the neutrons are slowed down and fission can't continue.

6. Ordinary water always has a small amount of heavy water. The process of extracting this heavy water consists of exchanging the deuterium between liquid water and hydrogen sulfide at 128ºC, then dissolving the D_2S in water at 32ºC causing the deuterium to migrate to the water, thus enriching its content of D_2O. Since heavy water boils at a higher temperature it can be separated from ordinary water when there is a 30% concentration of D_2O.

7. Radioactive isotopes can be used to produce energy, treat malignant tumours, sterilize vegetables, fruit, and grain, and to study the wearing of machine parts.

p. 620: Review Your Understanding

25. This is a fusion reaction.

26. a) $^{31}_{15}\text{P} + {}^{1}_{1}\text{H} \rightarrow {}^{28}_{14}\text{Si} + {}^{4}_{2}\text{He}$ b) $^{27}_{13}\text{Al} + {}^{4}_{2}\text{He} \rightarrow {}^{30}_{14}\text{Si} + {}^{1}_{1}\text{H}$ c) $^{23}_{11}\text{Na} + {}^{2}_{1}\text{H} \rightarrow {}^{1}_{1}\text{H} + {}^{24}_{11}\text{Na}$
d) $^{235}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{90}_{37}\text{Rb} + {}^{143}_{55}\text{Cs} + 2\,{}^{1}_{0}\text{n}$ e) $^{3}_{1}\text{H} + {}^{3}_{1}\text{H} \rightarrow {}^{4}_{2}\text{He} + 2\,{}^{1}_{0}\text{n}$ f) $^{228}_{90}\text{Th} \rightarrow {}^{4}_{2}\text{He} + {}^{224}_{88}\text{Ra}$
g) $^{12}_{5}\text{B} \rightarrow {}^{0}_{-1}\text{e} + {}^{12}_{6}\text{C}$

27. a) artificial transmutation b) artificial transmutation c) artificial transmutation
d) fission e) fusion f) radioactive decomposition
g) radioactive decomposition

28. The half-life of this radioactive isotope is 20 minutes.

p. 621: Apply Your Understanding

8. This is not an easy decision to make; however, as with anything else there are numerous possibilities. In my opinion Canada should not sell CANDU reactors to anyone that can buy them; however, nuclear reactors must be sold because it is a source of income for the country. A solution to prevent future danger is to include in the contract between Canada and the buying country, that the buyer cannot use CANDU reactors to obtain plutonium to produce nuclear weapons. Some people would say that this is not enough; however, it is a responsibility of both governments to ensure that the agreement is followed. If the country proposing to buy a reactor is not reliable the reactor must not be sold.

TEST QUESTIONS – NUCLEAR CHEMISTRY

1. Define radioactivity and describe the types of radioactive rays.

2. Who performed the lead block experiment? Describe the experiment.

3. Define and explain the factors used to predict the stability of a nucleus.

4. Balance the following nuclear equations:

   a) ${}^{6}_{3}\text{Li} + {}^{1}_{0}\text{n} \rightarrow {}^{3}_{1}\text{H} + ? + \text{Energy}$ b) ${}^{239}_{92}\text{U} \rightarrow ? + {}^{0}_{-1}\text{e}$ c) ${}^{9}_{4}\text{Be} + ? \rightarrow {}^{12}_{6}\text{C} + {}^{1}_{0}\text{n}$

5. Define and give examples (can be equations) of the types of nuclear reactions.

6. What are the applications of a nuclear reactor? What fuel, moderator, and coolant are used by CANDU reactors?

7. Name and explain the three shut-down methods of a CANDU reactor?

8. Name three commercial uses of radioactive isotopes.

9. What is a breeder reactor?
   a) the first reactor built by AECL b) reactor built in the US c) reactor using plutonium as fuel
   d) a reactor that produces more fissionable material than it consumes d) none of the above

10. Which of the following is an example of fusion?

    a) ${}^{239}_{93}\text{Np} \rightarrow {}^{239}_{94}\text{Pu} + {}^{0}_{-1}\text{e}$ b) ${}^{6}_{3}\text{Li} + {}^{1}_{0}\text{n} \rightarrow {}^{3}_{1}\text{H} + {}^{4}_{2}\text{He} + \text{Energy}$ c) $D_2O_{(l)} + H_2S_{(g)} \rightarrow H_2O_{(l)} + D_2S_{(g)}$

    d) ${}^{235}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{141}_{56}\text{Ba} + {}^{92}_{36}\text{Kr} + 3{}^{1}_{0}\text{n} + \text{Energy}$ d) none of the above

Review Questions II

1.How do alpha, beta and gamma rays differ from each other in terms of their properties?

2.What is the relationship between nuclear binding energy and the stability of a nucleus?

3.Write the equation for the emission of an alpha particle from:

$${}^{226}_{88}\text{Ra}$$

4.Write the equation for the emission of a beta particle from:

$${}^{214}_{92}\text{Pb}$$

5.Write the equation for successive emissions of an alpha particle and a beta particle from:

$${}^{214}_{84}\text{Po}$$

6.What is meant by the half-life of a radioactive element?

7.The half-life of Pm-253 is 4.5 days. What fraction of 1g of Pm would remain after13.5 days?

8.Why are neutrons better particles for bombarding atomic nuclei than protons or alpha particles?

9.What can happen when a neutron is fired at the nucleus of an atom?

10.What is meant by the term *transmutation*?

11.What is a fission reaction?

12. What nucleus is left out of the equation?

$$ {}^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \longrightarrow {}^{143}_{59}\mathrm{Pr} + \qquad + 3\,{}^{1}_{0}\mathrm{n} $$

13. What type of nuclear reaction is:

$$ {}^{2}_{1}\mathrm{H} + {}^{3}_{1}\mathrm{H} \longrightarrow {}^{4}_{2}\mathrm{He} + {}^{1}_{0}\mathrm{n} $$

14. Why do environmentalists complain about thermal pollution from nuclear power stations when it is well known that thermal generation stations (often the only alternative source of power) also gives off heat into the environment?

15. Complete the following nuclear equations:

$$ {}^{31}_{15}\mathrm{P} + {}^{1}_{1}\mathrm{H} \longrightarrow {}^{28}_{14}\mathrm{Si} + $$

$$ {}^{27}_{13}\mathrm{Al} + {}^{4}_{2}\mathrm{He} \longrightarrow \qquad + {}^{1}_{1}\mathrm{H} $$

$$ {}^{23}_{11}\mathrm{Na} + {}^{2}_{1}\mathrm{H} \longrightarrow {}^{1}_{1}\mathrm{H} + $$

$$ {}^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \longrightarrow {}^{90}_{37}\mathrm{Rb} + $$

$$ {}^{2}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} \longrightarrow {}^{4}_{2}\mathrm{He} + $$

$$ {}^{225}_{90}\mathrm{Th} \longrightarrow {}^{4}_{2}\mathrm{He} + $$

$$ {}^{12}_{5}\mathrm{B} \longrightarrow {}^{0}_{-1}\mathrm{e} + $$

16. State which type of nuclear reaction is illustrated by each equation in question 15.

17. Why could you expect ${}^{12}\mathrm{C}$ to behave the same chemically as radioactive ${}^{14}\mathrm{C}$? Explain.

18. Why is there no such thing as a pure radioactive isotope?

19. Why does a nuclear reaction usually involve the conversion of one element into another?

20. Describe a chain reaction and state how the fission of ^{235}U can produce a chain reaction.

21. In the CANDU system, what happens when the heavy water moderator is released into the dump tank? Why?

22. Describe the operation of a CANDU reactor under the following headings: fuel, moderator, controls, and coolant.

23. How many years will be needed for the decay of 15/16 of a given amount of radio-226 with its half-life of 1600 years.

24. The half-life of radon-222 is 3.823 days. After what time will only one-fourth of a given amount of radon remain?

25. The half-life of polonium-0210 is 138.4 days. What fraction remains after 415.2 days?