Nuclear Chemistry for Advanced Inorganic Chemistry

History

In 1895, Wilhelm Röntgen discovered x-rays while studying light from cathode ray tubes. He noticed that a sheet of paper coated with barium glowed when the tube was switched on although the tube was enclosed in a box which blocked the emission of visible light. He concluded that some other type of ray from the tube was penetrating the box. He also found that these rays would fog photographic film. Playing around with these properties led him to take photos of objects such as his hand, discovering that these rays revealed the inner structure of the objects. Since he did not know what they were or where they came from, he called them "x-rays" ("x" for unknown).[1]

In January 1896, these photographs (particularly the bones of a human hand) hit the newspapers and were an immediate sensation. Henri Bequerel heard about these experiments in a January meeting of the Acadèmie des Sciences. Upon questioning he learned that the ray which produced the x-rays was marked by fluorescence of the glass of the discharge tube.[2]

This led Bequerel to explore the relationship between fluorescence and x-rays. His experiment was to wrap a photographic plate in black paper so that light could not penetrate and expose the plate. He would then place a phosphorescent substance on the paper and expose it to the sun for several hours. When the plate was developed, an image of the substance would appear. He also performed experiments with glass between the plate and the phosphorescent compound, preventing the possibility of a chemical interaction.[2]

On the 26th and 27th of February 1896, Becquerel prepared the experiment using "the double salt of potassium uranium sulfate." ($K_2UO_2(SO_4)_2 \cdot 2H_2O$) Unfortunately, the sun refused to shine those days, so he put the prepared plates in a drawer. On March 1st, he decided to develop the unexposed plates anyway, expecting very weak images. To his surprise, the images were very clear. He decided to repeat the experiment, being careful not to expose the plates to light at all. The results were consistent.[2]

Various experiments of this phenomena continued. By May, Becquerel was able to conclude that (1) these rays were very similar to those discovered by Röntgen; (2) unlike fluorescence and phosphorescence, light does not induce these rays or have much effect on them; (3) only uranium produces these rays, but the form of uranium is not important (nonphosphorescent and even metallic uranium produce equally good images).[2]

At this time, Marie and Pierre Curie were working in Becquerel's laboratory. They undertook a study of this phenomena, which they named "radioactivity." They soon discovered that thorium was also radioactive and by following radioactivity clues discovered two new elements: radium and polonium (named for Marie's native country, Poland–Marie *Sklodowska* Curie).[2,3]

Rutherford went in a different direction with Bequerel's discovery. He characterized the rays (a, ß, ?) emanating from these materials. By 1903, he had classified three types of rays based on their relative ionizing and penetrating powers and their interactions with magnetic and electric fields.[2,3]

At this time atomic theory was just being developed, so explanations for this phenomena were not immediately apparent. The discovery of the electron by J.J. Thompson didn't even occur 1897, a year after Becquerel's experiments! However, these discoveries about radioactivity led to or at least influenced the atomic theory which followed: the relationship between mass and energy developed in 1905 by Einstein; Rutherford's nuclear model of the atom in 1911, isotopes were proposed by Frederick Soddy in 1913 and neutrons proposed in 1920 by Rutherford although their existence was not actually proven until James Chadwick's experiments in 1932; Otto Hahn and Fritz Strassman experimentally observed nuclear fission in 1939 although Lise Meitner and O.R. Frisch provided the explanation.[3]

Nuclear theory continues to develop, as does its applications. In the following sections, some of the language and theory of nuclear chemistry is discussed. It is not detailed, but hopefully there is enough information to ask intelligent questions about your specific application.

Nuclear Theory

Nuclear chemistry deals with reactions of the nucleus. Because nuclei are separated by distances much greater than their size (the radius of the nucleus of a heavy atom is 10^{-4} the radius of the entire atom), under ordinary circumstances nuclei do not interact with each other. This includes other atoms within the same molecule as well as other compounds in a mixture. Hence, conditions which are important in traditional chemistry and conditions which are important in nuclear chemistry can be dramatically different (See Table 1.) This requires new terms, theories and even new ways to write equations.

Nuclear Particles. There are two types of fundamental particles, leptons and quarks. Fundamental particles have no size or internal structure.[5] However, these particles probably do have mass (although in some cases it is too small to measure), and may have other properties including electrical charge, spin, color and flavor.[5] Each class of compounds has six types. The types of leptons are electron, electron neutrinos (usually just "neutrino"), tauon, tauon neutrino, muon and muon neutrino. The types of quarks are up, down, strange, charmed, top and bottom. (Selected particles, symbols and properties are listed in Table 2.)

For each of the fundamental particles, there is also an antiparticle. These are denoted by putting a bar over the symbol for the particle. The antiparticle has the same mass and spin as the particle, but differs in charge, color or flavor. An example of an antiparticle is the positron. It is the antiparticle of the electron that differs from the electron by having a positive charge. The collision of a particle with its antiparticle causes complete "annihilation", where the mass of both particles is completely converted to energy.

While leptons exist as isolated particles, quarks are always found in combinations called “hadrons.” Hadrons come in two classes, “mesons” which are a quark-antiquark pair and “baryons” which are composites of three quarks. Protons and neutrons (collectively, “nucleons”) fall into the latter category and are each combinations of up and down quarks. A unusual property of quarks is their fractional electrical charge. An up quark has a +2/3 charge and a down quark a -1/3 charge. A proton is made of two up quarks and one down quark, giving the proton its +1 net charge. A neutron is made of one up quark and two down quarks giving the neutron its zero net charge.[3,5]

Nuclear Forces. There are four basic forces in nature: gravitational, electromagnetic, strong and weak. Strong and weak forces are important only in nuclear interactions, since they only act over very short distances (10^{-13} cm for strong forces, 10^{-16} cm for weak forces).[3]

Gravity effects any substance with mass. However, of these forces, gravity is by far the weakest. Since it can act over extraordinarily long distances, it is important for the movement of plants, stars, etc., but it is not relevant to nuclear chemistry.

Electromagnetic forces affect any substance with charge. It is a relatively strong force which acts over fairly large distances. It is the force which attracts the negatively charged electrons to the positively charged nucleus. However, it is also a force which repels the protons within the nucleus from each other. How then, does nucleus stay together?

Strong forces affect substances with color. This allows them to act on quarks, but not on leptons. For two quarks at 10^{-18} m, this force is 25 times stronger than the electromagnetic force.[5] For two protons in a nucleus, this force is 20 times stronger than the electromagnetic force.[5] This force also has “exchange properties” and can be viewed as mediated by the exchange of mesons. According to the meson exchange theory, nucleons have a virtual meson cloud where mesons called “pions” (or pi-mesons) are constantly exchanged between nucleons[4] causing reactions along the lines of

$$p^{+} + p^{-} \Longleftrightarrow n^{0} \qquad (1)$$

This exchange theory explains some interesting experimental evidence such as the slightly greater mass of a neutron as compared to a proton and the observed decay of a free neutron to a stable proton, electron and antineutrino.[5] Hence, strong forces are what hold the nucleus together.

Weak forces affect substances with flavor, which includes both quarks and leptons. It is 0.8 of the the electromagnetic force[5] and is involved in several nuclear decay processes.[3]

So far, there is no “grand unified theory” to unify and explain all four basic forces. Quantum mechanical theories have unified electromagnetic and weak forces (electroweak theory) and described strong forces (quantum chromodynamics) but they have not been put together.[3,5] Gravity is eluding a quantum mechanical description altogether.[3]

Binding Energies/Nuclear Stability. The mass of a nucleus is not the same as the mass number (the sum of the number of protons and neutrons) or even the sum of the masses of the protons, neutrons and electrons. The mass difference has been converted to the energy which is used to hold the nucleons together. The difference in mass between the actual mass and the sum of the masses of nucleons (?) is called the “mass defect” (or “mass excess”–the absolute value is used) and the energy associated with this mass is the “binding energy.” Einstein’s equation

$$E = mc^2 \tag{2}$$

where E is energy, m is mass and c is the speed of light, can be used to calculate the relationship between mass and energy. Since mass defects are usually calculated in daltons (the modern replacement for atomic mass unit or amu), first exactly one dalton is converted to kilograms

$$1 \text{ dalton } (1 \text{ atom } {}^{12}\text{C}/12 \text{ dalton})(12 \text{ g}/6.022 \times 10^{23} \text{ atoms})(1 \text{ kg}/1000 \text{ g}) = 1.661 \times 10^{-27} \text{ kg} \tag{3}$$

This valued is used in equation 2

$$E = (1.661 \times 10^{-27} \text{ kg})(2.998 \times 10^{8} \text{ m/s})^2 = 1.4925 \times 10^{-10} \text{ kg·m}^2/\text{s}^2 = 1.4925 \times 10^{-10} \text{ J} \tag{4}$$

Since nuclear energies are traditionally calcuated in megaelectron-volts (MeV)

$$1.4925 \times 10^{-10} \text{ J } (1 \text{ eV}/1.602 \times 10^{-19} \text{ J})(1 \text{ MeV}/10^{6} \text{ eV}) = 931.7 \text{ MeV} \qquad (5)$$

To summarize,

$$1 \text{ dalton} = 1.492 \times 10^{-10} \text{ J} = 931.7 \text{ MeV} \qquad (6)$$

More stable atoms will have a higher binding energy per nucleon (typically about 8 MeV/nucleon).

Example 1. What is the binding energy and binding energy per nucleon of the carbon-13 nucleus (actual mass = 13.003354 daltons)?

Carbon-13 has 6 protons and 7 neutrons so

? = 13.003354- [6(1.007825) + 7(1.008665)] = 13.003354 - 13.107605 = 0.104251

0.104251 daltons (931.7 MeV/1 dalton) = 97.1 MeV = binding energy

97.1/13 = 7.5 MeV/nucleon

For stable isotopes, the binding energy per nucleon increases rapidly with mass number until about 50, then it flattens and begins to slowly decrease (See Figure 1). The isotope with the highest binding energy per nucleon is iron-56. Since nucleons are only attracted (via strong force) by their nearest neighbors, at low mass numbers the addition of a nucleon would increase the number of adjacent nucleons, thus the binding energy increases. But at high mass numbers, the number of adjacent nucleons is already maximized and electromagnetic repulsion (which is strong over a distance affecting the entire nucleus) increases since the number of protons is also increasing which would decrease stability of heavy atoms.

Arrangement of Nucleons. There are two major theories which describe the arrangement of nucleons within the nucleus. Each theory is useful to explain various experimental results, but neither is a complete description of the arrangement of nucleons.

Shell Model. This model was developed to explain the observation that certain numbers of protons or neutrons in a nucleus have exceptional stability. This values are called “magic numbers.” This model envisions nucleons arranged in shells similar to the way electrons are arranged in shells around the nucleus. Magic numbers for nucleons are: 2, 8, 20, 28, 50, 82, and 126. Some of the observations explained by the shell model include: elements which have a magic number of protons have a large number of stable isotopes; elements which have a magic number of neutrons have a low neutron-capture cross section; elements which either or both protons and neutrons are magic are the most abundant in their mass range; three of four nuclear decay chains end with a magic number of protons; an a decay to a magic number involves high energy release, whereas an a decay from a magic number is low energy.[3,4]

Liquid Drop Model. This theory treats the nucleus as a drop of liquid. It is a statistical model where properties of the individual nucleons are not considered. Like a drop of water, it is favorable for a nucleus to increase in size, until it reaches a maximum, when it will split. The liquid drop model is particularly useful to explain and predict low energy reactions and fission processes.[3] It is also the basis for "semi-empirical binding energy calculations."[3] This equation was developed by Weiszäcker to explain and predict binding energies of nuclei.

The semiempirical binding energy equation is[4]

$$BE = 14.0A - 0.585(Z^2/A) - 19.3(A-2Z)^2/A - 13.05A^{2/3} \pm 130/A \qquad (7)$$

where A = mass number and Z = atomic number. Each term of equation 7 accounts for a different force affecting the stability of the nucleus. The volume energy term, 14.0A, accounts for the direct dependence of binding energy on the number of nucleons. With an increase in nucleons there is an increase in the strong force between them. The coulomb energy term, $0.585(Z^2/A)$, accounts for the electromagnetic repulsion of the protons. The diffuse boundary correction term, $19.3(A-2Z)^2/A$, is a slight correction for the previous term which accounts for how the protons are distributed among the neutrons. The pairing energy term, 34/A, takes into account added stability for nucleon pairing. The term is positive if there is both an even number of protons and neutrons, negative if the number of both protons and neutrons is odd and zero if one is even and one is odd.

Nuclear Reactions.

In a nuclear reaction, charge, nucleons, bayrons and leptons must be conserved while atoms are not. To be able to show this conservation, it is generally convenient to use isotopic notation. Recall, with this notation, ^{A}E, A is the mass number and E is the symbol of the element or particle. It is also convenient to use "Z" representing the charge (generally equivalent to the number of protons) as a subscript below A, although this is not strictly necessary since the symbol also reflects the charge. Examples of using this notation are shown in Figure 2. Notice that in all the equations, the net value of A (number of nucleons) and the net value of Z (charge) balances. Mass numbers and charges of various radioactive particle are shown in Table 3.

In addition to mass and charge, the number of leptons must be balanced. The effect of this is most commonly encountered in the production of a beta particle (1 lepton) from a nucleus. In this reaction, an antineutrino (-1 lepton) is also produced. Thus, there is a net of zero leptons on each side of the equation. Bayrons must also be conserved. Each quark counts as 1/3 of a bayron (an anti-quark is -1/3). This usually works out without having to check for it specifically.

Generally in nuclear reactions, only nuclei are involved with no involvement of the electron shell. Consequently, nuclear reactions do not attempt to account for these electrons and they are not included. Reactants and products of nuclear reactions are referred to as "nuclides" to differentiate from atoms where the electron shell *is* considered.

One class of nuclear reactions are those induced by bombardment of a nuclide by a radioactive particle. The first experimentally induced nuclear reaction was conducted by Rutherford[3]

$$a + {}^{14}N \longrightarrow {}^{17}O + p \qquad (8)$$

Later, a bombarment induced reaction led Chadwick to discover the neutron

$$a + {}^{9}Be \longrightarrow {}^{12}C + n \qquad (9)$$

Bombardment reactions can also be written a simplified format (nuclear shorthand), where equation 8 would be written as

$$^{14}N(a, p)^{17}O \qquad (10)$$

In this style, the first species outside the parenthesis is the target nucleus, the first species inside the parenthesis is the bombarding particle, the second species in the parenthesis is the smaller mass product and the second species outside the parenthesis is the larger mass product. Using this system, equation 9 would be

$$^{9}Be(a, n)^{12}C \qquad (11)$$

Radioactive decay is the spontaneous emission of particles or electromagnetic radiation due to a transition within the nucleus. There are a variety of decay modes, but the most common are a-decay, ß-decay and ?-decay. Several natural decay chains have been identified (Figure 3). These decay chains include all of these common types of decay, although they primarily consist of a decay.

Alpha Decay. Alpha particles are the same as a helium nucleus. Consequently, an a decay will decrease the mass number of a nuclide by 4 and its atomic number by two. For example,

$$^{210}Po \text{ ----> } a + {}^{206}Pb + ? \qquad (12)$$

(The decay is almost always accompanied by the emission of a gamma ray although that is not always denoted.) The a particle is emitted at an energy characteristic of the reaction. For heavier nuclei, a particle energies range from 5-7 MeV; for lighter nuclei, the range is 1-2.5 MeV. The energy of the a particle (E_a) is related to the half-life of the reaction ($t_{1/2}$) by the Geiger-Nuttall Rule

$$\log t_{1/2} \text{ \% } 1/\log E_a \qquad (13)$$

therefore, the shorter the half-life, the higher the energy. According to theory, nuclides which are subject to a decay will have a mass of greater than 150 daltons. Experimentally, a decay is generally observed in nuclides with more than 83 protons. Some exceptions to this rule are ^{144}Nd, ^{147}Sm and ^{148}Sm.

Beta Decay. Beta particles are the same as an electron. However, unlike an electron, ß particles come from the nucleus! When a ß particle is emitted, the mass remains the same and the atomic number increases by one. For example,

$$^{90}Sr \text{ -----> } ^{90}Y + ß^- + ? \quad (14)$$

notice that along with the emission of a ß particle, an antineutrino is also emitted. This provides conservation of leptons. Unlike a particles, ß particles have a range of energies in a given reaction. This is attributed to variable splitting of the one energy produced by the reaction between the ß particle and the antineutrino. This splitting is evidence for neutrinos having mass (even though it is incredibly small). While there is no specific relationship between the energy of ß particles and half-life (like the Geiger-Nuttall equation for a particles), but generally the energies are higher with shorter half-lives. Nuclides which are subject to ß decay tend to be neutron-rich. This type of reaction is also called "negatron decay."

Positron Decay (also called Beta Plus decay). Position decay and electron capture are also classed as types ß decay, although the effect is opposite that of negatron decay. A positron has all the properties of a ß particle, except that it is positively charged. A positron is considered an antiparticle and therefore counts as -1 lepton. Consequently, positron decay is always accompanied by the emission of a neutrino.

$$^{22}Na \text{ ----> } ^{22}Ne + ß^+ + ? \quad (15)$$

Positrons tend to be hard to detect. As they are ejected from the nucleus, they must pass through the valence electrons and when an antiparticle (positron) meets its equivalent particle (electron) the two species are completely annilhilated.

$$ß^- + ß^+ \text{ —> } ?\text{(energy)} \quad (16)$$

Light, proton-rich nuclides are subject to positron decay.

Electron Capture. Electron capture has the same effect as positron decay (decrease atomic number, no mass change) but a different mechanism. It occurs if there is insufficient energy available to produce a positron decay. In electron capture, an orbital electron is captured by the nucleus and a neutrino is emitted.

$$^{93}Tc + e^{-} \;\text{----->}\; ^{93}Mo + ? \qquad (17)$$

In addition to the neutrino, x-rays, Auger electrons and inner bremmstrahlung radiation might be emitted. x-rays are due to the release of energy as an electron falls from a higher energy orbital into the "hole" created by the electron capture. Auger electrons are low energy orbital electrons emitted as an alternative to an x-ray. Inner bremmstrahlung radiation is a continuous spectrum of low-intensity electromagnetic energy emitted in all ß decay processes. It constitutes some of the energy normally attributed to neutrinos.[3] The most common form of electron capture is "K-capture." This denotes that the electron capture was from the 1s shell. Less common is "L-capture" in which the electron is captured from the 2s or 2p shell. L-capture becomes more probable as the elements get heavier. Electron capture is favored by heavier, proton-rich nuclides.

Gamma Decay. Gamma rays are highly energetic electromagnetic radiation and therefore have no mass nor charge. They emitted when an excited nucleus decays to the ground state. Nuclear reactions generally initially produce excited nuclei, therefore ? decay nearly always accompanies all types of nuclear reactions.

That a nucleus is in an excited state can be denoted in one of two ways: $^{110}Ag^*$ or ^{110m}Ag. The "m" denotes that the silver is in a "metastable" state. Because these excited states are specific, gamma rays are monoenergetic with energies ranging from 2 keV to 7 MeV.

Fission. Fission is the most famous form of radioactive decay, but is actually uncommon. The transuranium elements are the only ones for which a fission decay mode competes significantly with a decay.[3] (Remember, all transuranium elements are artificially produced.) This spontaneous fission is a decay process in which a nucleus breaks into two fragments with the emission of 2-3 neutrons.

$$^{252}Cf \longrightarrow {}^{98}Sr + {}^{152}Nd + 2n \qquad (18)$$

There is also neutron induced fission, which requires the capture of a neutron to initiate the fission process.

$$^{235}U + n \text{ ----> } {}^{140}Ba + {}^{94}Kr + 2n \qquad (19)$$

(This is one of its reactions. Uranium-235 decay actually averages 2.43 neutrons.)

Example 2. Predict the decay mode (write the reaction) for the following nuclides.
a. actinium-235 b. neodymium-151 c. antimony-117

a. With A>150 and Z>82, a decay is predicted

$^{235}Ac \longrightarrow a + {}^{231}Fr$

b. With A> 150, a decay becomes possible, but Z is low for that and A is only a little high...

However it has a much higher mass than the average atomic weight of the element (144.24), indicating an excess of neutrons, therefore negatron decay is predicted.

$^{151}Nd \longrightarrow ß^{-} + {}^{151}Pm + ?$

c. The atomic weight of stable Sb is 121.75 and this isotope is much lower, indicating a neutron poor compound. It could undergo either electron capture or positron decay. It's fairly heavy, so you might predict that electron decay is favored. In fact both occur and either answer would be acceptable.

$^{117}Sb \longrightarrow ? + ß^{+} + {}^{117}Sn$

$^{117}Sb + e \longrightarrow ? + {}^{117}Sn$

Kinetics of Nuclear Decay

Since nuclides are too far apart to interact with each other, *all* nuclear reactions are first order. Recall, a first order reaction is a reaction whose rate depends on the concentration of reactant. The rate law is written as

$$\text{rate} = -d[A]/dt = k[A] \quad (20)$$

where k is the rate constant and [A] is the concentration of reactant. For first order reactions, the half-life ($t_{1/.2}$, time for half of the initial concentration to react) is independent of reactant concentration and related to rate constant by

$$t_{1/2} = \ln 2/k \quad (21)$$

With nuclear chemistry, these concepts are still used, but the terminology is slightly different to account for the lack of collisions between reactants. Thus number of atoms (N) is used instead of concentration which means these calculations on a "per atom" instead of "per mole" basis (leading to different values and units). Instead of rate constant (k), the term decay constant or disintegration constant (?) is used. The rate is referred to as "activity" and is typically in units of disintegrations/s (dps). Consequently, instead of equation 20, the rate law for nuclear reactions is

$$\text{activity} = ?N \quad (22)$$

and half-life is related to activity and disintegration constant by

$$t_{1/2} = \ln 2/? = 0.693/? \quad (23)$$

The units for activity can also be expressed in becquerels (Bq) or curies (Ci) where

$$1 \text{ dps} = 1 \text{ Bq and } 3.7 \text{ X } 10^{10} \text{ dps} = 1 \text{ Ci} \quad (24)$$

One curie is the activity of one gram of radium (which was, of course, discovered by the Curies).

It is not unusual to have to convert between half-life and activity. Half-life is descriptive of the reaction, where activity is related to the effects of the reaction and is measurable. The integrated rate law

for a first order reaction is also useful when considering the effect of time.

$$\ln N_0 - \ln N = ?t \quad \textbf{(25)}$$

Example 3. What is the activity in Bq and mCi of 1.00 mg of ^{252}Cf. Its half-life is 2.64 years. What is its activity in Bq and mCi after 10.0 years?

Since Bq and mCi refer to seconds
2.64 years (365.25 day/1 year)(24 hr/1 day)(60 min/ 1 hr)(60 s/1 hr) = $8.33 \text{ X } 10^{7}$ s

Since activity is calculated per atom
1.00 mg (1 g/1000 mg)(1 mole/252 g)($6.022 \text{ X } 10^{23}$ atoms/1 mole) = $2.39 \text{ X } 10^{18}$ atoms

The decay constant can be calculated from half-life
$t_{1/2}$ = ln 2/? ? = ln 2/$t_{1/2}$? = 0.693/2.64 = 0.263 yr^{-1}
? = 0.693/$8.33 \text{ X } 10^{7}$ = $8.32 \text{ X } 10^{-9}$ s^{-1}

The activity is then determined from the rate law
activity = ?N = ($8.32 \text{ X } 10^{-9}$)($2.39 \text{ X } 10^{18}$) = $1.99 \text{ X } 10^{10}$ dps

Converting to the requested units
$1.99 \text{ X } 10^{10}$ dps = $1.99 \text{ X } 10^{10}$ Bq
$1.99 \text{ X } 10^{10}$ Bq (1 Ci/$3.7 \text{ X}10^{10}$ Bq)(1000 mCi/1 Ci) = $5.4 \text{ X } 10^{2}$ mCi

How much after 10 years, use the integrated rate law
ln ($2.39 \text{ X } 10^{18}$) - ln N = (0.263)(10.0)
ln N = 39.9 N = $2.11 \text{ X } 10^{17}$
and the rate law

Health Physics.

The study of the biological effects of radiation is known as "health physics." Biological effects depend on a variety of factors including type of radiation, distance from source and time of exposure. Consequently, a simple measurement of activity is not sufficient to assess health risks. In addition, radiation can interact with matter in a variety of ways, these include ionization, kinetic energy transfer, molecular and atomic excitation, nuclear reactions and radiative processes.[3] Ionization is the removal of an orbital electron; the ionized products can cause more ionization. This interaction is particularly important for heavy (one dalton or more) particles. Kinetic energy transfers impart kinetic energy to ion pairs (formed in ionization) or through elastic collisions between the radiation and absorbing particle. Molecular and atomic excitation occur when the energy of the interaction is insufficient to cause ionization. As the excited electrons fall back to the ground state, x-rays and Auger electrons may be emitted. Radiative processes are those in which the particle is decelerated by release of electromagnetic radiation such as bremmstrahlung radiation. Any of these events can cause cell damage.

Types of Nuclear Radiation. Nuclear reactions produce many types of radiation which can take the form of charged or uncharged particles or electromagnetic radiation. Therefore, the effects of each type of radiation, the methods of protection from exposure the radiation differ widely.

Alpha rays. Alpha rays are a stream of particles equivalent to a helium-4 nucleus. Consequently, they are massive (as particles go) and highly charged. Because of their large size and charge, they can do substantial damage. Fortunately, their large size also prevents them from being a major health concern. In air, a particles only travel about 2.5 (low energy) to 9 cm (high energy) from the source .[4] In denser materials, the distance is even shorter. The dead skin layers are generally a sufficient barrier for protection from a rays.

The most dangerous (maybe the only dangerous) a emitter is radon. Unlike other a emitters, this atom is a noble gas. As a gas, it can be breathed into the body where the a particles can directly damage the lungs. (i.e., alpha radiation is only a risk from internal exposure.)

Beta Rays. Beta rays are a stream of particles equivalent to an electron. Being less massive, their

effects are less damaging. However, ß particles do tend to travel 500 times further than a particles of the same energy.[4] Thus they also penetrate further into tissues. Still, ß radiation is generally limited to a "skin dose," although there is also an internal exposure risk.

Gamma Rays. Gamma rays are actually very short wavelength electromagnetic radiation (? ~

10^{-3} nm). Hence, they are highly energetic (more so than ultraviolet and even x-rays) with energies mostly between 0.1 and 2 MeV. While only slightly less damaging than ß rays, they are substantially more penetrating and generally require lead for shielding.

Other particles. Protons and neutrons can also be emitted as radioactive particles. While these are less common, both tend to be quite dangerous since they are somewhat massive. Neutrons are particularly hazardous. Since they are uncharged, their penetrating ability is high. While being uncharged means that they don't cause ionization directly, neutrons can induce other nuclear reactions or undergo elastic scattering which does produce charged particles. For example, the collision of a neutron with water can eject a proton.

Units of Measurement. Biological effects of radiation depend on the type of radiation and the amount of radiation to which an organism is exposed. Therefore, in addition to activity (the number of decay events in a given time), the amount of radiation actually received by the absorbing medium and the potential for adverse effects in the medium must also be considered.[3] Consequently, units which take into account these effects of radiation are needed.

Exposure. One of the easiest ways to see the effect of radiation is to measure the extent of ionization, which is often a primary or secondary effect. The amount of ionization can be determined by measuring electrical charge. The total electrical charge produced in a given mass (or volume) of air is called "exposure." The unit of radiation which measures exposure is the röntgen. One röntgen (R) is exactly 2.58 x 10^{-4} C/kg of air.

Dose. The quantity of energy actually put into a medium by incoming radiation is called the "dose." The traditional unit of dose is the "rad" where 1 rad is 0.01 J/kg of tissue. The newer, SI, unit for dose is the gray (Gy) where 1 Gy is 1J/kg of tissue. Therefore, 100 rad = 1 Gy.

One of the problems with this type of measurement is that identical doses of various types of radiation may not have identical effects. To account for the type of radiation, the term "dose equivalent (H)" is used. A dose equivalent has units of "rem" or "sieverts (Sv)."

The effect of the type of radiation is expressed with a "quality factor (Q)." Each type of radiation is assigned a quality factor based on the extent of its biological effects (See Table 3). Some values are still in dispute. To determine the dose equivalent, the dose is multiplied by the quality factor and

$$\text{rem} = Q \times \text{rad} \qquad (26)$$

$$\text{Sv} = Q \times \text{Gy} \qquad (27)$$

It is possible to estimate the dose for ß and ? rays from activity. (Since a rays rarely have biological consequences, a method for determining dose from activity is not commonly used.) For ß rays, the dose (mrads) is estimated from

$$\text{dose/hour} = 338{,}000\ A/d^2 \qquad (28)$$

where, A is the activity (mCi) and d is the distance from the source (cm). For ? rays, the dose (mrad) is estimated by

$$\text{dose/hour} = 6AEn/d^2 \qquad (29)$$

where A is activity (mCi), E is energy of the ? ray (MeV), n is the number of ? rays at that energy and d is the distance (ft). Notice that the units of distance are different for these two equations.

The biological effects of radiation fall into two broad classes, stochastic and nonstochastic effects. Stochastic effects are usually related to long term, low level or "chronic" exposure. Nonstochastic effects are normally related to short term high level exposure or "acute" exposure.

The word "stochastic" refers to an effect which occurs according to the laws of probability, rather than a direct cause and effect relationship. Cancer from smoking is an example of a stochastic event, because while the probability is high that you will get lung cancer from smoking there are many examples of people who do not and those who get lung cancer having never smoked. It is very difficult to accurately measure stochastic events because of their probabilistic nature (which requires a large number of test subjects) and the length of time involved before observable effects occur.

Generally, the higher the dose, the greater the probability of a stochastic event. At low dose levels, however, the relationship is unknown. It is generally assumed that the linear relationship between dose and probability continues without a “threshold level” (dose which does not cause damage). Estimates of the occurrence of radiation-induced stochastic events are based primarily on studies of groups of people exposed to high levels of radiation, specifically: survivors of the atomic bombs dropped on Japan, survivors of nuclear weapons tests, workers in plants using radium-containing paints (for luminous dials on watches) and persons exposed for medical reasons.[3]

Example 4. ^{210}Pb decay emits a ß ray and ? ray (E = 0.0465 MeV) with a half-life of 22.3 years. What is the dose equivalent for a person 1.5 feet from 3.0 µg of this isotope for 30 minutes?

First determine the activity in curies from equation 22

$22.3 \text{ yr } (365.25 \text{ day}/1 \text{ yr})(24 \text{ hr}/1 \text{ day})(3600 \text{ s}/1 \text{ hr}) = 7.04 \times 10^{8} \text{ s}$

$? = \ln 2/7.04 \times 10^{8} \text{ s} = 9.85 \times 10^{-10}$ (eqn 23)

$N = 3.0 \times 10^{-6} \text{ g } (1 \text{ mole}/210 \text{ g})(6.022 \times 10^{23} \text{ atoms}/1 \text{ mole}) = 8.6 \times 10^{15} \text{ atoms}$

$A = ?N = (9.85 \times 10^{-10})(8.6 \times 10^{15}) = 8.5 \times 10^{6} \text{ Bq}$

$8.5 \times 10^{6} \text{ Bq } (1 \text{ Ci}/3.7 \times 10^{10} \text{ Bq})(1000 \text{ mCi}/1 \text{ Ci}) = 0.23 \text{ mCi}$

1.5 ft = 46 cm

for the ß ray

$\text{dose/hr} = 338{,}000(0.23)/(46)^2 = 36.7 \text{ mrad/hr}$

for 1/2 hour = 18 mrad (Q = 1, so 18 mrem)

for the ? ray

$\text{dose/hr} = 6(0.23)(0.0465)(1)/(1.5)^2 = 0.029 \text{ mrad/hr}$

for 1/2 hour = 0.014 mrad (Q = 1, so 0.14 mrem)

total exposure = 18 + 0.014 = 18 mrem

There are three types of stochastic effects, somatic, genetic and teratogenic. Somatic effects are those which affect the person exposed. The most common somatic effect of radiation is cancer, with leukemia the most likely type although breast, thyroid and lung cancer are also common.[3] Genetic effects refers to changes induced in genes which are passed to future children. This has not been observed in humans, but has in some animals.[6] It is now generally accepted that genetic effects are less significant than somatic effects.[6] Teratogenic effects occur when a fetus or embryo is exposed and its development is affected.[6] The most sensitive stage is between the second and tenth weeks of pregnancy, where studies (of rodents) suggest that doses as low as 5 rads may produce gross congenital malformations.[6] Even below 5 rads, the fetus as an increased risk of cancer.[6]

Nonstochastic events do not occur by chance, but are directly related to the causative agent. For nonstochastic events, the higher the dose, the more serious effect. One measure of effect is the LD_{50},which is the dose which causes death in 50% of a population (normally after 30 days, sometimes designated as $LD_{50/30}$). One difference between stochastic and nonstochastic events, is that nonstochastic events do have a threshold value. For many substances, there are doses below the threshold value which actually improve health. For example, it is well known that vitamin D is necessary for good health, yet is has an LD_{50} of 10 mg vitamin/kg body weight which is the same as that for parathion (a pesticide) and sufficient to have it classed as a "poison.." (Government regulating agencies have made an exception for the labeling of vitamins and other assorted food products.) The nonstochastic or acute effects of radiation are listed in Table 4.

Protection from risks associated with radiation is governed (in the United States) by the Nuclear Regulatory Commission (NRC) and the Environmental Protection Agency (EPA). The objectives of these agencies is to prevent nonstochastic events and limit stochastic events (because of their probabilistic nature, complete elimination is impossible).[3] To reach these objectives, radiation exposure is limited by the following principles[3]

> (1) No practice shall be adopted unless its introduction produces a net positive benefit.
> (2) All exposures shall be kept as low as reasonably achievable (ALARA), economic and social factors being taken into account.
> (3) The dose equivalent to individuals shall not exceed the limits recomemmeded for the appropriate circumstances by the Commission.

For the general public, the limit is 500 mrem per person per year.[3] For those who are occupationally exposed, the limit is 5 rem per person per year where the acccumlated dose is limited by 5(N-18), when N is the individual's age in years.[3]

Table 1. Nuclear Chemistry Versus Traditional Chemistry

Traditional	*Nuclear*
reactivity depends primarily on valence electrons, nucleus does not participate	in a reaction, electrons are irrelevant, only nucleus is considered
mass is conserved	mass is converted to energy and back $E = mc^2$
atoms are same on both side	nucleons same on both sides
	energies involved much higher than traditional

Table 2. Properties of Elementary Particles

Class	name	symbol	charge	mass (me*)	other information
photon	gamma	?	0	0	
lepton	neutrino	?	0	0	associated with e or µ
	electron	e,$ß^-$	-1	1	
	positron	$ß^+$	+1	1	
	muon	$µ^{+,-}$	±1	207	µ6 e + ? + ?
hadron					
meson pion		$p^{+,-}$	±1	273.2	p 6 µ + ? (anti if -)
	pion	p^0	0	226.2	p6? + ?
	kaon	K^+, K^-	±1	966.1	
baryon	proton	p	+1	1836	
	neutron	n	0	1838.6	n! p + e + ?

*m_e is the mass of an electron 0.000549 dalton or 9.100 X 10^{-28} g

**neutrinos and antineutrinos have some mass, but it is too small to be measured.

Antiparticles are represented with a bar over the symbol. Charged antiparticles have all the same properties as the regular particle, but are opposite charges. A positron is the antiparticle of an electron.

Table 3. Types of Radioactive Emissions

type	symbol	mass (dalton)	charge	mass #	Q factor	velocity*	penetration
alpha	a	4.0026	+2	4	20	10% c	low
beta	$ß^-$, $^0ß$, ^0e	0.00055	-1	0	1	90% c	low to moderate
positron**	$ß^+$	0.00055	+1	0	1	90% c	low to moderate
gamma	?	0	0	0	1	c	high
proton	^1p	1.0073	+1	1	10	10% c	low to moderate
neutron	$_1n$	1.0087	0	1	2-10	10% c	very high
x-rays	x	0	0	0	1	c	high

* this is the maximum velocity, where c represents the speed of light

** positrons usually only exist for a nanosecond before being annhilated by colliding with an electron and being converted to energy

Table 4. Acute Effects of Radiation[3]

dose (rem)	effect
25-50	number of white blood cells decreases (temporary) temporary sterility
200	damage to bone marrow (not complete and reversible) GI symptons, nausea and vomiting general malaise and fatigue loss of hair some deaths
450	approximate $LD_{50}/30$ (50% of the population exposed to this dose would die in 30 days of exposure
400-600	complete but reversible loss of bone marrow function more severe symptoms as at 200 rem
700	irreversible bone marrow damage survival unlikely
1000	severe diarrhea, nausea and vomiting soon after exposure death probable in 1-2 weeks
2000	central nervous system damaged unconsciousness within minutes, death in hours or days

Appendix 1. Units in Nuclear chemistry

Bequerel (Bq) -- one disintegration per second

Curie (Ci) -- 3.7 X 10^{10} disintegrations per second

Dose -- quantity of energy that is actually put into a medium by the incoming radiation

Does equivalent (H) --- absorbed dose multiplied by the quality factor. Usual unit is “rem”

Exposure (X) ---total electrical charge (ionization) produced in a given mass (or volume) of air

Gray (Gy) -- dose that will deposit one joule of energy in one kilogram of absorbing material

Linear energy transfer (LET) -- rate at which energy is transferred to a given region of matter. Usual units are keV/µm

Quality factor (Q) -- related to LET to account for differences in types of radiation

Rad (rad) -- dose that will deposit 0.01 J of energy in one kilogram of absorbing material

Rem (rem) -- dose in rads times Q; measurement of dose equivalent

Röntgen (R) -- quantity of x of ? radiation that would produce 1 esu of electrical charge in 0.001293 g of dry air (1 cm^3 at STP).

Sievert (Sv) -- measurement of dose equivalent; dose in gray times Q

Equivalents

1 R / 2.58 X 10^{-4} C/kg	for ? rays only, 1 R . 1 rad
1 rad = 10^{-2} J/kg	rem = rad x Q
1 Gy = 1 J/kg = 100 rad	Sv = Gy x Q

For ? rays: Exposure Rate (mR/h) = 6 AEn/d^2

A = activity (mCi); E = energy of ? ray; n number of ? rays of energy E emitted per decay; d = distance to source (ft)

For ß rays: dose rate (mrad/h) = 338000 A/d^2
A = activity (mCi); d = distance (cm)

Appendix 2. Definition of Terms

antiparticle--same mass and spin number as the particle, but different in electric charge, color or flavor

baryon--composite particle consisting of “3 quarks in a bag” e.g., proton, neutron

Becquerel, Henri--discoverer of the radioactivity of uranium in 1896. Nobel Prize in Physics, 1903, with Marie and Pierre Curie

bremmstrahlung-- a continuous spectrum of photon energies in the x-ray region with the maximum energy equal to that of the ß particle (which usually induces it)

color--property of quark, a type of polarization similar to charge

Curie, Marie--Nobel Prize in Chemistry, 1911, for discovery of Po and Ra; Noble Prize in physics, 1903 for discovery and study of radioactivity (with husband, Pierre and Becquerel).

Curie, Irene –Nobel Prize in Chemistry, 1935, for production of artificial radioisotope (with husband, Frederic Joliot). Daughter of Marie Curie.

electron-- a type of lepton, negative charge

elementary particles--have no known internal structure, includes leptons, quarks and elementary vector bosons.

elementary vector bosons--group of elementary particles which mediate the forces that exist between subatomic particles; also called “field particle”

field particle–see elementary vector boson; e.g., photon, gluon, graviton

flavor--property of quark which is related to the amplitude of the photon coupling constant

gluons–elementary vector boson or field particle associated with strong force (parallel to a photon with electromagnetic force).

hadron--composite particle, subject to nuclear strong force

intermediate vector bosons--type of elementary vector boson which mediates the weak force between quarks.

isobars--nuclide having the same mass number, but different numbers of protons

isotones--nuclides that have the same number of neutrons, but a different number of protons

isotope--nuclides that have the same number of protons, but a different number of neutrons

LD_{50}–dose which cause death of 50% of a population

leptons--a group of elementary particles, not subject to nuclear strong force

magic number-- nuclei with this number of protons or neutrons are especially stable: 2, 8, 20, 28, 50 ,82, 126

meson--quark-antiquark pair, mediates strong force between hadrons. e.g., pions, kaons, etc.

muon--type of lepton

neutrino--a lepton, corresponding to electron, muon or tauon

nonstochastic effect– obvious cause and effect relationship

nuclear isomer--nuclides having the same atomic number and mass number but different states of nuclear excitation.

nuclide--atomic species characterized by specific values of the atomic number and mass number

Nuclear chemistry--application of procedure and techniques common to chemistry to study the structure of the nucleus and define the nature of fundamental particles.

nucleon---proton or neutron

neutron capture cross section--measure of probability of a neutron being captured related to a cross-sectional area of a target nucleus

photon-- uncharged, massless quanta of electromagnetic radiation traveling at the speed of light; type of elementary vector bosons which mediates electromagnetic interaction

quarks--group of elementary particles which possess fractional charges.

radioactive--spontaneous decomposition of a nuclide with emission of electromagnetic rays and/or particles

radiation--a form of energy or a particle carrying energy with it

Radiochemistry--application of the phenomenon of radioactive decay and techniques common to nuclear physics to solve problems in the field of chemistry.

Röntgen, Wilhelm C. --discovered x-rays in 1895. Noble Prize in Physics, 1901.

somatic-- disorder affecting the nonreproductive cells; the exposed person is the only one affected

Stochastic Effect-- one which occurs according to the laws of probability

Strong Force--strongest basic force (10^{38} times stronger than gravity), acts over very short distances, around 1 fm.

tauon--type of lepton

threshold level-- dose below which there is no biological effect

teratogenic– affects children exposed as a fetus or embryo

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Figure 1. The Effect of Mass Number on Binding Energy.

Figure 2. Examples of Nuclear Reactions.

Figure 3. Natural Decay Chains.