CHAPTER ONE

INTRODUCTORY CONCEPTS

1.1 INTRODUCTION

Nuclear chemistry consists of a four-pronged endeavor made up of: (a) studies of the chemical and physical properties of the heaviest elements where detection of radioactive decay is an essential part of the work (b) studies of nuclear properties such as structure, reactions, and radioactive decay by people trained as chemists (c) studies of macroscopic phenomena (such as geochronology or astrophysics) where nuclear processes are intimately involved and (d) the application of measurement techniques based upon nuclear phenomena (such as activation analysis or radiotracers) to study scientific problems in a variety of fields. The principal activity or "mainstream" of nuclear chemistry involves those activities listed under (b).

As a branch of chemistry, the activities of nuclear chemists frequently span several traditional areas of chemistry such as organic, analytical, inorganic and physical chemistry. Nuclear chemistry has ties to all branches of chemistry. For example, nuclear chemists are frequently involved with the synthesis and preparation of radio-labeled molecules for use in research or medicine. Nuclear analytical techniques are an important part of the arsenal of the modern analytical chemist. The study of the actinide and transactinide elements has involved the joint efforts of nuclear and inorganic chemists in extending knowledge of the periodic table. Certainly the physical concepts and reasoning at the heart of modern nuclear chemistry are familiar to physical chemists. In this book we will touch on many of these interdisciplinary topics and attempt to bring in familiar chemical concepts.
A frequently asked question is "What are the differences between nuclear physics and nuclear chemistry?" Clearly, the two endeavors overlap to a large extent, and in recognition of this overlap, they are collectively referred to by the catchall phrase "nuclear science." But we believe that there are fundamental, important distinctions between these two fields. Besides the continuing close ties to traditional chemistry cited above, nuclear chemists tend to study nuclear problems in different ways than nuclear physicists. Much of nuclear physics is focussed on detailed studies of the fundamental interactions operating between sub-atomic particles and the basic symmetries governing their behavior. Nuclear chemists, by contrast, have tended to focus on studies of more complex phenomena where "statistical behavior" is important. Nuclear chemists are more likely to be involved in applications of nuclear phenomena than nuclear physicists, although there is clearly a considerable overlap in their efforts. Some problems, such as the study of the nuclear fuel cycle in reactors or the migration of nuclides in the environment, are so inherently chemical that they involve chemists almost exclusively.

One term that is frequently associated with nuclear chemistry is that of radiochemistry. The term radiochemistry refers to the chemical manipulation of radioactivity and associated phenomena. All radiochemists are, by definition, nuclear chemists, but not all nuclear chemists are radiochemists. Many nuclear chemists use purely non-chemical, i.e., physical techniques to study nuclear phenomena, and thus, their work is not radiochemistry.

1.2 THE ATOM
Before beginning a discussion of nuclei and their properties, we need to understand the environment in which most nuclei exist, i.e., in the center of atoms. In elementary chemistry, we learn that the atom is the smallest unit a chemical element can be divided into that retains its chemical properties. As we know from our study of chemistry, the radii of atoms are approximately $1-5 \times 10^{-10}$ m, i.e., 1-5 Å. At the center of each atom we find the nucleus, a small object ($r \approx 1-10 \times 10^{-15}$ m) that contains almost all the mass of the atom (Figure 1.1). The atomic nucleus contains $Z$ protons where $Z$ is the atomic number of the element under study. $Z$ is equal to the number of protons and thus the number of positive charges in the nucleus. The chemistry of the element is controlled by $Z$ in that all nuclei with the same $Z$ will have similar chemical behavior. The nucleus also contains $N$ neutrons where $N$ is the neutron number. Neutrons are uncharged particles with masses approximately equal to the mass of a proton ($\sim 1$ u.) The protons have a positive charge equal to that of an electron. The overall charge of a nucleus is $+Z$ electronic charge units.

Most of the atom is empty space in which the electrons surround the nucleus. (Electrons are small, negatively charged particles with a charge of $-1$ electronic charge units and a mass of about $1/1840$ of the proton mass.) The negatively charged electrons are bound by an electrostatic (Coulombic) attraction to the positively charged nucleus. In a neutral atom, the number of electrons in the atom equals the number of protons in the nucleus.

Quantum mechanics tells us that only certain discrete values of $E$, the total electron energy, and $J$, the angular momentum of the electrons are allowed. These discrete states have been depicted in the familiar semi-classical picture of the atom (Figure 1.1) as a tiny
nucleus with electrons rotating about it in discrete orbits. In this book, we will examine nuclear structure and will develop a similar semiclassical picture of the nucleus that will allow us to understand and predict a large range of nuclear phenomena.

1.3 ATOMIC PROCESSES

The sizes and energy scales of atomic and nuclear processes are very different. These differences allow us to consider them separately.

1.3.1 Ionization

Suppose one atom collides with another atom. If the collision is inelastic, (the kinetic energies of the colliding nuclei are not conserved), one of two things may happen. They are: (a) excitation of one or both atoms to an excited state involving a change in electron configuration or (b) ionization of atoms, i.e., removal of one or more of the atom’s electrons to form a positively

Figure 1-1. Schematic representation of the relative sizes of the atom and the nucleus.
charged ion. For ionization to occur, an atomic electron must receive an energy that is at least equivalent to its binding energy, which for the innermost or K electrons, is $(Z_{\text{eff}}/137)^2(255.5)\text{ keV}$, where $Z_{\text{effective}}$ is the effective nuclear charge felt by the electron (and includes the effects of screening of the nuclear charge by other electrons). This effective nuclear charge for K-electrons can be approximated by the expression $(Z - 0.3)$. As one can see from these expressions, the energy necessary to cause ionization far exceeds the kinetic energies of gaseous atoms at room temperature. Thus, atoms must be moving with high speeds (as the result of nuclear decay processes or acceleration) to eject tightly bound electrons from other atoms.

1.3.2 X-ray Emission
The term "X-ray" refers to the electromagnetic radiation produced when an electron in an outer atomic electron shell drops down to fill a vacancy in an inner atomic electron shell (Figure 1.2), such as going from the M shell to fill a vacancy in the L shell. The electron loses potential energy in this transition (in going to a more tightly bound shell) and radiates this energy in the form of X-rays. (X-rays are not to be confused with generally more energetic γ-rays which result from transitions made by the neutrons and protons in the nucleus of the atom, not in the atomic electron shells.) The energy of the X-ray is given by the difference in the binding energies of the electrons in the two shells, which, in turn, depends on the atomic number of the element. Thus X-ray energies can be

Figure 1-2. Schematic diagram to show x ray emission to fill vacancy caused by nuclear decay. An L-shell electron (A) is shown filling a K-shell vacancy (B). In doing so, it emits a characteristic K x ray.
used to determine the atomic number of the elemental constituents of a material and are also regarded as conclusive proof of the identification of a new chemical element.

In x-ray terminology, X-rays due to transitions from the L to K shell are called $K_\alpha$ X-rays; X-rays due to transitions from the M to K shells are called $K_\beta$ X-rays. [In a further refinement, the terms $K_{\alpha_1}$, $K_{\alpha_2}$ refer to X-rays originating in different subshells ($2p_{3/2}$, $2p_{1/2}$) of the L shell.] X-rays from M to L transitions are $L_\alpha$ X-rays, etc. For each transition, the changes in orbital angular momentum, $\Delta \ell$, and total angular momentum, $\Delta j$, are required to be

$$\Delta \ell = \pm 1$$
$$\Delta j = 0, \pm 1$$

1-1

The simple Bohr model of the hydrogen-like atom (one electron only) predicts that the X-ray energy or the transition energy, $\Delta E$, is given as

$$\Delta E = E_{\text{final}} - E_{\text{initial}} = R_\infty \ h \ c \ Z^2 \left( \frac{1}{n_{\text{initial}}^2} - \frac{1}{n_{\text{final}}^2} \right)$$

1-2

where $R_\infty$, $h$, $c$, and $n$ denote the Rydberg constant, Planck's constant, the speed of light, and the principal quantum number for the orbital electron, respectively. Since the X-ray energy, $E_x$, is actually $-\Delta E$, we can write (after substituting values for the physical constants)

$$E_x = 13.6 \ Z^2 \left[ \frac{1}{n_{\text{final}}^2} - \frac{1}{n_{\text{initial}}^2} \right] \text{eV}$$

1-3
where $E_x$ is given in units of electron volts (eV).

For $K_\alpha$ X-rays from ions with only one electron

$$E_x^K = 13.6 \left( \frac{1}{1^2} - \frac{1}{2^2} \right) Z^2 \text{ eV}$$

while for $L_\alpha$ X-rays, we have

$$E_x^L = 13.6 \left( \frac{1}{2^2} - \frac{1}{3^2} \right) Z^2 \text{ eV}$$

In reality, many electrons will surround the nucleus and we must replace $Z$ by $Z_{\text{effective}}$ to reflect the screening of the nuclear charge by these other electrons. This correction was done by Moseley who showed that the frequencies, $\nu$, of the $K_\alpha$ series X-rays could be expressed as

$$\nu^{1/2} = \text{const} \ (Z - 1)$$

while for $L_\alpha$ series X-rays

$$\nu^{1/2} = \text{const} \ (Z - 7.4)$$

Moseley thus demonstrated the X-ray energies ($=h\nu$) depend on the square of some altered form (due to screening) of the atomic number. Also, the relative intensities of the $K_{\alpha 1}$, $K_{\alpha 2}$, etc, X-rays will be proportional to the number of possible ways to make the transition. 

Thus, we expect the $K_{\alpha 1}/K_{\alpha 2}$ intensity ratio to be $\sim 2$ as the maximum number of electrons in the $2p_{3/2}$ level is four while the maximum number of electrons in the $2p_{1/2}$ level is two.
The relative intensities of different X-rays depend on the chemical state of the atom, its oxidation state, bonding with ligands, etc. and other factors that affect the local electron density. These relative intensities are, thus, useful in chemical speciation studies. We should also note, as discussed extensively in Chapters 7-9, that X-ray production can accompany radioactive decay. Radioactive decay modes, such as electron capture or internal conversion, directly result in vacancies in the atomic electron shells. The resulting X-rays are signatures that can be used to characterize the decay modes and/or the decaying species.

1.4 THE NUCLEUS-NOMENCLATURE

A nucleus is said to be composed of nucleons, the neutrons and the protons. A nucleus with a given number of protons and neutrons is called a nuclide. The atomic number $Z$ is the number of protons in the nucleus while $N$, the neutron number, is used to designate the number of neutrons in the nucleus. The total number of nucleons in the nucleus is $A$, the mass number. Obviously $A = N + Z$. Note that $A$, the number of nucleons in the nucleus, is an integer while the actual mass of that nucleus, $m$, is not an integer.

Nuclides with the same number of protons in the nucleus but with differing numbers of neutrons are called isotopes. (This word comes from the Greek iso + topos, meaning "same place" and referring to the position in the periodic table.) Isotopes have very similar chemical behavior because they have the same electron configurations. Nuclides with the same number of neutrons in the nucleus, $N$, but differing numbers of protons, $Z$, are referred to as isotones. Isotones have some nuclear properties that are similar in analogy
to the similar chemical properties of isotopes. Nuclides with the same mass number, A, but differing numbers of neutrons and protons are referred to as *isobars*. Isobars are important in radioactive decay processes. Finally, the term *isomer* refers to a nuclide in an excited nuclear state that has a measurable lifetime (>10^-9 s). These labels are straightforward, but one of them is frequently misused, *i.e.*, the term "isotope." For example, radioactive nuclei (radionuclides) are often *incorrectly* referred to as radioisotopes, even though the nuclides being referenced do not have the same atomic numbers.

The convention for designating a given nuclide (with Z protons, N neutrons) is to write:

\[
\begin{array}{c}
A \\
\text{Chemical Symbol} \\
Z \\
N
\end{array}
\]

with the relative positions indicating a specific feature of the nuclide. Thus, the nucleus with 6 protons and 8 neutrons is \(^{6}\text{14C}_8\), or completely equivalently, \(^{14}\text{C}\). (The older literature used the form \(Z^N\text{Chemical Symbol}\), so \(^{14}\text{C}\) was designated as \(\text{C}^{14}\). This nomenclature is generally extinct.) Note that sometimes the atomic charge of the entity containing the nuclide is denoted as an upper right hand superscript. Thus a doubly ionized atom containing a Li nucleus with 3 protons and 4 neutrons and only one electron is designated sometimes as \(^7\text{Li}^{2+}\).

**Sample Problem 1.1**

Consider the following nuclei:

\(^{60}\text{Co}^m, \text{^{14C}}, \text{^{14N}}, \text{^{12C}}, \text{^{13N}}\)
Which are isotopes? isotones? isobars? isomers?

Answer:

\(^{60}\text{Co}\) is the isomer, \(^{14}\text{C}\) and \(^{12}\text{C}\) are isotopes of C, \(^{13}\text{N}\) and \(^{14}\text{N}\) are isotopes of N, \(^{14}\text{C}\) and \(^{14}\text{N}\) are isobars (A=14), while \(^{12}\text{C}\) and \(^{13}\text{N}\) are isotones (N=6).

We can now make an estimate of two important quantities, the size and the density of a typical nucleus. We can say

\[
\rho \equiv \text{density} = \frac{\text{mass}}{\text{volume}} \approx \frac{A \text{ amu}}{\frac{4}{3}\pi R^3}
\]

1-8

if we assume that the mass of each nucleon is about 1 u and the nucleus can be represented as a sphere. It turns out (Chapter 2) that a rule to describe the radii of stable nuclei is that radius R is

\[
R = 1.2 \times 10^{-13} A^{1/3} \text{ cm}
\]

1-9

Thus we have

\[
\rho = \frac{(A \text{ u})(1.66 \times 10^{-24} \text{ g/u})}{\frac{4}{3}\pi (1.2 \times 10^{13} A^{1/3} \text{ cm})^3}
\]

where we have used the value of 1.66x10^{-24} g for 1 u (Appendix A). Before evaluating the density \(\rho\) numerically, we note that the A factor cancels in the expression, leading us to conclude that all nuclei have approximately the same density. This is similar to the situation with different sized drops of a pure liquid. All of the molecules in a drop interact with each other with the same short-range forces and the overall drop size grows with the
number of molecules. Evaluating this expression and converting to convenient units, we have

\[ \rho \approx 200,000 \text{ metric tons/mm}^3 \]

A cube of nuclear matter that is one mm on a side contains a mass of 200,000 tonnes.

WOW! Now we can realize what all the excitement about the nuclear phenomena is about. Think of the tremendous forces that are needed to hold matter together with this density. Relatively small changes in nuclei (via decay or reactions) can release large amounts of energy. (From the point of view of the student doing calculations with nuclear problems, a more useful expression of the nuclear density is 0.14 nucleons/fm³.)
1.5 SURVEY OF NUCLEAR DECAY TYPES

Nuclei can emit radiation spontaneously. The general process is called radioactive decay. While this subject will be discussed in detail in Chapters 3, 7, 8 and 9, we need to know a few general ideas about these processes right away (which we can summarize below).

Radioactive decay usually involves one of three basic types of decay, α-decay, β-decay or γ-decay in which an unstable nuclide spontaneously changes into a more stable form and emits some radiation. In Table 1.1, we summarize the basic features of these decay types.

The fact that there were three basic decay processes (and their names) was discovered by Rutherford. He showed that all three processes occur in a sample of decaying natural uranium (and its daughters). The emitted radiations were designated α, β, and γ to denote the penetrating power of the different radiation types. Further research has shown that in α-decay, a heavy nucleus spontaneously emits a $^4\text{He}$ nucleus (an α-particle). The emitted α-particles are monoenergetic and as a result of the decay, the parent nucleus loses two protons and two neutrons and is transformed into a new nuclide. All nuclei with $Z>83$ are unstable with respect to this decay mode.

Nuclear beta decay occurs in three ways, $\beta^-$, $\beta^+$ and electron capture (EC). In these decays, a nuclear neutron (proton) changes into a nuclear proton (neutron) with the ejection of neutrinos (small neutral particles) and electrons (or positrons). (In electron capture, an orbital electron is captured by the nucleus, changing a proton into a neutron
with the emission of a neutrino.) The total number of nucleons, \( A \), in the nucleus does not change in these decays, only the relative number of neutrons and
### Table 1.1

Characteristics of Radioactive Decay

<table>
<thead>
<tr>
<th>Decay Type</th>
<th>Emitted Particle</th>
<th>$\Delta Z$</th>
<th>$\Delta N$</th>
<th>$\Delta A$</th>
<th>Typical Energy of Emitted Particle</th>
<th>Example</th>
<th>Occurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>$^4$He$^{++}$</td>
<td>-2</td>
<td>-2</td>
<td>-4</td>
<td>$4&lt; E_\alpha &lt;10 \text{ MeV}$</td>
<td>$^{238}\text{U} \rightarrow ^{234}\text{Th}+\alpha$</td>
<td>Z&gt;83</td>
</tr>
<tr>
<td>$\beta^+$</td>
<td>energetic e$^-$, $\nu_e$</td>
<td>+1</td>
<td>-1</td>
<td>0</td>
<td>$0&lt; E_{\beta^+} &lt;2 \text{ MeV}$</td>
<td>$^{14}\text{C} \rightarrow ^{14}\text{N}+\beta^- + \nu_e$</td>
<td>N/Z&gt;(N/Z)$_{\text{stable}}$</td>
</tr>
<tr>
<td>$\beta^-$</td>
<td>energetic e$^+$, $\nu_e$</td>
<td>-1</td>
<td>+1</td>
<td>0</td>
<td>$0&lt; E_{\beta^-} &lt;2 \text{ MeV}$</td>
<td>$^{22}\text{Na} \rightarrow ^{22}\text{Ne}+\beta^-+\nu_e$</td>
<td>(N/Z)&lt;(N/Z)$_{\text{stable}}$; light nuclei</td>
</tr>
<tr>
<td></td>
<td>$\nu_e$</td>
<td>-1</td>
<td>+1</td>
<td>0</td>
<td>$0&lt; E_\nu &lt;2 \text{ MeV}$</td>
<td>$e+^{207}\text{Bi} \rightarrow ^{207}\text{Pb}+\nu_e$</td>
<td>(N/Z)&lt;(N/Z)$_{\text{stable}}$; heavy nuclei</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>photon</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>$0.1&lt; E_\gamma &lt;2 \text{ MeV}$</td>
<td>$^{60}\text{Ni}^* \rightarrow ^{60}\text{Ni} + \gamma$</td>
<td>Any excited nucleus</td>
</tr>
<tr>
<td>IC</td>
<td>electron</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>$0.1&lt; E_e &lt;2 \text{ MeV}$</td>
<td>$^{125}\text{Sb}^m \rightarrow ^{125}\text{Sb} + e^-$</td>
<td>Cases where $\gamma$ emission is inhibited</td>
</tr>
</tbody>
</table>

Protons. In a sense, this process can “correct” or “adjust” an imbalance between the number of neutrons and protons in a nucleus. In $\beta^+$ and $\beta^-$ decays, the decay energy is shared between the emitted electrons, the neutrinos and the recoiling daughter nucleus. Thus, the energy spectrum of the emitted electrons and neutrinos is continuous ranging from zero to the decay energy. In EC decay, essentially all the decay energy is carried away by the emitted neutrino. Neutron-rich nuclei decay by $\beta^-$ decay while proton-rich nuclei decay by $\beta^+$ or EC decay. $\beta^+$ decay is favored in the light nuclei and requires the decay energy to be greater than 1.02 MeV (for reasons to be discussed later) while EC decay is found mostly in the heavier nuclei.
Nuclear electromagnetic decay occurs in two ways, $\gamma$-decay and internal conversion (IC). In $\gamma$-ray decay a nucleus in an excited state decays by the emission of a photon. In internal conversion the same excited nucleus transfers its energy, radiationlessly to an orbital electron that is ejected from the atom. In both types of decay, only the excitation energy of the nucleus is reduced with no change in the number of any of the nucleons.

**Sample Problem 1.2**

Because of the conservation of the number of nucleons in the nucleus and conservation of charge during radioactive decay (Table 1.1), it is relatively easy to write and balance nuclear decay equations. For example, consider

- the $\beta^-$ decay of $^{90}$Sr
- the $\alpha$ decay of $^{232}$Th
- the $\beta^+$ decay of $^{62}$Cu
- the EC decay of $^{256}$Md

These decay equations can be written, using Table 1.1, as

\[
\begin{align*}
^{90}\text{Sr} & \rightarrow ^{90}\text{Y}^* + \beta^- + \bar{\nu}_e \\
^{232}\text{Th} & \rightarrow ^{228}\text{Ra} + ^4_2\text{He} \\
^{62}\text{Cu} & \rightarrow ^{62}\text{Ni}^* + \beta^+ + \nu_e \\
e^- + ^{256}\text{Md} & \rightarrow ^{256}\text{Fm}^- + \nu_e
\end{align*}
\]

Besides its qualitative description, radioactive decay has an important quantitative description. Radioactive decay can be described as a first order reaction, *i.e.*, the number of decays is proportional to the number of decaying nuclei present. It is described by the integrated rate law

\[
N = N_0 e^{-\lambda t}
\]
where $N$ is the number of nuclei present at time $t$ while $N_0$ is the number of nuclei present at time $t=0$. The decay constant $\lambda$, a characteristic of each nucleus, is related to the half-life, $t_{1/2}$, by

$$\lambda = \ln 2 / t_{1/2}$$

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The half-life is the time required for the number of nuclei present to decrease by a factor of 2. The number of decays that occur in a radioactive sample in a given amount of time is called the activity $A$ of the sample. The activity is equal to the number of nuclei present, $N$, multiplied by the probability of decay per nucleus, $\lambda$, i.e., $A=\lambda N$. Therefore, the activity will also decrease exponentially with time, i.e.,

$$A = A_0 e^{-\lambda t}$$

1-12

where $A$ is the number of disintegrations per unit time at time $t$ and $A_0$ is the activity at time $t=0$.

The half-lives of nuclei with respect to each decay mode are often used to identify the nuclei.

Sample Problem 1.3

$^{14}\text{C}$ decays to $^{14}\text{N}$ by $\beta$-decay with a half-life of 5730 years. If a one-gram sample of carbon contains 15.0 disintegrations per minute, what will be its activity after 10,000 years?

Solution:

$$A = A_0 e^{-\lambda t}$$

$$\lambda = \frac{\ln 2}{5730 \text{ years}} = 1.210 \times 10^{-4} \text{ year}^{-1}$$
\[
A = (15 \text{ dis/min}) e^{-(1.21 \times 10^{-4})(10,000)} = 4.5 \text{ dis/min}
\]

All living things maintain a constant level of $^{14}$C per gram of carbon through exchange with their surroundings. When they die, this exchange stops and the amount of $^{14}$C present decreases exponentially with time. A measurement of the $^{14}$C content of a dead object can be used to determine the age of the object. This process and other geologically important decay processes are discussed in Chapter 3.

### 1.6 MODERN PHYSICAL CONCEPTS NEEDED IN NUCLEAR CHEMISTRY

While we shall strive to describe nuclear chemistry without using extensive mathematics and physics, there are several important concepts from modern physics that we need to review because we will use these concepts in our discussions.

#### 1.6.1 Types of Forces in Nature

Let us review briefly some physical concepts that we shall use in our study of nuclear chemistry. First, we should discuss the types of forces found in nature. There are four fundamental forces in nature (Table 1.2). All the interactions in the universe are the result of these forces. The weakest force is gravity, which is most significant when the interacting objects are massive, such as planets, stars, etc. The next strongest force is the weak interaction, which is important in nuclear β decay. The familiar electromagnetic force, which governs most behavior in our sensory world, is next in strength while the nuclear or strong interaction is the strongest force. Please note, as indicated earlier in our discussion of nuclear densities, that the strong or nuclear force is more than 100 times stronger than the electromagnetic force holding atoms together.

### Table 1.2

Types of Force Encountered in Nature
<table>
<thead>
<tr>
<th>Force</th>
<th>Range (m)</th>
<th>Relative Strength</th>
<th>Force Carrier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravitational</td>
<td>$\infty$</td>
<td>$10^{-38}$</td>
<td>Graviton</td>
</tr>
<tr>
<td>Weak</td>
<td>$10^{-18}$</td>
<td>$10^{-5}$</td>
<td>$W^\pm, Z^0$</td>
</tr>
<tr>
<td>Electromagnetic</td>
<td>$\infty$</td>
<td>$\alpha=1/137$</td>
<td>Photon</td>
</tr>
<tr>
<td>Strong</td>
<td>$10^{-15}$</td>
<td>1</td>
<td>Gluon</td>
</tr>
</tbody>
</table>

In the 19th century, electricity and magnetism were linked together. The 20th century has seen the demonstration that the electromagnetic and weak forces are just two different aspects of the same force, called the electroweak force. Current efforts are directed at unifying the strong and electroweak forces in a so-called *grand unified theory* or GUT. The final step in this direction would be to include gravity in a *theory of everything*. Discussion of these unified
theories is beyond the scope of this book; however, the relative strength and character of the forces will form an important part of our discussion of nuclear phenomena.

1.6.2 Elementary Mechanics

Let us recall a few elementary relationships from classical physics that we shall use.

Force can be represented as a vector, $\vec{F}$, that describes the rate of change of the momentum with time:
\[ \vec{F} = \frac{d\vec{p}}{dt} \]

where the momentum \( p = mv \) and where \( m \) is the mass and \( v \) is the velocity of the particle.

Neglecting relativistic effects (section 1.6.3) that are important for particles whose velocity approaches the speed of light, we can say that the kinetic energy of a moving body \( T \) is given as

\[ T = \frac{1}{2}mv^2 \]

1-14

For the situation depicted in Figure 1.3 for the motion of a particle past a fixed point, we can say that the orbital angular momentum of the particle, \( \ell \), with mass \( m \) with respect to the point \( Q \) is

\[ \vec{\ell} = \vec{r} \times \vec{p} \]

1-15

The quantity \( \vec{\ell} \) is a vector whose magnitude is \( mvr \) for circular motion.

For motion past a stationary point, the magnitude is \( mvb \) where \( b \) is the distance of closest approach called the impact parameter.

Let us also recall the relationship between the magnitude of a force \( F(r) \) that depends on the distance between two objects, \( r \), and the potential energy, \( V(r) \), i.e.,

\[ F = -\frac{\partial V}{\partial r} \]

1-16

Thus, if the Coulomb potential energy between two charged objects is given as
where $r_{12}$ is the distance separating charges $q_1$ and $q_2$ (and where $k$ is a constant), we can say the magnitude of the Coulomb force, $F_c$, is

$$F_c = \frac{-\partial V}{\partial r} = \frac{k q_1 q_2}{r_{12}^2}$$

Since forces are usually represented as vectors, it is more convenient when discussing nuclear interactions to refer to the scalar, potential energy. From the above discussion, we should always remember that a discussion of potential energy $V(r)$ is also a discussion of force $F(r)$.

### 1.6.3 Relativistic Mechanics

As Einstein demonstrated, when a particle moves with a velocity approaching that of light, the classical relations (Section 1.6.2) describing its motion in a stationary system are no longer valid. Nuclear processes frequently involve particles with such high velocities. Thus we need to understand the basic elements of relativistic mechanics. According to the special theory of relativity, the mass of a moving particle changes with speed according to the equation

$$m^* = \gamma m_0$$
where $m'$ and $m_0$ are the mass of a particle in motion and at rest, respectively. The Lorentz factor, $\gamma$, is given as

$$\gamma = (1 - \beta^2)^{-1/2}$$

where $\beta$ is the speed of the particle, $v$, relative to the speed of light, $c$, i.e., $\beta = v/c$. Thus, as the speed of the particle increases, the mass also increases; making further increases in speed more difficult. Since the mass $m'$ cannot be imaginary, no particle can go faster than the speed of light. The total energy of a particle, $E_{TOT}$, is given as

$$E_{TOT} = m'c^2$$

Since the total energy equals the kinetic energy plus the real mass energy, we can write

$$E_{TOT} = T + m_0c^2$$

where $T$ is the particle’s kinetic energy. Thus

$$T = (\gamma - 1) m_0 c^2$$

The space-time coordinates $(x,y,z,t)$ of a point in a stationary system are, according to the special theory of relativity, related to the space-time coordinates in a system moving along the x-axis $(x', y', z', t)$ by the relations:

$$x' = \gamma (x - \beta ct)$$
$$y' = y$$
$$z' = z$$
\[ t' = \gamma \left( t - \left( \frac{\beta}{c} \right) x \right) \]

These transformations from the stationary to the moving frame are called the Lorentz transformations. The inverse Lorentz transformation is obtained by reversing the sign of \( v \), so that

\[
\begin{align*}
  x &= \gamma \left( x' + \beta c t' \right) \\
  y &= y' \\
  z &= z' \\
  t &= \gamma \left( t' + \left( \frac{\beta}{c} \right) x' \right) \\
  \Delta t &= t_1 - t_2 = \gamma (\Delta t' + (\beta/c) \Delta x) \\
  \Delta x &= \Delta x' / \gamma
\end{align*}
\]

Since \( \gamma > 1 \), time is slowed down for the stationary observer and distance in the x direction is contracted.

One application of these equations in nuclear chemistry involves the decay of rapidly moving particles. The muon, a heavy electron, has a lifetime, \( \tau \), at rest, of 2.2 \( \mu \)sec. When the particle has a kinetic energy of 100 GeV (as found in cosmic rays), we observe a lifetime of \( \gamma \tau \) or about \( 10^3 \) \( \tau \). (This phenomenon is called time dilation and explains why such muons can reach the surface of the earth).

A series of relationships have been derived between the stationary coordinate system (the scientist in his or her laboratory) and a moving (intrinsic, invariant) coordinate system which can be compared to classical calculations of dynamic variables (Table 1.3).
<table>
<thead>
<tr>
<th>Classical Expression</th>
<th>Relativistic Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>( x )</td>
<td>( x = \gamma(x' + \beta ct') )</td>
</tr>
<tr>
<td>( y )</td>
<td>( y = y' )</td>
</tr>
<tr>
<td>( z )</td>
<td>( z = z' )</td>
</tr>
<tr>
<td>( t )</td>
<td>( t = \gamma(t' + \beta/c x') )</td>
</tr>
<tr>
<td>( \Delta t = t_2 - t_1 )</td>
<td>( \Delta t' = \gamma \Delta t )</td>
</tr>
<tr>
<td>mass ( m )</td>
<td>( m = \gamma m_0 ) (( m_0 ) = rest mass)</td>
</tr>
<tr>
<td>momentum ( p = mv )</td>
<td>( p = \gamma mv )</td>
</tr>
<tr>
<td>( T ) ( \circ ) kinetic energy = ( \frac{1}{2}mv^2 )</td>
<td>( T = (\gamma - 1) m_0 c^2 )</td>
</tr>
<tr>
<td>total energy ( E_{TOT} = E_k ) (free particle)</td>
<td>( E_{TOT} = \gamma m_0 c^2 )</td>
</tr>
<tr>
<td>energy momentum relationship ( E = \frac{p^2}{2m} )</td>
<td>( E_{TOT}^2 = p^2c^2 + m_0^2c^4 )</td>
</tr>
</tbody>
</table>
Note that for a particle at rest

\[ E_{\text{TOT}} = m_0 c^2 \]  

1-26

where \( m_0 \) is the rest mass and \( c \), the speed of light. For a massless particle, such as a photon, we have

\[ E_{\text{TOT}} = pc \]  

1-27

where \( p \) is the momentum of the photon. These equations make it clear why the units of MeV/c\(^2\) for mass and MeV/c for momentum are useful.

An important question is when do we use classical expressions and when do we use relativistic expressions? A convenient, but arbitrary criterion for making this decision is to use the relativistic expression when \( \gamma \geq 1.1 \). This corresponds roughly to a 13% error in the classical expression. What does this criterion mean, in practice? In Table 1.4, we indicate the values of the kinetic energy at which \( \gamma = 1.1 \) for different particles.
Table 1.4
When Does One Use Relativistic Expressions?

<table>
<thead>
<tr>
<th>Particle</th>
<th>T (MeV) when γ=1.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>γ, ν</td>
<td>0</td>
</tr>
<tr>
<td>e</td>
<td>0.051</td>
</tr>
<tr>
<td>μ</td>
<td>11</td>
</tr>
<tr>
<td>π</td>
<td>14</td>
</tr>
<tr>
<td>p, n</td>
<td>94</td>
</tr>
<tr>
<td>d</td>
<td>188</td>
</tr>
<tr>
<td>α</td>
<td>373</td>
</tr>
</tbody>
</table>

Thus, one should always use the relativistic expressions for photons, neutrinos, and electrons (when $T_e > 50$ keV) or for nucleons when the kinetic energy/nucleon exceeds 100 MeV.

Sample Problem 1.4 - Relativistic Mechanics

Consider a $^{20}\text{Ne}$ ion with a kinetic energy of 1 GeV/nucleon. Calculate its velocity, momentum and total energy.

Solution:

Total kinetic energy = 20 x 1 GeV/nucleon = 20 GeV = 20,000 MeV
But we know: $T = (\gamma - 1)m_o c^2$

The rest mass is approximately 20 u or (20)(931.5) MeV/c or 18630 MeV. So we can say

$$\gamma = \frac{T}{m_o c^2} + 1 = 1 + \frac{20000}{18630} = 2.07$$

But we know

$$\gamma = (1 - \beta^2)^{-\frac{1}{2}}$$
So we can say
\[ \beta = \left( 1 - \frac{1}{\gamma^2} \right)^{1/2} = 0.88 \]

So the velocity \( v \) is 0.88c or \((0.88)(3.00 \times 10^8 \text{ m/s}) = 2.6 \times 10^8 \text{ m/s} \). The momentum is given as
\[
p = \frac{mv}{\sqrt{1 - \beta^2}} = \gamma mv
\]
\[
= (2.07)(20)(1.67 \times 10^{-27} \text{ g})(2.6 \times 10^8)
\]
\[
= 1.8 \times 10^{-17} \text{ kg} \times \text{m/s}
\]
or in other units
\[
p_c = \frac{mcv}{\sqrt{1 - \beta^2}} = (931.5)(20)(0.88)(2.07)
\]
\[
= 33.9 \text{ GeV}
\]
\( p = 33.9 \text{ GeV/c} \)

The total energy
\[
E_{\text{TOT}} = E_k + M_0c^2
\]
\[
= \gamma m_0c^2 = (2.07)(20)(931.5) = 38.6 \text{ GeV}
\]

**1.6.4 De Broglie Wave length, Wave-Particle Duality**

There is no distinction between wave and particle descriptions of matter. It is simply a matter of convenience, which we choose to use in a given situation. For example, it is quite natural to describe matter in terms of particles with values of momenta, kinetic energies, etc. It is also natural to use a wave description for light. However, associated with each material particle there is a wave description in which the particle is assigned a wave length (the de Broglie wave length \( \lambda \)) whose magnitude is given as
\[
\lambda = \frac{h}{p}
\]
where \( p \) is the momentum of the particle and \( h \) is Planck’s constant. (Note that Planck’s constant is extremely small, \( 6.6 \times 10^{-34} \) J sec. Thus the wave length of a particle is only important when the momentum is small, such as with electrons whose mass is \( 9 \times 10^{-31} \) kg.)

The expression for the de Broglie wave length may be written in rationalized units

\[
\lambda = \frac{\hbar}{p}
\]

where \( \hbar \) is \( h/2\pi \). The above expressions are classical and should be replaced by their relativistic equivalents where appropriate, \( i.e., \)

\[
\lambda = \frac{\hbar c}{\sqrt{E_k \left(E_k + 2m_0c^2\right)}}^{1/2}
\]

We can calculate typical magnitudes of these wave lengths of particles encountered in nuclear chemistry (Table 1.5)
Table 1.5  
Typical Magnitudes of De Broglie Wave lengths

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>Photon</th>
<th>Electron</th>
<th>Proton</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>1.2x10^{-9}</td>
<td>3.7x10^{-10}</td>
<td>9.0x10^{-12}</td>
</tr>
<tr>
<td>1</td>
<td>1.2x10^{-10}</td>
<td>8.7x10^{-11}</td>
<td>2.9x10^{-12}</td>
</tr>
<tr>
<td>10</td>
<td>1.2x10^{-11}</td>
<td>1.2x10^{-11}</td>
<td>0.9x10^{-12}</td>
</tr>
<tr>
<td>100</td>
<td>1.2x10^{-12}</td>
<td>1.2x10^{-12}</td>
<td>2.8x10^{-13}</td>
</tr>
<tr>
<td>1000</td>
<td>1.2x10^{-13}</td>
<td>1.2x10^{-13}</td>
<td>0.7x10^{-13}</td>
</tr>
</tbody>
</table>

Given typical nuclear dimensions of $10^{-13}$ cm, the data of Table 1.5 indicate the energy at which such particles might have a wave length similar or smaller than nuclear dimensions. These particles can be used as probes of nuclear sizes and shapes.

In a similar manner, it is quite natural to associate a wave description to photons (Table 1.4). Here we recall that

$$\lambda = \frac{c}{\nu} = \frac{hc}{\gamma E_y}$$

where $\nu$ is the frequency associated with the wave of length $\lambda$. A convenient form of this equation is

$$\lambda (\text{cm}) = \frac{1.2397 \times 10^{-10}}{E_y (\text{MeV})}$$
which was used to calculate the values in Table 1.5. But it is often useful to speak of photons as particles particularly when they are emitted or absorbed by a nucleus, when we write

\[ E_\gamma = h\nu = pc \]

**Sample Problem 1.5 - de Broglie Wave length**

Consider the case of a beam of 1 eV neutrons incident on a crystal. First order Bragg reflections are observed at 11.8°. What is the spacing between crystal planes?

**Solution:** Low energy neutrons are diffracted like X-rays. The Bragg condition is that \( n\lambda = 2d \sin\Theta \) where the index \( n = 1 \) for first order diffraction.

\[
\lambda = 2d \sin \Theta \\
d = \frac{\lambda}{2 \sin \Theta} = \frac{h}{2 \sin \Theta} = \frac{h}{(2mE_k)^{1/2}} \\
(6.63 \times 10^{-34} \text{ J s}) \\
d = \frac{(2 \times 1.67 \times 10^{-27} \text{ kg} \times 1.60 \times 10^{-19} \text{ J})^{1/2}}{2 \sin (11.8°)} = 7.0 \times 10^{-11} \text{ m}
\]

**1.6.5 Heisenberg Uncertainty Principle**

Simply put, the Heisenberg Uncertainty Principle states that there are limits on knowing both where something is and how fast it is moving. Formally, we can write

\[ \Delta p_x \times \Delta x \geq \hbar \]

\[ \Delta p_y \times \Delta y \geq \hbar \]

\[ \Delta p_z \times \Delta z \geq \hbar \]

\[ \Delta E \times \Delta t \geq \hbar \]
where $\Delta p_x$, $\Delta x$ are the uncertainties in the x-component of the momentum and the x coordinate respectively, etc, while $\Delta t$ is the lifetime of a particle and $\Delta E$ is the uncertainty in its total energy. These limits on our knowledge are not due to the limitations of our measuring instruments. They represent fundamental limits even with ideal or perfect instruments.

It is instructive to consider a practical example to see the effect of these limits. Consider an electron with a kinetic energy of 5 eV. Its speed can be calculated (non-relativistically)

$$v = \left(\frac{2E_k}{m}\right)^{1/2} = \left(\frac{(2)(5)(1.602 \times 10^{-19} \text{ J/eV})}{9.11 \times 10^{-31} \text{ kg}}\right)^{1/2}$$

$$v = 1.33 \times 10^6 \text{ m/s}$$

Its momentum is then

$$p = mv = 1.21 \times 10^{-24} \text{ kg m/s}$$

Assume the uncertainty in its measured momentum is 1%. The uncertainty principle then tells us

$$\Delta x = \frac{\hbar}{\Delta p} = \frac{1.06 \times 10^{-34} \text{ J s}}{1.21 \times 10^{-26} \text{ kg m/s}} = 8.8 \times 10^{-9} \text{ m}$$

which is about 40 atomic diameters. In short, if you know the momentum relatively well, you don’t know where the electron is in space.

1.6.6 Units and Conversion Factors
Every field has its own special units of measure and nuclear chemistry is no different. The unit of length is the femtometer \((10^{-15} \text{ m})\), which is called a *fermi*. The unit of mass is the *atomic mass unit* (amu or u) which has a numerical value of \(\sim 1.66 \times 10^{-24} \text{ g}\) or expressed in units of MeV/c², it is 931.5 MeV/c². The unit of energy is MeV \((10^6 \text{ eV})\) which is \(\sim 1.602 \times 10^{-13} \text{ J}\), the energy gained when a proton is accelerated through a potential of \(10^6\) volts. Appendix A contains a list of the exact numerical values of these and other convenient units. Special attention is called to five very useful quantities

\[
\frac{e^2}{4\pi \varepsilon_0} = 1.43998 \text{ MeV fm}
\]

\[
\hbar = 6.58212 \times 10^{-22} \text{ MeV s}
\]

\[
c = 2.9979 \times 10^{23} \text{ fm s}^{-1} = 29.979 \text{ cm/ns}
\]

\[
\hbar c = 197.3 \text{ MeV fm}
\]

1 year (sidereal) \(= 3.1558 \times 10^7 \text{ s} \approx \pi \times 10^7 \text{ s}

### 1.7 Particle Physics

Elementary particle physicists ("high energy physicists") study the fundamental particles of nature and the symmetries found in their interactions. The study of elementary particle physics is an important endeavor in its own right and beyond the scope of this book. But we need to use some of the concepts of this area of physics in our discussion of nuclei.

Particles can be classified as **fermions** or **bosons**. Fermions obey the Pauli principle, have antisymmetric wave functions and half-integer spins. (Neutrons, protons and
electrons are fermions.) Bosons do not obey the Pauli principle, have symmetric wave functions and integer spins. (Photons are bosons.)
The Standard Model

All the *matter* in the Universe, including atoms, stars, rocks, plants and animals is made of...

**Fermions**

2 Types

**QUARKS**
The *protons* and *neutrons* of an atom's nucleus are themselves complex structures, made up of groups of three basic particles called *quarks*. Quarks can also bind with *antiquarks* to make other particles called *mesons*.

**LEPTONS**
Leptons are not made of quarks, and include the *electrons* that orbit the atomic nucleus, and their more exotic relatives, like *muons*, *taus* and *neutrinos*.

**Bosons**
A family of particles called *gauge bosons* transmit the forces between the fermions. There is a different kind of particle for each force:

- *Photons* (the particles of light) carry the electromagnetic force;
- *Gluons* carry the strong force;
- *W* and *Z* bosons carry the weak force;
- *Gravitons* — not yet observed — are believed to be responsible for gravity, which is not a part of the Standard Model.

**FORCES**
There appear to be four basic forces at work:

- *Strong force* is responsible for holding together protons and neutrons.
- *Weak force* causes certain forms of radioactivity.
- *Electromagnetic force* holds atoms and molecules together.
- *Gravity* is responsible for the large-scale structure of the Universe, binding stars and galaxies together.
Particle groups, like fermions, can also be divided into the *leptons* (such as the electron) and the *hadrons* (such as the neutron and proton). The hadrons can interact via the nuclear or strong interaction while the leptons do not. (Both particle types can, however, interact via other forces, such as the electromagnetic force.) Figure 1.4 contains an artist’s conception of the Standard Model, a theory that describes these fundamental particles and
their interactions. Examples of bosons, leptons, hadrons, their charges and masses are given in Table 1-6.

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Mass $\text{GeV}/c^2$</th>
<th>Electric Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e$ electron neutrino</td>
<td>$&lt;1 \times 10^{-11}$</td>
<td>0</td>
</tr>
<tr>
<td>electron</td>
<td>0.000511</td>
<td>-1</td>
</tr>
<tr>
<td>$\nu_\mu$ muon neutrino</td>
<td>$&lt;0.0002$</td>
<td>0</td>
</tr>
<tr>
<td>muon</td>
<td>0.106</td>
<td>-1</td>
</tr>
<tr>
<td>$\nu_\tau$ tau neutrino</td>
<td>$&lt;0.02$</td>
<td>0</td>
</tr>
<tr>
<td>tau</td>
<td>1.7771</td>
<td>-1</td>
</tr>
</tbody>
</table>

Table 1-6. A table of the leptons and their properties.

There are six different kinds of leptons (light particles) (Table 1-6) and they can be arranged in three pairs. The electron ($e$), the muon ($\mu$) and the tau lepton ($\tau$) each carry a charge of $-e$ and have associated with them, the electron ($\nu_e$), muon ($\nu_\mu$) and tau neutrinos ($\nu_\tau$). These neutrinos are electrically neutral and have small or zero rest mass. (The actual mass of the neutrinos is a subject of current research (see Chapter 12). The electron neutrino is seen in nuclear phenomena such as $\beta$ decay while the other neutrinos are involved in higher energy processes.

One important aspect of leptons is that their number is conserved in nuclear processes. Consider, for example, the decay of the free neutron
\[ n \rightarrow p^* + e^- + \overline{\nu}_e \]

(The symbol \( \overline{\nu}_e \) indicates the antiparticle of the electron neutrino.) In this equation, the number of leptons on the left is zero, so that number of leptons on the right must also be zero. This equivalence can only be true if we assign a lepton number \( L \) of 1 to electron (by convention) and \( L = -1 \) to the \( \overline{\nu}_e \) (being an antiparticle). Consider the reaction

\[ \overline{\nu}_e + p^* \rightarrow e^+ + n \]

Here \( L = -1 \) on both sides of the equation where we assign lepton numbers of +1 for every lepton and -1 for every anti-lepton (\( e^+ \) is an anti-lepton). By contrast, the reaction

\[ \nu_e + p^* \neq e^+ + n \]

is forbidden by lepton conservation. The law of lepton conservation applies separately to electrons, muons and tau muons.

**Sample Problem 1.7**

Is the reaction \( \mu^- \rightarrow e^- + \overline{\nu}_e + \nu_\mu \) possible?

**Solution:**

<table>
<thead>
<tr>
<th>Left-hand side</th>
<th>( L_\mu = 1 ), ( L_e = 0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right-hand side</td>
<td>( L_e = 1 + (-1) = 0 ) ( L_\mu = +1 )</td>
</tr>
</tbody>
</table>

Yes, the reaction is possible.

If we focus our attention on the neutrons and protons (the nucleons), we note the similar masses (~1 u). We also note the neutron is slightly (~0.14%) more massive than the proton with the mass difference being \( \sim 1.29 \text{ MeV/c}^2 \) (Appendix A). (This energy
difference causes a free neutron to decay to a proton with a half-life of approximately 10 minutes.) As remarked earlier, the neutron has no net electric charge while the proton has a positive charge equal in magnitude to the charge on the electron. The electric charge on the proton is uniformly and symmetrically distributed about the center of the proton with a charge radius of about 0.8 fm. The neutron, although electrically neutral, also has an extended charge distribution with a positive charge near the center being canceled out by a negative charge at larger values of the radius. The values of the magnetic dipole moment of the neutron and proton are indications of their complex structure (Chapter 2). As far as their interaction via the nuclear or strong force, the neutrons and protons behave alike (the "charge independence" of the nuclear force). They can be regarded collectively as "nucleons". The nucleon can be treated as a physical entity with a mass of 938 MeV/c². One can speak of excited states of the nucleon such as the one with a mass of 1232 MeV/c² (which is called the Δ state).

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Approx. Mass GeV/c²</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>u up d down</td>
<td>0.003</td>
<td>2/3</td>
</tr>
<tr>
<td></td>
<td>0.006</td>
<td>-1/3</td>
</tr>
<tr>
<td>c charm s strange</td>
<td>1.3</td>
<td>2/3</td>
</tr>
<tr>
<td></td>
<td>0.1</td>
<td>-1/3</td>
</tr>
<tr>
<td>t top b bottom</td>
<td>175</td>
<td>2/3</td>
</tr>
<tr>
<td></td>
<td>4.3</td>
<td>-1/3</td>
</tr>
</tbody>
</table>

Table 1-7  A table of the quarks and their properties.
The fermionic hadrons (called *baryons*) are thought to be made up of three fundamental fermions called *quarks*. There are six different kinds (or *flavors*) of quarks: \( u \) (up), \( d \) (down), \( s \) (strange), \( c \) (charm), \( t \) (top), and \( b \) (bottom). The masses and charges of the quarks are given in Table 1-7. The size of each quark is \(<10^{-18} \text{ m}\). The lightest two quarks, the \( u \) and \( d \) quarks, are thought to make up the nucleons. The proton is thought to be a \( uud \) combination with a charge of \((2/3 + 2/3 - 1/3) e\) while the neutron is a \( udd \) combination with a charge of \((2/3 - 1/3 - 1/3) e\). The diameter of the proton is about 1 fm. The up and down quarks are light \((m \sim 5-10 \text{ MeV}/c^2)\) and point-like. The quarks account for \(~2\%\) of the mass of the proton. The rest of the mass is in gluons which "connect" the quarks. The most massive of the quarks is the top quark with a mass approximately equivalent to that of a \(^{197}\text{Au}\) nucleus and a short lifetime \((\sim 10^{-24} \text{ sec})\).

Like the leptons, there is a number conservation law for baryons. To each baryon, such as the neutron or proton, we assign a baryon number \( B = +1 \) while we assign \( B = -1 \) to each antibaryon, such as the anti-proton. Our rule is that the total baryon number must be conserved in any process. Consider the reaction

\[
p^+ + p^+ \rightarrow p^+ + n + \pi^+
\]

On the left, \( B=2 \) as it does on the right (the \( \pi^+ \) is a meson and has \( B=0 \)).

As well as binding three quarks (antiquarks) together to make baryons (antibaryons), the nuclear or strong interaction can bind a quark and an antiquark to form unstable particles called *mesons* \((q, \bar{q})\). The \( \pi^+ \) and \( \pi^- \) mesons \((u\bar{d}, d\bar{u})\) are of especial importance in
nuclear science. The quark/antiquark pairs in the π mesons couple to have zero spin and thus these mesons are bosons. In fact, all mesons have integer spins and are thus bosons.

1.8 Exchange Particles and Force Carriers

The force carrier (or “exchange”) particles are all bosons. These particles are responsible for carrying the four fundamental forces. This family includes the strong interaction carrier, the gluon; the weak interaction carriers, the \( W^\pm \) and \( Z^0 \); the carrier of the electromagnetic force, the photon; and the postulated but unobserved carrier of the gravitational force, the graviton.

To understand how these force carriers work, let us consider the electromagnetic force acting between two positively charged particles. Quantum electrodynamics tells us that the force between these two particles is caused by photons passing between them. At first one may find that idea nonsensical because the emission of a photon should change the energy of the emitter/source (and it does not). The trick is that the uncertainty principle allows the emission of virtual particles (which violate energy conservation) if such emission and absorption occur within a time \( \Delta t \) given as

\[
\Delta t = \frac{\hbar}{\Delta E}
\]

where \( \Delta E \) is the extent to which energy conservation is violated. We will consider the range of forces in chapter 5.
Problems

1. Define or describe the following terms or phenomena: radiochemistry, isotone, internal conversion, gluon, lepton.

2. Define or describe the following phenomena: electron capture, exchange forces, time dilation.

3. Define or describe the following terms: quark, hadron, baryon, lepton, meson.

4. In an experiment one observes the characteristic $K_{\alpha}$ X-rays of two elements at energies of 6.930 eV and 7.478 eV. The higher energy line is due to Ni. What element is responsible for the lower energy line?

5. Using the Bohr theory, calculate the ratio of the energies of the $K_{\alpha}$ X-rays of I and Xe.

6. Given the following energies of the $K_{\alpha}$ X-rays for the following elements, make a Moseley plot of the data

<table>
<thead>
<tr>
<th>Element</th>
<th>Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
<td>4.952 eV</td>
</tr>
<tr>
<td>Cr</td>
<td>5.415</td>
</tr>
<tr>
<td>Mn</td>
<td>5.899</td>
</tr>
<tr>
<td>Fe</td>
<td>6.404</td>
</tr>
</tbody>
</table>

7. Predict the mode of decay of the following nuclei: $^{14}$C, $^{3}$H, $^{11}$C, $^{233}$U, $^{138}$La.
8. Write complete, balanced equations for the following decays:
   
a. the α decay of $^{230}$Th
   
b. the β⁻ decays of $^{95}$Zr
   
c. the β⁺ decay of $^{17}$F
   
d. the EC decay of $^{192}$Au

9. Consider the decay of $^{238}$U to $^{206}$Pb. How many α-particles and β⁻-particles are emitted in this decay?

10. If a rock has a ratio of $^{206}$Pb to $^{238}$U of 0.6, what is the age of the rock?

11. How long will it take for a sample of $^{239}$Pu ($t_{\frac{1}{2}} = 24, 119$ y) to decay to 1/10 its original amount?

12. If a radioactive sample of $^{59}$Fe ($t_{\frac{1}{2}} = 44.496$ d) has an activity of 1000 disintegrations per minute, what weight of $^{59}$Fe is present?

13. The environmental concentration of $^{239}$Pu ($t_{\frac{1}{2}} = 24, 119$ y) in a lake is $3.7 \times 10^{-6}$ disintegrations/s/liter. What is the molarity of the solution?
14. $^{32}\text{P}$ ($t_{1/2} = 14.262$ d) is a popular tracer in biochemistry. If I need to have $0.1 \times 10^6$ disintegrations/s 60 days from now, how $^{32}\text{P}$ tracer must I purchase today?

15. Calculate the speed of a particle whose kinetic energy is three times its rest energy.

16. Calculate the speed parameter $\beta$ and the Lorenz factor $\gamma$ for the following particles:
   an electron with $E_K = 1$ MeV; a proton with $E_K = 1$ MeV; a $^{12}\text{C}$ nucleus with $E_K = 12$ MeV.

17. Consider the following free particles: a 1 eV photon, a 1 MeV electron and a 10 MeV proton. Which is moving the fastest? slowest? has the most momentum? the least momentum?

18. How much energy is necessary to increase the speed of a proton from $0.2 \, c$ to $0.3 \, c$? from $0.98 \, c$ to $0.99 \, c$?

19. A non-relativistic particle is moving five times as fast as a proton. The ratio of their de Broglie wave lengths is ten. Calculate the mass of the particle.

20. What are the wave lengths of a 500 MeV photon, a 500 MeV electron and a 500 MeV proton?
21. What is the wavelength of a "thermal" neutron? (The kinetic energy of the neutron can be taken to be $3/2 \ kT$ where $T$ is the absolute room temperature.)

22. Consider a nuclear excited state with a lifetime of 10 ps that decays by the emission of a 2 MeV $\gamma$-ray. What is the uncertainty in the $\gamma$-ray energy?

23. Which of the following decays are allowed by conservation laws?

   a. $p \rightarrow e^+ + \gamma$
   b. $p \rightarrow \pi^+ + \gamma$
   c. $n \rightarrow p + \gamma$
   d. $p + n \rightarrow p + p + \pi^-$
   e. $p + p \rightarrow p + p + p + \bar{p}$

24. What is the quark composition of the anti-proton and the anti-neutron?
References

There are many fine textbooks for nuclear and radiochemistry that cover the material covered in this book. A limited selection of some of the authors' favorites appears below.

Simple Introductions to Nuclear Chemistry:


History:

An intriguing view of the beginning of nuclear chemistry.


G.T. Seaborg and W. Loveland, *Nuclear Chemistry*, [Hutchinson-Ross, Stroudsberg, 1982]. Reprints of the most significant papers in nuclear chemistry from the earliest work to present with annotations and English translations.

Intermediate Level Textbooks - Similar to This Book:


**More Advanced Textbooks:**


**General Physics Textbooks:**

**General References:**


E. Browne and R.B. Firestone, *Table of Radioactive Isotopes*, (Wiley, New York, 1986). An authoritative compilation of radioactive decay properties. Do note that the spontaneous fission half-lives are missing for several heavy nuclei.

R.B. Firestone and V.S. Shirley, Table of Isotopes, 8th Edition (Wiley, New York, 1996). Although available on the web, this reference is still useful because it contains simplified energy level schemes not easily found in other places.
Web References

The Living Textbook for Nuclear Chemistry (http://livingtextbook.orst.edu) A compilation of supplemental materials related to nuclear and radiochemistry.