CHAPTER 29

NUCLEAR CHEMISTRY

(Part 2)
SECTION 29.1 The Zone of Stability

Transmutations occur naturally in radioactive elements, since the nuclei of the atoms are unstable. As these nuclei "transmute," they form nuclei of elements which are more stable. Let's examine why this is so. Various factors are responsible for the stability of a nucleus. For now, let's consider just two of them: (1) the "zone of stability," and (2) the 1:1 neutron/proton ratio. These two factors are illustrated in Figure 29.1 below.

![Figure 29.1: The Zone of Stability of Stable Nuclei](image)

The neutron/proton ratios of the first 83 elements are shown as the zone of stability in figure 29.1. Locate the shaded zone of stability now. The number of neutrons in a nucleus is plotted along the vertical y axis, and the number of protons in the nucleus is plotted on the horizontal x axis. What is another term which refers to the number of protons in a nucleus? Find number 20 on the x axis and go straight up from there to the center of the zone of stability. From this position, move over to the y axis and determine the number of neutrons. Calculate the neutron/proton (N/P) ratio and enter it in Table 29.1. Repeat this procedure using 30, 40, 50, 60, and 70 protons on the x axis. Record all N/P ratios in the table.

<table>
<thead>
<tr>
<th>No. of Protons</th>
<th>No. of Neutrons</th>
<th>N/P Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>70</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Data Table 29.1: Neutron/Proton Ratio of Selected Elements
Are the N/P ratios which you calculated greater than 1 in value? What can you conclude about the relative number of protons and neutrons in these nuclei? Although your calculations stopped at 70 protons, this conclusion holds true for elements 20 through 83. Based on your calculations, how would you say the N/P ratio changes as the atomic mass (atomic weight) of elements 20 through 83 increases?

Note in Figure 29.1 that the zone of stability lies very close to the 1:1 N/P ratio line for nuclei which contain 1 to 20 protons. These nuclei are not radioactive. What conclusion can you draw about the stability of those nuclei which have N/P ratios that are equal to or close to 1:1?

(Hydrogen-1 has no neutrons and, therefore, no N/P ratio. However, it is stable.)

Nuclei which do not lie in the zone of stability will undergo transmutations that will result in the formation of new nuclei (of different elements) that do lie in the zone of stability. The graph in Figure 29.1 ends with atomic number 83, indicating that no stable nuclei exist in atoms with more than 83 protons. Find 50 protons on the x axis and go up from there to the center of the zone of stability. Next, look to the left at the y axis and estimate the number of neutrons. About how many neutrons would a nucleus with 50 protons have to lose to achieve a stable 1:1 N/P ratio?

SECTION 29.2 Types of Radioactive Decay

Naturally-occurring radioactive elements have isotopes which may undergo radioactive decay. This decay can occur in one step or in a series of steps which end with the formation of a nucleus which falls within the zone of stability. Let’s consider two kinds of decay: alpha and beta.

**Alpha Decay**

As you may recall from Chapter 25, an alpha particle is identical to the nucleus of the helium-4 atom. So, an alpha particle is actually a bundle of protons and neutrons. How many of each compose an alpha particle? protons, and neutrons.

Many isotopes with an atomic number of 84 or higher undergo transmutation by emitting an alpha particle and form products which are closer to the zone of stability. The emission of an alpha particle from a nucleus is known as alpha decay. An atom which emits an alpha particle is called an alpha emitter. Radium-226 with an atomic number of 88 will serve as an example of an alpha emitter. During its decay, an alpha particle is ejected which means that the nucleus loses protons and neutrons. After radium-226 undergoes an alpha decay, what will be the atomic number of the product? If this is true, what is the identity of the new element formed after alpha emission? (Check the periodic table.)

The equation for the alpha decay of radium-226 can be written:
In an alpha decay, the atomic number is reduced by (13)_________ and the mass number is reduced by (14)_________. An alpha decay results in the formation of a more stable product with (15)__________ mass and with (16)__________ protons and neutrons.

Beta Decay

Natural radioactive decay in which beta particles (electrons) are given off from the nucleus is called beta decay. An atom which emits a beta particle is called a beta emitter. Because a beta particle is an electron, it is natural to wonder how a nucleus can emit an electron when the nucleus doesn't contain any electrons! It so happens that a neutron in the nucleus can be transformed into a proton, an electron, and a neutrino.

The proton is a fundamental particle of the nucleus and remains in the nucleus after the neutron transformation. So, a neutron transformation reduces the number of neutrons in the nucleus by 1, but increases the number of protons by 1. Thus, the atomic number increases by 1, but the mass number remains the same.

Why is it that when a neutron is lost and a proton is formed in a nucleus that the mass number does not change? (17)_____________________________________________________________________

Since the electron is not a fundamental nuclear particle, it is emitted from the nucleus with a great amount of energy when a neutron is transformed.

The beta decay of thorium-234, which has an atomic number of 90, is shown in the following equation:

\[
^{234}\text{Th} \rightarrow ^{234}\text{Pa} + ^0\text{e}^{-1}
\]

Since the atomic number is increased by 1, the element formed as the product of the transmutation is one position "higher" than thorium on the periodic table. In any transmutation by beta decay, the new element formed as the product will be one position "higher" in the periodic table than the beta emitter. Note that the equation above is balanced. This means that the sum of the mass numbers of the products (0 + 234 = 234) equals the mass number of the reactant (234). Note, too, that the sum of the subscripts of the products (-1 + 91 = 90) is equal to that of the reactant (90).

Calculate the number of neutrons present in a thorium-234 nucleus: (18)_____________

Calculate the number of neutrons in a protactinium-234 nucleus: (19)_____________

Calculate the N/P ratio for thorium-234: (20)_____________

Calculate the N/P ratio for protactinium-234: (21)_____________

Based on your calculations above, in beta decay does the N/P ratio move closer to or farther from a 1:1 ratio? (22)_____________________________________________________________________

If this is true, then does a beta decay form products with more stability or less? (23)_________
SECTION 29.3 Decay Series

A series of elements from the periodic table which are related by a series of alpha and beta decays is called a decay series. Several such decay series are known among the naturally-occurring radioactive elements. The uranium-238 decay series shown in Figure 29.2 is a good example.

Note that this series of transformations begins in the upper left corner with U-238 and continues down to an isotope of lead in the lower right corner. Lead-206 (Pb-206) with atomic number 82 is stable – it lies within the zone of stability. You see that a beta decay results in a vertical rise in Figure 29.2; this is because a beta decay results in an increase in atomic number (y axis) and an unchanged mass number (x axis). An alpha decay results in a diagonal lowering because of decreases in both atomic number (y axis) and mass number (x axis). Note that on the x axis, the mass numbers are decreasing from left to right. If you carefully check Figure 29.2, you will see that two elements in the series are missing! The first missing element is the one that results from an alpha (α) emission from radium-226 (Ra-226). Write the nuclear notation of this missing element in the slot at right. Now fill in the space in Figure 29.2 with this nuclear notation.

The second missing element is found after a beta (β) emission from bismuth-210 (Bi-210). Write the nuclear notation for this missing element in the space at right. Now fill in the space in Figure 29.2 with this nuclear notation.

SECTION 29.4 The Half-Life of a Radioactive Element

At the present time, it is impossible to predict exactly when a particular radioactive nucleus will decay. The uranium-238 nucleus that breaks down today is exactly like the one that will do so a billion years from now. However, we can predict what fraction of a sample of nuclei will break down in a given amount of time. For example, one-half of the nuclei in a given sample of carbon-14 will decay in 5570 years. One-half of the remaining half (or one fourth of the original sample) will decay in another 5570 years. One-half of what is left (or one eighth of the original sample) will decay in another 5570 years, etc. Thus, carbon-14 is said to have a half-life of 5570 years.

The half-life of a radioisotope is the time that is required for half of any given sample of its nuclei to decay.

As shown in Figure 29.3, the amount of radioactivity emitted is directly proportional to the number of nuclei in any given sample of an isotope. In the case of the hypothetical radioisotope illustrated by the graph in Figure 29.3, the amount of radioactivity emitted from any given sample decreases with time. This is because the number of nuclei in the sample decreases with time as a result of decay.

According to Figure 29.3, what percent of radioactivity is emitted at zero minutes? How much time has passed when the amount of radioactivity emitted drops to 50%? So how much time was required for half of the nuclei to decay? What is the half-life (in minutes) of this radioisotope? If this is true, then how many total minutes should it take for the number of nuclei to decrease by one-half again (1/4 of the original sample)? What should the percent of radioactivity emitted be at this point? The graph in Figure 29.3 should verify your prediction. Does it? What fraction of the original number of nuclei will be left in this sample after twelve minutes have passed? What percent of the original amount of radioactivity is still present after twelve minutes?
Figure 29.2 The decay series for uranium-238 goes on this page. This page can be found on your ALICE disk listed as a separate file (ALICE CHP 29 pg 29-7).
The rate at which unstable atoms decay is constant and is not influenced by external forces such as temperature and pressure. At present, there is no method which can be used to alter the half-life of a radioisotope. The half-lives of different radioisotopes vary from a small fraction of a second to billions of years. Polonium-215 has a half-life of only 0.0018 second. Uranium-238, on the other hand, has one of the longest known half-lives, about 4.5 billion years (which is approximately the same as the age of the earth). Therefore, what fraction of uranium-238 remains on the earth today compared to when this planet was formed? \( \text{[35]} \)

Since the human lifespan is so short, you may wonder how we are able to determine a half-life of 4.5 billion years. Various indirect methods are used, including chemical ones. The main problems when trying to determine the length of a half-life are to identify the source of the radioactivity coming from a sample of a radioisotope and to determine its rate of decay. It is, of course, possible that some isotopes that we currently think are stable and do not decay actually have half-lives that are so long that we have not been observing them long enough to detect their radioactivity!

Let's take another look at the decay series for uranium-238 shown in Figure 29.2. Any rock containing U-238 will also contain all of the "daughter" elements of the series. (The daughter elements are those that are formed as a result of decay process.) The relative amounts of each daughter element present will depend on the age of the rock. Therefore, if we can measure the amounts of certain daughter elements in the rock, we can determine its age. The half-lives of the elements in the U-238 decay series are presented in Table 29.2.

Let's review now by answering the following questions and problems. Why is the atomic number of the transmuted element from an alpha decay always two less than the atomic number of the alpha emitter from which it came? \( \text{[36]} \)

Why is the atomic number of the transmuted element from a beta decay always one greater than the atomic number of the beta emitter from which it came? \( \text{[37]} \)

Since the nucleus does not contain any electrons, how is it possible for a nucleus to emit an electron in beta decay? \( \text{[38]} \)
Table 29.2
Half-Lives of Isotopes in the U-238 Decay Series

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Half-Life</th>
<th>Symbol</th>
<th>Half-Life</th>
</tr>
</thead>
<tbody>
<tr>
<td>U-238</td>
<td>$4.51 \times 10^9$ yrs</td>
<td>Po-218</td>
<td>3.05 minutes</td>
</tr>
<tr>
<td>Th-234</td>
<td>24.1 days</td>
<td>Pb-218</td>
<td>26.8 minutes</td>
</tr>
<tr>
<td>Pa-234</td>
<td>1.18 minutes</td>
<td>Bi-214</td>
<td>19.7 minutes</td>
</tr>
<tr>
<td>U-234</td>
<td>$2.48 \times 10^6$ yrs</td>
<td>Po-214</td>
<td>0.00016 sec</td>
</tr>
<tr>
<td>Th-230</td>
<td>$8.0 \times 10^4$ yrs</td>
<td>Bi-210</td>
<td>5.0 days</td>
</tr>
<tr>
<td>Ra-226</td>
<td>$1.62 \times 10^3$ yrs</td>
<td>Po-210</td>
<td>138.4 days</td>
</tr>
<tr>
<td>Rn-222</td>
<td>3.82 days</td>
<td>Pb-210</td>
<td>19.4 yrs</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pb-206</td>
<td>stable</td>
</tr>
</tbody>
</table>

What is the half-life of a radioisotope? [39]______________________________

How could a Geiger counter be used to measure the half-life of a given sample of a radioisotope? (Hint: see Figure 27.3) [40]______________________________

_____________________________________________________________________

Problem 1. Write a balanced nuclear equation for each of the following:

a) emission of a beta particle by protactinium-234 (Pa-234)

b) emission of an alpha particle by thorium-230 (Th-230)

c) emission of a beta particle by lead-214 (Pb-214)

Problem 2. If the half-life of a radioisotope is 120 days, how much of an 8.00 gram sample will be left after 360 days?

Problem 3. The bromine-35 nucleus has a half-life of 18 minutes. How many minutes are required for seven-eighths (7/8) of a sample to decay?

__________ min.
SECTION 29.5 The Mass Defect

The mass number of a proton or a neutron is taken to be 1, but their actual masses in atomic mass units (amu) are fractional values: proton = 1.00783 amu; neutron = 1.00867 amu. When writing nuclear equations we use mass numbers and the sum of the values of the mass numbers on both sides of the equation must be the same. However, if all calculations are performed using atomic mass units, then discrepancies occur. For example, when the mass of the protons and neutrons of a helium nucleus are examined separately, they are found to have more mass than when they are combined together forming a nucleus. The amu of the two protons and two neutrons in a helium nucleus, when not combined, can be calculated by simple multiplication as follows:

<table>
<thead>
<tr>
<th>Particles</th>
<th>mass in amu</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 protons</td>
<td>1.00783 X 2 = 2.01566 amu</td>
</tr>
<tr>
<td>2 neutrons</td>
<td>1.00867 X 2 = 2.01734 amu</td>
</tr>
<tr>
<td>Sum of the masses</td>
<td>= 4.03300 amu</td>
</tr>
</tbody>
</table>

So, the masses of 2 protons + 2 neutrons when not combined = 4.03300 amu. A helium-4 nucleus contains 2 protons and 2 neutrons. If the total mass of a helium-4 nucleus is determined, it is found to have less mass than the sum of the amu's of its protons and neutrons when they are not combined. (See Table 29.3 below.)

<table>
<thead>
<tr>
<th>Table 29.3</th>
<th>Mass of Particles in Helium Nucleus Separately and Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Helium nucleus Mass</td>
</tr>
<tr>
<td>Particles separate</td>
<td>4.03300 amu</td>
</tr>
<tr>
<td>Particles combined</td>
<td>4.00260 amu</td>
</tr>
<tr>
<td>Difference</td>
<td>0.0304 amu</td>
</tr>
<tr>
<td>Mass defect</td>
<td>0.0304 amu</td>
</tr>
</tbody>
</table>

This difference between the sum of the separate masses of the nuclear particles and the mass resulting from their merging is called the mass defect. A mass defect exists for every atom; that is, the sum of the masses of the individual protons and neutrons of any atom is greater than the mass of these particles when they have merged in any given nucleus. As shown in Table 29.3, the helium nucleus has a mass defect of 0.0304 amu. What has happened to this mass? Where does the 0.0304 amu of mass go when the particles join together?

You may recall Albert Einstein's famous equation $E = mc^2$ states that matter and energy are really different forms of the same thing. The missing matter of the helium nucleus has not been lost or destroyed, but converted into a large amount of energy when the nuclear parts are joined to form the helium nucleus. We know a relationship which allows us to convert units of mass (amu) into units of energy: 1 amu = 931 Mev. Mev stands for million electron volts. Since you are already familiar with joules as units of energy, it may help to express the relationship as 1 Mev = $1.59 \times 10^{-7}$ joules. Let's summarize all this below:

$$1 \text{ amu} = 931 \text{ Mev}$$

$$1 \text{ Mev} = 1.59 \times 10^{-7} \text{ joules}$$

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So, to convert the mass defect in helium into the energy equivalent:

\[
0.0304 \text{ amu} \times \frac{931 \text{ Mev}}{1 \text{ amu}} = 28.3 \text{ Mev of energy}
\]

OR

\[
0.0304 \text{ amu} \times \frac{931 \text{ Mev}}{1 \text{ amu}} \times \frac{1.59 \times 10^{-7} \text{ J}}{1 \text{ Mev}} = 4.50 \times 10^{-6} \text{ Joule}
\]

Note that when a very tiny mass like 0.0304 amu is converted into energy, the energy equivalent expressed in joules is very small. That's why a smaller unit of energy such as Mev is more suitable for these kinds of calculations. Thus, when 2 protons and 2 neutrons combine to form a helium nucleus, 28.8 Mev of energy (or 4.50 X 10^{-6} Joule) of energy are released. The protons and neutrons are found inside the nucleus which occupies only a tiny fraction of the volume of the atom. The protons each have a positive charge and repel each other with a large amount of force, since they occupy the nucleus at close distances. In order for the protons and neutrons to be held together in the nucleus, an even larger force must be present to overcome the repulsive forces. The amount of energy needed to hold the nuclear particles together in the nucleus is called the nuclear binding energy.

(Binding energy can also be defined as the energy needed to separate a nucleus into its individual particles.)

We have seen that when the protons and neutrons of helium combine to form the helium nucleus, there is a mass defect of 0.03040 amu. If you multiply this value by 931 Mev you obtain a binding energy of 28.3 Mev for the helium nucleus. The binding energy per individual proton or per individual neutron in the nucleus can be determined by dividing the bonding energy for the nucleus by the total number of particles in the nucleus. Since the helium nucleus contains 2 protons and 2 neutrons, the binding energy per particle is:

\[
\frac{28.3 \text{ Mev}}{4 \text{ particles}} = 7.08 \text{ Mev/particle}
\]

The greater the binding energy per particle, the more stable the nucleus. Helium has a relatively high binding energy per particle, as you might have guessed since it is a stable noble gas atom.

**Problem 4.** Suppose the nucleus of hypothetical element "X" has a mass defect of 0.0484 amu. The mass number of this element is 8. Determine the binding energy per particle in Mev for element X:

\[
\text{__________ Mev / particle}
\]

Is the nucleus of element X more or less stable than the helium nucleus? \[41]\]

Explain:\[42]\]
SECTION 29.6 Man-Made Isotopes - Stable and Radioactive

In the remainder of this chapter you will be reading about artificial (man-made) transmutations, nuclear fission, and nuclear fusion. Before that, however, let's review and extend our knowledge of how to write nuclear equations. It is not difficult to determine what new element is formed in a transmutation if the "secondary" particle which is formed can be identified. Secondary particles include neutrons, protons, alpha particles, beta particles, and positrons which are positively charged electrons (they were mentioned at the end of Chapter 25, remember?).

Problem 5. As a review, write the nuclear notation for each of the particles listed below.

a. neutron ________; b. proton ________; c. alpha particle ________; d. beta particle ________;

e. positron ________

We know that in nuclear reactions the total mass of the reactants only approximates the total mass of the products because of the mass defect. However, because the mass defect is so small, it is does not show up in the mass numbers (which are always whole numbers). Therefore, any nuclear equation, written as it is with mass numbers and atomic numbers both in whole numbers, must be in balance. That is, the total of the mass numbers (superscripts) must be equal on both sides of the equation, and the same is true for the total of the subscripts on both sides.

Let's consider an example of "alpha capture." Some of this will be a review of what you have already learned in Chapter 25. Examine the equation below. If a beryllium (Be) nucleus is bombarded with an alpha particle, the beryllium nucleus will capture it, making the nucleus unstable. The unstable nucleus disintegrates, releasing a \( \text{He}^{4} \) and forming a new element. In the equation below, the symbol of the new element is shown as "X." "A" is the mass number, and "Z" is the atomic number.

\[
\text{Be}^{9} + \text{He}^{4} \rightarrow A_{Z}^{A} X + 1_{0} n
\]

What is the sum of the mass numbers on the left side of the equation?____ So, what must the sum of the mass numbers be on the right side?____ What mass number must the newly formed element have?____ What is the sum of the atomic numbers on the left side of the equation?____ So, what must the sum of the atomic numbers be on the right side?____ Based on this atomic number, what is the symbol for the newly formed element?____ Now rewrite this equation below, substituting the correct nuclear notation for the newly formed element:

The nuclear equation you wrote above is an example of an artificial transmutation. Scientists produce this type of nuclear reaction by bombarding a nucleus with particles (nuclear projectiles) so as to cause nuclear disintegration and the formation of a new element. Artificial isotopes, produced by this method, may be stable or they may be radioactive.

Artificial Stable Isotopes

In 1919, Rutherford bombarded nitrogen gas with alpha particles which he obtained from a radioactive source. The reaction can be pictured as the capture of an alpha particle by the nitrogen nucleus to form an isotope of fluorine.

\[
\text{N}^{14}_{7} + \text{He}^{4}_{2} \rightarrow \text{F}^{18}_{9}
\]

Step 1: 

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This isotope of fluorine is unstable and emits a proton, leaving a stable isotope of oxygen-17:

\[
\begin{align*}
\text{Step 2: } & \quad \frac{18}{9}F \quad \longrightarrow \quad \frac{17}{8}O + \frac{1}{1}H
\end{align*}
\]

Steps 1 and 2 may be combined and written as an overall reaction:

\[
\begin{align*}
\frac{14}{7}N + \frac{4}{2}He \quad \longrightarrow \quad \frac{17}{8}O + \frac{1}{1}H
\end{align*}
\]

Since this first artificial transmutation, many different isotopes have been produced, not only by using radioactive sources, but also by using particles given very high velocities in special accelerators such as a linear accelerator and a cyclotron. When particles collide at very high velocities, transmutations can occur.

**Artificial Radioactive Isotopes**

In the 1930's the daughter of Madame Curie, Irene Joliot-Curie and her husband, Frederic Joliot, bombarded a stable aluminum nucleus (mass no. 27, atomic no. 13) with an alpha particle emitted by a radioactive source. The products were a phosphorus nucleus (mass no. 30, atomic no. 15) and a neutron. Write this nuclear equation in the space below:

\[
\text{__________________________}
\]

Note that this phosphorus-30 was produced by artificial transmutation. The Joliot-Curies expected that upon removal of the alpha source, the radioactivity would soon stop. However, unlike the oxygen-17 produced by Rutherford in the previous example above, the phosphorus produced by this reaction was not stable. Long after the removal of the radioactive source of bombarding particles, the sample of phosphorus continued to exhibit radioactivity. The primary product of this reaction was an artificially produced radioactive isotope (radioisotope). The ability to make a stable nucleus unstable (radioactive) by bombarding it with a high-energy projectile is known as induced radioactivity. A radioactive isotope may be the product of natural radioactive decay (alpha or beta), or it may be an artificial isotope (man-made). By far, most of the known radioactive isotopes are man-made.

The value of radioisotopes can be appreciated when it is realized that these isotopes can be detected wherever they are. Since a radioisotope reacts chemically in the same way as a stable isotope of the same element, a radioisotope can be substituted for the stable isotope in a chemical reaction. Since the radioisotope gives off radioactivity, its presence can always be detected no matter how it is chemically combined. Because of this, radioisotopes are called tracers or tagged atoms. Tracers are very valuable in helping scientists to study the sequence of chemical reactions in living things. For example, fertilizer containing many stable phosphorus atoms and some atoms of the radioisotope phosphorus-32 can be "fed" to plants. Radiation detection equipment can be used to determine where the greatest concentrations of phosphorus occur in the plant. Experiments of this kind are simple to perform.

The radioisotope carbon-14 is useful in dating old objects containing carbon. It has a half-life of 5570 years. An archeologist can use a Geiger counter to measure the radiation coming from an ancient wooden axe handle and thereby determine the amount of carbon-14 in a given sample (say one gram) of the wood. If the sample has only one-fourth as much carbon-14 as one gram of present-day wood, how many half-lives has the ancient wood experienced? About how old is the ancient wood? As the hunt for new isotopes continued, two German scientists, Otto Hahn and Fritz Strassmann, made a startling discovery. When they bombarded uranium-235 (atomic number 92) with neutrons, two elements and a great deal of energy were produced. Their chemical analysis indicated that barium (atomic number 56) was and krypton (atomic number 36) were the elements that were
produced. It was difficult to believe these results. No transmutation had been previously observed in which the atomic numbers of the products differed from the atomic number of the reactant as much as they did in this case:

$$^{235}_{92}U + ^1_0n \rightarrow ^{138}_{56}Ba + ^{95}_{36}Kr + 3^1_0n + \text{energy}$$

big difference!

The German chemists Lise Meitner and Otto Frisch concluded that if a heavy element were converted into two middleweight elements, large amounts of binding energy would be given off. The amount of energy liberated is roughly the difference in the total binding energy per nucleon (proton or neutron) of the elements in the reactants and the products. For example, suppose uranium-238 (with a binding energy of 7.6 Mev per nucleon) could be converted directly to iron (which has a high binding energy of about 8.8 Mev). This would result in $238 \times (8.8 - 7.6)\text{Mev} = 286 \text{Mev}$. It is not quite this simple in practice because the neutron/proton ratio and other factors influence results. Nevertheless, a great deal of energy is released during fission, the process by which a heavy nucleus is split into two lighter nuclei.

Now let's return to the reaction discovered by Hahn and Strassman. The fission of U-235 begins with a neutron capture. Write the nuclear equation below which shows what happens when a U-235 nucleus absorbs a neutron. Hint: the only product is a uranium isotope.

$$^{235}_{92}U + ^1_0n \rightarrow \text{u-236} + 3^1_0n + \text{energy}$$

The product of the above reaction is unstable and exists for a very short period of time and then undergoes spontaneous fission. The products of its fission are barium-141, krypton-92, 3 neutrons and energy. Write this nuclear equation in the space below.

Note that three neutrons are produced as a result of the fission of U-236. Perhaps some of these neutrons could be used to continue the reaction. If the neutrons produced by this reaction are used to begin other fissions, a chain reaction occurs. (See Figure 29.4.)
A chain reaction is one in which a product of one reaction (for example, a neutron) is used to cause the reaction to occur again. To keep a chain reaction going, we must be sure that at least one neutron from each fission causes another nucleus to undergo fission. A chain reaction has an efficiency of 1 if each fission causes 1 additional fission. If the efficiency can be maintained at about 1, a continuous supply of energy can be produced. When each reaction produces more than 1 reaction, the efficiency is greater than 1 and the amount of energy constantly increases.

An atomic bomb is a device with an efficiency of greater than 1; an atomic power plant must maintain an efficiency of approximately 1. In either an atomic bomb or a nuclear power plant, a minimum amount of nuclear fuel (uranium or plutonium) is needed to maintain the chain reaction. This minimum amount of nuclear fuel is called the critical mass. It is not possible to continue the chain reaction unless at least this amount of nuclear fuel is available to it.

A device capable of sustaining and regulating a chain reaction involving fission is an atomic pile, or more correctly, a nuclear reactor. The efficiency of a chain reaction depends on the fate of the neutrons produced by the fission reactions. The possible fates of these neutrons are:

1. They can escape from the sample of nuclear fuel.
2. They can be absorbed by nuclei of atoms other than those of the nuclear fuel.
3. They can be absorbed by the nuclear fuel and continue the chain reaction.

In nuclear reactors, moderators are used to assure a steady supply of neutrons, and control rods are employed to control the rate of the chain reaction. (See Figure 29.5 below.)

_A moderator_ is a material which will not absorb neutrons but will slow their rate of speed. As the neutrons produced by the fission of uranium collide with the moderator, they are slowed down and prevented from making a rapid escape from the nuclear reactor. Thus, by slowing down the neutrons, a moderator makes neutron capture more likely. Commonly used moderators are: carbon in the form of graphite, and "heavy water." (The water molecules of heavy water contain two atoms of the hydrogen isotope deuterium, hydrogen-2, instead of two atoms of ordinary hydrogen.)

We have noted that moderators do not absorb neutrons. Control rods, however, do absorb neutrons. For example, cadmium and boron effectively absorb neutrons. Rods of these materials (control rods) can be inserted into, maintained in, or removed from rows of uranium. When control rods are inserted, neutrons are absorbed by them and, consequently, the neutrons are no longer available to the
reaction. Accordingly, the insertion of control rods can be used to slow the reaction to an efficiency of 1. This efficiency can be maintained by simply keeping these control rods in position. The efficiency of a reaction can be increased by the removal of control rods.

**Problem 6.** The amount of energy released from the conversion of matter into energy in a nuclear reactor can be appreciated when it is considered that the conversion of only 1 gram of matter into energy releases the same amount of energy as the burning of over 2000 tons of coal! Calculate in the space below how many grams of coal this would be! (Useful information: 1 ton = 2000 lbs; 454 grams = 1 lb)

Answer = ____________________ grams

**SECTION 29.7 Fusion Reactions**

*Fusion* is the combination of the nuclei of light elements to make a heavier nucleus. Because the two light nuclei are positively charged and, therefore repel each other, it is difficult to bring them close enough together to make them fuse. An atomic bomb (fission bomb) can heat atoms so that they have enough energy to overcome the repulsive forces and combine. This heat from fission reactions is used to achieve fusion in weapons such as the *hydrogen bomb*. In essence, an atomic bomb is the “fuse” for a hydrogen bomb. Because extremely high temperatures are required to achieve fusion, the fusion reaction is known as a *thermonuclear reaction*.

Scientists are trying to heat gases of light elements with electricity or lasers and keep them close together for a thermonuclear reaction by enclosing them in a magnetic field. Such a controlled fusion reaction, if achieved, would be of great value. It would have advantages over fission reactions, which employ uranium in nuclear reactors. Few radioactive waste products are produced by fusion reactions. The radiation hazard would not be as great, and the radioactive wastes are much less dangerous than those produced in fission reactors. Furthermore, since hydrogen-2 is much more abundant than uranium, the world would be assured of a continuous supply of fuel.

The sun and other stars show large amounts of hydrogen and helium in their spectra, indicating that they may produce their energy as a result of fusion reactions. There are two proposed mechanisms for these fusion reactions - the *carbon cycle* and the *proton-proton chain*. Let’s briefly study both of them.

In the carbon cycle, carbon-12 acts as a catalyst and is regenerated in the final step enabling it to catalyze additional reactions. Parts of the six steps of the carbon cycle are shown in Problem 7 below.

**Problem 7.** Use your knowledge of nuclear reactions to predict the product of reaction "a" and put its nuclear notation in the blank. Put this same nuclear notation in the blank on the left side of reaction "b," and predict the notation of the product of reaction "b." Put this same notation in the blank on the left side of reaction "c", and predict the notation of the product of that reaction. Continue this process until you have completed all six reactions. If your work is correct, equation "f" will be properly balanced.

\[
a. \quad {^{12}}C_{6} + {^{1}}H_{1} \rightarrow \quad \quad + \quad \text{energy} \\
\]

\[
b. \quad \quad \quad \quad \quad \quad \rightarrow \quad \quad \quad + {^{0}}e_{+1} \\
\]

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c. \[ \text{_________} + ^1_1\text{H} \rightarrow \text{_________} + \text{energy} \]

d. \[ \text{_________} + ^1_1\text{H} \rightarrow \text{_________} + \text{energy} \]

e. \[ \text{_________} \rightarrow \text{_________} + ^0_1\text{e} \]

f. \[ \text{_________} + ^1_1\text{H} \rightarrow ^{12}_6\text{C} + ^2_2\text{He} \]

Note in the carbon cycle shown in Problem 7, that carbon-12 is used in reaction "a" and reproduced in reaction "f" as it should be since it is a catalyst.

Is equation "f" in Problem 7 balanced according to mass numbers and atomic numbers? _____________

The proton–proton chain pictures the fusion reaction as a continued combination of hydrogen nuclei (protons) until helium is formed:

a. \[ ^1_1\text{H} + ^1_1\text{H} \rightarrow ^2_1\text{H} + ^0_{-1}\text{e} + \text{energy} \]

b. \[ ^2_1\text{H} + ^1_1\text{H} \rightarrow ^3_2\text{He} + \text{energy} \]

c. \[ ^3_2\text{He} + ^3_2\text{He} \rightarrow ^4_2\text{He} + 2^1_1\text{H} + \text{energy} \]

Note that both the carbon cycle and the proton-proton chain use hydrogen-1 as a fuel and produce helium-4 as a product. Note also that the hydrogen we started with in reaction "a" ultimately is turned into helium in reaction "f." Fusion involves the conversion of hydrogen into helium.

The heaviest naturally-occurring nucleus is the isotope U-238, the most abundant isotope of uranium. As previously noted, the artificial radioactive elements (those above uranium on the periodic table) are the transuranium elements. All of the isotopes of the transuranium elements are radioactive. Some of them are very unstable having half-lives of only a tiny fraction of a second! The transuranium isotope, plutonium-239, is relatively stable having a half-life of 214,000 years. Uranium-238 can be used as a target for projectiles or "atomic bullets." These projectiles may be positively-charged particles which have been speeded up in particle accelerators by passing them through charged fields toward their targets. In all of the equations presented in this section, a high speed positively-charged ion is the atomic bullet. Some transuranium elements with atomic numbers above 93 can be synthesized by using U-238 as a target.
Problem 8. In the equations below, predict the products and enter the correct nuclear notations in the blanks. (Pay attention to the number of neutrons produced in each case.)

\[ ^{238}_{92}U + ^{2}_{1}H \longrightarrow \text{_________} + 2^1_{0}n \]

Name the element formed in equation "a" above: ____________________

\[ ^{238}_{92}U + ^{4}_{2}He \longrightarrow \text{_________} + 2^1_{0}n \]

Name the element formed in equation "b" above: ____________________

\[ ^{238}_{92}U + ^{12}_{6}C \longrightarrow \text{_________} + 5^1_{0}n \]

Name the element formed in equation "c" above: ____________________

\[ ^{238}_{92}U + ^{16}_{8}O \longrightarrow \text{_________} + 4^1_{0}n \]

Name the element formed in equation "d" above: ____________________

Some of these new elements are themselves used as targets for other bombardments. Thus, an isotope of plutonium has been used as a target in the production of other elements. Complete the equations below.

\[ ^{238}_{94}Pu + ^{4}_{2}He \longrightarrow \text{_________} + 3^1_{0}n \]

Name the element formed in equation "e" above: ____________________

The element formed in equation "e" above can then be used to produce still another new element. Use the element formed in equation 5 as the reactant in the equation below, and then complete the equation:

\[ \text{_________} + ^{4}_{2}He \longrightarrow \text{_________} + ^{1}_{1}H + 2^1_{0}n \]

Name the element formed in equation "f" above: ____________________

SECTION 29.8 Assorted Problems

Study the next two sample problems, and then solve those which remain.
Sample Problem: Polonium-210 undergoes alpha decay to form lead-206:

\[ ^{210}_{84}\text{Po} \rightarrow ^{206}_{82}\text{Pb} + ^{4}_{2}\text{He} \]

The half-life of Po-210 is 138.4 days. How many moles of alpha particles will be emitted if a 105 gram sample of Po-210 decays over a period of 138.4 days? Hint: since this problem deals with a specific isotope (Po-210) you should not use the atomic mass of polonium from the periodic table. In this case, it will be more accurate to use the mass number (or atomic mass, if known) of this specific isotope.

\[
\frac{105 \text{ g Po -210}}{210 \text{ g Po -210}} \times \frac{1 \text{ mole Po -210}}{210 \text{ g Po -210}} \times \frac{0.50 \text{ mole Po -210 decayed}}{1 \text{ mole Po -210 in sample}} \times \frac{1 \text{ mole } ^{4}\text{He produced}}{1 \text{ mole Po -210 decayed}} = 0.25 \text{ mole } ^{4}\text{He produced}
\]

Note in the problem above (as well as the one below) that 0.50 mole of the isotope has decomposed for each 1 mole present in the original sample. This is because one half-life had elapsed.

Sample Problem: How many moles of Po-210 are needed in a sample so that its decomposition will produce 4.2 moles of lead-206 in 138.4 days? Refer to the equation in the problem above.

\[
\frac{4.2 \text{ moles Pb -206 formed}}{1 \text{ mole Pb -206 formed}} \times \frac{1 \text{ mole Po -210 decayed}}{1 \text{ mole Pb -206 formed}} \times \frac{1 \text{ mole Po -210 in sample}}{0.50 \text{ mole Po -210 decayed}} = 8.4 \text{ moles Po -210 in sample (needed)}
\]

Problem 9.

a) Write the nuclear equation which shows the beta decay of bismuth-210 (Bi-210) to form a new element. (A beta particle (electron) is emitted.)

b) Using the equation above, calculate how many moles of electrons will be produced as a 166 gram sample of Bi-210 decays over a period of 10 days. (Check Table 29.2 for the half-life of Bi-210.)

Problem 10.

a) C-14 undergoes beta decay to N-14. Express this as a nuclear equation.
b) How many moles of C-14 will produce 3.0 moles of N-14 in 11,000 years? (The half-life of C-14 is 5570 years.)

Problem 11. Write the following nuclear equations:

a) an alpha capture in which C-12 and a neutron are the products.

b) a neutron capture in which U-236 is the only product.

SECTION 29.9 LEARNING OUTCOMES

This is the end of Chapter 29. Check the learning outcomes below when you are sure you have mastered them. Then arrange to take the exam on Chapter 29.

_____1. Define and/or describe nuclear terms including: zone of stability, half-life, mass defect, binding energy, chain reaction, decay series, induced radioactivity, critical mass, moderators, control rods, alpha decay, and beta decay.

_____2. Predict the products formed when a nucleus undergoes alpha or beta decay.

_____3. Solve problems involving mass defect and binding energy.

_____4. Solve problems involving the use of the half-life of an isotope.

_____5. Explain how alpha and beta decays affect the neutron/proton ratio, and explain the significance of a 1:1 N/P ratio.

_____6. Given sufficient information, predict the nuclear notation of a missing element in a decay series.

_____7. Describe the historical contributions of Hahn and Strassman, Meitner and Frisch, and Irene and Frederic Joliot.
SECTION 29.10  Answers to Questions and Problems

Questions:

{1} atomic number;  {2} yes (the first ratio = 1.0);  {3} more neutrons than protons;  {4} The N/P ratio gets larger;  {5} They are stable;  {6} about 25;  {7} 2;  {8} 2;  {9} 2;  {10} 2;  {11} 86;  {12} Radon (Rn);  {13} 2;  {14} 4;  {15} less;  {16} fewer;  {17} the SUM of protons and neutrons does not change;  {18} 144;  {19} 143;  {20} 1.6;  {21} 1.57;  {22} closer to;  {23} more;  {24} 222 \text{Rn};  {25} 210 \text{Po};  {26} 100%;  {27} 2 min;  {28} 2 min;  {29} 2 min;  {30} 4 min;  {31} 25%;  {32} yes;  {33} 1/64;  {34} 1.56%;  {35} one-half;  {36} Because of the loss of an alpha particle which contains 2 protons;  {37} Because the loss of a beta particle is accompanied by the formation of a proton (when a neutron decays);  {38} Neutron decay forms an electron (beta particle) and a proton;  {39} The time required for 1/2 of the atoms to decay;  {40} Use it to determine the time required for the measured radiation to drop by 50%;  {41} less stable;  {42} Less energy is required to break it apart;  {43} neutron;  {44} 13;  {45} 13;  {46} 12;  {47} 6;  {48} 6;  {49} C;

\[
\begin{align*}
\text{(50.) } & \frac{9}{4} \text{Be} + \frac{4}{2} \text{He} \longrightarrow \frac{12}{6} \text{C} + \frac{1}{0} \text{n} \\
\text{(51.) } & \frac{27}{13} \text{Al} + \frac{4}{2} \text{He} \longrightarrow \frac{30}{15} \text{P} + \frac{1}{0} \text{n}
\end{align*}
\]

\(\text{(52) two; (53) about 1393 yrs; }\)

\[
\begin{align*}
\text{(54.) } & \frac{235}{92} \text{U} + \frac{1}{0} \text{n} \longrightarrow \frac{236}{92} \text{U} \\
\text{(55.) } & \frac{235}{92} \text{U} \longrightarrow \frac{141}{56} \text{Ba} + \frac{92}{36} \text{Kr} + 3 \frac{1}{0} \text{n} + \text{energy}
\end{align*}
\]

Problems:

1. a. \(\frac{234}{91} \text{Pa} \longrightarrow \frac{234}{92} \text{U} + \frac{0}{-1} \text{e}\)

1. b. \(\frac{230}{90} \text{Th} \longrightarrow \frac{226}{88} \text{Ra} + \frac{4}{2} \text{He}\)

1. c. \(\frac{214}{82} \text{Pb} \longrightarrow \frac{214}{83} \text{Bi} + \frac{0}{-1} \text{e}\)

2. 1.00 gram
3. 54 minutes
4. 5.63 Mev/particle
5. \(\frac{1}{0} \text{n} + \frac{1}{1} \text{p} + \frac{4}{2} \text{He} + \frac{0}{-1} \text{e} + \frac{0}{+1} \text{e}\)
6. 18.16 grams
7. a. \( ^{12}_{6}C + ^{1}_{1}H \rightarrow ^{13}_{7}N + \text{energy} \)

7. b. \( ^{13}_{7}N \rightarrow ^{13}_{6}C + ^{0}_{-1}e \)

7. c. \( ^{13}_{6}C + ^{1}_{1}H \rightarrow ^{14}_{7}N + \text{energy} \)

7. d. \( ^{14}_{7}N + ^{1}_{1}H \rightarrow ^{15}_{8}O + \text{energy} \)

7. e. \( ^{15}_{8}O \rightarrow ^{15}_{7}N + ^{0}_{+1}e \)

7. f. \( ^{15}_{7}N + ^{1}_{1}H \rightarrow ^{12}_{6}C + ^{4}_{2}\text{He} \)

8. a. \( ^{238}_{92}U + ^{2}_{1}H \rightarrow ^{238}_{93}\text{Np} + ^{2}_{0}\text{n} \)

8. b. \( ^{238}_{92}U + ^{4}_{2}\text{He} \rightarrow ^{240}_{94}\text{Pu} + ^{2}_{0}\text{n} \)

8. c. \( ^{238}_{92}U + ^{12}_{6}C \rightarrow ^{245}_{98}\text{Cf} + ^{5}_{0}\text{n} \)

8. d. \( ^{238}_{92}U + ^{16}_{8}\text{O} \rightarrow ^{250}_{100}\text{Fm} + ^{4}_{0}\text{n} \)

8. e. \( ^{238}_{94}\text{Pu} + ^{4}_{2}\text{He} \rightarrow ^{239}_{96}\text{Cm} + ^{3}_{0}\text{n} \)

8. f. \( ^{239}_{96}\text{Cm} + ^{4}_{2}\text{He} \rightarrow ^{240}_{97}\text{Bk} + ^{1}_{1}\text{H} + ^{2}_{0}\text{n} \)

9. a. \( ^{210}_{83}\text{Bi} \rightarrow ^{210}_{84}\text{Po} + ^{0}_{-1}e \)

9. b. 0.59 mole

10. a. \( ^{14}_{6}C \rightarrow ^{14}_{7}N + ^{0}_{-1}e \)

10. b. 4 moles C-14
11. a. \[^{9}_{4}\text{Be} + ^{4}_{2}\text{He} \rightarrow ^{12}_{6}\text{C} + ^{1}_{0}\text{n}\]

11. b. \[^{235}_{92}\text{U} + ^{1}_{0}\text{n} \rightarrow ^{236}_{92}\text{U}\]
Figure 29.2
Decay Series of U-238