Physics 30 Lesson 35 Nuclear physics

Up to this point in our discussion of the nature of the atom we have been studying how the electrons behave around the nucleus. The study of the electrons around the nucleus is referred to as **atomic physics**. Now we turn our attention to the nucleus (**nuclear physics**) and the fundamental particles that atoms are composed of (**particle physics**).

I. Nuclear "physlish"

In order to discuss nuclear physics we must first understand the "short-hand" language that nuclear physicists use – i.e. nuclear physlish. Symbols for atoms and particles may be written as ${}^{A}_{Z}X$ where X is the atom's or particle's symbol
Z is the atomic number (# of protons) or, more generally, its charge
A is the atomic mass number (# of protons + # of neutrons = # of nucleons)

The element tungsten-186, for example, is written as ${}^{186}_{74}W$ which means that it has 74 protons and 186 – 74 = 112 neutrons. (Refer to Pearson page 790.)

II. Isotopes

Recall from Lesson 27 that in 1911 Rutherford discovered the nucleus and was also able to determine the approximate radius of the nucleus of an element. Rutherford determined that the nucleus contained **protons** because of its repulsive effect on alpha particles (α^{2+}) in the gold foil scattering experiments. Two years later, Henry Moseley, an assistant of Rutherford, determined that the charge on the nucleus was always a multiple of the charge on an electron but was positive in nature. Recall from Lesson 25 that Moseley's work led to the modern periodic table where elements are listed according to their atomic number.

Frederick Soddy discovered **isotopes** while studying the nature of radioactivity. **Isotopes of an element have the same atomic number but a different atomic mass**. For example, three isotopes of carbon are

carbon-12	carbon-13	carbon-14
${}^{12}_{6}C$	${}^{13}_{6}C$	${}^{14}_{6}C$

In order to explain the existence of isotopes, it was suggested by Rutherford that the nucleus must contain some neutral particle as well as the protons. It was not until 1932 that James Chadwick confirmed the existence of the **neutron** for which he was awarded the 1935 Nobel prize for physics. The general term **nucleon** refers to both protons and neutrons in the nucleus. The atomic mass is the total number of nucleons. (Refer to Pearson page 791.)

Example 1

Write the following isotopes in symbolic notation and state the number of protons, neutrons and electrons for each atom.

An atom has the same number of electrons as protons – i.e. it is electrically neutral.

oxygen-16 $^{16}_{8}O$ 8 protons, 16 – 8 = 8 neutrons, 8 electrons

tin-122 $^{122}_{50}Sn$ 50 protons, 122 – 50 = 72 neutrons, 50 electrons

III. Nuclear equations – conservation of charge & nucleons

Nuclear interactions are represented by **nuclear equations**. Nuclear interactions can involve the disintegration of a nucleus, the transmutation of a nucleus and a host of other interactions which we will be learning about. In nuclear equations, the original isotope(s) is/are often referred to as the **parent** isotope(s), while the final isotope(s) is/are called the **daughter** isotope(s). When writing nuclear equations it is important to **conserve electric charge** and to **conserve the number of nucleons**. In other words:

⇒ The sum of the **atomic numbers** on the parent side equals the sum of the atomic numbers on the daughter side.

⇒ The sum of the **atomic masses** on the parent side equals the sum of the atomic masses on the daughter side.

Example 2

When a boron-10 nucleus captures a neutron ($^{1}_{0}n$), a new element and an alpha particle ($^{4}_{2}He$) are produced. Write a complete nuclear equation for this interaction.

The described reaction is written as

$$^{1}_{0}n + ^{10}_{5}B \rightarrow ^{A}_{Z}? + ^{4}_{2}He$$

Using conservation of charge and conservation of nucleons, we can determine the new element:

$$^{1}_{0}n + ^{10}_{5}B \rightarrow ^{A}_{Z}? + ^{4}_{2}He$$

Atomic mass: 1 + 10 = A + 4
A = 7

Atomic number: 0 + 5 = Z + 2
Z = 3
(from the periodic table, element 3 is Li - lithium)

Therefore:

$$^{1}_{0}n + ^{10}_{5}B \rightarrow ^{7}_{3}Li + ^{4}_{2}He$$

IV. Atomic mass units

In previous lessons, when precision was less of an issue, we used 1.67 x 10^{-27} kg for the mass of a proton and a neutron when we converted from the number of nucleons to the mass in kilograms. In the context of nuclear masses and energies we need to be much more precise. In the table below, the precise masses of electrons, protons and neutrons are given. However, in nuclear physics we often use the **unified atomic mass unit** (u) rather than the actual kilogram value for different nucleons and subatomic particles. The unified atomic mass unit is defined as being exactly $\frac{1}{12^{th}}$ the mass of a carbon-12 nucleus. (Refer to Pearson pages 791 and 792.)

1 u = 1.660539 x 10^{-27} kg

Particle	charge (C)	mass (kg)	mass (u)
electron	–1.602177 x 10^{-19}	9.109 383 x 10^{-31}	5.485 799 x 10^{-4}
proton	+1.602177 x 10^{-19}	1.672 622 x 10^{-27}	1.007 276
neutron	0	1.674 927 x 10^{-27}	1.008 665

The atomic mass unit is merely an alternate mass unit to the kilogram.

V. Mass defect and mass–energy equivalence

After scientists discovered that the nucleus contained protons and neutrons, they were able to calculate the **theoretical mass** for a particular isotope by adding together the masses of protons and neutrons

$$m_{theoretical} = m_{protons} + m_{neutrons}$$

Using a mass spectrometer (see Lesson 20), scientists were able to find the **measured** mass. They were expecting the values to be identical, but, except for hydrogen, the **measured value is always less than the theoretical value**. For example, the theoretical mass of helium-4 is calculated by adding the masses of 2 protons and 2 neutrons. Using the table of atomic mass units above:

$$m_{theoretical} = 2 \times 1.007276 \text{ u} + 2 \times 1.008665 \text{ u} = \mathbf{4.031882} \text{ u}$$

Using a mass spectrometer, the **measured mass** of a helium-4 nucleus is **4.00260** u. Since the measured mass is less than the theoretical mass, physicists call the difference in mass the **mass defect** (Δm). In general

$$\Delta m = m_{measured} - m_{theoretical}$$

But what does the mass defect mean? A clue to the problem was provided by Albert Einstein who demonstrated, in a paper written in 1905, that mass and energy are equivalent:

$E = m c^2$ (Note: to use this equation the mass must be in kilograms)

The equation shows that a certain amount of **energy has an equivalent mass** and, conversely, a certain amount of **mass has an equivalent energy**. In other words, energy can be converted into mass and mass can be converted into energy.

Example 3

A nuclear reaction produces 9.0 x 10^{11} J of heat energy because of a conversion of mass into energy. What mass was converted?

$$E = mc^2$$

$$m = \frac{E}{c^2}$$

$$m = \frac{9.0\times10^{11}\,J}{(3.00\times10^{8}\,{}^{m}\!/\!{}_{s})^2}$$

$$m = \mathbf{1.0\times10^{-5}\,kg}$$

Based on the idea of mass-energy equivalence, physicists interpreted the mass defect as the **binding energy** that holds the protons and neutrons together in the nucleus. Due to the large repulsive electrostatic forces between protons, a large amount of energy and large forces are required to hold the nucleus together. The binding energy, resulting from what was later called the **strong nuclear force** (see Lesson 37), is equivalent to the mass defect using Einstein's equation. (Refer to Pearson page 793 to 796.)

Example 4

The mass of one nucleus of potassium-40 was measured to be 39.9687 u. What is the mass defect and the binding energy for potassium-40?

To find the mass defect (Δm), we first calculate the theoretical mass. Potassium-40 has 19 p^+ and 21 n. Using the masses provided in the atomic mass unit table:

$m_{theoretical}$ = 19 x 1.007276 + 21 x 1.008665 = 40.320209 u

$\Delta m = m_{measured} - m_{theoretical}$

Δm = 39.9687 u –40.320209 u = **–0.35151 u**

Δm = –0.3619 u x 1.660540 x 10^{-27} kg/u = **–5.83695 x 10^{-28} kg**

To find the binding energy we use

$$E = \Delta mc^2$$

$$E = -5.83695\times10^{-28}\,kg(3.00\times10^{8}\,{}^{m}\!/\!{}_{s})^2$$

$$E = -\mathbf{5.253\times10^{-11}\,J}\times\frac{1\,eV}{1.60\times10^{-19}\,J}$$

$$E = -\mathbf{328.3\,MeV}$$

VI. Conservation of mass-energy

After Einstein demonstrated that energy and mass are inter-convertible it became apparent that the laws of conservation of mass and conservation of energy were actually aspects of one law – the **conservation of mass-energy**. This idea allows us to imagine the creation of particles from kinetic or radiant energy and to imagine the annihilation of particles into radiant energy. In this conception we can think of an electron, for example, as having a mass of 9.109 383 x 10^{-31} kg or as an equivalent energy:

$$E_{e^-} = m_{e^-}c^2$$
$$E_{e^-} = 9.109383 \times 10^{-31}\text{kg}(2.997925 \times 10^8 \ \text{m/s})^2$$
$$E_{e^-} = 8.187107 \times 10^{-14}\,\text{J} \times \frac{1\text{eV}}{1.602177 \times 10^{-19}\,\text{J}}$$
$$E_{e^-} = 0.510999\,\text{MeV}$$

On your Physics Data Sheet, the masses for some first generation fermions (see Lesson 37) are given as an energy in eV or MeV over c^2. For example, an electron has a mass of

$$E = mc^2$$
$$m_{e^-} = \frac{E_{e^-}}{c^2}$$
$$m_{e^-} = \frac{0.510999\,\text{MeV}}{c^2}$$
$$m_{e^-} = 0.510999\,\frac{\text{MeV}}{c^2}$$

As we shall see in Lesson 37, this is a useful way of stating the mass of a particle because it is the amount of kinetic energy that must be generated in a particle accelerator in order to create that particular particle.

VII. Nuclear reactions

The presence of such huge quantities of energy within nuclei explains why nuclear reactions are so energetic. While the electron of a hydrogen atom can be ionized with a mere 13.6 eV, it takes about 8 MeV of energy to remove a nucleon from a nucleus. For this reason, gram for gram, a nuclear reaction can liberate millions of times more energy than a chemical reaction. There are four basic types of nuclear reactions: radioactivity, induced nuclear transmutations, fission and fusion. We will discuss radioactivity in Lesson 36.

Induced nuclear reactions

It is possible to bring about or "induce" the disintegration of a stable nucleus by striking it with another nucleus, an atomic or subatomic particle, or a γ-ray photon. A **nuclear reaction** is said to occur whenever the incident nucleus, particle, or photon causes a change to occur in a target nucleus. In 1919, for example, Ernest Rutherford observed that when an α particle ($^{4}_{2}He$) strikes a nitrogen nucleus ($^{14}_{7}N$), an oxygen nucleus ($^{17}_{8}O$) and a proton ($^{1}_{1}H$) are produced. This nuclear reaction is written as

$$^{4}_{2}He + ^{14}_{7}N \longrightarrow ^{17}_{8}O + ^{1}_{1}H$$

Since the incident α particle induces the transmutation of nitrogen into oxygen, this reaction is an example of an **induced nuclear transmutation**.

Example 5

An alpha particle strikes an aluminum-27 nucleus. As a result, a new nucleus and a neutron are produced. Identify the nucleus produced.

The described reaction is written as

$$^{4}_{2}He + ^{27}_{13}Al \longrightarrow ^{A}_{Z}? + ^{1}_{0}n$$

Using conservation of charge and conservation of nucleons, we can determine the nucleus:

$$^{4}_{2}He + ^{27}_{13}Al \longrightarrow ^{A}_{Z}? + ^{1}_{0}n$$

Atomic mass: 4 + 27 = A + 1
A = 30

Atomic number: 2 + 13 = Z + 0
Z = 15
(element 15 is P - phosphorous)

Therefore:

$$^{4}_{2}He + ^{27}_{13}Al \longrightarrow ^{30}_{15}P + ^{1}_{0}n$$

Induced nuclear transmutations can be used to produce isotopes that are not found naturally. In 1934, Enrico Fermi suggested a method for producing elements with a higher atomic number than uranium (Z = 92). These elements – neptunium (Z = 93), plutonium (Z = 94), americium (Z = 95), and so on – are known as **transuranium elements**. None of the transuranium elements occur naturally. They are created in a nuclear reaction between a suitably chosen lighter element and a small incident particle, usually a proton, neutron or an α particle. For example, a reaction that produces plutonium from uranium involves a neutron capture followed by several radioactive disintegrations.

$$^{238}_{92}U + ^{1}_{0}n \longrightarrow ^{239}_{92}U + \gamma \qquad (1)$$

$$^{239}_{92}U \longrightarrow ^{239}_{93}Np + ^{0}_{-1}e + \gamma \qquad (2)$$

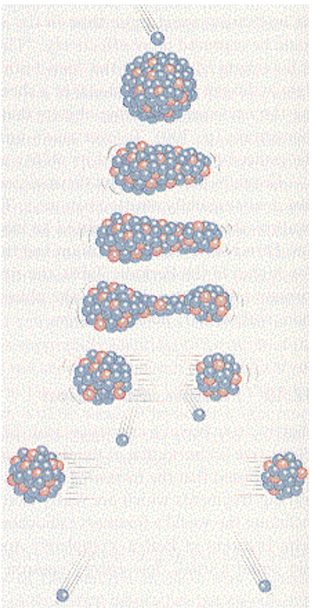
$$^{239}_{93}Np \longrightarrow ^{239}_{94}Pu + ^{0}_{-1}e + \gamma \qquad (3)$$

Reaction (1) involves a neutron captured by a uranium-238 nucleus producing uranium-239 and a γ-ray. The uranium-239 nucleus is radioactive (see Lesson 36) and decays into neptunium 239 Np (reaction (2)). Neptunium is also radioactive and disintegrates into plutonium-239 (reaction (3)). Plutonium is the final product.

Fission reactions

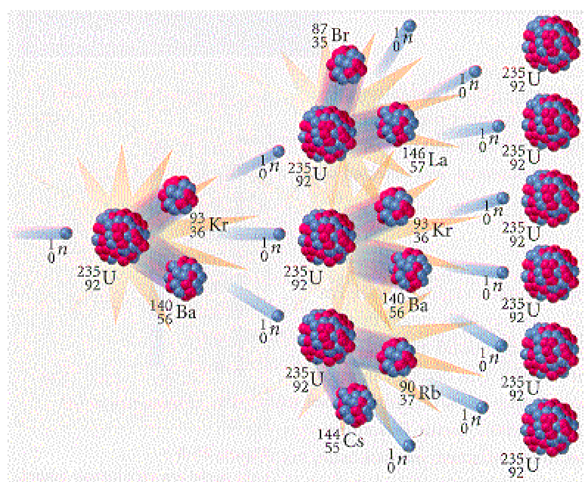
In **nuclear fission** we take heavy elements and break them apart to produce smaller nuclei. The process involves bombarding particular nuclei with neutrons. A neutron captured by a fissionable nucleus results in an unstable nucleus which splits. In the process some of the binding energy of the heavy element is converted into radiant energy. (Refer to Pearson pages 818 to 820.)

$$^{235}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{141}_{56}\text{Ba} + {}^{92}_{36}\text{Kr} + 3\,{}^{1}_{0}\text{n} + \text{energy}$$



A common misconception of fission reactions is that the neutron acts like a high speed bullet entering and exploding an egg. In nuclear reactions, if the neutron is too energetic it passes right through the target nucleus. If the neutron is too slow it will bounce off the target nucleus. At the right energy level, as shown on the left, the neutron enters the nucleus and causes it to oscillate uncontrollably resulting in the splitting of the nucleus. As the nucleus disintegrates 2, 3 or more free neutrons are released which can then invade new uranium-235 nuclei. Thus the reaction is self propagating and is referred to as a **chain reaction** which is shown below. In the chain reaction diagram below, note that different products can be formed for each fission reaction.

If the neutrons are shielded and reflected back into the uranium for long enough, about 1.0 ms, the reaction results in an atomic explosion. However, a controlling device can be used to control and reduce the rate of the reaction. A stable controlled reaction produces heat that can be used to heat water into steam and then drive a steam turbine to create electricity. Candu reactors use heavy water to slow down the chain reaction rate and to control the overall reaction.



The main problems with fission reactors are:

1. Fissionable uranium-235 is very rare (only 0.71 % of the uranium in uranium ore is uranium-235). Other isotopes like uranium-238 will not produce a chain reaction.
2. The process produces large amounts of deadly radioactive waste that must be carefully stored.
3. The reactors are subject to human and mechanical failures which can be catastrophic. Look up Chernobyl on the internet.

However, the process is environmentally safe in comparison with other forms of electrical energy production like coal burning and hydro power. The Candu reactor is one of the safest reactors in the world. We lead the United States in this technology.

Example 6

For the given reaction, calculate the energy released from the fission of one atom of uranium-235. The measured masses of the different isotopes are: uranium-235 = 234.9934 u, barium-141 = 140.88340 u, and krypton-92 = 91.90601 u.

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3\, ^{1}_{0}n + \text{energy}$$

The energy released is due to the difference in mass (Δm) between the products and the reactants. For one uranium-235 atom:

$$\Delta m = \Sigma\, m_{products} - \Sigma\, m_{reactants}$$
$$\Delta m = (140.88340 + 91.90601 + 3(1.008665)) - (1.008665 + 234.9934)$$
$$\Delta m = -0.18666 \text{ u}$$
$$\Delta m = -0.18666 \text{ u} \times 1.660540 \times 10^{-27} \text{ kg/u} = -3.099560 \times 10^{-28} \text{ kg}$$

To find the energy released we use

$$E = \Delta m\, c^2 = -3.099560 \times 10^{-28} \text{ kg} \times (3.00 \times 10^{8} \text{ m/s})^2 = \mathbf{-2.790 \times 10^{-11}\ J}$$
$$= \mathbf{-174.4\ MeV}$$

Fusion reactions

In **nuclear fusion** we take light elements and force them together to form larger sized atoms. (Refer to Pearson pages 821 to 824.) Examples are the fusion of two deuterium ($^{2}_{1}H$) nuclei to form a helium-3 nucleus.

$$^{2}_{1}H + ^{2}_{1}H \rightarrow ^{3}_{2}He + ^{1}_{0}n + \text{heat}$$

or the fusion of tritium ($^{3}_{1}H$) and deuterium ($^{2}_{1}H$) to form a helium-4 nucleus

$$^{3}_{1}H + ^{2}_{1}H \rightarrow ^{4}_{2}He + ^{1}_{0}n + \text{heat}$$

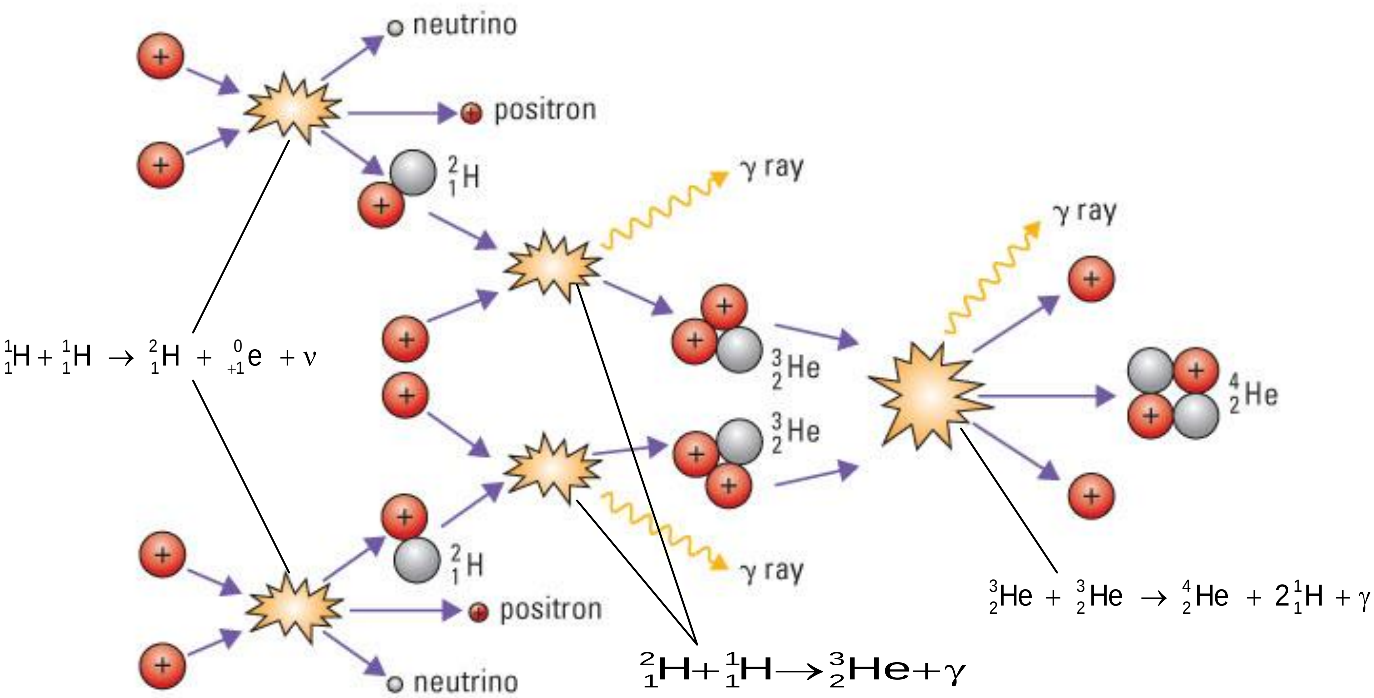
The problem to overcome in fusion reactions is to bring the parent nuclei together so that the electrostatic repulsion is overcome and the strong nuclear force (see Lesson 37) can take over. Nuclear fusion reactions require extremely high pressures and temperatures to get them started. Such pressures and temperatures are found within the core of a star like our Sun. In a star the nuclei are forced together due to the enormous gravitational forces involved. In turn, the forces created by the fusion reactions try to explode the star. Thus there is a balance between the forces of gravity and the forces produced by the fusion reactions.

The materials required to produce fusion reactions can be found in any pail of water. 4¢ of water has the potential to match 300 gallons of oil. The by-products are not radioactive. However, there is one little problem. Forcing two protons together is not easy. Millions of degrees of heat and millions of atmospheres of pressure are necessary to encourage the reaction to occur, i.e. the temperature and pressure at the core of a star. The only successful fusion reactions on Earth resulted in the hydrogen bomb which requires an atomic bomb to initiate the reaction.

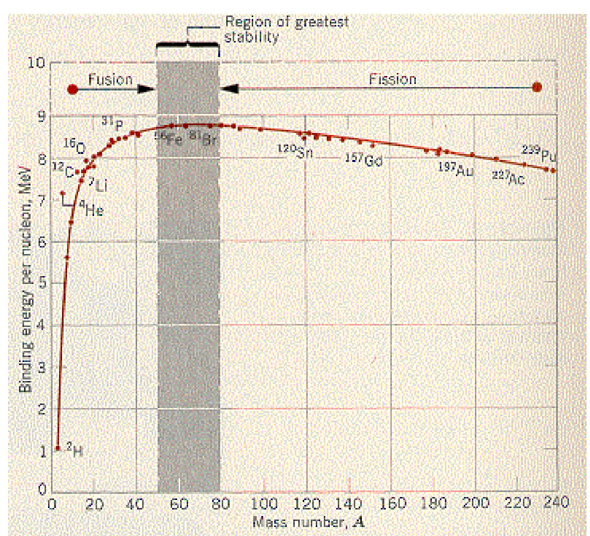
We currently do not have a “container” that will contain the hydrogen plasma at the required temperatures and pressures. However, at Princeton, scientists have successfully forced them together by suspending them as **plasma** (protons plus neutrons) in huge electromagnetic fields. At Chicago, scientists have used multiple lasers to implode a proton mass. Both reactions have worked at the lab scale, but nuclear fusion as a usable source of energy remains in the future. Maybe you can find the key.

VIII. Element formation

75% of the matter in the universe is in the form of hydrogen. In fact, it is from hydrogen that all elements are eventually synthesized. This process occurs through a series of **fusion reactions** within stars. Our Sun, for example, is an average star with an expected lifespan of between 10 to 11 billion years. It is currently half way through its life cycle. The main reaction that powers the Sun’s energy is a series of reactions leading to the formation of helium from hydrogen.



These reactions will continue until the hydrogen fuel has been mostly exhausted. As the reaction rate decreases the gravitational pressure will partially collapse the Sun which will lead to increased pressure in the core. When the pressure and temperature reach a critical point helium nuclei will begin to fuse to produce larger elements. Due to the more energetic helium fusion reactions, the increased fusion pressure will cause the Sun to expand in size into a red giant, swallowing the Earth in the process. The upper limit of this process is iron (Z = 26). Elements beyond iron are formed in truly spectacular



explosions called super novas. It is interesting to note that since the Earth has all elements within its crust, from hydrogen to uranium, the Earth and the solar system must have formed from the ashes of a star that went super nova many billions of years ago in this region of space.

The graph above indicates that smaller nuclei tend to undergo fusion reactions until the stability region is reached. In like manner, heavier elements will tend to undergo fission reactions where they may become the smaller, more stable isotopes like iron and bromine.

IX. Practice problems

1. A proton enters a beryllium-9 nucleus. The products are an alpha particle and another element. What is the element?

2. What is the binding energy in one atom of strontium-86 (85.9094 u)? What is the binding energy per nucleon? (731.37 MeV, 8.5043 MeV/nucleon)

3. Calculate the amount of energy released per atom when radium-226 undergoes alpha decay. (7.92078×10^{-13} J)

$$^{226}_{88}\text{Ra} \longrightarrow \, ^{4}_{2}\text{He} + \, ^{222}_{86}\text{Rn}$$

(226.0254 u) (4.00260 u) (222.0175 u)

X. Hand-in assignment

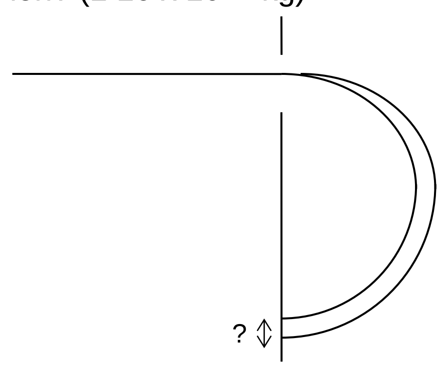
1. When a proton strikes a sodium-20 nucleus, a daughter nucleus and an alpha particle are produced. What is the daughter nucleus? Write an equation for the nuclear reaction.

2. Following are some equations of artificial transmutations produced by particle bombardment. Using a periodic table, if necessary, determine the other product in each case.
   a. $^{27}_{13}Al + ^{4}_{2}He \rightarrow ? + ^{1}_{1}H$
   b. $^{12}_{6}C + ^{2}_{1}H \rightarrow ? + ^{1}_{1}H$
   c. $^{9}_{4}Be + ^{1}_{1}H \rightarrow ? + ^{2}_{1}H$
   d. $^{14}_{7}N + ^{1}_{0}n \rightarrow ? + ^{14}_{6}C$
   e. $^{1}_{1}H + ^{1}_{0}n \rightarrow ?$
   f. $^{23}_{11}Na + ^{2}_{1}H \rightarrow ? + ^{1}_{1}H$
   g. $^{14}_{7}N + ^{4}_{2}He \rightarrow ? + ^{1}_{1}H$

3. Isotopes are separated by a mass spectrometer. Ions are accelerated through a potential difference and then allowed to pass through a velocity selector. The velocity selector is composed of a uniform 0.0400 T magnetic field and a uniform electric field perpendicular to each other. If the electric field is produced using parallel plates that are 1.50 cm apart, what is the potential difference between the plates that will permit singly charged ions with a speed of 4.20×10^5 m/s to pass undeflected through the selector? (252 V)

4. Single charged ions pass undeflected through the velocity selector of a mass spectrometer. This velocity selector has a magnetic field of 0.250 T and an electric field of 7000 V/m perpendicular to each other. These ions then enter a separation region where the magnetic field is the same as in the velocity selector. If the radius of the deflected ions is 8.13 mm, what is the mass of each ion? (1.16×10^{-26} kg)

5. An ion source contains two isotopes of magnesium: $^{24}_{12}Mg$ (23.98504 u) and $^{25}_{12}Mg$ (24.98584 u). These ions travel undeflected through the velocity selector (B = 0.850 T, $|\vec{E}| = 4.60 \times 10^5$ V/m) of a mass spectrometer. If both ions are doubly charged, how far apart are the ions in the ion detector (B = 0.250 T)? (0.0225 m)



6. A singly charged carbon ion travels in a circular path (r = 11.3 cm) through the ion separation region (B = 0.300 T) of a mass spectrometer. If the velocity selector has a magnetic field of 0.300 T and an electric field of 7.50×10^4 V/m perpendicular to each other, what is the mass number of the carbon isotope?(13)

7. Determine the mass defect of an atom of cobalt-59 which has a measured atomic mass of 58.9332. Express your answer in atomic mass units and kilograms. (–0.540532 u, -8.97575×10^{-28} kg)

8. Two isotopes of chlorine occur in nature. Their natural abundance is measured with a mass spectrometer. The chlorine-35 isotope has an atomic mass of 34.96885 u and a natural abundance of 75.77 %. The chlorine-37 isotope has anatomic mass of 36.96590 and a natural abundance of 24.23 %. By a calculation of your own, verify that the value of 35.45 on the periodic table is a weighted average of the isotopes.

9. Find the binding energy in MeV for lithium-7 (atomic mass = 7.0160 u). (–37.818 MeV)

10. For radium-226 (atomic mass = 226.0254 u) obtain (a) the mass defect, (b) the binding energy in MeV, and (c) the binding energy per nucleon. (–1.810658 u, –1691.25 MeV, –7.4834 MeV/nucleon)

11. The energy output of the Sun is approximately 4.0 x 10^{26} J/s. If all this energy results from mass-energy conversion in the fusion process, calculate the rate at which the Sun is losing mass. (4.4 x 10^{9} kg/s)

12. The energy released by the fission of one atom of uranium-235 is 3.2 x 10^{-8} J. the energy released by the atomic bomb dropped at Hiroshima was estimated to be the equivalent of 18 140 t of dynamite or 8.0 x 10^{13} J.
    a. How many atoms of uranium underwent fission? (~2.5 x 10^{21} atoms)
    b. What mass of uranium-235 was converted into energy? (8.9 x 10^{-4} kg)

13. Find the quantity of nuclear energy liberated in each of the following nuclear reactions:

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{140}_{54}Xe + ^{94}_{38}Sr + 2\,^{1}_{0}n$$

(235.043925 u) (1.00867 u) (139.92161 u) (93.915367 u) (1.00867 u)

$$^{3}_{2}He + ^{3}_{2}He \rightarrow ^{4}_{2}He + 2\,^{1}_{1}H$$

(3.01603 u) (3.01603 u) (4.00260 u) (1.00728 u)

(Answers: –2.96 x 10^{-11} J, –2.23 x 10^{-12} J)

14. A nuclear power reactor generates 3.0 x 10^{9} W of power. In one year, what is the change in mass of the nuclear fuel? (1.1 kg)