CHM 101 GENERAL CHEMISTRY

FALL QUARTER 2008

Section 2

Lecture Notes – 12/1/2008

(last revised: 12/2/08, 4:30:PM)

18.4 Detection and Uses of Radioactivity (This section is repeated from the notes of 11/24/08, because we only covered part of the section that night in class.)

- **Measuring Radioactivity:** The two most familiar instruments for making radioactivity measurements are the *Geiger – Müller counter* (also called simply *Geiger counter*) and the *scintillation counter*.
  - **The Geiger – Müller Counter:** The Geiger – Müller counter takes advantage of the fact that radioactive decay produces high-energy particles that can ionize the matter through which they pass. (Thus radiation like that produced by radioactive decay is often called *ionizing radiation*.) The probe of a Geiger – Müller counter is filled with argon gas, whose atoms will ionize when struck by high-energy particles:

$$\mathrm{Ar}\,(g) \xrightarrow{\text{high energy particle}} \mathrm{Ar}^{+}\,(g) + e^{-} \xrightarrow{\text{electric potential}} \mathrm{Ar}\,(g)$$

When the Geiger – Müller counter is turned on, it applies an electric potential across the argon tube. Since neutral argon gas does not conduct electricity, there is normally no flow of current across the tube. However current will flow momentarily each time an ion is produced by a high-energy particle. (The electric current converts the argon ion back to a neutral atom, thus shutting itself off.) Each time when there is current flow can be considered an "event," and these events can be counted and interpreted as the rate of radioactive decay of the decay source. Figure 18.7 illustrates how a Geiger – Müller counter works.

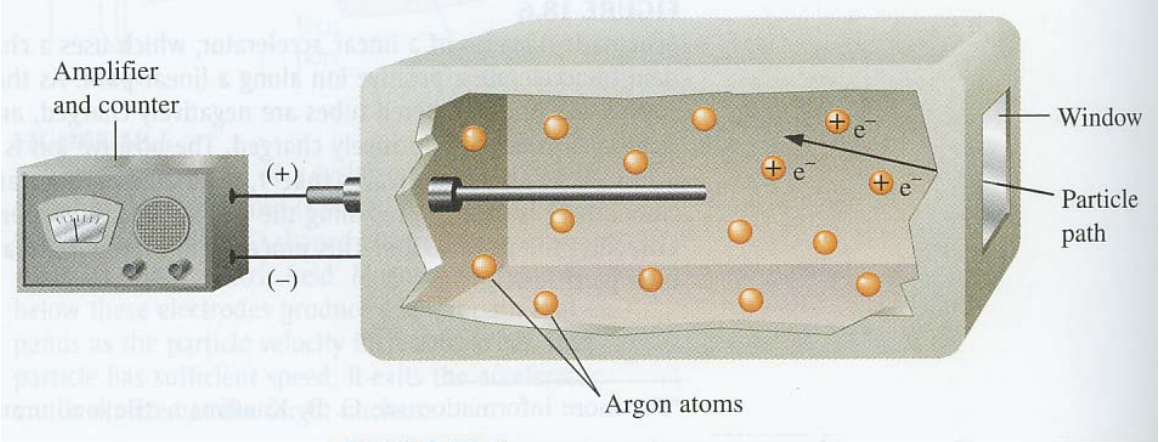

FIGURE 18.7
A schematic representation of a Geiger–Müller counter. The high-energy radioactive particle enters the window and ionizes argon atoms along its path. The resulting ions and electrons produce a momentary current pulse, which is amplified and counted.

- **The Scintillation Counter:** The detector in a scintillation counter is zinc sulfide, which emits light when struck by a high-energy particle. A photocell counts each flash from the detector and thus measures the rate of radioactive decay of the decay source.

- **Radioactive Dating:** Under certain conditions, measurements of radioactivity and/or analytical measurements of the amounts of radioactive materials in a sample can be used to date the sample, i. e., to determine how old it is. We will discuss *carbon-14 dating* and *dating by radioactivity*.

  - **Carbon-14 Dating:** *Carbon-14 dating* (also known as *radiocarbon dating*) can be used to determine the ages of ancient articles made from wood or fabric. The technique is based on measuring the ratio of carbon-14 to carbon-12 in the article. It works because carbon-14 is radioactive and decays with a half-life of 5,730 years. In principle, articles up to 10,000 and more years old can be dated by this technique.

    How It Works: Carbon-14 is generated when high-energy neutrons from space (a component of cosmic rays) collide with atmospheric nitrogen-14:

    $$^{14}_{7}\mathrm{N} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{14}_{6}\mathrm{C} + {}^{1}_{1}\mathrm{H}$$

    The resulting carbon-14 is radioactive, and it undergoes decay by beta particle emission:

$$^{14}_{6}\mathrm{C} \rightarrow {}^{14}_{7}\mathrm{N} + {}^{0}_{-1}\mathrm{e}$$

Over the centuries, the rates of these two reactions have become equal, and the amount of atmospheric carbon-14 has reached a constant (so-called *steady-state*) value.

The resulting atoms of carbon-14 are chemically reactive and they readily combine with atmospheric oxygen to make carbon-14 dioxide, a radioactive molecule with the same chemistry as ordinary carbon dioxide. Through photosynthesis, it is incorporated into biomass (including wood and plant fiber). As long as the biomass remains alive, its ratio of carbon-14 to carbon-12 will match that of the atmosphere through replenishment of its carbon content. However, when the biomass dies, its carbon-14 will begin to decay without replenishment while its carbon-12 content remains constant. Since the decay process of carbon-14 has a half-life of 5,730 years, the carbon-14 to carbon-12 ratio of a sample of this biomass will fall to half its initial value after 5,730 years have elapsed. The decay rate of its carbon-14 content will also fall to half the initial value over this 5,730 year period since the rate of decay is proportional to its carbon-14 content.

Systematic Errors in Carbon Dating: The half-life of carbon-14 is a well-established number, so its use does not introduce any systematic errors into radiocarbon dating results. However, what if the atmospheric ratio of carbon-14 to carbon-12 changes over time, and we try to use the current ratio in our dating calculation? We get a systematic error.

Suppose the cosmic ray neutron flux 5,730 years ago were 20% lower than it is now. This would have made the carbon-14 to carbon-12 ratio 20% lower at that time. Our measurement today of the carbon-14 to carbon-12 ratio in our 5,730 year old wood sample would be 50% of that lower starting value, and it would be 40% of the current value of the ratio. Thus we would overestimate the age of the sample.

And suppose that the carbon-12 content of the atmosphere (i. e., $^{12}CO_2$) were higher today than it was 5,730 years ago. This is probably the case, due to mankind's burning of fossil fuels, whose carbon is so old that all its original carbon-14 has long since decayed. Suppose also, that the cosmic ray neutron flux has remained constant. In this case we would underestimate the age of our sample.

Corrections for Systematic Errors: Fortunately, there are sources of ancient wood whose ages can be determined by counting

tree rings (a technique called *dendrochronology*). Samples of the wood of giant sequoias and bristlecone pines can thus be dated as far back as 5,000 years by tree-ring counting. Then radiocarbon dating of the same samples can be used to compute correction factors that can be used to calibrate other radiocarbon dating results.

- **Sample Exercise 18.5** (pp. 853-4): The remnants of an ancient fire showed a carbon-14 decay rate of 3.1 counts per minute per gram of carbon. Assuming that freshly-cut wood decays at a rate of 13.6 counts per minute (after correcting for changes in the atmospheric carbon-14 to carbon-12 ratio over time), calculate the age of the remains. The half-life of carbon-14 is 5,730 years.

  Recall that the decay rate ($Rate$) of our ancient sample is proportional to the number (N) of carbon-14 nuclides it contains:

$$Rate = kN$$

  And similarly that the decay rate ($Rate_0$) is proportional to its number (N_0) of carbon-14 nuclides:

$$Rate_0 = kN_0$$

  Thus we can compute the ratio of the two rates:

$$\frac{Rate}{Rate_0} = \frac{kN}{kN_0}$$

  Now we can let the k's cancel out, and we can plug in our rate measurements:

$$\frac{N}{N_0} = \frac{3.1}{13.6}$$

  This gives us the input we need in order to use the integrated rate law:

$$\ln\left(\frac{N}{N_0}\right) = -kt$$

We can compute the rate constant, k, from the half-life:

$$k = \frac{\ln 2}{t_{1/2}} = \frac{\ln 2}{5730 \text{ yr}}$$

Now we can solve the rate law for the time, *t*, and plug in our numbers:

$$t = -\frac{1}{k}\ln\left(\frac{N}{N_0}\right) = -\frac{1}{\left(\frac{\ln 2}{t_{1/2}}\right)}\ln\left(\frac{N}{N_0}\right) = -\frac{t_{1/2}}{\ln 2}\ln\left(\frac{N}{N_0}\right)$$

$$t = -\frac{5730 \text{ yr}}{\ln 2}\ln\left(\frac{3.1}{13.6}\right) = 12,000 \text{ yr}$$

We can check to see if our result makes sense. Our quantity (N/N_0) would be 0.25 after two half-lives (11,460 yr) and 0.125 after 3 (17,190 yr). Its actual value is (3.1/13.6) = 0.23, so we expect that the answer would be slightly more than 2 half lives, in good agreement with our result of 12,000 years.

- **Radiocarbon Dating by Mass Spectrometry:** "Conventional" radiocarbon dating requires that samples be burned with recovery of carbon dioxide and measurement of the radioactive decay rates. This requires relatively large samples (up to several grams). Mass spectrometry has the advantages of requiring much smaller samples (around 1 milligram) and yielding direct and accurate measurements of the carbon-12 to carbon-14 ratios.
- **Dating by Radioactivity:** Carbon-14 is not the only radioactive nuclide that can be used for age measurements. For example, the decay of uranium-238, eventually producing lead-206, is useful under some circumstances for making estimates of the age of uranium-containing rocks. Since uranium-238 has a half-life (4.5 billion years) that is nearly as long as the age of the earth, it can be used to determine the ages of some really old rocks. And if an even longer half-life is needed, lutecium-176 might be the answer, with a half-life of over 37 billion years.
- **Sample Exercise 18.6** (pp. 854-5): A rock containing uranium-238 and lead-206 was analyzed to determine its approximate age.

The analysis showed that the ratio of lead-206 atoms to uranium-238 atoms was 0.115. You may assume that there was no lead originally present, that all of the lead generated by the decay chain is still present in the sample, and that the content of the intermediate nuclides in the decay chain is negligible. The half-life of uranium-238 is 4.5×10^9 years. Estimate the age of the rock.

We can use the integrated first order rate law:

$$\ln\left(\frac{N}{N_0}\right) = -kt$$

And we can compute the rate constant from the half-life:

$$k = \frac{\ln 2}{t_{1/2}} = \frac{\ln 2}{4.5 \times 10^9 \text{ yr}}$$

Our measured lead-206 to uranium-238 ratio is the amount of lead produced by uranium-238 decay divided by the remaining uranium-238 that has not decayed.

$$0.115 = \frac{\text{atoms of } {}^{206}_{82}\text{Pb now present}}{\text{atoms of } {}^{238}_{92}\text{U now present}}$$

The present number of uranium-238 atoms is the value of N that we need for the rate law equation. But for N_0 we need the number of uranium-238 atoms originally present. This number can be written:

$$\text{atoms of } {}^{238}_{92}\text{U originally present} = \text{atoms of } {}^{238}_{92}\text{U now present} + \text{atoms of } {}^{206}_{82}\text{Pb now present}$$

If we assume that we now have 1,000 uranium-238 atoms, we can solve for the number of lead atoms:

$$0.115 = \frac{\text{atoms of } {}^{206}_{82}\text{Pb now present}}{\text{atoms of } {}^{238}_{92}\text{U now present}} = \frac{\text{atoms of } {}^{206}_{82}\text{Pb now present}}{1000}$$

$$\text{atoms of } {}^{206}_{82}\text{Pb now present} = 0.115 \times 1000 = 115$$

Now we can compute the number of uranium-238 atoms originally present:

$$\text{atoms of } {}^{238}_{92}\text{U originally present} = \text{atoms of } {}^{238}_{92}\text{U now present} + \text{atoms of } {}^{206}_{82}\text{Pb now present}$$

$$\text{atoms of } {}^{238}_{92}\text{U originally present} = 1000 + 115 = 1115$$

Now we have:

$$N = 1000 \quad \text{and} \quad N_0 = 1115$$

Now we have all the numbers we need to plug into the rate equation to solve for *t*:

$$t = -\frac{1}{k}\ln\left(\frac{N}{N_0}\right) = -\left(\frac{4.5\times10^{9}\ \text{yr}}{\ln 2}\right)\ln\left(\frac{1000}{1115}\right) = 7.1\times10^{8}\ \text{yr}$$

- **Radiotracers in Medicine:** Radioactive nuclides have proven to be quite valuable in biological research and in medicine. Here are some examples:
  - **Iodine-131:** Iodine when ingested will concentrate in the thyroid gland. When a patient drinks a solution of sodium iodide containing small amounts of iodine-131, the uptake of iodine by the thyroid gland can be monitored by imaging the radiation produced by decay of the iodine-131, as seen in Figure 18.8:

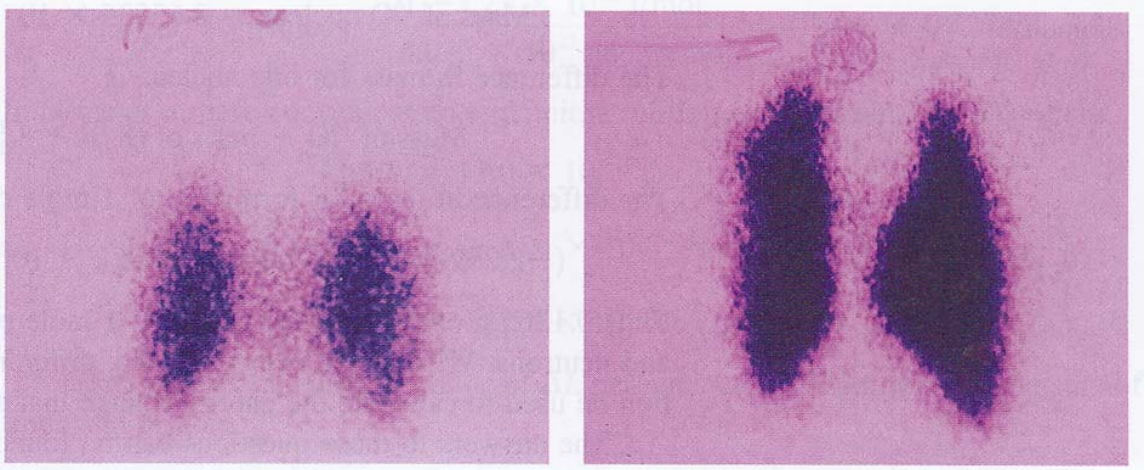

FIGURE 18.8
After consumption of $Na^{131}I$, the patient's thyroid is scanned for radioactivity levels to determine the efficiency of iodine absorption. (left) A normal thyroid. (right) An enlarged thyroid.

- **Thallium-201:** When thallium is ingested, it concentrates in healthy heart tissue. Thallium-201 thus will form an image in healthy heart tissue and show by its relative absence those parts of the heart damaged by a heart attack.
- **Technicium-99m:** Technecium-99m behaves similarly to thallium-201 and can also be used to help assess damage to the heart by a heart attack.
- **Other Medically Useful Nuclides:** Table 18.5 lists some other radioactive nuclides useful as diagnostic tracers in medicine.

TABLE 18.5 Some Radioactive Nuclides, with Half-Lives and Medical Applications as Radiotracers

Nuclide	Half-Life	Area of the Body Studied
^{131}I	8.1 days	Thyroid
^{59}Fe	45.1 days	Red blood cells
^{99}Mo	67 hours	Metabolism
^{32}P	14.3 days	Eyes, liver, tumors
^{51}Cr	27.8 days	Red blood cells
^{87}Sr	2.8 hours	Bones
^{99m}Tc	6.0 hours	Heart, bones, liver, and lungs
^{133}Xe	5.3 days	Lungs
^{24}Na	14.8 hours	Circulatory system

- **Characteristics of a Useful Radiotracer:**

  It must be chemically non-toxic.

It needs to concentrate in the tissue of interest and not in surrounding tissue.

Its decay must produce a detectable signal.

The radiation produced by its decay must not cause the organism undue harm.

The nuclides produced by its decay must be chemically non-toxic.

18.5 Thermodynamic Stability of the Nucleus: The changes in energy that accompanies a nuclear transformation is so large that the sum of the masses of the products is different from the sum of the masses of the reactants. Thus the change in energy can be calculated by using Einstein's famous formula for the mass equivalence of energy, $E = mc^2$.

- **Calculating Mass Differences:** We cannot use the atomic masses from the list in the inside front cover of your text because these are average values for the elements weighted by the abundances of the various isotopes of each element. We must instead refer to a table of isotopic masses, such as the one found on the NIST website. We can use Avogadro's number to convert between atomic mass units and units of grams per atom.

  One thing to keep in mind is that these isotopic masses include both nuclei and electrons, but we do not need to be concerned about the masses of electrons. As long as electrons are not involved in the transformation, their masses subtract out when we calculate the mass difference for the transformation. Alternatively, if we are given the masses of the bare nuclei, we again do not need to be concerned about electrons because in this case, electron masses are not included in the starting data. The following table shows the nuclear masses and the isotopic masses for several common nuclides. It also shows masses for the electron, the neutron, and the proton (listed as hydrogen-1). Note how the masses of the isotopes are larger than the masses of the nuclei by the masses of the electrons included with the isotopes. We will use numbers from this table to perform the two sample exercises immediately below.

Species	Symbol	Mass of Particle or Nucleus AMU	Mass of Particle or Nucleus g	Isotopic Mass AMU	Isotopic Mass g
electron	$^{0}_{-1}e$	0.000549	9.10939×10^{-28}	N/A	
neutron	$^{1}_{0}n$	1.00866	1.67493×10^{-24}	N/A	
hydrogen-1	$^{1}_{1}H$	1.00728	1.67262×10^{-24}	1.007825	1.67353×10^{-24}
helium-4	$^{4}_{2}He$	4.001506	6.64466×10^{-24}	4.002602	6.64648×10^{-24}
oxygen-16	$^{16}_{8}O$	15.9909	2.65535×10^{-23}	15.9949	2.65602×10^{-23}

Example Calculation: As an example, we will calculate the change in mass for the hypothetical process in which an oxygen-16 nucleus is assembled from 8 protons and 8 neutrons:

$$8\ {}^{1}_{0}n\ +\ 8\ {}^{1}_{1}H\ \rightarrow\ {}^{16}_{8}O$$

Let us systematically calculate the total mass of reactants needed to make one oxygen-16 nucleus and subtract the mass of that nucleus to obtain the change in mass, Δm, also known as the *mass defect*. Finally, we can use Avogadro's number to convert the result to grams of mass lost per mole of nuclei formed.

Component	Unit Mass (g)	Number	Mass (g)
$^{1}_{0}n$	1.67493×10^{-24}	8	1.33994×10^{-23}
$^{1}_{1}H$	1.67262×10^{-24}	8	1.33810×10^{-23}
total reactant mass			2.67804×10^{-23}
$^{16}_{8}O$	2.65535×10^{-23}	1	2.65535×10^{-23}
total product mass			2.65535×10^{-23}
Δm = product mass – reactant mass (the mass defect for one nucleus)			-2.269×10^{-25}
Avogadro's number			6.022×10^{23}
Δm = product mass – reactant mass (the mass defect for one mole of nuclei)			–0.1366

- **Converting from Mass to Energy:** Now we can use Einstein's mass-energy relationship ($\Delta E = \Delta mc^2$) to obtain the change of energy for

the reaction. We will convert the mass defect to units of kg, and for the speed of light we will use:

$$c = 3.00 \times 10^{8} \text{ m/sec}$$

This will yield the answer in Joules per mole, since our mass defect is for one mole of oxygen-16 nuclei.

$$\Delta E = \Delta m c^2 = -(1.366 \times 10^{-4} \text{ kg/mol}) \times (3.00 \times 10^{8} \text{ m/sec})^2$$

$$\Delta E = -1.23 \times 10^{13} \text{ J/mol}$$

The minus sign indicates that this is an exothermic process, i. e., that energy is given off as a result of the reaction. It is interesting to compare this with the energy released by exothermic chemical reactions which typically release up to around 1000 kJ/mol (10^6 J/mol). The result for our nuclear synthesis is 7 orders of magnitude (10 million) times greater.

- **Nuclear Binding Energy:** The energy result we just obtained represents the energy released by the formation of a mole of oxygen-16 nuclei from its constituent nucleons. Consequently, it would take $+1.23 \times 10^{13}$ J to break a mole of oxygen-16 nuclei back into its constituent neutrons and protons. This amount of energy is the *binding energy* of a mole of oxygen-16 nuclei relative to 8 moles of protons and 8 moles of neutrons. Let us calculate the binding energy of a single oxygen-16 nucleus. There are two ways we can do this, given the calculations we have just performed. We can follow the book and divide our binding energy for one mole of nuclei (1.23×10^{13} J/mol) by Avogadro's number. Or we could apply Einstein's mass-to-energy conversion to our mass defect for the formation of a single nucleus. Let's do it that way:

$$\Delta E = \Delta m c^2 = (2.269 \times 10^{-28} \text{ kg/nucleus}) \times (3.00 \times 10^{8} \text{ m/sec})^2$$

$$\Delta E = 2.04 \times 10^{-11} \text{ J/nucleus}$$

Nuclear binding energies are commonly expressed in units of millions of electron volts (MeV). The conversion expression for Joules and MeV is:

$$1 \text{ MeV} = 1.60 \times 10^{-13} \text{ J}$$

We multiply our energy by the appropriate unit factor to convert from Joules to MeV:

$$\Delta E = (2.04 \times 10^{-11} \text{ J/nucleus}) \times \frac{1 \text{ MeV}}{1.60 \times 10^{-13} \text{ J}} = 1.28 \times 10^{2} \text{ MeV/nucleus}$$

By convention, and in order to make meaningful comparisons among nuclei of different nuclides, we divide this result by the mass number (16 for oxygen-16) to get our final result for the binding energy (BE) in MeV/nucleon:

$$\mathrm{BE} = \Delta\mathrm{E}({}^{16}_{8}\mathrm{O}) = -\frac{(1.28\times10^{2}\ \mathrm{MeV/nucleus})}{(16\ \mathrm{nucleons/nucleus})} = 7.98\ \mathrm{MeV/nucleon}$$

For comparison, the binding energy for a hydrogen atom relative to a bare proton and an unbound electron is 13.6 eV, about a million times less.

- **Sample Exercise 18.8** (pp. 858-9): Calculate the binding energy per nucleon for a helium-4 nucleus. You may use the isotopic masses (including the electrons) for hydrogen-1 (1.0078 amu) and helium-4 (4.0026 amu). The mass of a neutron is 1.0087.

  We write the equation for the reaction:

$$2\left({}^{1}_{1}\mathrm{H} + {}^{0}_{-1}\mathrm{e}\right) + 2\ {}^{1}_{0}\mathrm{n} \rightarrow \left({}^{4}_{2}\mathrm{He} + 2\,{}^{0}_{-1}\mathrm{e}\right)$$

  The expressions in parentheses represent, respectively, atoms of hydrogen-1 and helium-4. The electrons act only as "spectator particles" in the reaction. When we calculate the mass defect from the isotopic masses, the masses of these electrons will subtract out and not affect the result. We'll use the same systematic procedure we used on the earlier mass defect example:

Component	Unit Mass (amu)	Number	Mass (amu)
${}^{1}_{0}\mathrm{n}$	1.0087	2	2.0174
${}^{1}_{1}\mathrm{H} + {}^{0}_{-1}\mathrm{e}$	1.0078	2	2.0156
total reactant mass			4.0330
${}^{4}_{2}\mathrm{He} + 2\,{}^{0}_{-1}\mathrm{e}$	4.0026	1	4.0026
total product mass			4.0026
Δm = product mass – reactant mass (the mass defect for one nucleus)			–0.0304

  Let's convert the result to kg, using the conversion expression from the table in the inside back cover of your text:

$$1 \text{ amu } = 1.66\times10^{-27} \text{ kg}$$

$$\Delta m = -\left(0.0304 \text{ amu/nucleus}\right)\times\left(1.66\times10^{-27} \text{ kg/amu}\right) = -5.04\times10^{-29} \text{ kg/nucleus}$$

Now we can use Einstein's equation to convert this mass defect to a change in energy (recall that c = 3.00x10^8 m/sec):

$$\Delta E = \Delta mc^2 = -\left(5.04\times10^{-29} \text{ kg/nucleus}\right)\times\left(3.00\times10^{8} \text{ m/sec}\right)^2$$

$$\Delta E = -4.54\times10^{-12} \text{ J/nucleus}$$

Thus, in the hypothetical synthesis of helium-4 from 2 protons and 2 neutrons, –4.54x10^{-12} Joules of energy are released for each helium-4 nucleus that forms. This means that the reverse reaction, the decomposition of a helium-4 nucleus back to its constituent 2 protons and 2 neutrons, would require an input of 4.54x10^{-12} Joules. If we divide that by 4, the number of nucleons in a helium-4 nucleus, we get the binding energy (BE) per nucleon:

$$BE = \frac{\left(4.54\times10^{-12} \text{ J/nucleus}\right)}{\left(4 \text{ nucleons/nucleus}\right)} = 1.14\times10^{-12} \text{ J/nucleon}$$

Finally, we convert this result to MeV:

$$BE = \Delta E\left({}^{4}_{2}\text{He}\right) = \left(1.14\times10^{-12} \text{ J/nucleon}\right)\times\left(\frac{1 \text{ MeV}}{1.60\times10^{-13} \text{ J}}\right) = 7.13 \text{ MeV/nucleon}$$

- **Binding Energies of the Various Nuclides:** The binding energy of any nuclide can be calculated if its atomic mass is well known. Figure 18.9 shows a graph of binding energies (per nucleon) for nuclides spanning the periodic table:

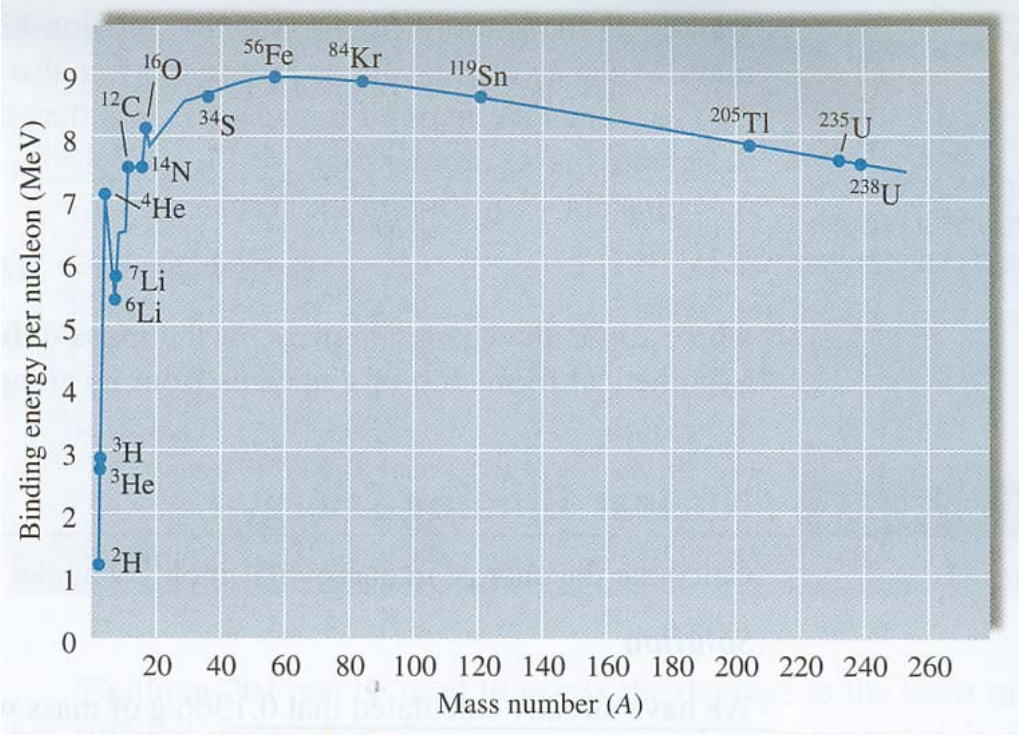

FIGURE 18.9
The binding energy per nucleon as a function of mass number. The most stable nuclei are at the top of the curve. The most stable nucleus is $^{56}_{26}$Fe.

Note how the curve rises sharply from the origin, peaks at about 9 MeV for iron-56, then gradually subsides to about 7.5 MeV for uranium-238. Note also the local peaks in binding energy that indicate the extraordinarily high stabilities of helium-4, carbon-12, and oxygen-16. Food for thought: what is the binding energy for hydrogen-1?

18.6 Nuclear Fission and Nuclear Fusion: The shape of the binding energy curve in Figure 18.9 suggests that there might be two different kinds of exothermic nuclear reactions, i. e., reactions where energy is released and the binding energies of the products exceed the binding energies of the reactants. That is indeed the case as illustrated in Figure 18.10 from your text:

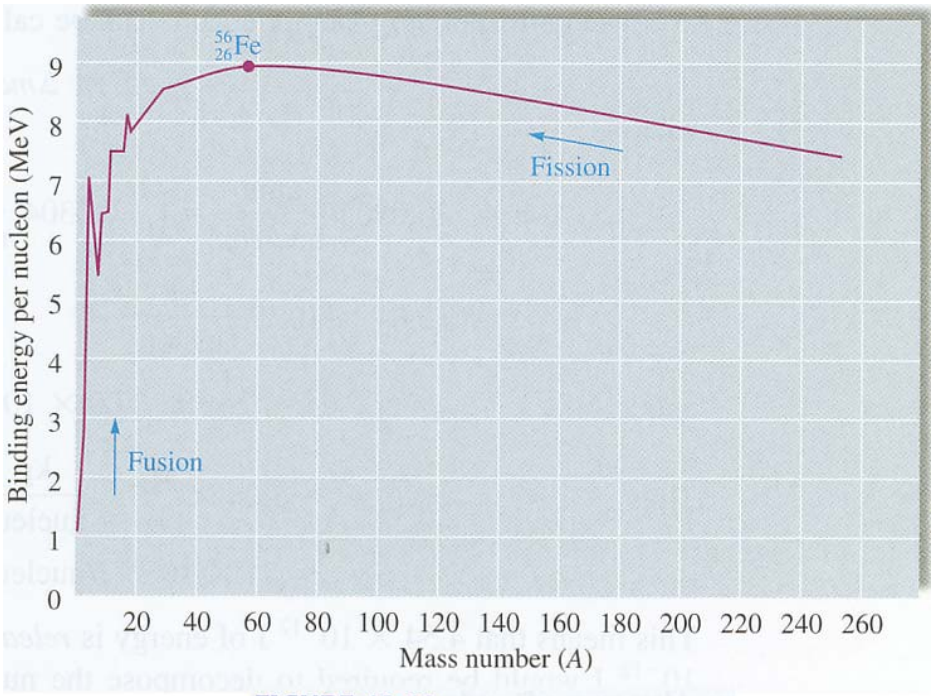

FIGURE 18.10
Both fission and fusion produce more stable nuclides and are thus exothermic.

Two light nuclei can combine to form a heaver, more stable nucleus in a process called *nuclear fusion*. This is the major reaction that takes place during the explosion of a hydrogen bomb.

One heavy nucleus can divide into two smaller, but more stable nuclei in a process called *nuclear fission*. Nuclear fission reactions drove the explosions of the two atomic bombs that were dropped in Hiroshima and Nagasaki, Japan to help end World War II. Nuclear fission has since been harnessed to generate electricity for commercial electric power and to provide on-board power to drive nuclear submarines.

Since nuclear binding energies are on the order of a million times greater than chemical bond energies, the energies released during nuclear reactions are also on the order of a million times greater than the energies released during chemical reactions.

- **Nuclear Fission:** You may recall from Section 18.3 that Fermi's experiment to subject uranium to neutron bombardment produced results that defied interpretation, at first. (Click here for a web page with a good discussion of this topic.) These experiments were revisited in 1938 and 1939 by the German radiochemists, Otto Hahn and Fritz Strassmann, and the Austrian physicist, Lise Meitner. They were able to characterize a radioactive isotope of barium as a reaction product of the neutron bombardment of uranium-235. They gave the correct

interpretation that the uranium-235 had undergone nuclear fission following absorption of a neutron. They also predicted that the fission reaction also produced neutrons that could bombard additional uranium-235 atoms leading to a chain reaction and violent explosion. Hahn would win the 1944 Nobel Prize in Chemistry for this discovery. (Click here for the Wikipedia article about the life and scientific career of Otto Hahn.)

- **The Nuclear Fission of Uranium-235:** Let's look at the nuclear reaction that produced the radioactive barium:

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

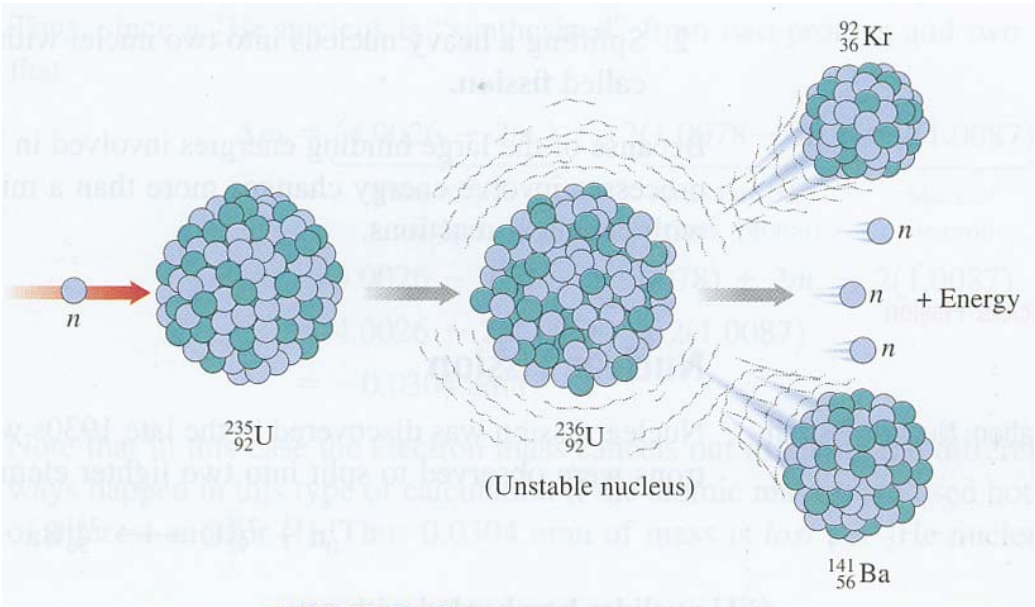

FIGURE 18.11
On capturing a neutron, the $^{235}_{92}$U nucleus undergoes fission to produce two lighter nuclides, free neutrons (typically three), and a large amount of energy.

The reaction (pictured in Figure 18.11) releases 3.5×10^{-11} J of energy per event, or (multiplying by Avogadro's number) 2.1×10^{13} J/mol of uranium-235. This is 26 million times the energy released by the combustion of one mole of methane (8.0×10^{5} J/mol).

This is not the only fission reaction that uranium-235 undergoes after neutron bombardment. Another is:

$$ {}^{1}_{0}\mathrm{n} + {}^{235}_{92}\mathrm{U} \rightarrow {}^{137}_{52}\mathrm{Te} + {}^{97}_{40}\mathrm{Zr} + 2\ {}^{1}_{0}\mathrm{n} $$

Approximately 100 different fission reactions have been observed, producing around 200 isotopes of 35 different elements. (No wonder Fermi's initial experiment was so hard to interpret.)

- **Chain Reactions:** The two above reactions produce neutrons. Each of these neutrons is capable of colliding with another uranium-235 nucleus and triggering another fission reaction, producing more neutrons and triggering still more fission reactions. The outcome depends on how many of these neutrons actually collide with uranium-235 nuclei and how many pass to the surroundings without colliding. There are three possible outcomes:

  A Subcritical Process: If on average, less than one neutron from a fission event causes another, the process will soon die out for lack of neutrons.

  A Critical Process: If, on average, exactly one neutron from a fission event causes another, the process is self-sustaining and takes place at a steady rate.

  A Supercritical Process: If, on average, more than one neutron from a fission event causes another, the process rapidly escalates and the release of energy causes a violent explosion. Figure 18.12 illustrates a supercritical process, also called a chain reaction:

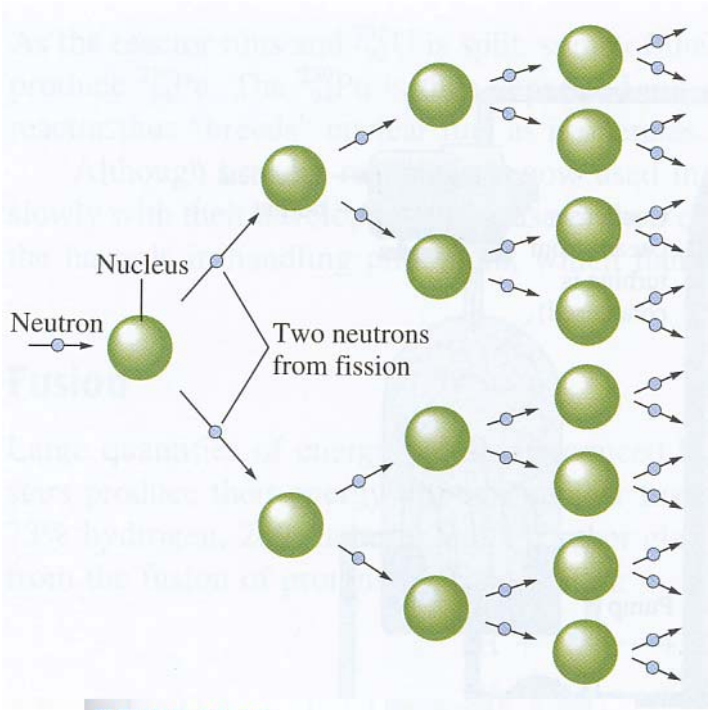

FIGURE 18.12
Representation of a fission process in which each event produces two neutrons, which can go on to split other nuclei, leading to a self-sustaining chain reaction.

- **Critical Mass:** The outcome of a fission process depends on the amount of fissionable material (like uranium-235 or plutonium-239

lies in the vicinity of a fission event. The amount needed to sustain the fission process at the critical level is called the *critical mass*. If the mass is *subcritical* (too small), too many neutrons escape, and any reaction soon dies out. If the mass is *supercritical* (large enough), the chain reaction multiplies and a nuclear explosion is the result. These two possibilities are shown in Figure 18.13 from the text:

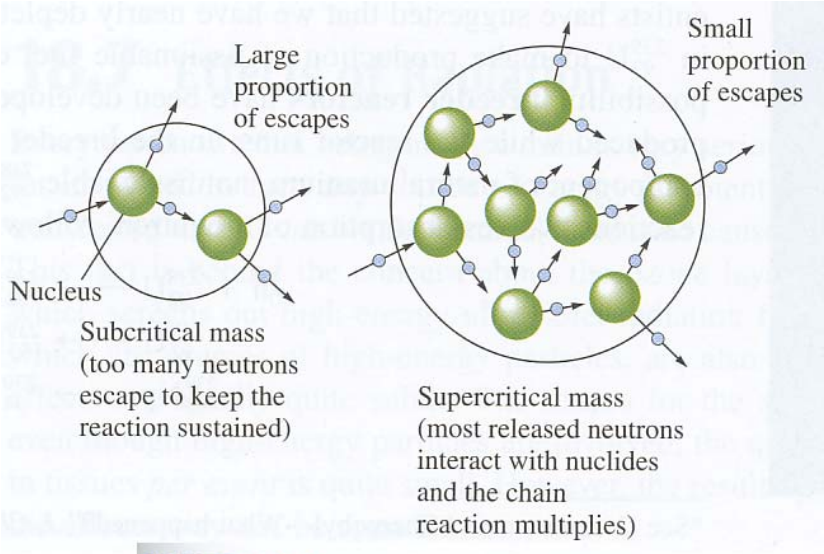

FIGURE 18.13
If the mass of fissionable material is too small, most of the neutrons escape before causing another fission event, and the process dies out.

- **Nuclear Bombs:** A successful nuclear bomb is a device engineered to hold two or more subcritical masses of fissionable material until a trigger goes off and causes the masses to assemble suddenly into one supercritical mass that explodes.

  The difficult part is to prepare the material for the subcritical masses. No amount of natural uranium is large enough to constitute a critical mass of its fissionable component, uranium-235. Natural uranium contains only 0.7% uranium-235, and it is necessary to "enrich" this to over 90%, a long and tedious manufacturing process. But it is possible to produce the needed subcritical masses of enriched uranium to make a "successful" bomb, like the one that was exploded over Hiroshima. Click here for a web page with thumbnail descriptions of several types of nuclear and thermonuclear bombs.

- **Nuclear Reactors:** Whereas a *nuclear bomb* depends on assembling a *supercritical mass* of fissionable material and letting

the reaction go *out of control* (to produce an explosion), a *nuclear reactor* depends on assembling a *critical mass* and keeping the reaction under *careful control* so that it remains critical, neither going supercritical nor falling subcritical. Under these conditions, a steady output of heat can be generated and used to create steam to drive a turbine that generates electric power. Figure 18.14 illustrates a nuclear powered electric generating plant.

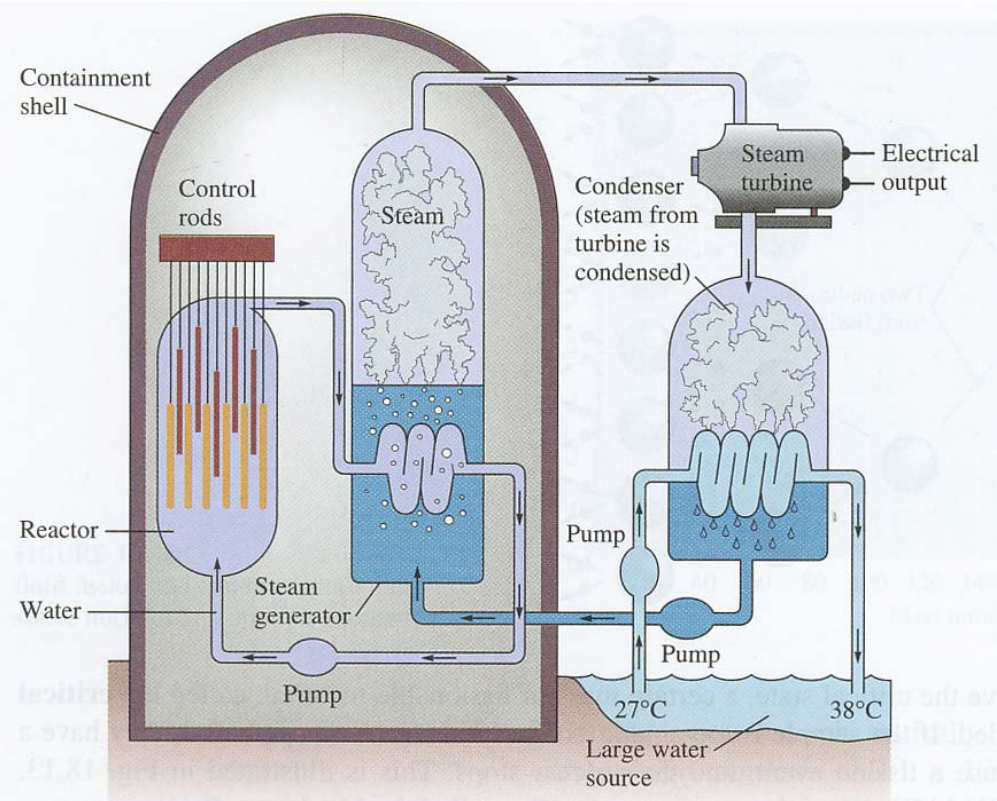

FIGURE 18.14
A schematic diagram of a nuclear power plant.

The Reactor Core deserves a closer look. It is designed to contain and control the nuclear reaction. Its principal components are the *fuel rods*, the *control rods*, the *moderator*, and the *coolant*. Figure 18.15 gives us a close-up schematic of a reactor core:

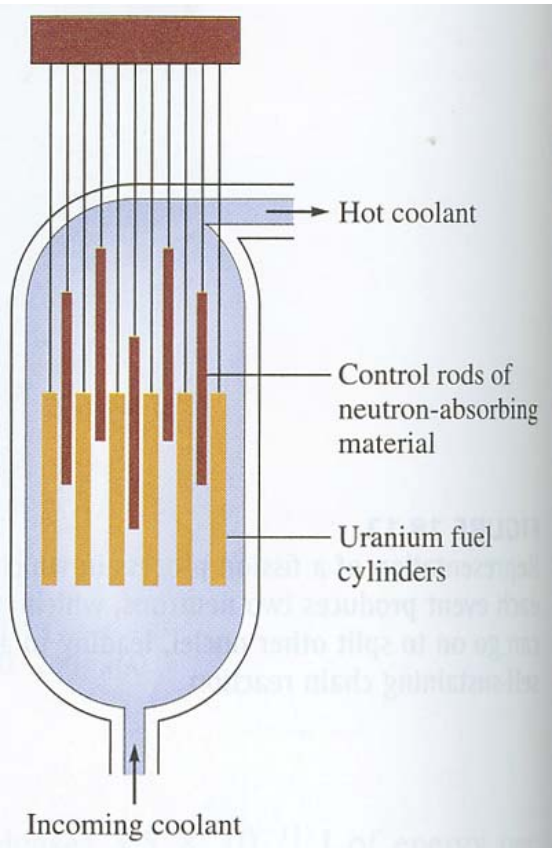

FIGURE 18.15
A schematic of a reactor core. The position of the control rods determines the level of energy production by regulating the amount of fission taking place.

- **Fuel Rods:** The fuel rods contain the fissionable nuclear fuel. A typical composition is uranium dioxide (UO_2) in which the uranium is enriched to 3% uranium-235, but other compositions can be used, depending on the overall reactor design. The assembly of fuel rods is designed to be slightly supercritical, but still controllable.
- **Control Rods:** The control rods are made of materials that strongly absorb neutrons and are assembled so they can be lowered and raised into and out of the spaces in the fuel assembly. When fully lowered into the core, they absorb enough neutrons so as to shut off the fission reaction. The extent to which they are raised governs the extent of the fission reaction allowed to take place, hence the name, *control rods*.
- **Moderator:** The moderator (not explicitly shown in our diagram) has the function of slowing fast neutrons down to thermal velocities. (The neutrons generated by uranium-235 fission are fast

neutrons.) Thermal neutrons are more likely than fast neutrons to be absorbed by uranium-235 and thus trigger a fission reaction. They function as an accelerator for the reactor as opposed to the control rods functioning as the brake.

- **Coolant:** Coolant is an essential part of a reactor core. It serves to convey the heat produced by the fission reaction out of the reactor core and into a heat exchanger where it produces steam to drive the turbine. Water is commonly used as a coolant, and when this is the case it actually also serves as moderator.

  Containment and Safety: Nuclear power generation is controversial because of public concern for safety. Construction of nuclear power plants essentially stopped in the US after the core meltdown at Three Mile Island in 1979. And the Chernobyl Incident in 1986 was an environmental disaster of epic proportions when reactor containment failed and radioactive debris spewed into the surrounding countryside. Good reactor design prevented a similar disaster at Three Mile Island. Operator error caused a core meltdown, but the reactor vessel remained intact, and there was no release of radioactivity, even to the rest of the plant itself.

  More Information about Nuclear Reactors: Click here for the Wikipedia article about nuclear reactors.

- **Breeder Reactors:** Nuclear reactors have been designed to *make* nuclear fuel instead of or in addition to "burning" fissionable material to produce energy. As we have already discussed, a uranium-238 nucleus can absorb a neutron and, after it emits two beta particles, be converted to fissionable plutonium-239:

$$ {}^{1}_{0}\mathrm{n} + {}^{238}_{92}\mathrm{U} \rightarrow {}^{239}_{92}\mathrm{U} $$

$$ {}^{239}_{92}\mathrm{U} \rightarrow {}^{239}_{93}\mathrm{Np} + {}^{0}_{-1}\mathrm{e} $$

$$ {}^{239}_{93}\mathrm{Np} \rightarrow {}^{239}_{94}\mathrm{Pu} + {}^{0}_{-1}\mathrm{e} $$

  Thermal neutrons are very effective for triggering nuclear fusion when they collide with uranium-235 but their collisions with uranium-238 are relatively less effective at producing neutron absorption than neutrons of higher energy. Thus the choice of a material to act as a moderator governs how effectively the reactor functions as a breeder of plutonium-239 for reactor fuel.

  From time to time, the fuel rods in a breeder reactor can be removed and reprocessed to separate the plutonium from the remaining enriched uranium fuel.

Breeder reactors are used commercially in France, but their use in the United States is controversial because of the potential of the plutonium falling into the wrong hands for fabrication of nuclear weapons. Moreover plutonium is very difficult to handle because of the flammability of plutonium metal and because of its extreme toxicity. (We will discuss this point further in Section 18.7.)

- **Nuclear Fusion:** Nuclear fusion is the source of solar energy. The composition of the sun is 73% hydrogen, 26% helium, and 1% other elements, and according to the function plotted in Figure 18.9, if four hydrogen nuclei (with zero binding energy) were to combine to form a helium nucleus (and two positrons), there would be a release of just over 7 MeV of binding energy for each of the starting hydrogens.

$$4\ {}_{1}^{1}\mathrm{H} \rightarrow {}_{2}^{4}\mathrm{H} + 2\ {}_{1}^{0}\mathrm{e}$$

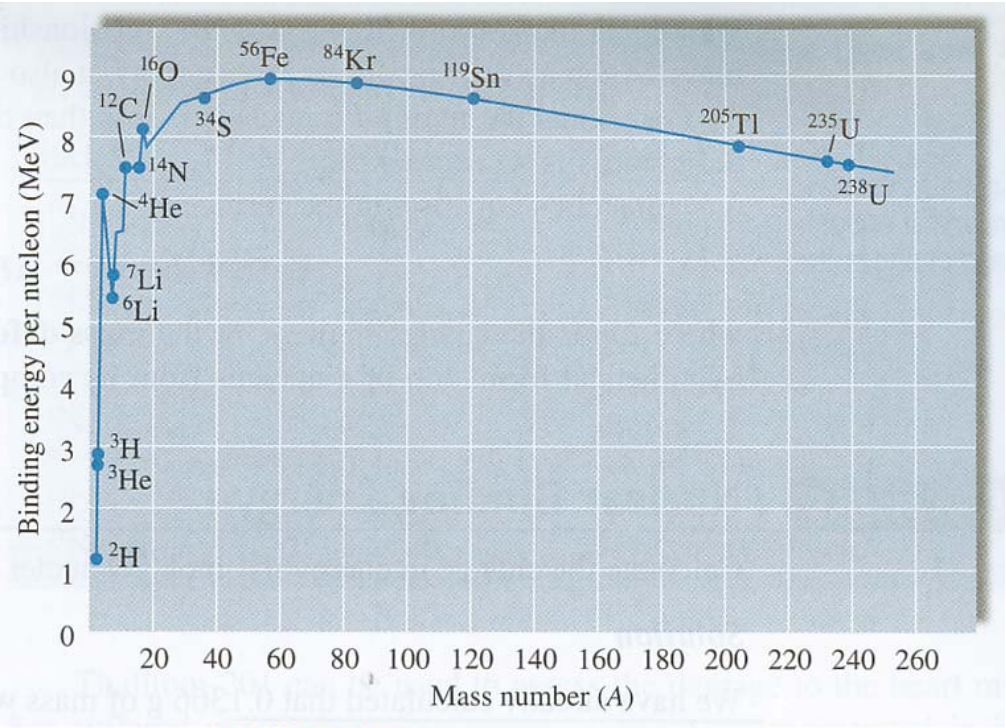

FIGURE 18.9
The binding energy per nucleon as a function of mass number. The most stable nuclei are at the top of the curve. The most stable nucleus is $^{56}_{26}$Fe.

This reaction takes place inside the sun, and its mechanism has been worked out. It takes place in steps, each consisting of the fusion of two nuclei to form one heavier nucleus. There may or may not be other reaction products.

$$ {}^{1}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{2}_{1}\mathrm{H} + {}^{0}_{1}\mathrm{e} $$

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

$$ {}^{3}_{2}\mathrm{He} + {}^{3}_{2}\mathrm{He} \rightarrow {}^{4}_{2}\mathrm{He} + 2\,{}^{1}_{1}\mathrm{H} \qquad {}^{3}_{2}\mathrm{He} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{0}_{1}\mathrm{e} $$

Note that there are two alternatives for the last step of the reaction.

The energy barrier to this reaction is quite formidable. The nuclear attractive force between two protons is quite large when they are close enough to touch, but it is essentially zero unless they can be brought within about 10^{-13} cm of each other, at which point, the electrostatic repulsion is quite high, as seen in Figure 18.16:

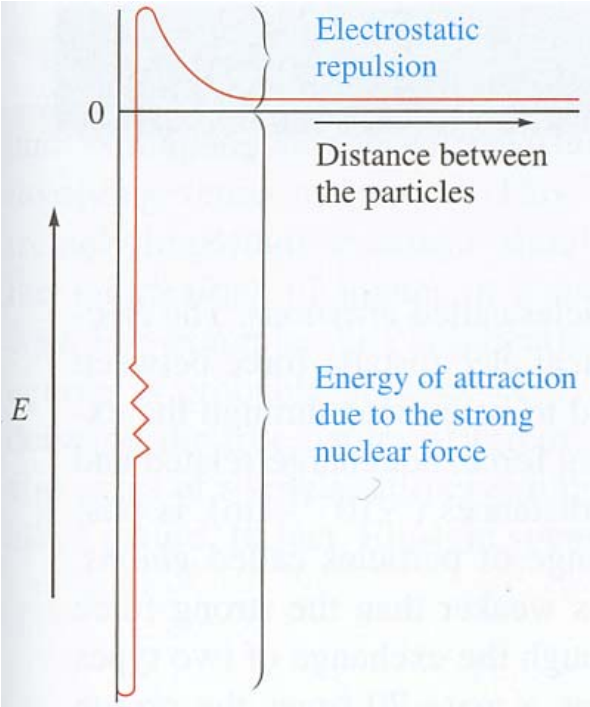

FIGURE 18.16
A plot of energy versus the separation distance for two ${}^{2}_{1}\mathrm{H}$ nuclei. The nuclei must have sufficient velocities to get over the electrostatic repulsion "hill" and get close enough for the nuclear binding forces to become effective, thus "fusing" the particles into a new nucleus and releasing large quantities of energy. The binding force is at least 100 times the electrostatic repulsion.

Thus if two protons are to fuse, they must be heated to a temperature of $4x10^7$ K (40 *million* Kelvins) in order to attain sufficient velocities to overcome the electrostatic repulsion barrier.

Applications of Nuclear Fusion: Nuclear fusion has been achieved on earth. The first *Hydrogen Bombs* (or thermonuclear bombs) were successfully tested over 50 years ago. Fortunately, they have never been used in warfare. Nuclear fusion has also been observed in laboratory scale *Fusion Reactors.* And some fusion reactors have even made to produce more energy than they consume over short periods of time, but mankind has yet to develop a Nuclear Fusion Reactor capable of being a practical source of energy.

18.7 Effects of Radiation: When radioactive elements undergo nuclear reactions, they produce high-energy particles. Since any type of energy exposure to an organism can be potentially harmful through energy transfer to cells and consequent bond-breaking, we need to be concerned about the radiation produced by radioactive nuclides.

- **Radiation Damage:** Radiation damage to an organism can be either *somatic* or *genetic*.
  - **Somatic Damage:** *Somatic damage* is damage to the organism itself. The effects can be immediate, as when a large dose of radiation causes radiation sickness (and often death), or they can be delayed as when smaller doses cause damage which later develops into cancer.
  - **Genetic Damage:** Genetic damage is damage to the genetic apparatus of the organism causing malfunctions in its offspring.
- **Factors Influencing Biological Effect of Radiation:** The effects of radiation depend on its *energy*, its *penetrating ability*, its *ionizing ability*, and the *chemical properties of its source*:
  - **Energy:** The higher the absorbed dose, the more damage it can cause. Radiation doses are measured in **rads** (short for **r**adiation **a**bsorbed **d**ose), where 1 rad corresponds to 10–2 J of energy absorbed per kg of tissue.
  - **Penetrating and Ionizing Ability:** The different kinds of nuclear radiation can penetrate human tissue to different extents. Their abilities to extract electrons from biological molecules, thus forming ions, also vary significantly:

    γ-rays: Gamma-rays are highly penetrating, but only occasionally will cause ionization.

β-particles: Beta particles can penetrate to approximately 1 cm. Since they are charged particles, they are also capable of causing ionization.

α-particles: Alpha-particles do not penetrate the skin, but are powerful ionizing agents when ingested. Thus, ingestion of plutonium, or some other alpha particle producer, is especially harmful.

- **Chemistry of the Source:** For radioactive nuclides that are ingested, their effectiveness depends not only on the intensity and ionizing ability of their radiation, but also on the amount of time they are resident (*residence time*) in the body. That, in turn, depends on their chemistry. Take, for example, krypton-85 and strontium-90, both of which are beta-particle producers. Krypton, being chemically inert, is rapidly eliminated from the body and is thus relatively harmless. Strontium, chemically rather like calcium, will accumulate in the bones, not be eliminated, and ultimately can cause leukemia or bone cancer.

- **Relative Biological Effectiveness (RBE) of Radiation:** The rad measures only the energy dose of a given source of radiation. So another measure is needed to take account of the potential of a given dose of radiation to cause biological damage. Thus the **rem** (short for **r**oentgen **e**quivalent for **m**an) is defined as:

  Number of rems = (number of rads)x(RBE)

  Here **RBE** (**r**elative **b**iological **e**ffectiveness) is defined as the relative effectiveness of the radiation in causing biological damage. In other words, RBE takes into account the penetrating and ionizing ability of the radiation and its residence time in the body. Table 18.6 shows the biological effects of various exposures to radiation. Note that the doses are measured in rem:

TABLE 18.6 Effects of Short-Term Exposures to Radiation

Dose (rem)	Clinical Effect
0–25	Nondetectable
25–50	Temporary decrease in white blood cell counts
100–200	Strong decrease in white blood cell counts
500	Death of half the exposed population within 30 days after exposure

We are all exposed to radiation, but even in this age of nuclear power generation, medical x-rays, and residues from the nuclear weapons

testing of a half-century ago, our exposure is still predominantly from natural sources, as shown in Table 18.7:

TABLE 18.7 Typical Radiation Exposures for a Person Living in the United States (1 millirem = 10^{-3} rem)

	Exposure (millirems/year)
Cosmic radiation	50
From the earth	47
From building materials	3
In human tissues	21
Inhalation of air	5
Total from natural sources	126
X-ray diagnosis	50
Radiotherapy	10
Internal diagnosis/ therapy	1
Nuclear power industry	0.2
TV tubes, industrial wastes, etc.	2
Radioactive fallout	4
Total from human activities	67
Total	193

An interesting point in Table 18.7 is the rather low number for the nuclear power industry. Despite the near-insignificance of the actual exposure caused by nuclear power generation, its use is still rather controversial. People are concerned about the potential for near-disasters like Three Mile Island and real disasters like Chernobyl. And there is real concern for the handling of nuclear waste. Just think of the controversy surrounding the proposed storage of nuclear waste in a central repository at Yucca Mountain.

- **Effects of Low Levels of Radiation:** There is also controversy over the chronic effects of low levels of radiation. Some will argue that

there is no effect; that there is a threshold below which no damage occurs. They support the so–called *threshold model* for radiation dose and consequent damage. Others will argue that there is no such thing as a no effect dose; that any amount of radiation will cause harm. They support the so-called *linear model*. These two models are shown in Figure 18.17:

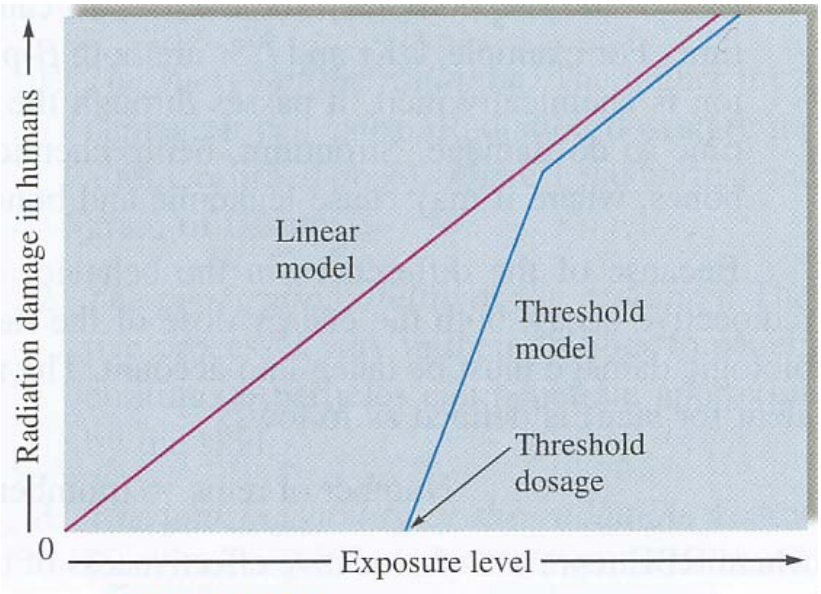

FIGURE 18.17
The two models for radiation damage. In the linear model, even a small dosage causes a proportional risk. In the threshold model, risk begins only after a certain dosage.