

Chapter 23 Worksheet 4 (ws23.4)
Nuclear Energy: Nuclear Binding Energy, Fission, and Fusion

Einstein discovered that matter could be converted to energy (and vice-versa). The equation that expresses this mass-energy equivalency is:

$$E = mc^2 \quad (c = 3.00 \times 10^8 \text{ m/s})$$

or

$$\Delta E = (\Delta m)c^2$$

Every process that releases energy is accompanied by an equivalent loss of mass. Every process that absorbs energy results in a gain of mass. The mass changes accompanying chemical reactions are too small to measure but mass changes due to nuclear reactions can be measured using a **mass spectrometer**. The following process releases energy (how do you know?):



Thus, the mass of a nucleus is less than the sum of the masses of the protons and neutrons from which it is composed! The difference in mass is called the *mass defect* (Δm):

$$\Delta m = \text{mass of protons} + \text{mass of neutrons} - \text{mass of nucleus}$$

(Note: In some problems instead of the nuclear mass you will be given the atomic mass. In such cases, to calculate the nuclear mass you must subtract the mass of the electrons.)

You can calculate the energy released in this process using Einstein's equation. The energy equivalent of the mass defect is called the *nuclear binding energy*, ΔE :

$$\Delta E = (\Delta m)c^2$$

(If energy is in joules what must the unit be for mass?)

The binding energy represents the amount of energy that must be supplied to break the nucleus into its individual protons and neutrons. (Conversely, it is the energy released when the nucleus is formed from individual protons and neutrons.) For a *single nucleus*, the magnitude of the binding energy is typically between 10^{-10} to 10^{-12} J. (For convenience, nuclear binding energies are sometimes expressed in mega electron volts (MeV), where $1 \text{ MeV} = 10^6 \text{ eV} = 1.60 \times 10^{-13} \text{ J}$)

A more useful quantity for comparing the stability of nuclides is the *binding energy per nucleon*:

$$\text{Binding Energy per nucleon} = \Delta E/A$$

where A = the mass number of the isotope (number of nucleons). The greater the binding energy per nucleon, the more stable the nucleus.

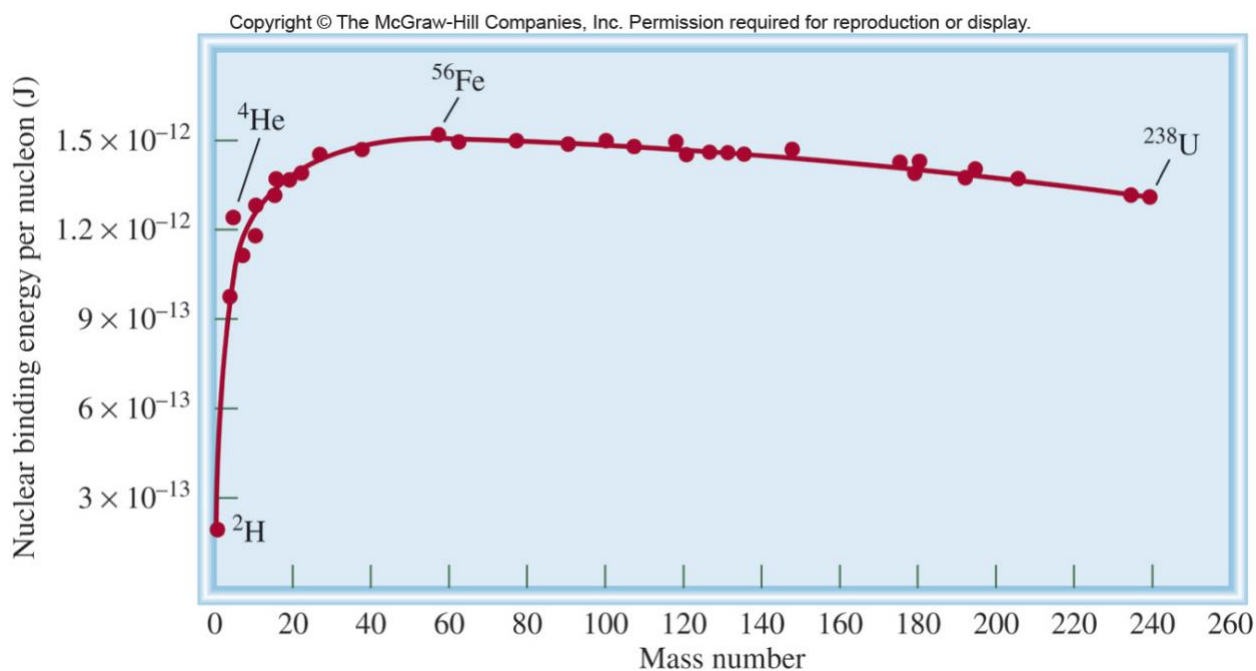
1. Determine the nuclear binding energy (ΔE) and the binding energy per nucleon ($\Delta E/A$) for Osmium-190.

mass of $^{190}\text{Os} = 189.95863$ amu

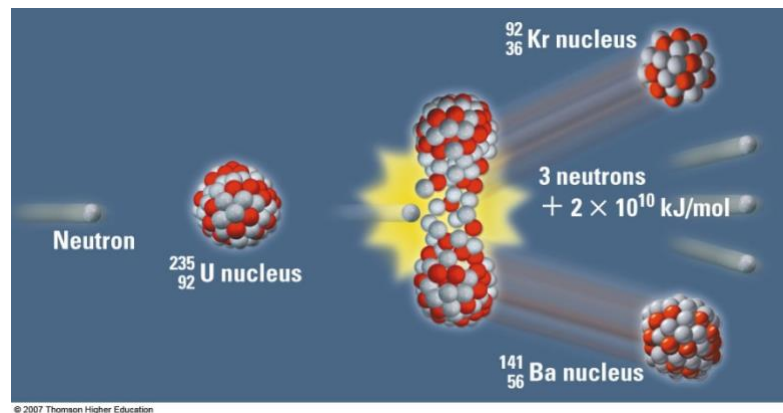
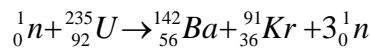
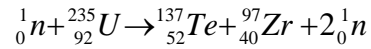
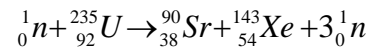
mass of neutron = 1.008664 amu

mass of proton = 1.007276 amu

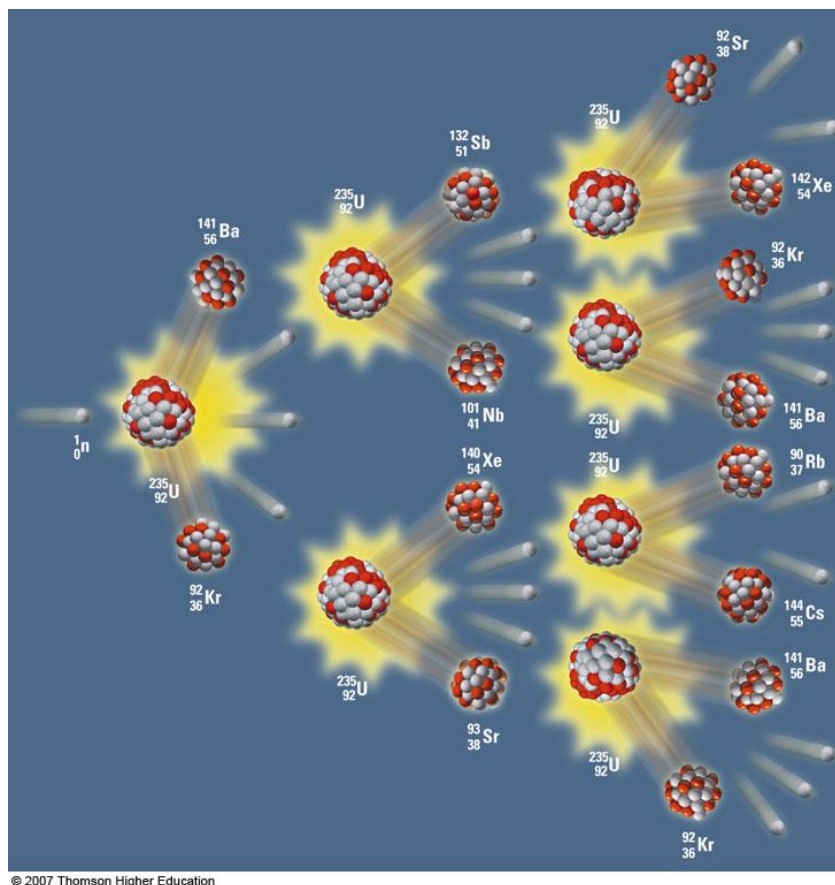
The binding energy per nucleon for most nuclei falls around 1.3×10^{-12} J (8 MeV). A plot of binding energy per nucleon vs. mass number shows that the most stable nuclei occur around $A = 50$ to 60 . **Fe-56 is the most stable nucleus in the universe.** The existence of a maximum in this curve indicates that energy is released in either a fission or fusion process in which more stable nuclei (i.e., closer to ^{56}Fe) are produced.



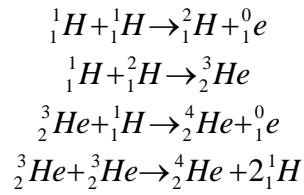
Fission = the splitting of a heavy nucleus into two nuclei with smaller mass numbers. This process is *induced* by absorption of a neutron by the reactant nucleus, and results in the release of energy and an additional 2 or 3 neutrons as products. For example 3 of the **many** possible outcomes of uranium-235 fission are:



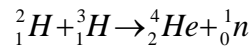
The neutrons produced can initiate additional fission reactions. If the fissionable material exceeds the **critical mass**, then an uncontrolled chain reaction occurs (nuclear explosion!)



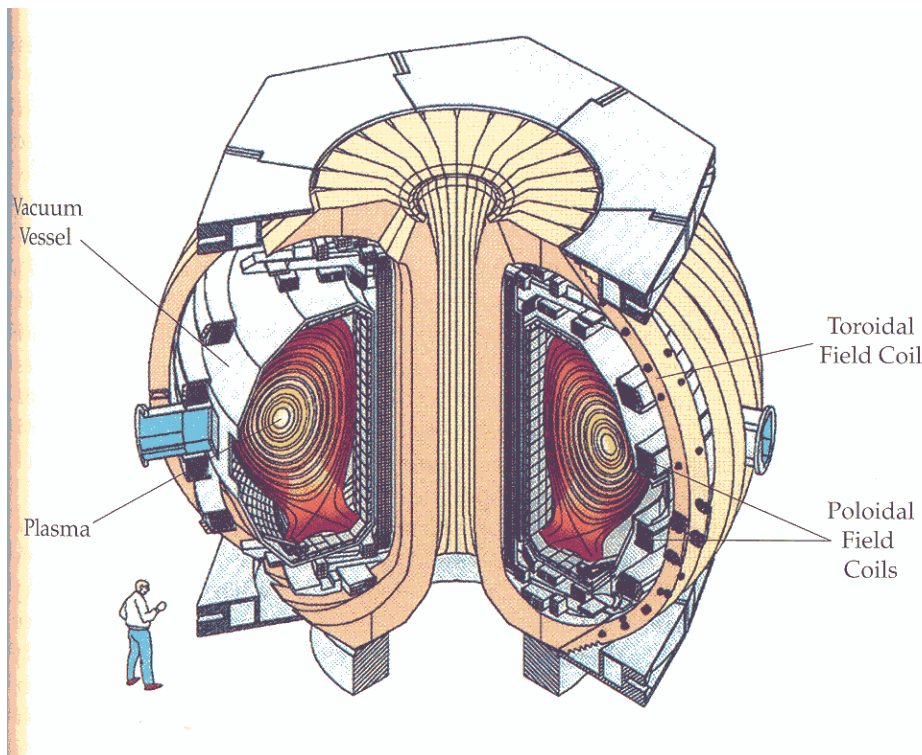
Fusion - the combining of two light nuclei to form a heavier, more stable nucleus. For example, the following reactions (among others) take place in the sun:



Fusion reactions have very high activation energies (why?) so only occur at very high temperatures. The fusion reaction which requires the lowest temperature (40,000,000 K!) is:



Because no known material can withstand such high temperatures, fusion reactors use strong magnetic fields to confine the reaction.



Because of the large binding energies involved in a nucleus, both fission and fusion involve energy changes of more than a million times larger than those energy changes associated with chemical reactions.

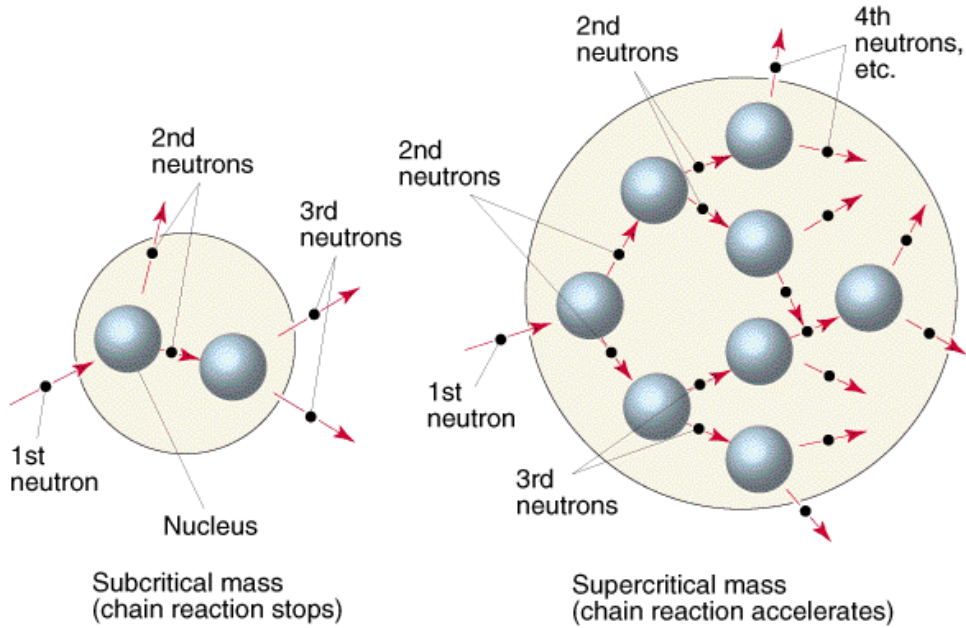
2. Calculate the amount of energy released (in kJ) when 1 mole (235 g) of ^{235}U undergoes fission to form Te-137 and Zr-96 (Given: $m(^{235}\text{U}) = 235.043915$ amu; $m(^1_0\text{n}) = 1.008664$ amu; $m(^{137}\text{Te}) = 136.925449$ amu; $m(^{96}\text{Zr}) = 95.908286$ amu)

3. Calculate the amount of energy released when 1 mole of ^2H fuses with 1 mole of ^3H to make one mole of ^4He (There is one more product. Figure out what it is.) The required masses are:

^2H : 2.014102 amu; ^3H : 3.016029 amu; ^4He : 4.002603 amu

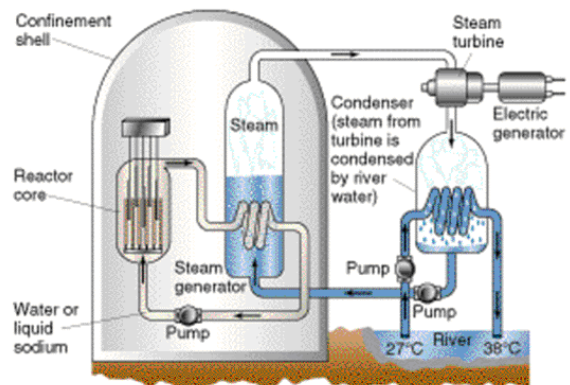
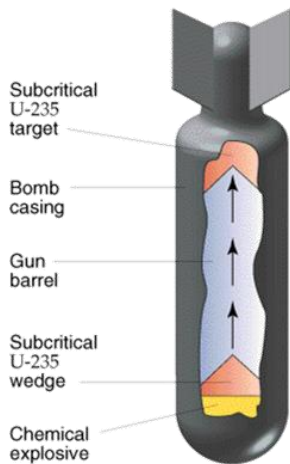
4. Compare the energy produced in problems 3 and 4 per gram of fuel. How do these compare to the energy produced in a typical combustion reaction?

Concept of Critical Mass



Fission bomb generates a supercritical mass of U-235 (exponential rate of energy release)

Reactor maintains constant reaction rate



SEE NAVAL APPLICATIONS OF CHEMISTRY FOR MORE ON FISSION REACTORS AND <http://www.nrc.gov/materials/fuel-cycle-fac/ur-enrichment.html> FOR DISCUSSION OF URANIUM-235 ENRICHMENT.

