Preview of Period 12: Nuclear Reactions

12.1 Nuclear Binding Energy

How can the binding energy of a nucleus be estimated from a binding energy graph?

12.2 Mass as a Form of Energy

How can the binding energy of a nucleus be calculated?

12.3 Particle Accelerators

How can accelerators produce endothermic nuclear reactions?

12.4 Nuclear Reactions in Stars

What is the energy source of stars? How are the chemical elements formed?

12.5 Types of Stars

How does an Hertzsprung-Russell diagram illustrate the types of stars?

Nuclear Fission and Fusion

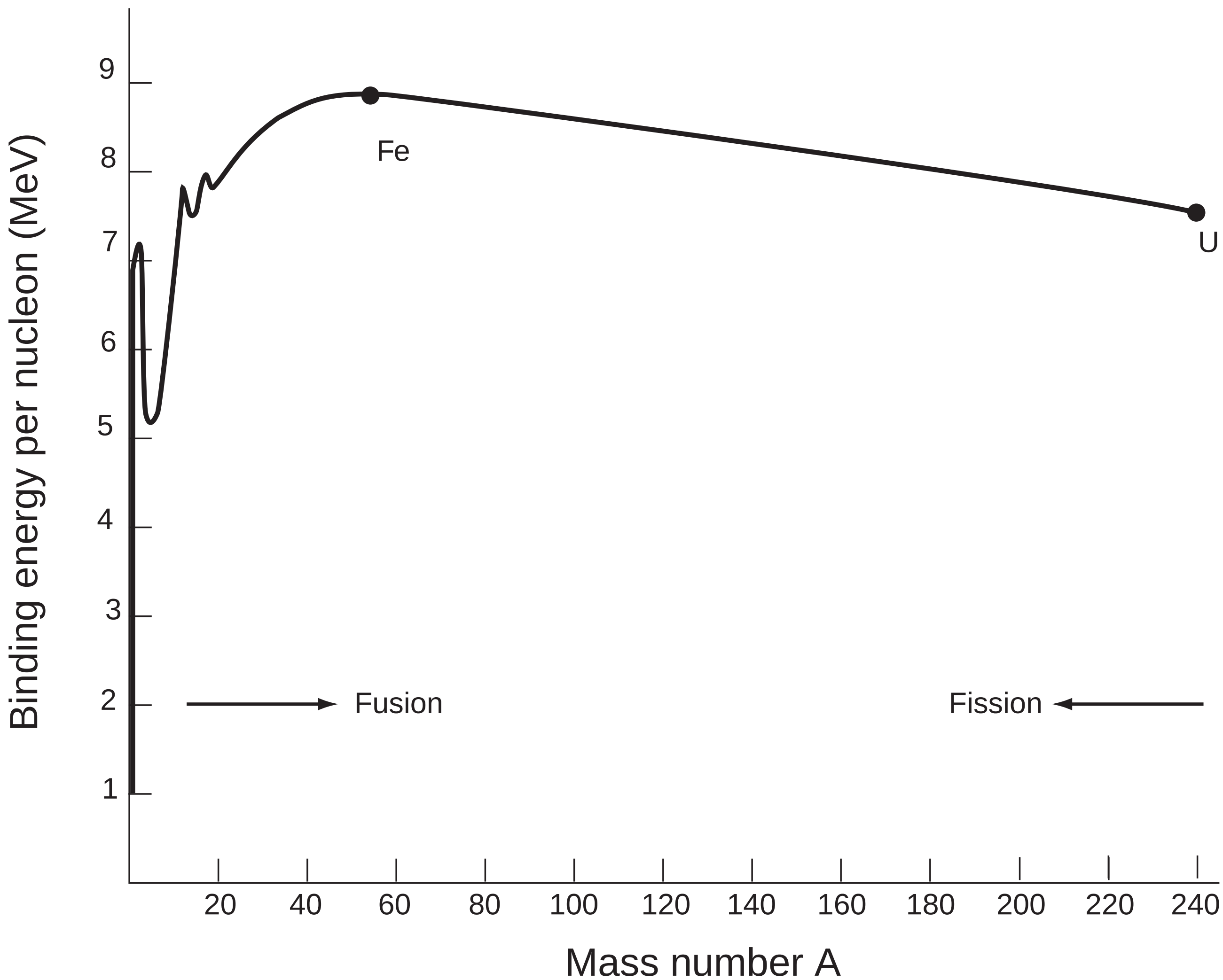
Nuclear fission occurs when an unstable nucleus breaks into smaller fragments.

Uranium-235 ($^{235}_{92}U$) is the only nucleus that fissions spontaneously. Other unstable nuclei require the input of activation energy to fission.

Nuclear fusion occurs when nucleons fuse into a nucleus. Two protons, with one proton changing into a neutron, may fuse into a deuterium nucleus.

Energy is released as a product of both fission and fusion reactions.

Nuclear Binding Energy Graph



9
8
7
6
5
4
3
2
1
Binding energy per nucleon (MeV)
Fe
U
Fusion
Fission
20
40
60
80
100
120
140
160
180
200
220
240
Mass number A

Nuclear Binding Energy Calculation: $E = Mc^2$

Binding energy =

[(mass of unbound protons + neutrons)
– (mass of nucleus)] c^2

Binding energy = $[Z\,M_p + (A - Z)\,M_n - M_{nuc}]\,c^2$

M_p = mass of a free proton = 1.6726×10^{-27} kg
M_n = mass of a free neutron = 1.6749×10^{-27} kg
M_{nuc} = mass of the assembled nucleus in kg
Z = number of protons in the nucleus
A-Z = number of neutrons in the nucleus
c^2 = (speed of light)^2 = $(3 \times 10^8\ \mathrm{m/s})^2$

Binding energy per nucleon = $\dfrac{\text{binding energy}}{\text{number of nucleons}}$

converting units between MeV and joules:

1 Mev = 10^6 eV = 1.6×10^{-13} joules
or
1 joule = 6.25×10^{12} MeV

Nuclear Particle Accelerators

Particle accelerators give particles kinetic energy by accelerating them with an electric force.

When accelerated particles collide, some of their kinetic energy is converted into the energy required for endothermic nuclear reactions.

Endothermic nuclear reactions can produce unstable particles that do not exist in nature.

Accelerators may accelerate particles along straight or circular paths.

The major challenge of fusion reactors is producing the activation energy needed to push protons together for fusion.

Stars smaller than 1.2 times the mass of the Sun use a hydrogen-burning proton-proton chain as their primary fusion process.

- In the P-P chain, two hydrogen nuclei fuse to form a nucleus of deuterium.

$$^{1}H + ^{1}H \longrightarrow ^{2}H + e^{+} + \nu_e \quad (+1.44\ MeV)$$

- Deuterium fuses with another hydrogen to form the isotope of helium called tritium.

$$^{2}H + ^{1}H \longrightarrow ^{3}He + \nu \quad (+\ 5.49\ MeV)$$

- Two tritium fuse to form a stable helium nucleus plus two hydrogen nuclei.

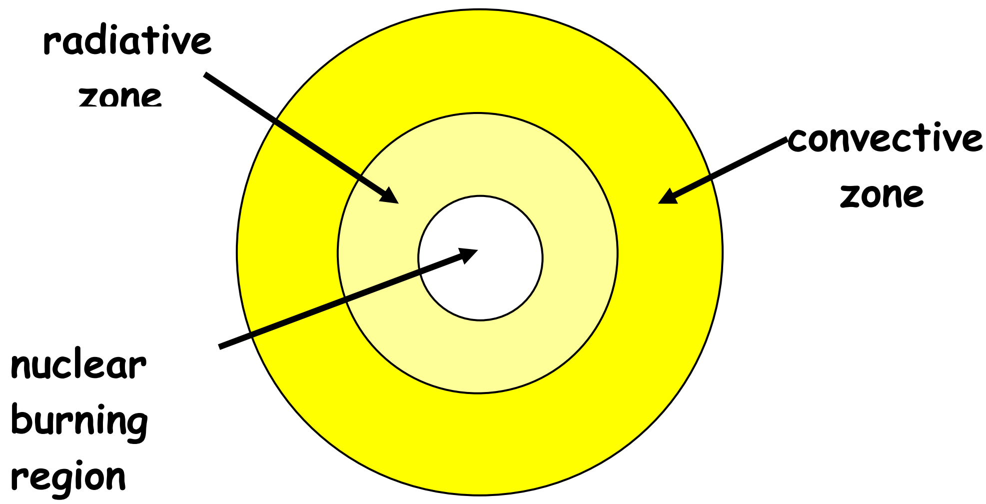
$$^{3}He + ^{3}He \longrightarrow ^{4}He + ^{1}H + ^{1}H \quad (+12.86\ MeV)$$

Energy Release in a Star

Nuclear fusion in the core of a star releases energy.

Convection transfers heat through hot gases. Convection occurs when hotter gases rise toward the surface and colder gases drop inward.

Energy transfer by radiation occurs when photons randomly scatter through a layer.



Formation of Chemical Elements

12-7

Most of the hydrogen, helium and lithium in the Universe was created during the Big Bang.

Carbon is formed when two alpha particles fuse into an unstable isotope of beryllium.

$$^{4}He + ^{4}He \longrightarrow ^{8}Be \qquad (-\ 0.1\ MeV)$$

If a 3rd alpha is added before the beryllium nucleus decays back into two alphas, carbon is formed.

$$^{8}Be + ^{4}He \longrightarrow ^{12}C \qquad (+\ 7.4\ MeV)$$

Heavier elements through iron are formed when stars more massive than 5 times the mass of the Sun collapse violently. Increasingly massive elements are fused until iron is produced.

Elements heavier than iron are formed when large stars collapse one last time and explode violently in a type II supernova. Enough energy is released to begin endothermic fusion reactions of heavy elements.

Period 12 Summary

12.1 **Nuclear binding energy is the energy required to hold nucleons together into nuclei.**

The most stable nuclei have the greatest binding energy per nucleon.

12.2 **The energy released when nuclei fuse or fission is calculated from $E = Mc^2$**

Binding energy = [(mass of unbound protons + neutrons) – (mass of nucleus)] c^2

12.3 **Nuclear reactions can be produced in accelerators when particles with large kinetic energies are allowed to collide. The result can be changes to the particles or the production of particles not present before the collision.**

12.4 **Energy is released in stars when nuclei fuse to form a more tightly bound nucleus.**

Stars smaller than 1.2 times the mass of the Sun use a hydrogen-burning proton-proton chain. More massive stars are dominated by the carbon-nitrogen-oxygen chain reaction.

12.5 **Most of the hydrogen, helium and lithium in the Universe was created during the Big Bang.**

Period 12 Summary, Continued

Small amounts of less massive elements between helium and boron and almost all more massive elements were made in fusion processes in stars or supernovae that occur when massive stars explode at the end of their lifetime.

Stars with masses less than 5 times the mass of the Sun end as white dwarfs.

If the core of a white dwarf in a binary system reaches 1.4 solar masses, the star explodes as a violent type Ia supernova.

Massive stars can end as red giants, when their mantle of matter is blown away, leaving a small, rapidly burning core surrounded by a huge, red outer mantle.

Massive stars may collapse so violently that they begin burning heavier elements until iron is produced.

After burning is completed, heavier stars collapse into a type II supernova. These explosions release so much energy that endothermic fusion reactions can occur and create elements more massive than iron. The supernova explosion blows most of the star outward, distributing the heavier elements formed in the star throughout the Universe.

12.6 **The color of stars is determined by their surface temperature. An H-R diagram illustrates the life stages of stars.**

Period 12 Review Questions

R.1 **If you know the mass of a nucleus and the number of protons and neutrons that make up the nucleus, how would you find the binding energy of the nucleus?**

R.2 **What is a nuclear fission reaction? What is a fusion reaction? Where do we see examples of fission and fusion reactions?**

R.3 **When were the lightest chemical elements (hydrogen, helium, and lithium) formed? How are the elements through oxygen formed?**

R.4 **How are the elements from oxygen through iron formed? How are elements heavier than iron formed?**

R.5 **What can a Hertzberg-Russell (H-R) diagram tell about a main sequence star?**