Nuclear Physics

Some Properties of Nuclei

- All nuclei are composed of protons and neutrons
    - Exception is ordinary hydrogen with just a proton
- The *atomic number*, Z, equals the number of protons in the nucleus
- The *neutron number*, N, is the number of neutrons in the nucleus
- The *mass number*, A, is the number of nucleons in the nucleus
    - A = Z + N
    - Nucleon is a generic term used to refer to either a proton or a neutron
    - The mass number is not the same as the mass

Symbolism

- Symbol: $^{A}_{Z}X$
  - X is the chemical symbol of the element
- Example:

$^{27}_{13}Al$

- Mass number is 27
- Atomic number is 13
- Contains 13 protons
- Contains 14 (27 – 13) neutrons

  - The Z may be omitted since the element can be used to determine Z

More Properties

- The nuclei of all atoms of a particular element must contain the same number of protons
- They may contain varying numbers of neutrons
  - *Isotopes* of an element have the same Z but differing N and A values
  - Example: $^{11}_{6}C$ $^{12}_{6}C$ $^{13}_{6}C$ $^{14}_{6}C$

Charge

- The proton has a single positive charge, +e
- The electron has a single negative charge, -e
- The neutron has no charge
  - Makes it difficult to detect
- e = 1.602 177 33 x 10^{-19} C

Mass

- It is convenient to use *unified mass units,* u, to express masses
  - 1 u = 1.660 559 x 10^{-27} kg
  - Based on definition that the mass of one atom of C-12 is exactly 12 u
- Mass can also be expressed in MeV/c^2
  - From $E_R = m c^2$
  - 1 u = 931.494 MeV/c^2

Summary of Masses

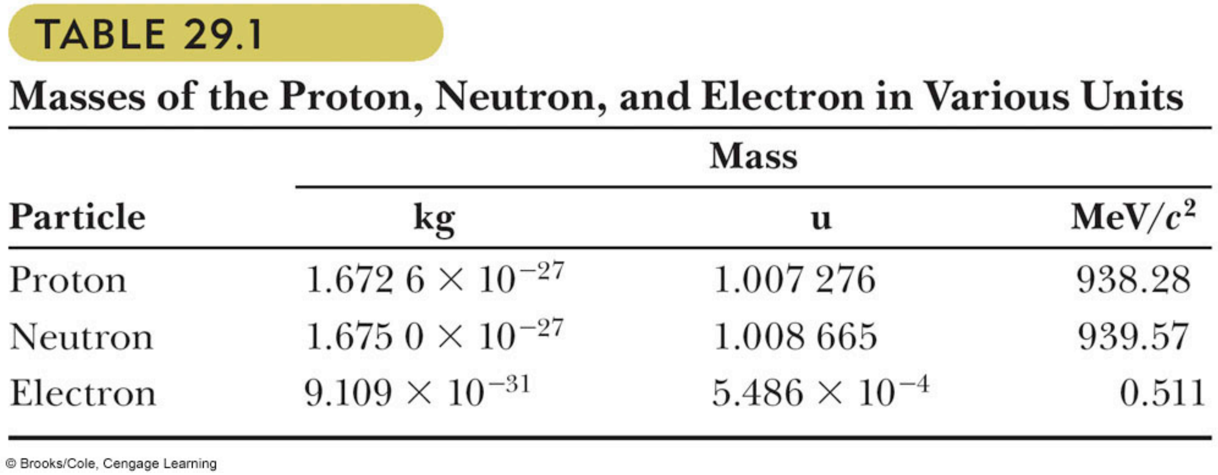
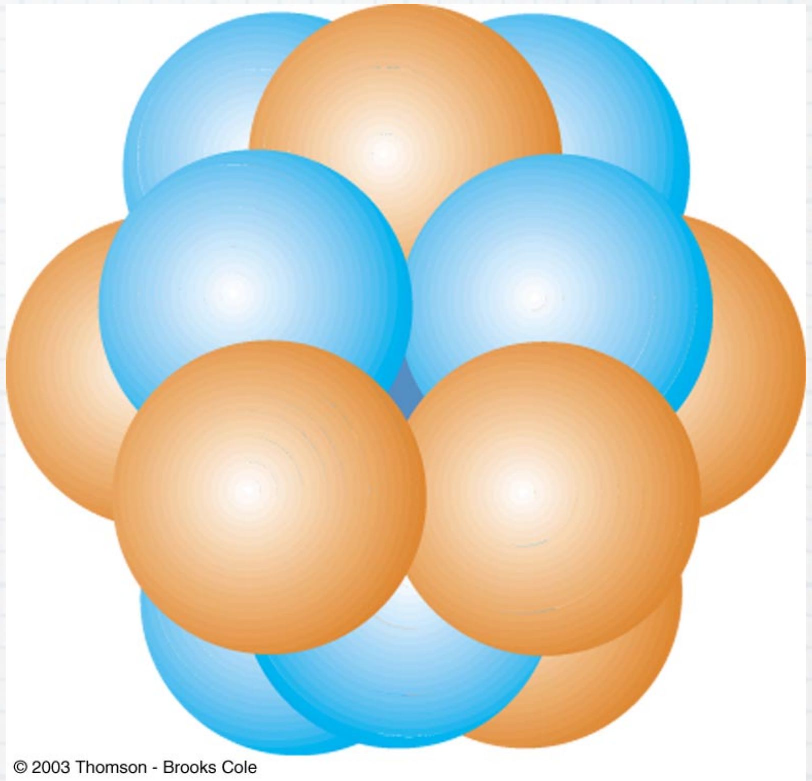


TABLE 29.1

Masses of the Proton, Neutron, and Electron in Various Units

	Mass		
Particle	**kg**	**u**	**MeV/c^2**
Proton	$1.672\,6 \times 10^{-27}$	1.007 276	938.28
Neutron	$1.675\,0 \times 10^{-27}$	1.008 665	939.57
Electron	9.109×10^{-31}	5.486×10^{-4}	0.511

The Size of the nucleus



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- is $r_{nucleus} = r_0 \times A^{1/3}$
- r_0 = 1.2 fm
- where 1 fm = 10^{-15} meters
- let's do an example

Binding Energy

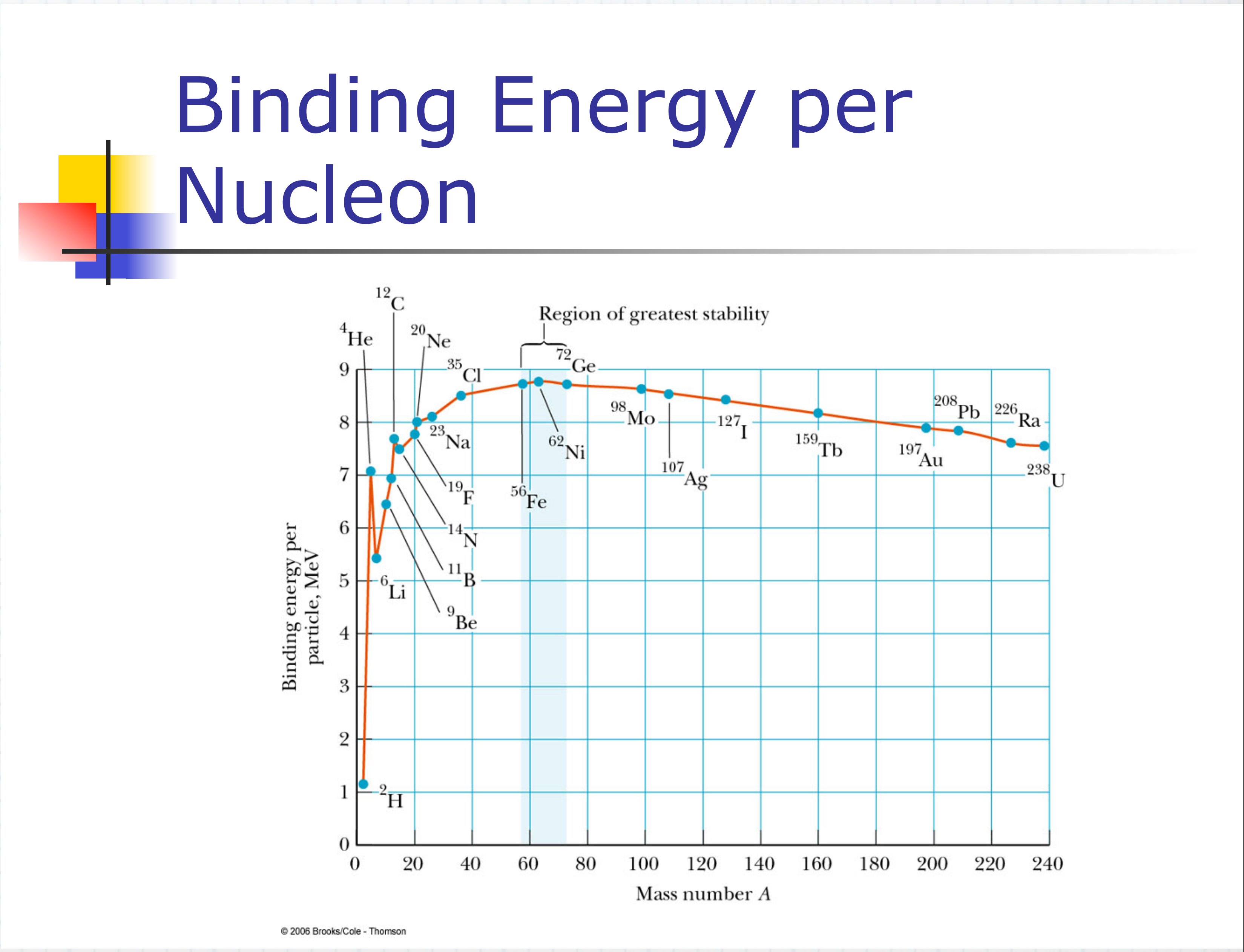
- The combined mass of the nucleus is less than the mass of the nucleons when they are separate
- The difference in the combined and separate masses gives the binding energy
- Think about this 1+1 does not equal two in nuclear physics

Example

- The Deuteron 1 proton and 1 neutron
- Together $m_{deuteron}$ = 2.014102 u
- individually $m_{individual}$ = 1.007825 u + 1.008665 u
- Δm = .002388 u
- $E = \Delta mc^2$ or 2.224 MeV
- Show

Binding energy per nucleon

- Calculate the binding energy then divide by the number of nucleons



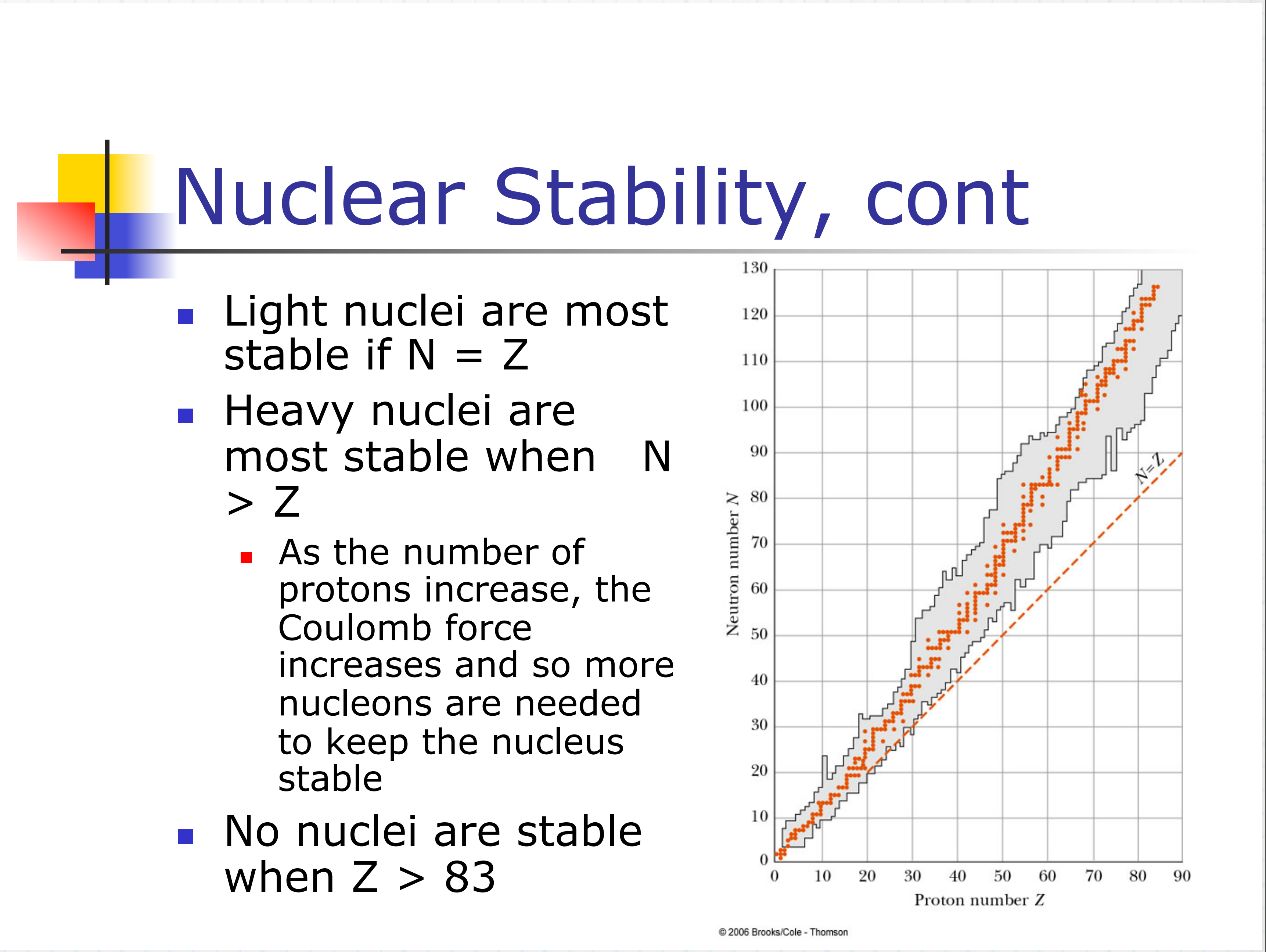
Binding Energy per Nucleon

This has serious ramifications

- What happens when the curve turns over at iron?
- More later

For now

- Notice more massive nucleons have less binding energy per nucleon
- As particles become more massive they become less stable
- They radioactively decay



Nuclear Stability, cont

- Light nuclei are most stable if N = Z
- Heavy nuclei are most stable when N > Z
  - As the number of protons increase, the Coulomb force increases and so more nucleons are needed to keep the nucleus stable
- No nuclei are stable when Z > 83

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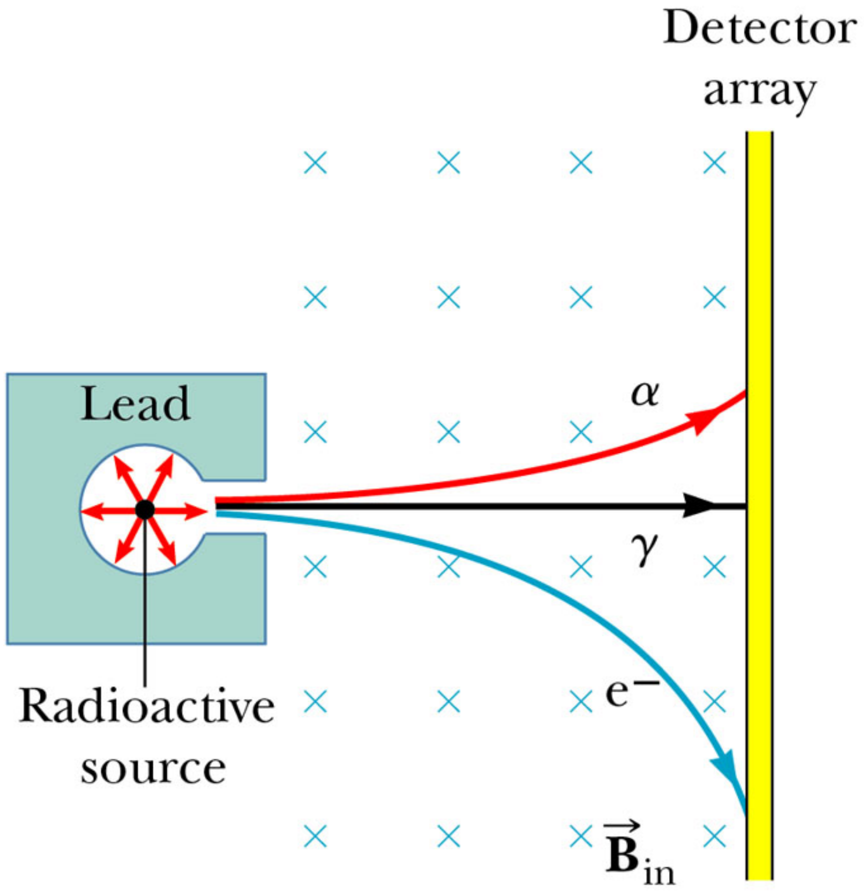
Radioactivity

- Large nuclei decay by the emission of a
- gamma ray - photon/radiation
- beta ray - electron or positron
- alpha particle - helium nucleus

Distinguishing Types of Radiation

- A radioactive beam is directed into a region with a magnetic field
- The gamma particles carry no charge and they are not deflected
- The alpha particles are deflected upward
- The beta particles are deflected downward
  - A positron would be deflected upward



Penetrating Ability of Particles

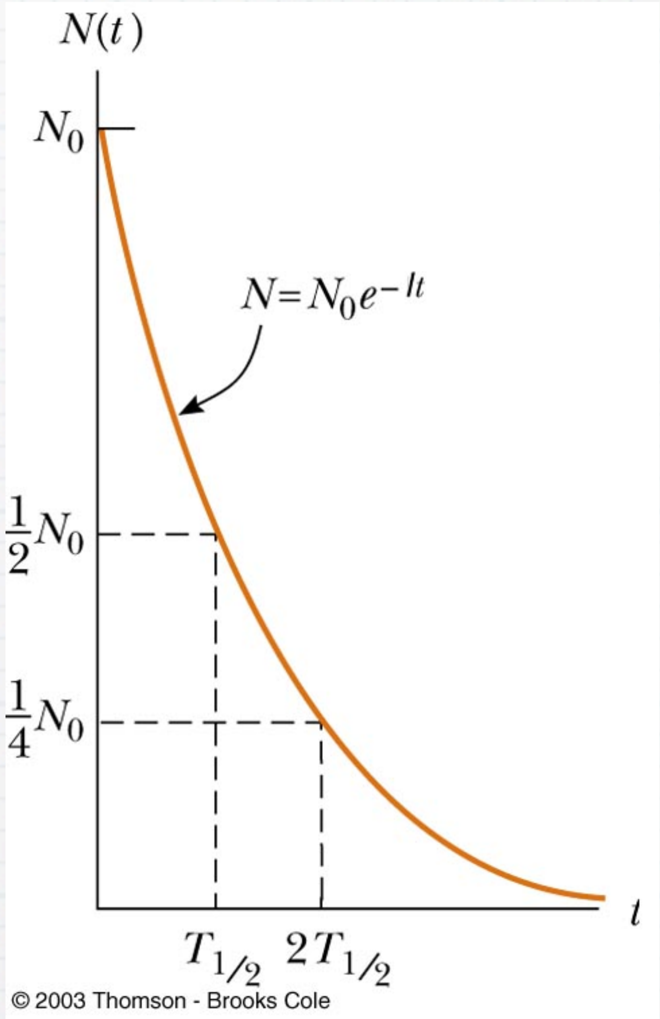
- Alpha particles
  - Barely penetrate a piece of paper
- Beta particles
  - Can penetrate a few mm of aluminum
- Gamma rays
  - Can penetrate several cm of lead

Decay Rates

- The number of nuclei as a function of time is given by

$$N(t) = N_0 e^{-\lambda t}$$

- lambda is the decay constant
- The number of decays per second is given by the activity R =λN



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Half lifes

- The half life of a substance is the amount of time it takes for one half of a radioactive material to radioactively decay $T_{1/2} = .693/\lambda$
- After n half lives there will be $N = N_0(1/2)^n$ left

Units

- The unit of activity, R, is the *Curie, Ci*
  - 1 Ci = 3.7 x 10^{10} decays/second
- The SI unit of activity is the *Becquerel, Bq*
  - 1 Bq = 1 decay / second
    - Therefore, 1 Ci = 3.7 x 10^{10} Bq
- The most commonly used units of activity are the mCi and the μCi

Let's do an example

Decay – General Rules

- When one element changes into another element, the process is called *spontaneous decay* or *transmutation*
- The sum of the mass numbers, A, must be the same on both sides of the equation
- The sum of the atomic numbers, Z, must be the same on both sides of the equation
- Conservation of mass-energy and conservation of momentum must hold

Alpha Decay

- When a nucleus emits an alpha particle it loses two protons and two neutrons
  - N decreases by 2
  - Z decreases by 2
  - A decreases by 4
- Symbolically ${}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He$
  - X is called the *parent nucleus*
  - Y is called the *daughter nucleus*

Beta Decay

- During beta decay, the daughter nucleus has the same number of nucleons as the parent, but the atomic number is changed by one
- Symbolically

$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + e^{-} $$

$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + e^{+} $$

Beta Decay

- During beta decay, the daughter nucleus has the same number of nucleons as the parent, but the atomic number is changed by one
- Symbolically

$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + e^{-} $$

$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + e^{+} $$

Beta Decay – Completed

- Symbolically

$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + e^{-} + \bar{\nu} $$

$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + e^{+} + \nu $$

  - ν is the symbol for the neutrino
  - $\bar{\nu}$ is the symbol for the antineutrino
- To summarize, in beta decay, the following pairs of particles are emitted
  - An electron and an antineutrino
  - A positron and a neutrino

Neutrino

- To account for this “missing” energy, in 1930 Pauli proposed the existence of another particle
- Enrico Fermi later named this particle the *neutrino*
- Properties of the neutrino
  - Zero electrical charge
  - Mass much smaller than the electron, recent experiments indicate definitely some mass
  - Spin of ½
  - Very weak interaction with matter

Gamma Decay

- Gamma rays are given off when an excited nucleus "falls" to a lower energy state
  - Similar to the process of electron "jumps" to lower energy states and giving off photons
  - The photons are called gamma rays, very high energy relative to light
- The excited nuclear states result from "jumps" made by a proton or neutron
- The excited nuclear states may be the result of violent collision or more likely of an alpha or beta emission

Gamma Decay – Example

- Example of a decay sequence
  - The first decay is a beta emission
  - The second step is a gamma emission

$$^{12}_{5}\mathrm{B} \rightarrow {}^{12}_{6}\mathrm{C}^* + e^- + \bar{\nu}$$

$$^{12}_{6}\mathrm{C}^* \rightarrow {}^{12}_{6}\mathrm{C} + \gamma$$

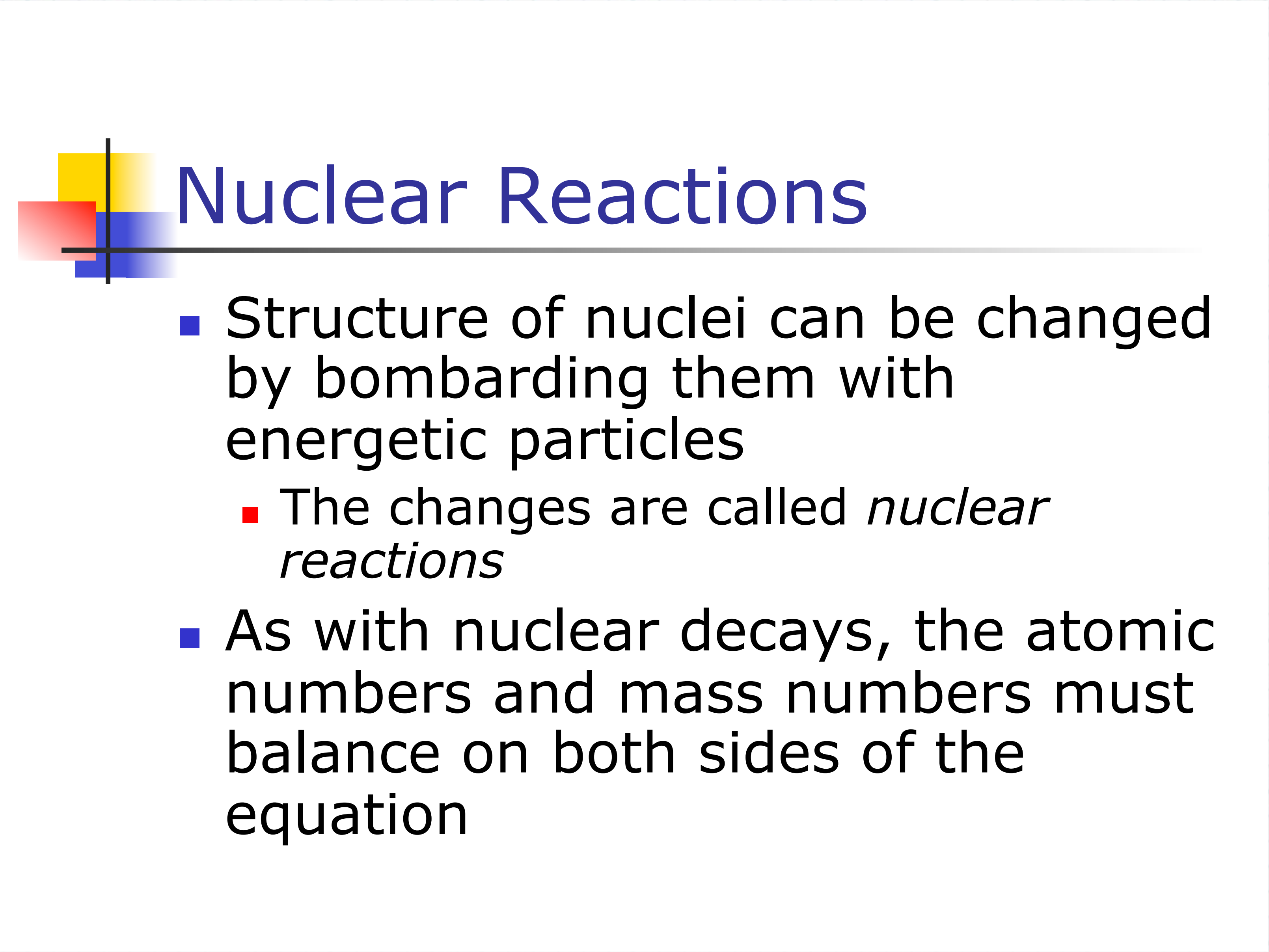
  - The C* indicates the Carbon nucleus is in an excited state
  - Gamma emission doesn't change either A or Z

Let's do an example

Uses of Radioactivity

- Carbon Dating
- Smoke Detectors
- Radon Detection

Nuclear Reactions



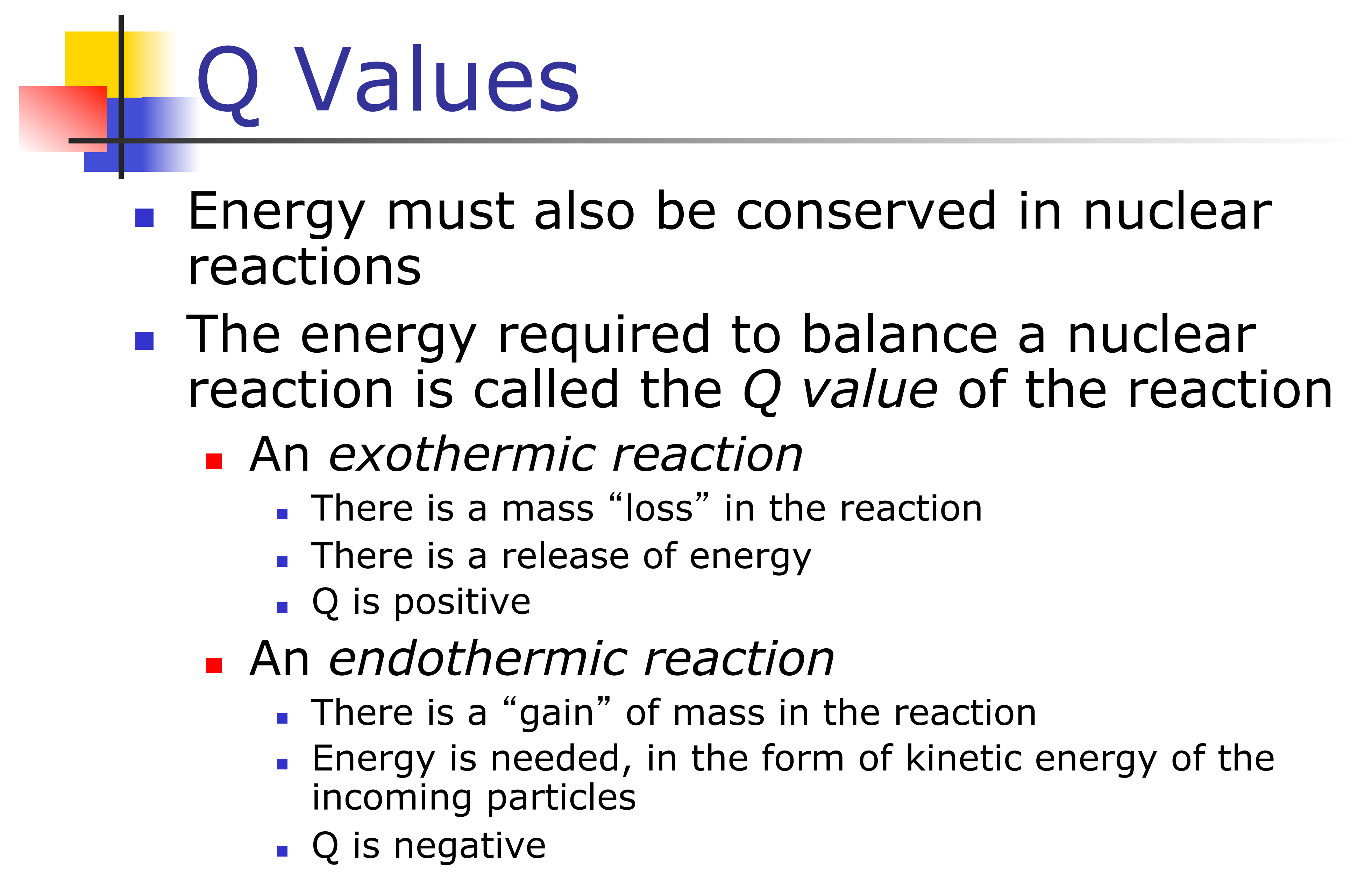
Nuclear Reactions

- Structure of nuclei can be changed by bombarding them with energetic particles
  - The changes are called *nuclear reactions*
- As with nuclear decays, the atomic numbers and mass numbers must balance on both sides of the equation

Example

- 4+14=18 ${}^{4}_{2}He + {}^{14}_{7}N \rightarrow ? + {}^{1}_{1}H$
- 2+7 = 9
- So ${}^{4}_{2}He + {}^{14}_{7}N \rightarrow {}^{17}_{8}? + {}^{1}_{1}H$
- ? = 0

Q Values



Q Values

- Energy must also be conserved in nuclear reactions
- The energy required to balance a nuclear reaction is called the *Q value* of the reaction
  - An *exothermic reaction*
    - There is a mass “loss” in the reaction
    - There is a release of energy
    - Q is positive
  - An *endothermic reaction*
    - There is a “gain” of mass in the reaction
    - Energy is needed, in the form of kinetic energy of the incoming particles
    - Q is negative

Exothermic - energy released by reaction

$$^2_1H + ^{14}_7N \rightarrow ^{12}_6C + ^4_2He$$

- Calculate mass difference between left and right side 16.017176 u - 16.002602 u = .014574 u
- E = 13.576 MeV, this is Q, positive energy is released

Endothermic - energy needed

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

- 18.005676 u - 18.006958 u = - .001282 u
- Q is - 1.194 MeV
- ?
- This reaction ends up with less energy
- Not possible unless kinetic energy is used
- Energy USING reaction

Minimum kinetic energy needed

$$A + B \rightarrow C + D$$

$$KE_{min} = (1 + \frac{m_A}{M_B})|Q|$$

Example

Huge ramifications

- If you get energy from a reaction you get to use fusion for energy
- If you need energy for a reaction you use fission for energy