NUCLEAR PHYSICS

A part of the Course

ELEMENTS OF MODERN PHYSICS

B.Sc. Physics (Hons.) Semester: IV (CBCS); Course: CC-XI

B.Sc. Physics (Hons.) Old syllabus: Paper-X

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Introduction: Development of Nuclear Physics

- 1896 – the birth of nuclear physics
  - Becquerel discovered radioactivity in uranium compounds
- Rutherford showed the radiation had three types
  - Alpha (He nucleus)
  - Beta (electrons)
  - Gamma (high-energy photons)
- 1911 Rutherford, Geiger and Marsden performed scattering experiments
  - Established the point mass nature of the nucleus
  - *Nuclear force* was a new type of force
- 1919 Rutherford and coworkers first observed nuclear reactions in which naturally occurring alpha particles bombarded nitrogen nuclei to produce oxygen
- 1932 Cockcroft and Walton first used artificially accelerated protons to produce nuclear reactions
- 1932 Chadwick discovered the neutron
- 1933 the Curies discovered artificial radioactivity
- 1938 Hahn and Strassman discovered nuclear fission
- 1942 Fermi achieved the first controlled nuclear fission reactor

29.1 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
- Notation $^{A}_{Z}X$ where 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

Charge and mass

Charge:

- The electron has a single negative charge, -e (e = $1.60217733 \times 10^{-19}$ C)
- The proton has a single positive charge, +e
  - Thus, charge of a nucleus is equal to Ze
- The neutron has no charge
  - Makes it difficult to detect

Mass:

- It is convenient to use *atomic mass units,* u, to express masses
  - 1 u = 1.660559×10^{-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

	Masses		
Particle	***kg***	***u***	***MeV/c²***
Proton	1.6726×10^{-27}	1.007276	938.28
Neutron	1.6750×10^{-27}	1.008665	939.57
Electron	9.101×10^{-31}	5.486×10^{-4}	0.511

Quick problem: protons in your body

What is the order of magnitude of the number of protons in your body? Of the number of neutrons? Of the number of electrons? Take your mass approximately equal to 70 kg.

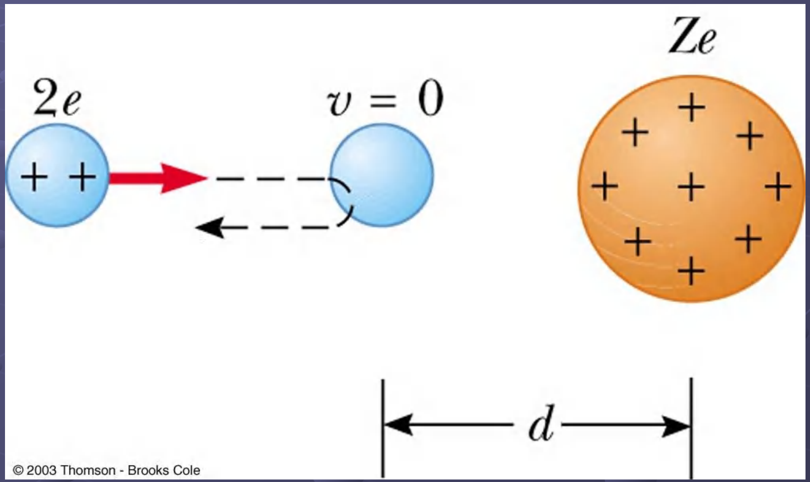
An iron nucleus (in hemoglobin) has a few more neutrons than protons, but in a typical water molecule there are eight neutrons and ten protons. So protons and neutrons are nearly equally numerous in your body, each contributing 35 kg out of a total body mass of 70 kg.

$$N = 35kg\left(\frac{1\,\text{nucleon}}{1.67\times10^{-27}\,kg}\right) \approx 10^{28}\,\text{protons}$$

Same amount of neutrons and electrons.

The Size of the Nucleus

- First investigated by Rutherford in scattering experiments
- He found an expression for how close an alpha particle moving toward the nucleus can come before being turned around by the Coulomb force
- The KE of the particle must be completely converted to PE



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$$\frac{1}{2}mv^2 = k_e\frac{q_1q_2}{r} = k_e\frac{(2e)(Ze)}{d}$$

or

$$d = \frac{4k_eZe^2}{mv^2}$$

- For gold: d = 3.2×10^{-14} m, for silver: d = 2×10^{-14} m

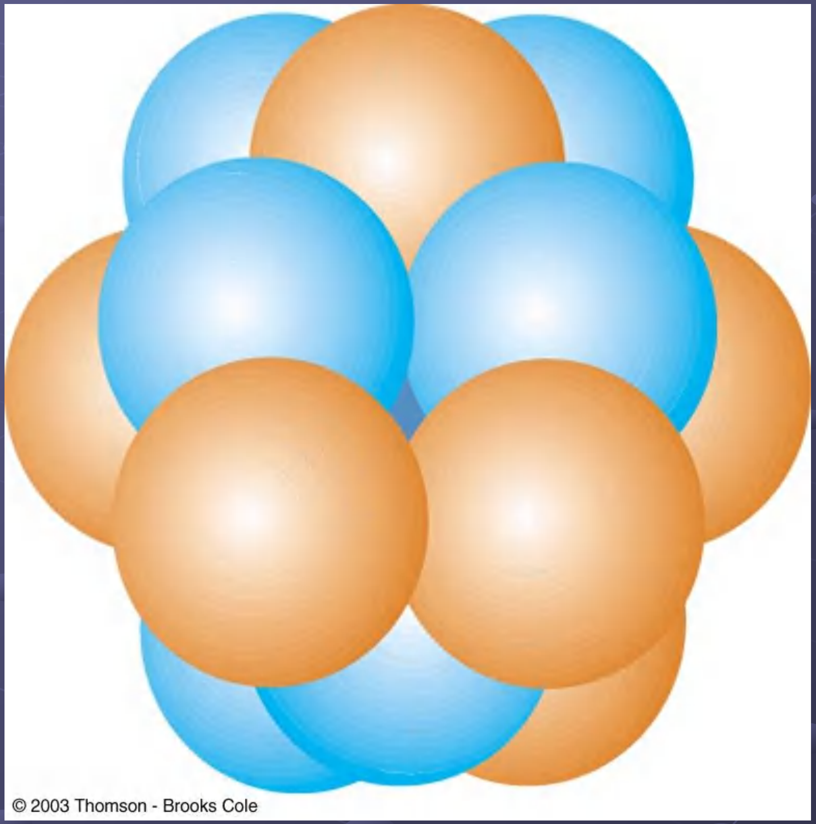
Such small lengths are often expressed in *femtometers* where 1 fm = 10^{-15} m (also called a fermi)

Size of Nucleus

- Since the time of Rutherford, many other experiments have concluded the following
  - Most nuclei are approximately spherical
  - Average radius is

$$r = r_o A^{1/3}$$

  - $r_o = 1.2 \times 10^{-15}$ m



Density of Nuclei

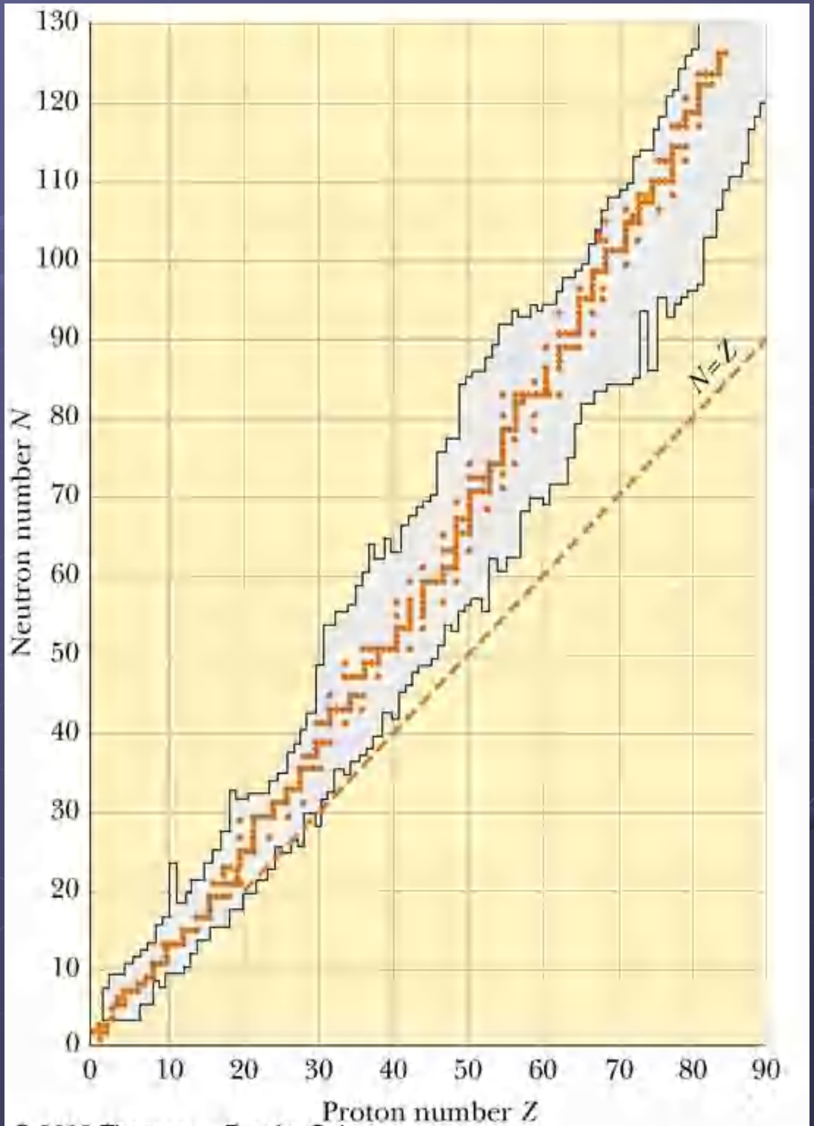
- The volume of the nucleus (assumed to be spherical) is directly proportional to the total number of nucleons
- This suggests that *all nuclei have nearly the same density*
- Nucleons combine to form a nucleus as though they were tightly packed spheres

Nuclear Stability

- There are very large repulsive electrostatic forces between protons
  - These forces should cause the nucleus to fly apart
- The nuclei are stable because of the presence of another, short-range force, called the *nuclear (or strong) force*
  - This is an attractive force that acts between all nuclear particles
  - The nuclear attractive force is stronger than the Coulomb repulsive force at the short ranges within the nucleus

Nuclear Stability chart

- 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

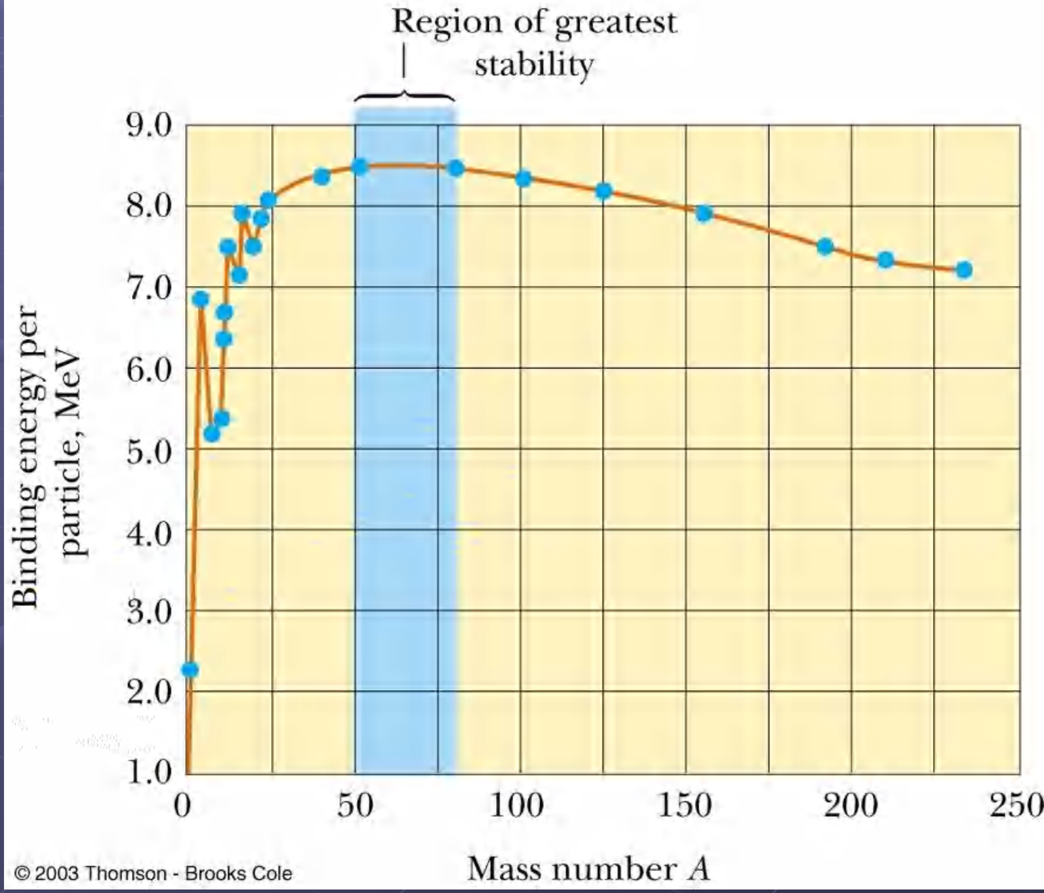


Isotopes

- 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: $^{11}_{6}C$ $^{12}_{6}C$ $^{13}_{6}C$ $^{14}_{6}C$

29.2 Binding Energy

- The total energy of the bound system (the nucleus) is less than the combined energy of the separated nucleons
  - This difference in energy is called the *binding energy* of the nucleus
    - It can be thought of as the amount of energy you need to add to the nucleus to break it apart into separated protons and neutrons



Binding Energy per Nucleon

Problem: binding energy

Calculate the average binding energy per nucleon of ${}^{93}_{41}Nb$

Calculate the average binding energy per nucleon of $^{93}_{41}Nb$

Given:

m_p= 1.007276u
m_n= 1.008665u

Find:

E_b = ?

In order to compute binding energy, let's first find the mass difference between the total mass of all protons and neutrons in Nb and subtract mass of the Nb:

Number of protons: $N_p = 41$

Number of neutrons: $N_n = 93 - 41 = 52$

Mass difference:

$$\Delta m = 41 m_p + 52 m_n - m_{Nb}$$
$$= 41(1.007825u) + 52(1.008665u) - (92.9063768u)$$
$$= 0.865028u$$

Thus, binding energy is

$$E_b = \frac{(\Delta m)c^2}{A} = \frac{(0.865028u)(931.5\,MeV/u)}{93} = 8.66\,MeV/\text{nucleon}$$

Binding Energy Notes

- Except for light nuclei, the binding energy is about 8 MeV per nucleon
- The curve peaks in the vicinity of $A = 60$
  - Nuclei with mass numbers greater than or less than 60 are not as strongly bound as those near the middle of the periodic table
- The curve is slowly varying at $A > 40$
  - This suggests that the nuclear force saturates
  - A particular nucleon can interact with only a limited number of other nucleons

Intrinsic Magnetic Moment

- The proton's intrinsic magnetic moment points in the same direction as its intrinsic spin angular momentum (as it is positive).
- Nuclear magnetic moments are measured in units of the nuclear magneton μ_N.

$$\mu_N = \frac{e\hbar}{2m_p}$$

- The divisor in calculating μ_N is the proton mass m_p, which makes the nuclear magneton 1836 times smaller than the Bohr magneton.
- The proton magnetic moment is $\mu_p = 2.79\ \mu_N$.
- The magnetic moment of the electron is $\mu_e = -1.00116\ \mu_B$. (1 in last chapter as there was no internal structure)
- The neutron magnetic moment is $\mu_n = -1.91\ \mu_N$.
- The *nonzero* neutron magnetic moment implies that the neutron has negative and positive internal charge components at different radii.

→ Complex internal *charge distribution*.

The Liquid Drop Model

- Treats the nucleus as a collection of interacting particles in a liquid drop.
- The total binding energy, the semi-empirical mass formula (due to Weizäcker) is

$$B\left({}^{A}_{Z}X\right) = a_V A - a_A A^{2/3} - \frac{3}{5}\frac{Z(Z-1)e^2}{4\pi\varepsilon_0 r} - a_S \frac{(N-Z)^2}{A} + \delta$$

- The volume term (a_v) indicates that the binding energy is approximately the sum of all the interactions between the nucleons.
- The second term is called the *surface effect* because the nucleons on the nuclear surface are not completely surrounded by other nucleons.
- The third term is the Coulomb energy

The Liquid Drop Model

- The fourth term is due to the so called “symmetry energy”. In the absence of Coulomb forces, the nucleus prefers to have $N \approx Z$ and has a quantum-mechanical origin, depending on the exclusion principle.
- The last term is due to the pairing energy and reflects the fact that the nucleus is more stable for even-even nuclides. Use values given by Fermi to determine this term.

$a_V = 14$ MeV	Volume
$a_A = 13$ MeV	Surface
$a_S = 19$ MeV	Symmetry

$$\text{Pairing } \delta = \begin{cases} +\Delta & \text{for even-even nuclei} \\ 0 & \text{for odd-}A\text{ (even-odd, odd-even) nuclei} \\ -\Delta & \text{for odd-odd nuclei} \end{cases}$$

where $\Delta = 33\text{ MeV}\cdot A^{-3/4}$.

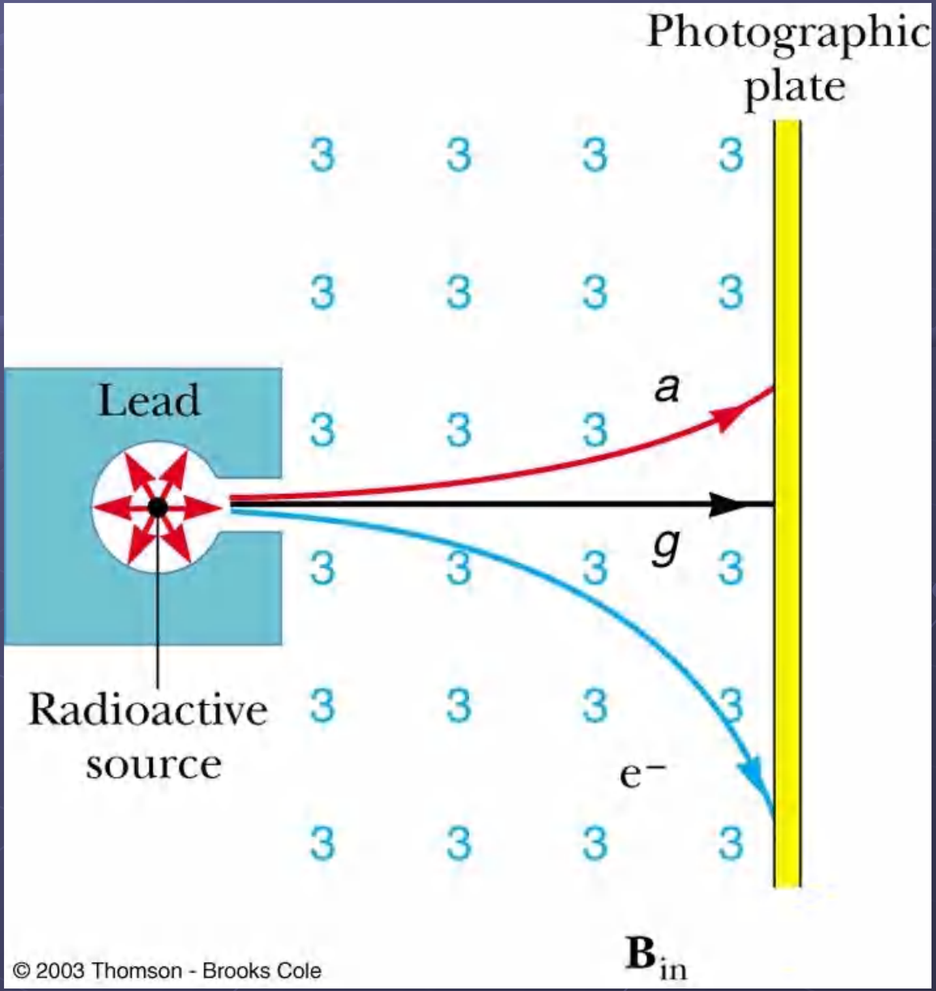
- No nuclide heavier than $^{238}_{92}U$ has been found in nature. If they ever existed, they must have decayed so quickly that quantities sufficient to measure no longer exist.

Radioactivity

- *Radioactivity* is the spontaneous emission of radiation
- Marie Curie and her husband Pierre discovered polonium and radium in 1898.
- Experiments suggested that radioactivity was the result of the decay, or disintegration, of unstable nuclei
- Three types of radiation can be emitted
  - Alpha particles
    - The particles are ^{4}He nuclei
  - Beta particles
    - The particles are either electrons or positrons
      - A positron is the *antiparticle* of the electron
      - It is similar to the electron except its charge is +e
  - Gamma rays
    - The “rays” are high energy photons

Distinguishing Types of Radiation

- The gamma particles carry no charge
- 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

The Decay Constant

- The number of particles that decay in a given time is proportional to the total number of particles in a radioactive sample

$$\Delta N = -\lambda N \left(\Delta t \right)$$

  - λ is called the *decay constant* and determines the rate at which the material will decay

- The *decay rate* or *activity*, R, of a sample is defined as the number of decays per second

$$R = \left| \frac{\Delta N}{\Delta t} \right| = \lambda N$$

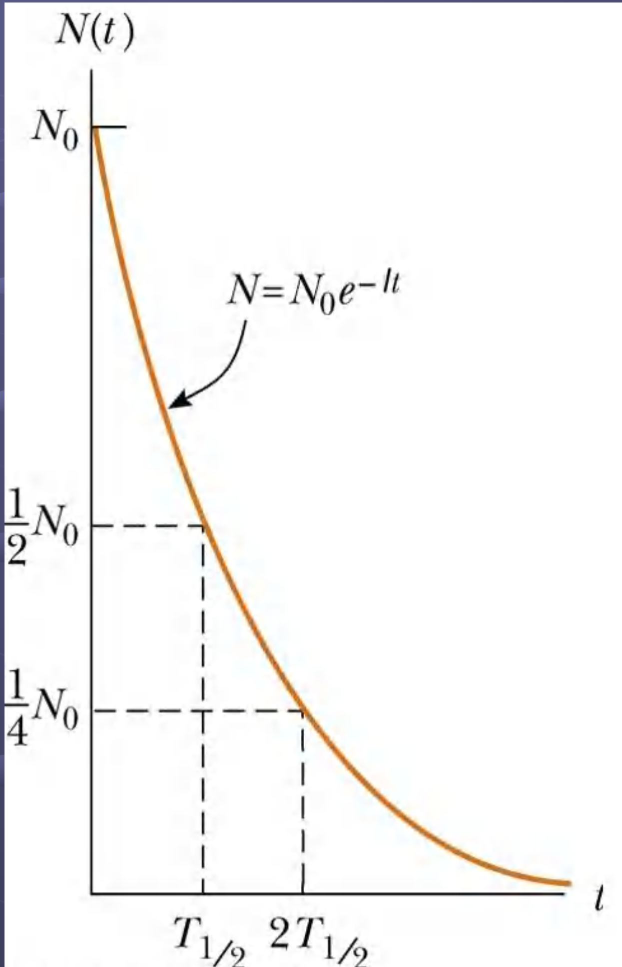
Decay Curve

- The decay curve follows the equation

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

- The *half-life* is also a useful parameter
- The half-life is defined as the time it takes for half of any given number of radioactive nuclei to decay

$$T_{1/2} = \frac{\ln 2}{\lambda} = \frac{0.693}{\lambda}$$



Units

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

QUICK QUIZ

What fraction of a radioactive sample has decayed after two half-lives have elapsed?

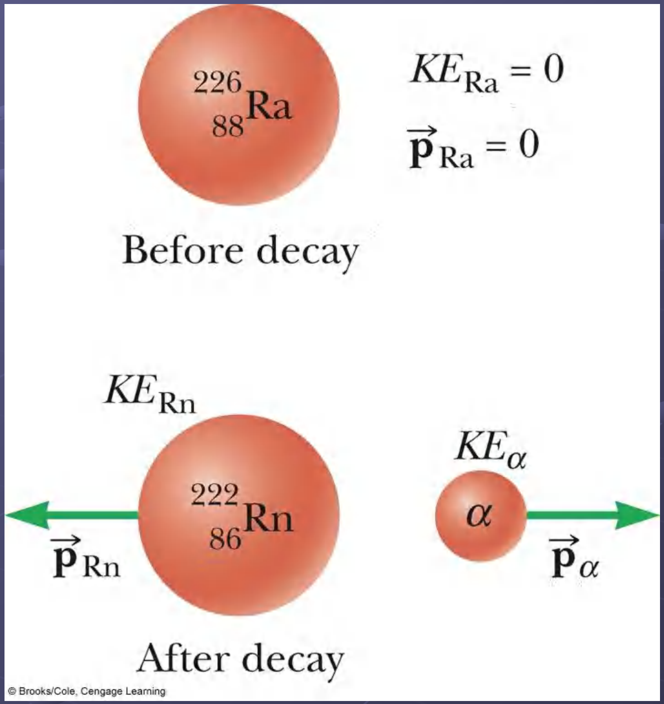
(a) 1/4 (b) 1/2 (c) 3/4
(d) not enough information to say

(c). At the end of the first half-life interval, half of the original sample has decayed and half remains. During the second half-life interval, half of the remaining portion of the sample decays. The total fraction of the sample that has decayed during the two half-lives is:

$$\frac{1}{2}+\frac{1}{2}\left(\frac{1}{2}\right)=\frac{3}{4}$$

Alpha Decay

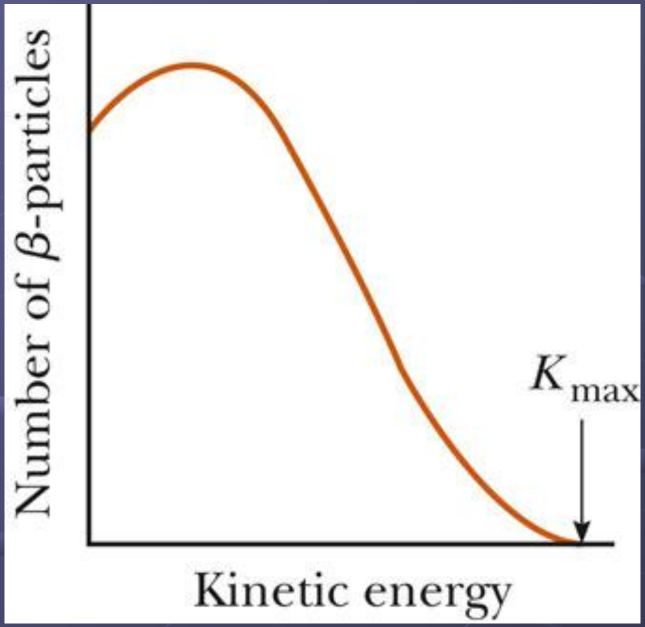
- Unstable nucleus emits α particle (i.e., a helium nucleus) spontaneously
- Mass of parent is greater than mass of daughter plus α particle
- Most of KE carried away by α particle



$$^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}\mathrm{He}$$

Beta Decay

- Involves conversion of proton to neutron or vice-versa
- Involves the weak nuclear force
- *KE* carried away by electron/antineutrino or positron/neutrino pair
- Neutrinos: $q = 0$, $m < 1\ \text{eV}/c^2$, spin ½, very weak interaction with matter



$$^{1}_{0}n \rightarrow {}^{1}_{1}p + e^{-} + \bar{\nu}$$
$$^{1}_{1}p \rightarrow {}^{1}_{0}n + e^{+} + \nu$$

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

Gamma (γ) Decay

- Following radioactive decay, nucleus may be left in an excited state
- Undergoes nuclear de-excitation: protons/neutrons move to lower energy level
- Nucleus emits high energy photons (γ rays)
- No change in A or Z results

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

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

Natural Radioactivity

- Three series of naturally occurring radioactivity
- ^{232}Th more plentiful than ^{238}U or ^{235}U
- Nuclear power plants use enriched uranium
- Other series artificially produced

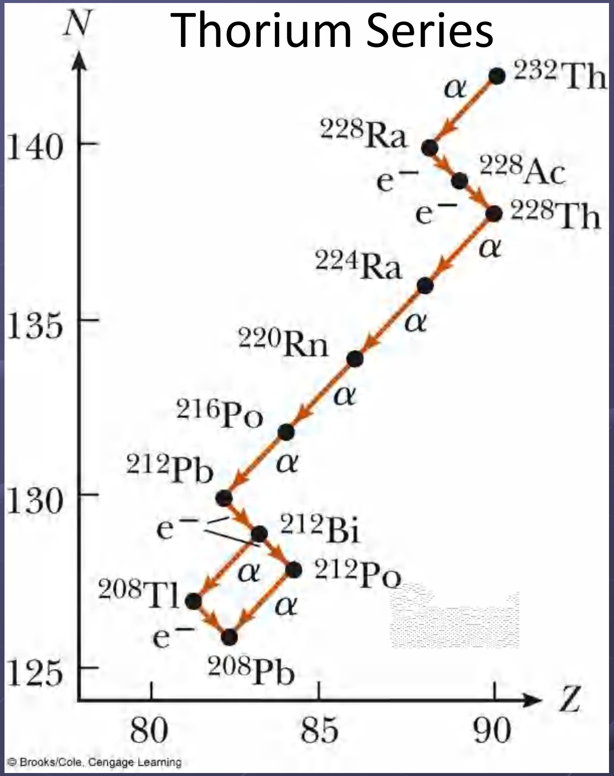


Table 29.2 The Four Radioactive Series

Series	Starting Isotope	Half-life (years)	Stable End Product
Uranium	$^{238}_{92}U$	4.47×10^9	$^{206}_{82}Pb$
Actinium	$^{235}_{92}U$	7.04×10^8	$^{207}_{82}Pb$
Thorium	$^{232}_{90}Th$	1.41×10^{10}	$^{208}_{82}Pb$
Neptunium	$^{237}_{93}Np$	2.14×10^6	$^{209}_{82}Pb$

Nuclear Reactions

- Accelerators can generate particle energies up to $1\ \mathrm{TeV}$
- Bombard a nucleus with energetic particles
- Nucleus captures the particle
- Result is fission or fusion

$$KE_{min} = \left(1 + \frac{m}{M}\right)|Q|$$

- Atomic and mass numbers (Z and A) must remain balanced
- Mass difference before and after reaction determines Q value
  - Exothermic: $Q > 0$
  - Endothermic: $Q < 0$
- Endothermic requires incoming particle to have KE_{min}

Fusion and Fission