RADIOACTIVITY

Becquerel

- In 1896 Henri Becquerel discovered that certain uranium compounds would fog photographic plates as if exposed to light.

- He discovered that a magnetic field could deflect the radiation that caused the fogging.

Pierre and Marie Curie

Marie and Pierre Curie investigated further.

- They discovered that thorium is also radioactive, and discovered two new elements: radium and polonium (named for Marie's native Poland).
- Marie coined the term radioactivity.

- THE NUCLEAR FORCE
- The force that binds together protons and neutrons
- inside the nucleus is called the Nuclear Force.
- Some characteristics of the nuclear force are:
- 1.It does not depend on charge.
- 2.It is very short range.
- 3.It is much stronger than the electric force.
- 4.It is saturated force .
- 5.It favours formation of pairs of nucleons with opposite
- spins.
- TAU

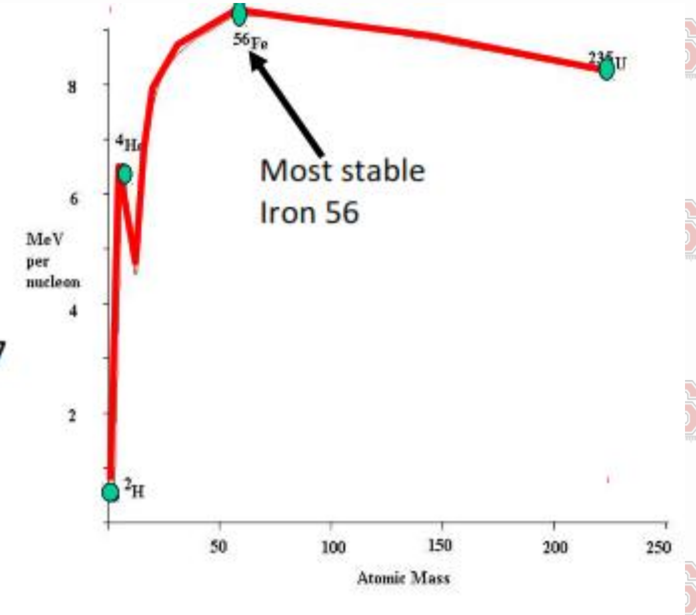
- NUCLEAR BINDING ENERGY
- The total rest energy(mass) of the separated nucleons
- is greater than the rest energy(mass) of the nucleus.
- Eg:- Deuteron
- 2
- H (1 proton + 1 neutron+1 electron)
- mp
- =1.007276u +
- mn
- =1.008665u But m2H
- =2.014102 u
- mp+n
- =2.016490 u
- mp+n
- -m2H
- =0.002338u
- The deuteron is 0.002338 u lighter than the sum of
- the separate proton and the neutron.
- This is the binding energy and is the energy needed
- to break that nucleus apart in its separate constituents

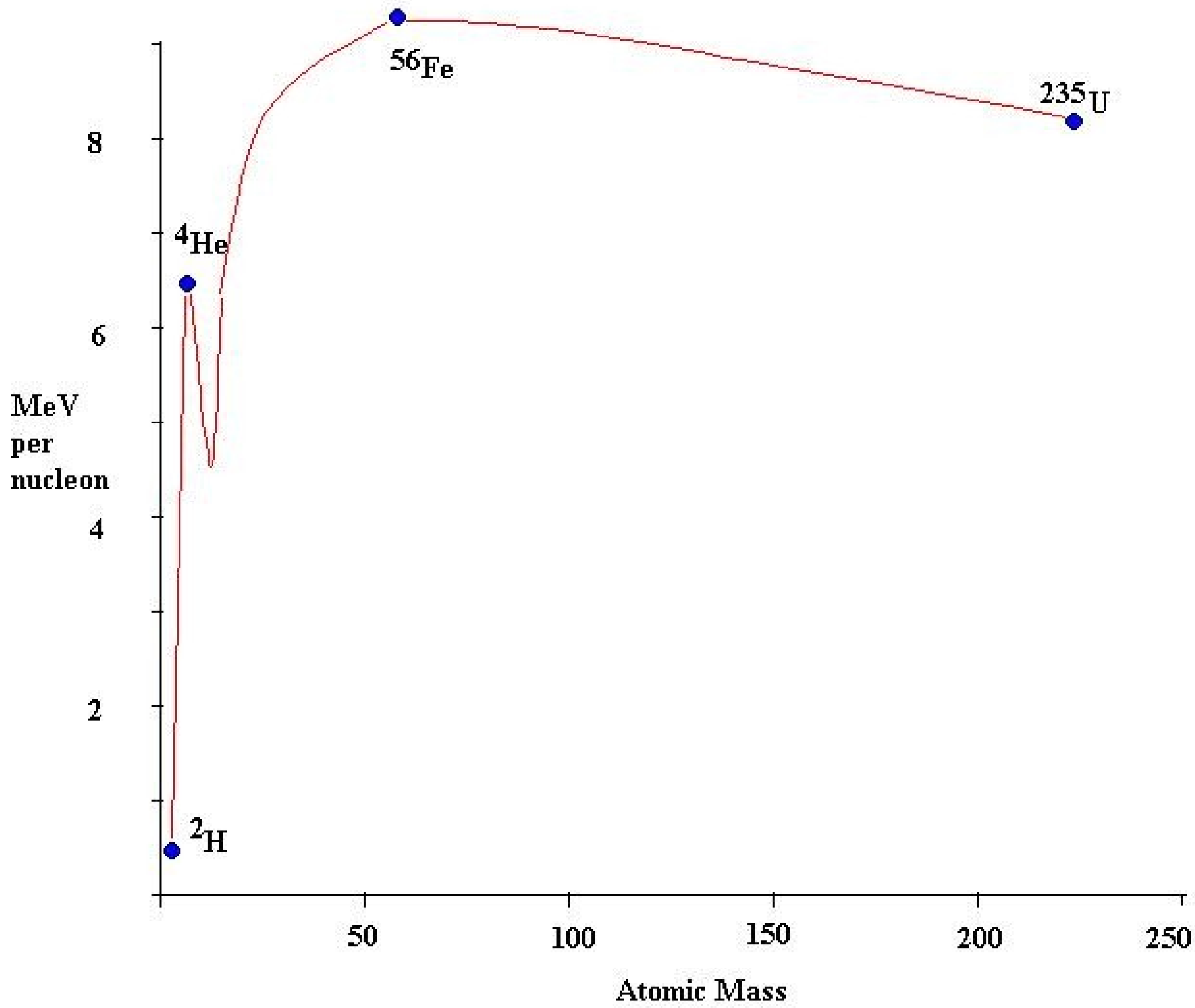
- **NUCLEAR BINDING ENERGY**
- The total rest energy(mass) of the separated nucleons is greater than the rest energy(mass) of the nucleus.
- Eg:- Deuteron 2H (1 proton + 1 neutron+1 electron)

- $m_p = 1.007276u +$
- $m_n = 1.008665u$ But $m_{2H} = 2.014102$ u
  $m_{p+n} = 2.016490$ u
- $m_{p+n} - m_{2H} = 0.002338u$
- The deuteron is 0.002338 u lighter than the sum of
- the separate proton and the neutron.
- This is the binding energy and is the energy needed
-

to break that nucleus apart in its separate constituents

- BINDING ENERGY PER NUCLEON
- ⍰ Nuclei with the
- largest binding
- energy per
- nucleon are the
- most stable.
- Most stable
- Iron 56
- ⍰ The largest
- binding energy
- per nucleon is 8.7
- MeV, for mass
- number A = 56.
- ⍰ Beyond bismuth,
- A = 209, nuclei
- are unstable.





MeV
per
nucleon
8
6
4
2
50
100
150
200
250
Atomic Mass
^{2}H
^{4}He
^{56}Fe
^{235}U

RADIO-ISOTOPES

Generate electrical power :

Nuclear fission is used to generate electricity as an alternative energy source.

Dating- Finding the age

Even the age of fossils or rocks can be determined by using radioactive isotopes.

- Carbon occurs naturally in three isotopes.
- All of these atoms have the same number of protons but different numbers of neutrons.
- The number of neutrons and protons determines the mass, so the masses are different.
- ^{14}C is radioactive.

APPLICATION OF RADIO-ISOTOPES

- RESEARCH
- INDUSTRY
- MEDICINE
- AGRICULTURE
- ANIMAL HUSBUNDARY

CARBON DATING

- Radioactive ^{14}C acts chemically just like ^{12}C, so it becomes incorporated into plants an animals.
- When the animal/plant dies the ^{14}C begins to decay into ^{14}N at a know rate, so we can determine how long ago the organism died.
- This is called Carbon Dating.
- It's only good for about 50,000 years.

RAD

Positron Decay

- The β^+decay reaction is written as

$$^{A}_{Z}P \rightarrow [_{Z-1}^{\ \ A}D] + {}^{o}_{+1}e + \upsilon$$

The positron has the same physical properties as an electron, except that it has one unit of positive charge.

Structure and Properties of the Nucleus

Notation: a specific nucleus or **`nuclide'** can be specified as

$$^{A}_{Z}\mathrm{X}$$

X is the chemical symbol for the element, Z may not be included – the element symbol dictates Z

Nuclei with the same Z – so they are the same element – but different A (and N) are **`isotopes'**.

Natural abundance is the percentage of an element that consists of a particular isotope in nature.

Atomic Masses are measured with reference to the carbon-12 atom, which is assigned a mass of exactly 12u. 'u' is an atomic mass unit.

$$1\ \mathrm{u} = 1.6605 \times 10^{-27}\ \mathrm{kg} = 931.5\ \mathrm{MeV}/c^2.$$

Rest Masses in Kilograms, Unified Atomic Mass Units, and MeV/c^2

	Mass		
Object	**kg**	**u**	**MeV/c^2**
Electron	9.1094×10^{-31}	0.00054858	0.51100
Proton	1.67262×10^{-27}	1.007276	938.27
$^1_1$H atom	1.67353×10^{-27}	1.007825	938.78
Neutron	1.67493×10^{-27}	1.008665	939.57

Binding Energy and Nuclear Forces

The total mass of a stable nucleus is always less than the sum of the masses of its separate pieces; the protons and neutrons.

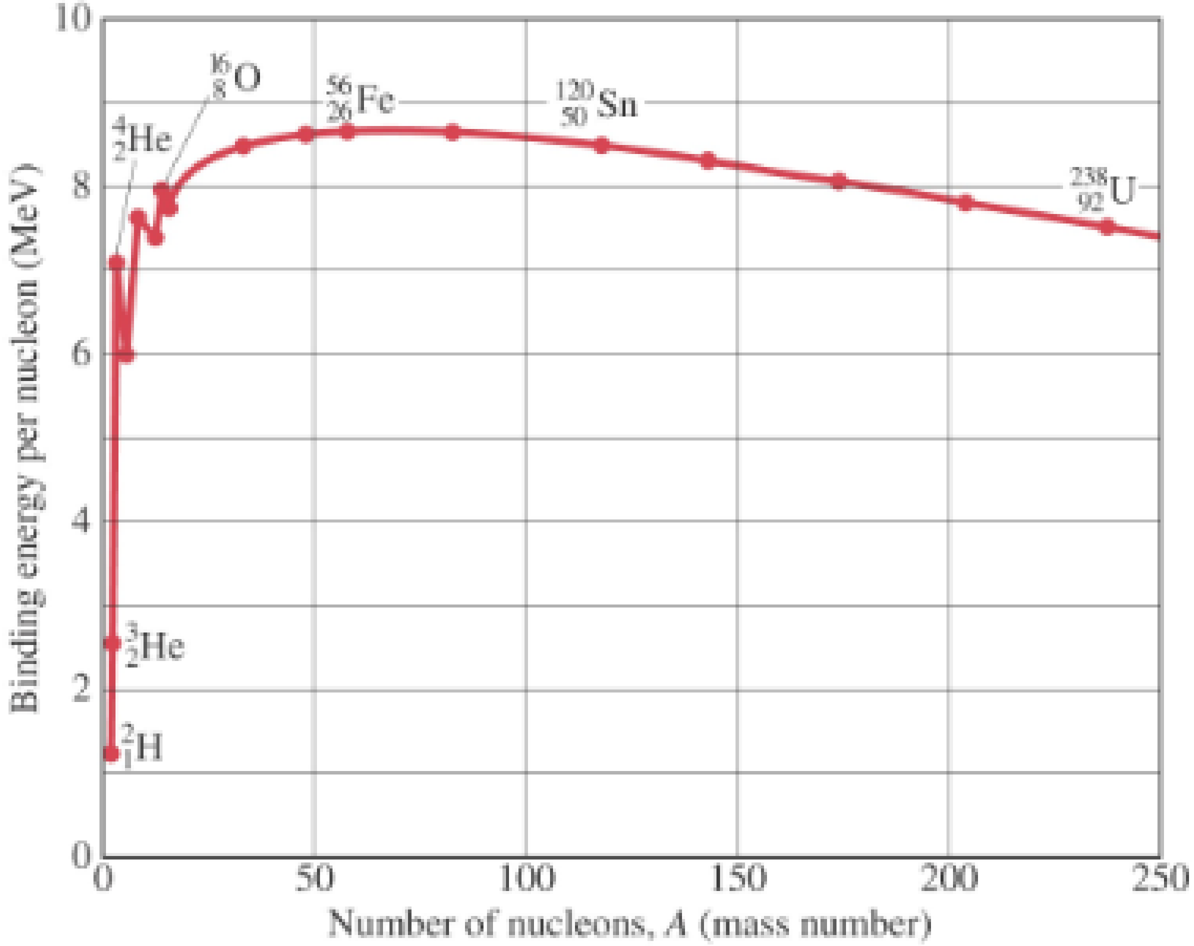
Where has the mass gone?

Energy, as radiation or kinetic energy, is released during formation of a nucleus by ‘fusion’ of smaller nuclei, giving a net mass difference.

This difference between the total mass of separate nucleons and the mass of the final nucleus is then the total binding energy of that nucleus.

Binding Energy and Nuclear Forces

To compare how tightly bound different nuclei are, we divide the binding energy by A to get the binding energy per nucleon.



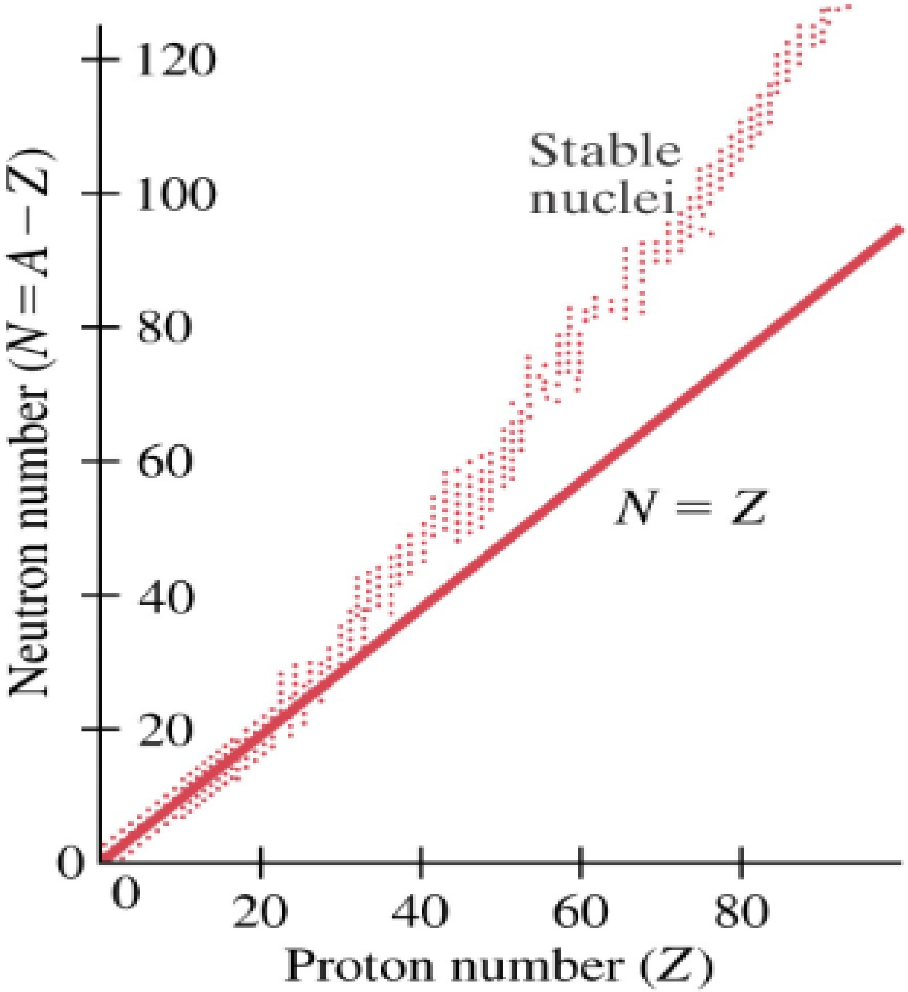
Note:

- -stable isotopes have the same number of protons and neutrons
- -elements with more than 83 protons are unstable and transmutate into stable nuclei with higher binding energies

Binding Energy and Nuclear Forces

The higher the binding energy per nucleon, the more stable the nucleus.

More massive nuclei require extra neutrons to overcome the Coulomb repulsion of the protons in order to be stable.



Binding Energy and Nuclear Forces

The force that binds the nucleons together is called the **strong nuclear force.**

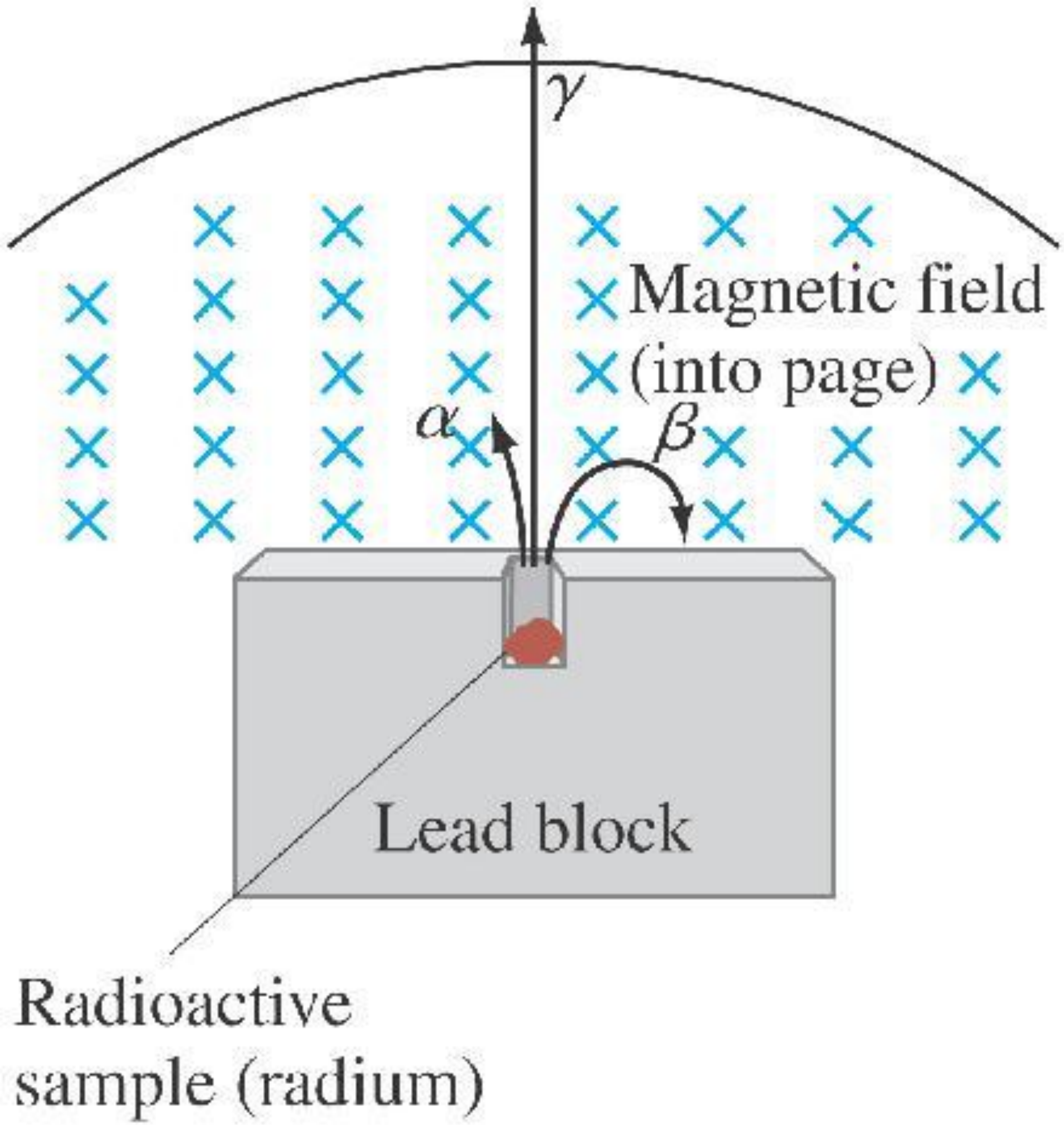
This is a very strong, but very short-range, force. It is essentially zero if the nucleons are more than about 10^{-15} m apart, which roughly corresponds to the size of a nucleus. The Coulomb force is long-range; this is why extra neutrons are needed for stability of high-Z nuclei.

Unstable nuclei decay; some decays are governed by another force, called the **weak nuclear force.**

Radioactivity

- *Radioactivity* is the spontaneous emission of radiation
- Radioactivity is the result of the decay, or disintegration, of unstable nuclei
- Three types of radiation can be emitted
  - Alpha particles *α particles are ^4He nuclei
  - Beta particles *β particles are electrons
  - Gamma rays *ϒ "rays" are high energy photons

Alpha and beta rays are bent in opposite directions in a magnetic field, while gamma rays are not bent at all.



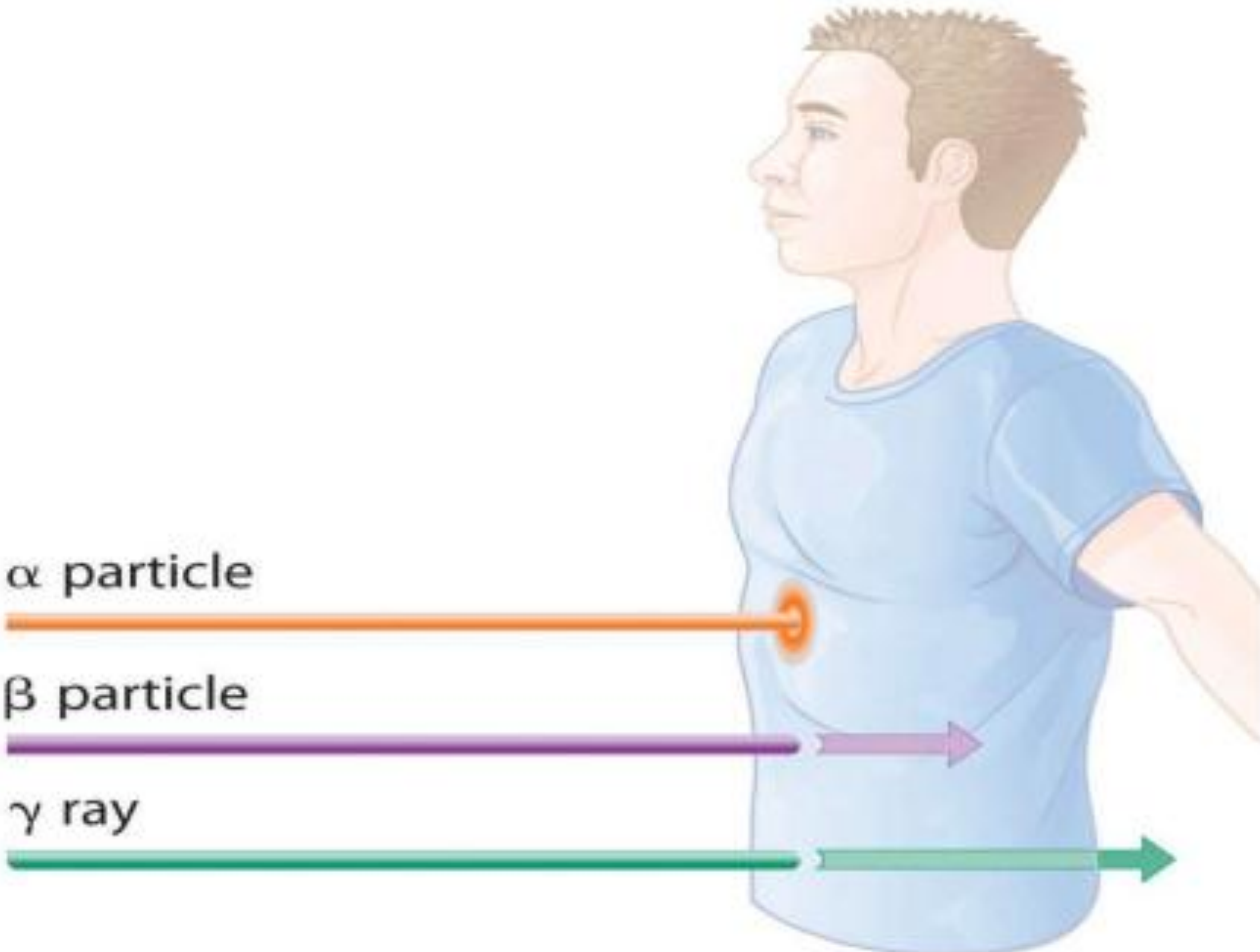
Properties of α, β and γ rays

The three types of radiation

Use this table to find information about and to compare α, β and γ radiation

	Alpha (α)	Beta (β)	Gamma (γ)
Nature	It's a nucleus of helium $^{4}_{2}He$. Two protons and two neutrons	It's an electron e^-	It's an electromagnetic wave
Charge	+2	-1	0
Mass	Relatively large	Very small	No mass
Speed	Slow	Fast	Speed of light
Ionizing effect	Strong	Weak	Very weak
Most dangerous	When source is inside the body	When source is outside the body	When source is outside the body

Radiation Penetration Ability



Alpha Decay

In general, an alpha decay process can be written:

$$ {}^{A}_{Z}\mathrm{N} \rightarrow {}^{A-4}_{Z-2}\mathrm{N}' + {}^{4}_{2}\mathrm{He} $$

Alpha decay occurs when the strong nuclear force cannot hold a large nucleus together. The mass of the parent nucleus is greater than the sum of the masses of the daughter nucleus and the alpha particle; this difference is called the disintegration energy.

Alpha particles themselves are very stable.

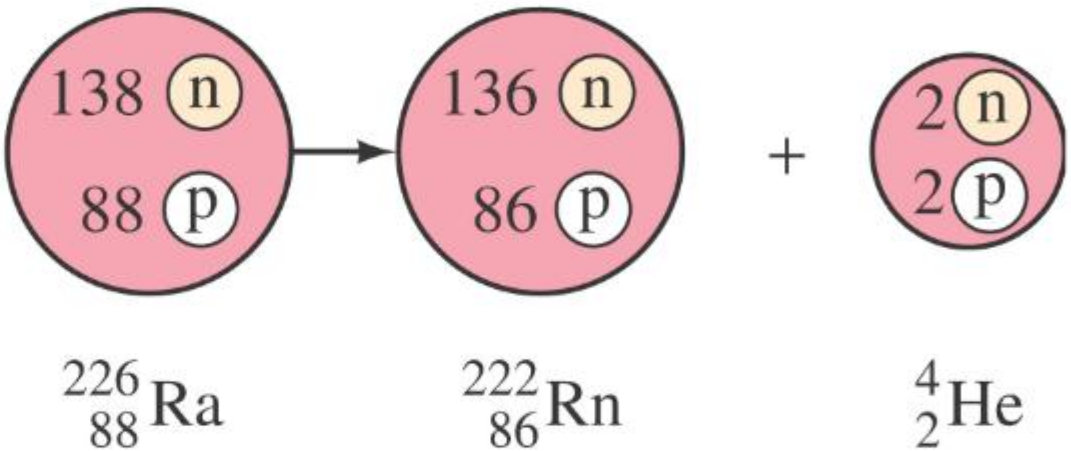
$$ \alpha^{+2} \;, {}^{4}_{2}He, He^{+2} $$

Alpha Decay

Example of alpha decay:

Radium-226 will alpha-decay to **Radon-222**

$$^{226}_{88}\text{Ra} \rightarrow {}^{222}_{86}\text{Rn} + {}^{4}_{2}\text{He}$$



Conservation In Nuclear Reactions

Charge: Net charge remains constant: total charge of the reactants = total charge of the products.

Atomic mass number: The total atomic mass number for the products = total atomic mass number for the reactants.

A. Is this reaction possible?

$$^{230}_{90}Th \rightarrow\ ^{226}_{88}Ra +\ ^{4}_{2}\alpha$$

1. Charge: (p^+ are +)

   $^{+}90 = {}^{+}88 + {}^{+}2$ (Z -charge is balanced)

2. Atomic mass number:

   230 = 226 + 4 (A is balanced)

The reaction is possible.

B. Is this reaction possible?

neutron

$$^{60}_{27}Co \rightarrow \; ^{60}_{28}Ni + \; ^{1}_{0}n$$

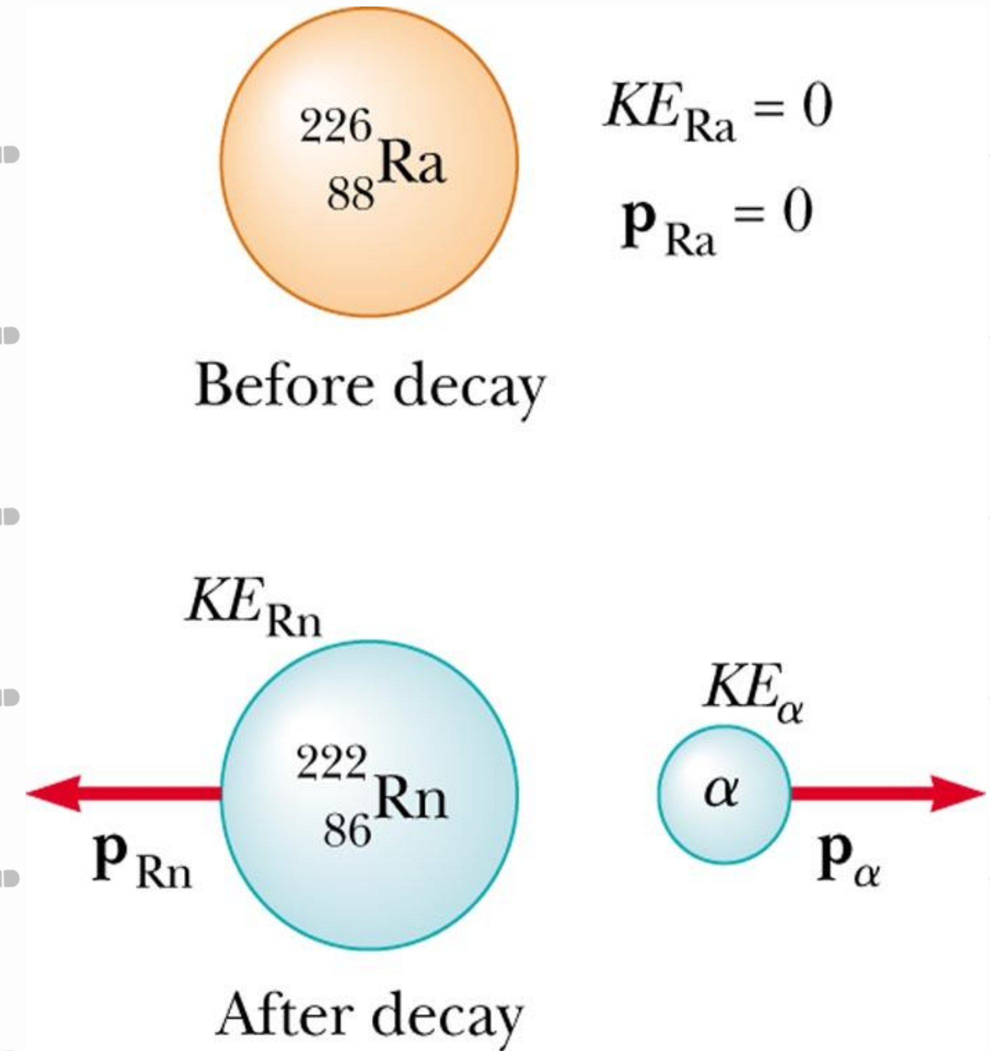
1. Charge:
   $^{+}27 \neq {}^{+}28 + 0$ (Z -charge not balanced)

2. Atomic mass number:
   $60 = 60 + 1$ (A - not balanced)
   The reaction is not possible.

Decay of ^{226}Ra

$$^{226}_{88}\mathrm{Ra} \rightarrow {}^{222}_{86}\mathrm{Rn} + {}^{4}_{2}\mathrm{He}$$

- Excess mass is converted into kinetic energy
- Momentum of the two particles is equal and opposite



QUIZ

If a nucleus such as ^{226}Ra that is initially at rest undergoes alpha decay, which of the following statements is true?

(a) The alpha particle has more kinetic energy than the daughter nucleus.
(b) The daughter nucleus has more kinetic energy than the alpha particle.
(c) The daughter nucleus and the alpha particle have the same kinetic energy.

(a). Conservation of momentum requires the momenta of the two fragments be equal in magnitude and oppositely directed. Thus, from $KE = p^2/2m$, the lighter alpha particle has more kinetic energy that the more massive daughter nucleus.

Energy in alpha decay

- Mass defect, and mass-energy equivalence can be used to determine the maximum E_k an emitted alpha particle will have.
- Q1, Determine the mass defect in the reaction of alpha decay process for the radium-226 and its energy equivalence. This energy will be the maximum E_k an alpha particle could have in the reaction.

Mass defect

$$\Delta m = m_{parent} - m_{products}$$

$$= {}^{226}_{88}Ra - (m_{{}^{222}_{86}Rn} + m_{{}^{4}_{2}\alpha})$$

$$= 226.025410\ u - (222.017578\ u + 4.002603\ u)$$

$$= 0.005229\ u$$

Note: if Δm were negative, this means no energy was released, so the decay would not happen.

Energy equivalence

$$\Delta m = 0.005229 \text{ u} \times 1.660539 \times 10^{-27} \text{ kg / u}$$

$$\Delta m = 8.62829\ldots \times 10^{-30} \text{kg}$$

$$E = mc^2$$

$$= 8.66829\ldots \times 10^{-30} \text{kg} \times (3.00 \times 10^{8} \text{ m / s})^2$$

$$= 7.8146\ldots \times 10^{-13} \ J$$

$$= 4.88 \ eV$$

- Most of this energy will be E_k of the alpha particle.

Q2, Polonium 212 decays into lead 208 by emitting an alpha particle. The rest masses of these three are:

3.51986×10^{-25} kg 3.45324×10^{-25} kg 6.646×10^{-27} kg

$$ {}^{212}_{84}Po \rightarrow {}^{208}_{82}Pb + {}^{4}_{2}He $$

Reactants **Products**

(a) Calculate the difference between the initial rest mass and the total final rest mass. **1.6×10^{-29} kg**

(b) This mass decrease appears in the form of Kinetic energy. Calculate the kinetic energy released in this reaction. **1.44×10^{-12} J**

(c) Assume the Alpha particle, being much less massive than the lead nucleus, gets almost all this energy. Calculate its speed just after the decay.

2.1×10^{7} m/s

Beta Decay

Beta decay occurs when a nucleus emits an electron. An example is the decay of carbon-14:

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

The nucleus still has 14 nucleons, but it has one more proton and one fewer neutron.

In general, beta decay can be written:

$$ {}^{A}_{Z}\mathbf{X} \rightarrow {}^{A}_{Z+1}\mathbf{Y} + {}^{0}_{-1}\mathbf{e} + \overline{\boldsymbol{\nu}} $$

The fundamental process is a neutron decaying to a proton, electron, and neutrino:

$$ \mathrm{n} \rightarrow \mathrm{p} + \mathrm{e}^{-} + \overline{\text{a neutrino}} $$

$$ {}^{1}_{0}\mathbf{n} \rightarrow {}^{1}_{1}\mathbf{p} + {}^{0}_{-1}\mathbf{e} + \overline{\boldsymbol{\nu}} $$

- The electron in beta decay is not an atomic orbital electron; it is created in the nucleus during the decay.

*β 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

Antimatter

- The antimatter of the electron e^{-} or ${}^{0}_{-1}\beta$

is a positron, e^{+} or ${}^{0}_{+1}\beta$

The antimatter of a neutrino (v) is an antineutrino ($\bar{\text{V}}$)

Beta Decay

Neutrinos are notoriously difficult to detect, as they interact only weakly, and direct evidence for their existence was not available until more than 20 yrs had passed after they were 'predicted'.

10^{-35}kg

The symbol for the neutrino is the Greek letter nu, ν We can write the beta decay of carbon-14 as:

$$^{14}_{6}\mathrm{C} \rightarrow {}^{14}_{7}\mathrm{N} + e^{-} + \bar{\nu}.$$

Properties of the neutrino (invisible particle)

- Zero electrical charge
- Mass much smaller than the electron, probably not zero(10^{-35}kg)
- Spin of ½
- Very weak interaction with matter

Beta Decay

- 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

Beta Decay

Beta decay can also occur where the nucleus emits a positron rather than an electron:

$$^{19}_{10}\mathrm{Ne} \rightarrow {}^{19}_{9}\mathrm{F} + e^{+} + \nu$$

A nucleus can also capture one of its inner electrons.

$$^{7}_{4}\mathrm{Be} + e^{-} \rightarrow {}^{7}_{3}\mathrm{Li} + \nu$$

The nucleus still has 7 nucleons, but it has one more neutron and one fewer protons.

In general, positron emission can be written:

$$^{A}_{Z}\mathrm{X} + {}^{0}_{-1}\mathrm{e} \rightarrow {}^{A}_{Z-1}\mathrm{Y} + \nu$$

The fundamental process in an electron capture:

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

Problem 1

What is the maximum KE of the emitted β particle during the decay of $^{60}_{27}\mathrm{Co}$

The reaction is $^{60}_{27}\mathrm{Co} \rightarrow {}^{60}_{28}\mathrm{Ni} + {}^{0}_{-1}\mathrm{e} + \nu$

$$KE_{max} = \Delta mc^2 = \left[m\left({}^{60}_{27}\mathrm{Co}\right) - m\left({}^{60}_{28}\mathrm{Ni}\right) - m\left({}^{0}_{-1}\mathrm{e}\right)\right]c^2$$

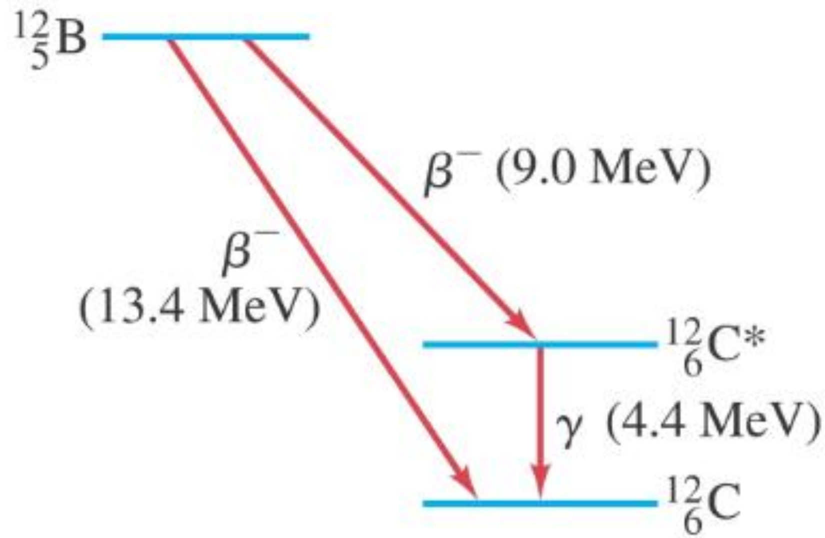
$$= \left[(59.933822\,\mathrm{u}) - (59.930791\,\mathrm{u}) - (0.000549\,\mathrm{u})\right](931.5\ \mathrm{MeV/u})$$

$$\boxed{KE_{max} = 2.31\ \mathrm{MeV}}$$

The energy released in the decay process should almost all go to kinetic energy of the electron

Gamma Decay (or Emission)

Gamma rays are very high-energy photons. They are emitted when a nucleus decays from an excited state to a lower state, just as photons are emitted by electrons returning to a lower state.



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

In general, gamma emission can be written:

$$^{A}_{Z}X^* \rightarrow \, ^{A}_{Z}X + \gamma$$

Gamma Decay

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

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

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

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

Radioactive Dating

Radioactive dating can be done by analyzing the fraction of carbon in organic material that is carbon-14.

The ratio of carbon-14 to carbon-12 in the atmosphere has been roughly constant over thousands of years. A living plant or tree will be constantly exchanging carbon with the atmosphere, and will have the same carbon ratio in its tissues.

Radioactive Dating

When the plant dies, this exchange stops. Carbon-14 has a half-life of about 5730 years; it gradually decays away and becomes a smaller and smaller fraction of the total carbon in the plant tissue. This fraction can be measured, and tissue age deduced.

Objects older than about 60,000 years cannot be dated this way – there is too little carbon-14 left.

Other isotopes are useful for geologic time scale dating.Uranium-238 has a half-life of 4.5×10^9 years, and has been used to date the oldest rocks on Earth as about 4 billion years old.

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 Constant (λ)

- Suppose a radioactive element A (i.e. at $t = 0$ be N_0) disintegrates into another substance B.
- Now as the time passes, the element A disintegrates and hence the amount of A goes on decreasing while that of B goes on increasing.
- Suppose that after t time, the amount of A left

undisintegrated is N.

- $(N_0 - N)$ is the amount of A that gets disintegrated into B after time t.

Now if a small amount, dN of A gets disintegrated into B in a small time dt, then the rate of a disintegration (i.e. rate of decrease) of A into B is equal to – dN/dt which is proportional to the amount of A left undisintegrated (N).

$-\ dN/dt \propto N$

or $-\ dN/dt = \lambda N$

Where λ = is amount of proportionality which is called disintegration or decay constant

$-dN/N = \lambda.\ dt$ ………….. (i)

λ is expressed in $time^{-1}$ units i.e. in s^{-1}, min^{-1}, hrs^{-1}, $days^{-1}$, yrs^{-1}

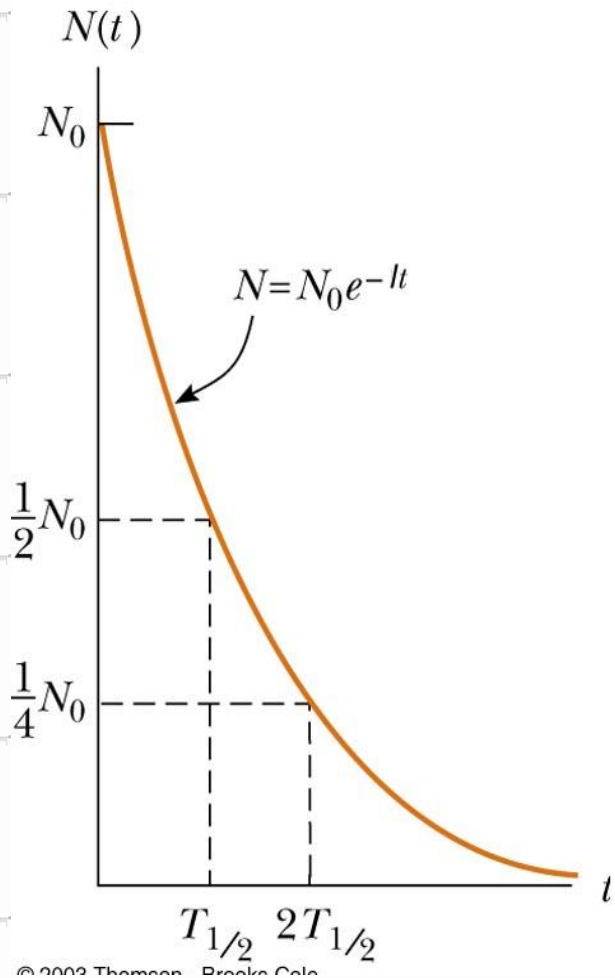
Decay Curve

- The decay curve follows the equation

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

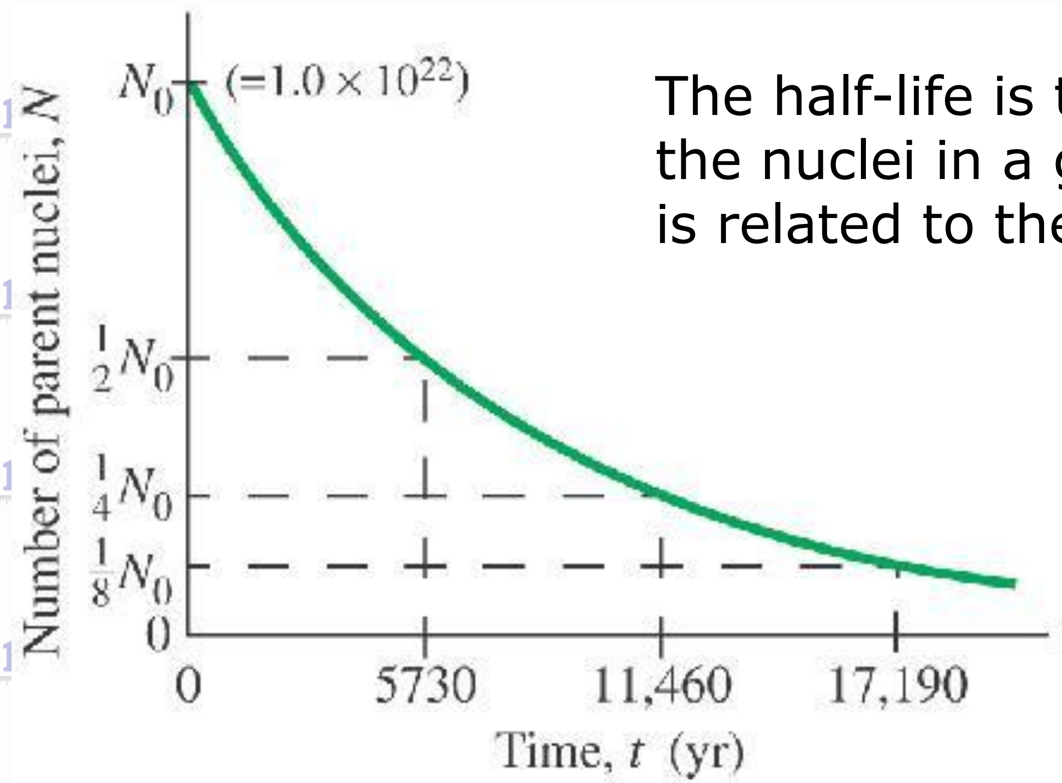
- The *half-life* is also a useful parameter
- The half-life is defined as the time it takes for half of any given number of radioactive nuclei to decay

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



This equation can be solved, using calculus, for *N* as a function of time:

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



The half-life is the time it takes for half the nuclei in a given sample to decay. It is related to the decay constant:

$$T_{\left(\frac{1}{2}\right)} = \frac{\ln 2}{\lambda} = \frac{0.693}{\lambda}$$

Half-Life and Rate of Decay

The **half-life** of a particular nuclide is the time it takes for half the nuclei in a given sample to decay. This is related to the decay constant by

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

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:

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

29.4 The Decay Processes – 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

Uses of Radioactivity

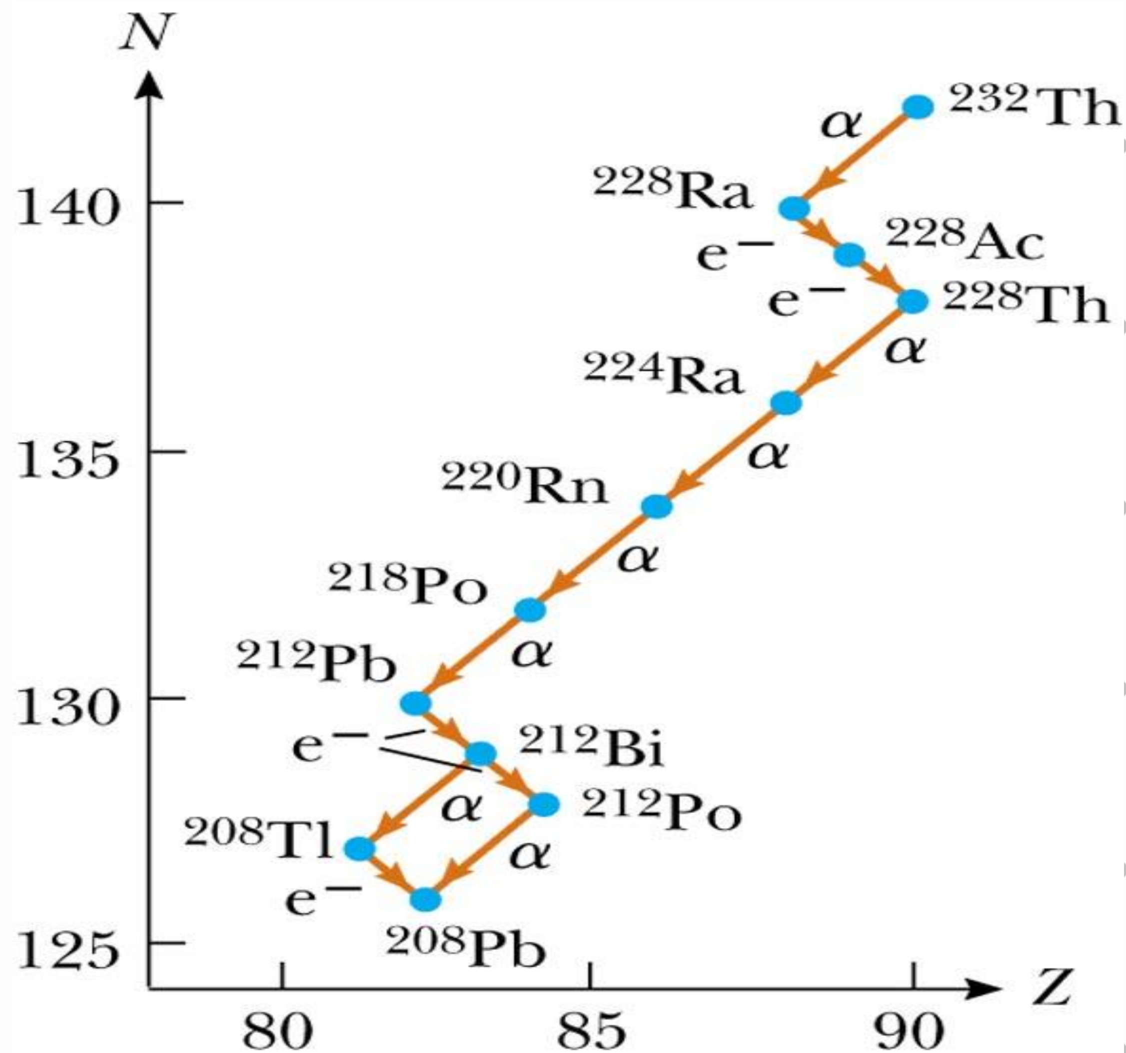
- Carbon Dating
  - Beta decay of ^{14}C is used to date organic samples
  - The ratio of ^{14}C to ^{12}C is used
- Smoke detectors
  - Ionization type smoke detectors use a radioactive source to ionize the air in a chamber
  - A voltage and current are maintained
  - When smoke enters the chamber, the current is decreased and the alarm sounds
- Radon pollution
  - Radon is an inert, gaseous element associated with the decay of radium
  - It is present in uranium mines and in certain types of rocks, bricks, etc that may be used in home building
  - May also come from the ground itself

29.5 Natural Radioactivity

- Classification of nuclei
  - Unstable nuclei found in nature
    - Give rise to *natural radioactivity*
  - Nuclei produced in the laboratory through nuclear reactions
    - Exhibit *artificial radioactivity*
- Three series of natural radioactivity exist
  - Uranium
  - Actinium
  - Thorium

Decay Series of ^{232}Th

- Series starts with ^{232}Th
- Processes through a series of alpha and beta decays
- Ends with a stable isotope of lead, ^{208}Pb



Decay Series

A decay series occurs when one radioactive isotope decays to another radioactive isotope, which decays to another, and so on. This allows the creation of nuclei that otherwise would not exist in natu