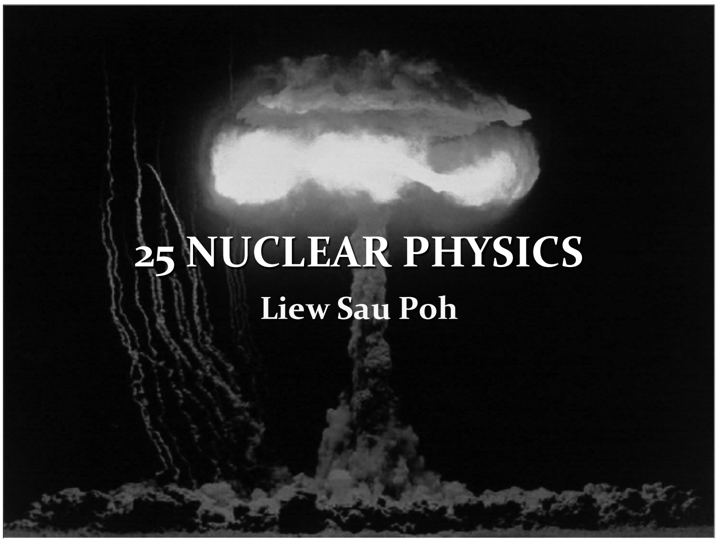
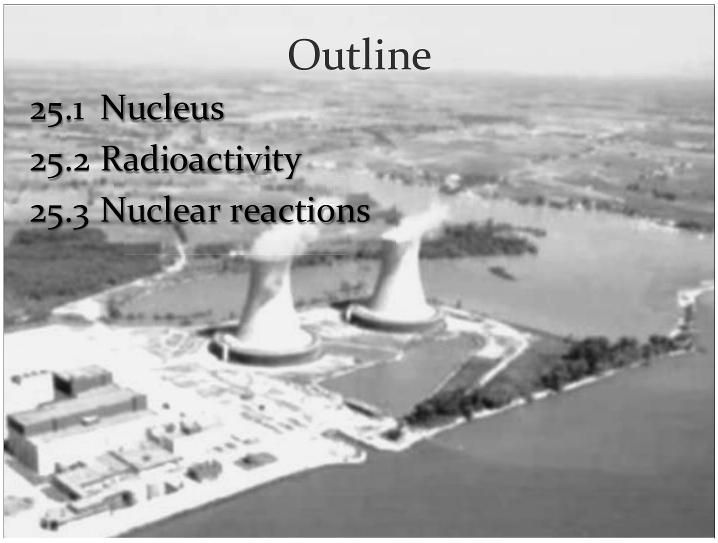


25 NUCLEAR PHYSICS

Liew Sau Poh

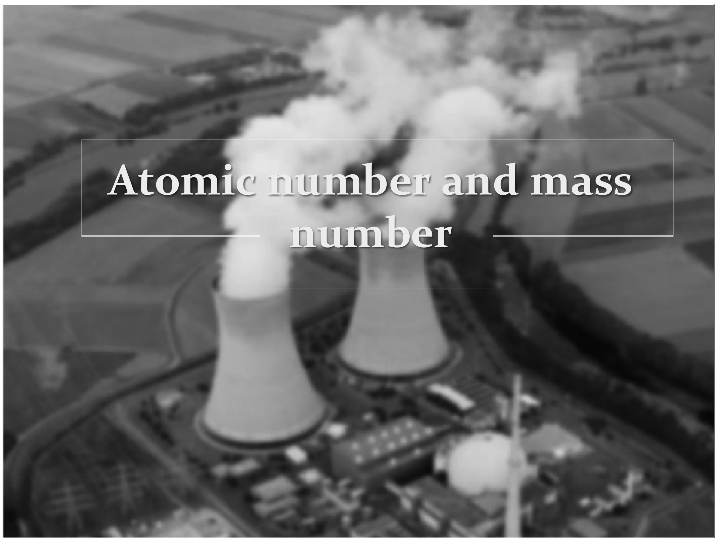


Outline

25.1 Nucleus

25.2 Radioactivity

25.3 Nuclear reactions



Atomic number and mass number

Objectives

a) describe the discovery of neutrons

b) explain mass defect and binding energy

c) use the formula for mass-energy equivalence $\Delta E = \Delta mc^2$

d) relate and use the units u and eV

e) sketch and interpret a graph of binding energy per nucleon against nucleon number

f) explain radioactive decay as a spontaneous and random process

g) define radioactive activity

Objectives

h) state and use the exponential law $dN/dt = -\lambda N$ for radioactive decay

i) define decay constant

j) derive and use the formula $N = N_0 e^{-\lambda t}$

k) define half-life and derive the relation $\lambda = \ln 2/t_{1/2}$

l) solve problems involving the applications of radioisotopes as tracers in medical physics

m) state and apply the conservation of nucleon number and charge in nuclear reactions

Objectives

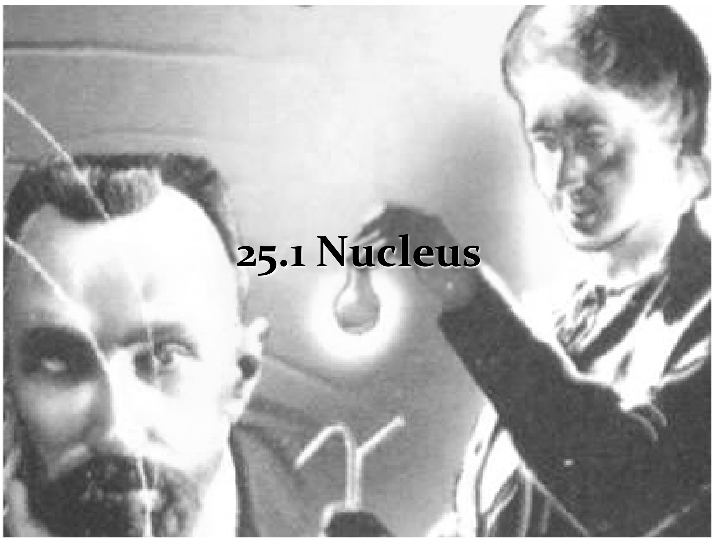
n) apply the principle of mass-energy conservation to calculate the energy released (Q – value) in a nuclear reaction

o) relate the occurrence of fission and fusion to the graph of binding energy per nucleon against nucleon number;

p) explain the conditions for a chain reaction to occur

q) describe a controlled fission process in a reactor

r) describe a nuclear fusion process which occurs in the Sun.



25.1 Nucleus

Discovery of neutrons

- We've been studying atomic structure – the Rutherford model of the atom, where electrons orbit around a nucleus.
- And now we know that it takes Quantum Mechanics to correctly describe the nature of these orbits.
- But what about the nucleus? Well, so far we just know about protons.
- But, in 1932 scattering experiments by English physicist James Chadwick discovered another particle in the nucleus which had no charge → neutron.

Discovery of neutrons

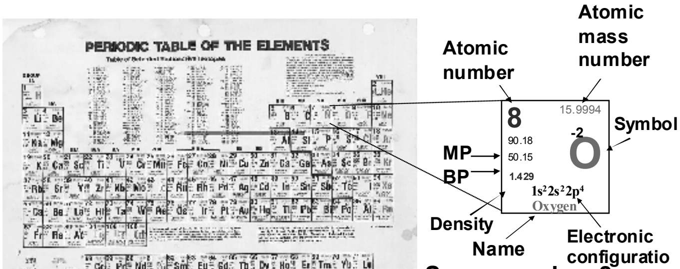
$^{9}_{4}Be + ^{4}_{2}He$ (alpha particle) $\rightarrow$ $^{12}_{6}C + ^{1}_{0}n$ (neutron)

- When Beryllium is bombarded by alpha particle, a beam of high penetrating power is produced.
- This beam is not deflected by electric and magnetic fields.
- Further experiments show that this is a beam of natural particles namely neutrons.

Nuclear Structure

- Nucleus is composed of positive protons and neutral neutrons.
- These are called nucleons.
- What distinguishes different elements in the periodic table is the # of protons they have in their nucleus, which is the Atomic Number (*Z*).
- Each element also has an Atomic Weight or Atomic Mass Number (*A*).
- Let *N* be the # of neutrons in the nucleus, then: $A = Z + N$

Nuclear Structure



So oxygen has 8 protons and
$N = A - Z = 16 - 8 = 8$

8 Neutrons!

Nuclear Structure

Shorthand notation for element representation:

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

So oxygen would be: $^{16}_{8}O$

The mass of the elements is usually given in atomic mass units (u).

$$\boxed{1\text{u} = 1.6605 \times 10^{-27}\ \text{kg}}$$

Nuclear Structure

Nuclei that contain the same number of protons but a different number of neutrons are called isotopes.

For example, boron exists in nature as two stable isotopes: $^{11}_{5}B$ $^{10}_{5}B$

Most boron atoms have 6 neutrons (81.1%), but some (18.9%) have only 5 neutrons.

The atomic mass number (A) listed on the periodic table is the average atomic mass of the isotopes, for boron this is 10.811.

Neutrons

- James Chadwick in 1932 analyzed the results of α-particle scattering on thin Be films.
- Chadwick recognized existence of massive neutral particles which he called neutrons.
  - Chadwick discovered the neutron.

Mass Number

- Mass number is given the symbol A.
- A is the sum of the number of protons and neutrons.
  - Z = proton number N = neutron number
  - $A = Z + N$
- A common symbolism used to show mass and proton numbers is

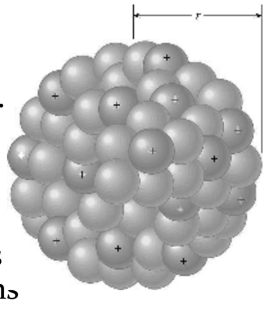
$$^{A}_{Z}E \text{ for example } ^{12}_{6}C,\ ^{48}_{20}Ca,\ ^{197}_{79}Au$$

- Can be shortened to this symbolism

$$^{14}N,\ ^{63}Cu,\ ^{107}Ag, \text{etc.}$$

Mass defect and binding energy

- The protons and neutrons are clustered together in a blob that is approximately spherical. The radius of the nucleus is ~ 1 fm = 1×10^{-15} m.



Experiments show that:

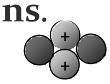
$$\boxed{r \approx (1.2 \times 10^{-15}\ \text{m})A^{1/3}}$$

The Nucleon Density, which is the # of protons and neutrons per unit volume, is the same for all atoms.

Mass defect and binding energy

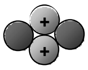
- So we have this spherical blob of positive protons and neutral neutrons. How does it stay together???
- For hydrogen, there's no problem. It's just one proton.
- But what about the next simplest element, helium (He)?
  - 2 protons and 2 neutrons:

He nucleus, 2 protons and 2 neutrons.



- 2 protons very close together.
- We know that like charges repel, and we can calculate the repulsive force between the two protons using Coulomb's Law.
- Assuming the charges are separated by 1 fm, we get a force of 231 N. This results in an acceleration of the protons = 1.4×10^{29} m/s^2. HUGE.

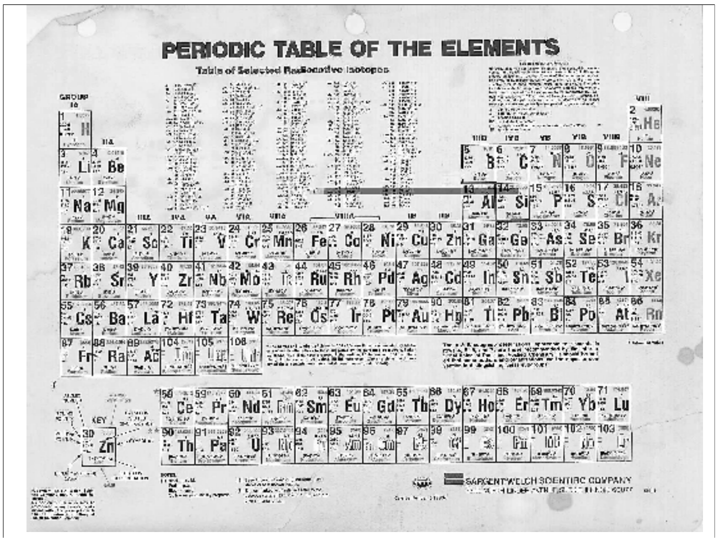
He nucleus, 2 protons and 2 neutrons.



- So why don't the protons, and thus the nucleus, just fly apart?
- There must be an attractive force holding them together, and it's not gravity, because the gravitational attraction between to subatomic particles is very small: ~1.9×10^{-34} N.
- It is one of the fundamental forces, along with gravity and the electroweak force.

Characteristics of the strong nuclear force

1. It is independent of charge. Thus, the attractive force between 2 protons is the same as that between 2 neutrons or between a neutron and a proton.
2. The range of the force is extremely short. It is very strong for distances ~1 fm and essentially zero at farther distances.



PERIODIC TABLE OF THE ELEMENTS

Table of Selected Radioactive Isotopes

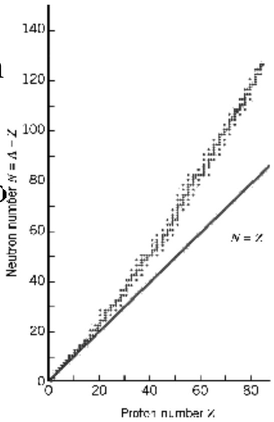
SARGENT-WELCH SCIENTIFIC COMPANY

Periodic Table of Elements

- Most nuclei listed in the periodic table are stable, but some are not.
- The stability of a nucleus depends on the balancing between the electrostatic repulsion between protons and the strong nuclear attractive force between all nucleons.
- Every proton in the nucleus feels Coulombic repulsion from every other proton, since the electro-static force is long-ranged.

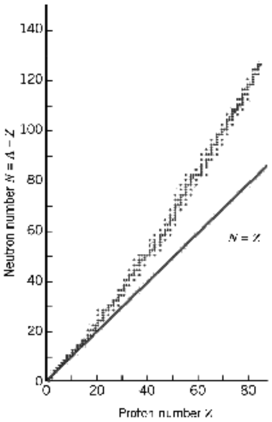
Periodic Table of Elements

- But each proton and neutron only feels the strong nuclear force from its closest neighbors.
- To compensate for this, the more protons I add to the nucleus, an even greater number of neutrons must be added to try and balance the electrostatic force.



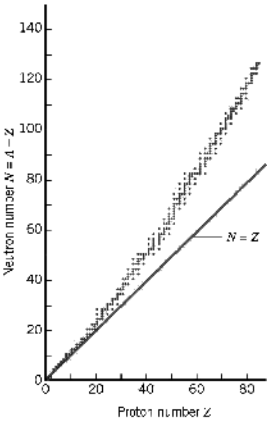
Periodic Table of Elements

- As a larger and larger nuclei is created, the neutron number keeps getting bigger and bigger.
- Notice how the neutron # deviates from the N = Z line for large nuclei.



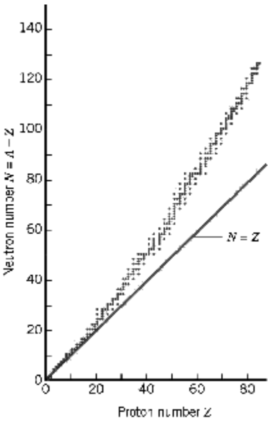
Periodic Table of Elements

- Eventually, as more and more protons are added, no # of extra neutrons can compensate for the large electrostatic repulsion, and the nucleus breaks apart.
- This occurs at Z = 83, which is bismuth (Bi).



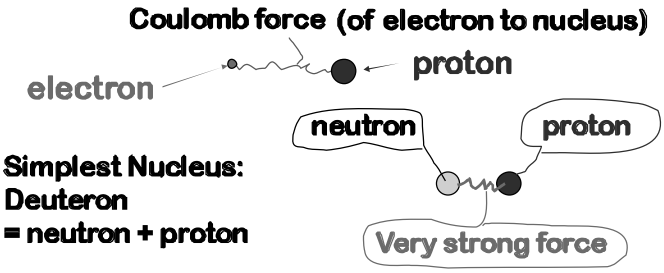
Periodic Table of Elements

- Any element with an atomic number $Z > 83$ will be unstable and break apart over time. It will rearrange itself into a stable nuclei. This process is called Radioactivity.



Strong Nuclear Force (Binding energy)

Hydrogen atom: Binding energy =13.6eV



Coulomb force (of electron to nucleus)

electron

proton

Simplest Nucleus: Deuteron = neutron + proton

neutron

proton

Very strong force

Binding energy of deuteron = $2.2 \times 10^6\,\text{eV}$ **or 2.2Mev! That's around 200,000 times bigger!**

Smaller is Bigger!

Comparing Nuclear and Atomic sizes

Hydrogen Atom: Bohr radius = $5.29 \times 10^{-11}\,\text{m}$

Nucleus with nucl number A: $r \approx A^{1/3} \cdot (1.2 \times 10^{-15}\,\text{m})$

Example A Z $^{27}_{13}\text{Al}$ has radius $r \approx 3.6 \times 10^{-15}\,\text{m}$

Note the TREMENDOUS difference

Nucleus is 10^4 times smaller and binding energy is 10^5 times larger!

Binding Energy

Einstein's famous equation $E = m c^2$

Proton: $mc^2 = 938.3\text{MeV}$

Neutron: $mc^2 = 939.5\text{MeV}$

Adding these, get 1877.8MeV

Deuteron: $mc^2 = 1875.6\text{MeV}$

Difference is Binding energy, 2.2MeV

$M_{\text{Deuteron}} = M_{\text{Proton}} + M_{\text{Neutron}} - |\text{Binding Energy}|$

Where does the energy released in the nuclear reactions of the sun come from?

(1) covalent bonds between atoms

(2) binding energy of electrons to the nucleus

[✓ (3) binding energy of nucleons]

Einstein's Mass-Energy Equivalence Relationship

- In 1905, while developing his special theory of relativity, Einstein made the startling suggestion that energy and mass are equivalent.
- He predicted that if the energy of a body changes by an amount E, its mass changes by an amount m given by the equation
- $E = mc^2$

Einstein's Mass-Energy Equivalence Relationship

- where c is the speed of light.
- Everyday examples of energy gain are much too small to produce detectable changes of mass.
- The changes of mass accompanying energy changes in chemical reactions are not much greater and cannot be used to prove Einstein's equation.

Einstein's Mass-Energy Equivalence Relationship

- However, radioactive decay, which is a spontaneous nuclear reaction, is more helpful.
- Thus for a radium atom, the combined mass of the alpha particle it emits and the radon (Rn) atom to which it decays is, by atomic standards, appreciably less than the mass of the original radium atom.
- Atomic masses can now be measured to a very high degree of accuracy by mass spectrographs.

Einstein's Mass-Energy Equivalence Relationship

- Mass appears as energy and the two can be regarded as equivalent.
- In nuclear physics mass is measured in **unified atomic mass units** (u),
- 1 u being one twelfth of the mass of the carbon-12 atom
- and equals 1.66 x 10^{-27} kg.
- It can readily be shown using $E = mc^2$ that
- 931 MeV has mass 1 u

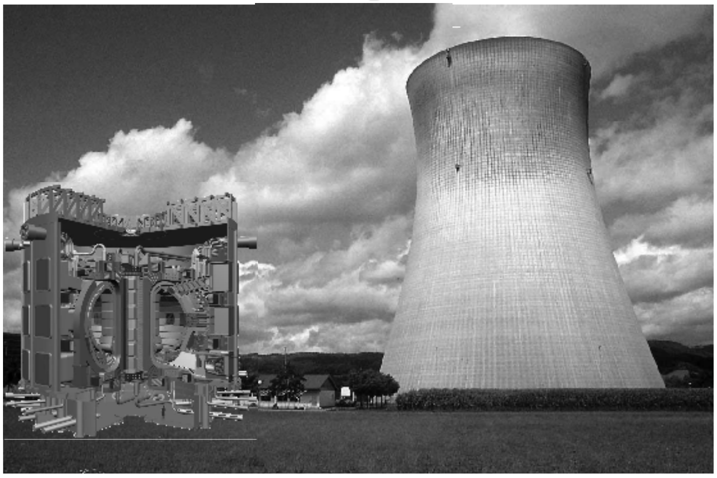
Einstein's Mass-Energy Equivalence Relationship

- A unit of energy may therefore be considered to be a unit of mass, and in tables of physical constants the masses of various atomic particles are often given in MeV as well as in kg and u.
- For example, the electron has a rest mass of about 0.5 MeV

Einstein's Mass-Energy Equivalence Relationship

- If the principle of conservation of energy is to hold for nuclear reactions it is clear that mass and energy must be regarded as equivalent.
- The implication of $E = mc^2$ is that any reaction producing an appreciable mass decrease is a possible source of energy.
- Shortly we will consider two types of nuclear reaction in this category.

Isotopes



Isotopes

- Isotopes are atoms of the same element but with different neutron numbers.
  - Isotopes have different masses and A values but are the same element.
- Almost all elements exist as isotopes.

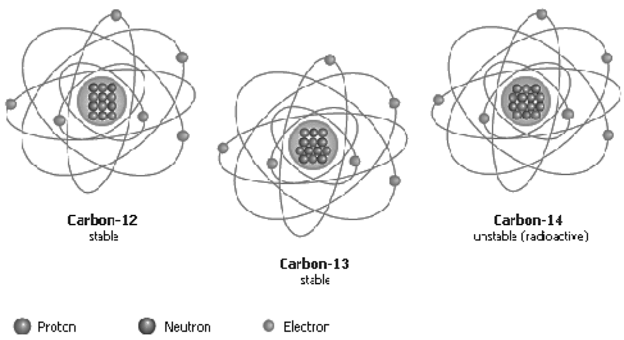
Example 1: Carbon isotopes

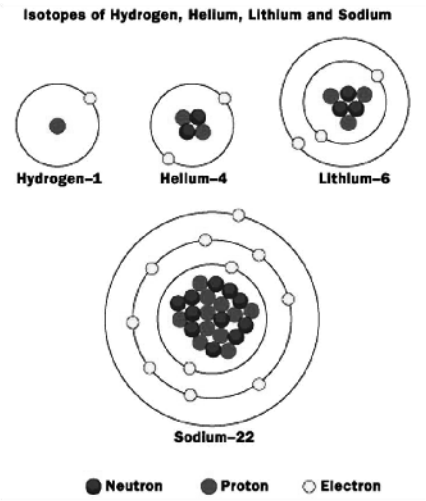
- There are three different Carbon-12 accounts for 98.89% of all carbon atoms (Stable)
- Carbon-13 is the only magnetic carbon isotope (Stable)
- Carbon-14 is produced by cosmic ray bombardment of nitrogen (Unstable)

Example 1: Carbon isotopes

- Carbon-14 is produced by cosmic ray bombardment of nitrogen (Unstable)
- Carbon-14 is radioactive (half-life 5760 years), and it is used to date ancient objects by studying the mounts of C-14 in them.

Example 1: Carbon isotopes





Example 1: Carbon isotopes

- ^{12}C
  - 6 proton and 6 neutrons
- ^{13}C
  - 6 proton and 7 neutron
- ^{14}C
  - 6 proton and 8 neutrons

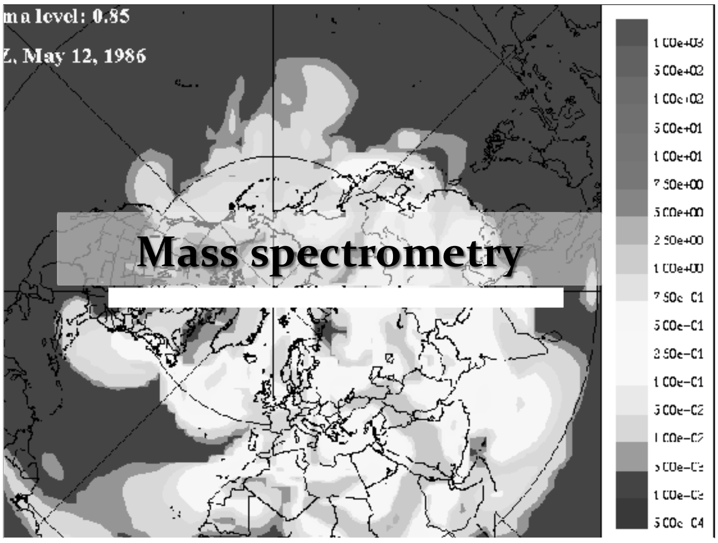
Example 1: hydrogen isotopes

- ^{1}H or protium is the most common hydrogen isotope.
  - 1 proton and no neutrons
- ^{2}H or deuterium is the second most abundant hydrogen isotope.
  - 1 proton and 1 neutron
- ^{3}H or tritium is a radioactive hydrogen isotope.
  - 1 proton and 2 neutrons

Example 2: oxygen isotopes

- ^{16}O is the most abundant stable O isotope.
  - 8 protons and 8 neutrons
- ^{17}O is the least abundant stable O isotope.
  - 8 protons and 9 neutrons
- ^{18}O is the second most abundant stable O isotope.
  - 8 protons and 10 neutrons

Mass spectrometry



Mass Spectrometry

- Research into cathode rays showed that a cathode-ray tube also produced ***positive*** particles.
- Unlike cathode rays, these
- positive particles were ions.
- The metal of the cathode:
- M → e– + M+

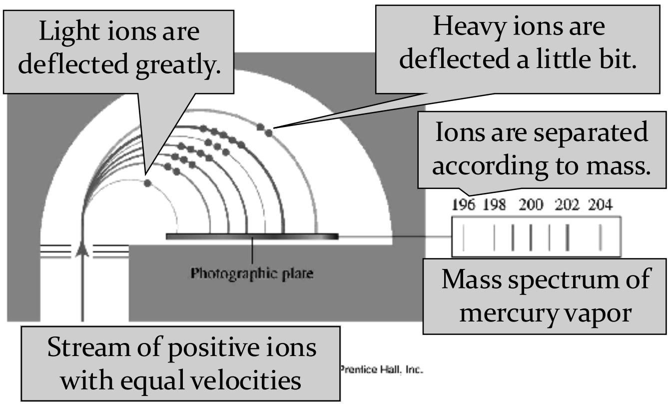
Positive particles

Cathode rays

Mass Spectrometry

- In *mass spectrometry* a stream of positive ions having equal velocities is brought into a magnetic field.
- All the ions are deflected from their straight line paths.
- The lightest ions are deflected the most; the heaviest ions are deflected the least.
- The ions are thus separated by ***mass***.
  - Actually, separation is by *mass-to-charge ratio (m/e)*, but the mass spectrometer is designed so that most particles attain a 1+ charge.

Mass Spectrometer



Light ions are deflected greatly.

Heavy ions are deflected a little bit.

Ions are separated according to mass.

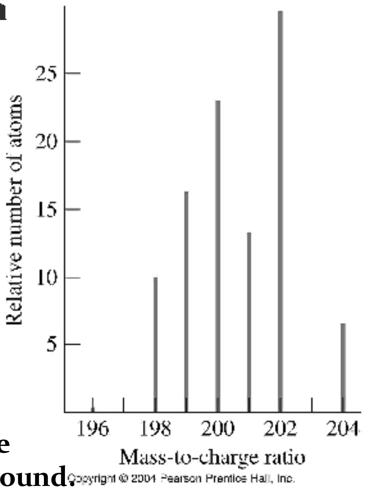
Mass spectrum of mercury vapor

Stream of positive ions with equal velocities

Mass Spectrum for Mercury

Mass spectrum of an *element* shows the abundance of its isotopes. What are the three most abundant isotopes of mercury?

Mass spectrum of a *compound* can give information about the structure of the compound.



Example

1. Two different nuclei have different numbers of protons and a different number of neutrons. Which of the following could be true?
   - They are different isotopes of the same element.
   - They have the same electric charge.
   - Their nucleon density is the same.

25.2 Radioactivity

Radioactivity

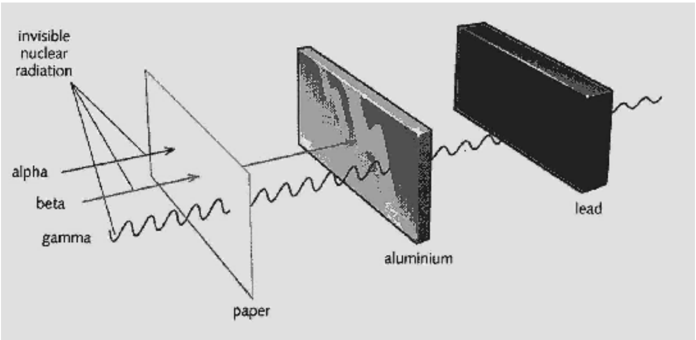
- In 1896, Henri Becquerel discovered, almost by accident, that uranium can blacken a photographic plate, even in the dark.
- Uranium emits very energetic radiation - it is radioactive.

Radioactivity

- Then Marie and Pierre Curie discovered more radioactive elements including polonium and radium.
- Scientists soon realised that there were three different types of radiation.
- These were called alpha (α), beta (β), and gamma (γ) rays
- from the first three letters of the Greek alphabet.

Alpha, Beta and Gamma

Penetrating effect



Properties

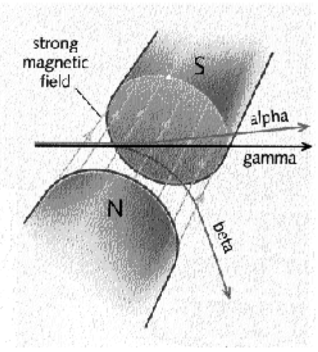
Type of radiation	Alpha particles, α	Beta particles, β	Gamma particles, γ
	2 protons + 2 neutrons (^{4}He)	An electron as nucleus decay	EM-waves (similar to X-ray)
Relative charges	+2	-1	0
Mass	High (compare to β)	low	0
Speed	0.1 × the speed of light	0.9 × the speed of light	the speed of light

Properties

Type of radiation	Alpha particles, α	Beta particles, β	Gamma particles, γ
Ionizing effect	Strong	Weak	Very weak
Penetrating effect	Weak stopped by a sheet of paper, skin or a few cm of air	Penetrating, Stopped by a few mm of Al (or others metal)	Strong, Never Stopped. Leak and thick concrete used to decrease intensity
Effects on fields	Deflected by Magnetic and Electric fields	Deflected by Magnetic and Electric fields	Not deflected by Magnetic and Electric fields

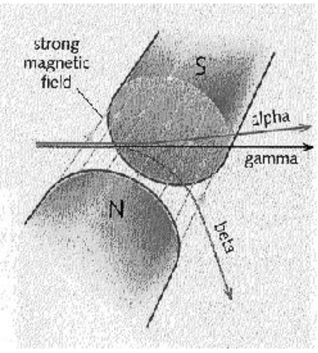
Properties

- The diagram on the right shows how the different types are affected by a magnetic field.
- The alpha beam is a flow of positively (+) charged particles, so it is equivalent to an electric current.



Properties

- It is deflected in a direction given by Fleming's left-hand rule - the rule used for working out the direction of the force on a current-carrying wire in a magnetic field.

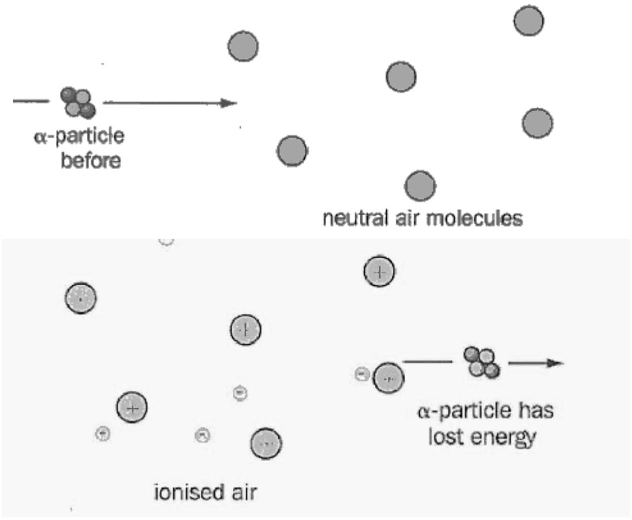


Properties

- The beta particles are much lighter than the alpha particles and have a negative (-) charge, so they are deflected more, and in the opposite direction.
- Being uncharged, the gamma rays are not deflected by the field.
- Alpha and beta particles are also affected by an electric field - in other words, there is a force on them if they pass between oppositely charged plates.

Ionising Properties

- α -particles, β -particles and γ -ray photons are all very energetic particles.
- We often measure their energy in electron-volts (eV) rather than joules.
- Typically the kinetic energy of an α -particle is about 6 million eV (6 MeV).
- We know that radiation ionises molecules by `knocking' electrons off them.
- As it does so, energy is transferred from the radiation to the material.
- The next diagrams show what happens to an α-particle



Decay constant and half-life

Alpha Decay

- An alpha-particle is a helium nucleus and is written $^{4}_{2}He$ or $^{4}_{2}\alpha$.
- It consists of 2 protons and 2 neutrons.
- When an unstable nucleus decays by emitting an α -particle
- it loses 4 nucleons and so **its nucleon number decreases by 4.**
- Also, since it loses 2 protons, **its proton number decreases by 2**

Alpha Decay

- The nuclear equation is

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

- Note that the top numbers balance on each side of the equation. So do the bottom numbers.

Beta Decay

- Many radioactive nuclides (radio-nuclides) decay by β-emission.
- This is the emission of an electron *from the nucleus.*
- But there are no electrons in the nucleus!

Beta Decay

- What happens is this:
- one of the neutrons changes into a proton (which stays in the nucleus) *and* an electron (which is emitted as a β-particle).
- This means that **the proton number increases by 1,**
- while the total **nucleon number remains the same.**

Beta Decay

- The nuclear equation is

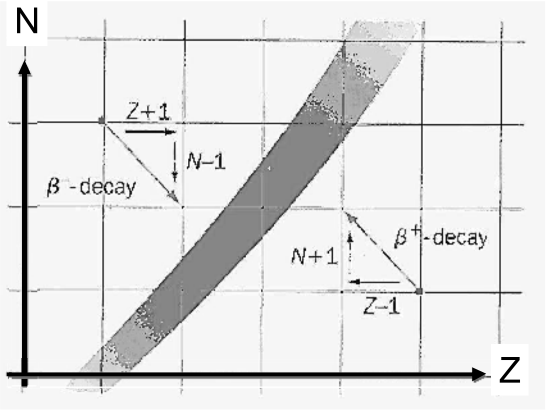
$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + {}^{0}_{-1}e $$

- Notice again, the top numbers balance, as do the bottom ones.

Beta Decay

- A radio-nuclide *above* the stability line decays by β-emission.
- Because it loses a neutron and gains a proton, it moves diagonally *towards* the stability line, as shown on this graph

Beta Decay



Gamma Decay

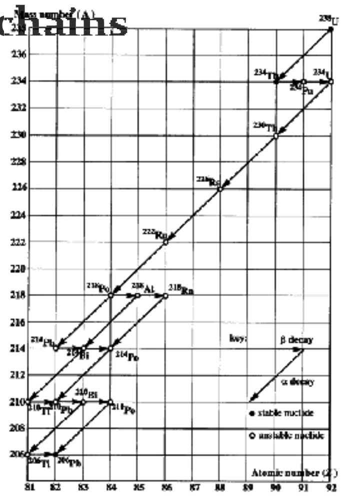
- Gamma-emission does not change the structure of the nucleus, but it does make the nucleus more stable
- because it reduces the energy of the nucleus.

Decay chains

- A radio-nuclide often produces an unstable daughter nuclide.
- The daughter will also decay, and the process will continue until finally a stable nuclide is formed.
- This is called a decay chain or a decay series.
- Part of one decay chain is shown below

$$ {}^{238}_{92}\mathrm{U} \xrightarrow{\alpha} {}^{234}_{90}\mathrm{Th} \xrightarrow{\beta} {}^{234}_{91}\mathrm{Pa} \xrightarrow{\beta} {}^{234}_{92}\mathrm{U} \xrightarrow{\alpha} {}^{230}_{90}\mathrm{Th} \xrightarrow{\alpha} {}^{226}_{88}\mathrm{Ra} $$

Decay chains



- When determining the products of deacy series, the same rules apply as in determining the products of alpha and beta, or artificial transmutation.
- The only difference is several steps are involved instead of just one.

Half Life

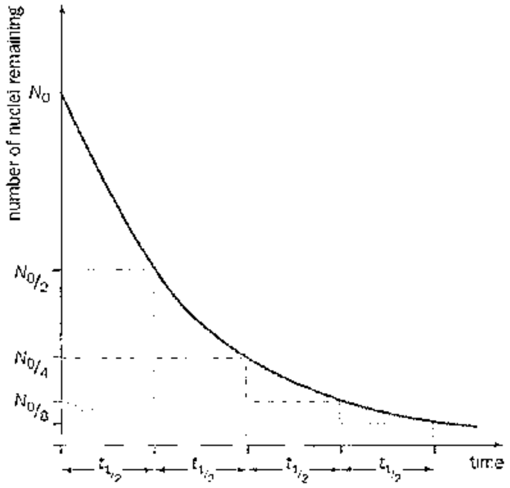
- Suppose you have a sample of 100 identical nuclei.
- All the nuclei are equally likely to decay, but you can never predict which individual nucleus will be the next to decay.
- The decay process is completely **random.**
- Also, there is nothing you can do to `persuade' one nucleus to decay at a certain time.
- The decay process is **spontaneous.**

Half Life

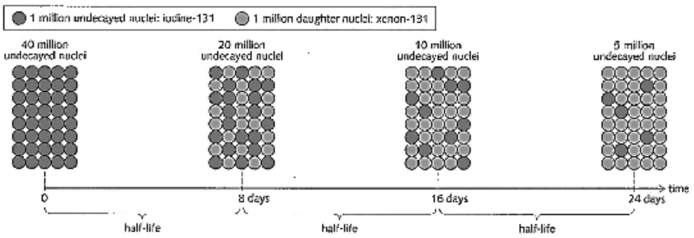
- Does this mean that we can never know the rate of decay?
- No, because for any particular radio-nuclide there is a certain **probability** that an individual nucleus will decay.
- This means that if we start with a large number of identical nuclei we can predict how many will decay in a certain time interval.

Half Life

- Iodine-131 is a radioactive isotope of iodine.
- The chart on the next slide illustrates the decay of a sample of iodine-131.
- On average, 1 nucleus disintegrates every second for every 1000 000 nuclei present.



Half Life



- **Suppose there are 40 million nuclei.**
- **8 days later, half of these have disintegrated.**
- **With the number of undecayed nuclei now halved, the number of disintegrations over the next 8 days is also halved.**
- **It halves again over the next 8 days... and so on.**
- **Iodine-131 has a half-life of 8 days.**

Definition 1

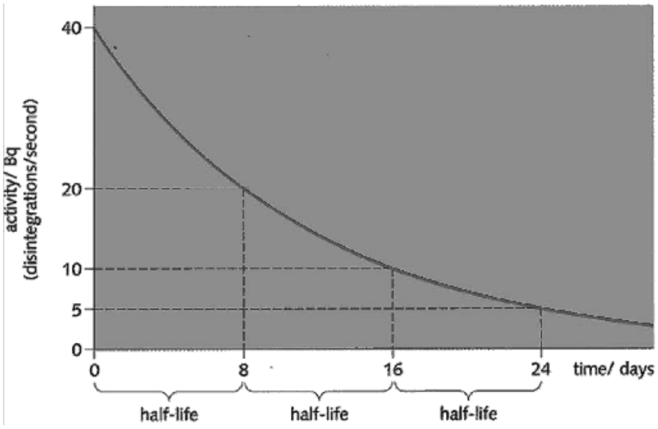
- The half-life of a radioactive isotope is the time taken for half the nuclei present in any given sample to decay.

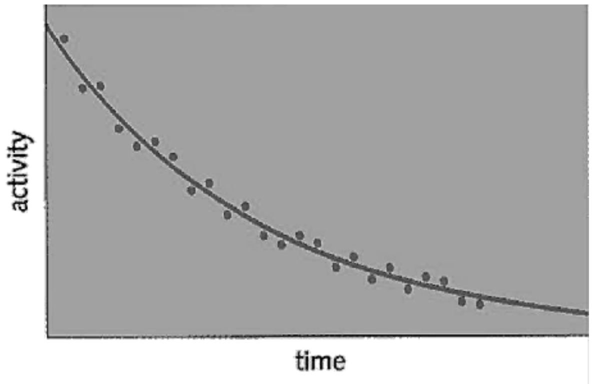
Activity and half-life

- In a radioactive sample, the average number of disintegrations per second is **called the activity.**
- The SI unit of activity is the **Becquerel (Bq).**
- An activity of, say, 100 Bq means that 100 nuclei are disintegrating per second.
- Activity, A = dN/dt (Bq)

Activity and half-life

- The graph on the next slide of the next page shows how, on average, the activity of a sample of iodine-131 varies with time.
- As the activity is always proportional to the number of undecayed nuclei, it too halves every 8 days.
- So `half-life' has another meaning as well:





▲ Radioactive decay is a random process. So, in practice, the curve is a 'best fit' of points which vary irregularly like this.

Definition 2

- The half-life of a radioactive isotope is the time taken for the activity of any given sample to fall to half its original value.

Exponential Decay

- Any quantity that reduces by the same fraction in the same period of time is called an exponential decay curve.
- The half life can be calculated from decay curves
- Take several values and the take an average

Rate of Decay

- Rate of decay =

$$-\frac{\Delta N}{\Delta t}$$

- N=undecayed nuclei at time (an instant) t.

  Negative sign: no. of nuclei is decreasing
- The rate of nuclear disintegration at a particular moment depends on the number of undecayed nuclei at that moment,
- Hence,

$$\frac{\Delta N}{\Delta t} \propto N$$

Rate of Decay

$$\frac{\Delta N}{\Delta t} \propto N$$

- Let $\Delta t \rightarrow 0$,
- then $\Delta N/\Delta t \rightarrow dN/dt$ (the rate of decay)
- Hence, $\frac{dN}{dt} = -\lambda N$, λ = decay constant
- Activity, A = dN/dt (Bq)

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

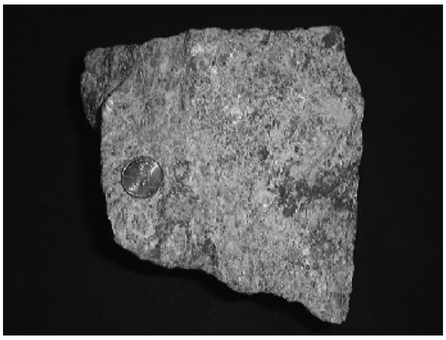
Radioactive Decay Problems

- λ **is the decay constant**, a positive constant used to describe the rate of exponential decay.

  $N(t) = N_0 e^{-\lambda t}$
  - N_0 is the initial value of N
  - $N(t)$ is the value of N at time t
  - t is the time
  - Half-life : $T_{1/2} = (\ln 2)/\lambda$

Rare Earth Elements

- Rare earth ore, shown with a United States penny for size comparison



Rare Earth Elements

- These rare-earth oxides are used as tracers to determine which parts of a watershed are eroding. Clockwise from top center: praseodymium, cerium, lanthanum,neodymium, samarium, and gadolinium.[1]

Rare Earth Elements

- As defined by IUPAC, **rare earth elements** or **rare earth metals** are a set of seventeen chemical elements in the periodic table, specifically the fifteenlanthanoids plus scandium and yttrium.[2] Scandium and yttrium are considered rare earth elements since they tend to occur in the same ore deposits as thelanthanoids and exhibit similar chemical properties.

Rare Earth Elements

- Despite their name, rare earth elements (with the exception of the radioactive promethium) are relatively plentiful in the Earth's crust, with cerium being the 25th most abundant element at 68 parts per million (similar to copper). However, because of their geochemical properties, rare earth elements are typically dispersed and not often found in concentrated and economically exploitable forms known as rare earth minerals.[3] It was the very scarcity of these minerals (previously called "earths") that led to the term "rare earth". The first such mineral discovered was gadolinite, a compound of cerium, yttrium, iron, silicon and other elements. This mineral was extracted from a mine in the village of Ytterby in Sweden; many of the rare earth elements bear names derived from this location.

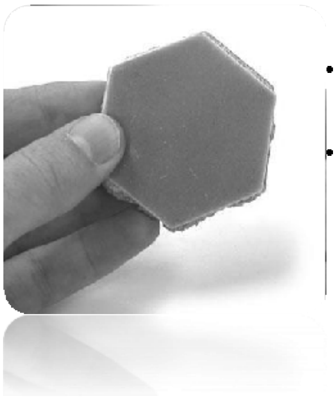
Additional knowledge:
Radiation in Our Environment

Uranium
A Naturally Occurring Radioactive Element in the Earth's Crust

Fiesta Ware

- Some of these plates are glazed with uranium
- The uranium has the chemical form U_3O_8
- This form is called "yellowcake" because it is bright yellow in color
- Firing the plate in a kiln turns the color orange

Green Bathroom Tile



- Dates from the 1930's but certainly before 1943
- Analysis showed it contains natural uranium
- Dose rate in the bathroom was about 10 times the normal background (0.1 mR/h)

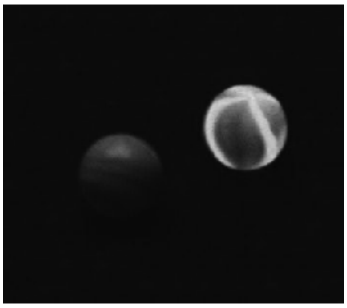
Uranium Glass

- Uranium was discovered in 1792 by a German chemist named Klaproth
- It has been used in making glass since the early 1800's
- Concentration of uranium as well as temperature and annealing procedure can determine the colors

Vaseline Glass

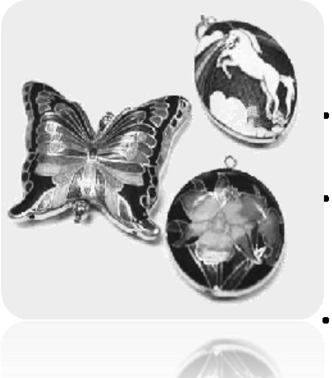
Under UV Light

A Uranium Glass Marble



Under UV Light

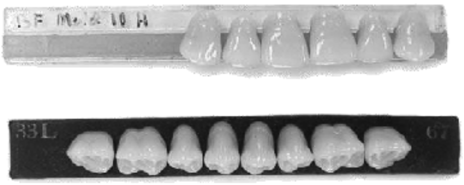
Cloisonné Jewelry



- Fine jewelry formed on metal frame with fine glass powder poured into frame
- Glass is melted at about 850 °C
- Uranium oxide is used to produce ivory, yellow and gold colors
- Typically about 7% UO_2

Dentures

- Uranium is added to false teeth to provide a shine to the material (about 10% of the teeth)
- Concentration of uranium is quite low – about 300 parts per million



Phosphate Fertilizer

- About 150 million tons of phosphate are mined annually
- Ore contains uranium, thorium and radium as well as K-40
- Produces 12 to 15 million tons of phosphate fertilizer
- Total activity of Ra-226 in the fertilizer tonnage is about 12 Ci

Cat Litter

- Most cat litter made from clay (e.g., bentonite)
- Contains elevated levels of naturally occurring radionuclides
- Contains 4 pCi/g of uranium series, 3 pCi/g of thorium series, and 8 pCi/g of K-40

Penetrators

- Armor-piercing bullets and shells
- Are made from "depleted" uranium (DU)
- DU is the U-238 left when most of the U-235 had been removed
- Uranium metal is very dense and it burns spontaneously upon impact

THORIUM
A Naturally Occurring Radioactive Element in the Earth's Crust

"Spot Plate"

- The are higher concentrations of thorium than uranium
- This plate has been glazed with ThO_2
- It is used in a number of applications

Thorium Lantern Mantles

Welding Rods

- Thorium oxide is also used in tungsten welding rods
- It increases the current carrying capacity of the rod
- Production is 1-5 million rods per year
- Concentration of ThO_2 is usually 1-2% (15-30 µCi)
- Some welding rods have concentrations up to 4%

Camera Lenses

- Th-232 is added to the lenses to increase the index of refraction
- Some lenses have up to 12% thorium
- Use began around the late 1930's
- Use ceased in the late 1980's
- Military lenses may still show radioactivity

Other Uses of Thorium

- This tape dispenser has sand mixed with epoxy resin in its base
- The sand is called Monazite (a black sand)
- Monazite sand contains up to 10% thorium

OTHER RADIONUCLIDES

Revigator

- In the 1920-1930's many believed that drinking water containing radium (Ra-226, Ra-228) was good for your health
- This water "jug" produced "radium water" from fresh water, on demand, because it had a radium-ore cone inside

Smoke Detectors

- Smoke detectors save lives and are important in commercial and residential structures
- About 80% of U.S. homes have at least one detector
- The detector is really an ionization chamber containing a small radioactive source

Smoke Detectors

- The radioactive source used in current detectors is Am-241
- The total activity is low, about 1 μCi
- The detector and source are enclosed in the cover shown at the right

Static Eliminator

- Many devices use radioactive sources to eliminate static electricity
- Copy machines and other such machines used static eliminators
- The usual radioactive source is Po-210, initial activity 200 - 500 μCi

RADIOACTIVITY IN FOODSTUFFS

Bananas

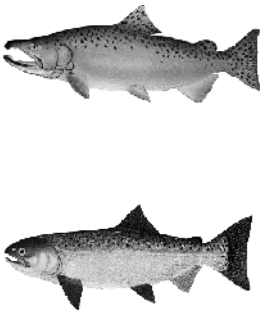
- Bananas contain the radionuclide K-40 or ^{40}K
- This is a naturally occurring isotope of the element potassium
- Potassium is essential in muscle function and concentrates in the muscle
- Who is more radioactive, males or females?

Salt Substitute

- Some individuals cannot use regular salt (NaCl) tc season their food
- They use KCl instead
- But the KCl is radioactive because of the K-40 that is present in the salt substitute
- Activity about 450 pCi/g

Salmon

- Salmon are born in fresh water but live their life in the ocean
- Natural radioactivity from the rocks and soil is washed into the oceans
- The salmon tend to concentrate this radioactive material in their flesh – typical values are 20 pCi/g



Brazil Nuts

- These nuts concentrate Ra-226 from the soil

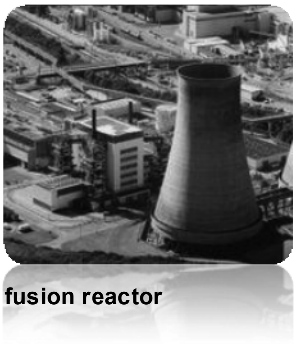
These nuts are probably the most radioactive foodstuff we consume

Yet the radioactivity is so low that it is difficult to measure it

- From 0.2 to 7 pCi/g

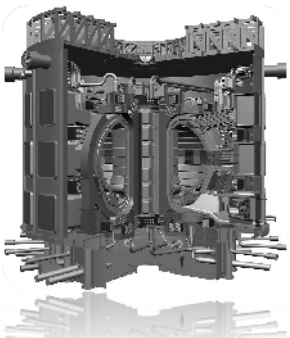
25.3 Nuclear reaction

Nuclear Reactors



fusion reactor

use fission of heavy elements like uranium



Nuclear Reactions

- **A nuclear reaction takes place when a nucleus is struck by another nucleus or particle.**
- **An example:**

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

Nuclear Reactions

- First nuclear reaction was a nitrogen target bombarded with alpha particles, which emitted protons. The reaction is written as:

$$ \alpha + {}^{14}_{7}\mathrm{N} \rightarrow p + {}^{17}_{8}\mathrm{O} $$

- The first particle is the projectile and the second is the nitrogen target. These two nuclei react to form proton projectiles and the residual oxygen target.
- The reaction can be rewritten in shorthand as: ${}^{14}\mathrm{N}(\alpha, p){}^{17}\mathrm{O}$.
- In general a reaction $x + X \rightarrow y + Y$ can be rewritten as $X(x, y)Y$

Reaction Energy

- $x + X \rightarrow y + Y$
- *Sum of masses of* $x + X >$ *sum of masses of* $y + Y$
- *Decrease in mass due to some mass is converted to energy*
- *Thus*

  $x + X \rightarrow y + Y + Q$ *(energy)*

  Where $Q = (\Delta m)c^2$; Δm = *mass (lost)*
- *If Q is positive* → *exothermic, if Q is negative* → *endothermic*

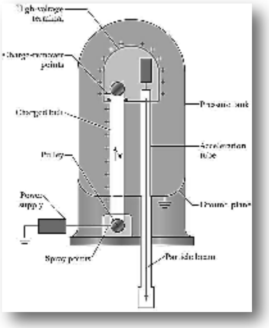
Reaction Energy

- *A proton strikes a tritium nucleus and the following nuclear reaction takes place*

  ${}^{1}H + {}^{3}H \rightarrow n + {}^{3}He$
- *Determine the energy released in MeV. (Masses:* ${}^{3}H = 3.016050$ *u,* ${}^{1}H = 1.007276$ *u,* ${}^{3}He = 3.016030$ *u,* ${}^{1}n = 1.008665$ *u,* ${}^{1}u = 931.5MeV$*)*
- $\Delta m = ({}^{3}H + {}^{1}H) - ({}^{3}He + {}^{1}n) = -0.001369$ *u*
- $Q = \Delta m$ *(in MeV)* $= (-001369)(931.5) = -1.275MeV$ → *endothermic*

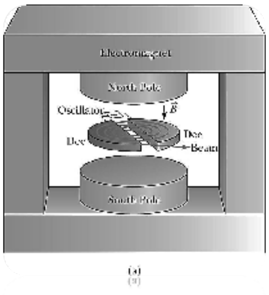
Important Technological Advances

- The high-voltage multiplier circuit was developed in 1932 by J.D. Cockcroft and E.T.S. Walton. This compact circuit produces high-voltage, low-current pulses. High voltage is required to accelerate charged particles.
- The Van de Graaff electrostatic accelerator was developed in 1931. It produces a high voltage from the friction between two different materials.



Important Technological Advances

The first cyclotron (at left) was built in 1932. It accelerated charged particles using large circular magnets.



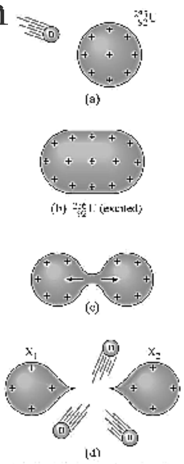
(a)

Types of Reactions

- **Nuclear photodisintegration** is the initiation of a nuclear reaction by a photon.
- **Neutron or proton radioactive capture** occurs when the nucleon is absorbed by the target nucleus, with energy and momentum conserved by gamma ray emission.
- The projectile and the target are said to be in the *entrance channel* of a nuclear reaction. The reaction products are in the *exit channel.*
- In *elastic scattering*, the entrance and exit channels are identical and the particles in the exit channels are not in excited states.
- In *inelastic scattering*, the entrance and exit channels are also identical but one or more of the reaction products is left in an excited state.
- The reaction product need not always be in the exit channel.

Nuclear Fission

- After absorbing a neutron, a uranium-235 nucleus will split into two roughly equal parts.
- One way to visualize this is to view the nucleus as a kind of liquid drop.



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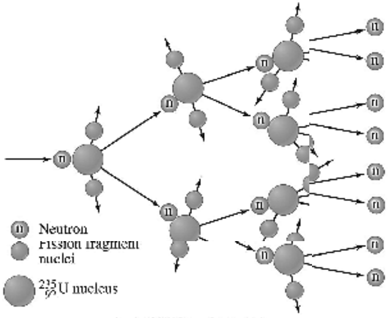
Nuclear Fission

The energy release in a fission reaction is quite large. Also, since smaller nuclei are stable with fewer neutrons, several neutrons emerge from each fission as well.

These neutrons can be used to induce fission in other nuclei, causing a chain reaction.



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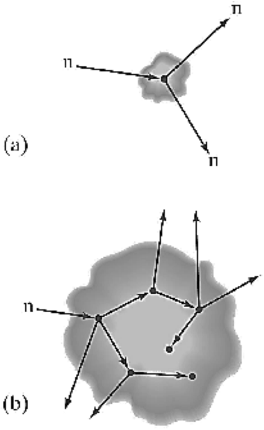
Nuclear Fission; Nuclear Reactors

- In order to make a nuclear reactor, the chain reaction needs to be self-sustaining – it will continue indefinitely – but controlled.

Nuclear Fission; Nuclear Reactors

- Neutrons that escape from the uranium do not contribute to fission. There is a critical mass below which a chain reaction will not occur because too many neutrons escape.



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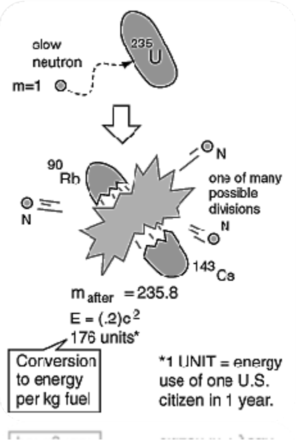
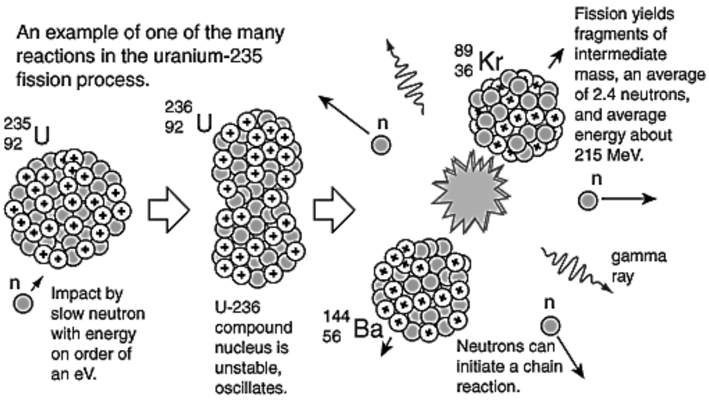
Nuclear Fission

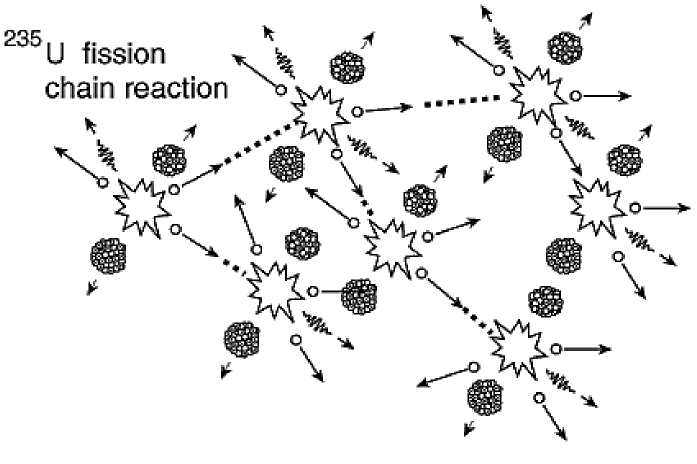
- Fission – The splitting of heavy nuclei into lighter, more-tightly bound, pieces
- Spontaneous fission – nuclei splits without initiating event
- Neutron-induced fission – nuclei splits after being hit by a neutron
- Fissionable – Nuclei which can undergo neutron-induced fission
- Fissile isotopes – Nuclei in which fission can be induced by a “slow” neutron. Examples: ^{233}U, ^{235}U, ^{239}Pt



Fission of U-235

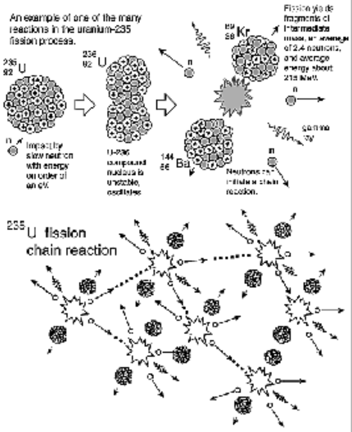


U-235 Chain Reaction



Nuclear Chain Reaction

- Neutrons can induce fission, which can release additional neutrons
- Chain reaction – process becomes “self-sustaining”
- Subcritical – one fission leads to less than one fission
- Critical – one fission leads to one fission
- Supercritical – one fission leads to more than one fission
- Enrichment – For example, increasing ^{235}U relative to ^{238}U



Nuclear Fusion

- **The lightest nuclei can fuse to form heavier nuclei, releasing energy in the process.**
- Go to the other end of the scale
- Put small nuclei together to form bigger ones and also releasing energy

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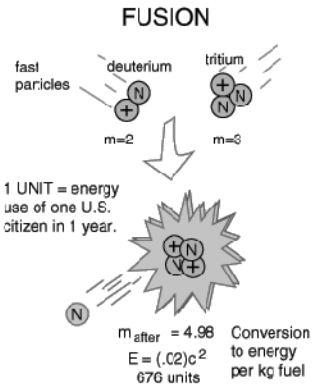
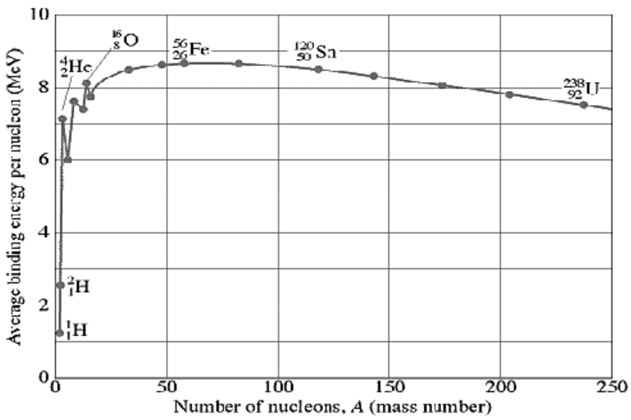
Nuclear Fusion

- Fusion – The combining of light nuclei into a heavier, more-tightly bound, pieces
- *What is the challenge in inducing fusion?*
- Energy mechanism of Sun – Sun converts
- H→ He→ Li→ Be→ B→ …→Fe



Nuclear Fusion



Nuclear Fusion

- Powers the sun and stars with various cycles leading to iron

$$p+p\to d+e^{+}+\nu$$

$$p+d\to {}_{2}^{3}He+\gamma$$

$${}_{2}^{3}He+{}_{2}^{3}He\to {}_{2}^{4}He+p+p$$

$$4p\to {}_{2}^{4}He+2e^{+}+2\nu+2\gamma$$

Counting positron-electron annihilation the net energy output is 26.7 MeV. Not as much as fission, but per kg of fuel a much bigger yield.

Nuclear Fusion

- **The sequence of fusion processes that change hydrogen into helium in the Sun. They are listed here :**

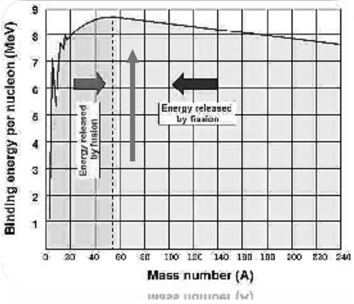
$${}_{1}^{1}H + {}_{1}^{1}H \to {}_{1}^{2}H + e^{+} + \nu$$

$${}_{1}^{1}H + {}_{1}^{2}H \to {}_{2}^{3}He + \gamma$$

$${}_{2}^{3}He + {}_{2}^{3}He \to {}_{2}^{4}He + {}_{1}^{1}H + {}_{1}^{1}H$$

Fusion

- In a nuclear fusion reaction, two lesser nuclei combine to make a heavier one. The nuclei again go from loose binding to tight. The slope is much higher – so the energy released is much greater!



Note the scale: 0 to 9 MeV. Mass of a nucleon is about 932 MeV, so even in a fusion reaction only a fraction of one percent of the total mass is converted to energy

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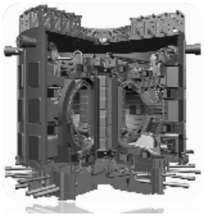
Fusion: endless supply of energy. Just not quite available yet.

- Fusion energy comes from very mundane everyday stuff. Like water. Typical fusion reaction: $^{2}D + ^{2}D \to ^{4}He$

(here ^{2}D is deuterium, heavy isotope of hydrogen. It is found naturally; about 1% of water is “heavy”.)

- However, *controlled* fusion is still an elusive goal. The uncontrolled version of fusion exists in the form of hydrogen bomb.

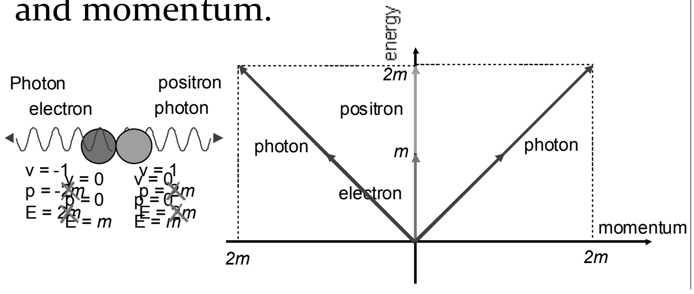


Annihilation: all mass goes into energy

- Annihilation is an interaction between a particle and its own antiparticle. Result of annihilation is electromagnetic radiation – photons.
- Simple example: an electron and a positron, both at rest (nearly), annihilate. How many photons come out?
- One big photon? Or many small ones? Conservation of energy-momentum helps us answer this question…

Energy-momentum diagram for annihilation

- Before annihilation: two particles of mass *m* each, at rest, so: $p = 0$, $E = 2m$
- After: photon(s) of mass 0, equal energy and momentum.



Annihilation: all mass goes into energy - 2

- Annihilation is a very simple, but by no means the only possible outcome of a particle-antiparticle collision. More exciting, and more interesting from the point of view of physics, are collisions that produce new *massive* particles.
- Annihilation may be a source of energy (even more efficient than fusion – 100% of mass goes into energy), but we first need a source of antimatter.

Mass production of antimatter

- Antihydrogen can be made by combining antiprotons (the nucleus) and positrons (the "electron"). Other anti-elements are much harder to make: first, the anti-nucleus must be formed our of antiprotons and antineutrons, a very difficult process.
- Two experiments at CERN are trying to make antihydrogen in large quantities (thousands to millions of anti-atoms).

Uses of antimatter

- Antihydrogen is of interest to physicists who look for violation of certain symmetries. Hydrogen atom has been measured to an unbelievable precision; if we can now do spectroscopy on antihydrogen to a precision that is anywhere near that, small deviations can be discovered that lead to new understanding of laws of Nature. To make such high-precision measurements, many antihydrogen atoms are needed, millions or more.
- Curious fact: when NASA learned about antihydrogen production experiments, they immediately asked if CERN could send them 1 mg of antihydrogen in a bottle. Well, magnetic bottle. Still how many atoms is that? 1 gram of hydrogen (or antihydrogen) is about 6 x 1023 atoms, so 1 milligram is about 6 x 1020 atoms – a far cry from what is possible.

Special Applications

- A specific isotope of a radioactive element is called a **radioisotope**.
- Radioisotopes are produced for useful purposes by different methods:
  1) By particle accelerators as reaction products
  2) In nuclear reactors as fission fragments or decay products
  3) In nuclear reactors using neutron activation
- An important area of applications is the search for a very small concentration of a particular element, called a *trace* element.
- Trace elements are used in detecting minute quantities of trace elements for forensic science and environmental purposes.

Medicine

- Over 1100 radioisotopes are available for clinical use.
- Radioisotopes are used in **tomography**, a technique for displaying images of practically any part of the body to look for abnormal physical shapes or for testing functional characteristics of organs. By using detectors (either surrounding the body or rotating around the body) together with computers, three-dimensional images of the body can be obtained.
- They use single-photon emission computed tomography, positron emission tomography, and magnetic resonance imaging.

Archaeology

- Investigators can now measure a large number of trace elements in many ancient specimens and then compare the results with the concentrations of components having the same origin.
- Radioactive dating indicates that humans had a settlement near Clovis, New Mexico 12,000 years ago. Several claims have surfaced in the past few years, especially from South America, that dispute this earliest finding, but no conclusive proof has been confirmed.
- The Chauvet Cave, discovered in France in 1995, is one of the most important archaeological finds in decades. More than 300 paintings and engravings and many traces of human activity, including hearths, flintstones, and footprints, were found. These works are believed, from ^{14}C radioactive dating, to be from the Paleolithic era, some 32,000 years ago.

Art

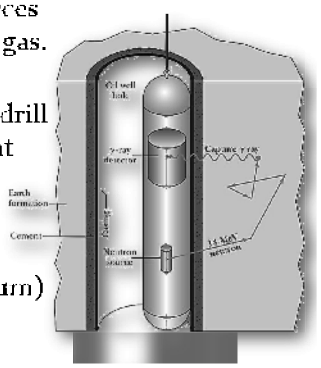
- **Neutron activation** is a nondestructive technique that is becoming more widely used to examine oil paintings. A thermal neutron beam from a nuclear reactor is spread broadly and evenly over the painting. Several elements within the painting become radioactive. X-ray films sensitive to beta emissions from the radioactive nuclei are subsequently placed next to the painting for varying lengths of time. This method is called an *autoradiograph*.
- It was used to examine Van Dyck's *Saint Rosalie Interceding for the Plague-Stricken of Palermo*, from the New York Metropolitan Museum of Art collection and revealed an over-painted self-portrait of Van Dyck himself.

Crime Detection

- The examination of gunshots by measuring trace amounts of barium and antimony from the gunpowder has proven to be 100 to 1000 times more sensitive than looking for the residue itself.
- Scientists are also able to detect toxic elements in hair by neutron activation analysis.

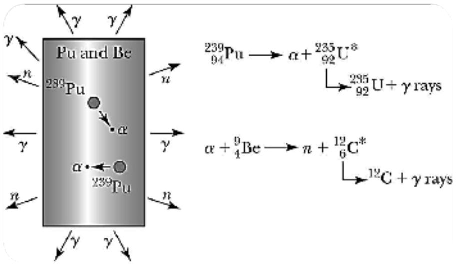
Mining and Oil

- Geologists and petroleum engineers use radioactive sources routinely to search for oil and gas.
- A source and detector are inserted down an exploratory drill hole to examine the material at different depths.
- Neutron sources called PuBe (plutonium and beryllium) or AmBe (americium and beryllium) are particularly useful.



Mining and Oil

- The neutrons activate nuclei in the material surrounding the borehole, and these nuclei produce gamma decays characteristic of the particular element.

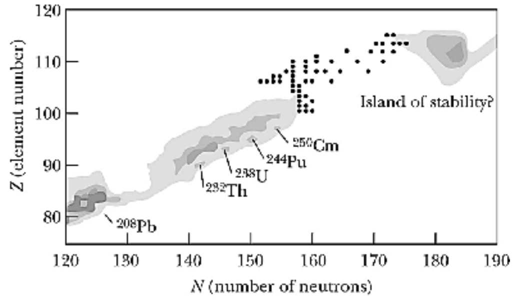


Small Power Systems

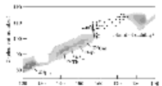
- Alpha-emitting radioactive sources have been used as power sources in heart pacemakers.
- Smoke detectors use ^{241}Am sources of alpha particles as current generators. The scattering of the alpha particles by the smoke particles reduces the current flowing to a sensitive solid-state device, which results in an alarm.
- Spacecraft have been powered by radioisotope generators (RTGs) since the early 1960s.

New Elements

- No **transuranic** elements—those with atomic number greater than $Z = 92$ (uranium)—are found in nature because of their short half-lives.



New Elements

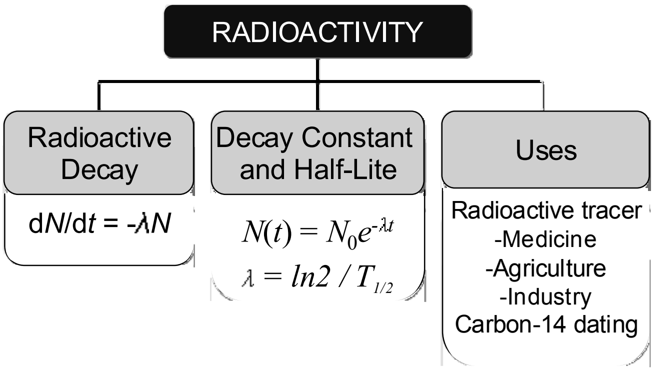


- Reactors and especially accelerators have been able to produce 22 of these new elements up to $Z = 116$.
- Over 150 new isotopes heavier than uranium have been discovered.
- Physicists have reasons to suspect from shell model calculations that superheavy elements with atomic numbers of 110–120 and 184 neutrons may be particularly long-lived.

Summary

- Nuclues:
  - Atomic number & Mass number: $_Z^AX$
  - Mass defect
    - $\Delta m = [Z_{mp} + (A - Z)_{mn}] - M_N$
  - Binding Energy
    - E_B = (mass defect) X c^2
  - Discovery of Neutrons
  - Isotopes
  - Mass Spectrometry
    - Selected velocity, $v = E/B$
    - In magnetic field, $qvB = mv^2/r$

Summary



RADIOACTIVITY

Radioactive Decay

$dN/dt = -\lambda N$

Decay Constant and Half-Lite

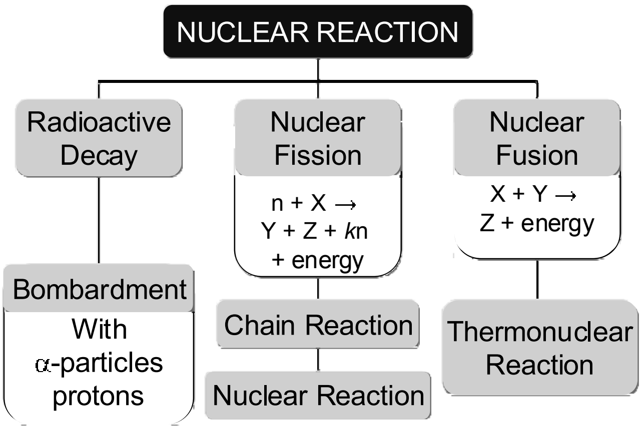
$N(t) = N_0 e^{-\lambda t}$

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

Uses

Radioactive tracer
-Medicine
-Agriculture
-Industry
Carbon-14 dating

Summary



NUCLEAR REACTION

Radioactive Decay

Bombardment

With
α-particles
protons

Nuclear Fission

$n + X \rightarrow$
$Y + Z + kn$
$+ \text{energy}$

Chain Reaction

Nuclear Reaction

Nuclear Fusion

$X + Y \rightarrow$
$Z + \text{energy}$

Thermonuclear Reaction

End of Chapter