PEN205
MODERN PHYSICS

Nuclear Structure and Radioactivity -II

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Radioactivity

Radioactivity (radioactive decay, radioactive disintegration, nuclear disintegration) is the process by which an unstable atomic nucleus loses energy by radiation.
A material containing unstable nuclei is considered **radioactive**.

Nobel price in 1903

Marie Curie (1867-1934)

M. Curie

http://tr.wikipedia.org/wiki/Marie_Curie

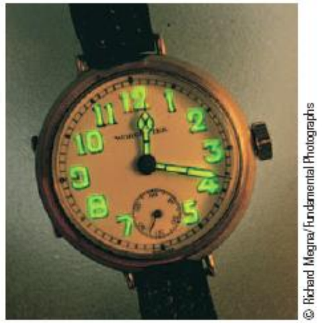
- **Becquerel (1896)**
  - Accidentally discovered that uranium salt crystals emit an invisible radiation that can darken a photographic plate even if the plate is covered to exclude light.
  - He concluded that the radiation emitted by the crystals was of a new type, one requiring no external stimulation.
- **Marie and Pierre Curie**
  - After several years of careful and laborious chemical separation processes on tons of pitchblende, a radioactive ore, the Curies reported the discovery of two previously unknown elements, both of which were radioactive.
  - These were named polonium and radium.
  - They discovered that radioactivity was the result of the decay, or disintegration of unstable nuclei.

http://tr.wikipedia.org/wiki/Henri_Becquerel

Henri Becquerel
1852-1903

http://tr.wikipedia.org/wiki/Henri_Becquerel

Becquerel's photographic film showing radioactivity emitted from uranium salt



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The hands and numbers of this luminous watch contain minute amounts of radium salt. The radioactive decay of radium causes the phosphors to glow in the dark.

Types of radiation emitted by a radioactive substance

Alpha (α) particles

- The emitted particles are ^{4}He nuclei
- Alpha particles barely penetrate a sheet of paper

Beta (β) particles

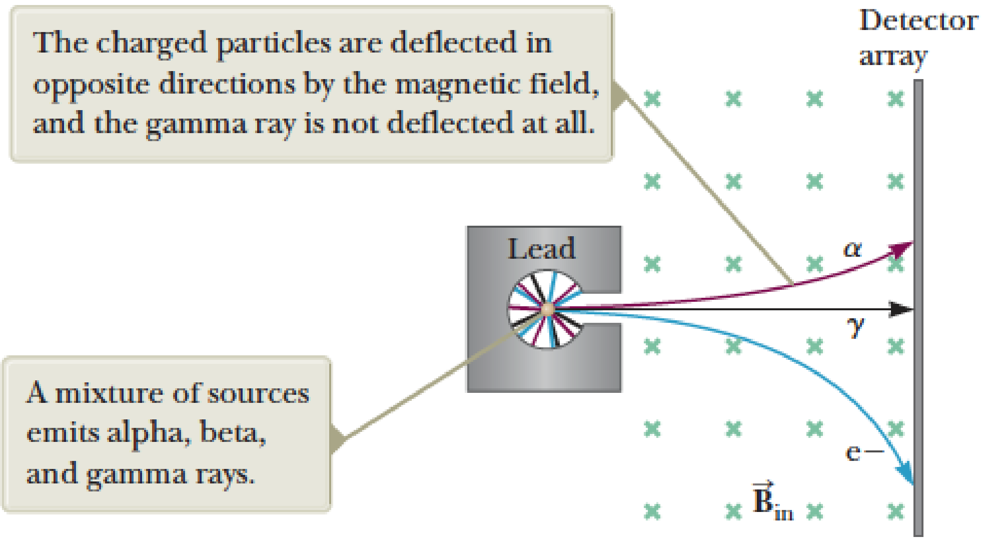
- The emitted particles are either electrons (e$^-$) or positrons (e$^+$)

(The positron is the antiparticle of the electron)

- Beta particles can penetrate a few millimeters of aluminum

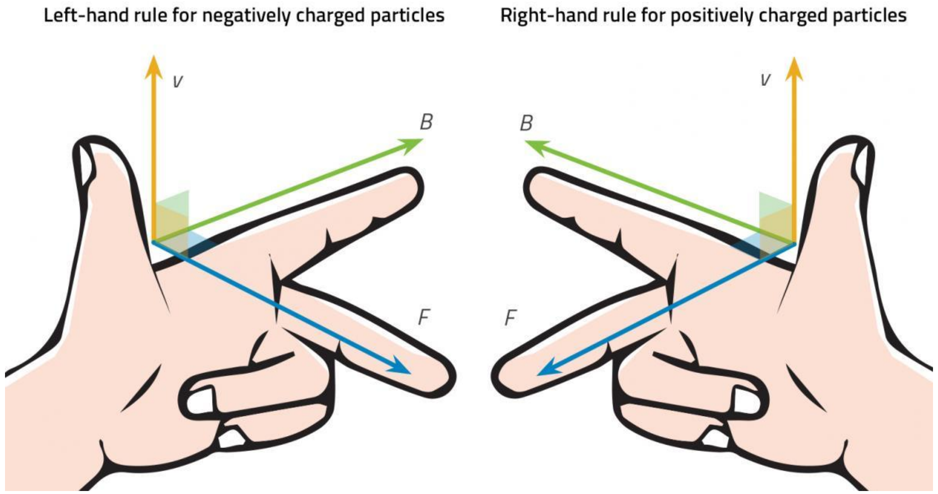
Gamma (γ) particles

- The emitted “rays” are high-energy photons.
- Gamma rays can penetrate several centimeters of lead.


The charged particles are deflected in opposite directions by the magnetic field, and the gamma ray is not deflected at all.

A mixture of sources emits alpha, beta, and gamma rays.

The radiation from radioactive sources can be separated into three components by using a magnetic field to deflect the charged particles. The detector array at the right records the events.


Left-hand rule for negatively charged particles

Right-hand rule for positively charged particles

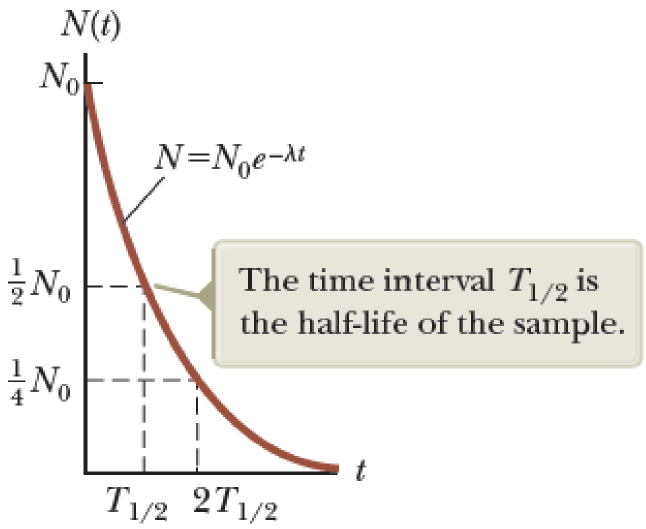
- The decay process is probabilistic in nature and can be described with statistical calculations for a radioactive substance of macroscopic size containing a large number of radioactive nuclei.

- The rate at which a particular decay process occurs in a sample is proportional to the number of radioactive nuclei present (that is, the number of nuclei that have not yet decayed).

If N is the number of undecayed radioactive nuclei present at some instant, the rate of change of N with time is:

$$\frac{dN}{dt} = -\lambda N \longrightarrow N = N_0 e^{-\lambda t}$$

N : number of radioactive nuclei at a given time
λ : decay constant
N_0 : number of radioactive nuclei at t_0 time



The time interval $T_{1/2}$ is the half-life of the sample.

Exponential decay of radioactive nuclei

The decay rate (R): the number of decays per second → activity

$$R = \left|\frac{dN}{dt}\right| = \lambda N = \lambda N_0 e^{-\lambda t} = R_0 e^{-\lambda t}$$

Half-life of a radioactive substance: time interval during which half of a given number of radioactive nuclei decay.

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

The Units of Activity (R)

The unit of activity *R* is the **curie** (Ci), defined as the activity of 1 g of radium.

$\boxed{1\text{Ci}= 3{,}7\text{x}10^{10}\ \text{decay / s}}$

The SI unit of activity is the **becquerel** (Bq):

$\boxed{1\ \text{Bq}= 1\ \text{decay / s}}$

$\boxed{1\text{Ci}= 3{,}7\text{x}10^{10}\ \text{Bq}}$

Example: Carbon-14 is a radioactive isotop of Carbon with 5730 years half-life. Find the remaining number of nuclei of 1000 carbon-14 nuclei after 22920 years?

1 $T_{1/2}$ (5720 years) later→ *N/2=500* nuclei left.

2 $T_{1/2}$ (11460 years) later → *N/4=250* nuclei left.

3 $T_{1/2}$ (17190 years) later → *N/8 = 125* nuclei left.

4 $T_{1/2}$ (22920 years) later → *N/16 = 62* nuclei left.

Example: The half-life of the radioactive nucleus is 1,6x103 years. What is the decay constant (λ) of this nucleus?

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

$T_{1/2}=(1{,}6\text{x}10^3\ \text{yr})(365\ \text{dy/yr})(24\ \text{hr/dy})(60\ \text{min/hr})(60\ \text{s/min})$

$T_{1/2}=5\text{x}10^{10}\ \text{s}$

$$\lambda = \frac{0{,}693}{T_{1/2}} = \frac{0{,}693}{5\times10^{10}} = 1{,}4\times10^{-11}\quad \text{s}^{-1}$$

Decay Processes

A radioactive nucleus spontaneously decays by one of three processes: alpha decay, beta decay, or gamma decay.

Alpha Decay

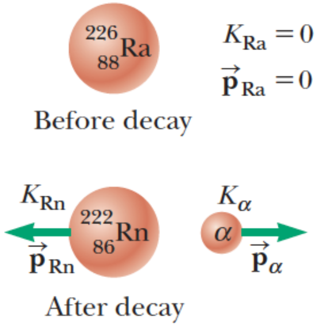
A nucleus emitting an alpha particle ${}^{4}_{2}He$ loses two protons and two neutrons. →

the atomic number Z → decreases by 2
the mass number A → decreases by 4
the neutron number N → decreases by 2

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

parent nucleus

daughter nucleus



As a general rule in any decay expression;

(1) the sum of the mass numbers A must be the same on both sides of the decay.

(2) the sum of the atomic numbers Z must be the same on both sides of the decay.

${}^{238}_{92}\mathrm{U} \rightarrow {}^{234}_{90}\mathrm{Th} + {}^{4}_{2}\mathrm{He}$ → $T_{1/2}$= 4,47x10^9 years

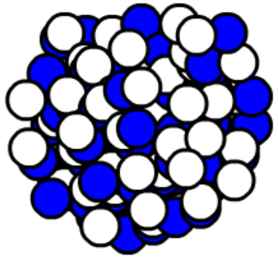
${}^{226}_{88}\mathrm{Ra} \rightarrow {}^{222}_{86}\mathrm{Rn} + {}^{4}_{2}\mathrm{He}$ → $T_{1/2}$= 1,6x10^3 years

Alpha Decay of U-238

Decay energy Q:

$$\boxed{\underset{\downarrow \atop \text{Joule}}{Q} = (\underset{\downarrow \atop \text{kg}}{M_X} - M_Y - M_\alpha)\underset{\downarrow \atop 3\text{x}10^8\ m/s}{C^2}}$$

$$\boxed{Q = (M_X - M_Y - M_\alpha) \times 931{,}494 MeV/u}$$



$^{238}_{92}\mathrm{U}$

$$^{238}_{92}\mathrm{U} \longrightarrow {}^{234}_{90}\mathrm{Th} + {}^{4}_{2}\mathrm{He}$$

- Q is the amount of rest energy transformed and appears in the form of kinetic energy in the daughter nucleus and the alpha particle
- Most of the kinetic energy is carried away by the alpha particle because it is much less massive than the daughter nucleus.
- For spontaneous emission →Q>0
- Emitting alpha particle from nuclei takes place with quantum mechanical tunneling.
- Alpha particles can penetrate only a few mm into aluminum plate. Therefore, they can be stopped easily.

Beta Decay

- When a radioactive nucleus undergoes β decay, either electron (β^-), or it's antiparticle positron (β^+) is emitted.
- In a β decay, the daughter nucleus has the same number of nucleons as the parent nucleus, but the atomic number is changed by 1.

$$\underbrace{\begin{array}{l} {}^{A}_{Z}\mathrm{X} \;\rightarrow\; {}^{\;\;A}_{Z+1}\mathrm{Y} + \mathrm{e}^{-} \\ {}^{A}_{Z}\mathrm{X} \;\rightarrow\; {}^{\;\;A}_{Z-1}\mathrm{Y} + \mathrm{e}^{+} \end{array}}_{\text{(incomplete expression)}}$$

→ electron (β-) decay

→ positron (β+) decay

$$\Longrightarrow$$

$$\underbrace{\begin{array}{l} {}^{A}_{Z}\mathrm{X} \;\rightarrow\; {}^{\;\;A}_{Z+1}\mathrm{Y} + \mathrm{e}^{-} + \bar{\nu} \\ {}^{A}_{Z}\mathrm{X} \;\rightarrow\; {}^{\;\;A}_{Z-1}\mathrm{Y} + \mathrm{e}^{+} + \nu \end{array}}_{\text{(complete expression)}}$$

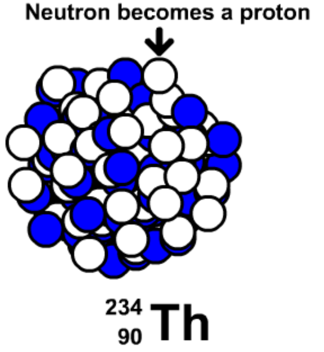
→ antineutrino

→ neutrino

Emitted electron is created in the nucleus by a process in which a neutron is transformed into a proton → $\boxed{\mathrm{n} \;\rightarrow\; p + e^{-} + \bar{\nu}}$

A similar process occurs in e^+ decay → $\boxed{{}^{1}_{1}\mathrm{p} \longrightarrow {}^{1}_{0}\mathrm{n} + \mathrm{e}^{+}}$

Beta Decay of Th-234



$${}^{234}_{90}\mathrm{Th} \longrightarrow {}^{234}_{91}\mathrm{Pa} + {}^{0}_{-1}\mathrm{e}$$

electron capture (K capture) → A process that competes with e^+ decay..

occurs when a parent nucleus captures one of its own orbital electrons and emits a neutrino.

The final product after decay is a nucleus whose charge is Z – 1.

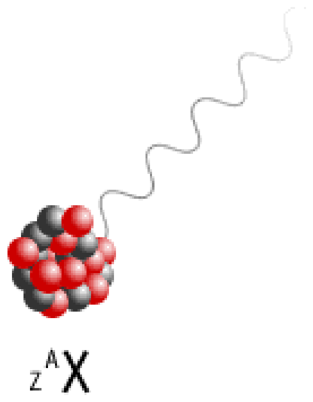
$${}^{A}_{Z}\mathrm{X} + {}^{\;\,0}_{-1}\mathrm{e} \;\rightarrow\; {}^{\;\;A}_{Z-1}\mathrm{Y} + \nu$$

Gamma Decay

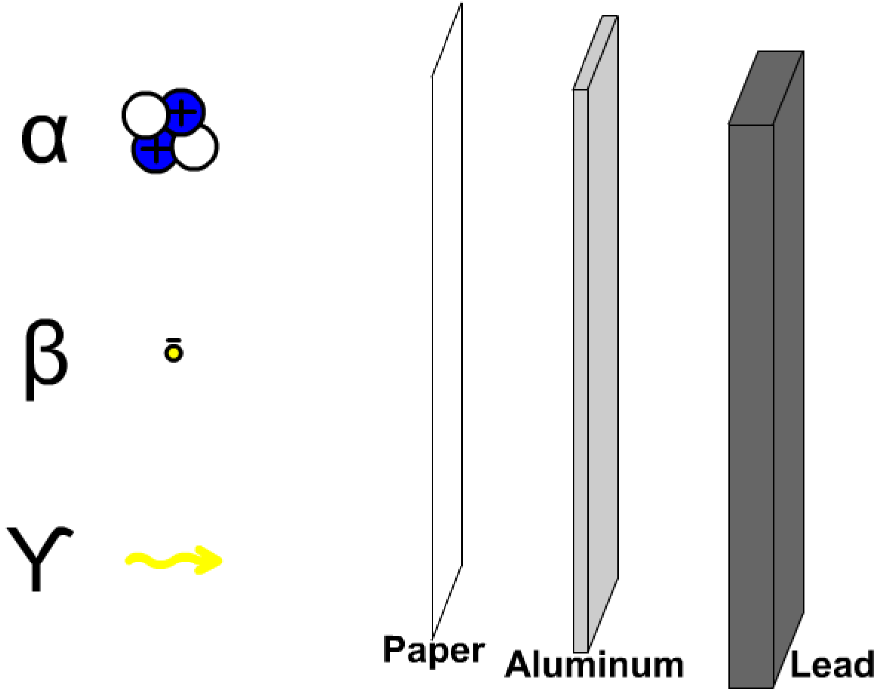
- Very often a nucleus that undergoes radioactive decay is left in an excited energy state.
- The nucleus can then undergo a second decay to a lower energy state—perhaps even to the ground state—by emitting one or more high-energy photons.
- The photons emitted in the process are called **gamma rays**, which have very high energy relative to the energy of visible light.

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

nucleus in an excited state



Gamma (γ) decay



- HOMEWORK:

- Study the problems for Decay Processes

- Prepare a homework for Practical Uses of Radioactivity