Radioactivity

szerző: PGY

Other modes of emission

Spillation - S

High energy decomposition of a nucleus

A cascade of small particle emissions occurs.

Literally - the atom falls apart.

Discovery of radioactivity

Becquerel - 1896

Studied phosphoresence of uranium salts.

He felt that X-rays were produced when the salts were exposed to sunlight.

This would have been the first reported example of higher energy being produced by fluorescence.

Discovery of radioactivity

Due to poor weather conditions, an experiment that he had started could not be completed.

The partially 'exposed' plate and salt were placed in a drawer so that the experiment could be completed at a later time.

When he later remembered about the plate, he decided to develop it and get what information he could.

Discovery of radioactivity

The exposed plate had an even more intense image that those exposed for long periods to sunlight.

He studied this effect under a number of conditions and discovered that:

No exposure to sunlight was required to obtain an image on the film.

The uranium salt could discharge an electroscope, even when there was no direct contact.

The Curies

The Curies, 1898

Marie Curie first used the term 'radioactivity.'

She noted that thorium could emit rays similar to uranium and that some uranium ores were more radioactive than uranium.

She 'conned' the Austrian government to donate a ton of depleted pitchblende for here to study. (uranium ore - 75% U_3O_8)

The Curies

Using a qual scheme and an electroscope, the Curies spent four years isolating the radioactive components.

These components were found in two fractions.

Fraction 1 - mostly barium

Fraction 2 - mostly bismuth

Each fraction contained a 'new' radioactive element.

The Curies

A third element was isolated byDebinerne (an associate of the Curies).

He had discovered actinium which was present at 1 part per 10^{10} in pitchblende.

Radium became quite popular.

Used to paint watch faces & roulette balls.

Radium Cocktails.

The radium isolated by the Curies still exists.

Nature of the radiations

The Curies, J.J. Thomson and others knew that radiation could

- Discharge an electroscope by ionization of the surrounding air - producing a measurable current.
- Expose a photographic plate.

Studies of radiation increased our understanding of radioactivity and nature of the atom.

Rutherford - 1898

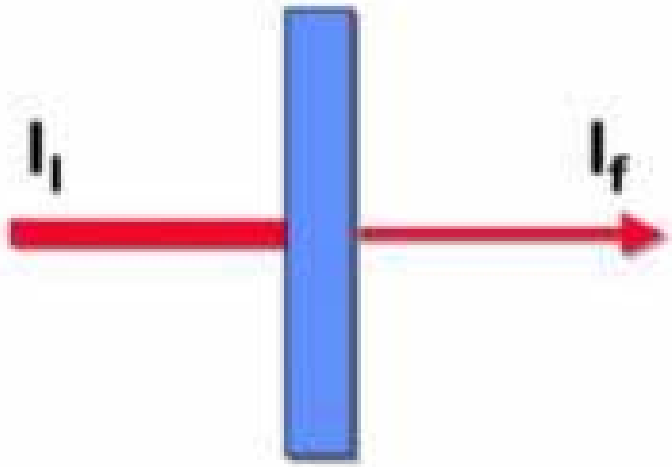
Studies the properties of the rays produced by radioactive elements.

Using metal foils to measure radiation absorption, he discovered two components:

- One could be stopped by a thin film of Al - call alpha radiation, discoveredfirstst.
- The other required a film about 100 times thicker - called beta radiation, discovered second.

Rutherford

He determined that the ionization effect was reduced as a function of absorber thickness.



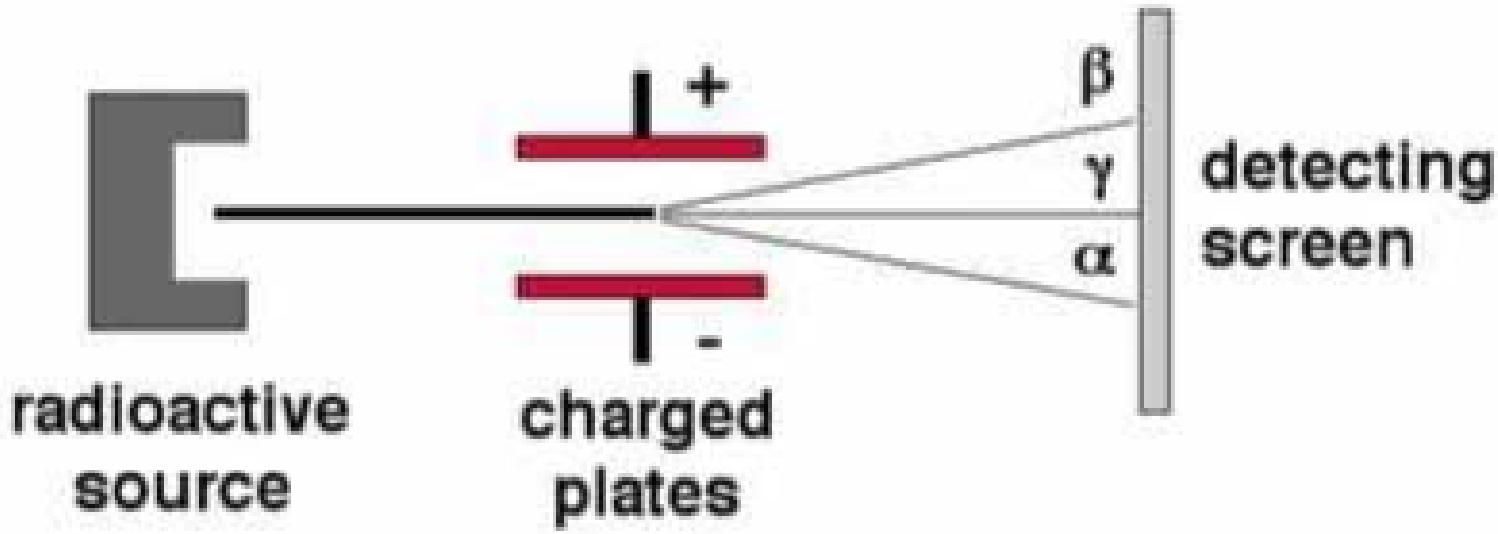
$I_f = I_I e^{-ud}$

d - absorbent thickness
u - absorption coefficient

u was found to increase with increasing atomic number - a significant property.

Later studies

Electrostatic and magnetic deflection studies led to a better understanding of the types of radiation.



Later studies

- Beta rays were considered to be electrons moving near the speed of light.
- Alpha rays were much for massive that beta.
  - found to be He^{2+} moving at about 0.1 C.
  - helium was found in association with uranium and thorium ores.
- A third, more penetrating radiation (gamma) was discovered that was unaffected by electrostatic or magnetic fields.

Radioactive decay

Rutherford and Soddy Transform Hypothesis (1900).

- It was noted that erratic electrometer readings were obtained when working with thorium and radium salts.
- The effect was studied by diffusion of an inert gas into a counting tube in the presence of these species.

Radioactive decay

It was observed that:

- The activity of a radioactive substance did not continue for ever. It diminished with a time scale characteristic of the substance.
- Radioactive process were accompanied by a change in the chemical properties of the active atoms.

Remember - there was no clear concept of the nucleus at this point.

Radioactive decay

E. Von Schweidler, 1905

Used the concept of disintegration to explain the changes in radioactivity.

Assumptions.

The probability (p) of a disintegration in a known time interval (dt) was independent of past history.

p depended only on dt.

Radioactive decay

For small time periods:

$$p = \lambda \Delta t$$

where:

λ = a proportionality constant for a specific radioactive species.

The probability of an atom not disintegrating would be:

$$1 - p = 1 = \lambda \Delta t$$

Radioactive decay

The probability of an atom surviving n time periods would be:

$$1 - p = (1 - \lambda \Delta t)^n$$

Since the total time (t) = n Δt, the probability of an atom remaining unchanged after time t would be:

$$1 - p = e^{-\lambda t}$$

Radioactive decay

If we consider a large initial number of atoms, we can determine the fraction remaining unchanged after a know time period by

$$\frac{N_t}{N_0} = e^{-\lambda t}$$

where

N_0 - initial number of atoms

N_t - atoms remaining at time t

So decay is an exponential process.

Radioactive decay

We can also recognize radioactive decay as a first order rate expression where"

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

By integration, we obtain:

$$\ln N = -\lambda t + a$$

When t =0, a = $\ln(N_0)$ so:

$$\ln(N/N_0) = \lambda t$$

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

Radioactive decay

The decay constant (λ) is dependent on the specific radioactive species.

- It is one significant characteristic of a radioactive isotope.
- We commonly use a modified form of this constant - $t_{1/2}$
- The time required for a specific radioactive species to decay by 50%.

Radioactive decay

If $t = t_{1/2}$, $N = N_0/2$ so:

$$\ln(1/2) = -\lambda\, t_{1/2}$$

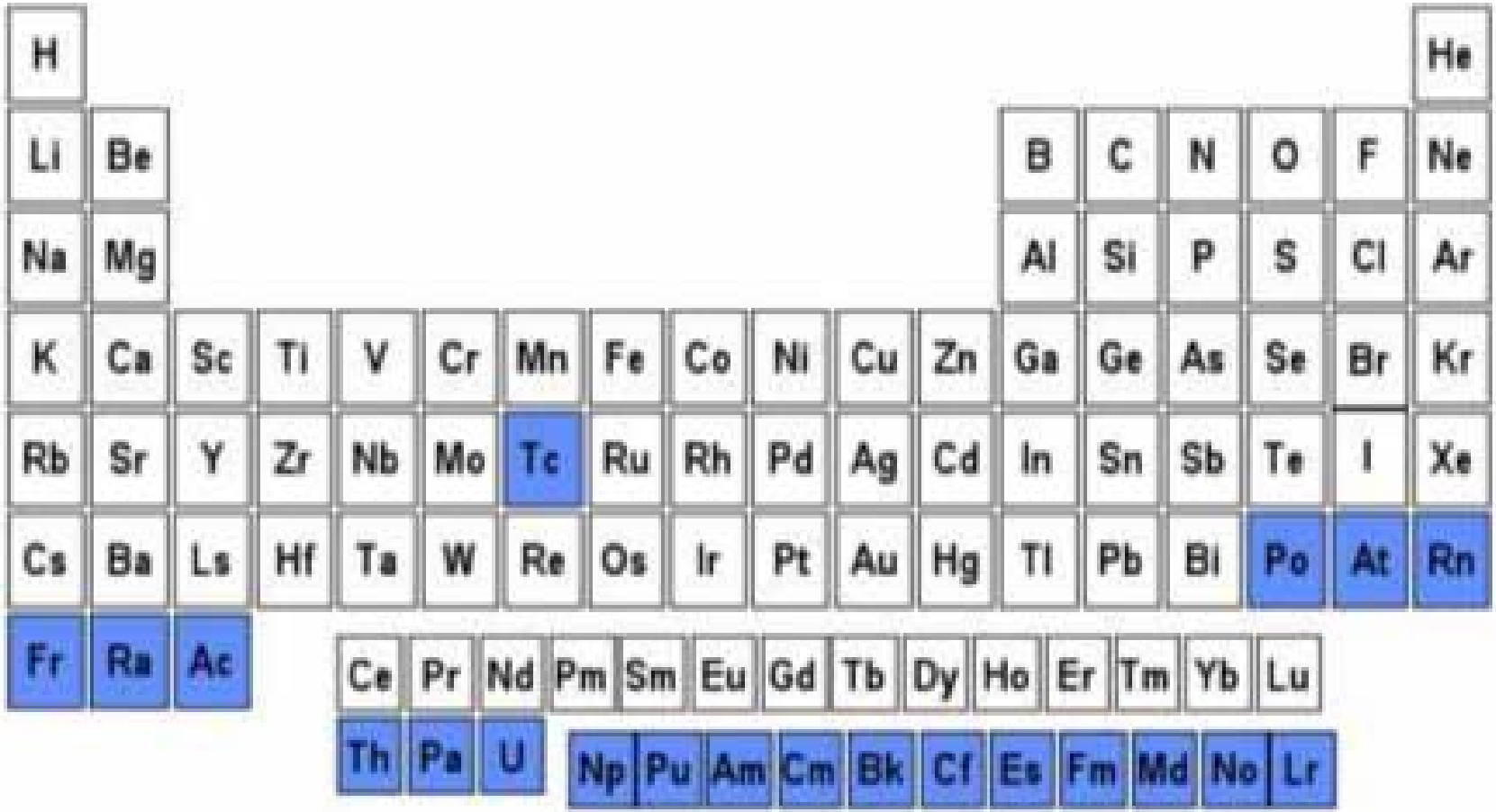
or

$$t_{1/2} = \ln(2) / \lambda = 0.693 / t$$

so

$$N = N_0\, e^{-0.693\, t / t_{1/2}}$$

The radioactive elements



Man made elements

The radioactive elements

All elements with X > 83 are radioactive.

Most elements with A $\geq$ 140 are also unstable but are considered as stable by chemists if its $t_{1/2}$ is $\geq 10^{12}$ years.

If A $\geq$ 200, the species are unstable with respect to spontaneous fission (SF).

Half-life values range from about 10^{21} seconds to over 10^{12} years.

Radioactive isotopes

Radioactive isotopes are known for all elements - either man-made or natural.

We use two formats to denote isotopes.

^{14}C	standard chemistry format
C-14	inline format

We will use both formats in this course.

Activity

In practice, we can't directly evaluate N or even dN/dt.

A useful approach is to determine activity.

Activity = disintegrations / unit time

or you can use

Activity = counts / unit time

If the detection method is not 100% but is proportional to the number of disintegrations.

Activity

Since activity is proportional to N, we can use the following relationships:

$$A = A_0 e^{-\lambda t}$$

or

$$A = A_0 e^{-0.693\, t / t_{1/2}}$$

This assumes that we are only measuring a single species. Decays from multiple sources can result in counting errors

Activity

Common units

dps	disintegrations per second
dpm	disintegrations per minute
Ci	Curie
	3.7×10^{10} dps
	2.22×10^{12} dpm

We commonly use μCi or mCi amounts in radioanalytical studies.

Radioactivity

A property of some nuclei in which they under go a transformation to a lower (more stable) energy state.

This is commonly observed by the spontaneous emission of particles and/or energy from a nucleus.

So why does it happen?

Reasons for a decay

Too many nucleons

Characterized by α emission.

Too many protons

β^+ emission or electron capture.

Too many neutrons

β^- emission.

Too much energy

Emission of a γ. Typically associated with other types of emission.

The common types of radioactive emissions

While there are many modes of radioactive emission, the three most common are α, β and γ.

These types of emission are the most common and most often used when developing analytical methods.

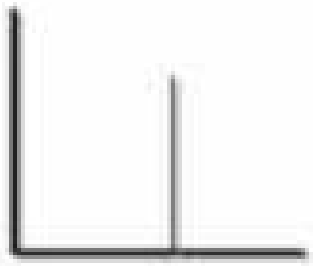
Lets review each.

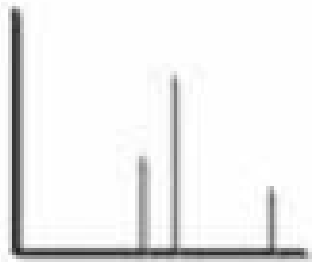
α - alpha radiation

$^{4}He^{2+}$ that is emitted monoenergetically or in a few monoenergetic groups.

Energy range: 1.5 - 11.7 Mev

(^{142}Ce ^{212m}Po)



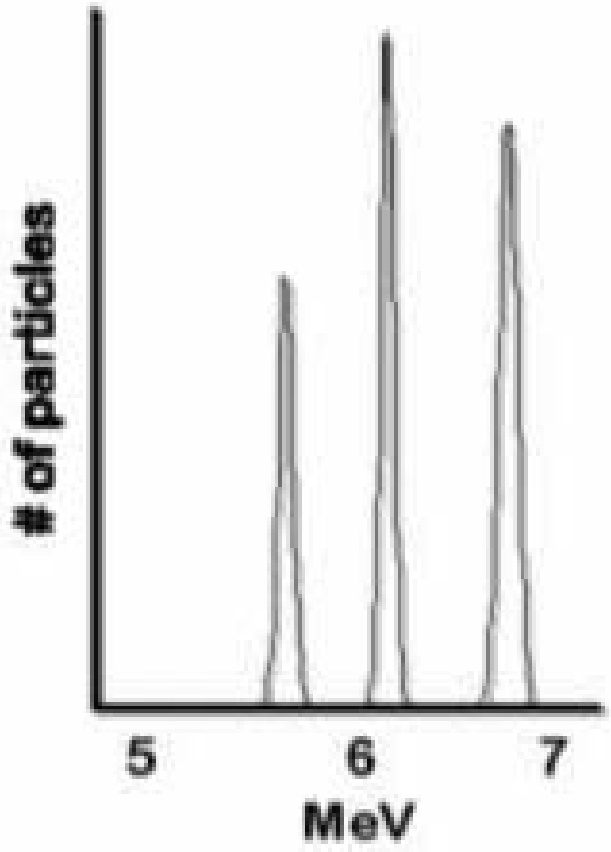


Note: 1 Mev = 1.6×10^{-7} j

α particles

Ideally, the energy spectrum should be simple lines.

Line 'widths' are observed because of the uncertainty principal and the methods used to measure the particles.



α particles

Geiger-Nuttall rule.

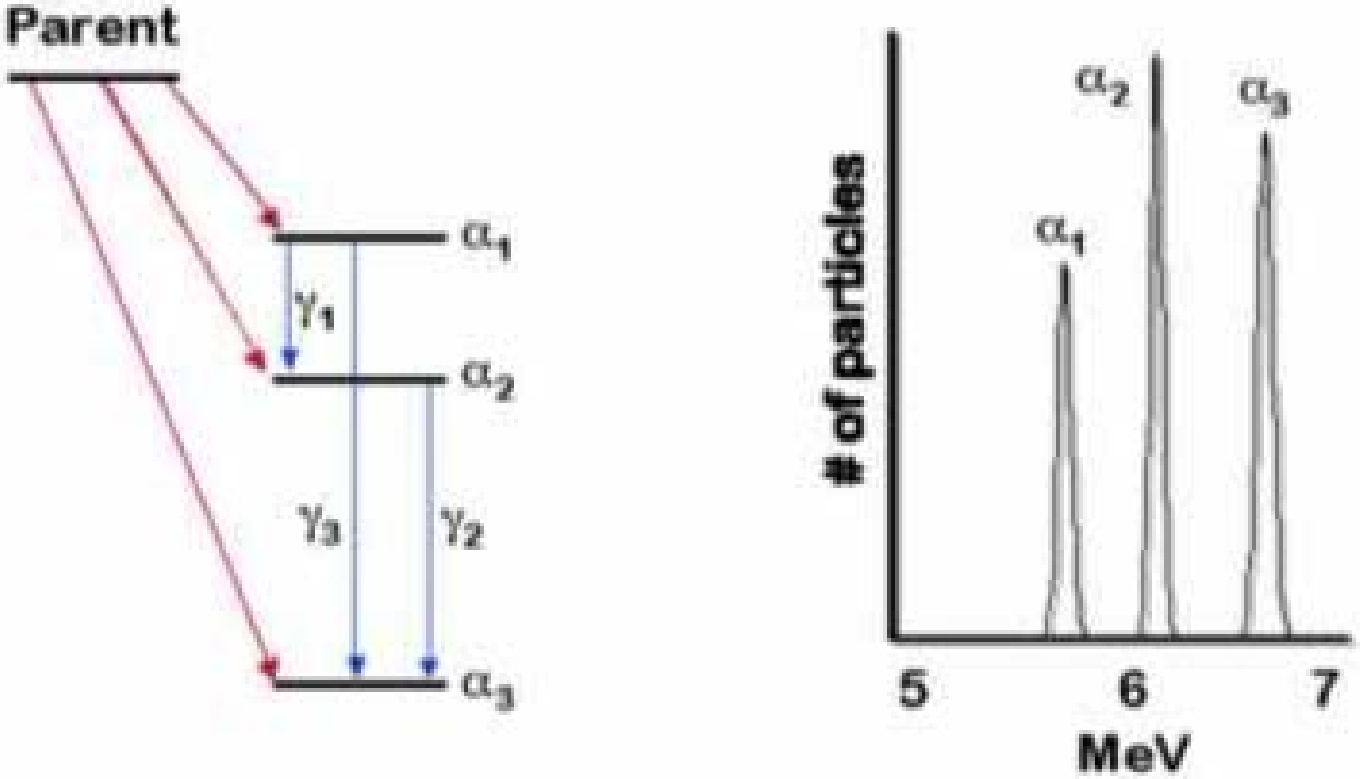
An inverse relationship is observed between the α energies and $t_{1/2}$.

$$\log t_{1/2} \propto (\log E_\alpha)^{-1}$$

So, isotopes with longer $t_{1/2}$ emit lower energy α.

Isotope	$t_{1/2}$	MeV α
Np-237	2.16×10^6 y	4.9
Am-243	7370 y	5.3
Cf-249	351 y	6.1
Es-254	275.7 d	6.5
Fm-253	3.00 d	7.1

α particles



Multiple lines will result if more than one route for α decay are possible - γ can also be emitted.

α particles

Recoil energy

- The energy of an a particle is no exactly equal to the total energy of the transition.
- To conserve momentum, some energy is imparted to the daughter nucleus.

$$E_{trans} = E\alpha + E_{recoil}$$

- E_{recoil} can be easily calculated based on kinetic energy and the law of conservation of momentum.

α particles

Recoil energy.

Kinetic energy $E = 0.5\ mv^2$

Momentum $p = mv$

Both the α and the daughter will have the same kinetic energy so:

$$E_{recoil} = (m_{\alpha} / m_{daughter})\ E_{\alpha}$$

It is then possible to determine the total energy for a transition.

α particles

Recoil energy.

Determine the recoil energy and the total transition energy for a 4.00 MeV α emitter that produces a daughter with a mass of 200.

E_{recoil} = (4/200)(4.00) = 0.08 MeV

E_{trans} = 4.00 MeV + 0.08 MeV = 4.08 MeV

Since α emitters (and their daughters) are typically large, the recoil energy is not an overly significant part of the total energy.

β - beta radiation

Emission occurs in three modes.

Negatron - β^-

- Electron emitted from nucleus.
- Typically emitted by neutron rich nuclei.
- Emission is in conjunction with an antineutrino (conserves momentum.)

$$X \longrightarrow Y + \beta^- + \bar{\nu}$$

β - beta radiation

Positron - β^+

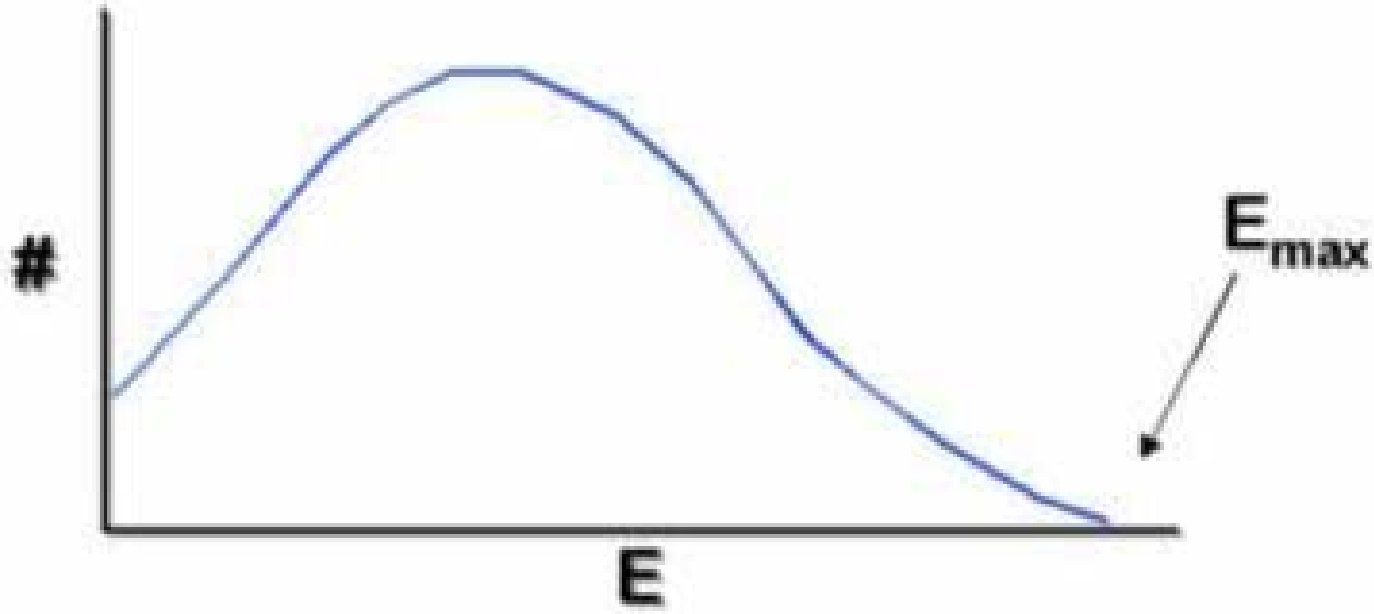
- e^+ emitted from nucleus.
- Typically emitted by proton rich nuclei.
- Emission is in conjunction with an neutrino (conserves momentum.)

$$X \longrightarrow Y + \beta^+ + \nu$$

β - beta radiation

β^+ and β^- are emitted over an energy range.

- Affected by the electrons around the atom.
- Exhibit a characteristic E_{max} value.



β - beta radiation

β^+ are not stable - antimatter.

β^+ and e^- will rapidly find each other and one of two things can happen.

$\beta^+ + e^- \longrightarrow 2\gamma$ (0.51 Mev)

Emitted in opposite directions to conserve momentum.

β^+ (slow) + $e^- \longrightarrow \gamma$ (1.02 Mev)

Much less common.

β - beta radiation

As you'll learn, the 0.51 Mev gamma is pretty common.

It represents the annihilation of a beta or electron.

It will not be very useful in identification of a nucleon.

β - beta radiation

Electron capture (EC)

A mode of decreasing Z while maintaining A. It competes with β^+ emission.

It is viewed as an electron being pulled into the nucleus from the K shell.

It is the preferred mode when the decay energy is $< 2mC^2$.

β - beta radiation

Electron capture

Nuclear emission is not typically observed after electron capture except when the atom is left in an excited state (metastable).

What you can see is an outer electron falling into the K shell 'hole', resulting in X-ray emission for the new element.

γ - gamma emission

A portion of the EM spectrum that overlaps the x-ray region.

0.1 - 10 MeV although > 5 MeV is rare.

Occurs along with α and β emission which may leave the atom in an excited state.

$$X \longrightarrow {}^{*}Y + \alpha \text{ or } \beta \longrightarrow Y + \gamma$$

γ - gamma emission

Typically, the γ emission is so fast that the $t_{1/2}$ can't be measured.

In some cases, it is slow enough to be measured (>10^{-14}sec) resulting in a metastable isotope which decays by internal transition (IT).

$^{107m}Ag \xrightarrow{IT,\ t1/2\ 44sec} {}^{107}Ag + \gamma\ (0.0931\ MeV)$

$^{105m}Rh \xrightarrow{IT,\ t1/2\ 38sec} {}^{105}Rh + \gamma\ (0.129\ MeV)$

γ - gamma emission

Gamma rays are emitted monoenergetically or occur as a few monoenergetic groups

Other modes of emission

Spontaneous Fission (SF)

SF an occur when A $\geq$ 100 since these nuclei have a negative binding energy with regards to fission.

Spontaneous fission is not observed unless A $\geq$ 232. In general, this mode of emission is rarely seen and the half-lives are long.

$$^{238}U \xrightarrow[t_{1/2} \sim 10^{16}\ \text{years}]{\text{SF}} 2\ \text{ff} + \text{energy}$$

Other modes of emission

Delayed-Neutron emission.

- Fission products are often neutron rich species that undergo β^- decay.
- After β^- decay, the nucleus is usually in an excited state and often followed by γ emission.
- In some cases, the daughter will emit a neutron.

Other modes of emission

Delayed - Neutron emission

Rare - only about 100 examples known.

Only observed for certain neutron rich, man-made isotopes.

Example ^{252}Cf

Used as a neutron source.

Other modes of emission

Delayed - Proton emission

- Similar to delayed neutron emission but occurs less frequently.
- Proton rich decay products - produced by charged particle bombardment.
- After bombardment, the particle will decay either by proton emission or positron decay.