Modes Of Decay

General information

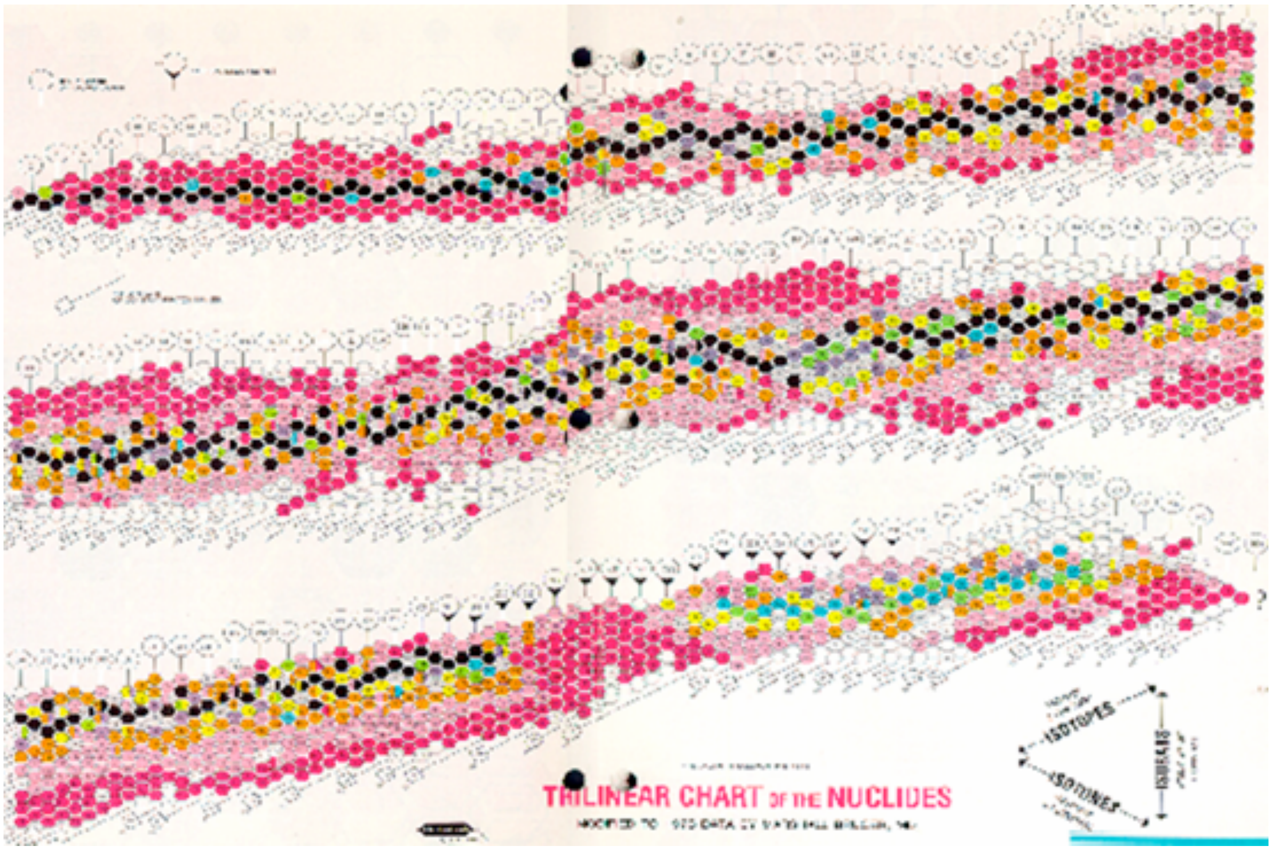
- Nuclei are composed of combinations of nucleons (protons and neutrons); certain combinations of these nucleons (i.e., certain nuclides) possess a high degree of stability while others are relatively unstable.

- Thus, one radioactive nuclide may have a high n/p ratio while for another the ratio may be low. A radionuclide may have an odd number of protons and an even number of neutrons, while for another the reverse may be true.

- Because radioactive nuclides do differ from one another in so many respects, it is not surprising, then, that various modes of decay are possible, depending upon the nature of the nuclide and the type of instability.

- Unstable nuclei are said to be radioactive because they emit radiation as they undergo spontaneous decay. This radiation is emitted either from the nucleus itself or as a result of alterations in the configuration of orbital electrons about it. The nature of this radiation is a function of the mode of decay of a particular nuclear species.

- There are approximately 3,000 known nuclides, approximately 8-10% of which are stable; the other ~90% is radioactive and only a very small percent of these isotopes occurs in nature. In the following diagram, the black dots represent stable isotopes; all other colors represent different half-lives; for example, red = seconds, pink = minutes, orange = hours, yellow = days, etc.



- Types of radiation resulting from radioactive decay can be summarized in a simple chart. Only X-rays, Auger electrons and internal conversion electrons arise from the outer orbitals; all other emissions are from the nucleus.
    - alpha particles
    - beta particles
        - positrons
        - negatrons
    - electromagnetic radiation γ-, X-rays
    - internal conversion electrons
    - Auger electrons

NUCLEAR STABILITY

Important Factors

- The neutron-to-proton ratio (n/p), the most stable ratio being that indicated by the stability curve
- Pairing of nucleons as indicated by the even-odd rules
- The binding energy, which is related to the mass defect and the packing fraction

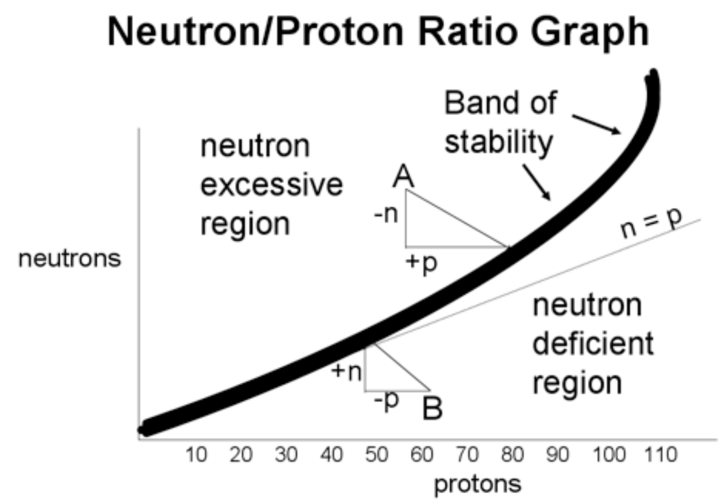
The Even-Odd Rules

- There is instability when there is an odd number of neutrons or protons in the nucleus
- Of the 300 stable nuclides, about 200 have both an even number of protons and neutrons.
- Only 4 stable nuclides exist having both an odd number of protons and neutrons, e.g., deuterium which has 1 proton and 1 neutron

The Even-Odd Rules

Example	# of p^+	# of n	stability
$_{8}O^{16}_{8}$	even	even	stable
$_{9}F^{18}_{9}$	odd	odd	unstable
$_{10}F^{19}_{9}$	odd	even	? Stability
$_{1}He^{3}_{2}$	even	odd	? Stability

Neutron/Proton Ratio Graph



1. If one plots the # of neutrons in the nucleus of a particular radionuclide vs the number of protons for the same nuclide for all three thousand known nuclides, the graph above will be obtained. The black band represents the “band of stability” and its edges are not as smooth as in the diagram. Any nuclide falling in the band of stability will be stable and therefore not radioactive.

2. Only about 8% of all known nuclides are stable; the remainder plot in a region above the curve known as the “neutron excessive region” or a region below the curve known as the “neutron deficient region”.

3. If a nuclide plots in the “neutron excessive region” represented by point A in the diagram, the implication is that it has too many neutrons per proton and, as reflected in the diagram, must lose a neutron and gain a proton to decrease the ratio and achieve stability. On the other hand, if a nuclide plots in the “neutron deficient region” represented by point B in the diagram, the implication is that it has too few neutrons per proton and, as reflected in the diagram, must lose a proton and gain a neutron to increase the ratio and achieve stability.

4. As indicated in the diagram, the curve is not linear but gently curves upward as a function of increased proton number, meaning that to achieve stability, the number of neutrons must increase at a somewhat greater rate than the number of protons. For example, for a Z number of 80, it might require 120 neutrons and 80 protons to achieve stability whereas for a Z number of 10, it would take 10 neutrons and 10 protons to achieve stability. These would represent n/p ratios of 1.5:1.0 and 1:0:1.0, respectively. In reality, the relationship is linear only through Z = 8, after which there are deviations. For example, F-18 has 9 neutrons and 9 protons, with a n/p ratio of 1:0:1.0, but it is radioactive.

DECAY BY α- PARTICLE EMISSION

The α-particle consists of 2 protons and 2 neutrons and is a relatively large particle. For a nucleus to be capable of releasing so large a particle, the nucleus must be relatively large itself. With few exceptions, nuclei which decay by α emission have a Z # >83

α-Emission: Decay of Rn^{222}

$$ {}_{136\;\,86}^{\quad\;222}\mathrm{Rn} \longrightarrow {}_{134\;\,84}^{\quad\;218}\mathrm{Po} + {}_{2\;\,2}^{\;\;4}\mathrm{He} $$

Note that both the Z and N numbers decrease by 2 while the mass number A decreases by 4.

n/p ratios for decay of Rn^{222}

$$ {}_{136\;\,86}^{\quad\;222}\mathrm{Rn} \longrightarrow {}_{134\;\,84}^{\quad\;218}\mathrm{Po} + {}_{2\;\,2}^{\;\;4}\mathrm{He} $$

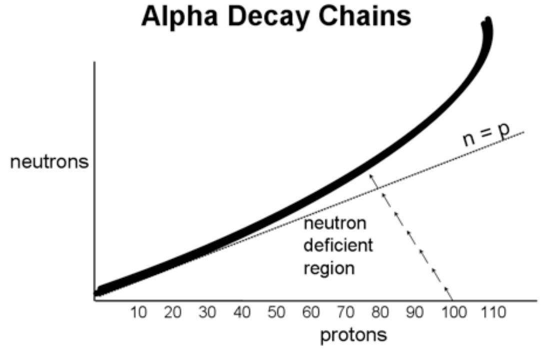
136/86 = 1.58 134/84 = 1.60

represents a 1.26% increase in n/p ratio

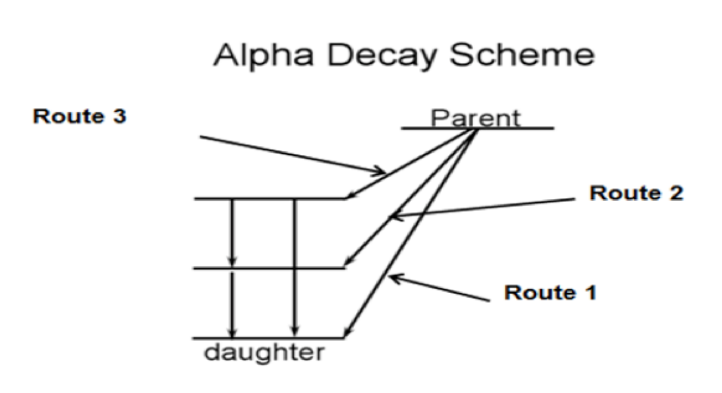
ALPHA DECAY CHAINS

- Many alpha-emitters decay from parent to daughter to granddaughter in chains that may have as many as 12 steps (refer to diagram below). Each represents a small increase in the n/p ratio so it takes multiple steps to achieve stability.

Neutron/Proton Ratio Graph: Alpha Decay Chains



- **A typical alpha-decay scheme is displayed below:**



- In the alpha decay scheme, there are three possible routes of decay from parent to ground state of the daughter; for all 3 routes, the only mode of decay is alpha.
- In Route 1, the decay is directly to the ground state. There is no excited or metastable state formed and no gamma rays are released.
- In Route 2, there is decay by alpha to a metastable state of the daughter, followed by emission of a gamma ray and transition to the ground state.
- In Route 3, there is alpha decay to a highly excited state of the daughter, followed by gamma ray emission either directly to the ground state or indirectly to the ground state through sequential emission of two separate gamma rays. Regardless of the route taken, the energy expended in transition from parent to daughter is a fixed amount.

ENERGY BALANCE

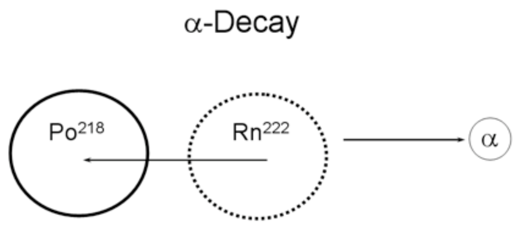
Although the total energy change for the decay of Rn-222 to Po-218 is 5.58 MeV, the energy of the alpha particle is only 5.48 MeV. The difference of 0.10 MeV is the recoil energy imparted to the newly formed Po218 nucleus. Assuming the validity of nonrelativistic mechanics, this recoil energy can be calculated:

$Mass_{alpha} \times Energy_{alpha} = Mass_{atom} \times Energy_{alpha}$

for Po-218, E_{recoil} is (4) (5.48) / 218= 0.101 MeV

α-particles from a specific nuclear transformation are monoenergetic.

ALPHA RECOIL REACTIONS



A Rn^{222} nucleus has decayed into a Po^{218} nucleus and an α-particle. The Po^{218} nucleus recoils when α- particle is ejected.

DECAY BY NEGATRON EMISSION

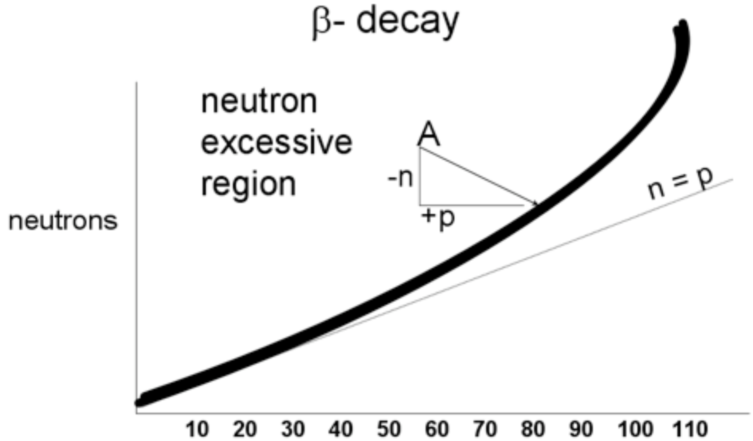
If the n/p ratio is too large, a β- particle may be emitted to establish greater nuclear stability. β- emission is the only mode of decay that takes place in the neutron excessive region (see diagram below). The paradoxical emission of an electron from a nucleus containing only protons and neutrons may be explained by the following particle reaction.

$$n^{1}_{0} \longrightarrow p^{1}_{1} + e^{0}_{-1} + \nu + E$$

The neutron is converted into a proton, which remains in the nucleus, increasing the Z number by 1 and decreasing the N number by 1. The electron is ejected along with a antineutrino, the two of which share E, the energy of transition. There is very little change in atomic mass since the mass of proton and neutron vary by less than 0.5% and the mass of the ejected electron is only 0.00005 of 1 atomic mass unit.

Neutron/Proton Ratio Graph

β- decay



GENERIC EQUATION FOR β^- DECAY

$$^{A}_{N\ Z}X \longrightarrow {}^{A}_{N-1\ \ Z+1}Y + {}^{0}_{-1}e + \nu + E$$

- Z has increased by 1
- N has decreased by 1
- A remains nominally the same. The n/p ratio decreases from N/Z to (N-1)/(Z+1)

n/p Ratios for β- Decay

$$ {}^{\;\;\;32}_{17\;\;15}\mathrm{P} \longrightarrow {}^{\;\;\;32}_{16\;\;16}\mathrm{S} $$

17/15 = 1.13 16/16 = 1.00
represents 11.5% decrease in n/p ratio

QUIZ

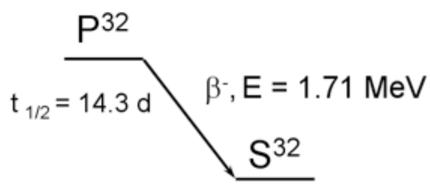
In the following equation, is the A associated with X less than, greater than, or equal to the A associated with Y?

$$ {}^{\;\;\;A}_{N\;\;Z}\mathrm{X} \longrightarrow {}^{\;\;\;\;\;\;\;A}_{N-1\;\;Z+1}\mathrm{Y} + {}^{\;0}_{-1}e + \nu + E $$

CHANGE IN ATOMIC MASS

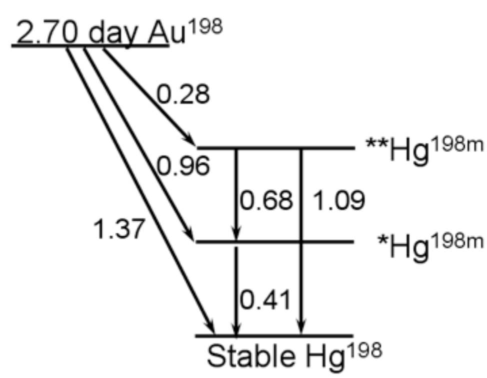
In the equation above, the A associated with X is very slightly greater than the A associated with Y. In fact, in all modes of decay, the atomic mass of the parent is greater than that of the daughter. Note that they appear to be the same if we look at the whole round numbers, but there will always be a difference in the 3rd or 4th decimal place.

Decay Scheme of P^{32}



P^{32} decays directly to ground state, bypassing excited state, so γ-ray emission does not occur

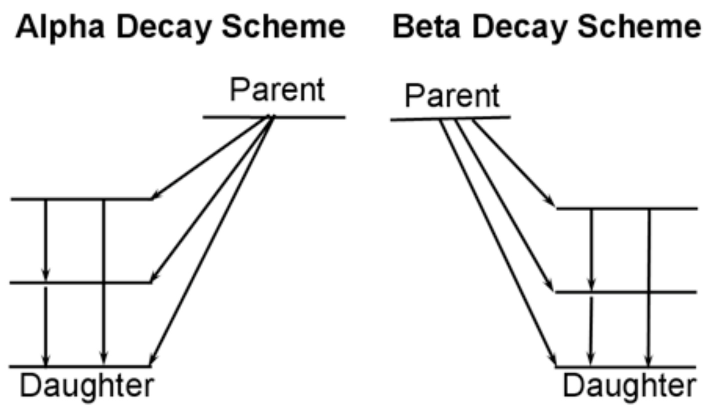
Decay Scheme of Au^{198}



Analogous to the earlier example of alpha decay, in the β- decay scheme, there are three possible routes of decay from parent to ground state of the daughter; the only mode of decay is alpha.

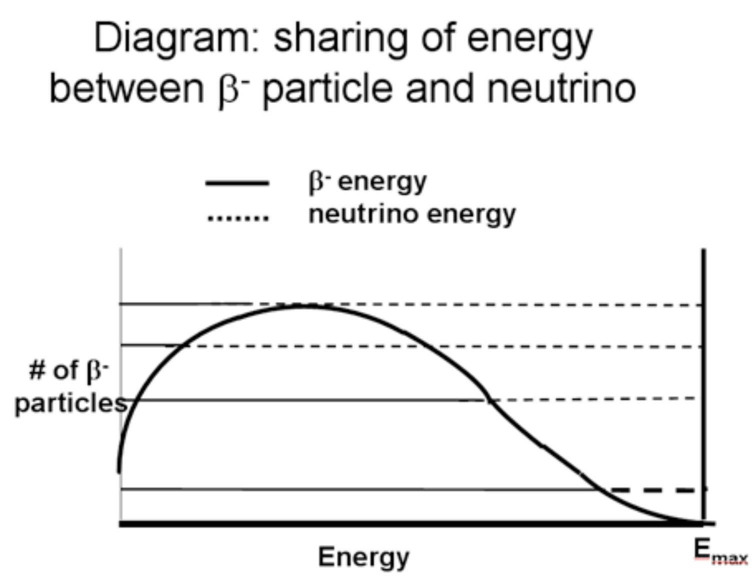
- In Route 1, the decay is directly to the ground state. There is no excited or metastable state formed and no gamma rays are released.
- In Route 2, there is decay by beta to a metastable state of the daughter, followed by emission of a gamma ray and transition to the ground state.
- In Route 3, there is beta decay to a highly excited state of the daughter, followed by gamma ray emission either directly to the ground state or indirectly to the ground state through sequential emission of two separate gamma rays. Regardless of the route taken, the energy expended in transition from parent to daughter is a fixed amount.

COMPARISON OF ALPHA- AND BETA- DECAY SCHEMES



ß- PARTICLE ENERGY SHARING

The literature value for energy of beta emitters is E_{max}. The decay of P32to S32 is associated with a change in energy of 1.71 MeV. This energy is shared between the β- particle and a neutrino. This very strange particle has a mass of zero and a charge of zero, but possesses momentum and energy. Unlike α particles which are monoenergetic, ß- particles are emitted with a range of energies lying between 0 MeV and E_{max} for a particular isotope. This can be shown by means of a magnetic field which can be used to spread out ß- radiation from a particular source into a continuous spectrum. Diagram: sharing of energy between β- particle and neutrino.

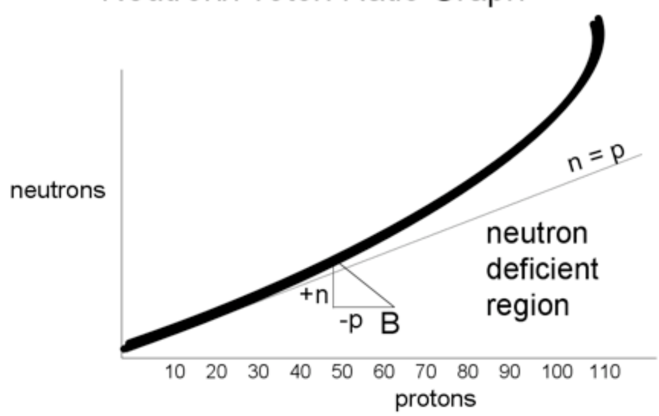


Positron Decay

If the n/p ratio is too low, it may be increased by disintegration of a proton in the nucleus. This process is represented by the following equation:

$$ {}^{1}_{1}p \longrightarrow {}^{1}_{0}n + {}^{0}_{+1}e + \nu + \text{Energy} $$

Neutron/Proton Ratio Graph



Generic Equation for β^{+} Decay

$$ {}^{A}_{N \;\; Z}X \longrightarrow {}^{A}_{N+1 \;\; Z-1}Y + {}^{0}_{+1}e + \nu + \text{Energy} $$

Note that in positron decay, the Z number decreases by 1, N number increases by 1, and there is essentially no change in atomic mass.

Positron Decay

- Z number decreases by 1
- N number increases by 1
- Essentially no change in atomic mass.

$$ {}^{65}_{35\ 30}\mathrm{Zn} \longrightarrow {}^{65}_{36\ 29}\mathrm{Cu} + {}^{0}_{+1}e + \nu + \text{Energy} $$

n/p Ratios for β+ Decay

$$ {}^{65}_{35\ 30}\mathrm{Zn} \longrightarrow {}^{65}_{36\ 29}\mathrm{Cu} $$

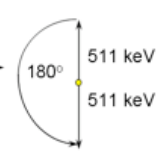
35/30 = 1.1667 36/29 = 1.241

represents 6.3% increase in n/p ratio

Fate of Positrons in Matter

Positrons have a very short lifetime in matter- they readily annihilate electrons. The radiation emitted is referred to as *annihilation radiation* and is always 2 photons emitted at a 180° angle with an energy of 511 keV.

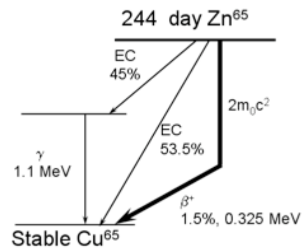
$e^{+} + e^{-} \longrightarrow$



ELECTRON ENERGY EQUIVALENCE

By Einstein's equation, the rest mass of an electron converted to pure energy is equivalent to 0.511 MeV. The 2 electrons have annihilated each other and produced energy in accordance with the Laws of Conservation of Matter and Energy

Decay Scheme for β⁺ Emitting Zn^{65}



Vertical line represents the rest mass of the 2 electrons. Energy equivalence: 1.02 MeV

Vertical bolded line represents the activation energy required for this mode of decay to take place. Energy equivalence is 1.02 MeV The angled bolded line represents the β+ portion of the decay scheme. Note that no excited states are associated with the β+ decay, although one is associated with the electron capture portion. β+ decay and Electron Capture are considered to be competing modes of decay.

DECAY BY ELECTRON CAPTURE

Electron capture often competes with positron emission. When the n/p ratio is low and sufficient energy is not available for positron emission, this ratio may be increased by the capture of an orbital electron by a proton in the nucleus. This process is also called K-capture since a K-shell electron is most often involved. With the loss of an electron in the K, L, or M shell, a vacancy exists, which is filled with an electron from a higher energy level. This is accompanied by emission of X-rays with energy levels characteristic of the daughter nuclide. It is by these characteristic X-rays that a nuclide decaying by EC can be detected.

PARTICLE REACTION FOR ELECTRON CAPTURE

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

Generic Equation for EC

$$ {}^{A}_{Z}X_{N} \longrightarrow {}^{A}_{Z-1}Y_{N+1} + \nu + \text{Energy} $$

In Electron Capture Decay, the Z number decreases by 1, the N number increases by 1, and there is essentially no change in atomic mass.

Electron Capture Decay

- Z number decreases by 1
- N number increases by 1
- Essentially no change in atomic mass.

$$ {}^{65}_{30}Zn_{35} \longrightarrow {}^{65}_{29}Cu_{36} + \nu + \text{Energy} $$

n/p Ratios for EC Decay

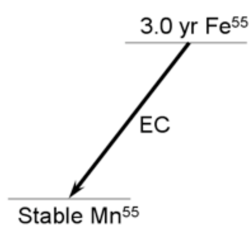
$$^{65}_{30}\text{Zn} \longrightarrow {}^{65}_{29}\text{Cu}$$

35 30 → 36 29

35/30 = 1.1667 36/29 = 1.241

represents 6.3% increase in n/p ratio

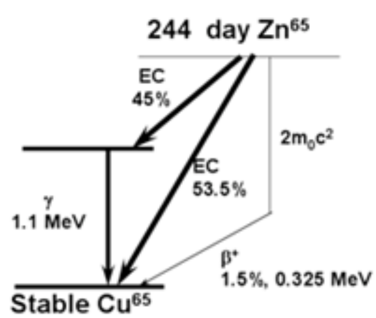
DECAY SCHEME: ELECTRON CAPTURE



Since there are no excited states of the daughter, no gamma rays are emitted. Is Fe^{55} an imageable isotope?

A: YES, MAYBE- even though gamma ray emission does not take place due to the absence of an excited state, characteristic X-rays are ALWAYS emitted in EC. If the energy is within the imageable energy range, an image can be formed.

Decay Scheme for EC Emitting Zn^{65}

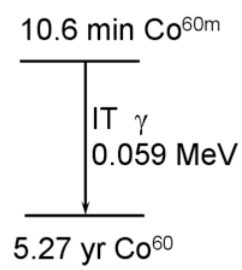


Note 2 routes of decay by electron capture. One involves formation of an excited state of Cu^{65}, which de-excites itself by emitting a gamma ray. The other route goes directly to the ground state and bypasses the excited state.

ISOMERIC TRANSITION

When an excited state of a radionuclide decays to the de-excited state by gamma-ray emission, we call this transition "isomeric"; that is, there are no changes in A, Z, or N numbers, but only in nuclear energy levels. The parent and daughter nuclides are called nuclear isomers. The parent nuclide in Isomeric Transition is said to be METASTABLE, that is, it has a measurable half-life (longer than 1 μsec).

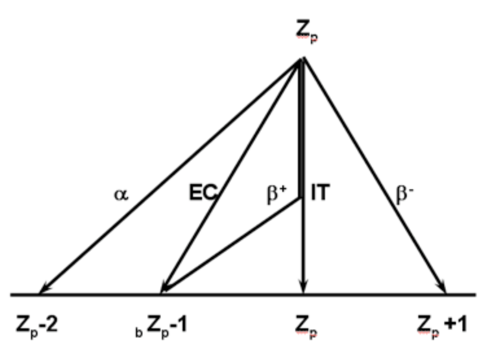
DECAY SCHEME: ISOMERIC TRANSITION



COMPOSITE DIAGRAM SHOWING ALL MODES OF DECAY

This diagram shows the correct angle for the lines in all modes of decay. In addition, the relationship of Z number of parent and daughter is shown.

SUMMARY OF ALL DECAY MODES



CONCLUSIONS:

- When a nucleus is in a neutron excessive condition, the only mode of decay that can occur is β- emission.
- When a nucleus is in a neutron deficient condition, β- emission is not possible and the modes of decay that can occur are α emission, β+ emission and Electron Capture.
- Gamma ray emission can occur in every mode of decay as long as an excited or metastable state is formed
- In all modes of decay other than Isomeric Transition, there will be a significant change in the Z and N numbers and a very small change in the A number
- The lines drawn in a decay scheme are at an angle that reflects whether the Z number of the daughter is greater than, equal to, or less than the Z number of the parent.

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