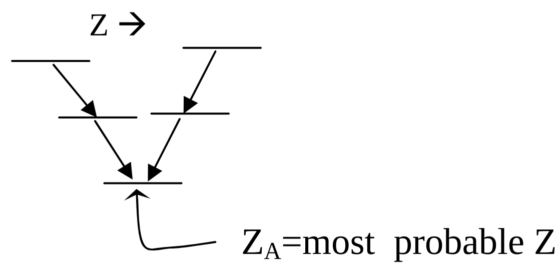
SECTION 11: Beta Decay

Beta decay involves transformation of a neutron into a proton, or vice versa. Three types of beta decay exist:

- Negatron (β^-) decay: conversion of a neutron into a proton,
- Positron (β^+) decay: conversion of a proton into a neutron, and
- Electron capture (EC): the reaction of a proton with an atomic electron to produce a neutron.

Note that both β^+ and EC decays produce the same final nucleus.

Since beta decay involves only the transformation of one nucleon type into another (neutron ←→ proton), the mass number does not change; i.e. beta decay connects a chain of **isobars**, as was illustrated by the isobaric mass formula results in Figs 8.4 and 8.5, indicated schematically below.



NEUTRON EXCESS

Negatron Decay
$n \rightarrow {}^1H + \beta^- + \bar{\nu}$

PROTON EXCESS

Positron/Electron-Capture Decay
${}^1H \rightarrow {}^1n + \beta^+ + \nu$
${}^1H + e^- \rightarrow {}^1n + \nu$

Specifically, nuclei with an excess number of neutrons relative to the most probable atomic number Z_A for a given isobar A will undergo negatron decay to form nuclei with a higher Z. Those with an excess number of protons will reduce their atomic number by undergoing positron or electron capture.

Examination of the above equations for beta decay indicates the need to introduce a new particle, the **neutrino (ν),** and a new concept, that of **antiparticles**. Early measurements of beta decay appeared to violate the conservation of momentum. Unlike two-body alpha decay, where the two particles are emitted 180^o from one-another, the observed angle between the beta particle and the heavy recoil nucleus is less than 180^o for beta decay. To account for this observation, Wolfgang Pauli postulated that a third particle – with no charge and little mass – must account for the missing momentum. But since detector techniques usually depend on either mass or charge to register a signal, it was many years before the neutrino would be detected experimentally. In a Nobel-prize-winning experiment in 1953, Fred Reines and Clyde Cowan made the first direct observation of the neutrino. Since that time the neutrino has played a central role in the study of phenomena ranging from beta decay to understanding the behavior of stellar objects such as our Sun and supernova explosions.

Beta particles and neutrinos constitute a class of particles called **leptons**, just as neutrons and protons are classified as nucleons. For every particle there exists an antiparticle, with opposite charge and mass, usually indicated by a bar over the particle. However, the **antiparticle of the electron**, the **positron**, is usually written as β^+. Two principles must be observed in any balanced nuclear equation. First, the **total number of leptons must be conserved**; i.e. the number of reactant leptons must equal the number of product leptons, just as is the case for nucleons and electric charge. Second, an **antilepton (or antinucleon) cancels out a lepton (or nucleon)**. The reaction that powers our Sun involves the reaction between two protons to form deuterium, ^2H, and provides the following example:

	$^1H^+$		$^1H^+$	→	$^2H^+$		β^+		ν		
Leptons =	0	+	0	=	0	+	(-1)	+	1	=	0
Nucleons	1	+	1	=	2	+	0	+	0	=	2
Charge	1	+	1	=	1	+	1	+	0	=	2

If the positron were a negative electron, leptons and charge would not be balanced. Similarly, if the neutrino were an antineutrino, leptons would not be balanced. Appendix 11-1 describes the measurement of neutrinos emitted by our Sun performed by nuclear chemist Ray Davis, for which he received the Nobel Prize.

Negatron Decay

As indicated above negatron decay is characteristic of nuclei that have an excess of neutrons relative to the most probable charge Z_A for a given set of isobars, schematically shown below.

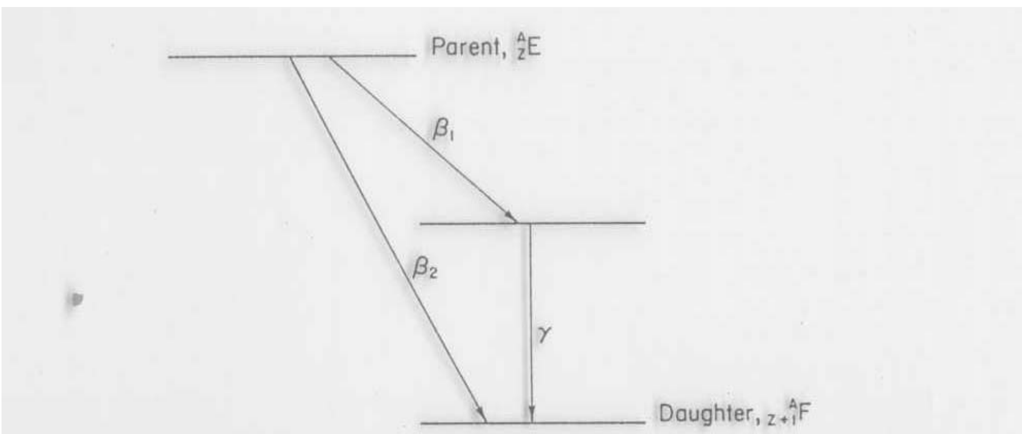


Fig. 11.1 Decay scheme for negatron decay to an excited state of the daughter β_1 and to the ground state β_2. Decay from the excited state top the ground state involves gamma decay Sec. 12).

The generic equation for negatron decay is

$$\left[{}^{A}_{Z}X \dashrightarrow {}^{A}_{Z+1}Y + {}^{0}_{-1}\beta^{-} + \bar{\nu} + Q_{\beta^{-}} \right],$$

where the product Y is a cation, Y^{+} . The ionization states of products following nuclear decay can lead to some unusual chemistry. For example, the decay of ^{20}F produces ^{20}Ne in the +1 oxidation state. Two examples of negatron decay that have important applications as chronometers are

$$ {}^{3}_{1}H \rightarrow {}^{3}_{2}He + {}^{0}_{-1}\beta^{-} + \bar{\nu} \; ; \; t_{1/2} = 12.3 \text{ y}$$

$$ {}^{14}_{6}C \rightarrow {}^{14}_{7}N + {}^{0}_{-1}\beta + \bar{\nu} \quad ; \; t_{1/2} = 5730\text{y} \; .$$

Both of these isotopes are produced when cosmic rays collide with the atmosphere.

Q-values for negatron are calculated as follows:

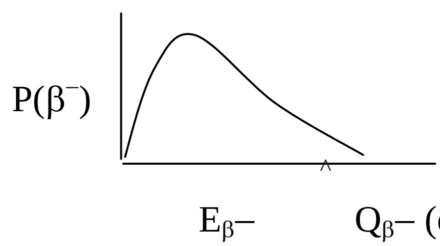
$$Q_{\beta-} = \Delta(^{A}X) - [\Delta(^{A}Y^{+}) + \Delta_{\beta-} + \Delta_{\nu}]$$

$$\Delta_{\nu} \approx 0 \text{ and } ; \; \Delta_{e-} = \Delta_{\beta-} \; ; \quad \Delta(^{A}Y) = \Delta(^{A}Y^{+}) + \Delta_{e-}$$

$$\mathbf{Q_{\beta-} = \Delta(^{A}X) - \Delta(^{A}Y)} \qquad \text{(Eq.11.1)}$$

Therefore, if the mass defect of the parent nucleus is greater than that of the daughter, negatron decay is energetically permissible. Typical $Q_{\beta-}$ values are less than ~ 5 MeV.

A schematic kinetic energy spectrum of the negatrons emitted in beta decay is shown below



One observes that the spectrum is continuous, in contrast to the discrete lines observed in the spectrum of alpha decay (Fig. 10.1), which is a two-body breakup process . The continuous spectrum observed in negatron decay is the signature of a three-body decay, where the momentum and energy can be shared an infinite number of ways among the three particles. This observation provided some of the earliest evidence for the existence of the neutrino.

<u>Positron Decay</u>

As stated above, positron decay is characteristic of nuclei with an excess of protons Z > Z_A. The generic equation can be written as follows:

$$\left[{}^{A}_{Z}X \dashrightarrow {}^{0}_{1}\beta^{+} + {}^{A}_{Z-1}Y + \nu \right]$$

where the heavy product nucleus is in the -1 oxidation state, Y^{-1}. Thus, the decay of ^{22}Na produces $^{22}Ne^{-1}$ ions hardly an 'inert gas'. A typical example of positron decay is given by the decay of ^{11}C,

$$ {}^{11}_{6}C \rightarrow {}^{0}_{1}\beta^{+} + {}^{11}_{5}B + \nu + Q_{\beta^+} \qquad (t_{1/2} = 21 \text{ min}) $$

^{11}C is an important isotope in nuclear medicine, along with 13N and 15O, also positron emitters. These isotopes can be produced in small cyclotrons that are located in many hospitals around the world and then used to tag molecules for use as biological tracers.

The energetics of positron decay are more complex than in negatron decay because an antiparticle is created in the decay, requiring additional energetic factors. The generic Q-value for positron decay is illustrated in the following set of equations:

$$ Q_{\beta+} = \Delta(X) - [\Delta(Y^-) + \Delta\beta^+ + \Delta\nu]\ ;\ \Delta(e^-) = \Delta(\beta^+) $$

$$ Q_{\beta+} = \Delta(X) - [\Delta(Y) + \Delta(e) + \Delta\beta^+ + 0]\ ;\ \Delta(\nu) \approx 0 $$

$$ = \Delta(X) - \Delta(Y) - 2\Delta e \quad ; \quad \Delta(e^-) = 0.511 \text{ MeV} $$

$$ \boxed{Q_{\beta+} = \Delta(X) - \Delta(Y) - 1.022 \text{ MeV}} $$

Thus, in order for positron emission to occur, the mass defect of the parent nucleus must be at least 1.022 MeV greater than the daughter. This amount of energy is required in order to create the positron, in essence the amount of energy required to raise the positron from the antimatter state to the matter state, or twice the mass-energy of the positron. This energy must be extracted from the mass of the parent nucleus. As with negatron decay, most observed $Q_{\beta+}$ values are of order 5 MeV or less.

The relative spectrum shape of a typical positron emitter compared to that of a negatron emitter is shown in Fig 7.2.

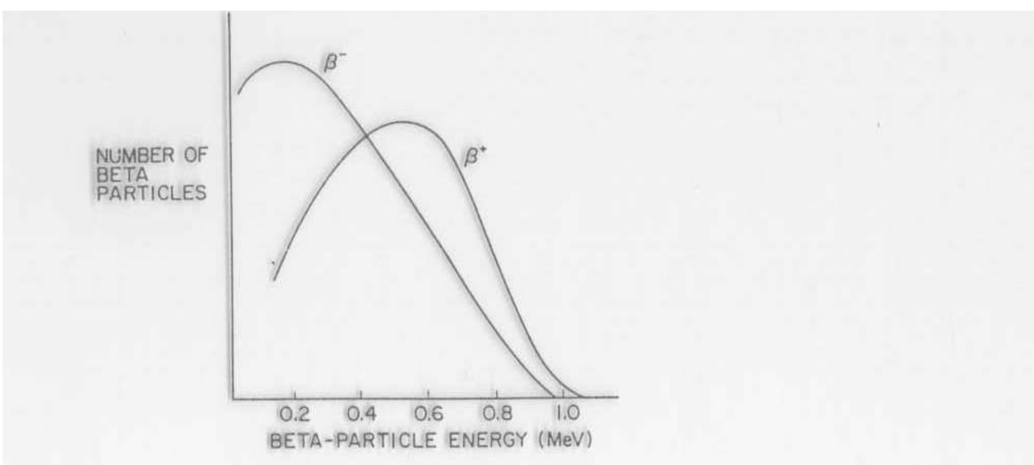


Fig. 11.2 Probability for emitting a negatron and a positron with approximately the same Q-values.

The shift in spectrum shape toward higher kinetic energies for the positron can be accounted for by the positive Coulomb field of the emitting nucleus; i.e. positrons are accelerated due to their mutual positive charges and negatrons are decelerated because of the attraction of opposite charges.

The fate of the positron enables a very important diagnostic tool for positron emitters. Once free of its atomic environment, positrons --which do not occur free in nature --experience three stages on their return to the antimatter world:

(1) **Thermalization** – the positron loses kinetic energy via collisions with atomic electrons until it reaches room temperature, 3kT/2.

(2) **Positronium Formation** – once thermalized, the positron is attracted to a negative electron to form the lightest molecule, **positronium**, which has a lifetime of order 10^{-10} seconds.

$$e^{+} + e^{-}$$

The lifetime of positronium depends on the chemical environment in which the electron exists and therefore can serve as a probe of chemical binding. Two forms of positronium exist, depending on spin orientation, **ortho** (J= 1) in which the spins are aligned parallel to one another (→→) and **para** (J = 0) in which the spins are opposed (→←) .

(3) **Annihilation** – The electron and positron annihilate one another, converting all of their mass into energy in the form of high energy photons, or gamma rays. The two 0.511 MeV monoeneergetic photons are called **annihilation radiation** and are emitted 180^{o} to one another, which provides a highly specific probe for investigating the location of the decaying nucleus. This is the basic principle behind PET (positron emission tomography) scans that are widely used for both medical diagnosis and research. By attaching the atoms of a positron-emitting nucleus such as ^{11}C or ^{99m}Tc to a site-specific reagent and injecting it into the body, the coincident photons can be scanned in a position-sensitive detector array, thereby locating the organ of interest with high resolution. Fig. 11.3 shows a brain scan obtained with PET.

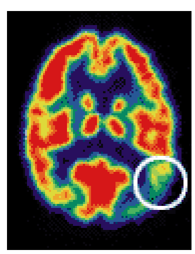


Fig 11.3 PET brain scan. Circled area shows an area of abnormal glucose metabolism that may be associated with seizures.

Electron Capture Decay

An alternative mechanism to positron decay in proton-rich nuclei is electron capture (EC), which leads to the **same daughter nucleus**. Electron capture involves the interaction of a nuclear proton with an orbital atomic electron to produce a neutron.

$$ {}^{1}_{1}H + {}^{0}_{-1}e^{-} \rightarrow {}^{1}_{0}n + \nu + Q_{EC} $$

This reaction violates energy conservation (i.e. the neutron is heavier than the proton) but can convert binding energy in the parent nucleus into mass-energy in order to enable the reaction. The generic equation for electron capture is

$$ \underbrace{{}^{A}_{Z}X^{+} + {}^{0}_{-1}e^{-}}_{{}^{A}X_{Z}} \rightarrow {}^{A}_{Z-1}Y + \nu + Q_{EC} $$

In this equation both the parent and daughter atoms are neutral. However, the daughter electrons are not in their ground states, as will be discussed below. An important example of electron capture decay is

$$ {}^{37}_{18}Ar + {}^{0}_{-1}e^{-} \rightarrow {}^{37}_{17}Cl + \nu \;\; ; t_{1/2} = 35.0 \text{ d} $$

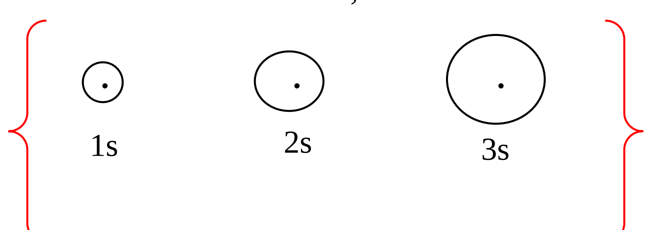
This reaction is the reverse of the reaction used to measure solar neutrino production, discussed in Appendix 11.1.

As in negatron decay, the Q-value for electron capture is the difference in mass defect between the parent and daughter

$$ Q_{EC} = \Delta(x) - \Delta(y) \qquad \text{(Eq. 11.3)} $$

Therefore, if $\Delta(x) > \Delta(y)$, then EC decay is possible. Note that $Q_{EC} = Q_{\beta^+} + 1.022$ MeV.

The **atomic effects** associated with electron capture decay are important in allowing EC detection. Both decay products are very difficult to observe experimentally , the daughter nucleus because of its very low recoil energy and the neutrino because of its lack of charge and negligible mass. Electron capture occurs preferentially from atomic orbitals nearest the nucleus (low quantum number n) where the probability for being inside the nucleus is greatest. For a heavy element such as uranium (Z = 92) the 1s electron actually spends most of its time inside the nuclear volume. The following schematic diagram serves a reminder of the nomenclature of atomic orbitals,



K-shell L-shell M-shell

Consequently the capture probability P_{EC} decreases as n increases, i.e.

$$P_{EC}(K) > P_{EC}(L) > P_{EC}(M) \ldots \text{etc.}$$

For a fixed quantum number n, the EC capture probability decreases as the orbital angular quantum number ℓ increases. This follows since higher ℓ-wave orbitals have a more diffuse wave function and therefore have a lower probability of being inside the nucleus. For example

$$P_{EC}(3s) > P_{EC}(3p) > P_{EC}(3d) \ldots \text{etc.}$$

If the atomic orbitals are included in the equation for the decay of ^{37}Ar in the example above, the result for capture from the is level would be

$$^{37}_{18}Ar\ (1s^2 2s^2 2p^6 3s^2 3p^6) \Rightarrow {}^{37}Cl\ [1s^1 2s^2 2p^6 3s^2 3p^6]$$

Because the primary radiation in EC decay (daughter recoil and neutrino) are very difficult to measure, one relies on secondary radiation from electron rearrangement for EC detection. These consist of:

(1) **x-rays –** The filling of the electron vacancy created by electron capture produces a cascade of x-rays and lower energy photons characteristic of the daughter atom as the atom rearranges to its ground state configuration ($1s^2 2s^2 2p^6 3s^2 3p^5$) in the example above.

(2) **Auger electrons –** in the atomic rearrangement process, x-rays may interact with outer orbital electrons which are then ejected as low energy electrons. This mechanism is very much like an internal photoelectric effect. The probability for x-ray emission relative to Auger electron emission increases with the atomic number Z of the daughter atom.

$$(P(\text{x-ray}) / P(\text{Auger}) \ \alpha\ Z$$

This behavior is explained in terms of the fact that as Z increases, x-ray energies increase. Due to the shorter wave length of the x-ray, the probability of interaction with an orbital electron decreases; i.e. there is a lower probability for wave function overlap.

(3) **Gamma Rays –** In some cases EC decay populates excited states of the daughter nucleus, as shown in Figs. 11.1 and 11.3 and discussed in the following section. In this case a monoenergetic gamma ray is emitted, which can be readily detected.

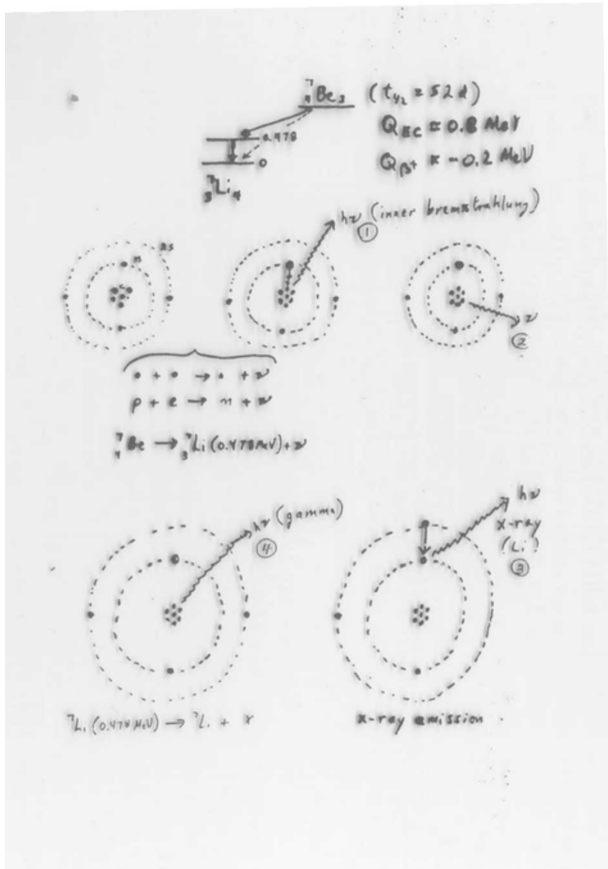


Fig. 11.3 Schematic stages of electron capture in ^{7}Be involving decay to both ground and excited states.

Since electron capture and positron emission both lead to the same final nucleus, they are competitive processes. Of course if Q_{EC} is less than 1.022 MeV, only EC can occur. If Q_{EC} is greater than 1.022 MeV, the two processes compete with one another. The relative probability of EC compared to positron decay also depends on the Z of the parent

$$P(EC)/P(\beta^{+}) \;\alpha\; Z.$$

The explanation for this behavior is twofold. First, the probability that an atom's 1s electron is inside the nucleus increases with atomic number Z. In addition, there is Coulomb barrier inhibition for the positively-charged positron.

<u>Beta-decay Half-lives</u>

The lifetimes for beta decay are governed by the fact that leptons are involved and therefore decay rates are determined by the **weak nuclear force**. The weak force places a constraint on the decay process that restricts the shortest lifetimes to 10^{-3} seconds or greater. This value is to be compared with minimum lifetimes of order 10^{-21} seconds for alpha decay, which is governed by the strong nuclear force. Two factors are primarily responsible for controlling beta decay rates:

(1) **Q-value** -- large Q-values favor shorter half-lives, and

(2) **Nuclear structure –** minimum spin and parity changes favor rapid decay rates.

The structure effect can hinderi decay rates significantly. An important example is the isotope that is the major source of radiation in our bodies, ^{40}K. The Q-values for negatron and electron capture are relatively large, 1.2 and 1.4 MeV, respectively, which would suggest a rapid decay rate. However, the spin and parity state of ^{40}K is 4- while that of the daughters ^{40}Ar and ^{40}Ca are both 0+. This spin and parity change results in a half-life of 1.29 x 10^9 years, which accounts for its existence in nature and makes ^{40}K a valuable tool for dating the age of our planet.