# Chem 481 Lecture Material
**2/4/09**

## Nature of Radioactive Decay

## Positron ($\beta^+$) Decay

In $\beta^+$ decay a proton is converted to a neutron with the subsequent emission of a high-energy positron ($e^+$) and an electron neutrino ($v_e$).

general $\beta^+$ decay equation: ${}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}X^- + {}^{0}_{+1}e + {}^{0}_{0}v_e + Q \rightarrow {}^{A}_{Z-1}X + {}^{0}_{-1}e + {}^{0}_{+1}e + {}^{0}_{0}v_e + Q$

example: ${}^{22}_{11}Na \rightarrow {}^{22}_{10}Ne + {}^{0}_{-1}e + {}^{0}_{+1}e + {}^{0}_{0}v_e + Q$

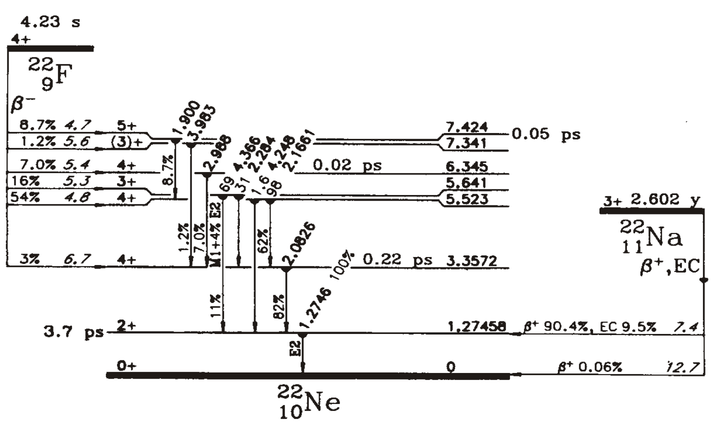
For $\beta^+$ decay, $Q = \dfrac{931.5\ MeV}{amu}(M_Z - M_{Z-1} - 2M_{e^-})$

For the $\beta^+$ decay of ${}^{22}_{11}Na$, $Q = \dfrac{931.5\ MeV}{amu}(M_{Na-22} - M_{Ne-22} - 2M_{e^-}) = 1.820\ MeV$

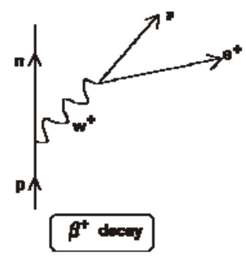
This represents the energy available for positron decay. However, the Chart of the Nuclides indicates a decay energy of 2.8422 MeV. This discrepancy was originally accounted for by thinking of the conversion of a proton into a neutron as:

$$p + e^- \rightarrow n + v_e$$

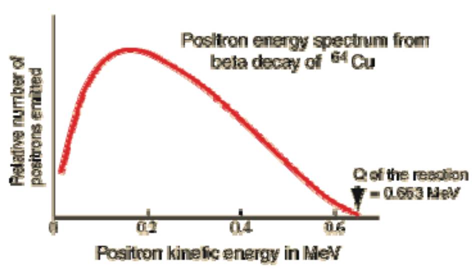
For positron decay, the needed electron, along with the emitted positron, are created in the nucleus. This requires an energy equivalent to the rest mass of an electron plus the rest mass of a positron (0.511 MeV + 0.511 Mev = 1.022 MeV). Thus, positron decay is only possible if the decay energy exceeds 1.022 MeV. Note that 1.820 MeV + 1.022 MeV = 2.842 MeV, the decay energy listed. Since the positron is antimatter, when it encounters an electron they will annihilation to produce energy equivalent to their masses (=1.022 MeV). Usually this energy is released in the form of two 0.511 MeV gamma rays emitted in exactly opposite directions. The decay scheme for $^{22}$Na is shown below.



The Standard Model describes positron decay in terms of the conversion of one of the up quarks in a proton to a down quark by the weak interaction. Since the up quark has a charge of 2/3 and the down quark has a charge of -1/3, this process is mediated by a virtual W+ particle, which carries away a (+1) charge. The proton has now become a neutron. A positron and an electron neutrino emerge from the virtual W+ boson and are emitted from the nucleus. This process is diagrammed below.




As expected, a continuous range of $\beta^+$ energies are observed as illustrated in the positron spectrum for $^{64}$Cu below.




## Electron Capture (EC) Decay

For neutron-deficient nuclides that have a decay energy less than 1.022 MeV, conversion of a proton into a neutron can occur by capture of an orbital electron by the excited nucleus.

general EC decay equation: $^{A}_{Z}X \rightarrow {}^{A}_{Z-1}X + {}^{0}_{0}\nu_e + Q$ Note that the daughter is the same as for $\beta^+$ decay.

example: $^{22}_{11}Na \rightarrow {}^{22}_{10}Ne + {}^{0}_{0}\nu_e + Q$

For EC decay, $Q = \frac{931.5\ MeV}{amu}(M_Z - M_{Z-1})$

For the EC decay of $^{22}_{11}$Na, $Q = \frac{931.5\ MeV}{amu}(M_{Na-22} - M_{Ne-22}) = 2.842\ MeV$

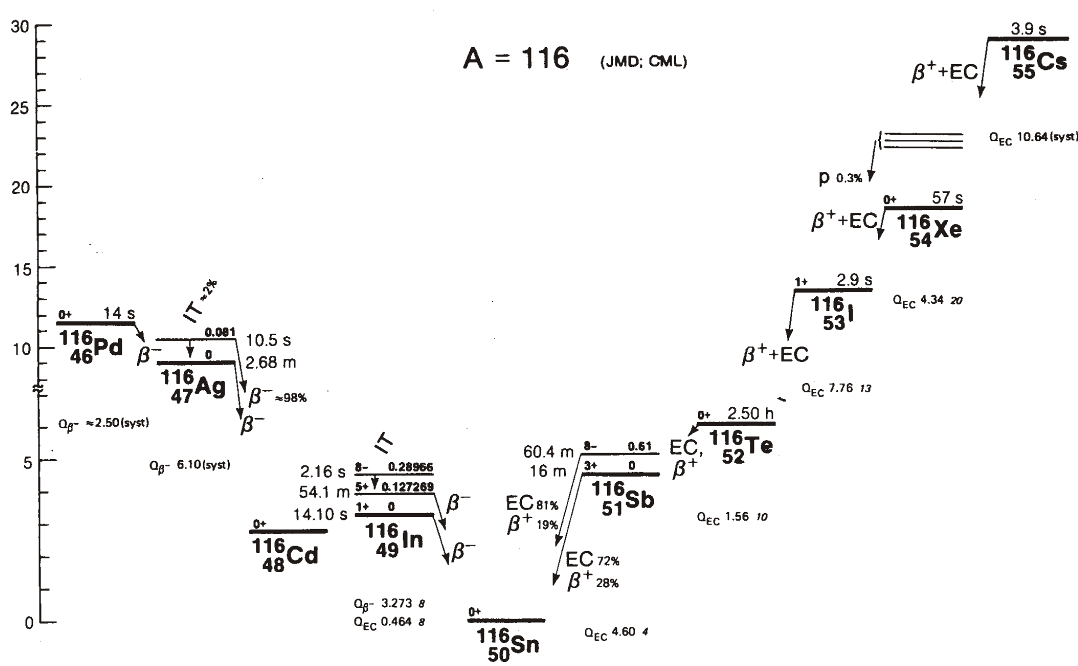
The emitted neutrinos are monoenergetic with energy given by $E_{\nu_e} = Q - E_{be}^{e^-}$ where $E_{be}^{e^-}$ is the binding energy of the captured electron. The likelihood of capture is highest for n=1 electrons (K capture) and steadily decreases with increasing n. Capture of an inner shell electron creates a vacancy that is filled by an outer shell electron with the simultaneous emission of a x-ray photon (fluorescence) or the ejection of an outer shell electron (Auger electron). For nuclides like $^{22}$Na that can decay by either $\beta^+$ or EC, electron capture is favored when the decay energy is low and Z of the parent is high.

## Isomeric Transition (IT)

Isomeric transition is the emission of gamma rays as a nucleus decays from an isomeric state.

example: $^{207m}$Pb → $^{207}$Pb + 2γ

Two additional examples of IT are shown in the figure below.



## Internal Conversion (IC)

An isomeric state may de-excite by transferring energy to an orbital electron which is then ejected from the atom. No gamma ray is emitted. The electron possesses a kinetic energy equal to the difference between the energy of the nuclear transition and the binding energy of the electron. The vacancy created by ejection of the electron results in x-ray or Auger electron emission from the atom. The internal conversion coefficient (α) is given by:

$$\alpha = \frac{\textit{fraction of decays by IC}}{\textit{fraction of decays by IT}}$$

There is more conversion for low transition energy, high Z and lower electron energy level ($\alpha_K > \alpha_L > \alpha_M$, etc.).

## Spontaneous Fission (SF)

Spontaneous fission is the break-up of a nuclide into two fragments with the release of 2-3 neutrons.

example: $^{252}_{98}Cf \rightarrow {}^{132}_{50}Sn + {}^{117}_{48}Cd + 3\,{}^{1}_{0}n$

Since $E_B/A$ decreases with increasing A (from A~56), all nuclides with $A \geq 100$ are unstable with respect to SF, but a high Coulomb barrier for emission of fission fragments makes measures SF decay rates only for $A \geq 230$. Neutrons are released because the fissioning nucleus has a higher N/Z than is favored for the product nuclides. $^{252}Cf$ ($t_{½}$ = 2.64 y) serves as a useful source of neutrons because it readily undergoes SF.

## Gamma Recoil

When energetic gamma rays are emitted, the nucleus can experience a significant recoil. The recoil energy ( R ) is given by:

$$R(eV) = \frac{537\,E_\gamma^2}{M}$$

where $E_\gamma$ is the gamma ray energy in MeV and M is the mass of he nuclide in amu. For $E_\gamma$ = 2 MeV and M = 100 amu, R = 21 eV, sufficient energy to break chemical bonds.