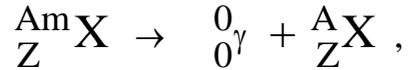## SECTION 12: Gamma Decay

Gamma decay involves photon emission from an excited nucleus, a process directly analogous to photon emission from excited atoms or molecules (xrays, uv IR, etc.). Thus, gamma decay converts the nucleus to a lower energy state, according to the following schematic equation

$$ {}^{Am}_{Z}X \rightarrow {}^{0}_{0}\gamma + {}^{A}_{Z}X \; , $$

where the superscript **m** stands for metastable and indicates the nucleus is in an specific excited state. Because the mass of the gamma ray photon is zero, the recoil energy is negligible for nuclear purposes; i.e. $E_\gamma \approx Q_\gamma$. However, the recoil energy is comparable to chemical energies and finds application to the study of chemical binding in the form of the inverse process of gamma ray absorbtion, the **Mossbauer effect** (Nobel Prize 1961).

$$ Q_\gamma = E_\gamma + E_R \; ; \; E_R \sim eV $$

Schematically, the nuclear de-excitation process from one level of spin I_i and parity π to another can be illustrated as follows, as was illustrated in Sec. 9 (shell Model).

E_2 _____ I_2, π

E_1 _____ I_2, π

E_0 _____ I_0, π
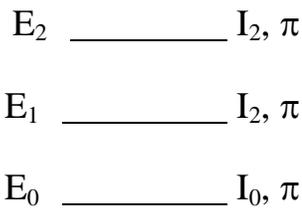
In the above scheme three gamma rays are possible:

$E_\gamma(1) = E_2 - E_1$
$E_\gamma(2) = E_1 - E_0$
$E_\gamma(3) = E_2 - E_0 = E_\gamma(1) + E_\gamma(2)$

As in the case of alpha and beta decay, gamma decay probabilities are a function of the transition energy, spin, and parity.

Gamma decay occurs as nuclei de-excite after nuclear reactions or during radioactive decay. The **electromagnetic interaction** governs the rate of gamma decay, resulting in minimum half-lives of

$$ t_{1/2}(\gamma) \gtrsim 10^{-14} s. $$

Thus, minimum gamma decay half-lives are intermediate between the lower lifetime limits for alpha decay (10^{-21} s; strong nuclear interaction) and beta decay (10^{-3} s; weak nuclear interaction). A rule of thumb is as follows:

Short $t_{1/2}(\gamma)$: Large E_γ, $\Delta I = 0$, $\Delta\pi = NO$
Long $t_{1/2}(\gamma)$: Small E_γ, $\Delta I = large$, $\Delta\pi = YES$

Unusually long-lived gamma emitters, arbitrarily defined as those with $t_{1/2} \gtrsim 10^{-6}$s, are called **isomers**. One of the longest-known isomers is ^{210m}Bi

$$^{210m}_{83}\text{Bi}(I\pi = 9-) \quad \xrightarrow{10^5 \text{y}} \quad ^{210}_{83}\text{Bi}(I\pi = 1-) + \gamma,$$
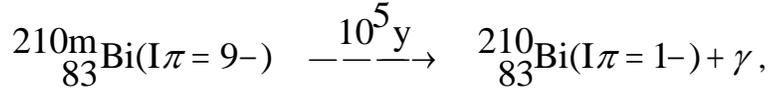
for which the spin change of 8 is unusually large. Isomers in the minute-to-day range are particularly useful as radioactive tags for analytical and medical purposes, as gamma ray energies are very sharp and provide highly precise elemental fingerprints.

There are three competing mechanisms for gamma decay:
  (1) **Photon (gamma ray) emission**, in which an energetic photon is emitted as a result of a transition between energy states in an excited nucleus, as depicted in the above equations.
  (2) **Internal Conversion (IC),** in which the gamma ray transition energy is transferred to an orbital atomic electron, usually from the innermost orbitals, n = 1 (K) or n= 2 (L)

$$^{Am}_{Z}\text{X} \rightarrow \ ^{A}_{Z}\text{X}^{+} + \text{e}^{-},$$

The energy of the emitted electron is given by the gamma ray energy E_γ, minus the atomic binding energy of the emitted electron $BE(e^-)$
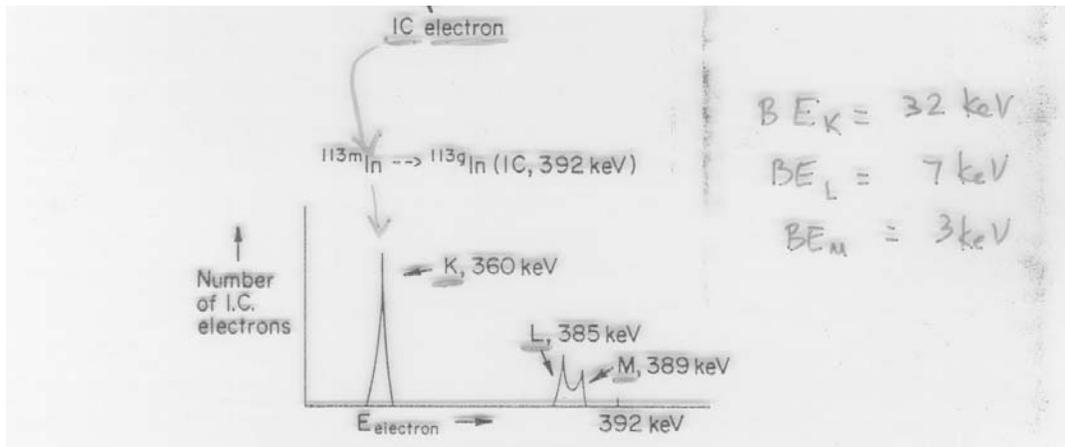
$$E_e = E_\gamma - BE(e^-). \tag{Eq. 12.1}$$

Fig. 12.1 – Spectrum of internal conversion electrons emitted in the decay of ^{113m}In, for which the gamma ray transition energy is 392 keV.

The vacancy in the atomic orbital after emission of an atomic electron is then filled by an atomic electron from a higher orbital, accompanied by the emission of a lower-energy x-ray, just as in the case for Electron Capture (EC) in beta decay. This leads to a cascade of electronic rearrangements in the atom that subsequently produces Auger electrons and low-energy photons as well. Schematically, the mechanism can be depicted as follows
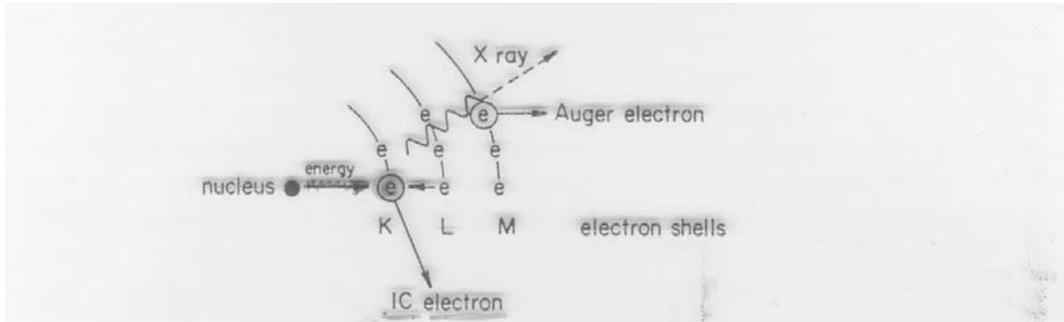
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Fig. 12.2 Cascade of processes involved in internal conversion decay.

Thus we observe three types of electrons in radioactive decay:
- Negatrons – distinguished by a continuous energy spectrum ($E_e \sim$ MeV),
- IC electrons – discrete energies comparable to E_γ (keV to MeV energies), and
- As in the case of alpha and beta decay, gamma decay half-lives are a function of the energy of the transition, spin, and parity.
  Auger electrons in both EC and IC from atomic rearrangements (eV energies).

It should be noted that x-rays emitted in IC are characteristic of the parent atom ($\Delta Z = 0$), whereas in EC they are associated with the daughter ($\Delta Z = -1$), i.e. the proton has been converted to a neutron before the x-ray is emitted.

(3) Pair Production, a process that is the reverse of annihilation; i.e. instead of an electron and a positron annihilating one another to form photons, the gamma ray transition energy interacts with the nucleus to form an electron-positron pair:

$$^{Am}_{Z}X \rightarrow {}^{A}_{Z}X + \beta^- + \beta^- + Q_{pp}$$

Because the electron-positron pair must be created, it takes extra energy in order for this mechanism to become possible.

$$Q_{pp} = \Delta\left(^{Am}X\right) - [\Delta\,{}^{A}X + \Delta\beta^+ + \Delta\beta^-] \; ; \Delta\beta^+ = \Delta\beta^- = \Delta e^-$$

$$\Delta\left(^{Am}X\right) - \Delta\left(^{A}X\right) - 2\Delta e^- = Q_\gamma$$

$$Q_{pp} = \boxed{Q_\gamma - 1.022 \text{ MeV}} = E_{\beta+} + E_{\beta-} \qquad \text{(Eq. 12.2)}$$

These equations tell us that pair production cannot occur unless the gamma ray transition energy is at least 1.022 MeV. From momentum and energy conservation, the kinetic energies of the electron and positron must be equal, so that

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$$E_{\beta\pm} = \frac{E_\gamma - 1.022 \text{ MeV}}{2} \quad . \qquad \text{(Eq. 12.3)}$$

Note that eventually the positron thermalizes and annihilates, giving our matter world back its 1.022 MeV.

Gamma ray emission, internal conversion and pair production are competitive modes of disposing of the transition energy in a transition between nuclear levels. Internal conversion competes most favorably when the transition energy is low (momentum conservation favors transfer of energy to the electron) and when the Z of the emitting nucleus is high (higher probability for the innermost electrons to be inside the nucleus). When the transition energy is large (>> 1,022 MeV), then pair production becomes more favorable.