Beta Emission Processes

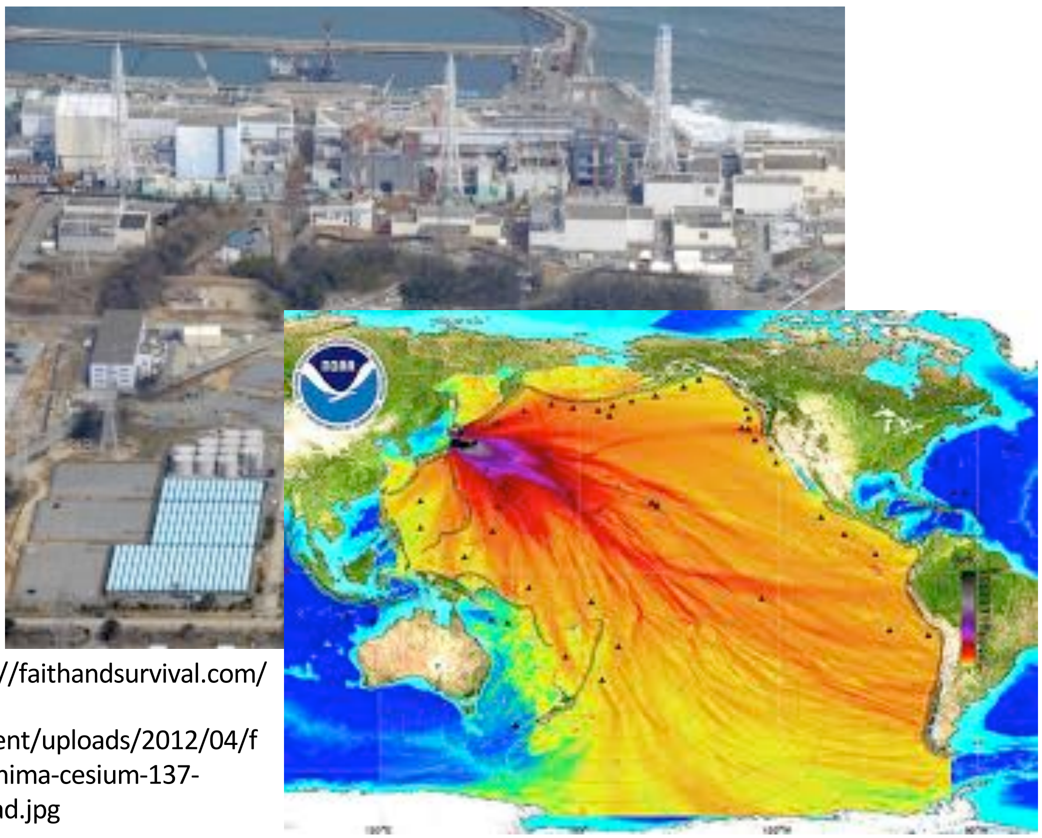
- Three favors of beta decay
- Energy spectrum of beta particles through beta decay
- Other processes involving beta emission, internal conversion, photoelectric effect and Auger electrons.
- Major health hazards related to beta emission

Understanding the Radiation from Cs-137

Decay scheme:

$$^{137}_{55}\mathrm{Cs} \rightarrow {}^{137}_{56}\mathrm{Ba} + {}^{0}_{-1}\beta + {}^{0}_{0}\bar{\nu}.$$

What will happen to the excited Ba-137 nucleus?



http://faithandsurvival.com/wp-content/uploads/2012/04/fukushima-cesium-137-spread.jpg

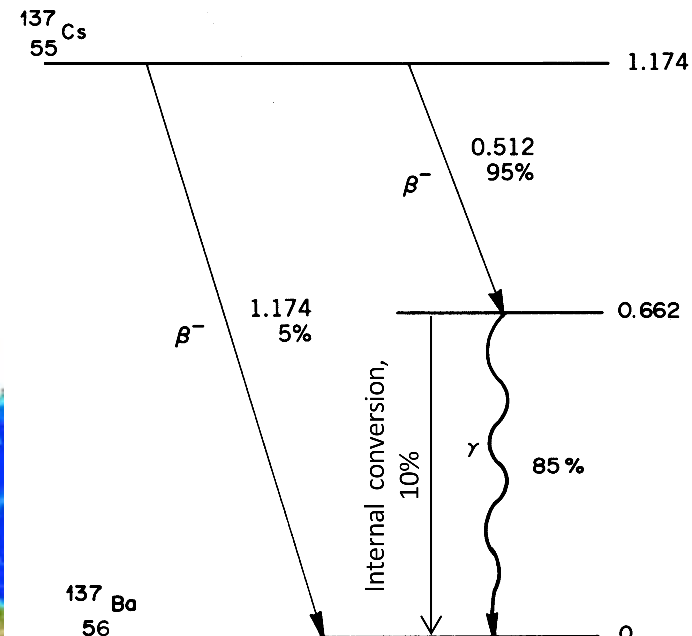
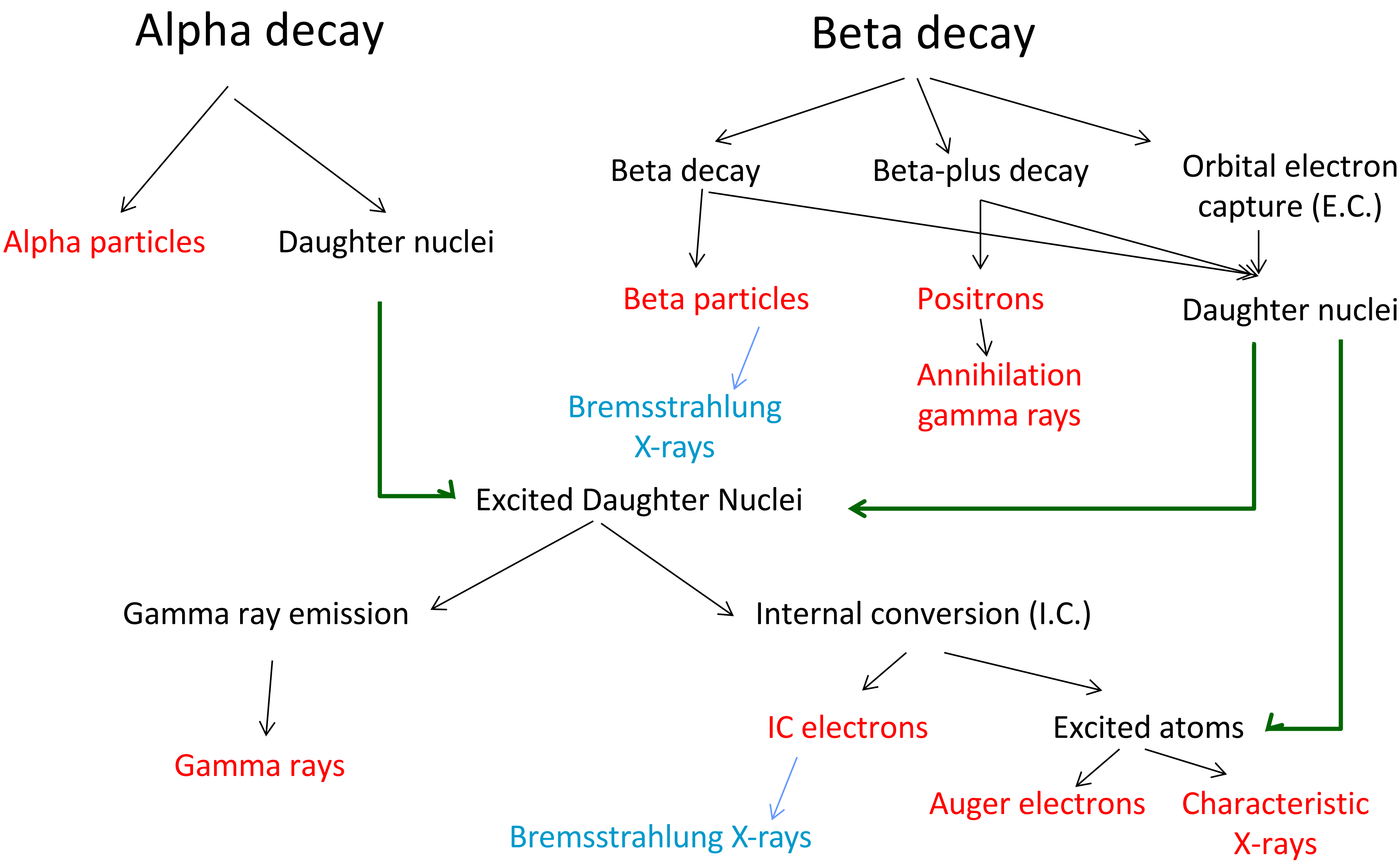


FIGURE 3.8. Decay scheme of $^{137}_{55}$Cs.

Typical Decay Products from Unstable Radioisotopes



Beta Radiation – Submersion Dose from Kr-85

An example. Cember, pp. 231.

Calculate the dose rate to the skin of a person immersed in a large cloud of ^{85}Kr at a concentration of 37 kBq/m^3 (10^{-6} μCi/mL).

$$\dot{D}_b = 2.45 \times 10^{-7} \times C \sum_i f_i \bar{E}_i e^{-\mu_{\beta i,t} \times 0.007} \frac{\text{mGy}}{\text{h}}$$

Solution

Krypton-85 is a pure beta emitter that is transformed to ^{85}Rb by the emission of a beta particle whose maximum energy is 0.672 MeV and whose average energy is 0.246 MeV. The tissue absorption coefficient is calculated with Eq. (6.21):

$$\mu_{\beta,\text{t}} = 18.6(0.672 - 0.036)^{-1.37} = 34.6 \text{ cm}^2/\text{g},$$

and the skin dose is calculated with Eq. (6.38):

$$\dot{D}_b = 2.45 \times 10^{-7} \times C \times \bar{E} \times e^{-(\mu_{\beta,\text{t}} \times 0.007)} \text{ mGy/h}$$

$$\dot{D}_b = 2.45 \times 10^{-7} \times 3.7 \times 10^4 \times 0.246 \times e^{-(34.6 \times 0.007)}$$

$$\dot{D}_b = 1.8 \times 10^{-3} \text{ mGy/h (0.18 mrads/h)}.$$

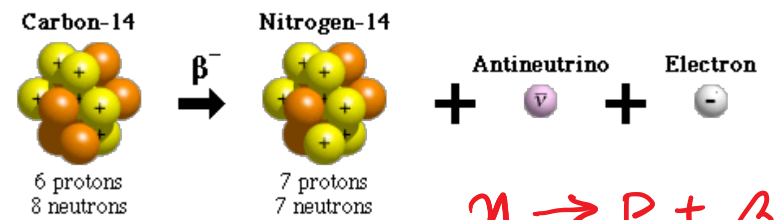
The Fukushima nuclear disaster is estimated to have released between 20-200 megacuries of Krypton 85 from three melted down reactors

Beta Emission

- Beta particle is an ordinary electron. Many atomic and nuclear processes result in the emission of beta particles.
- One of the most common source of beta particles is the beta decay of nuclides, in which

Beta decay

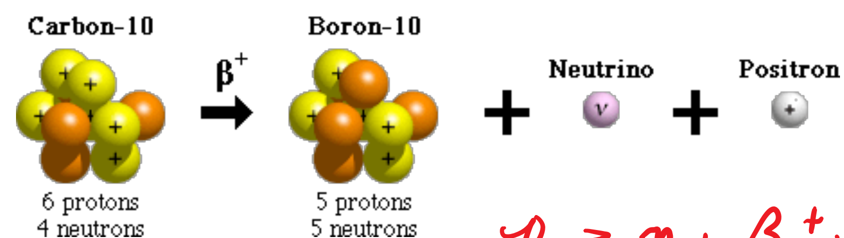
$$^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + {}^{0}_{-1}\beta + \overline{\upsilon}$$



$$n \rightarrow p + \beta^- + \overline{\upsilon}$$

Beta-plus decay

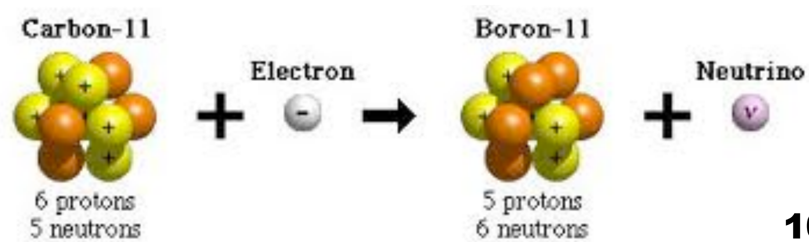
$$^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + {}^{0}_{1}\beta + \upsilon$$



$$p \rightarrow n + \beta^+ + \upsilon$$

Electron capture

$$^{A}_{Z}X + e^- \rightarrow {}^{A}_{Z-1}Y + \upsilon$$

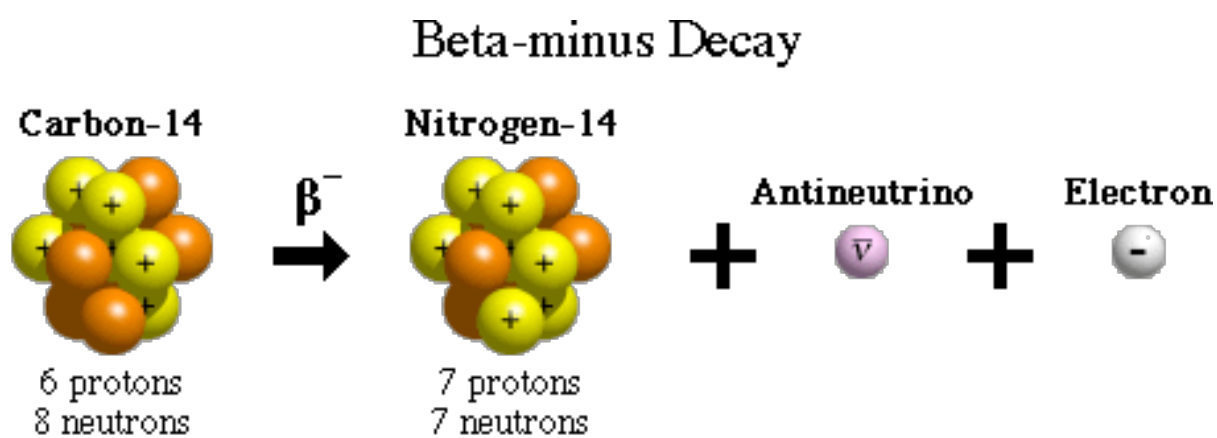


Energy Release of Beta Decay

The energy release in a beta decay is given as

$$Q = M_p - (M_d + M_e)$$

- The energy release is once again given by the conversion of a fraction of the mass into energy. Note that atomic electron bonding energy is neglected.
- For a beta decay to be possible, the energy release has to be positive.



Atomic Mass Unit

The atomic mass unit (symbol: u) or is the standard unit that is used for indicating mass on an atomic or molecular scale (atomic mass). One unified atomic mass unit is approximately the mass of one nucleon (either a single proton or neutron) and is numerically equivalent to 1 g/mol. It is defined as one twelfth of the mass of an unbound neutral atom of carbon-12 in its nuclear and electronic ground state, and has a value of $1.660538921 \times 10^{-27}$ kg.

Energy Release of Beta Decay

An example

$$ {}^{32}_{15}\mathrm{P} \rightarrow {}^{32}_{16}\mathrm{S} + {}^{0}_{-1}\mathrm{e} $$

The corresponding energy release is given by

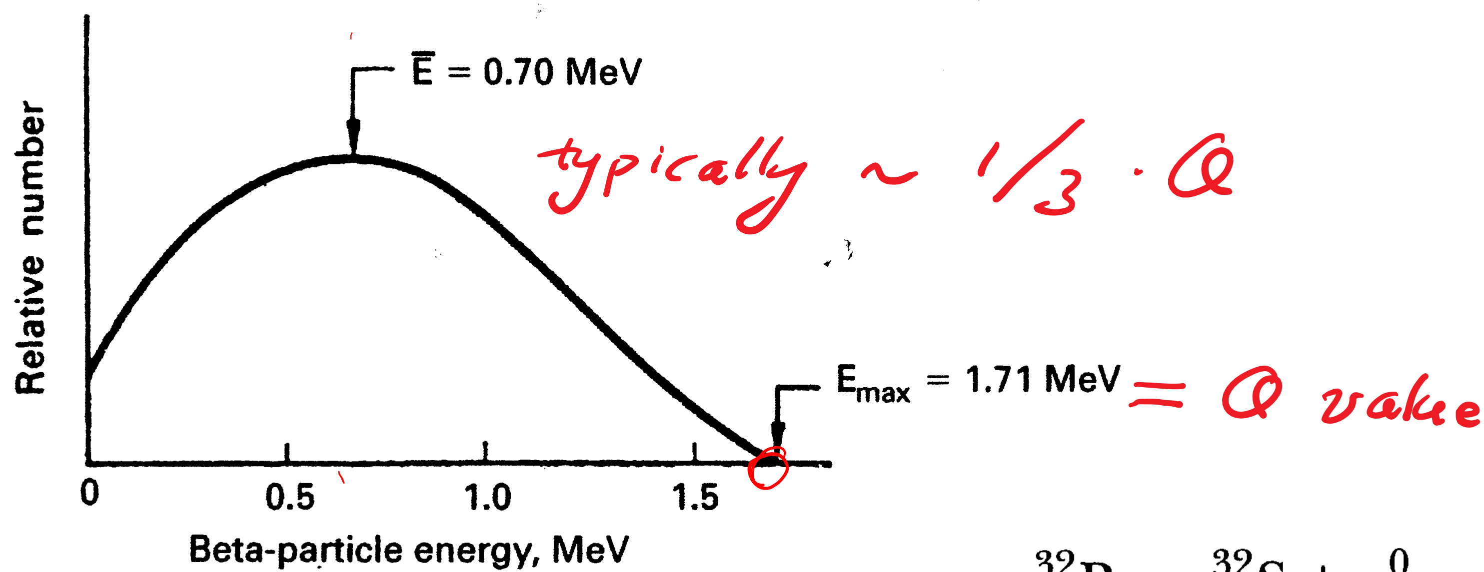
$$Q = M_p – M_d - M_e = 0.001837 \text{ AMU}$$

or equivalently

$$Q = 1.71 \text{ MeV}$$

Similar to the case of alpha decay, the energy shared by the recoil nucleus is $M_e/(M_p+M_e) \times Q$?? … So the electron generated will be mono-energetic ??

Typical Energy Spectrum of Beta Particles



$$^{32}_{15}P \rightarrow ^{32}_{16}S + ^{0}_{-1}e$$

The energy release is shared by all three daughter products. Due to the relatively large mass of the daughter nucleus, it attains only a small fraction of the energy. Therefore, the kinetic energy of the beta particle is

$$E_{\beta^-} \approx Q - E_{\bar{\nu}}$$

Examples for Beta Decay

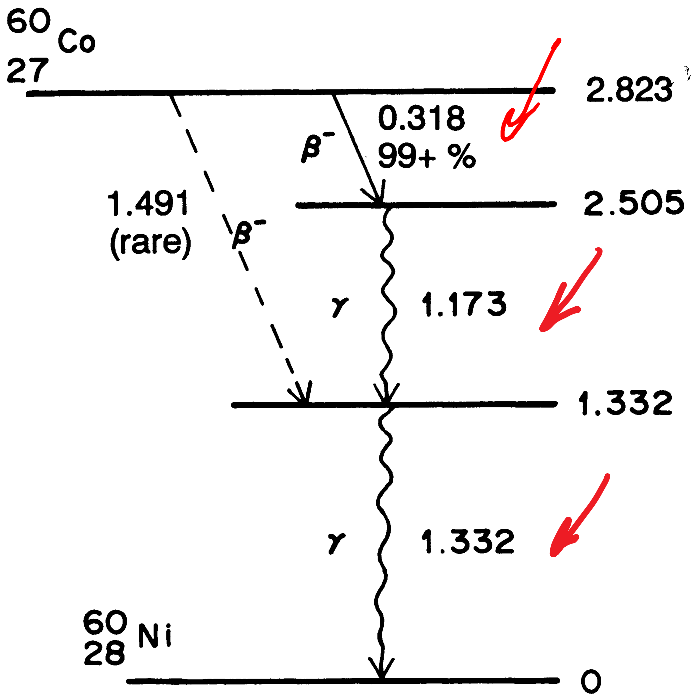


FIGURE 3.6. Decay scheme of $^{60}_{27}$Co.

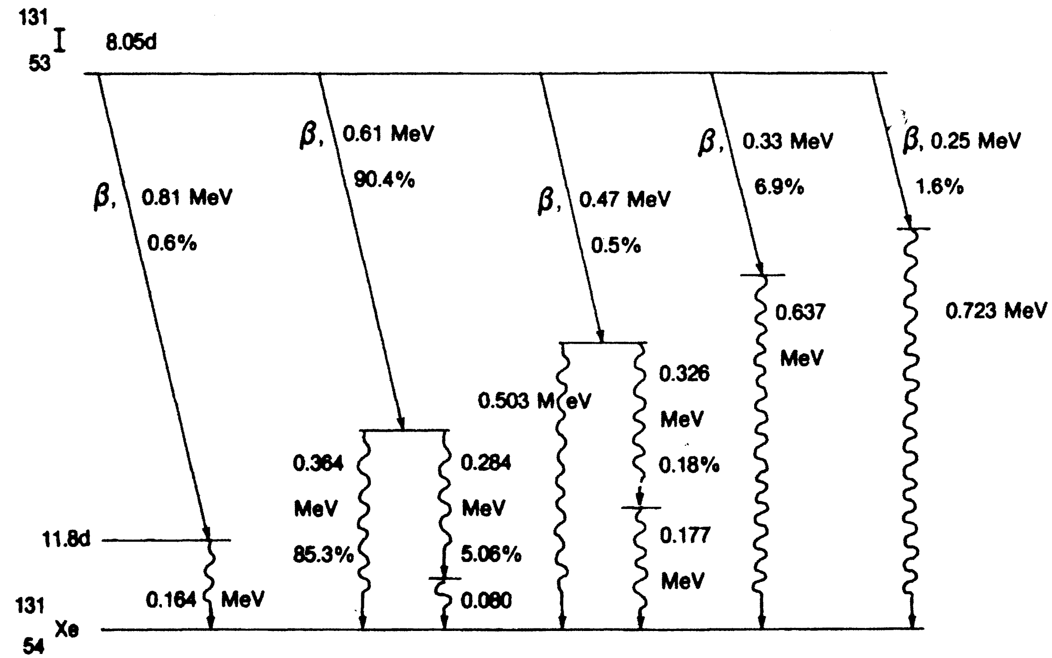


FIGURE 4.7. Iodine-131 transformation (decay) scheme.

- Beta emissions are normally associated with complicated decay schemes and the emission of other particles such as gamma rays.
- There exist the so called "pure beta emitters", such as ^{3}H, ^{14}C, ^{32}P and ^{90}Sr, which have no accompanying gamma rays.

Positron Emission

- A positron is the anti-particle of electrons, which carries the same mass as an electron but is positively charged.
- Positrons are normally generated by those nuclides having a relatively low neutron-to-proton ratio.
- An typical example of positron emitter is

$$^{22}_{11}Na \rightarrow ^{22}_{10}Ne + ^{0}_{1}\beta + \upsilon$$

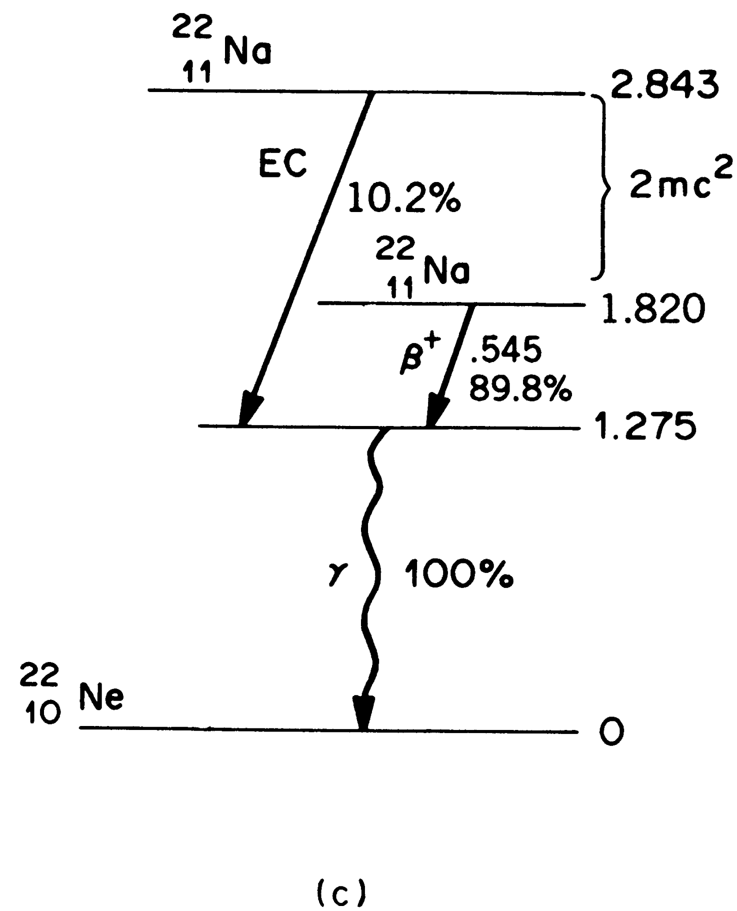
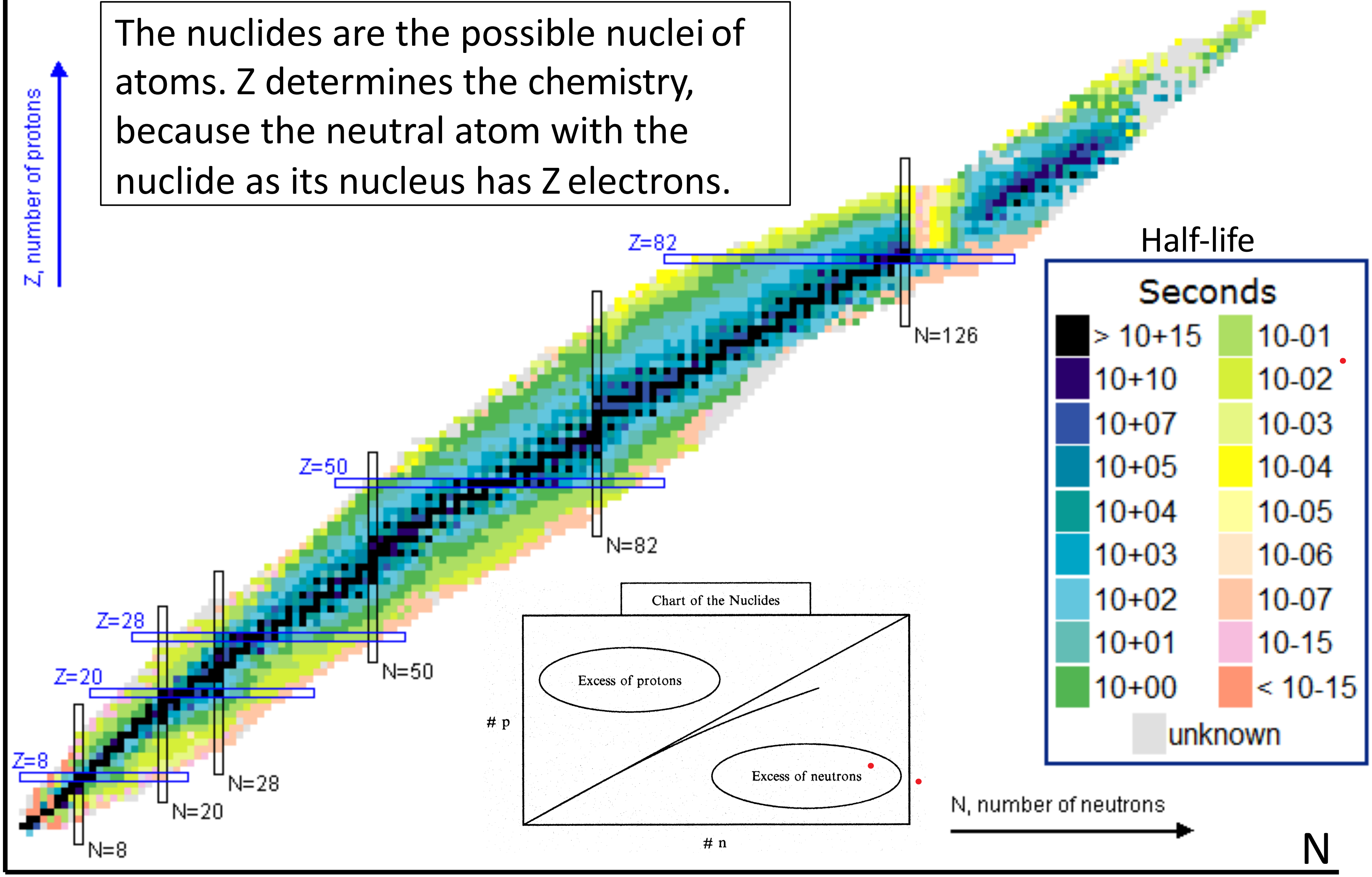


FIGURE 3.11. Decay scheme of $^{22}_{11}Na$.

Chart of the Nuclides

(177, 117)

The nuclides are the possible nuclei of atoms. Z determines the chemistry, because the neutral atom with the nuclide as its nucleus has Z electrons.



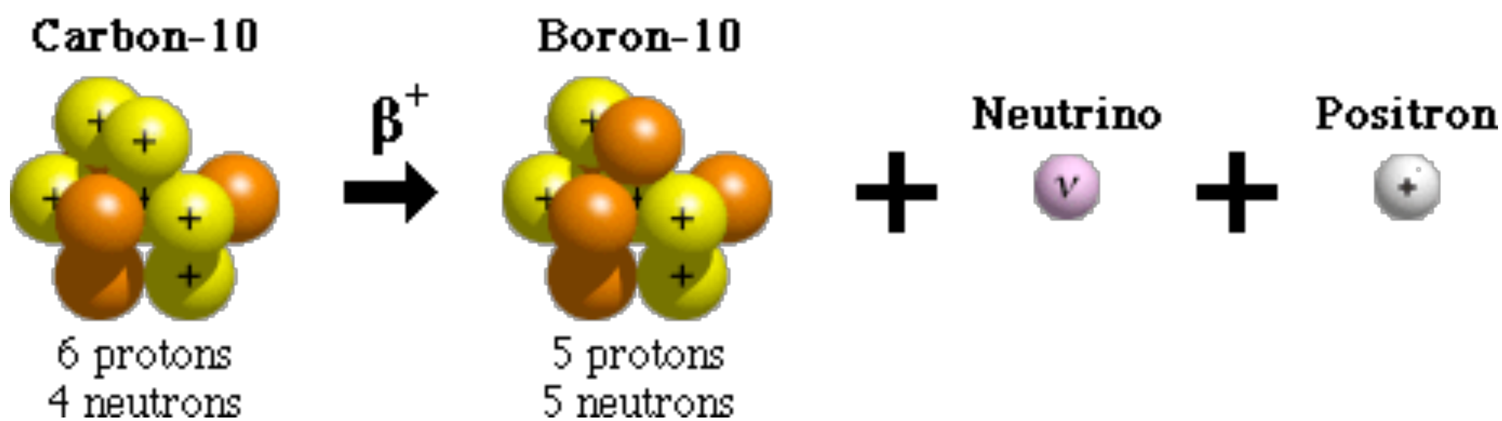
Source: http://www.nndc.bnl.gov/chart/reZoom.jsp?newZoom=5

Energy Release Through Positron Decay

The energy release Q associated with the positron emission process is given by

$$Q \approx M_p - M_d - M_e - M_{e^+} = M_p - (M_d + 2M_e)$$

where the atomic electron binding energy is ignored.



Orbital Electron Capture

In electron capture (EC), one of the atomic electrons is captured by the nucleus and unites with an proton to form an neutron with the emission of a neutron

$$ {}_{Z}^{A}X + e^{-} \rightarrow {}_{Z-1}^{A}Y + \upsilon $$

$$ {}_{-1}^{0}e + {}_{1}^{1}H \rightarrow {}_{0}^{1}n + \upsilon $$

- For neutron deficient atoms to attain stability through positron emission, it must exceed the weight of the daughter by at least two electron masses. If this condition can not be satisfied, the neutron deficiency can be overcome by the EC process.
- For example,

$$ {}_{46}^{103}\mathrm{Pd} + {}_{-1}^{0}\mathrm{e} \rightarrow {}_{45}^{103m}\mathrm{Rh} + {}_{0}^{0}\nu . $$

Positron Decay and Orbital Electron Capture are Competing Processes

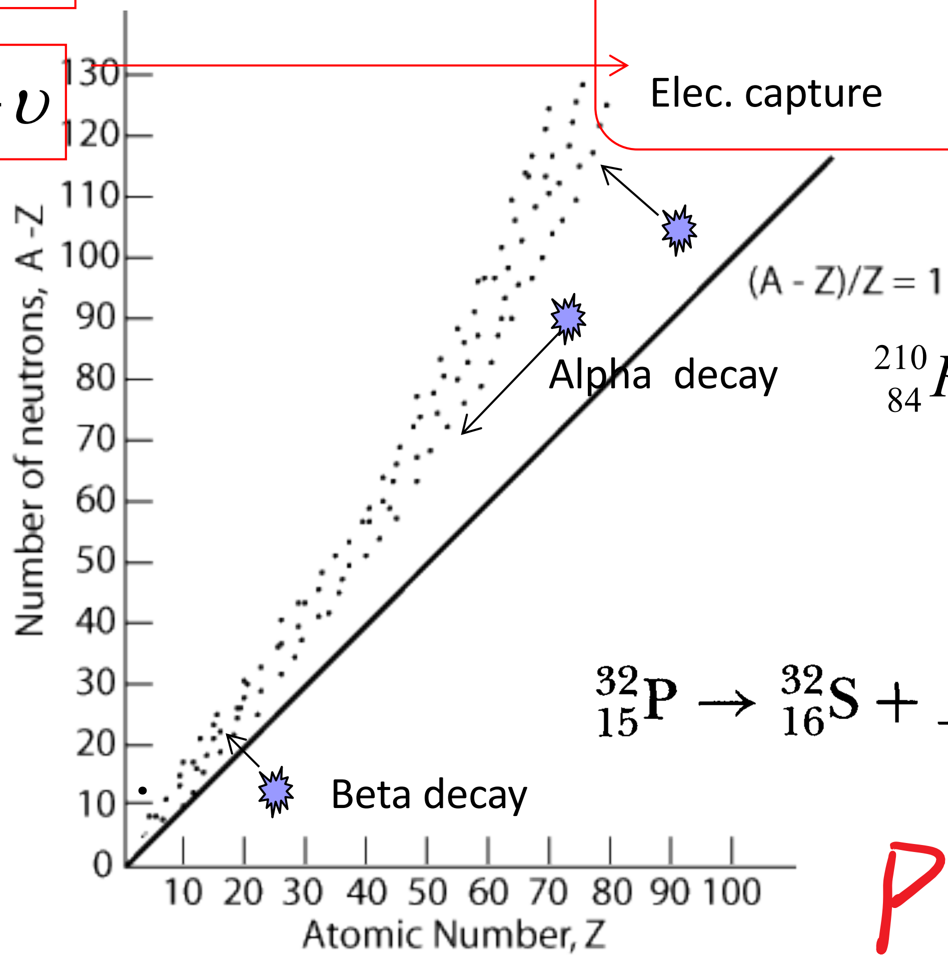
N

$${}^{1}_{1}p \rightarrow {}^{1}_{0}n + {}^{0}_{1}e + \overline{\upsilon}$$

$${}^{0}_{-1}e + {}^{1}_{1}p \rightarrow {}^{1}_{0}n + \upsilon$$

Positron decay $${}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + {}^{0}_{1}e + \upsilon$$

Elec. capture $${}^{A}_{Z}X + e^{-} \rightarrow {}^{A}_{Z-1}Y + \upsilon$$



$${}^{210}_{84}Po \rightarrow {}^{206}_{82}Pb + {}^{4}_{2}He$$

$${}^{32}_{15}\mathrm{P} \rightarrow {}^{32}_{16}\mathrm{S} + {}^{0}_{-1}\mathrm{e}$$

P

Energy Release Through Orbital Electron Capture

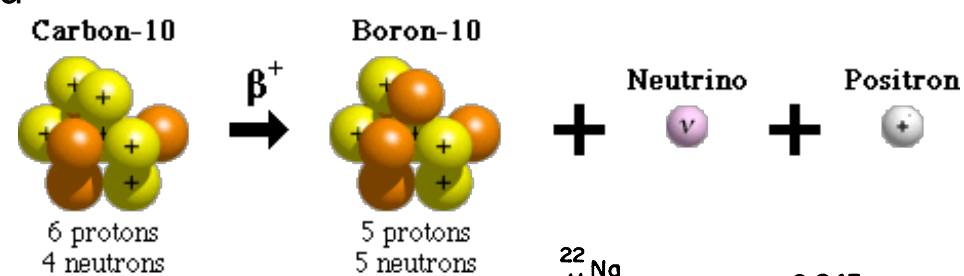
For positron decay to be possible, we need

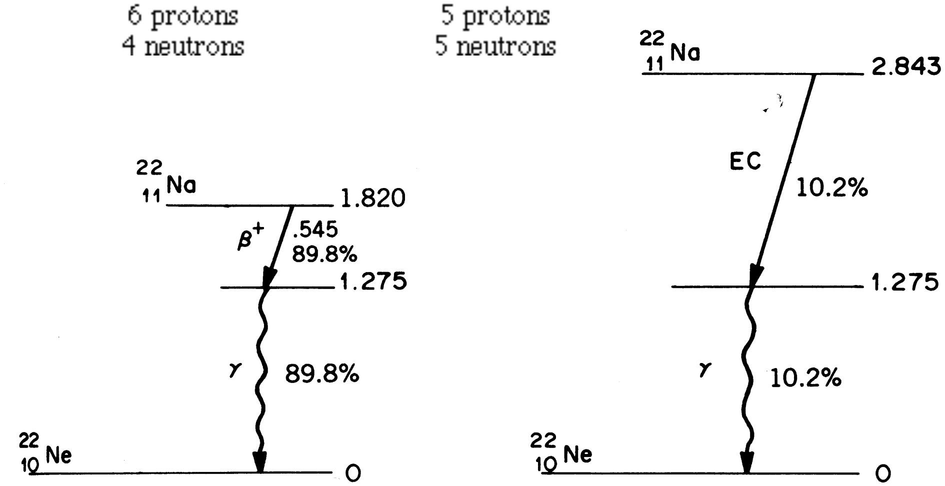
$$Q = M_p - M_d - M_e - M_{e^+} > 0,$$

so

$$M_p > M_d + M_e + M_{e^+} = M_d + 2M_e$$

M_p and M_d are the atomic masses of the parent and daughter atoms





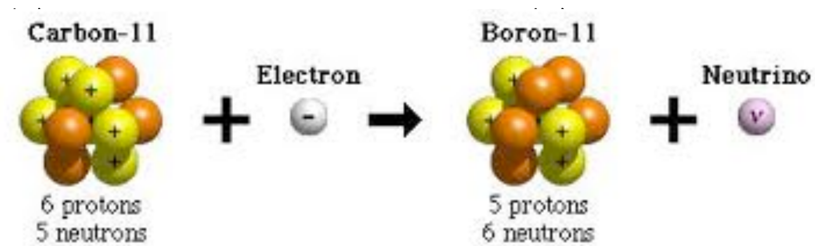
For Electron Capture to occur,

$$Q = M_p - M_d - \phi > 0$$

so that

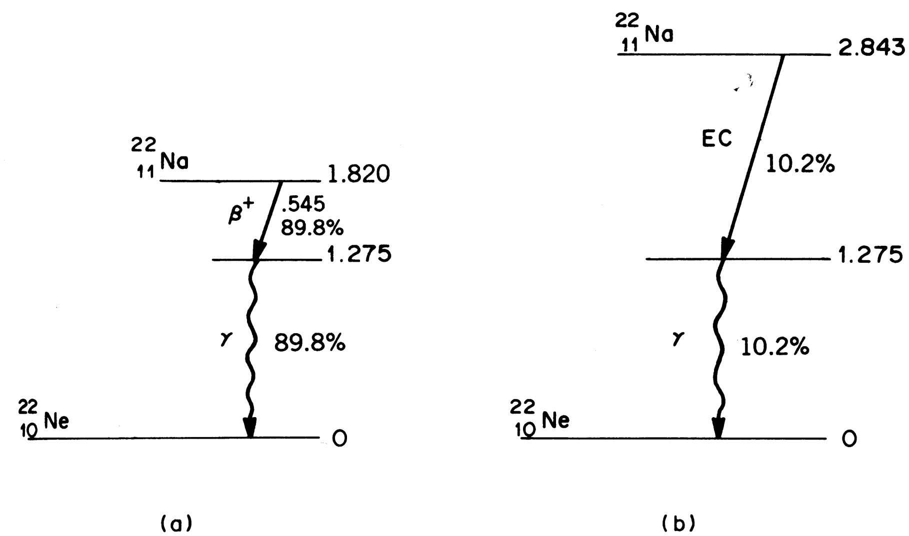
$$M_p > M_d + \phi$$

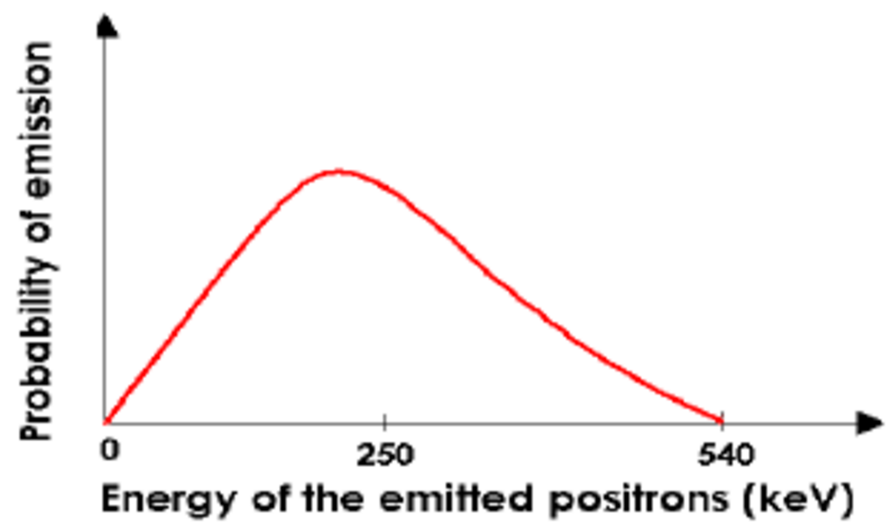
where ϕ is the binding energy of the orbital electron



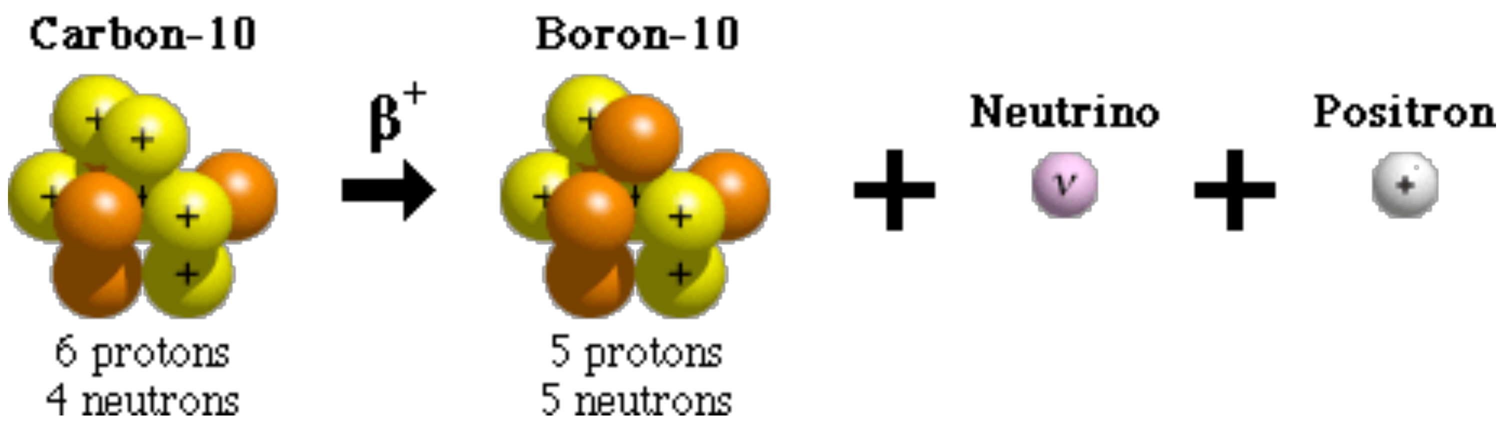
Orbital Electron Capture and Positron Decay

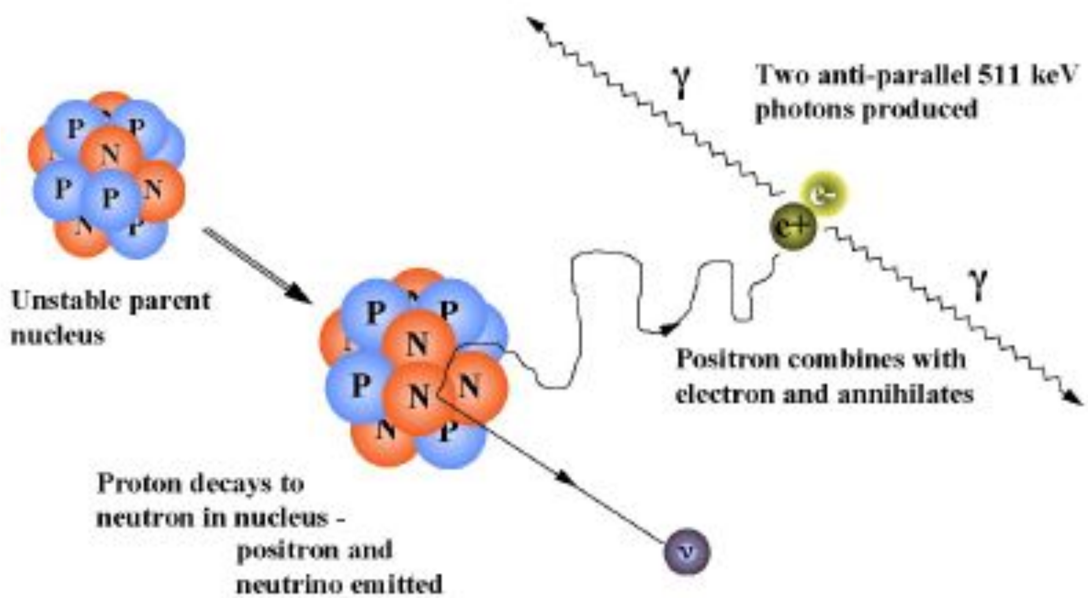
- Electron capture and positron decay are normally competing processes through which a neutron deficient nucleus may attain an increased stability.
- Both the emission of a positron and the capture of an electron, a neutrino is always emitted in order to conserve energy.
- In positron decay, the neutrino carries the difference between the energy release and the energy of the resultant positron. In electron capture, however, the neutrino must be mono-energetic.





Positron Annihilation following Positron Decay





Examples for Beta Decay

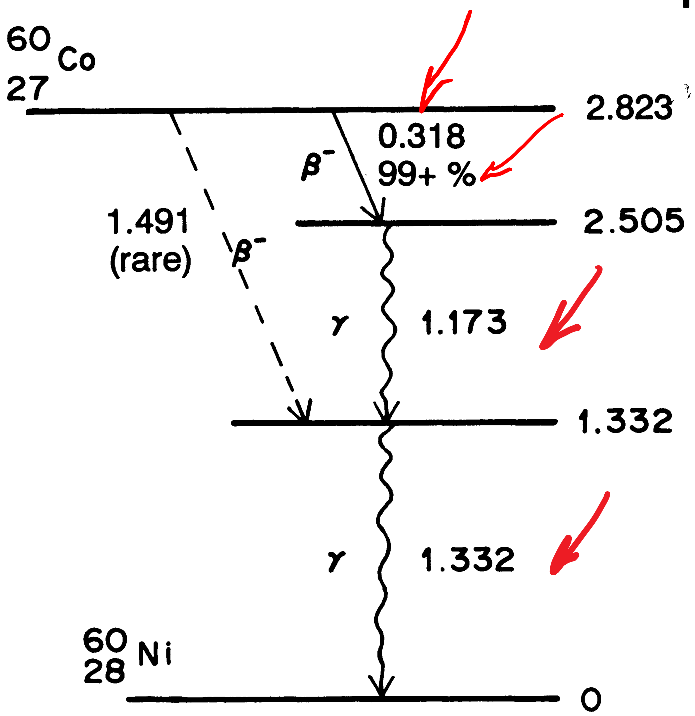


FIGURE 3.6. Decay scheme of $^{60}_{27}$Co.

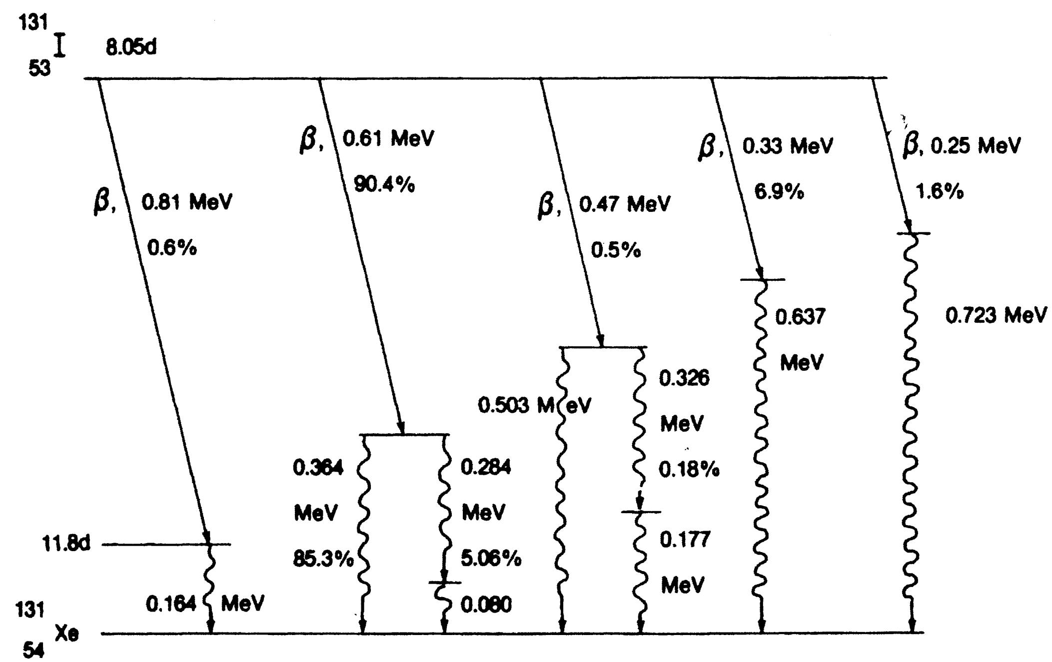


FIGURE 4.7. Iodine-131 transformation (decay) scheme.

- Beta emissions are normally associated with complicated decay schemes and the emission of other particles such as gamma rays.

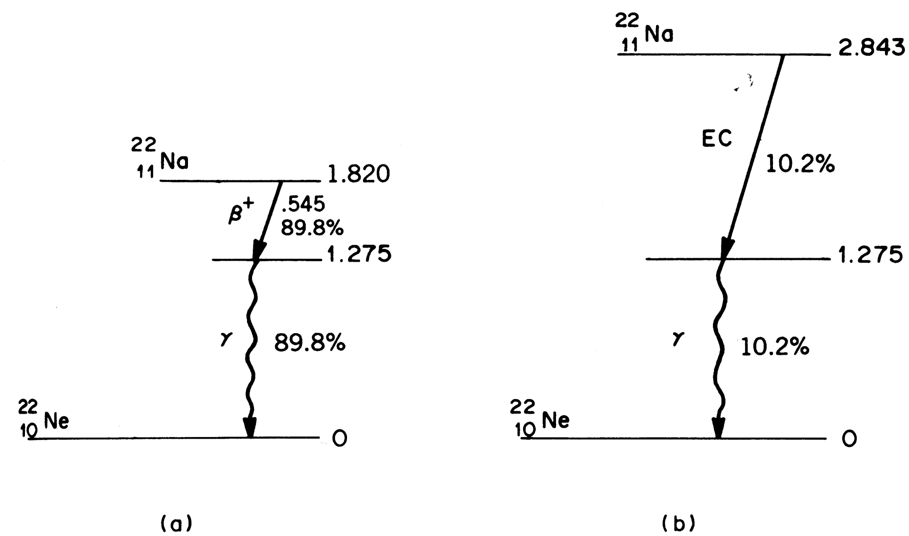
- There exist the so called "pure beta emitters", such as ^{3}H, ^{14}C, ^{32}P and ^{90}Sr, which have no accompanying gamma rays.

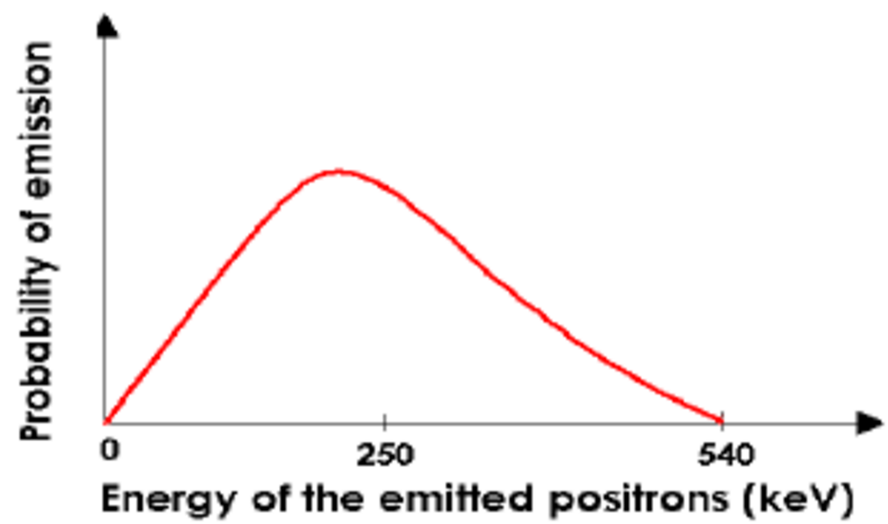
Orbital Electron Capture and Positron Decay (Revisited)

- Electron capture and positron decay are normally competing processes through which a neutron deficient nucleus may attain an increased stability.

- Both the emission of a positron and the capture of an electron, a neutrino is always emitted in order to conserve energy.

- In positron decay, the neutrino carries the difference between the energy release and the energy of the resultant positron. In electron capture, however, the neutrino must be mono-energetic.





An Example

24. Nuclide A decays into nuclide B by β^+ emission (24%) or by electron capture (76%). The major radiations, energies (MeV), and frequencies per disintegration are, in the notation of Appendix D:

β^+: 1.62 max (16%), 0.98 max (8%)

γ: 1.51 (47%), 0.64 (55%), 0.511 (48%, $\gamma^{\pm}$)

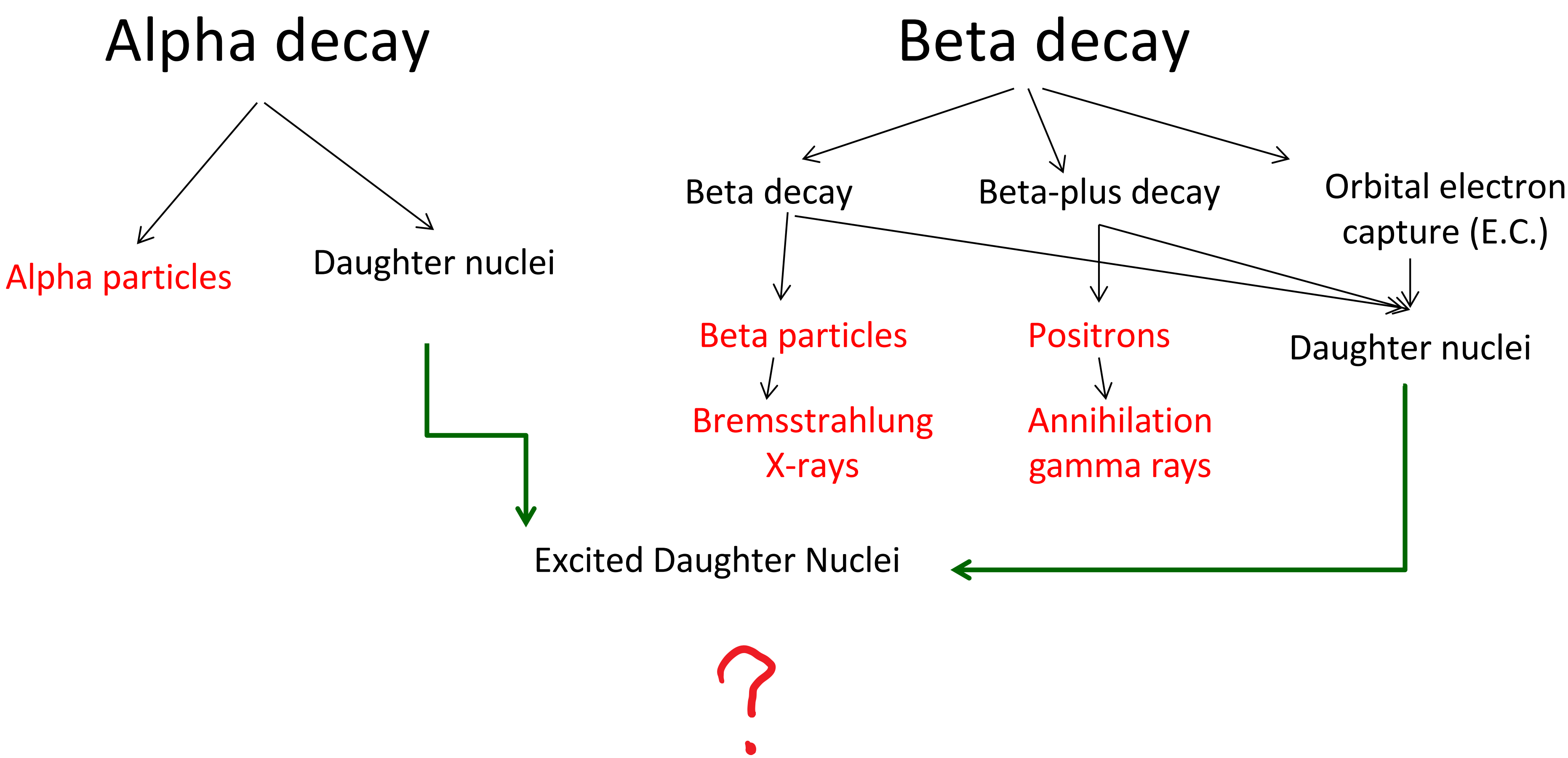
Daughter X rays

e^-: 0.614

(a) Draw the nuclear decay scheme, labeling type of decay, percentages, and energies.

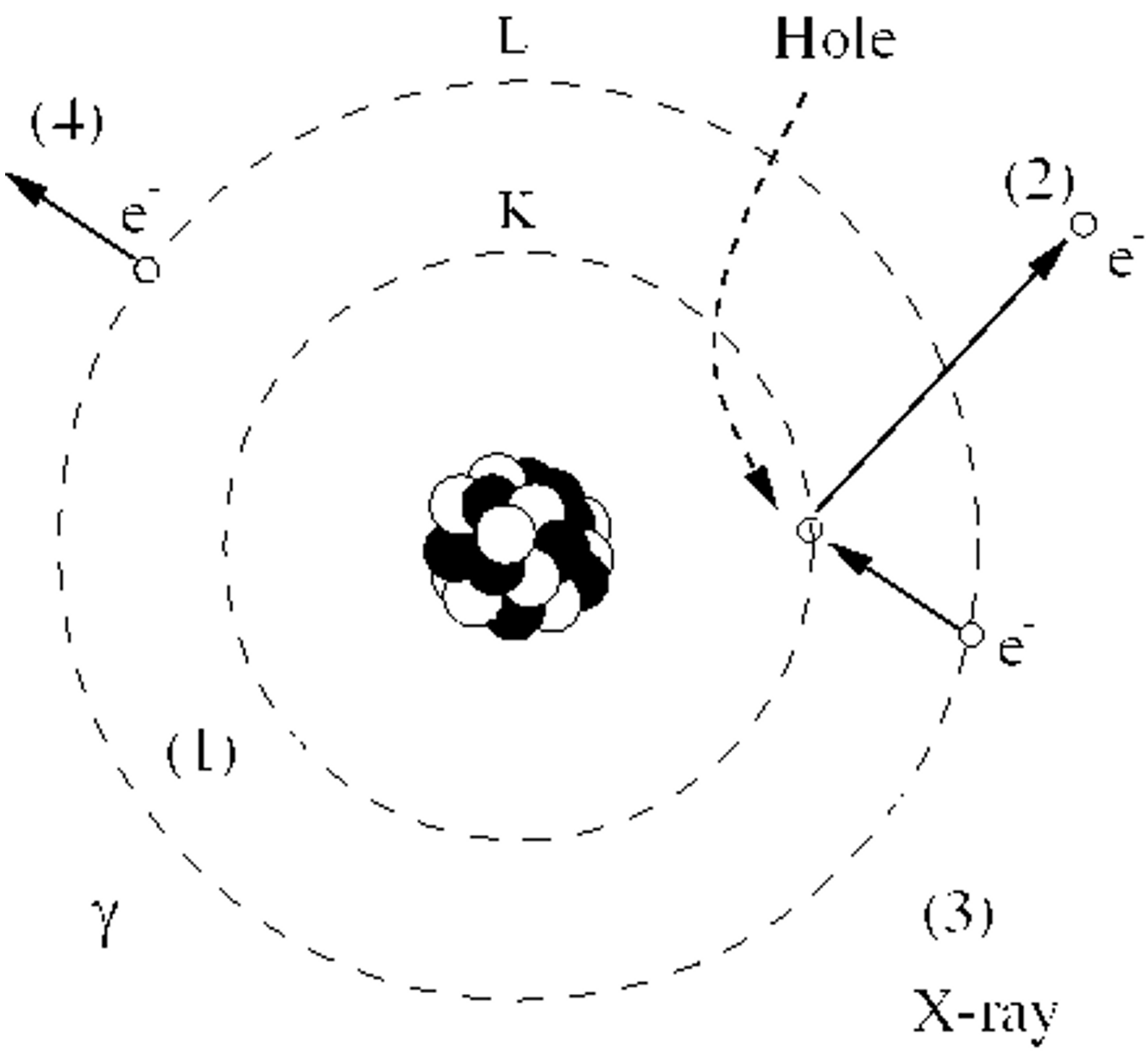
(b) What leads to the emission of the daughter X rays?

Typical Decay Products from Unstable Radioisotopes



Gamma Ray Emission following Beta Decay

Excited Nucleus vs Excited Atom



Internal Conversion

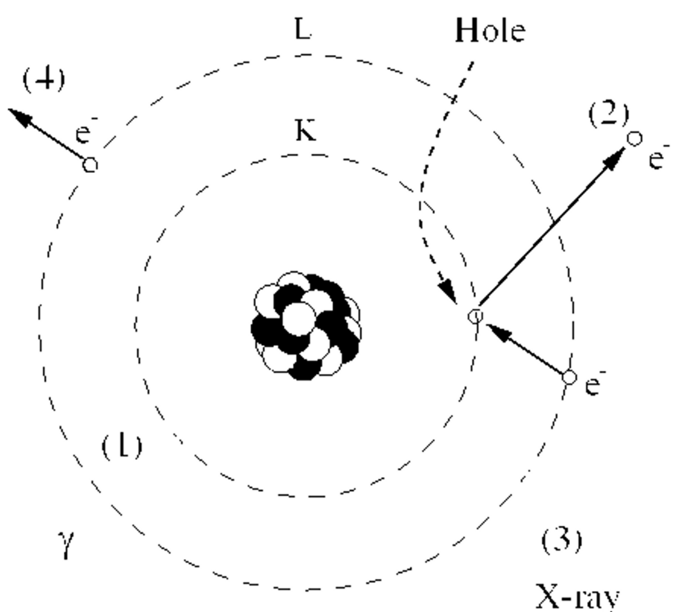
An excited nucleus

De-excite through the emission of a gamma ray

➔ Gamma Ray Emission

The excitation energy is transferred directly to an orbital electron, causing it to be ejected from the atom

➔ Internal Conversion



Conversion electron with an energy

$$E_{\beta^-} = E_{ex} - E_b$$

$$\text{IC Coefficient (or Branching Ratio)} = \frac{N_\gamma}{N_e}$$

Gamma Ray Emission

- Gamma rays are emitted from nuclei following the transition between different nuclear states.
- Gamma rays are emitted with discrete energy. A gamma ray spectrum is characteristic to the particular radionuclide that are present.

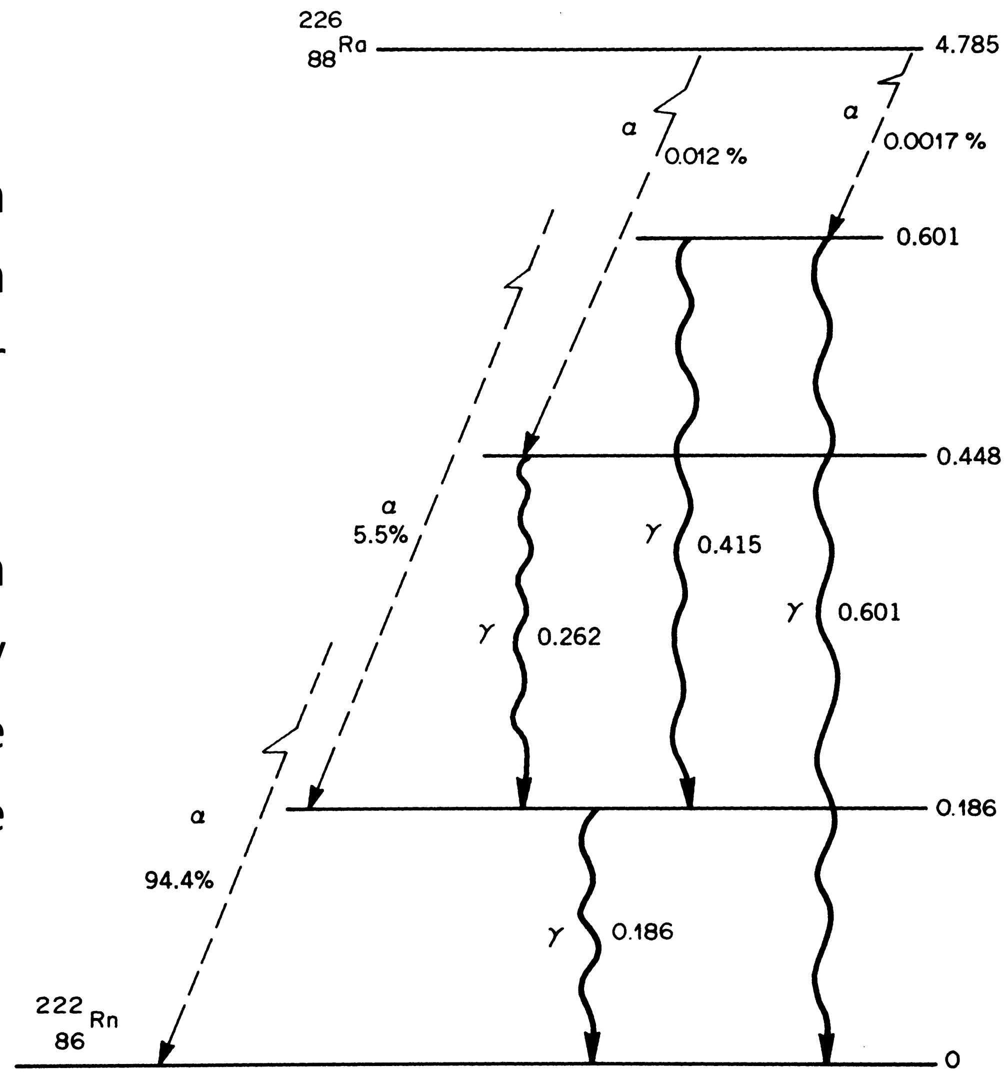


FIGURE 3.7. Detailed decay scheme for $^{226}_{88}$Ra, showing origin of photons found in its gamma spectrum (position of initial $^{226}_{88}$Ra energy level not to scale).

Metastable Nuclear States and Gamma Ray Emission

The lifetimes of nuclear excited states vary, but $\sim 10^{-10}$ s can be regarded as typical. Thus, gamma rays are usually emitted quickly after radioactive decay to an excited daughter state.

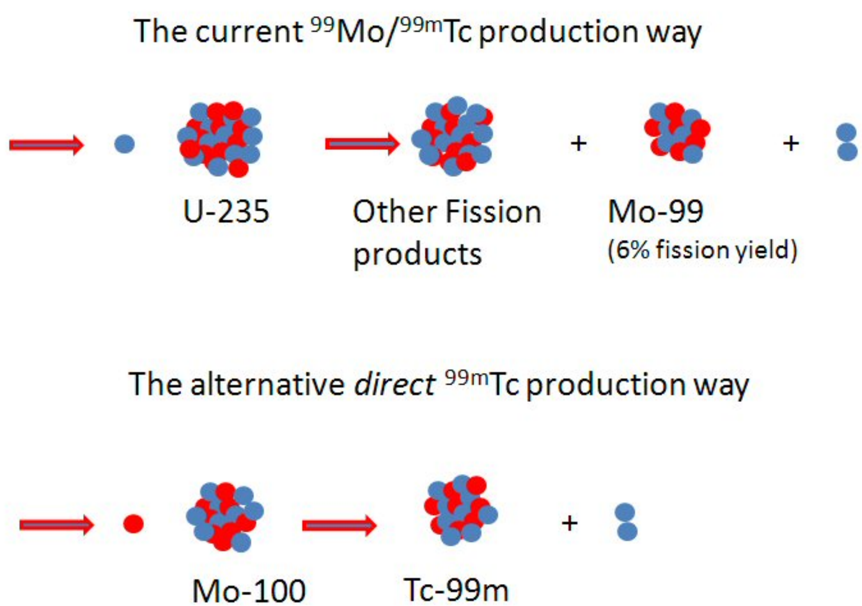
In some cases, however, selection rules prevent photon emission for an extended period of time. The excited state of $^{137}_{56}Ba$ following the decay of $^{137}_{55}Cs$ has a half-life of 2.55 min. Such a long-lived nuclear state is termed *metastable* and is designated by the symbol m: $^{137m}_{56}Ba$.

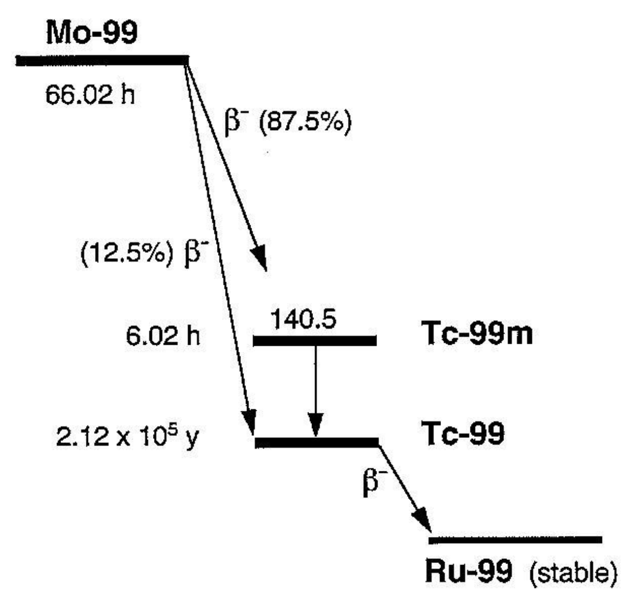
Another example of a metastable nuclide is $^{99m}_{43}Tc$, which results from the beta decay of the molybdenum isotope $^{99}_{42}Mo$.

Important Gamma Ray Emitter: Tc-99m

Decay scheme: $$^{99m}_{43}\mathrm{Tc} \rightarrow {}^{99}_{43}\mathrm{Tc} + {}^{0}_{0}\gamma.$$

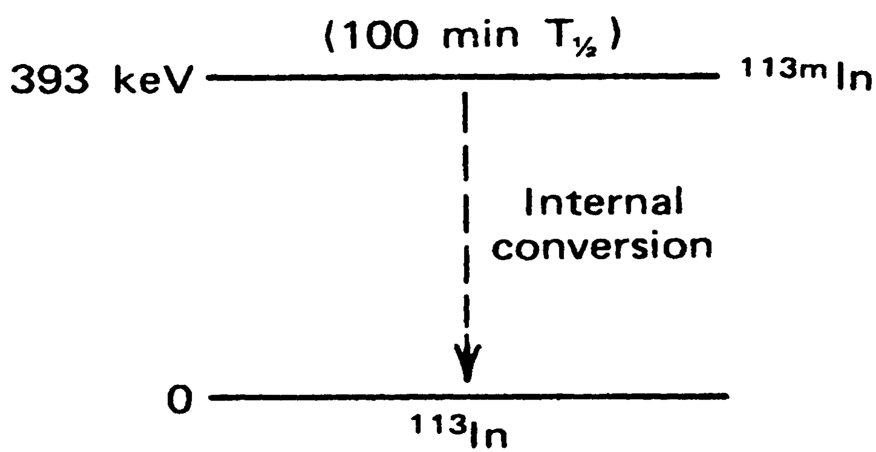
- Tc-99m accounts for >90% of imaging studies in nuclear medicine and therefore subject to extensive dosimetry study.
- Half-life: ~6h; gamma energy: 140keV, both ideal for imaging applications.
- Tc-99m is obtained from the decay of the molybdenum isotope ^{99}Mo.

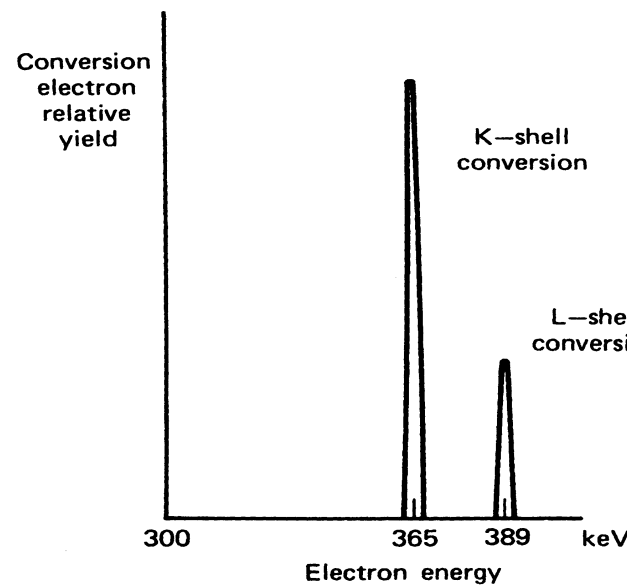




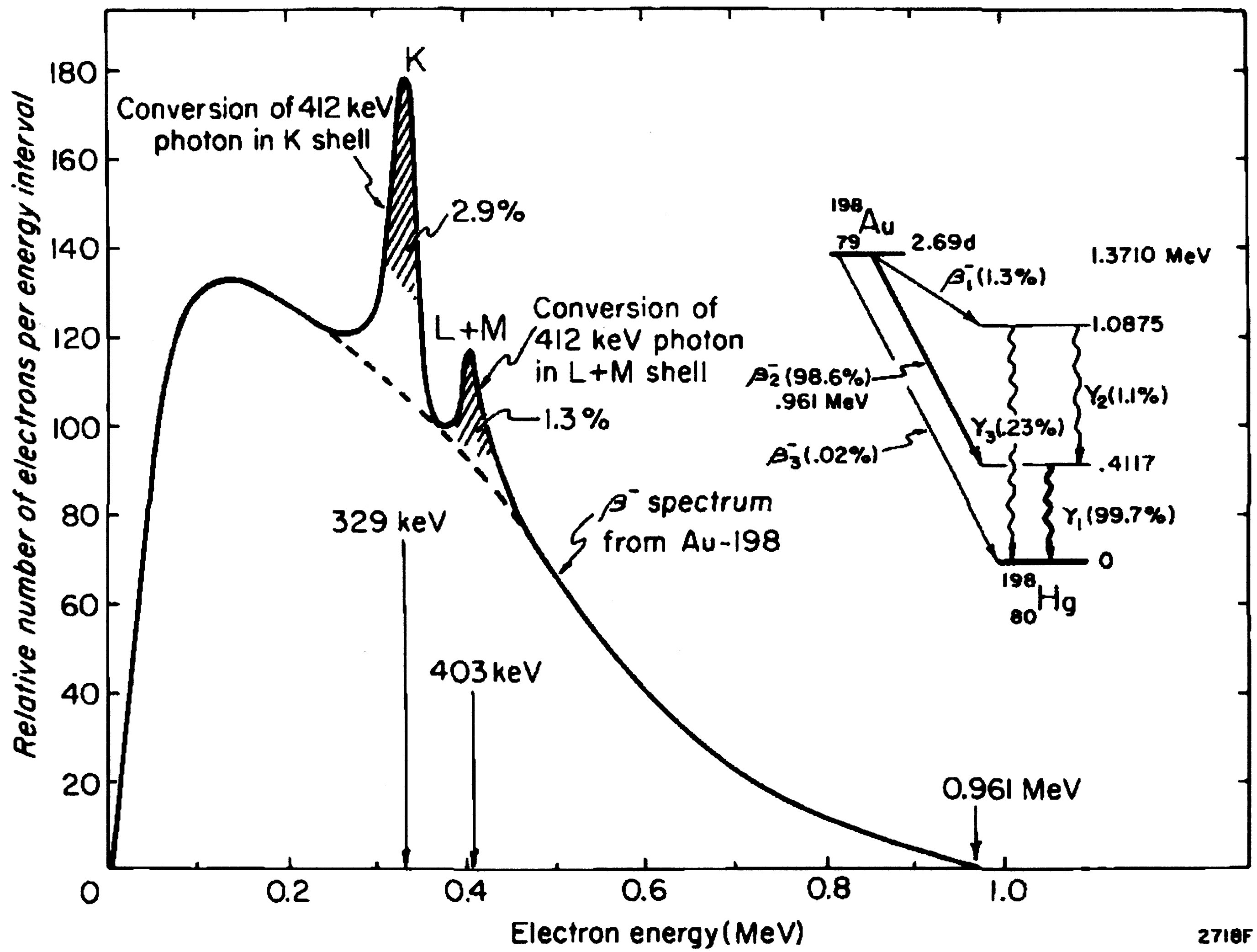
Internal Conversion

- Conversion electrons can originate from several different electron shells within the atom, a single excited state generally leads to several groups of electrons with different energies.
- The only practical laboratory scale source of mono-energetic electron groups in high keV to MeV energy range.



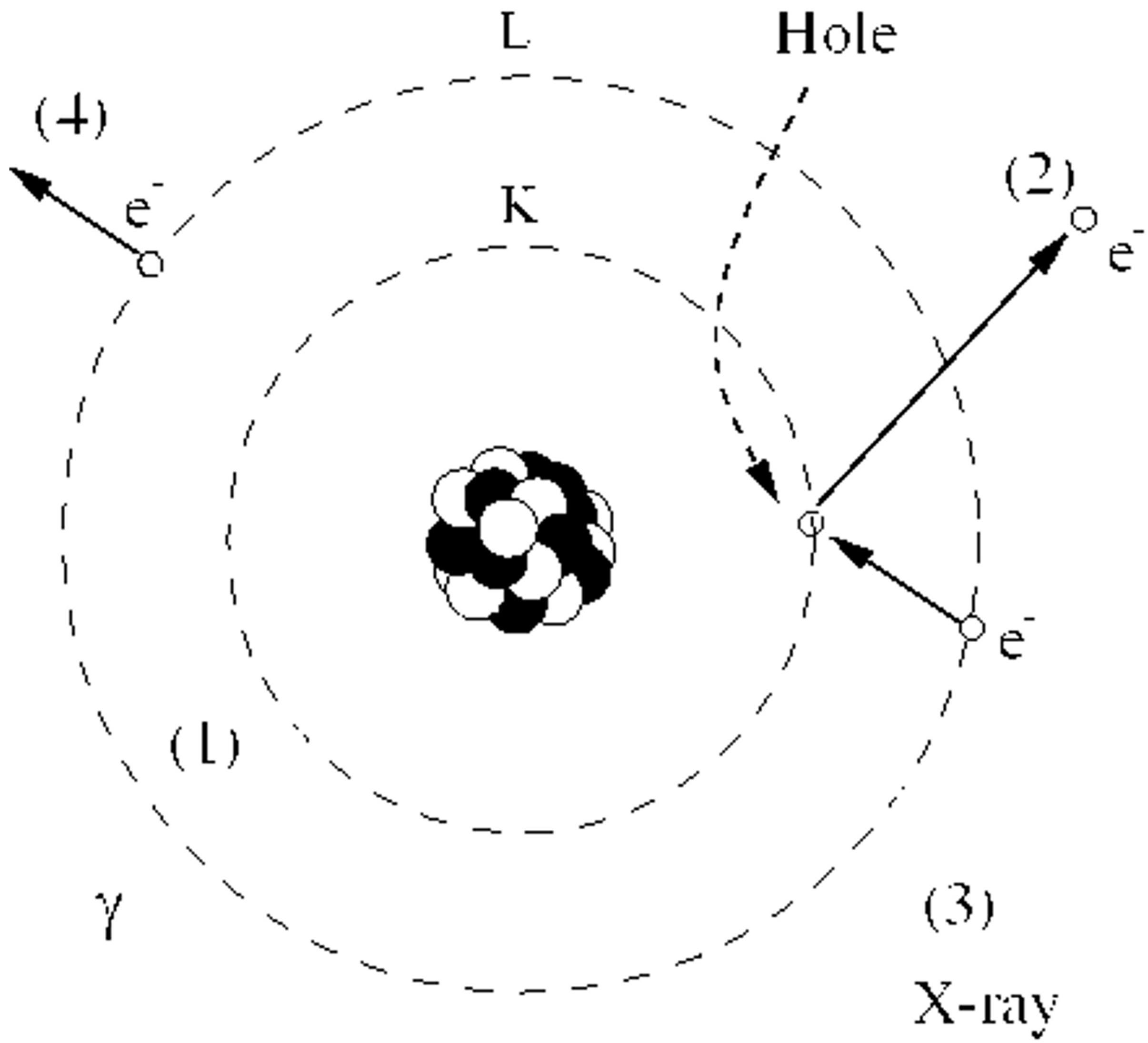


Internal Conversion



From The Physics of Radiology, Fourth Edition.

Excited Nucleus vs Excited Atom



Auger Electrons

- The excitation energy of the atom may be transferred to one of the outer electrons, causing it to be ejected from the atom.
- Auger electrons are roughly the analogue of internal conversion electrons when the excitation energy originates in the atom rather than in the nucleus.

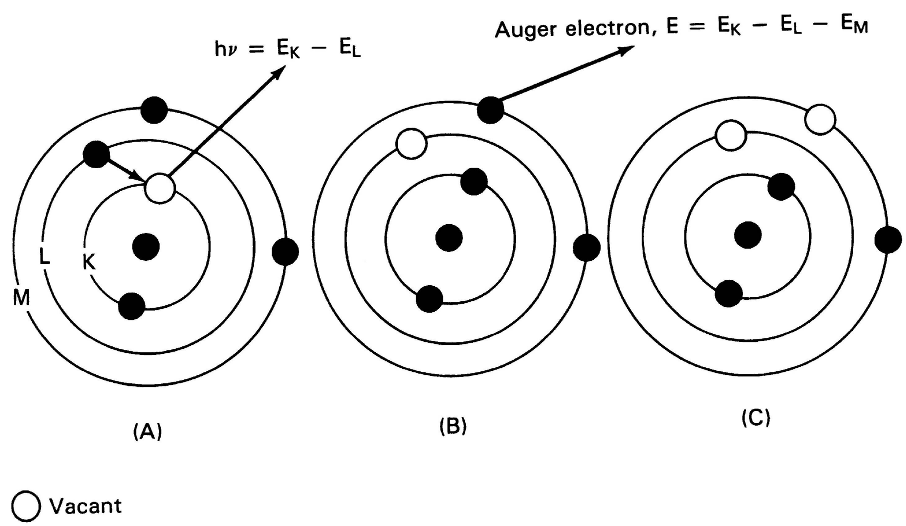
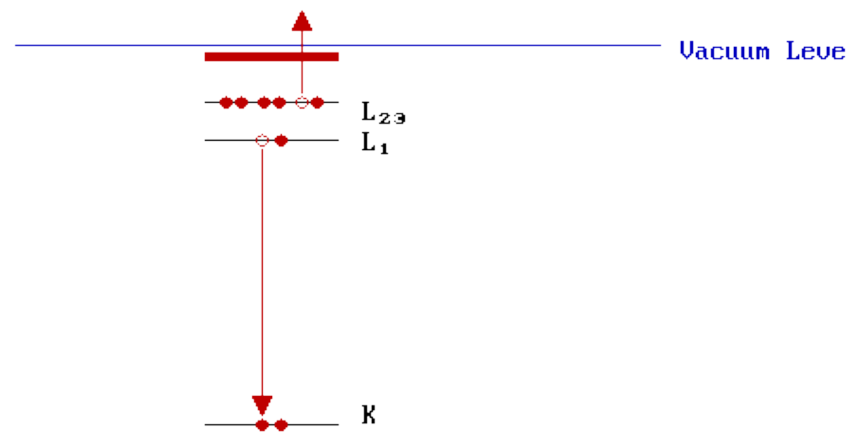


Figure 3.7 (A) The usual emission of a K characteristic X-ray, $h\nu$, energy equal to $E_K - E_L$, the difference in binding energy for the two orbital electrons, K and L. (B) $h\nu$ has been absorbed and a monoenergetic Auger electron is emitted, in the example shown, from the M shell, the energy of which is $E_K - E_L - E_M$. (C) In its final state the atom has vacancies in the L and M orbitals.



$$E_{a.e.} = (E_K - E_{L_1}) - E_{L_{23}}$$

Auger Electrons

The relative probability of the emission of characteristic radiation to the emission of an Auger electron is called the fluorescent yield, ω:

$$\omega_K = \frac{\text{Number K x ray photons emitted}}{\text{Number K shell vacancies}} \qquad (3\text{-}12)$$

Values for ω_K are given in Table 3-1. We see that for large Z values fluorescent radiation is favored, while for low values of Z Auger electrons tend to be produced.

From this table we see that if a nucleus with Z = 40 had a K shell hole, then on the average 0.74 fluorescent photons and 0.26 Auger electrons would be emitted.

TABLE 3-1
Fluorescent Yield

Z	ω_K	Z	ω_K	Z	ω_K
10	0	40	.74	70	.92
15	.05	45	.80	75	.93
20	.19	50	.84	80	.95
25	.30	55	.88	85	.95
30	.50	60	.89	90	.97
35	.63	65	.90		

From Evans (E1)

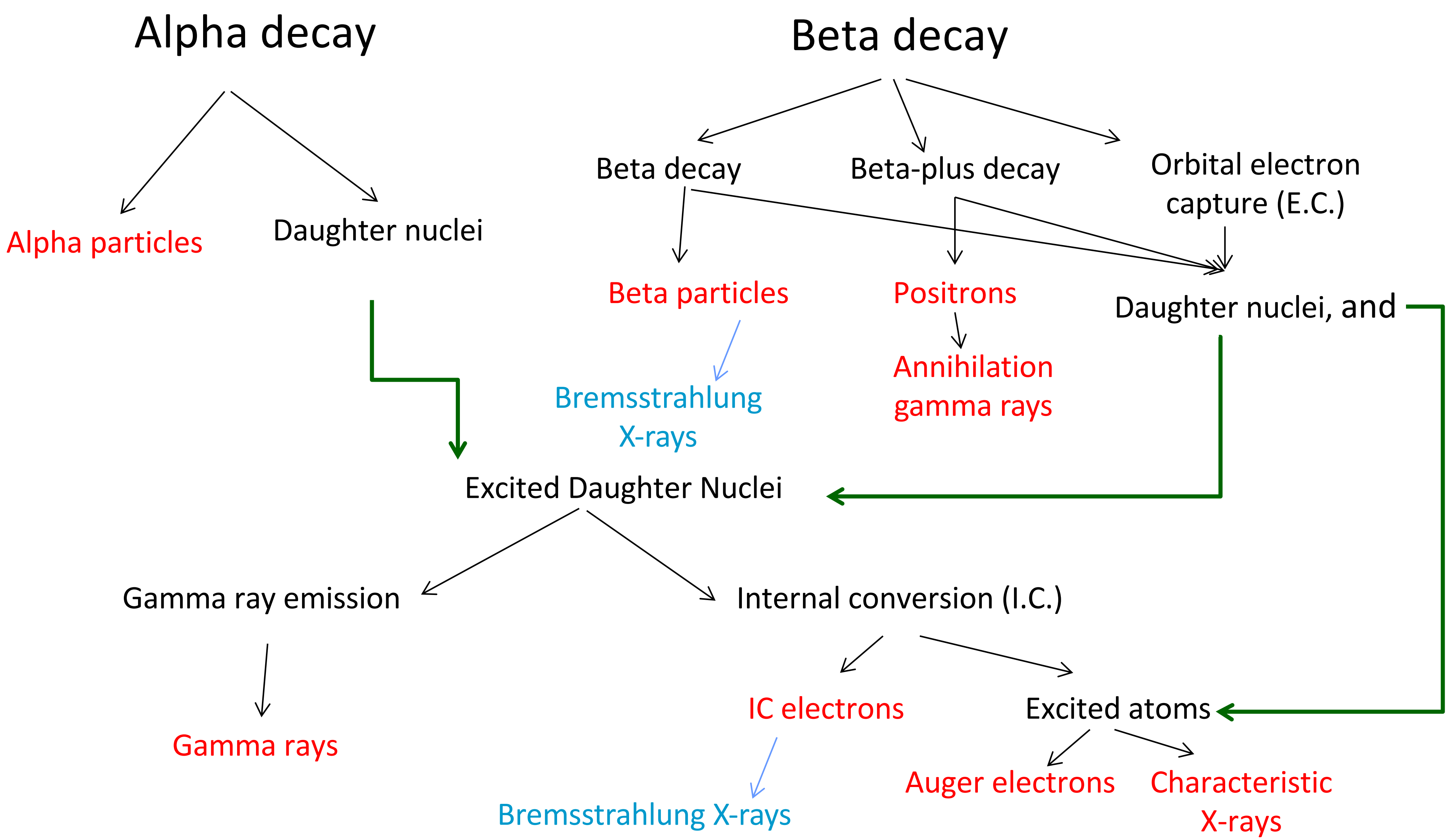
Radiation Concerns of Beta Particles

- Energetic beta particles may penetrate the skin and lead to external hazard. In general, beta particles with an energy less than 200keV (such as from ^{35}S and ^{14}C) are not considered to be external radiation hazard. If deposited inside the body, beta particles normally lead to a certain degree of radiation exposure.

- Beta emitters may also emit gamma rays that leads to extra radiation exposure. For example, beta-decay of Co-60 leads to gamma emission…

- Beta particles in the MeV range also interact with surrounding materials (especially those contain high Z elements) through bremsstrahlung and therefore induces x-rays. So extra care has to be taken for a proper shielding of an energetic beta source.

Typical Decay Products from Unstable Radioisotopes

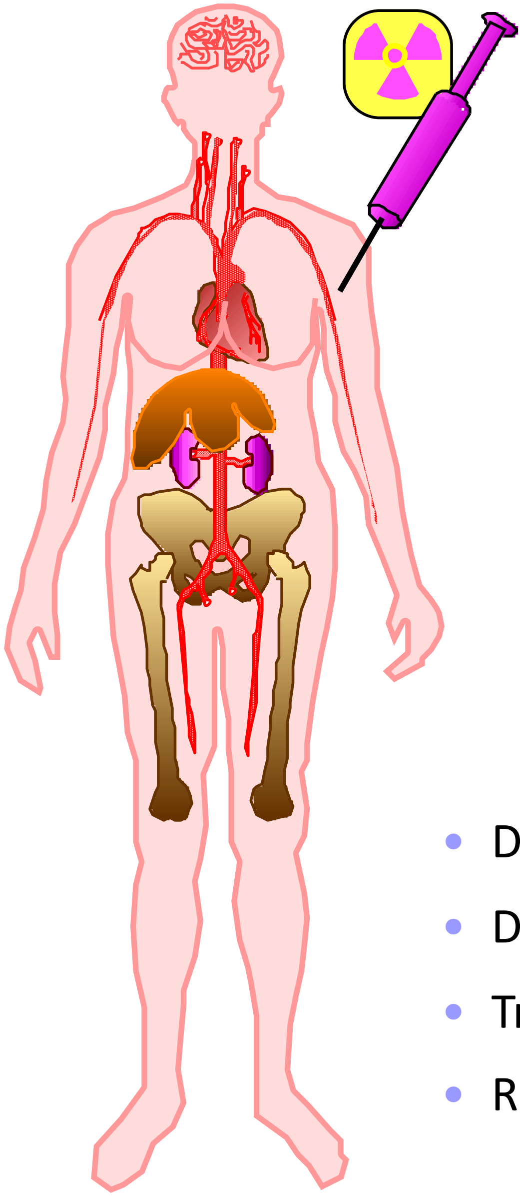


Potential Health Hazards from Beta Particles

Health Concerns Related to Beta Particles

- Beta particles often carry a sufficient amount of sufficient energy to penetrate the skin and thus be an external radiation hazard.
- Internal beta emitters are also a hazard.
- Beta-decays are often accompanied by gamma emission.
- Some beta decays could also lead to secondary transformations, such as internal conversion (IC), which give rise to further beta emissions …
- beta decay typically leads to X-ray emission …

Radiation Risk from Medical Procedures
Single Photon Emission Computed Tomography

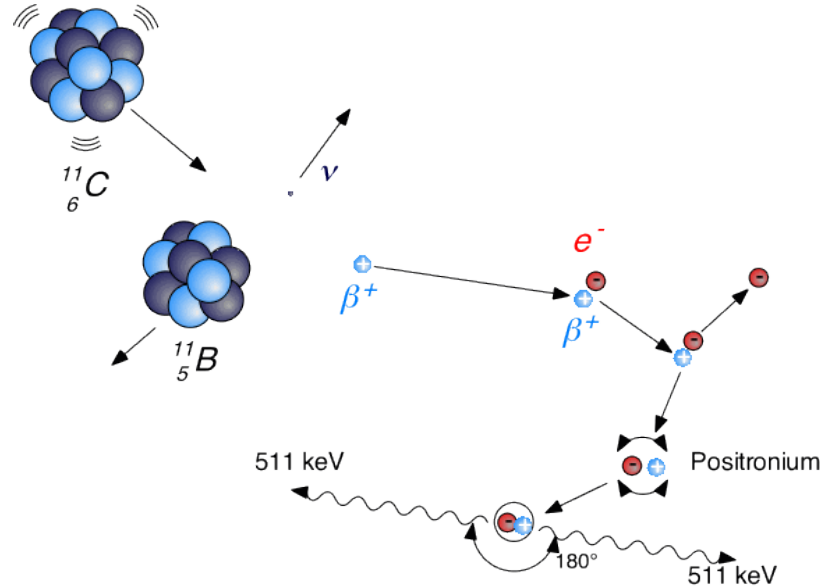


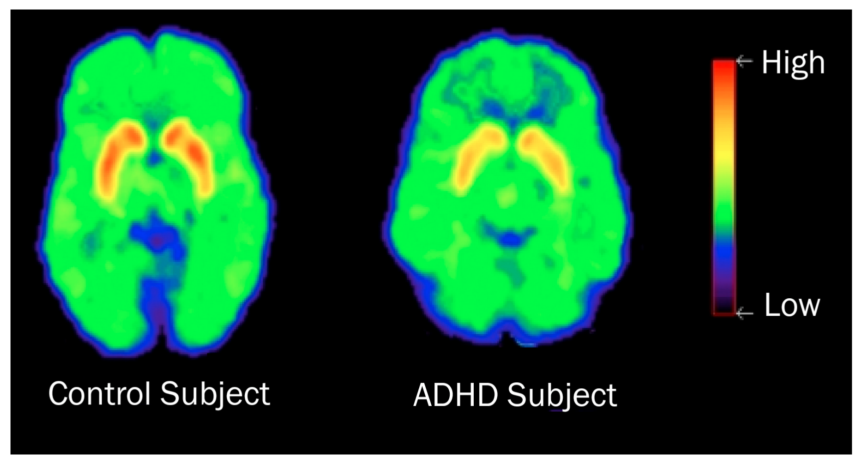
- Drug is labeled with radioisotopes that emit gamma rays.
- Drug localizes in patient according to metabolic properties of that drug.
- Trace (pico-molar) quantities of drug are sufficient.
- Radiation dose fairly small (<1 rem).

Radiation Risk from Medical Procedures
Single Photon Emission Computed Tomography

Radiation Concerns:

- Radiation concerns of positron emission is very similar to that of beta particles.
- When positrons are annihilated with electrons, gamma rays with (~)511 keV are generated, which makes all positron-emitters potential external radiation hazard.





Radiation Risk from Medical Procedures
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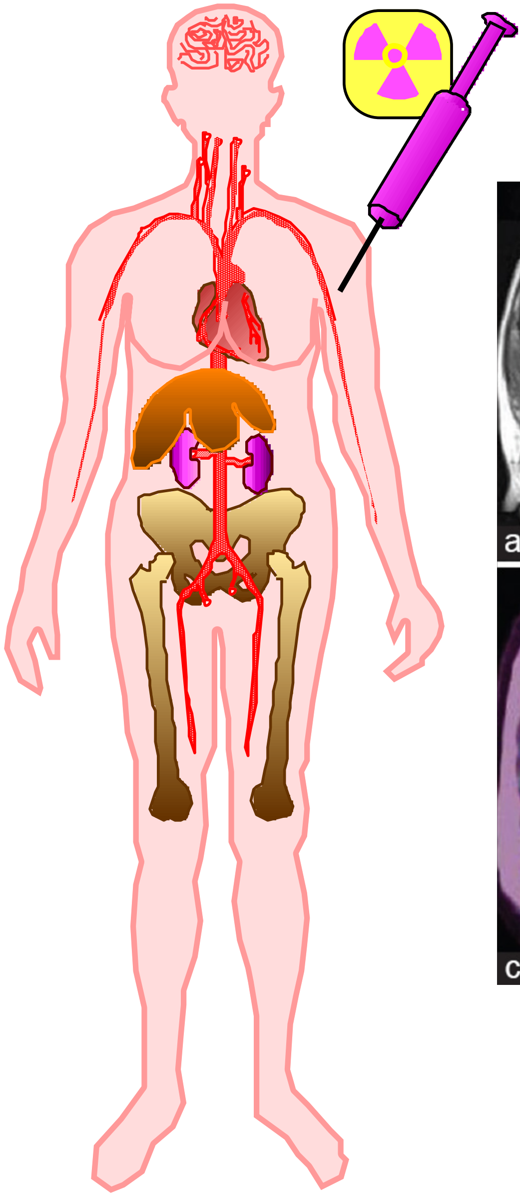
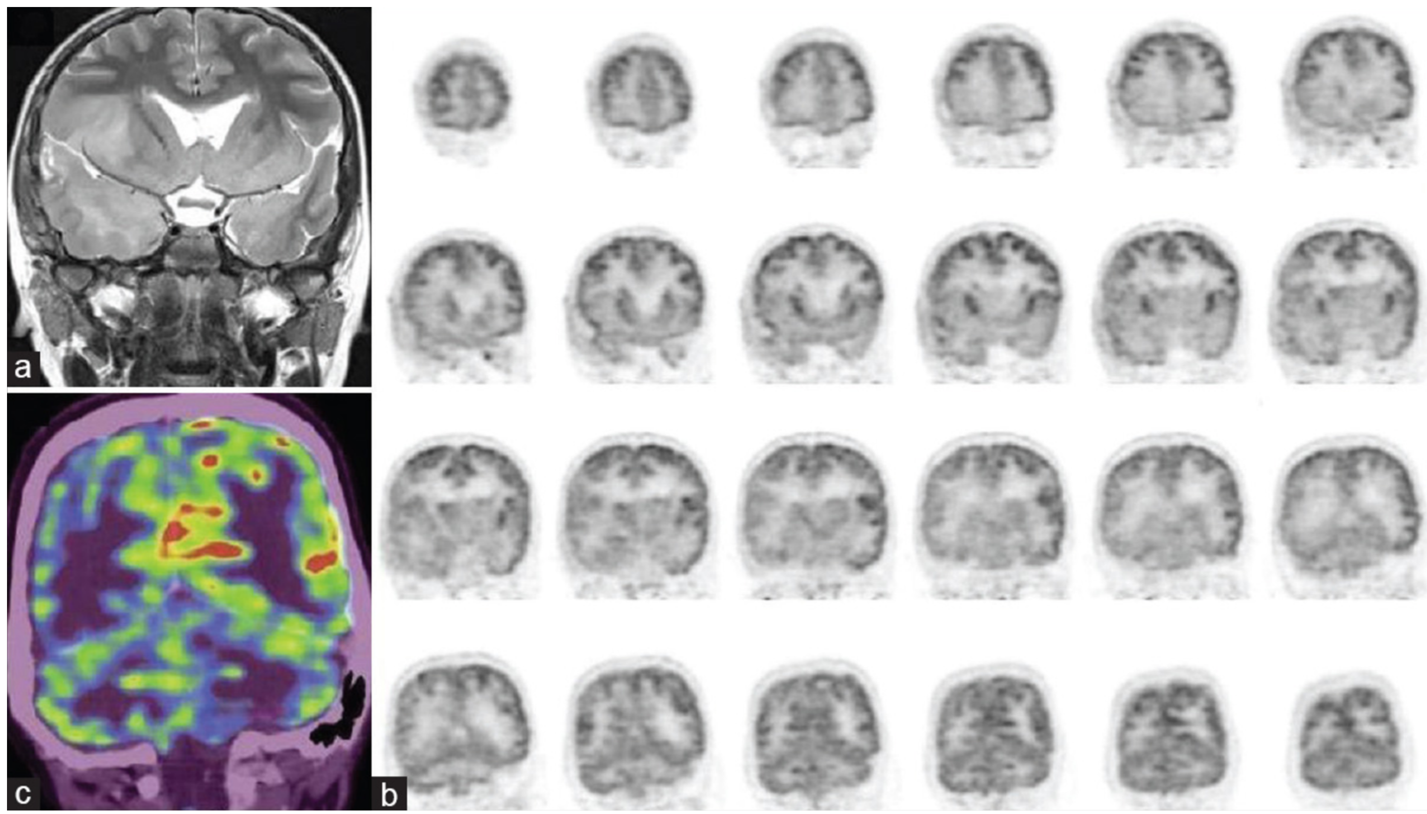




C-11 PET scan

Examples for Beta Decay

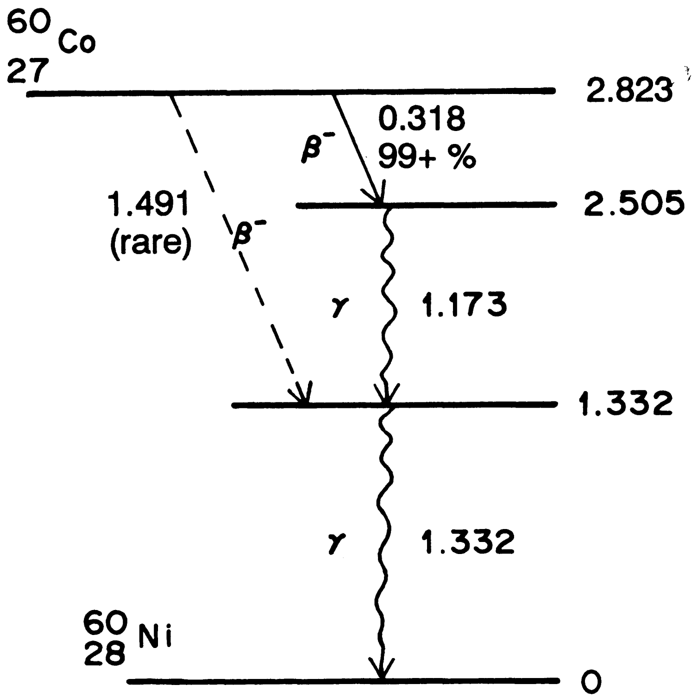


FIGURE 3.6. Decay scheme of $^{60}_{27}$Co.

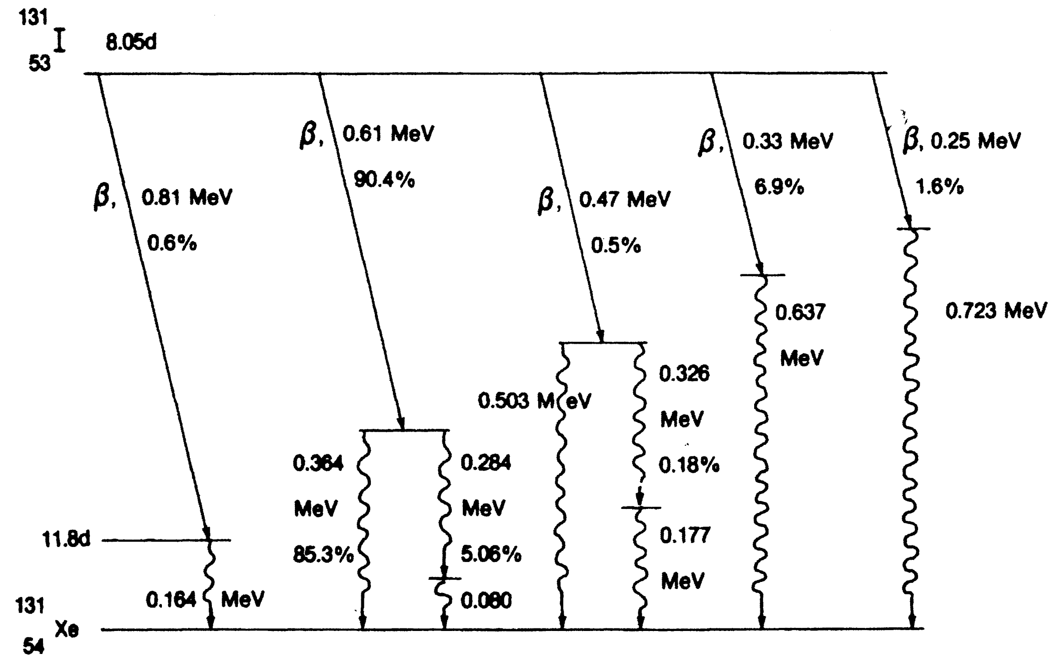


FIGURE 4.7. Iodine-131 transformation (decay) scheme.

- Beta emissions are normally associated with complicated decay schemes and the emission of other particles such as gamma rays.

- There exist the so called "pure beta emitters", such as ^{3}H, ^{14}C, ^{32}P and ^{90}Sr, which have no accompanying gamma rays.

Radionuclides in Biology & Medicine

Nuclide	$T_{1/2}$	R/A	Nuclide	$T_{1/2}$	R/A
^{3}H	12 y	R	^{67}Ga	3.3d	A
^{11}C	20 m	A	^{68}Ga	68m	A/G
^{14}C	5730y	R	^{82}Rb	75s	A/G
^{15}O	122s	A	^{99}Mo	66h	R
^{18}F	110m	A	^{99m}Tc	6h	R/G
^{32}P	14.3d	R	^{111}In	2.8d	A
^{51}Cr	27.7d	R	^{123}I	13.1h	A
^{62}Cu	9.7m	A/G	^{131}I	8.1d	R
^{67}Cu	61.7h	R/A	^{201}Tl	73h	A

R = Reactor, A = Accelerator, G = Generator

Bond-Seeking Beta Emitters

Table 1 - Physical and nuclear characteristics of bone-seeking therapeutic radionuclides[1]

	Maximum energy (MeV)	Average energy (MeV)	Average Range (mm)	T_{half} (days)	γphoton (MeV)
Strontium-89	1.46	0.58	2.4	50.5	None
Phosphorus-32	1.71	0.70	3.0	14.3	None
Tin-117m	0.13[2] 0.15[2]	--- ---	0.22 0.29	14.0	0.159 (86%)
Erbium-169	0.34	0.11	0.30	9.3	None
Lutetium-177	0.50	0.14	0.35	6.7	0.208 (11%)
Rhenium-186	1.08	0.33	1.05	3.7	0.137 (9%)
Samarium-153	0.81	0.22	0.55	1.9	0.103 (29%)
Holmium-166	1.84	0.67	3.3	1.1	0.081 (6%)
Rhenium-188	2.12	0.64	3.8	0.71	0.155 (10%)

[1]Arranged in order of decreasing half-life
[2]Conversion electrons with discrete energies (and range).

Beta Particles Related Health Concerns
An Example – Autoradiography

Radioisotopes

If 1 or more radioactive atoms is incorporated into a small molecule such as a sugar, amino acid, or nucleotide that molecule can then be traced.

Examples

^{3}H-thymidine
^{35}S-methionine
^{3}H-mannose
^{3}H-choline
^{3}H-acetate
^{32}P-CTP
^{32}P-ATP
^{14}C-chloramphenicol

Auger Electrons

- The excitation energy of the atom may be transferred to one of the outer electrons, causing it to be ejected from the atom.
- Auger electrons are roughly the analogue of internal conversion electrons when the excitation energy originates in the atom rather than in the nucleus.

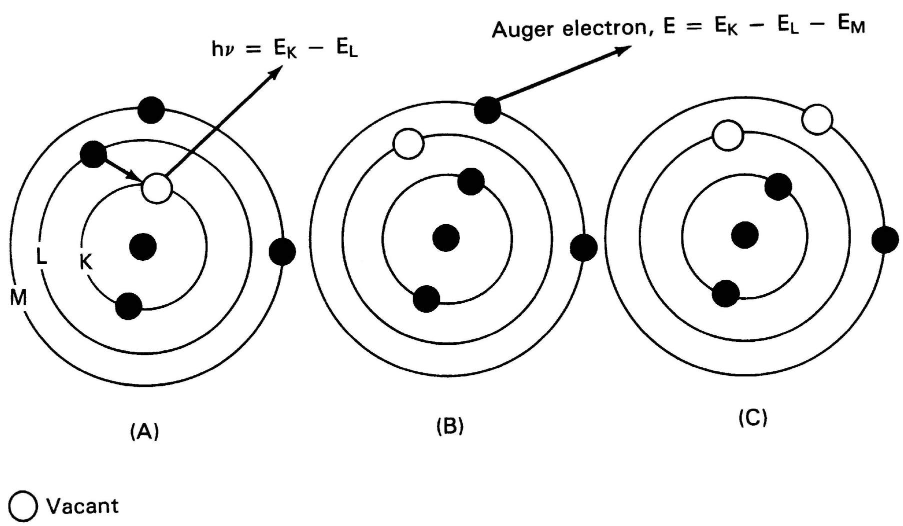
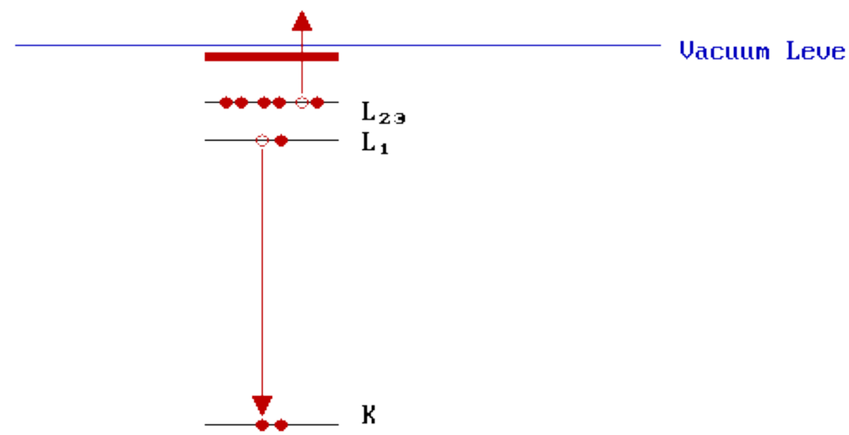
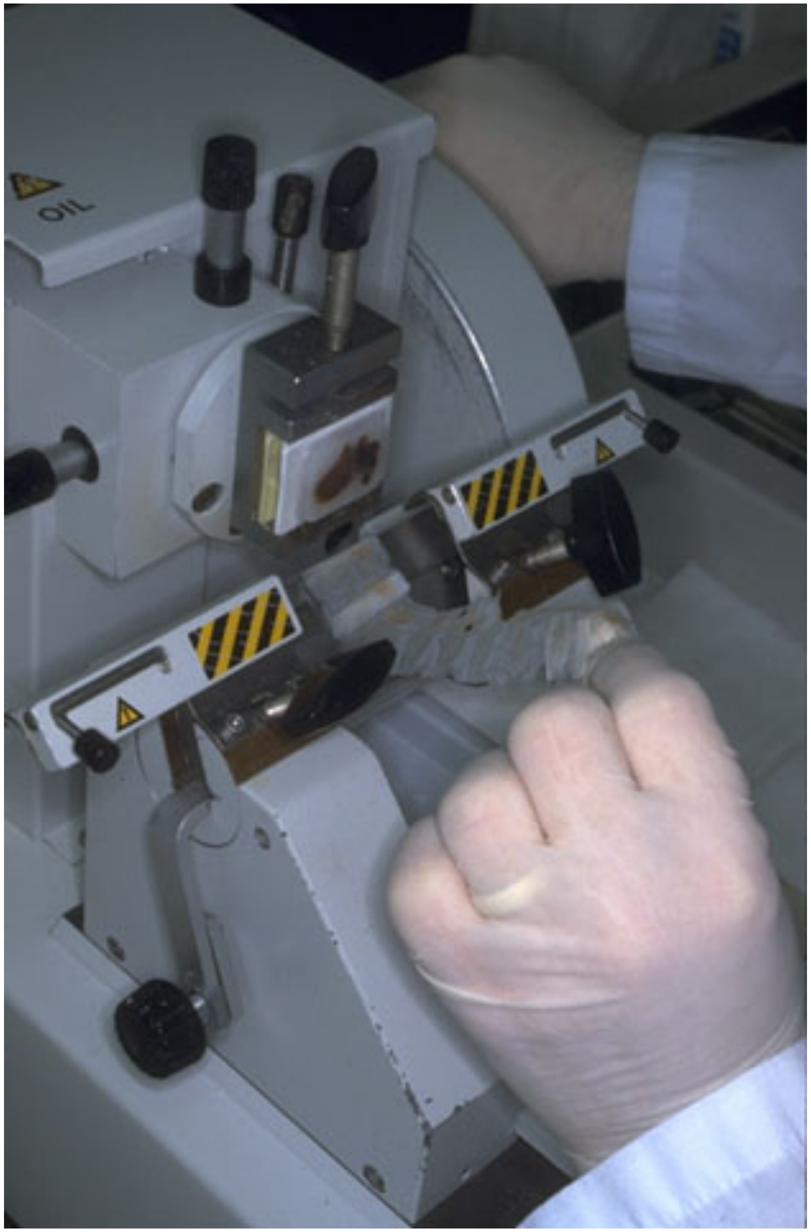


Figure 3.7 (A) The usual emission of a K characteristic X-ray, $h\nu$, energy equal to $E_K - E_L$, the difference in binding energy for the two orbital electrons, K and L. (B) $h\nu$ has been absorbed and a monoenergetic Auger electron is emitted, in the example shown, from the M shell, the energy of which is $E_K - E_L - E_M$. (C) In its final state the atom has vacancies in the L and M orbitals.



$$E_{a.e.} = (E_K - E_{L_1}) - E_{L_{23}}$$

Sectioning of Tissue…



…on Microtome (wax)

…on Cryostat (frozen)

Mounting of Tissue sections…

Energy Release from Nuclear Transitions

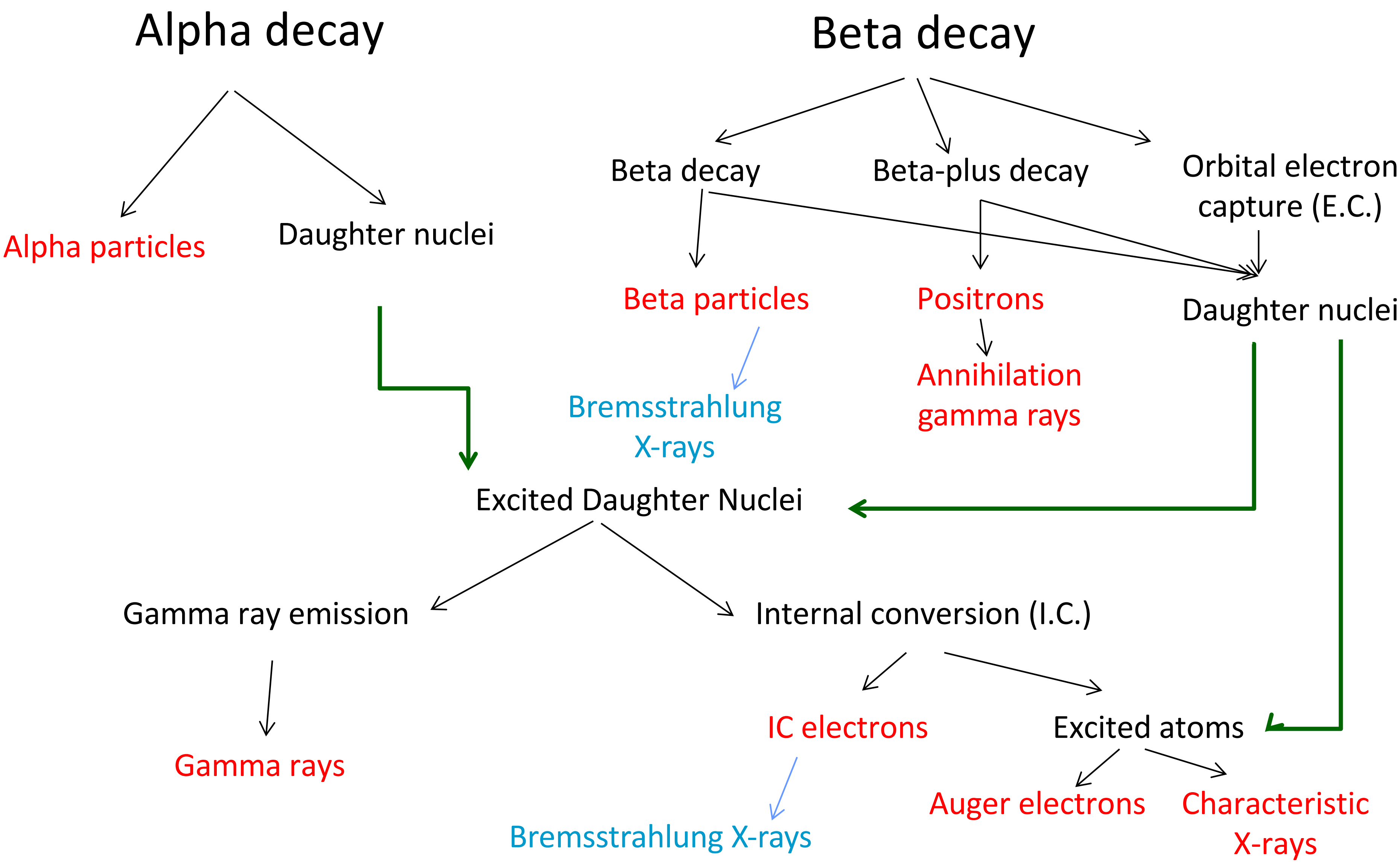
Decay scheme:

Table 3.1 Formulas for Energy Release, Q, in Terms of Mass Differences, Δ_P and Δ_D, of Parent and Daughter Atoms

Type of decay	Formula	Reference
α	$Q_\alpha = \Delta_P - \Delta_D - \Delta_{He}$	Eq. (3.13)
β^-	$Q_{\beta^-} = \Delta_P - \Delta_D$	Eq. (3.25)
γ	$Q_{IT} = \Delta_P - \Delta_D$	Eq. (3.30)
EC	$Q_{EC} = \Delta_P - \Delta_D - E_B$	Eq. (3.35)
β^+	$Q_{\beta^+} = \Delta_P - \Delta_D - 2mc^2$	Eq. (3.41)

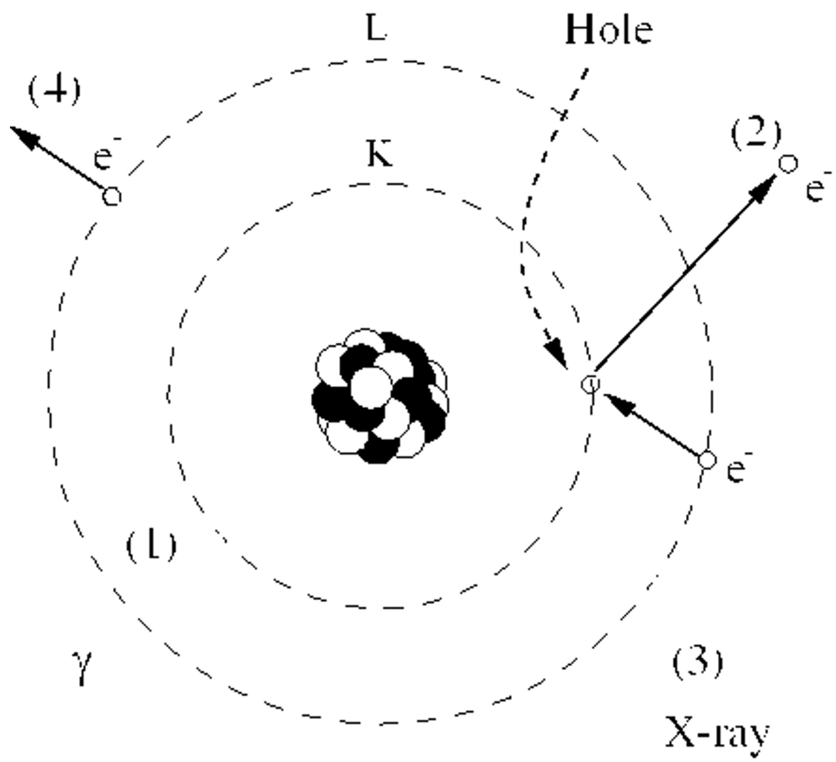
- Binding energy of electrons is ignored.
- These equations are discussed in James E Turner, Atoms, Radiation, and Radiation Protection, Third Edition, Chapter 3.

Typical Decay Products from Unstable Radioisotopes



Understanding the Radiation from Cs-137

What will happen to the excited Ba-137 nucleus?



Beta emission for sure, what else?

1. Gamma ray emission

2. Internal conversion leading to beta emission

3. Emission of characteristic X-ray

4. Auger electrons

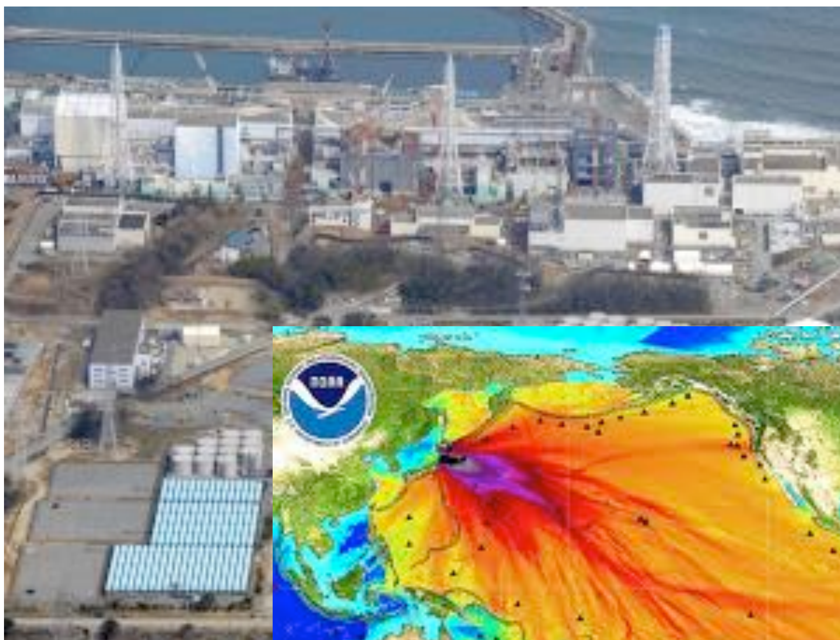
The bonding energies of k-shell and l-shell electrons in Ba-137 atom are 38 keV and 6 keV respectively.

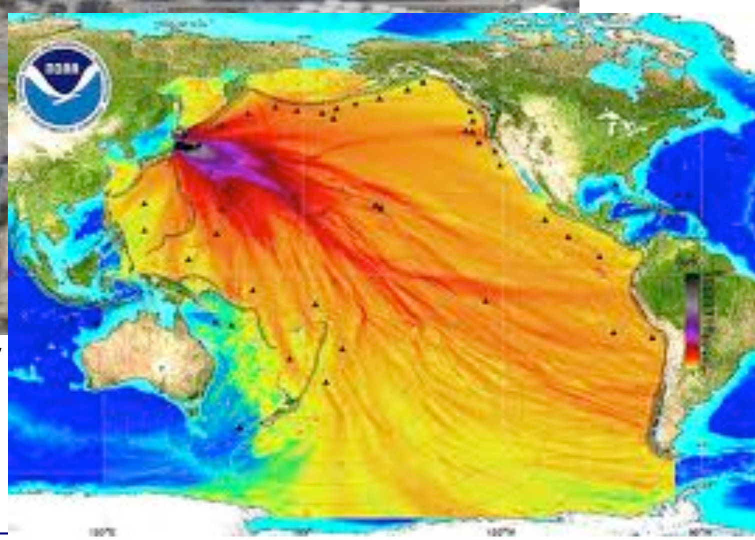
Understanding the Radiation from Cs-137

Decay scheme:

$$^{137}_{55}\mathrm{Cs} \rightarrow {}^{137}_{56}\mathrm{Ba} + {}^{0}_{-1}\beta + {}^{0}_{0}\overline{\nu}.$$

What will happen to the excited Ba-137 nucleus?





http://faithandsurvival.com/wp-content/uploads/2012/04/fukushima-cesium-137-spread.jpg

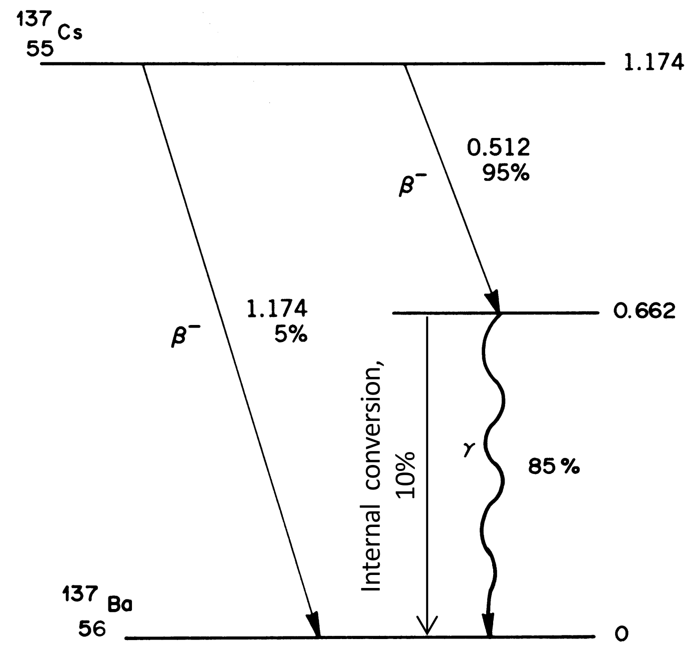


FIGURE 3.8. Decay scheme of $^{137}_{55}$Cs.