Authorized User / Radiation Safety Officer Training for Veterinary Users

Module 2: Radioactivity

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Introduction

- This module introduces basic terminology and common concepts of atomic physics, including atomic structure, radioactivity, and the decay model.
- Upon completion, the reader should be knowledgeable about:
  - Radioactive decay
  - Nuclear transformation
  - How to read and understand the decay scheme of a radionuclide
- Specific properties of common veterinary radionuclides: radioiodine (^{131}I), IsoPet® (^{90}Y),and Synovetin OA™ (^{117m}Sn) and are discussed in the last section.
- Recommended reading:

2.1. For ^{131}I treatment: Roberts, E., J. M. Gray, E. Gunn, and I.K. Ramsey. A novel method of continuous cage-side monitoring of hyperthyroid cats treated with radio-iodine. Veterinary Record, July 4, 2015.

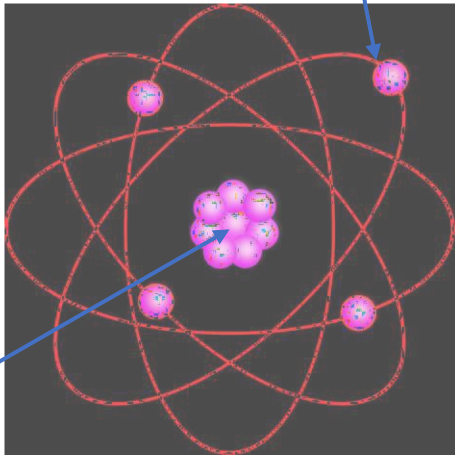
2.2. Turner, James E. 2007. Atoms, Radiation, and Radiation Protection. Wiley-VCH, Germany. (optional textbook)

Outline

- **Part I: The Atom**
  - Atomic structure
  - Atomic number and mass number
  - Chart of nuclides
- **Part II: Radioactive Decay**
  - Activity
  - Half-life
  - Decay equation
  - Alpha decay
  - Beta decay
  - Gamma emission
  - Internal conversion
  - Biological Elimination and Effective Half Life
  - Decay scheme
- **Part III: Properties of Radioiodine (Na^{131}I), IsoPet® (^{90}Y), and Synovetin OA™ (^{117m}Sn)**
- **Part IV: Quiz**

Part I: The Atom – Atomic Structure

- Atoms are the basic building blocks of matter and are extremely small units. The diameter of one atom is in the range of 10^{-10} m, or about a million times smaller than the width of human hair.
- In nature, the atom is an electrically neutral particle: it is neither positively nor negatively charged. However, atoms are made up of electrons, protons, and neutrons:
  - An electron has one unit of negative charge.
  - A proton has one unit of positive charge.
  - A neutron is electrically neutral.
- A unit of positive or negative charge is approximately 1.6×10^{-19} coulombs (C). The coulomb is the SI (metric) unit of charge.
- Protons and neutrons (collectively called nucleons) are fused together through strong nuclear force to form the center of an atom, or nucleus. A nucleus is positively charged.

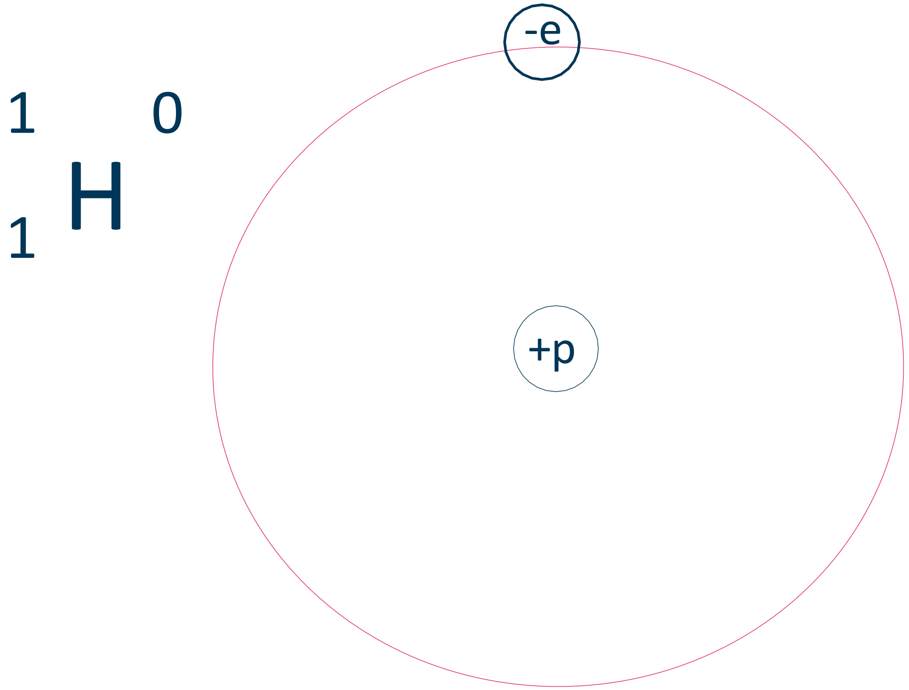


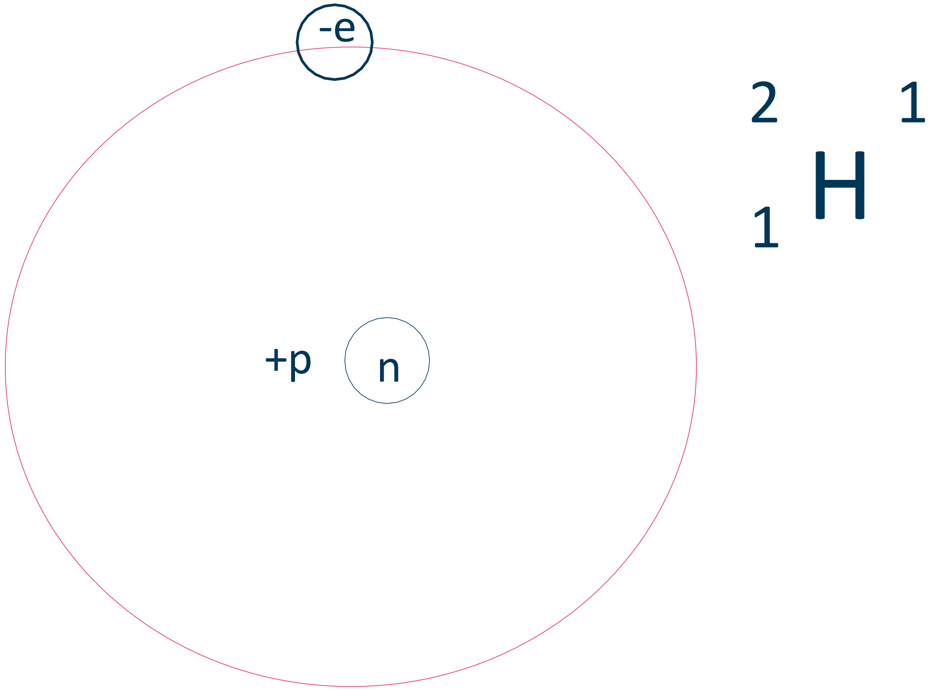
Part I: The Atom – Atomic Structure *(continued)*

- Most of the mass of an atom is from its nucleus.
- The masses of a proton (m_P) and neutron (m_N) are similar:
  - m_P is about 1.67 x 10^{-27} kg
  - m_N is about 1.69 x 10^{-27} kg
- The mass of an electron (m_e) is much less: about 9.11 x 10^{-31} kg, or 1800 times lighter.
- The negatively charged electrons are attracted to and orbit around the positively charged nucleus by electric force.
- Most atomic events are dictated by the mass of the nucleus through attractive forces between the nucleus and electrons.

Part I: The Atom – Atomic Structure *(continued)*

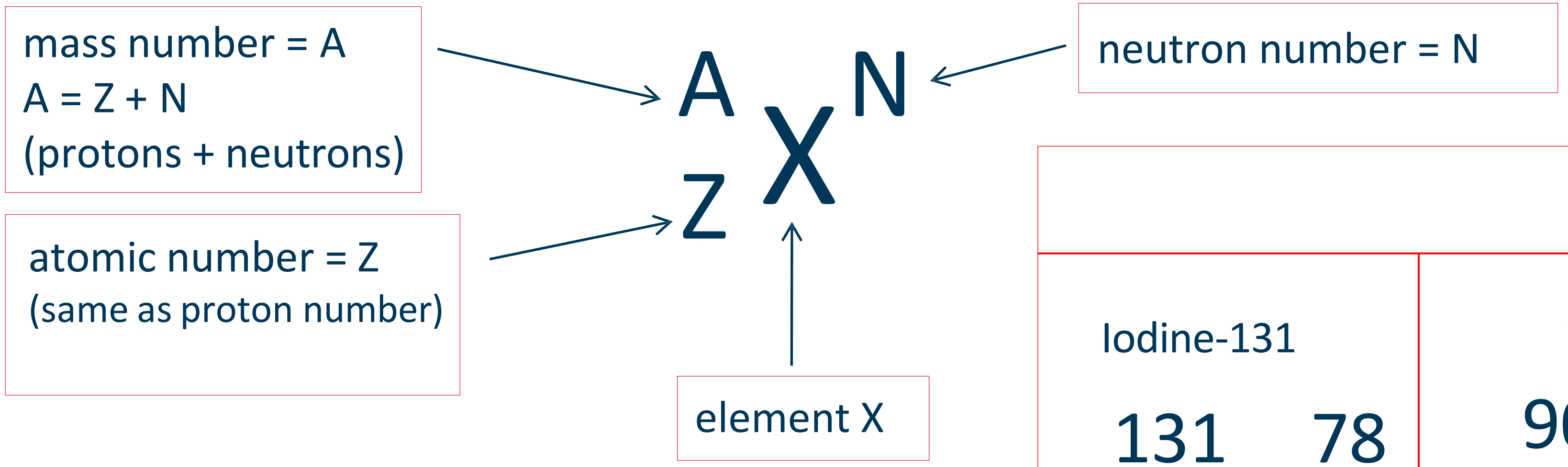
- The hydrogen atom (below left) - with one electron and one proton - is the simplest example of atomic structure:
  - The nucleus contains just one proton.
  - One electron orbits around the nucleus.
- The Deuterium atom (below right) - with one electron, one neutron, and one proton - is an example of an isotope of Hydrogen:
  - The nucleus contains one proton and one neutron.
  - One electron orbits around the nucleus.





Part I: The Atom – Atomic Number and Mass Number

- Atoms are identified by the **number of protons** they possess. This is called the **atomic number** and is designated by the capital letter **Z**.
- The **number of neutrons** in the atom is designated by the capital letter **N**.
- The **mass number** of an atom is the sum of the number of protons (Z) and neutrons (N).   It is designated by the capital letter **A**.
- Therefore, mass number = atomic number + neutron number, or **A = Z + N**.



mass number = A
A = Z + N
(protons + neutrons)

$${}^{A}_{Z}\mathrm{X}^{N}$$

neutron number = N

atomic number = Z
(same as proton number)

element X

Examples		
Iodine-131	Yttrium-90	Tin-117m
${}^{131}_{53}\mathrm{I}^{78}$	${}^{90}_{39}\mathrm{Y}^{51}$	${}^{117m}_{50}\mathrm{Sn}^{67}$

Part I: The Atom – Atomic Number and Mass Number *(continued)*

- Atoms with same Z and different N are called **isotopes**. [same **p**roton number]
- Atoms with same N and different Z are called **isotones**. [same **n**eutron number]

Example of Isotopes

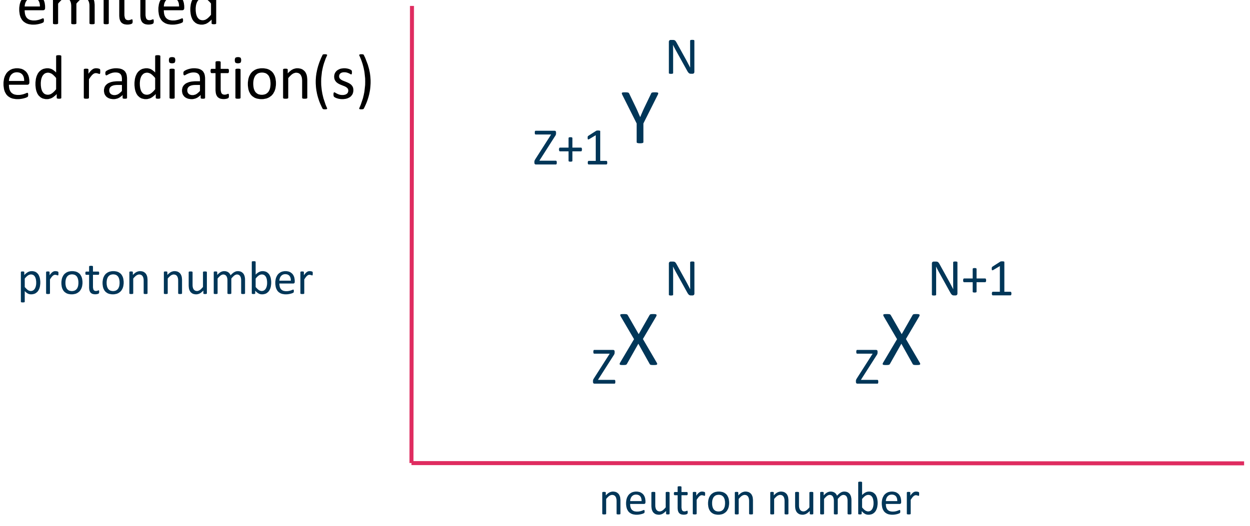
$${}^{1}_{1}\mathrm{H}^{0} \qquad {}^{2}_{1}\mathrm{H}^{1} \qquad {}^{3}_{1}\mathrm{H}^{2}$$

Example of Isotones

$${}^{12}_{5}\mathrm{B}^{7} \qquad {}^{13}_{6}\mathrm{C}^{7}$$

Part I: The Atom – Chart of Nuclides

- An atom is specified by its proton number and neutron number. An atom with certain P and N is called a **nuclide**.
- A **chart of nuclides** is a map that distinguishes isotopes and isotones:
  - The neutron number increases along the x-axis
  - The proton number increases along the y-axis
  - Isotopes move along the graph below with increasing N or number of neutrons
  - Isotones move along the graph below with increasing P or number of protons
- Note that each radionuclide has unique characteristics, just as each human has a unique signature or fingerprint. These characteristics include:
  - Type(s) of radiation emitted
  - Energy of the emitted radiation(s)
  - Half-life



Part II: Radioactive Decay

- **Radioactive decay** is a process of emitting particles and energy that causes:
  - A nuclide to transform into another nuclide
  - An atom or nucleus to transform from its unstable state to a stable state
- Examples of radioactive decay caused by particle emission:

The nucleus of ^{90}Y emits a **beta particle**, transforming radioactive yttrium-90 to stable zirconium-90

The nucleus of ^{226}Ra emits an **alpha particle**, transforming radioactive radium-226 to radioactive radon-222

- Example of radioactive decay caused by energy emission:

The nucleus of the radionuclide ^{99m}Tc (Technetium 99-metastable) is at an unstable energy state. It decays to its ground energy state by emitting excess energy in the form of **gamma rays**. ^{117m}Sn is also metastable, decaying into stable ^{117}Sn by emitting monoenergetic conversion electrons and gamma rays

X-rays can also emitted during decay, for instance by iodine-125, or when energetic beta particles collide with high-Z (high atomic number) elements.

Collectively, gamma rays and x-rays are called **photons**.

Radioisotopes may decay be emitting primarily only one type of radiation (*e.g.*, a 'pure beta' emitter, such as ^{3}H, ^{14}C, ^{32}P, ^{90}Y), or by combinations of emissions (*e.g.,* 'beta-gamma' emitters ^{137}C, ^{131}I)

Iodine-131 predominantly emits beta particles of 3 energies, and gamma photons of 5 energies, to transform into stable Xenon-131

Part II: Radioactive Decay – Activity

- A nuclide which experiences a decay process is said to be radioactive.
- **Radioactivity** describes the rate of decay of a radioactive nuclide. It is a measure of the number of disintegrations of atoms or nuclei per unit time.
- The SI unit of activity is the **Becquerel (Bq)**. The Bq describes an extremely small amount of activity: 1 Becquerel = 1 disintegration (or decay) per second.
- The US traditional unit of activity is the **Curie (Ci)**, named after Marie Curie. It was originally used to describe the activity of 1g of ^{226}Ra.
- It is still more common to use Ci in the US: **1 Ci = 1000 mCi = 3.7x10^{10} Bq.**
- For example, a 5 mCi ^{90}Y source of radioactivity experiences a loss of 1.85x10^{8} unstable ^{90}Y particles in one second:

  5 mCi = 1.85x10^{8} Bq = 185,000,000 decays per second

  - Note that SI is the abbreviation for the International System of Units.
  - For distance, meters are the SI unit for distance but in the United States we traditionally use feet.

Part II: Radioactive Decay – Physical Half-Life

- As explained on Page 10, radioactive decay is the process of emitting particles and energy of unstable nuclides. The activity diminishes during the decay process as the unstable becomes stable.

- **Half-life ($T_{½}$)** is the time it takes for the number of radioactive nuclides to be reduced by half. Strictly speaking, the proper term is **physical half life**, since no biological processes are included in this description.

- Half-life is a very important parameter for radioactive decay, as it describes the speed of decay. A short half-life means the unstable nuclides will transform to stable nuclides in a short period of time.

- After each half life, half of the starting activity remains. Each radioisotope has its unique half life, which can range from nano-seconds to millions of years.

^{131}I has a half life of 8.04 days.

^{90}Y has a half life of 64.1 hours, or 2.67 days.

^{117m}Sn has a half life of 14 days.

Literature values for half life will vary by a few percent.

Part II: Radioactive Decay – Decay Equation

- The activity of a radioactive source is calculated by: **$A(t)=A_0\, e^{-\lambda t}$** *[the expression e to the negative lambda times t means you take the* ***exponent*** *of negative lambda times t]*
  - **A_0** is the initial activity at time 0
  - **A(t)** is the activity at time **t;** t in calculations is elapsed time in the same units as used for half life (hours, days, years, etc).
  - **λ** is the decay constant of the radionuclide
    - The decay constant λ is equal to the natural log of 2 divided by the nuclide specific half-life:
      $\lambda = \ln(2)/T_{½} = 0.693 / T_{½}$ *[the natural log of 2 is 0.693]*

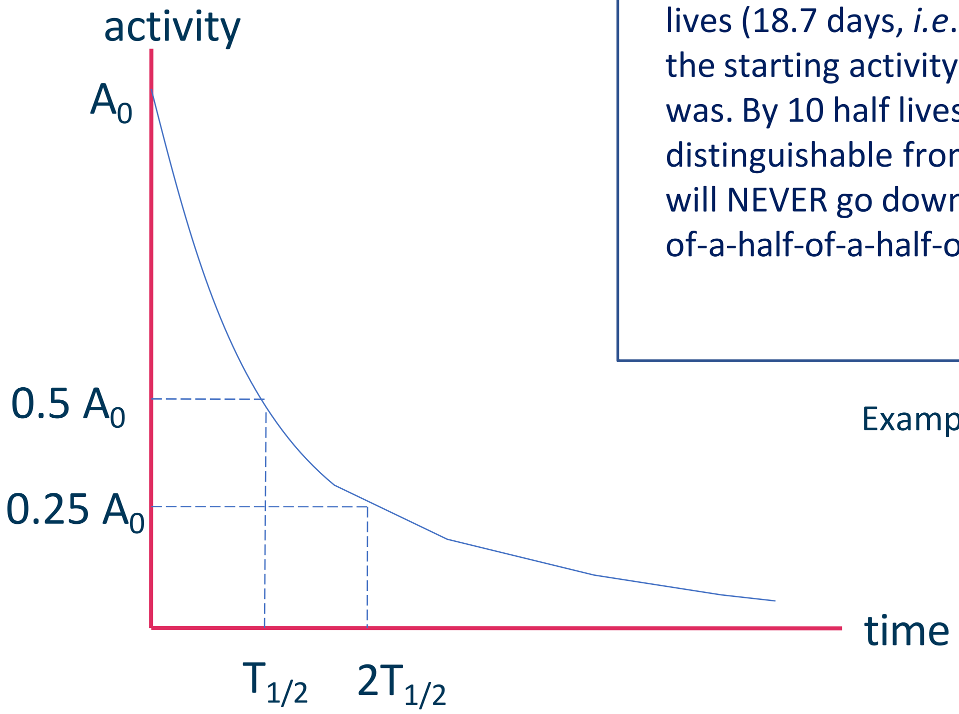
- The **decay equation** is an exponential function with respect to time. The minus sign in the equation indicates that activity decreases with time. At $t = T_{½}$, source activity is half of its initial value.
- Example 1: An IsoPet® dose is calibrated for 4.5 mCi at 12:00 noon on June 6. The treatment is delayed by one day, and the dose will only be injected at 9:00 am on June 7. What is its activity at time of injection?

Elapsed time = 21h $T_{½}$ = 64.1h λ = ln(2) / 64.1 h = 0.693 / 64.1 h = 0.0108/h

Activity at 21h = A(t) = 4.5 mCi x $e^{-0.0108/h \times 64.1h}$ = 4.5 mCi x 0.5058 = **2.27 mCi**

Part II: Radioactive Decay – Decay Equation *(continued)*

- The decay equation is plotted below:
  - At one half-life, the activity drops to half of the initial activity
  - At two half-lives, the activity drops to a quarter of the initial activity



Here's an example of 100 mCi of ^{90}Y at the starting point. By 7 half lives (18.7 days, *i.e.*, a little more than 2 weeks), less than 1% of the starting activity remains, irrespective of how high that activity was. By 10 half lives (about a month), activity is not distinguishable from background in most cases. In theory, activity will NEVER go down to zero; since the progression is always half-of-a-half-of-a-half-of-a-half-of-a-half….

0 h	100 mCi at start
64.1 h (1 half life):	50 mCi remains
128.2 h (2 half lives):	25 mCi remains
192.3 h (3 half lives):	12.5 mCi remains
256.6 h (4 half lives):	6.25 mCi remains
320.5 h (5 half lives):	3.125 mCi remains
384.6 h (6 half lives):	1.5625mCi remains
448.7 h (7 half lives):	0.78125 mCi remains
512.8 h (8 half lives):	0.390625 mCi remains
576.9 h (9 half lives):	0.1953125 mCi remains
641.0 h (10 half lives):	0.09765625 mCi remains

Example 2: 1.5 mCi of IsoPet® waste is stored for decay on 7 June. What is its activity on 23 June?

Elapsed time = 16 d $T_{½} = 2.67$ d $\lambda = \ln(2) / 2.67\ d = 0.693 / 2.67\ d = 0.2596/d$

Activity at 16 d = 1.5 mCi x $e^{-0.2596/d\ \times\ 16d}$ = 1.5 mCi x 0.0157 = **0.0235 mCi** = **23.5 µCi**

Part II: Radioactive Decay – Decay Equation *(continued)*

Example 3: A 3 mCi dose of ^{131}I is to be injected in a hyperthyroid cat. Suppose the cat is not admitted on time and the treatment is delayed by 4 days. What is the activity available in the syringe to be injected?

Elapsed time = 4 d $T_{½}$ = 8.04 d λ = ln(2) / 8.04 d = 0.693 / 8.04 d = 0.0862/d

Activity at 4 d = A(t) = 3 mCi x $e^{-0.0862/d \times 4\,d}$ = 3 mCi x 0.708 = **2.13 mCi**

Suppose the elapsed time in the above example was exactly 8.04 days. The Activity remaining at that time would be:

3 mCi x e -0.0862/d x 8.04 d = 3 mCi x 0.500 = **1.5 mCi.**

This example illustrates that when one half life has passed, the activity decreases to a half of what one starts off with.

Example 4: If you have a dose of ^{117m}Sn sitting around for a 10 days, and is measured to be 5.3 mCi. What would have its activity been at the starting point, 10 days earlier?

$T_{½}$ = 14 d λ = ln(2) / 14 d = 0.693 / 14 d = 0.0495/d

$A(t)=A_0\, e^{-\lambda t}$ **Therefore, $A_0 = A(t) / e^{-\lambda t}$**

Initial activity = 5.3 mCi / $e^{-0.0495/d \times 10\,d}$ = 5.3 mCi / 0.6096 = **8.69 mCi**

So, now it can be seen that the decay equation allows one to calculate activity at a past time as well.

Part II: Radioactive Decay – Decay Chart

You will notice from the example calculations that the exponent in the decay equation, *i.e.*, **$e^{-\lambda t}$** works out to be a *fraction*, or a *factor* that can be multiplied by the initial activity, to give a result of final activity. This **decay factor** depends on the elapsed time, and is conveniently provided as a **decay chart**. Simply multiply the decay factor for a given elapsed time by the initial activity, to obtain final activity for that elapsed time. The **decay chart for ^{90}Y** is also provided on the IsoPet® device label. This is an alternative method to the use of the decay equation.

$A(t)=A_0$ x decay factor

Hours	Decay Factor
0.5	0.995
1	0.989
2	0.979
3	0.968
4	0.956
5	0.947
6	0.937
7	0.927
8	0.917
9	0.907
10	0.898
11	0.888
12	0.878
24	0.772
36	0.678
48	0.595
72	0.459

Example 5: If the activity of ^{90}Y is 6.7 mCi at a given start time;

(a) what is the activity 8 hours later?

(b) What is the activity 15 hours later?

(a) At 8 hours, activity = 6.7 mCi x 0.917 = **6.14 mCi**

(b) For 15 hours, decay factor can be calculated as factor at 10h x factor at 5h = 0.898 x 0.947 = 0.8504. Therefore, activity at 15 h = 6.7 mCi x 0.8504 = **5.70 mCi.**

The same result can be obtained by any other combination, such as factor for 12h x factor for 3h, or factor for 9h x factor for 6h.

Part II: Radioactive Decay – Decay Chart *(continued)*

Decay charts for ^{131}**I** and ^{117m}**Sn** are presented here.

Example 6: A dose of 3.5 mCi of ^{133}Iwill decay to how much in 17 days? In 63 days? In 80 days?

On day 17: 3.5 mCi x 0.231 = **0.809 mCi**

On day 63: To get the factor, multiply factors for
30 day x 30 days x 3 days = 0.075 x 0.075 x 0.772 = 0.00434.
Therefore, activity = 3.5 mCi x 0.00434 = **0.015 mCi**

On day 80: factor = 0.075 x 0.075 x 0.178 = 0.001
Therefore, activity = 3.5 mCi x 0.001 = 0.0035 mCi

Notice that when about ***10 half lives*** (80 days) have passed, the final activity is ***one thousandth*** of the initial activity. This is true for any radioisotope.

Decay Chart for I-131 (Tp = 8.04 d)

Days	Decay factor	Days	Decay factor	Days	Decay factor
1	0.917	11	0.387	21	0.164
2	0.842	12	0.355	22	0.150
3	0.772	13	0.326	23	0.138
4	0.708	14	0.299	24	0.126
5	0.650	15	0.274	25	0.116
6	0.596	16	0.252	26	0.106
7	0.547	17	0.231	27	0.098
8	0.502	18	0.212	28	0.089
9	0.460	19	0.194	29	0.082
10	0.422	20	0.178	30	0.075

Decay Chart for Sn-117m (Tp = 14 d)

Days	Decay factor	Days	Decay factor	Days	Decay factor
1	0.952	11	0.580	21	0.354
2	0.906	12	0.552	22	0.337
3	0.862	13	0.525	23	0.320
4	0.820	14	0.500	24	0.305
5	0.781	15	0.476	25	0.290
6	0.743	16	0.453	26	0.276
7	0.707	17	0.431	27	0.263
8	0.673	18	0.410	28	0.250
9	0.641	19	0.390	29	0.238
10	0.610	20	0.372	30	0.227

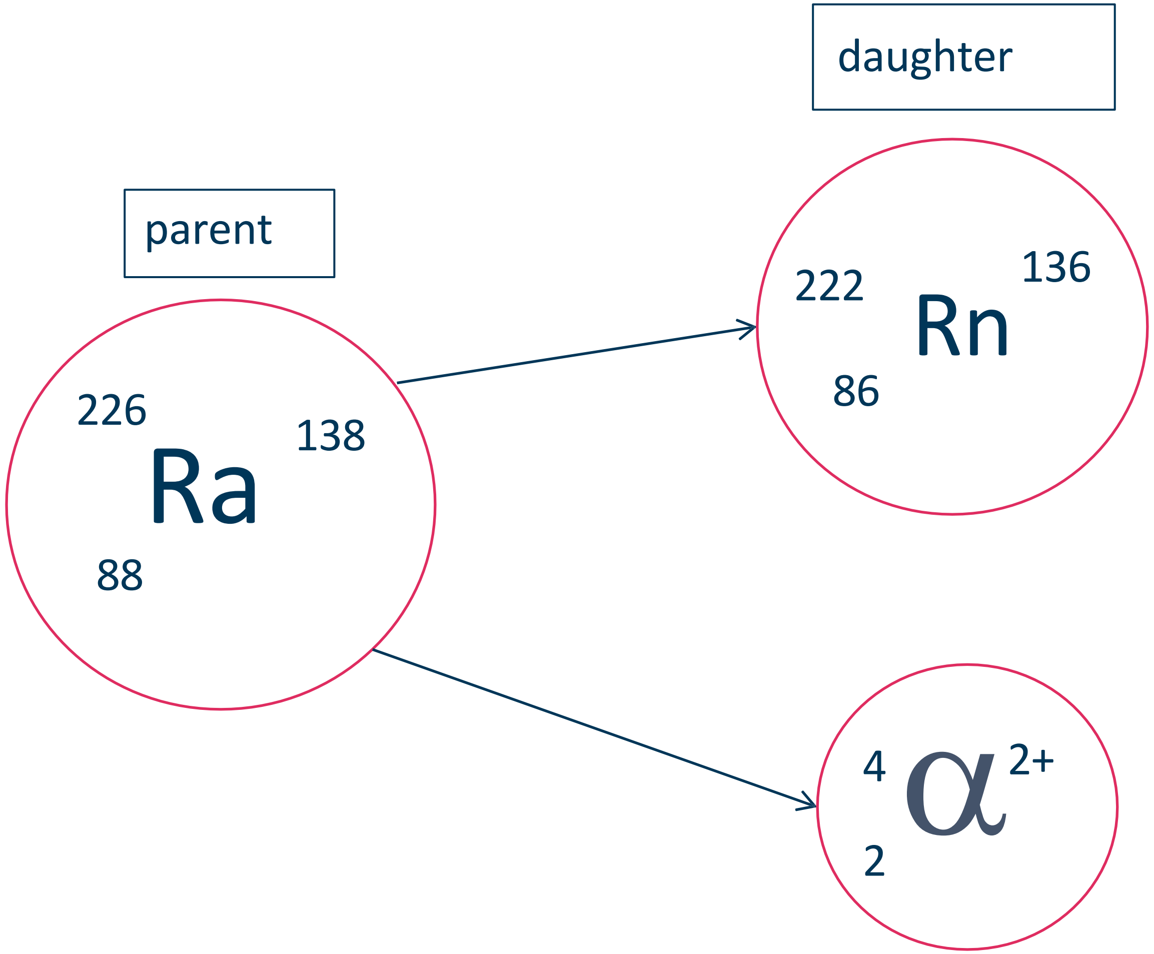
Part II: Radioactive Decay– Alpha Decay

- **Alpha decay** is the spontaneous emission of an alpha [α] particle from a heavy atomic nucleus, for example ^{226}Ra.
- The alpha particle is the same as a Helium nucleus. An alpha particle consists of 2 protons and 2 neutrons and carries a +2 positive charge.
- An alpha particle travels a very short range in tissue, and it can not penetrate the dead layer of skin. However, it has a strong ability to produce intense ion pair tracks when traveling inside tissue. Therefore, the primary biologic concern is internal exposure to alpha emitters, for instance, if they are inhaled and bombard the lungs with alpha particles.

$$^{A}_{Z}X = {}^{A-4}_{Z-2}Y + \left[{}^{4}_{2}He\right]^{2+}$$

Part II: Radioactive Decay – Alpha Decay *(continued)*

Example of alpha decay process: ^{226}Ra decays to ^{222}Rn, emits $^{4}_{2}\alpha^{2+}$



Part II: Radioactive Decay – Beta Decay

- Another form of radioactive decay is **beta decay**, where the radionuclide emits an electron [β^-]or positron [β^+].
- If a nucleus has an excess number of neutrons compared to the number of protons, an electron is emitted; then a neutron becomes a proton in the nucleus. This nuclear transformation is called **beta minus (β^-)** decay. In this process, an antineutrino particle is also emitted from the nucleus. The antineutrino release is not a biological concern. The β^- particle is essentially an electron, with the difference that it originates from within the nucleus as opposed to outside the nucleus.
- If a nucleus has an excess number of protons compared to the number of neutrons, a positron is emitted; then a proton becomes a neutron in the nucleus. This process of nuclear transformation is called **beta plus (β^+)** decay. A neutrino particle is also emitted from the nucleus with β^+.
- The energy of emitted beta particles has a **spectral distribution**, from 0 to a maximum energy. This means, all particles do not have the same energy. Beta emissions are characterized by average energy and maximum energy in MeV (million electron volts).

Part II: Radioactive Decay – Beta Decay *(continued)*

Beta minus (β^-) decay equation

$$ {}^{A}_{Z}X = {}^{A}_{Z+1}Y + \beta^{-} + \overline{\nu} $$

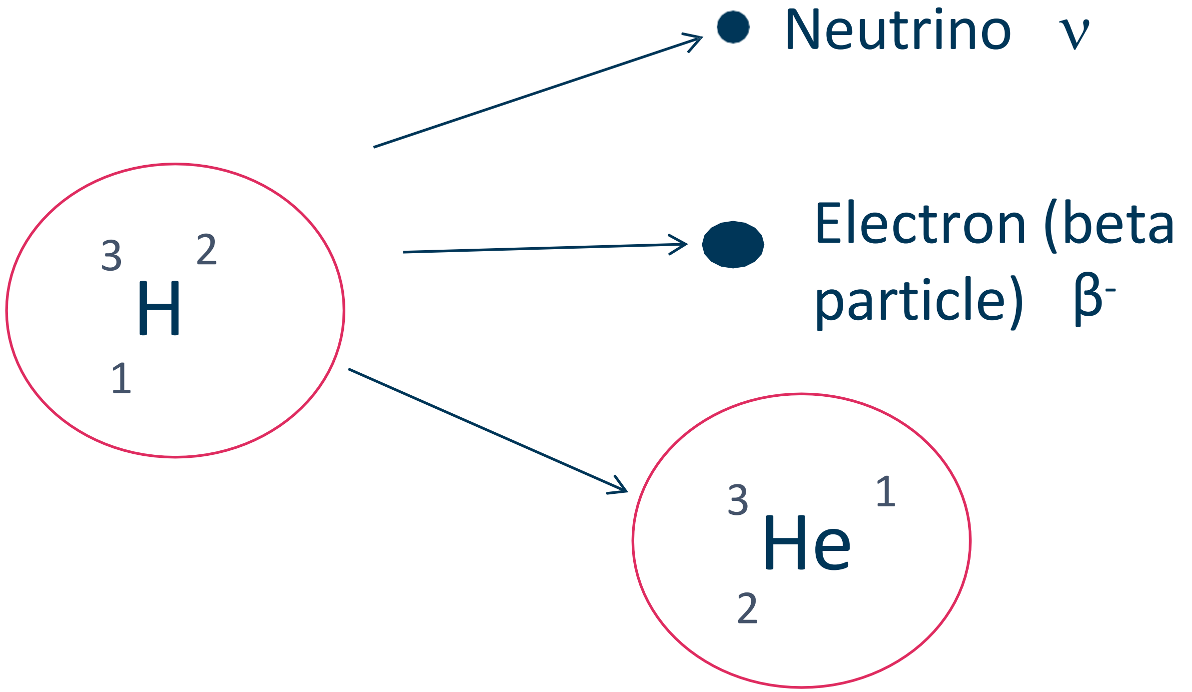
Beta plus (β^+) decay equation

$$ {}^{A}_{Z}X = {}^{A}_{Z-1}Y + \beta^{+} + \nu $$

*Note that ν (or Greek Nu) is the added neutrino (ν)/ antineutrino ($\overline{\nu}$)release of energy. These are sometimes generalized to the single term, neutrino.

Part II: Radioactive Decay – Beta Decay *(continued)*

- Beta minus (β^-) decay process: parent nuclide Tritium decays to Helium-3



Neutrino ν

Electron (beta particle) β^-

${}^{3}_{1}\mathrm{H}^{2}$

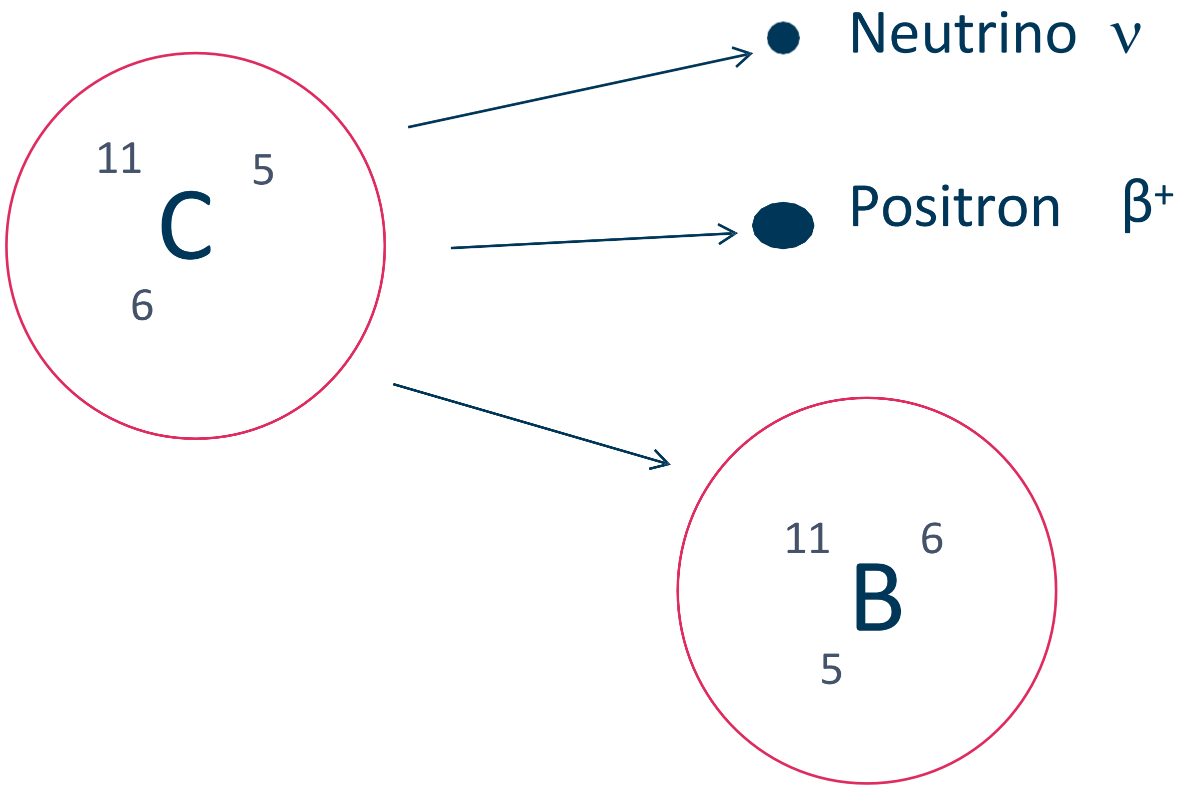
${}^{3}_{2}\mathrm{He}^{1}$

Yttrium-90 decays to stable Zirconium-90 by beta minus decay

$${}^{90}_{39}\mathrm{Y}^{51} \xrightarrow{\beta^-,\ \nu} {}^{90}_{40}\mathrm{Zr}^{50}$$

Part II: Radioactive Decay – Beta Decay *(continued)*

- Beta plus (β^+) decay process: a parent nuclide Carbon-11 decays to stable Boron-11



A positron is the anti-particle of an electron. It has a resting energy of 0.511 MeV. After traveling for a few mm in matter (such as soft tissue), it encounters a ‘free’ electron (which also has a resting energy of 0.511 MeV), and undergoes **annihilation**, as a result of which two gamma photons are ejected in opposite directions, each carrying 0.511 MeV. It is these photons that are detected in PET (Positron Emission Tomography) imaging.

Part II: Radioactive Decay – Gamma Emission

- After a nuclear transformation, the daughter nucleus is sometimes in an unstable state.
- The unstable nucleus de-excites excess energy in the form of gamma ray [γ] photons. A typical example is when ^{99m}Tc decays to ^{99}Tc by emitting 0.1405 MeV (98.6%) and 0.1426 MeV (1.4%) gamma rays.
- If the gamma ray is not emitted instantaneously from the nucleus with a half life more than (in the order of) 10^{-12} s, the nucleus is said to be in a "metastable" state, denoted by "m". For example, ^{99m}Tc is in the metastable state and decays to the ground state of ^{99}Tc by emitting gamma rays, with a half life of 6 hours.
- Technetium-99m is the most commonly used radioisotope used in human nuclear medicine. It is routinely used in equine nuclear medicine and has a similar gamma energy signature to ^{117m}Sn.

Part II: Radioactive Decay – Internal Conversion

- The de-excitation of a nucleus does not always involve the emission of gamma rays. **Internal conversion (IC)** is an alternative means of releasing excess energy.

- During IC, de-excitation energy is completely transferred to an orbital electron, typically a K, L, or M shell electron. A converted electron is emitted from the nucleus instead of a gamma ray.

- Unlike beta particles that carry a spectrum of energies, internal conversion electrons have **discrete** energies.

Part II: Radioactive Decay – Description of Energy

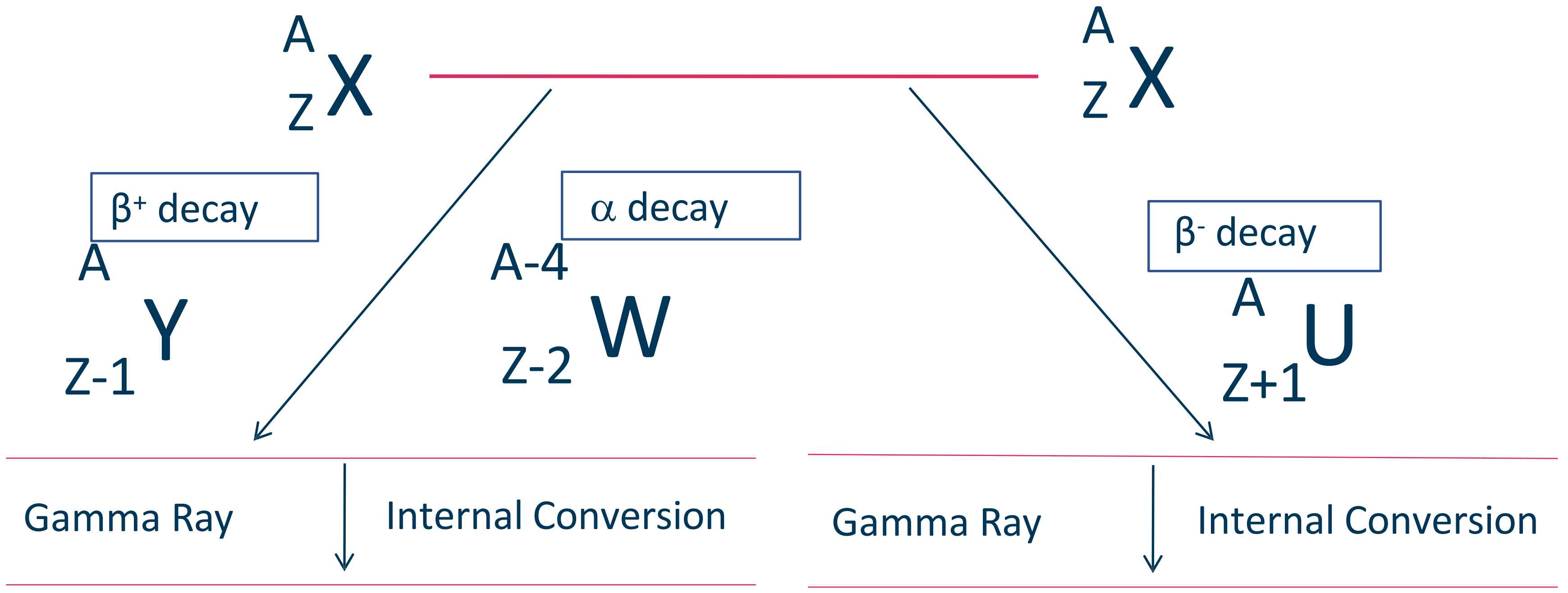
- No matter what type of decay (particulate of photon) a radioisotope undergoes, its emissions are characterized by the energy they carry. This energy is quantified in **million electron volts** (**MeV**). Lower energy emissions are quantified in **kilo electron volts** (**keV**).

- The higher the energy, the greater is the distance that the radiation travels (typically quoted for air). For alpha and beta particulate emissions, not every particle carries the same energy, and consequently, they do not all travel the same distance. Energies therefore are quoted in **maximum** and **average** values.   Average energies or radiative emission are *approximately* one-third of maximum values, although for some isotopes, they fall below the one-third mark and for others, they fall above the one-third mark.

- Radioisotopes may decay by emission of more than one energy of any type of radiation they emit.

Part II: Radioactive Decay– Decay Scheme

- Nuclear decay can be summarized by a “decay scheme”. The decay scheme shows the relevant changes to each component inside the decay pattern.
- The top horizontal line represents the parent nuclide, the bottom horizontal line represents the daughter nuclide, the intermediate line represents a metastable state of the daughter nuclide. A diagonal arrow pointing to the left indicates a decrease in Z and a diagonal arrow pointing to the right indicates an increase in Z.



$^{A}_{Z}X$

$^{A}_{Z}X$

β^{+} decay

$^{A}_{Z-1}Y$

α decay

$^{A-4}_{Z-2}W$

β^{-} decay

$^{A}_{Z+1}U$

Gamma Ray

Internal Conversion

Gamma Ray

Internal Conversion

Where U, Y, and W are different elements

Part II: Biological Elimination and Effective Half Life

- Besides physical decay, biological elimination processes act on radionuclides administered to humans or animals. If the radiopharmaceutical is metabolized, it can move from one body compartment to another, eventually exiting the body through urine, feces, sweat, or other body fluids.

- The combination of physical decay and biological elimination gives rise to **Effective Half Life** of a radioisotope in a patient.

- Mathematically, $\boldsymbol{\lambda_e = \lambda_p + \lambda_b}$**,** and $\mathbf{T_e = T_p \times T_b / (T_p + T_b)}$**,** Where **λ** is the decay constant, **T** is the half life, and the subscripts $_{e}$, $_{p}$, and $_{b}$ refer to effective, physical decay and biological elimination.

- Due to the chemical and physical properties of ^{90}Y Isopet® and ^{117m}Sn Synovetin OA^{TM} formulations, as well as the nature of these treatments, biological elimination is not a significant removal mechanism for these radioisotopes. The only relevant decrease in activity comes from physical decay.

- After ^{131}I NaI is administered, it is rapidly absorbed from the blood stream and distributed in extracellular fluid. The majority is then taken up by the thyroid gland, where its beta emissions bombard thyroid cells and constitute its therapeutic effect. The thyroid is therefore the primary long term compartment for this radioisotope. The remaining ^{131}I is primarily excreted via urine.

- The **effective half life** of ^{131}I in hyperthyroid cats has been estimated to be around **2.3** to **5.4 days**

Part III: Properties of ^{131}I Sodium Iodide ($Na^{131}I$)

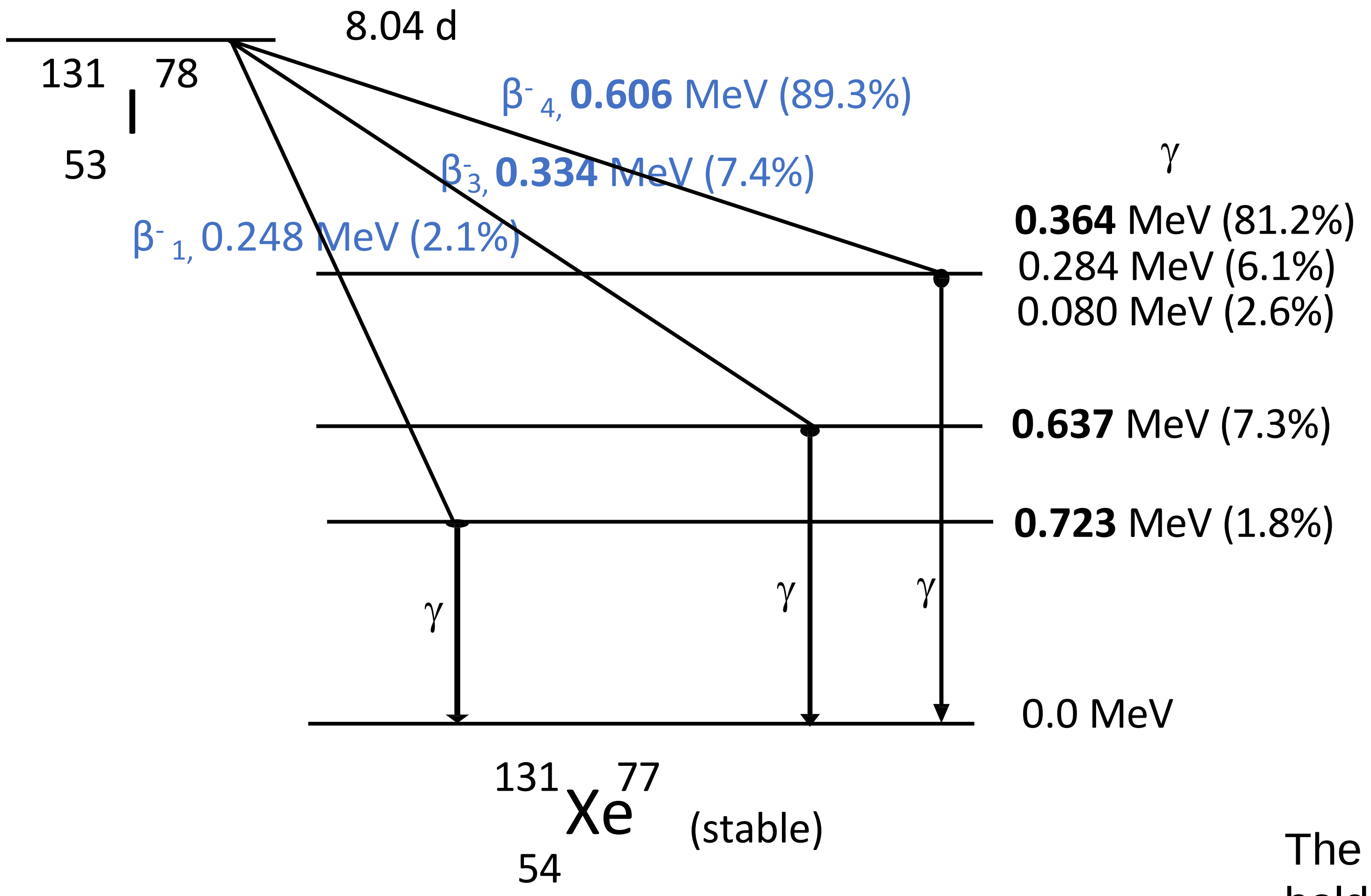
- For veterinary uses, ^{131}I is administered in the liquid form of Sodium Iodide. For human use, the predominant mode of administration is as capsules, except in cases where a patient is unable to swallow the capsule, in which case liquid NaI is injected.

- ^{131}I decays primarily by high energy beta-minus (β-) emissions of 6 energies, 3 of which are significant. It also emits gamma photons of 14 energies, of which 5 are significant, as well as conversion electrons of 8 energies. A simplified decay scheme is shown on the next page. The prominent emissions, with maximum and average beta energies are:

Type of Emission	**Energy (MeV)**		**Probability of emission**
	Maximum	**Average**	
Beta	0.606	0.192	89.3%
Beta	0.334	0.097	7.4 %
Beta	0.248	0.069	2.1 %
Gamma	0.364		81.2 %
Gamma	0.637		7.3 %
Gamma	0.723		1.8 %

Part III: Properties of ^{131}I Sodium Iodide (Na^{131}I) *(continued)*

^{131}I decay scheme (simplified)



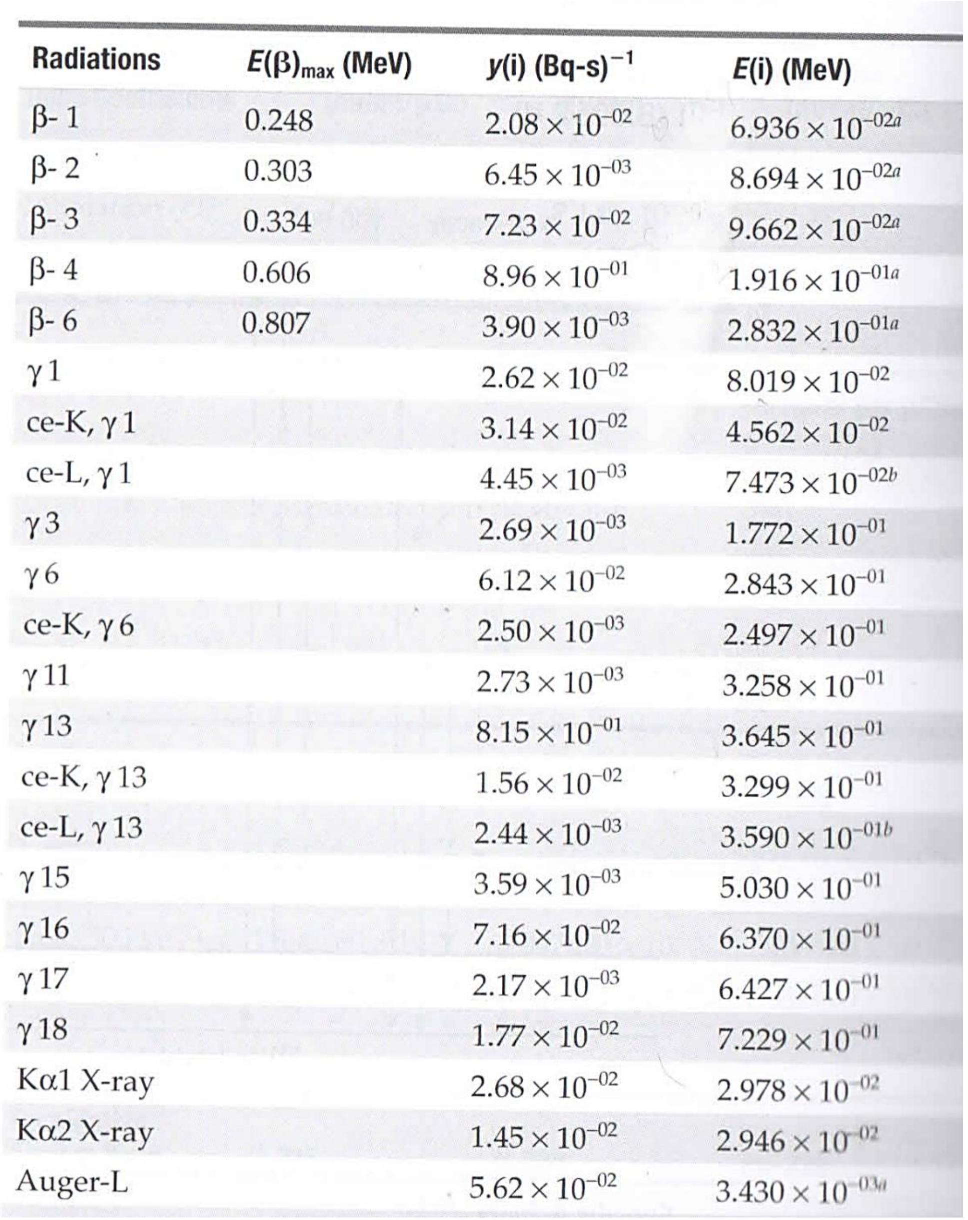
Emission of 606 keV beta particle with 89.3% yield decreases the energy of the parent nuclide to 364 keV, which is emitted as multiple gamma photon, of energies 364, 284 and 80 keV. These are the major beta and gamma emissions of ^{131}I.

Emission of 334 keV beta particle with 7.4% yield decreases the energy of the parent nuclide to 637 keV, which is emitted as a gamma photons with 7.3% yield

Emission of 248 keV beta particle with 2.1% yield decreases the energy of the parent nuclide to 723 keV, which is emitted as a gamma photon with a yield of 1.8%.

The most prominent emissions are shown in bold. A more elaborate list is provided on the next page

Part III: Properties of ^{131}I Sodium Iodide (Na^{131}I) *(continued)*



Radiations	$E(\beta)_{max}$ (MeV)	y(i) (Bq-s)$^{-1}$	E(i) (MeV)
β- 1	0.248	2.08×10^{-02}	6.936×10^{-02a}
β- 2	0.303	6.45×10^{-03}	8.694×10^{-02a}
β- 3	0.334	7.23×10^{-02}	9.662×10^{-02a}
β- 4	0.606	8.96×10^{-01}	1.916×10^{-01a}
β- 6	0.807	3.90×10^{-03}	2.832×10^{-01a}
γ 1		2.62×10^{-02}	8.019×10^{-02}
ce-K, γ 1		3.14×10^{-02}	4.562×10^{-02}
ce-L, γ 1		4.45×10^{-03}	7.473×10^{-02b}
γ 3		2.69×10^{-03}	1.772×10^{-01}
γ 6		6.12×10^{-02}	2.843×10^{-01}
ce-K, γ 6		2.50×10^{-03}	2.497×10^{-01}
γ 11		2.73×10^{-03}	3.258×10^{-01}
γ 13		8.15×10^{-01}	3.645×10^{-01}
ce-K, γ 13		1.56×10^{-02}	3.299×10^{-01}
ce-L, γ 13		2.44×10^{-03}	3.590×10^{-01b}
γ 15		3.59×10^{-03}	5.030×10^{-01}
γ 16		7.16×10^{-02}	6.370×10^{-01}
γ 17		2.17×10^{-03}	6.427×10^{-01}
γ 18		1.77×10^{-02}	7.229×10^{-01}
Kα1 X-ray		2.68×10^{-02}	2.978×10^{-02}
Kα2 X-ray		1.45×10^{-02}	2.946×10^{-02}
Auger-L		5.62×10^{-02}	3.430×10^{-03a}

Emissions of ^{131}I.

Source: Johnson, T.E, and B.K. Birky, 2012. Health Physics and Radiological Health, 4th ed. Lippincott Williams and Wilkins.

Part III: Properties of ^{131}I Sodium Iodide ($Na^{131}I$) *(continued)*

- The physical half life of ^{131}I is **8.04 days.**

- In Hyperthyroid cats, its effective half life has been estimated by different researchers as **2.3** or **2.54 days**.

- The high energy beta particles from ^{131}I can travel **1.65 meters (5.4 feet) in air**, **2 mm in water**, and **0.5 to 2 mm** (average **0.8 mm) in thyroid tissue**. The mechanism of action is bombardment of hyperthyroid cells by these beta particles, causing cell death and thereby rendering the cat euthyroid or hypothyroid.

- The dose rate over an unshielded 1 mCi dose of ^{131}I is **2200 mR/h** at 1 cm. Its beta and gamma emissions can present an external hazard to the skin and eyes. Accidental uptake of ^{131}I can present a significant internal hazard, with the thyroid being the critical organ affected.

- The appropriate shielding for ^{131}I is lead. Steel provides shielding as well. Low density materials such as plastic, acrylic, plexiglass or wood do not provide any shielding value.

- Any person who handles a dose of liquid ^{131}I must have a thyroid bioassay performed in the 48-72 hour period after handling, to determine possible internal contamination and uptake.

Part III: Properties of ^{90}Y- IsoPet®

- Yttrium-90 is the radionuclide in IsoPet®. Chemically, it consists of yttrium-phosphate. Physically, it is in the form of insoluble Y-90 microspheres, 0.5 to1.5 micrometers (microns) in diameter, dispersed within a bio-absorbable polymer matrix. This matrix is a liquid at room temperature, but transforms into a solid polymer matrix at internal body temperature.
- ^{90}Y decays by high energy beta-minus (β-) emissions of 3 energies, only one of which is significant. It is considered a 'pure beta' emitter with no primary gamma emissions. However, it does have some non-significant positron (β+), gamma and x-ray emissions (listed on page 28). The positron emission can be utilized for PET imaging of tumors post-treatment.
- Maximum energy of the three betas are:

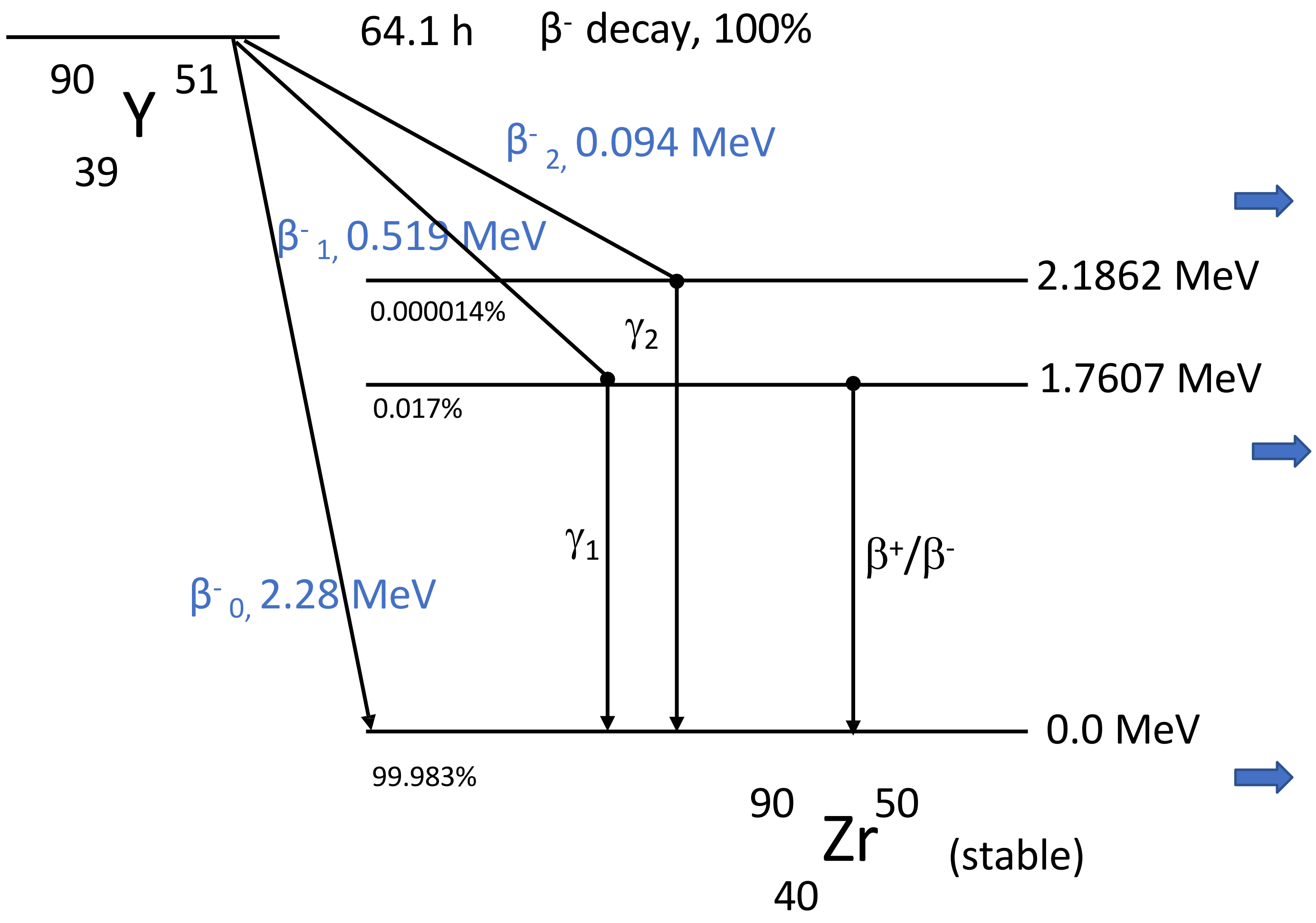
2.280 MeV, emitted with a probability of 99.983%

0.519 MeV, emitted with a probability of 0.017%, and

0.094 MeV, emitted with a probability of 1.4 x 10^{-6} %

- The overall maximum energy is **2.284 MeV**, generally abbreviated to **2.3 MeV.**
- Average energy is **0.93 MeV**, slightly higher than 1/3 max.

Part III: Properties of ^{90}Y- IsoPet® *(continued)*



^{90}Y decay scheme

Emission of 0.094 MeV β^-_2 decreases the energy of the parent nuclide to 2.1862 MeV, which then emits 2.1862 MeV γ to bring the energy to ground state. However, the probability of this pathway is diminishingly small (1.4 x 10^{-6} %)

Emission of 0.519 MeV β^-_1 decreases the energy of the parent nuclide to 1.7607 MeV, which then emits 1.743 and 1.758 MeV γ to bring the energy to ground state. The probability of this pathway is low (0.017 %). An electron / positron pair pathway with low probability (3.2 x 10^{-5} %) has also been discovered, which opens up the possibility of PET imaging of ^{90}Y containing matter.

Emission of 2.280 MeV β^-_0 decreases the energy of the parent to ground state. This is the overwhelmingly dominant pathway (99.983% probability)

Part III: Properties of ^{90}Y- IsoPet® *(continued)*

^{90}Y decay emissions

Radiations	Yield (%)	Energy (MeV)
β^{-}_{2}	1.4E-6	0.094
β^{-}_{1}	0.017	0.519
β^{-}_{0}	99.983	2.280
ce-K, γ1	0.0102	1.743
ce-L, γ1	1.26E-3	1.758
ce-K, γ2	1.4E-6	158.6
Kα1 X-ray	4.14E-3	2.186
Kα1 X-ray	2.16E-3	1.578E-2
Kβ X-ray	1.21E-3	1.770E-2
L X-ray	3.88E-4	2.040E-3
Auger-K	2.72E-3	1.34E-2
Auger-L	0.0118	2.020E-3
β^{+}	3.2E-5	0.511

Very minor /negligible

Part III: Properties of ^{90}Y- IsoPet® *(continued)*

- The half life of ^{90}Y is 64.1 hours, or 2.67 days. After 10 half lives, which is 26.7 days or approximately 1 month, the starting activity decays to near-background levels. Wastes containing ^{90}Y are therefore stored for a month (by which time, 99.9% of the starting activity would have decayed), and then disposed off as regular waste after verifying with a survey meter.
- The maximum range of the 2.3 MeV beta particles in air is about 30 feet.
- In soft tissues, they travel a maximum of 11 mm, and an average of 4.7 mm.
- The therapeutic action of ^{90}Y – IsoPet® comes from bombardment of the tumor by these high energy betas, once the particles are implanted by injection. Since the implanted dose solidifies within the injected volume, the radioactivity is confined within the tumor: it has been confirmed that the particles do not migrate to surrounding tissues.
- Treatment with ^{90}Y-IsoPet® is considered **brachytherapy**, since the suspension contains insoluble microsphere particles. Brachytherapy ('treatment at a short distance') is the type of radiation therapy where an insoluble / sealed source of radiation is placed within, or close to the tumor tissue to be treated.

Part III: Properties of ^{117m}Sn Synovetin OA^{TM}

- ^{117m}Sn is the radionuclide in Synovetin OA. Synovetin OA has a physical form of a colloid in ammonium salt.
- ^{117m}Sn emits monoenergetic conversion electrons and gamma radiation. Once injected, these low energy conversion electrons are absorbed in the joint which stimulate a response to reduce inflammation.
- The conversion electron is an alternative decay method competing with gamma decay. It can be thought that some of the gamma rays released from the ^{117m}Sn nuclei hit the orbital electrons of the Tin nucleus and eject electrons out of their orbits to become the released conversion electrons.

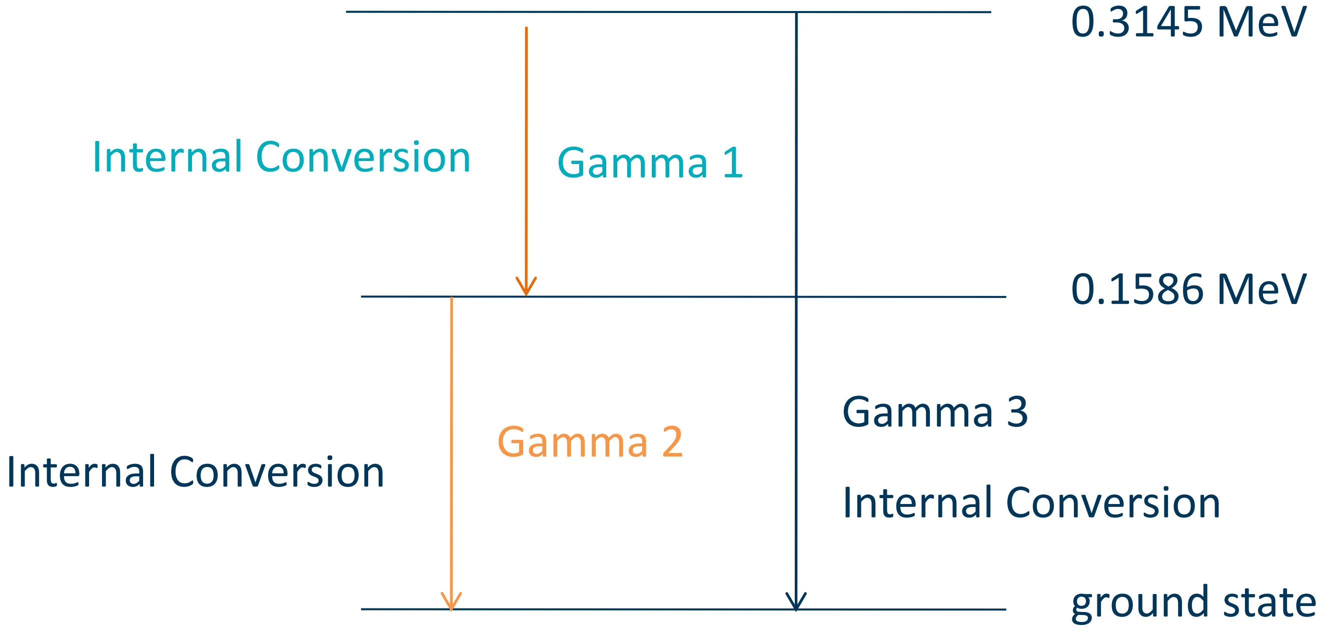
Part III: Properties of ^{117m}Sn Synovetin OA^{TM} *(continued)*

- The half life of ^{117m}Sn is 14 days. This means that 3 mCi of ^{117m}Sn becomes 1.5 mCi after 14 days and 0.75 mCi after 14 more days.
- ^{117m}Sn decays by emitting internal conversion electrons and gamma rays. Conversion electrons have discrete energies ranging from 127keV to 158keV, with a total yield of about 114%. Emitted gamma rays contain three energies, 156keV, 158.6keV, and 314.3keV. Among the three energies, 158.6keV is the most abundant with an 86.4% yield, it can be used for diagnostic imaging and verification of an injection site.

  - Note that decay yield or abundance is the fraction of that energy in total decay. A 158.6keV gamma ray with 86.4% abundance means that 86.4% of the time a photon of 158.6keV is emitted, and the other 13.6% of the time the ^{117m}Sn nucleus emits gammas of other energies.

Part III: Properties of ^{117m}Sn Synovetin OA^{TM} *(continued)*

^{117m}Sn decay scheme



0.3145 MeV

Internal Conversion

Gamma 1

0.1586 MeV

Gamma 2

Internal Conversion

Gamma 3

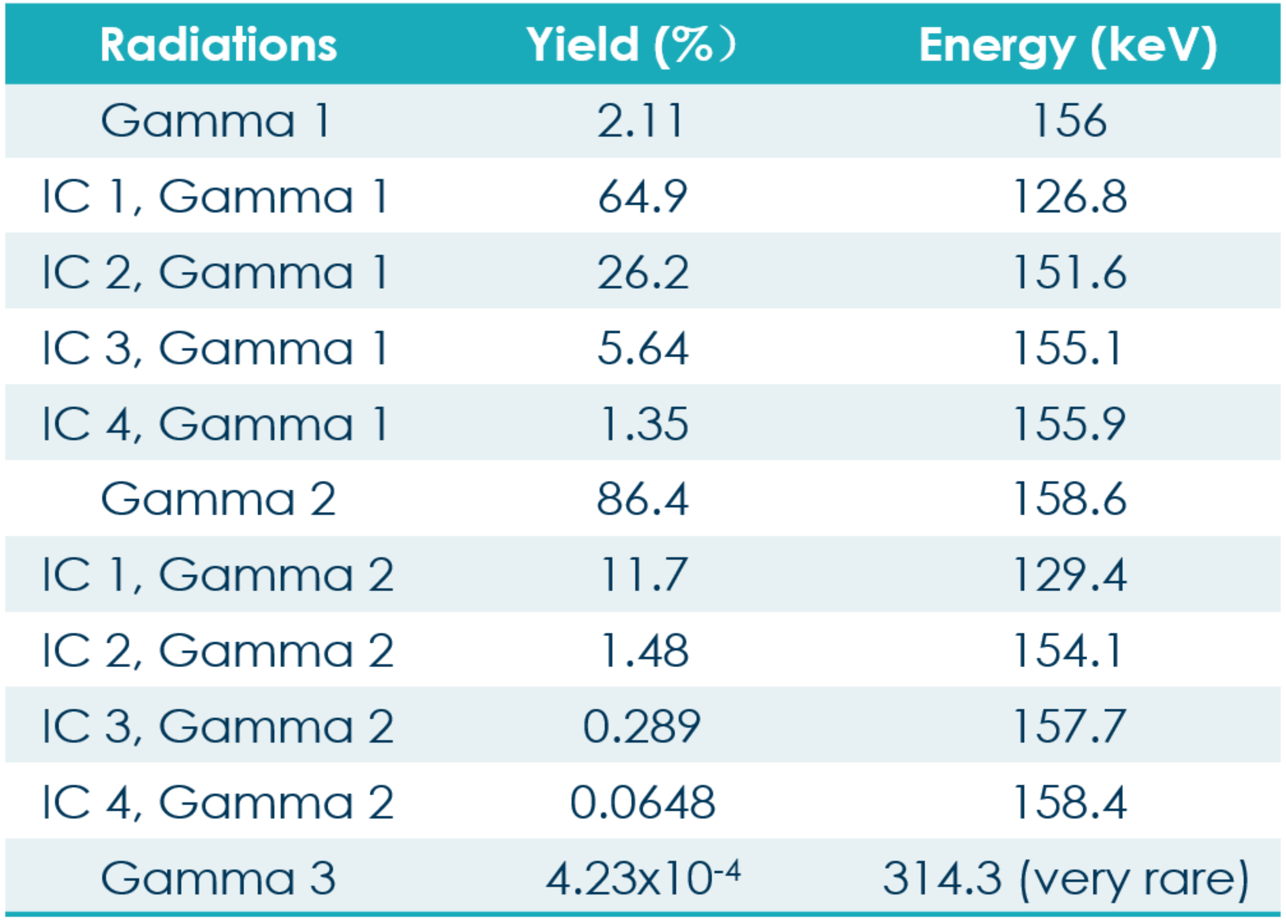
Internal Conversion

ground state

Part III: Properties of ^{117m}Sn Synovetin OA^{TM} *(continued)*

- ^{117m}Sn decay energy table, total Internal Conversion electron yield is about 114%

IC = Internal Conversion electron



Radiations	Yield (%)	Energy (keV)
Gamma 1	2.11	156
IC 1, Gamma 1	64.9	126.8
IC 2, Gamma 1	26.2	151.6
IC 3, Gamma 1	5.64	155.1
IC 4, Gamma 1	1.35	155.9
Gamma 2	86.4	158.6
IC 1, Gamma 2	11.7	129.4
IC 2, Gamma 2	1.48	154.1
IC 3, Gamma 2	0.289	157.7
IC 4, Gamma 2	0.0648	158.4
Gamma 3	4.23×10^{-4}	314.3 (very rare)

Reference: https://www.orau.org/PTP/PTP%20Library/library/DOE/bnl/nuclidedata/MIRSn117.htm

Conclusion

- Atoms are characterized by atomic number (or proton number Z) and mass number (sum of the number of protons and neutrons).
- Each radionuclide has its own signature with unique characteristics of type of radiation emitted, energy of radiation emitted, and half life.
- The chart of the nuclides is an excellent resource for all things related to radioactivity.
- Half life measures how fast a radionuclide decays. The activity of a radionuclide decreases by half after one half life.
- Nuclear decay is a process of nuclear transformation, including alpha decay, beta minus decay, and beta plus decay.

Recommended Reading:

2.1. For ^{131}I treatment: Roberts, E., J. M. Gray, E. Gunn, and I.K. Ramsey. A novel method of continuous cage-side monitoring of hyperthyroid cats treated with radio-iodine. Veterinary Record, July 4, 2015.

2.2. Turner, James E. 2007. Atoms, Radiation, and Radiation Protection. Wiley-VCH, Germany (optional textbook)