Alpha Decay

Key concepts

- Coulomb barrier and energy release through alpha decay.
- Energy spectrum of alpha particles.
- Major health hazards related to alpha emission

Average Binding Energy Per Nucleon

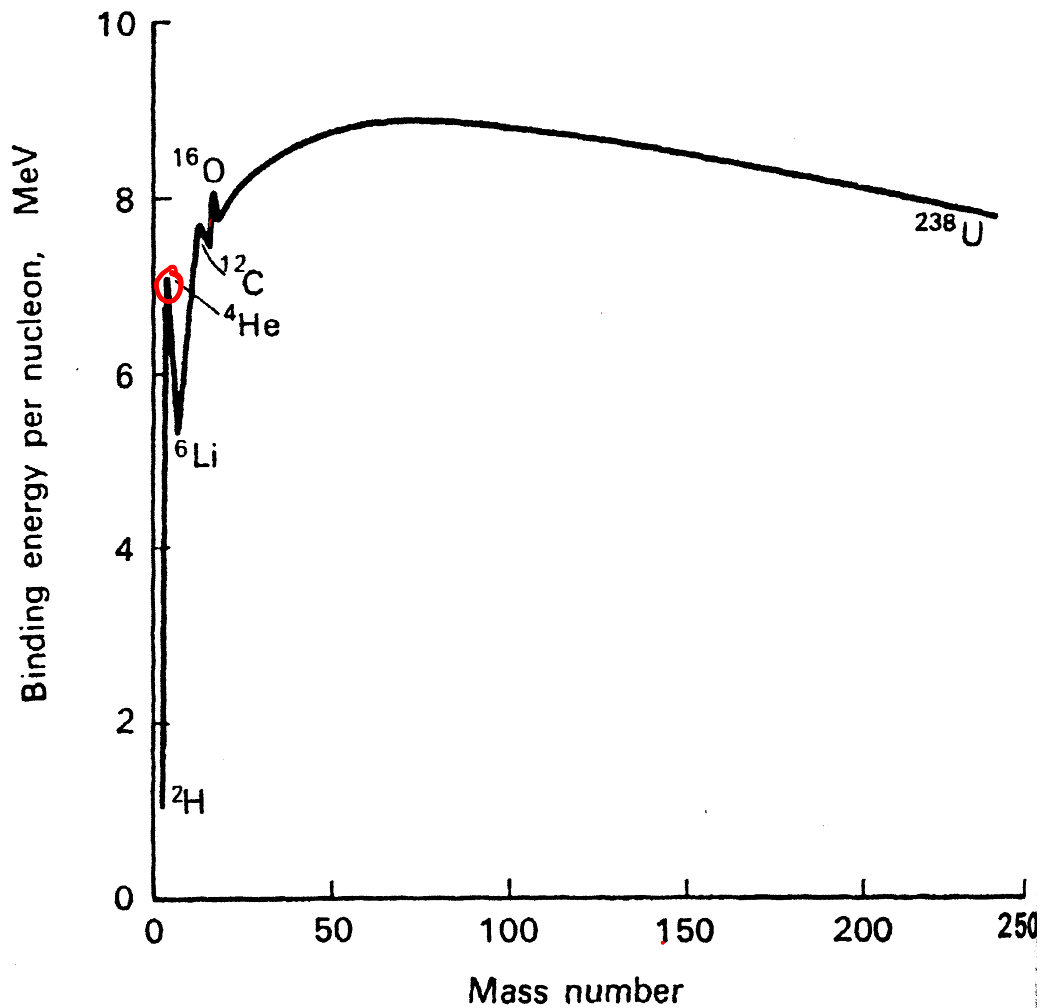
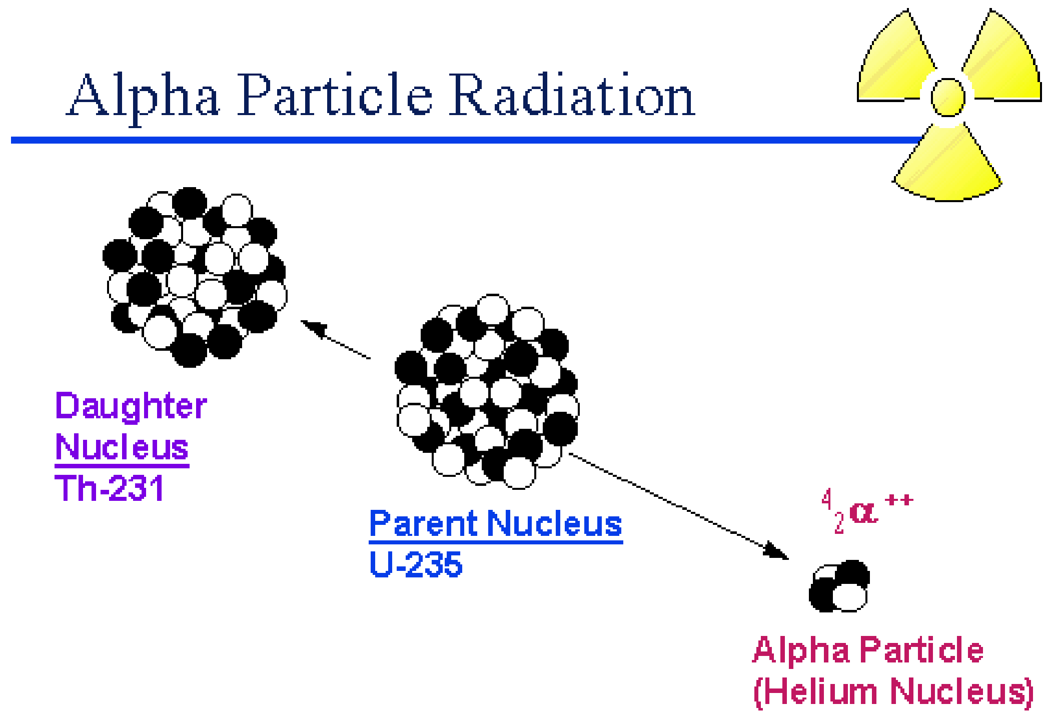


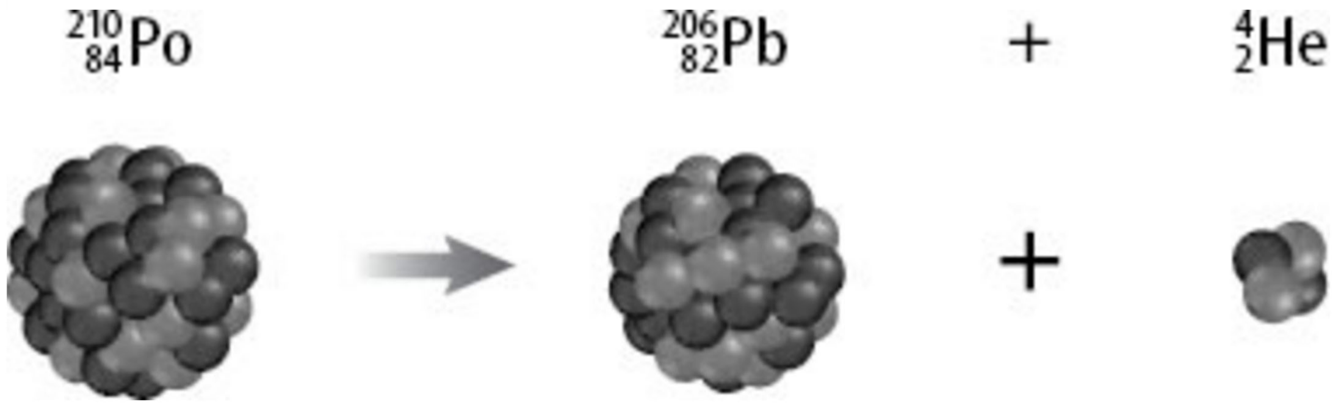
FIGURE 3.5. Variation of binding energy per nucleon with atomic mass num

Alpha Emission

- An alpha particle is a highly energetic helium nucleus consisting of two neutrons and 2 protons.
- It is normally emitted from isotopes when the neutron-to-proton ratio is too low – called the alpha decay.
- Atomic number and atomic mass number are conserved in alpha decays



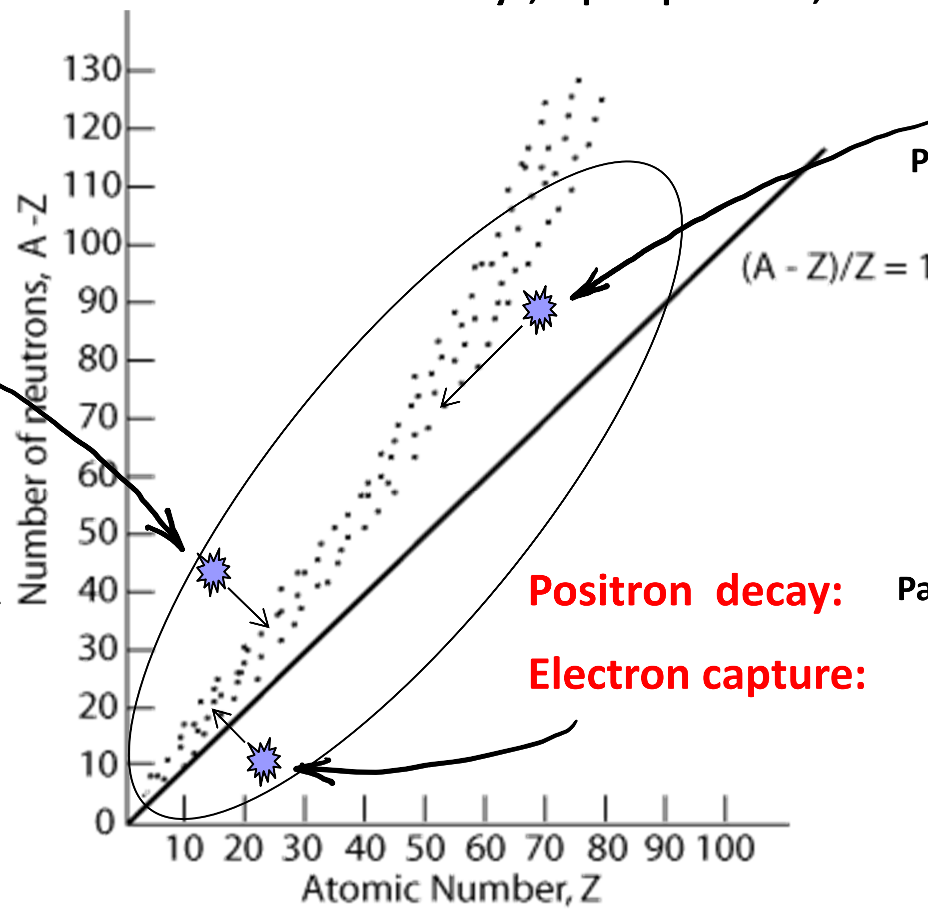
Alpha Decay – An Example



- Half-life: 138.376 days; Decay mode: alpha-decay (branching ratio: 100%); Energy release: 5.407MeV
- ^{210}Po has a neutron-to-proton ratio of 126 to 84 (1.5:1) and ^{206}Pb has a neutron-to-proton ratio of 124 to 82 (~1.51:1)→ increased neutron-to-proton ratio.
- Alpha decay is also accompanied by the loss of two orbital electrons.

Nuclear Stability and the Origin of Radioactivity

Secondary radiations, e.g., gamma-rays, X-rays, alpha-particles, and electrons



Alpha decay

Parent (Z, N) → Daughter (Z-2, N-2)

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

Beta decay:

Parent (Z, N) → Daughter (Z+1, N-1)

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

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

Positron decay: **Parent (Z, N) → Daughter (Z-1, N+1)**

Electron capture:

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

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

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

Alpha Emission

In heavy elements, It would require a minimum kinetic energy of ~3.8MeV for the alpha particle to “tunneling through” the potential well …

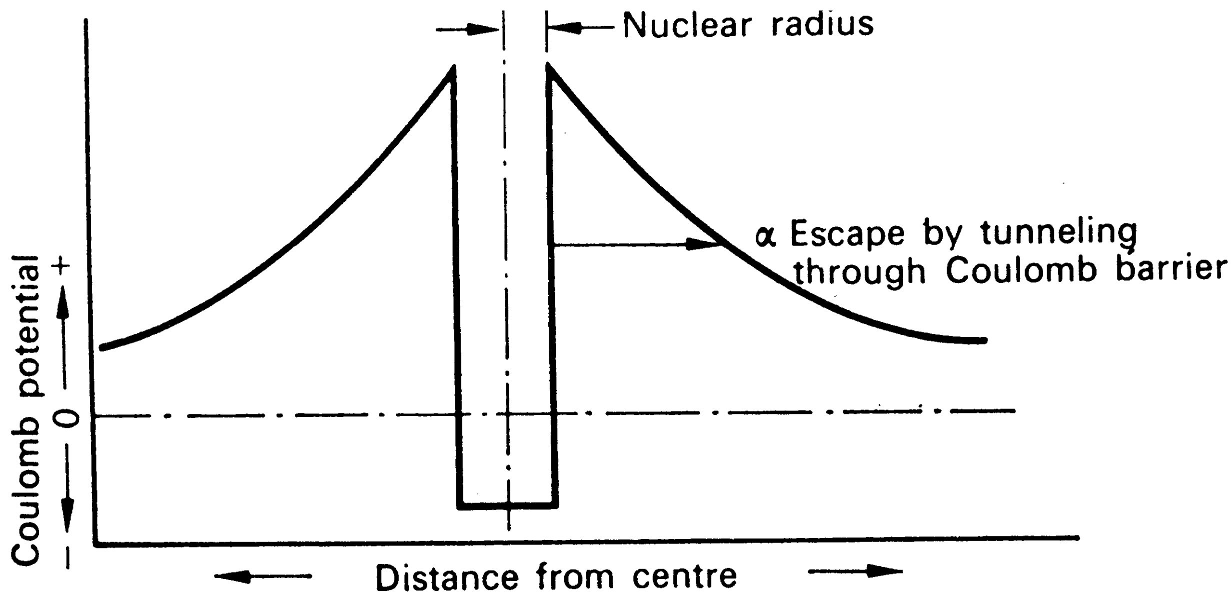


FIG. 4.1. Potential inside and in the vicinity of a nucleus.

Alpha Decay

With only a few exceptions (Samarium-147), **naturally occurring alpha decay is found only among elements of atomic number greater than 82** because of the following reasons:

- **Electrostatic repulsive force in heavy nuclei increases much more rapidly with the increasing atomic number than the cohesive nuclear force**. The magnitude of the electrostatic repulsive force may closely approach or even exceed that of the nuclear force.

- **Emitted alpha particles must have sufficiently high kinetic energy to overcome the potential barrier** resulting from the strong nuclear force.

Internal Dose from Indoor Radon

(more detailed discussions coming soon …)

From <<Radiation Protection and Dosimetry>>, by Michael Stabin.

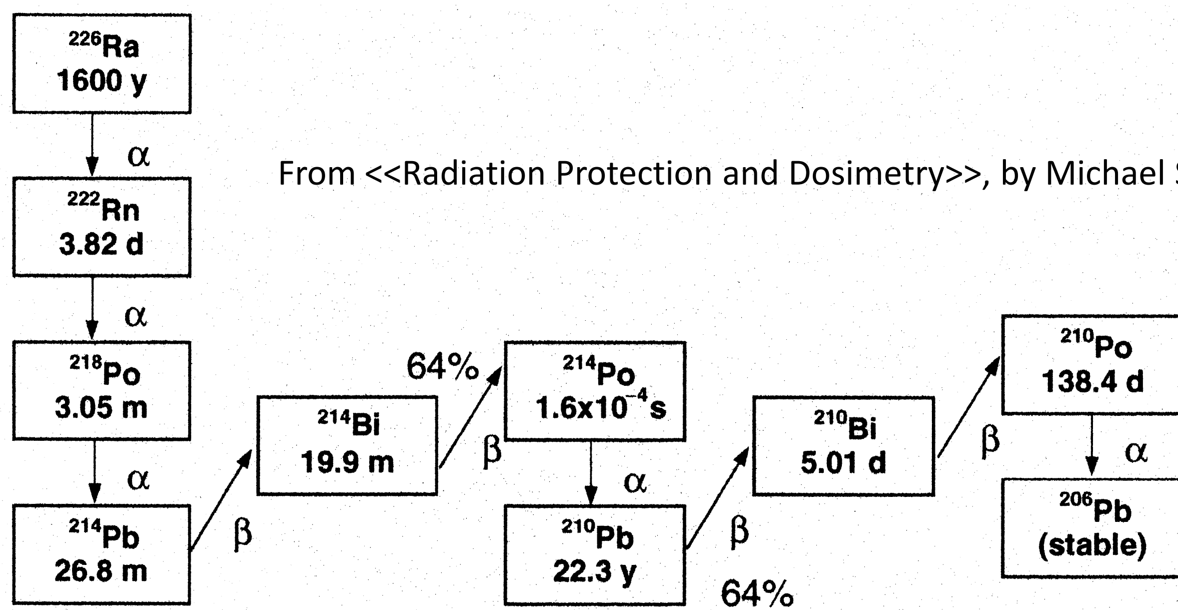


Figure 3.11 The ^{226}Ra decay series.

We can continue on with a species D, E, F, and so on, but the relationships among the species obviously become more complicated and are difficult to categorize. If Species A is very long-lived, however, relative to other members of the chain, after a long time (seven to ten half-lives of the longest-lived progeny species), all the members of the chain will be in secular equilibrium and decaying with the half-life of Species A, and all having the same activity as Species A. An important example is the ^{226}Ra decay series (Figure 3.11).

Energy Release from Alpha Decay

An example: Alpha decay of ^{226}Ra

$$^{226}_{88}\text{Ra} \rightarrow {}^{222}_{86}\text{Rn} + {}^{4}_{2}\text{He}.$$

The energy Q released in the decay arises from a net loss in the masses $M_{\text{Ra,N}}$, $M_{\text{Rn,N}}$, and $M_{\text{He,N}}$, of the radium, radon, and helium nuclei:

$$Q = M_{\text{Ra,N}} - M_{\text{Rn,N}} - M_{\text{He,N}}.$$

The energy release can be found using the data shown in the table previously used for deriving binding energy

$$Q_\alpha = \Delta_\text{P} - \Delta_\text{D} - \Delta_\text{He}.$$

$$Q = 23.69 - 16.39 - 2.42 = 4.88\ \text{MeV}.$$

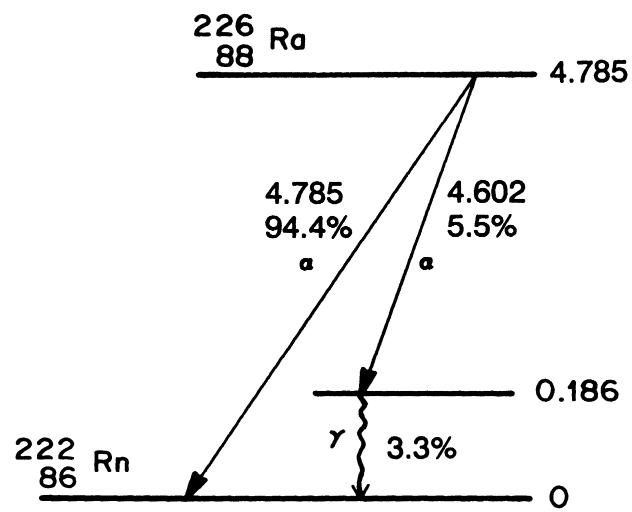


FIGURE 3.4. Nuclear decay scheme of $^{226}_{88}$Ra.

Understanding the Mass Defect and Nuclear Binding Energy

Nuclide	Natural Abundance (%)	Mass Difference $\Delta = M - A$ (MeV) (at. mass – at. mass No.)	Type of Decay	Half-Life	Major Radiations, Energies (MeV), and Frequency per Disintegration (%)
$^{22}_{11}Na$	—	–5.182	β^+ 89.8% EC 10.2%	2.602 y	β^+ : 0.545 max (avg 0.215) γ : 0.511 (180%, $\gamma^{\pm}$), 1.275 (100%), Ne X rays
$^{23}_{11}Na$	100.	–9.528	—	—	—
$^{24}_{11}Na$	—	–8.418	β^-	15.00 h	β^- : 1.390 max (avg 0.554) γ : 1.369 (100%), 2.754 (100%)
$^{24}_{12}Mg$	78.60	–13.933	—	—	—
$^{26}_{12}Mg$	11.3	–16.214	—	—	—
$^{26}_{13}Al$	—	–12.211	β^+ 81.8% EC 18.2%	7.16×10^5 y	β^+ : 1.174 max (avg 0.544) γ : 0.511 (164%, $\gamma^{\pm}$), 1.130 (2.5%), 1.809 (100%), Mg X rays
$^{26m}_{13}Al$	—	–11.982	β^+	6.4 s	β^+ : 3.21 max γ : 0.511 (200%, $\gamma^{\pm}$)
$^{32}_{15}P$	—	–24.303	β^-	14.29 d	β^- : 1.710 max (avg 0.695) No γ
$^{32}_{16}S$	95.0	–26.013	—	—	—
$^{35}_{16}S$	—	–28.847	β^-	87.44 d	β^- : 0.167 max (avg 0.0488) No γ
$^{37}_{16}S$	—	–27.0	β^-	5.06 min	β^- : 1.6 max (90%) 4.7 max (10%) γ : 3.09 (90%)
$^{38}_{16}S$	—	–26.8	β^-	2.87 h	β^- : 1.1 max (95%), 3.0 max (5%) γ : 1.88 (95%) Daughter radiations from ^{38}Cl

Energy Release in Alpha Emission
A more accurate version

The required kinetic energy has to come from the decrease in mass following the decay process.

The relationship between mass and energy associated with an alpha emission is given as

$$M_p = M_d + M_\alpha + 2M_e + Q, \tag{4.1}$$

where M_p, M_d, M_α, and M_e are respectively equal to the masses of the parent, the daughter, the emitted alpha particle, and the two orbital electrons that are lost during the transition to the lower atomic numbered daughter, while Q is the total energy release associated with the radioactive transformation.

Energy Release from Alpha Decay

An example: Alpha decay of ^{226}Ra

$$^{226}_{88}\text{Ra} \rightarrow\, ^{222}_{86}\text{Rn} + {}^{4}_{2}\text{He}.$$

The same example, when considering the daughter atom to have two less electrons,

The energy equation describing α decay is:

$$M_p = M_d + M_\alpha + 2M_e + Q$$

$$Q = M_p - M_d - M_\alpha - 2M_e.$$

Here, M_p is the mass of the parent, and M_d is the mass of the progeny, M_α is the mass of the α particle, M_e is the mass of an electron, and Q is the energy released in the reaction. For the ^{226}Ra example above:

$$Q = 226.025 - 222.0176 - 4.0015 - 2(0.00055)$$

$$Q = 0.00523 \text{ amu} = 4.78 \text{ MeV}$$

Note:
$M_{d,}$ M_d: masses of the parent and daughter atoms

What is the energy of the alpha particle?

Energy Spectra of Alpha Particles

Radium-226 will decay either with or without an accompanying γ-ray emis-sion. With the γ emission (0.186 MeV, 3.6% of decays), the α particle has ar energy of about 4.6 MeV). When there is no γ emission in this case, the α particle has the full energy of 4.78 MeV, and we can look also at the energy oi the recoil nucleus from a simple consideration of conservation of energy anc momentum:

$$Q = MV^2/2 + mv^2/2$$

$$MV = mv$$

$$V = \frac{mv}{M}$$

m is the mass of the alpha particle, and M is the mass of the recoil nucleus.

$$Q = \frac{Mm^2v^2}{2M^2} + \frac{mv^2}{2}$$

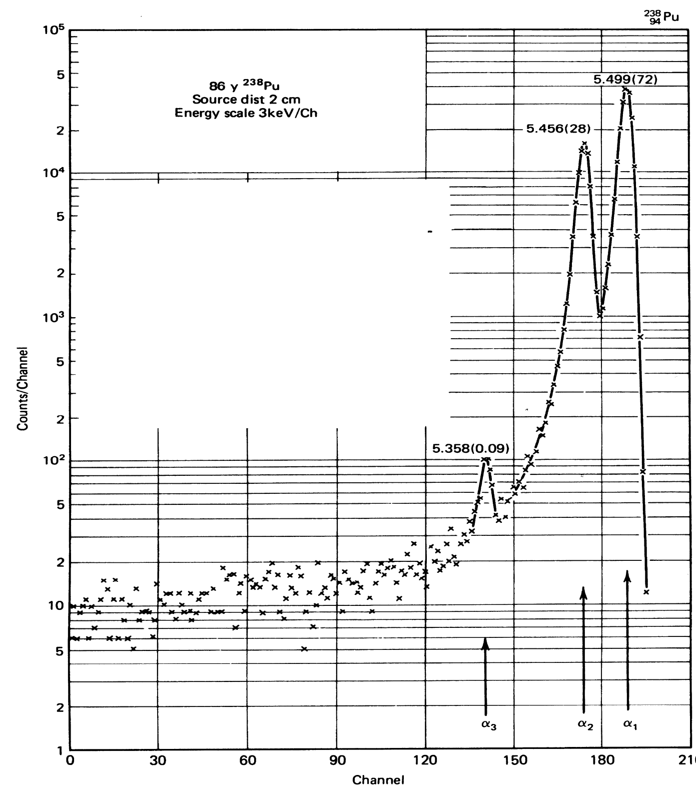
$$E = \frac{mv^2}{2}$$

$$Q = E\left(\frac{m}{M} + 1\right)$$

$$E = \frac{Q}{1 + m/M}$$

$$E = \frac{4.78}{1 + 4/222} = 4.6954 \text{ MeV}$$

$$E_{\text{recoil}} \approx 0.088 \text{ MeV}$$



Measured energy spectrum of alpha particles emitted from the decay of ^{238}Pu.

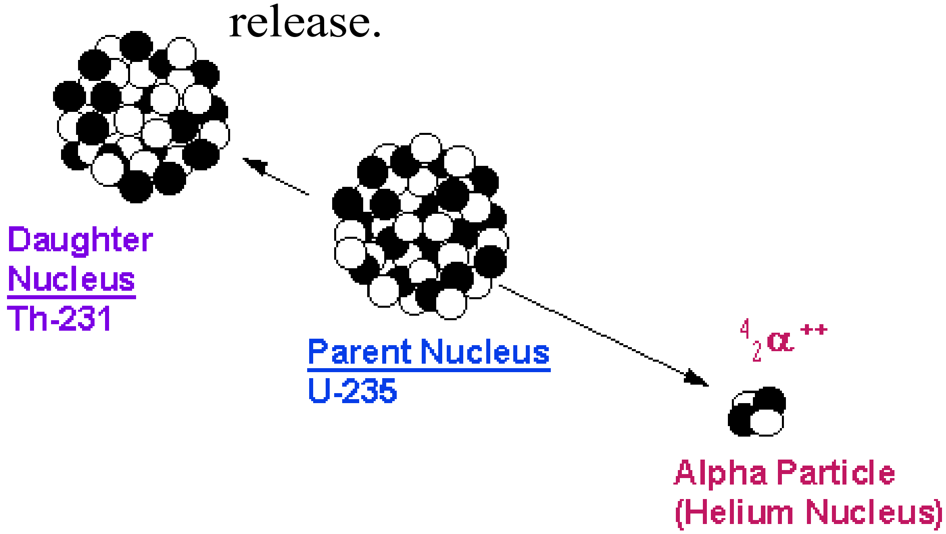
Energy Spectra of Alpha Particles

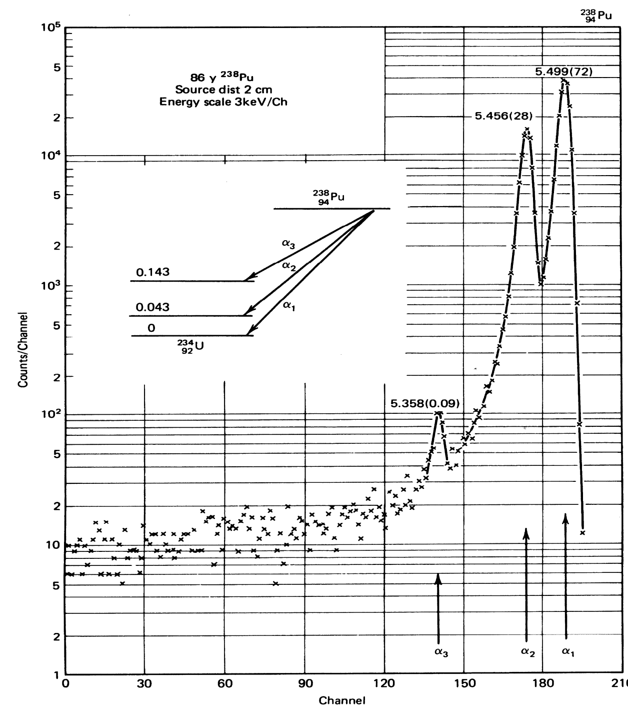
Alpha decays are sometimes accompanied by the excited daughter products which complicates the resultant alpha particle spectra.

The kinetic energy of alpha particles is given by

$$E_\alpha = Q \cdot (A-4)/A,$$

where A is the atomic mass number of the parent nucleus and Q is the energy release.





Measured energy spectrum of alpha particles emitted from the decay of ^{238}Pu.

Half-Life of Alpha Emitters

The most energetic alpha particles are found to come from radionuclide having relatively short half-lives.

An early empirical rule known as the Geiger-Nuttall law implies that

$$-\ln T = a + b \ln R$$

where T and R are the half - life of an alpha emitter and the range of the particles emitted. a and b are constants.

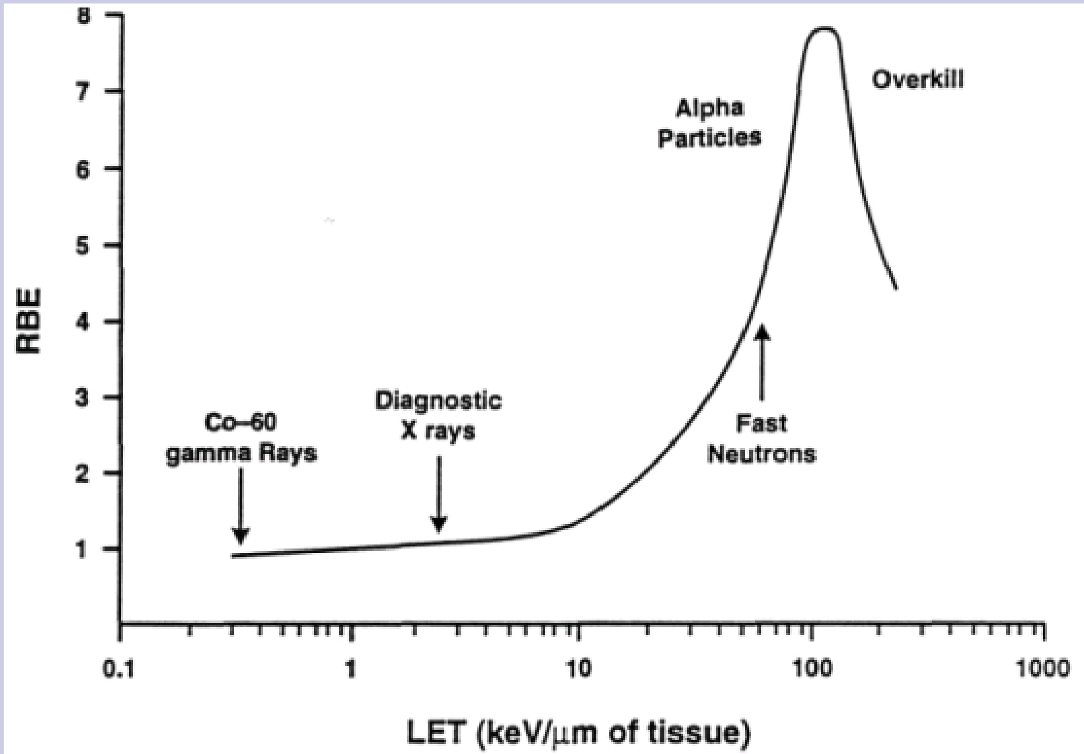
A Few Remarks

- Q value has to be positive for alpha decay.
- Energy of the alpha particles generally increases with the atomic number of the parent. For example, 1.8 MeV for ^{144}Nd to 11.6 MeV for ^{212m}Po.
- All nuclei with mass numbers greater than A of 150 are thermodynamically unstable against alpha emission (Q is positive). However, alpha emission is a dominant decay process only for heaviest nuclei, A≥210.

Alpha Emission and Potential Health Concerns

Radiation Effect and Dose Delivery

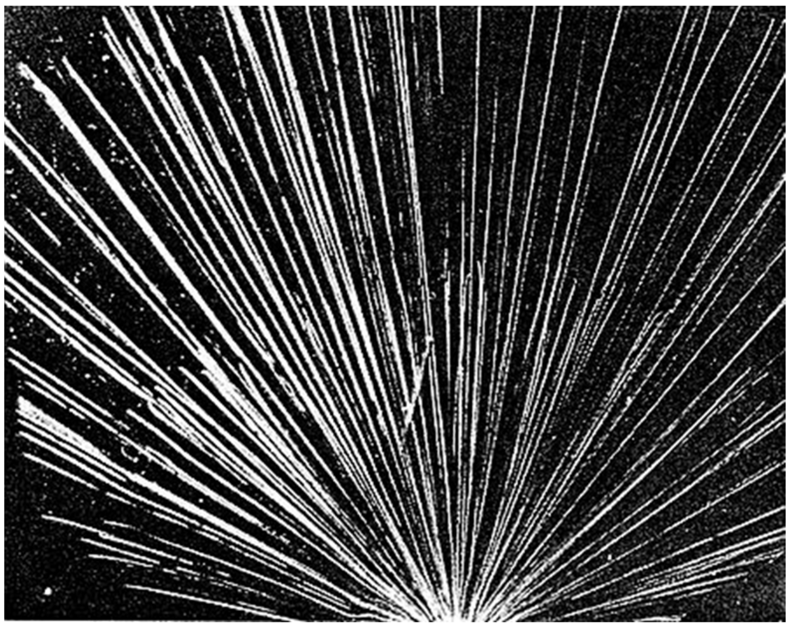
For low LET radiation, $\Rightarrow$ RBE (Relative Biologic Effectiveness) $\propto$ LET (Linear Energy Transfer), for higher LET the RBE increases to a maximum, the subsequent drop is caused by the overkill effect.



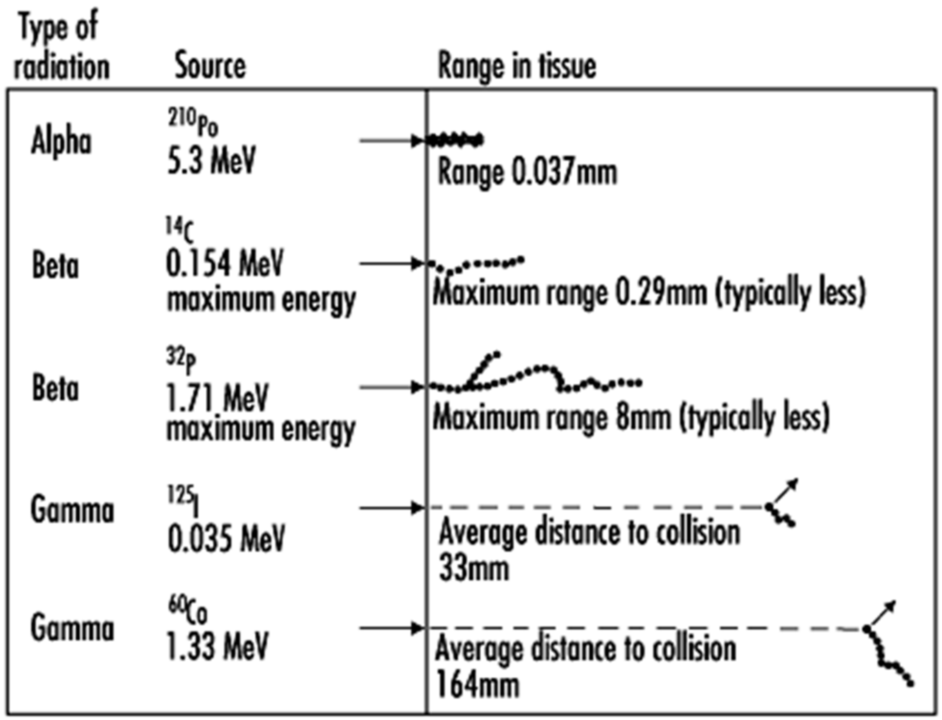
$$RBE = \frac{Dose\ of\ 150\ V\ X-rays\ required\ to\ cause\ effect\ x}{Dose\ of\ radiation\ required\ to\ cause\ effect\ x}$$

These high energies are sufficient to kill more cells than actually available!

Alpha Emission and Radiation Hazard



J. Chadwick, Cavendish Laboratory, University of Cambridge.



Source: Shapiro 1972.

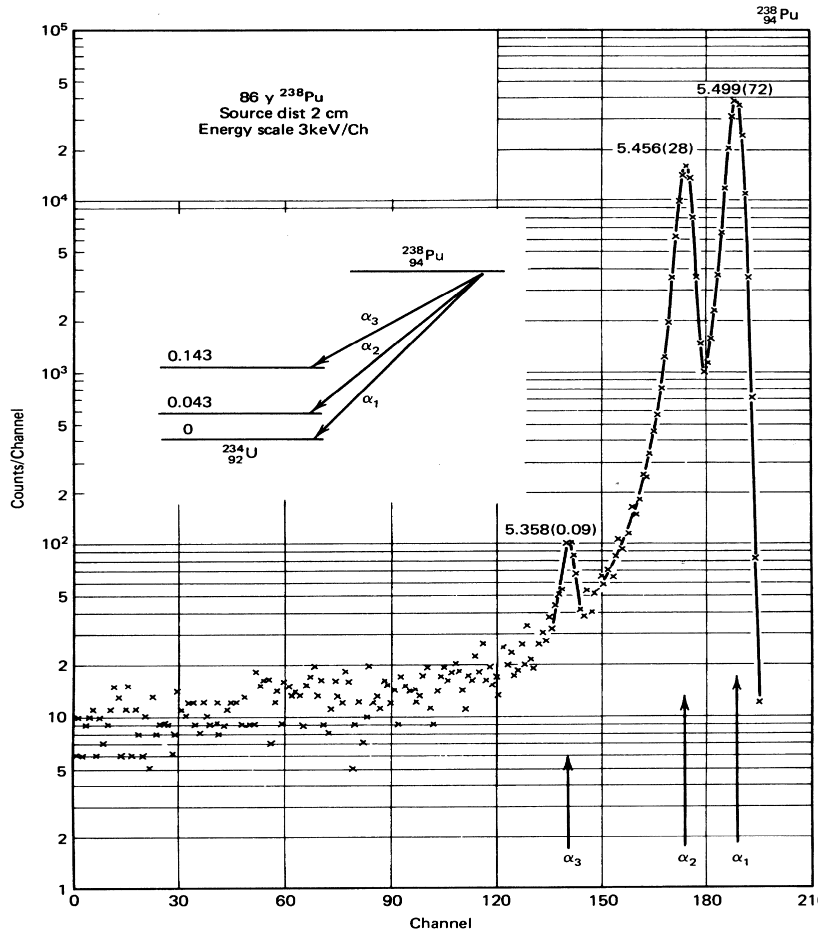
Encyclopaedia of Occupational Health and Safety 4th Edition, from the International Labor Office

Alpha particles have extremely short ranges (micros to tens of microns in tissue). They can not penetrate the outer layer of dead skin and in general pose no direct external hazard to the body.

https://www.youtube.com/watch?v=lA8pUZTDmyc

Alpha Emission and Radiation Hazard

(Left) Measured energy spectrum of alpha particles emitted from the decay of ^{238}Pu.



In addition to the internal hazard, alpha particles, one can generally expect gamma ray emission with an alpha source. Also, many alpha emitters have radioactive daughters that present radiation protection concerns.

Article | Open Access | Published: 15 January 2021

Quantitative estimation of track segment yields of water radiolysis species under heavy ions around Bragg peak energies using Geant4-DNA

Kentaro Baba, Tamon Kusumoto, Shogo Okada, Ryo Ogawara, Satoshi Kodaira, Quentin Raffy, Rémi Barillon, Nicolas Ludwig, Catherine Galindo, Philippe Peaupardin & Masayori Ishikawa

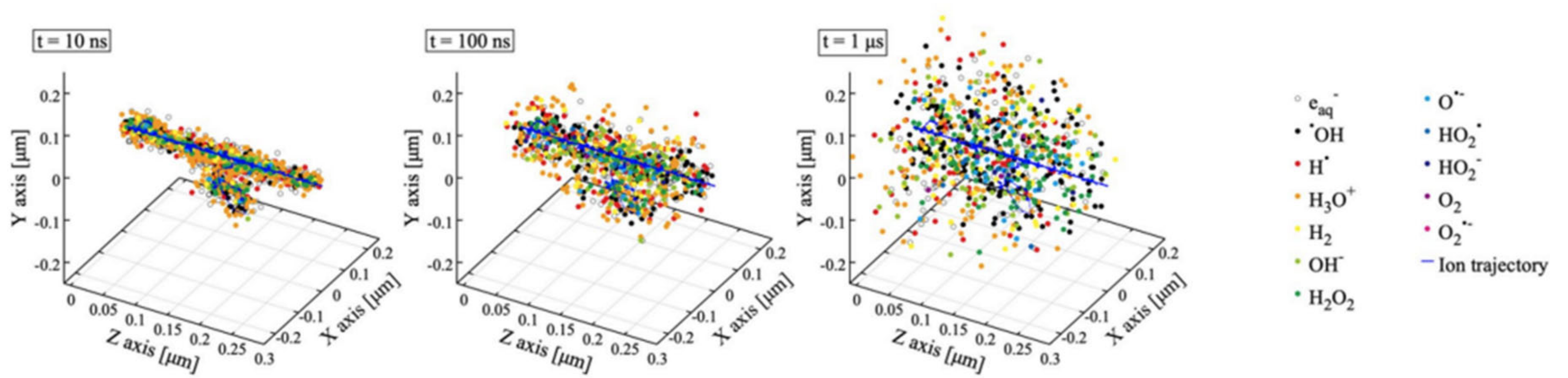
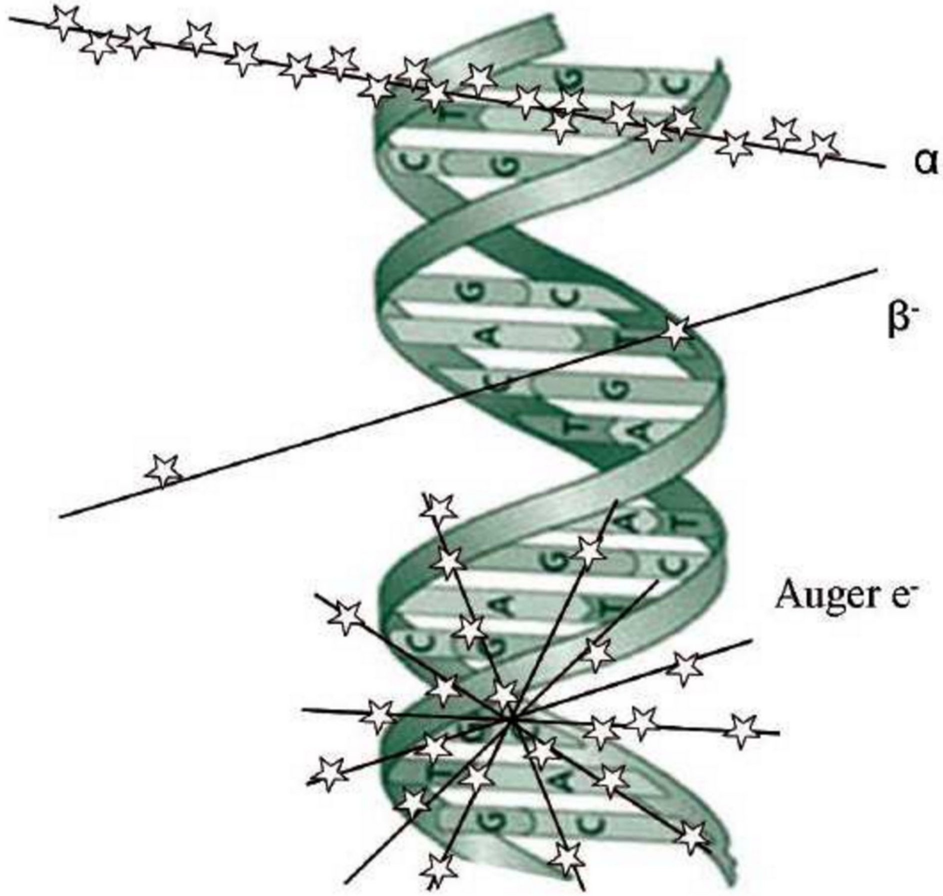


Figure 1. Chemical evolution of 400 MeV/u carbon ion track in water in the time 1 ps to 1 μs.

Alpha Emission and Radiation Hazard



However, when inhaled or entering through a wound, an alpha source can present a hazard as internal emitter.

An Overview of Radiation Exposure to US Population

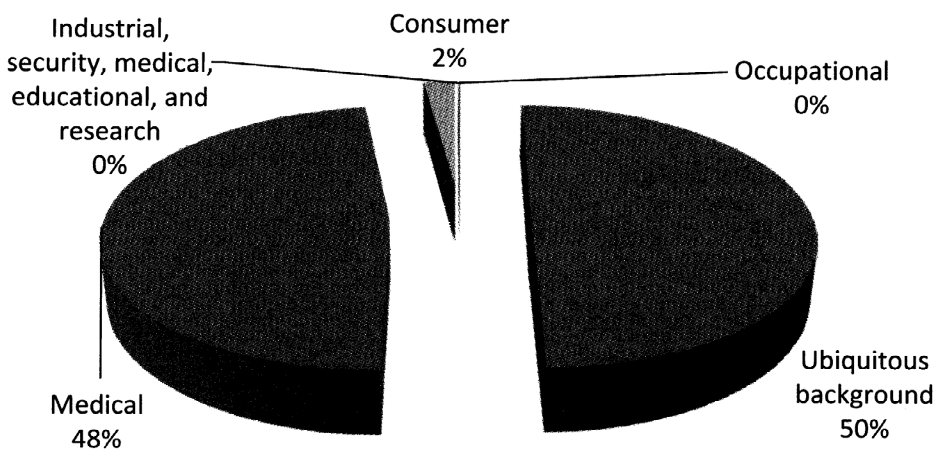


Figure 1.1 ◆ Exposure by Major Categories

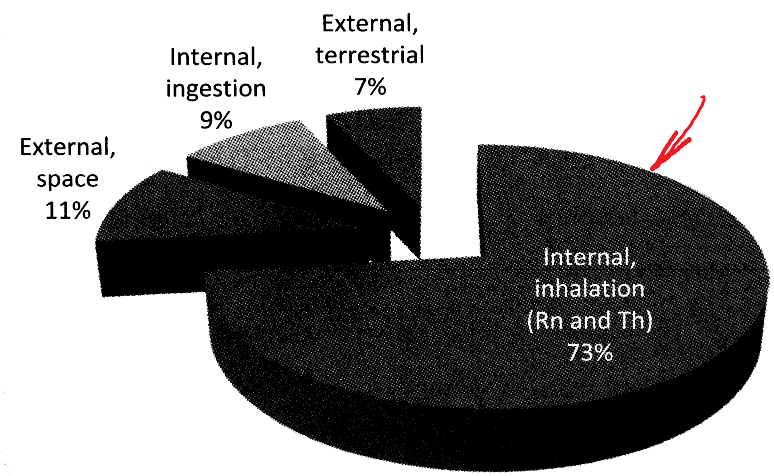


Figure 1.2 ◆ Ubiquitous Background

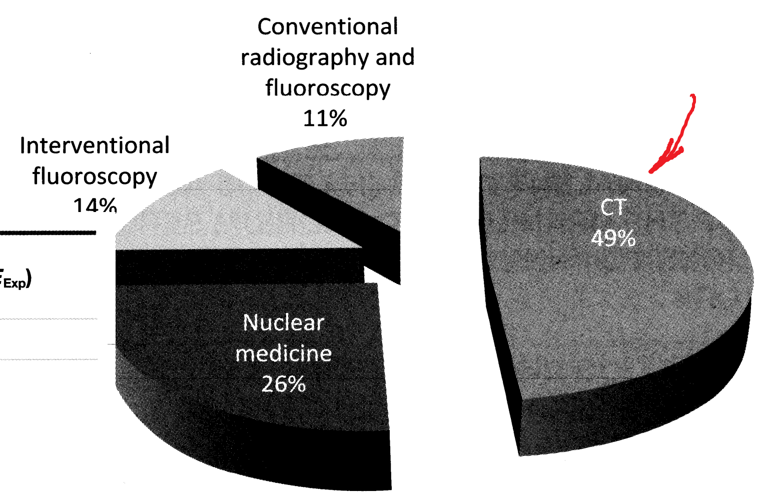
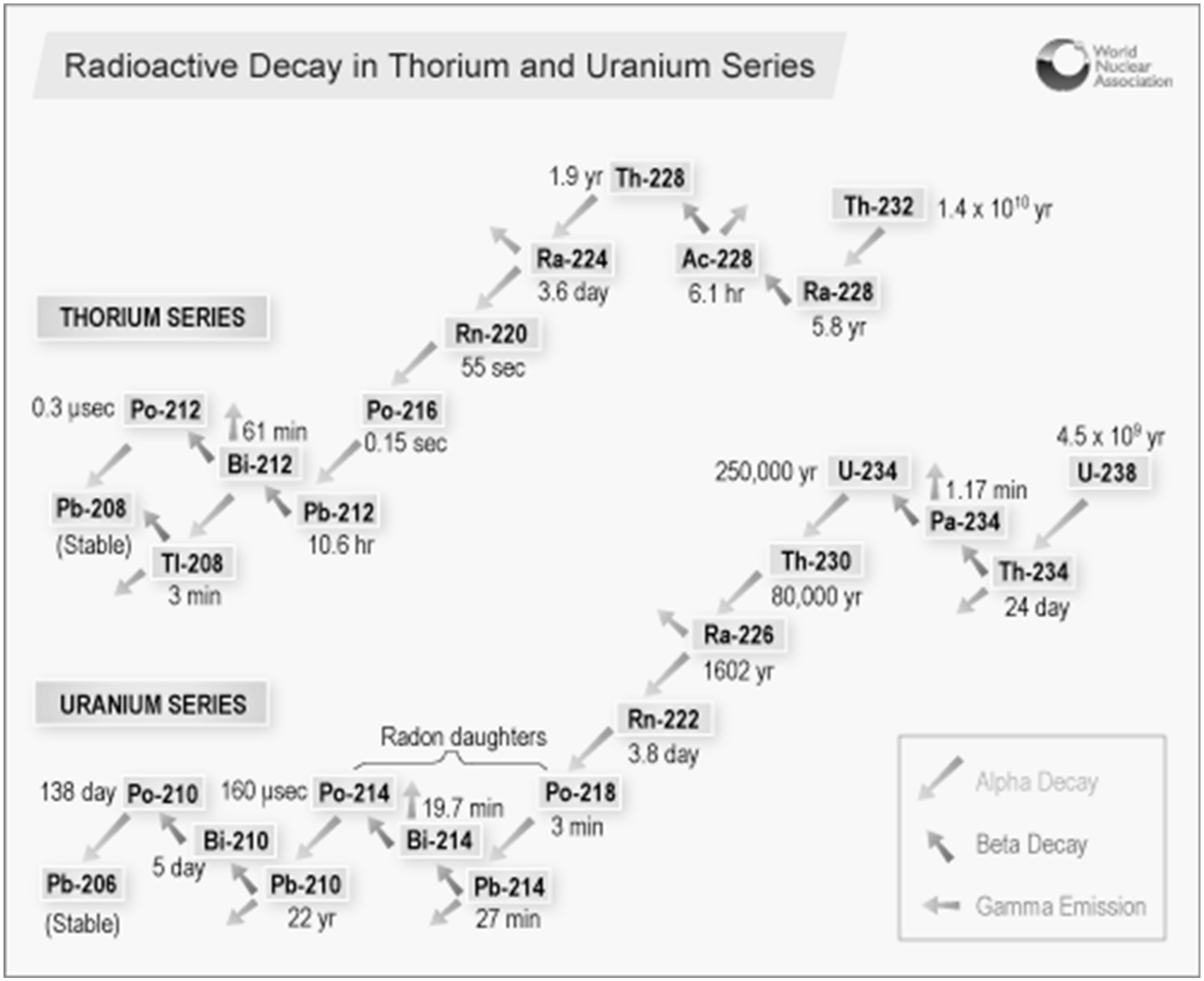


Figure 1.3 ◆ Medical

Table 1.4 COLLECTIVE EFFECTIVE DOSE (S), EFFECTIVE DOSE PER INDIVIDUAL IN THE US POPULATION (E_{US}), AND AVERAGE EFFECTIVE DOSE FOR THE EXPOSED GROUP (E_{Exp}) FROM MEDICAL PROCEDURES FOR 2006 (After NCRP Report No. 160, 2009)

Exposure Category	*S* (person-Sv)	E_{US} (mSv)	E_{Exp} (mSv)
Medical			
CT	440,000	1.47	[a]
Nuclear medicine	231,000	0.77	[a]
Interventional fluoroscopy	128,000	0.43	[a]
Conventional radiography and fluoroscopy	100,000	0.33	[a]
Total	899,000	3	[a]

[a]Not determined for the medical category because the number of patients exposed is not known, only the number of procedures.



http://www.world-nuclear.org/info/inf30.html

Naturally Occurring Radioactivity

Common characteristics of radioactive series:

- The first member of each series is very long-lived – ^{232}Th: 1.39×10^{10} years, ^{238}U: 4.51×10^{9} years and ^{235}U: 7.13×10^{8} years.

- All three naturally occurring series each has a gaseous member.

$$^{222}_{86}Rn \text{ appears in uranium series and is called Radon}$$

$$^{220}_{86}Rn \text{ appears in thorium series and is called Thoron}$$

$$^{219}_{86}Rn \text{ appears in actinium series and is called Actinon}$$

Artificially created radioactive series, such as the neptunium series has no gaseous member.

- The end product of all three naturally occurring radioactive series is lead.

$$^{206}_{82}Pb \text{ appears in uranium series}$$

$$^{208}_{82}Pb \text{ appears in thorium series}$$

$$^{207}_{82}Pb \text{ appears in actinium series}$$

Naturally Occurring Radioactivity – Other Isotopes of Radon

All three isotopes of radon have radioactive daughters, so they are all potentially hazardous.

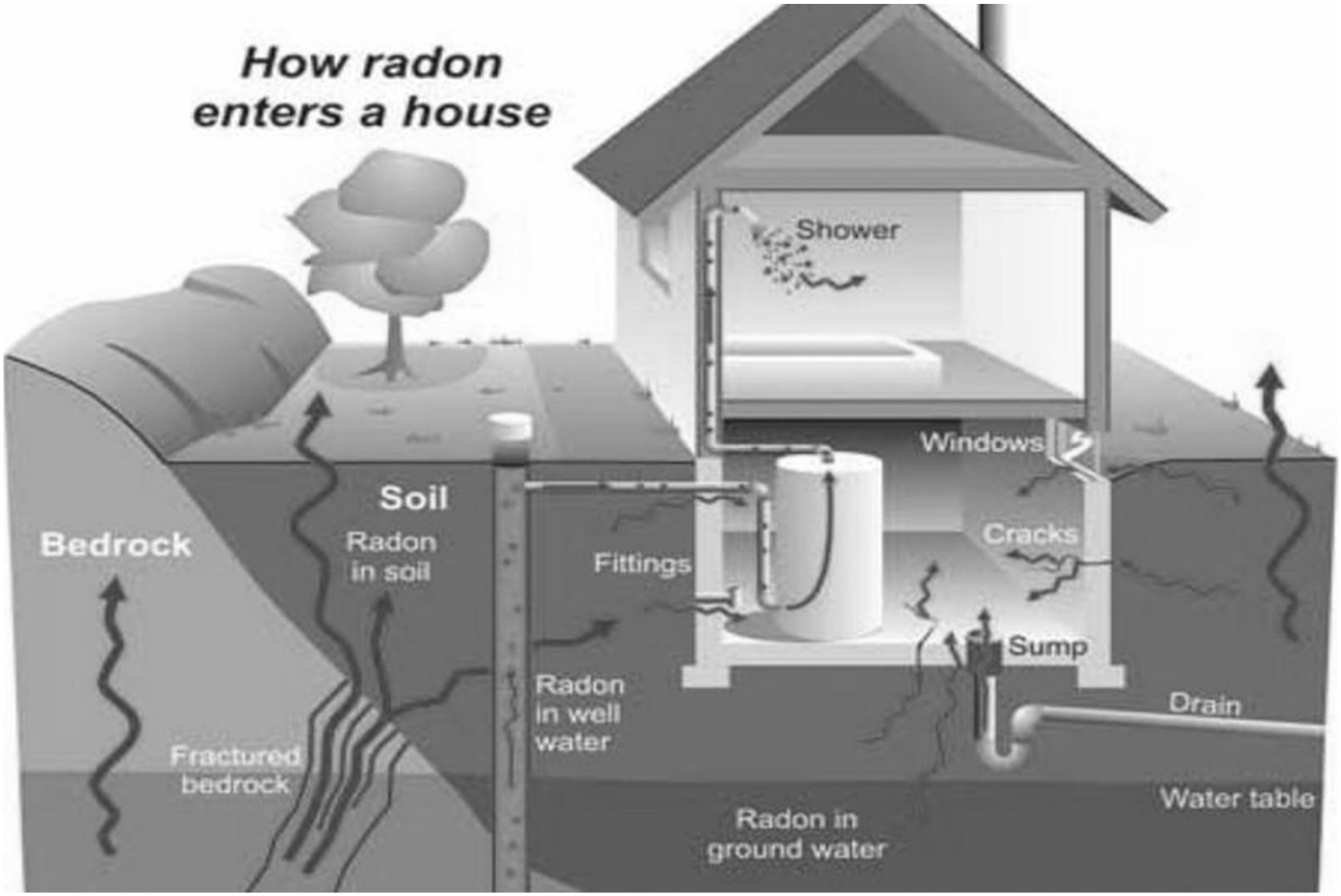
The health concerns of these isotopes are determined by two factors:

- The rate of production from their parent nuclides.
- The probability of decay before get airborne.

$$^{222}_{86}Rn\ \text{(Radon)}: \text{from }^{238}\text{U, T} = 3.81\,\text{days}$$
$$^{220}_{86}Rn\ \text{(Thoron)}: \text{from }^{232}\text{Th, T} = 56\ \text{seconds}$$
$$^{219}_{86}Rn\ \text{(Actinon)}: \text{from }^{235}\text{U, T} = 4\ \text{seconds}$$

The contributions from the daughters of ^{220}Rn and ^{219}Rn to internal exposure are usually negligible compared with that from ^{222}Rn.

Indoor Radon



Naturally Occurring Radioactivity – Health Concerns of Radon Gas

- Airborne radon itself poses little health hazard. It is not retained in significant amounts by the body.
- The health hazard is closely related to the short-lived daughters of radon.

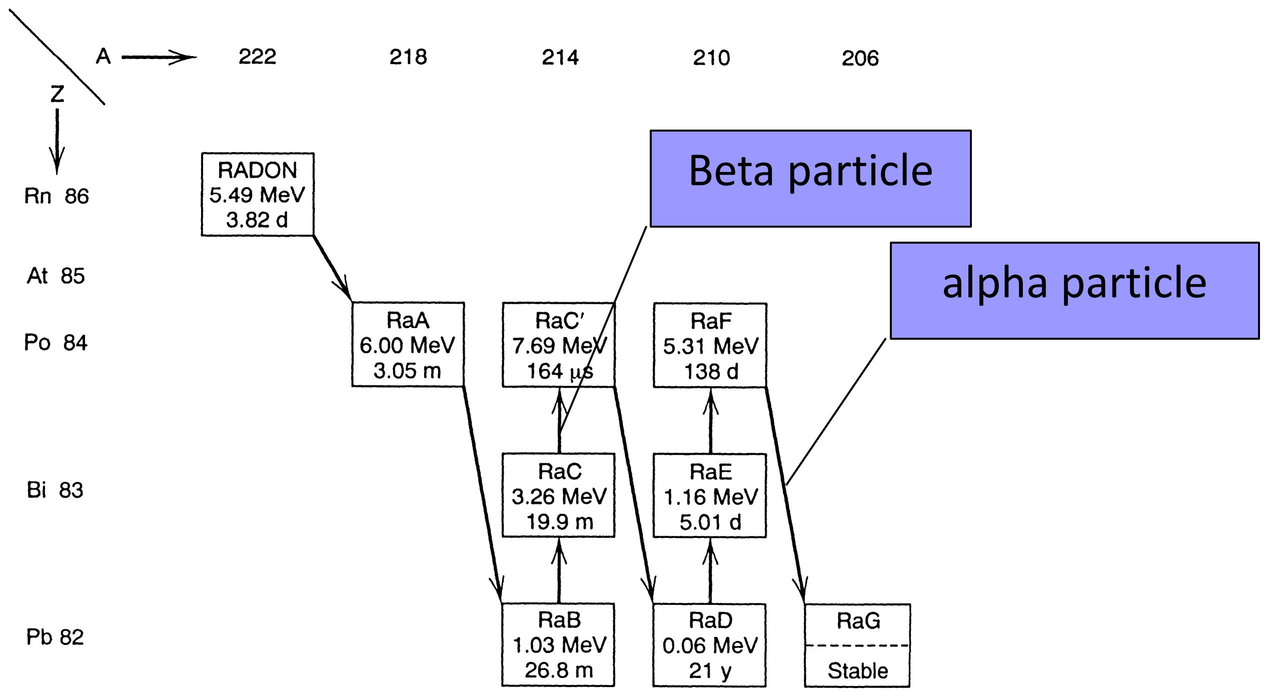
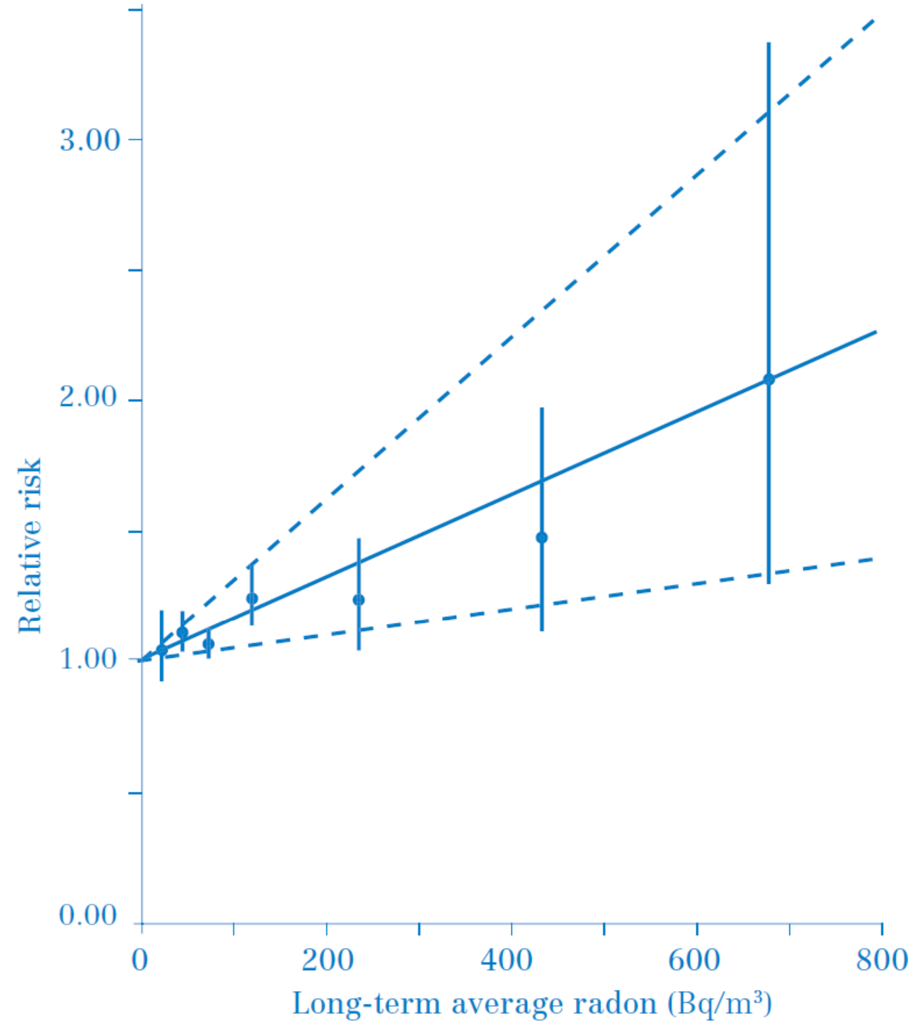


FIGURE 4.7. Radon and radon daughters. Alpha emission is represented by an arrow slanting downward toward the right; beta emission, by a vertical arrow. Alpha-particle and average beta-particle energies and half-lives are shown in the boxes.



Source: Darby et al. 2005
Relative risks and 95% confidence intervals are shown for categorical analyses and also best fitting straight line.
Risks are relative to that at 0 Bq/m^3.

Figure 1. Relative risk of lung cancer versus long-term average residential radon concentration in the European pooling study

Table 3. Risk increase of radon-related lung cancer per 100 Bq/m³ of measured indoor radon concentration based on the results of the European and North American pooling studies

	European pooling study[a]		North American pooling study[b]	
		% risk increase (95% CI)		% risk increase (95% CI)
Sex				
	Men	11 (4,21)	Men	3 (-4, 24)
	Women	3 (-4,14)	Women	19 (2, 46)
	p for heterogeneity	*0.19*		
Age at disease occurrence (years)				
	<55	<0 (<0, 20)	<60	2 (<0, 35)

The WHO predicts that "The risk of lung cancer increased by 8% per 100 Bq/m³ increase in measured radon concentration (95% confidence interval)." (from the WHO Indoor Radon Handbook)

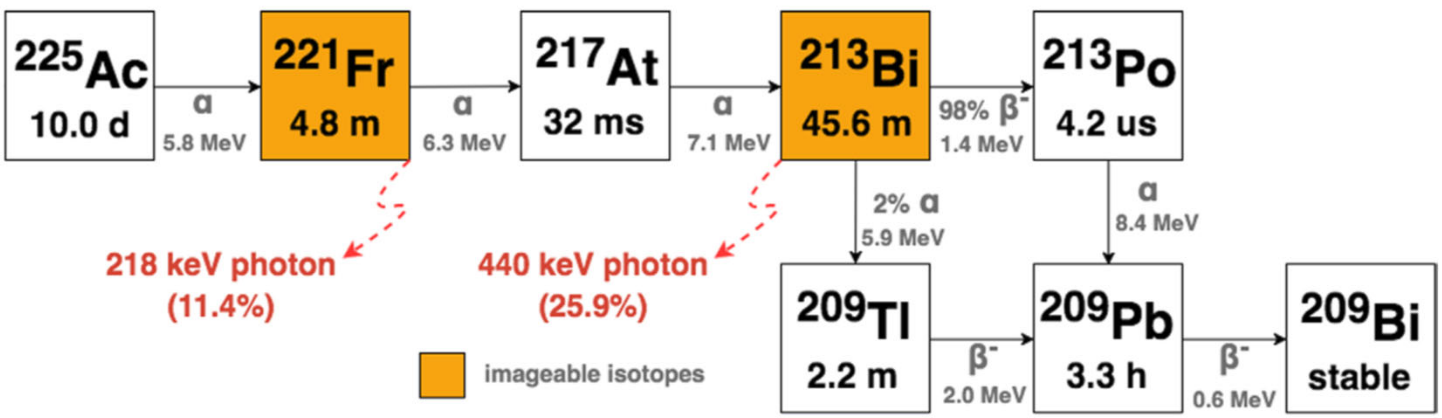
Smoking status				
	Current cigarette smoker	7 (-1, 22)	Never smoked cigarettes	10 (-9, 42)
	Ex-smoker	8 (0, 21)		
	Lifelong non-smoker	11 (0, 28)	Current or ex-cigarette smoker	10 (-2, 33)
	Other	8 (-3, 56)		
	p for heterogeneity	*0.92*		
Overall				
	Based on measured radon	8 (3, 16)	Based on measured radon	11 (0, 28)

Sources: [a]Darby et al. (2005, 2006), [b]Krewski et al. (2005, 2006).
CI = confidence interval, p-values less than 0.05 denote statistical significance.

^{225}Ac-PSMA-617 for PSMA-Targeted α-Radiation Therapy of Metastatic Castration-Resistant Prostate Cancer

Clemens Kratochwil*[1], Frank Bruchertseifer*[2], Frederik L. Giesel[1], Mirjam Weis[2], Frederik A. Verburg[3], Felix Mottaghy[3], Klaus Kopka[4], Christos Apostolidis[2], Uwe Haberkorn[1], and Alfred Morgenstern[2]

[1]Department of Nuclear Medicine, University Hospital Heidelberg, Heidelberg, Germany; [2]European Commission, Joint Research Centre, Institute for Transuranium Elements, Karlsruhe, Germany; [3]Department of Nuclear Medicine, RWTH University Hospital Aachen, Aachen, Germany; and [4]Division of Radiopharmaceutical Chemistry, German Cancer Research Center, Heidelberg, Germany



Article | Open Access | Published: 15 January 2021

Quantitative estimation of track segment yields of water radiolysis species under heavy ions around Bragg peak energies using Geant4-DNA

Kentaro Baba, Tamon Kusumoto, Shogo Okada, Ryo Ogawara, Satoshi Kodaira, Quentin Raffy, Rémi Barillon, Nicolas Ludwig, Catherine Galindo, Philippe Peaupardin & Masayori Ishikawa

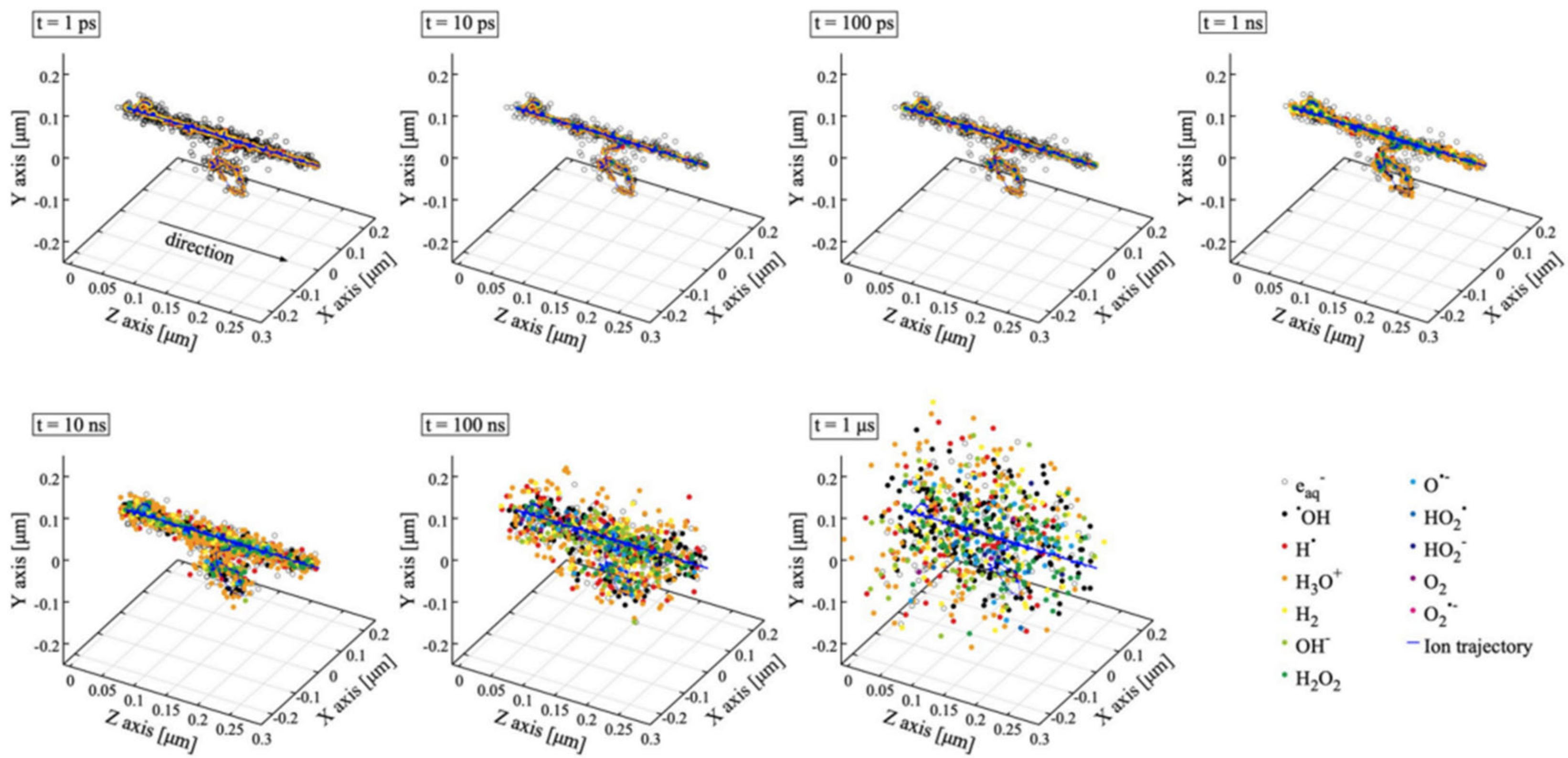


Figure 1. Chemical evolution of 400 MeV/u carbon ion track in water in the time 1 ps to 1 μs.

^{225}Ac-PSMA-617 for PSMA-Targeted α-Radiation Therapy of Metastatic Castration-Resistant Prostate Cancer

Clemens Kratochwil*[1], Frank Bruchertseifer*[2], Frederik L. Giesel[1], Mirjam Weis[2], Frederik A. Verburg[3], Felix Mottaghy[3], Klaus Kopka[4], Christos Apostolidis[2], Uwe Haberkorn[1], and Alfred Morgenstern[2]

[1]*Department of Nuclear Medicine, University Hospital Heidelberg, Heidelberg, Germany;* [2]*European Commission, Joint Research Centre, Institute for Transuranium Elements, Karlsruhe, Germany;* [3]*Department of Nuclear Medicine, RWTH University Hospital Aachen, Aachen, Germany; and* [4]*Division of Radiopharmaceutical Chemistry, German Cancer Research Center, Heidelberg, Germany*

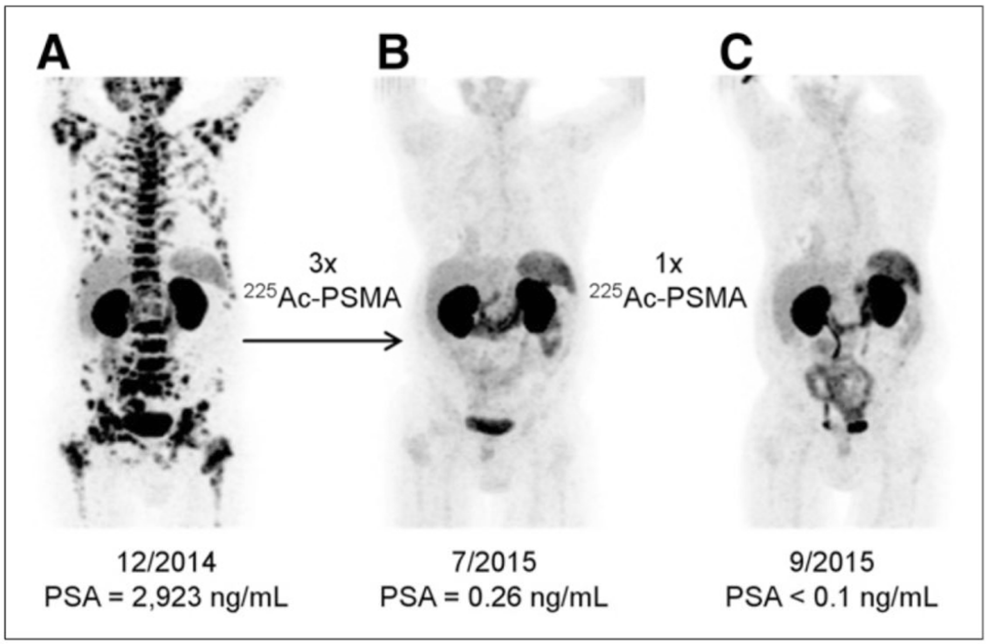
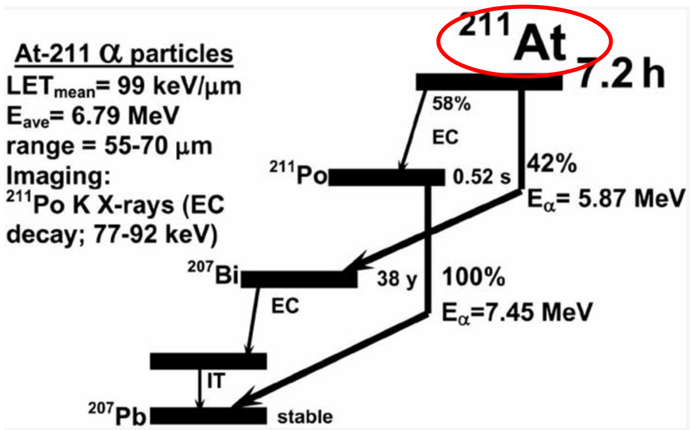
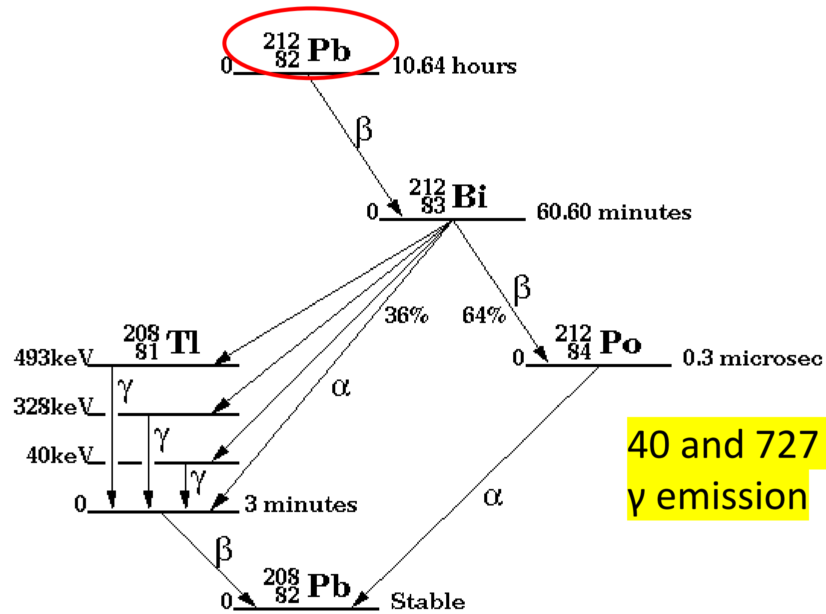


FIGURE 1. ^{68}Ga-PSMA-11 PET/CT scans of patient A. Pretherapeutic tumor spread (A), restaging 2 mo after third cycle of ^{225}Ac-PSMA-617 (B), and restaging 2 mo after one additional consolidation therapy (C).

α-Emitters of Human Interest (1)

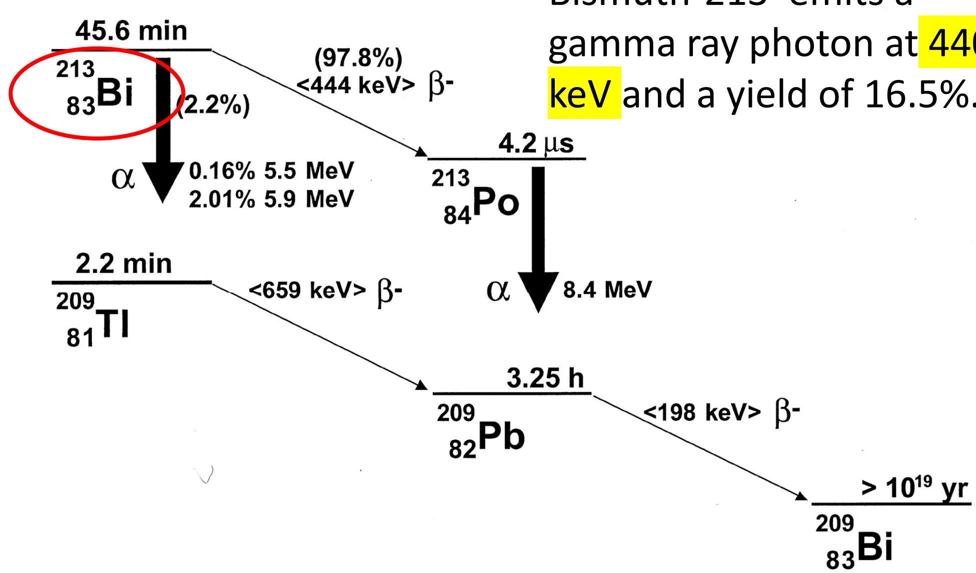


Po K Xrays are emitted that permit external imaging, the two most abundant of these X-rays have energies of 77 and 80 keV, 12 and 20% of all photon emissions, respectively.



40 and 727 keV γ emission

Bismuth-213 emits a gamma ray photon at 440 keV and a yield of 16.5%.



Example of Therapeutic Alpha Emitters

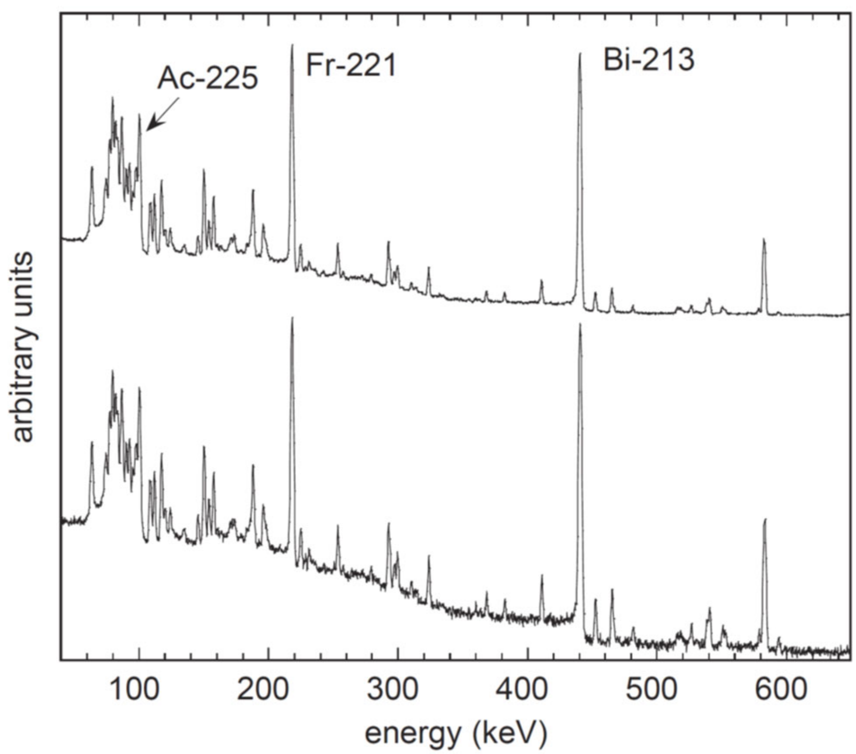
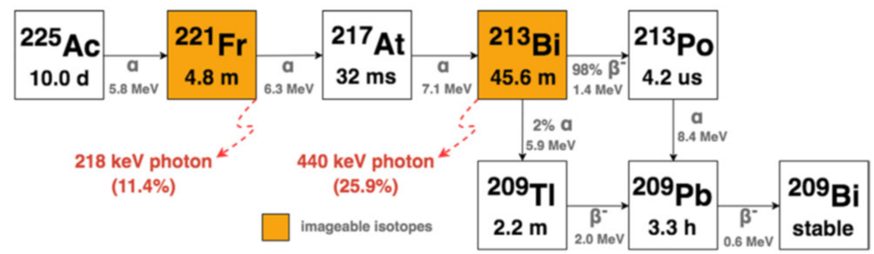


Fig. 4. Gamma spectra of purified Ac-225 produced via cyclotron irradiation (upper spectrum) and Ac-225 extracted from Th-229 (lower spectrum).

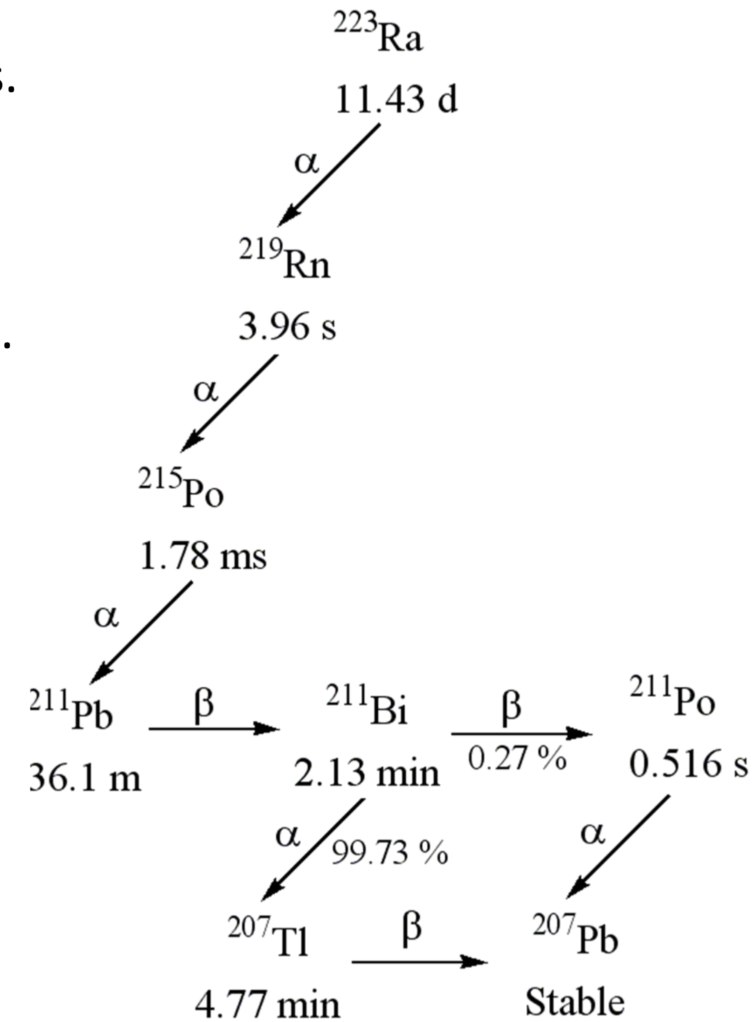


The 225Ac decay chain. Photons with a branching ratio >3% relative to 225Ac decay are shown.

Cyclotron production of Ac-225 for targeted alpha therapy, C.Apostolidis, Applied Radiation and Isotopes, 2005

An Example – ^{223}Ra

- ^{223} Ra has inherent bone-seeking properties.
- Could become logged and irradiate an individual over a relatively long period.
- Could also be used as a therapeutic isotope.



Radium 223 Dichloride

(RAY dee um two twenty-three dye KLOR ide)

Generic Name: Radium 223 Dichloride

Trade Name(s): Xofigo®

Radium 223 Dichloride is the generic name for the trade name drug Xofigo®. In some cases, health care professionals may use the trade name Xofigo® when referring to the generic drug name radium 223 dichloride.

Drug Type:

Radium 223 Dichloride is an alpha particle-emitting radioactive therapeutic agent. This medication is classified as an "radiopharmaceutical". (For more detail, see "How Radium 223 Dichloride works" below)

What Radium 223 Dichloride Is Used For:

The treatment of patients with prostate cancer that is resistant to medical or surgical treatments that lower testosterone and has spread to bones with symptoms, but not to other parts of the body.

Note: If a drug has been approved for one use, physicians may elect to use this same drug for other problems if they believe it may be helpful.

How Radium 223 Dichloride Is Given:

- Radium-223 dichloride is given through a vein (intravenously, IV), as a slow [intravenous] injection, over about 1 minute.
- There is no pill form of radium-223 dichloride.
- It is given in a clinic or facility where healthcare providers or technicians have been trained to give radiation therapy.
- It is given once every 4 weeks for a maximum of 6 doses.

The amount of radium-223 dichloride that you will receive depends on many factors, including your weight, and your general health or other health problems. Your doctor will determine your exact dosage and schedule.

Radium 223 Dichloride Side effects:

Important things to remember about the side effects of radium-223 dichloride:

- Most people will not experience all of the radium-223 dichloride side effects listed.

Learning Objectives Related to Alpha Decay

You should be able to

- define the nuclear binding energy, and calculate the binding energy for given radionuclides,
- calculate the energy-release, or the Q-value, for a given nuclear transformation,
- understand the Chart of Nuclides, identify potential radioactive decay scheme (e.g., alpha decay or beta decay), and extract useful information (e.g., half-life, decay product, and energies of the radioactive products),
- calculate the energy release from a given alpha decay and derive the amount of energy carried by the alpha particles as decay products,
- explain why alpha particles could potentially cause more radiation effect to living tissue than X- and gamma-rays, and
- understand the origin of the indoor radon problem.

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:

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

What will happen to the excited Ba-137 nucleus?

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

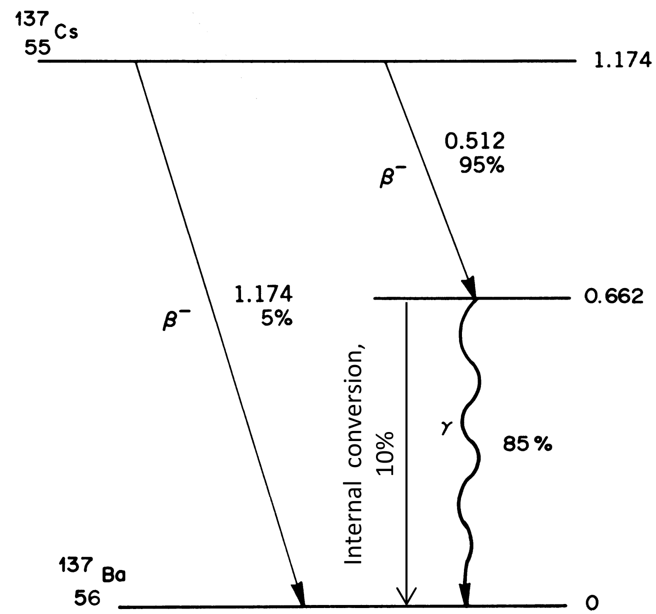
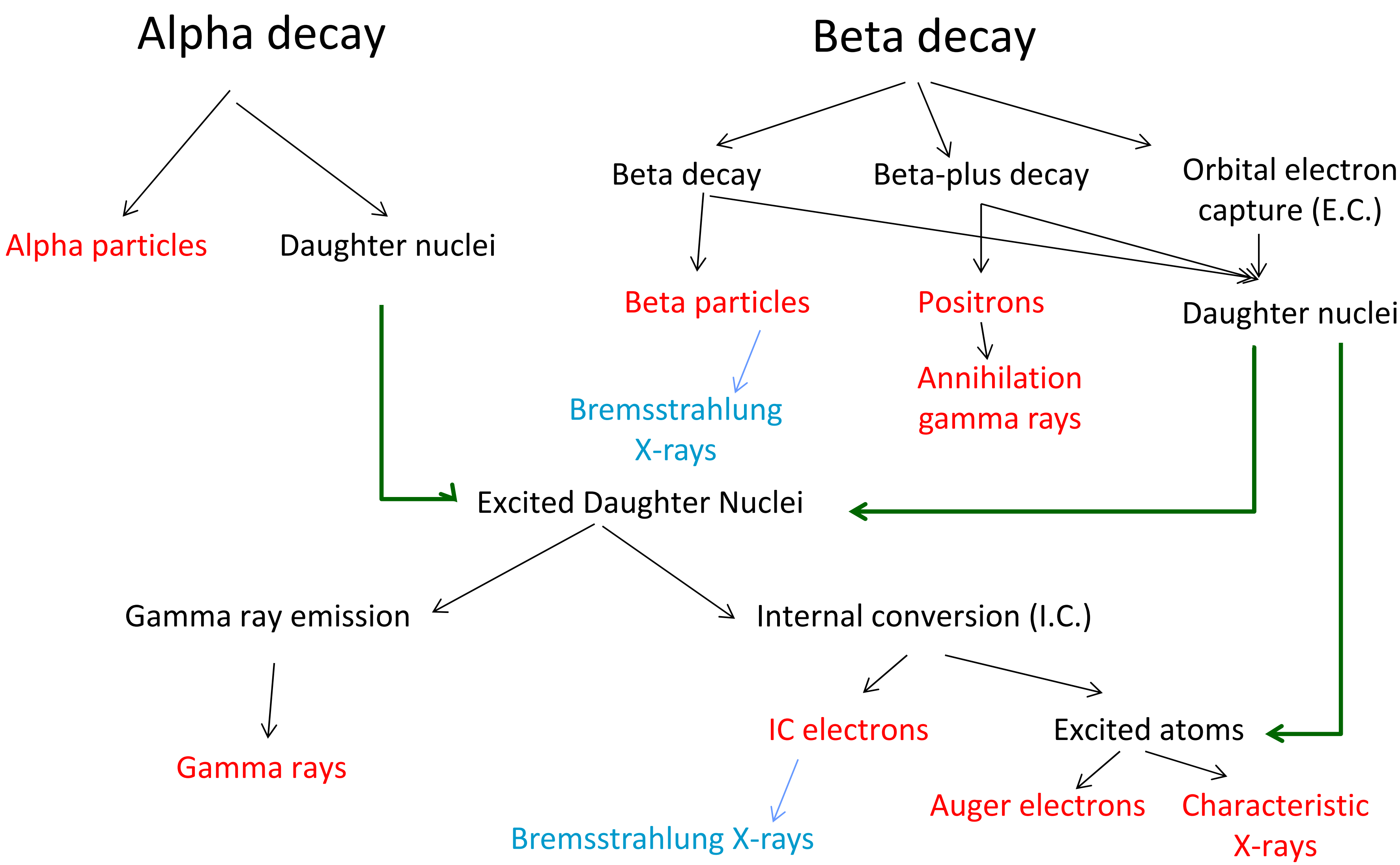


FIGURE 3.8. Decay scheme of $^{137}_{55}$Cs.

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).

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

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

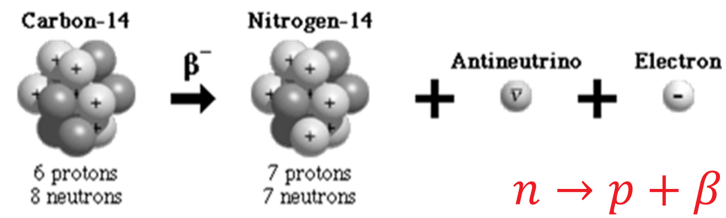
What is Beta Decay?

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

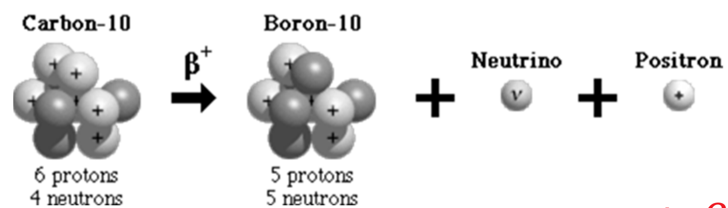
$$^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + {}^{0}_{-1}\beta + \overline{\upsilon}$$



$$n \rightarrow p + \beta^{-} + \bar{\nu}$$

Beta-plus decay

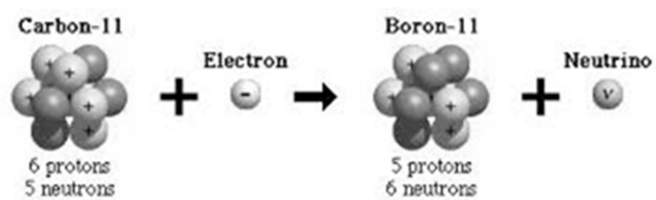
$$^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + {}^{0}_{1}\beta + \upsilon$$



$$p \rightarrow n + \beta^{+} + \nu$$

Electron capture

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



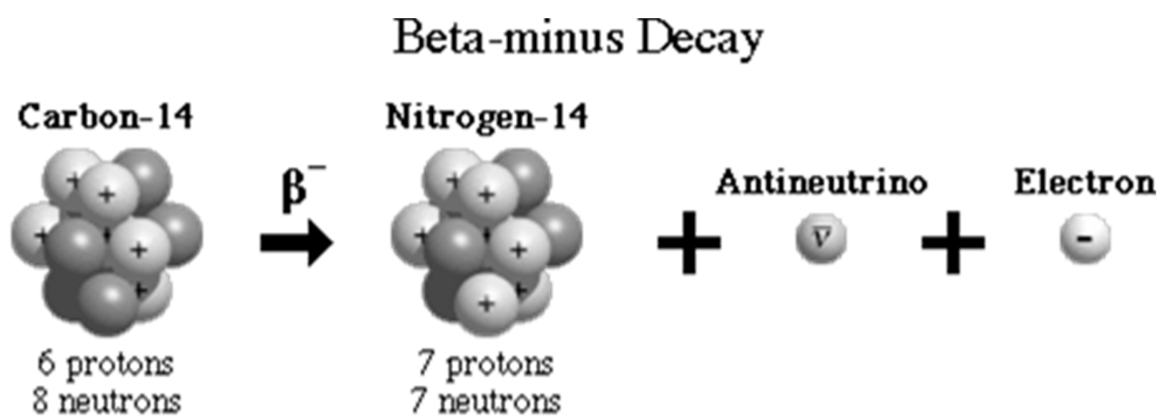
$$p + \beta^{-} \rightarrow n + \nu$$

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

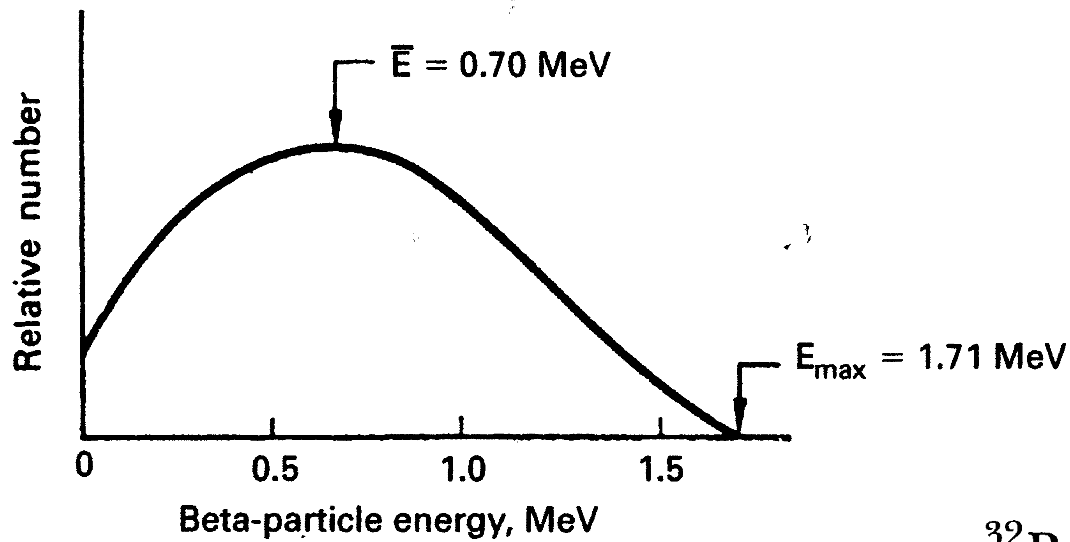
$$Q = M_p - M_d - M_e = 0.001837 \text{ AMU}$$

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



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

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

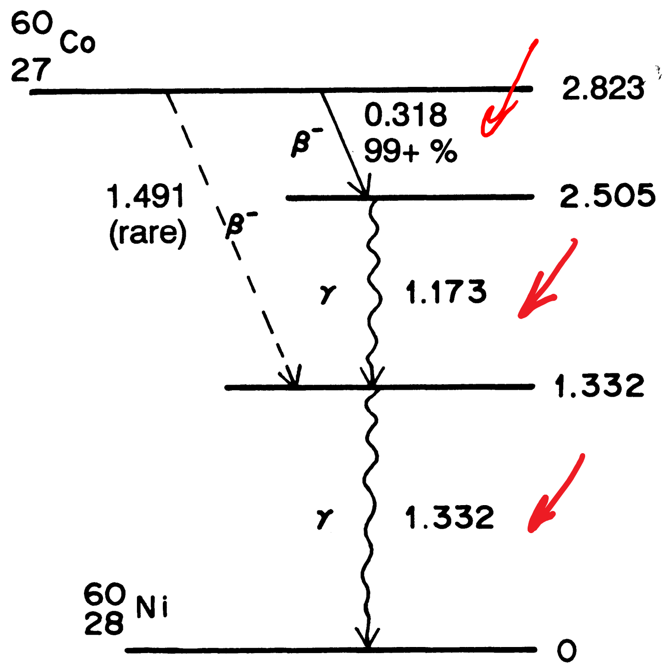


FIGURE 3.6. Decay scheme of $^{60}_{27}Co$.

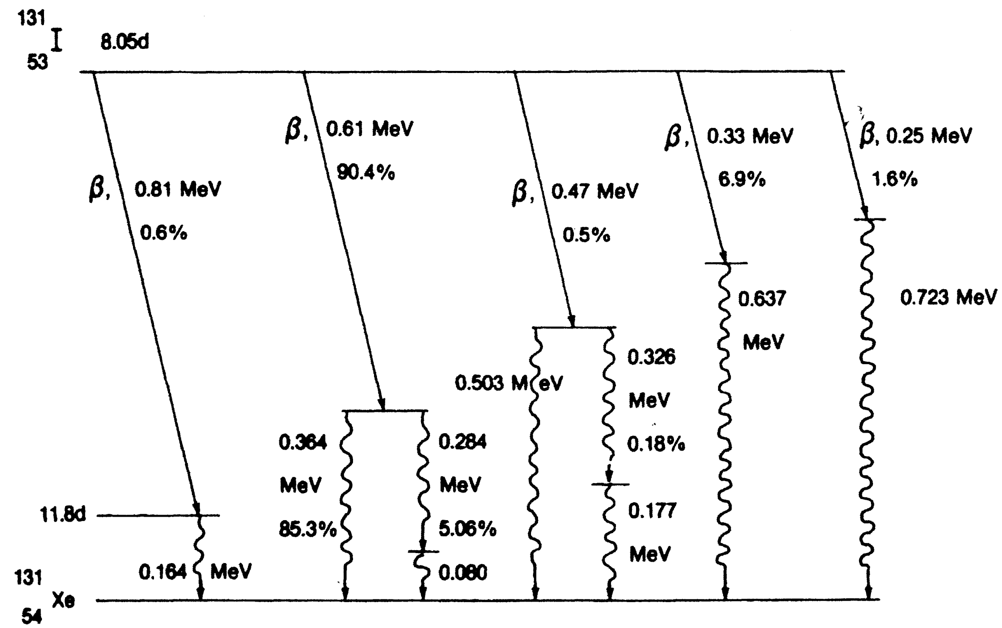


FIGURE 4.7. Iodine-131 transformation (decay) scheme.

- 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.
- A typical example of positron emitter is

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

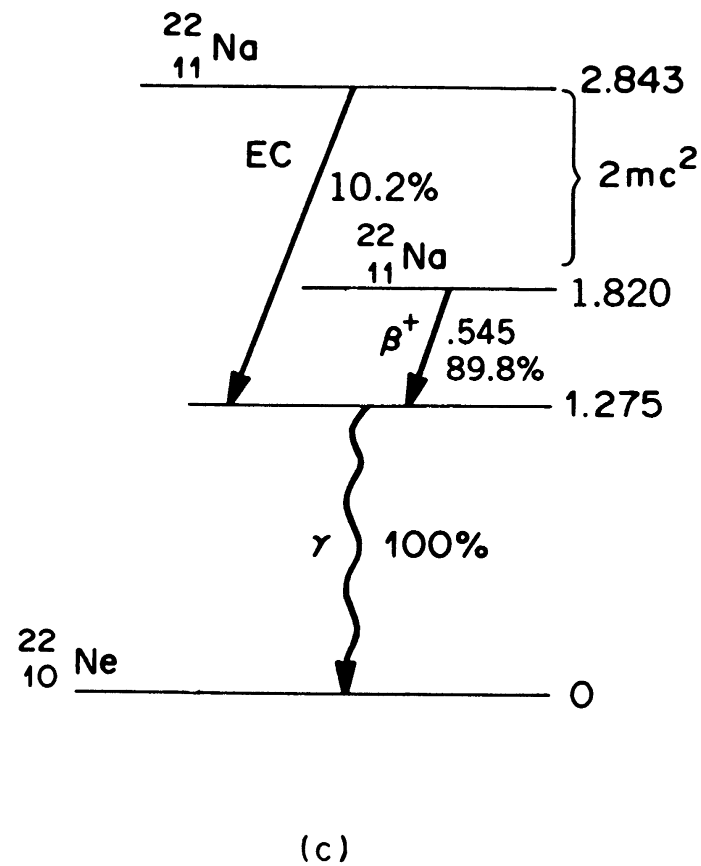


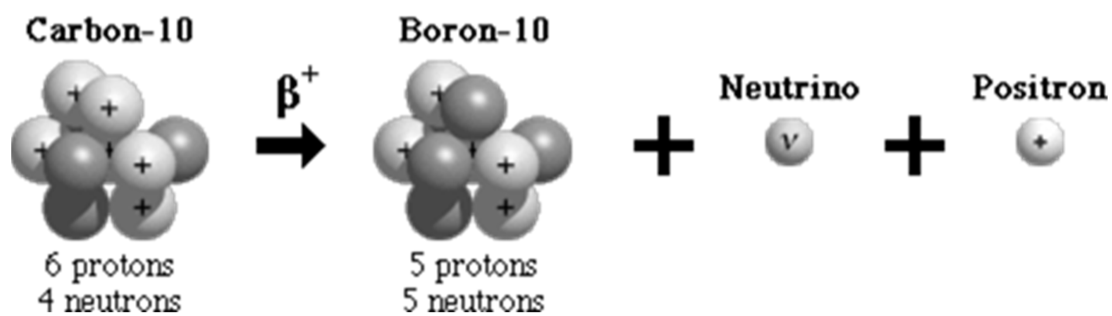
FIGURE 3.11. Decay scheme of ${}_{11}^{22}$Na.

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

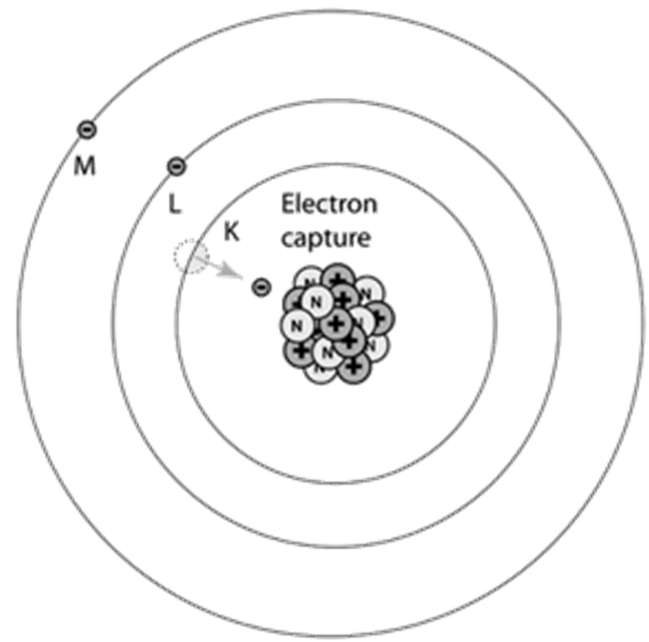
In electron capture (EC), one of the atomic electrons is captured by the nucleus and unites with a proton to form a neutron with the emission of a neutron

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

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

- 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,

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



http://sciencewise.info/resource/Electron_capture/hyperphysics.phy-astr.gsu.edu

Energy Release Through Orbital Electron Capture

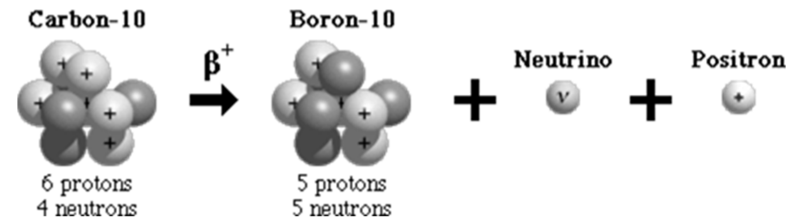
For positron decay to be possible, we need

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

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



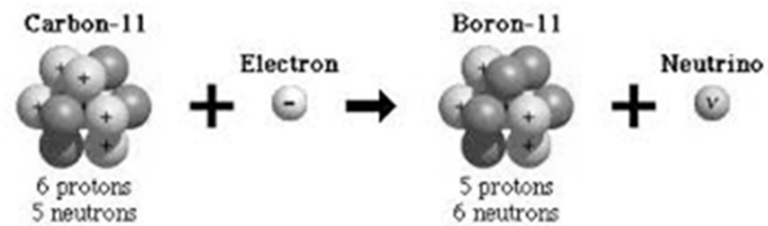
For Electron Capture to occur,

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

so that

$$M_p > M_d + \phi$$

where ϕ is the binding energy of the orbital electron

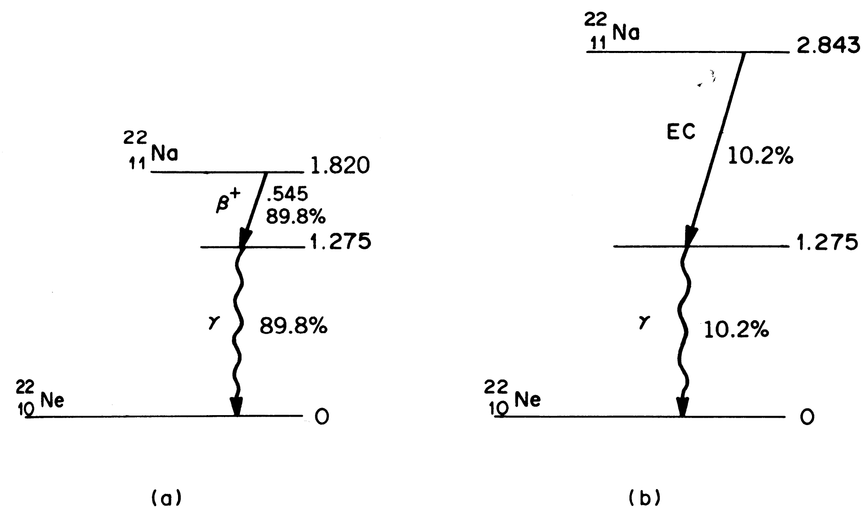


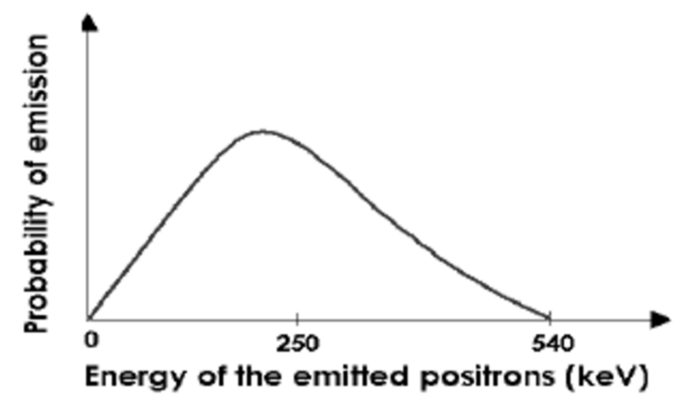
Orbital Electron Capture and Positron Decay

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

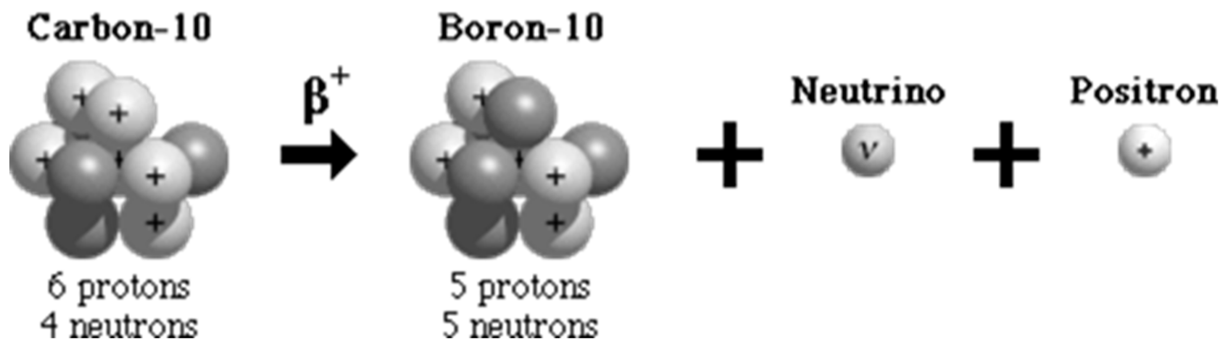
- Both the emission of a positron and the capture of an electron, a neutrino is always emitted in order to conserve energy.

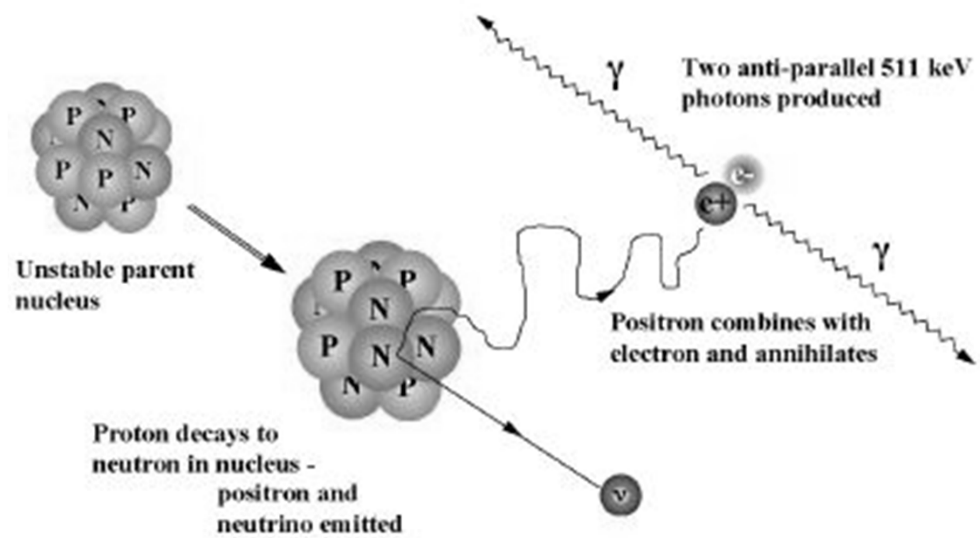
- In positron decay, the neutrino carries the difference between the energy release and the energy of the resultant positron. In electron capture, however, the neutrino must be mono-energetic.





Positron Annihilation following Positron Decay





Examples for Beta Decay

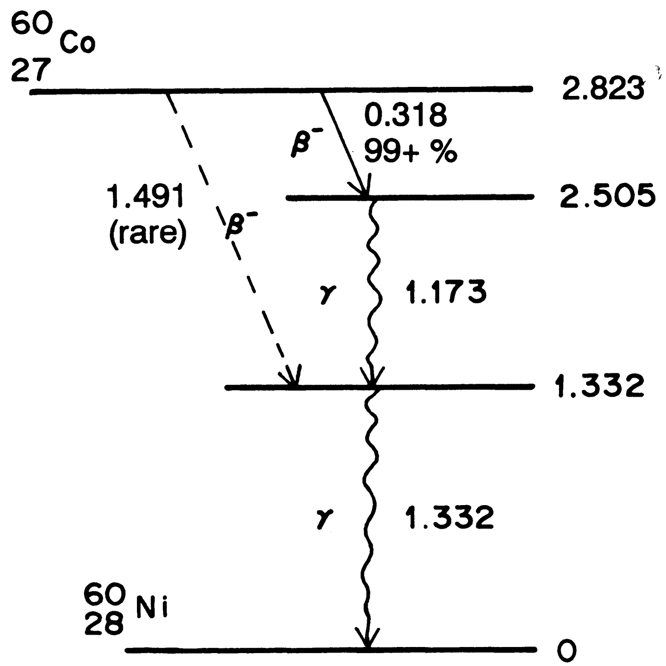


FIGURE 3.6. Decay scheme of $^{60}_{27}$Co.

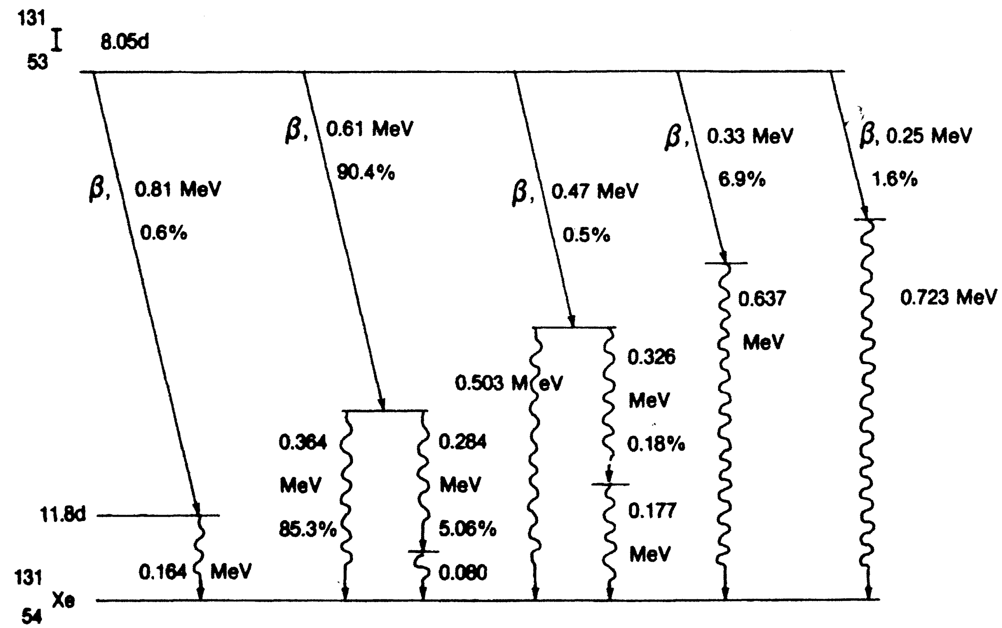


FIGURE 4.7. Iodine-131 transformation (decay) scheme.

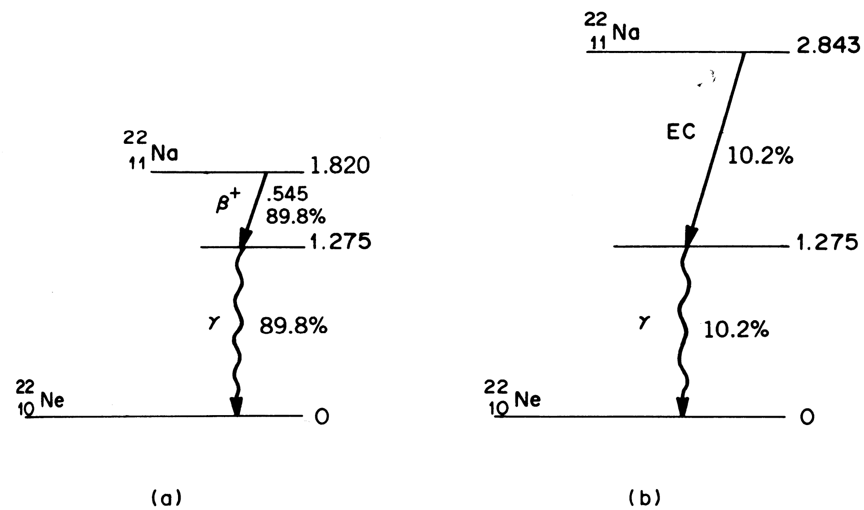
- Beta emissions are normally associated with complicated decay schemes and the emission of other particles such as gamma rays.
- There exist the so called “pure beta emitters”, such as ^{3}H, ^{14}C, ^{32}P and ^{90}Sr, which have no accompanying gamma rays.

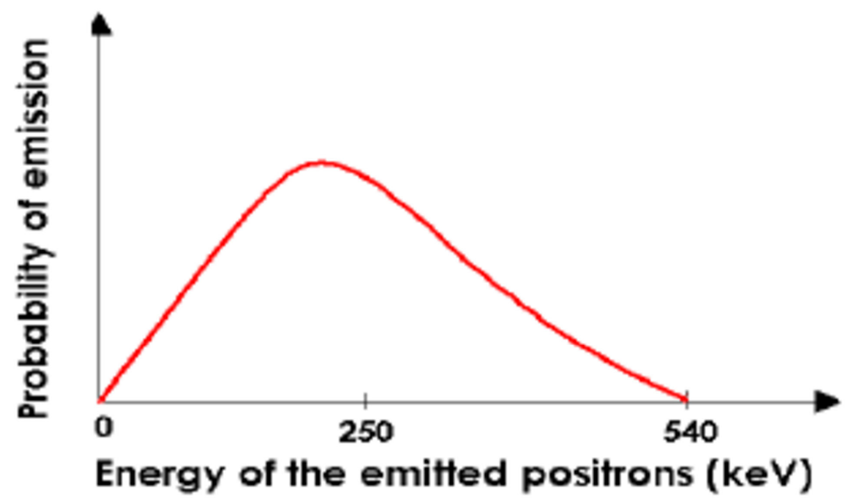
Orbital Electron Capture and Positron Decay (Revisited)

- 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.



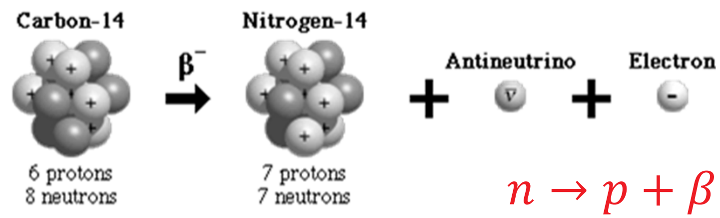


Beta Emission

- 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

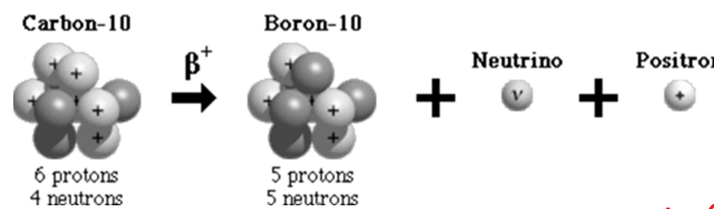
$${}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + {}^{0}_{-1}\beta + \overline{\upsilon}$$



$$n \rightarrow p + \beta^{-} + \bar{\nu}$$

Beta-plus decay

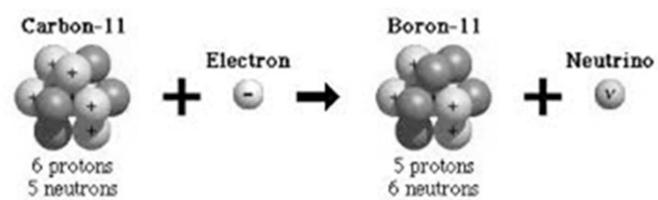
$${}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + {}^{0}_{1}\beta + \upsilon$$



$$p \rightarrow n + \beta^{+} + \nu$$

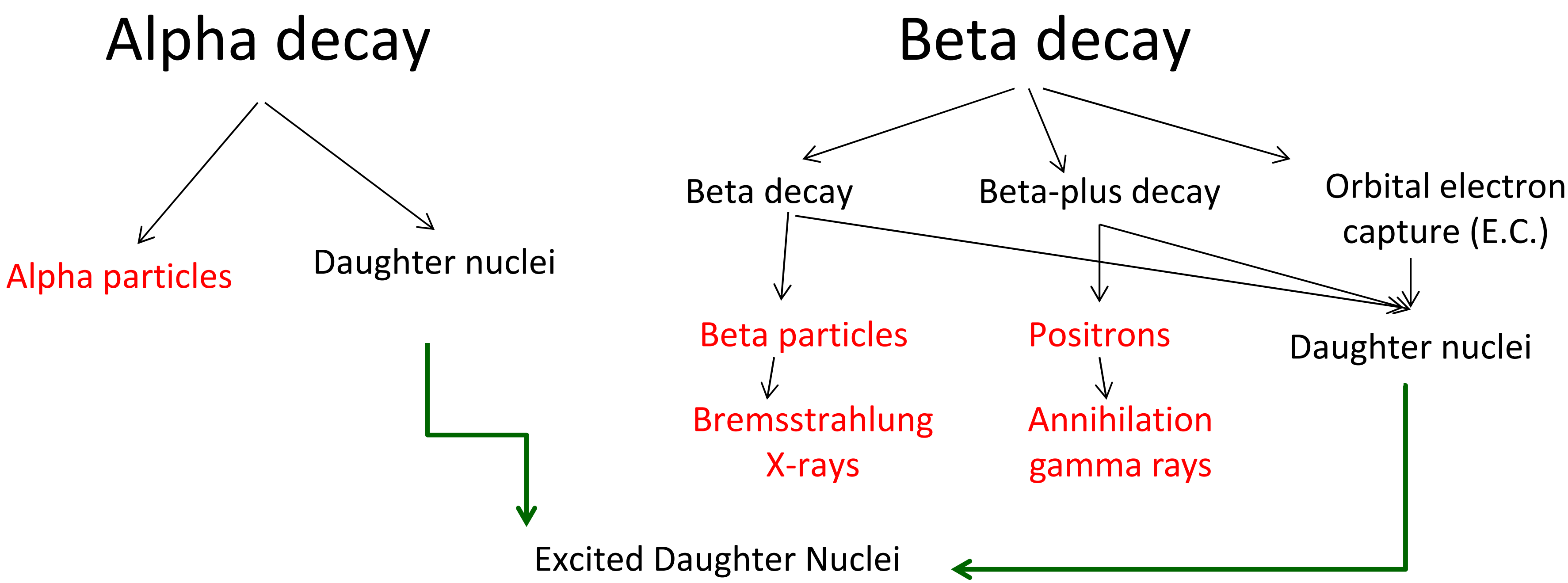
Electron capture

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



$$p + \beta^{-} \rightarrow n + \nu$$

Typical Decay Products from Unstable Radioisotopes



What Happens After Beta Decay?

Examples for Beta Decay

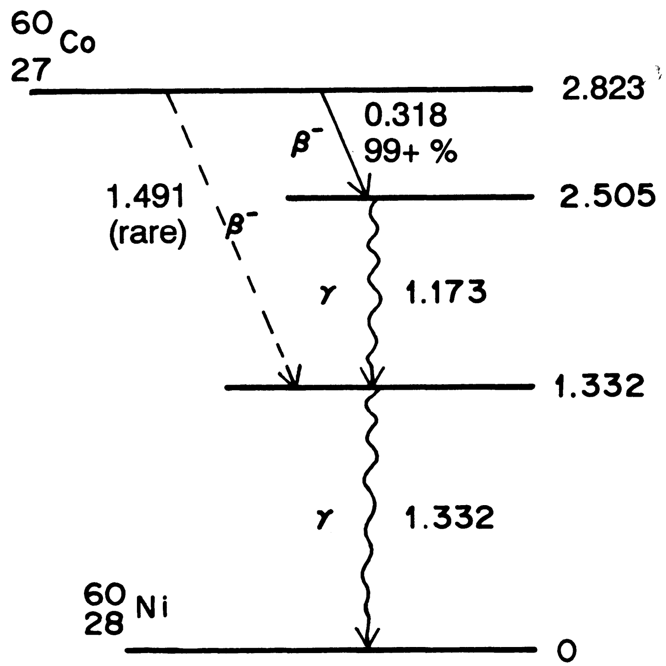


FIGURE 3.6. Decay scheme of ${}^{60}_{27}Co$.

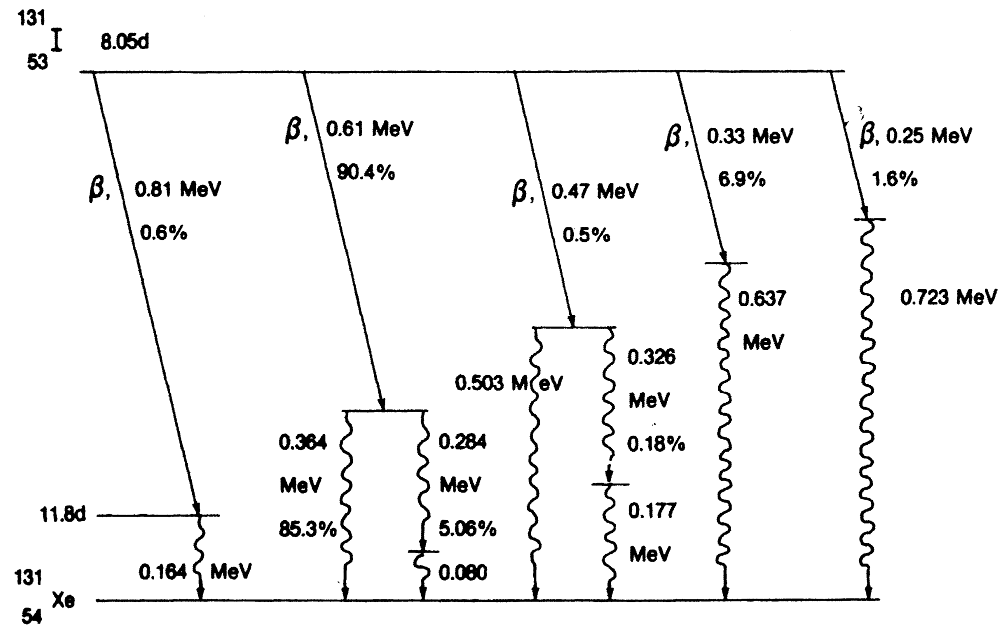
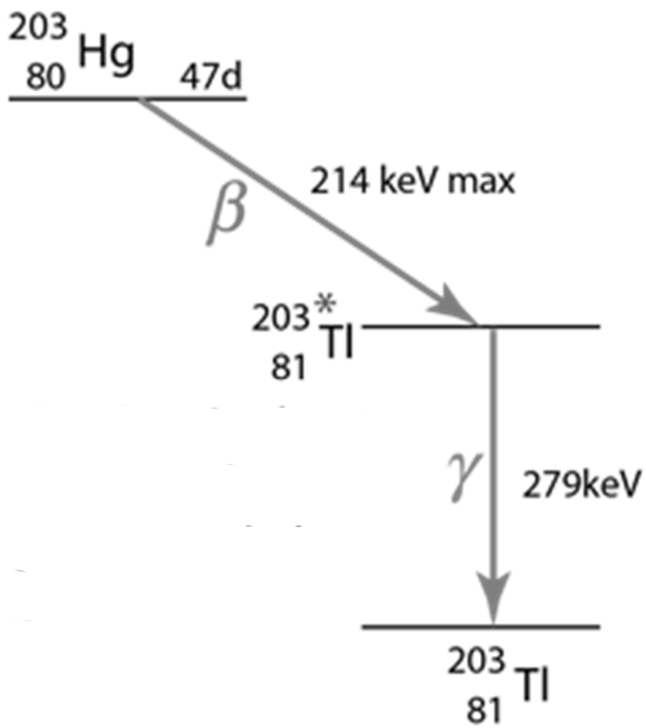


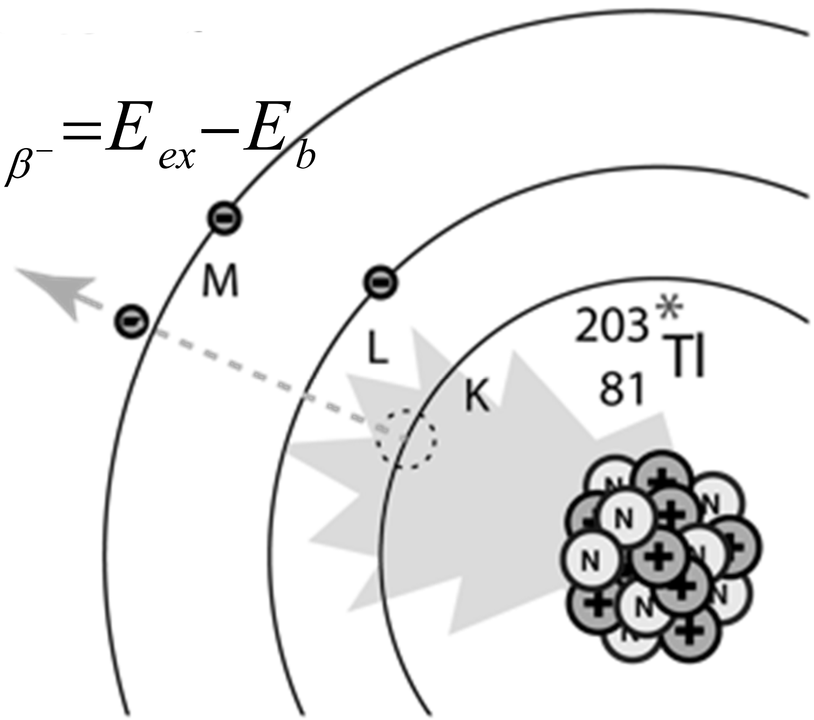
FIGURE 4.7. Iodine-131 transformation (decay) scheme.

- 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.

Gamma-Ray Emission and Internal Conversion



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

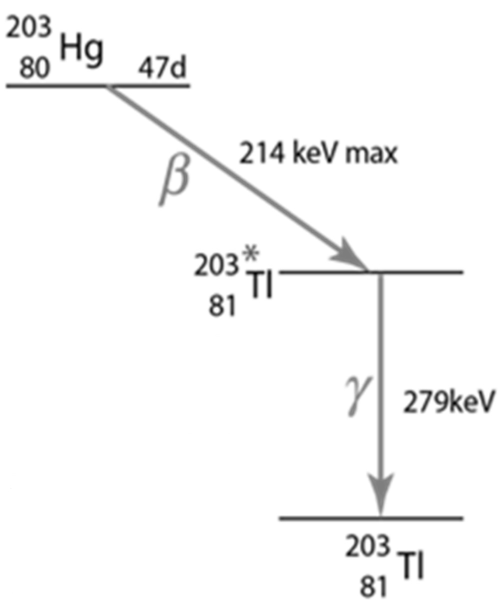


Gamma-ray emission vs **Internal Conversion**

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

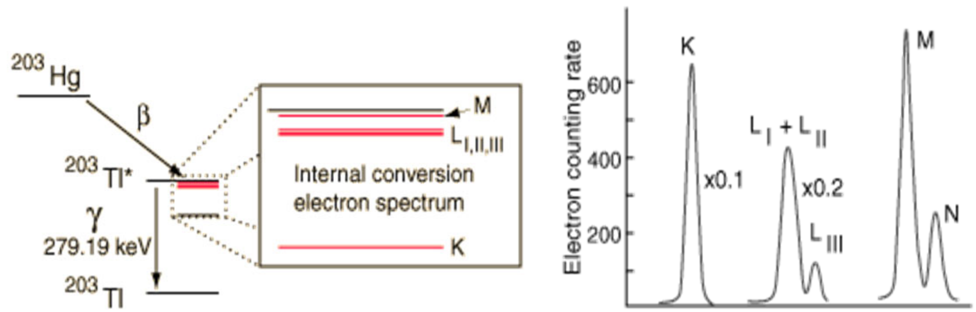
http://hyperphysics.phy-astr.gsu.edu/hbase/Nuclear/radact2.html

Different Types of Radiation from Hg-203 Beta Decay



Gamma-ray transition

- Energy of the beta particles?
- Relative frequency per decay?



Binding energies for ^{203}Tl	
K	85.529 keV
L_I	15.347 keV
L_{II}	14.698 keV
L_{III}	12.657 keV
M	3.704 keV

Internal conversion

- Energy of the beta particles?
- Relative frequency per decay?

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

$$E_{i.c.} = E_{exc} - E_b$$

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.

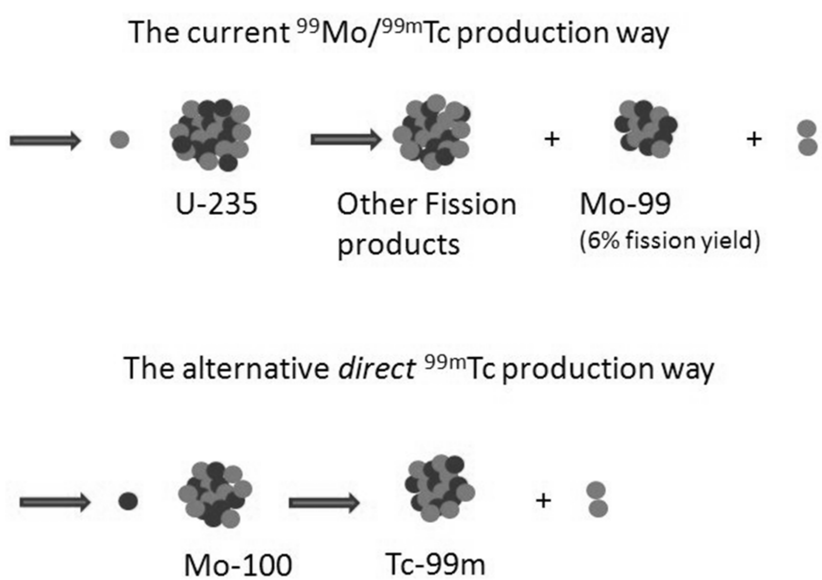
In some cases, however, selection rules prevent photon emission for an extended period of time. The excited state of $^{137}_{56}Ba$ following the decay of $^{137}_{55}Cs$ has a half-life of 2.55 min. Such a long-lived nuclear state is termed *metastable* and is designated by the symbol m: $^{137m}_{56}Ba$.

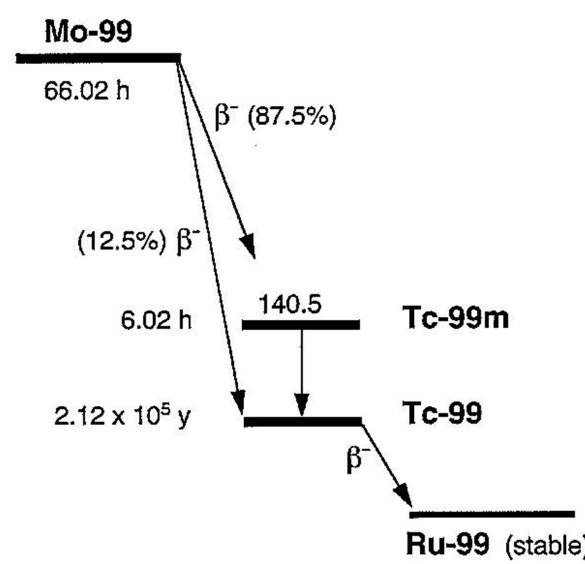
Another example of a metastable nuclide is $^{99m}_{43}Tc$, which results from the beta decay of the molybdenum isotope $^{99}_{42}Mo$.

Important Gamma Ray Emitter: Tc-99m

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

- 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.

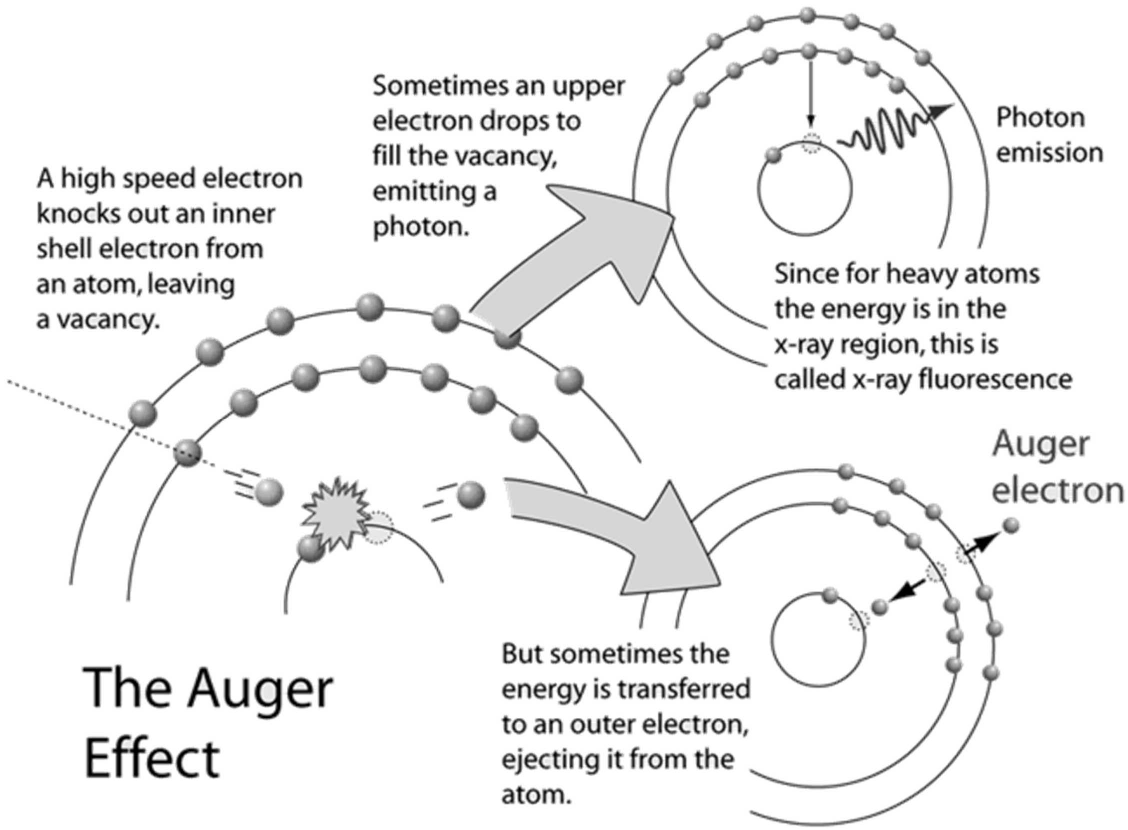




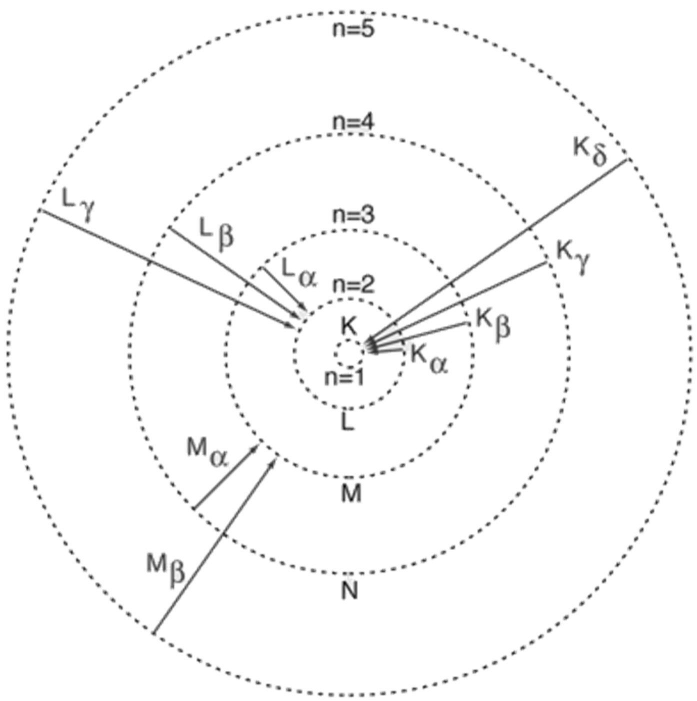
Atomic Level Transitions following Beta Decay
Characteristic X-rays and Auger Electrons

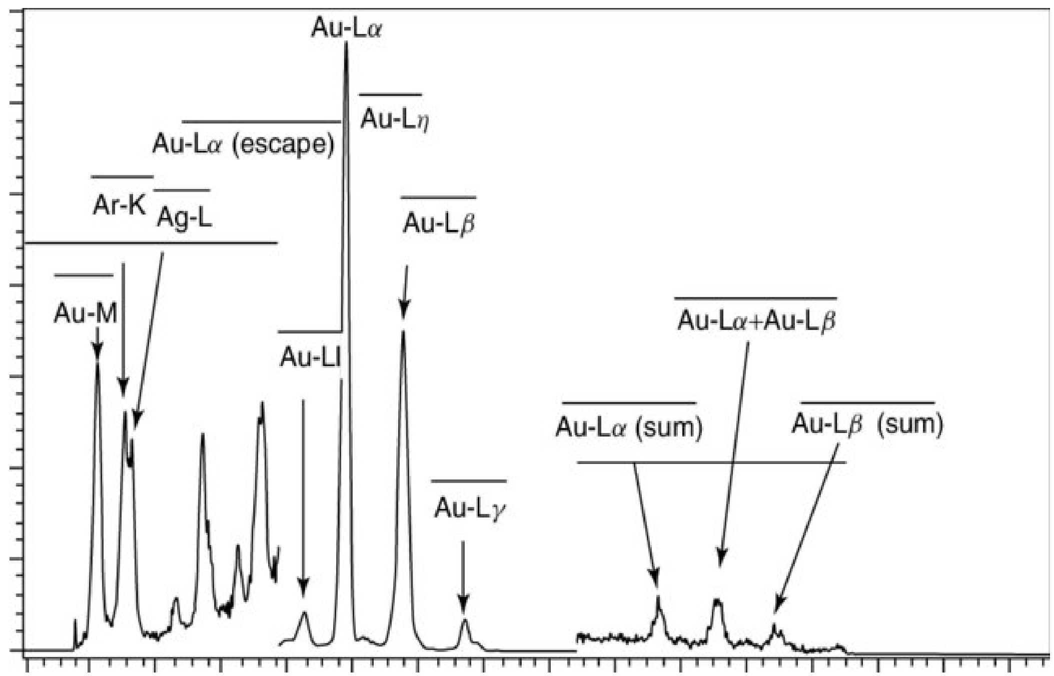
Radiation from Excited Atoms

Characteristic X-ray vs Auger Electron



Radiation from Excited Atoms





Possible X-ray Transitions

X-ray spectrum of a gold sheet irradiated by an X-ray tube with Ag-anode working at 28 kV.

http://hyperphysics.phy-astr.gsu.edu/hbase/quantum/moseley.html

("Portable systems for energy-dispersive X-ray fluorescence analysis of works of art", Hjxfwjt, 2007)

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.

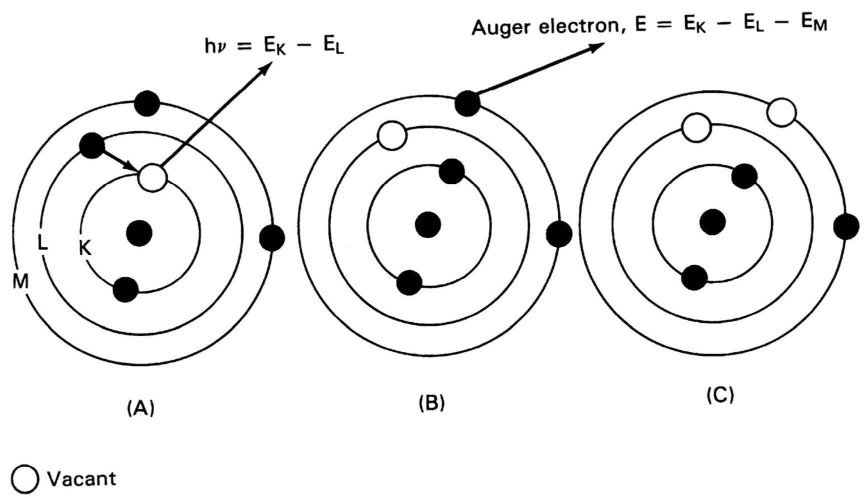
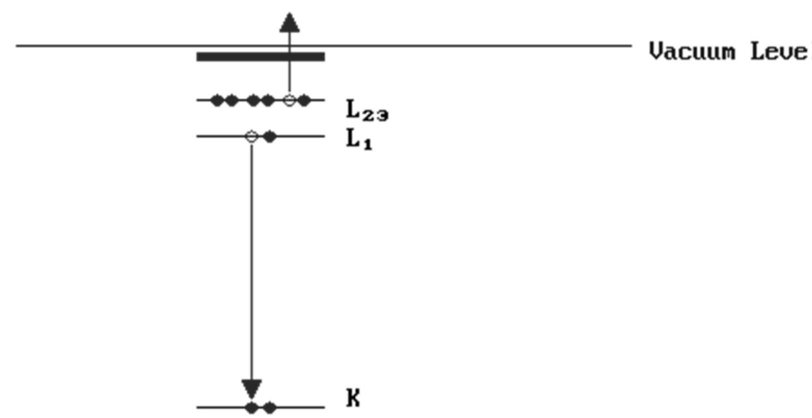


Figure 3.7 (A) The usual emission of a K characteristic X-ray, $h\nu$, energy equal to $E_K - E_L$, the difference in binding energy for the two orbital electrons, K and L. (B) $h\nu$ has been absorbed and a monoenergetic Auger electron is emitted, in the example shown, from the M shell, the energy of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



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

Radioprotection 51(4), 279-285 (2016)
© EDP Sciences 2016
DOI: 10.1051/radiopro/2016073

SFRP
Available online at:
www.radioprotection.org

ARTICLE

Effect of nanomaterials on the absorbed dose during an X-ray exposure

F. Benlakhdar, A.S.A. Dib* and A.H. Belbachir

Université des Sciences et de la Technologie d'Oran Mohamed Boudiaf, USTO-MB, BP 1505 EL M'naouer, 31000 Oran, Algeria.

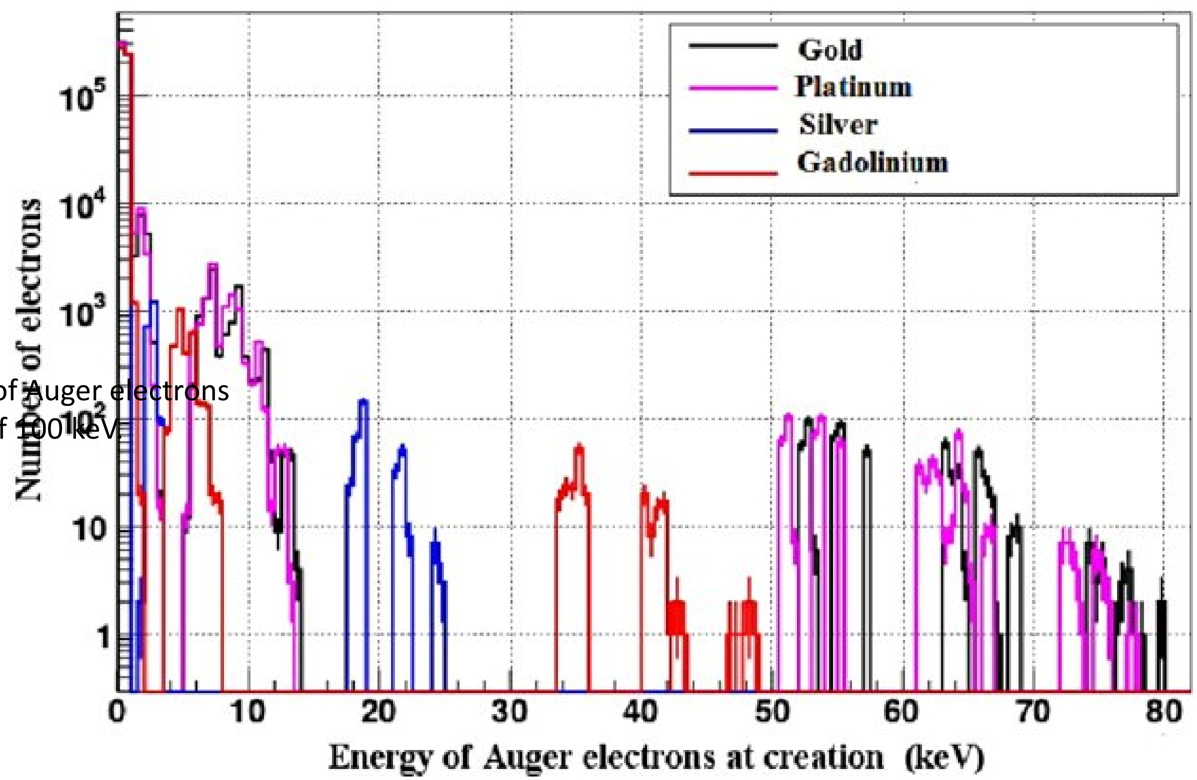


Figure 5. Spectrum of Auger electrons at an X-ray energy of 100 keV

Atomic Radiation from Excited Atoms

Characteristic X-ray vs Auger Electron

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)

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.

$^{203}_{80}\mathrm{Hg}_{123}$

1 Decay Scheme

The simple and consistent decay scheme is dominated by beta decay to the first excited state of Tl-203, followed by a single gamma transition to the ground state.
Le mercure 203 se désintègre par émission bêta moins vers le niveau excités de 279 keV du thallium 203.

2 Nuclear Data

$T_{1/2}(^{203}\mathrm{Hg})$	:	46,594	(12)	d
$Q^-(^{203}\mathrm{Hg})$	:	491,8	(12)	keV

2.1 β^- Transitions

	Energy keV	Probability × 100	Nature	lg ft
$\beta^-_{0,1}$	212,6 (12)	99,99 (1)	Allowed	6,455
$\beta^-_{0,0}$	491,8 (12)	0,01 (1)	1st Forbidden Unique	11,6

2.2 Gamma Transitions and Internal Conversion Coefficients

	Energy keV	$P_{\gamma+ce}$ × 100	Multipolarity	α_K	α_L	α_M	α_T
$\gamma_{1,0}$(Tl)	279,1969 (12)	99,99 (1)	M1+75%E2	0,1640 (10)	0,0476 (2)	0,0155 (2)	0,2271 (12)

3 Atomic Data

3.1 Tl

ω_K	:	0,963	(4)
$\bar{\omega}_L$	:	0,367	(15)
n_{KL}	:	0,812	(5)

3.1.1 X Radiations

		Energy keV		Relative probability
X_K				
	$K\alpha_2$	70,8325		59,24
	$K\alpha_1$	72,8725		100
	$K\beta_3$	82,118	}	
	$K\beta_1$	82,577	}	
	$K\beta_5''$	83,115	}	34
	$K\beta_2$	84,838	}	
	$K\beta_4$	85,134	}	10,1
	$KO_{2,3}$	85,444	}	
X_L				
	$L\ell$	8,953		
	$L\alpha$	10,172 – 10,268		
	$L\eta$	10,994		
	$L\beta$	11,812 – 12,643		
	$L\gamma$	14,291 – 14,738		

3.1.2 Auger Electrons

	Energy keV	Relative probability
Auger K		
KLL	54,587 – 59,954	100
KLX	66,37 – 72,86	56
KXY	78,12 – 85,50	7,7
Auger L	5,18 – 10,13	3370

4 Electron Emissions

		Energy keV	Electrons per 100 disint.
e_{AL}	(Tl)	5,18 - 10,13	10,1 (1)
e_{AK}	(Tl)		0,49 (6)
	KLL	54,587 - 59,954	}
	KLX	66,37 - 72,86	}
	KXY	78,12 - 85,50	}
$ec_{1,0\ T}$	(Tl)	193,66 - 279,18	18,5 (1)
$ec_{1,0\ K}$	(Tl)	193,66 (1)	13,37 (6)
$ec_{1,0\ L}$	(Tl)	263,85 - 266,54	3,88 (2)
$ec_{1,0\ M}$	(Tl)	275,49 - 279,18	1,26 (1)
$\beta^-_{0,1}$	max:	212,6 (12)	99,99 (1)
$\beta^-_{0,1}$	avg:	57,8 (4)	
$\beta^-_{0,0}$	max:	491,8 (12)	0,01 (1)
$\beta^-_{0,0}$	avg:	154,4 (4)	

5 Photon Emissions

5.1 X-Ray Emissions

		Energy keV		Photons per 100 disint.	
XL	(Tl)	8,953 — 14,738		5,43 (9)	
$XK\alpha_2$	(Tl)	70,8325		3,75 (4)	} $K\alpha$
$XK\alpha_1$	(Tl)	72,8725		6,33 (6)	}
$XK\beta_3$	(Tl)	82,118	}		
$XK\beta_1$	(Tl)	82,577	}	2,15 (4)	$K'\beta_1$
$XK\beta''_5$	(Tl)	83,115	}		
$XK\beta_2$	(Tl)	84,838	}		
$XK\beta_4$	(Tl)	85,134	}	0,639 (16)	$K'\beta_2$
$XKO_{2,3}$	(Tl)	85,444	}		

5.2 Gamma Emissions

	Energy keV	Photons per 100 disint.
$\gamma_{1,0}$(Tl)	279,1952 (10)	81,48 (8)

6 Main Production Modes

Au – 203(β^-)Hg – 203

Tl – 204(γ,p)Hg – 203

Hg – 202(n,γ)Hg – 203

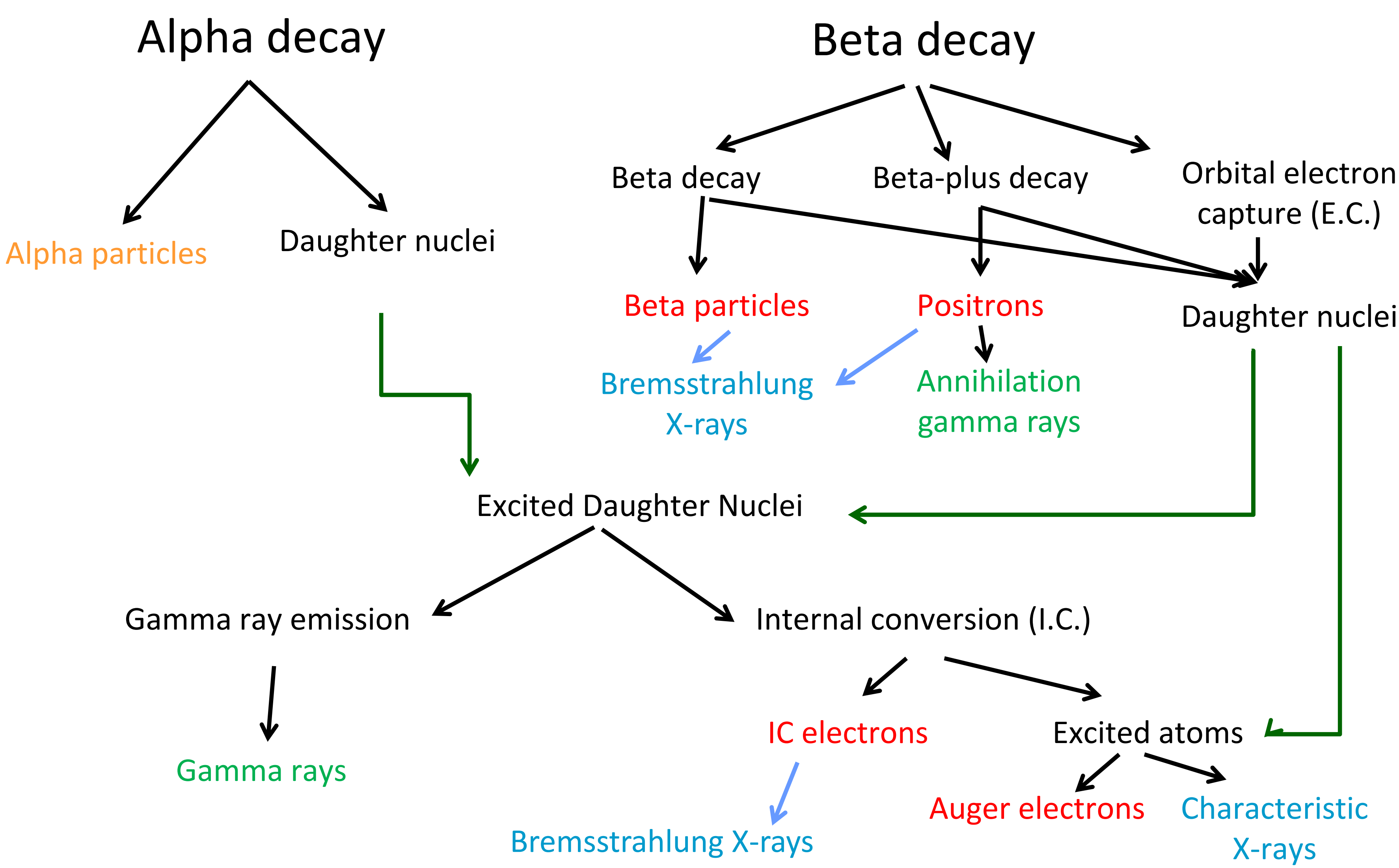
Hg – 202(d,p)Hg – 203

Hg – 204(d,t)Hg – 203

7 References

- N. Marty. Comp. Rend. Acad. Sci. (Paris) 240B (1955) 291-294
  (Beta-particle emission probabilities)
- A. H. Wapstra, G. J. Nijgh. Nucl. Phys. 1 (1956) 245-258
  (Internal conversion coefficients)
- J. L. Wolfson. Can. J. Phys. 34 (1956) 256-264
  (Beta-particle emission probabilities, transition type)
- G.J. Nijgh, A. H. Wapstra, L. Th. M. Ornstein, N. Salomons-Grobben, J. R. Huizenga, O. Almen. Nucl. Phys. 9 (1958) 528-537
  (Internal conversion coefficients)
- R. W. Peelle. ORNL Report ORNL-3016 (1960) 116-125
  (Internal conversion coefficients)
- Z. Sujkowski. Ark. Fysik 20, No. 16 (1961) 243-267
  (Internal conversion coefficients)
- J. G. V. Taylor. Can. J. Phys. 40 (1962) 383-392
  (Internal conversion coefficients)
- R. Burmeister, H. Graber, J. Schintlmeister, R. Weibrecht. Nucl. Phys. 42 (1963) 56-61
  (Internal conversion coefficients)
- W. L. Croft, B. G. Pettersson, J. H. Hamilton. Nucl. Phys. 48 (1963) 267-272
  (Internal conversion coefficients)
- C. J. Herrlander, R. L. Graham. Nucl. Phys. 58 (1964) 544-560
  (Internal conversion coefficients)
- F. Lagoutine, Y. Le Gallic, J. Legrand. Int. J. Appl. Radiat. Isot. 19 (1968) 475-482
  (Half-life)
- J. F. Emery, S. A. Reynolds, E. I. Wyatt, G. I. Gleason. Nucl. Sci. Eng. 48 (1972) 319-323
  (Half-life)
- K. F. Walz, H. M. Weiss, E. Funck. PTB Jahresbericht (1972) 150-151
  (Internal conversion coefficients)
- H. S. Sahota. Indian J. Phys. 46 (1972) 86-92
  (Internal conversion coefficients)
- H. H. Hansen, D. Mouchel. Z. Phys. 267 (1974) 371-377
  (Internal conversion coefficients)
- F. Rösel, H. M. Fries, K. Alder, H. C. Pauli. At. Data. Nucl. Data Tables 21 (1978) 291-514
  (Internal conversion coefficients)

Typical Decay Products from Unstable Radioisotopes



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.

Potential Health Concerns from Beta Decay

- Gamma-ray dose
- Beta dose from internally administrated beta emitters
- Beta dose from surface contaminations

Examples for Beta Decay

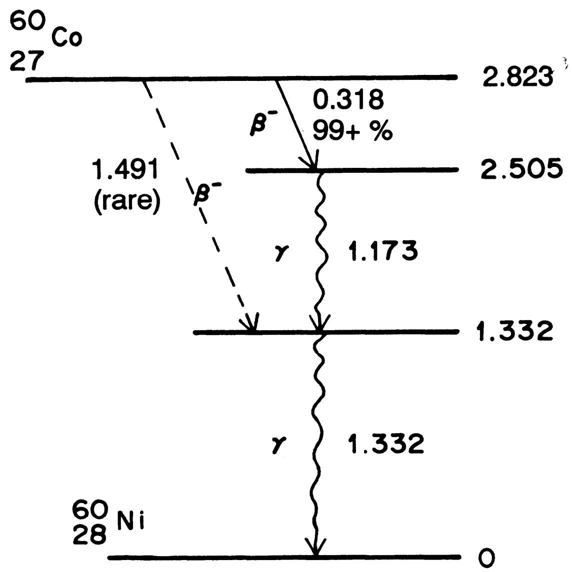


FIGURE 3.6. Decay scheme of $^{60}_{27}Co$.

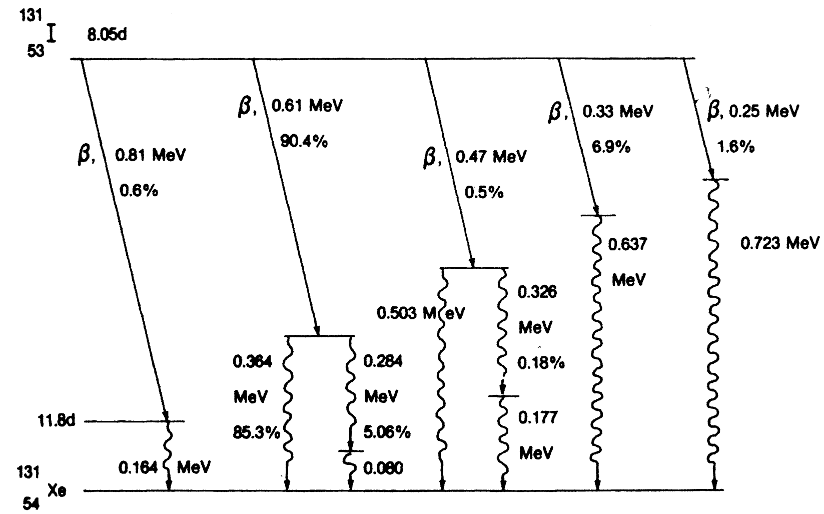
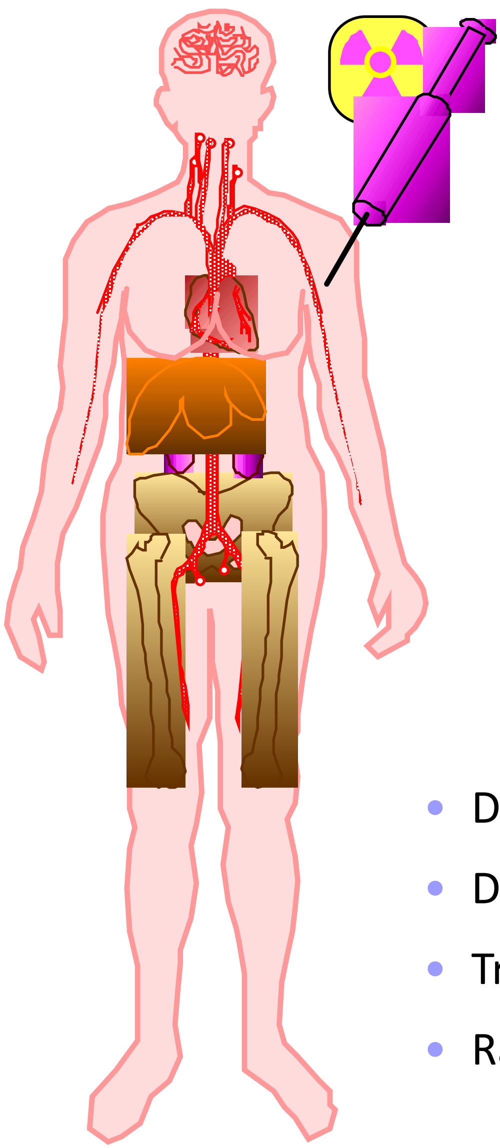


FIGURE 4.7. Iodine-131 transformation (decay) scheme.

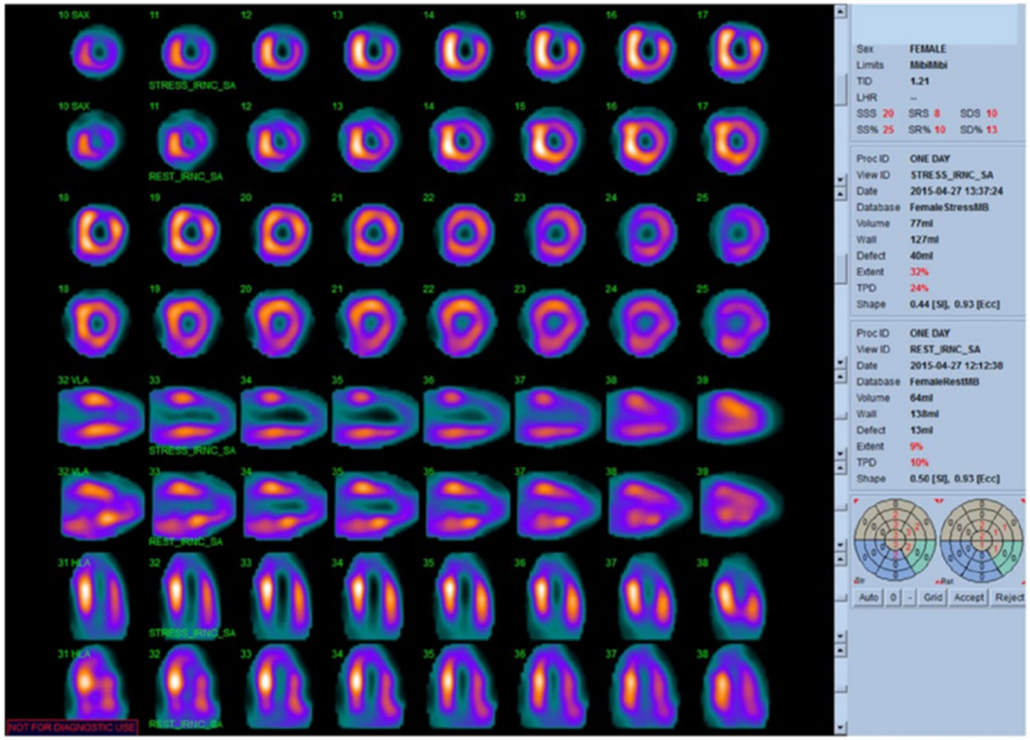
- Beta emissions are normally associated with complicated decay schemes and the emission of other particles such as gamma rays.
- There exist the so called "pure beta emitters", such as ^{3}H, ^{14}C, ^{32}P and ^{90}Sr, which have no accompanying gamma rays.

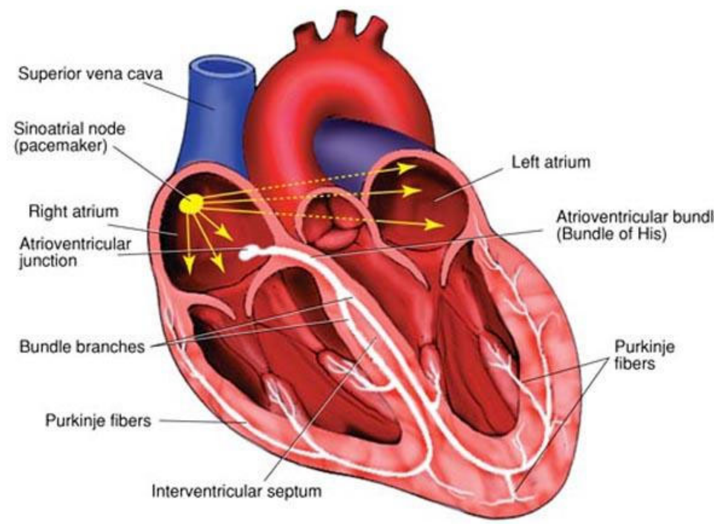
Radiation Risk from Medical Procedures
Single Photon Emission Computed Tomography



- 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).

Tc-99m Sestamibi Myocardial Perfusion Imaging (MPI)





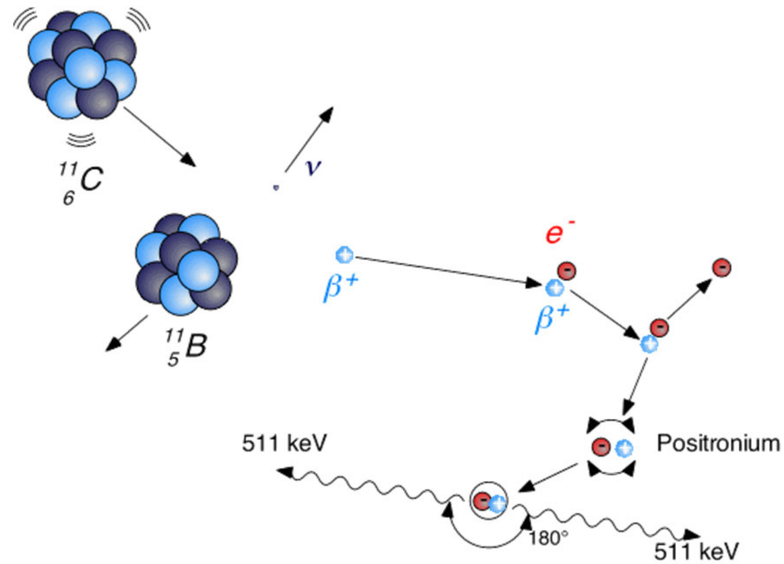
Exercise stress Tc-99m Sestamibi single day myocardial perfusion SPECT images of the female patient with a significant (80%) distal left main coronary artery disease. Classic features of the high-risk scan are present: severe partially reversible perfusion defect, involvement of the LAD and LCX territory, visual transient ischemic dilation and abnormal TID ratio (1.21). The patient presented with symptoms of stable atypical angina. No significant ECG or hemodynamic changes were noted during the stress portion of the test.

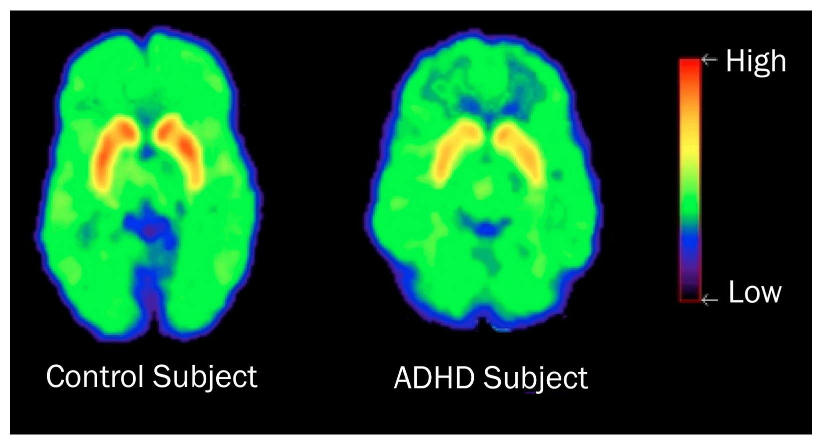
https://www.researchgate.net/figure/Exercise-stress-Tc-99m-Sestamibi-single-day-myocardial-perfusion-SPECT-images-of-the_fig1_283448406

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.

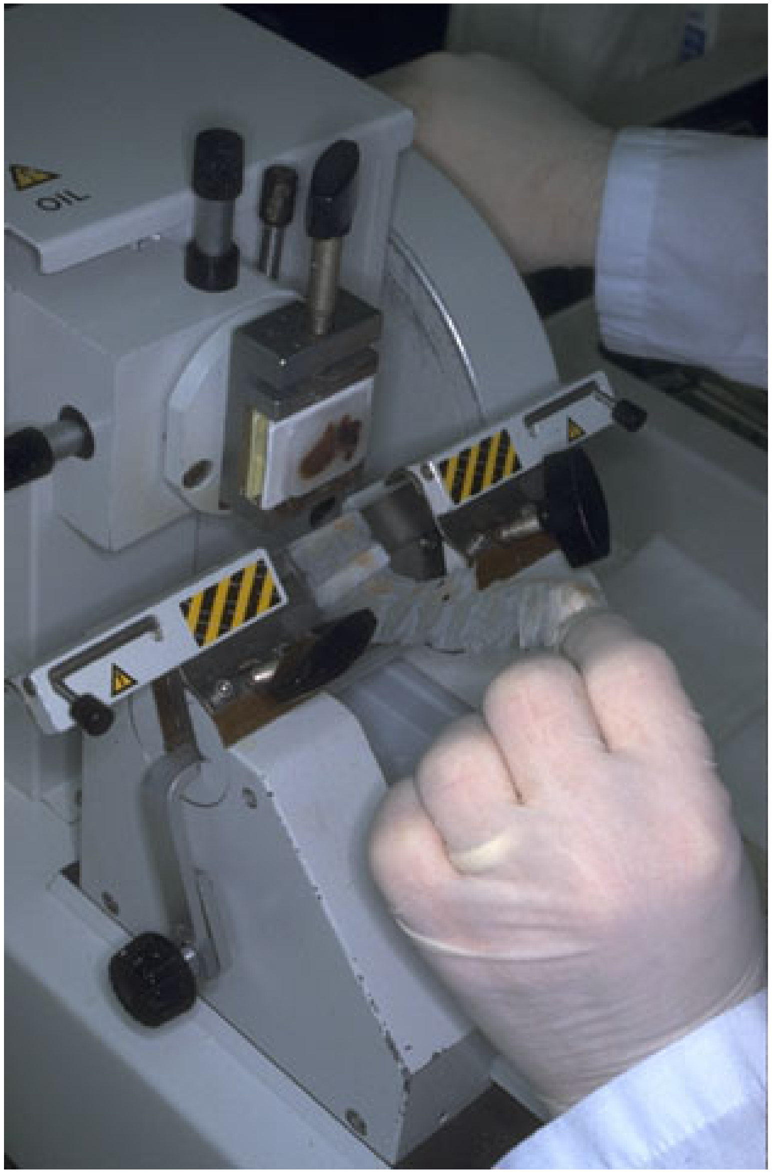




Radionuclides in Medicine

Radionuclide	half-life	energy (KeV)	emitter	source
^{64}Cu	12.7 h	653	β^+	cyclotron
^{67}Ga	78.3 h	93,185	γ	cyclotron
^{89}Sr	50.6 d	1460	β^-	reactor
^{90}Y	64.1 h	2270	β^-	reactor
^{99m}Tc	6.02 h	141	γ	generator
^{111}In	67.9 h	171,247	γ	cyclotron
^{153}Sm	46.3 h	702,810;103	β^-,γ	reactor
^{177}Lu	6.7 d	176,497;113,208	β^-,γ	reactor
^{186}Re	90.6 h	936,1070;137	β^-,γ	reactor
^{188}Re	16.9 h	1500;155	β^-,γ	generator
^{201}Tl	73.1 h	135,167	γ	cyclotron

Sectioning of Tissue…



…on Microtome (wax)

…on Cryostat (frozen)

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

Bond-Seeking Beta Emitters as Radiotherapy Agents

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

	Maximum energy (MeV)	Average energy (MeV)	Average Range (mm)	T_{ha} lf (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).

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.

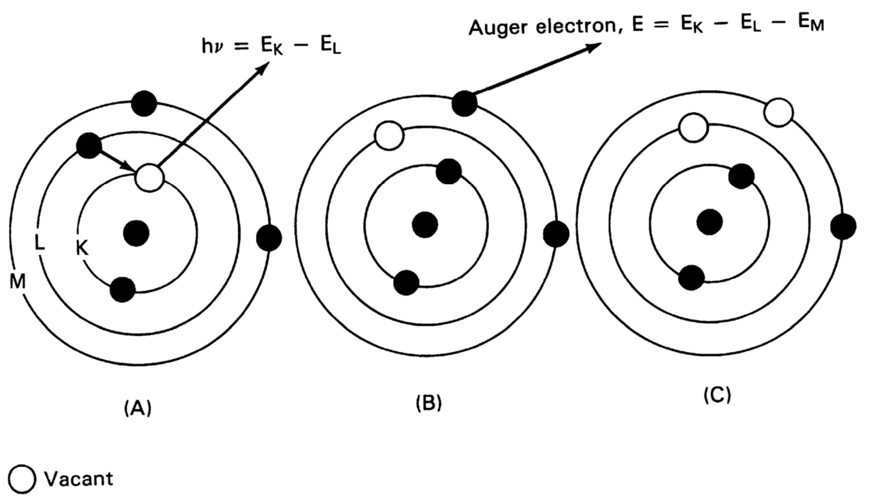
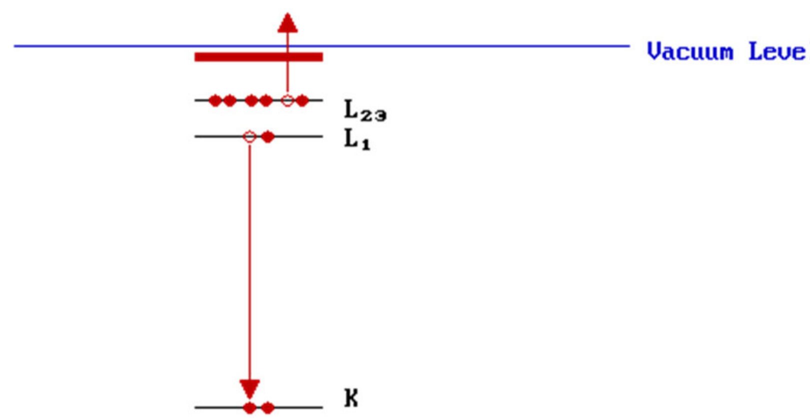


Figure 3.7 (A) The usual emission of a K characteristic X-ray, $h\nu$, energy equal to $E_K - E_L$, the difference in binding energy for the two orbital electrons, K and L. (B) $h\nu$ has been absorbed and a monoenergetic Auger electron is emitted, in the example shown, from the M shell, the energy of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



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

Ku *et al. EJNMMI Radiopharmacy and Chemistry* (2019) 4:27
https://doi.org/10.1186/s41181-019-0075-2

EJNMMI Radiopharmacy and Chemistry

REVIEW **Open Access**

Auger electrons for cancer therapy – a review

Anthony Ku[1†], Valerie J. Facca[1†], Zhongli Cai[1] and Raymond M. Reilly[1,2,3,4*]

* Correspondence: raymond.reilly@utoronto.ca
†Anthony Ku and Valerie J. Facca contributed equally to this work.
[1]Department of Pharmaceutical Sciences, University of Toronto, Toronto, ON, Canada
[2]Department of Medical Imaging, University of Toronto, Toronto, ON, Canada
Full list of author information is available at the end of the article

Abstract

Background: Auger electrons (AEs) are very low energy electrons that are emitted by radionuclides that decay by electron capture (e.g. ^{111}In, ^{67}Ga, ^{99m}Tc, ^{195m}Pt, ^{125}I and ^{123}I). This energy is deposited over nanometre-micrometre distances, resulting in high linear energy transfer (LET) that is potent for causing lethal damage in cancer cells. Thus, AE-emitting radiotherapeutic agents have great potential for treatment of cancer. In this review, we describe the radiobiological properties of AEs, their radiation dosimetry, radiolabelling methods, and preclinical and clinical studies that have been performed to investigate AEs for cancer treatment.

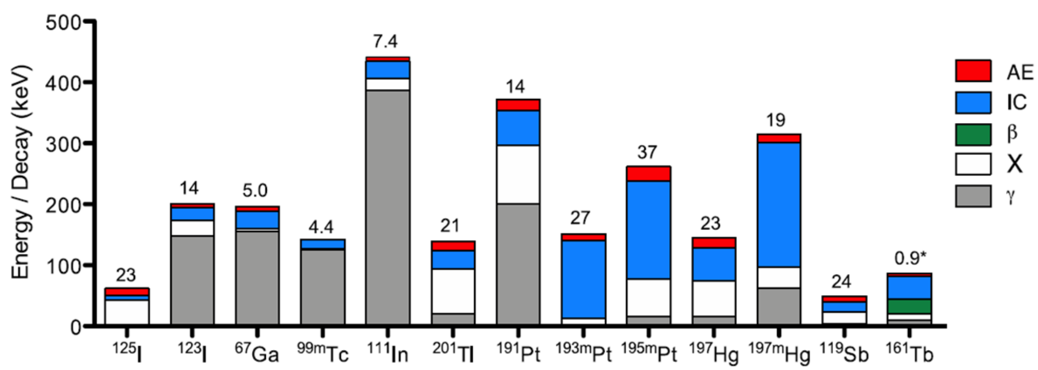


Fig. 1 Energy contribution of γ-photons, X-rays, β-particles, internal conversion (IC) electrons, and Auger electrons (AEs) per decay event for several radionuclides. Energy estimates are based on MIRD Radionuclide Data and Decay Schemes (Eckerman and Endo 2008), and the National Nuclear Data Center for ^{161}Tb (65-Terbium-161 2011). * Number of K- and L- shell Auger electrons only

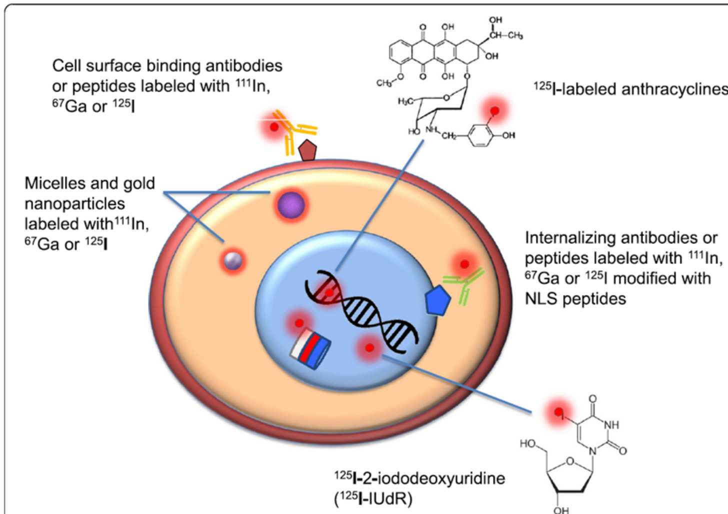
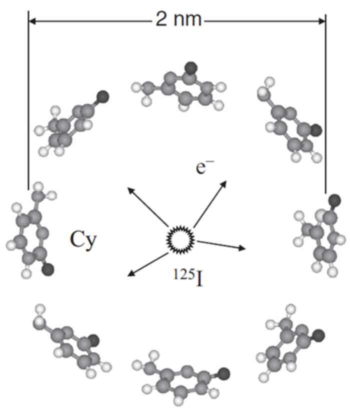


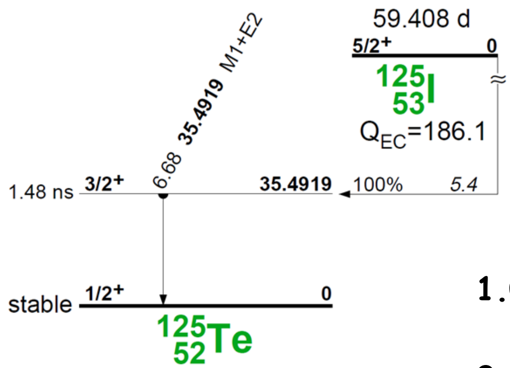
Fig. 6 Examples of targeting vehicles for delivery of Auger electron (AE)-emitting radionuclides to cancer cells. Non-internalising monoclonal antibodies (mAbs) or peptides bind to cell-surface receptors and may kill cells through damaging the cell membrane. Internalising mAbs or peptides may be transported to the cell nucleus by appending nuclear localisation sequence (NLS) peptides or by an endogenous NLS present in some cell-surface receptors (e.g. EGFR or HER2) or combine internalising, endosomal escape and nuclear localizing sequences (modular nanotransporters). Nuclear localisation causes lethal DNA double-strand breaks (DSBs). Micelles or gold nanoparticles may be modified with mAbs or peptides to target cell surface receptors or are internalised non-specifically into cancer cells by endocytosis. ^{125}I-labelled anthracyclines diffuse into cancer cells and intercalate into DNA, while ^{125}I-2-iododeoxyuridine (^{125}I-IUdR) is taken up by nucleoside transporters and incorporated into DNA. These agents cause lethal DNA DSBs

Correlation between energy deposition and molecular damage from Auger electrons

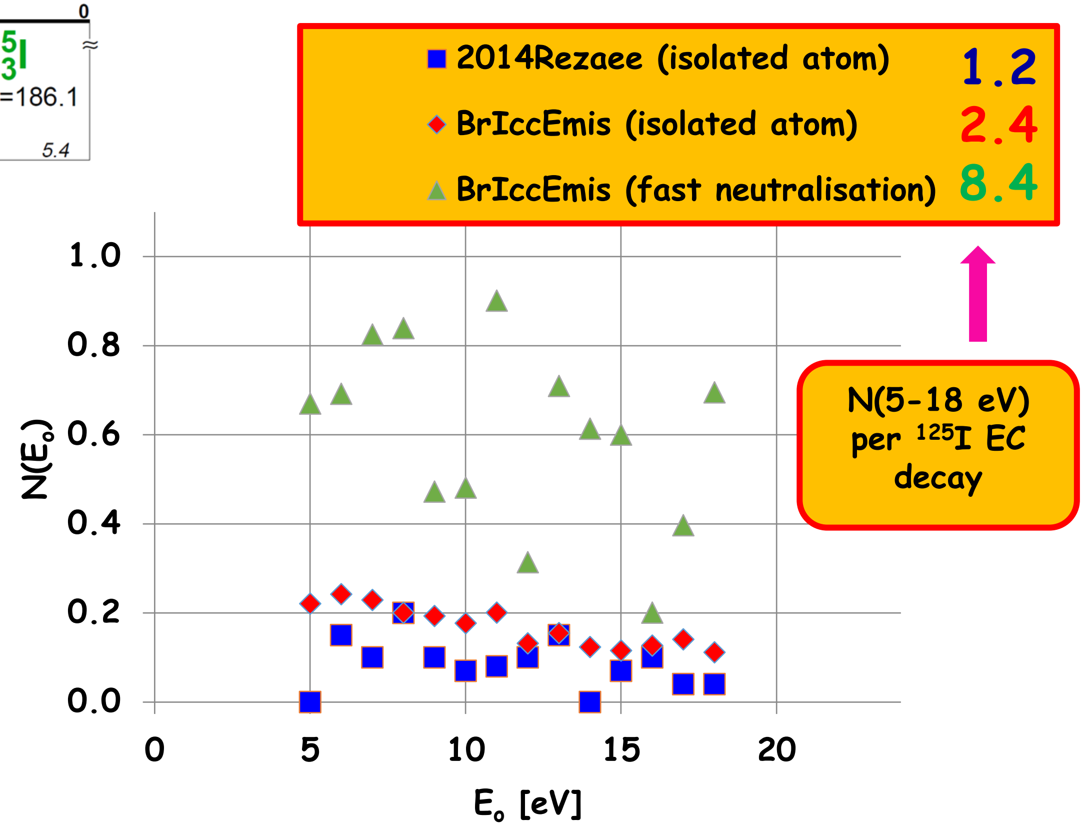
A case study of ultra-low energy (5–18 eV) electron interactions with DNA
M. Rezaee, D.J. Hunting, L. Sanche, *Univ. de Sherbrooke, Sherbrooke, Québec, Canada*
Med. Phys. 41 (2014) 072502



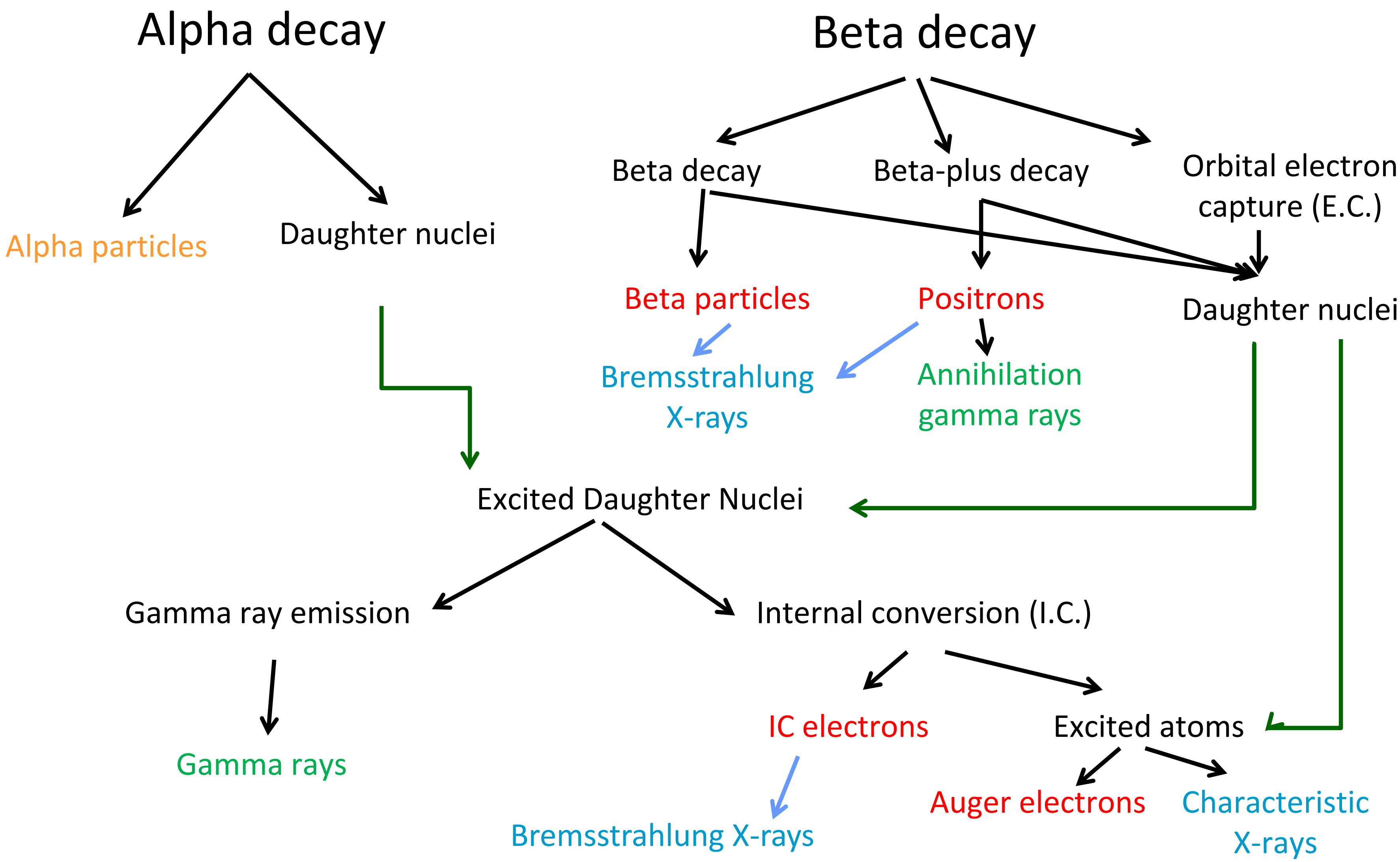
Model of DNA



Nanodosimetric model ($V=4.3\ nm^3$!) based on the medical internal radiation dose (MIRD) schema (M. Michaud et al. Phys. Rev E **87** (2013) 032701)



Typical Decay Products from Unstable Radioisotopes



Understanding the Radiation from Cs-137

Decay scheme:

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

Understanding the Radiation from Cs-137

What will happen to the excited Ba-137 nucleus?

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

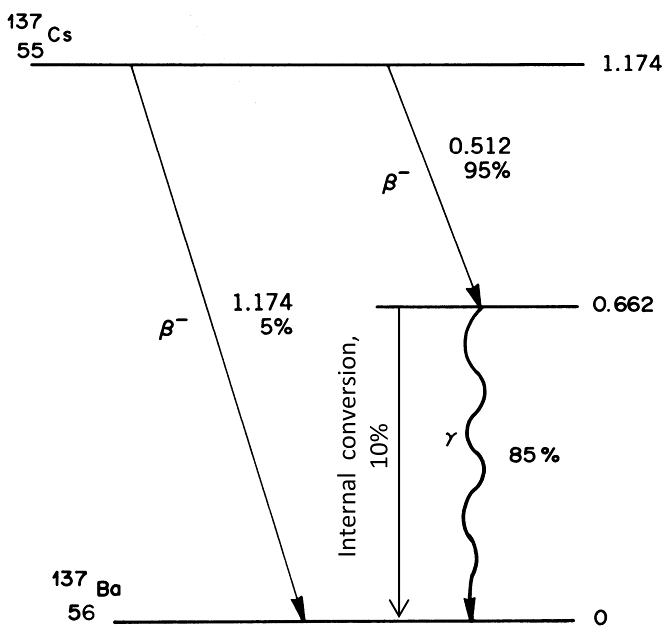


FIGURE 3.8. Decay scheme of $^{137}_{55}Cs$.

1. Beta particles for sure, what else?
2. Gamma-rays
3. Internal conversion electrons
4. Emission of characteristic X-ray
5. Auger electrons
6. Bremsstrahlung X-rays

If you are holding a Cs-137 source, what are the radiations that your hand/body is exposed to?

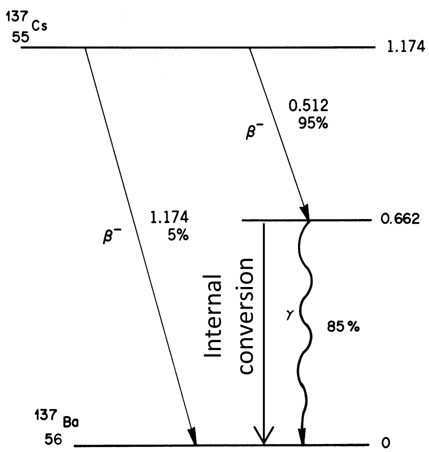
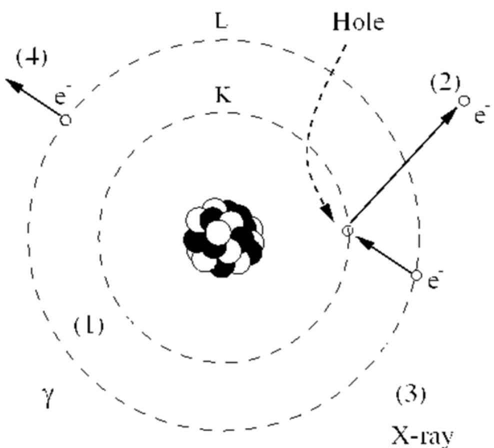
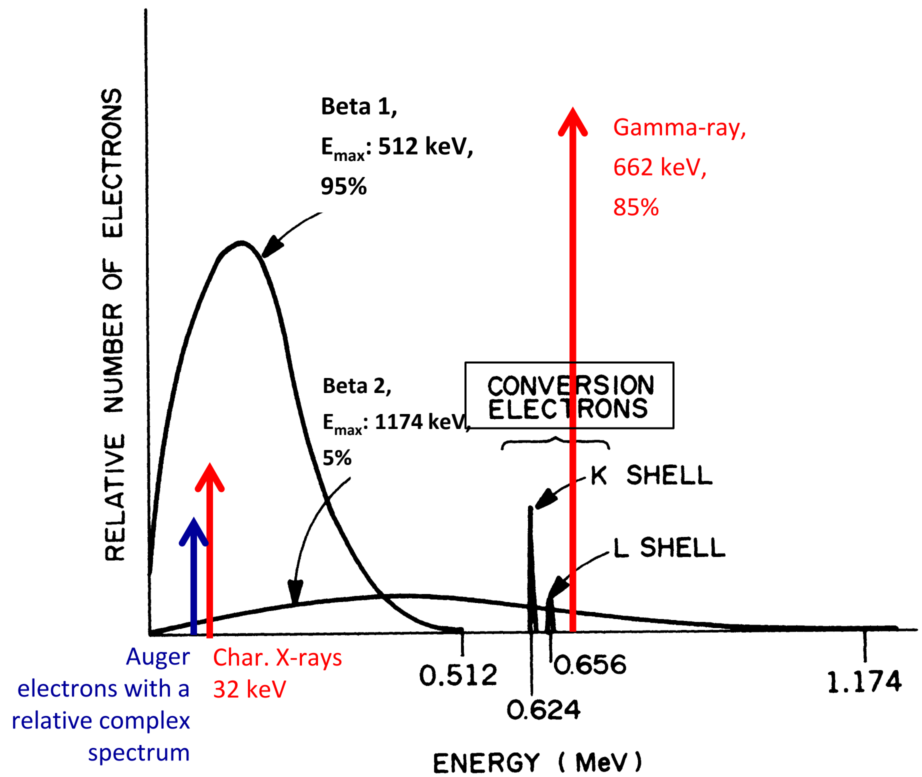


FIGURE 3.8. Decay scheme of $^{137}_{55}Cs$.

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





http://www.nuclear.kth.se/courses/lab/latex/internal/internal.html