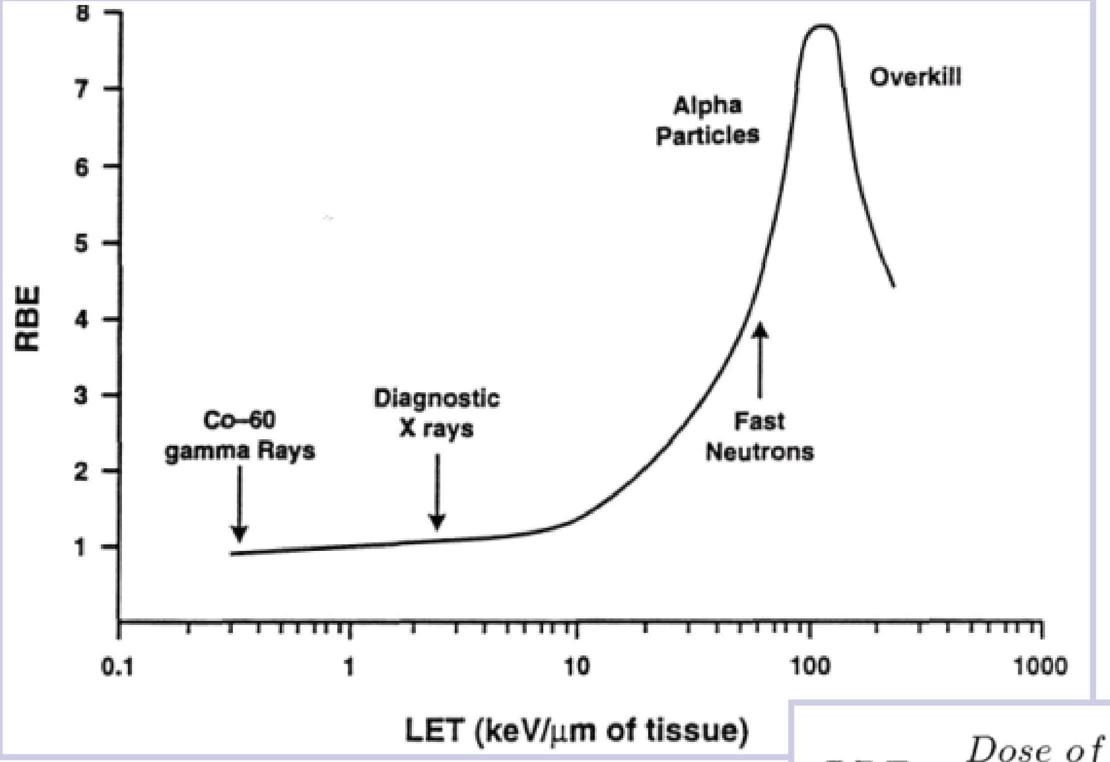
Alpha Emission and Potential Health Concerns

Radiation Effect and Dose Delivery

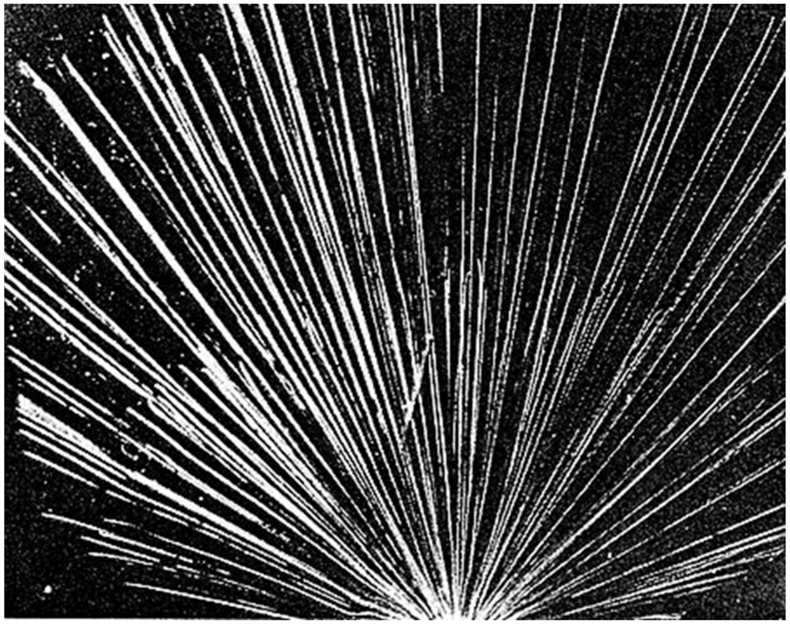
For low LET radiation, $\Rightarrow$ RBE $\propto$ LET, for higher LET the RBE increases to a maximum, the subsequent drop is caused by the overkill effect.



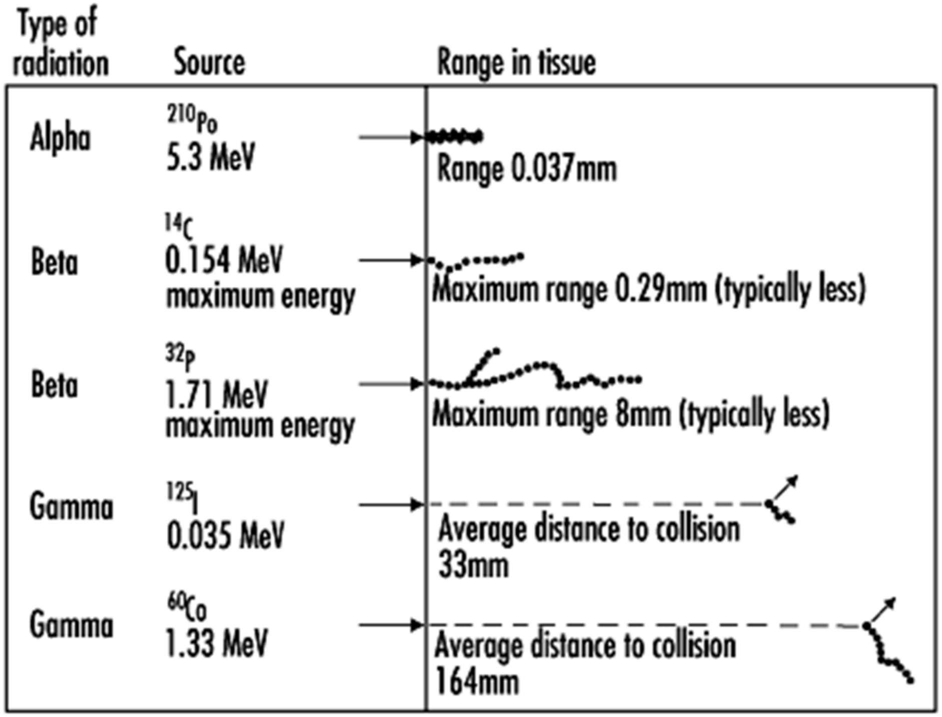
$$RBE = \frac{Dose\ of\ 150\ V\ \ X-rays\ required\ to\ cause\ effect\ x}{Dose\ of\ radiation\ required\ to\ cause\ effect\ x}$$

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

Alpha Emission and Radiation Hazard



J. Chadwick, Cavendish Laboratory, University of Cambridge.



Type of radiation	Source	Range in tissue
Alpha	^{210}Po 5.3 MeV	Range 0.037mm
Beta	^{14}C 0.154 MeV maximum energy	Maximum range 0.29mm (typically less)
Beta	^{32}P 1.71 MeV maximum energy	Maximum range 8mm (typically less)
Gamma	^{125}I 0.035 MeV	Average distance to collision 33mm
Gamma	^{60}Co 1.33 MeV	Average distance to collision 164mm

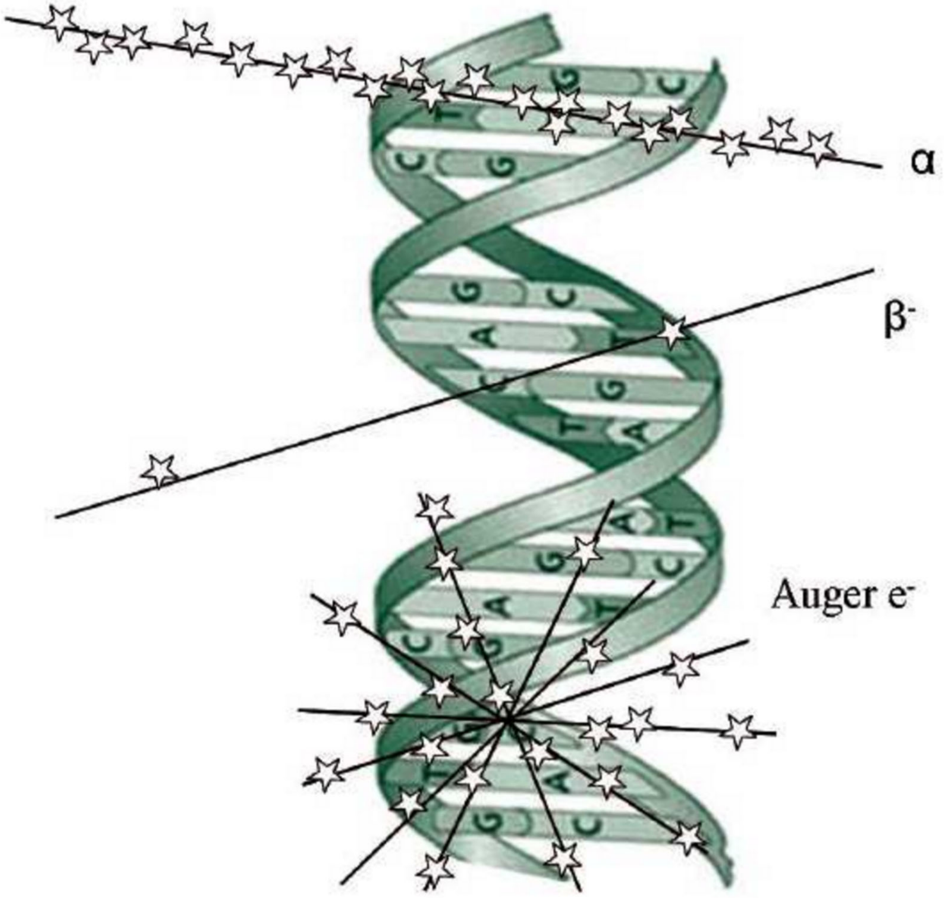
Source: Shapiro 1972.

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

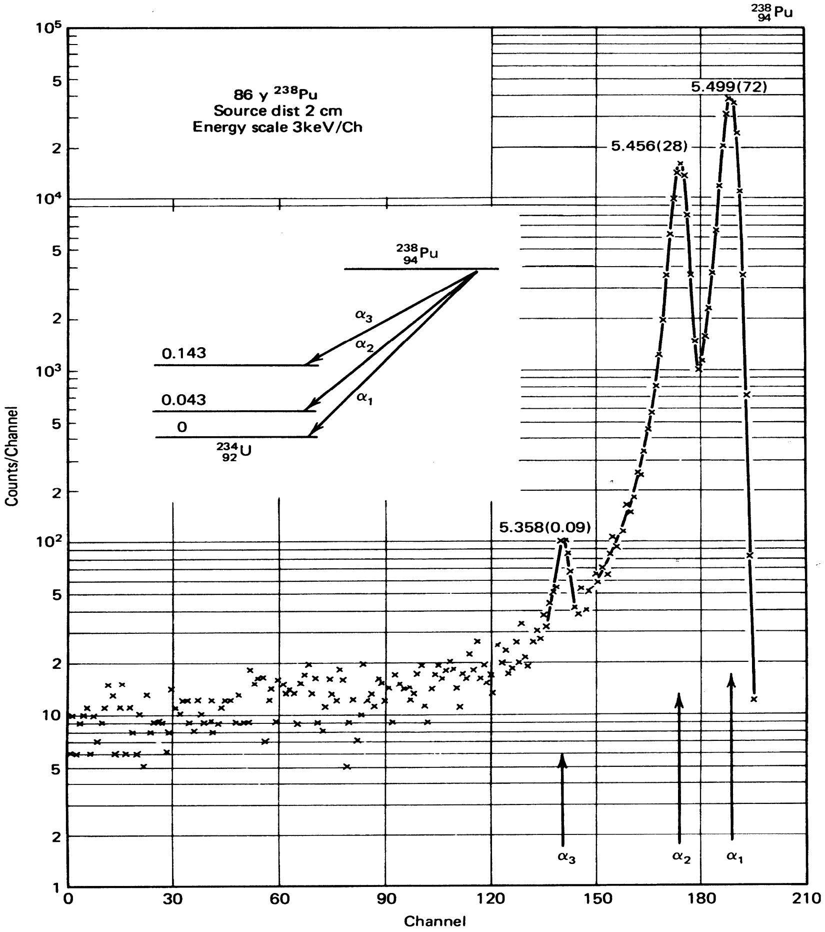
Alpha Emission and Radiation Hazard



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

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.

An Overview of Radiation Exposure to US Population

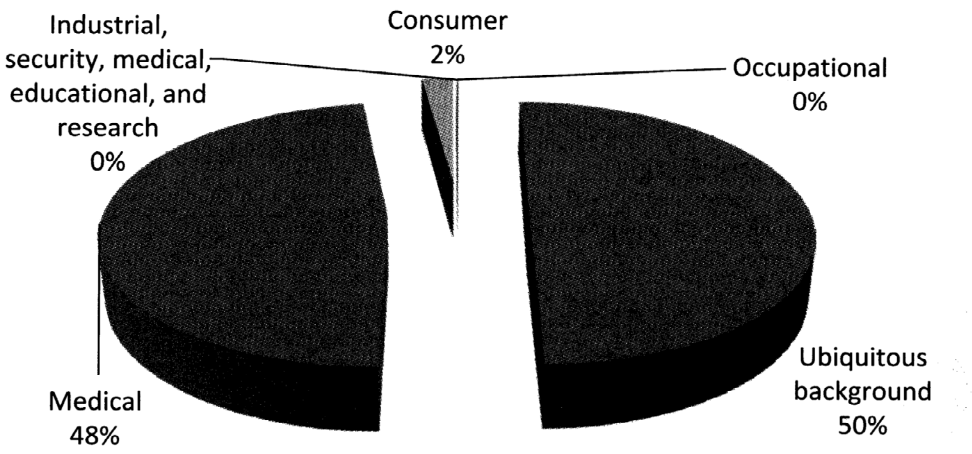


FIGURE 1.1 ◆ Exposure by Major Categories

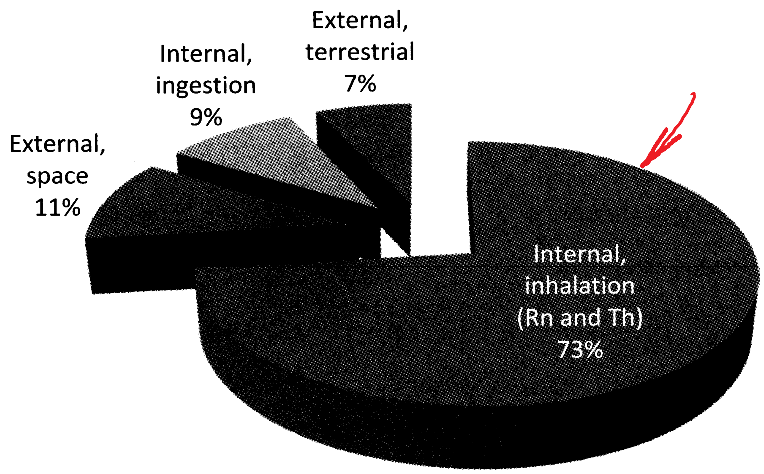


FIGURE 1.2 ◆ Ubiquitous Background

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.

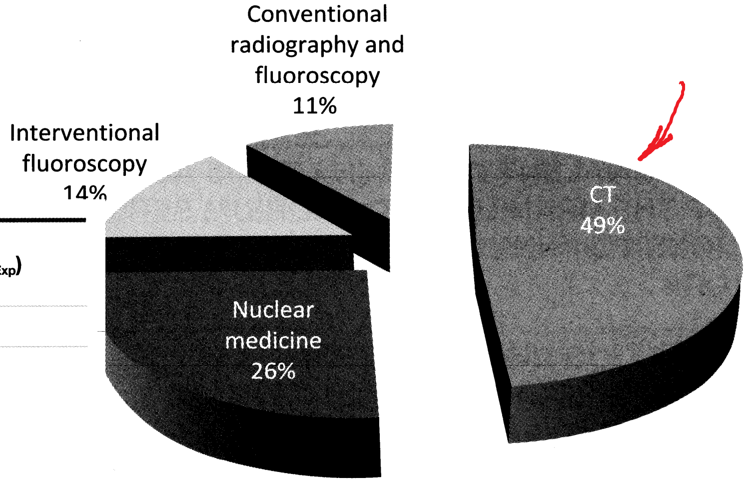
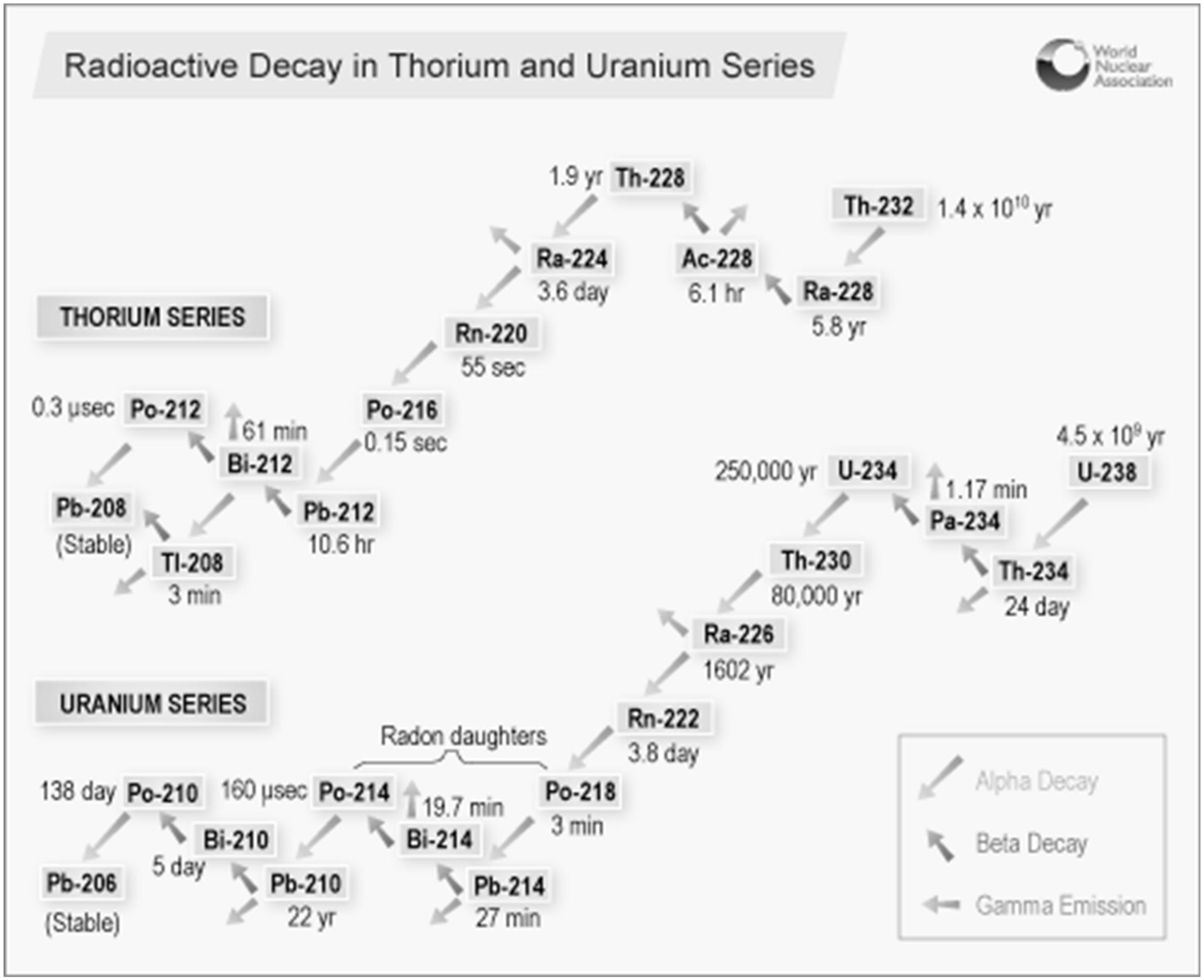


FIGURE 1.3 ◆ Medical



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.

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

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

$^{219}_{86}Rn$ 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.

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

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

$^{207}_{82}Pb$ 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.

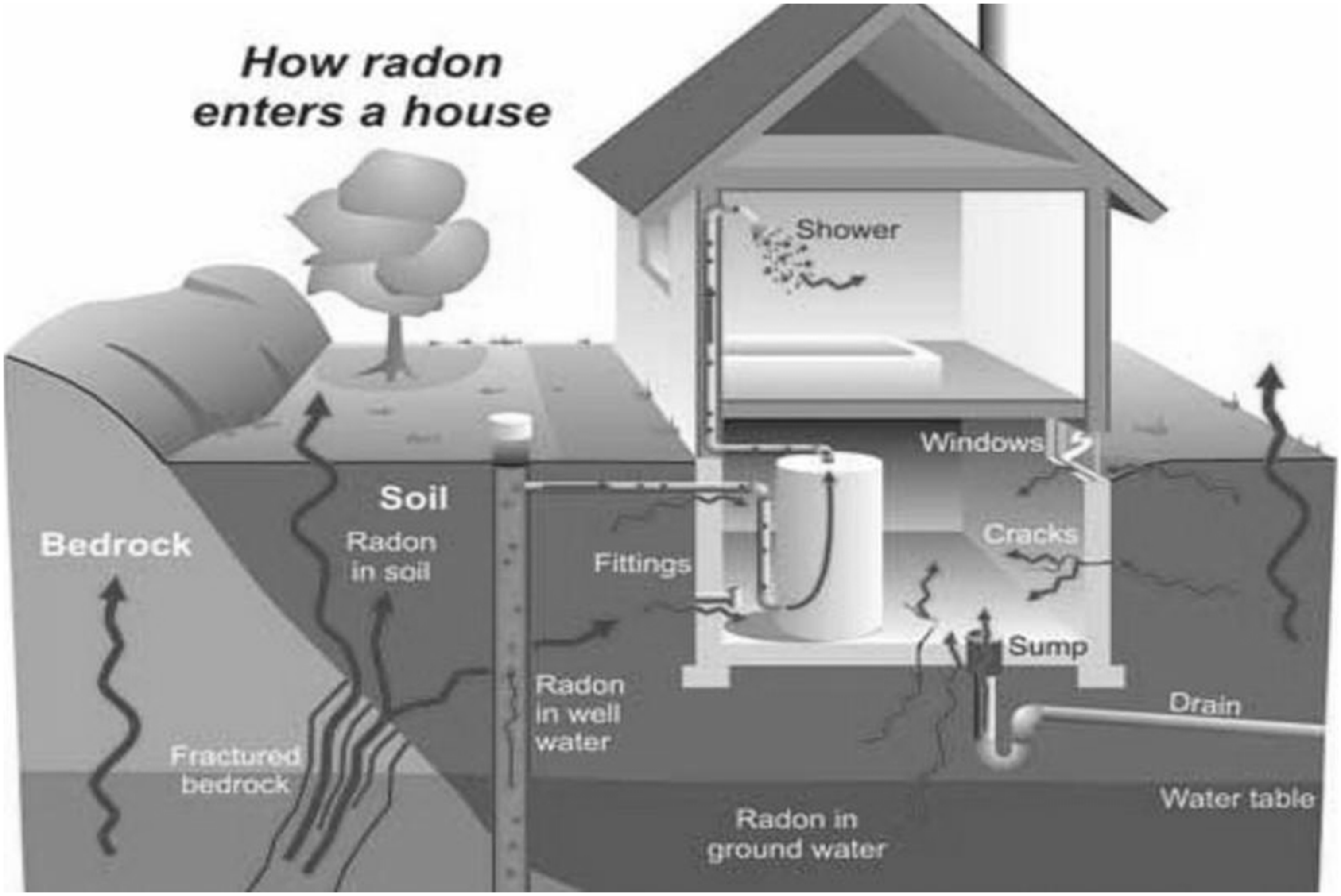
The health concerns of these isotopes are determined by two factors:

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

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

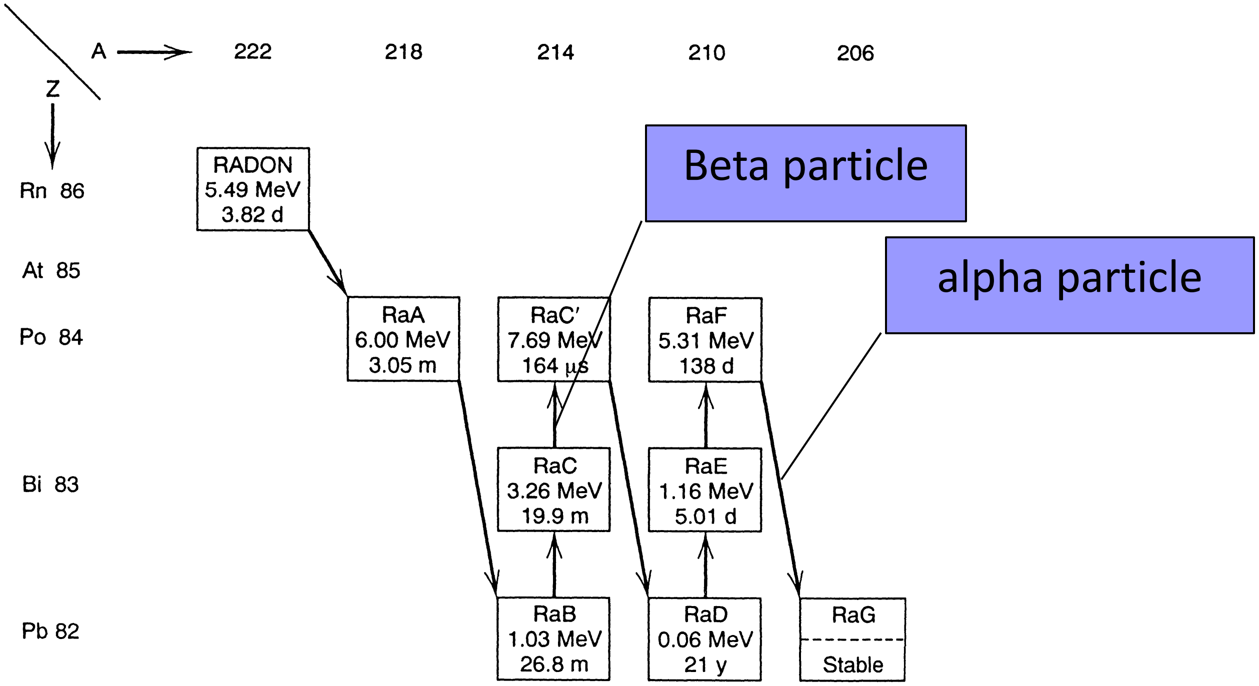
The contributions from the daughters of ^{220}Rn and ^{219}Rn to internal exposure are usually negligible compared with that from ^{222}Rn.

Indoor Radon



Naturally Occurring Radioactivity – Health Concerns of Radon Gas

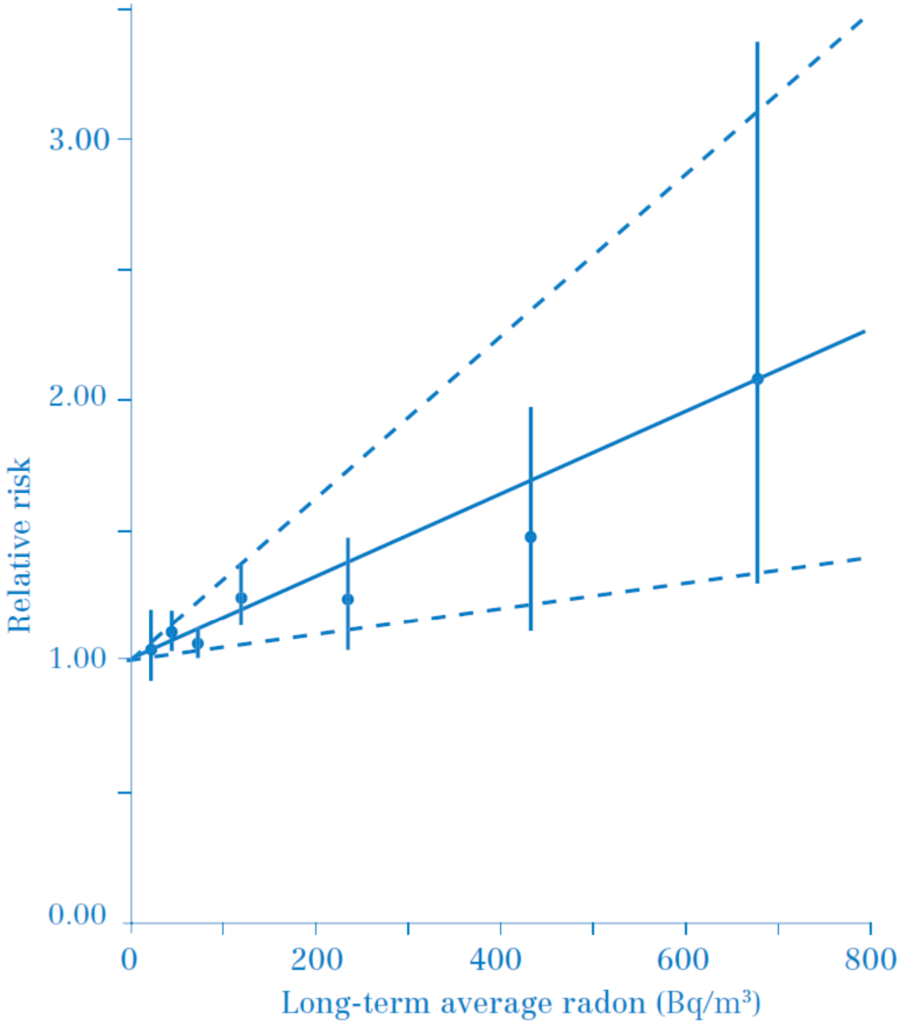
- Airborne radon itself poses little health hazard. It is not retained in significant amounts by the body.
- The health hazard is closely related to the short-lived daughters of radon.



Beta particle

alpha particle

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/m³.

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

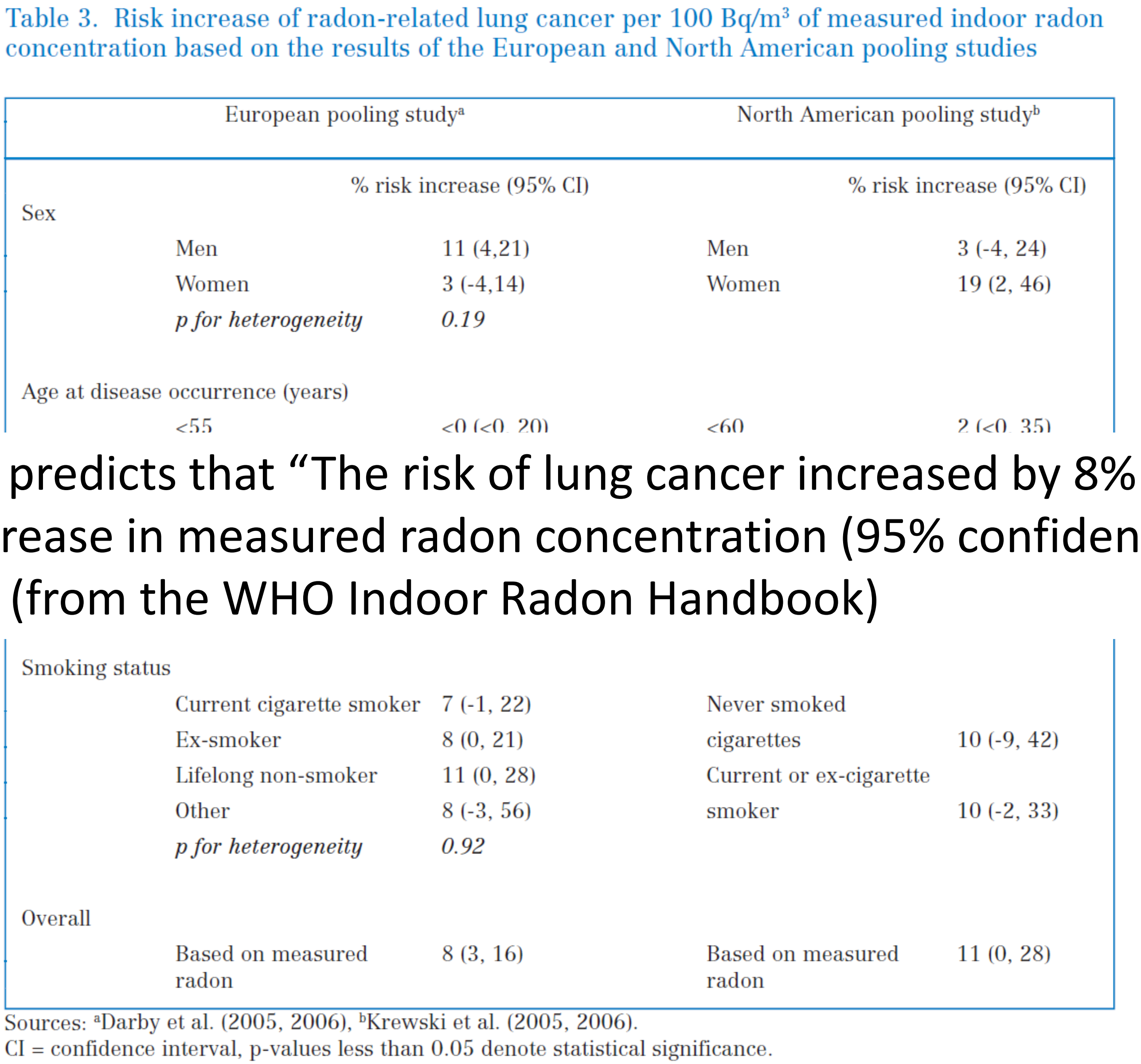
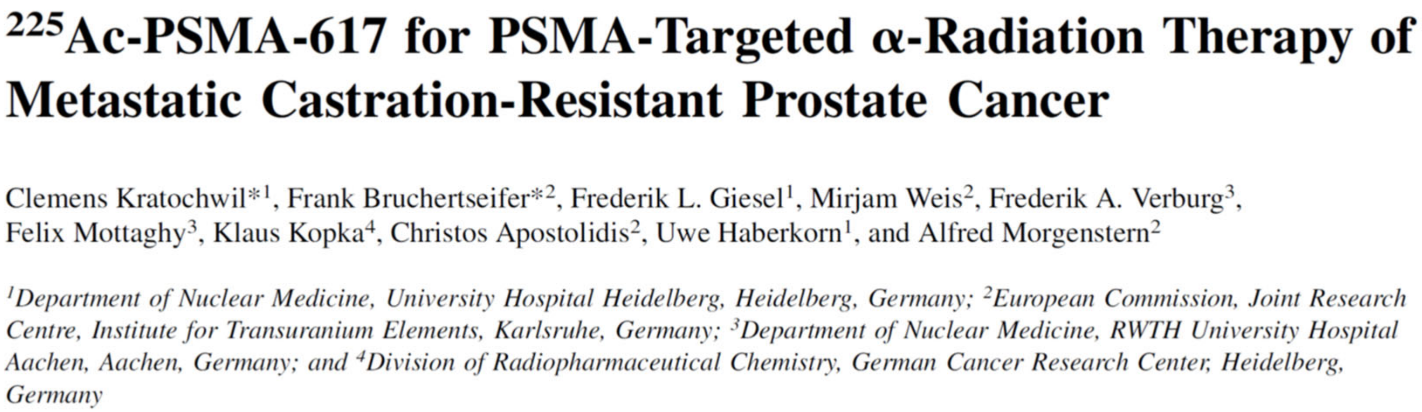


Table 3. Risk increase of radon-related lung cancer per 100 Bq/m^3 of measured indoor radon concentration based on the results of the European and North American pooling studies

	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)
Smoking status				
	Current cigarette smoker	7 (-1, 22)	Never smoked	
	Ex-smoker	8 (0, 21)	cigarettes	10 (-9, 42)
	Lifelong non-smoker	11 (0, 28)	Current or ex-cigarette	
	Other	8 (-3, 56)	smoker	10 (-2, 33)
	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.

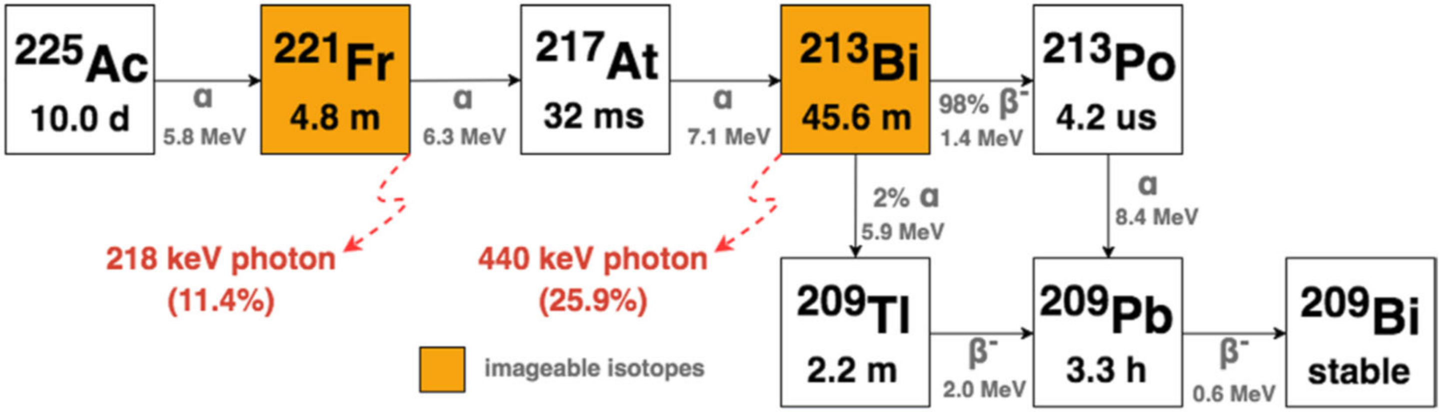
The WHO predicts that “The risk of lung cancer increased by 8% per 100 Bq/m^3 increase in measured radon concentration (95% confidence interval).” (from the WHO Indoor Radon Handbook)



^{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



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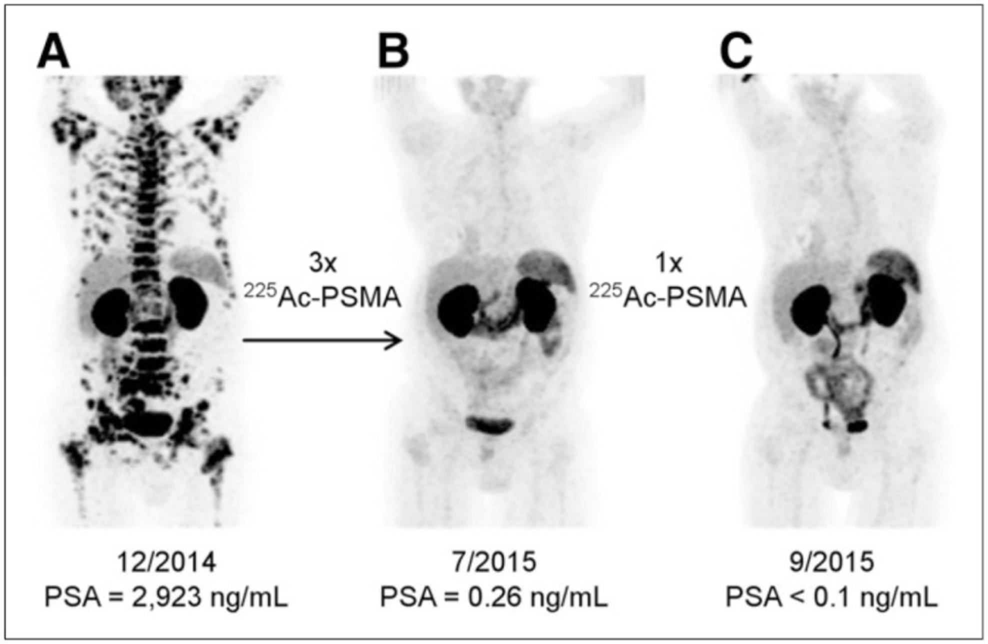
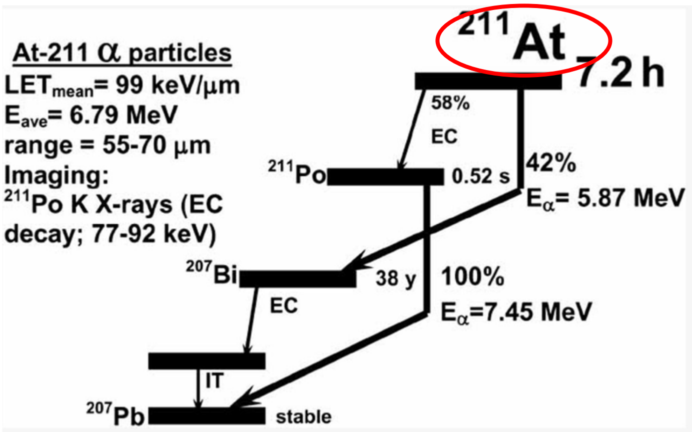
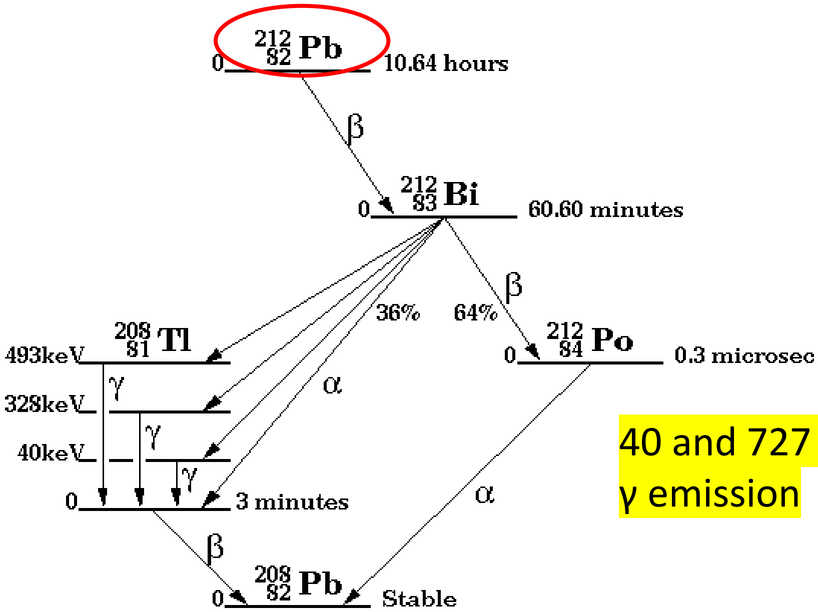


FIGURE 1. ^{68}Ga-PSMA-11 PET/CT scans of patient A. Pretherapeutic tumor spread (A), restaging 2 mo after third cycle of ^{225}Ac-PSMA-617 (B), and restaging 2 mo after one additional consolidation therapy (C).

α-Emitters of Human Interest (1)

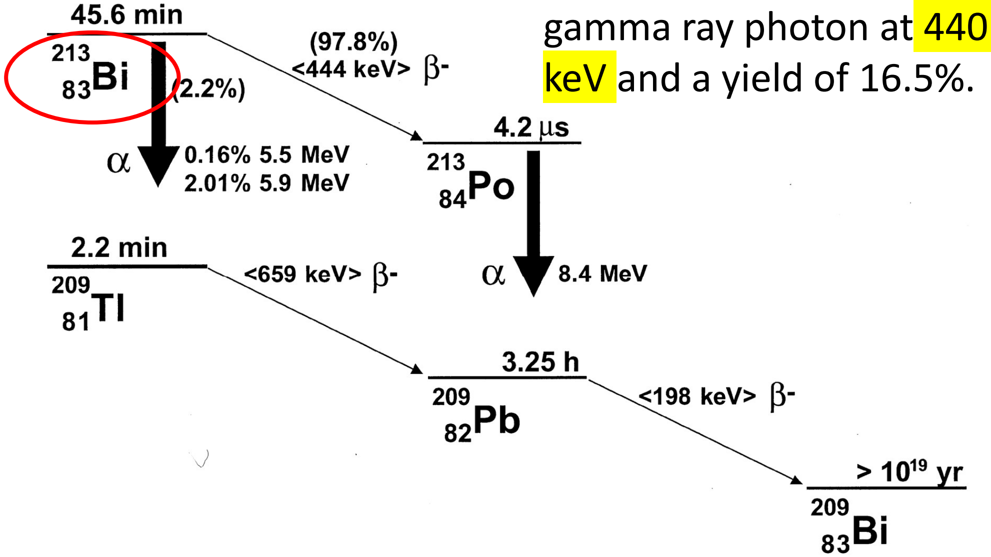


Po K Xrays are emitted that permit external imaging, the two most abundant of these X-rays have energies of 77 and 80 keV, 12 and 20% of all photon emissions, respectively.



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

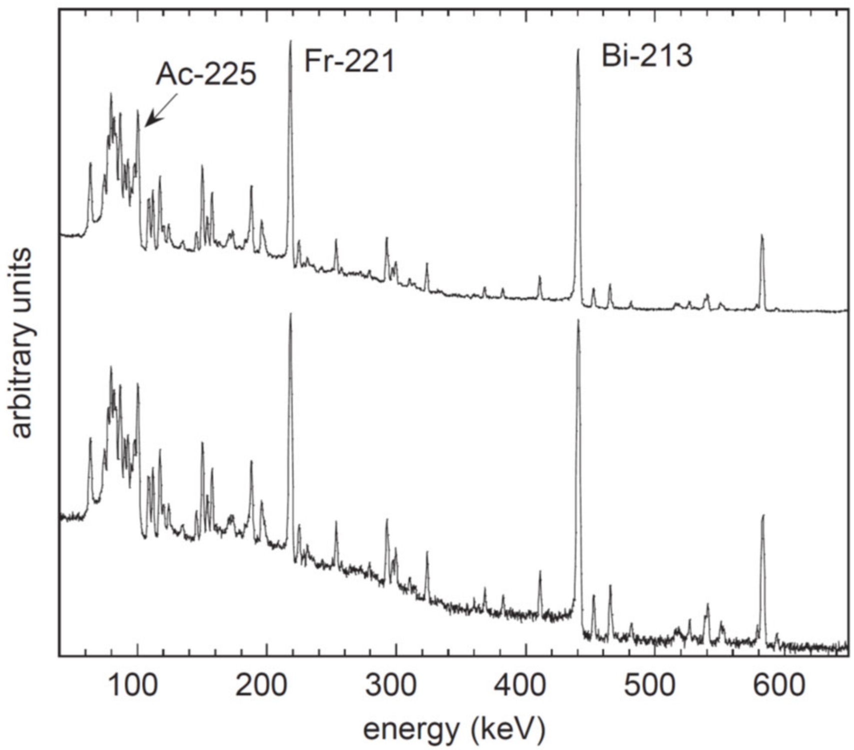
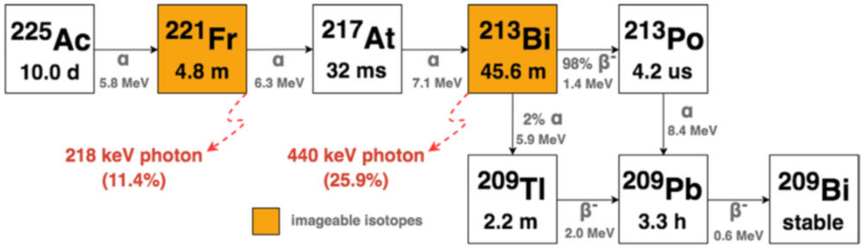


Fig. 4. Gamma spectra of purified Ac-225 produced via cyclotron irradiation (upper spectrum) and Ac-225 extracted from Th-229 (lower spectrum).

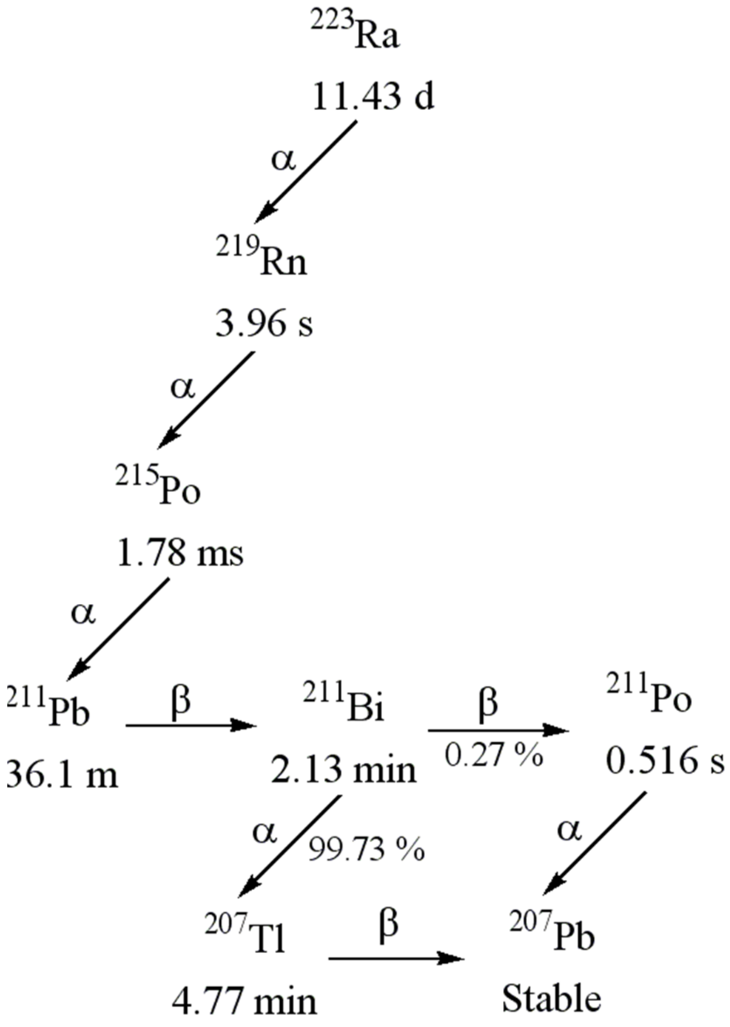


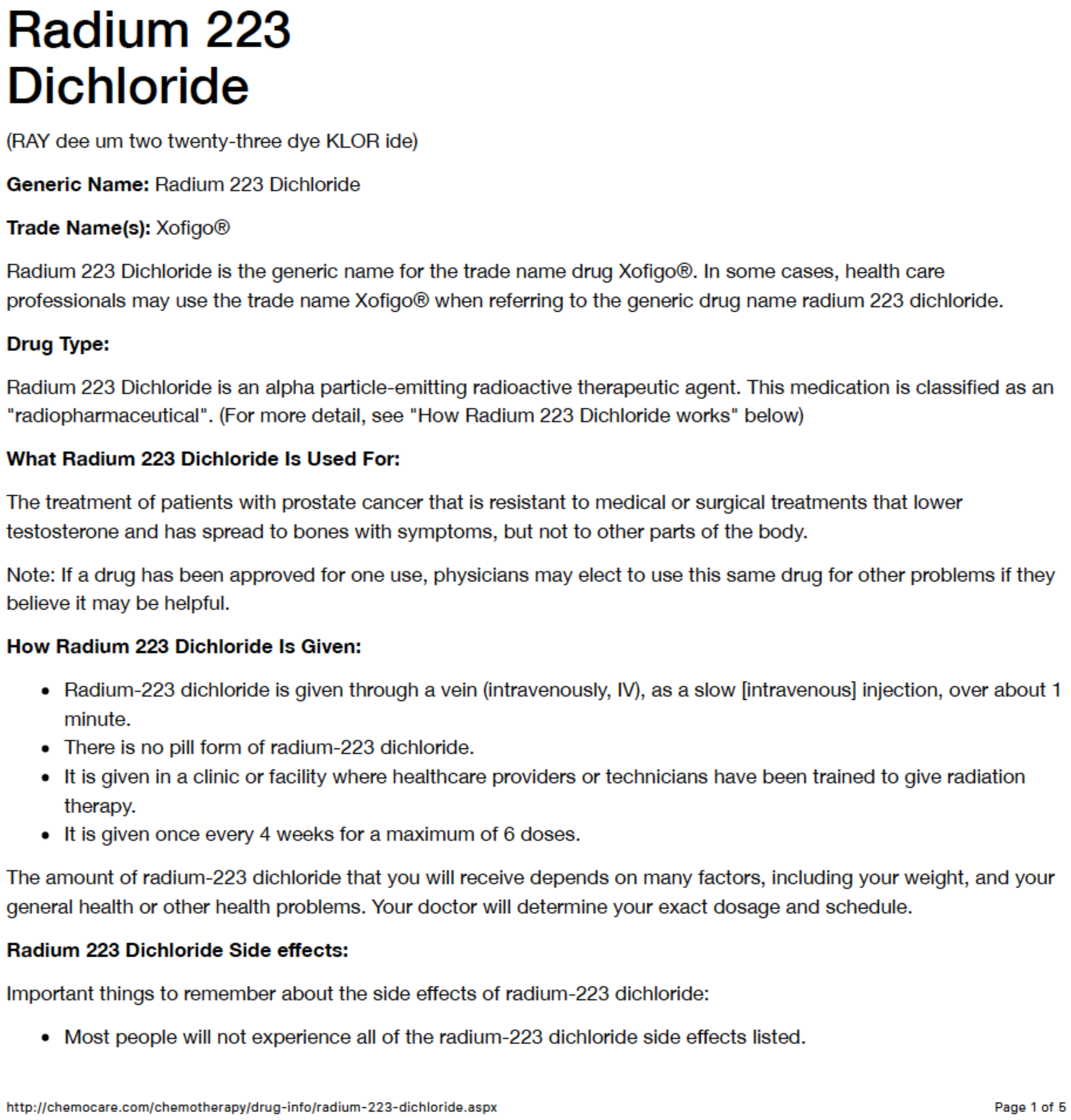
The 225Ac decay chain. Photons with a branching ratio >3% relative to 225Ac decay are shown.

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.

http://chemocare.com/chemotherapy/drug-info/radium-223-dichloride.aspx

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:

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

What will happen to the excited Ba-137 nucleus?

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

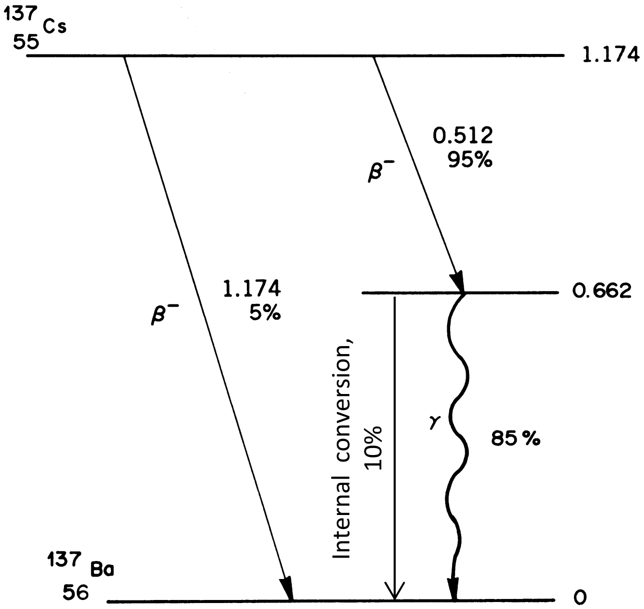
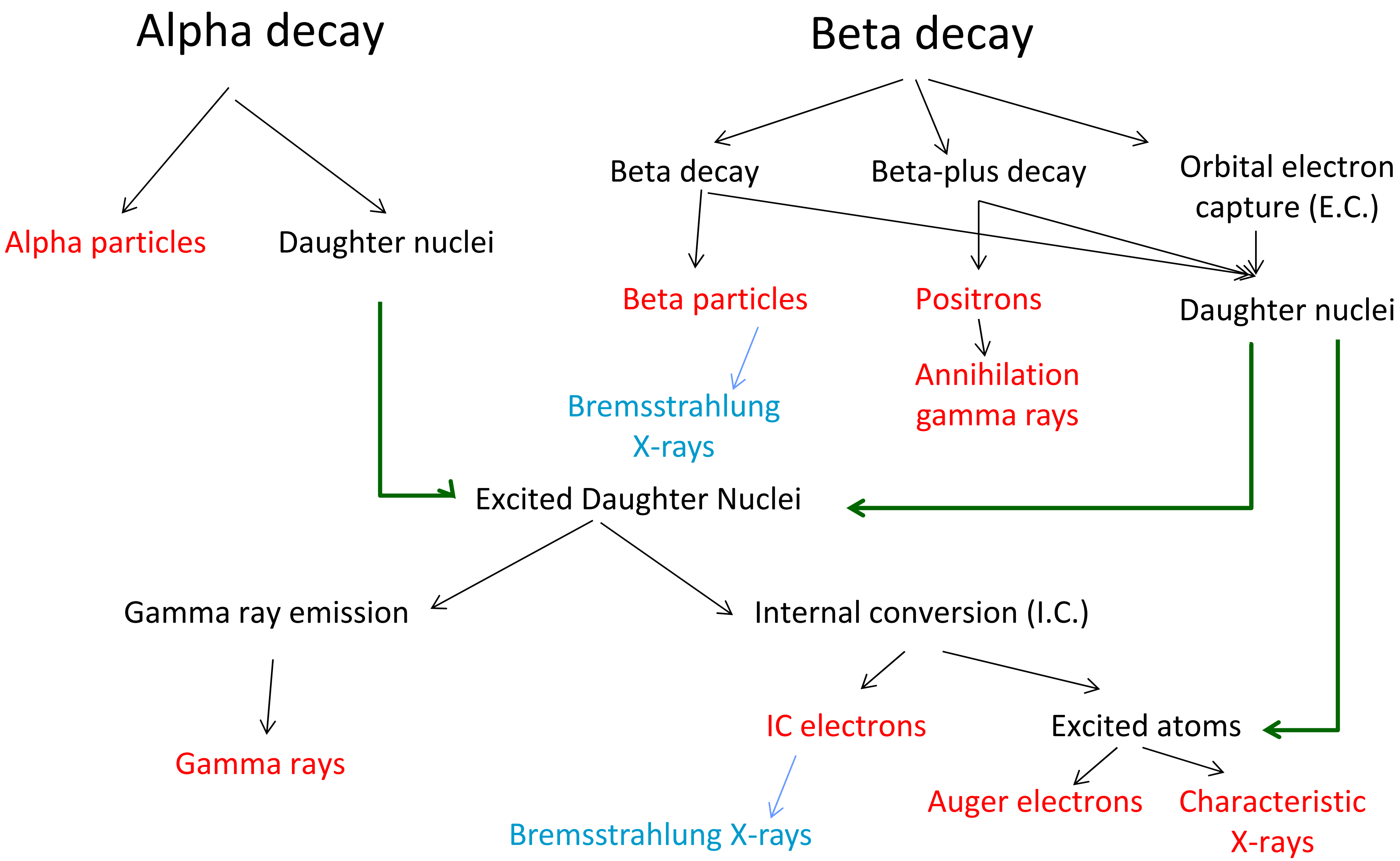


FIGURE 3.8. Decay scheme of $^{137}_{55}$Cs.

Typical Decay Products from Unstable Radioisotopes



Alpha decay

Alpha particles

Daughter nuclei

Beta decay

Beta decay

Beta-plus decay

Orbital electron capture (E.C.)

Beta particles

Positrons

Daughter nuclei

Bremsstrahlung X-rays

Annihilation gamma rays

Excited Daughter Nuclei

Gamma ray emission

Internal conversion (I.C.)

Gamma rays

IC electrons

Excited atoms

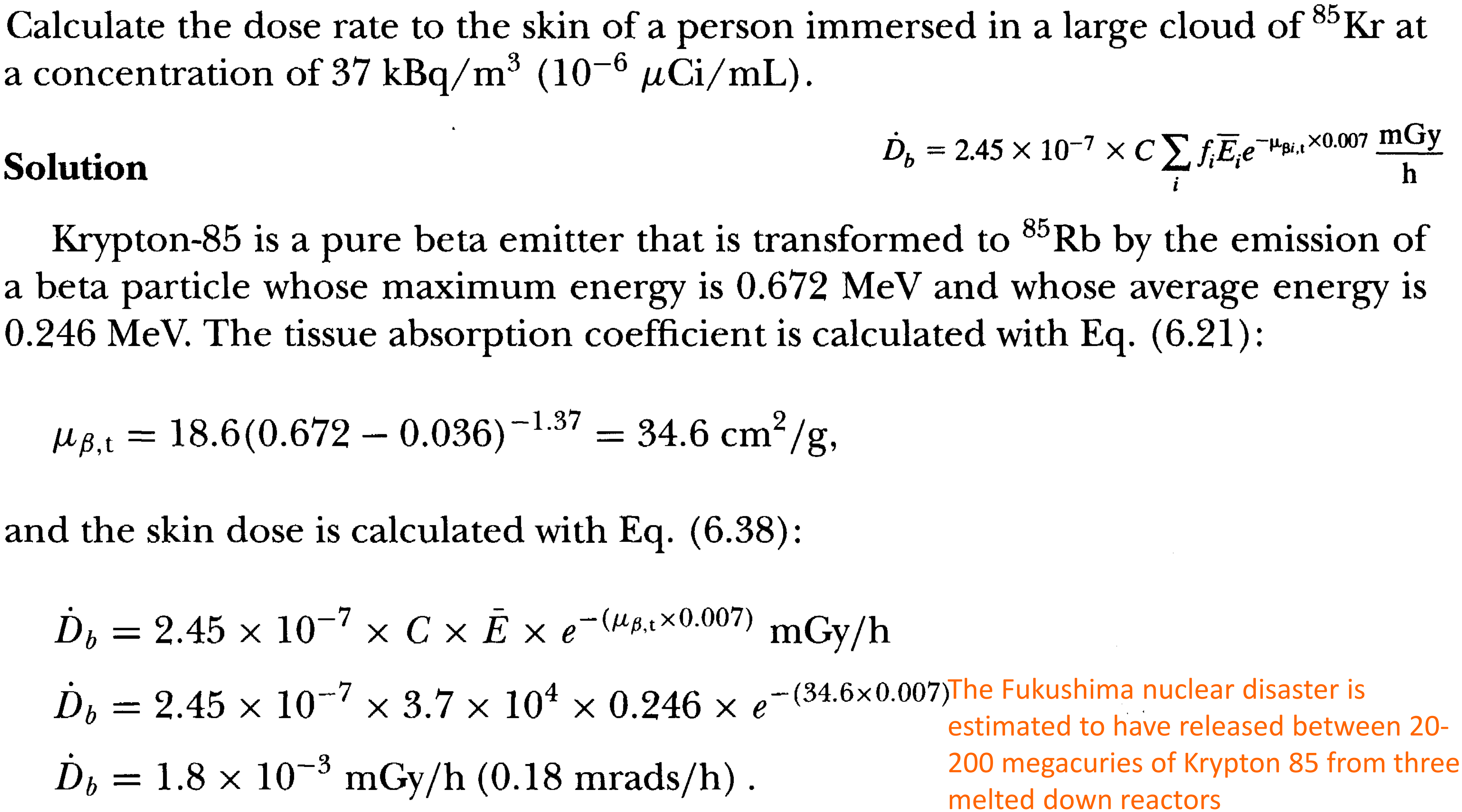
Bremsstrahlung X-rays

Auger electrons

Characteristic X-rays

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):

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

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

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

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

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

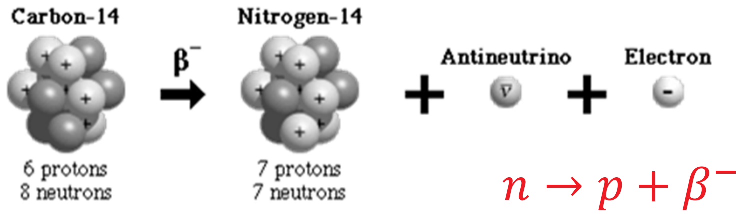
The Fukushima nuclear disaster is estimated to have released between 20-200 megacuries of Krypton 85 from three melted down reactors

Beta Emission

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

Beta decay

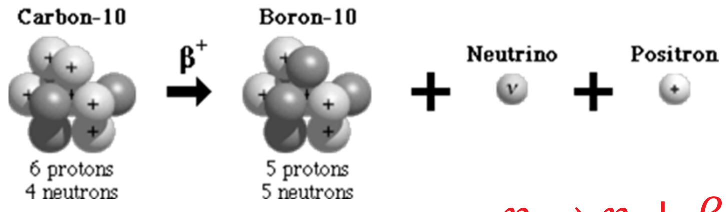
$${}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + {}^{0}_{-1}\beta + \overline{\upsilon}$$



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

Beta-plus decay

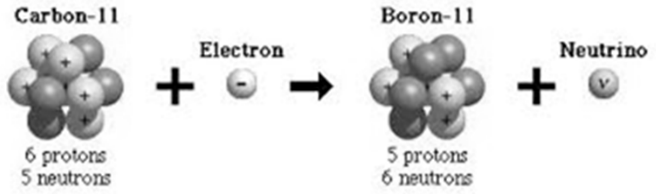
$${}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + {}^{0}_{1}\beta + \upsilon$$



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

Electron capture

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



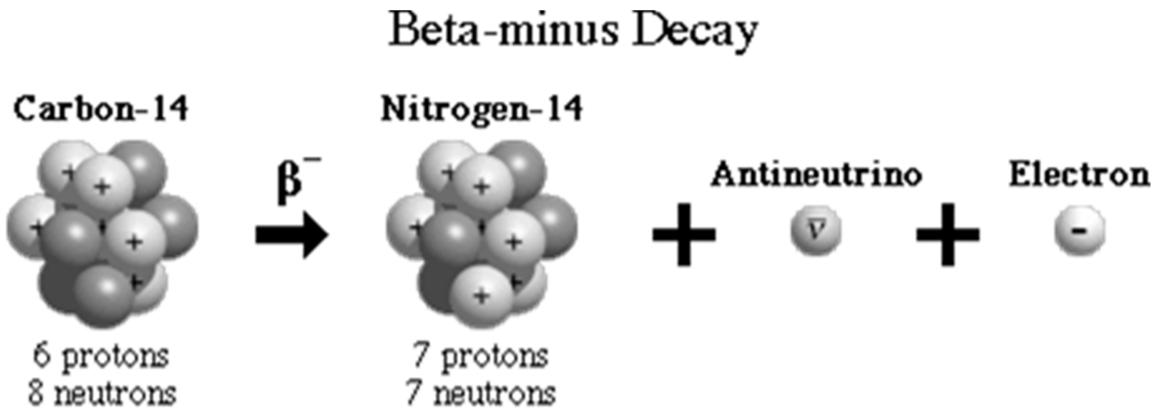
$$p + \beta^{-} \rightarrow n + \nu$$

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 $1.660538921\times10^{-27}$ 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

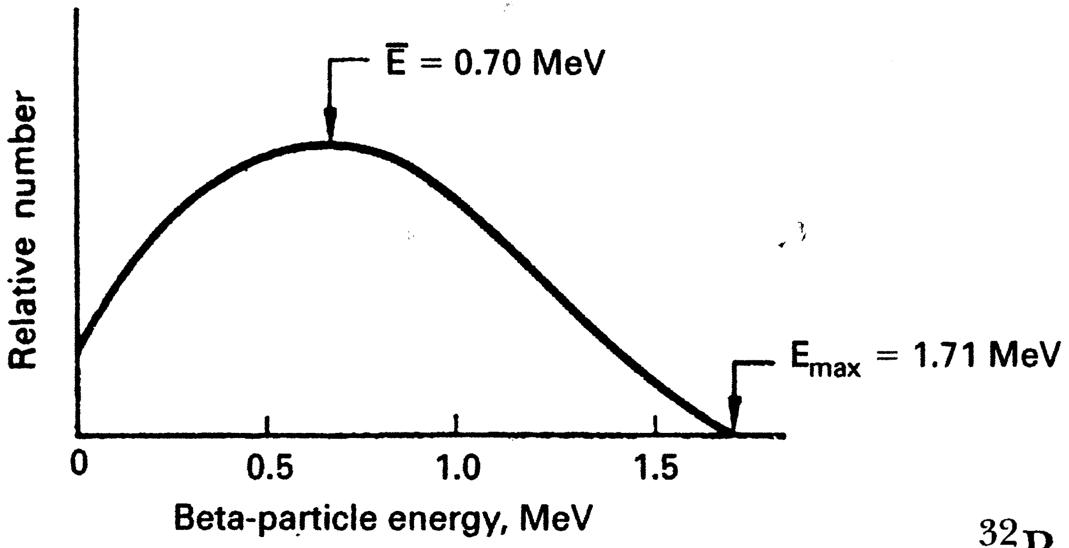
$$Q = M_p - M_d - M_e = 0.001837 \text{ AMU}$$

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

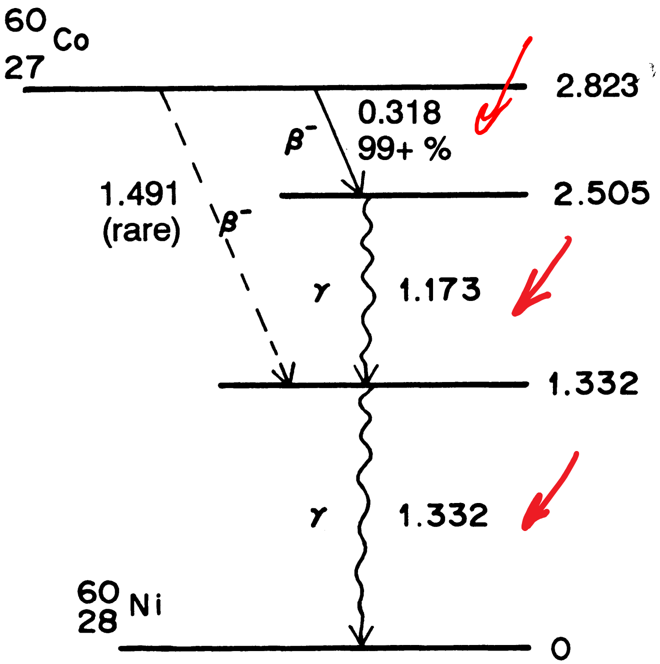


FIGURE 3.6. Decay scheme of $^{60}_{27}$Co.

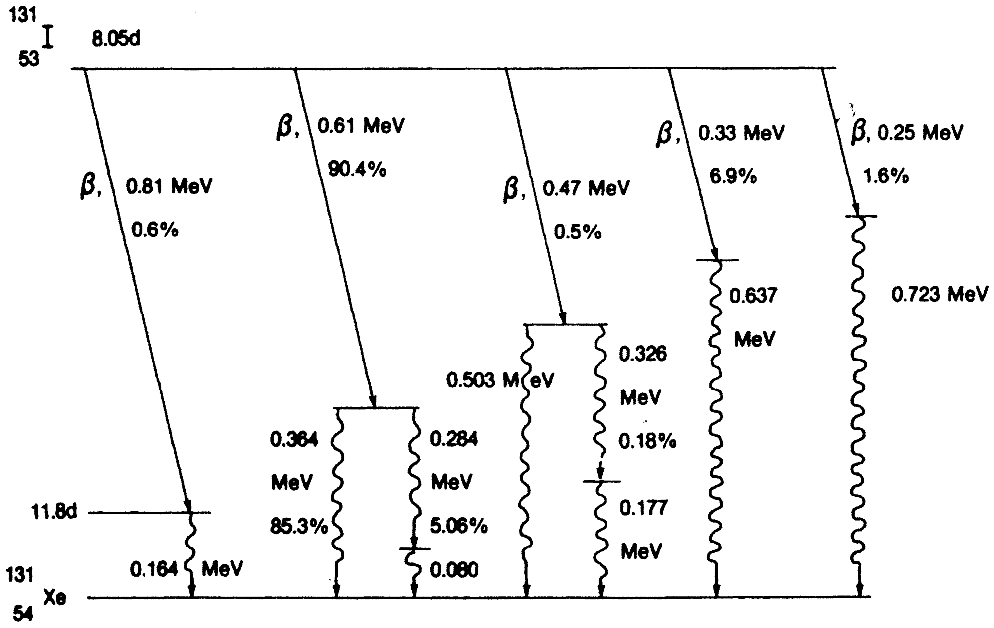


FIGURE 4.7. Iodine-131 transformation (decay) scheme.

- 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

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

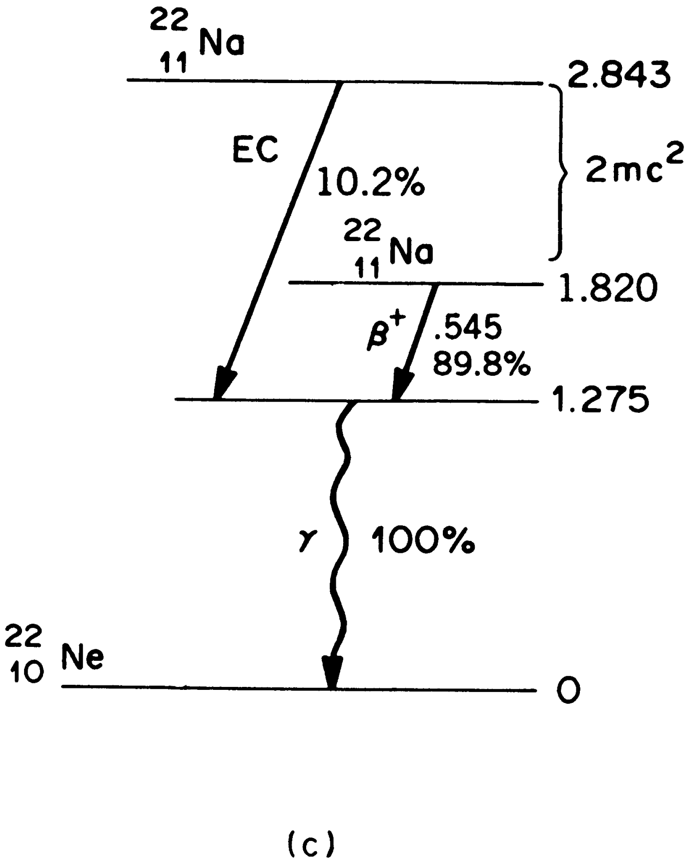


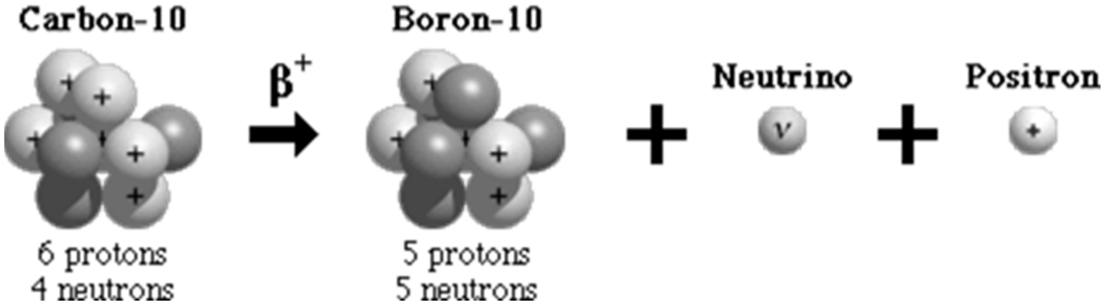
FIGURE 3.11. Decay scheme of $^{22}_{11}$Na.

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

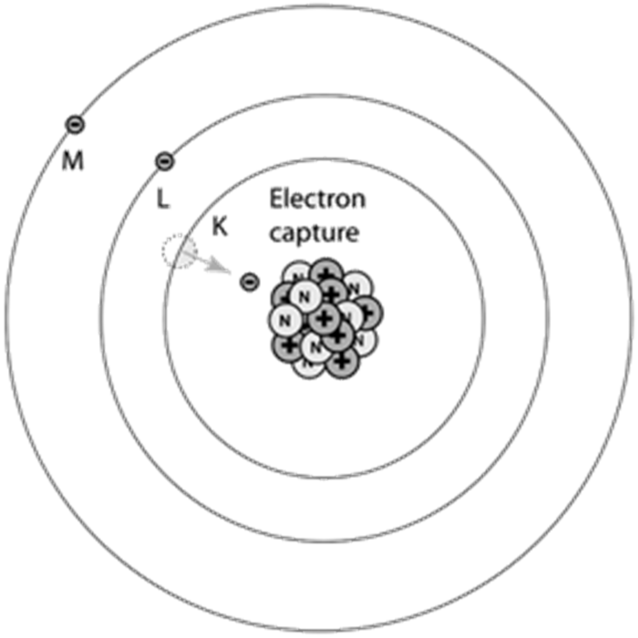
In electron capture (EC), one of the atomic electrons is captured by the nucleus and unites with a proton to form a neutron with the emission of a neutron

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

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

- 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

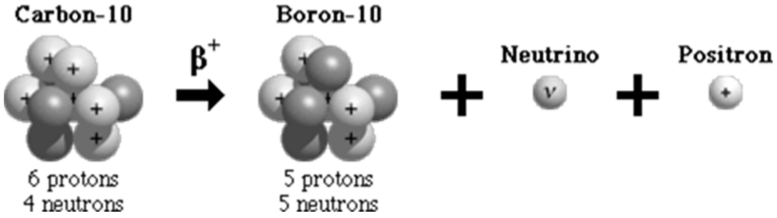
For positron decay to be possible, we need

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

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



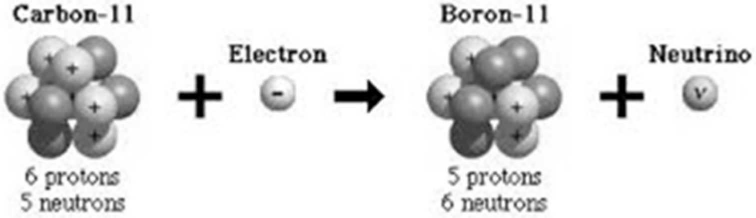
For Electron Capture to occur,

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

so that

$$M_p > M_d + \phi$$

where ϕ is the binding energy of the orbital electron

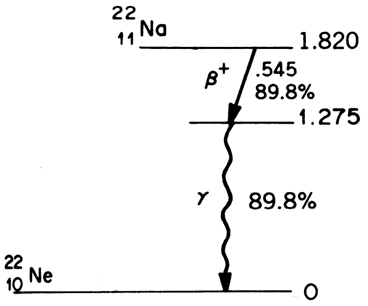


Orbital Electron Capture and Positron Decay

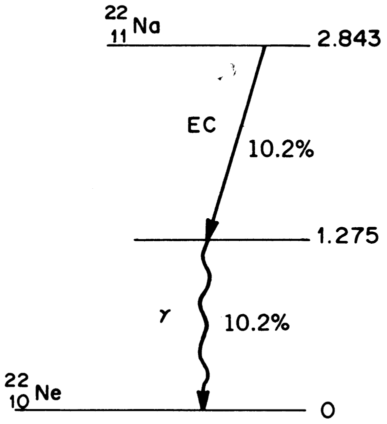
- Electron capture and positron decay are normally competing processes through which a neutron deficient nucleus may attain an increased stability.

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

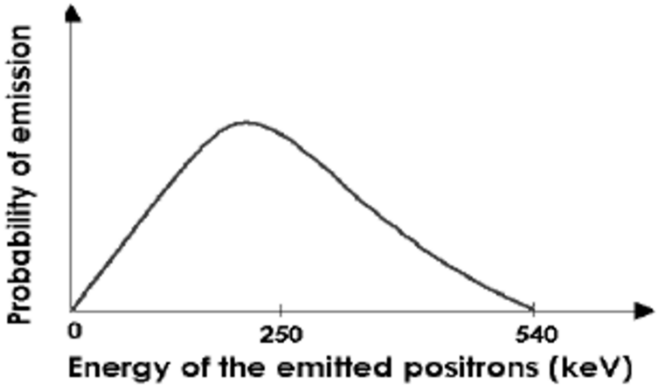
- In positron decay, the neutrino carries the difference between the energy release and the energy of the resultant positron. In electron capture, however, the neutrino must be mono-energetic.



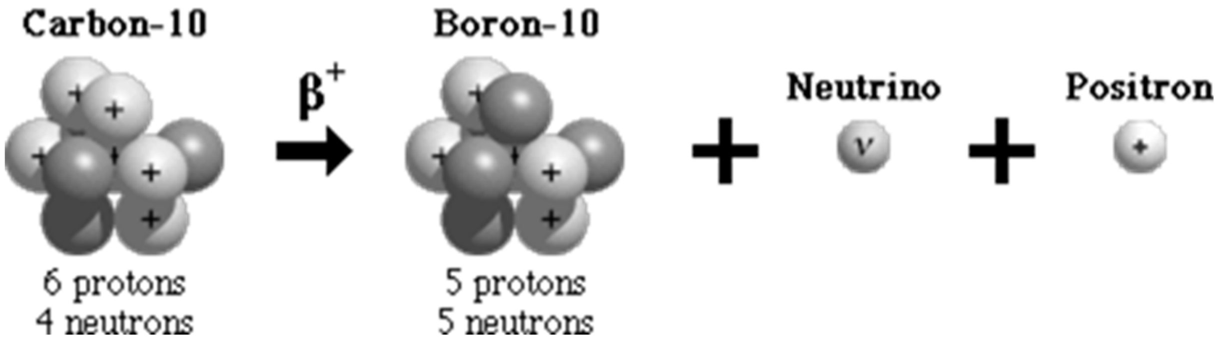
(a)

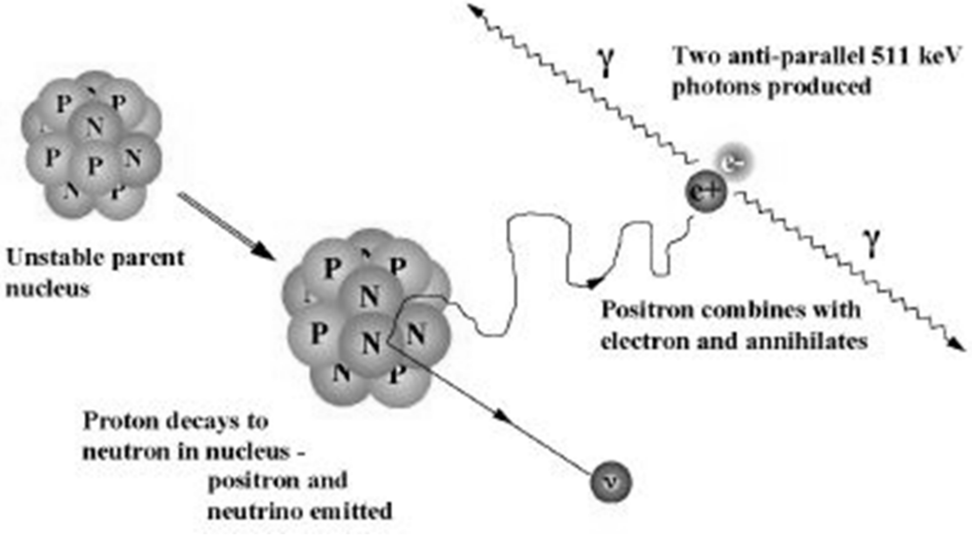


(b)



Positron Annihilation following Positron Decay





Examples for Beta Decay

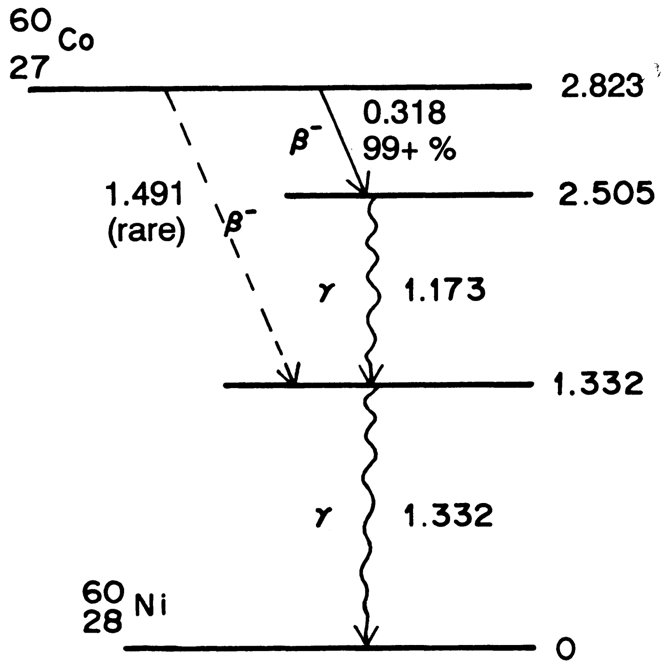


FIGURE 3.6. Decay scheme of ${}^{60}_{27}$Co.

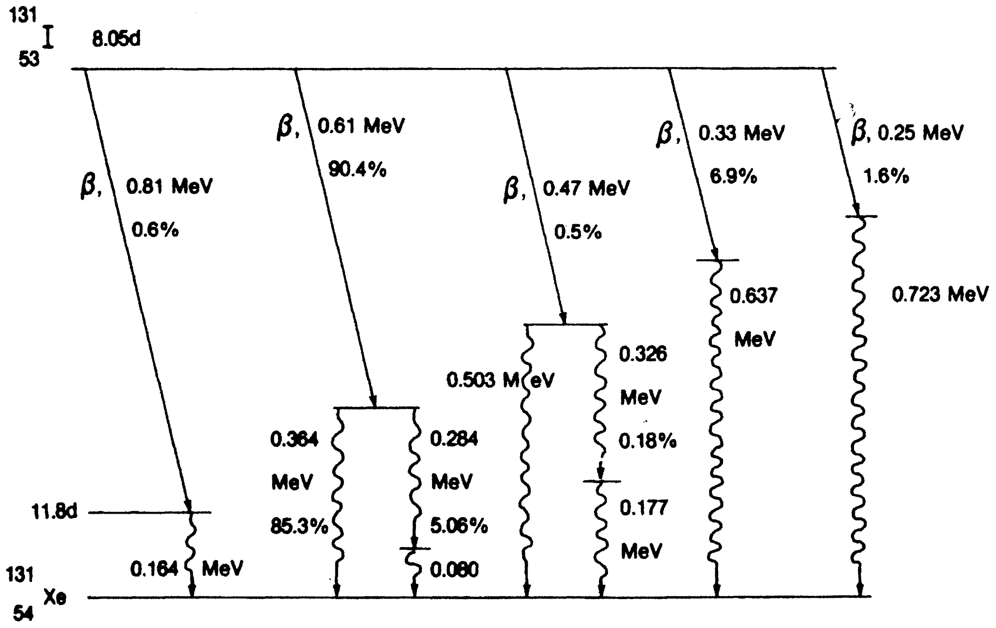


FIGURE 4.7. Iodine-131 transformation (decay) scheme.

- 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.

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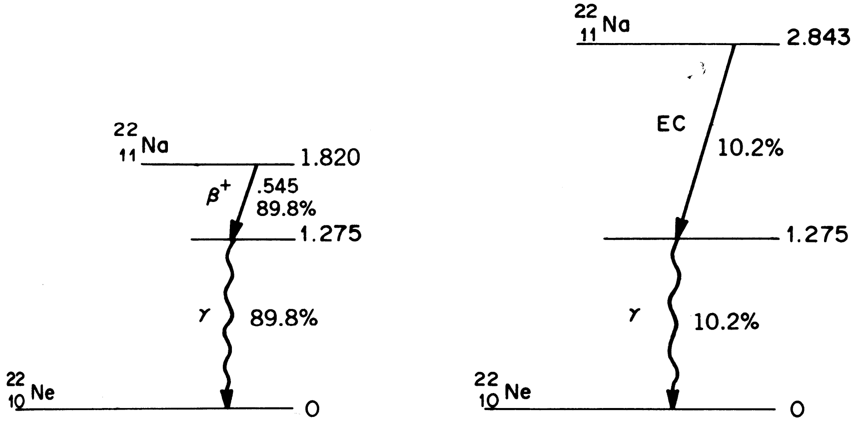
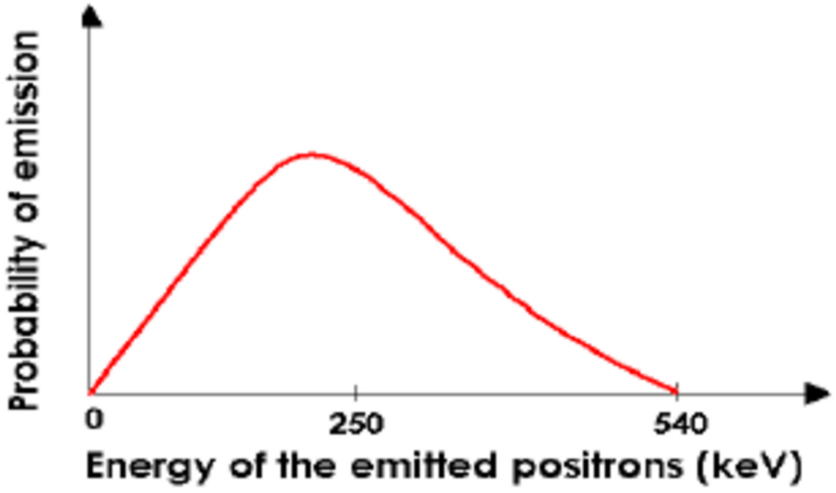


(a) (b)

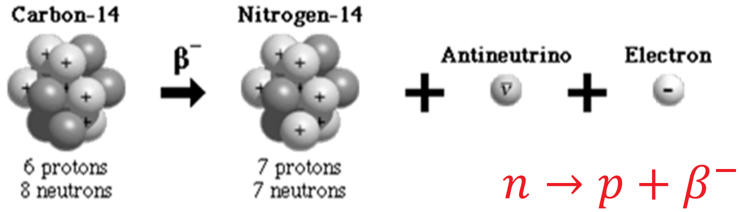


Beta Emission

- 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

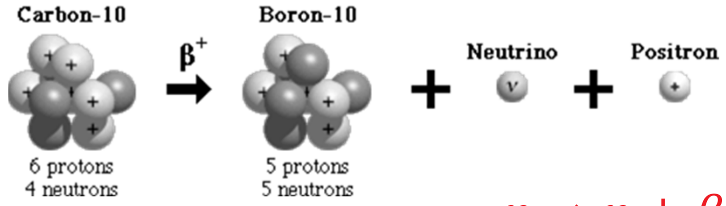
$${}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + {}^{0}_{-1}\beta + \overline{\upsilon}$$



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

Beta-plus decay

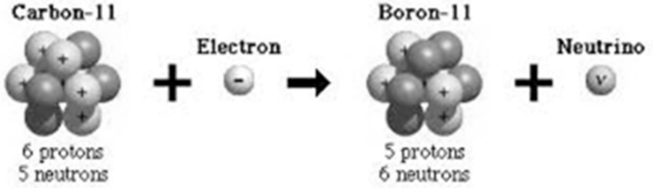
$${}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + {}^{0}_{1}\beta + \upsilon$$



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

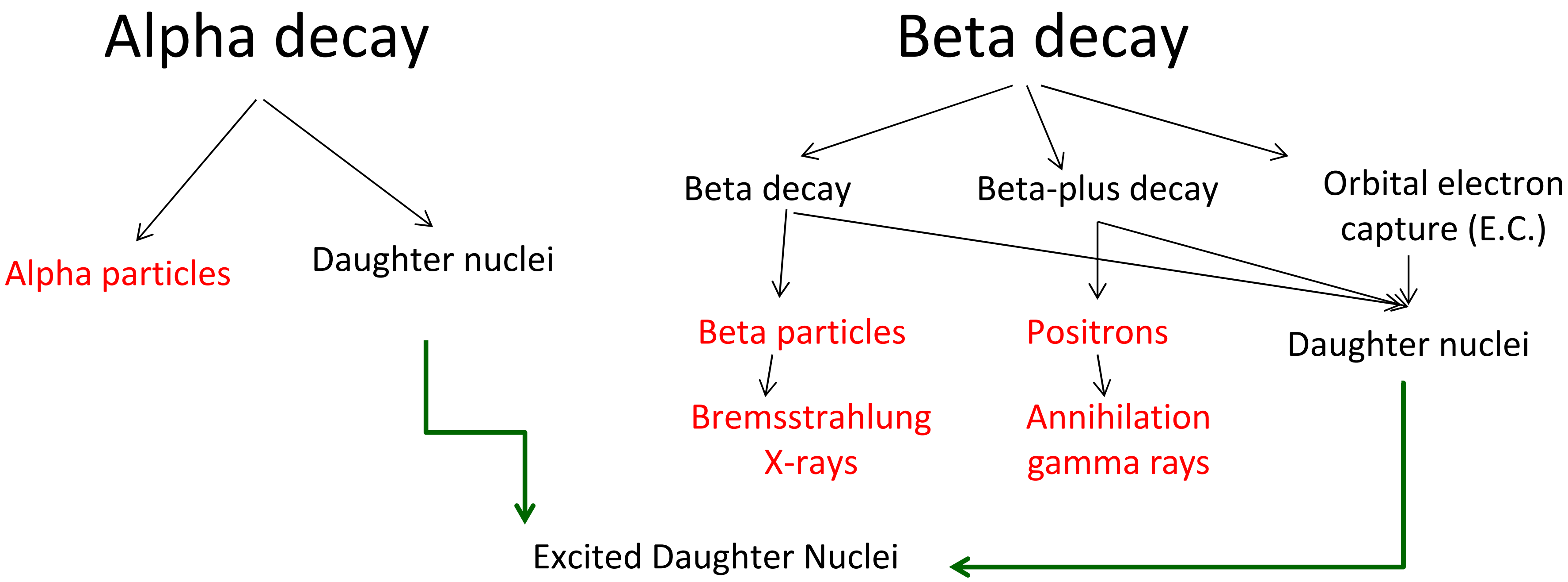
Electron capture

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



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

Typical Decay Products from Unstable Radioisotopes



Alpha decay

Alpha particles

Daughter nuclei

Beta decay

Beta decay

Beta-plus decay

Orbital electron capture (E.C.)

Beta particles

Bremsstrahlung X-rays

Positrons

Annihilation gamma rays

Daughter nuclei

Excited Daughter Nuclei

Gamma Ray Emission following Beta Decay

Examples for Beta Decay

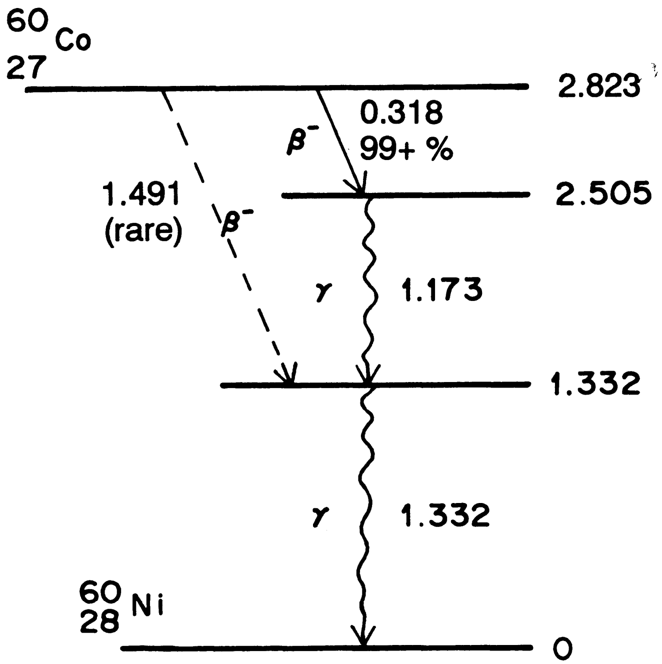


FIGURE 3.6. Decay scheme of $^{60}_{27}$Co.

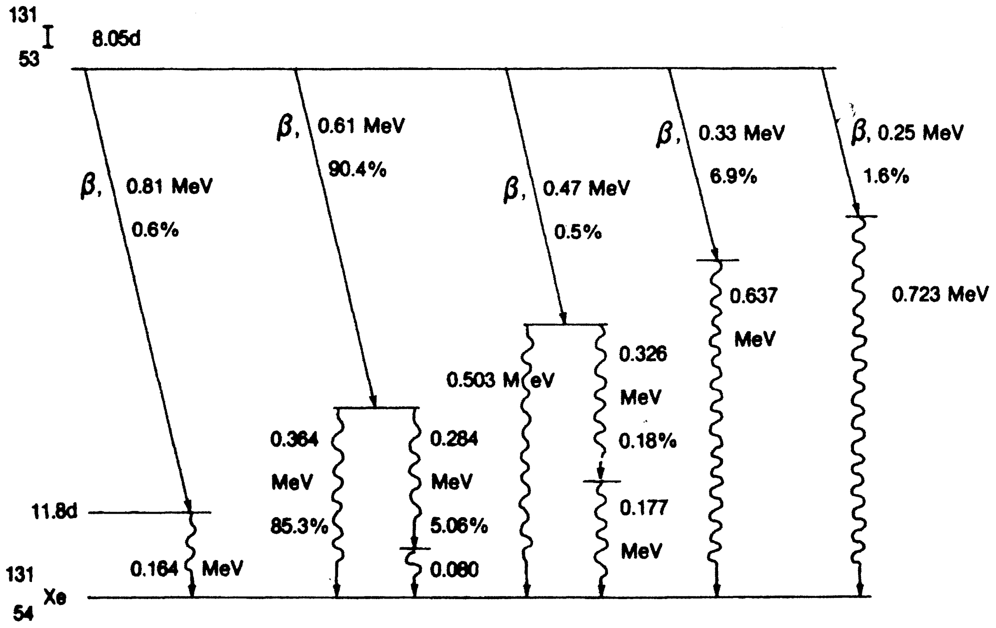


FIGURE 4.7. Iodine-131 transformation (decay) scheme.

- 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.

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 $^{137}_{56}\mathrm{Ba}$ following the decay of $^{137}_{55}\mathrm{Cs}$ has a half-life of 2.55 min. Such a long-lived nuclear state is termed *metastable* and is designated by the symbol m: $^{137\mathrm{m}}_{56}\mathrm{Ba}$.

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

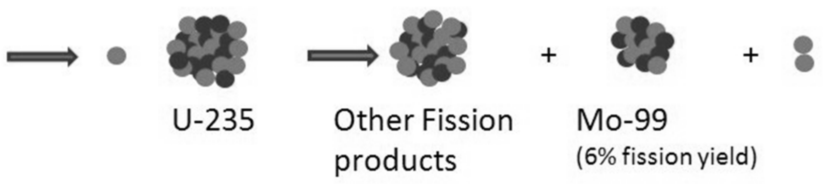
Important Gamma Ray Emitter: Tc-99m

Decay scheme:

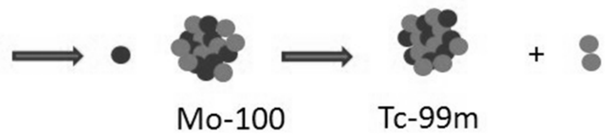
$$^{99m}_{43}\mathrm{Tc} \rightarrow {}^{99}_{43}\mathrm{Tc} + {}^{0}_{0}\gamma.$$

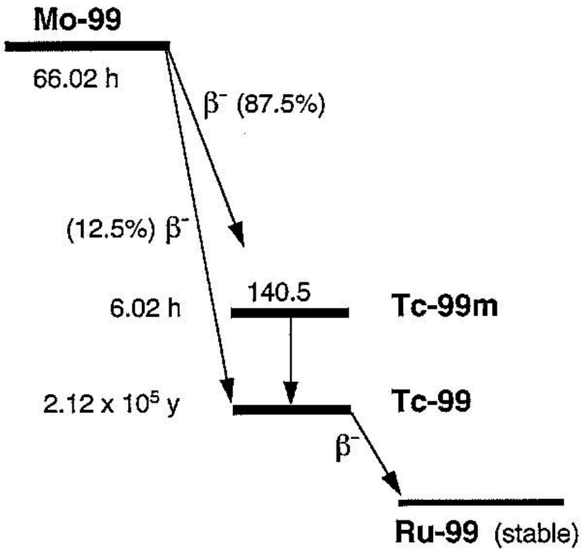
- Tc-99m accounts for >90% of imaging studies in nuclear medicine and therefore subject to extensive dosimetry study.
- Half-life: ~6h; gamma energy: 140keV, both ideal for imaging applications.
- Tc-99m is obtained from the decay of the molybdenum isotope ^{99}Mo.

The current ^{99}Mo/^{99m}Tc production way

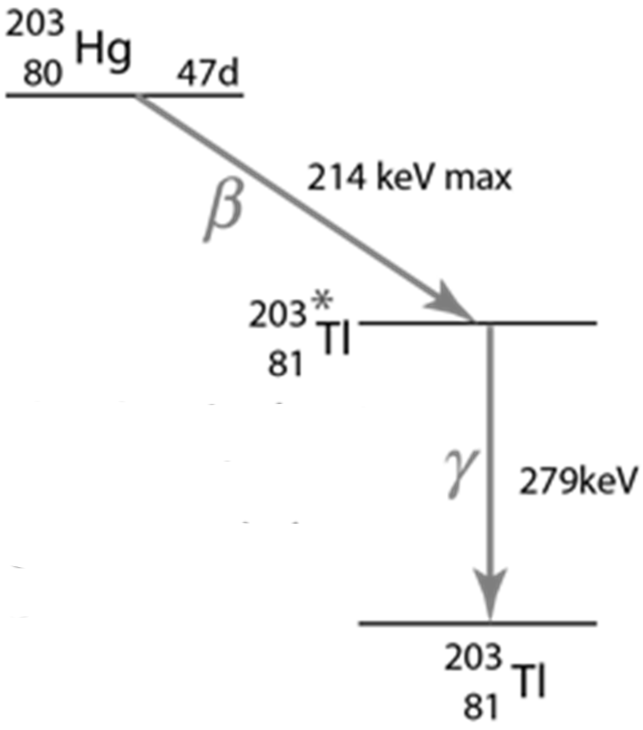


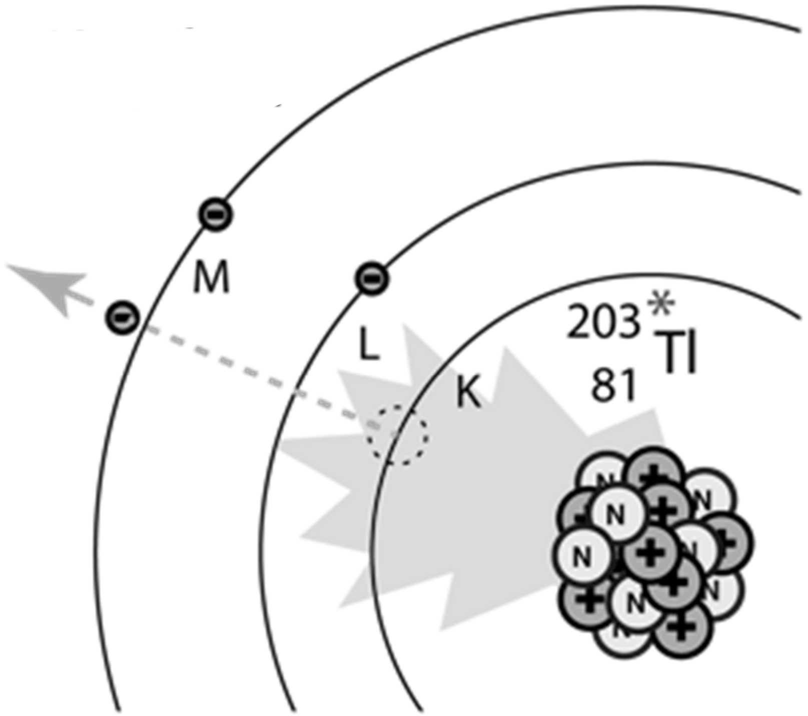
The alternative *direct* ^{99m}Tc production way





Internal Conversion

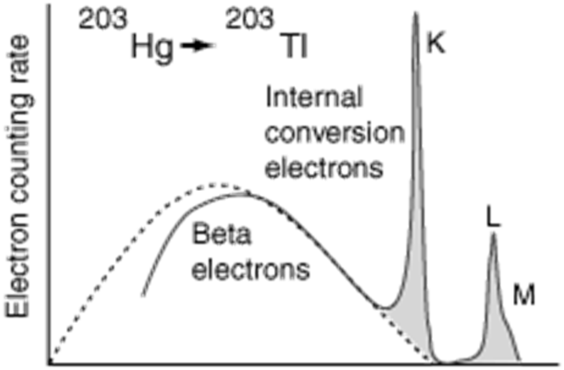




Gamma-ray emission vs **Internal Conversion**

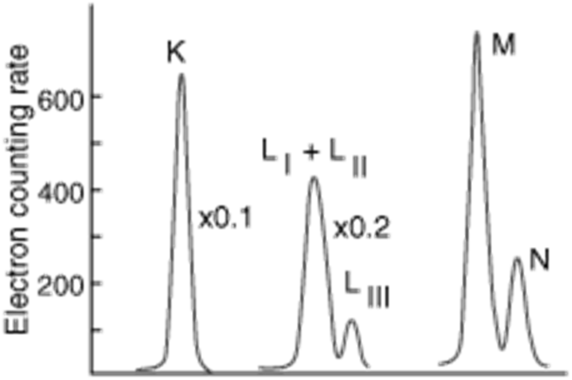
http://hyperphysics.phy-astr.gsu.edu/hbase/Nuclear/radact2.html

Internal Conversion

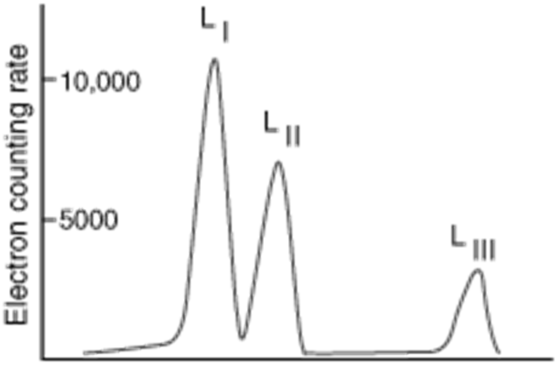


Electron emissions from the Hg-203 to Tl-203 decay, measured by A. H. Wapstra, et al., Physica 20, 169 (1954).

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



At higher resolution, the internal conversion electrons from the L, M and N shells can be resolved. Z. Sujkowski, Ark. Fys. 20, 243 (1961).



At even higher resolution, the three L shells can be resolved. From C. J. Herrlander and R. L. Graham, Nucl. Phys. 58, 544 (1964).

Above figures and text extracted from http://hyperphysics.phy-astr.gsu.edu/hbase/Nuclear/radact2.html

Internal Conversion

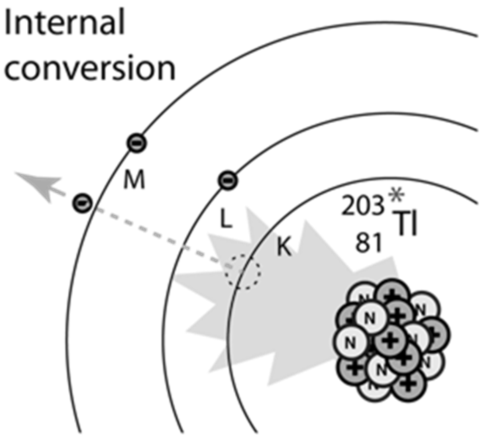
An excited nucleus

De-excite through the emission of a gamma ray

➔ Gamma Ray Emission

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

➔ Internal Conversion

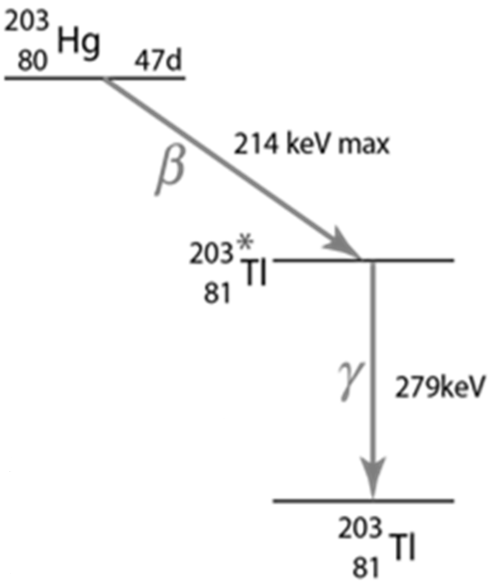


Conversion electron with an energy

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

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

Different Types of Radiation from Hg-203 Beta Decay

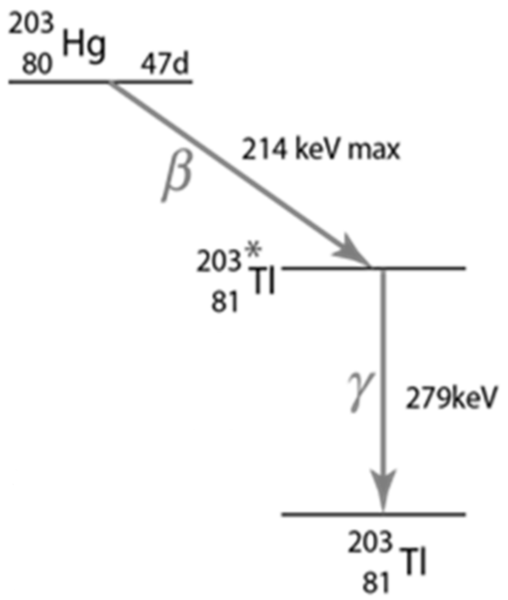


Beta particles

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

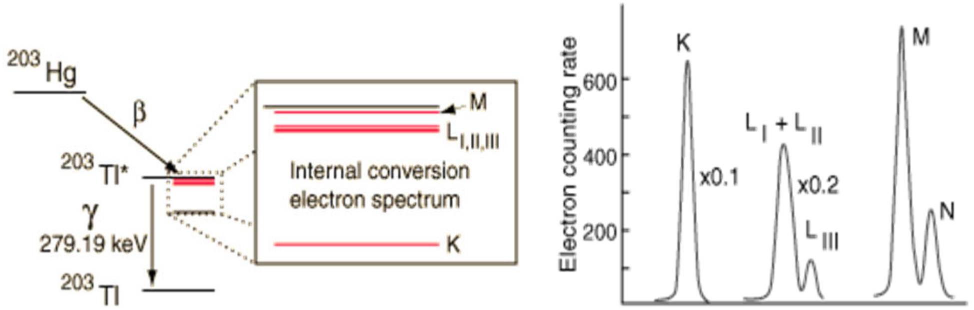
http://hyperphysics.phy-astr.gsu.edu/hbase/Nuclear/radact2.html

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

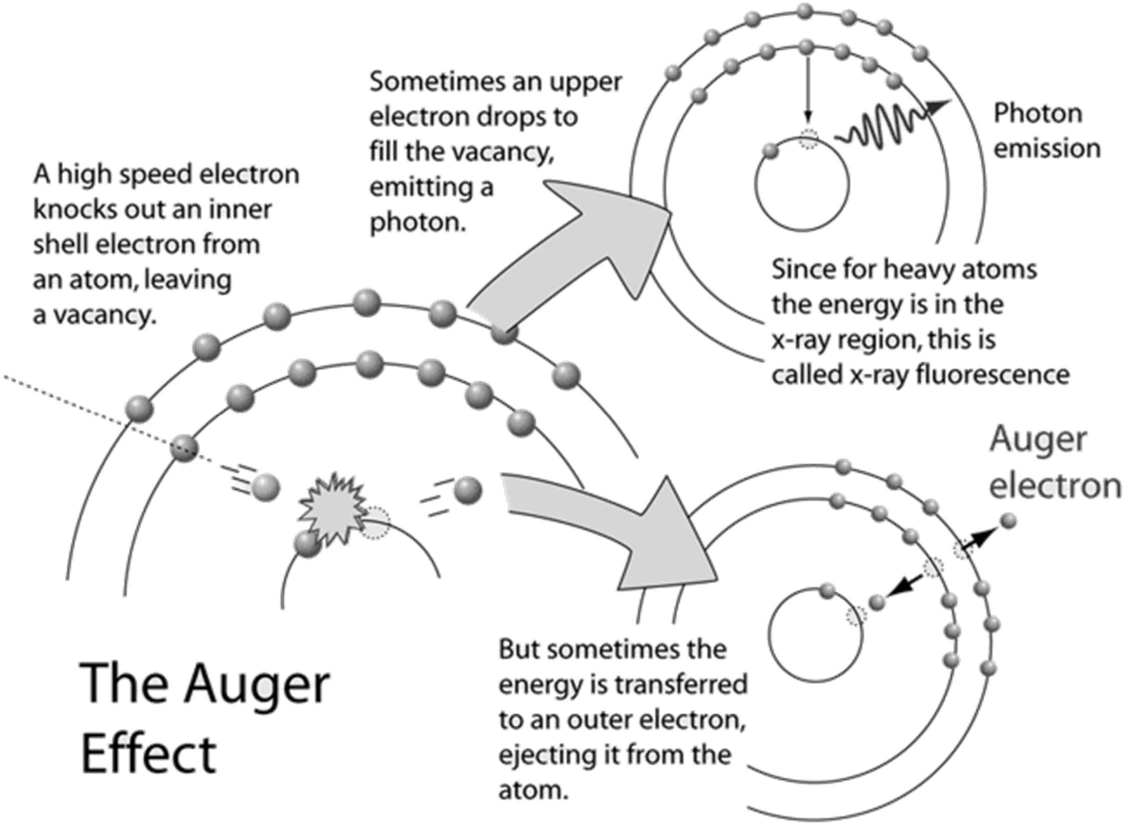
Internal conversion

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

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

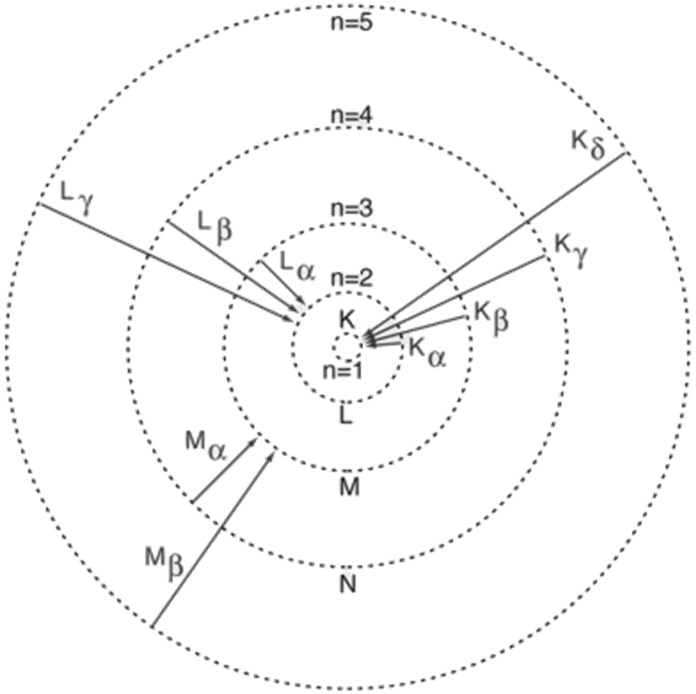
Atomic Radiation from Excited Atoms

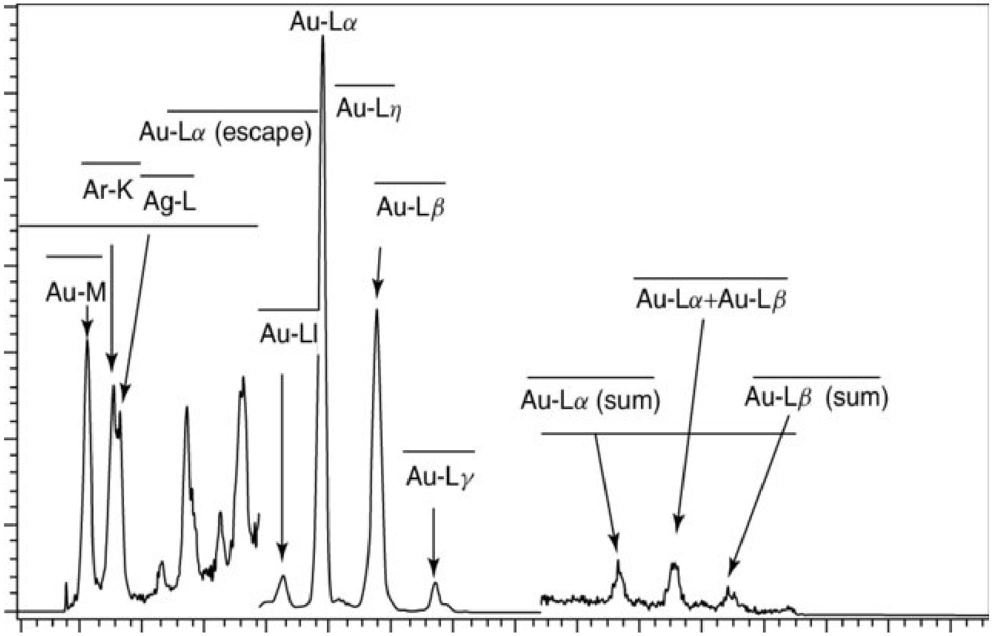
Characteristic X-ray vs Auger Electron



Atomic Radiation from Excited Atoms

A few remarks on characteristic X-ray emission





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”, Cesareo, 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.

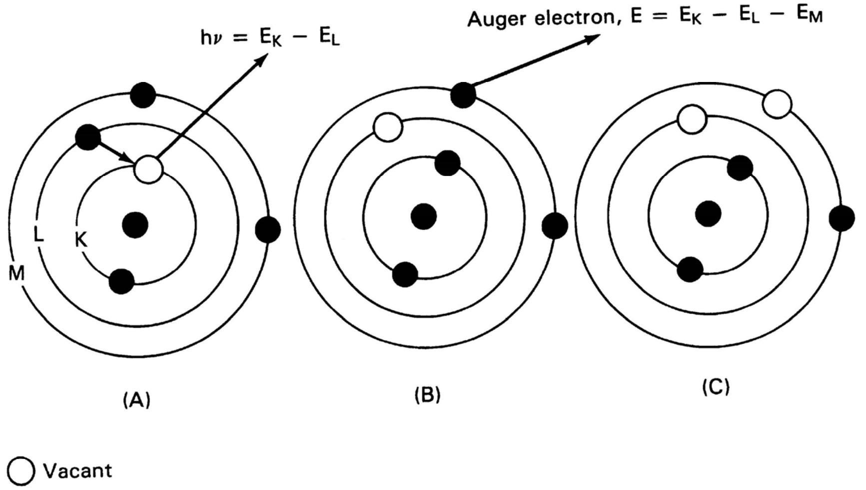
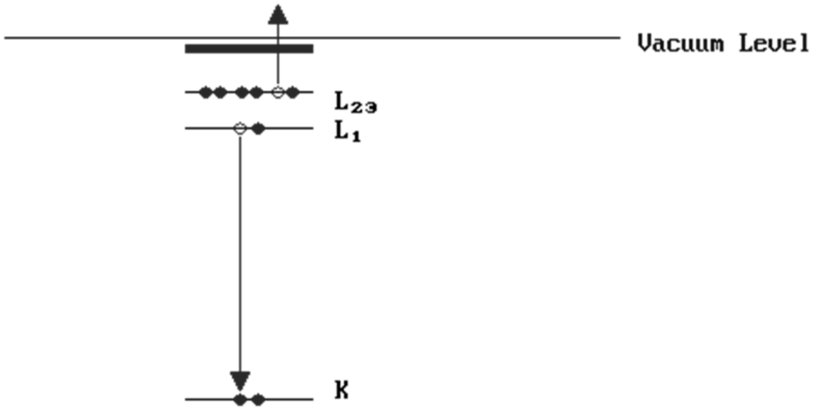


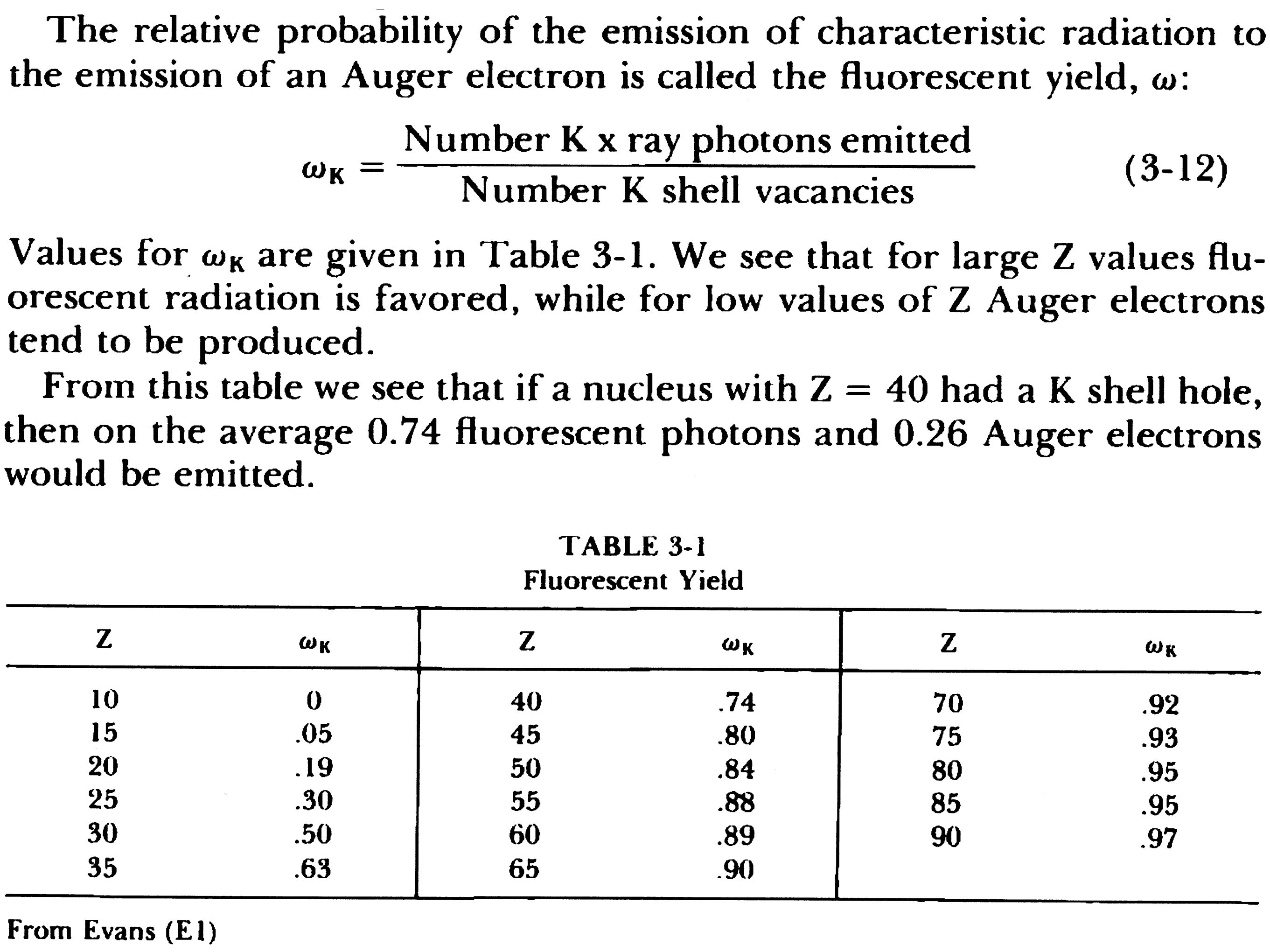
Figure 3.7 (A) The usual emission of a K characteristic X-ray, $h\nu$, energy equal to $E_K - E_L$, the difference in binding energy for the two orbital electrons, K and L. (B) $h\nu$ has been absorbed and a monoenergetic Auger electron is emitted, in the example shown, from the M shell, the energy of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



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

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

$Au-203(\beta^-)Hg-203$

$Tl-204(\gamma,p)Hg-203$

$Hg-202(n,\gamma)Hg-203$

$Hg-202(d,p)Hg-203$

$Hg-204(d,t)Hg-203$

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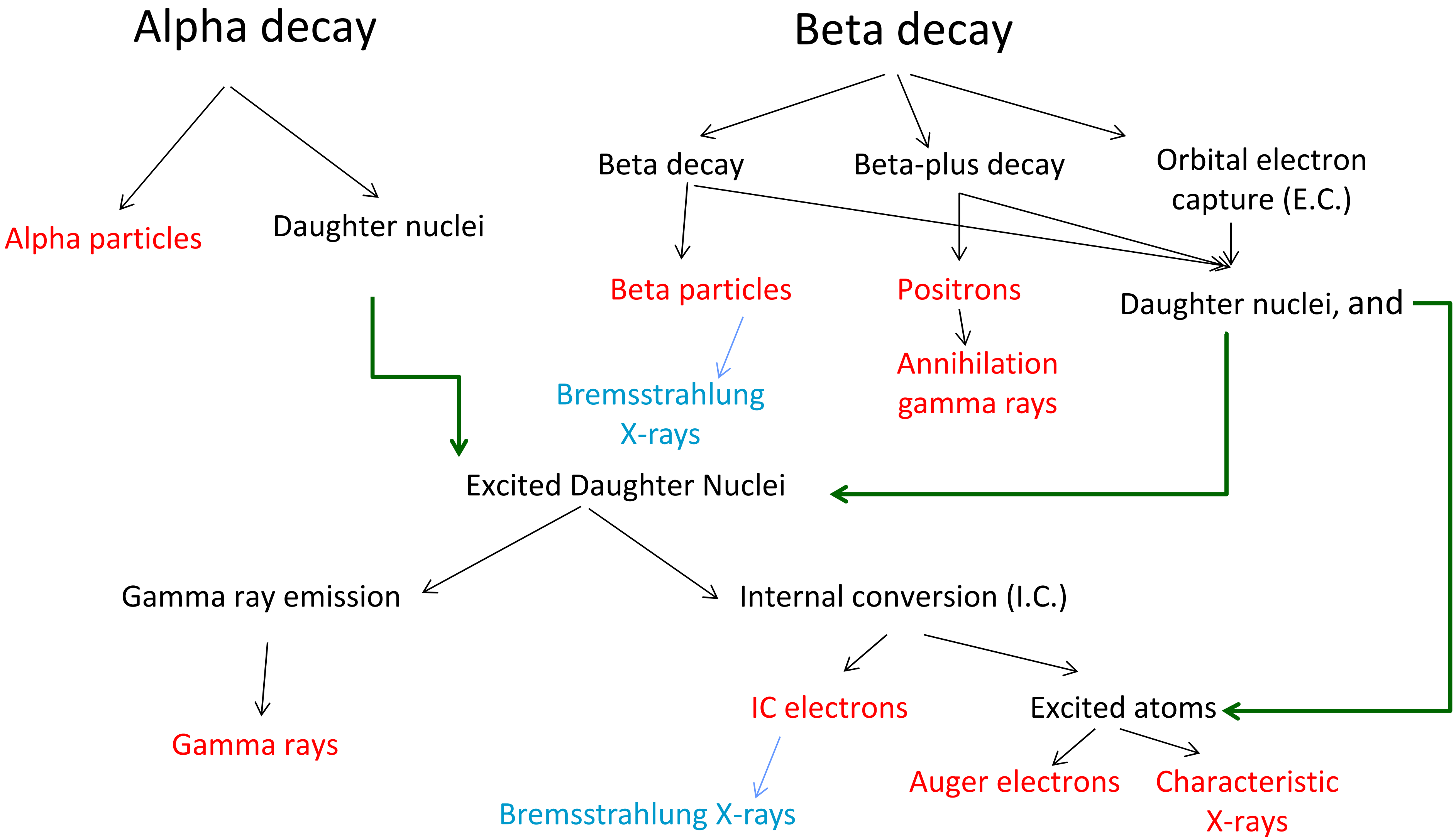
Radiation Concerns of Beta Particles

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

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

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

Typical Decay Products from Unstable Radioisotopes



Alpha decay

Alpha particles

Daughter nuclei

Beta decay

Beta decay

Beta-plus decay

Orbital electron capture (E.C.)

Beta particles

Positrons

Daughter nuclei, and

Bremsstrahlung X-rays

Annihilation gamma rays

Excited Daughter Nuclei

Gamma ray emission

Internal conversion (I.C.)

Gamma rays

IC electrons

Excited atoms

Bremsstrahlung X-rays

Auger electrons

Characteristic X-rays

Potential Health Hazards from Beta Particles

Health Concerns Related to Beta Particles

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

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.

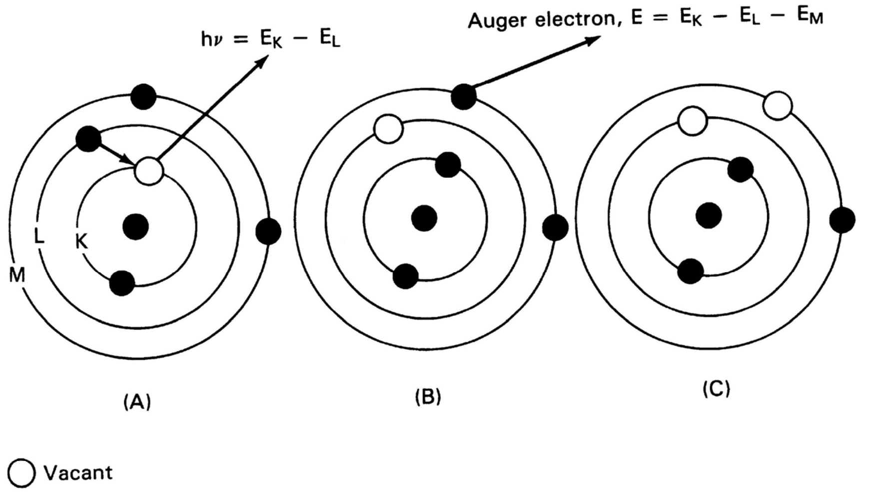
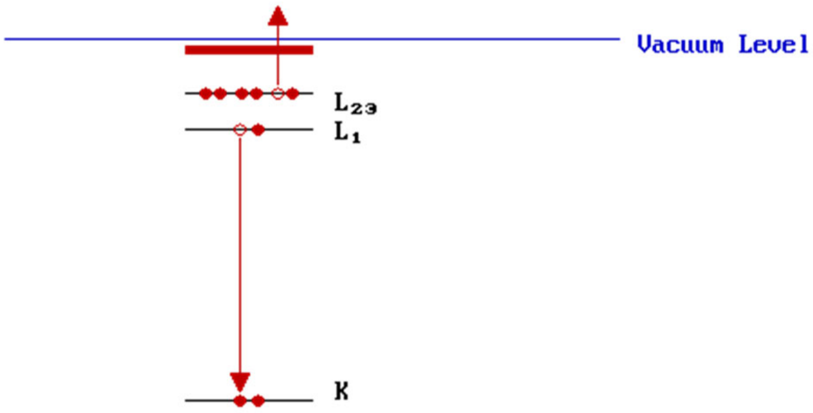


Figure 3.7 (A) The usual emission of a K characteristic X-ray, $h\nu$, energy equal to $E_K - E_L$, the difference in binding energy for the two orbital electrons, K and L. (B) $h\nu$ has been absorbed and a monoenergetic Auger electron is emitted, in the example shown, from the M shell, the energy of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



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

Bond-Seeking Beta Emitters

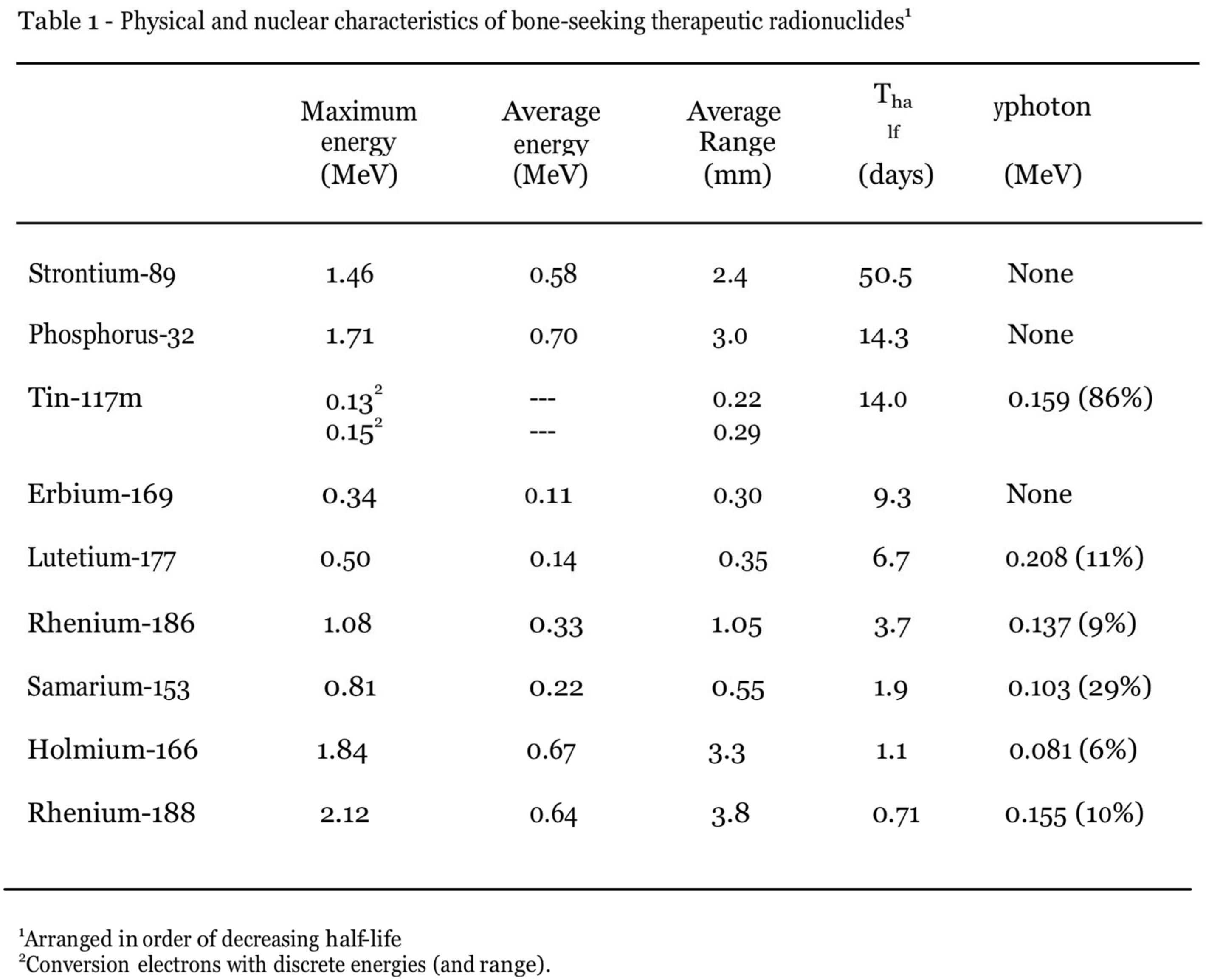


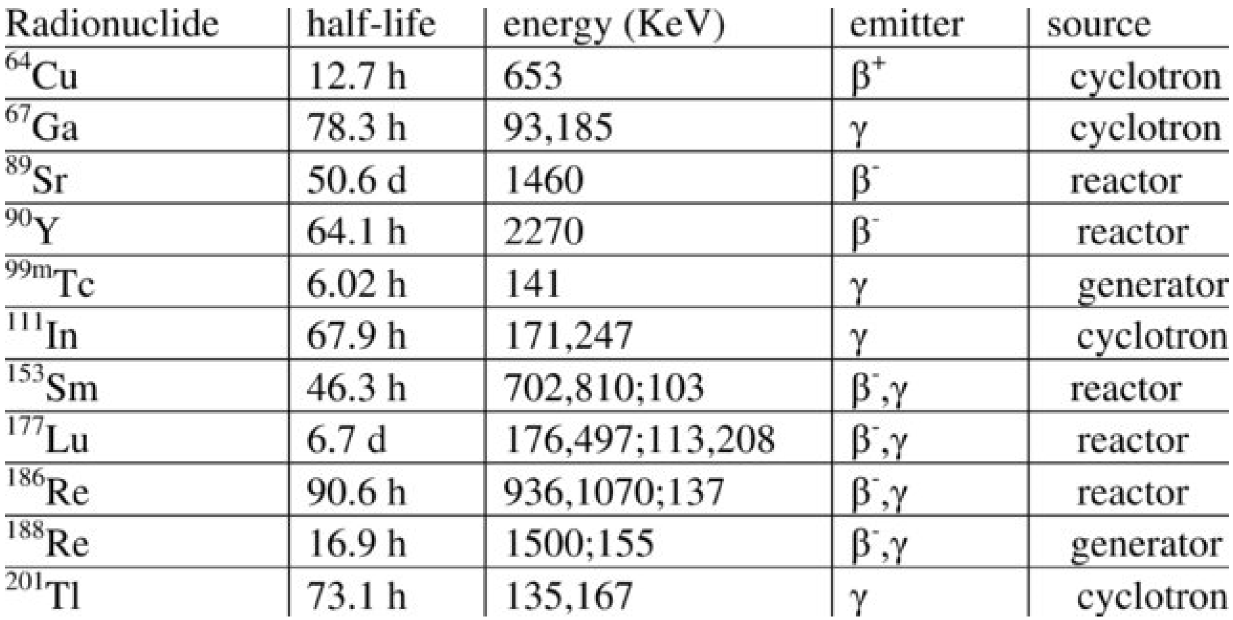
Table 1 - Physical and nuclear characteristics of bone-seeking therapeutic radionuclides[1]

	Maximum energy (MeV)	Average energy (MeV)	Average Range (mm)	T_{half} (days)	yphoton (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

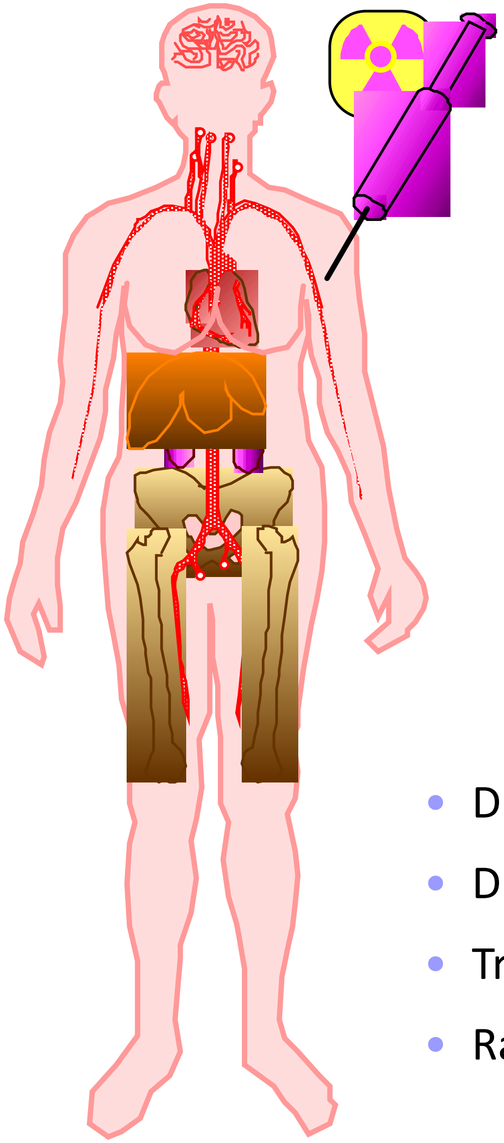
[2] Conversion electrons with discrete energies (and range).

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

Radiation Risk from Medical Procedures
Single Photon Emission Computed Tomography

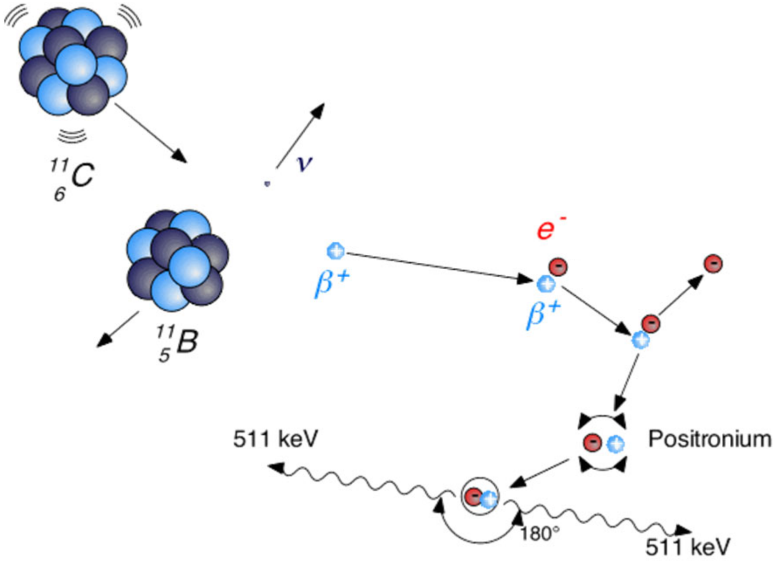


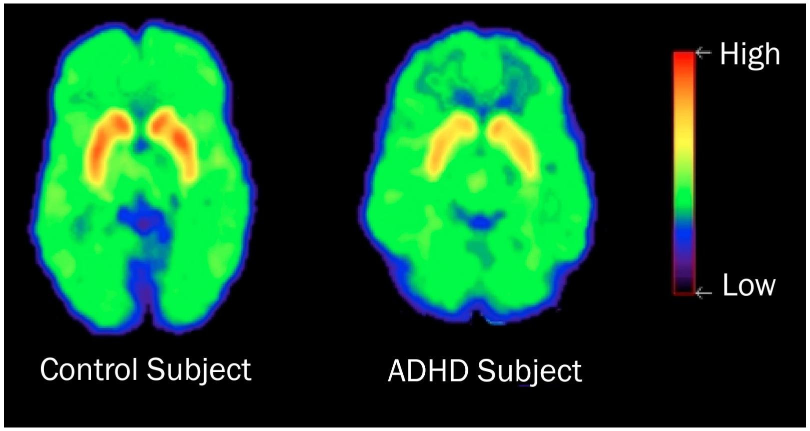
- Drug is labeled with radioisotopes that emit gamma rays.
- Drug localizes in patient according to metabolic properties of that drug.
- Trace (pico-molar) quantities of drug are sufficient.
- Radiation dose fairly small (<1 rem).

Radiation Risk from Medical Procedures
Single Photon Emission Computed Tomography

Radiation Concerns:

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





Examples for Beta Decay

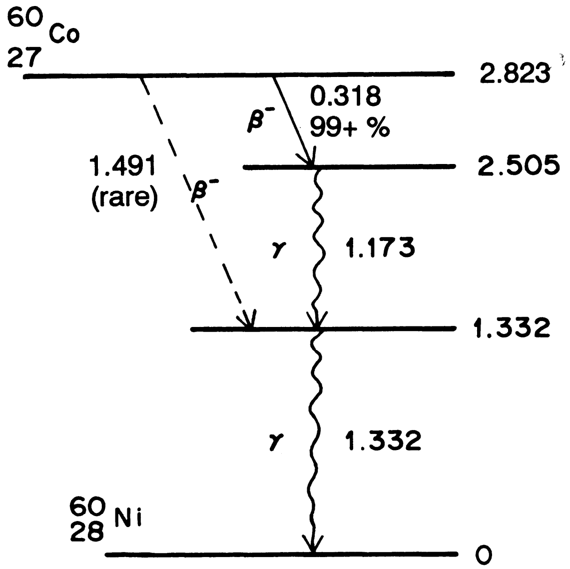


FIGURE 3.6. Decay scheme of $^{60}_{27}$Co.

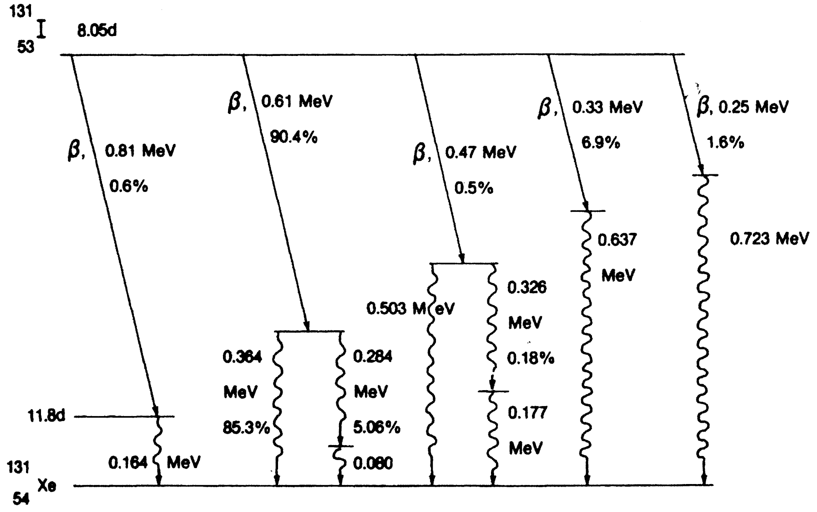


FIGURE 4.7. Iodine-131 transformation (decay) scheme.

- 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.

Autoradiography

Autoradiography

with ^{14}C, ^{3}H, ^{35}S, ^{125}I labeled tracers

Beta Particles Related Health Concerns
An Example – Autoradiography

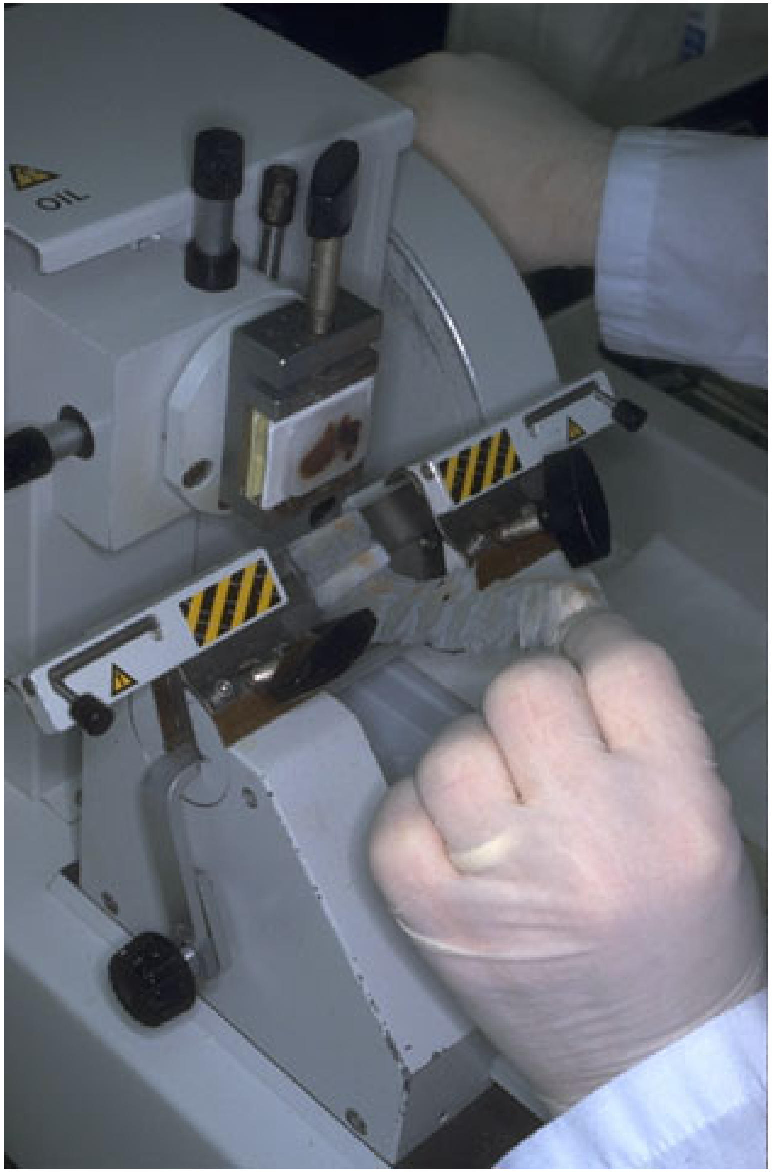
Radioisotopes

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

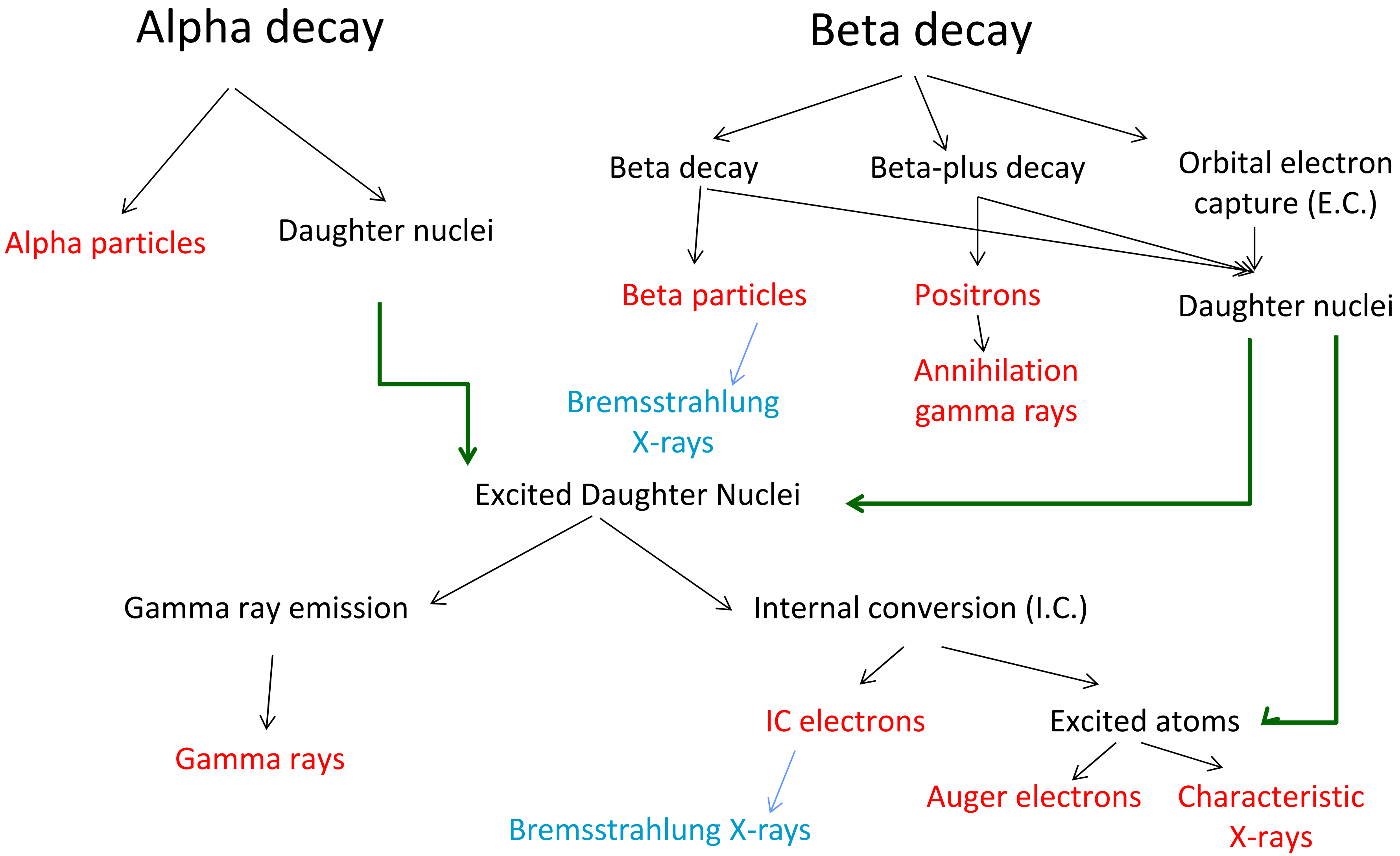
Sectioning of Tissue…



…on Microtome (wax)

…on Cryostat (frozen)

Typical Decay Products from Unstable Radioisotopes



Alpha decay

Alpha particles

Daughter nuclei

Beta decay

Beta decay

Beta-plus decay

Orbital electron capture (E.C.)

Beta particles

Positrons

Daughter nuclei

Bremsstrahlung X-rays

Annihilation gamma rays

Excited Daughter Nuclei

Gamma ray emission

Internal conversion (I.C.)

Gamma rays

IC electrons

Excited atoms

Bremsstrahlung X-rays

Auger electrons

Characteristic X-rays

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?

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

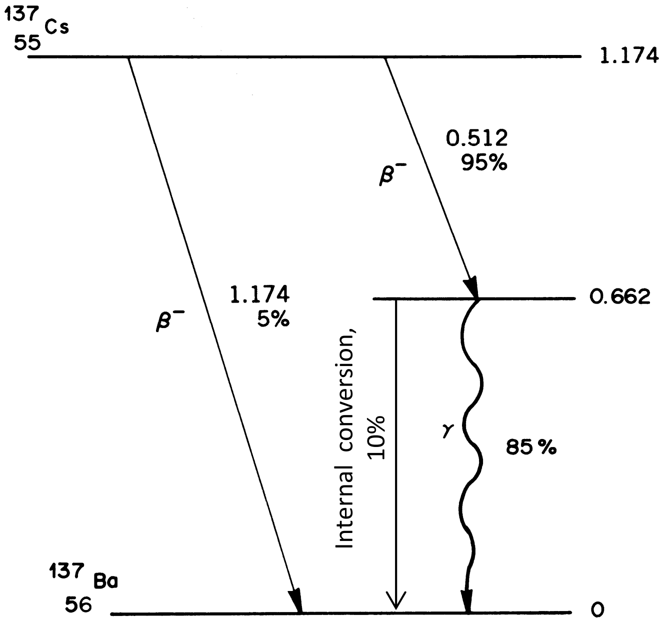


FIGURE 3.8. Decay scheme of $^{137}_{55}\mathrm{Cs}$.

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

NPRE441 Quiz #1,
Jan. 23th, 2021

Name: _________________

Q1: Please plot the energy spectrum for all types of radiation emitted by a Cs-137 source

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

Note:

1. The binding energies for k-shell and L-shell electrons in a Ba-137 atom are 38 keV and 6 keV.
2. Within the energy spectrum, please draw all the sub-spectra corresponding to beta particles, conversion electrons, gamma rays, auger electrons, characteristics X-rays, etc. (25 points)
3. Please also mark on the individual sub-spectra with the following information: the energy characteristics and relative intensity (probability of emission per Cs-137 decay) of each type of particle. (25 points)

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

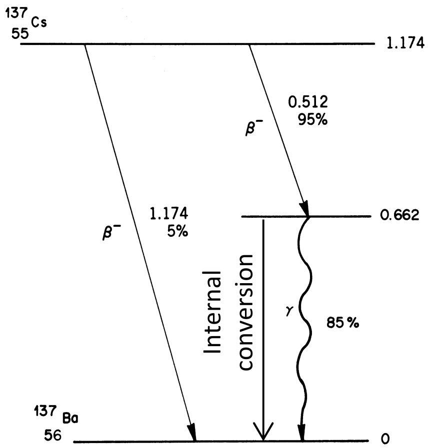
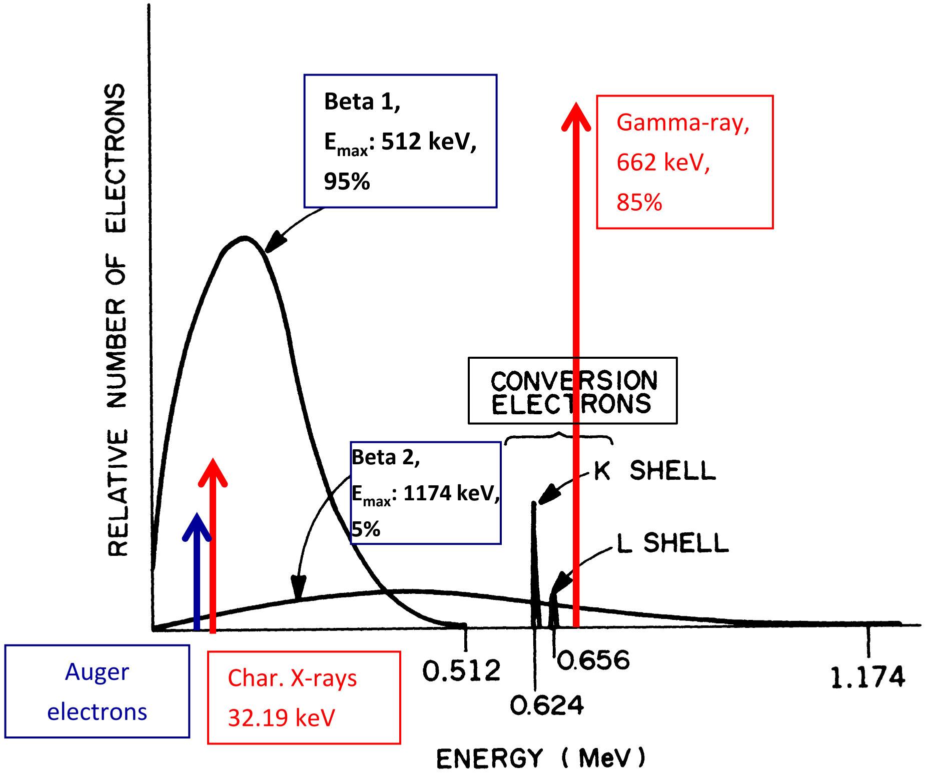


FIGURE 3.8. Decay scheme of $^{137}_{55}$Cs.

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



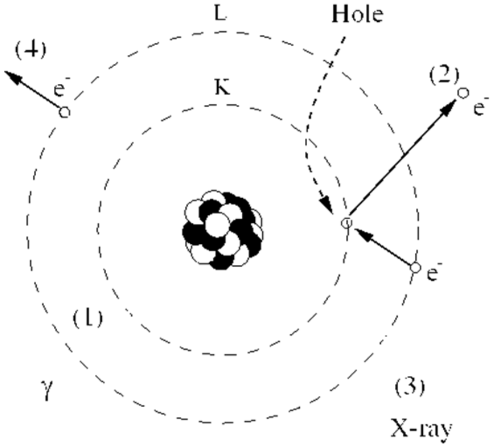
Beta 1,
E$_{max}$: 512 keV,
95%

Gamma-ray,
662 keV,
85%

Beta 2,
E$_{max}$: 1174 keV,
5%

Auger electrons

Char. X-rays
32.19 keV



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

An Example

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

β^+: 1.62 max (16%), 0.98 max (8%)
γ: 1.51 (47%), 0.64 (55%), 0.511 (48%, $\gamma^{\pm}$)
Daughter X rays
e^-: 0.614

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

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