Overview of Radiation Dose to General Public

An Overview of Radiation Exposure to US Population

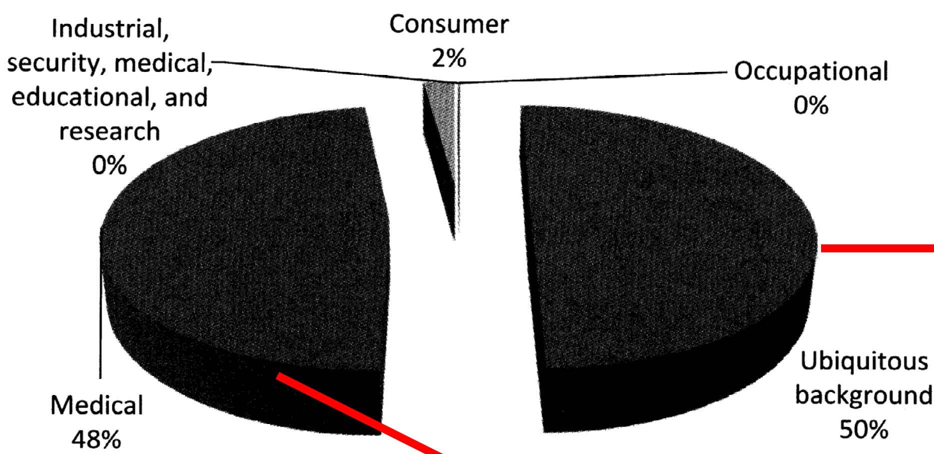


FIGURE 1.1 ◆ Exposure by Major Categories

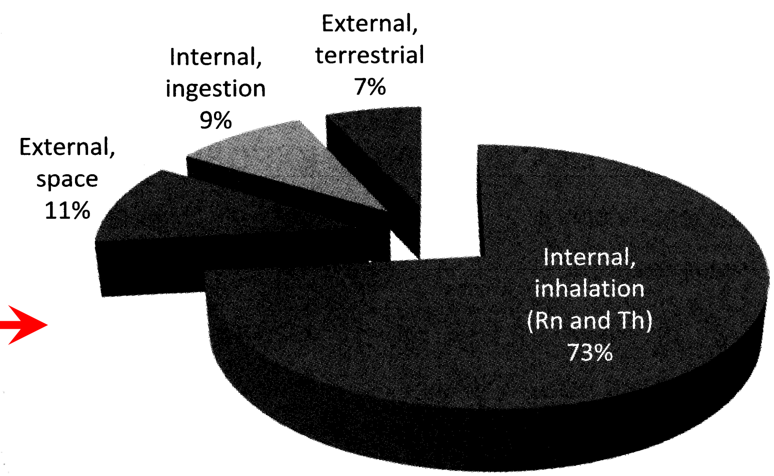


FIGURE 1.2 ◆ Ubiquitous Background

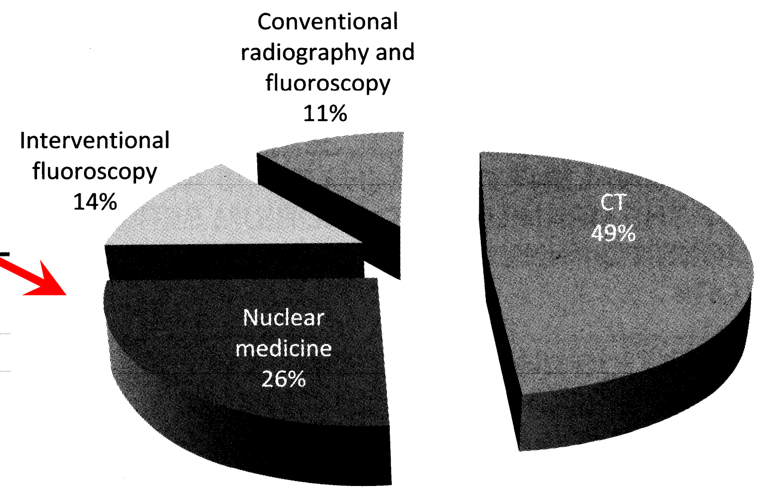


FIGURE 1.3 ◆ Medical

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)

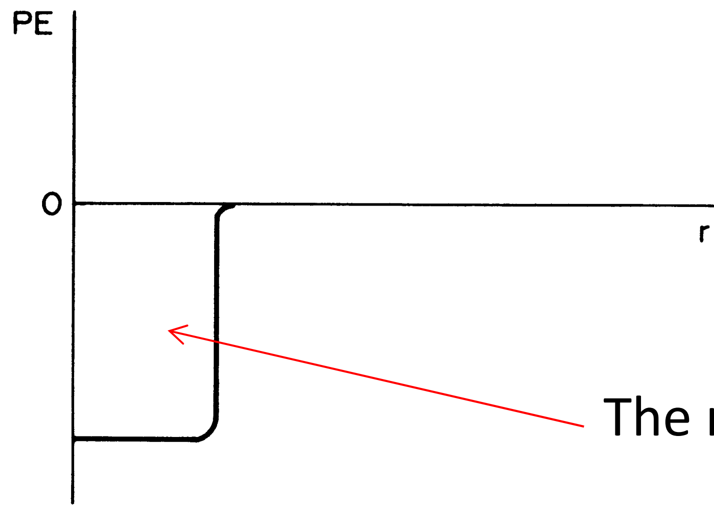
Exposure Category	S (person-Sv)	E_{US} (mSv)	E_{Exp} (mSv)
Medical			
CT	440,000	1.47	[a]
Nuclear medicine	231,000	0.77	[a]
Interventional fluoroscopy	128,000	0.43	[a]
Conventional radiography and fluoroscopy	100,000	0.33	[a]
Total	899,000	3	[a]

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

Nuclear Binding Energy and Energy Release

Nuclear Binding Energy

$$ {}^{1}_{0}\mathrm{n} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{2}_{1}\mathrm{H} + {}^{0}_{0}\gamma, $$



The nuclear binding energy

(b) NEUTRON - NUCLEUS

${}^{1}_{0}n$ ${}^{1}_{1}H$ ${}^{2}_{1}H$

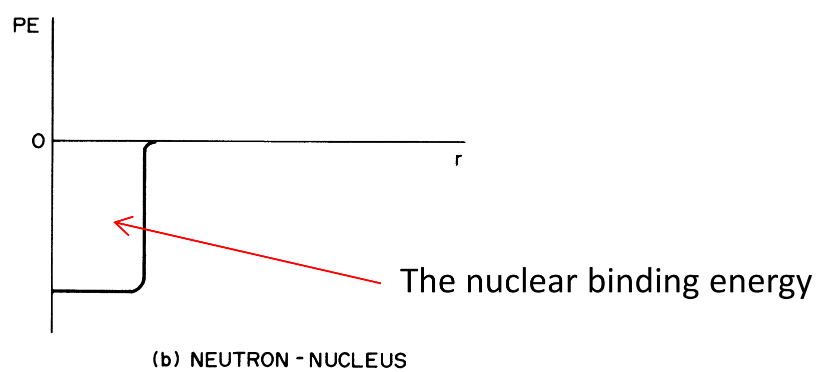
In this case, the binding energy for the deuterium nucleus is given by

$$ Q = 8.0714 + 7.2890 - 13.1359 = 2.2245\ \text{MeV}. $$

Nuclear Binding Energy

- Nuclei are made up of protons and neutron, but the mass of a nucleus is always less than the sum of the individual masses of the protons and neutrons which constitute it.
- This difference is a measure of the **nuclear binding energy**, which holds the nucleus together. The binding energy can be calculated from the Einstein relationship:

$$\text{Nuclear binding energy} = \Delta m \bullet c^2$$



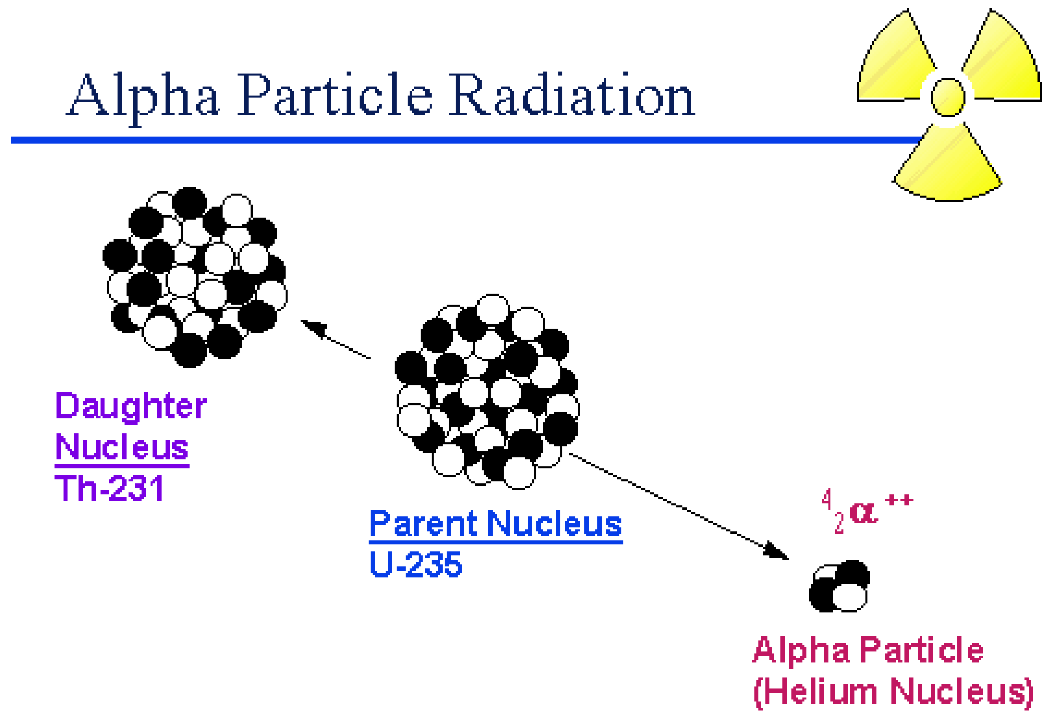
Alpha Decay

Key concepts

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

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



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

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

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 emission. With the γ emission (0.186 MeV, 3.6% of decays), the α particle has an 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 of the recoil nucleus from a simple consideration of conservation of energy and 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.

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

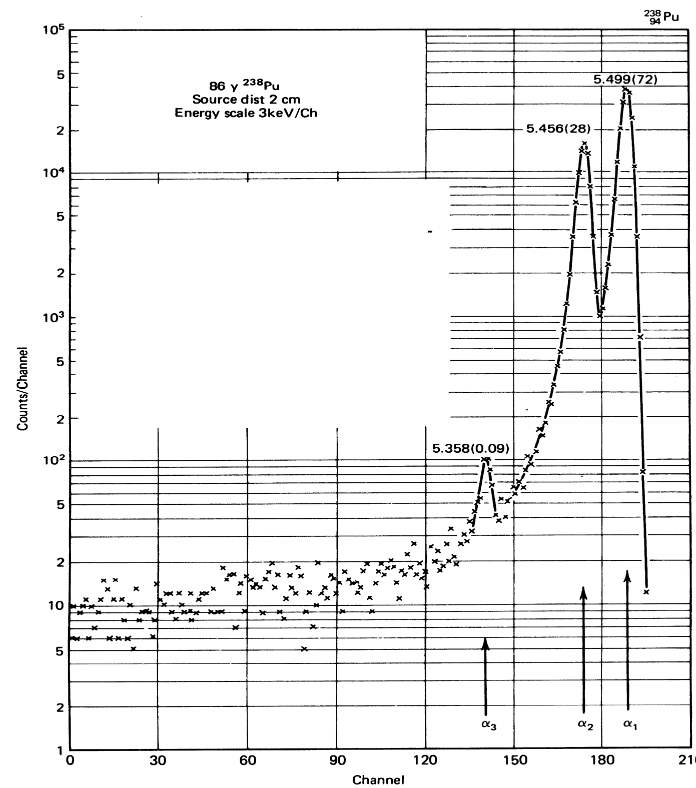
$$E = \frac{mv^2}{2}$$

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

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

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

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

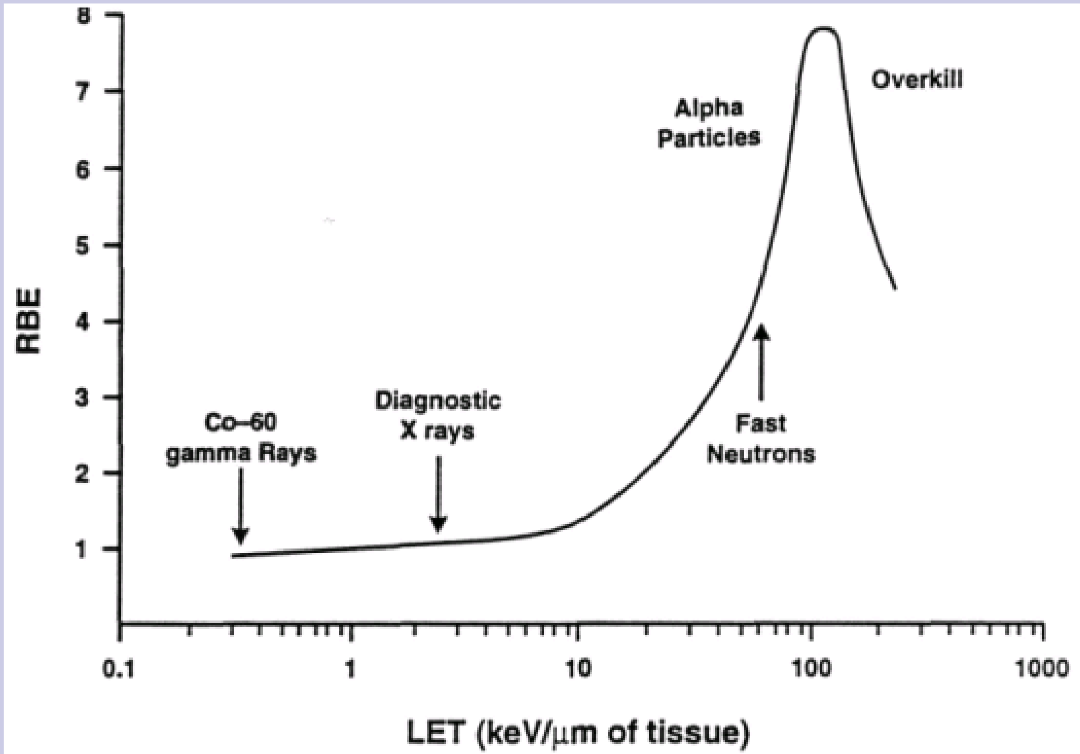


Measured energy spectrum of alpha particles emitted from the decay of ^{238}Pu.

Alpha Emission and Potential Health Concerns

Radiation Effect and Dose Delivery

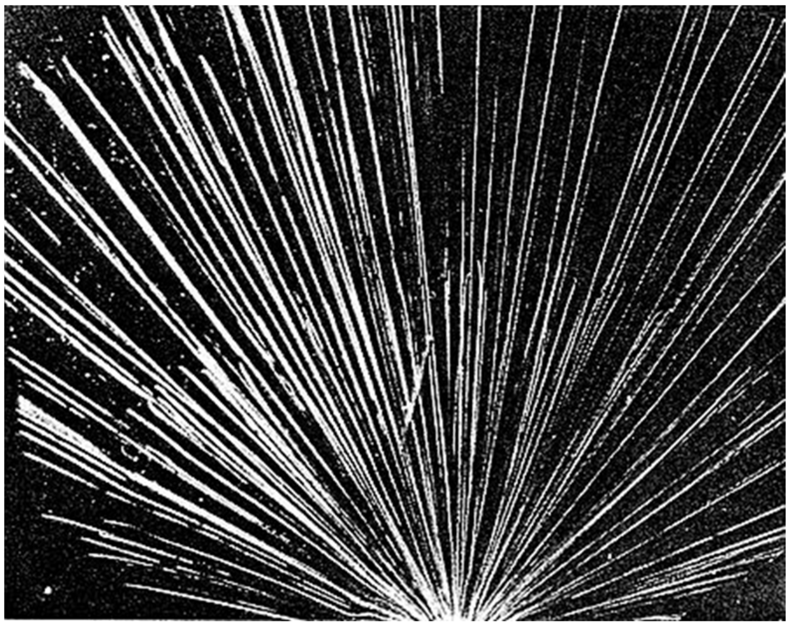
For low LET radiation, $\Rightarrow$ RBE (Relative Biologic Effectiveness) $\propto$ LET (Linear Energy Transfer), for higher LET the RBE increases to a maximum, the subsequent drop is caused by the overkill effect.



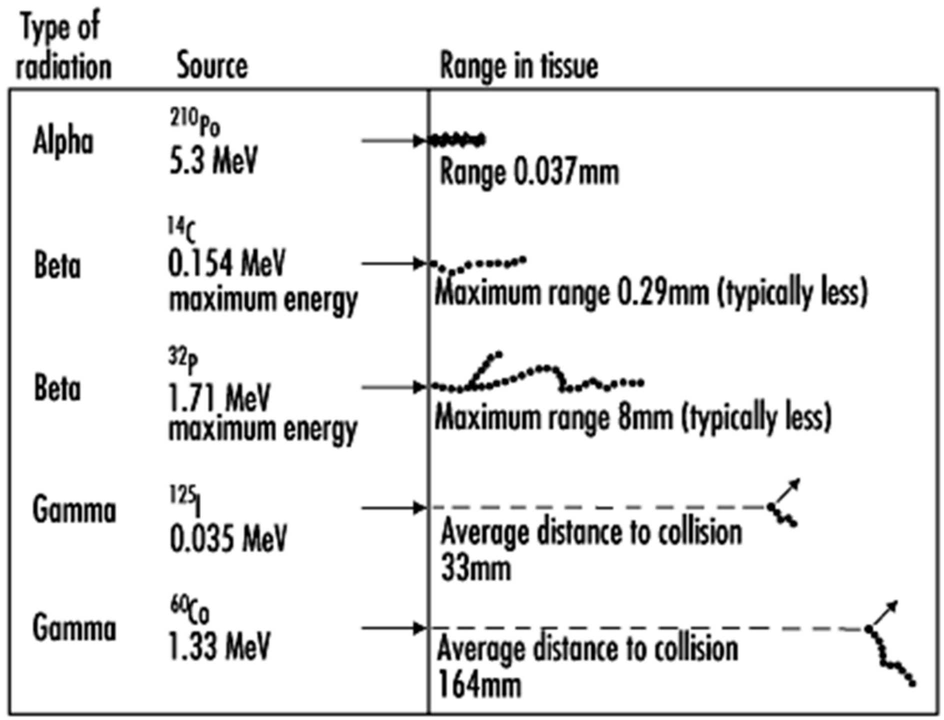
$$RBE = \frac{Dose\ of\ 150\ V\ \ X-rays\ required\ to\ cause\ effect\ x}{Dose\ of\ radiation\ required\ to\ cause\ effect\ x}$$

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

Alpha Emission and Radiation Hazard



J. Chadwick, Cavendish Laboratory, University of Cambridge.



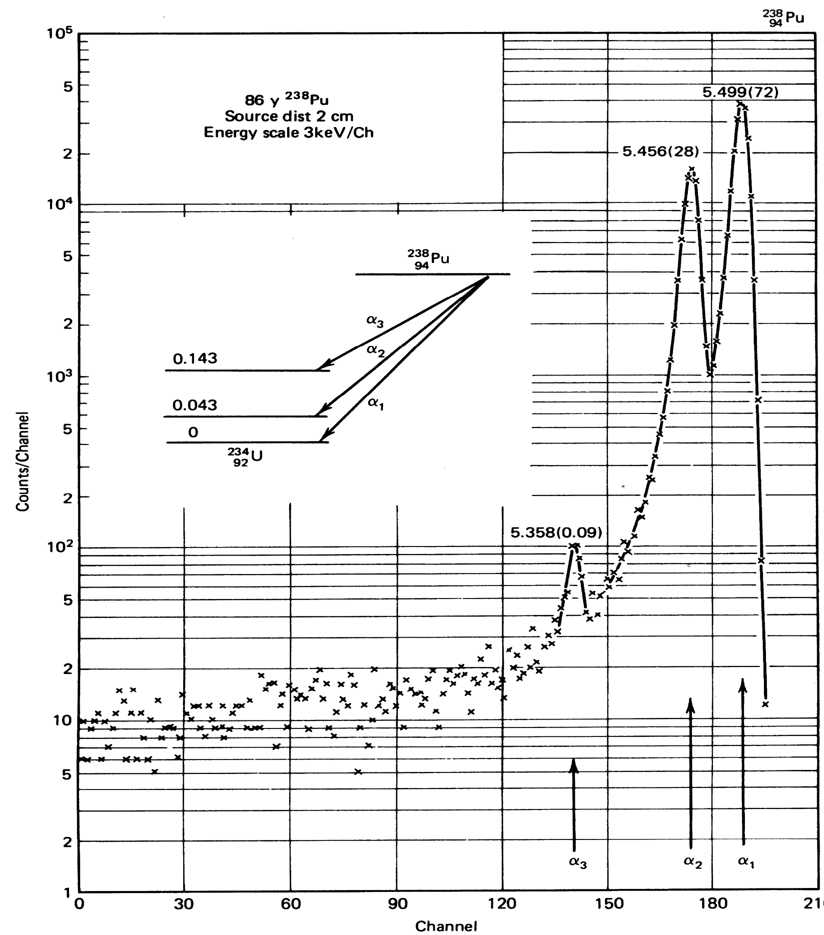
Source: Shapiro 1972.

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.

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

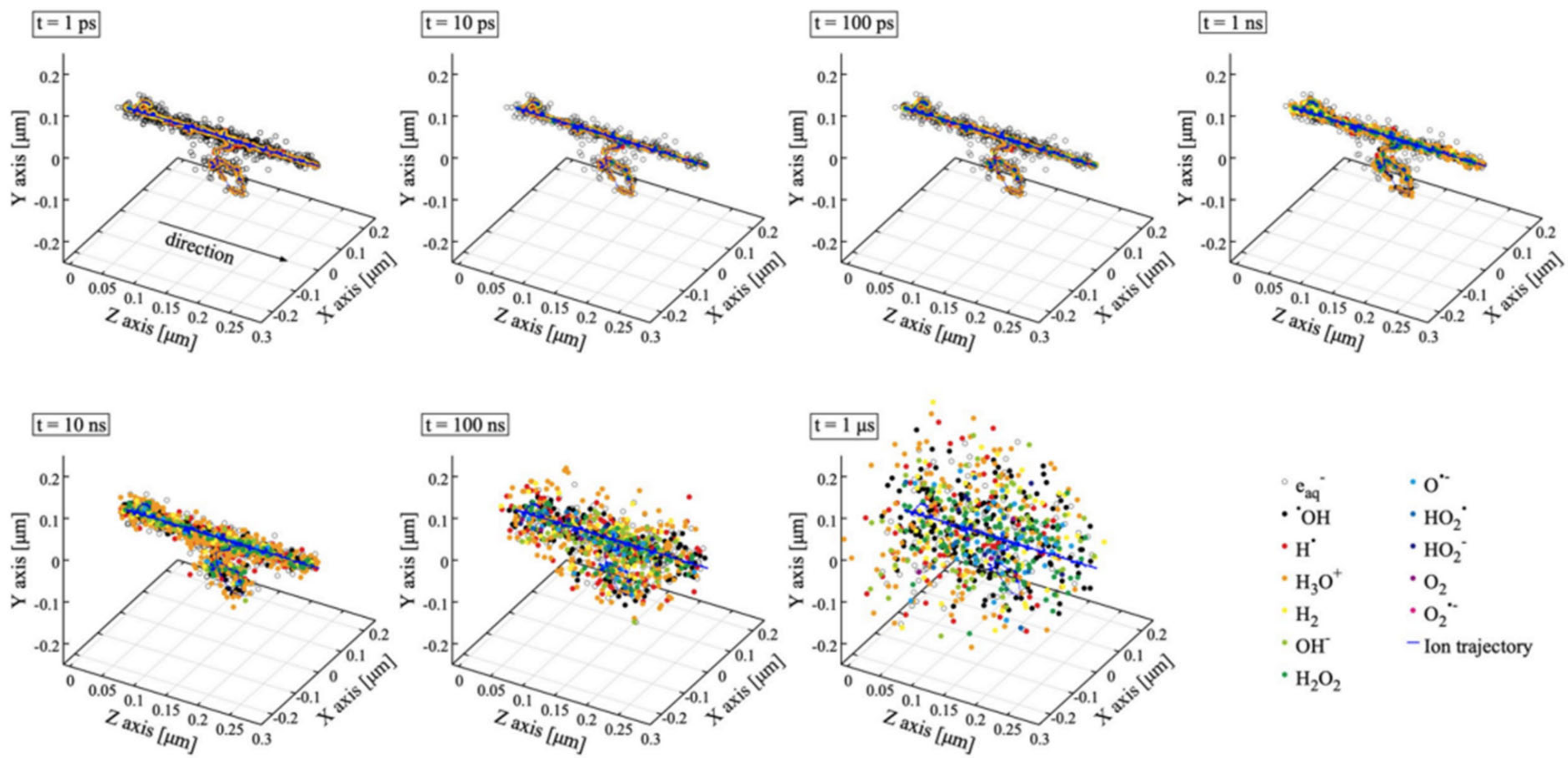


Figure 1. Chemical evolution of 400 MeV/u carbon ion track in water in the time 1 ps to 1 μs.

The Indoor Radon Dose

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.

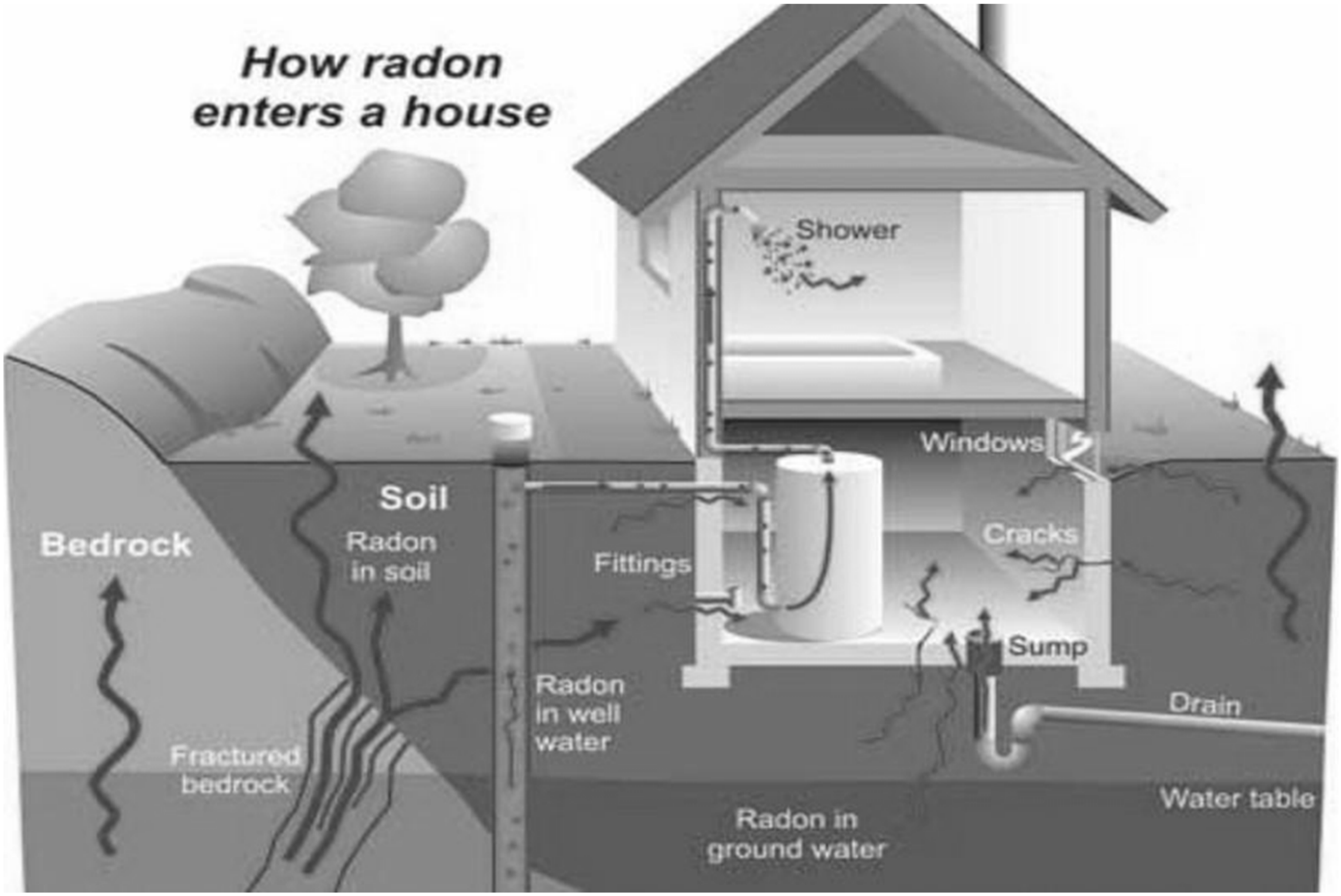
The health concerns of these isotopes are determined by two factors:

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

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

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.

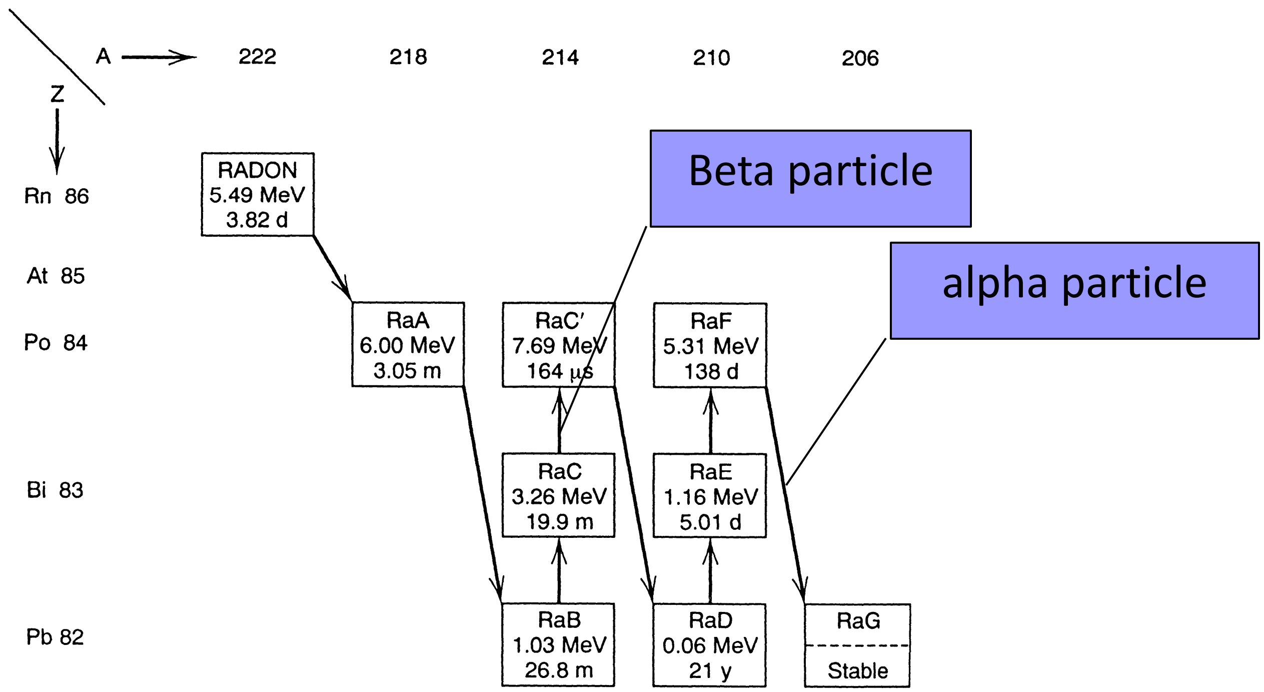


FIGURE 4.7. Radon and radon daughters. Alpha emission is represented by an arrow slanting downward toward the right; beta emission, by a vertical arrow. Alpha-particle and average beta-particle energies and half-lives are shown in the boxes.

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

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)

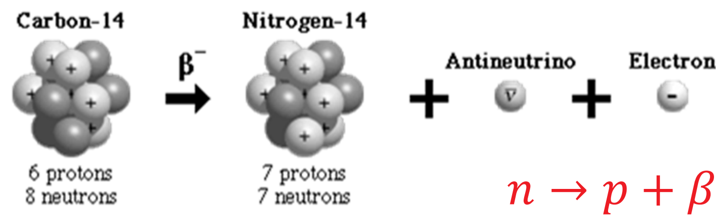
What is beta decay?

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

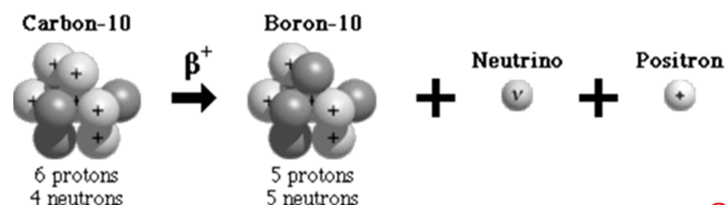
$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + {}^{0}_{-1}\beta + \overline{\upsilon} $$



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

Beta-plus decay

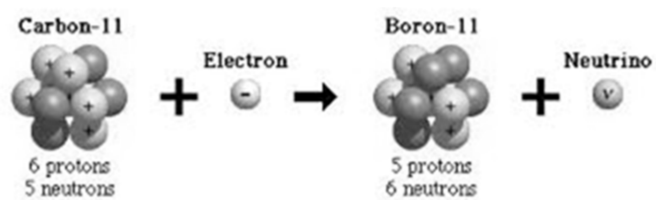
$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + {}^{0}_{1}\beta + \upsilon $$



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

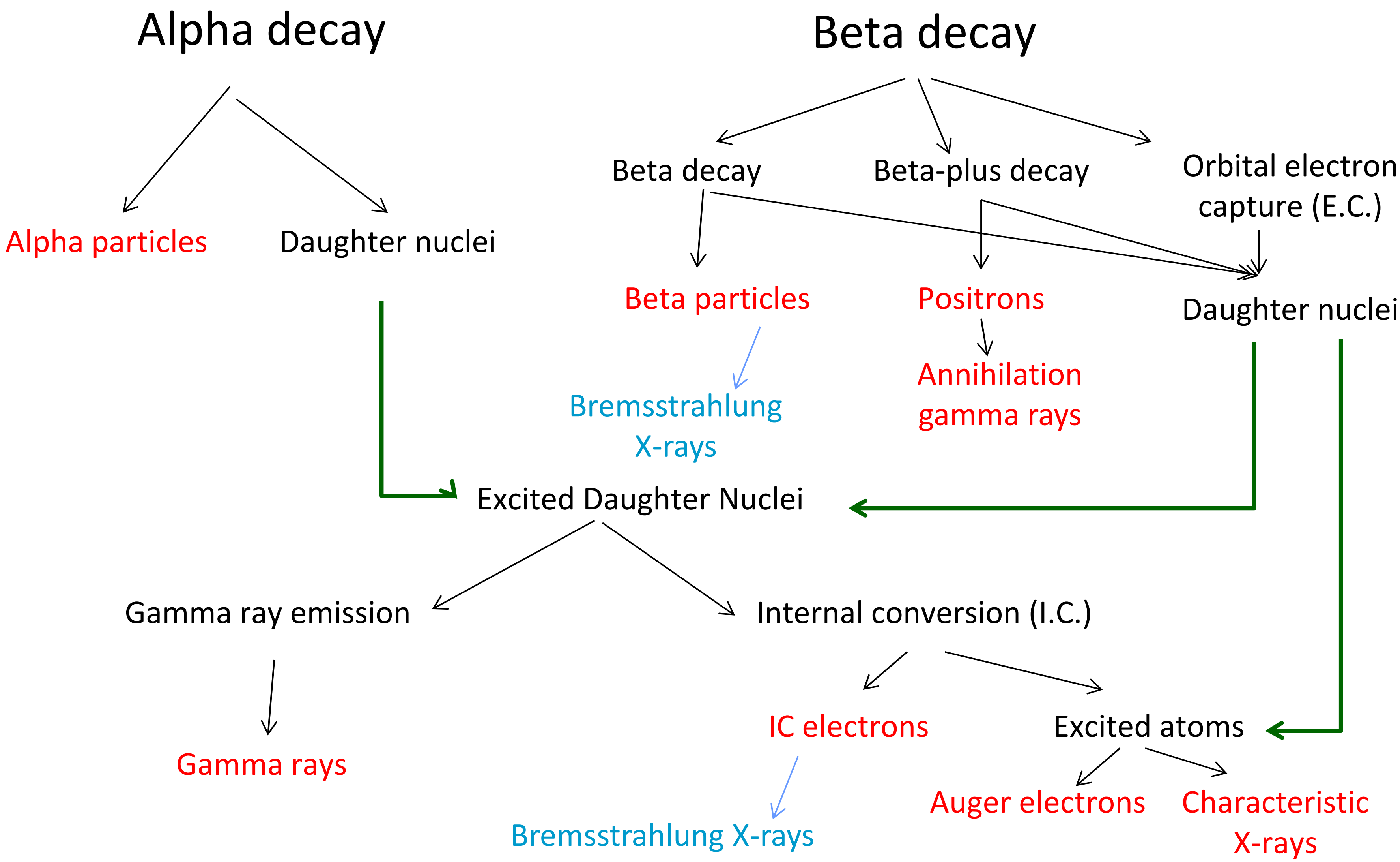
Electron capture

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



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

Typical Decay Products from Unstable Radioisotopes

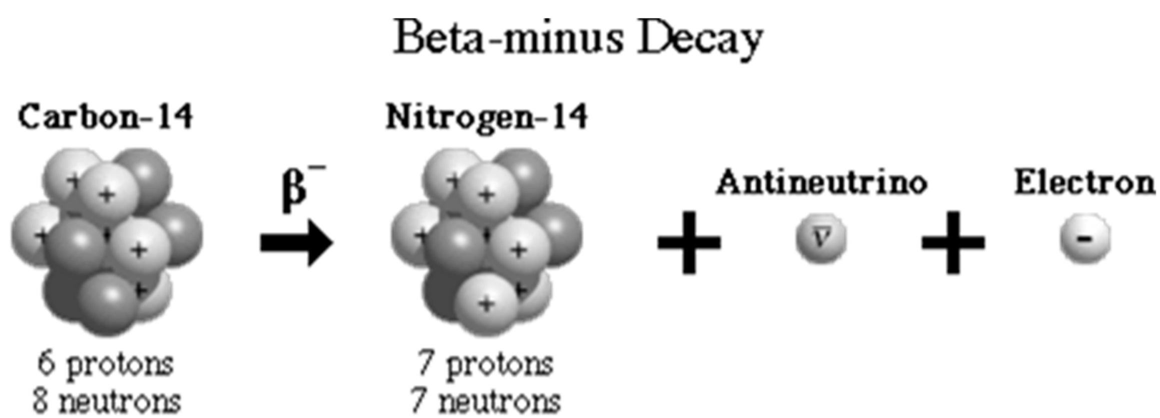


Energy Release of Beta Decay

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.



Energy Release Through Orbital Electron Capture

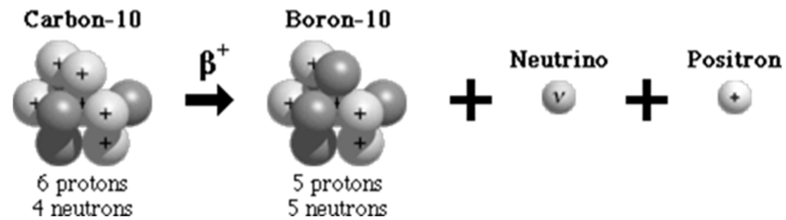
For positron decay to be possible, we need

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

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



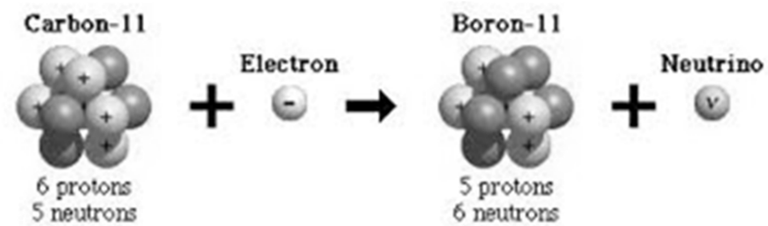
For Electron Capture to occur,

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

so that

$$M_p > M_d + \phi$$

where ϕ is the binding energy of the orbital electron

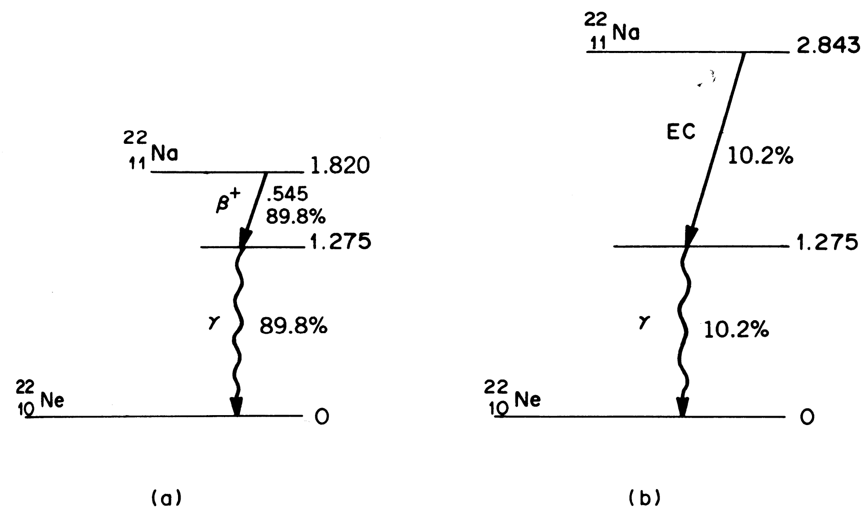


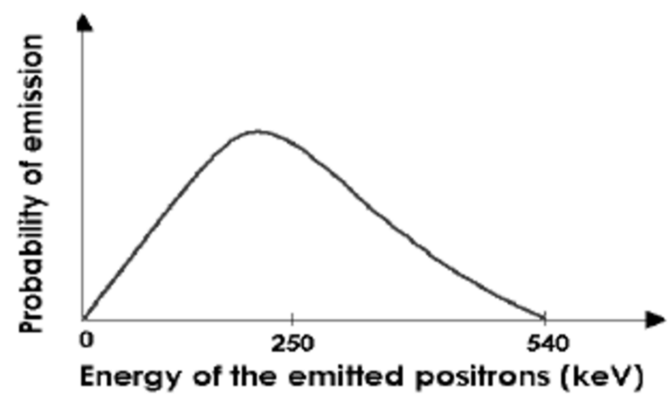
Orbital Electron Capture and Positron Decay

- 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.





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.
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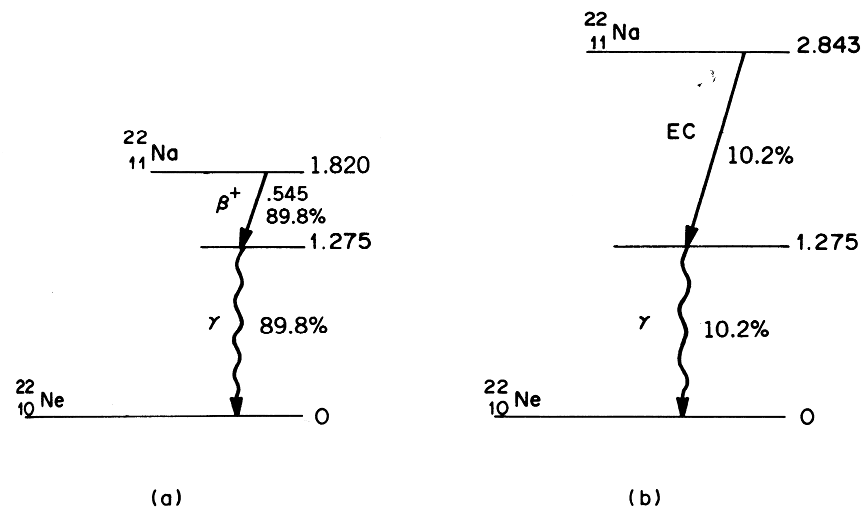
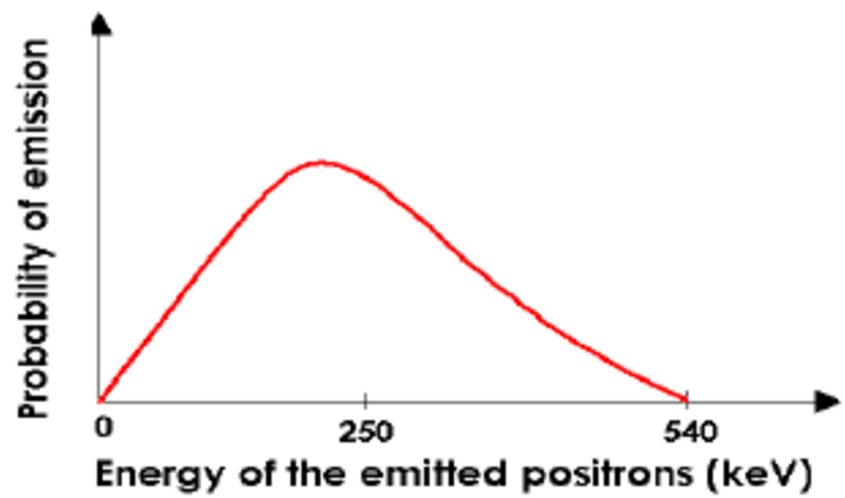




Understanding the Radiation from Cs-137

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

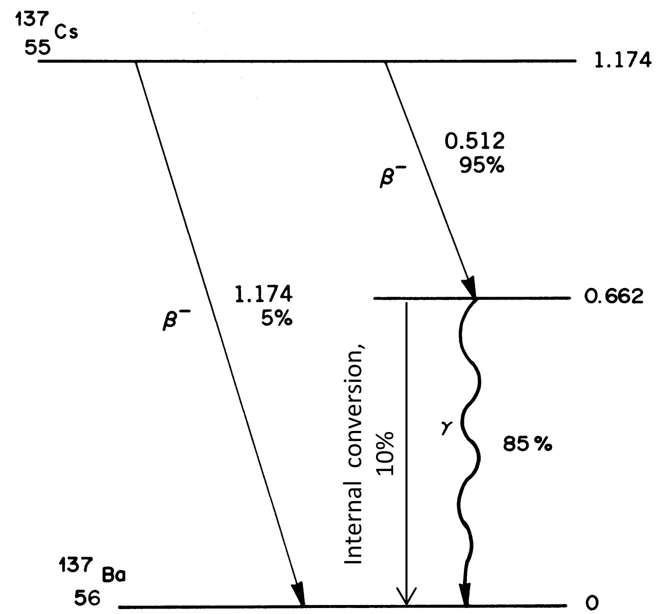
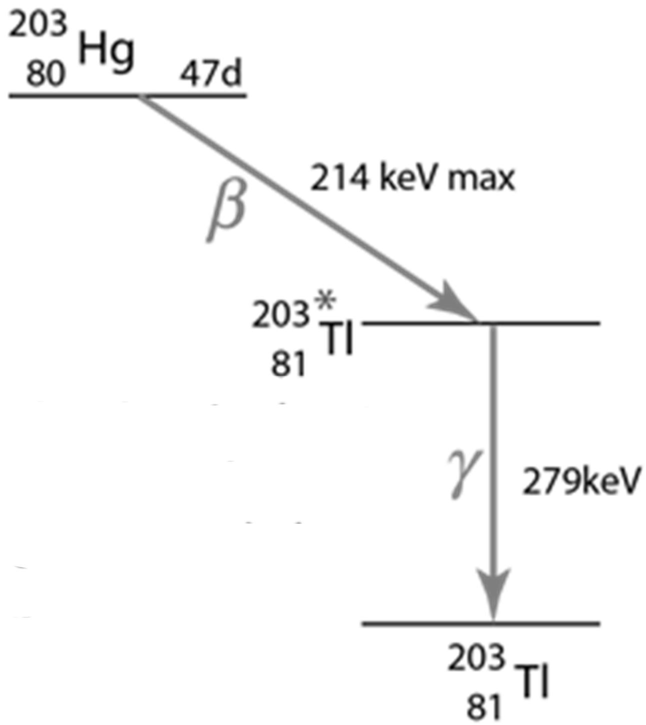
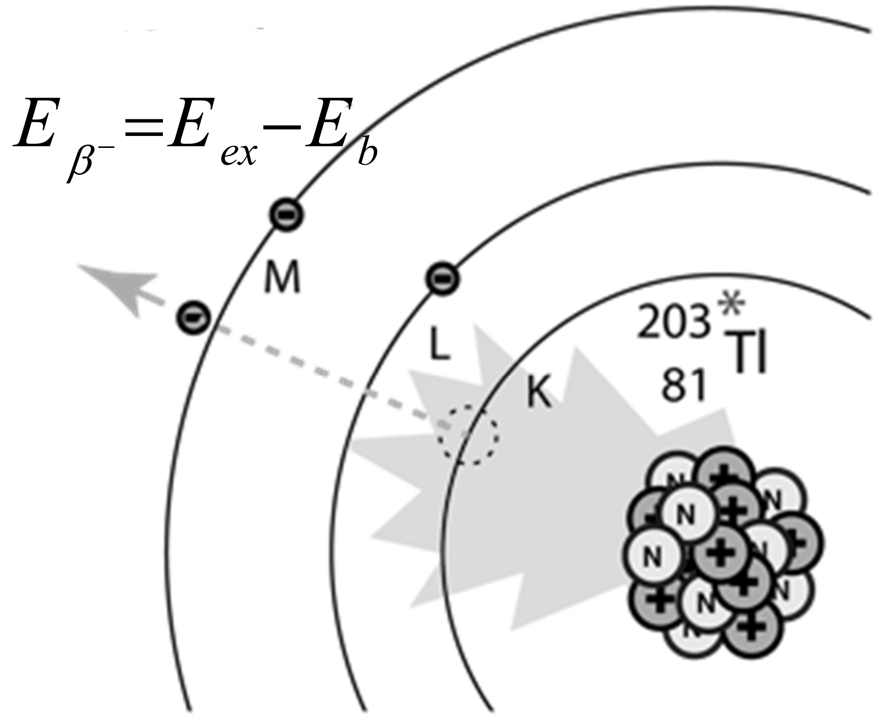


FIGURE 3.8. Decay scheme of $^{137}_{55}$Cs.

Following the initial alpha or beta decay, what are the nuclear and atomic level transformations that could lead to secondary radiation?

Gamma-Ray Emission and Internal Conversion



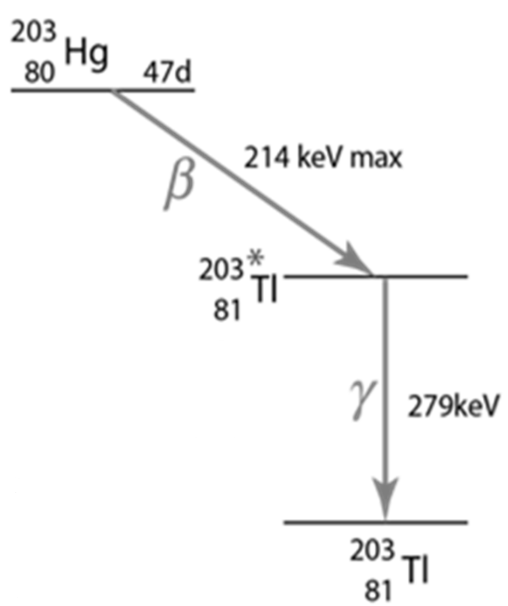


Gamma-ray emission vs **Internal Conversion**

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

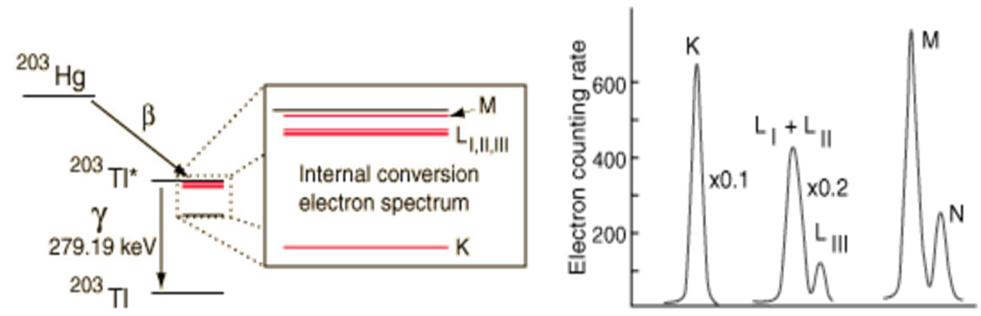
http://hyperphysics.phy-astr.gsu.edu/hbase/Nuclear/radact2.html

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

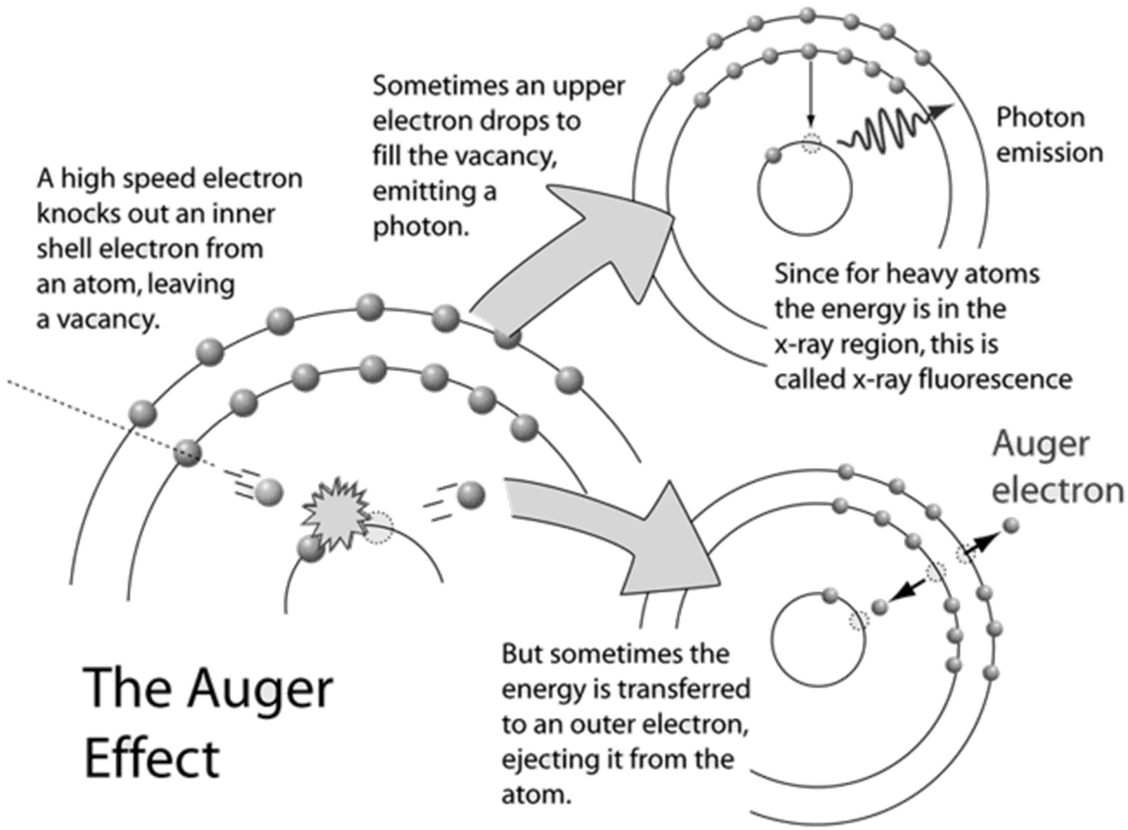
- Energy of the beta particles?
- Relative frequency per decay?

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

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

Radiation from Excited Atoms

Characteristic X-ray vs Auger Electron



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.

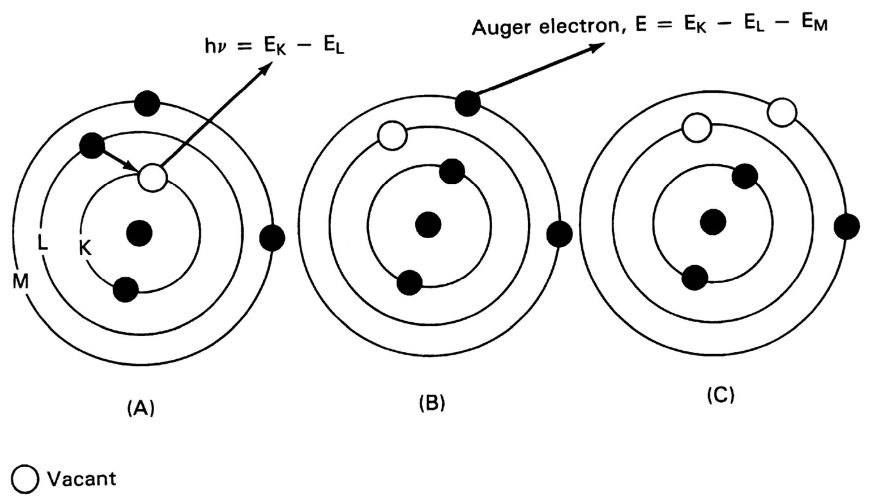
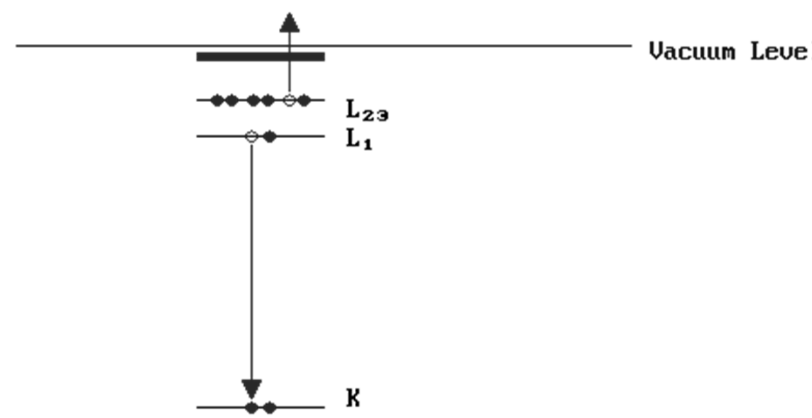
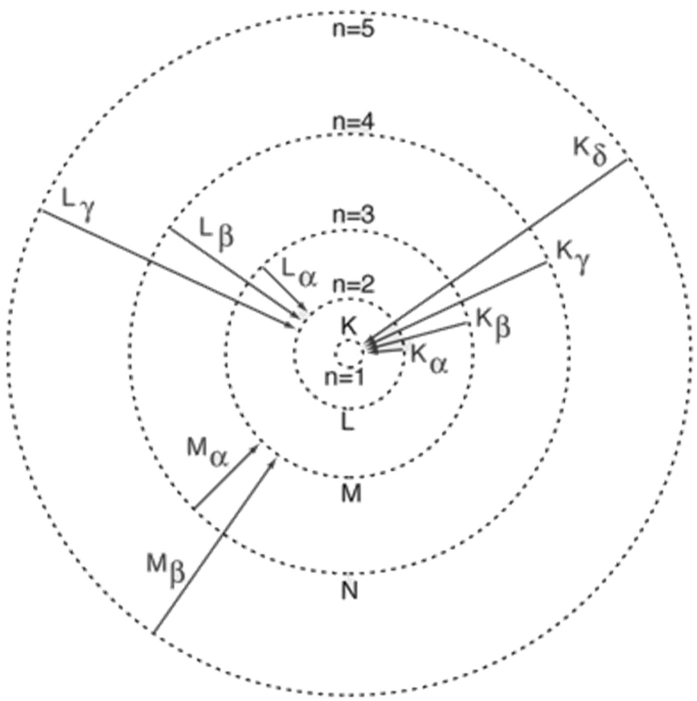


Figure 3.7 (A) The usual emission of a K characteristic X-ray, $h\nu$, energy equal to $E_K - E_L$, the difference in binding energy for the two orbital electrons, K and L. (B) $h\nu$ has been absorbed and a monoenergetic Auger electron is emitted, in the example shown, from the M shell, the energy of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



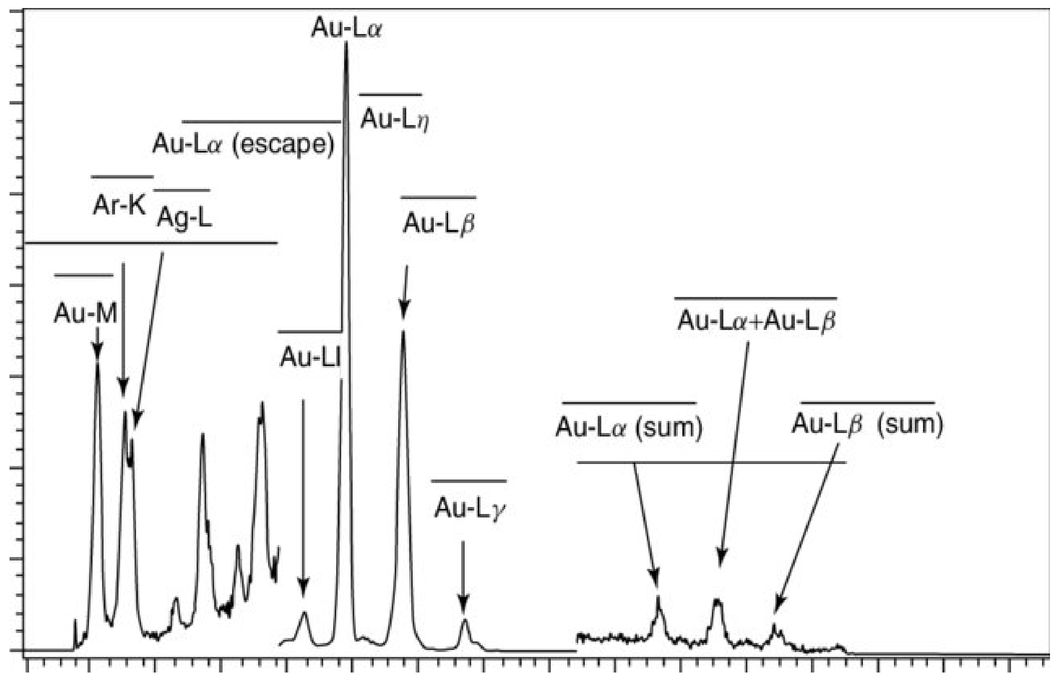
$$E_{a.e.} = (E_K - E_{L_1}) - E_{L_{23}}$$

Radiation from Excited Atoms



Possible X-ray Transitions

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



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

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

Radioprotection 51(4), 279-285 (2016)

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ARTICLE

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

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

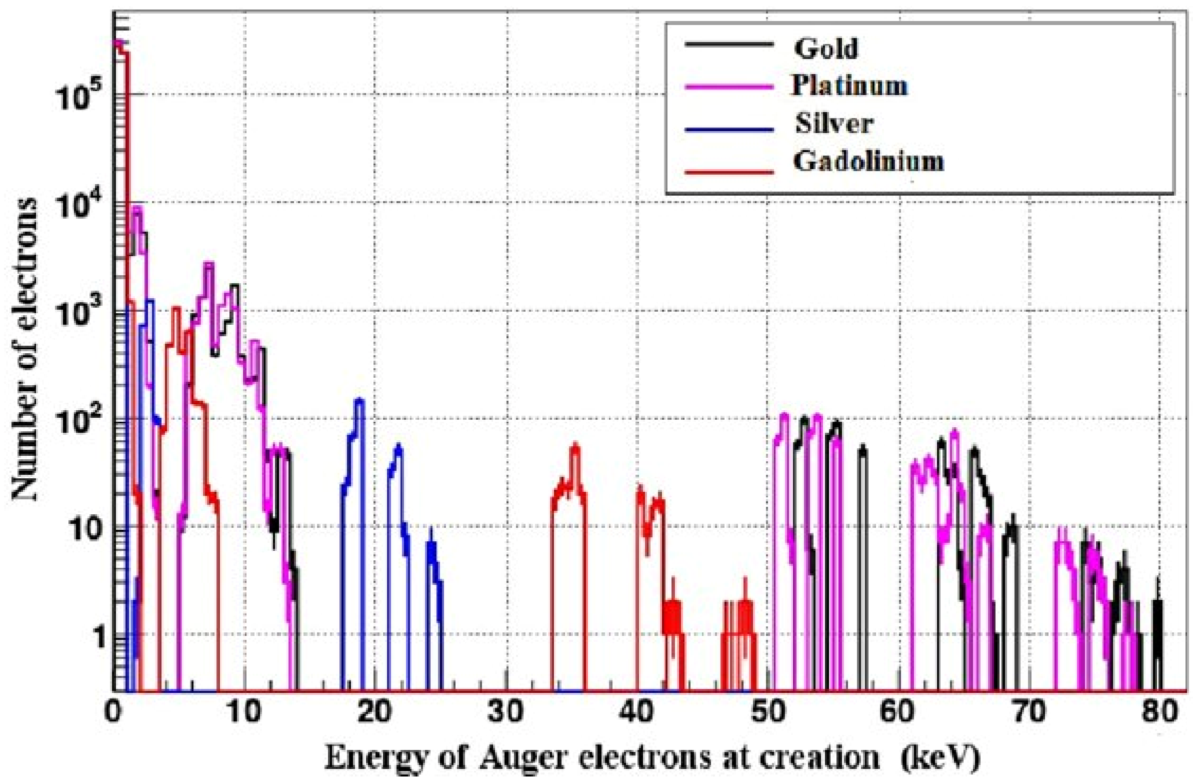


Figure 5. The spectrum of Auger electrons at an X-ray energy of 100 keV.

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:

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

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.

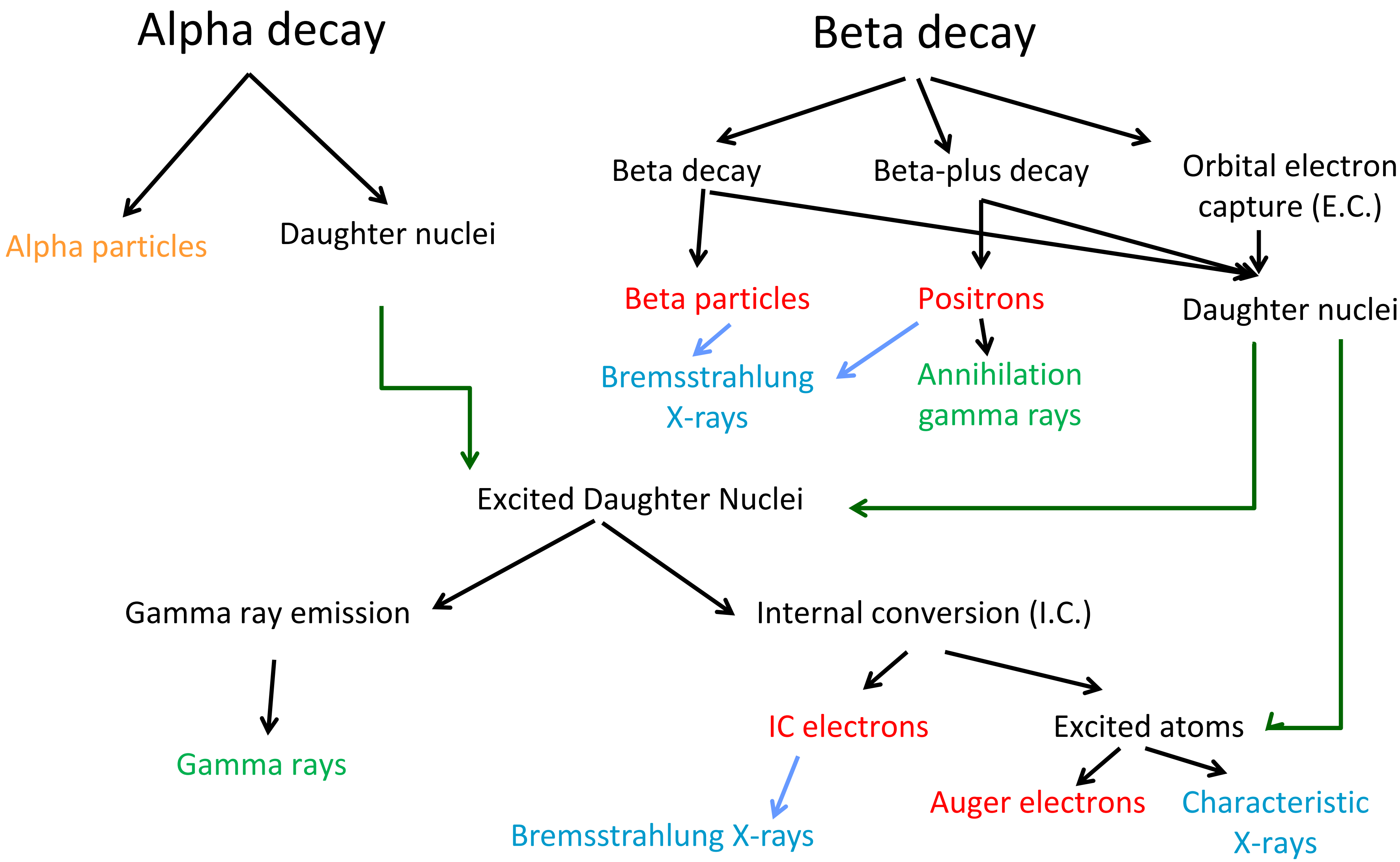
From this table we see that if a nucleus with Z = 40 had a K shell hole, then on the average 0.74 fluorescent photons and 0.26 Auger electrons would be emitted.

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)

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?

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

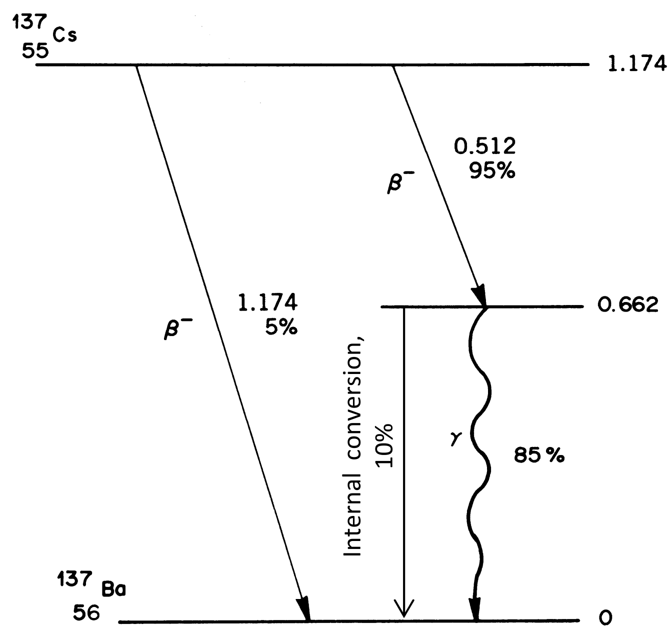


FIGURE 3.8. Decay scheme of $^{137}_{55}$Cs.

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?

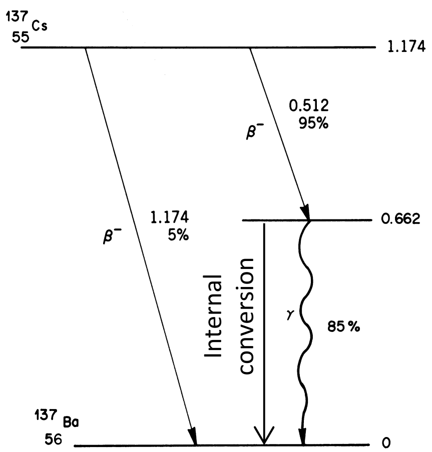
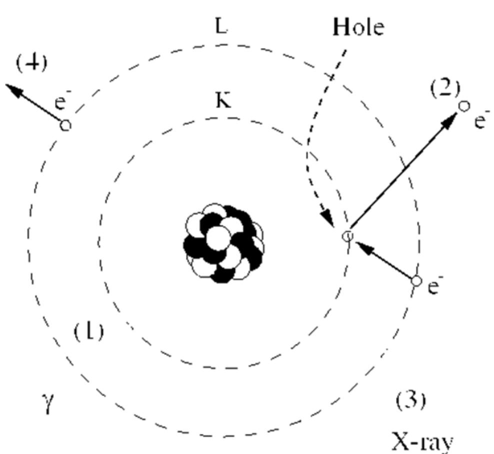
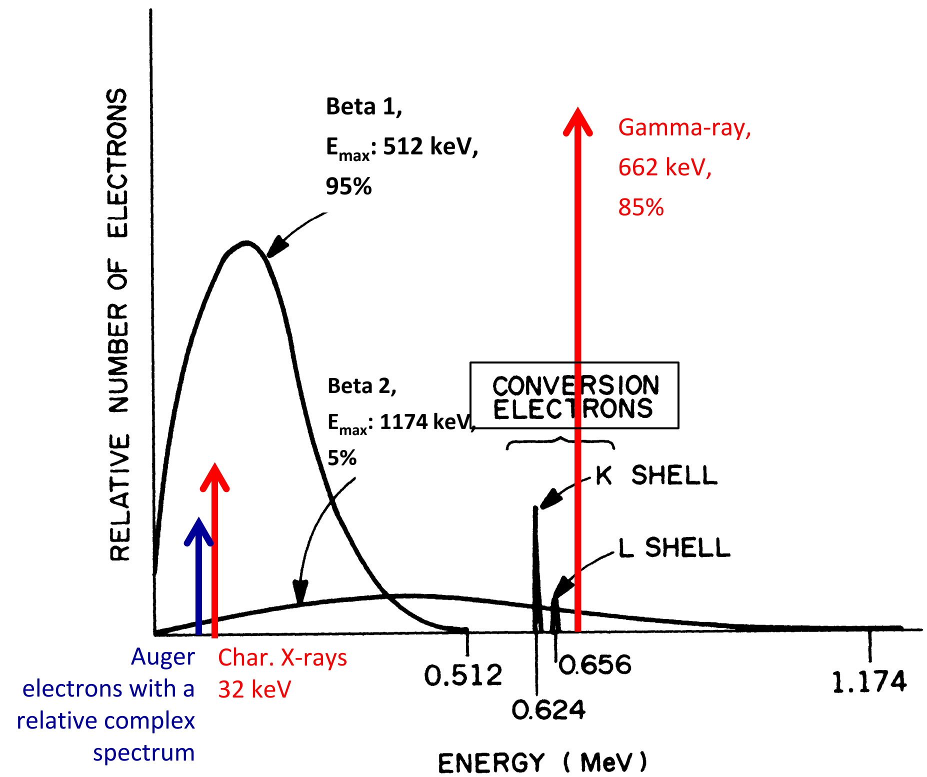


FIGURE 3.8. Decay scheme of $^{137}_{55}$Cs.

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



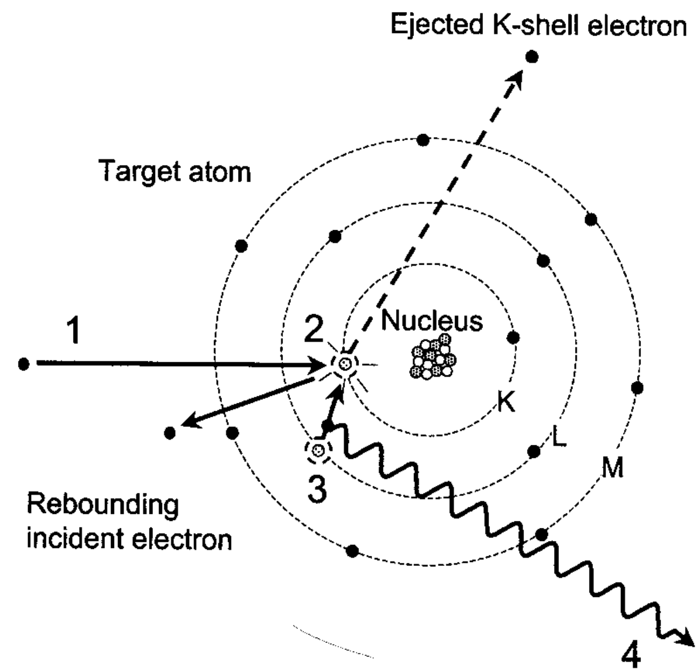
http://www.nuclear.kth.se/courses/lab/latex/internal/internal.html



X-ray Emission

X-ray Generation – Characteristic X-rays

- e^- of the target atom have a binding energy (BE)that depends on atomic Z (rem: $BE_K \propto Z^2$) and the shell ($BE_K > BE_L > BE_M > \ldots$)
- When e^-(KE) incident on the target exceeds the target atom e^-(BE), it's energetically possible for a collisional interaction to eject the bound electron and ionize the atom.
- What would happen then?



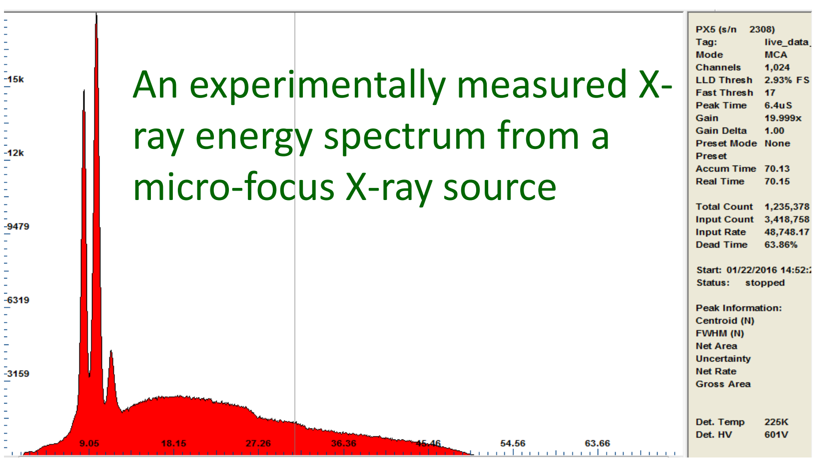
X-ray Generation – Characteristic X-rays

- Within each shell (other than K) there are discrete E orbitals (ℓ = 0, 1, ... , n-1) → characteristic x-ray fine E splitting
- Characteristic x-rays other than those generated through K-shell transitions are unimportant

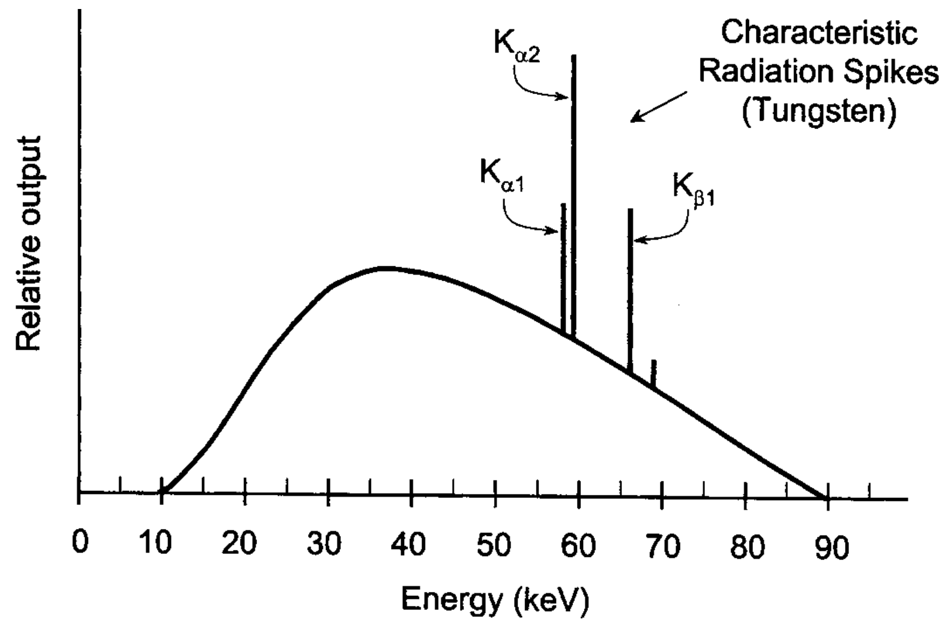
TABLE 5-2. K-SHELL CHARACTERISTIC X-RAY ENERGIES (keV) OF COMMON X-RAY TUBE TARGET MATERIALS[a]

Shell Transition	Tungsten	Molybdenum	Rhodium
$K_{\alpha 1}$	59.32	17.48	20.22
$K_{\alpha 2}$	57.98	17.37	20.07
$K_{\beta 1}$	67.24	19.61	22.72

[a] *Note:* Only prominent transitions are listed.



An experimentally measured X-ray energy spectrum from a micro-focus X-ray source



Neutron Sources

Neutron Sources – Spontaneous Fission

Cf-252 neutron source can be made extremely compact

An engineer tests the prototype Timed Neutron Detector, a device that detects landmines. The neutron source of the landmine detector holds a tiny amount of californium-252. (Photo credit: Pacific Northwest National Lab)

TABLE 7.1 NEUTRON TERMINOLOGY

Term	Energy Range	Velocity
Ultracold	$<2 \times 10^{-7}$ eV	6 m/s
Very cold	2×10^{-7} eV to 5×10^{-5} eV	100 m/s
Cold neutrons	5×10^{-5} eV to 0.025 eV	—
Thermal[c]	0.025 eV	2200 m/s
Epithermal	1 eV–1 keV	4.4×10^{5} m/s
Cadmium	<0.4 eV	8800 m/s
Epicadmium	>0.6 eV	1.1×10^{4} m/s
Slow	<1 to 10 eV	1.4×10^{4} m/s
Resonance[a]	1 to 300 eV	2.4×10^{5} m/s
Intermediate	1 keV to 0.1 MeV	4.4×10^{6} m/s
Fast	>0.1 MeV	1.4×10^{7} m/s
Ultra fast (relativistic)	>20 MeV	—
Fission[b]	100 keV to 15 MeV	—

[a] In pile neutron physics usually refers to neutrons which are strongly captured in the resonance of U-238, and of a few commonly used detectors, e.g., In, Au.

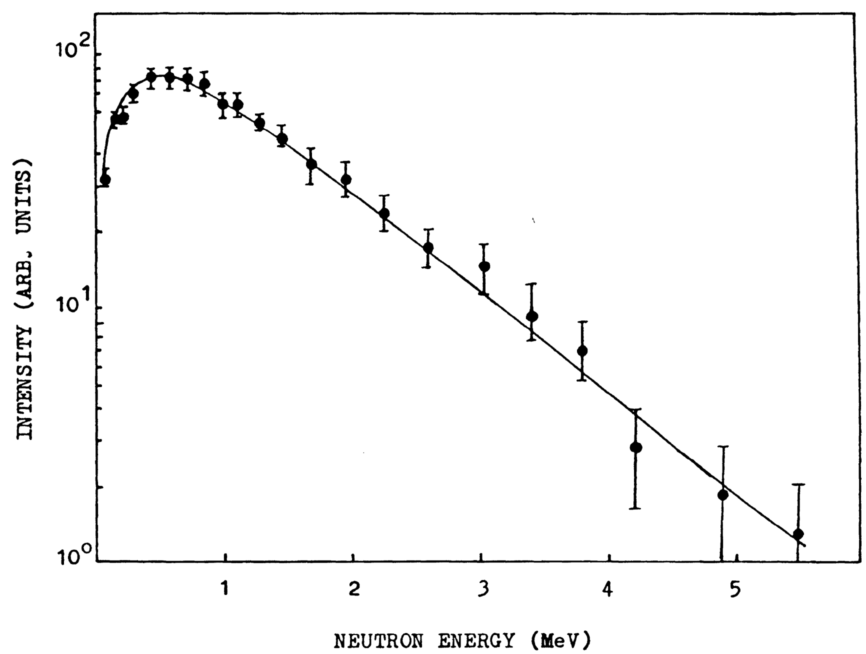
[b] Most probable energy 0.8 MeV, Average energy 2.0 MeV.

[c] Maxwellian distribution of 20°C extends to about 0.1 eV.

Neutron Sources – Spontaneous Fission

Spontaneous fission of tarnsuranic heavy nuclides, such as ^{252}Cf, produces several fast neutrons, in addition to heavy fission products, prompt fission gamma rays and beta and gamma ray activities.

- Half-life: 2.65 years
- Neutron yield: 0.116n/s per Bq, or 2.3×10^6 n/s per mg
- Neutron energy peaking at 0.5MeV and extends beyond 10MeV.



Measured neutron energy spectrum from spontaneous fission of ^{252}Cf

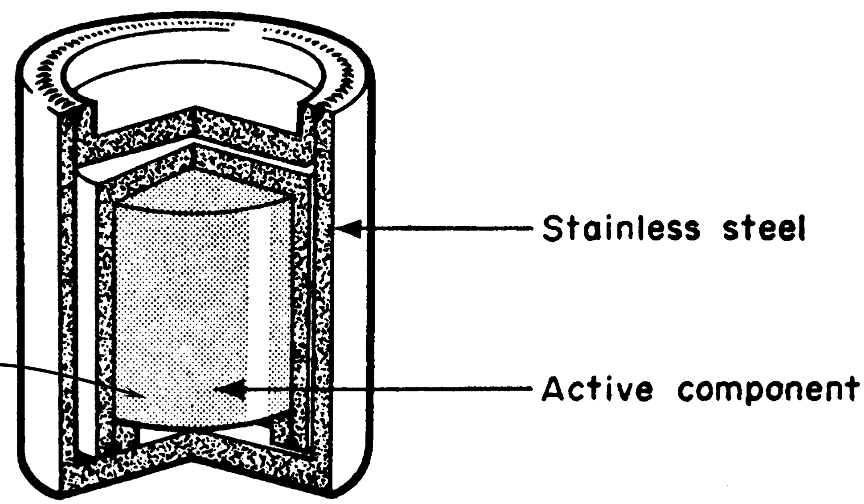
Page 19-27, Radiation Detection and Measurements, Third Edition, G. F. Knoll, John Wiley & Sons, 1999.

Neutron Sources – Radioisotope (α,n) Sources

Energetic alpha particles can induce (α,n) reaction in certain target materials.

$$ {}_{2}^{4}\alpha + {}_{4}^{9}Be \Rightarrow {}_{6}^{12}C + {}_{0}^{1}n \qquad \text{Q-value}: 5.71\,\text{MeV} $$

The source is normally prepared in the form of alloy (MBe_{13}), where M is alpha-emitting radioisotopes



A practical neutron source

Page 19-27, Radiation Detection and Measurements, Third Edition, G. F. Knoll, John Wiley & Sons, 1999.

Neutron Sources – Radioisotope (α,n) Sources

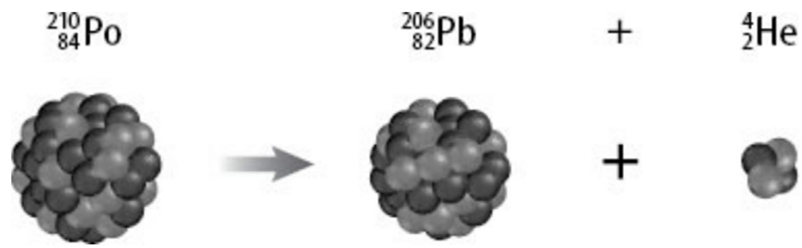


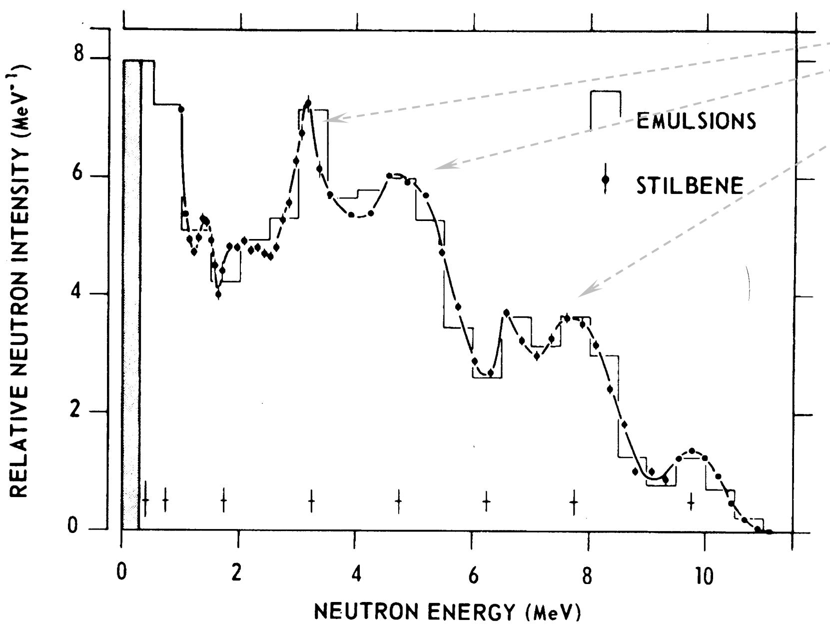
TABLE 9.2. (α,n) Neutron Sources

Source	Average Neutron Energy (MeV)	Half-life
^{210}PoBe	4.2	138 d
^{210}PoB	2.5	138 d
^{226}RaBe	3.9	1600 y
^{226}RaB	3.0	1600 y
^{239}PuBe	4.5	24100 y

James Tuner, Atoms, radiation and Radiation Protection, p210-p211.

Neutron Sources – Radioisotope (α,n) Sources

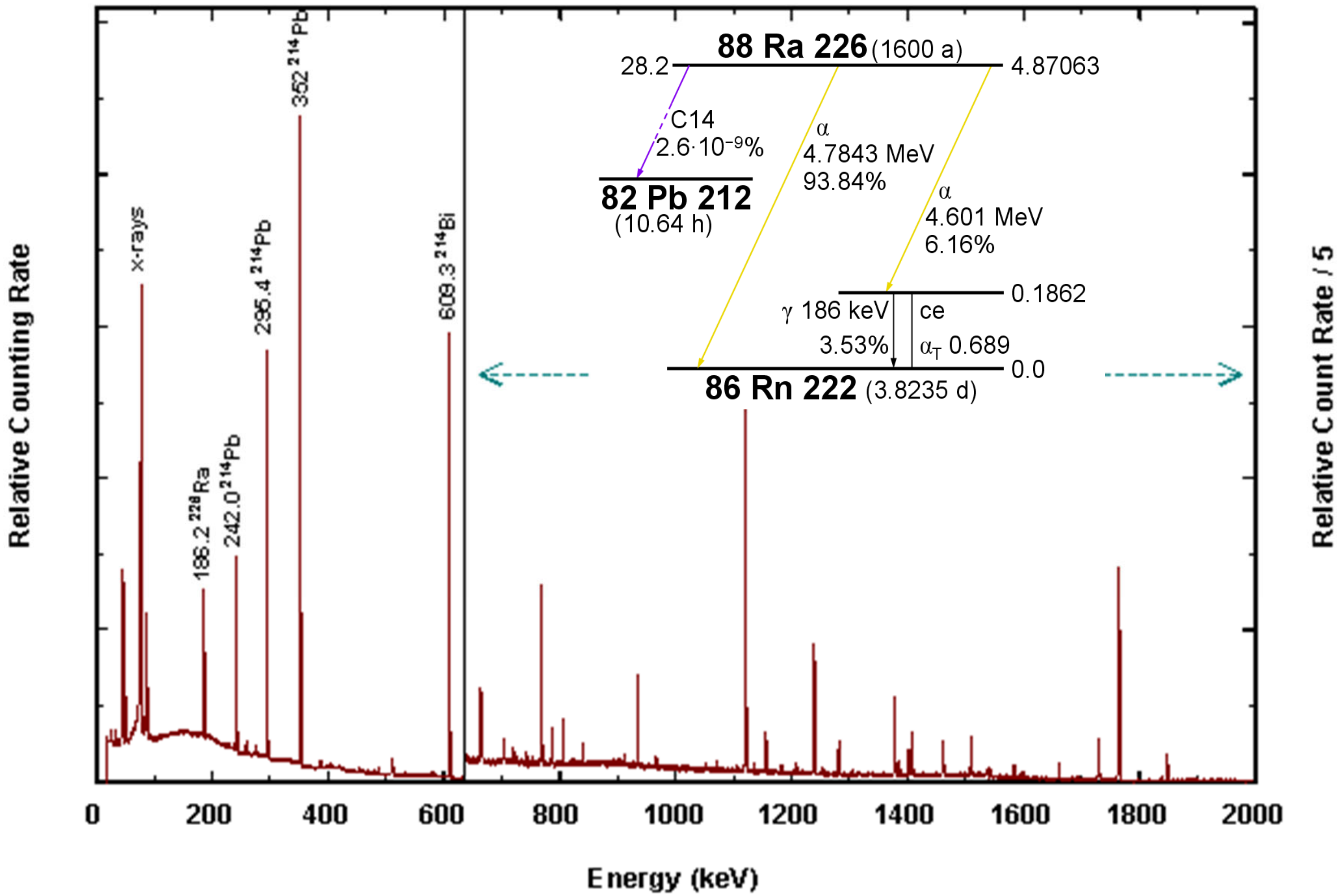
A typical neutron energy spectrum from an ^{239}Pu/Be source.



- The various peak and valley are due to the distinct excited states of the ^{12}C product nucleus.
- The continuum is the result of variable energy possessed by the alpha particles before reaction.

Page 19-27, Radiation Detection and Measurements, Third Edition, G. F. Knoll, John Wiley & Sons, 1999.

Neutron Sources – Radioisotope (α,n) Sources



Radium-226 gamma ray spectrum from high purity germanium (HPGe) detector

Neutron Sources – Photon-Neutron Sources

- Some radioisotope gamma ray emitters can also be used to produce neutrons when combined with an appropriate target material.

$$
{}^{9}_{4}Be + h\nu \Rightarrow {}^{8}_{4}Be + {}^{1}_{0}n, \quad Q-value: -1.666MeV
$$

$$
{}^{2}_{1}H + h\nu \Rightarrow {}^{1}_{1}H + {}^{1}_{0}n, \quad Q-value: -2.226MeV
$$

- A gamma ray photon with an energy greater than the negative of the Q -value is required.

- Some practical gamma ray emitter include: ^{226}Ra, ^{124}Sb, ^{72}Ga, ^{140}La and ^{24}Na.

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Neutron Sources – Photo-neutron Sources

If the gamma rays are monoenergetic, the neutrons are also nearly monoenergetic!

$$E_n(\theta) \cong \frac{M(E_\gamma + Q)}{m+M} + \frac{E_\gamma[(2mM)(m+M)(E_\gamma + Q)]^{1/2}}{(m+M)^2}\boxed{\cos(\theta)}$$

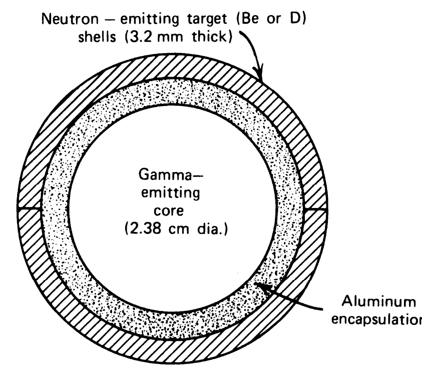
where

$\theta =$ angle between gamma photon and neutron direction

$\mathrm{E}_\gamma =$ gamma energy

$\mathrm{M} =$ mass of recoil nucleus $\times\, \mathrm{c}^2$

$\mathrm{m} =$ mass of neutron $\times\, \mathrm{c}^2$



Typical structure of photon neutron sources

The neutron energy is blurred by

- The slight angular dependency.
- Neutron scattering inside the source.

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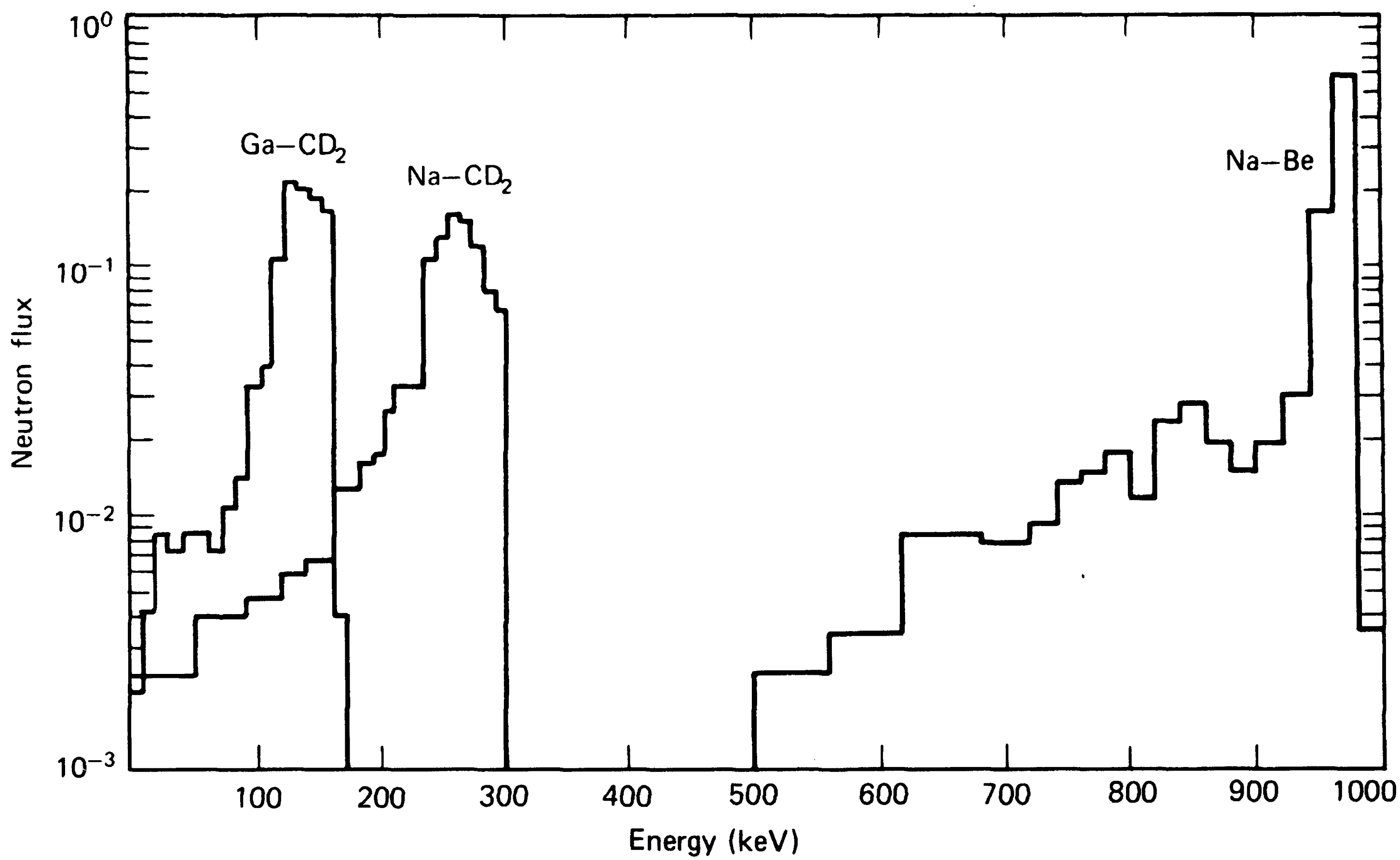
Neutron Sources – Photo-neutron Sources



Calculated neutron energy spectra

Table 7.2 SOURCES OF NEUTRONS (From ICRU 26, 1977)

Source	Reaction	Half Life	Average Neutron Energy (MeV)	Yield n/s/Ci	Characte[r] Problems
Mock Fission (Po+Be+B+Li+F)	α,n	134.4 d	Fission spectrum	4×10^5	α
^{24}Na + Be	γ,n	15 h	0.83	1.3×10^5	γ
^{24}Na + D_2O	γ,n	15 h	0.22	2.7×10^5	γ
^{56}Mn + Be	γ,n	2.58 h	0.1 (90%) 0.3 (10%)	2.9×10^4	γ
^{56}Mn + D_2O	γ,n	2.58 h	0.22	3.1×10^3	γ
^{72}Ga + Be	γ,n	14.1 h	0.78	5×10^4	γ
^{72}Ga + D_2O	γ,n	14.1 h	0.13	6×10^4	γ
^{88}Y + Be	γ,n	107 d	0.16	1×10^5	γ
^{88}Y + D	γ,n	107 d	0.31	3×10^3	γ
^{116}In + Be	γ,n	14 s	0.30	8.2×10^3	γ
^{124}Sb + Be[b]	γ,n	60.2 d	0.024	1.9×10^5	γ
^{140}La + Be	γ,n	40.3 h	0.62	3×10^3	γ
^{140}La + D_2O	γ,n	40.3 h	0.15	8×10^3	γ
^{228}Ra + Be	γ,n	5.75 y	0.83	3.5×10^4	γ
^{228}Ra + D_2O	γ,n	5.75 y	0.20	9.5×10^4	γ
^{226}Ra + Be	α,n	1600 y	Spectrum	3.0×10^4	α, γ, Rn
^{226}Ra + Be	α,n	1600 y	5.0	1.7×10^7	α, γ, Rn
^{226}Ra + B	γ,n	1600 y	3.0	6.8×10^6	α, γ, Rn
^{226}Ra + D_2O	α,n	1600 y	0.12	1×10^3	α, γ, Rn
^{222}Rn + Be	α,n	3.82 d	5	1.5×10^7	α, γ, Rn
^{210}Po + Be	α,n	134.4 d	4	3×10^6	α
^{210}Po + B	α,n	134.4 d	2.5	9×10^5	α
^{210}Po + F	α,n	134.4 d	1.4	4×10^5	α
^{210}Po + Li	α,n	134.4 d	0.42	9×10^4	α
^{227}Ac + Be	α,n	21.8 y	—	—	α
^{238}Pu + Be	α,n	87.7 y	4.5	2.3×10^6	α
^{239}Pu + Be	α,n	2.41×10^4 y	4 (3.2)	1.7×10^6	α
^{241}Am + Be	α,n	432 y	4.5	2.2×10^6	α
^{241}Am + Li	α,n	432 y	0.54	6.0×10^4	α
^{239}Pu (WG)[c]	Spon. Fission	2.41×10^4 y	1.94	63.6	α
^{252}Cf	Spon. Fission	2.64 y	Fission spectrum[a] (2.35)	10^6	α

[a]3.80 ± 0.035 neutrons per fission.
[b]Typically used in reactors – inserted as ^{123}Sb and resultant activation to ^{124}Sb occurs.
[c]WG = Weapons grade, >93% Pu-239.

Neutrons Generated by Accelerated Charged Particles

Neutrons Generated by Accelerated Charged Particles

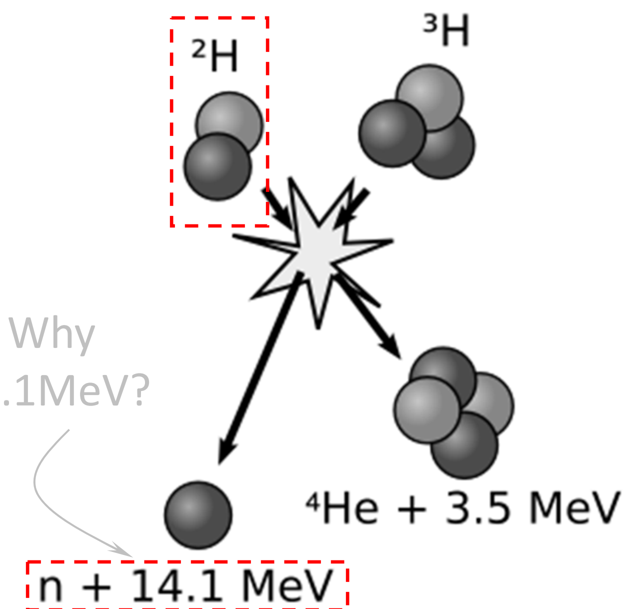
- Neutrons can be produced by nuclear reaction between accelerated charged particles.

The D-D reaction: $^{2}_{1}H + ^{2}_{1}H \Rightarrow ^{3}_{2}He + ^{1}_{0}n$, Q-value: 3.26MeV, En=2.5MeV

The D-T reaction: $^{2}_{1}H + ^{3}_{1}H \Rightarrow ^{4}_{2}He + ^{1}_{0}n$, Q-value: 17.6MeV, En=14.1MeV

Why accelerated?

Why 14.1MeV?



- Due to the Coulomb barrier between the incident deuteron and the light target nucleus, a relatively small accelerating potential is required (about 100 to 300kV) to induce the reaction.

- The neutrons produced by a given nuclear reaction (D-D or D-T) have roughly the same energies.

Page 19-27, Radiation Detection and Measurements, Third Edition, G. F. Knoll, John Wiley & Sons, 1999.

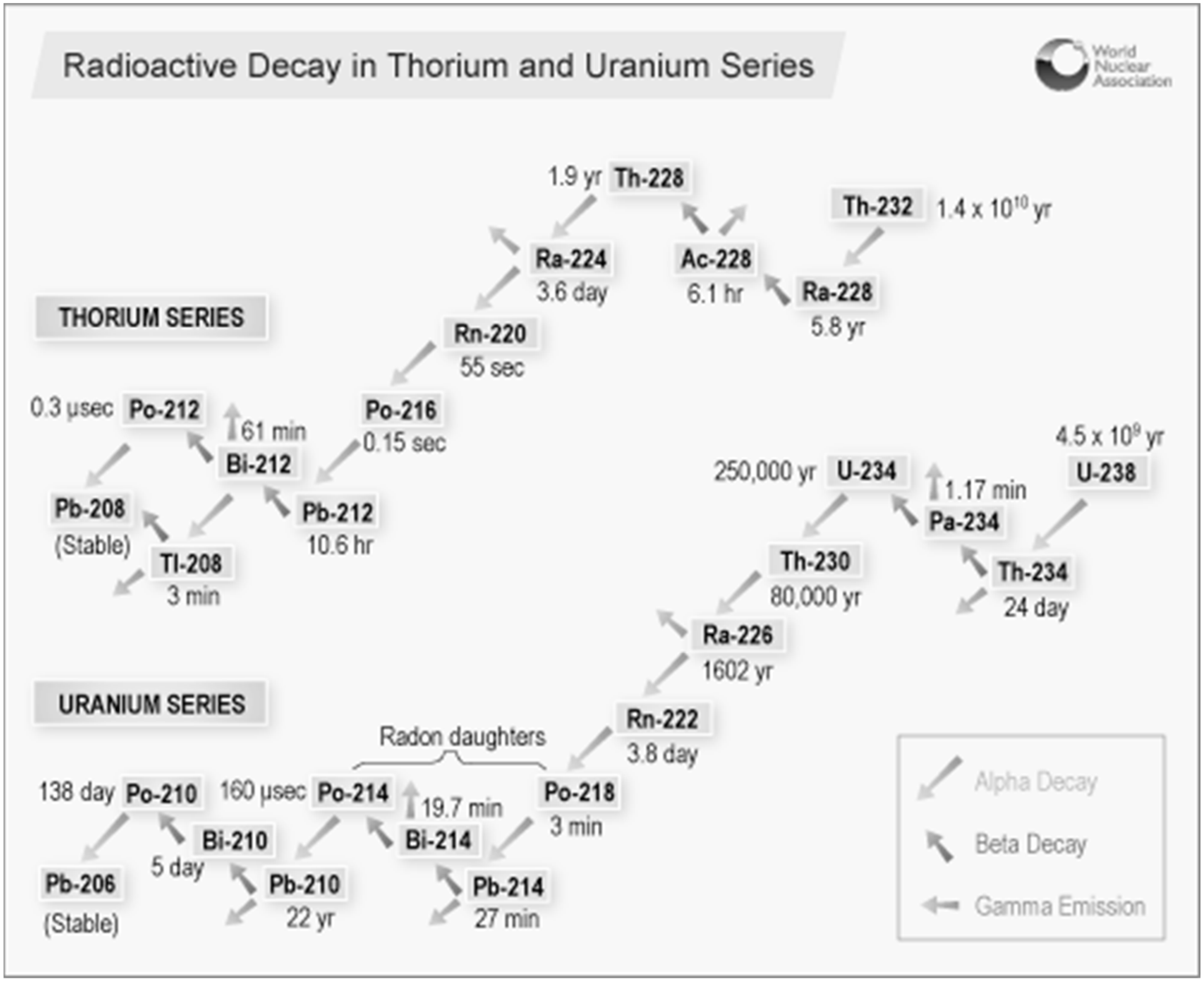
Neutrons Generated by Accelerated Charged Particles

TABLE 9.1. Reactions Used to Produce Monoenergetic Neutrons with Accelerated Protons (p) and Deuterons (d)

Reaction	Q Value (MeV)
$^{3}H(d,n)^{4}He$	17.6
$^{2}H(d,n)^{3}He$	3.27
$^{12}C(d,n)^{13}N$	−0.281
$^{3}H(p,n)^{3}He$	−0.764
$^{7}Li(p,n)^{7}Be$	−1.65

James Tuner, Atoms, radiation and Radiation Protection, p210-p211.

Chapter 1.2: Transformation Kinetics



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

Transformation Kinetics

Exponential Decay

- Different isotopes are characterized by their different rate of transformation (decay).
- The activity of a pure radionuclide decreases exponentially with time. For a given sample, the number of decays within a unit time window around a given time t is a Poisson random variable, whose expectation is given by

$$Q = Q_0 e^{-\lambda \cdot t}$$

- The decay constant λ is the probability of a nucleus of the isotope undergoing a decay within a unit period of time.

Units for Radioactivity

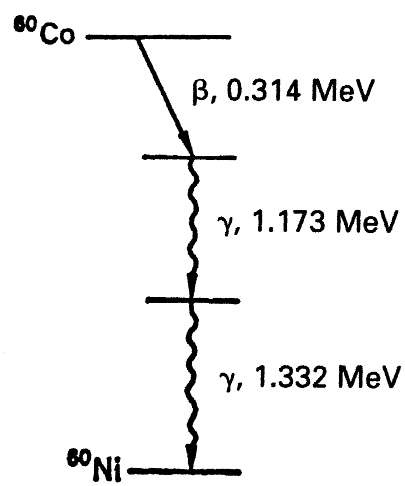
The Becquerel (Bq) – SI standard unit for radioactivity

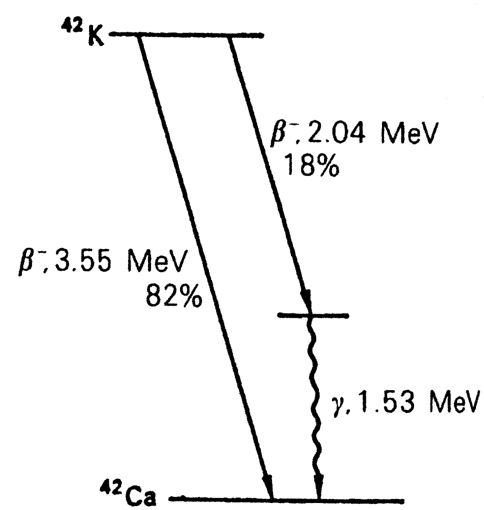
The Becquerel is the quantity of radioactive material in which one atom is transform per second.

$$1Bq = 1tps$$

$$1Curie(Ci) = 3.7 \times 10^{10}\, Bq$$

Note that a Becquerel is not the number of particles emitted by the radioactive isotope in 1 s.





Specific Activity (SA)

Specific activity of a sample is defined as its activity per unit mass, given in units of Bq/g or Ci/g.

Specific activity for pure radioisotopes is defined as the number of Becquerels per unit mass.

$$\text{Specific Activity} = \boxed{\frac{6.03\times10^{23}(atoms/mole)}{A(g/mole)}} \times \lambda \quad Bq/g$$

Activity per unit mass

Number of atoms per unit mass

The probably of an atom decaying within a unit time span

SA can be related to the half-life (T) of the radionuclide by

$$SA = \frac{4.18\times10^{23}}{A\cdot T} Bq/g$$

Derivation of radioactivity as a function of time

General Case

Consider a more general case, in which (a) the half-life of the parent can be of any conceivable value and (b) no restrictions are applied on the relative half-lives of both the parent and the daughter.

$$A \xrightarrow{\lambda_A} B \xrightarrow{\lambda_B} C,$$

The number of atoms of the parent A and the daughter B at any given time t are therefore related by

$$N_B = \frac{\lambda_A N_{A_0}}{\lambda_B - \lambda_A}\left(e^{-\lambda_A t} - e^{-\lambda_B t}\right)$$

Proof of the Previous Serial Decay Equation
From Cember, p123-124

of the daughter, it follows that secular equilibrium is a special case of a more general situation in which the half-life of the parent may be of any conceivable magnitude, but greater than that of the daughter. For this general case, where the parent activity is not relatively constant,

$$A \xrightarrow{\lambda_A} B \xrightarrow{\lambda_B} C,$$

the time rate of change of the number of atoms of species B is given by the differential equation

$$\frac{dN_B}{dt} = \lambda_A N_A - \lambda_B N_B. \tag{4.42}$$

In this equation, $\lambda_A N_A$ is the rate of transformation of species A and is exactly equal to the rate of formation of species B, the rate of transformation of isotope B is $\lambda_B N_B$, and the difference between these two rates at any time is the instantaneous rate of growth of species B at that time.

According to Eq. (4.18), the value of λ_A in Eq. (4.42) may be written as

$$N_A = N_{A_0} e^{-\lambda t}. \tag{4.43}$$

Equation (4.42) may be rewritten, after substituting the expression above for N_A and transposing $\lambda_B N_B$, as

$$\frac{dN_B}{dt} + \lambda_B N_B = \lambda_A N_{A_0} e^{-\lambda_A t}. \tag{4.44}$$

Proof of The Serial Decay Equation (Continued)

$$\frac{\mathrm{d}N_B}{\mathrm{d}t} + \lambda_B N_B = \lambda_A N_{A_0} e^{-\lambda_A t}. \tag{4.44}$$

Equation (4.44) is a first-order linear differential equation of the form

$$\frac{\mathrm{d}y}{\mathrm{d}t} + P(t)y = Q(t) \tag{4.45}$$

and may be integrable by multiplying both sides of the equation by

$$e^{\int P\,\mathrm{d}x} = e^{\int \lambda_B\,\mathrm{d}t} = e^{\lambda_B t},$$

and the solution to Eq. (4.45) is

$$y(t) = \frac{\int \mathrm{e}^{\int P(t)\cdot \mathrm{d}t} \cdot Q(t) \cdot \mathrm{d}t}{\mathrm{e}^{\int P(t)\cdot \mathrm{d}t}} \qquad \begin{cases} P(t) = \lambda_B \\ Q(t) = \lambda_A N_{A_0} \mathrm{e}^{-\lambda_A t} \end{cases} \tag{4.46}$$

Since N_B, λ_B, and $\lambda_A N_{A_0} e^{-\lambda_A t}$ from Eq. (4.44) are represented in Eq. (4.46) by y, P, and Q, respectively, the solution of Eq. (4.44) is

$$N_B e^{\lambda_B t} = \int e^{\lambda_B t} \lambda_A N_{A_0} e^{-\lambda_A t}\,\mathrm{d}t + C \tag{4.47}$$

or, if the two exponentials are combined, we have

$$N_B e^{-\lambda_B t} = \int \lambda_A N_{A_0} e^{(\lambda_B - \lambda_A)t}\,\mathrm{d}t + C. \tag{4.48}$$

Proof of The Serial Decay Equation (Continued)

$$N_B e^{-\lambda_B t} = \int \lambda_A N_{A_0} e^{(\lambda_B - \lambda_A)t}\,\mathrm{d}t + C. \tag{4.48}$$

If the integrand in Eq. (4.48) is multiplied by the integrating factor $\lambda_B - \lambda_A$, then Eq. (4.48) is in the form

$$\int e^v \mathrm{d}v = e^v + C \tag{4.49}$$

and the solution is

$$N_B e^{\lambda_B t} = \frac{1}{\lambda_B - \lambda_A} \lambda_A N_{A_0} e^{(\lambda_B - \lambda_A)t} + C. \tag{4.50}$$

The constant C may be evaluated by applying the boundary conditions

$$N_B = 0 \text{ when } t = 0$$

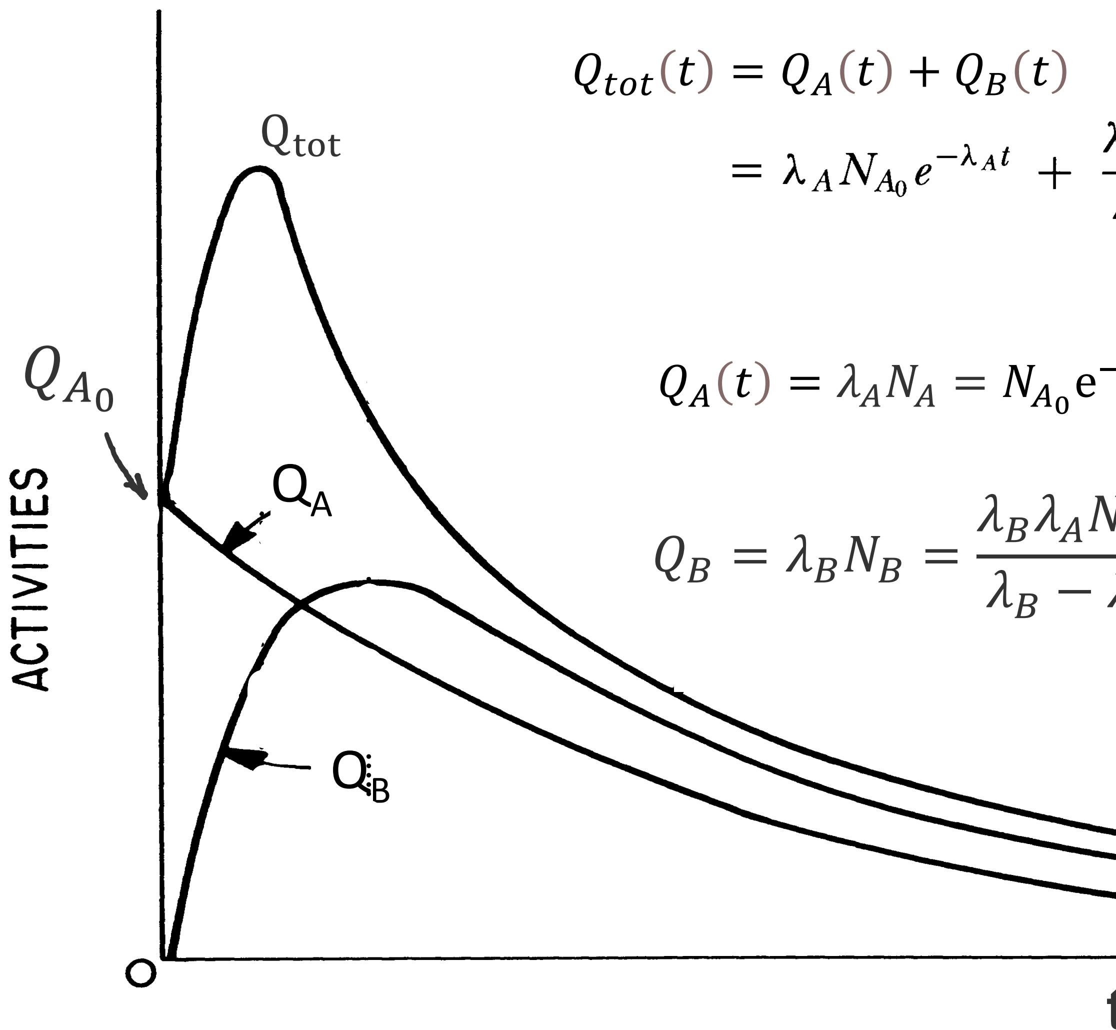
$$0 = \frac{1}{\lambda_B - \lambda_A} \lambda_A \times N_{A_0} + C$$

$$C = -\frac{\lambda_A N_{A_0}}{\lambda_B - \lambda_A}. \tag{4.51}$$

If the value for C, from Eq. (4.51), is substituted into Eq. (4.50), the solution for N_B

$$N_B = \frac{\lambda_A N_{A_0}}{\lambda_B - \lambda_A}\left(\mathrm{e}^{-\lambda_A t} - \mathrm{e}^{-\lambda_B t}\right)$$

Activity Peaking Times Under General Case



$$Q_{tot}(t) = Q_A(t) + Q_B(t)$$
$$= \lambda_A N_{A_0} e^{-\lambda_A t} + \frac{\lambda_B \lambda_A N_{A_0}}{\lambda_B - \lambda_A}\left(e^{-\lambda_A t} - e^{-\lambda_B t}\right).$$

$$Q_A(t) = \lambda_A N_A = N_{A_0} \mathrm{e}^{-\lambda_A t}$$

$$Q_B = \lambda_B N_B = \frac{\lambda_B \lambda_A N_{A0}}{\lambda_B - \lambda_A}\left(\mathrm{e}^{-\lambda_A t} - \mathrm{e}^{-\lambda_B t}\right)$$

Activity Peaking Time Under General Case

The peak-reaching-time for the activity from the daughter can be derived as the following:

Start from the equation for the general case

$$\lambda_B N_B = \frac{\lambda_B \lambda_A N_{A_0}}{\lambda_B - \lambda_A}\left(e^{-\lambda_A t} - e^{-\lambda_B t}\right)$$

Differentiate respect to t and set to zero

$$\frac{\mathrm{d}(\lambda_B N_B)}{\mathrm{d}t} = \frac{\lambda_B \lambda_A N_{A_0}}{\lambda_B - \lambda_A}\left(-\lambda_A e^{-\lambda_A t} + \lambda_B e^{-\lambda_B t}\right) = 0,$$

$$\lambda_A e^{-\lambda_{At}} = \lambda_B e^{-\lambda_B t}$$

and therefore

$$\ln \frac{\lambda_\mathrm{B}}{\lambda_\mathrm{A}} = (\lambda_B - \lambda_A)\, t$$

$$t = t_\mathrm{md} = \frac{\ln(\lambda_\mathrm{B}/\lambda_\mathrm{A})}{\lambda_B - \lambda_A} = \frac{2.3 \log(\lambda_B/\lambda_A)}{\lambda_B - \lambda_A}.$$

Activity Peaking Time Under General Case

Similarly, the peak reaching times for the total activity is …

The total activity is

$$Q(t) = \lambda_A N_A(t) + \lambda_B N_B(t)$$

Since

$$Q_B(t) = \lambda_B N_B = \frac{\lambda_B \lambda_A N_{A_0}}{\lambda_B - \lambda_A}\left(e^{-\lambda_A t} - e^{-\lambda_B t}\right) \quad \text{and} \quad Q_A(t) = N_{A_0} \mathrm{e}^{-\lambda_A t}$$

then

$$Q_{tot}(t) = \lambda_A N_{A_0} e^{-\lambda_A t} + \frac{\lambda_B \lambda_A N_{A_0}}{\lambda_B - \lambda_A}\left(e^{-\lambda_A t} - e^{-\lambda_B t}\right).$$

Differentiate respect to t and set to zero, we have

$$\frac{dQ_{tot}(t)}{dt} = -\lambda_A^2 N_{A_0} e^{-\lambda_A t} + \frac{\lambda_B \lambda_A N_{A_0}}{\lambda_B - \lambda_A}\left(-\lambda_A e^{-\lambda_A t} + \lambda_B e^{-\lambda_B t}\right) = 0.$$

Solving for *t*, it can be shown that

$$t = t_{\mathrm{mt}} = \frac{1}{\lambda_B - \lambda_A} \ln\left(\frac{\lambda_B^2}{2\lambda_A \lambda_B - \lambda_A^2}\right)$$

Activity Peaking Times Under General Case

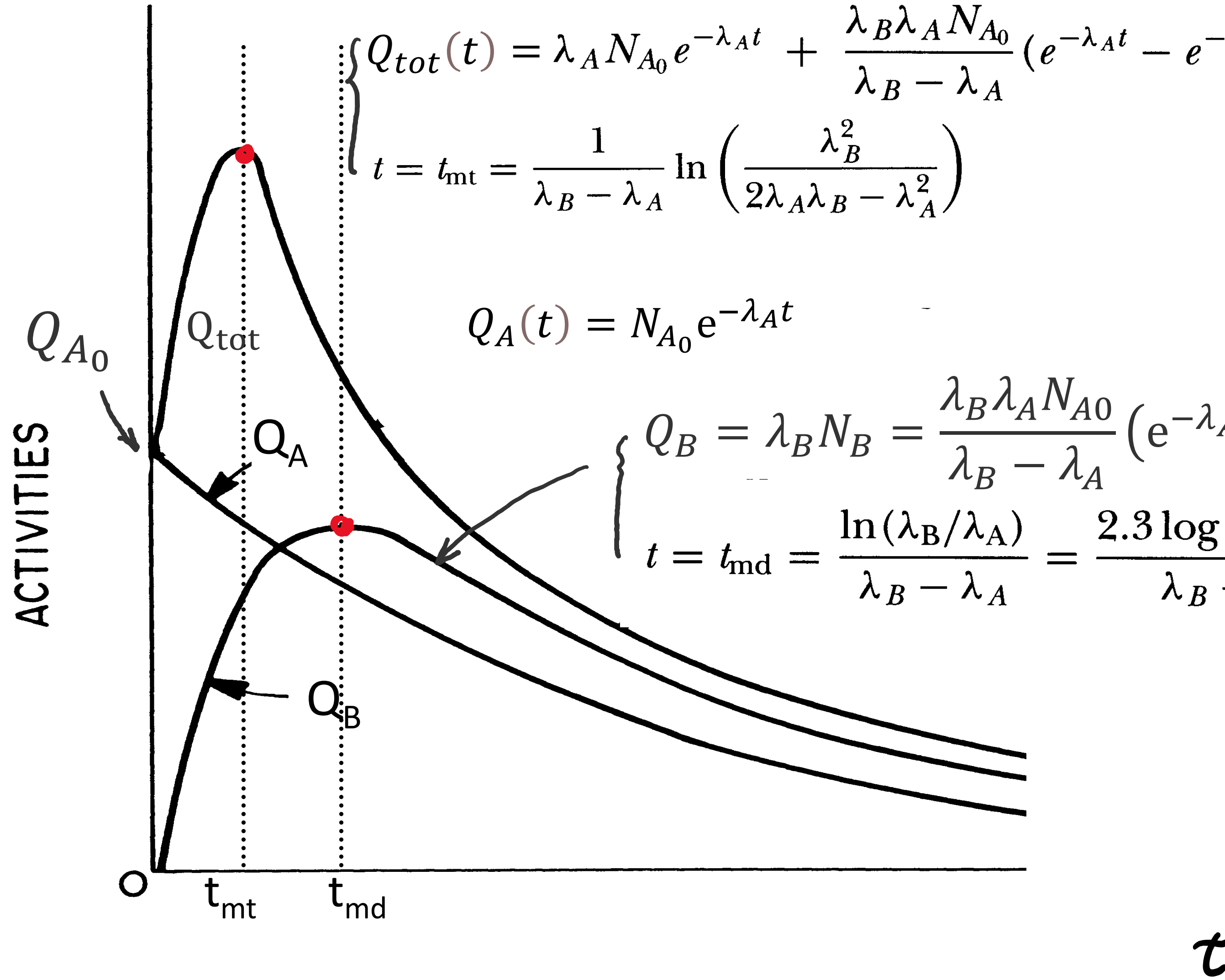
$$Q_{tot}(t) = \lambda_A N_{A_0} e^{-\lambda_A t} + \frac{\lambda_B \lambda_A N_{A_0}}{\lambda_B - \lambda_A}\left(e^{-\lambda_A t} - e^{-\lambda_B t}\right).$$

$$t = t_{\mathrm{mt}} = \frac{1}{\lambda_B - \lambda_A} \ln\left(\frac{\lambda_B^2}{2\lambda_A\lambda_B - \lambda_A^2}\right)$$

$$Q_A(t) = N_{A_0} \mathrm{e}^{-\lambda_A t}$$

$$Q_B = \lambda_B N_B = \frac{\lambda_B \lambda_A N_{A0}}{\lambda_B - \lambda_A}\left(\mathrm{e}^{-\lambda_A t} - \mathrm{e}^{-\lambda_B t}\right)$$

$$t = t_{\mathrm{md}} = \frac{\ln(\lambda_\mathrm{B}/\lambda_\mathrm{A})}{\lambda_B - \lambda_A} = \frac{2.3 \log(\lambda_B/\lambda_A)}{\lambda_B - \lambda_A}$$



Further Discussions on Serial Transformations

Now, I know the question burning in your mind is, "What if species C is also radioactive?" This is certainly possible; in fact some of the most important and interesting problems in health physics involve long chains of products, one decaying to the next until a stable species is reached. So now let's solve for the situation:

$$A \xrightarrow{\lambda_A} B \xrightarrow{\lambda_B} C \xrightarrow{\lambda_C} D$$

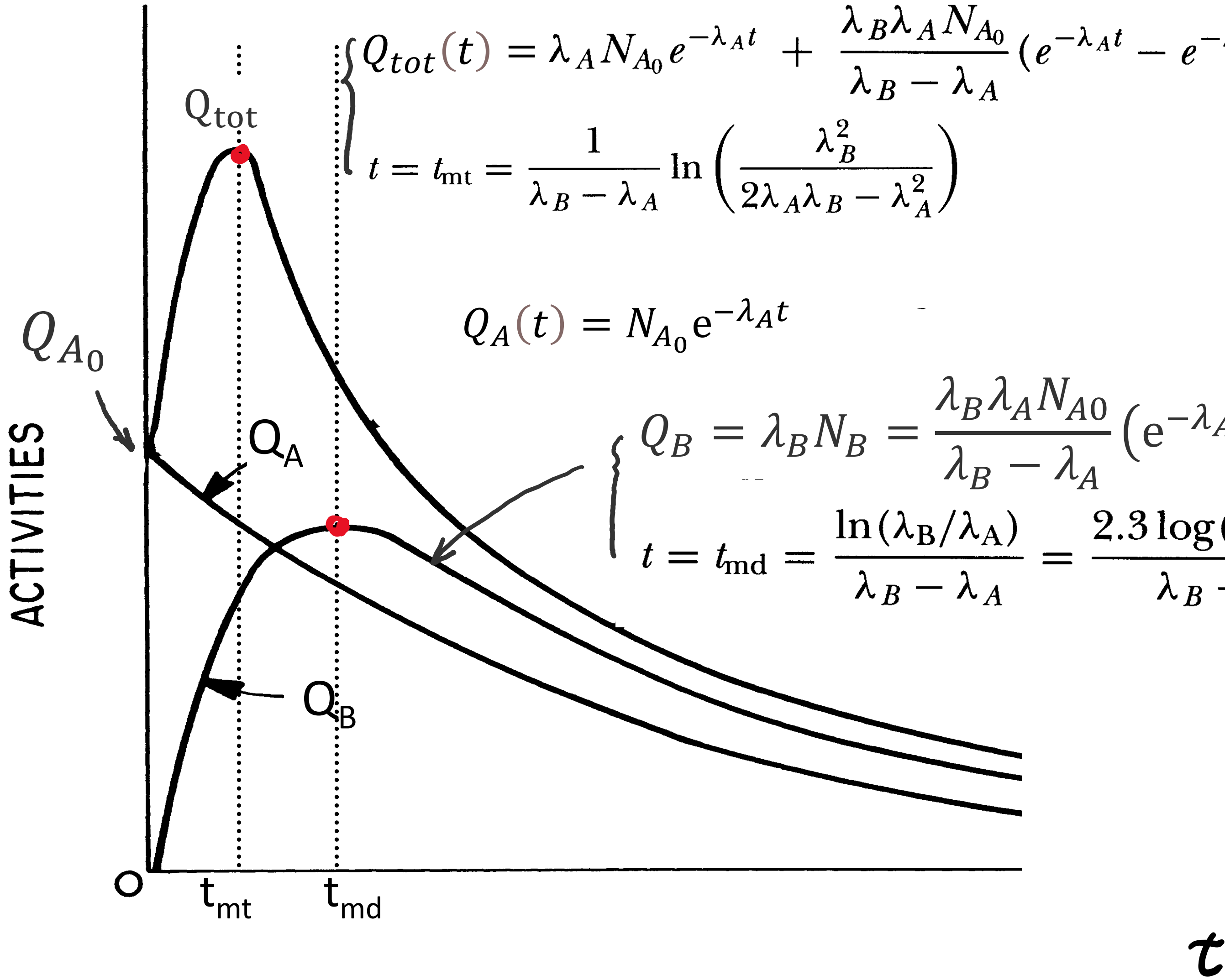
Several Special Cases

Activity Peaking Times Under General Case

$$\begin{cases} Q_{tot}(t) = \lambda_A N_{A_0} e^{-\lambda_A t} + \dfrac{\lambda_B \lambda_A N_{A_0}}{\lambda_B - \lambda_A}\left(e^{-\lambda_A t} - e^{-\lambda_B t}\right). \\ t = t_{\mathrm{mt}} = \dfrac{1}{\lambda_B - \lambda_A} \ln\left(\dfrac{\lambda_B^2}{2\lambda_A\lambda_B - \lambda_A^2}\right) \end{cases}$$

$$Q_A(t) = N_{A_0} \mathrm{e}^{-\lambda_A t}$$

$$\begin{cases} Q_B = \lambda_B N_B = \dfrac{\lambda_B \lambda_A N_{A0}}{\lambda_B - \lambda_A}\left(\mathrm{e}^{-\lambda_A t} - \mathrm{e}^{-\lambda_B t}\right) \\ t = t_{\mathrm{md}} = \dfrac{\ln(\lambda_{\mathrm{B}}/\lambda_{\mathrm{A}})}{\lambda_B - \lambda_A} = \dfrac{2.3 \log(\lambda_B/\lambda_A)}{\lambda_B - \lambda_A} \end{cases}$$



Secular Equilibrium: $T_A >> T_B$ ($\lambda_A << \lambda_B$)

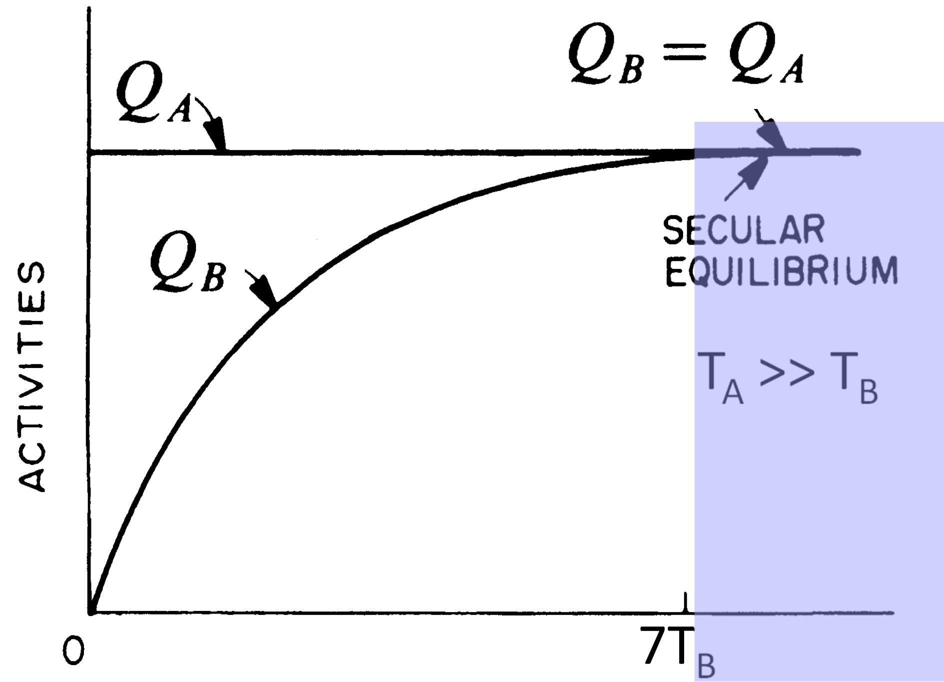
From this relationship,

$$N_B = \frac{\lambda_A N_A}{\lambda_B}(1 - e^{-\lambda_B t}).$$

$$Q_B = Q_A(1 - e^{-\lambda_B t}),$$

one can see that

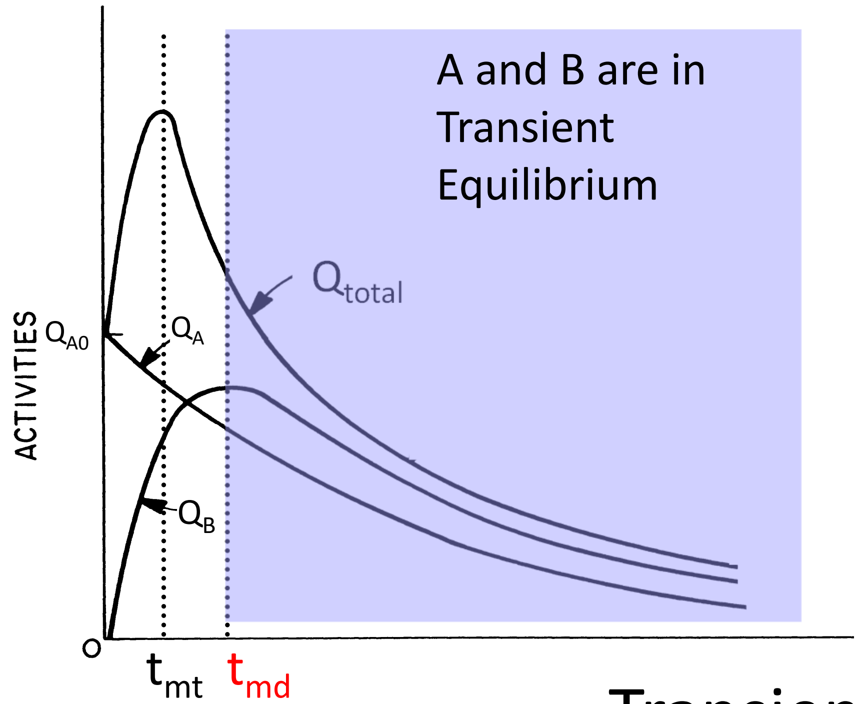
1. As the time goes by, $e^{-\lambda_B t}$ decreases and Q_B approaches Q_A. At equilibrium, we have



$$\boxed{\lambda_A N_A = \lambda_B N_B \ \ and \ \ Q_A = Q_B}$$

2. Since A has a relatively long half life, Q_A may be considered as a constant. So the total activity converges to a constant.

Transient Equilibrium: $T_A \geq T_B$ ($\lambda_A \leq \lambda_B$) and $t > t_{md}$



General case

$$\lambda_B N_B = \frac{\lambda_B \lambda_A N_{A_0}}{\lambda_B - \lambda_A}(e^{-\lambda_A t} - e^{-\lambda_B t})$$

$$\approx 0$$

Transient Equilibrium

$$\lambda_B N_B \cong \frac{\lambda_B \lambda_A N_A}{\lambda_B - \lambda_A}$$

$$Q_B \cong \frac{\lambda_B}{\lambda_B - \lambda_A} Q_A$$

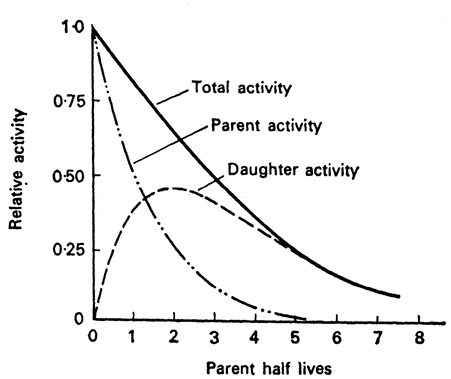
Summary of Serial Transformations

$$A \xrightarrow{\lambda_A} B \xrightarrow{\lambda_B} C,$$

General case

$T_A > T_B$

$$\boxed{N_B = \frac{\lambda_A N_{A_0}}{\lambda_B - \lambda_A}\left(e^{-\lambda_A t} - e^{-\lambda_B t}\right)}$$

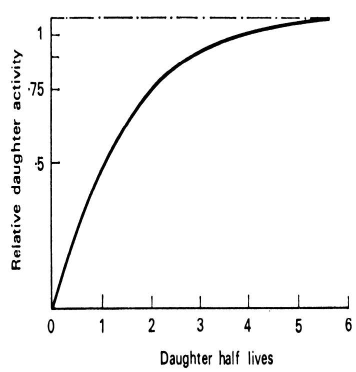


Secular Equilibrium

$T_A >> T_B$,

$t > 7T_B$

$$\boxed{Q_B = Q_A}$$

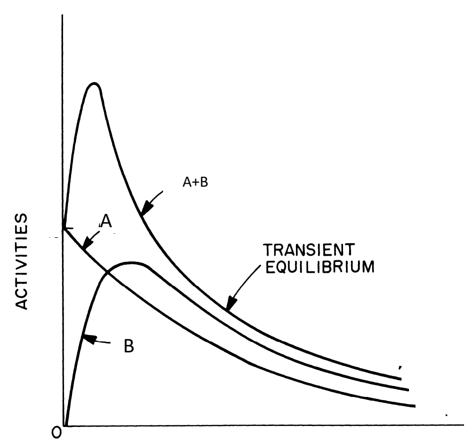


Transient Equilibrium

$T_A \geq T_B$

$t > T_{md}$

$$\boxed{Q_B = \frac{\lambda_B}{\lambda_B - \lambda_A} Q_A}$$



No Equilibrium

$T_A < T_B$
