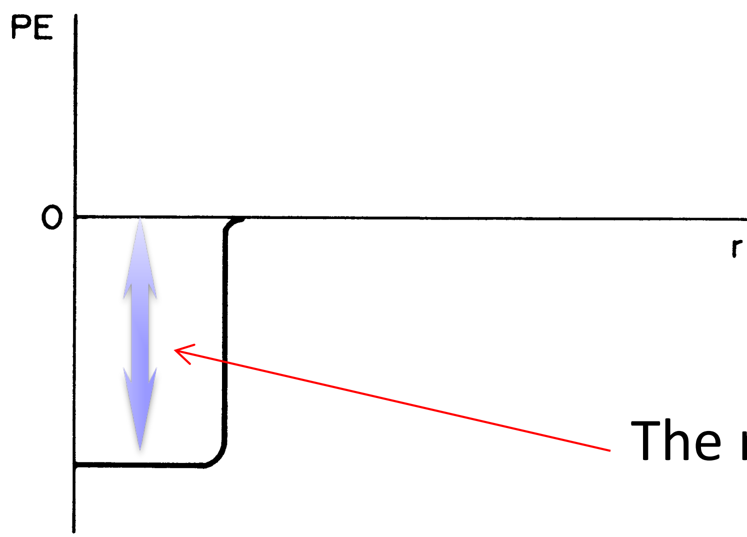
Alpha Decay

Key concepts

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

Nuclear Binding Energy

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



The nuclear binding energy

(b) NEUTRON - NUCLEUS

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

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

Average Binding Energy Per Nucleon

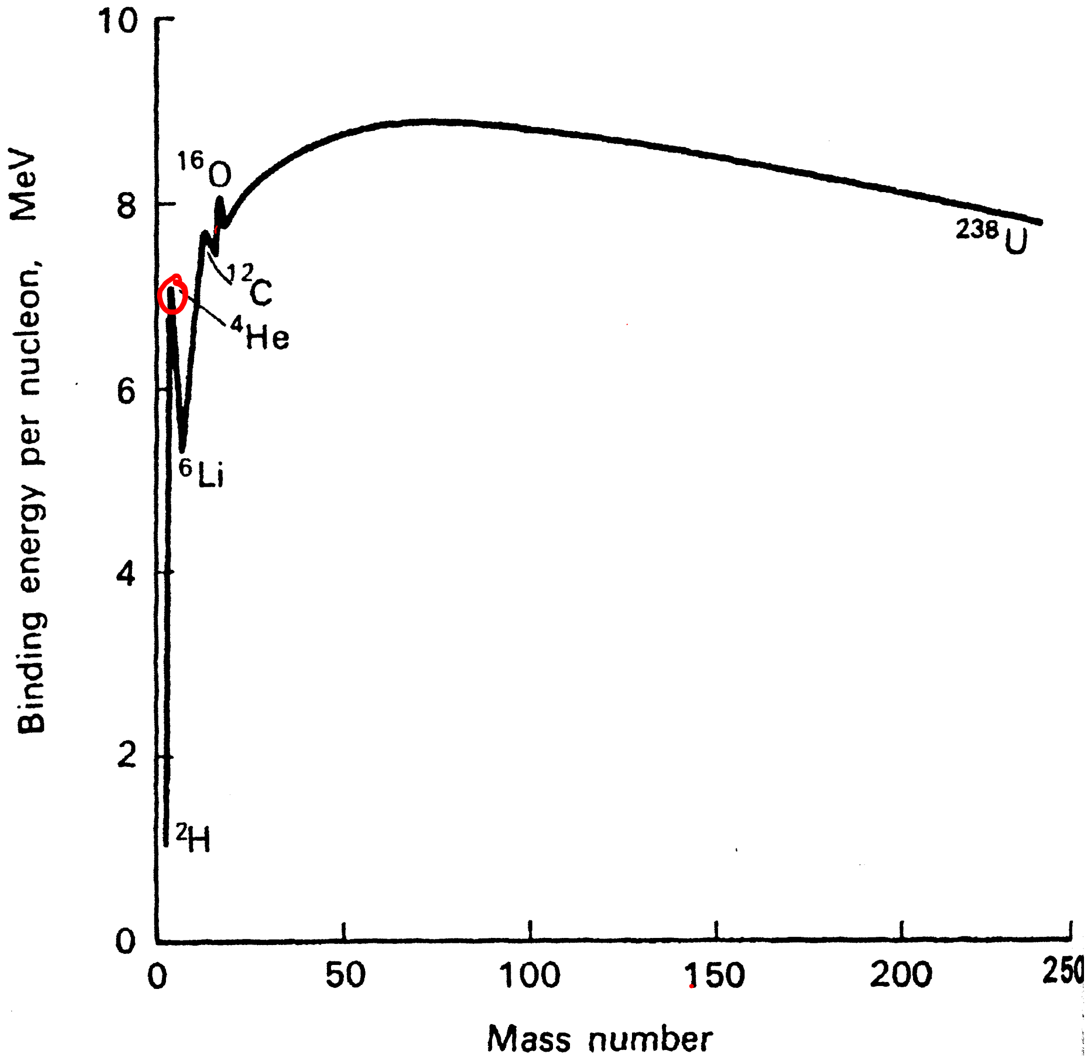
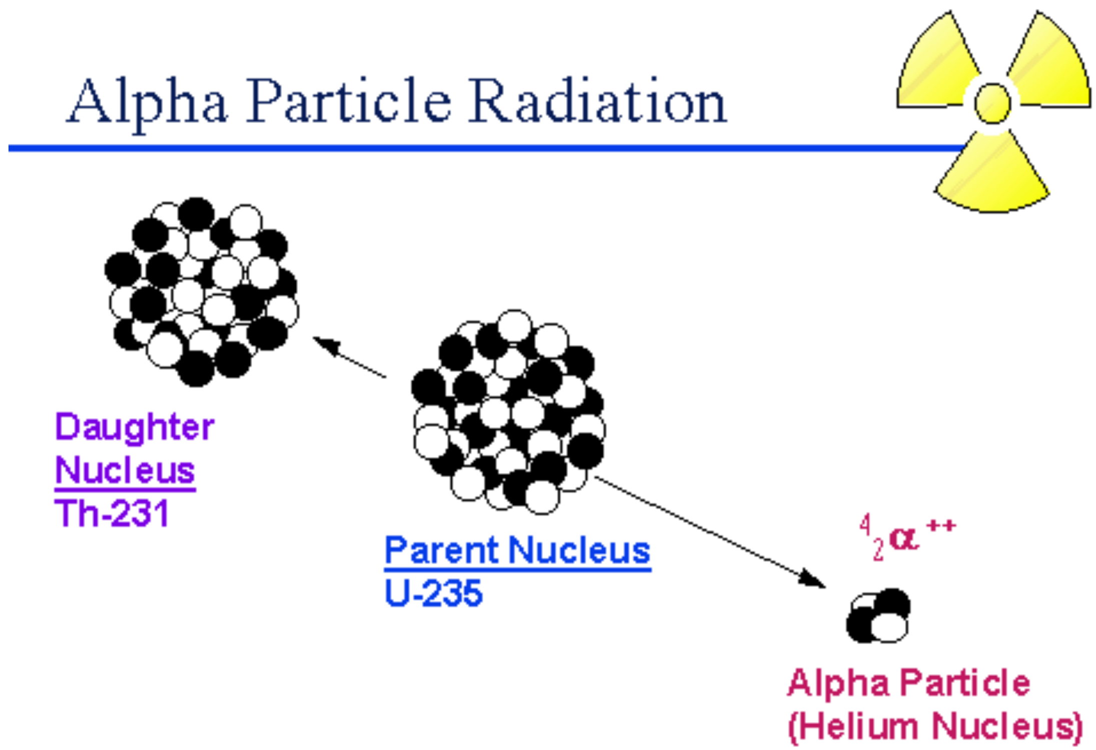


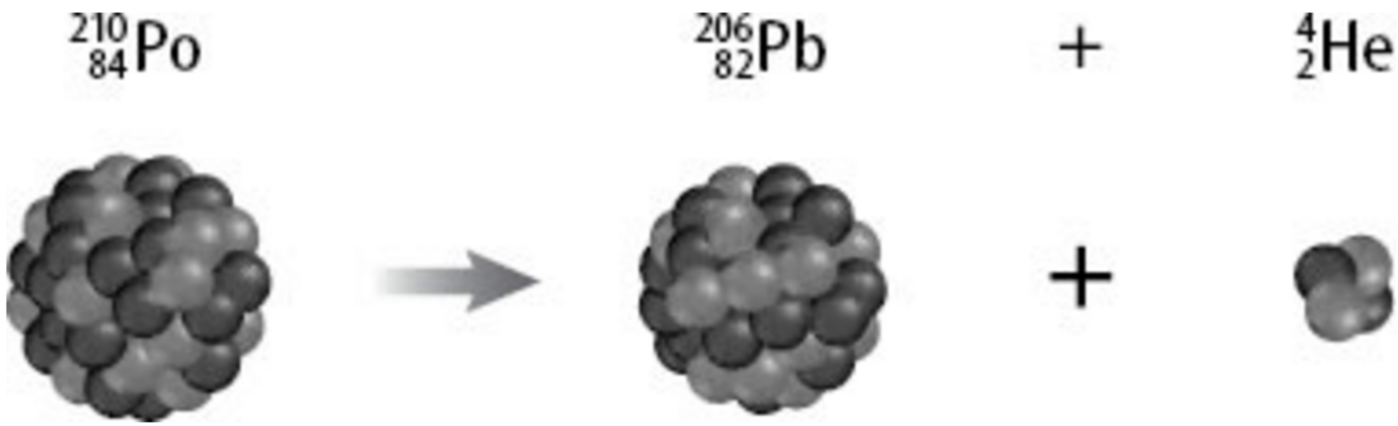
FIGURE 3.5. Variation of binding energy per nucleon with atomic mass num

Alpha Emission

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

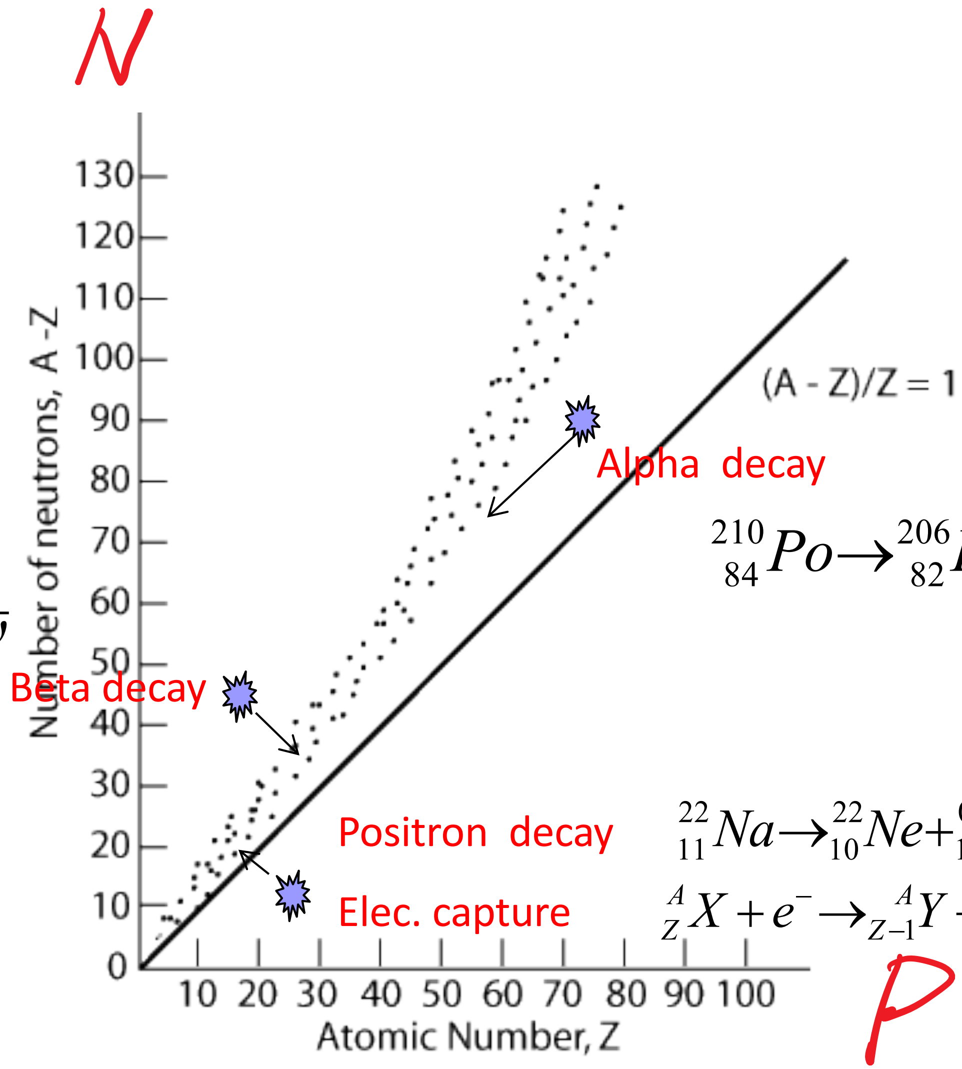


Alpha Decay – An Example



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

Ways to Achieve Increased Nuclear Stability and the Origin of Nuclear Radiation



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

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

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

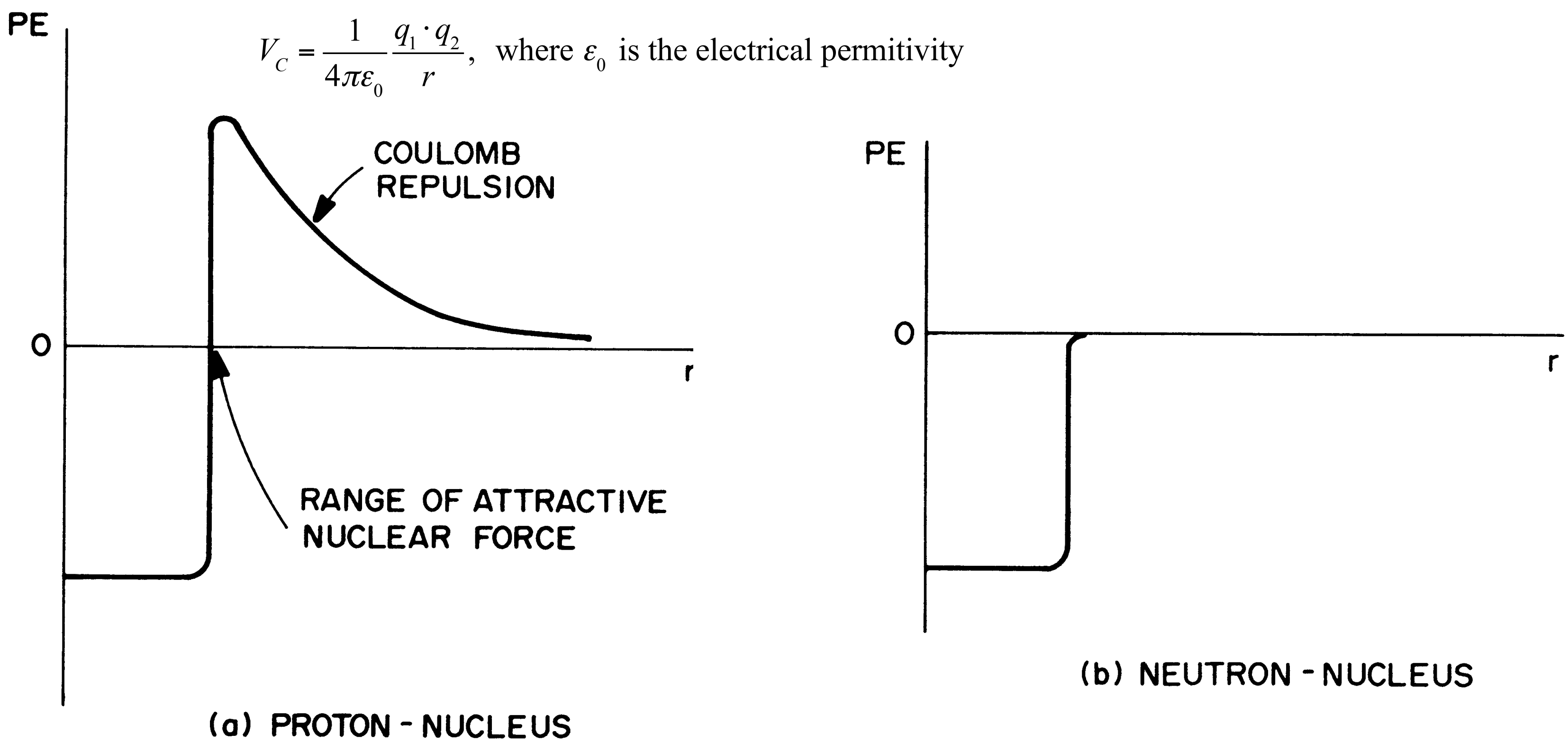
Elec. capture: $${}^{A}_{Z}X + e^{-} \rightarrow {}^{A}_{Z-1}Y + \upsilon$$

Potential Energy of Nucleus

- Nucleons are bounded together in nucleus by the strong force, which has a short range of ~10^{-15}m.
- The strong force is powerful enough to overcome the Coulomb repulsion between the positively charged protons.

Coulomb potenital

$$V_C = \frac{1}{4\pi\varepsilon_0}\frac{q_1 \cdot q_2}{r},$$ where ε_0 is the electrical permitivity



Alpha Emission

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

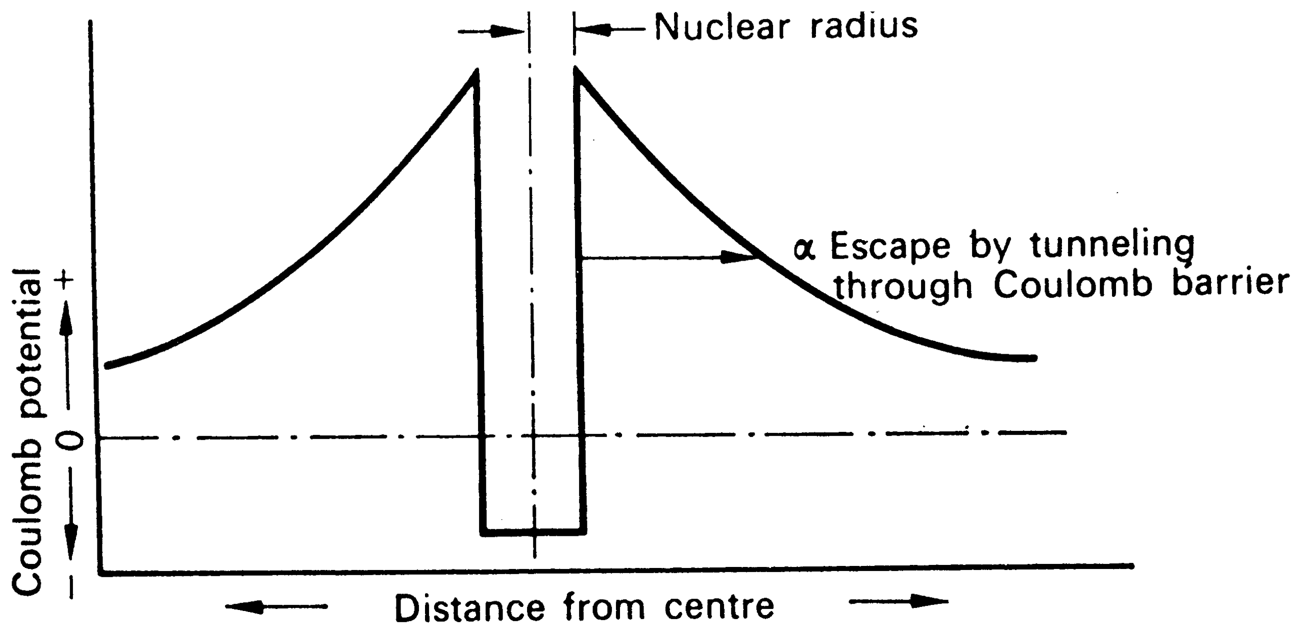


FIG. 4.1. Potential inside and in the vicinity of a nucleus.

Alpha Decay

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

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

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

Energy Release from Alpha Decay

An example: Alpha decay of ^{226}Ra

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

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

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

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

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

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

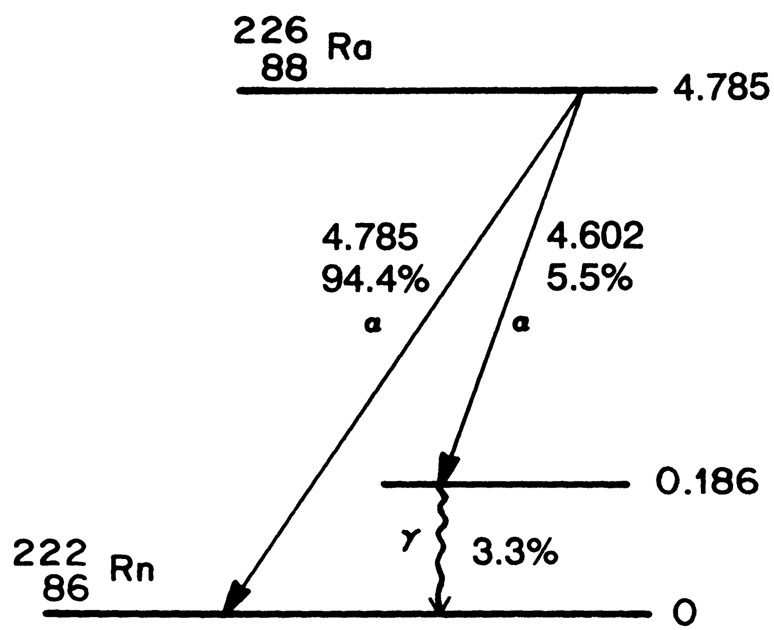


FIGURE 3.4. Nuclear decay scheme of $^{226}_{88}$Ra.

Understanding the Mass Defect and Nuclear Binding Energy Table

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

Energy Release in Alpha Emission

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:

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

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

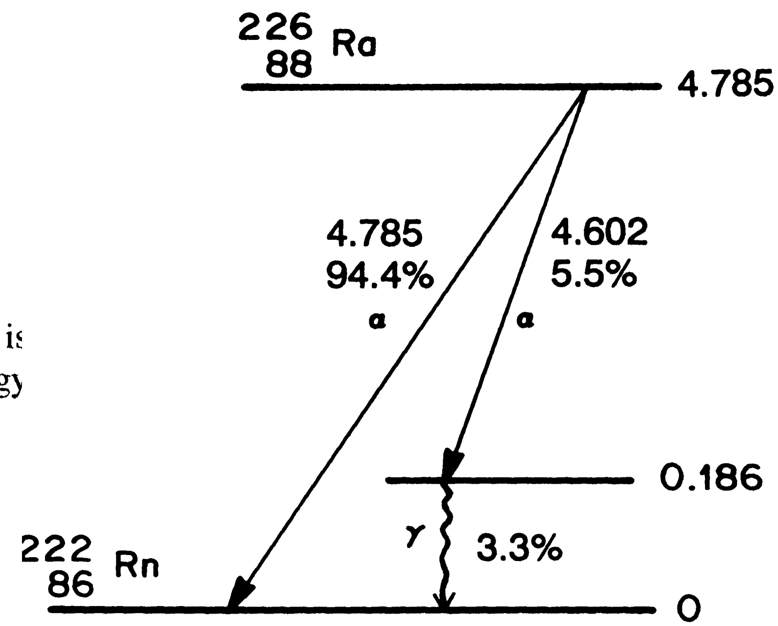


FIGURE 3.4. Nuclear decay scheme of $^{226}_{88}$Ra.

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.

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

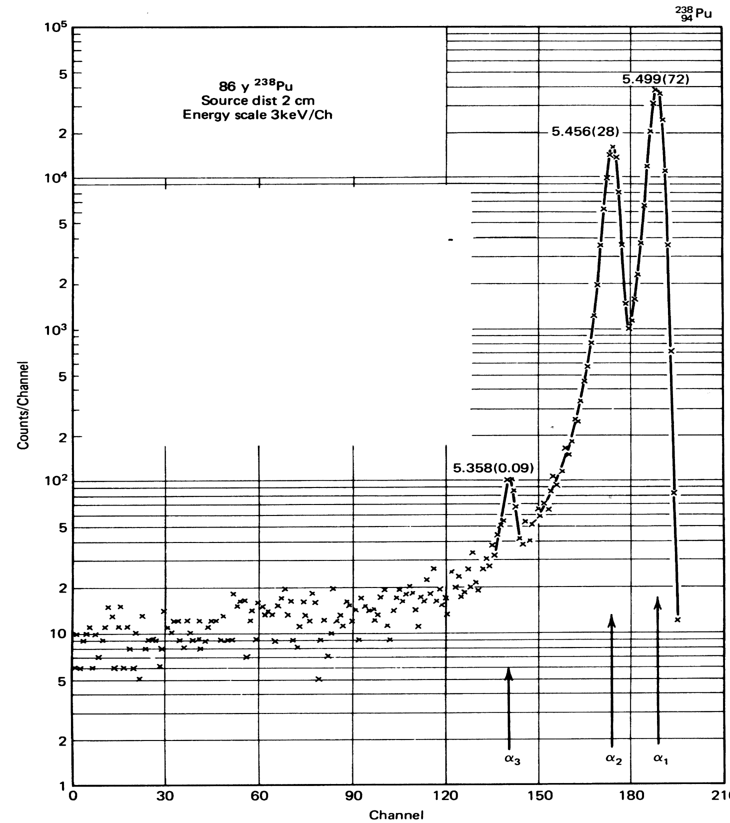
$$E = \frac{mv^2}{2}$$

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

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

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

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



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

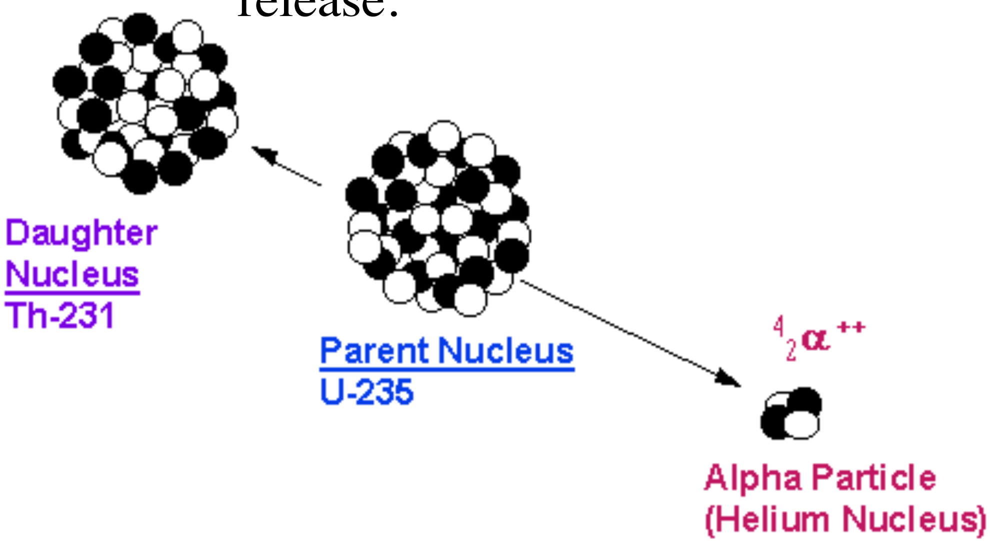
Energy Spectra of Alpha Particles

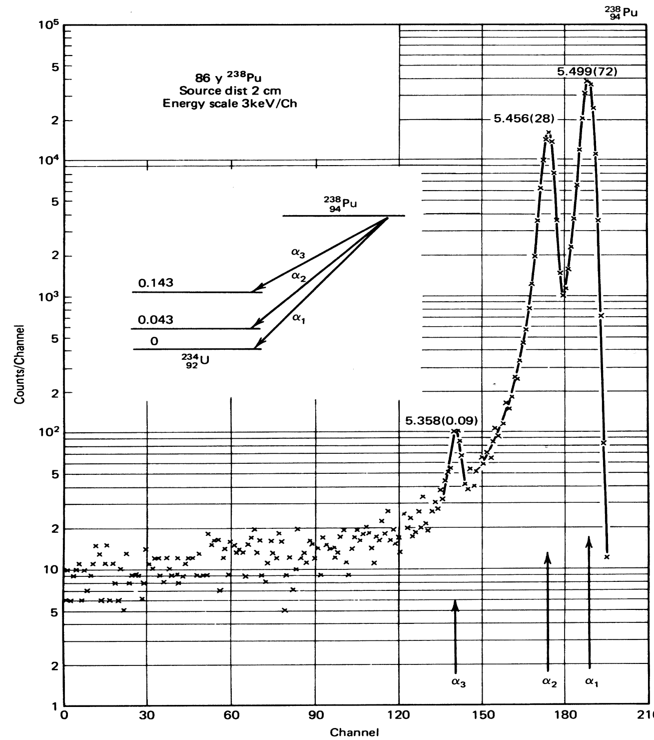
Alpha decays are sometimes accompanied by the excited daughter products which complicates the resultant alpha particle spectra.

The kinetic energy of alpha particles is given by

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

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





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

Half-Life of Alpha Emitters

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

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

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

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

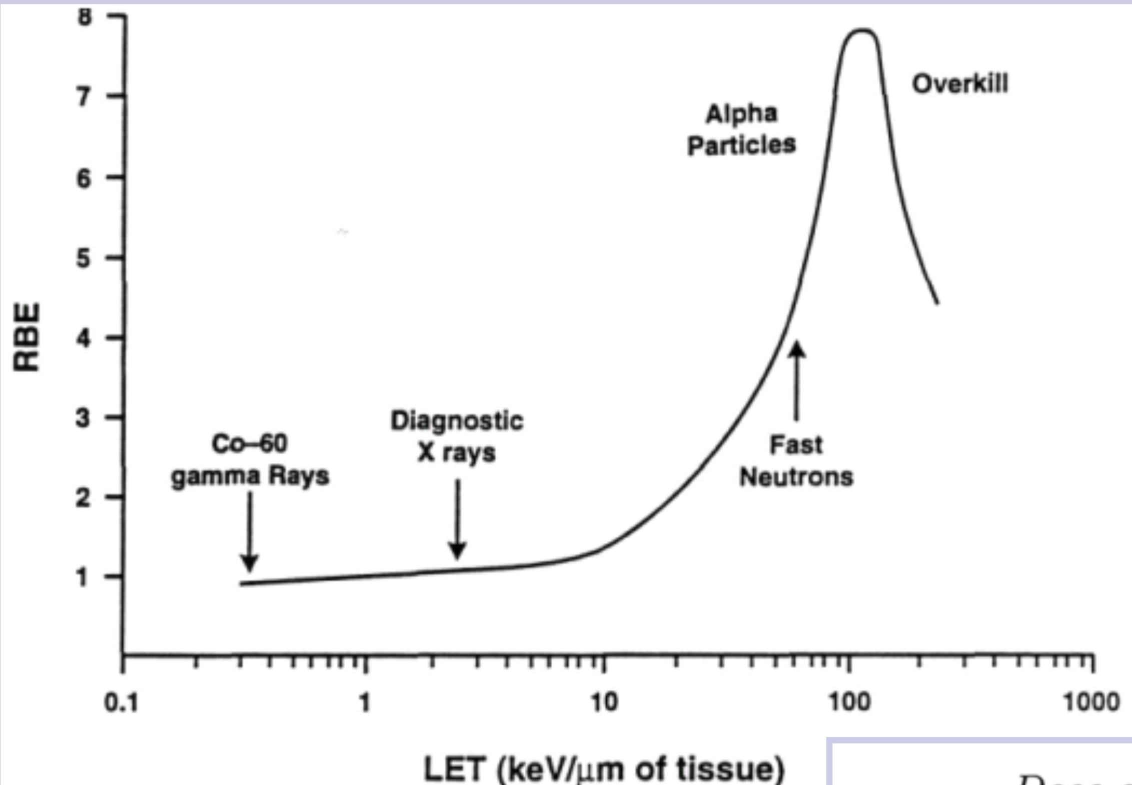
A Few Remarks

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

Alpha Emission and Potential Health Concerns

Radiation Effect and Dose Delivery

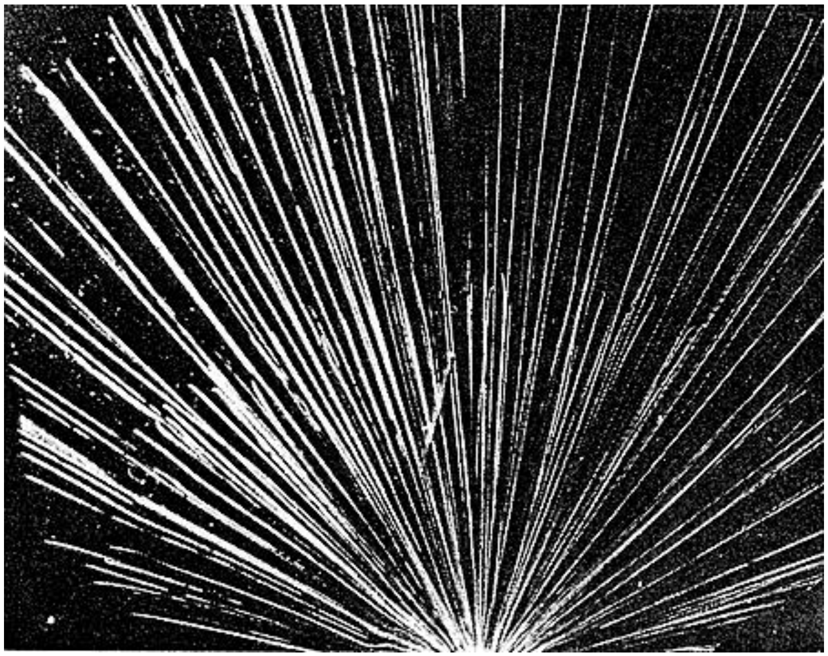
For low LET radiation, ⇒ RBE ∝ LET, for higher LET the RBE increases to a maximum, the subsequent drop is caused by the overkill effect.



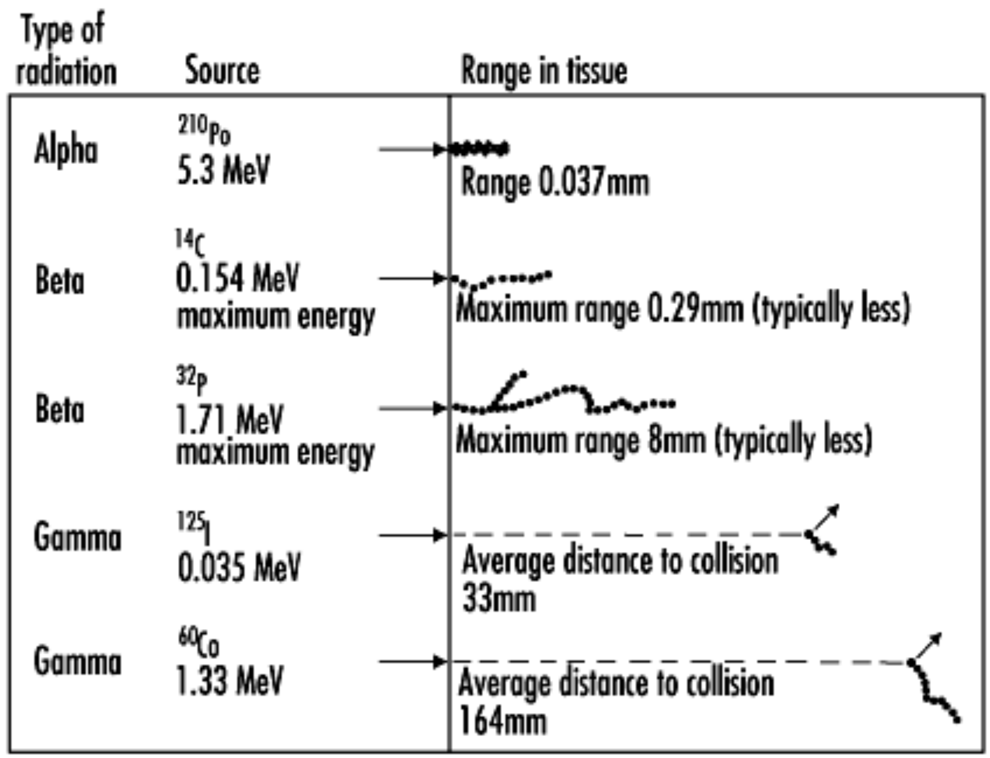
$$RBE = \frac{Dose\ of\ 150\ V\ \ X - rays\ required\ to\ cause\ effect\ x}{Dose\ of\ radiation\ required\ to\ cause\ effect\ x}$$

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

Alpha Emission and Radiation Hazard



J. Chadwick, Cavendish Laboratory, University of Cambridge.



Source: Shapiro 1972.

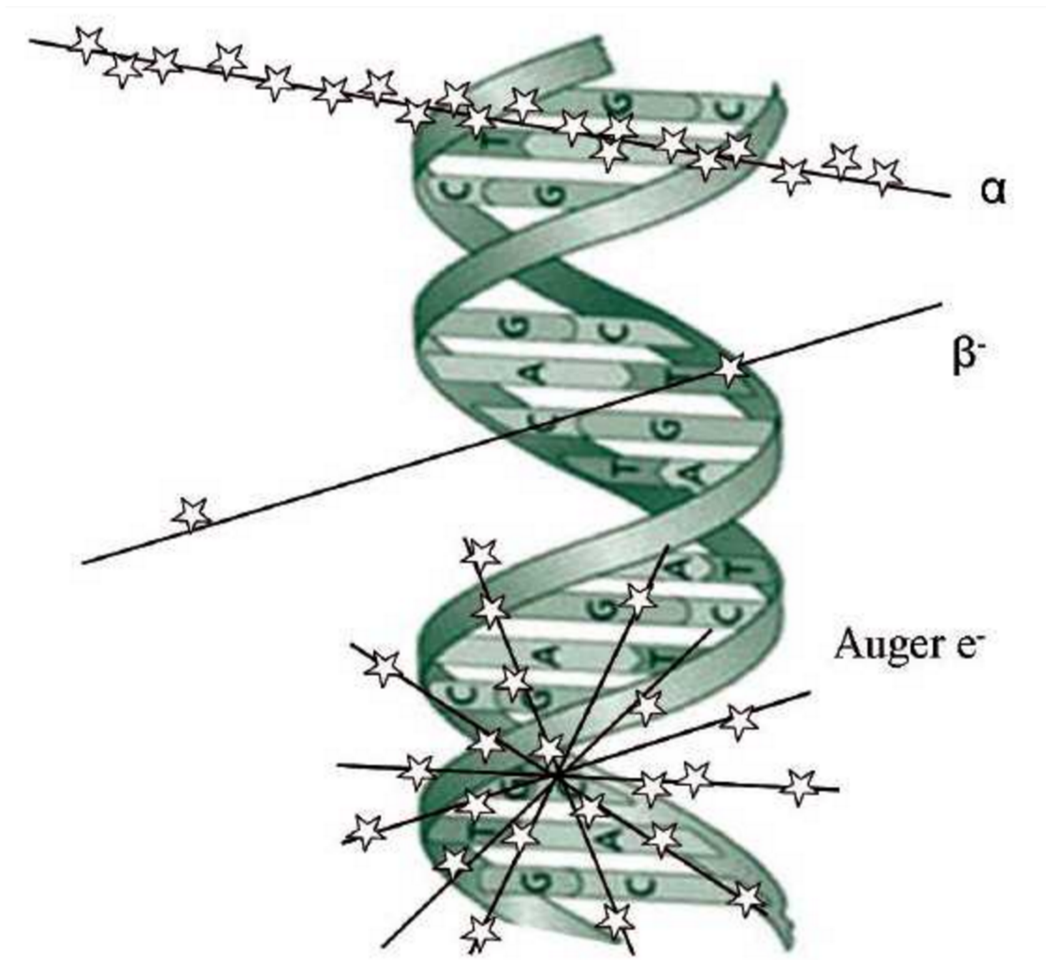
Encyclopaedia of Occupational Health and Safety 4th Edition, from the International Labor Office

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.

Rn-220 in the Cloud Chamber

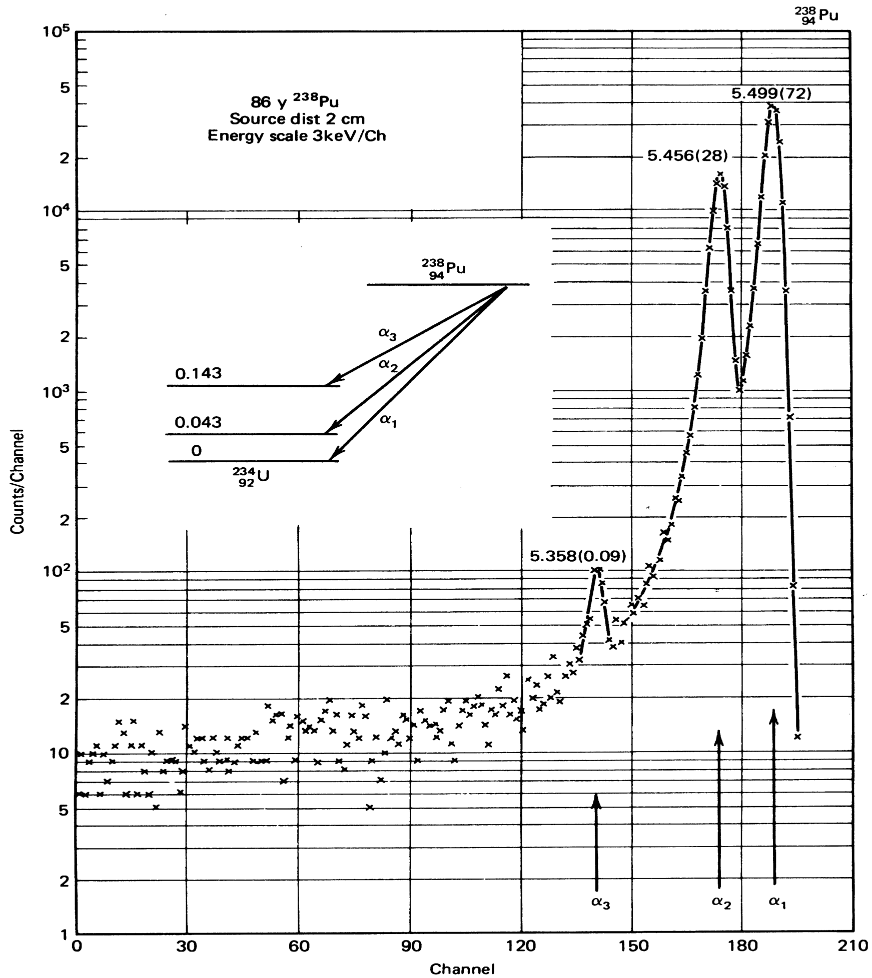
https://www.youtube.com/watch?v=Q252mAH7hnI&t=184s

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

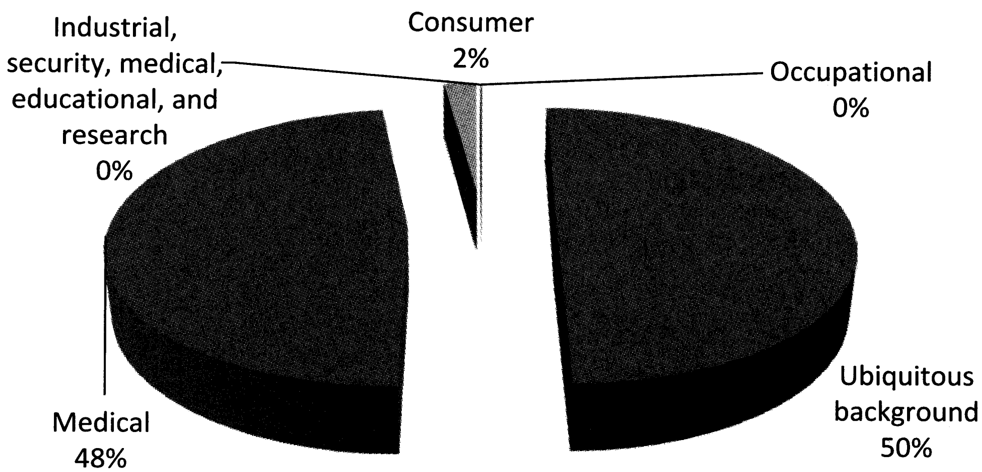


FIGURE 1.1 ◆ Exposure by Major Categories

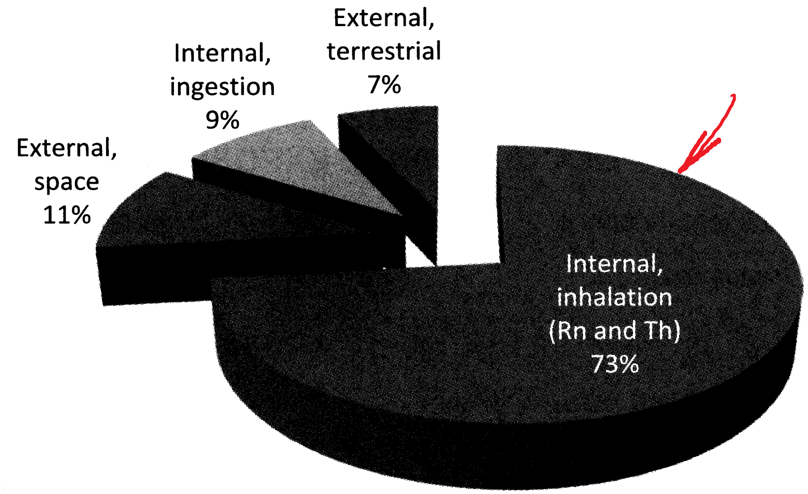


FIGURE 1.2 ◆ Ubiquitous Background

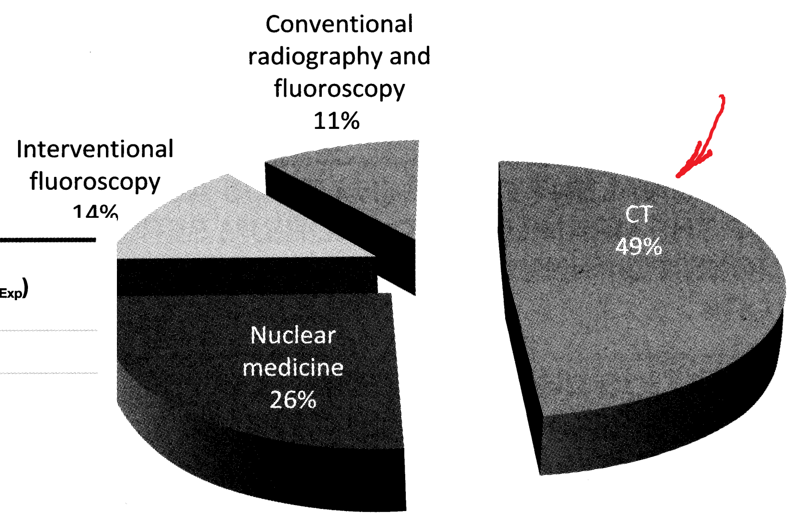


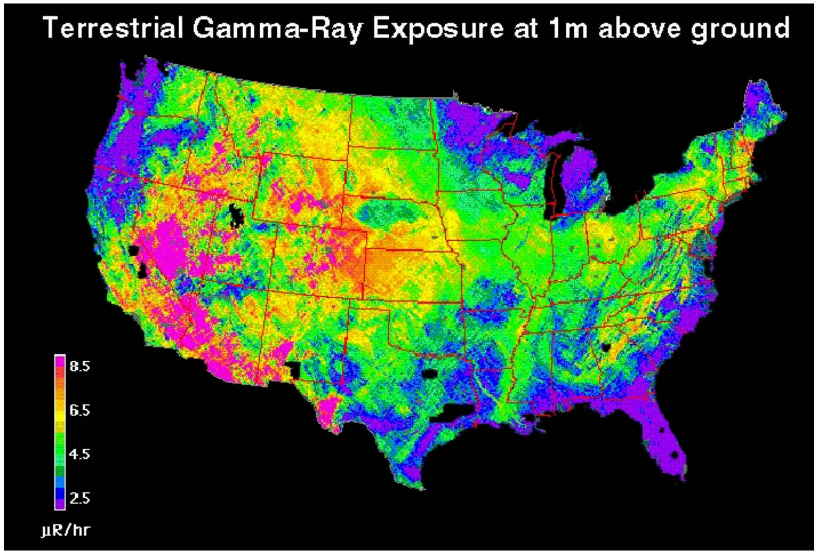
FIGURE 1.3 ◆ Medical

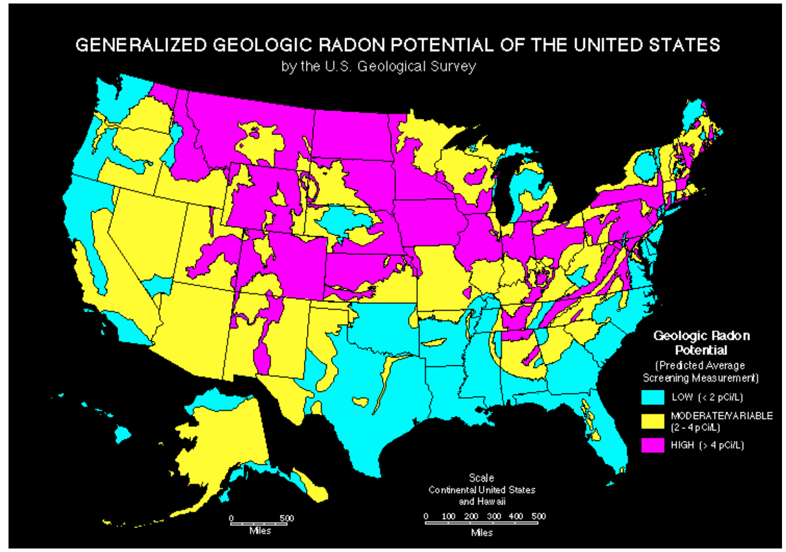
TABLE 1.4 COLLECTIVE EFFECTIVE DOSE (*S*), EFFECTIVE DOSE PER INDIVIDUAL IN THE US POPULATION (E_{US}), AND AVERAGE EFFECTIVE DOSE FOR THE EXPOSED GROUP (E_{Exp}) FROM MEDICAL PROCEDURES FOR 2006 (After NCRP Report No. 160, 2009)

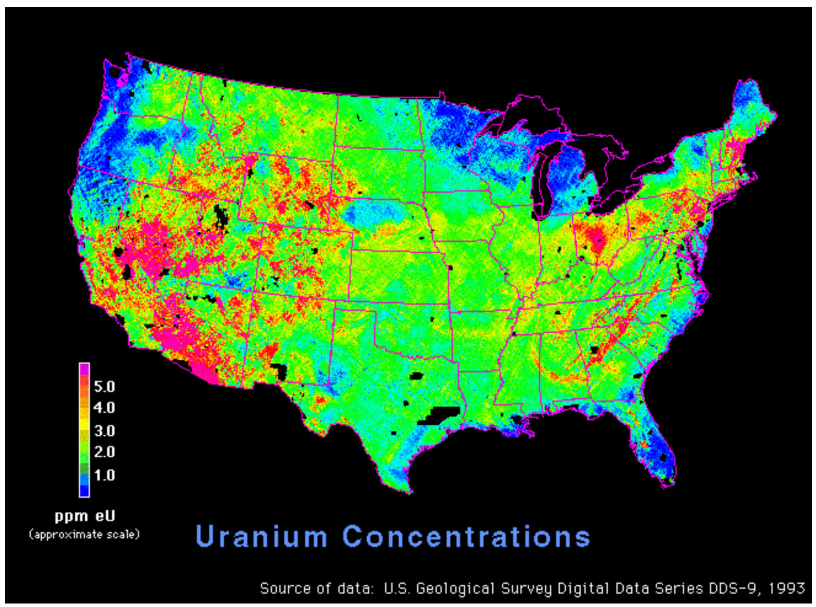
Exposure Category	*S* (person-Sv)	E_{US} (mSv)	E_{Exp} (mSv)
Medical			
CT	440,000	1.47	[a]
Nuclear medicine	231,000	0.77	[a]
Interventional fluoroscopy	128,000	0.43	[a]
Conventional radiography and fluoroscopy	100,000	0.33	[a]
Total	899,000	3	[a]

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

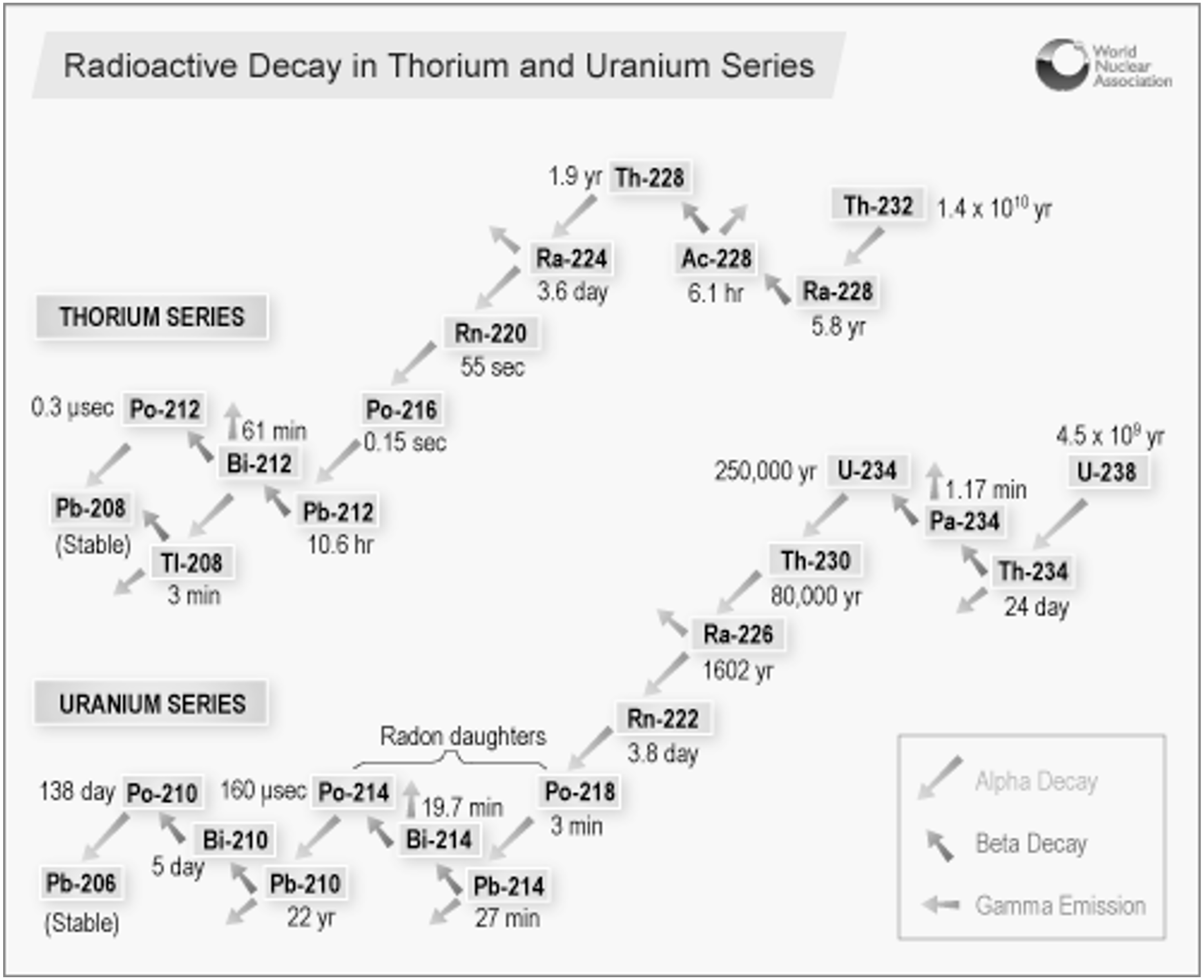
Terrestrial Naturally Occurring Radioactive Materials (NORM)







http://www.blackcatsystems.com/GM/safe_radiation.html



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

Naturally Occurring Radioactivity

Common characteristics of radioactive series:

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

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

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

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

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

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

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

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

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

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

Naturally Occurring Radioactivity – Other Isotopes of Radon

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

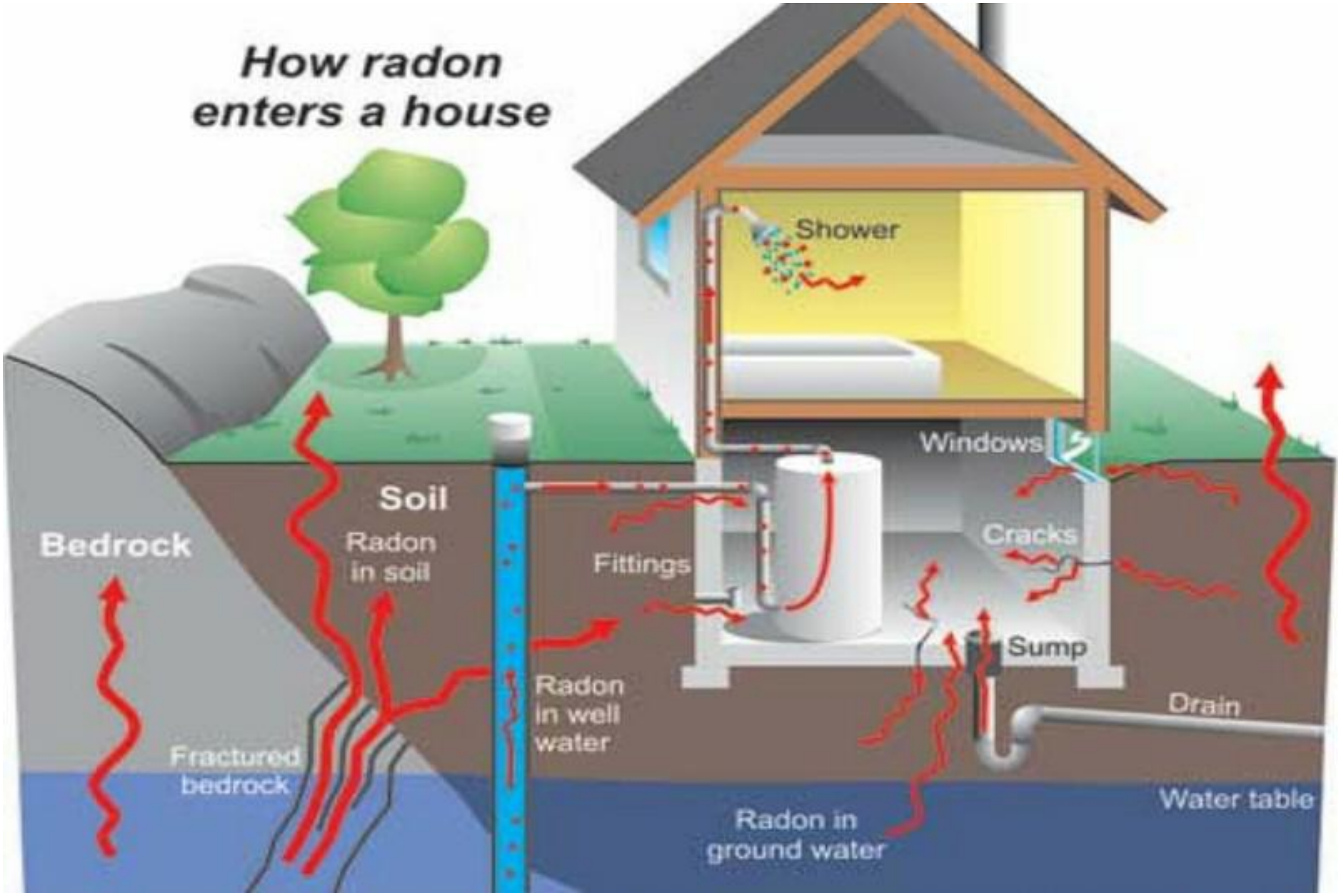
The health concerns of these isotopes are determined by two factors:

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

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

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

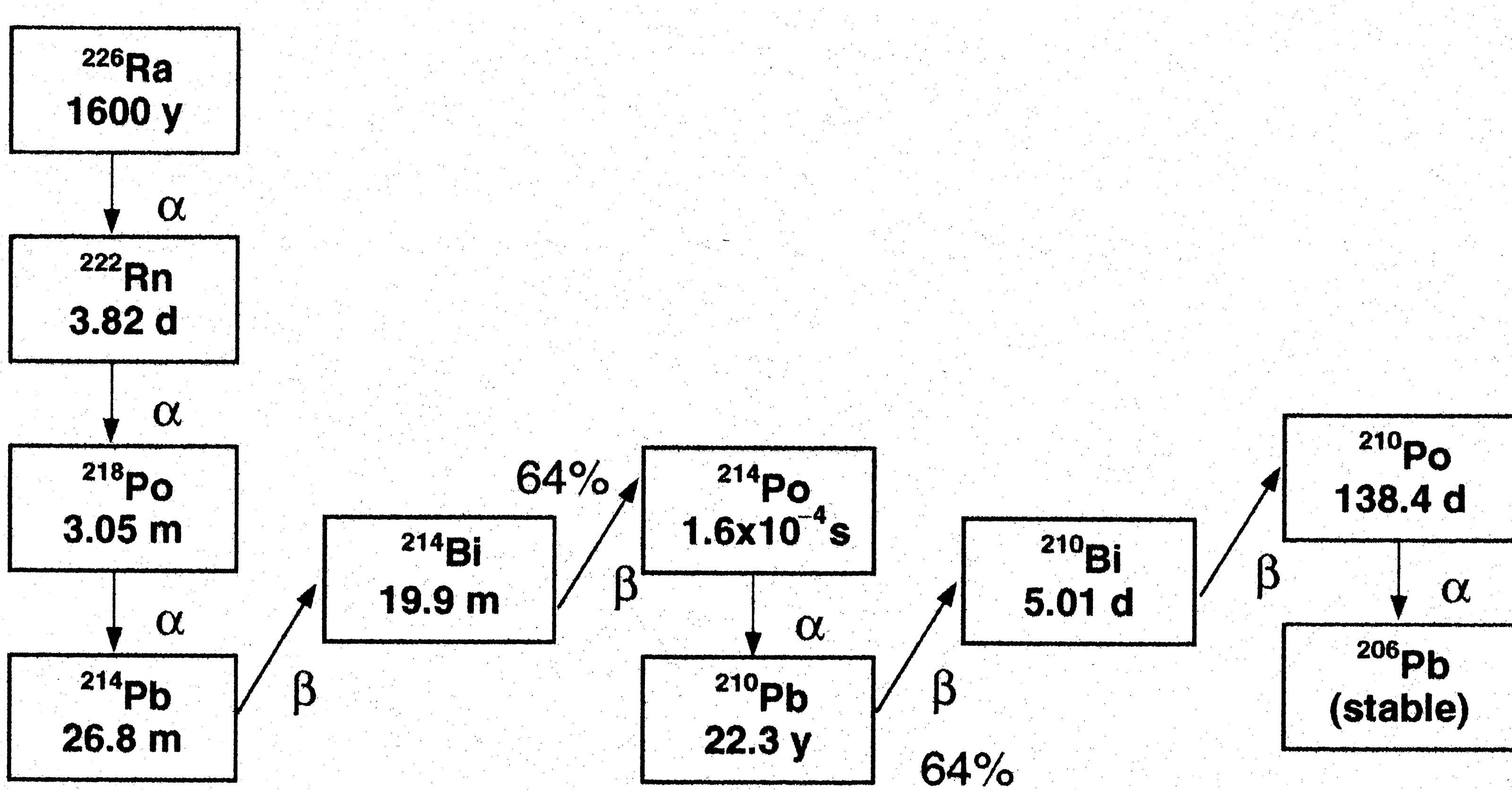


Figure 3.11 The ^{226}Ra decay series.

Naturally Occurring Radioactivity – Health Concerns of Radon Gas

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

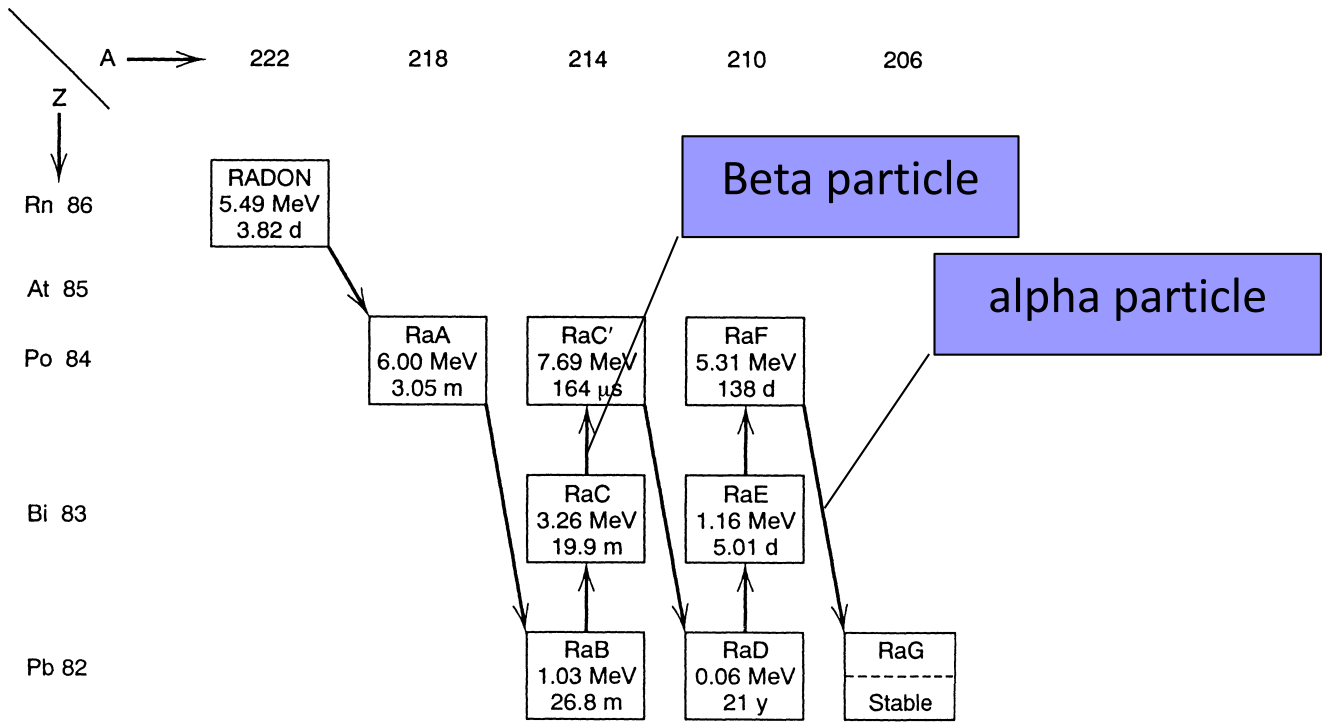
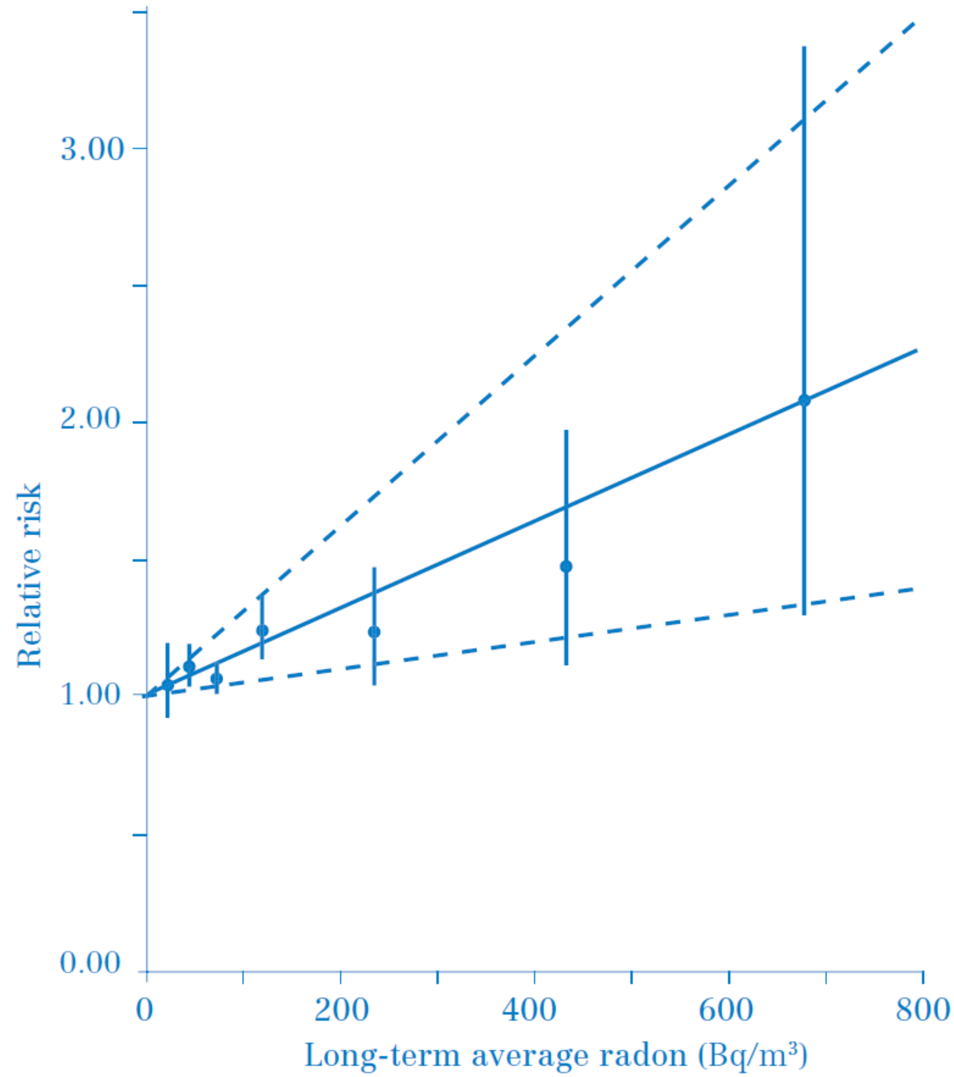


FIGURE 4.7. Radon and radon daughters. Alpha emission is represented by an arrow slanting downward toward the right; beta emission, by a vertical arrow. Alpha-particle and average beta-particle energies and half-lives are shown in the boxes.



Source: Darby et al. 2005
Relative risks and 95% confidence intervals are shown for categorical analyses and also best fitting straight line.
Risks are relative to that at 0 Bq/m³.

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

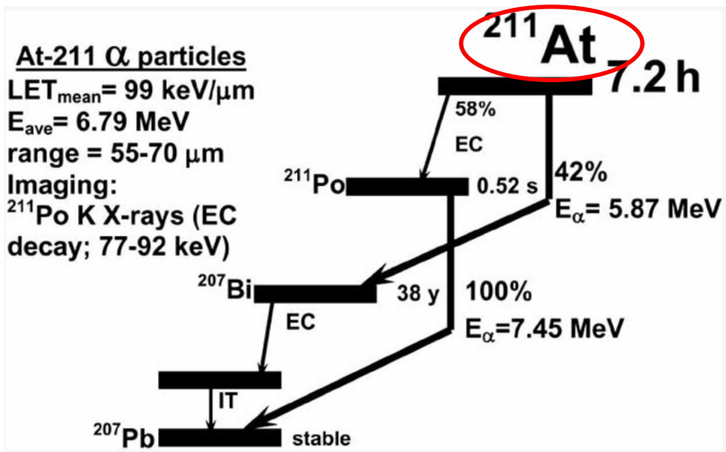
Table 3. Risk increase of radon-related lung cancer per 100 Bq/m^3 of measured indoor radon concentration based on the results of the European and North American pooling studies

	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 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)

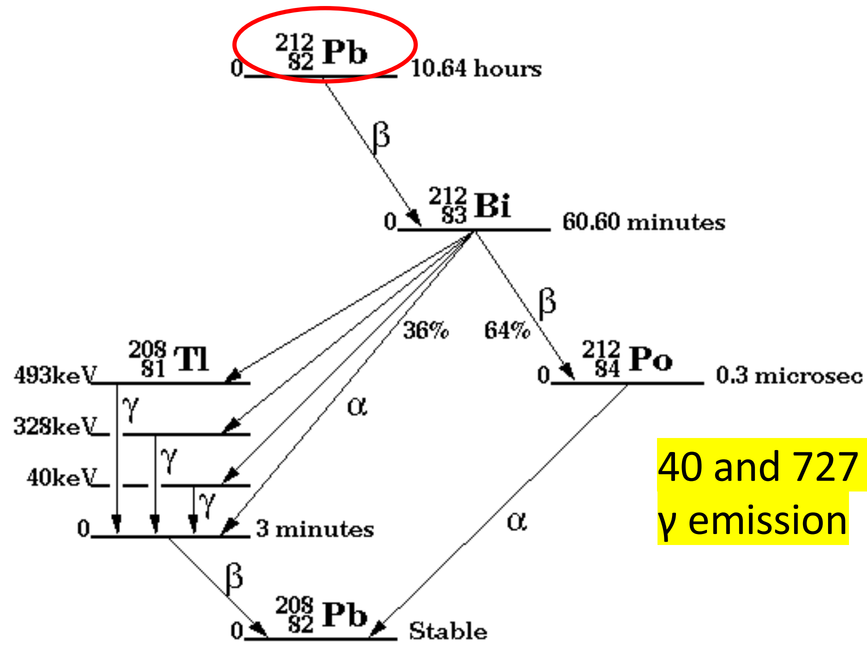
Sources: [a]Darby et al. (2005, 2006), [b]Krewski et al. (2005, 2006).
CI = confidence interval, p-values less than 0.05 denote statistical significance.

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)

α-Emitters of Human Interest (1)

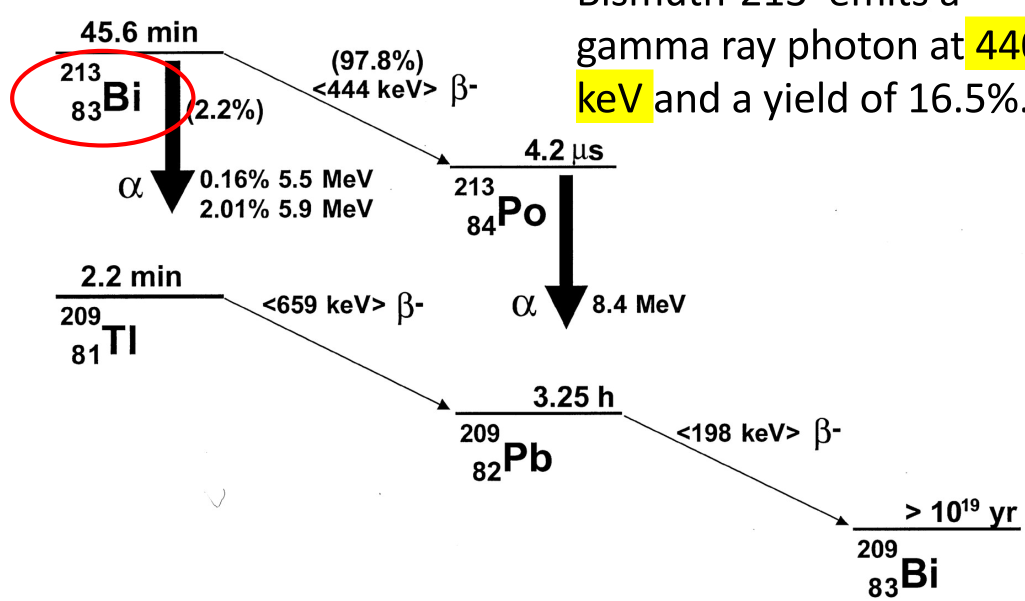


Po K Xrays are emitted that permit external imaging, the two most abundant of these X-rays have energies of 77 and 80 keV, 12 and 20% of all photon emissions, respectively.



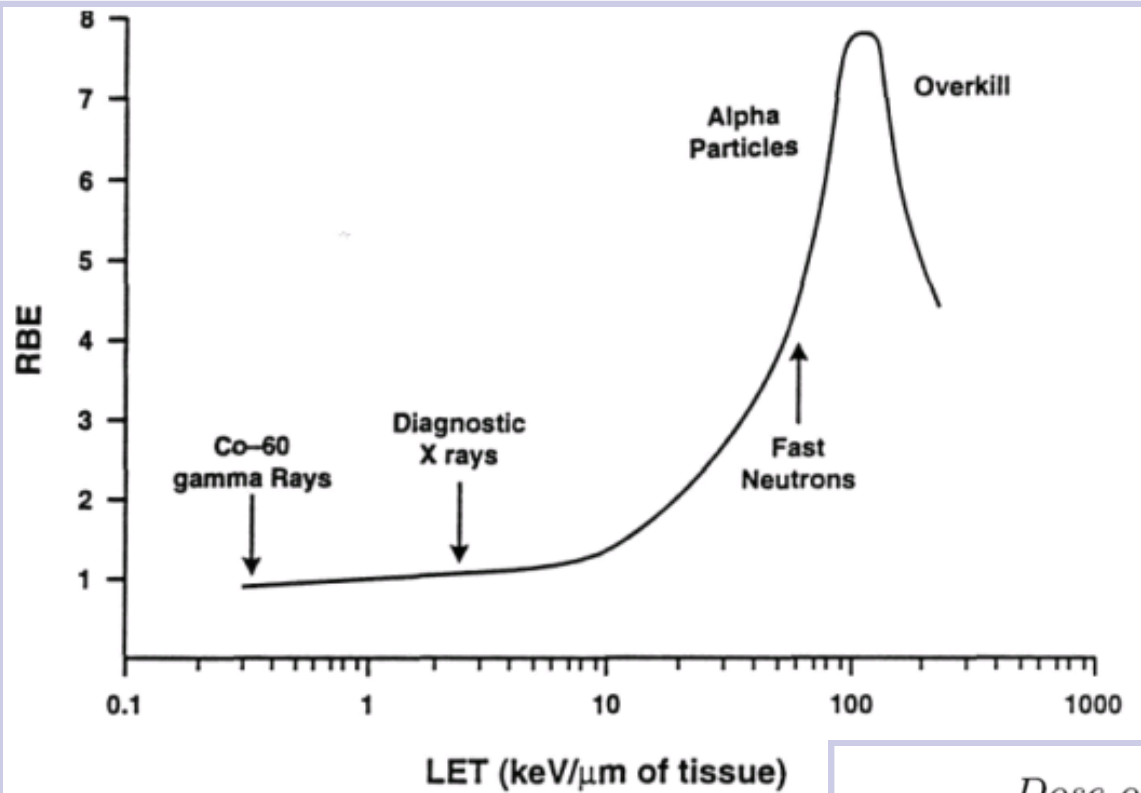
40 and 727 keV γ emission

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



Radiation Effect and Dose Delivery

For low LET radiation, ⇒ RBE ∝ 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!

^{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]

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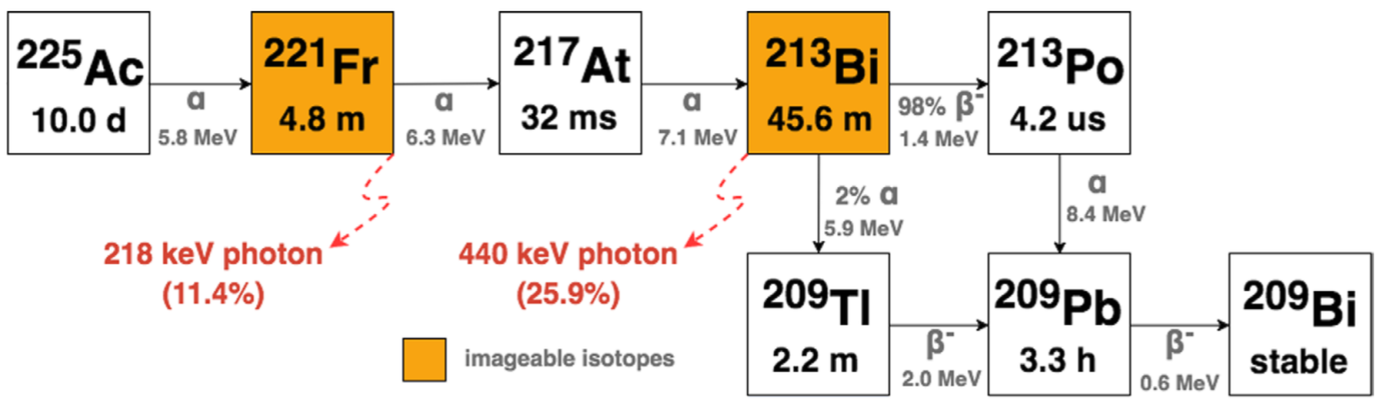

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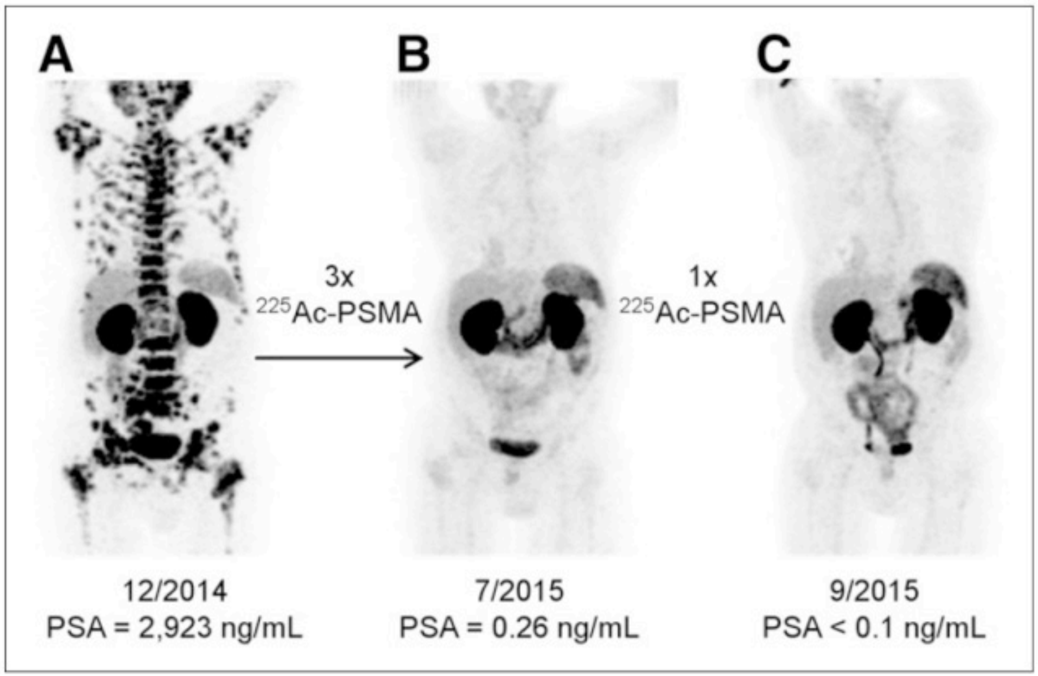


FIGURE 1. ^{68}Ga-PSMA-11 PET/CT scans of patient A. Pretherapeutic tumor spread (A), restaging 2 mo after third cycle of ^{225}Ac-PSMA-617 (B), and restaging 2 mo after one additional consolidation therapy (C).

Example of Dual-Isotope SPECT Imaging

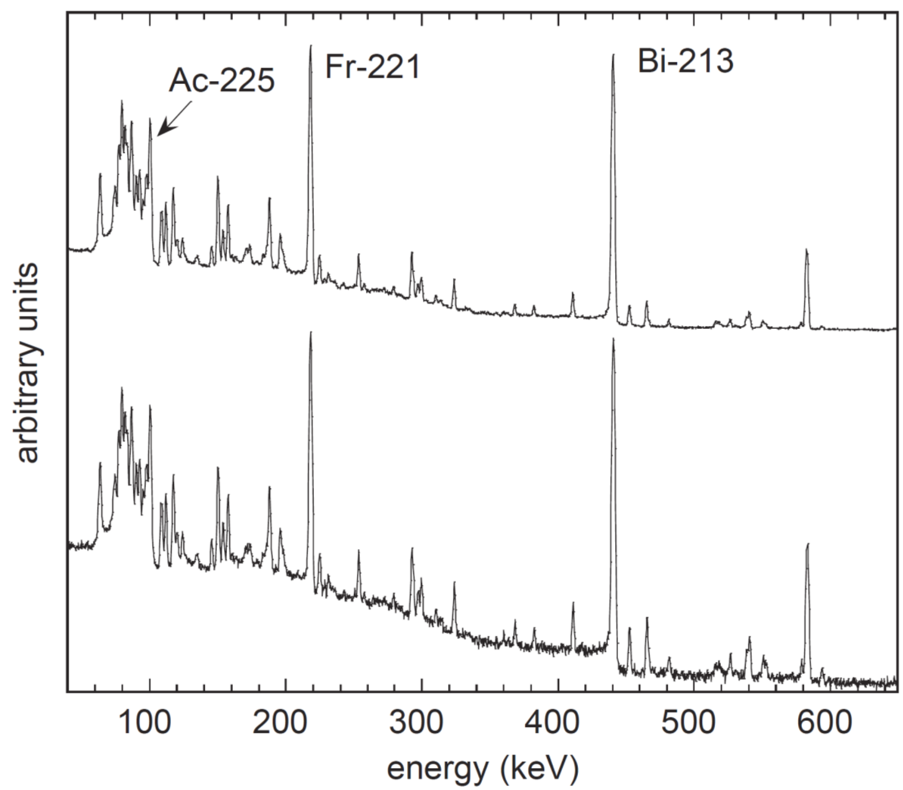
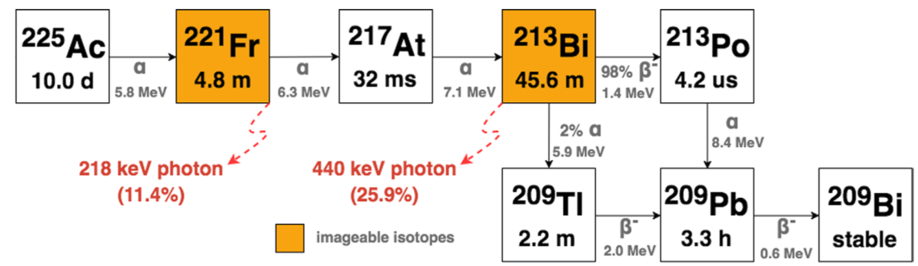
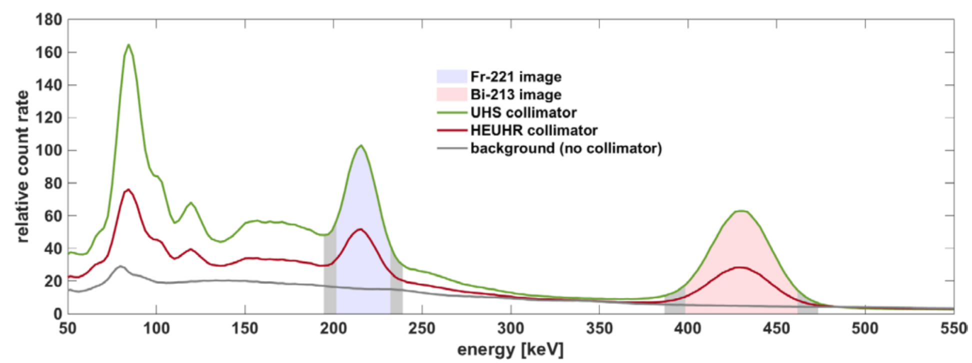


Fig. 4. Gamma spectra of purified Ac-225 produced via cyclotron irradiation (upper spectrum) and Ac-225 extracted from Th-229 (lower spectrum).



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

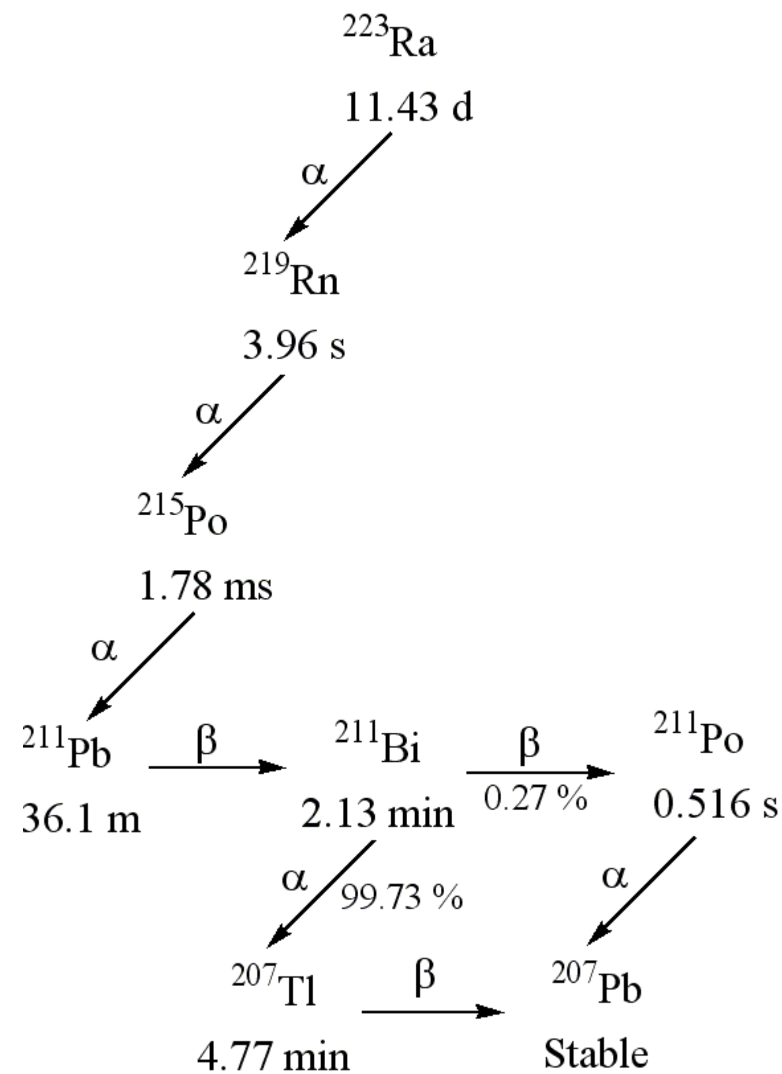


Energy spectra, normalized by acquisition time, acquired by the VECTor scanner for both HEUHR (red) and UHS (green) collimators with a comparison to a background spectrum (grey) acquired with no collimator or activity present. Spectra were acquired using a uniform source containing 1.05 MBq (28.3 μCi) of 225Ac. The energy regions used to reconstruct the 221Fr and 213Bi are shown in blue and red, respectively. The adjacent grey regions indicate the energy windows defined for background and scatter correction.

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.