Lecture 7: Alpha Decay, Uranium Chains, and the Radon Hazard: Notes

CBE 30235: Introduction to Nuclear Engineering — D. T. Leighton

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1 The Physics of Alpha Emission (Lamarsh §2.8)

Alpha decay is the emission of a $^4_2$He nucleus (2 protons, 2 neutrons). This is the dominant decay mode for heavy nuclei ($A > 200$) because it is the most efficient way for a massive nucleus to shed excess mass and charge.

1.1 Tunneling and Monoenergeticity

Unlike beta decay, which shares energy with a neutrino, alpha decay is a two-body problem. Consequently, alpha particles are **monoenergetic**—they carry a specific kinetic energy characteristic of the parent-daughter transition.

- **Quantum Tunneling:** Classically, an alpha particle is bound by the strong nuclear force. George Gamow (1928) showed that the alpha particle "tunnels" through the Coulomb barrier.
- **Geiger-Nuttall Law:** There is a direct mathematical relationship between the decay constant (λ) and the energy of the alpha particle (E). High-energy alphas tunnel more easily, leading to much shorter half-lives.

1.2 The Isotopic Zig-Zag: Moving Toward Stability

To understand why heavy chains (like Uranium) involve both alpha and beta decays, we must look at the **Neutron-to-Proton (N/Z) ratio**.

- **Alpha Emission and the Ratio:** An alpha particle removes 2 protons and 2 neutrons. Because $N > Z$ for heavy nuclei, removing equal numbers of both actually **increases** the N/Z ratio.
- **The Valley of Stability:** For heavy atoms, the "ideal" stable ratio is approximately 1.5 (e.g., Lead-206 has $124/82 \approx 1.51$). If an alpha decay pushes the nucleus too far to the neutron-rich side of the valley, the nucleus becomes unstable to **Beta Minus (β^-)** decay.
- **Beta's Counter-Correction:** A β^- decay converts a neutron into a proton, effectively **decreasing** the N/Z ratio and shifting the atom back toward the center of the valley.

1.3 The Search for Stability

In the Uranium decay series, the atom "zig-zags" down the chart of nuclides. The alpha decays reduce the total mass, while the beta decays "fine-tune" the charge-to-mass ratio. However, for elements with $Z > 82$, there is no truly stable configuration; the nucleus is simply too large for the short-range Strong Force to overcome the long-range Coulomb repulsion of the protons. The chain only terminates when it reaches **Lead ($Z = 82$)**, which sits at a "magic number" of protons and represents a stable local minimum in the potential energy surface.

1.4 Linear Energy Transfer (LET) and Range

From a safety engineering perspective, alpha particles are high-LET radiation.

- **Mass and Charge:** Being heavy and +2 charged, they interact strongly with electrons in matter.
- **The Bragg Peak:** They deposit nearly all their energy at the very end of their track. In tissue, an alpha particle typically travels only **40–80 μm**, about the width of a few human cells.
- **The Shielding Paradox:** A sheet of paper or the dead layer of skin (*stratum corneum*) is sufficient to stop an alpha particle. Thus, they are an **internal hazard** only (via inhalation or ingestion), but once inside, they are roughly 20 times more biologically damaging than gammas or betas.

References for Further Reading: Tunneling and Alpha Kinetics

- **Gamow, G. (1928):** "The Quantum Theory of Nuclear Disintegration." *Nature*, 122, 805. This is the seminal paper that applied the new wave mechanics to the nucleus, proving that alpha particles tunnel through a potential barrier.
- **The Geiger-Nuttall Law:** Geiger, H., and Nuttall, J. M. (1911). "The ranges of the α particles from uranium." *Philosophical Magazine*, 22(130), 612-621. This empirical law, discovered before quantum mechanics, showed that $\log(\lambda)$ is proportional to $\log(E)$, a mystery Gamow's tunneling theory eventually solved.
- **Physics Libre Texts:** Alpha Decay. A somewhat technical discussion of the connection between Gamow's theory and the Geiger-Nuttall Law.

2 Uranium and Thorium Decay Series

The Earth's natural radioactive background is dominated by three "primordial" decay chains. These chains follow the $4n$ **rule**, where the mass number A of every isotope in a series can be described by a specific mathematical remainder when divided by 4.

2.1 The Three Extant Natural Chains

As discussed in **Lamarsh Section 9.7**, there are three main series still found in nature:

1. **The Uranium Series ($4n + 2$):** Begins with ^{238}U, passes through ^{226}Ra and ^{222}Rn, and terminates at ^{206}Pb.

2. **The Thorium Series ($4n$):** Begins with ^{232}Th and terminates at ^{208}Pb. The key daughter is **Radon-220** (Thoron), which has a half-life of only 55.6 seconds.

3. **The Actinium Series ($4n + 3$):** Begins with ^{235}U and terminates at ^{207}Pb. It produces **Radon-219** (Actinon), with a half-life of 3.96 seconds.

2.2 Secular Equilibrium and the "Radon Leak"

In geological formations, these chains exist in **Secular Equilibrium** ($A_{parent} = A_{daughter}$). This is a consequence of steady-state: the rate of production of each intermediate must equal the rate of decay. However, the equilibrium may be physically broken at the Radon step.

- **Noble Gas Exception:** Radon is the only element in these chains that does not form chemical bonds with the surrounding rock matrix.
- **Emanation:** While its "parents" (Uranium and Radium) are locked in the mineral grains, Radon can escape into the pore spaces between grains.

2.3 Concentration by Human Activity: The Coal Cycle

While these elements are "natural," engineering processes can concentrate them to hazardous levels. As noted in **USGS Fact Sheet 163-97**, burning coal for power concentrates the non-volatile Uranium and Thorium into the **fly ash** by a factor of 10 or more relative to the raw coal. This "Technologically Enhanced Naturally Occurring Radioactive Material" (TENORM) is a major focus of coal ash waste management.

References for Section 2

- **Lamarsh, J. R., & Baratta, A. J.:** *Introduction to Nuclear Engineering*, 4th Ed., **Section 9.7**.
- **USGS Publications Warehouse:** FS-163-97: Radioactive Elements in Coal and Fly Ash.
- **Wikipedia:** Decay Chain (An excellent discussion of the key decay chains).

3 The Radon Problem: Transport and Ingress

Radon-222 (^{222}Rn, $T_{1/2} = 3.82$ days) is the most significant source of human exposure to ionizing radiation. Because it is a noble gas, it acts as a mobile link in the Uranium decay chain, escaping the solid earth to enter the human environment.

3.1 Emanation and Diffusion

The journey of Radon begins with **emanation**: the physical escape of the Radon atom from a mineral grain into the surrounding pore space.

- **Recoil Mechanism:** When ^{226}Ra decays, the resulting ^{222}Rn atom recoils with enough energy ($\sim$100 keV) to travel roughly 30 nm in rock. If the decay occurs near the grain surface, the atom "kicks" itself into the pore.
- **Diffusion (Fick's Law):** In the absence of pressure gradients, Radon moves through the soil pore air via molecular diffusion. The diffusion length (L) is given by $L = \sqrt{D/\lambda}$, where D is the diffusion coefficient and λ is the decay constant. For most soils, $L \approx 1$ meter.

3.2 Advection: The "Sump" Effect

While diffusion exists, the primary driver for high indoor Radon levels is **advection** (bulk fluid flow).

- **Pressure Gradients:** A house often operates at a slightly lower pressure than the surrounding soil (the "Stack Effect"). Warm air rising or wind blowing across the roof creates a vacuum in the basement (typically 1–10 Pa).
- **Darcy's Law:** The flow rate of soil gas (J) into the basement is governed by the soil permeability (κ) and the pressure gradient (∇P):

$$J = -\frac{\kappa}{\mu}\nabla P \tag{1}$$

  where μ is the viscosity of the soil gas. Even tiny cracks in a concrete slab act as "high-conductivity" channels for this gas.

3.3 Concentration Units: The Curie vs. The Becquerel

In the US, Radon is measured in **picoCuries per liter (pCi/L)**.

- **EPA Action Level:** 4.0 pCi/L ($\approx$ 148 Bq/m^3).
- **Outdoor Baseline:** Typical outdoor air is $\sim$0.4 pCi/L.
- **Indoor Extremes:** In regions with high Uranium content (e.g., the Reading Prong in PA), levels can exceed 1,000 pCi/L, equivalent to smoking hundreds of cigarettes a day.

3.4 The Watras Case: From Miners to Homeowners

Historically, Radon was viewed as a localized risk for underground miners. This changed in December 1984 due to the experience of Stanley Watras, an engineer at the Limerick Nuclear Power Plant (Pennsylvania).

- **The Detection Paradox:** Watras triggered the plant's radiation alarms while *entering* the facility. Because the plant's monitors were highly sensitive to alpha-emitting progeny on his clothing, they detected the "background" he was bringing from home.
- **The Magnitude:** His home was found to have a concentration of 2,700 pCi/L. This remains one of the highest indoor radon measurements ever recorded in a residential structure.
- **Regulatory Impact:** This event led directly to the **Indoor Radon Abatement Act (IRAA)**, establishing the national goal that indoor air be as free of radon as the ambient outdoor air.

3.5 Radon Progeny and Lung Cancer

A common misconception is that Radon gas itself causes cancer. Because it is a noble gas with a relatively long half-life, most inhaled ^{222}Rn is simply exhaled. The dose is delivered by the **Radon Progeny** (Short-lived daughters).

- **The Daughters:** ^{222}Rn decays into solid, chemically reactive isotopes: ^{218}Po, ^{214}Pb, ^{214}Bi, and ^{214}Po.

- **The Working Level (WL):** In engineering practice, we use the "Working Level" to describe the concentration of short-lived progeny. Because of ventilation and "plate-out" (daughters sticking to walls), the daughters are rarely in secular equilibrium with the Radon gas.
- **Mechanism of Injury:** These solid particles attach to aerosols (dust/smoke). When inhaled, they "plate out" on the bronchial epithelium. The alpha decays of ^{218}Po and ^{214}Po deliver a high-LET dose directly to the nuclei of the basal cells.

3.6 Engineering Mitigation

Reducing Radon exposure is a matter of pressure management and ventilation.

- **Sub-Slab Depressurization:** A fan is used to create a vacuum under the basement floor, intercepting Radon gas before it enters the structure and venting it above the roofline.
- **Sealing:** Closing "preferential pathways" like French drains, sump pits, and floor cracks.

References for Section 3

- **Nazaroff, W. W. (1992):** "Radon Transport from Soil to Air." *Reviews of Geophysics*, 17, 1-18. (The definitive engineering review on transport math).
- **EPA Assessment:** "Health Risk of Radon." Provides the statistical basis for the 4.0 pCi/L action level.
- **Lamarsh, J. R., & Baratta, A. J.:** *Introduction to Nuclear Engineering*, 4th Ed., **Section 9.7**.
- **radon-ohio.com:** "The Stanley Watras Story." (Account of the discovery of Radon contamination in the home).

4 Conclusion: The Geology of Health

The Radon hazard illustrates that nuclear engineering is not confined to reactors; it is a fundamental part of our built environment. Understanding the decay kinetics of the Uranium series allows us to quantify and mitigate a major public health risk.

Lecture 7 Addendum: Physics of the Radon Hazard: Kinetics, Dosimetry, and Detection

1 The Radon "Delivery Vehicle"

Radon-222 (^{222}Rn) is a noble gas, making it chemically inert and highly mobile. However, its hazard is entirely "outsourced" to its daughter products—heavy metals that act as localized alpha-particle emitters.

1.1 The Slaved Equilibrium and Bifurcations

In a closed system (e.g., a basement), the short-lived progeny reach **Secular Equilibrium** with the Radon source within ≈ 4 hours. When the Radon decays it forms highly charged daughters that rapidly attach to dust particles which can then be inhaled. While the decay chain is largely linear, rare bifurcations also exist:

Isotope	Half-Life ($T_{1/2}$)	Main Path (%)	Rare Branch (%)	Outcome of Branch
^{222}Rn	3.82 d	$\alpha \to {}^{218}$Po (100)	—	Entry Point (Noble Gas)
^{218}Po	3.10 min	$\alpha \to {}^{214}$Pb (99.98)	$\beta^- \to {}^{218}$At (0.02)	Reconverges at ^{214}Bi
^{214}Bi	19.9 min	$\beta^- \to {}^{214}$Po (99.98)	$\alpha \to {}^{210}$Tl (0.02)	Reconverges at ^{210}Pb
^{214}Po	164 μs	$\alpha \to {}^{210}$Pb (100)	—	**The 7.7 MeV "Zap"**
^{210}Pb	22.3 y	$\beta^- \to {}^{210}$Bi (99.999)	$\alpha \to {}^{206}$Hg (1.9×10^{-6})	The "Bottleneck"
^{210}Bi	5.01 d	$\beta^- \to {}^{210}$Po (99.999)	$\alpha \to {}^{206}$Tl (0.0001)	Reconverges at ^{206}Pb
^{210}Po	138 d	$\alpha \to {}^{206}$Pb (100)	—	Final Alpha to Stable

2 The Kinetic Race: Attachment vs. Decay

The hazard begins with the "Attachment Rate" (λ_a). When ^{218}Po is formed, it is a highly reactive ion.

- **The Attachment Window:** In typical air, $\lambda_a \approx 1$ to 6 min^{-1}. This means an atom attaches to dust in 10–60 seconds. Since $T_{1/2}(^{218}Po) = 186$ s, the vast majority of Po-218 successfully plates out or attaches before decaying.
- **The Energy Split:** Because ^{214}Pb and ^{214}Bi have longer half-lives (≈ 47 min combined), they provide a "delivery window" that allows deeper inhalation and longer residence time. Consequently, the **7.7 MeV alpha** from ^{214}Po accounts for $\approx 60\%$ of the total dose, while the **6.0 MeV alpha** from ^{218}Po accounts for $\approx 40\%$ depending on environmental conditions (aerosol concentration, ventilation, and attachment rates).

3 Biological Kinetics: The Race Against Clearance

The "hazard" is defined by whether an atom decays *in situ* or is cleared by the body. We define the **Effective Half-Life** (T_{eff}):

$$\lambda_{eff} = \lambda_{physical} + \lambda_{biological} \implies T_{eff} = \frac{T_p T_b}{T_p + T_b} \tag{2}$$

3.1 The High-Energy "Zappers"

- **Short-Lived Progeny (^{218}Po, ^{214}Po):** T_p (minutes/μs) $\ll T_b$ (hours/days). These "sprinters" decay almost immediately upon contact with the lung mucosal layer, delivering 6.0–7.7 MeV alpha hits to cellular DNA.
- **The Lead-210 Bottleneck:** ^{210}Pb ($T_p = 22.3$ y). Here, $T_b \ll T_p$. The body clears the lead atom years before it can decay into the toxic ^{210}Po. Thus, ^{210}Pb is a *permanent* contamination hazard for labs (why "old lead" is useful for shielding a radioactivity counter), but a *less significant* inhalation hazard for humans.

4 Environmental Detection Physics

4.1 Charcoal Adsorption (Short-term)

The canister acts as a "Radon Sponge." It does not trap the daughters for analysis; it traps the **Radon Gas**.

1. **Sealing:** Once closed, the trapped ^{222}Rn supports its progeny.
2. **Measurement:** The lab counts the Gamma peaks of ^{214}Pb (295, 352 keV) and ^{214}Bi (609 keV).
3. **Correction:** The original concentration C_0 is back-calculated using $e^{\lambda t}$, where t is the mail delay. If the seal is compromised, the "Noble" gas leaks, leading to a False Negative.
4. **Pros and Cons:** Test results are returned more rapidly, and it is cheaper (about \$20 at Menards). It is less reliable, but useful as a screening test.

4.2 Alpha-Track Detectors (Long-term)

This method uses **Solid State Nuclear Track Detection (SSNTD)**. It records physical "scars" on a polycarbonate sheet. This is a purely cumulative, time-weighted average that is immune to mail delays and "outgassing." It takes much longer (3 months to 1 year exposure) and is more expensive (about \$30 at Menards).

Industrial Spotlight: Track-Etched Membranes

The physics of the Alpha-Track radon test is identical to the production of **Nuclepore™** filters, with one key difference in the **Irradiation Source**:

- **Radon Test:** Random, low-mass alpha particles (^{4}He) create *conical pits* used for statistical counting.
- **Nuclepore:** High-energy **Heavy Ion Beams** (e.g., Argon, Krypton) from an accelerator create *cylindrical latent tracks* through thin films.

When etched in NaOH, the **Track Etch Ratio** ($S = V_{track}/V_{bulk}$) for heavy ions is so high (> 1000) that the acid creates perfectly uniform, straight-through pores. This "Industrial Tracking" allows for the creation of sieves precise enough to filter bacteria (0.22μm) based purely on the time spent in the etching bath.

Lecture 7 Addendum: The Relationship Between Radon and Smoking

1 The Multiplicative Risk Model

The relationship between radon exposure and tobacco smoke is not additive (1+1=2), but multiplicative ($1 \times 1 = 10$). Let R_0 be the baseline risk of lung cancer. The total lifetime risk is modeled as:

$$\text{Total Risk} \approx R_0 \times (1 + \text{ERR}_{smoking}) \times (1 + \text{ERR}_{radon})$$

Example Comparison (at 4 pCi/L):

- **Never Smoker:** Risk increases from $\approx 0.7\%$ to $\approx 2.0\%$.
- **Current Smoker:** Risk increases from $\approx 10.0\%$ to $\approx 16.0\%$.

Note: While the **relative** increase is similar in both cases, the **absolute** increase for the smoker (6.0%) is nearly five times the total lifetime risk of the non-smoker (1.3%).

2 Mechanism I: The Physics of "Aerosol Loading"

Radon progeny (^{218}Po and ^{214}Po) are metallic ions that are chemically "sticky." Their delivery to the lung depends on their **unattached** vs. **attached** state.

- **High Particle Density:** Cigarette smoke creates a massive increase in the concentration of ambient sub-micron particles.
- **The Hitchhiker Effect:** In clean air, many radon progeny "plate out" onto walls (becoming harmless). In a smoke-filled room, the progeny attach to smoke particles. These particles are the perfect size (0.1–1.0 μm) to stay suspended in the "breathing zone" and bypass the upper respiratory filters, delivering the alpha-emitters deep into the bronchi.
- **Second Hand Smoke:** Because particulates are present in second hand smoke, this mechanism also affects radon exposure in non-smokers.

3 Mechanism II: Biological Impairment and Residence Time

Once inhaled, the damage is determined by how long the alpha-emitter stays in contact with the bronchial epithelium.

- **Ciliastasis:** Tobacco smoke contains hydrogen cyanide and formaldehyde, which paralyze and eventually destroy the *cilia*.
- **Failure of the Escalator:** In a healthy lung, the "mucociliary escalator" clears particles within minutes. In a smoker's lung, these particles become stagnant.
- **The 7.7 MeV Zap:** Because ^{214}Po has a half-life of only 164 μs, it will decay exactly where it lands. If the "escalator" is broken, the 7.7 MeV alpha particle dumps its entire **Bragg Peak** energy directly into the DNA of the basal cells of the lung lining.

4 References

1. **National Research Council (1999).** *Health Effects of Exposure to Radon: BEIR VI.* https://doi.org/10.17226/5499

2. **Darby, S., et al. (2005).** "Radon in homes and risk of lung cancer: collaborative analysis of 13 European case-control studies." *BMJ*, 330(7485). https://doi.org/10.1136/bmj.38308.477650.63

Lecture 7 Addendum: The Geiger–Nuttall Law: Empirical Correlations and Quantum Tunneling

1 The Empirical Observation (1911)

Hans Geiger and John Mitchell Nuttall observed that alpha-emitting isotopes fall on approximately straight lines when plotting the logarithm of the decay constant (λ) against the logarithm of the range (R) of the alpha particle in air. Different isotopic series form distinct, roughly parallel lines.

$$\log_{10} \lambda = A + B, \log_{10} R \tag{3}$$

Using Geiger's empirical range–velocity relationship for alpha particles,

$$R \propto v^3 \propto E^{3/2}, \tag{4}$$

one obtains an approximate power-law dependence

$$\lambda \propto E^k, \qquad k = \tfrac{3}{2}B. \tag{5}$$

1.1 Sensitivity of the Decay Constant

Inspection of the original Geiger–Nuttall plots shows that the decay constant varies by many orders of magnitude over a relatively narrow range of alpha-particle energies. This dramatic sensitivity is the central empirical fact: modest changes in E correspond to enormous changes in λ.

The numerical value of the slope B depends on the specific isotopic series and on how the range is defined. Large effective exponents ($k \gg 1$) arise when the data are locally approximated by a power law, but these should be understood as *phenomenological* fits rather than fundamental constants.

2 Quantum Explanation via the WKB Approximation

In 1928, Gamow (and independently Gurney and Condon) explained the Geiger–Nuttall correlation by treating alpha decay as a quantum tunneling process. The alpha particle is modeled as a quasi-bound state that penetrates the Coulomb barrier of the daughter nucleus.

2.1 WKB Tunneling Probability

The Wentzel–Kramers–Brillouin (WKB) approximation applies when the potential varies slowly on the scale of the de Broglie wavelength. The barrier penetration probability (often called the Gamow factor) is

$$P = \exp! \left[-2 \int_{R_n}^{b} \sqrt{\frac{2\mu}{\hbar^2}\big(V(r) - E\big), dr} \right], \tag{6}$$

where R_n is the nuclear radius, b is the classical turning point, and μ is the reduced mass of the alpha–daughter system.

For a purely Coulomb potential,

$$V(r) = \frac{zZe^2}{r}, \qquad z = 2, \tag{7}$$

the integral can be evaluated analytically. To leading order, the result yields an exponential dependence of the form

$$P \sim \exp! \left(-\frac{2\pi z Z e^2}{\hbar v} \right), \tag{8}$$

where v is the alpha-particle velocity. Corrections involving the finite nuclear radius and angular momentum modify the prefactor and additive constants but do not change the dominant energy dependence.

3 Modern Geiger–Nuttall Form

The WKB analysis leads directly to the modern formulation of the Geiger–Nuttall law:

$$\log_{10} T_{1/2} = a, \frac{Z}{\sqrt{E}} + b, \tag{9}$$

where a and b are empirical constants for a given decay series. The key theoretical result is the *inverse square-root* dependence on alpha-particle energy, not a true power law in E.

Why the Early Power Law Appeared to Work

The original power-law correlation was remarkably successful because:

1. **Limited Energy Range:** Naturally occurring alpha decays span a narrow interval (roughly 4–9 MeV). Over such a range, the function $E^{-1/2}$ can be locally approximated by a steep effective power law.

2. **Dominant Exponential Sensitivity:** The tunneling probability depends exponentially on $1/\sqrt{E}$, overwhelming smaller corrections due to nuclear radius, shell structure, or angular momentum.

Thus, expressions such as $\lambda \propto E^k$ should be viewed as convenient local approximations, not fundamental decay laws.

4 Illustration: Radon Decay Chain

- **Radon-222:** $E_\alpha = 5.49$ MeV, $\quad T_{1/2} = 3.8$ days.
- **Polonium-214:** $E_\alpha = 7.69$ MeV, $\quad T_{1/2} = 164\ \mu$s.

Although the alpha-particle energy increases by only about 40%, the half-life decreases by many orders of magnitude corresponding to a power law exponent of approximately 64! This striking contrast is a direct manifestation of quantum tunneling through the Coulomb barrier and encapsulates the physical content of the Geiger–Nuttall law.