Lecture 11: The Physics of Fission

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

February 6, 2026

1 Introduction: The Destination

In Lecture 10, we discussed the "Journey" of the neutron: slowing down from 2 MeV to 0.025 eV, avoiding resonance traps, and thermalizing. Today, we discuss the "Destination": **Fission**.

What exactly happens when a thermal neutron strikes a uranium nucleus? How does the nucleus split? And most importantly for engineers, where specifically does the energy come from?

2 The Liquid Drop Model (Bohr & Wheeler, 1939)

To understand the mechanics of fission, we model the heavy nucleus not as a collection of hard spheres, but as a drop of incompressible, charged fluid. The stability of this drop is determined by a tug-of-war between two fundamental forces:

1. **Nuclear Force (Surface Tension):** The strong nuclear force acts between nearest neighbors. Just like surface tension in a water drop, this force tries to keep the nucleus spherical (minimizing surface area).

2. **Coulomb Force (Repulsion):** The nucleus contains 92 protons (for Uranium) all repelling each other. This force tries to tear the nucleus apart.

2.1 The Activation Energy

In a stable nucleus like ^{235}U, the surface tension is just strong enough to contain the Coulomb repulsion. However, the equilibrium is fragile.

- When a neutron is absorbed, it adds **Binding Energy** ($\sim$6 MeV) and kinetic energy to the system.
- This energy excites the nucleus, causing it to vibrate and oscillate.
- If the oscillation deforms the sphere into a "dumbbell" or peanut shape, the Coulomb distance between the two lobes increases, but the surface tension (neck area) decreases.
- **Critical Deformation:** Once the nucleus stretches past a certain point, the Coulomb repulsion between the two lobes overcomes the restoring force of the surface tension. The split becomes inevitable.

3 The Dynamics of "The Snap"

The actual moment of separation is violent and complex. As Chemical Engineers, we can visualize this using a familiar fluid dynamics analogy.

3.1 The "Satellite Droplet" Analogy

Consider the breakup of a viscous liquid jet or a dripping faucet. As the drop stretches, a thin fluid "neck" forms between the two main lobes. Due to the Rayleigh-Plateau instability, this neck eventually snaps.

1. **In Fluid Mechanics:** When the neck breaks, the fluid contained within it does not simply vanish. It often breaks up into tiny, secondary droplets known as **Satellite Droplets** that are found between the two main drops.

2. **In Nuclear Fission:** The "nuclear fluid" in the neck behaves identically. When the neck snaps, the nucleons in that region are left stranded. They are ejected immediately as free neutrons.

This mechanism gives rise to the **Prompt Neutrons** (ν) that sustain our chain reaction. They come from two distinct sources during the snap:

- **Scission Neutrons (∼10%):** These are the "satellite droplets" ejected directly from the snapping neck at the moment of separation ($t \approx 10^{-20}$ s).
- **Evaporation Neutrons (∼90%):** Immediately after the snap, the two large fragments are highly deformed and incredibly "hot." As they relax into spherical shapes, they "boil off" excess neutrons to cool down ($t \approx 10^{-17}$ s).

Result: On average, the fission of ^{235}U releases $\nu \approx 2.43$ neutrons.

4 Fissile vs. Fissionable (Revisited)

Now that we understand the Liquid Drop mechanism, we can clarify the distinction made in Lecture 10 regarding fuel types.

- **Fissile Isotopes (^{235}U, ^{239}Pu):** When these isotopes absorb a *thermal* neutron (kinetic energy ≈ 0), the binding energy released by simply capturing the neutron is **greater** than the critical threshold required to deform the drop. *Result:* Fission occurs with slow neutrons.
- **Fissionable Isotopes (^{238}U):** When ^{238}U captures a neutron, the binding energy is **lower** than the critical threshold (due to pairing energy effects). The drop vibrates, but not enough to break. To cause fission, the incoming neutron must bring significant *Kinetic Energy* (> 1 MeV) to make up the deficit. *Result:* Fission only occurs with fast neutrons.

5 The Products of Fission

Fission is rarely symmetric. The nucleus does not split into two equal halves ($A \approx 118$). Instead, quantum mechanical shell effects cause it to split asymmetrically.

5.1 The Mass Yield Curve

If we plot the probability of producing a fragment of mass A, we see a distinctive "double-humped" curve (the Camel Plot).

- **Light Peak:** Centered around $A \approx 95$ (e.g., Strontium, Krypton).
- **Heavy Peak:** Centered around $A \approx 140$ (e.g., Xenon, Cesium, Iodine).
- **The Valley:** Symmetric fission ($A \approx 118$) is very rare (probability drop of ~600x).

5.2 Why are they Radioactive?

The heavy nucleus (^{235}U) has a huge neutron-to-proton ratio (~1.55) to overcome Coulomb repulsion. Stable light elements ($A \approx 100$) prefer a ratio closer to 1.3.

- When the nucleus splits, the fragments inherit the "parent's" neutron-heavy ratio.
- They are **Neutron Rich** (far too many neutrons for stability).
- To stabilize, they must convert neutrons into protons via **Beta Decay** (β^-). This is the source of the intense radioactivity of nuclear waste.

6 The Energy Balance (Where is the heat?)

We often quote the energy release of fission as **200 MeV**. As engineers, we need to know exactly where this energy is deposited to design our heat transfer systems.

Energy Form	Approx. Energy	Range	Recoverable?
1. KE of Fission Fragments	168 MeV	$\sim 10\mu$m	**Yes** (Fuel)
2. KE of Neutrons	5 MeV	cm to m	**Yes** (Moderator)
3. Prompt Gamma Rays	7 MeV	m	**Yes** (Shield/Structure)
4. Decay Heat (Betas/Gammas)	~15–20 MeV	N/A	**Yes** (Delayed)
5. Neutrinos	10–12 MeV	∞	**No** (Lost)
Total Recoverable Heat	$\approx$ **190–200 MeV**		

Table 1: Distribution of Fission Energy

Key Engineering Insights:

- **The Fuel Gets Hot:** Over 80% of the energy (Item 1) is Kinetic Energy of the heavy fragments. Because these are highly charged, they interact strongly with matter and stop within micrometers. *All this heat is generated inside the fuel pellet.*
- **The Moderator Gets Warm:** The neutron kinetic energy (Item 2) is deposited in the water/graphite as they slow down.
- **Safety:** Item 4 (Decay Heat) is generated *after* the fission event, over seconds, days, and years. Even if the reactor is shut down, this heat source remains. This is the driver for all meltdown scenarios (e.g., Fukushima).

7 Prompt vs. Delayed Neutrons

While 99.35% of neutrons are "Prompt" (emitted at the moment of fission), a tiny fraction ($\beta \approx 0.0065$) are "Delayed."

- **Origin:** Certain fission products (precursors) undergo beta decay and *then* emit a neutron seconds later.
- **Significance:** If all neutrons were prompt, the reactor would respond to changes in 10^{-4} seconds—too fast to control. The delayed neutrons increase the average "generation time" to effectively seconds, allowing human/mechanical control.

8 Defining the Multiplication Factors

We have discussed how neutrons are born (ν) and how they interact. To model a reactor, we must convert these physical processes into probabilities. This leads us to the definitions found in Lamarsh Section 3.7.

8.1 The Reproduction Factor (η)

We know that ν neutrons are produced per *fission*. However, not every neutron absorbed by the fuel causes fission; some are merely captured (n, γ). We define η (eta) as the number of fission neutrons produced per **absorption** in the fuel:

$$\eta = \nu \frac{\sigma_f}{\sigma_a} = \nu \frac{\sigma_f}{\sigma_f + \sigma_\gamma} \tag{1}$$

For pure ^{235}U, $\eta \approx 2.08$. For natural uranium (mostly ^{238}U, which absorbs but doesn't fission), $\eta \approx 1.3$. This drop is why we need enrichment.

8.2 The Fast Fission Factor (ϵ)

Fission neutrons are born fast (2 MeV). Before they leave the fuel rod, they have a small chance of striking a ^{238}U nucleus and causing a "fast fission" event (as discussed in Section 4).

- This creates a small "bonus" to our neutron population.
- ϵ is defined as the ratio of total fission neutrons to those produced by thermal fission alone.
- Typically, $\epsilon \approx 1.03$ (a 3% bonus).

8.3 The Resonance Escape Probability (p)

As the neutron slows down, it must pass through the "Valley of Death" (the resonance region of ^{238}U) discussed in Lecture 10.

- p is the probability that a neutron successfully reaches thermal energy without being captured in a resonance.
- In a typical LWR, $p \approx 0.7$ (meaning 30% of neutrons are lost here).

8.4 The Thermal Utilization Factor (f)

Once thermalized, the neutron will eventually be absorbed. But will it be absorbed by the fuel (useful) or by the water/steel/control rods (waste)?

$$f = \frac{\Sigma_{a,fuel}}{\Sigma_{a,total}} \tag{2}$$

This is the ratio of absorption in the fuel to total absorption in the reactor.

9 Looking Ahead

We have now rigorously defined the four key factors: η, ϵ, p, f. In **Lecture 12 (Monday)**, we will multiply these together to derive the **Four Factor Formula** (and combining them with the finite reactor geometry obtain the Six Factor Formula) to calculate k_{eff} and determine if our reactor is Critical, Supercritical, or Subcritical.

References

1. Lamarsh, J. R., & Baratta, A. J. *Introduction to Nuclear Engineering*, 4th Ed. Pearson, 2017. (Section 3.7).

2. Bohr, N., & Wheeler, J. A. "The Mechanism of Nuclear Fission." *Phys. Rev.* **56**, 426 (1939).