Chemical Engineering 412

Introductory Nuclear Engineering

Lecture 10

Nuclear Fission

Spiritual Thought

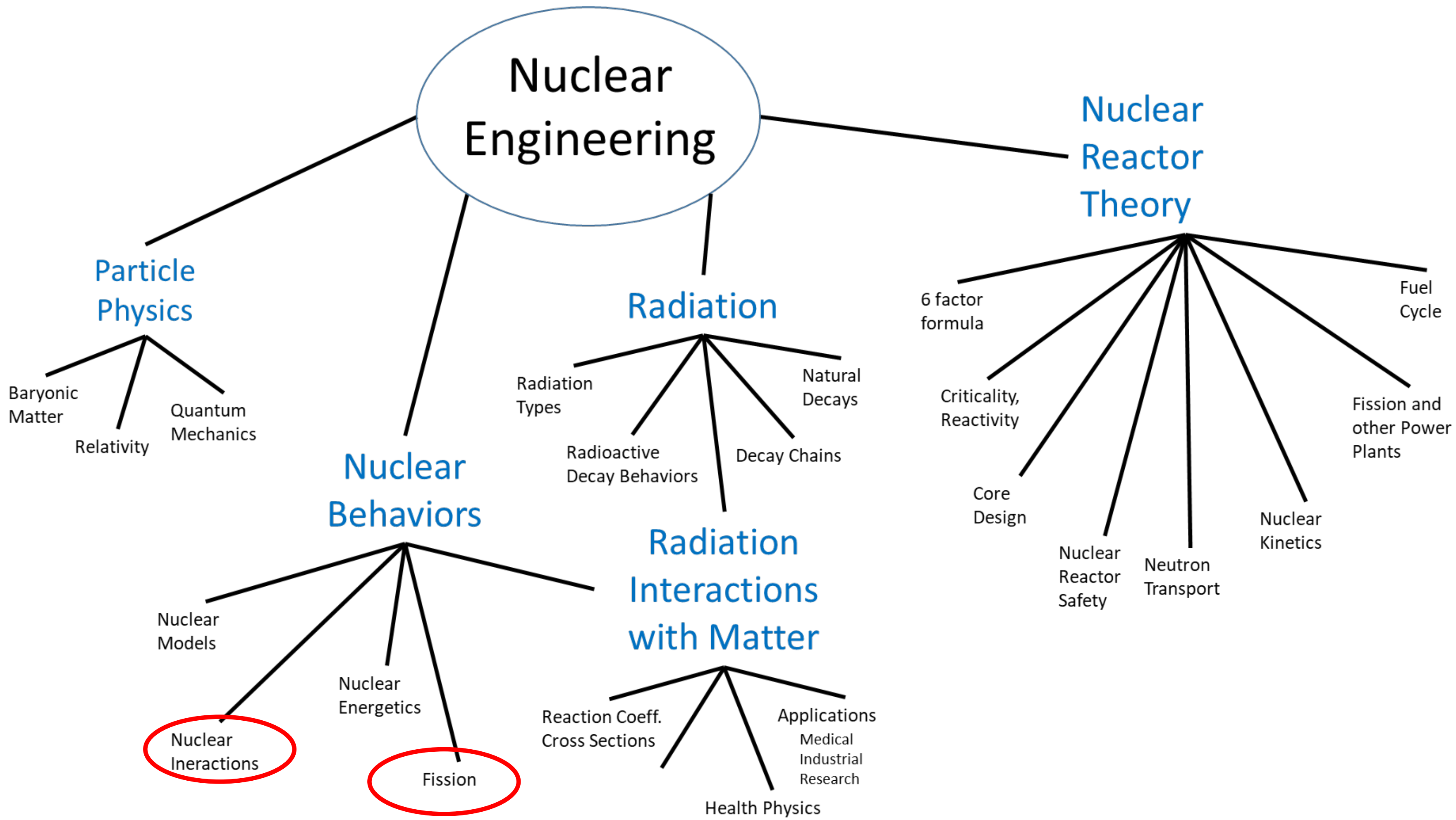
D&C 121:41-43

No power or influence can or ought to be maintained by virtue of the priesthood, only by persuasion, by long-suffering, by gentleness and meekness, and by love unfeigned;

By kindness, and pure knowledge, which shall greatly enlarge the soul without hypocrisy, and without guile—

Reproving betimes with sharpness, when moved upon by the Holy Ghost; and then showing forth afterwards an increase of love toward him whom thou hast reproved, lest he esteem thee to be his enemy;

The BIG Picture



Neutron Interactions

- Elastic scattering (n,n) – collision with no reaction and no change in total kinetic energies. Energy neutral.
- Inelastic scattering (n,n’) – collisions with energy absorption by nucleus. endoergic
- Radiative capture (n,γ) – Capture of neutron by nucleus followed by γ-ray emission. exoergic.
- Charged particle reactions (n,α) – Neutron reaction to form α particles or protons. endoergic and exoergic.
- Neutron producing reactions (n,*x*n) – Reactions with a net increase in neutrons. endoergic. (n,2n) important for ^{2}H and ^{9}Be.
- Fission (n,) forms multiple products – Nucleus forms daughters. Generally exoergic.

Capture and Absorption

- Decelerating Neutrons from fission energies (2-5 MeV) to thermal energies (0.025 eV)
  - Requires many collisions
  - Smaller Nuclides
  - Risk of “capture”
- Capture occurs in “resonance energy regions” (fuel)
- Also could be absorbed by the “moderator” (water)
- Can calculate probability of capture or absorption
  - Resonance integral
  - Absorption cross-sections

How to Decelerate a Neutron

$$\alpha = \left(\frac{A-1}{A+1}\right)^2$$

collision parameter

$$\frac{\Delta E}{E} = \frac{1-\alpha}{2}$$

$$u = \ln\frac{E_M}{E}$$

Lethargy;
E_M is an arbitrary E, usually the highest neutron energy in the system. As neutrons decelerate, u increases.

$$\xi = \Delta u = 1 - \frac{(A-1)^2}{2A}\ln\frac{A+1}{A-1} = 1 + \frac{\alpha}{1-\alpha}\ln\alpha \cong \frac{2}{A+\frac{2}{3}}$$

$$\lim_{A\to 1}\xi = 1$$

Neutron Energies

- Fission neutrons
  - Distribution of speeds
  - 2 MeV typical
  - Interested “slowing” neutrons
  - Collisions required to slow from energy E_1 to E_2 is given by:

$$n = \frac{1}{\xi} \ln \frac{E_1}{E_2}$$

- Thermal neutrons:
  - equilibrated with the vibrating atomic nuclei at room temperature (293 K)
  - Average energy of 0.025 eV (2200 m/s)
  - Maxwellian distribution of speeds
  - likely to lose OR GAIN energy from medium nuclei
  - Readily produce fissions in U^{235}, U^{233}, Pu^{239}

Collision parameters

Atom	A	α	ξ	n
H	1	0.000	1.000	18.2
H_2O	1, 16		0.920	19.8
D	2	0.111	0.725	25.1
D_2O	2, 16		0.509	35.8
He	4	0.360	0.425	42.8
Be	9	0.640	0.207	88.1
B	11	0.694	0.171	106.3
C	12	0.716	0.158	115.3
O	16	0.779	0.120	151.7
Na	23	0.840	0.084	215.4
Fe	56	0.931	0.035	515.6
^{238}U	238	0.983	0.008	2171.6

n values here assume a neutron slowing from 2 MeV to 0.025 eV

Neutrons Eventually Are Captured

$$n + {}_{Z}^{A}X \rightarrow \left[{}_{Z}^{A+1}X\right]^{*} \rightarrow \left[{}_{Z}^{A+1}X\right] + \gamma$$

Control rods

$$n + {}_{5}^{10}B \rightarrow [{}_{5}^{11}B]^{*} \rightarrow [{}_{3}^{7}Li] + \gamma + \alpha$$

“Fertile” isotopes form “fissile” isotopes through neutron absorption

$$n + {}_{90}^{232}Th \rightarrow [{}_{90}^{233}Th]^{*} \rightarrow [{}_{90}^{233}Th] + \gamma \underset{22\ m}{\overset{\beta^{-}}{\rightarrow}} {}_{91}^{233}Pa \underset{27\ d}{\overset{\beta^{-}}{\rightarrow}} {}_{92}^{233}U$$

$$n + {}_{92}^{238}U \rightarrow [{}_{92}^{239}U]^{*} \rightarrow [{}_{92}^{239}U] + \gamma \underset{24\ m}{\overset{\beta^{-}}{\rightarrow}} {}_{93}^{239}Np \underset{56\ h}{\overset{\beta^{-}}{\rightarrow}} {}_{94}^{239}Pu$$

Fission Reactions

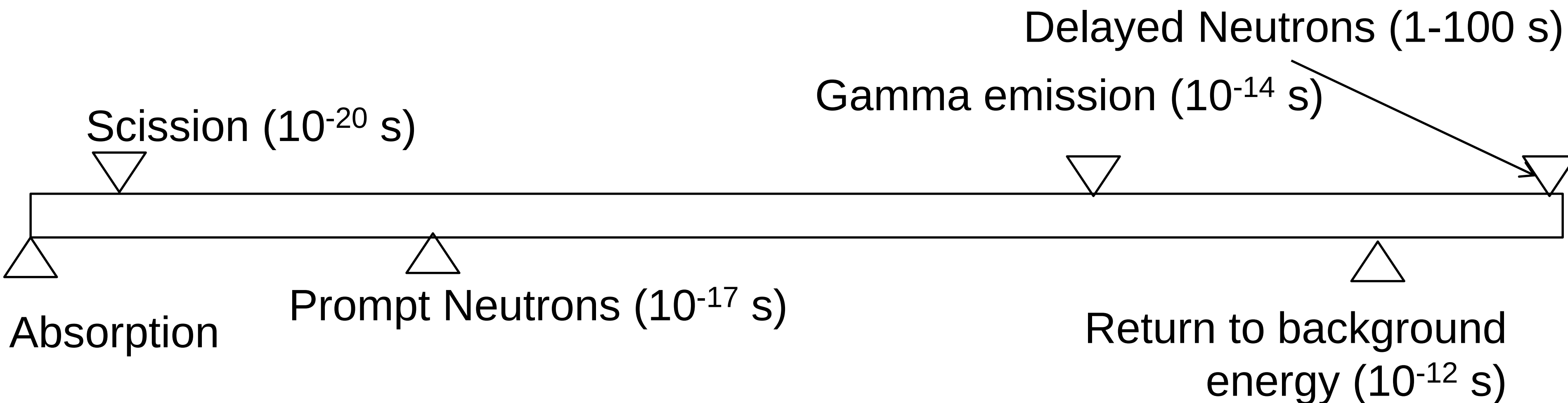
$^{235}_{92}U$ is fissile (undergoes fission)

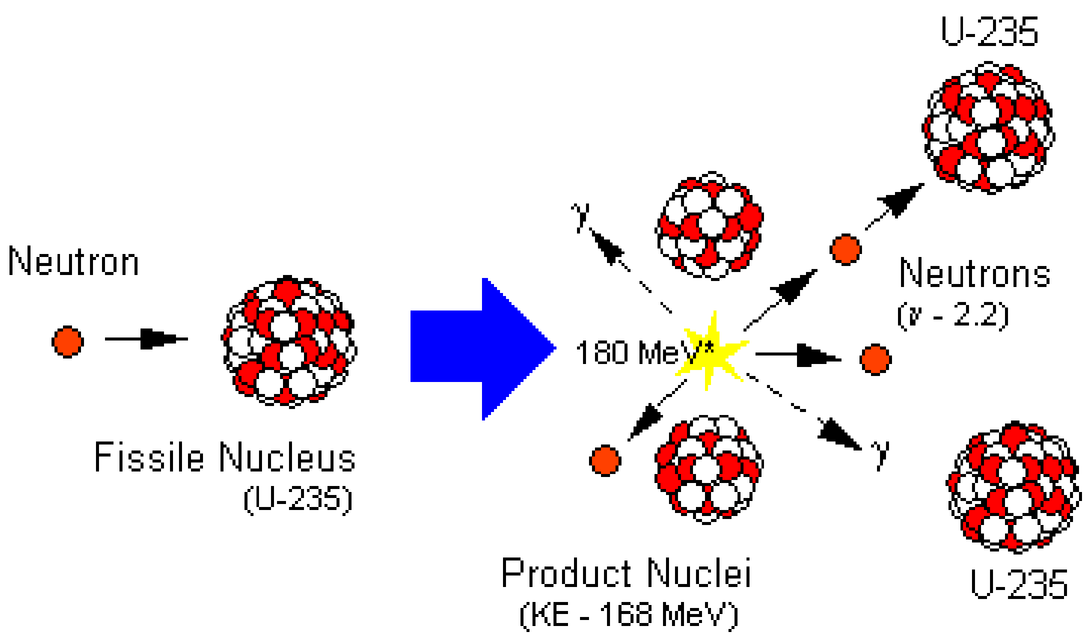
$^{238}_{92}U$ is fertile (converts to a fissionable isotope)

Possible outcomes of $^{235}_{92}U$ reaction with neutron

$$n + {}^{235}_{92}U \rightarrow \begin{cases} {}^{235}_{92}U + n & elastic\ scatter \\ {}^{235}_{92}U + n + \gamma & inelastic\ scatter \\ {}^{236}_{92}U + \gamma & radiative\ capture \\ Y_H + Y_L + y_1 + y_2 + \cdots & fission \end{cases}$$

Fission (logarithmic) Timeline



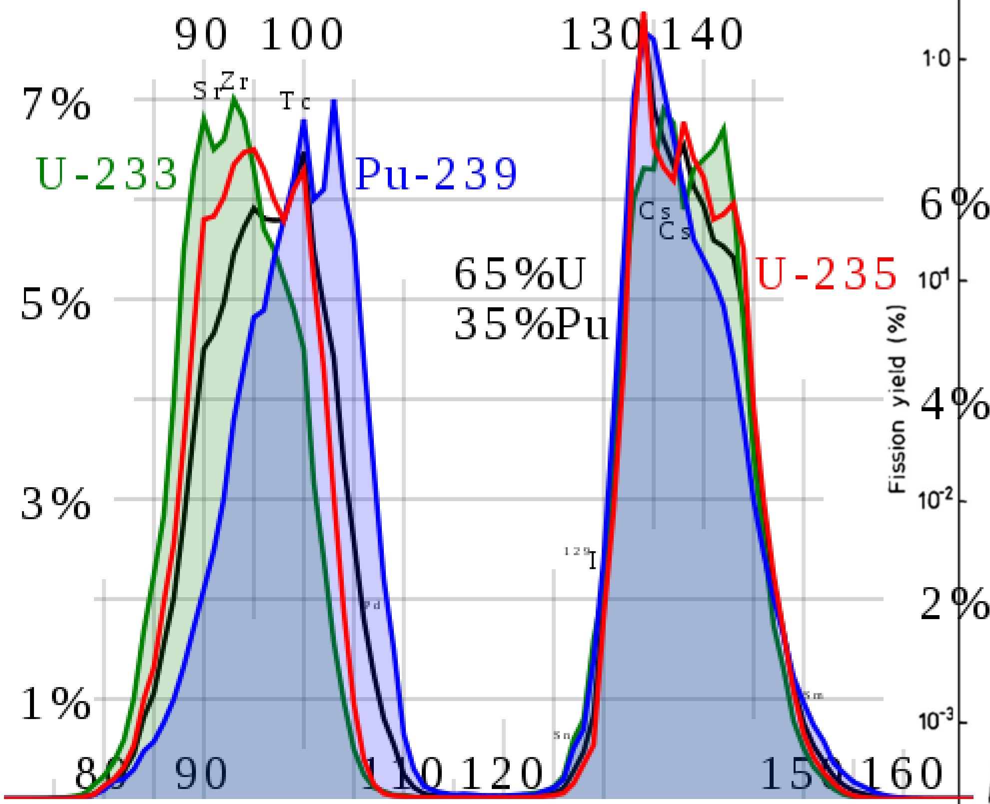


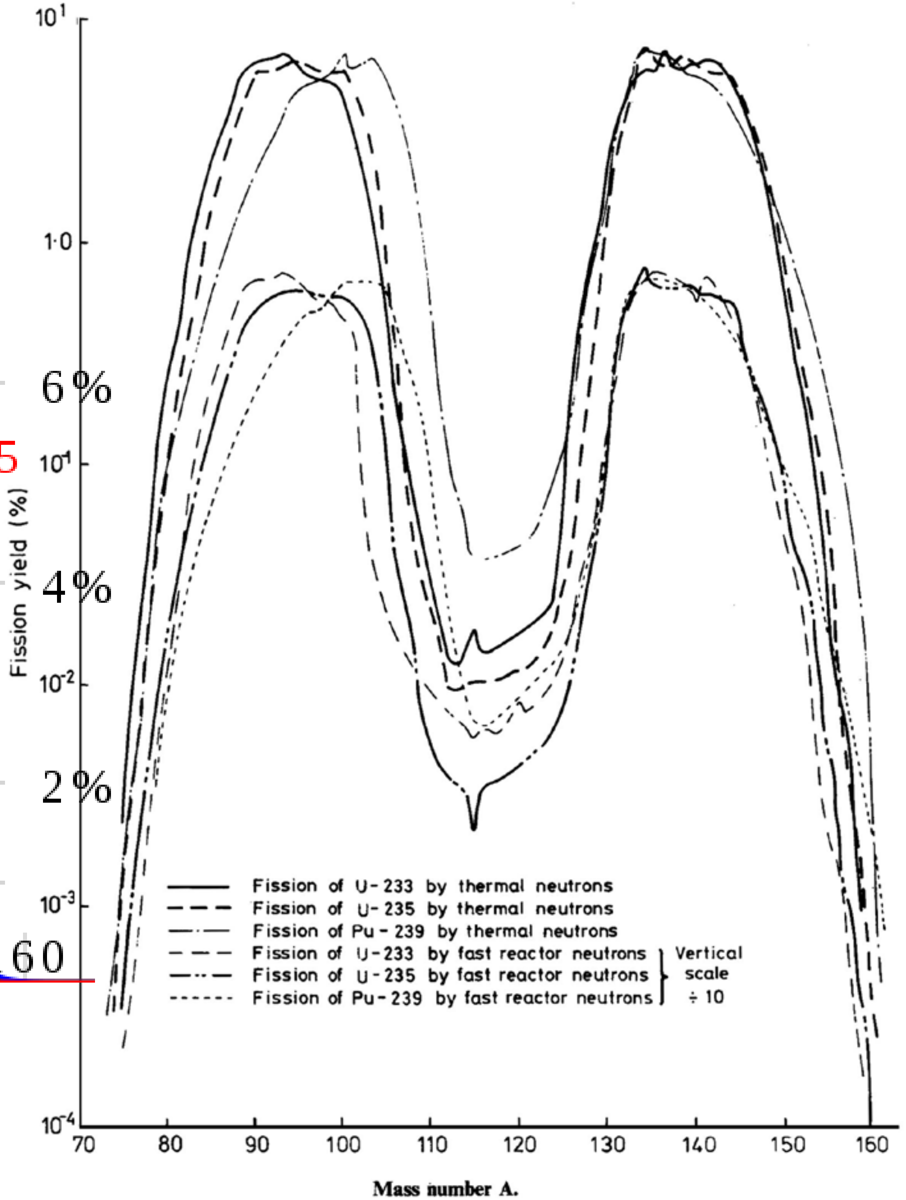
Emitted/Recoverable Energy

TABLE 3.6 EMITTED AND RECOVERABLE ENERGIES FOR FISSION OF ^{235}U

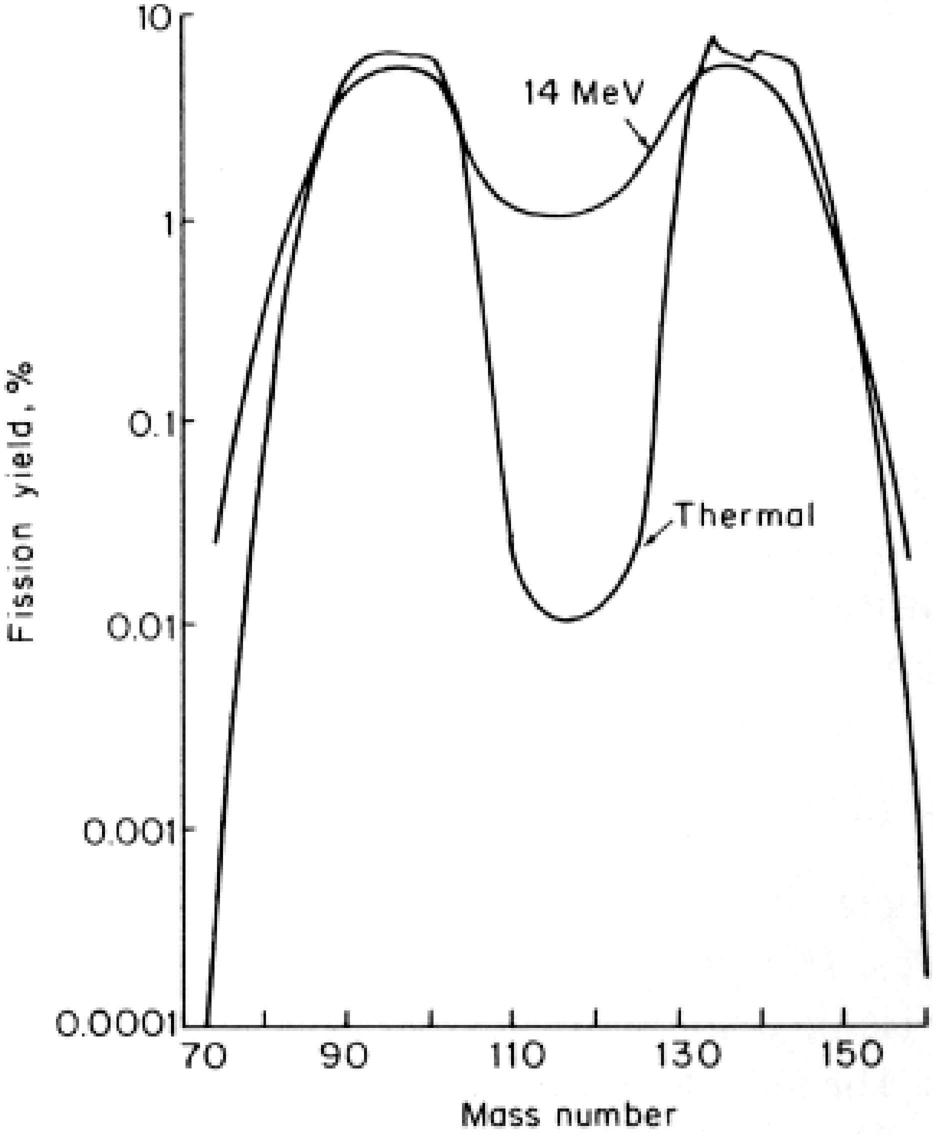
Form	Emitted Energy, MeV	Recoverable Energy, MeV
Fission fragments	168	168
Fission-product decay		
β-rays	8	8
γ-rays	7	7
neutrinos	12	—
Prompt γ-rays	7	7
Fission neutrons (kinetic energy)	5	5
Capture γ-rays	—	3–12
Total	207	198–207

Fission Product Distribution





Product Distribution at High Energy



Delayed Neutrons

- A small fraction (<1%) of total neutron production occur seconds or minutes after scission, represented by $\boldsymbol{\beta}$ below. These delayed neutrons are essential to reactor control.
- Fast neutron emission alone is far too rapid to allow control.

	Fast Fission		Thermal Fission	
Nuclide	$\overline{\nu}$	β	$\overline{\nu}$	β
^{235}U	2.57	0.0064	2.43	0.0065
^{233}U	2.62	0.0026	2.48	0.0026
^{239}Pu	3.09	0.0020	2.87	0.0021
^{241}Pu	–	–	3.14	0.0049
^{238}U	2.79	0.0148	–	–
^{232}Th	2.44	0.0203	–	–
^{240}Pu	3.3	0.0026	–	–

Source: Keepin [1965].

Delayed Neutron Data

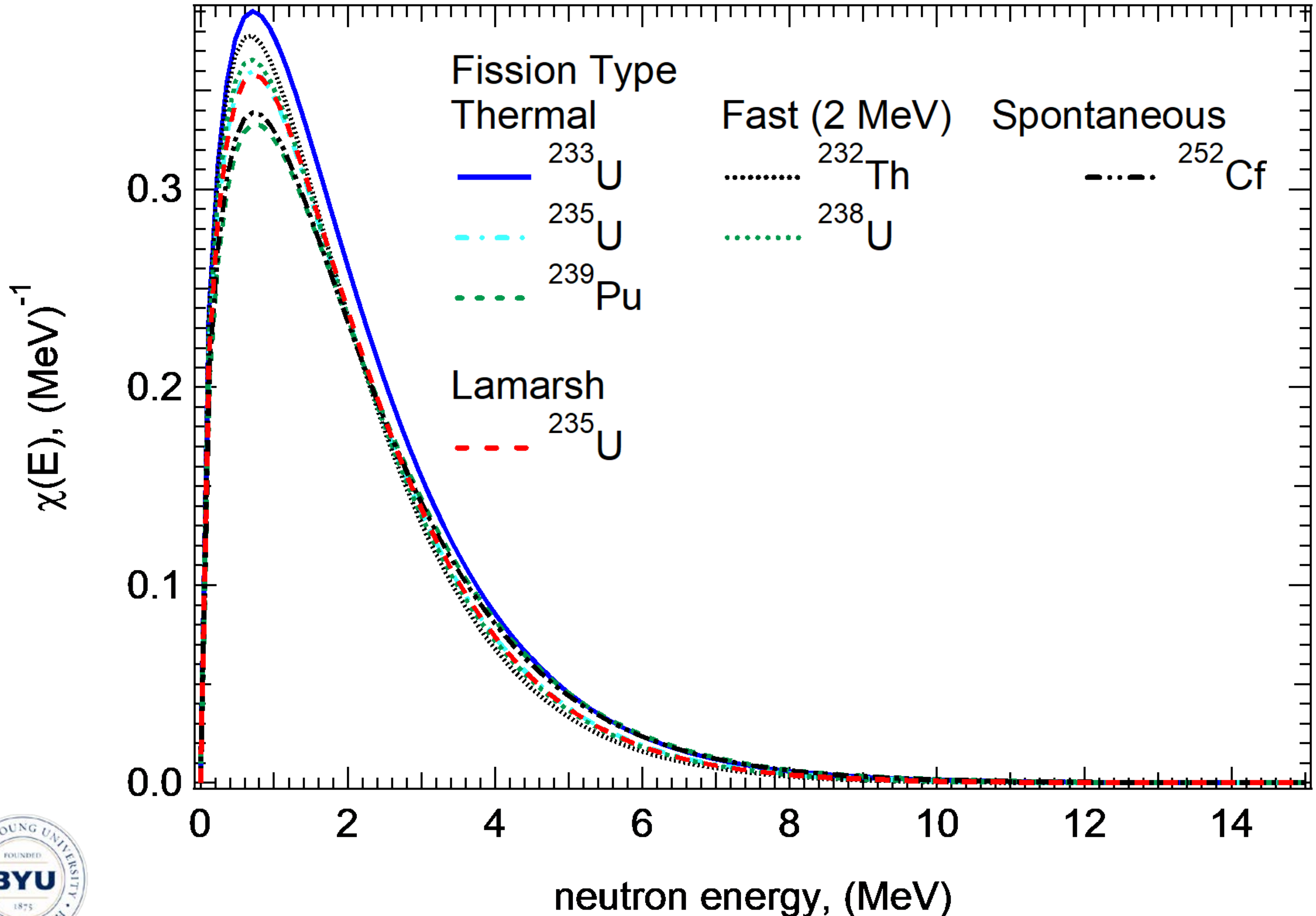
TABLE 3.5 DELAYED NEUTRON DATA FOR THERMAL FISSION IN ^{235}U*

Group	Half-Life (sec)	Decay Constant (l_i, sec^{-1})	Energy (ke V)	Yield, Neutrons per Fission	Fraction (β_i)
1	55.72	0.0124	250	0.00052	0.000215
2	22.72	0.0305	560	0.00346	0.001424
3	6.22	0.111	405	0.00310	0.001274
4	2.30	0.301	450	0.00624	0.002568
5	0.610	1.14	—	0.00182	0.000748
6	0.230	3.01	—	0.00066	0.000273

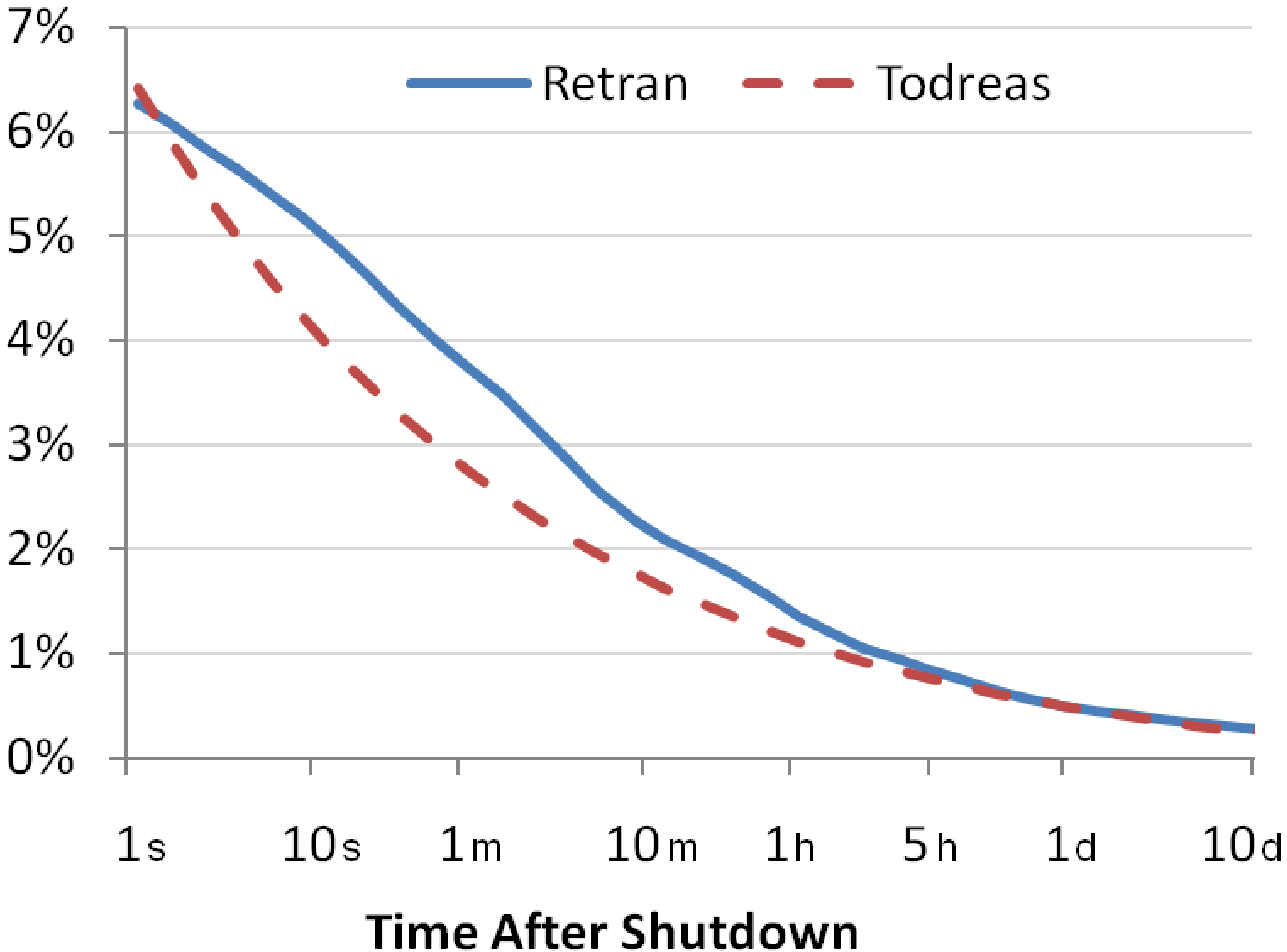
Total yield: 0.0158
Total delayed fraction (β): 0.0065

*Based in part on G. R. Keepin, *Physics of Nuclear Kinetics*, Reading, Mass.: Addison-Wesley, 1965.

Neutron Energy Spectrum



Decay Heat



7%
6%
5%
4%
3%
2%
1%
0%
Retran
Todreas
1s
10s
1m
10m
1h
5h
1d
10d
Time After Shutdown