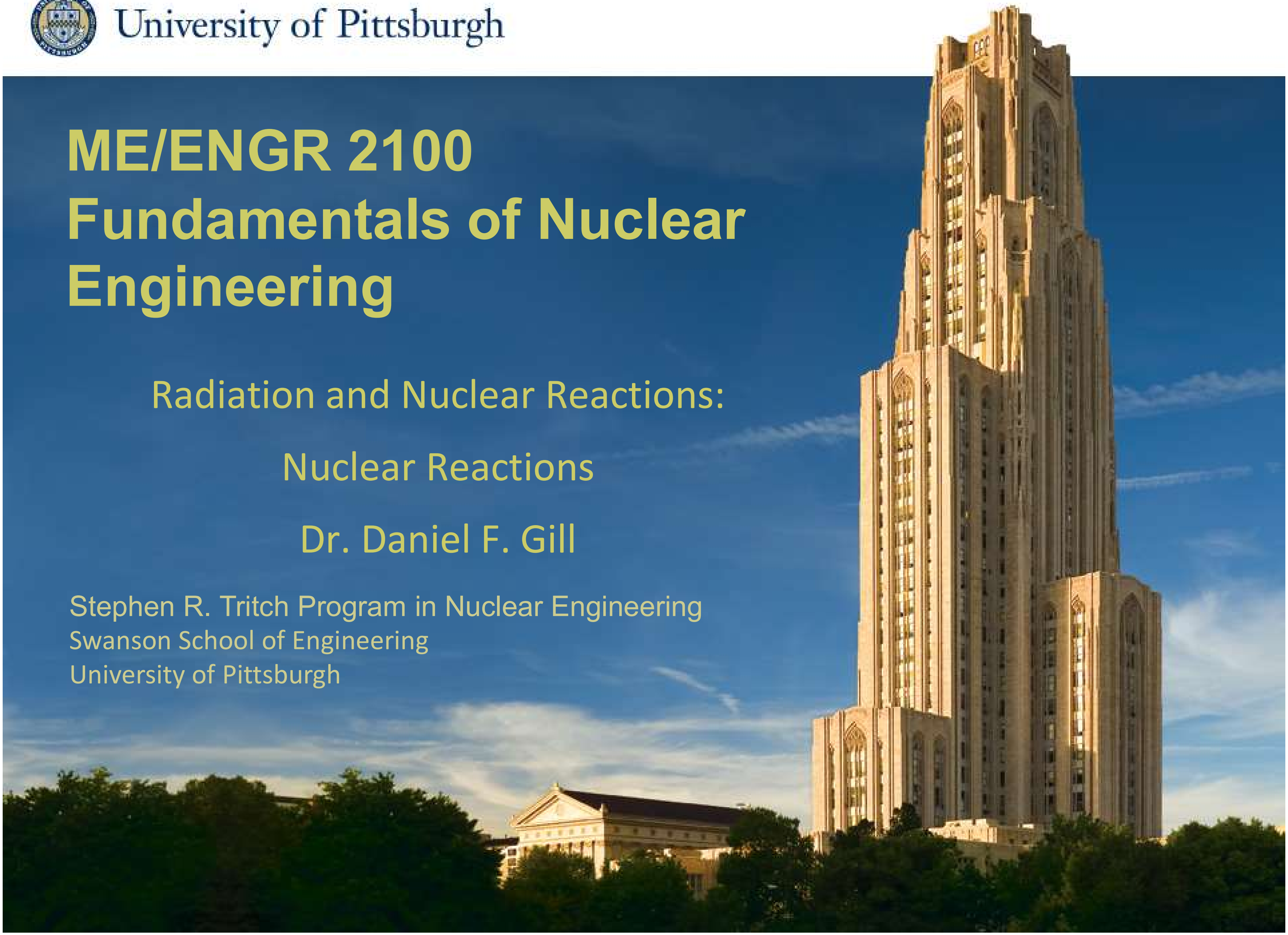

University of Pittsburgh

ME/ENGR 2100 Fundamentals of Nuclear Engineering

Radiation and Nuclear Reactions:

Nuclear Reactions

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Relevant Reading Assignments

- Chapter 2/3 of "Introduction to Nuclear Engineering," Lamarsh and Baratta, 3rd edition, Prentice-Hall (2001)
- Chapter 2 of "Nuclear Engineering: Theory and Technology of Commercial Nuclear Power," Knief, 2nd edition, American Nuclear Society (1992, reprint by ANS 2008)
- Chapter 2 of "Nuclear Reactor Analysis," Duderstadt and Hamilton, Van Nostrand (1976)
- Module 1 of DOE Fundamentals Handbook, "Nuclear Physics and Reactor Theory," U.S.DOE (1993)Available at:

https://www.standards.doe.gov/standards-documents/1000/1019-bhdbk-1993-v1

- Not required but useful and clear is the discussion of nuclear masses and binding energies at the beginning of Chapter 7 of "Concepts of Nuclear Physics" by Bernard L. Cohen, McGraw-Hill, 1971, available in most scientific libraries.

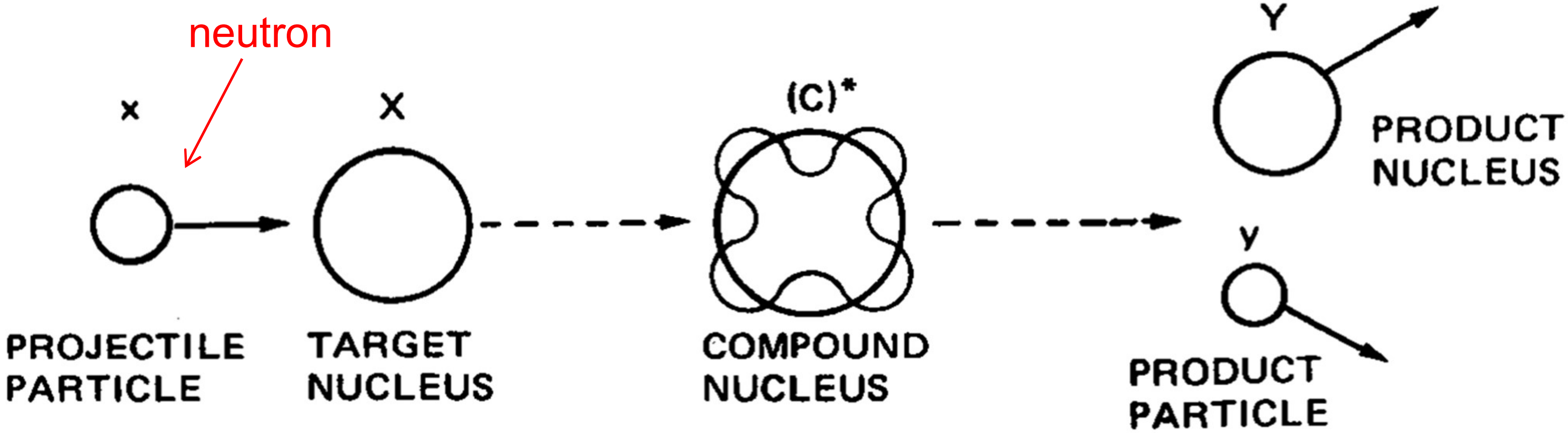
Learning Objectives

- Be able to write nuclear reactions / balance equations and calculate the Q value of a given reaction

Nuclear Reactions

- For this class, reactions between a subatomic particle (neutron) and a nucleus are of particular interest.
- Nuclear reactions are most easily caused by neutrons
  - Except at **HIGH** kinetic energy, charged particles cannot reach nucleus due to electrostatic forces
- For convenience we use a shorthand notation to describe nuclear reactions
  - Like everything else in nature, nuclear reactions must obey balance equations.

Nuclear Reactions



Notation Examples

$^{1}H + n \rightarrow {}^{2}H + \gamma$

$^{1}H(n,\gamma)^{2}H$

$^{1}H(n,\gamma)$

Reaction Energy Balance

- For the reaction

$$A + B \rightarrow C + D$$

- the energy balance can be written mathematically as:

$$E_A + M_A c^2 + E_B + M_B c^2 = E_C + M_C c^2 + E_D + M_D c^2$$

- E_x – Sensible energy of constituent x
  - Kinetic energy for particles with mass ($=M_x v^2/2$) --or--
  - Energy of EM radiation involved in reaction (γ rays)
- $M_X c^2$ – Mass equivalent energy (called "rest energy) of constituent x
  - Zero for EM radiation (or neutrinos) involved in reaction
- This is just conservation of energy for the system before and after the reaction.

Reaction Energy Balance

- The energy balance can be rewritten to give

$$E_A + M_A c^2 + E_B + M_B c^2 = E_C + M_C c^2 + E_D + M_D c^2$$

$$\underbrace{(E_C + E_D)}_{\text{Products}} - \underbrace{(E_A + E_B)}_{\text{Reactants}} = \underbrace{(M_A + M_B - M_C - M_D)c^2}_{\text{=Q-Value (change in binding energy)}}$$

Sensible energy change during reaction

=Q-Value
(change in binding energy)

- Q-Value – Sensible energy change during reaction
  - $Q > 0$: Exothermic Reaction (Energy released)
  - $Q < 0$: Endothermic Reaction (Energy absorbed)
- Threshold Reactions
  - Some reactions require a minimum energy for reactants for a reaction to take place

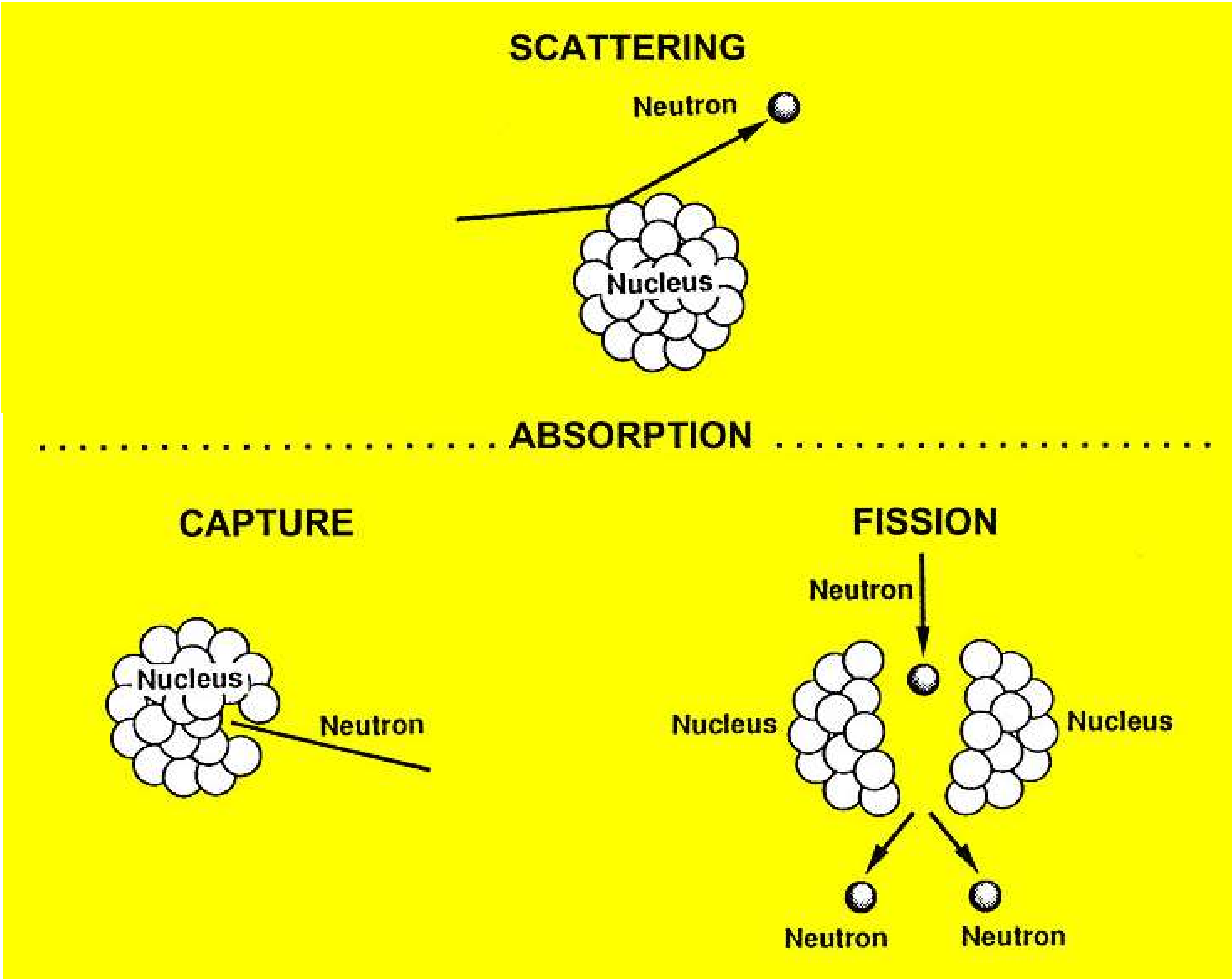
Nuclear Reactions

An incident neutron can produce a variety of outcomes, each with its own probability of occurring.

$$^{235}_{92}U + ^{1}_{0}n \longrightarrow \left(^{236}_{92}U\right)^{*} \longrightarrow$$

- (n,n): $^{235}_{92}U + ^{1}_{0}n$ — ELASTIC SCATTERING
- (n,n′): $^{235*}_{92}U + ^{1}_{0}n$ — INELASTIC SCATTERING
- (n,γ): $^{236}_{92}U + ^{0}_{0}\gamma$ — RADIATIVE CAPTURE
- (n,2n): $^{234}_{92}U + 2\ ^{1}_{0}n$ — MULTIPLE NEUTRON
- (n,f): FISSION

- After formation, unstable compound nuclei may stabilize through one of several decay mechanisms.


SCATTERING
Neutron
Nucleus
ABSORPTION
CAPTURE
Nucleus
Neutron
FISSION
Neutron
Nucleus
Nucleus
Neutron
Neutron

Nuclear Reactions

- Neutron Induced Reactions
  - Elastic Scattering (n,n)

$$^{1}_{1}H+^{1}_{0}n \rightarrow (^{2}_{1}D)^{*} \rightarrow ^{1}_{1}H+^{1}_{0}n$$

  - Inelastic Scattering (n,n)

$$^{56}_{26}Fe+^{1}_{0}n \rightarrow (^{57}_{26}Fe)^{*} \rightarrow ^{56*}_{26}Fe+^{1}_{0}n$$

  - (Radiative) Capture (also called n, γ reactions)

$$^{235}_{92}U+^{1}_{0}n \rightarrow (^{236}_{92}U)^{*} \rightarrow ^{236}_{92}U+^{0}_{0}\gamma$$

$$^{23}_{11}Na+^{1}_{0}n \rightarrow (^{24}_{11}Na)^{*} \rightarrow ^{24}_{11}Na+^{0}_{0}\gamma$$

Nuclear Reactions

- Neutron Induced Reactions
  - Charged Particle (n ,α) (n,p) (n,d) (n,2p) . . .

$$^{10}_{5}\mathrm{B}+^{1}_{0}\mathrm{n}\rightarrow(^{11}_{5}\mathrm{B})^{*}\rightarrow\,^{7}_{3}\mathrm{Li}+\,^{4}_{2}\alpha$$

[Notation: this can also be written as ^{10}B(n,α) ^{7}Li]

  - Multiple Neutron (n,2n) (n,3n) . . . .

$$^{233}_{92}U+^{1}_{0}n\rightarrow(^{234}_{92}U)^{*}\rightarrow^{232}_{92}U+2\;^{1}_{0}n$$

  - Fission (n,f)

$$^{235}_{92}U+^{1}_{0}n\rightarrow(^{236}_{92}U)^{*}\rightarrow F_1+F_2+x\;^{1}_{0}n+y\;^{0}_{0}\gamma$$

Nuclear Reactions

- Other Nuclear Reactions (Neutron as a Product)
  - Alpha (α,n) – note as in previous slide, α in, n out

$$^{9}_{4}Be + ^{4}_{2}\alpha \rightarrow (^{13}_{6}C)^{*} \rightarrow ^{12}_{6}C + ^{1}_{0}n$$

Neutron source

  - Gamma (γ,n)

$$^{2}_{1}D + ^{0}_{0}\gamma \rightarrow (^{2}_{1}H)^{*} \rightarrow ^{1}_{1}H + ^{1}_{0}n$$

Neutron source

Referred to as a photoneutron reaction

(Note that there are other reactions which also produce neutrons, and there are commercial neutron sources based on them.)