Interactions of Neutron with Matter

General

General

- Neutrons have no charge. They interact via physical collisions with nuclei (target nuclei).
- A neutron might scatter off the nucleus or combine with the nucleus.

General

General

- Neutrons, like other indirectly ionizing radiation (e.g., gamma rays), can travel substantial distances

- The probability that a given type of reaction will occur depends on:
    - The neutron energy
    - The identity of the target nuclide

General

Neutron Energies

- The types of reactions that are possible and their probability depends on the neutron kinetic energy.
- Neutrons are classified according to energy. There is no agreement as to the precise classification. The following is approximate:
    - Thermal (0.025 eV)
    - Slow (< 10 eV)
    - Intermediate (10 eV - 100 keV)
    - Fast (>100 keV)

General

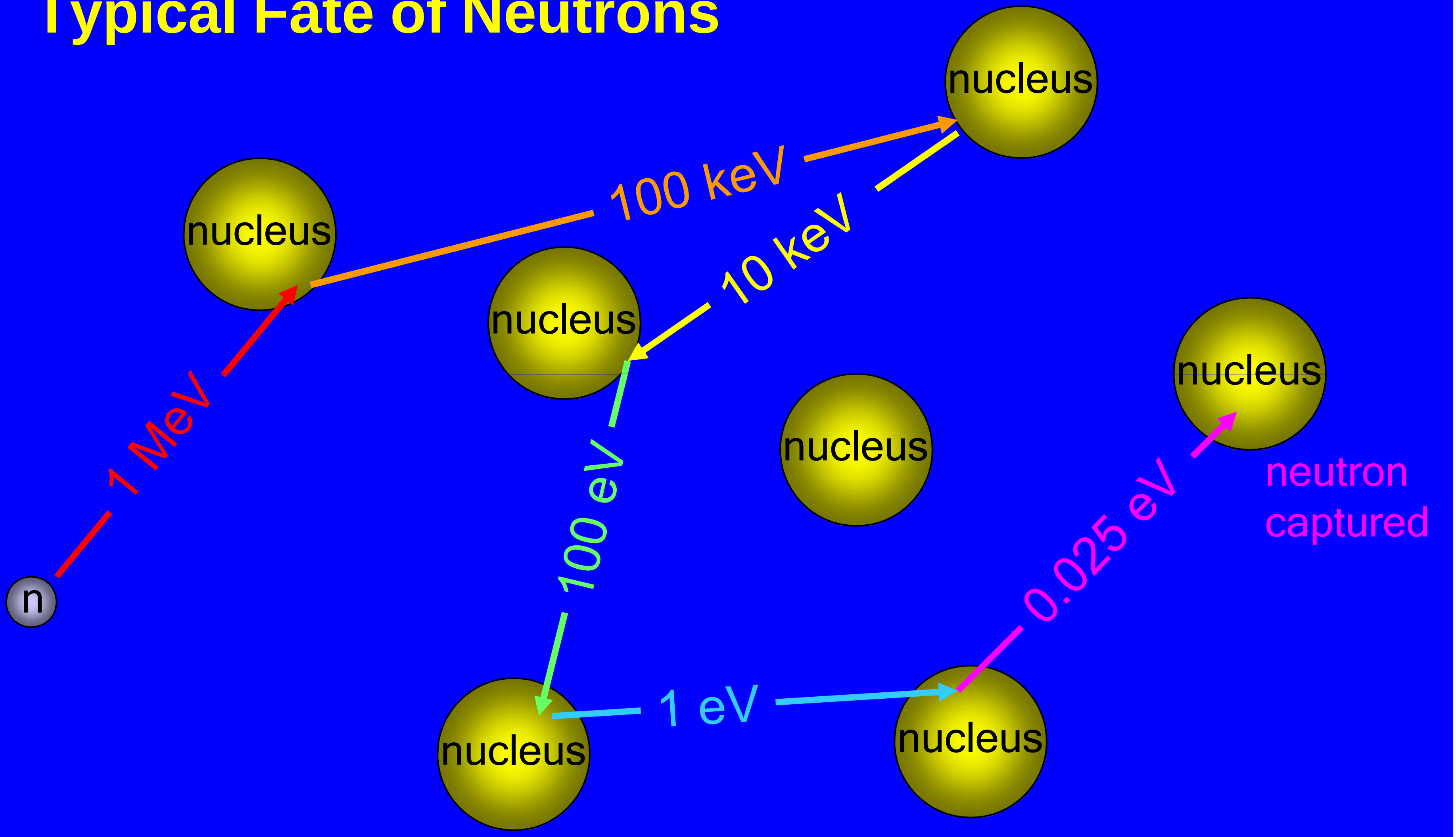
Typical Fate of Neutrons

- Neutrons are born fast. They slow down due to scattering (referred to as moderation) until they reach thermal energies. Finally, they are absorbed by a target nucleus.

Fast neutron → Thermal Neutron → Capture

General

Typical Fate of Neutrons



NEUTRON CROSS SECTIONS

Neutron Cross Sections

General

- Each type of interaction can be characterized by its cross section.
- The cross section, given the symbol F, describes the probability of the interaction.
- It depends on: the nuclide (e.g., H-1 vs H-2)
  the neutron energy
- The unit of the cross section is the barn. One barn is 10^{-24} cm^{2}

Neutron Cross Sections

Types of Interactions

Scattering: Elastic	${}^{A}M(n,n){}^{A}M$	F_{el} , F_{s} , $F_{n,n}$
Inelastic	${}^{A}M(n,n'){}^{A}M$	F_{inl} , F_{i} , $F_{n,n'}$
Proton	${}^{A}M(n,p){}^{A}N$	F_{p}
Alpha	${}^{A}M(n,\alpha){}^{A-3}N$	F_{α}
Neutron	${}^{A}M(n,2n){}^{A-1}M$	F_{2n}
Neutron-proton	${}^{A}M(n,np){}^{A-1}N$	F_{np}
Capture	${}^{A}M(n,(){}^{A+1}M$	$F_{(}$
Fission	${}^{A}M(n,fp)$	F_{f}

Neutron Cross Sections

Total Cross Section

- The total cross section for a given nuclide is the sum of the individual cross sections for that nuclide

$$F_T = F_{el} + F_{inel} + F_p + F_\alpha + F_{2n} + F_{np} + F_{(} + F_f$$

Microscopic Cross Section

So far, we have only considered what is known as the microscopic cross section, the cross section per atom of a given nuclide.

Neutron Cross Sections

Macroscopic Cross Section

The macroscopic cross section is the total cross section of all the atoms of a given nuclide in a cubic centimeter. The units of the macroscopic cross section are cm^{-1} (i.e., cm^2/cm^3).

$$E_T \;=\; N\,F_T \;=\; (6.02 \times 10^{23})\,(F_T)\,(D/A)$$

E_T is the total macroscopic cross section (cm^{-1})

N is the number of atoms of the nuclide per cm^3

F_T is the microscopic cross section (cm^2)

D is the density (g/cm^3)

A is the isotopic mass (g/mole)

Neutron Cross Sections

Removal Cross Section

The microscopic removal cross section (F_R) and the macroscopic removal cross section (E_R) are sometimes used in neutron shielding calculations.

The removal cross section is approximately 2/3 to 3/4 of the total cross section.

In neutron shielding calculations, we sometimes use the mass attenuation coefficient symbolized E_R/D

Neutron Cross Sections

Mass Attenuation Coefficient

According to Schaeffer (1973), the mass attenuation coefficient (E_R/D) for fast neutrons can be approximated with your choice of one of the following:

$$E_R/D = 0.19\, Z^{-0.743} \quad \text{cm}^2/\text{g} \quad (Z \leq 8)$$

$$= 0.125\, Z^{-0.565} \quad \text{cm}^2/\text{g} \quad (Z > 8)$$

$$E_R/D = 0.206\, A^{-1/3} Z^{-0.294} \sim 0.206\, (A\, Z)^{-1/3}$$

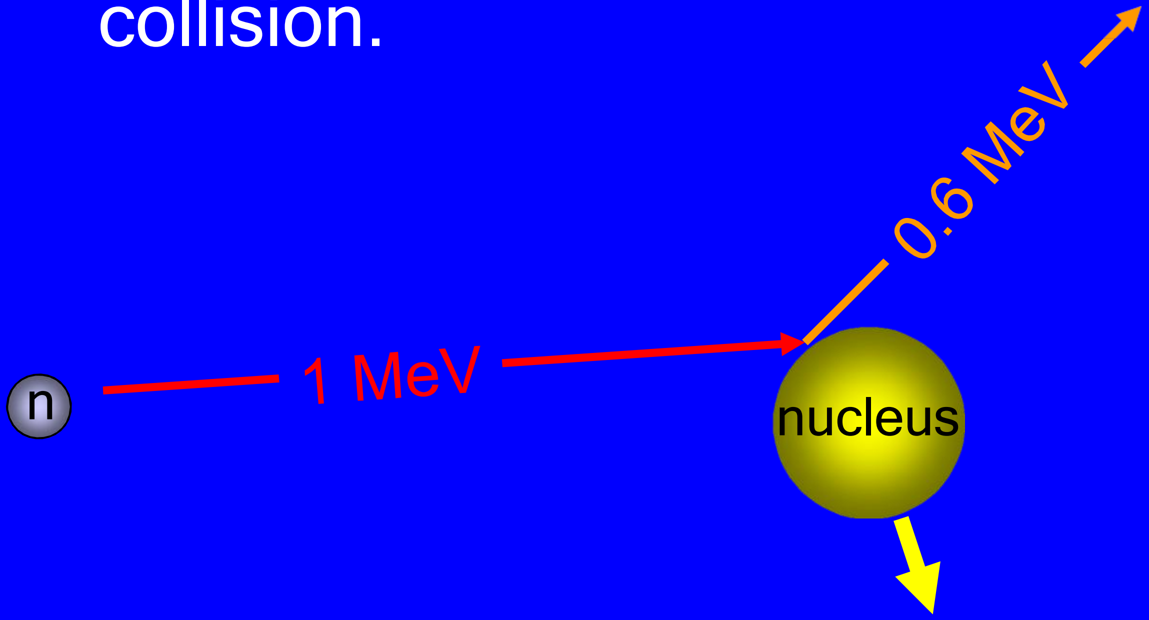
$$E_R/D = 0.21\, A^{-0.58}$$

SCATTERING

Scattering

Elastic Scattering

- Elastic scattering is a billiard ball type of collision where kinetic energy is conserved, i.e., the total kinetic energy is the same before and after the collision.



Kinetic energy of target nucleus = 0.4 MeV

Scattering

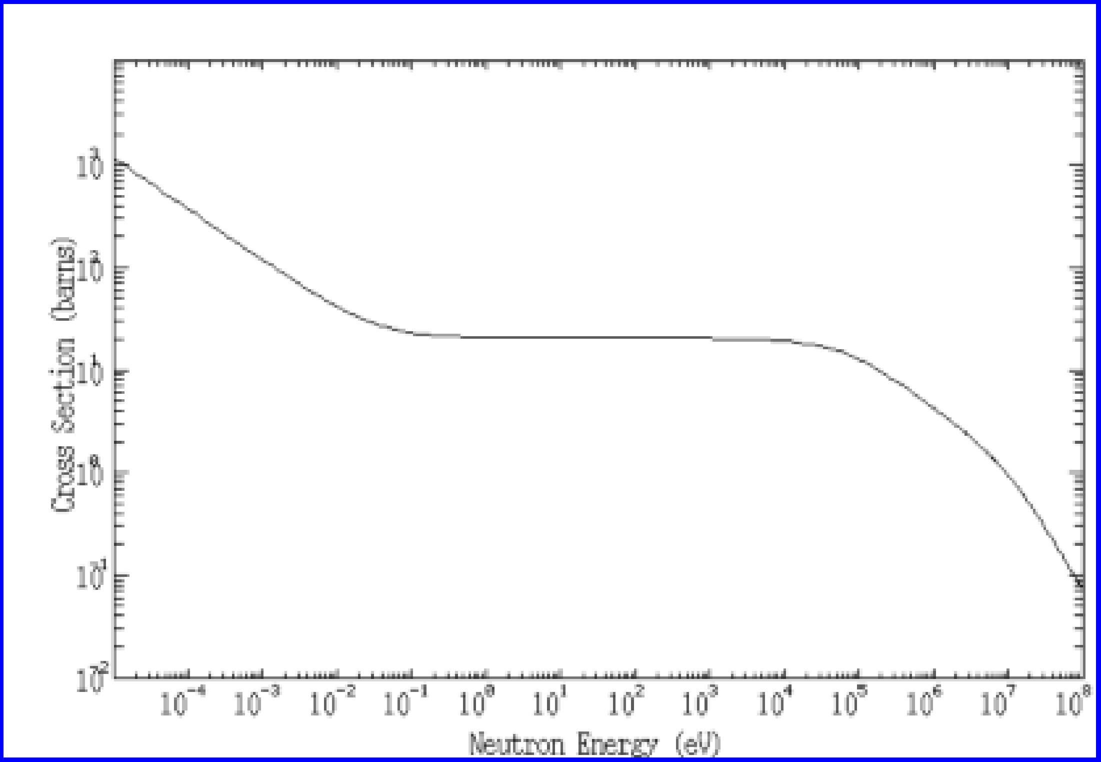
Elastic Scattering

- Elastic scattering is the most likely interaction for almost all nuclides and neutron energies.
- The greatest amount of energy can be transferred from the neutron to a target nucleus when the latter has the same mass as the neutron. As such, the lower the atomic mass number of the target, the more effective it is as a moderator.
- Moderators (e.g., water, paraffin, plastic, and graphite) slow neutrons by elastic scattering.

Scattering

Elastic Scattering

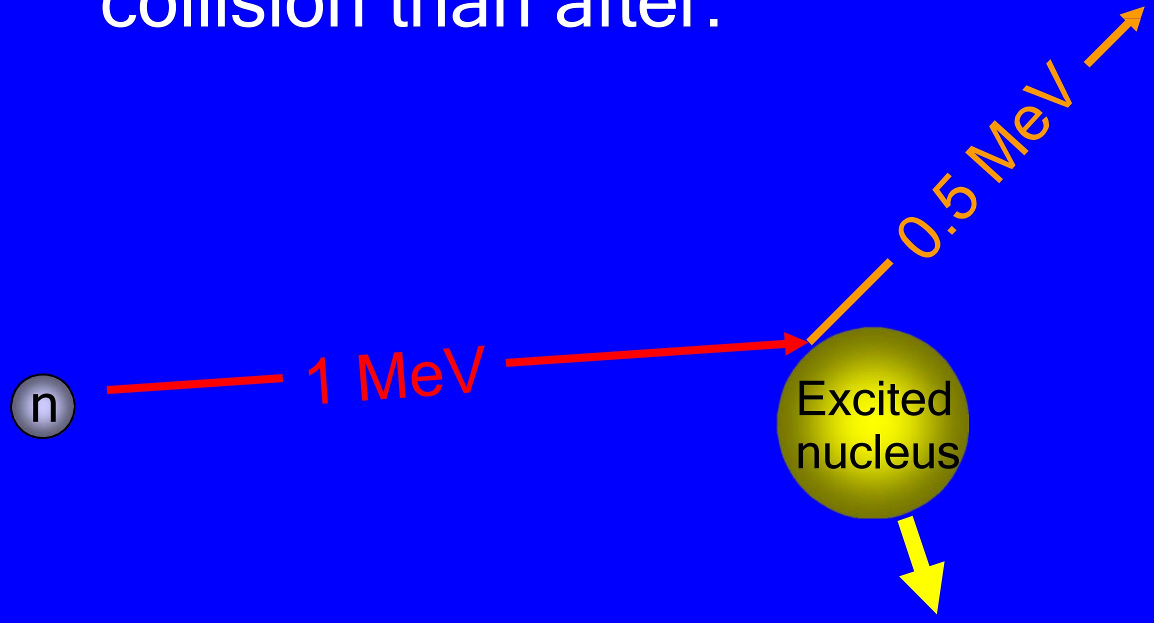
- This curve shows the dependence of the H-1 elastic scattering cross section on neutron energy.



Scattering

Inelastic Scattering

- Inelastic scattering is a type of scattering collision where kinetic energy is not conserved. The total kinetic energy was greater before the collision than after.



Kinetic energy of excited target nucleus = 0.3 MeV

Scattering

Inelastic Scattering

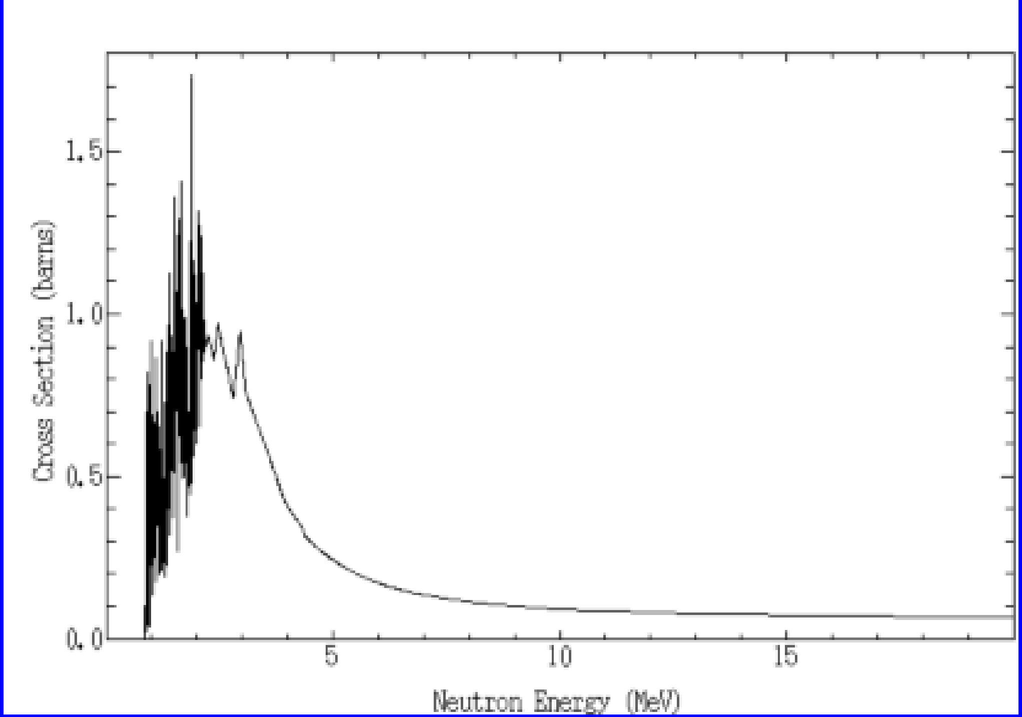
- The remaining energy is given to the target nucleus as excitation energy.
- When the scattered nucleus de-excites, it emits one or more gamma rays.
- Inelastic scattering is not common. When it does occur, it is most likely to involve high Z nuclei and high energy neutrons.
- It is sometimes used as a mechanism to moderate very high energy neutrons.

Scattering

Inelastic Scattering

- This curve shows the dependence of the Fe-56 inelastic scattering cross section on neutron energy.

Inelastic scattering does not occur below a certain threshold – the minimum energy required to excite the target nucleus



CHARGED PARTICLE REACTIONS

Charged Particle Reactions

General

- The target nucleus absorbs a neutron to form a compound nucleus. The latter then emits a charged particle (e.g., proton, alpha particle).
- If the final nucleus is left in an excited state, gamma rays might also be emitted.
- Some reactions are exothermic (no neutron energy threshold) and some are endothermic (neutron energy threshold).

Charged Particle Reactions

Example Charged Particle Reactions

- ^{3}He(n,p)^{3}H

  n + He-3 → H-3 + H-1 (proton)

  Large thermal neutron cross section: 5330 barns.

- ^{10}B(n,α)^{7}Li

  n + B-10 → Li + alpha (α)

  Large thermal neutron cross section: 3840 barns.

Charged Particle Reactions

Example Charged Particle Reactions

- $^{32}S(n,p)^{32}P$

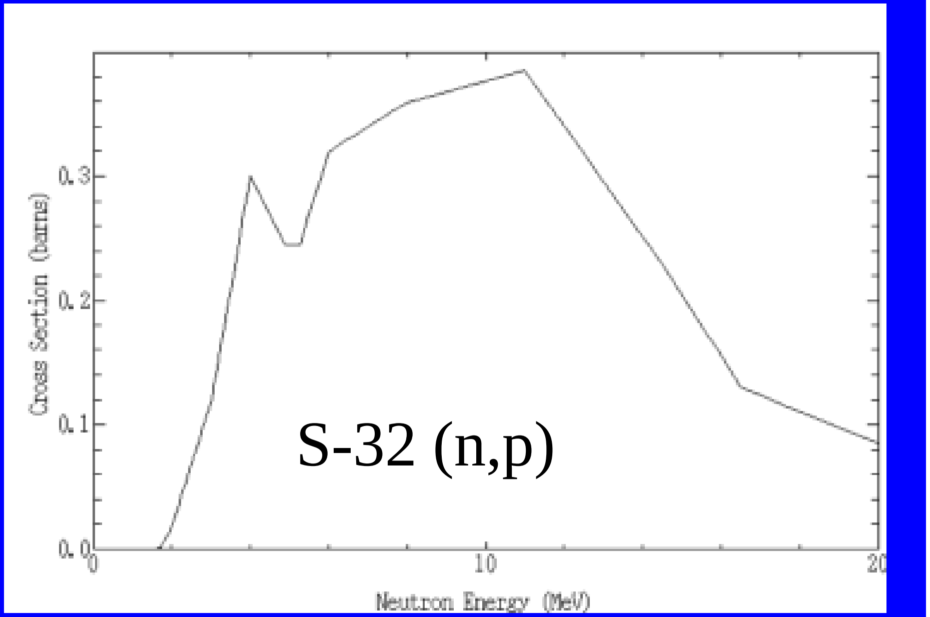
$$n + S\text{-}32 \rightarrow P\text{-}32 + H\text{-}1 \text{ (proton)}$$

This is an endothermic reaction with a neutron energy threshold of 0.96 MeV. Exothermic reactions tend to involve lower Z elements.

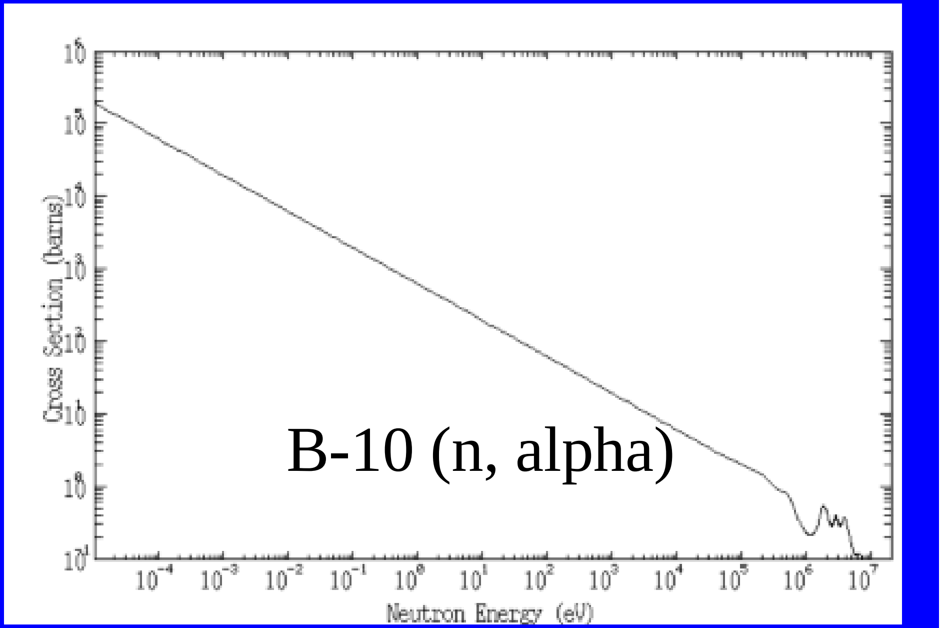
Charged Particle Reactions

Cross Section as a Function of Energy

- These curves show the dependence of S-32 and B-10 charged particle reactions on neutron energy.



S-32 (n,p)



B-10 (n, alpha)

CAPTURE REACTIONS

Capture Reactions

General

- The target nucleus absorbs a neutron. The resulting nucleus is left in an excited state. The latter deexcites with the emission of one or more “prompt” gamma rays (also known as capture gammas).
- These gamma rays are often high energy.
- The product might or might not be stable.
- This reaction is most likely with thermal neutrons.

Capture Reactions

Example Capture Reaction: H-1(n,()H-2

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

$$n + H\text{-}1 \rightarrow H\text{-}2 + \text{gamma } (\gamma)$$

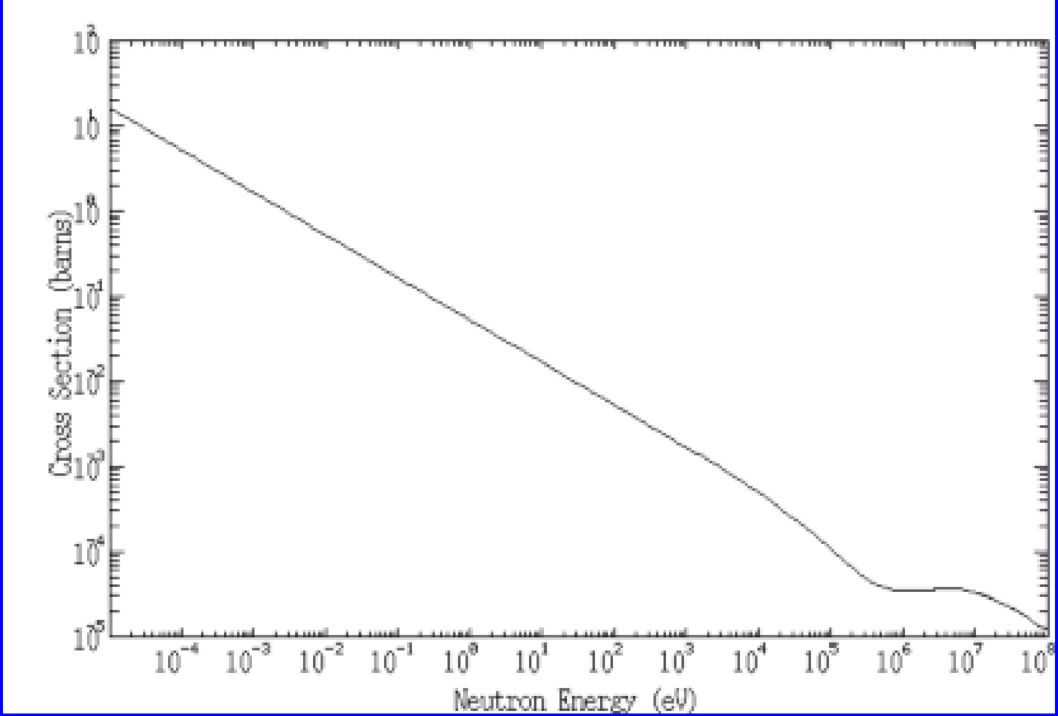
- The cross section for thermal neutrons is 0.33 barns.
- A 2.22 MeV gamma ray is emitted 100% of the time.
- Hydrogen moderates neutrons and absorbs them.

Capture Reactions

Example Capture Reaction: H-1(n,()H-2

- These curves show the dependence of the capture reaction with H-1 on neutron energy.

The probability of the reaction varies with 1/E



FISSION

Fission

General

- ${}^{A}M(n,fp)$

$$n + {}^{A}M \rightarrow 2 \text{ fission products} + 2\text{-}4 \text{ neutrons}$$

- The absorption of the neutron produces a compound nucleus that gains the kinetic energy of the neutron and the binding energy of the neutron.
- If this energy exceeds the “critical energy of fission,” the nucleus will split.

Fission

Fissile vs. Fissionable

- A fissile nuclide can be induced to fission by thermal neutrons, e.g., U-233, U-235, Pu-239, Pu-241. Most fissile nuclides are alpha emitters and all have odd atomic mass numbers.

- A fissionable nuclide requires fast neutrons to induce fission, e.g., U-238.

- Fission usually produces two fission products. The split is asymmetric. With U-235, one fission product has an atomic mass number in the 90-110 range while the other is in the 130-150 range.

NEUTRON SHIELDING

Neutron Shielding

The Three Steps

Shielding neutrons involves three steps:

1. Slow the neutrons
2. Absorb the neutrons
3. Absorb the gamma rays

Neutron Shielding

The Three Steps

1. Slow the neutrons

- Neutrons are slowed to thermal energies with hydrogenous material: water, paraffin, plastic.
- Water can evaporate or leak, paraffin is flammable and plastic is expensive.
- To slow down very fast neutrons, iron or lead might be used in front of the hydrogenous material.

Neutron Shielding

The Three Steps

2. Absorb the neutrons

- Hydrogenous materials are also very effective at absorbing neutrons - the cross section for neutron capture by H-1 is 0.33 barns.
- Unfortunately, a difficult to shield 2.2 MeV gamma ray is emitted when H-1 absorbs a neutron.
- Boron can be incorporated into the shield - it has a large cross section for neutron absorption and only emits a low energy capture gamma ray.
- To slow down very fast neutrons, iron or lead might be used in front of the hydrogenous material.

Neutron Shielding

The Three Steps

3. Absorb the gamma rays

- Gamma rays are produced in the neutron shield by neutron (radiative) capture, inelastic scattering, and the decay of activation products.

Neutron Shielding

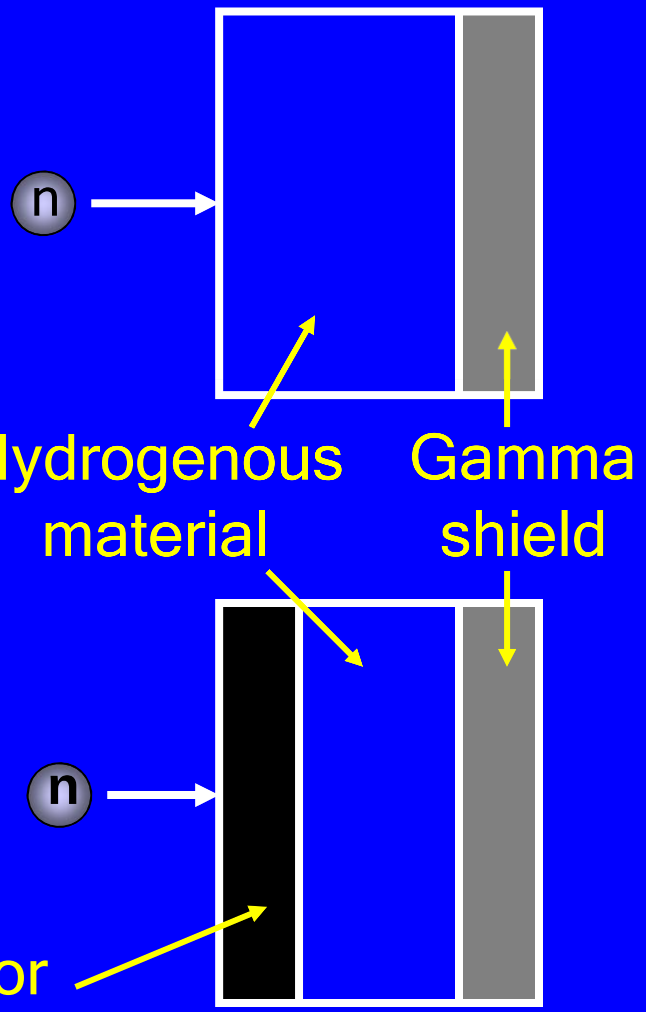
Multipurpose Materials for Neutron Shields

- Concrete, especially with barium mixed in, can slow and absorb the neutrons, and shield the gamma rays.

- Plastic with boron is also a good multipurpose shielding material.

Neutron Shielding

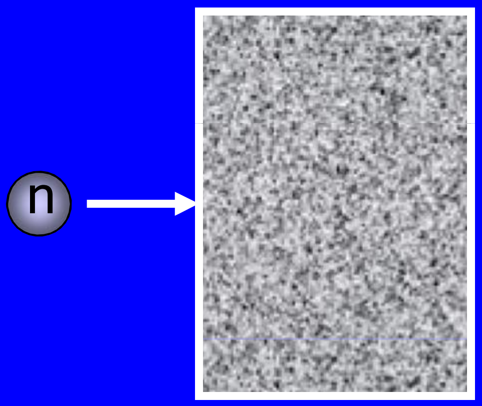
Possible Neutron Shields



Hydrogenous material

Gamma shield

Hi Z moderator for fast neutrons



Combination material e.g., borated plastic or concrete with barium

Neutron Shielding

Neutron Shielding Calculations

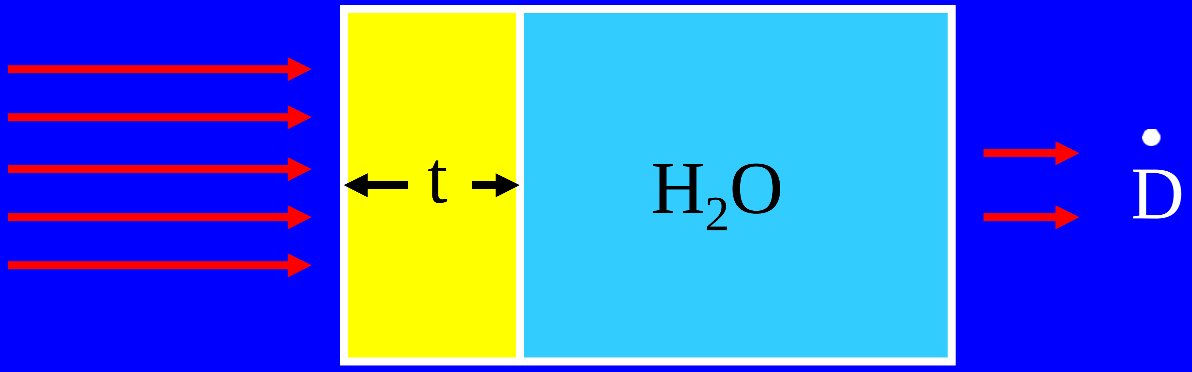
Neutron shielding calculations are best done by computers. Nevertheless, in some limited situations, it is possible to employ a simplistic exponential equation similar to that used for monoenergetic photons.

The following equation (Schaeffer 1973) describes the effect of a given shielding material (e.g., steel) on fast neutron dose rate. It only works if the there is at least 50 cm of water (or equivalent hydrogenous material) behind the shield.

Neutron Shielding

Neutron Shielding Calculations

$$\dot{D} = \dot{D}_0 \, e^{-\Sigma_R \, t}$$



$\dot{D}$ is the dose rate with shield

$\dot{D}_0$ is the dose rate without shield

t is the shield thickness

Neutron Shielding

Neutron Shielding Calculations

The following equation (modified from one in from NBS Handbook 63) describes the effect of shield thickness on the neutron dose rate associated with a radioactive neutron source (e.g., AmBe).

$$\dot{D} = B\,\dot{D}_0\,e^{-\sum_R t}$$

$\dot{D}$ is the dose rate with the shield

$\dot{D}_0$ is the dose rate without the shield

t is the shield thickness

B is a buildup factor usually assumed to be 5

Neutron Shielding

Neutron Shielding Calculations

Cross sections are from NBS Handbook 63

Material	Removal Cross Section E_R (cm^{-1})
water	0.103
iron	0.1576
ordinary concrete	0.0942
barytes concrete	0.0945
graphite	0.0785

NEUTRON INTERACTIONS IN TISSUE

Key Neutron Interactions in Tissue

Thermal Neutrons (< 0.5 eV)

$$^{14}\text{N (n, p) }^{14}\text{C}$$
$$^{1}\text{H (n, () }^{2}\text{H}$$

- Thermal neutrons interact within a short distance of the tissue surface. The dose to the surface tissue in the body is primarily due to the protons produced in the n-p reaction with ^{14}N.

- The dose to the deeper tissues is due to the 2.2 MeV gamma rays from the n-gamma reaction involving H-1.

Key Neutron Interactions in Tissue

Thermal Neutrons (< 0.5 eV)

- When large volumes of tissue are considered (e.g., the size of the torso), the absorbed dose due to the n-gamma reaction with hydrogen can be as much as 100 times the dose due to the n-p reaction involving nitrogen.

Key Neutron Interactions in Tissue

Intermediate (0.5-10 keV) and Fast (>10 keV) Neutrons

- The largest dose from neutrons at these energies is due to elastic scattering with hydrogen.

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

- Varying amounts of energy are transferred to the hydrogen nucleus (a proton). The latter might travel up to 10 um in tissue.
- Elastic scattering involving oxygen and to a lesser extent carbon and nitrogen might contribute 1% to 20% of the total dose.

Key Neutron Interactions in Tissue

Intermediate (0.5-10 keV) and Fast (>10 keV) Neutrons

- At most, inelastic scattering contributes a few percent of the total dose.
- Above 20 MeV, nuclear reactions, especially with oxygen become significant and can contribute 20% of the total dose.
- Spallation, the fragmentation of nuclei, becomes significant at 100 MeV where it might contribute 20% of the total dose.

Key Neutron Interactions in Tissue

Neutron Interactions and the Quality Factor

- Below 10 keV, the neutron dose in the body is dominated by the $^{1}H(n, ()^{2}H$ reaction. Since the quality factor (Q) for gamma rays is low and more or less independent of energy, so too is the neutron quality factor.

- Above 10 keV, the neutron dose is more and more dominated by the $^{1}H(n,n)^{1}H$ elastic scattering reaction. Since Q for the recoil proton is greater than Q for gamma rays, the neutron quality factor increases rapidly above this energy.

Key Neutron Interactions in Tissue

Neutron Interactions and the Quality Factor

- Above 1 MeV, the neutron quality factor begins to decrease. This is because the increasing energy of the recoil proton results in a decreasing stopping power. As the stopping power decreases, so does the proton’s quality factor.

Key Neutron Interactions in Tissue

Neutron Interactions and the Quality Factor