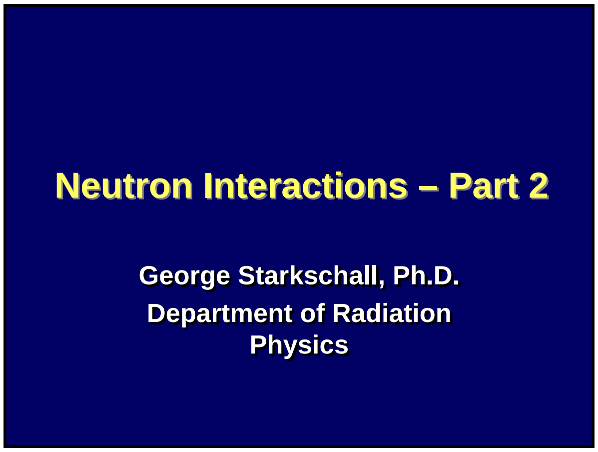

Neutron Interactions – Part 2

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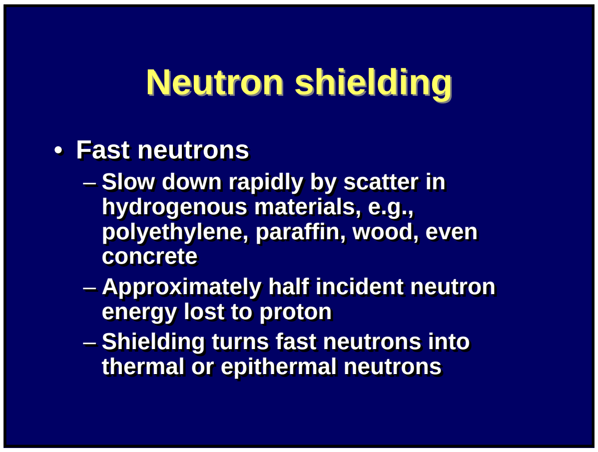
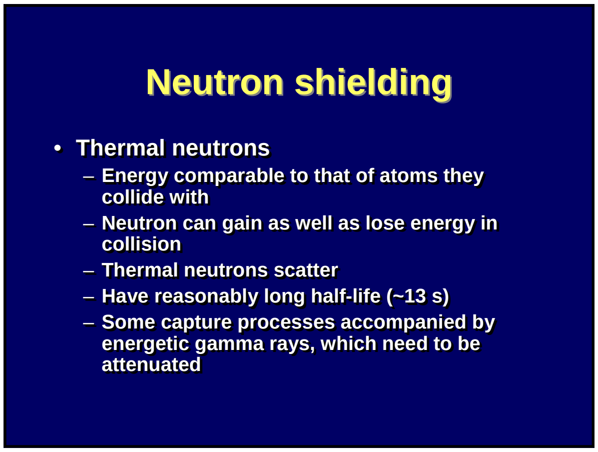


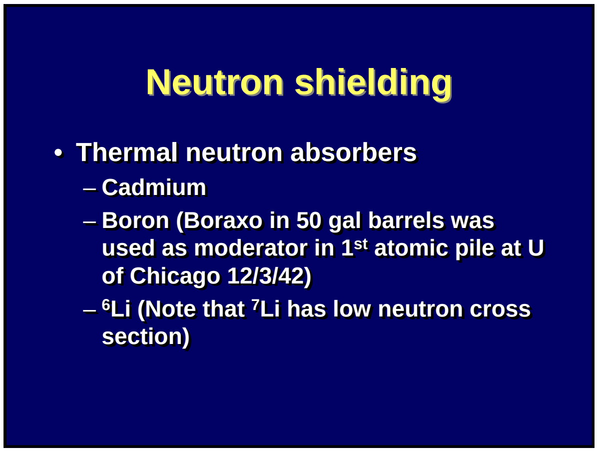
Neutron shielding

- Fast neutrons
  - Slow down rapidly by scatter in hydrogenous materials, e.g., polyethylene, paraffin, wood, even concrete
  - Approximately half incident neutron energy lost to proton
  - Shielding turns fast neutrons into thermal or epithermal neutrons



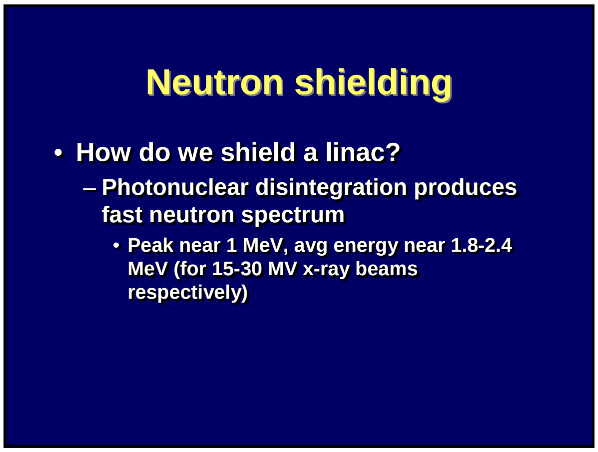
Neutron shielding

- Thermal neutrons
  - Energy comparable to that of atoms they collide with
  - Neutron can gain as well as lose energy in collision
  - Thermal neutrons scatter
  - Have reasonably long half-life (~13 s)
  - Some capture processes accompanied by energetic gamma rays, which need to be attenuated



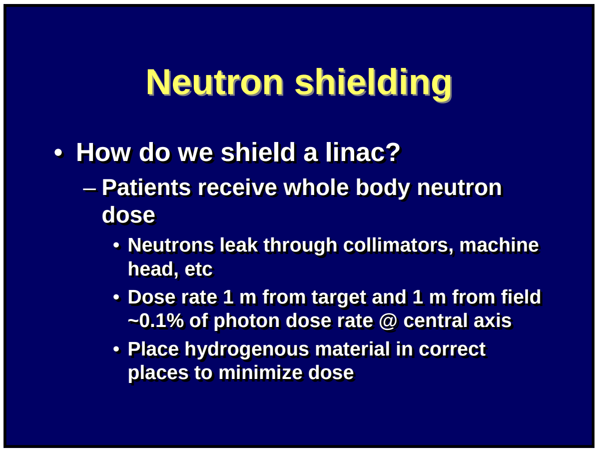
Neutron shielding

- Thermal neutron absorbers
  - Cadmium
  - Boron (Boraxo in 50 gal barrels was used as moderator in 1st atomic pile at U of Chicago 12/3/42)
  - ^{6}Li (Note that ^{7}Li has low neutron cross section)



Neutron shielding

- How do we shield a linac?
  - Photonuclear disintegration produces fast neutron spectrum
    - Peak near 1 MeV, avg energy near 1.8-2.4 MeV (for 15-30 MV x-ray beams respectively)



Neutron shielding

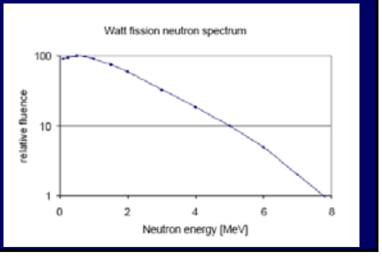
- How do we shield a linac?
  - Patients receive whole body neutron dose
    - Neutrons leak through collimators, machine head, etc
    - Dose rate 1 m from target and 1 m from field ~0.1% of photon dose rate @ central axis
    - Place hydrogenous material in correct places to minimize dose

Neutron shielding

- Outside therapy room
  - Primary barriers – concrete required to shield photons sufficient to shield neutrons
  - Neutrons scatter – shielding concern is doors and mazes for AC, power, etc
  - Shielding sequence
    - Hydrogenous materials to thermalize neutrons
    - Impregnate with boron to absorb thermal neutrons
    - Steel or lead to stop gamma rays

Neutron sources

- Reactors – fission spectrum
  - Note peak at ~1 MeV, with rapid falloff (10% by 4 – 5 MeV)



Neutron sources

- Accelerators
  - Cyclotrons
    - ^{2}H or ^{1}H incident on Be is popular
    - MDACC cyclotron (many years ago) used 42 MeV ^{1}H on Be to generate neutron depth dose curve that looked much like 6 MV x-ray beam

Neutron sources

- Accelerators
  - D-T generator

    $^{3}H\ (^{2}H,^{1}n)\ ^{4}He + 14\ MeV$
    - Kinetic energy goes to neutron
    - Accelerate deuterium to 250 keV (very low energy)
    - Strike tritium target
    - Produces monoenergetic 14 MeV beam
    - Fluence not high enough for therapy
    - Useful in oil well logging

Neutron sources

- Radioactive sources
  - ^{252}Cf – spontaneous fission
    - Used for brachytherapy for a while
    - 5 yr half life
    - Radiation safety concerns

Neutron sources

- Radioactive sources
  - $^{9}Be\ (\alpha,n)\ ^{12}C$
    - Use α from various isotopes: ^{234}Pu, ^{241}Am, ^{210}Po, ^{226}Ra
    - Mean neutron energy near 4 MeV with maximum near 12 MeV

Neutron dose

- Fast neutrons – elastic scatter
  - Energy dissipated locally

$$D_n(E) = \phi E \sum_i N_i \sigma_i f_i$$

  - ϕ – neutron fluence rate [neutrons cm^{-2} sec^{-1}]
  - E – neutron energy
  - N_i – atoms per kg of ith element
  - σ_i – scattering cross section of the ith element
  - f_i – mean fractional energy transferred to atom of mass M

Neutron dose

- Recall that

$$f = \frac{2M}{(M+1)^2}$$

Neutron dose in tissue

- Soft tissue assumed to have composition

$$C_{0.5}H_8O_{3.5}N_{0.14}$$

- Formula weight of 72

Tissue composition

Element	N_i (atom kg^{-1})	f_i
H	6.70×10^{25}	0.500
C	4.18×10^{24}	0.142
N	1.17×10^{24}	0.124
O	2.93×10^{25}	0.111

Example

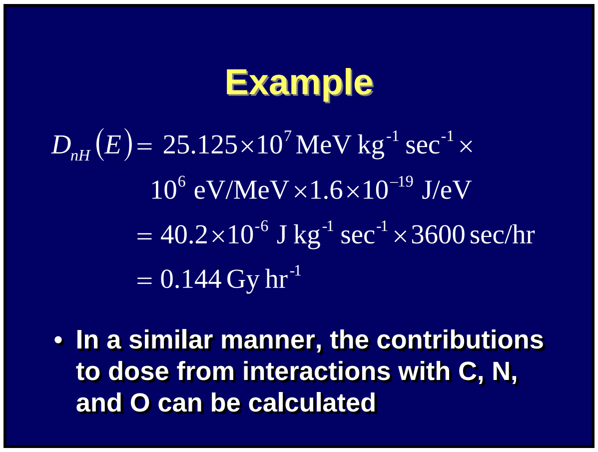
- What is the dose rate to soft tissue in a beam of 5 MeV neutrons whose fluence rate is 10^6 neutrons cm^{-2} sec^{-1}?
- Need scattering cross sections for 5 MeV neutrons:

H	1.50×10^{-24} cm^2
C	1.65×10^{-24} cm^2
N	1.00×10^{-24} cm^2
O	1.55×10^{-24} cm^2

Example

- For H,

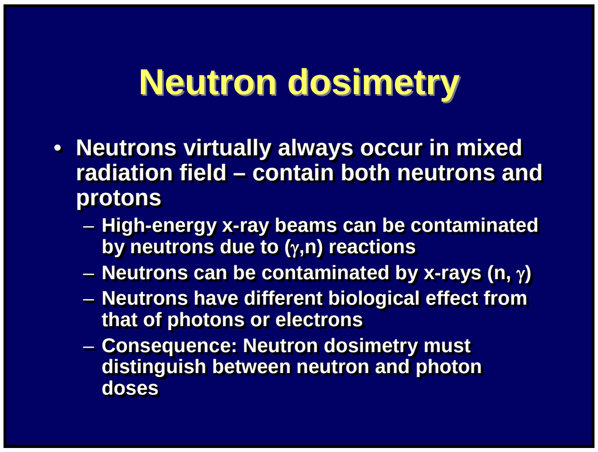
$$\begin{aligned} D_{nH}(E) &= \phi E N_H \sigma_H f_H \\ &= 10^{6} \text{ neut cm}^{-2} \text{ sec}^{-1} \times 5 \text{ MeV/neut} \times \\ &\quad 6.70 \times 10^{25} \text{ atom kg}^{-1} \times \\ &\quad 1.50 \times 10^{-24} \text{cm}^{2}/\text{atom} \times 0.500 \end{aligned}$$



Example

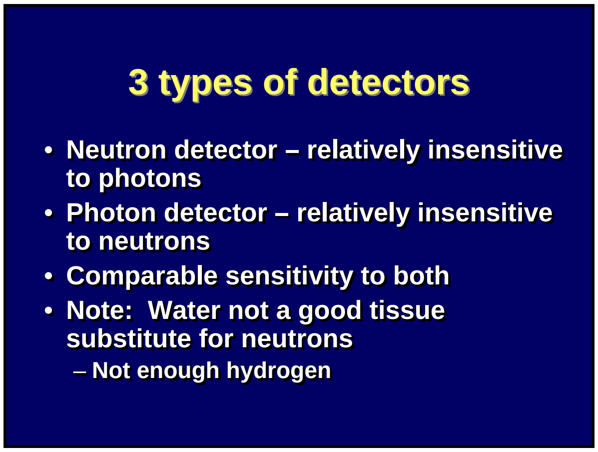
$$\begin{aligned} D_{nH}(E) &= 25.125\times10^{7}\,\text{MeV kg}^{-1}\,\text{sec}^{-1}\times \\ &\quad 10^{6}\ \text{eV/MeV}\times1.6\times10^{-19}\ \text{J/eV} \\ &= 40.2\times10^{-6}\ \text{J kg}^{-1}\ \text{sec}^{-1}\times3600\,\text{sec/hr} \\ &= 0.144\,\text{Gy hr}^{-1} \end{aligned}$$

- In a similar manner, the contributions to dose from interactions with C, N, and O can be calculated



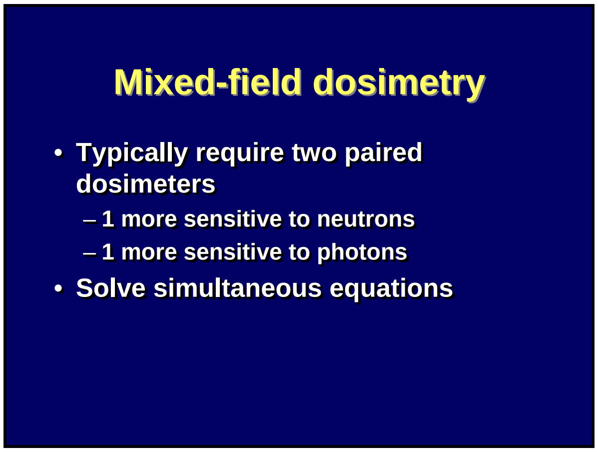
Neutron dosimetry

- Neutrons virtually always occur in mixed radiation field – contain both neutrons and protons
  - High-energy x-ray beams can be contaminated by neutrons due to (γ,n) reactions
  - Neutrons can be contaminated by x-rays (n, γ)
  - Neutrons have different biological effect from that of photons or electrons
  - Consequence: Neutron dosimetry must distinguish between neutron and photon doses



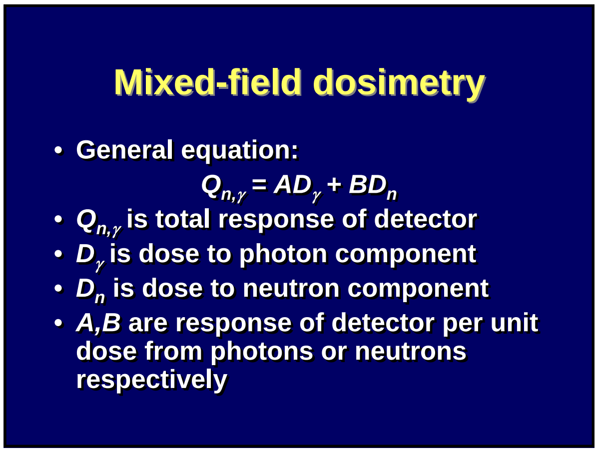
3 types of detectors

- Neutron detector – relatively insensitive to photons
- Photon detector – relatively insensitive to neutrons
- Comparable sensitivity to both
- Note: Water not a good tissue substitute for neutrons
  - Not enough hydrogen



Mixed-field dosimetry

- Typically require two paired dosimeters
  - 1 more sensitive to neutrons
  - 1 more sensitive to photons
- Solve simultaneous equations

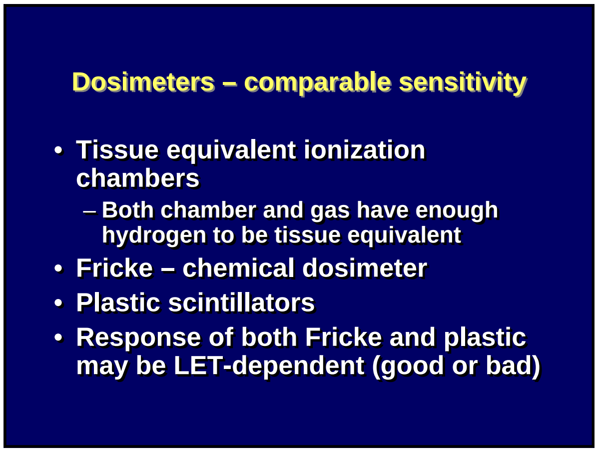


Mixed-field dosimetry

- General equation:

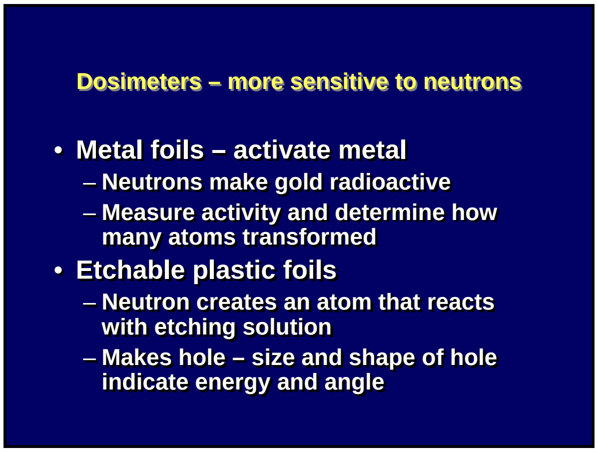
$$Q_{n,\gamma} = AD_\gamma + BD_n$$

- $Q_{n,\gamma}$ is total response of detector
- D_γ is dose to photon component
- D_n is dose to neutron component
- A,B are response of detector per unit dose from photons or neutrons respectively



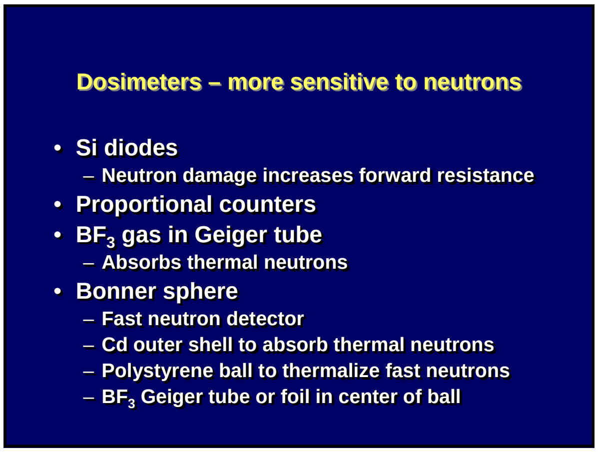
Dosimeters – comparable sensitivity

- Tissue equivalent ionization chambers
  - Both chamber and gas have enough hydrogen to be tissue equivalent
- Fricke – chemical dosimeter
- Plastic scintillators
- Response of both Fricke and plastic may be LET-dependent (good or bad)



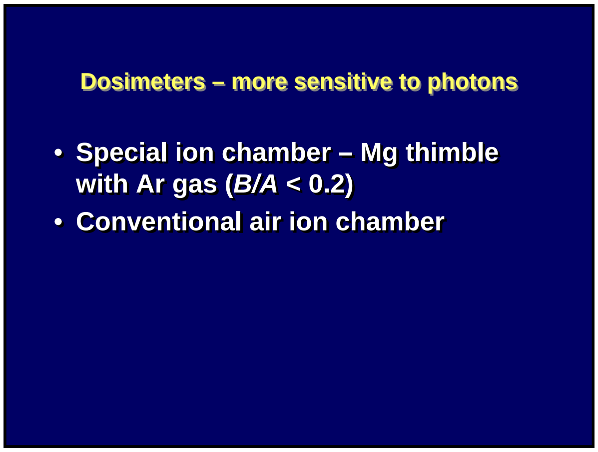
Dosimeters – more sensitive to neutrons

- Metal foils – activate metal
  - Neutrons make gold radioactive
  - Measure activity and determine how many atoms transformed
- Etchable plastic foils
  - Neutron creates an atom that reacts with etching solution
  - Makes hole – size and shape of hole indicate energy and angle



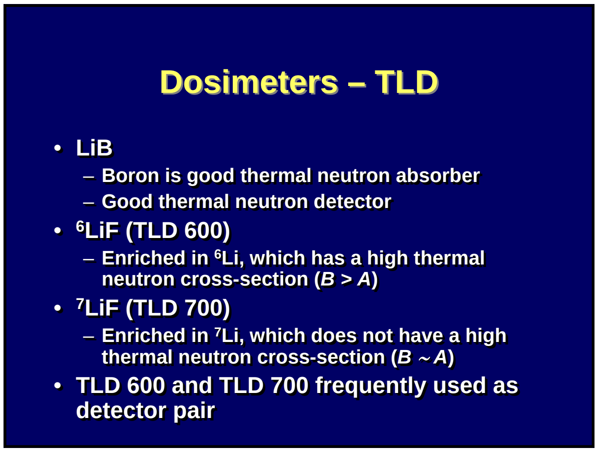
Dosimeters – more sensitive to neutrons

- Si diodes
  - Neutron damage increases forward resistance
- Proportional counters
- BF_3 gas in Geiger tube
  - Absorbs thermal neutrons
- Bonner sphere
  - Fast neutron detector
  - Cd outer shell to absorb thermal neutrons
  - Polystyrene ball to thermalize fast neutrons
  - BF_3 Geiger tube or foil in center of ball



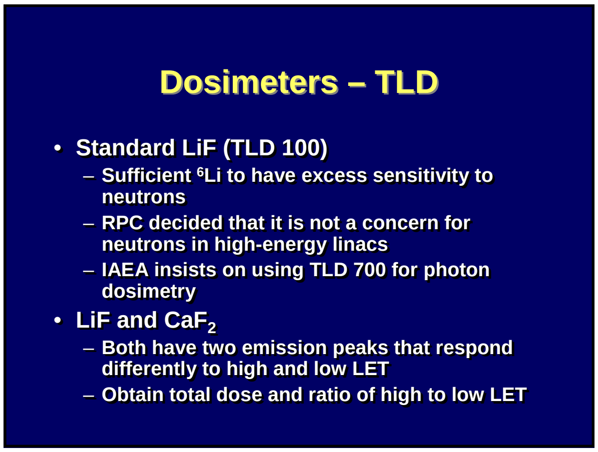
Dosimeters – more sensitive to photons

- Special ion chamber – Mg thimble with Ar gas ($B/A < 0.2$)
- Conventional air ion chamber



Dosimeters – TLD

- LiB
  - Boron is good thermal neutron absorber
  - Good thermal neutron detector
- ^{6}LiF (TLD 600)
  - Enriched in ^{6}Li, which has a high thermal neutron cross-section ($B > A$)
- ^{7}LiF (TLD 700)
  - Enriched in ^{7}Li, which does not have a high thermal neutron cross-section ($B \sim A$)
- TLD 600 and TLD 700 frequently used as detector pair



Dosimeters – TLD

- Standard LiF (TLD 100)
  - Sufficient ^{6}Li to have excess sensitivity to neutrons
  - RPC decided that it is not a concern for neutrons in high-energy linacs
  - IAEA insists on using TLD 700 for photon dosimetry
- LiF and CaF_2
  - Both have two emission peaks that respond differently to high and low LET
  - Obtain total dose and ratio of high to low LET