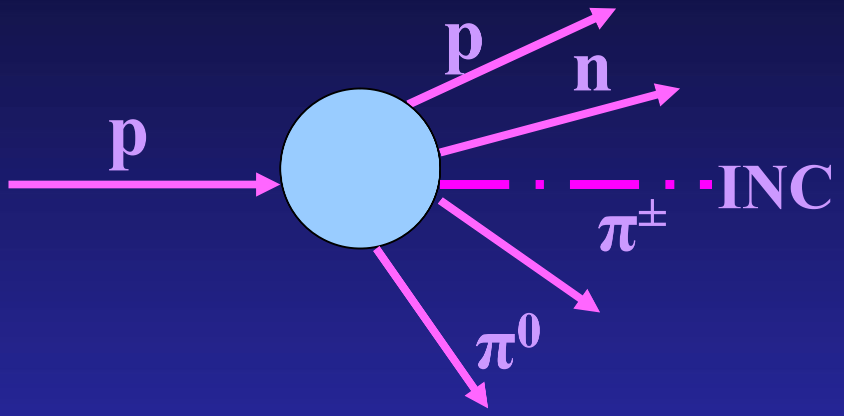
Shielding Design Considerations for Proton Therapy Facilities



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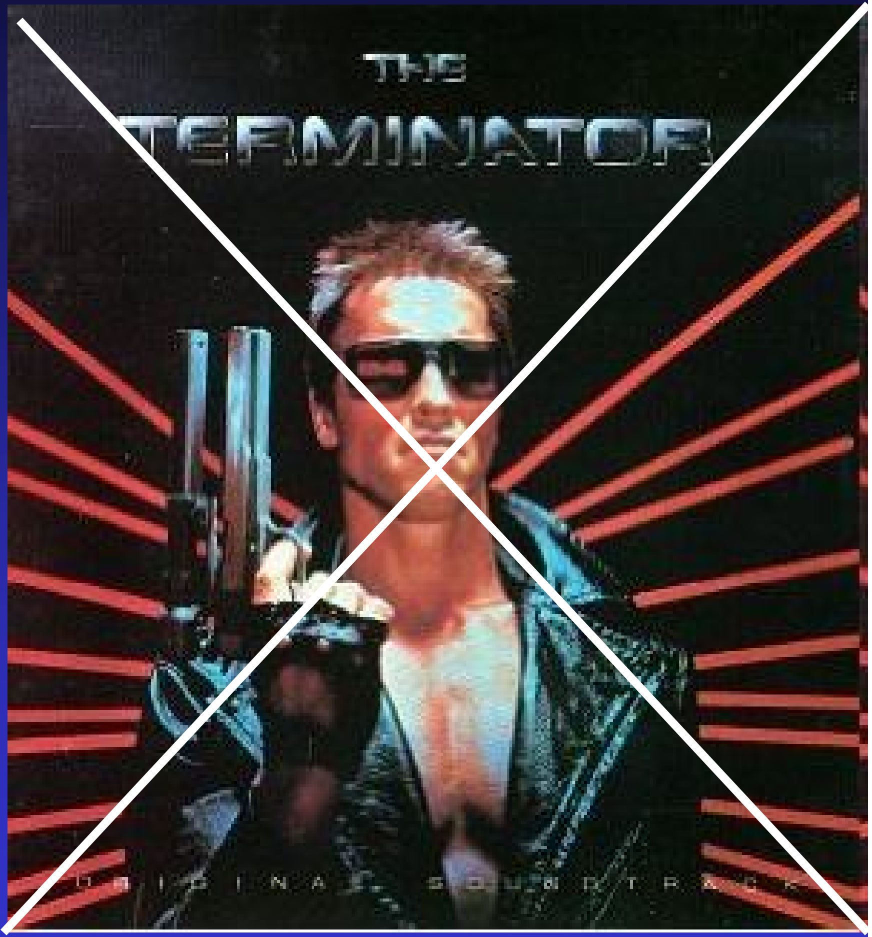
"Doing the right thing, doing it right"

Shielding Design

- **Shielding is NOT the TERMINATOR**
  - Radiation dose cannot be made = 0
- **Shielding is the ATTENUATOR**
  - Primary purpose is to attenuate or reduce the radiation dose to levels below some regulatory or design limit <u>UNDER EXPECTED USAGE CONDITIONS</u>
- **Requires understanding of secondary radiation production, beam losses , nuclear and neutron interactions**
- **Knowledge of various other parameters**



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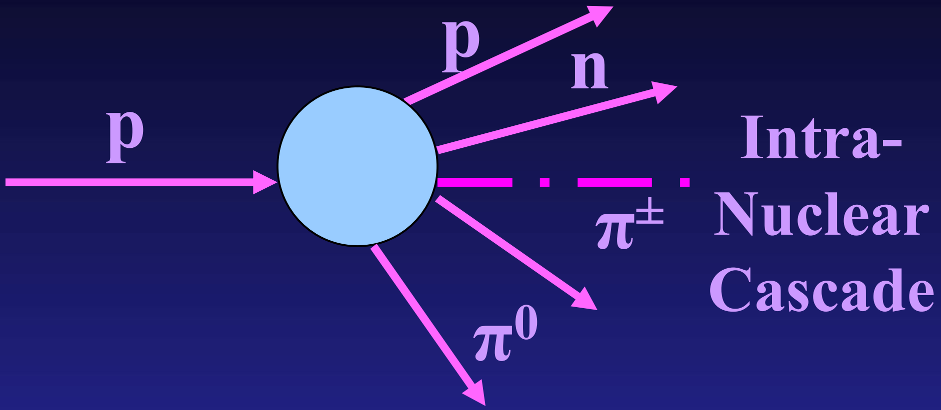
Secondary Radiation

- **Produced by interaction of protons with any material in its path**
- **Consists of:**
  - **Prompt radiation which is on only when the machine is on**
  - **Residual radiation from activation which remains even after the machine is turned off**
- **Produced at locations where beam losses occur**
  - **In synchrotron and cyclotron during injection, acceleration and extraction**
  - **During energy degradation in cyclotron**
  - **During beam transport to treatment room**
  - **In beam shaping devices located in treatment nozzle**
- **Also produced in patient, dosimetric phantom and beam stopper**
- **Important to understand physics behind secondary radiation production**

Physics: Intra-Nuclear Cascade



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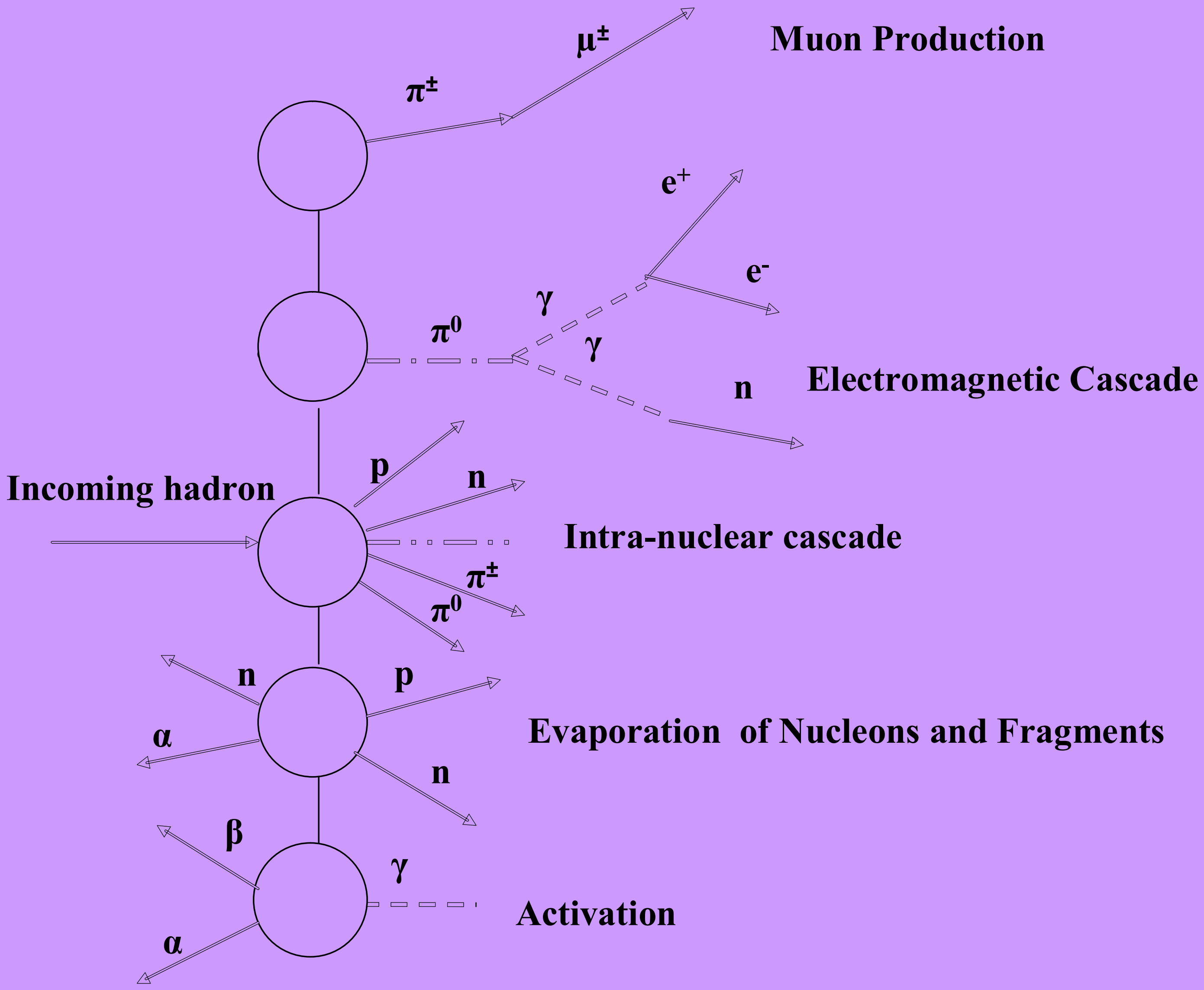
- The interaction of protons with matter results in an intra-nuclear cascade
- Important in shielding design for protons in the therapeutic energy range of 67 MeV - 330 MeV
- Similar to a water cascade, there is a succession of stages in an intra-nuclear cascade

Stages: Intra-Nuclear Cascade



Muon Production

Electromagnetic Cascade

Incoming hadron

Intra-nuclear cascade

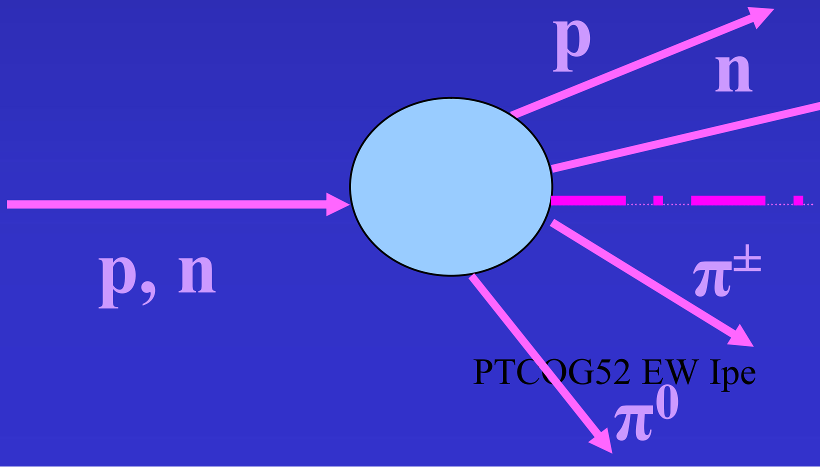
Evaporation of Nucleons and Fragments

Activation

Intra-Nuclear Cascade

- Incoming hadron (p, n) interacts with individual nucleons (p and n) in nucleus, producing a spray of particles
- Neutral and charged pions are produced above ~ 135 and 140 MeV, respectively.
- Scattered and recoiling nucleons proceed through nucleus
- Each nucleon may interact with other nucleons leading to development of cascade
- Some nucleons escape nucleus

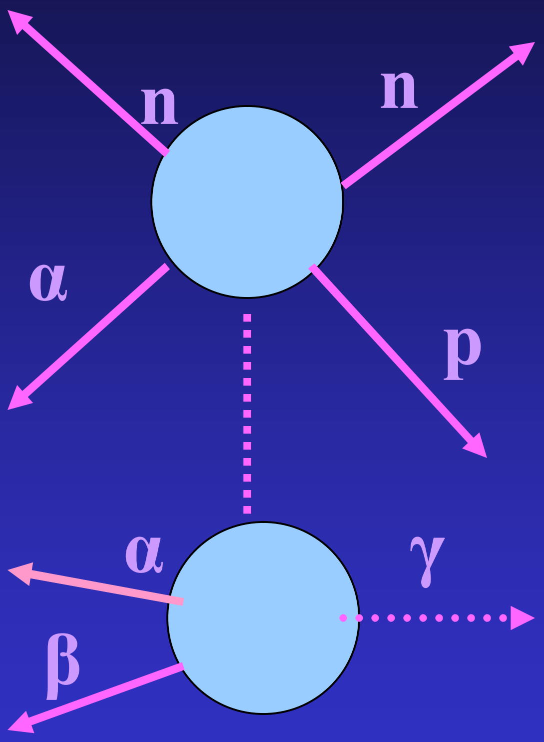
- Large fraction of energy transferred to single nucleon
- This <u>nucleon</u> with E > 150 MeV is <u>forward peaked</u> and propagates the cascade
- Nucleons with energies between 20 and 150 MeV transfer energy by nuclear interactions to several nucleons (< 10 MeV/nucleon)
- Charged particles are quickly stopped by ionization
- Neutrons predominate at low energies



Intra-Nuclear Cascade

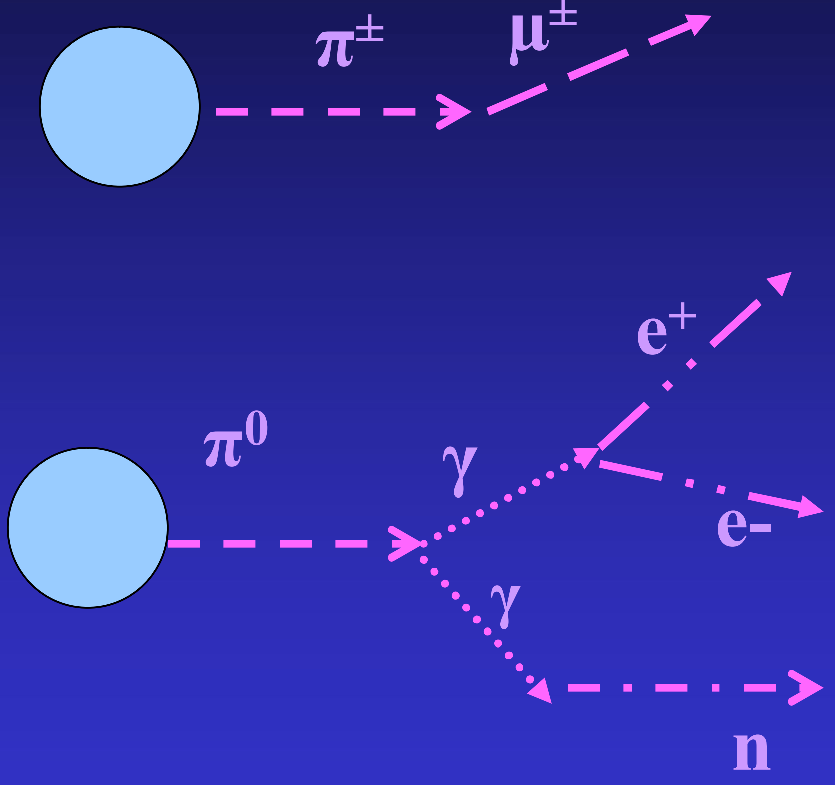
Evaporation and Activation

- Energy of nucleons that do not escape nucleus is distributed among remaining nucleons
- Original nucleus is left in an excited state
- It de-excites by emitting "evaporation nucleons", alphas and fragments
- Low-energy charged particles deposit energy locally
- Evaporation nucleons are emitted isotropically



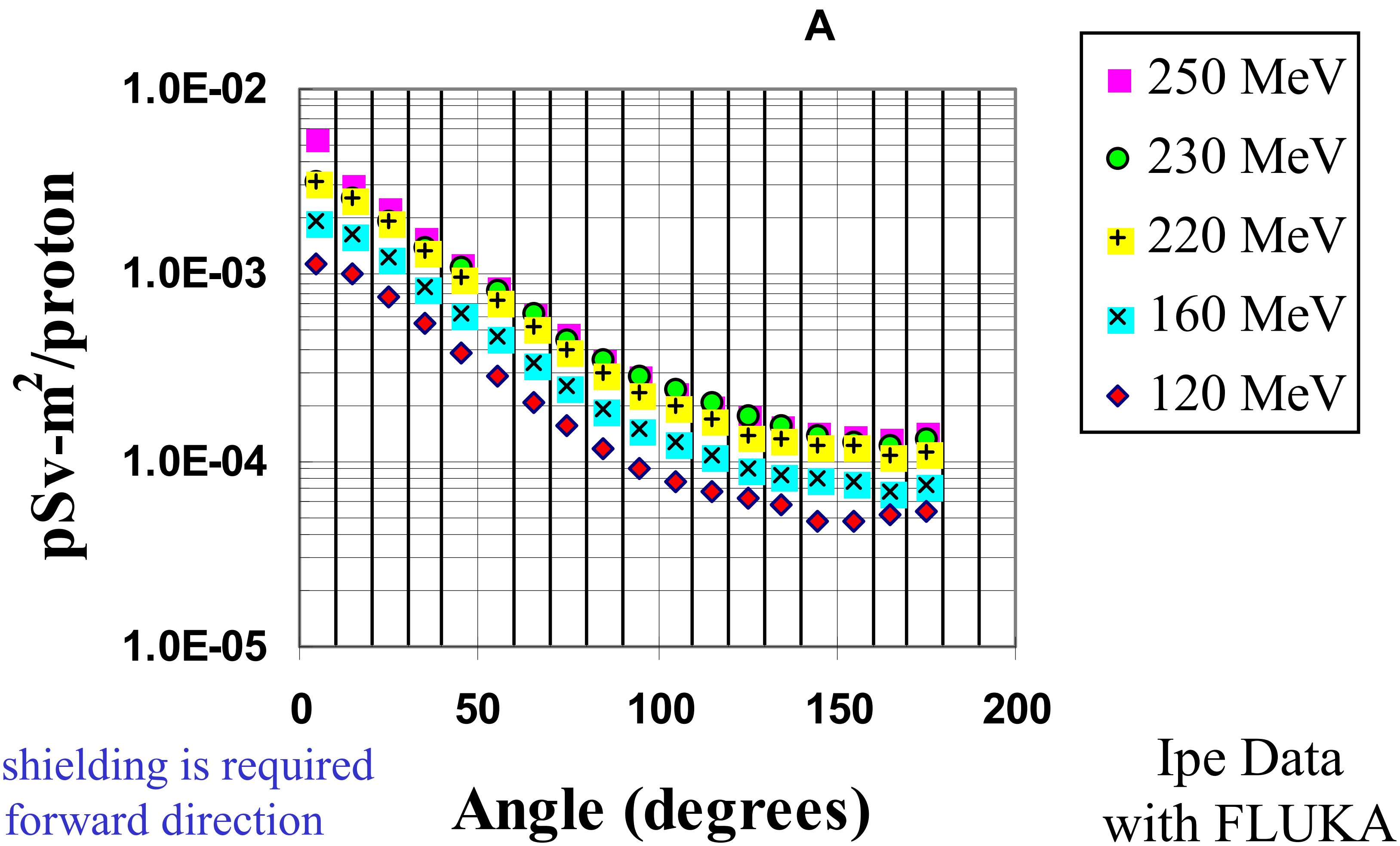
- Energy of evaporation neutrons extends to 8 MeV
- Neutrons travel long distances depositing energy continuously
- Remaining excitation energy emitted as gammas
- De-excited nucleus may be radioactive (activation)

Muons and Electromagnetic Cascade



- Charged pions decay to muons
- Muons are penetrating and deposit energy by ionization; photonuclear reactions also possible
- Neutral pions decay to gammas which initiate electromagnetic (EM) cascades
- EM cascades do not contribute significantly to energy transport
- Neutrons are principal propagators of cascade with increasing depth, since protons and pions (E < 450 MeV) have a high rate of energy loss

Angular Dose Profiles from Unshielded Thick Tissue Targets For Various Proton Energies



More shielding is required
in the forward direction

Ipe Data
with FLUKA

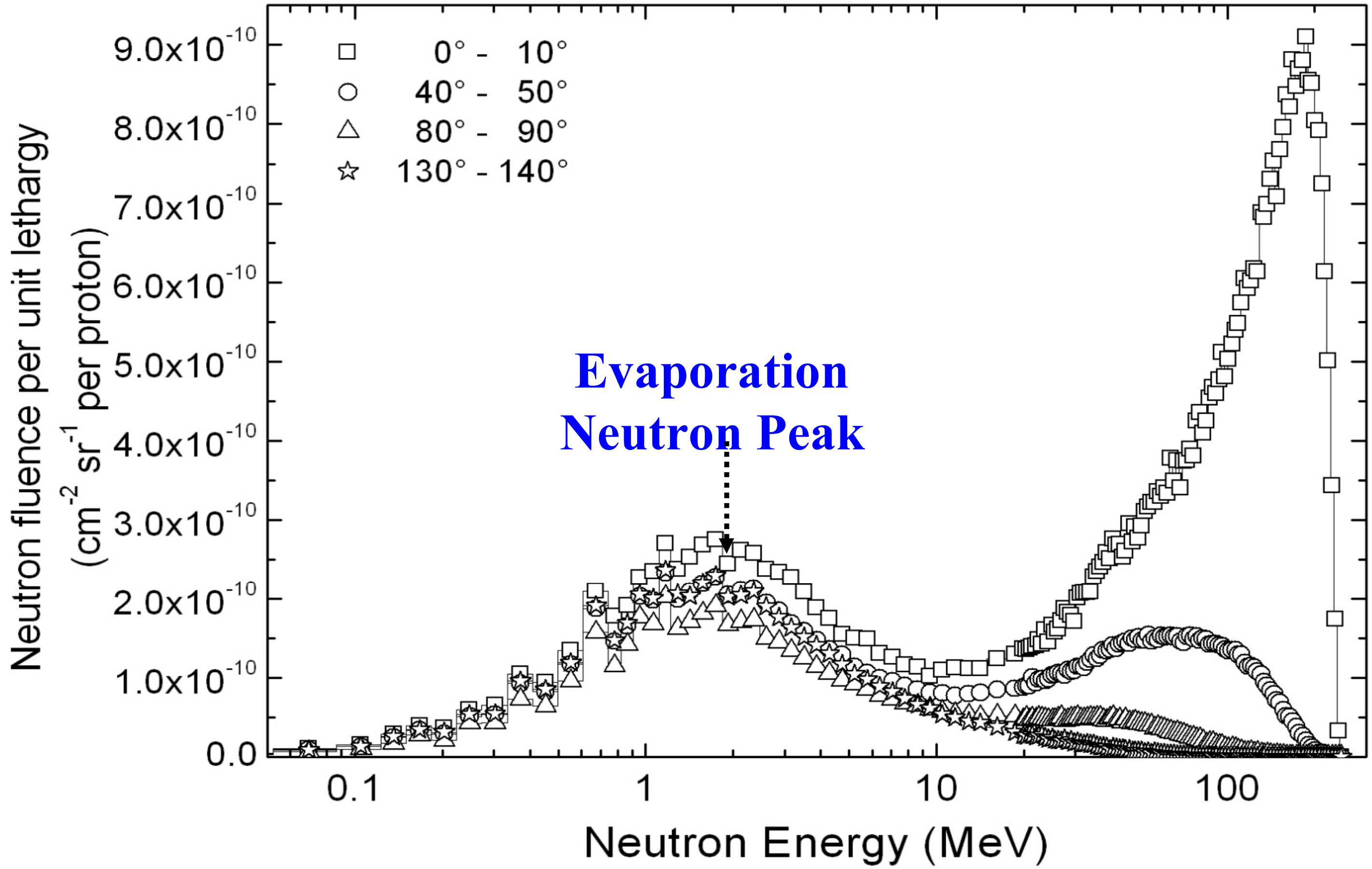
1 pSv = 10^{-12} Sv

Neutron Yields for Protons Incident on a Thick Iron Target (FLUKA)

Proton Energy, E_p (MeV)	Range (mm)	Iron Target		Neutron Yield (n/p)		
		Radius (mm)	Thickness (mm)	E_n <19.6 MeV	E_n > 19.6 MeV	Total
100	14.45	10	20	0.118	0.017	0.135
150	29.17	15	30	0.233	0.051	0.284
200	47.65	25	50	0.381	0.096	0.477
250	69.30	58	75	0.586	0.140	0.726

Agosteo et al., NIM Phys. Res. B265, 581-589. 2007

Unshielded Neutron Spectra for 250 MeV Protons Incident on Thick Iron Target For Various Production Angles (FLUKA)



Evaporation Neutron Peak

Agosteo *et al.*, *NIM Phys. Res.* B265, 581-589. 2007

Characteristics of Shielded Neutron Field

- High-energy cascade neutrons propagate cascade in shield
- Continuously regenerate lower-energy neutrons and charged particles at all depths in the shield via inelastic reactions
- Yield of lower-energy neutrons increases as proton energy increases
- Greater yield of lower-energy neutrons is more than compensated for by greater attenuation in shield, because of higher cross-sections at lower neutron energies
- Radiation field reaches equilibrium condition beyond a few mean free paths within shield
- Deep within shield, high-energy neutrons (E_n > 150 MeV) regenerate cascade, but are few in number; and accompanied by low-energy neutrons
- Typical neutron spectrum observed outside a thick shield in the forward direction consists of peaks at ~ 2 MeV and at ~ 100 MeV

Secondary Radiation Field

- Quite complex
- For structural (bulk) shielding, neutrons are the dominant component
- For mazes and penetrations, neutrons and capture gamma rays contribute to dose
- Important to understand how neutrons interact

Neutron Energy Classification and Interactions

- Thermal: $\bar{E}_n = 0.025$ eV at 20ºC
  Typically $E_n \leq 0.5$ eV
- Intermediate : $0.5 \text{ eV} < E_n \leq 10 \text{ keV}$
- Fast: $10 \text{ keV} < E_n \leq 20 \text{ MeV}$
  - Include evaporation neutrons
- Relativistic $E_n > 20$ MeV
  - Include cascade neutrons

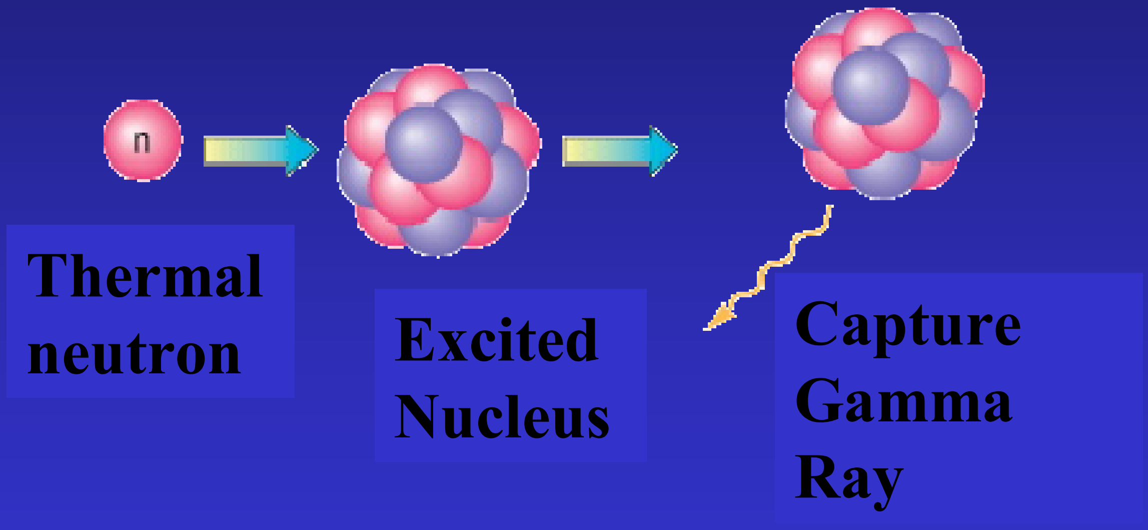
For $E_n < 20$ MeV, nearly all interactions are elastic or inelastic scatters

Absorption is important at thermal energies and at a few resonances in keV region

Thermal Neutron Capture

- Thermal neutrons gain and lose very little energy by elastic scatter
- They diffuse about and are captured by the nucleus
- Excited nucleus emits capture gamma rays
- Capture cross section (< 1 keV) decreases with increasing neutron energy
- Energy of capture gamma from hydrogen is 2.22 MeV (polyethylene)
- Energy of capture gamma from boron is 0.478 MeV (borated polyethylene)
- Boron capture cross-section is ~10,000 x higher

Borated polyethylene is used in instead of polyethylene for shielding maze doors



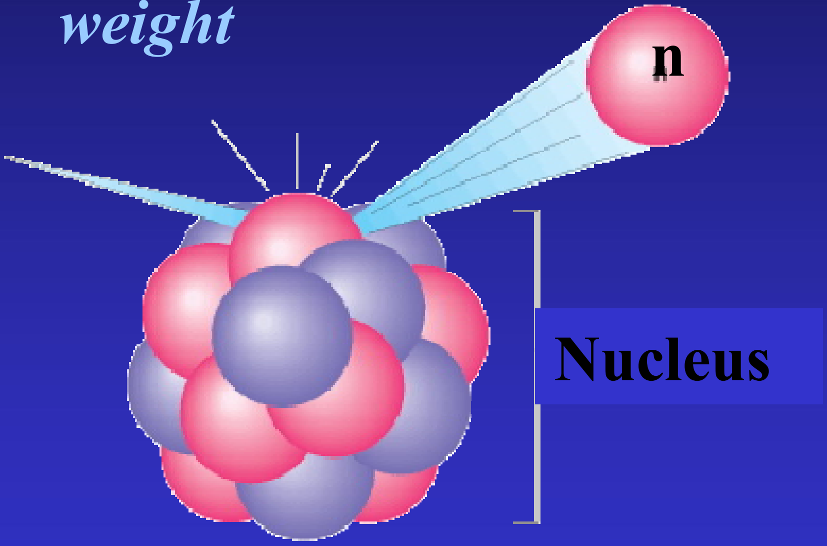
http://www.glossary.oilfield.slb.com/Display.cfm?Term=inelastic%20neutron%20scattering

Elastic Scatter

- **Kinetic energy and momentum are conserved**
- **Fast neutrons lose energy by elastic scatter and become thermal neutrons**
- **Interaction with hydrogen is like a billiard ball collision**
- **Primary process of energy loss below 1 MeV in hydrogenous materials (concrete, polyethylene, etc.)**
- **Dominant interaction below 10 MeV for all materials**

Hydrogenous materials are most effective for fast neutron shielding

Water content of concrete should be at least 5.5% by weight

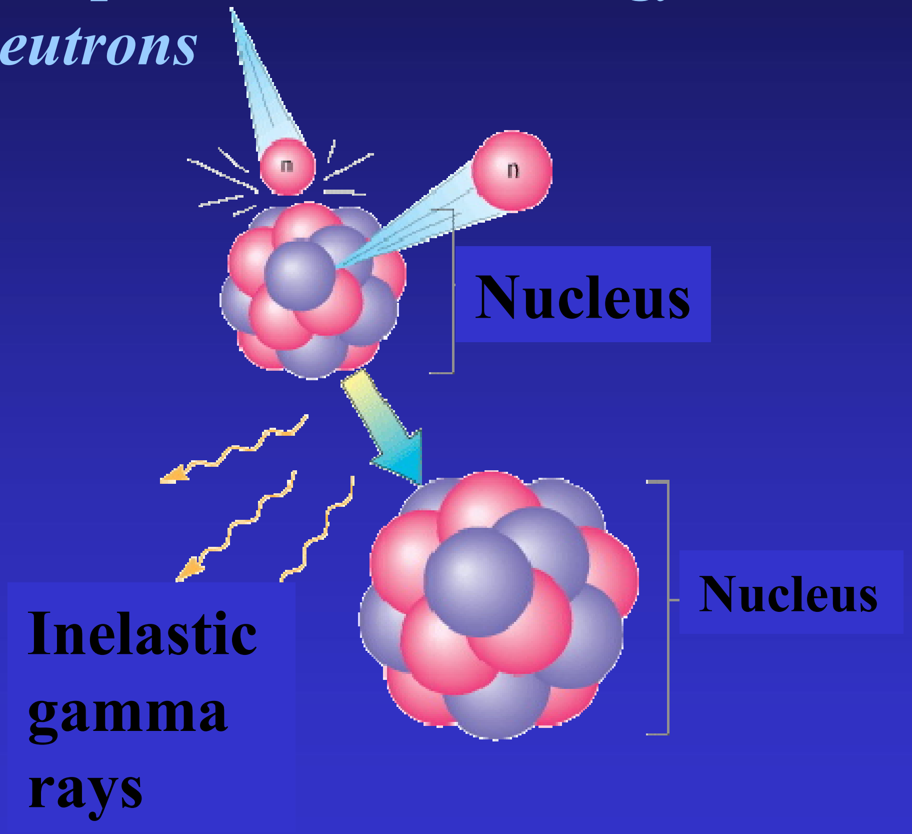


http://www.glossary.oilfield.slb.com/Display.cfm?Term=elastic%20neutron%20scattering

Inelastic Scatter (n,n/)

- **Kinetic energy is not conserved**
- **Occurs only above lowest excited state in material (847 keV in ^{56}Fe)**
- **Nucleus absorbs energy and is left in an excited state**
- **De-excites emitting gamma rays**
- **Is dominant process above 10 MeV in all materials**
- **In high-Z materials, inelastic scattering reduces neutron energy, thus making hydrogenous material that follows more effective**

Lead or steel must always be followed by a hydrogenous material because high-z materials are transparent to lower energy neutrons

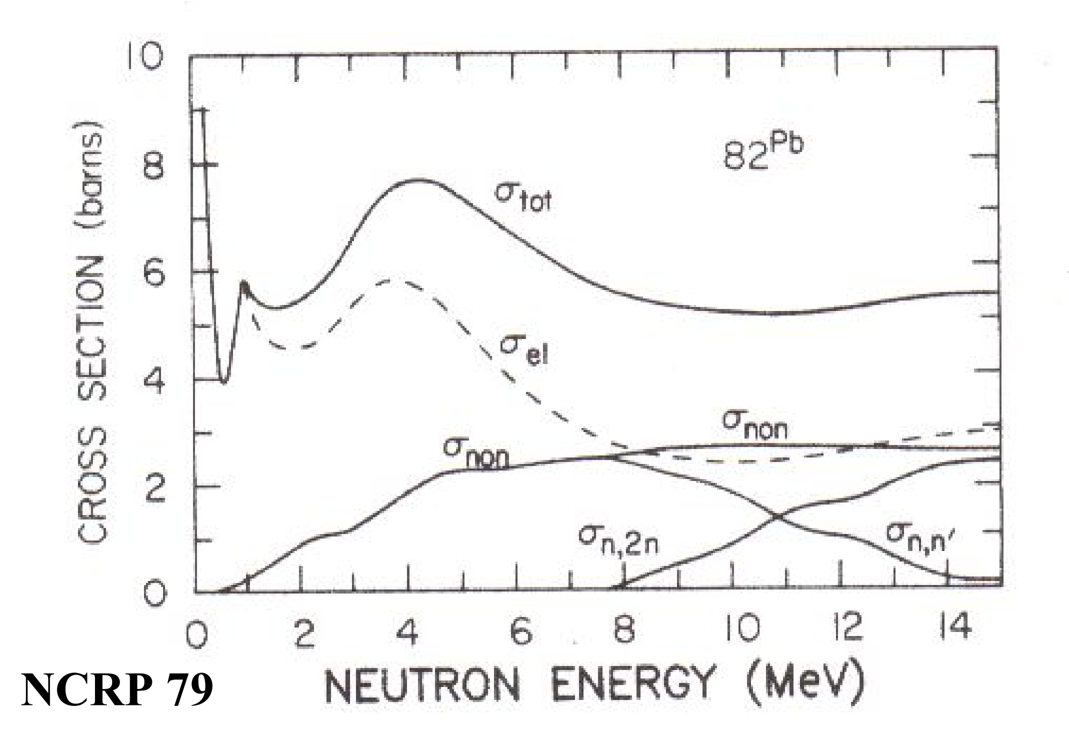


http://www.glossary.oilfield.slb.com/Display.cfm?Term=inelastic%20neutron%20scattering

Fast Neutron Interactions

- Neutrons can also be absorbed or captured: (n, 2n), (n, p), (n, α) or (n, γ)
- Non-elastic cross-section is sum of inelastic (n, n') and (n, 2n) cross-sections for $E_n < 20$ MeV
- Inelastic reactions dominate at lower energies
- (n, 2n) reactions dominate at higher energies
- (n, 2n) reaction produces large number of lower-energy neutrons

Cross-Sections in Lead



NCRP 79

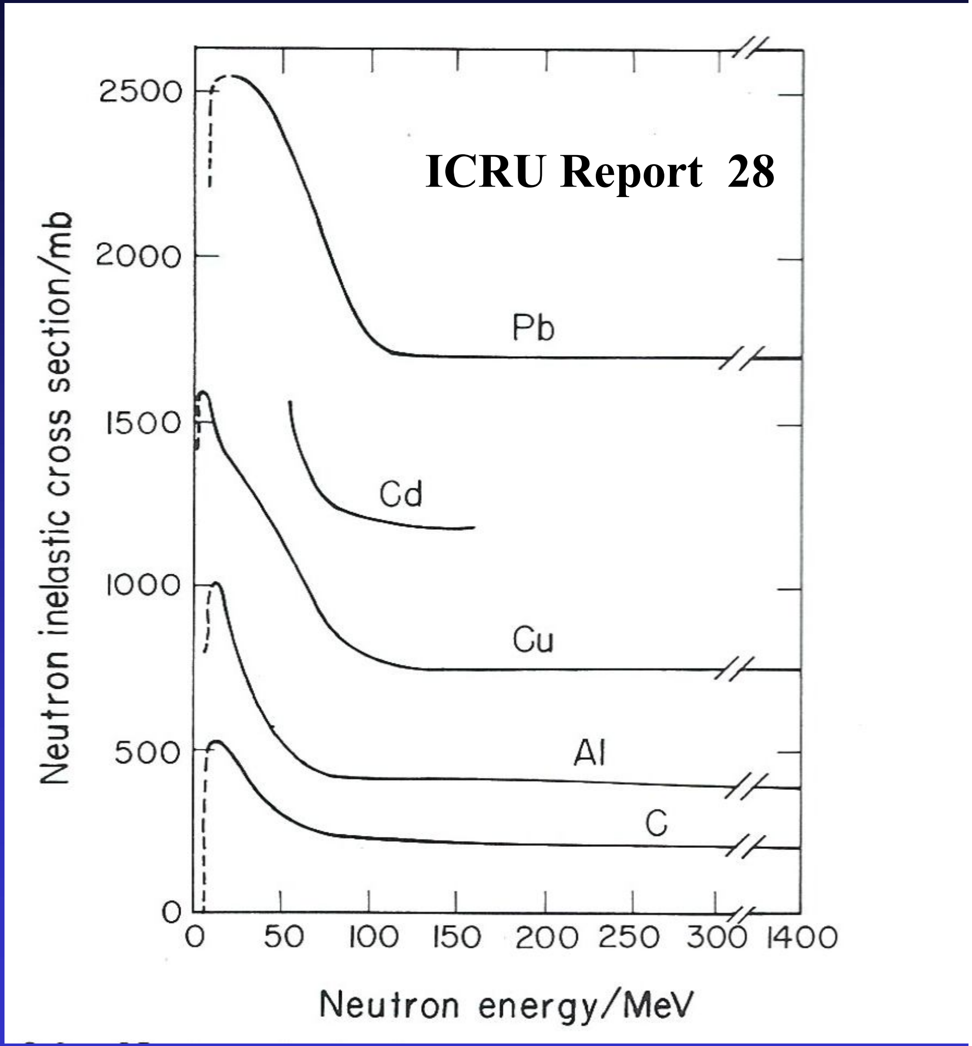
1 barn = 10^{-24} cm^2

Relativistic Neutron Interactions

- **Relativistic neutrons arise from cascade processes in proton accelerators**
- **Cascade neutrons can have energies as high as the primary proton beam**
- **Neutrons with $E_n > 150$ MeV**
  - **Propagate cascade through shielding**
  - **Continuously regenerate lower-energy neutrons and charged particles at all depths via inelastic reactions**
  - **Low-energy neutrons undergo capture reactions resulting in production of capture gamma rays**

Neutron Inelastic Cross Sections for Various Materials

- Cross sections increase with increasing mass number, A
- Cross sections decrease with increasing energy to a constant value above ~ 150 MeV
- Neutrons with $E_n > 150$ MeV will control radiation environment for $E_p > 150$ MeV



Relativistic Neutron Interactions

- Neutrons (50 MeV < E_n <150 MeV)
  - Intra-nuclear cascade
  - Evaporation nucleons
  - Activation
- Neutrons (20 MeV < $E_n \leq$ 50 MeV)
  - Evaporation nucleons
  - Activation (not included in this talk)
    - Air, water, shielding material and beam line components can become radioactive
    - Cooling water in the vaults should be confined to a self-contained loop

Calculational Methods

1. **Monte Carlo (MC) Codes**
   - FLUKA, MCNP, MCNPX, GEANT, etc.
   - Full computer simulation modeling accelerator, beam line and room geometry can be performed
   - Requires knowledge of composition and density of shielding materials
   - Full Monte Carlo simulations for specific room design is time consuming and not very cost effective during schematic design phase for determining bulk shielding
   - Should be used for all scatter calculations (maze scatter and penetrations)

Calculational Methods

2. Analytical Methods

- Most models are line-of-sight and assume point source
- Limited to transverse shielding and simple geometries
- Don't account for changes in angle of production, target material and dimensions, shielding material, density and composition, etc.

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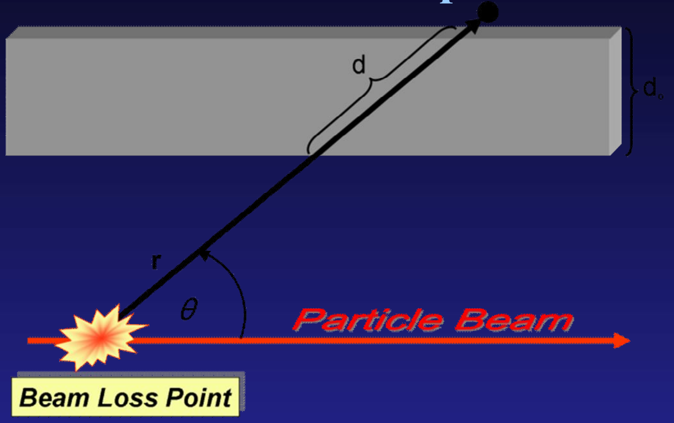


$$H = \frac{H_0}{r^2} \exp\left[-\frac{d}{\lambda}\right]$$

H = dose at point of interest

H_0 = dose at 1 m from source

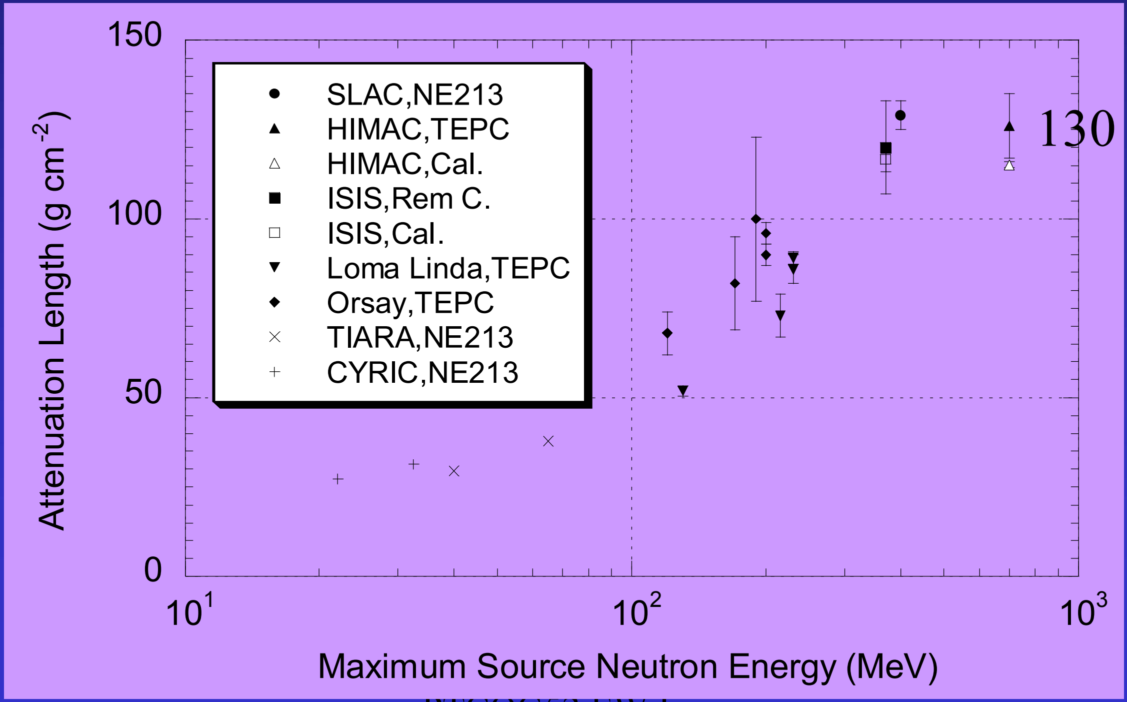
d = slant thickness

r = distance to shield

λ = attenuation length

Attenuation Length

- Attenuation length (λ) is penetration distance in which intensity of radiation is reduced to 37% of its value
- Measured in cm, or in g-cm^{-2}
- λ changes with depth and reaches an equilibrium value
- Measured neutron attenuation lengths in concrete from various sources are shown below



Nakamura, T. in *Proc. SATIF-7,* 2004, NEA, OECD, Paris

Calculation Methods

3. Computational Models

- **Hybrid approach**
  - Monte Carlo and Analytical Methods
- **Source terms and attenuation lengths that are independent of geometry are derived using Monte Carlo**
- **Various parameters are considered**
  - Particle energy, angle of production, target material, dimensions, shielding material, composition and density
- **Computational models are particularly useful during schematic design phase for bulk shielding calculations**
  - Facility layout undergoes several iterations
  - They are faster than Monte Carlo calculations

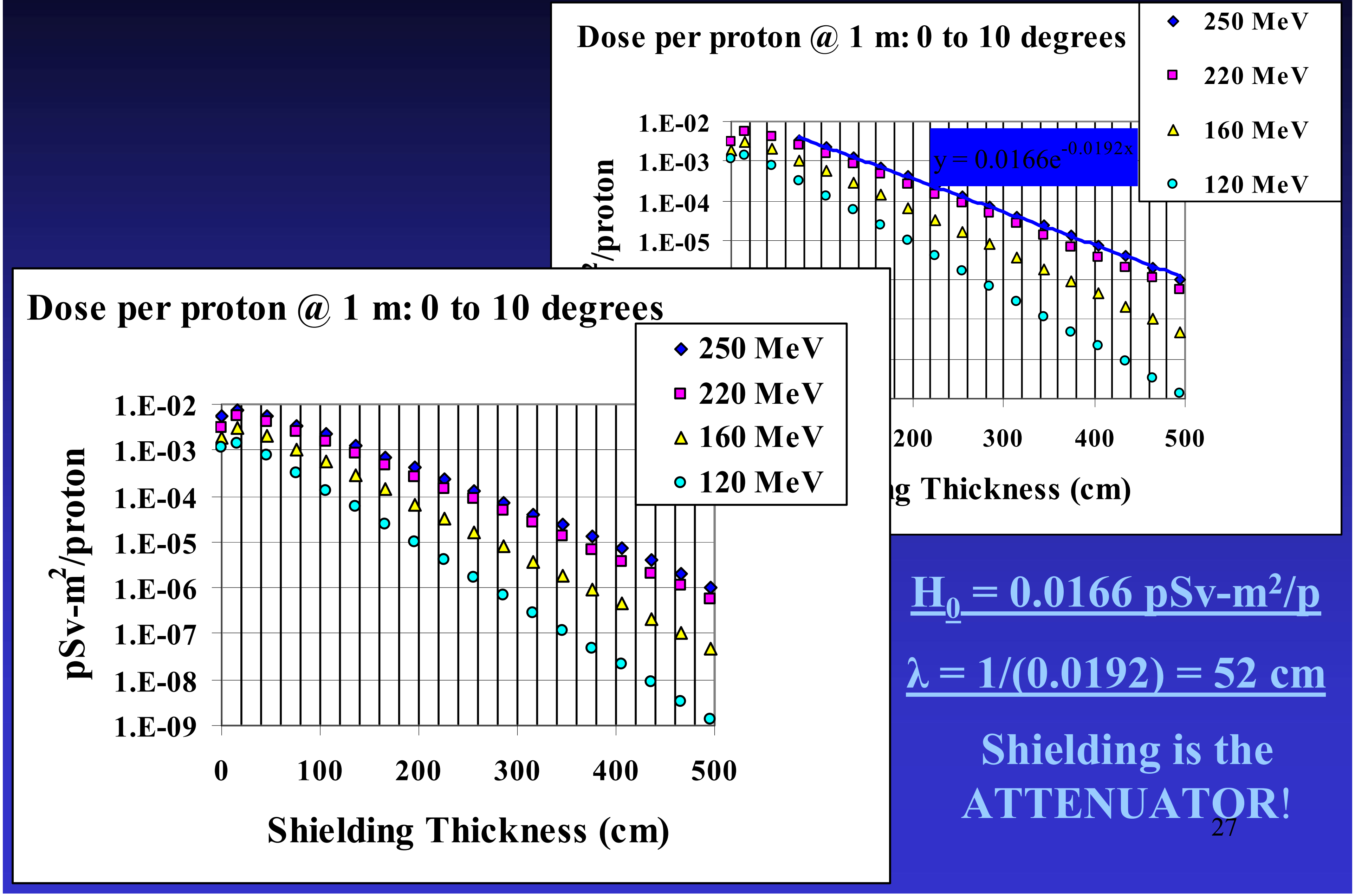
$\frac{H_0(E_p,\theta)}{r^2}\exp\left[-\frac{d}{\lambda_\theta g(\theta)}\right]$

Computational Models

$$\boldsymbol{H(E_p, \theta, d/\lambda g(\theta))} = \frac{H_0(E_p,\theta)}{r^2}\exp\left[-\frac{d}{\lambda_\theta g(\theta)}\right]$$

Where:
H is the dose equivalent at the outside the shield,
H_0 is source term at an angle θ with respect to the incident beam, and is assumed to be geometry independent
r is the distance between the target and the point at which the dose equivalent is scored,
d is the thickness of the shield
d/g(θ) is the slant thickness of the shield at an angle θ
λ_θ is the attenuation length at an angle θ
g(θ) is cosθ for forward shielding
g(θ) is sinθ for lateral shielding
g(θ) = 1 for spherical geometry

Dose in Forward Direction as a Function of Concrete Thickness for Protons incident on Tissue (FLUKA)

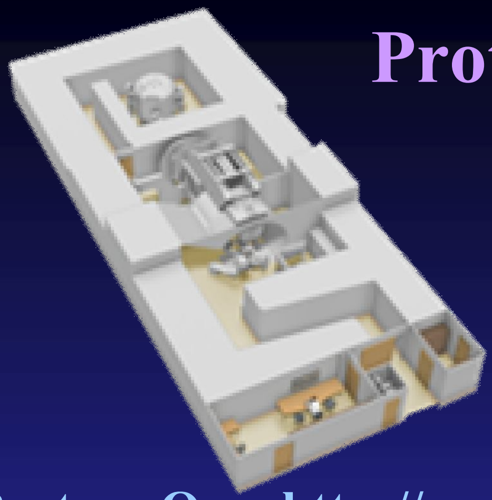


$H_0 = 0.0166$ pSv-m^2/p

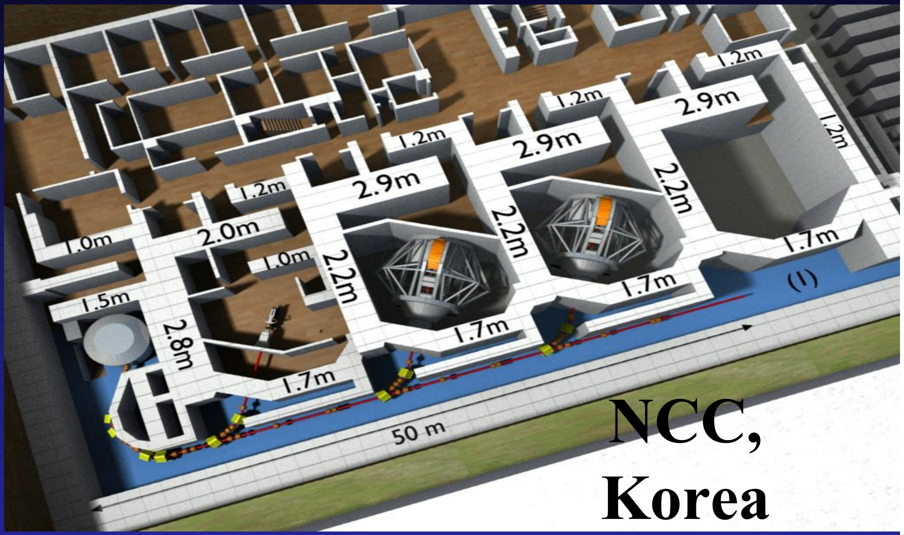
$\lambda = 1/(0.0192) = 52$ cm

Shielding is the ATTENUATOR!

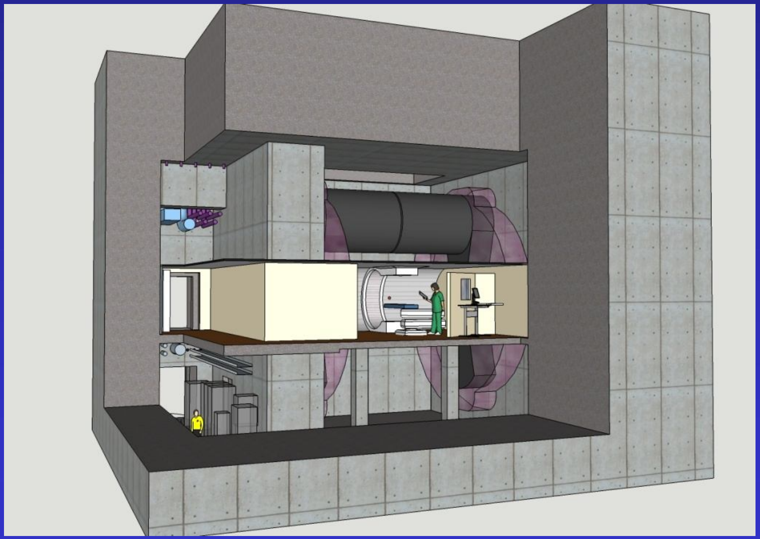
Proton Therapy Facilities



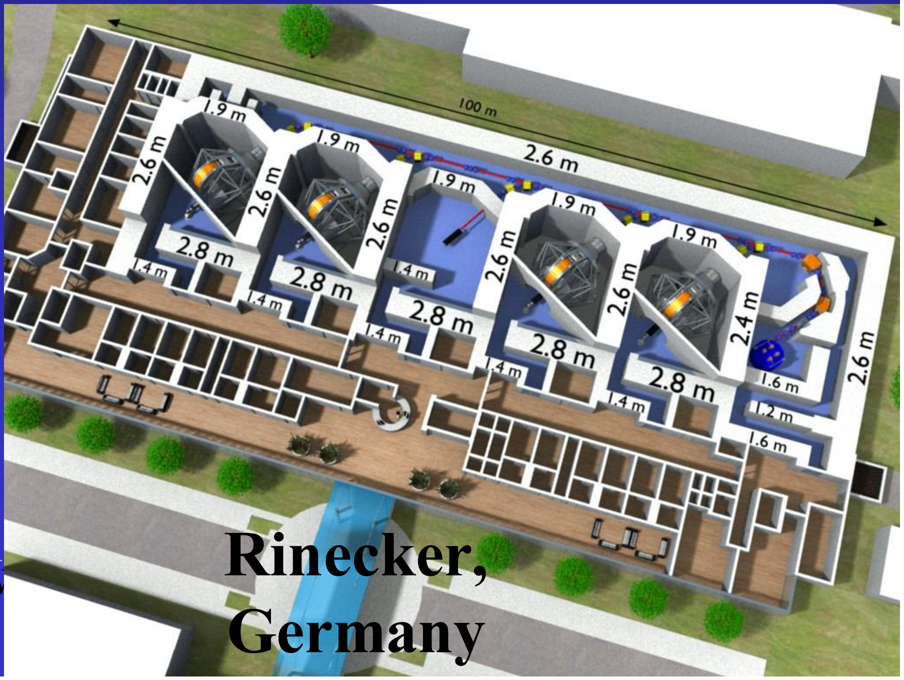
Proteus One, http://www.iba-protontherapy.com/proteusseries



NCC, Korea



Mevion S250, Courtesy of The Benham Companies, An SAIC Company



Rinecker, Germany

Shielding Design Considerations

- **Treatment and Beam Parameters**
  - **Particle type *(proton)***
  - **Energies**
  - **Current at each energy to deliver a certain dose rate**
  - **Beam shaping and delivery *(scanning vs. scattering, etc.)***
  - **No. of patients/year**
  - **No. of fractions/patient at each energy**
  - **Dose delivered per fraction**
  - **Beam-on time**
  - **Beam size**
  - **Beam losses and locations**
  - **Target materials and dimensions**

Parameters vary from facility to facility

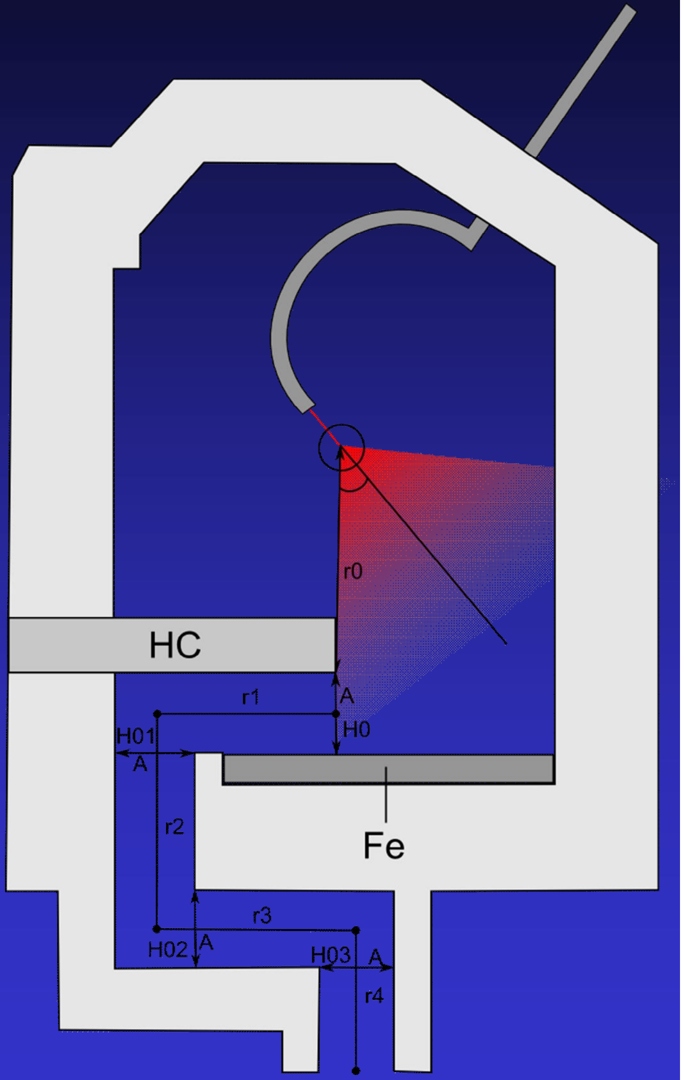
Shielding Design Considerations

- **Accelerator Type**
  - Synchrotron
  - Cyclotron
- **Shielding Material**
  - Composition
  - Density
  - Water content
- **Facility Layout**
  - Adjacent occupancies
  - Type of Area (Controlled, Public, etc.)
  - Above ground, underground..
- **Country/State Specific Regulatory Dose Limit**

Shielding design is facility dependent!

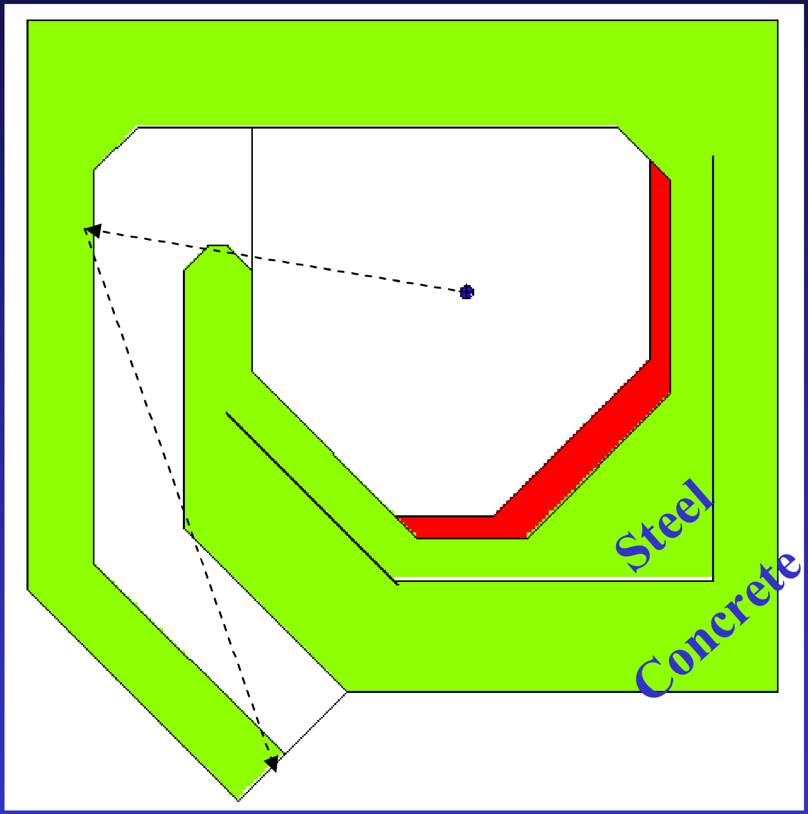
Mazes

- Radiation at maze entrance consists of neutrons that scatter through the maze; and capture gamma rays
- Forward-directed radiation from target should never be aimed toward the maze opening
- Sum of thicknesses of each maze wall should = thickness of the direct-shielded wall
- As number of legs increases, the attenuation increases
- The legs should be perpendicular to each other
- Reducing maze cross-section area reduces dose at entrance
- At least two scatters are desirable

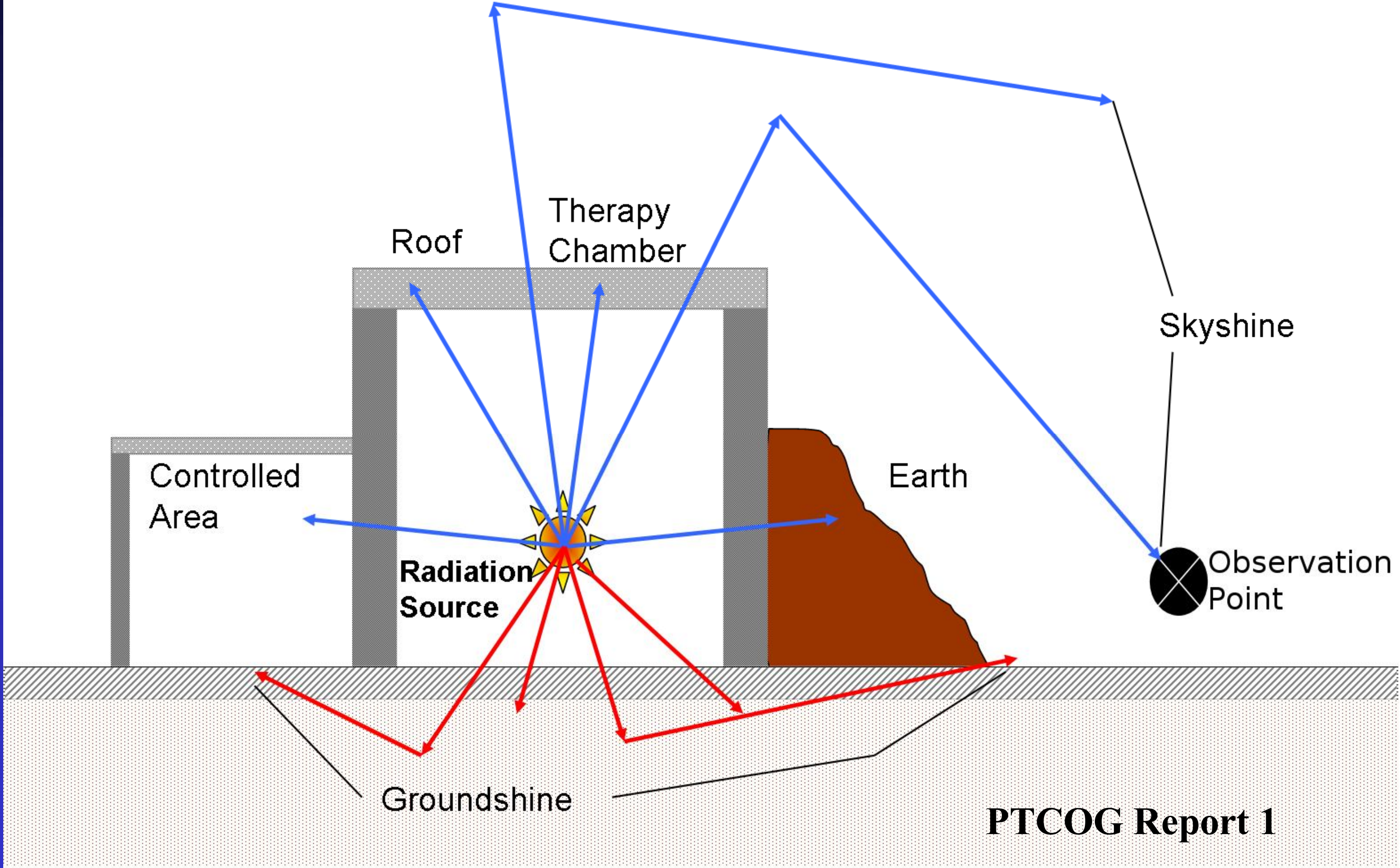


Pseudo Maze

- Maze appears to have two legs
- Legs are not at 90 degrees to each other
- Single scatter from source reaches maze entrance with very little attenuation
- Poor design



Skyshine and Groundshine



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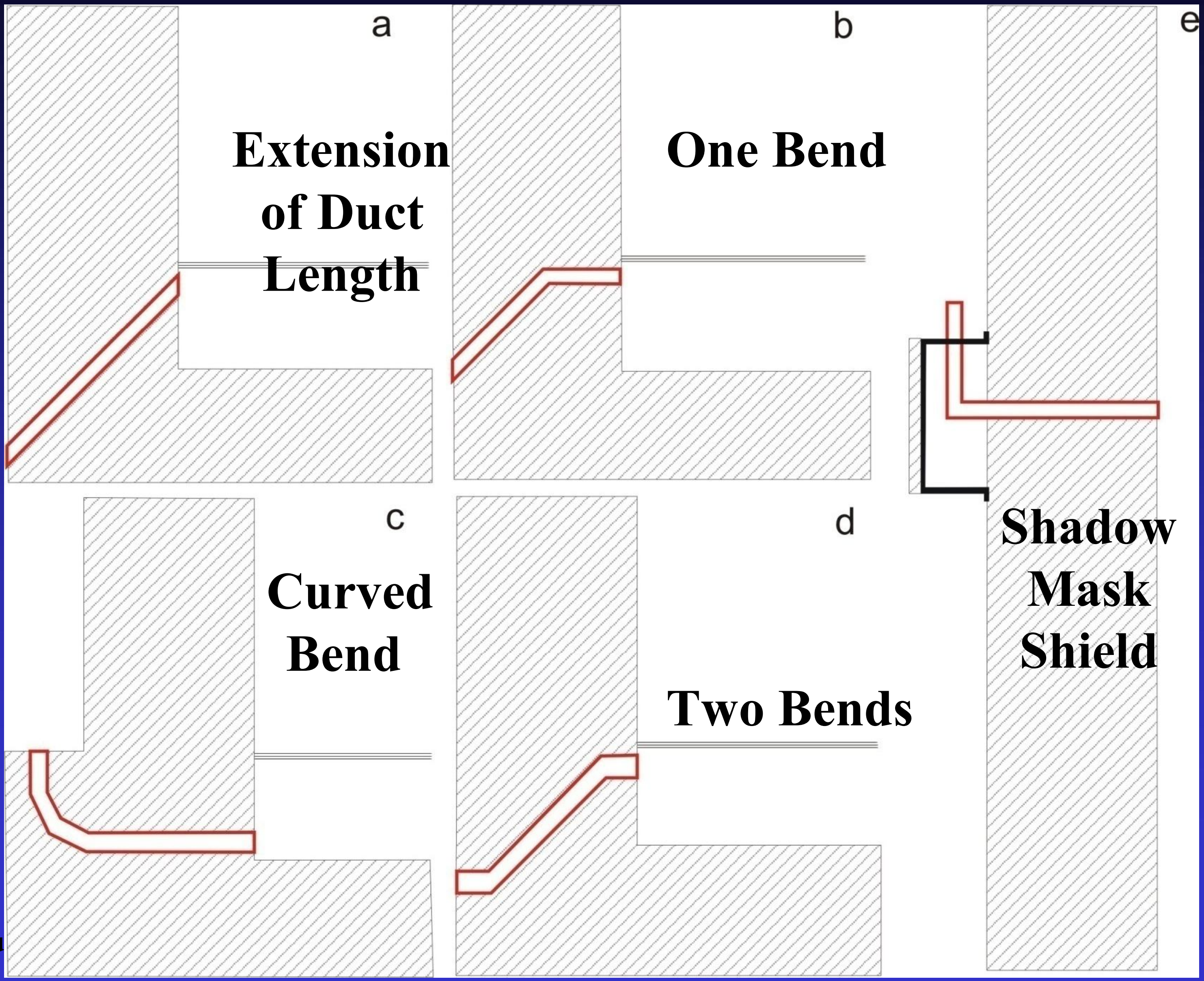
Ducts/Penetrations (PTGOG Report 1)



Extension of Duct Length

One Bend

Shadow Mask Shield

Curved Bend

Two Bends

PTCOG REPORT 1: Shielding Design and Radiation Safety of Charged Particle Therapy Facilities

(http://ptcog.web.psi.ch/archive_reports.html)

1. **Introduction – N. E. Ipe**
2. **Radiological Aspects of Charged Particle Therapy Facilities – N. E. Ipe**
3. **Shielding Design Considerations – G. Fehrenbacher & N. E. Ipe**
4. **Radiation Monitoring – Y. Uwamino & G. Fehrenbacher**
5. **Activation – Y. Uwamino**
6. **Monte Carlo Codes - S. Roesler**
7. **Patient Dose from Secondary Radiation – H. Paganetti & I. Gudowska**
8. **Safety Systems and Interlocks – M. Schippers**

Advisors: A. Smith, A. Mazal and D. Jones

Consultants: S. Ban and H. Yashima

Thank You

DANKESEHR