Prompt Radiation Fields at Accelerators

Vashek Vylet, TJNAF

HPS Professional Development School, Oakland, CA
January 31 – February 2, 2008

Overview

- Introduction
- Prompt Fields at Electron Accelerators
- Prompt Fields at Proton and Ion Accelerators
- Some Specific Aspects of Accelerator Radiation Fields (if time permits…)

Introduction

- Primary particles: charged particles (CP) that are produced and accelerated
- Every primary CP ends up interacting with matter somewhere (where intended or not)
- Interactions of energetic primary CP generate "prompt" secondary particles – our topic here
- Residual nuclei at interaction site may be radioactive – residual activity

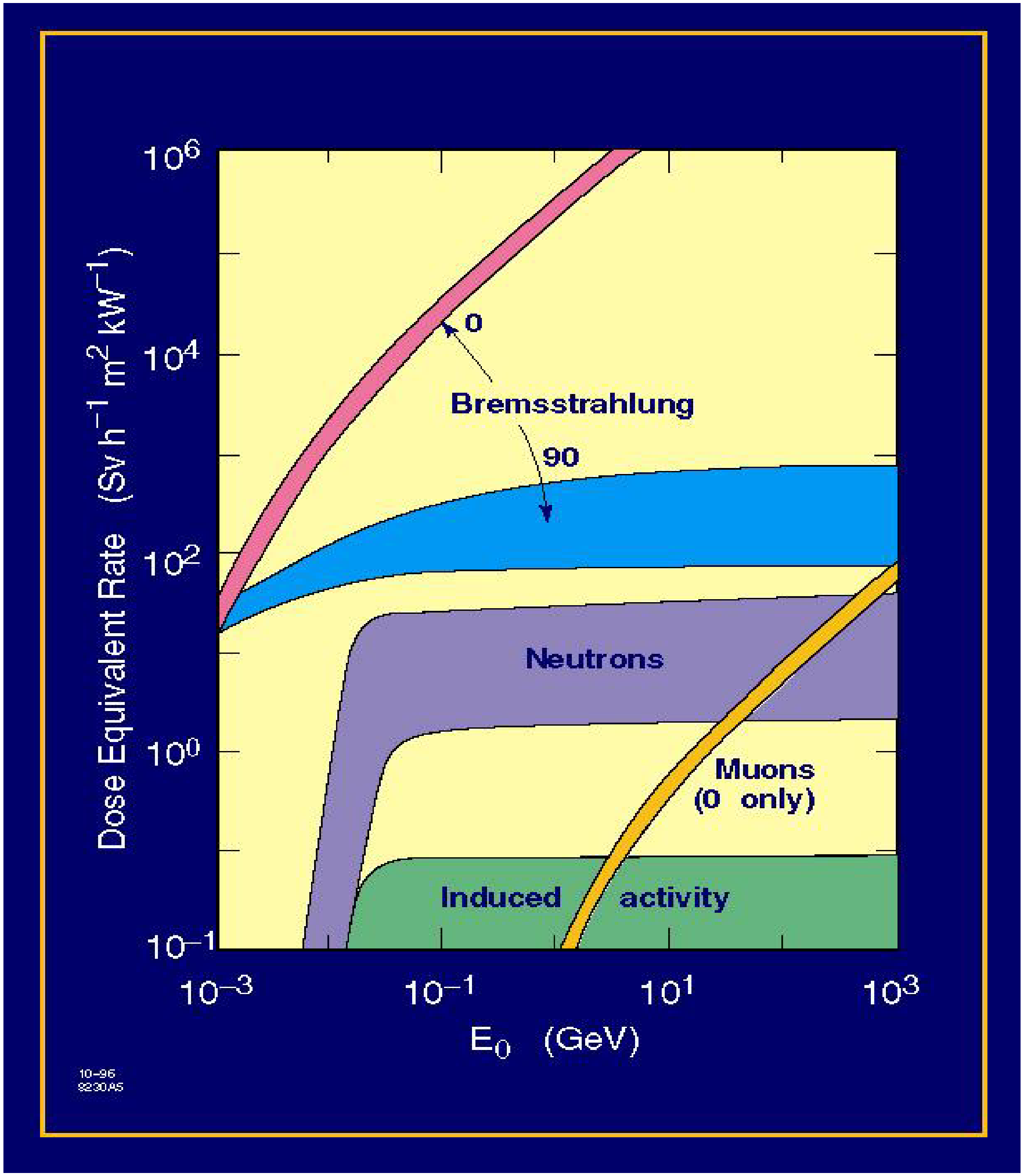
Introduction

- Prompt radiation stops as soon as accelerator is turned off (unlike residual activity)
- Source term: concept quantifying yield of secondary radiation: $S = Q_2/Q_1$
- Q_2 - dose, dose rate, fluence, …
- Q_1 - particle, charge, current, power …

Electron Facilities

Sources of Prompt Radiation

- Primary Electrons
- Bremsstrahlung
- Electromagnetic shower
- Neutrons
- Muons
- Synchrotron Radiation (covered elsewhere)



Source term for thick target: Dose Equivalent at 1 m per unit power

Primary Electrons

- Dose in primary beam

$$D(\text{Gy}) \approx 1.602\times10^{-10}\ \Phi\cdot(S/\rho)_{col}$$

- In-beam irradiation (Swanson rule-of-thumb for 1 – 100 MeV e^-)

$$\dot{H}\left[rem\right]=1.6\times10^{-6}\varphi\left[cm^{-2}s^{-1}\right]$$

- Range of e^- in air: R[m] ≈ 5.*E*[MeV]

Bremsstrahlung

Critical energy $\boldsymbol{E_c}$**:**

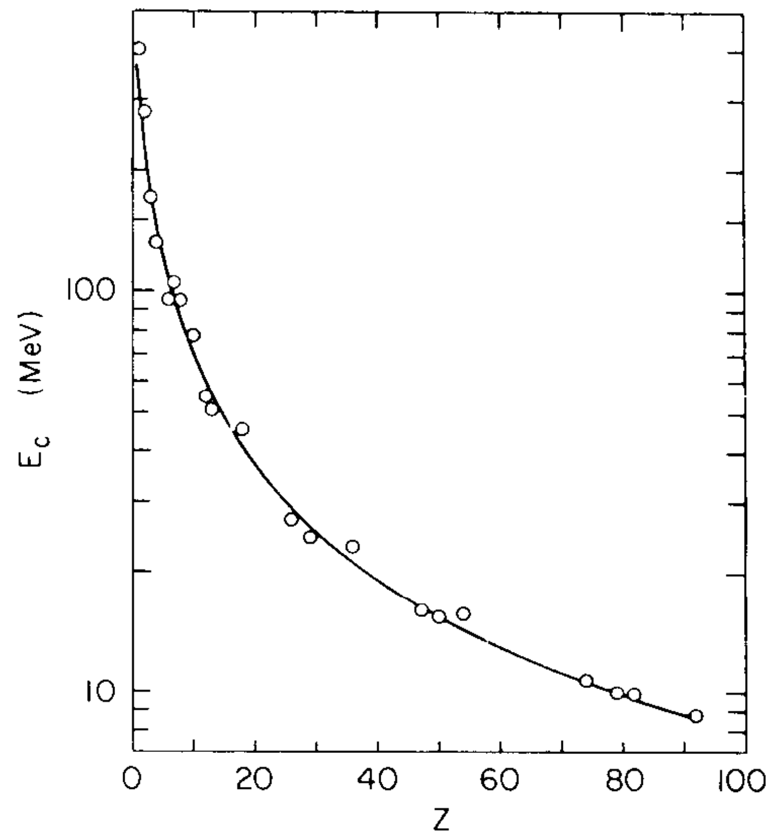
$dE/dx|_{col} = dE/dx|_{rad}$

$\boldsymbol{E_c}$ [MeV] = $800/(Z + 1.2)$

Radiative losses dominate

for $\boldsymbol{E} > \boldsymbol{E_c}$

	E_c [MeV]
Pb	9.51
Fe	27.4

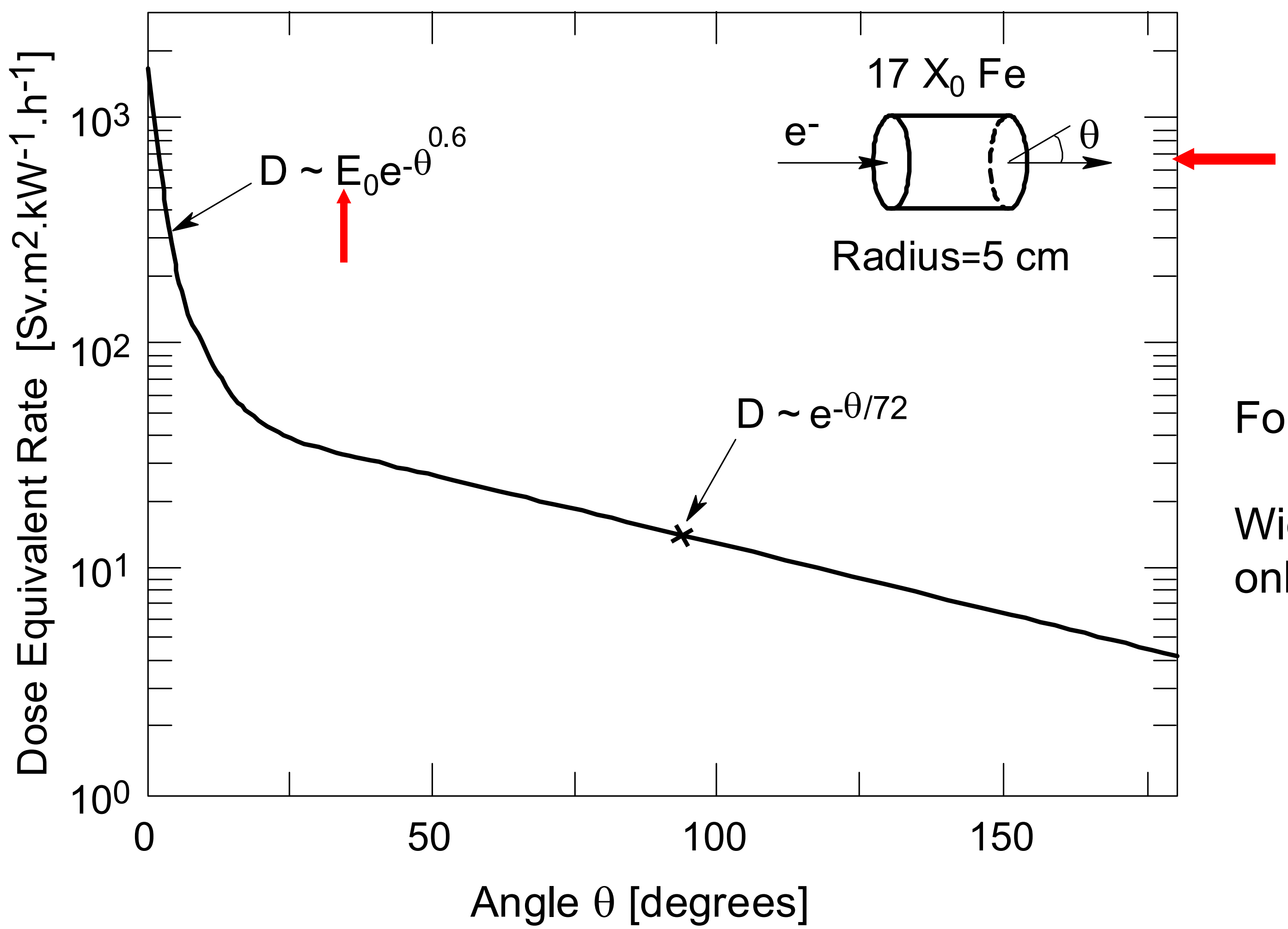


Bremsstrahlung

- Highest radiation hazard near target
- Forward-peaked: $\theta_{1/2}(^{\circ}) = 100 / E_0(\mathrm{MeV})$
- $\theta_{1/2}$ = 1° for 100 MeV, 0.01 ° for 10 GeV
- Two components: sharp forward @ small angles, mild variation at wide angles

$$\frac{1}{E_0}\frac{dN}{d\Omega} = 4.76 E_0 \exp(-\theta^{-06}) + 1.08 \exp(-\theta / 72)$$

Angular Brems. Distribution

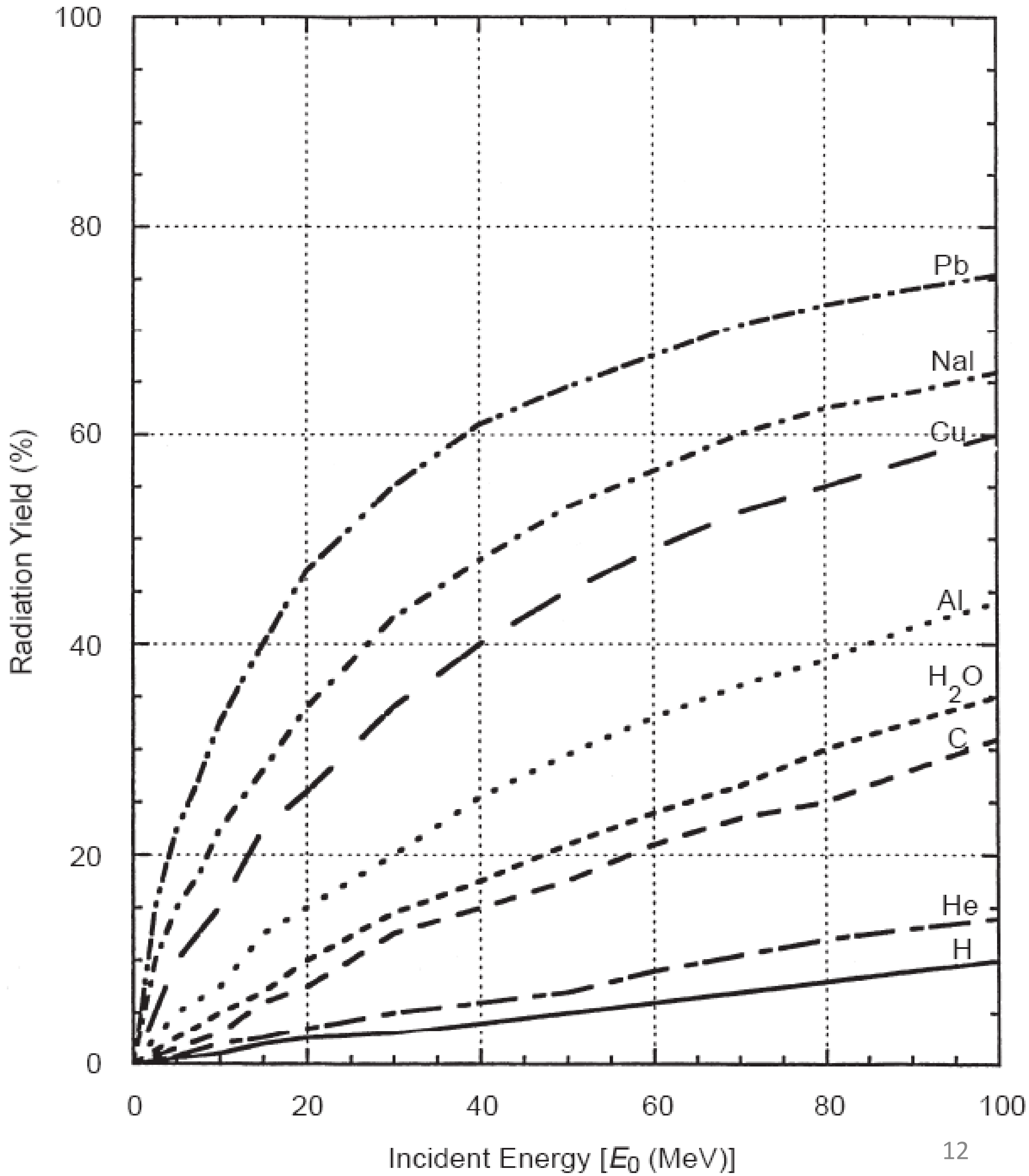


Thick target

Forward ~E.P

Wide angle only ~P

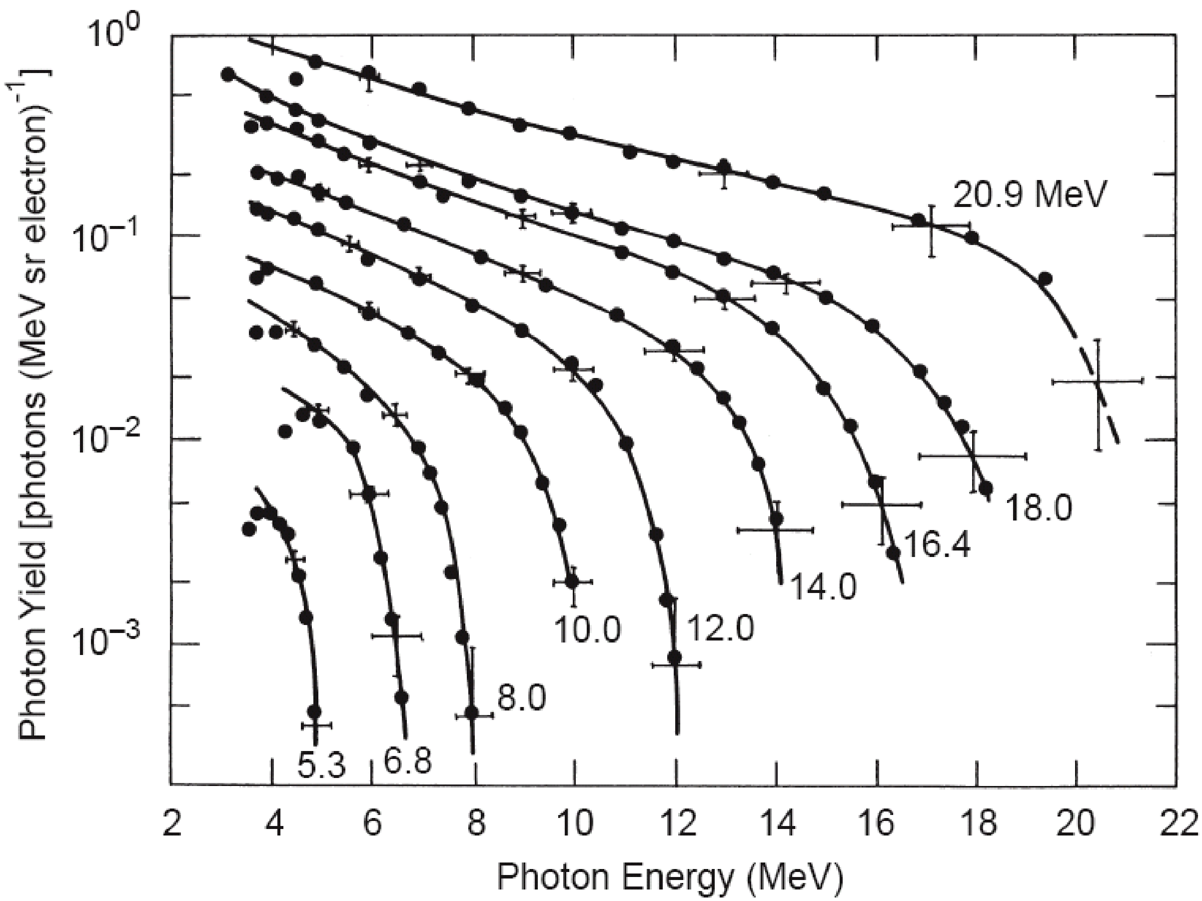
BREMS YIELD



100
80
60
40
20
0
Radiation Yield (%)
0
20
40
60
80
100
Incident Energy [E_0 (MeV)]
Pb
NaI
Cu
Al
H_2O
C
He
H

Forward Brems Spectra

Extend up to energy of electron beam



- Thin target: 1/k
- Thick target: ~$1/k^2$

Brems Source Terms ($Gy.h^{-1}.kW^{-1}.m^2$)

- at 0°, $E_0 < 20$ MeV

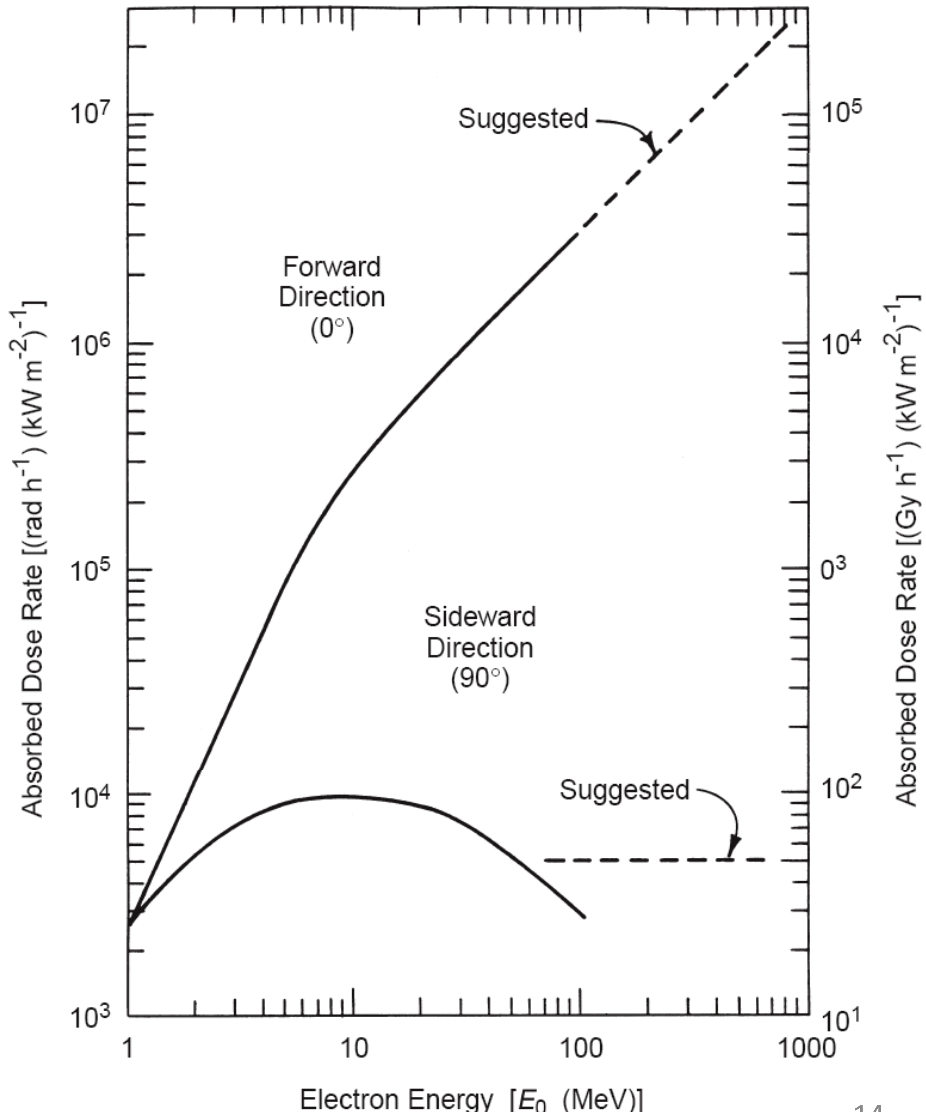
$$\dot{D} \approx 20 E_0^2$$

- 0°, $E_0 > 20$ MeV

$$\dot{D} \approx 300 E_0$$

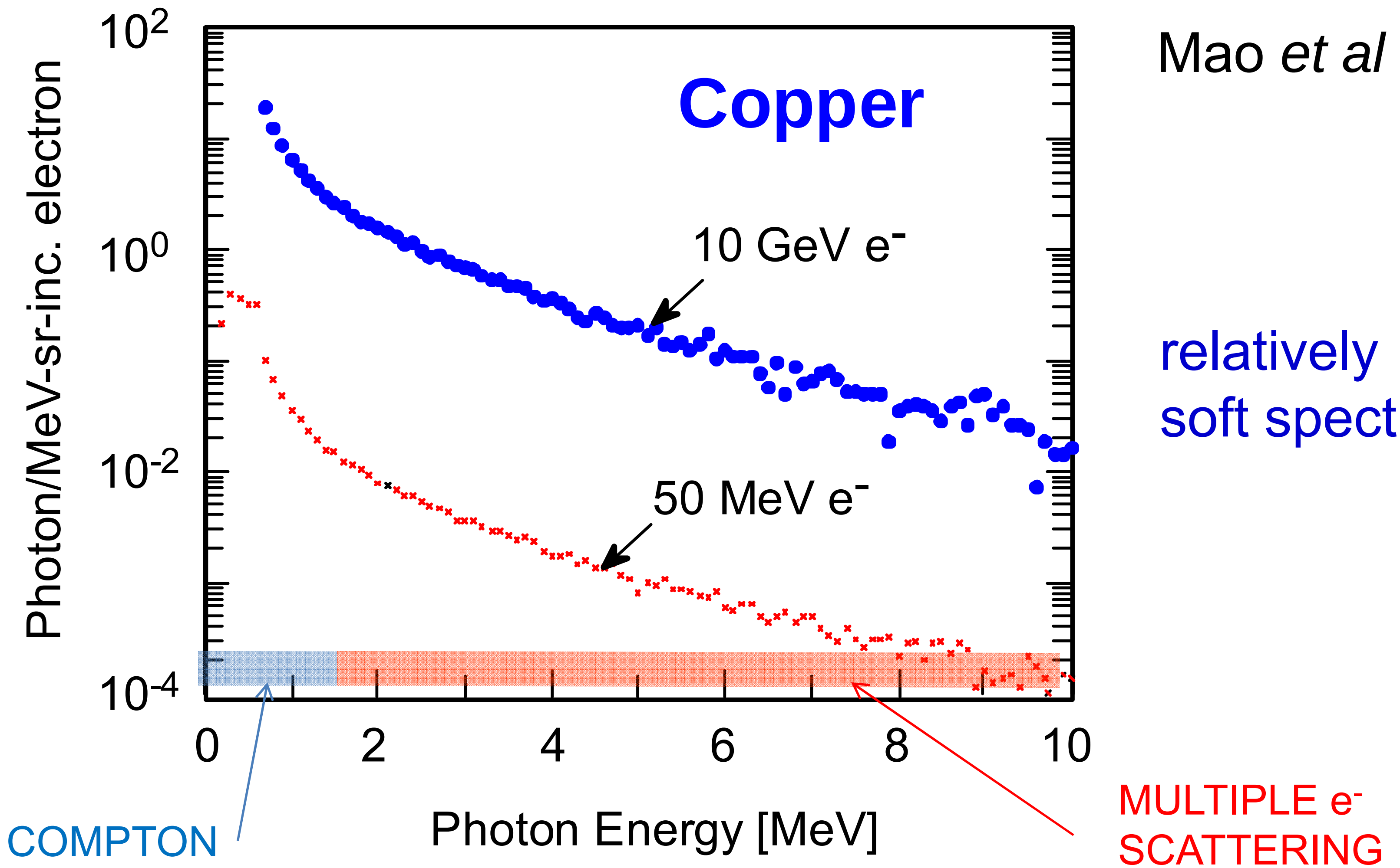
- at 90°, $E_0 > 100$ MeV

$$\dot{D} \approx 50$$



90° Bremstrahlung

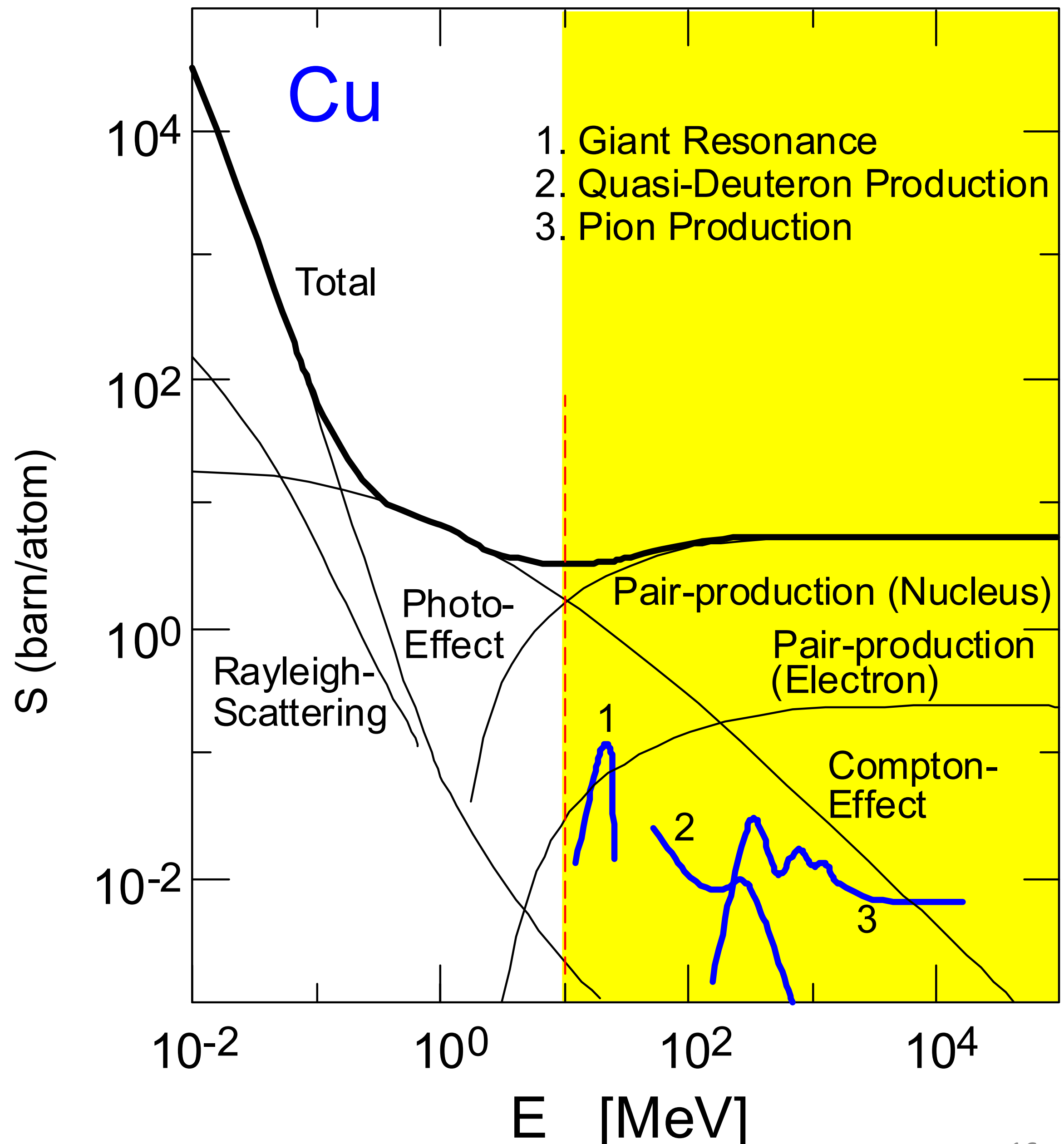
Of interest – shielding often closest to beam at 90 degrees



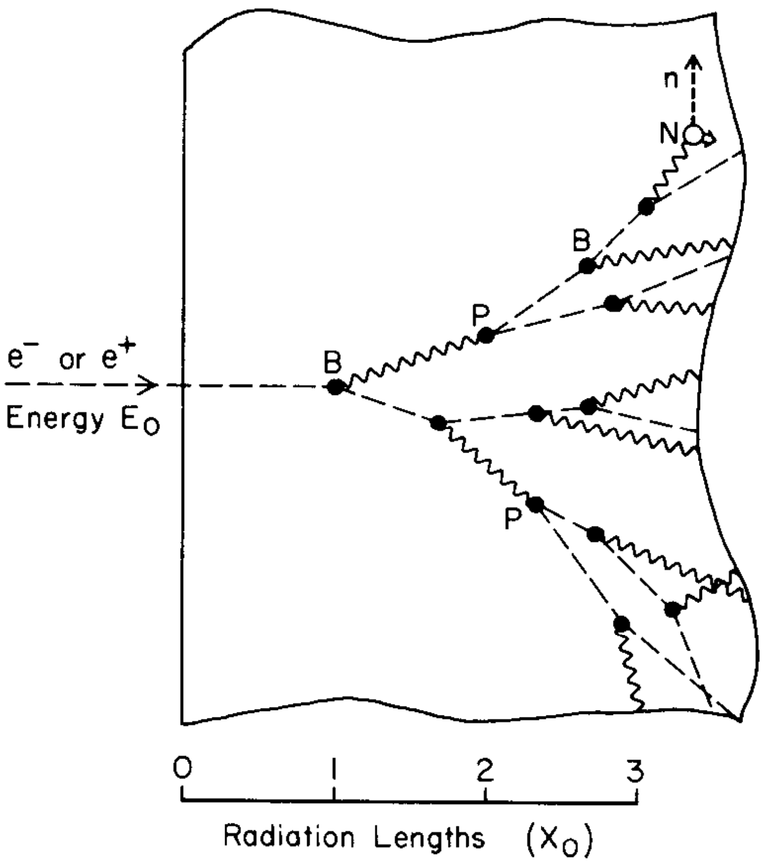
Mao *et al*

relatively soft spectra

Photon Interactions



EM Cascade (shower)



Brems ➡ pair ➡ brems …

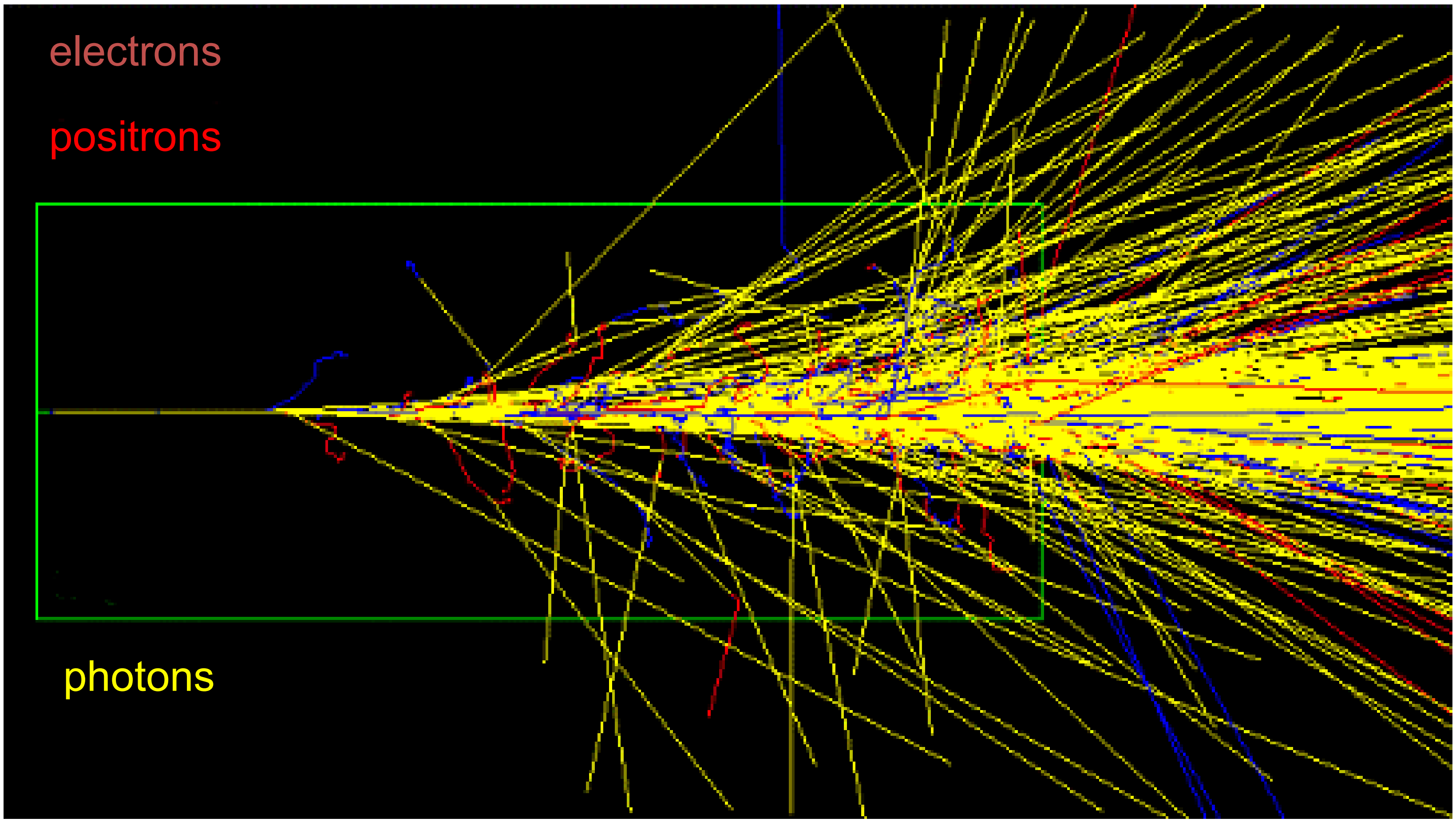
1 step ~1 X_0 for electons, ~9/7X_0 for photons

X_0 = radiation length (e^- energy reduced to 1/e)

Multiplication stops when E_e drops below E_c

Shower in W (E_0 = 10 GeV)

Simulate showers online at http://www2.slac.stanford.edu/vvc/egs/basicsimtool.html



EM Cascade (shower)

- Distance and energy measured in units of X_0 and E_{c}: **t** $= x/X_0$ **y** $= E/E_c$

$$\frac{dE}{dt} = E_0 b \frac{(bt)^{a-1} e^{-bt}}{\Gamma(a)}$$

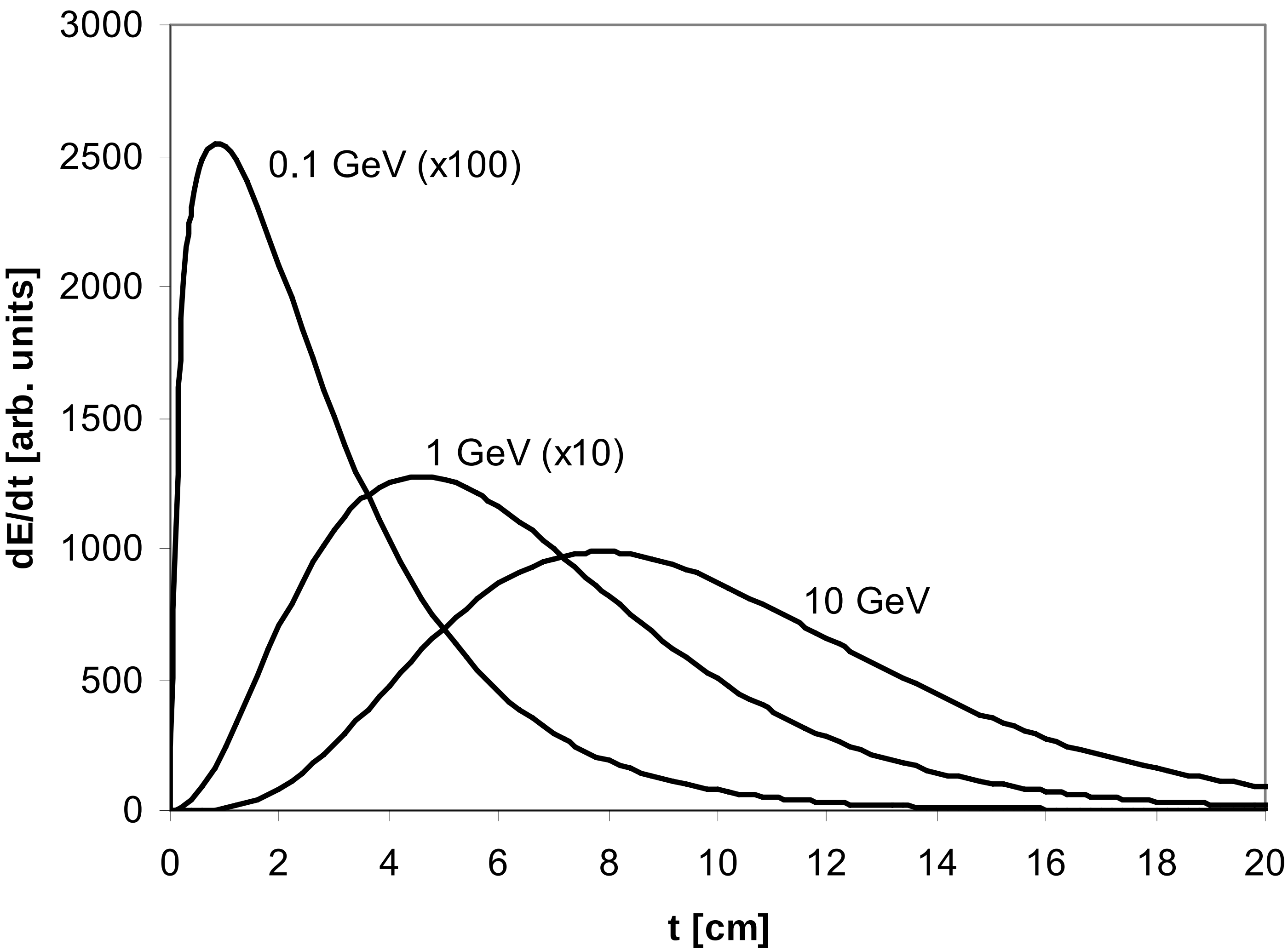
- En. deposition:

$$t_{\max} = \frac{a-1}{b} = 1.0 \times (\ln y + C_j)\ *$$

C_e=-0.5 C_g=+0.5

- **b** varies, but ≈ 0.5, **a** obtained from *

Shower Maximum



EM Shower – radial spread

- Molière radius

$$X_m = \frac{X_0 E_S}{E_c}$$

- E_S = 21.2 MeV

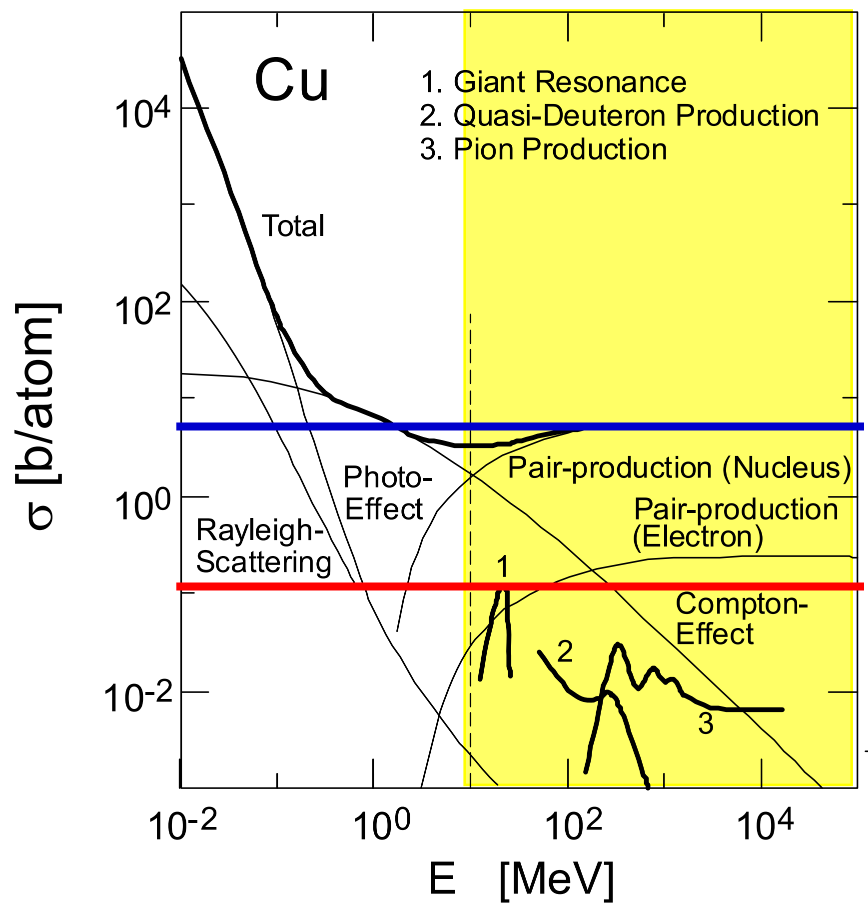
- 90% of energy deposited by the shower within radius $r = 1\ X_m$,   99% for $r = 3.5\ X_m$

EM Shower – radial spread

- E_c and X_m estimated from earlier equations, X_0 from Particle Data Booklet

	$_{6}C$	$_{13}Al$	$_{26}Fe$	$_{29}Cu$	$_{74}W$	$_{82}Pb$	$_{92}U$
E_c [MeV]	111	56.3	29.4	26.5	10.6	9.62	8.58
X_0 [cm]	18.8	8.9	1.76	1.43	0.35	0.56	0.32
X_m [cm]	3.59	3.35	1.27	1.14	0.70	1.23	0.79

Neutrons

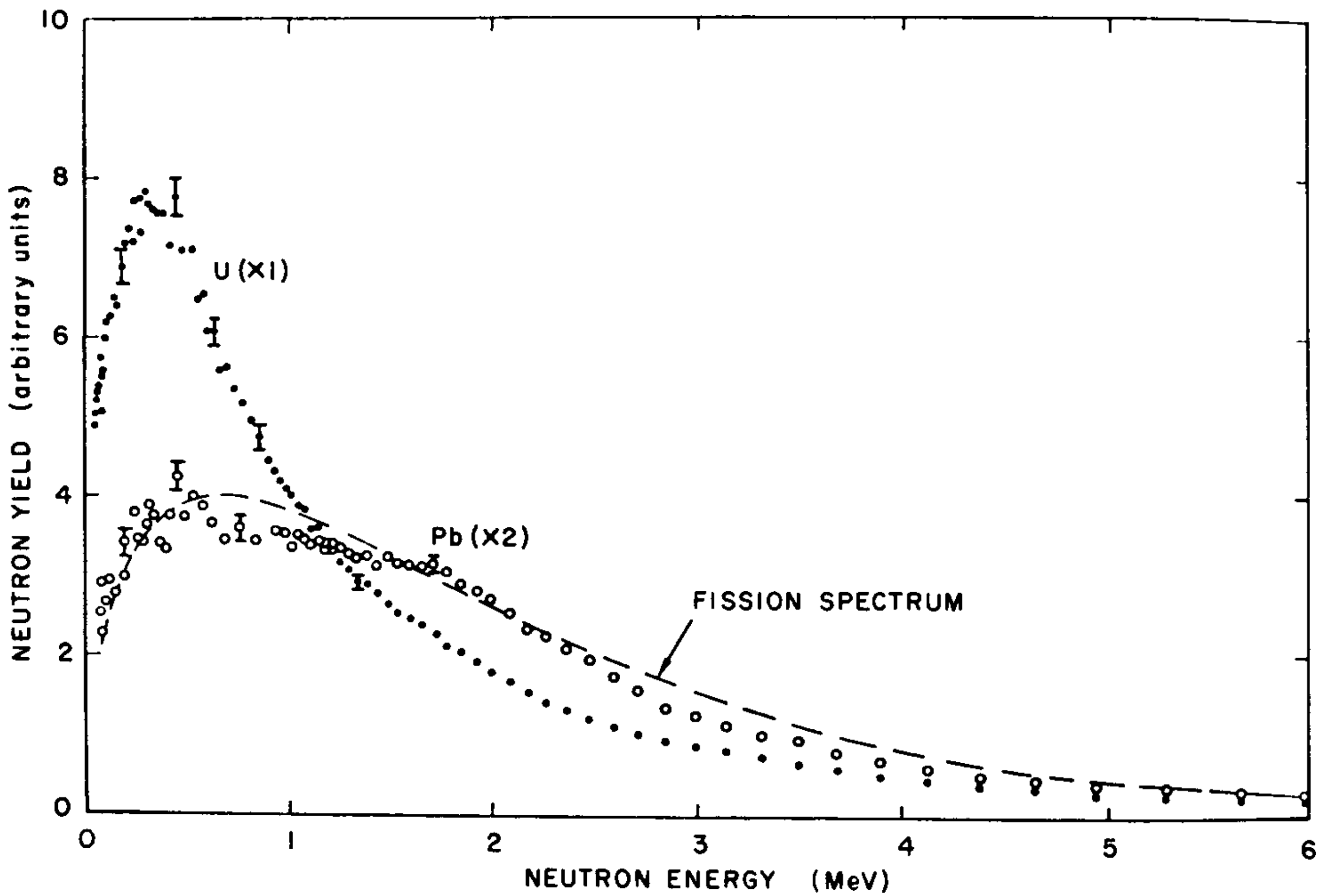


- Much lower yield compared to photons, but more penetrating ➡ important behind shielding

Giant Resonance Neutrons

- Two step process: excitation by γ absorption, followed by n emission ➡ isotropic distribution ($\lambda_\gamma = hc/k$ ~ size of nucleus)
- Peak σ at 20-23 MeV for light (A<40) nuclei, 13-18 MeV for heavier ones: $k_{max} \approx 80A^{-1/3}$ MeV
- Two components: Evaporation (Maxwell – dominant) and direct emission (higher E tail)

GNR spectra for Pb and U
($3X_0$ target)



Pseudo-Deuteron Production

- Beyond GR, photon more likely interacts with proton-neutron pair (pseudodeuteron); neutron produced by pseudodeuteron breakup
- For 50<k<125 MeV $\sigma \sim 1/k$; this low energy part is most heavily weighted
- for 5 MeV < E_n < $E_0/2$:

α = 1.7 to ~3.6

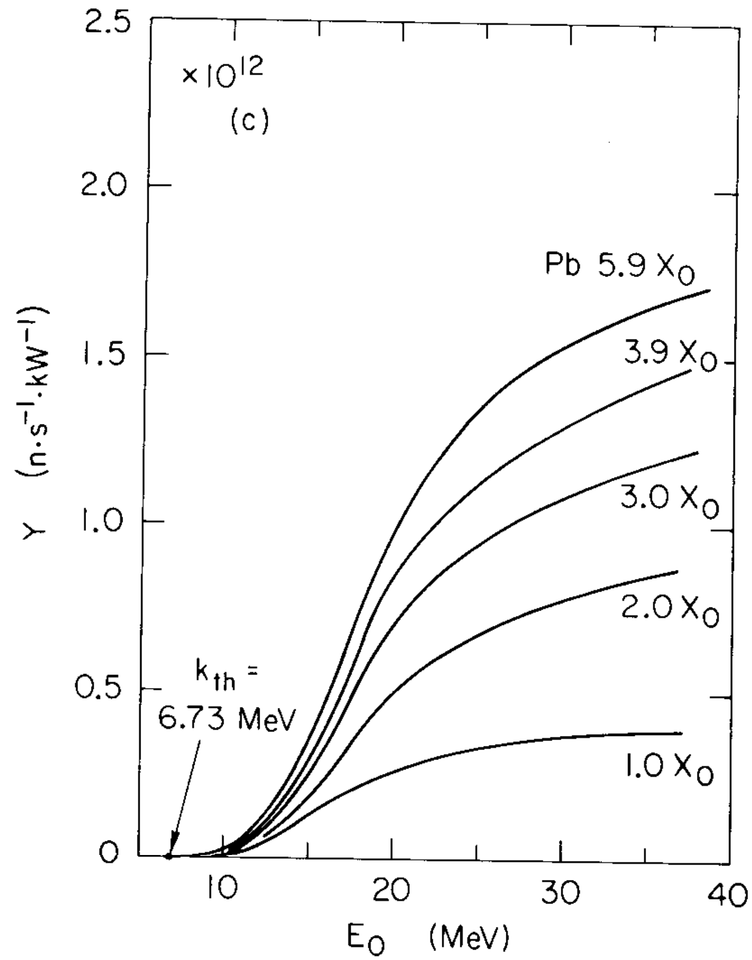
(increase with Z)

$$\frac{dN}{dE_n} \approx E_n^{-\alpha}$$

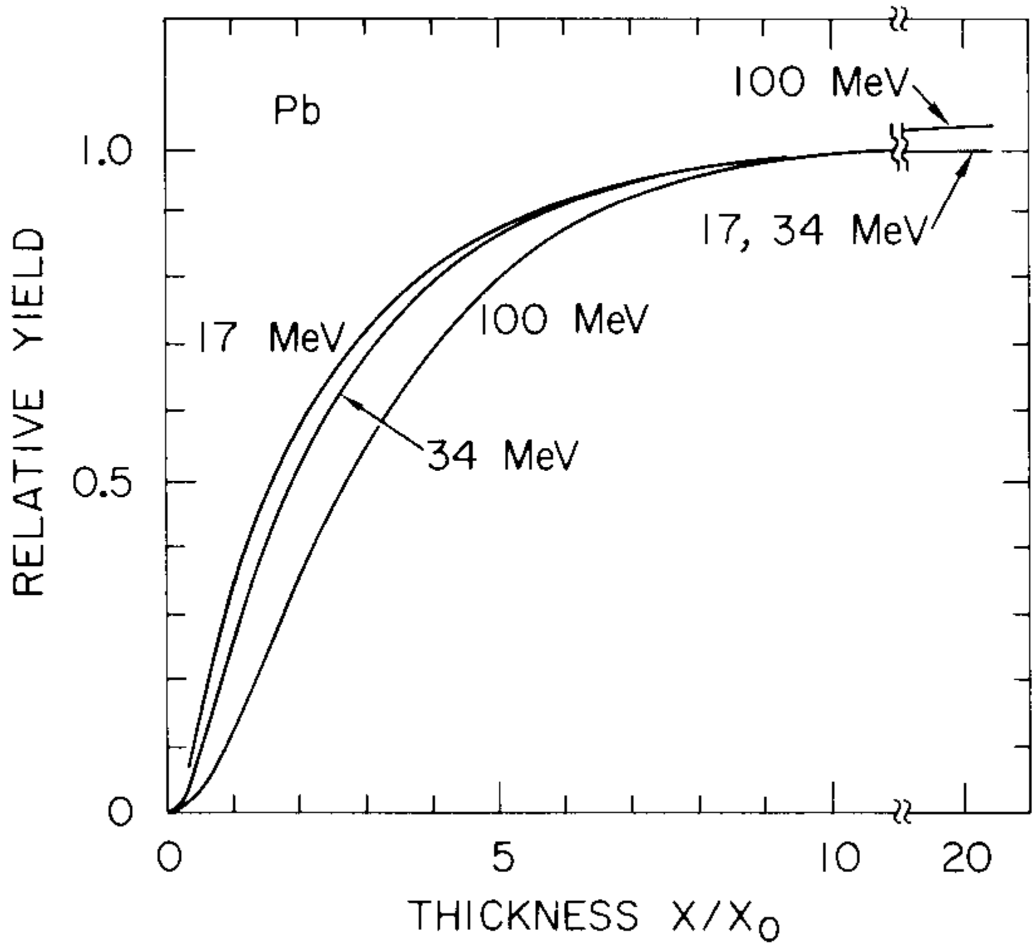
Photopion Production

- For k > ~140 MeV pions can be produced; neutrons produced as companions and in subsequent reaction
- Largest resonance ~300 MeV, $\sigma \approx$ const in GeV region (again, 1/k or $1/k^2$ weighting)
- Most penetrant, generate evaporation "following" in their path ➡ "equilibrium" spectra behind thick shielding

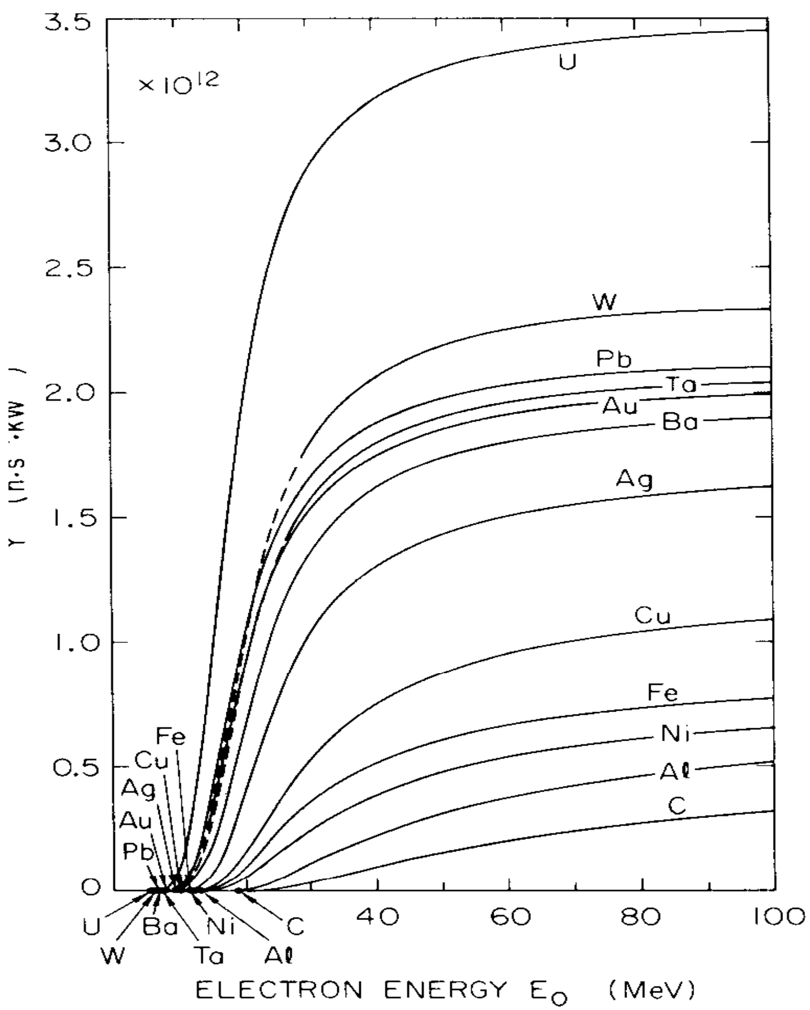
N. Yield as f(E) & thickness (for Cu)



N. Yield as f. of thickness (Pb)



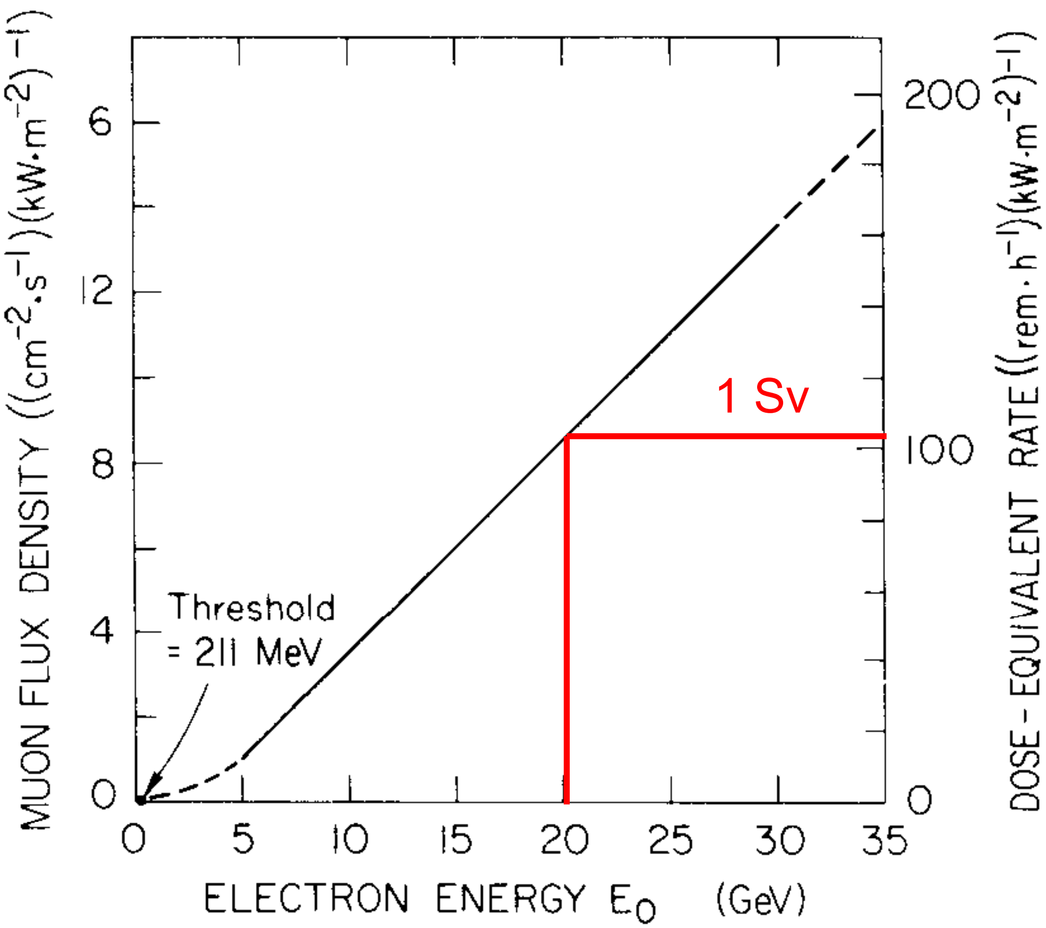
N. Yield as f(E,Z)



Muon Pair Production

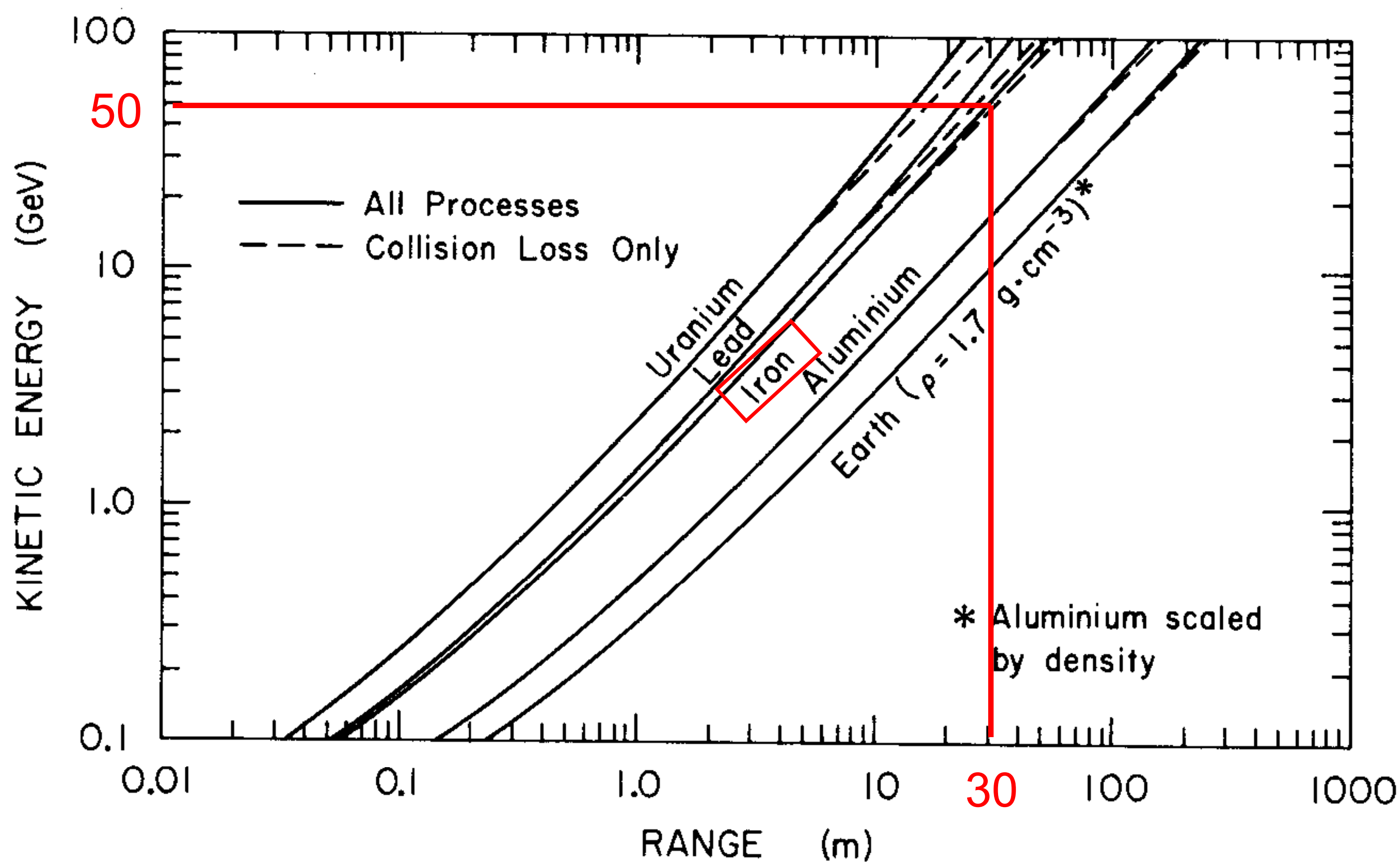
- Possible for photon energy k > 211 MeV
- $\sigma(e^+,e^-)/\ \sigma(\mu^+,\ \mu^-) \approx (m_\mu/m_e)^2 \approx 4.10^4$
- Important above E_0 ~ 1 GeV
- Energy loss only by ionization (<100 GeV); very penetrating & forward peaked
- Yield ~ E_0 (per unit beam power)
- Problem mainly at ~0° behind beam dumps

Muon Source Term at 0°



~ E_0

Muon Range



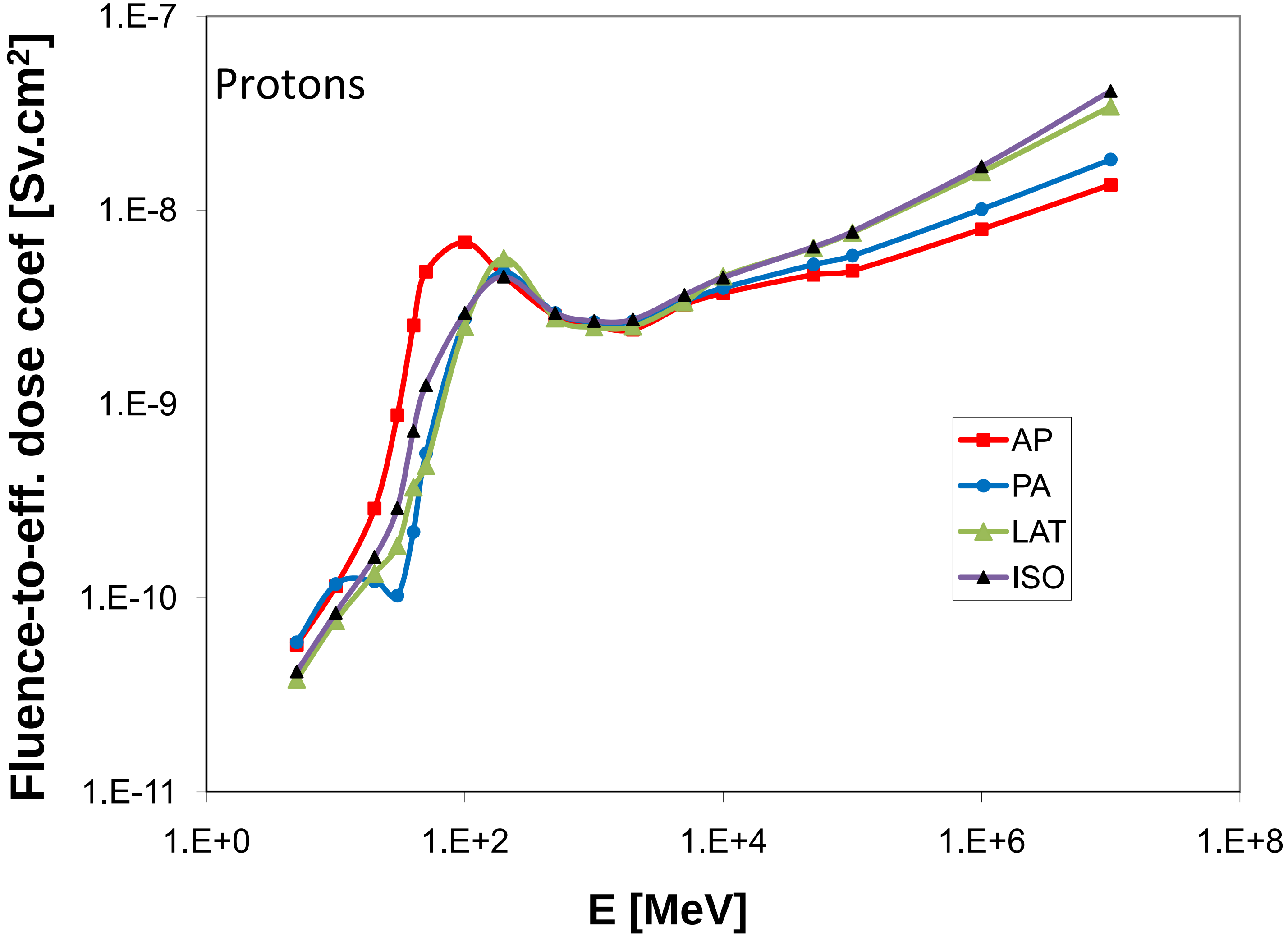
100
50
10
1.0
0.1
KINETIC ENERGY (GeV)
All Processes
Collision Loss Only
Uranium
Lead
Iron
Aluminium
Earth (ρ = 1.7 g·cm^{-3})*
* Aluminium scaled by density
0.01
0.1
1.0
10
30
100
1000
RANGE (m)

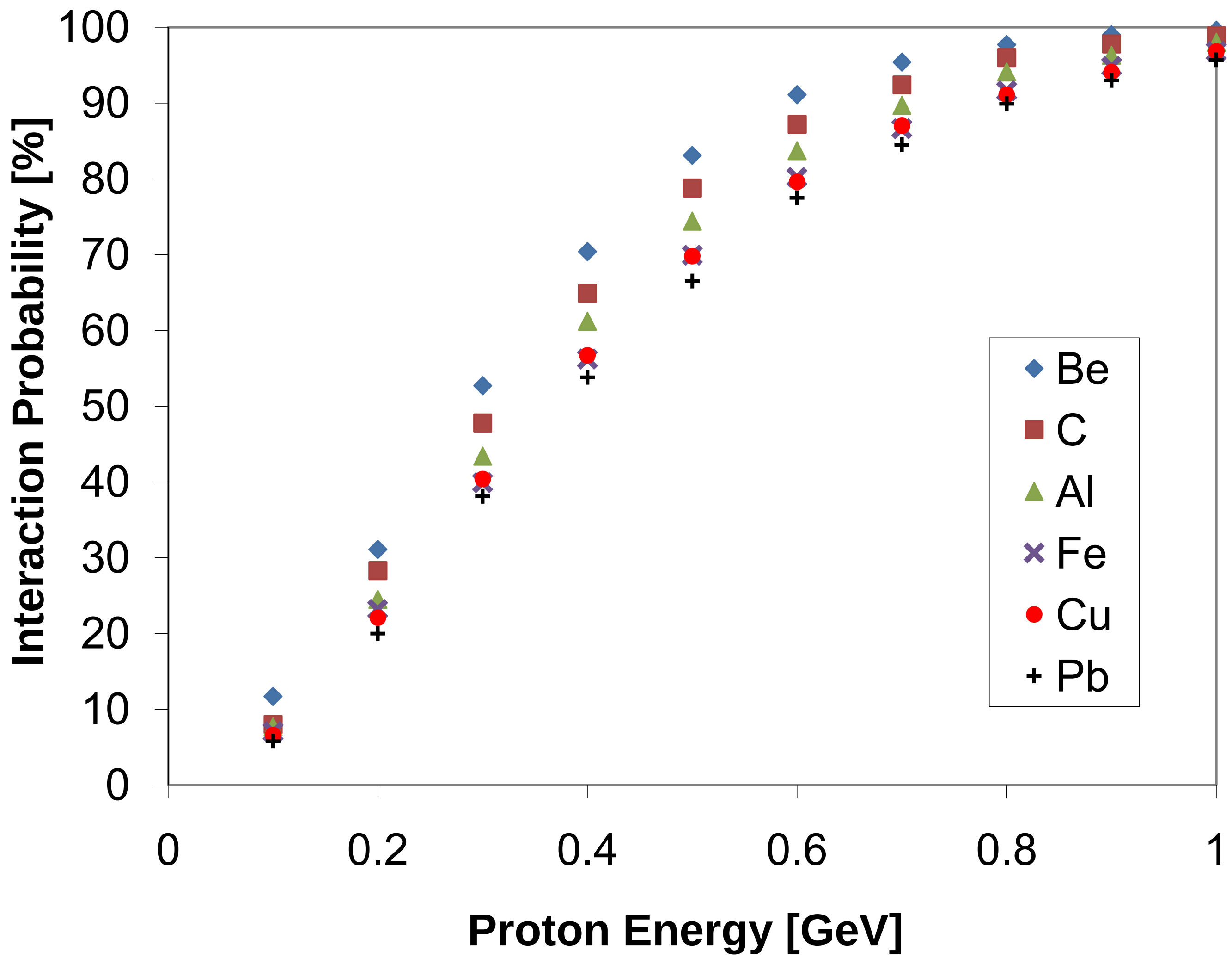
Proton and Ion Facilities

Protons

- High LET, high w_R compared to electrons
- Interactions:
  - Coulomb with atomic electrons ➡ range
  - Nuclear, producing secondary hadrons
- At high-enough energies protons initiate nuclear interactions before ranging out
- Radiative losses negligible till close to TeV

Pellicioni: h_ϕ for protons



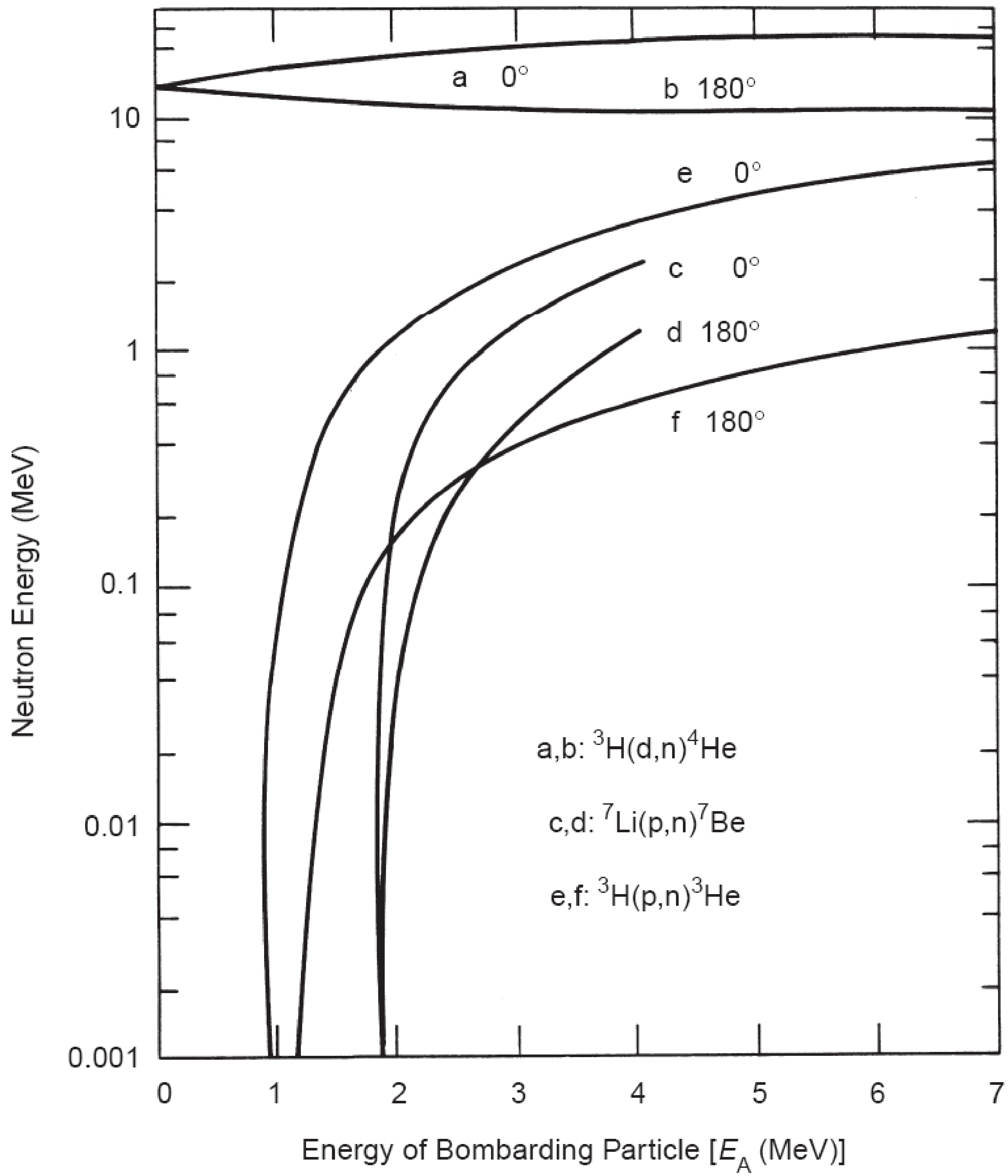


Interaction Probability [%]
100
90
80
70
60
50
40
30
20
10
0
0
0.2
0.4
0.6
0.8
1
Proton Energy [GeV]
Be
C
Al
Fe
Cu
Pb

Neutrons: $E_p < 10$ MeV

- Several (p,n) reactions with threshold < 10 MeV some materials (^{3}H, ^{7}Li) used as targets for neutron production

Reaction	Threshold energy [MeV]
$^{3}H(p,n)^{3}He$	1.019
$^{7}Li(p,n)^{7}Be$	1.882
$^{45}Sc(p,n)^{45}Ti$	2.908
$^{51}V(p,n)^{51}Cr$	1.5656
$^{63}Cu(p,n)^{63}Zn$	4.214
$^{65}Cu(p,n)^{65}Zn$	2.1646



Note: d-T reaction is exoenergetic – no threshold
$Q \approx 17.5$ MeV

Neutrons: 10 MeV < E_p < 200 MeV

- Evaporation neutrons (at lower energies): equilibrium and pre-equilibrium emission

- Equilibrium emission:
  - proton absorbed in nucleus ➡ excitation
  - multiple energy transfers among nucleons
  - Proton direction "forgotten", stat. equilibrium
  - One neutron "boils off"
  - Neutron emission in uncorrelated direction to p^+

Neutrons: 10 MeV < E_p < 200 MeV

- Evaporation neutrons: isotropic emission, Maxwell energy spectrum (T ≈ few MeV)

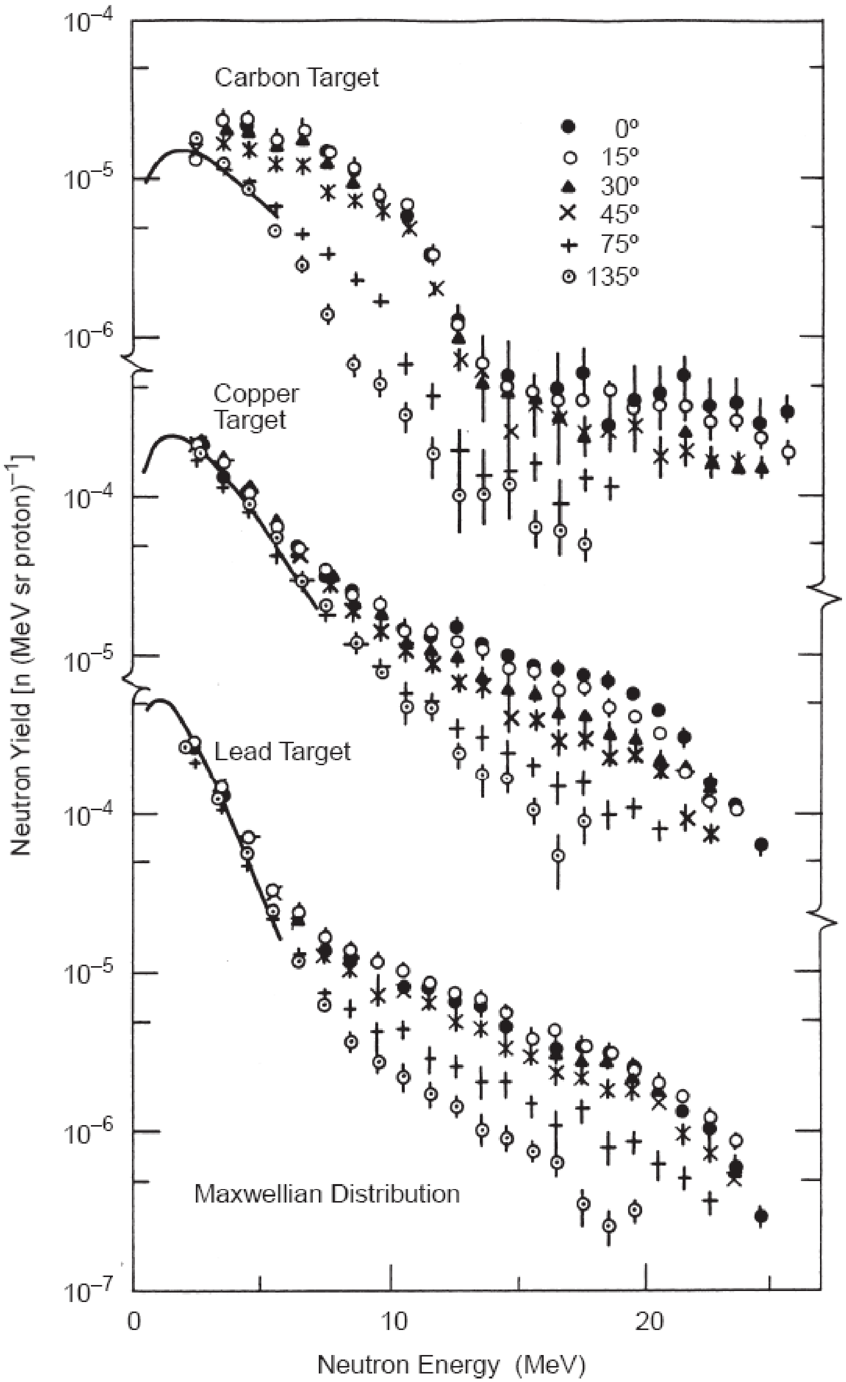
- Pre-equilibrium: neutron emitted only after few energy transfers ➡ emission forward-peaked, somewhat correlated to p^+ direction

Neutrons: 10 MeV $< E_p <$ 200 MeV

- Intranuclear cascade – at higher energies proton collides with individual nucleons, these collide further ➡ cascade of nucleons

- Multiple nucleons may be emitted

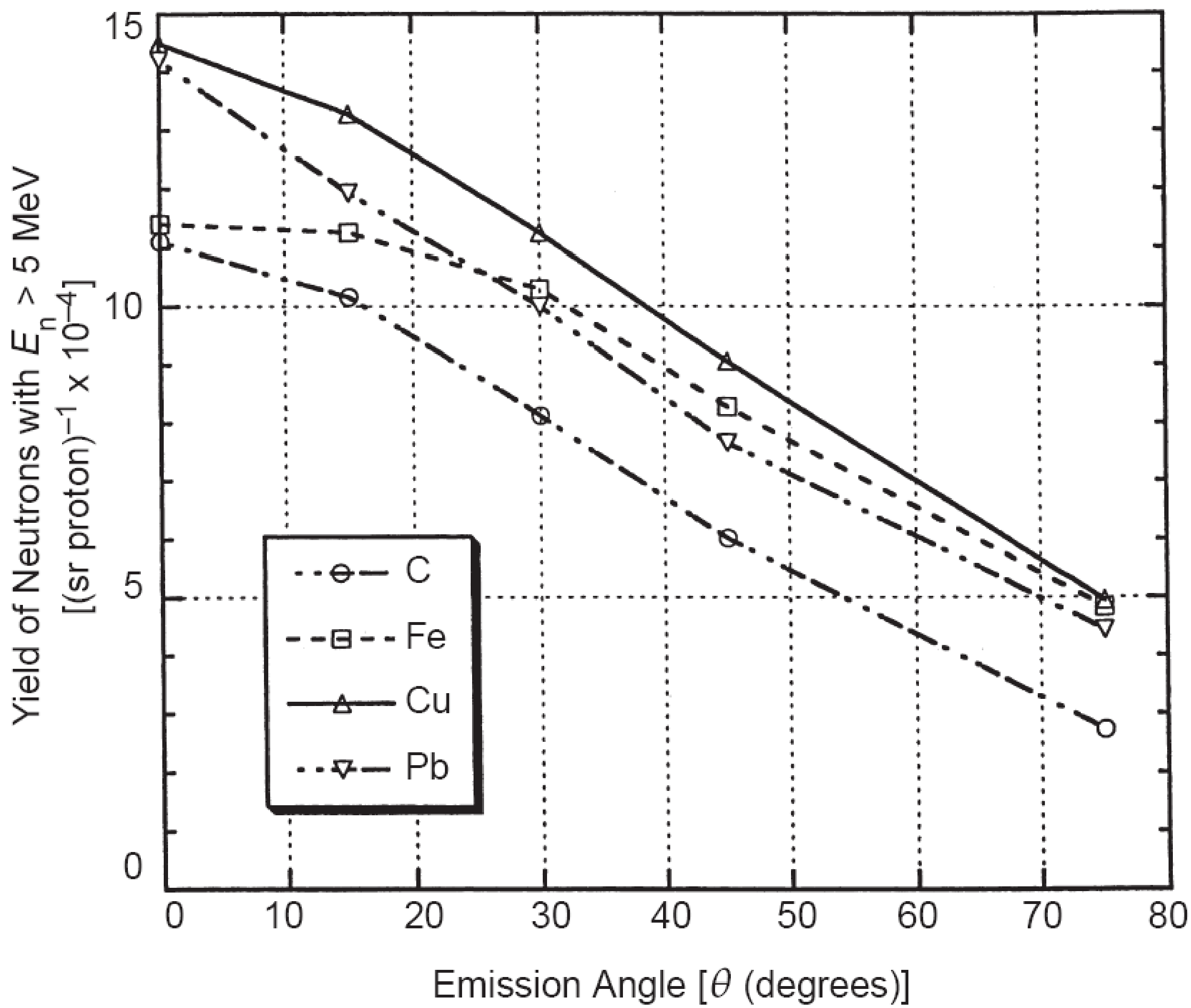
- Excited nucleus may de-excite by evaporation



Neutron spectra from targets bombarded by 30 MeV protons

Solid line: evaporation Maxwell spectrum component

Angular distribution of neutrons from targets bombarded by 52 MeV protons. Pre-equilibrium and intranuclear cascade enhance the forward component.

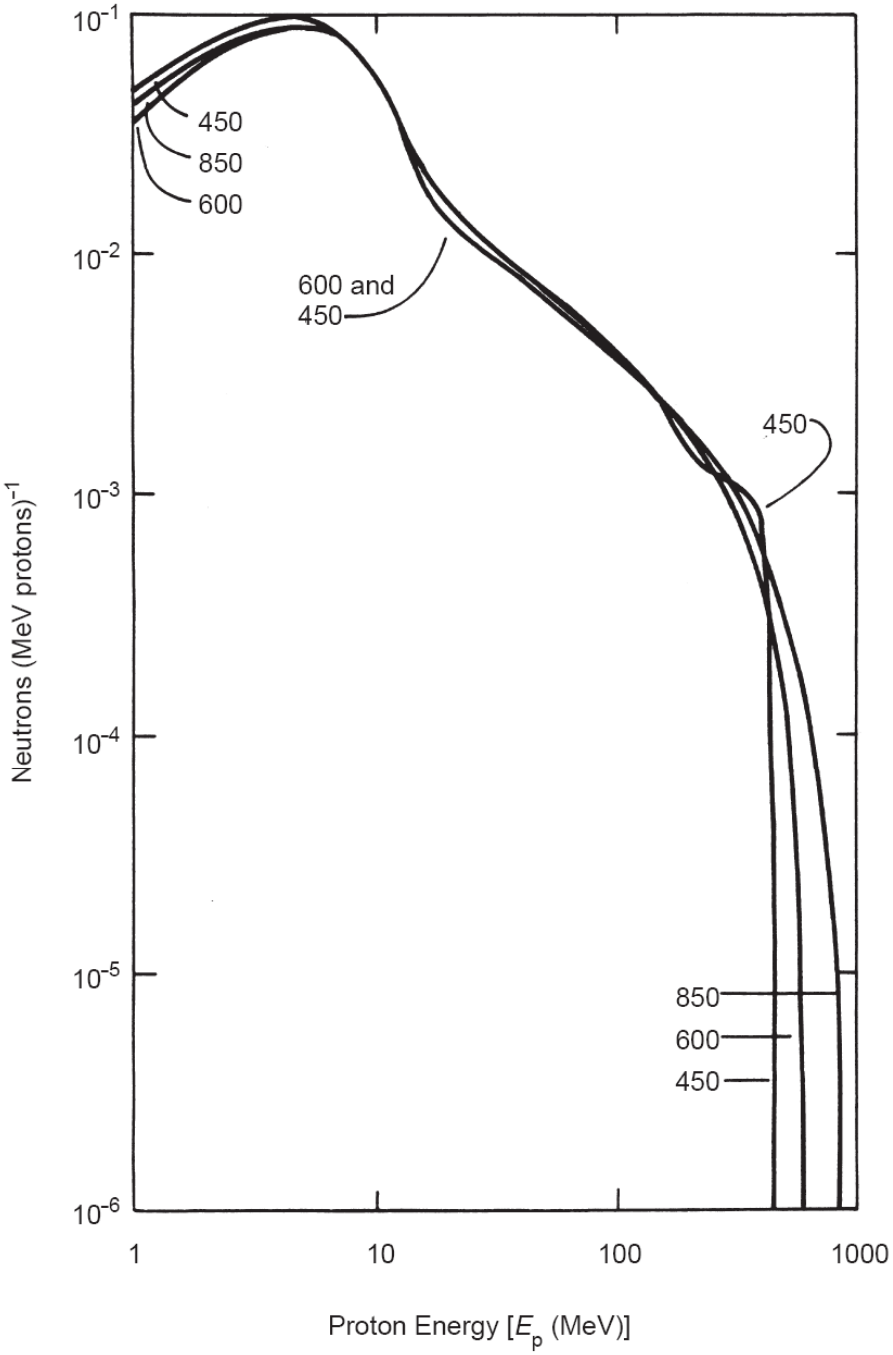


Neutrons: 200 MeV <E_p< 1 GeV

- "Intermediate" energy – more reactions possible, more particles emitted; # of protons equals # neutrons at higher energies

- Hadronic cascades + evaporation neutrons

- Distribution of secondary particles more forward-peaked than before

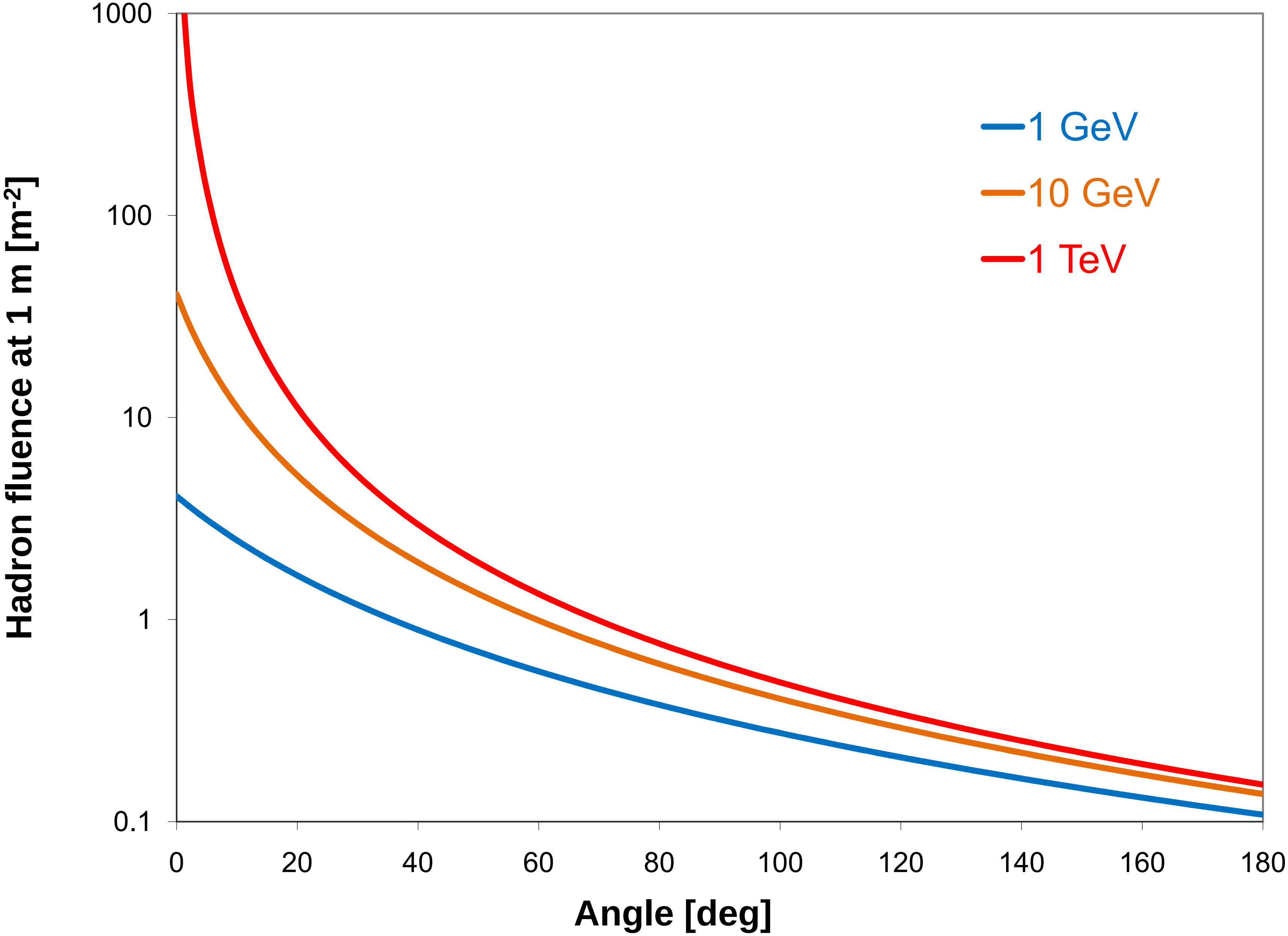


Neutron spectra below E_p not very sensitive to E_p

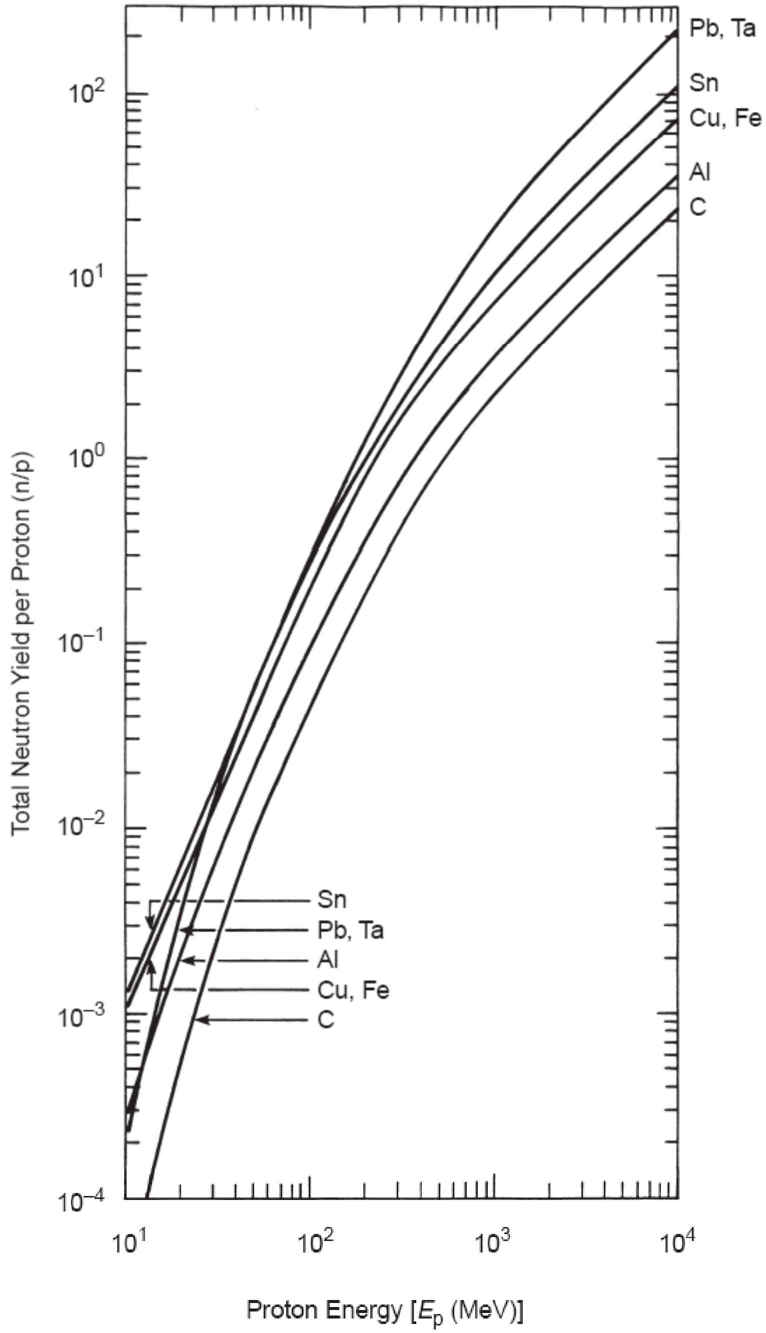
Neutrons: $E_p > 1$ GeV

- High energy range: many more reactions possible
- Hadronic showers may extend beyond initial target ➡ complicated source term
- Sullivan: production of hadrons with E>40 MeV by protons 1 GeV < E_p < 1000 GeV for thin Fe or Cu targets (< 1 removal mfp for hi-E proton)

$$\Phi(\theta) = \frac{5000}{\left(\theta + 35\big/\sqrt{E_0}\right)^2} \quad [\mathrm{m}^{-2}\ \mathrm{proton}^{-1}]$$

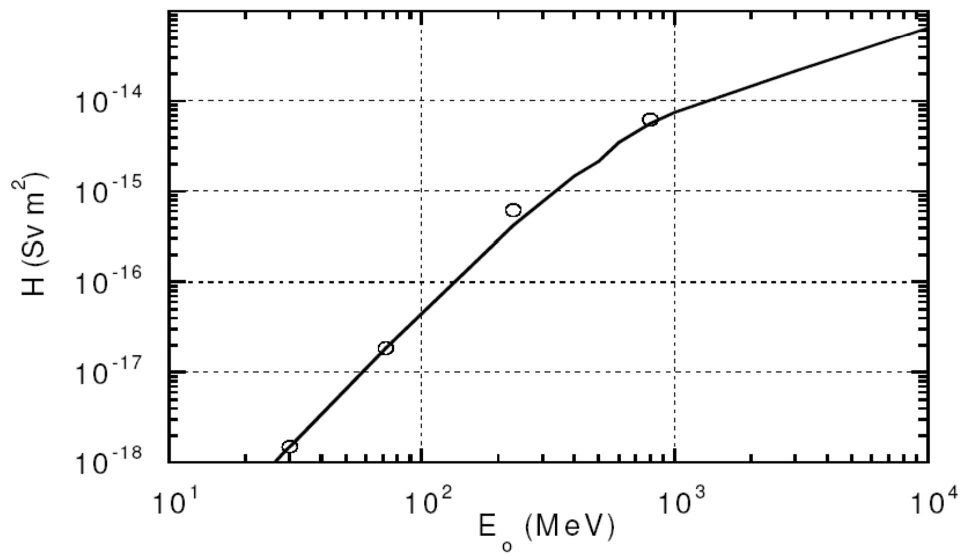


1000
100
10
1
0.1
0
20
40
60
80
100
120
140
160
180
Angle [deg]
Hadron fluence at 1 m [m-2]
1 GeV
10 GeV
1 TeV



Total neutron yield per proton

Neutron dose equivalent per proton at 90° at 1 m from a copper target

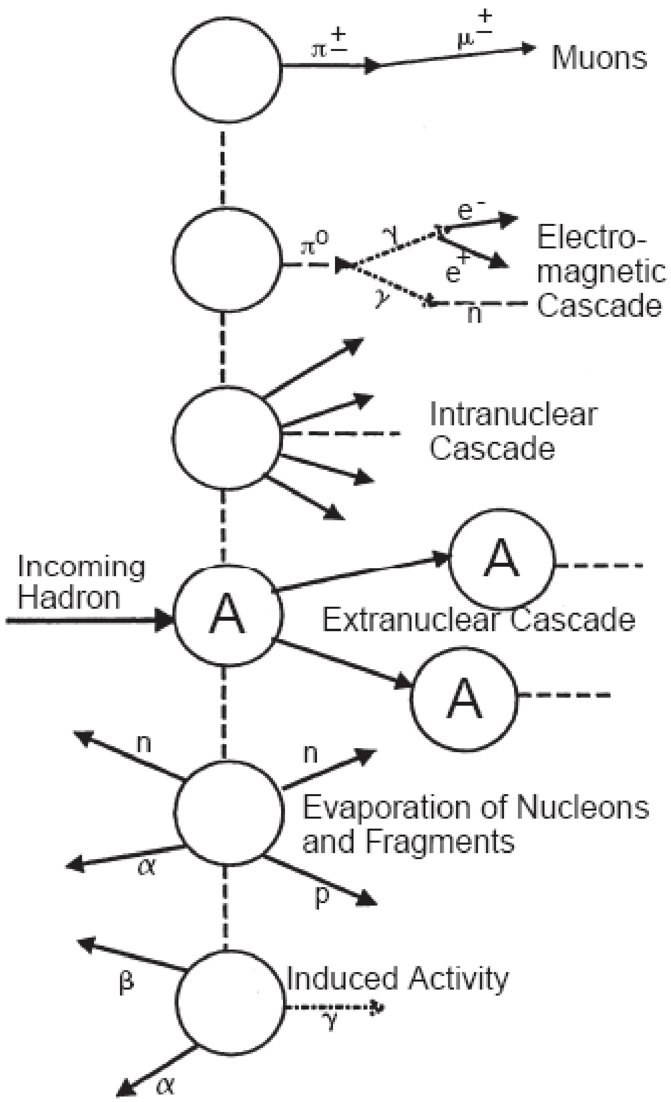


Muons

- Generated by decay of charged pions and kaons
- $m_{\pi}c^2$ = 140 MeV, important for E_p > 300 MeV; decay quickly to muons: $\pi^{\pm} \Rightarrow \mu^{\pm} + \nu_{\mu}$
- $m_{K}c^2$ = 494 MeV , important for E_p > 1 GeV; decay quickly to muons: $K^{\pm} \Rightarrow \mu^{\pm} + \nu_{\mu}$
- Extremely forward-peaked emission
- At very high eneries: so-called “direct” muon production

Hadronic Cascade

- Extranuclear cascade: propagated by hi-en secondary nucleons – mostly neutrons up to ~450 MeV; protons, pions important above this energy (and kaons even higher)
- Neutral pion π^0 decays into photon pair, initiates elmag cascade – this generates a leading hadron spike at very high E_p (>100 GeV)



Most Numerous Participants	Time Scale (s)	Typical Energy per Particle (MeV)	Percent of Energy Deposition
$\pi, K \rightarrow \mu$	10^{-8}	any	10
$\pi^{o} \rightarrow e, \gamma$	10^{-16}	any	20
p, n, π, K	10^{-22}	<200	30
p, n, π, K	10^{-23}	>200	30
p, n, d, α	10^{-19}	<30	10
α, β, γ	seconds to years	<10	<1

Ion Accelerators

- Radiation fields in many aspects similar to proton machines
- Primary ions – shorter range ($dE/dx \sim z^2$)
- Low-energy light ion machines: use specific exoenergetic (d-d, d-T) and endoenergetic reactions to produce neutron beams

Ion Accelerators

- Energetic ions generate secondary nucleons; from there follow processes described before
- Neutron yield by heavy ions (Kurosawa):

$$Y = \frac{1.5 \times 10^{-6}}{N_T^{1/3}} W_P^2 \left(A_P^{1/3} + A_T^{1/3} \right)^2 N_P \frac{A_P}{Z_P^2}$$ [neutrons.particle^{-1}]

P – projectile, T - target

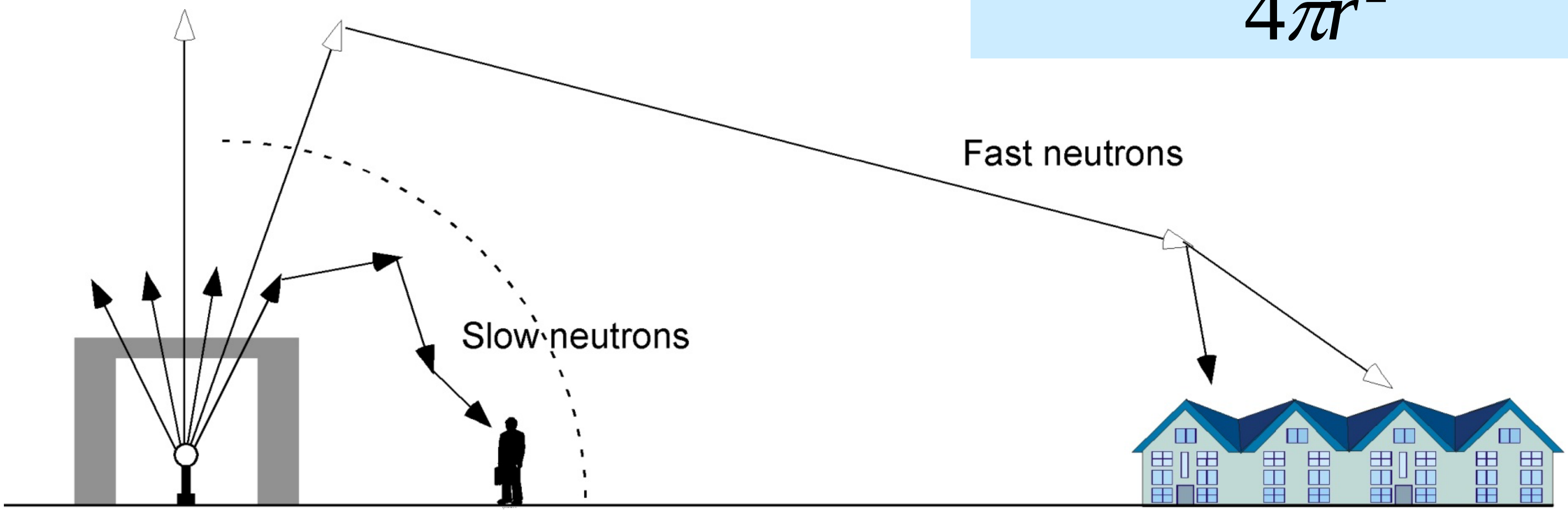
- Early shielding calculations for ion machines used scaled source terms for protons

THE END

But wait, there is more:
Skyshine
Neutron Spectra

Neutron Skyshine

$$H(r) = \frac{q}{4\pi r^2} e^{-r/\lambda}$$

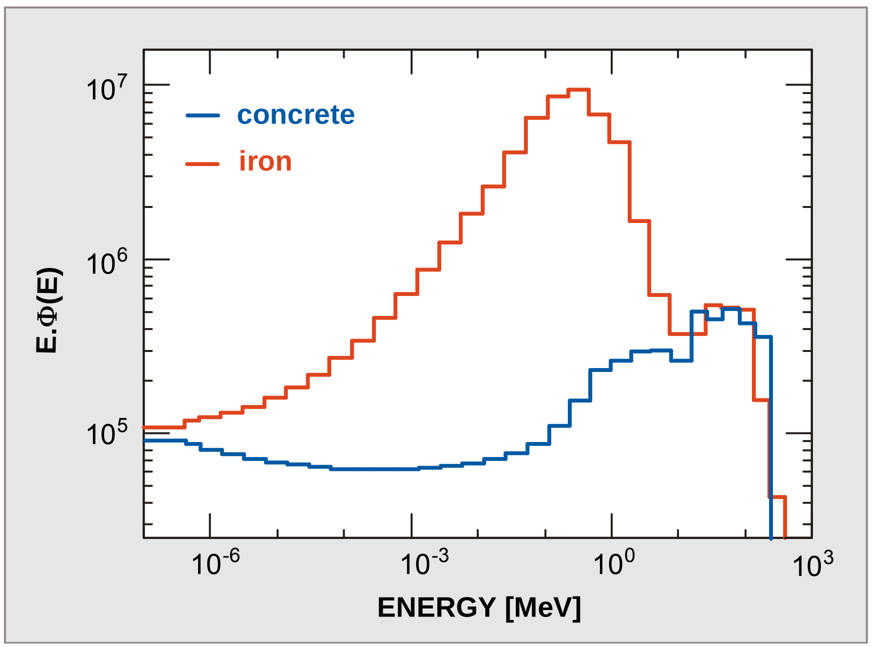


- Spectrum hardens with distance
- At close distance $1/r^2$ not good
- More complex models exist

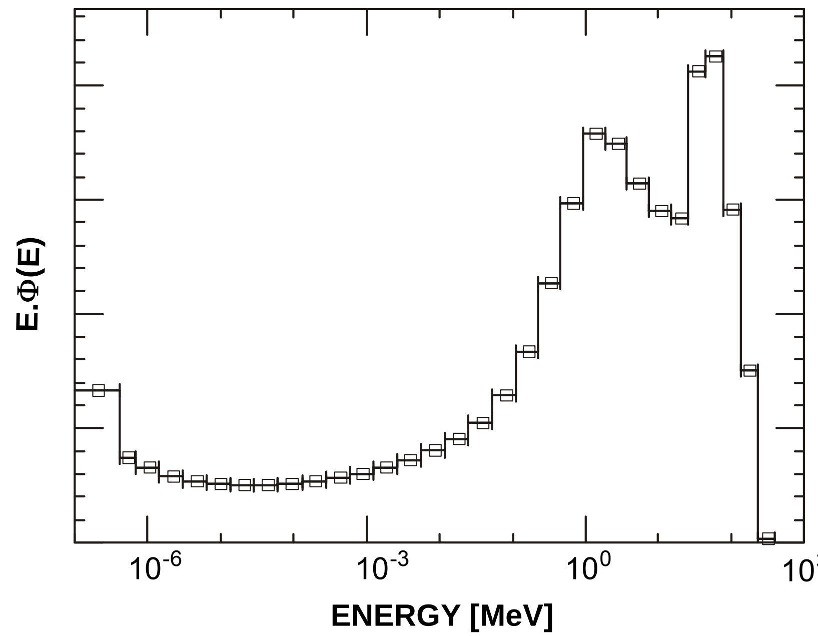
Equilibrium Neutron Spectra

Most penetrating part: neutrons >150 MeV (for E>150 MeV σ_{inel} reaches a constant minimum: $\sigma_{inel} = 43.1\ A^{0.70}$)

CERN

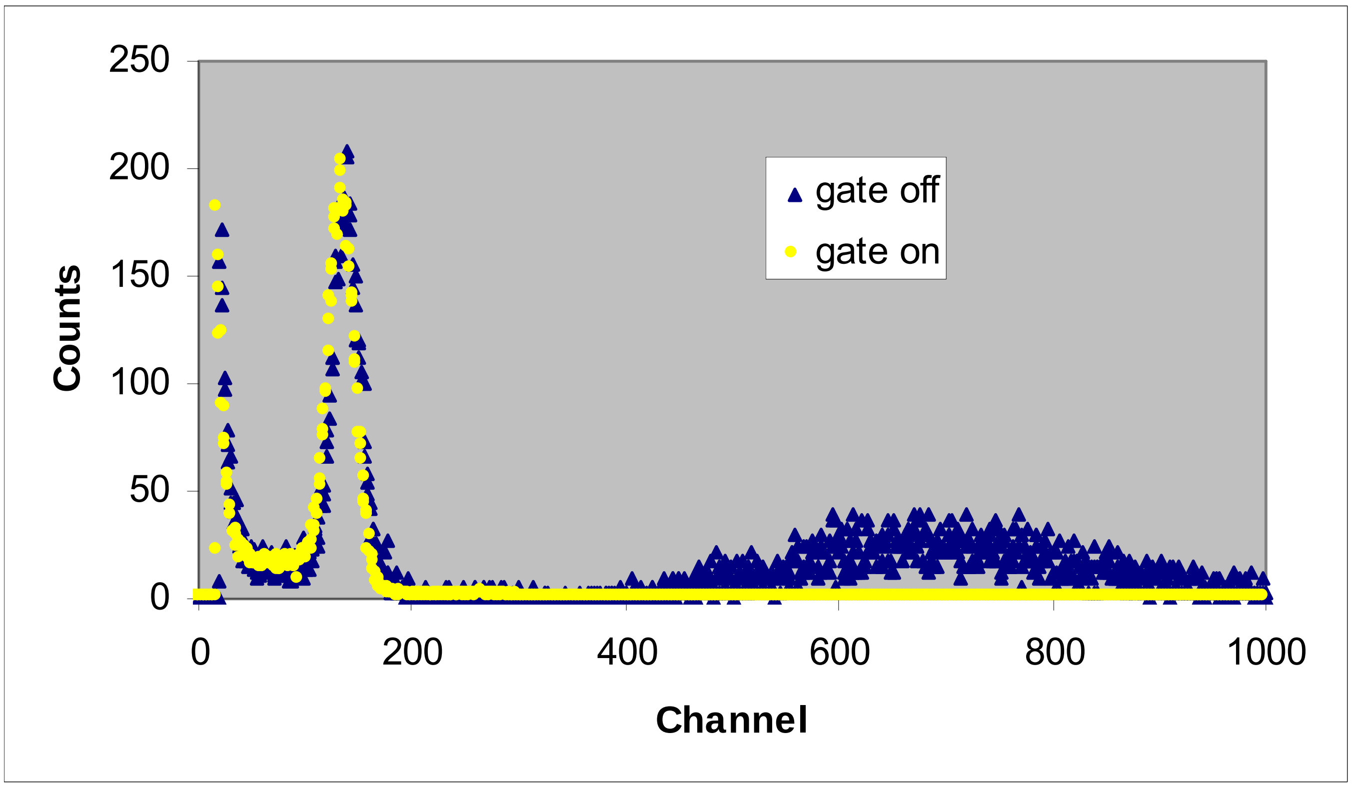


SLAC



SLAC SSRL

- Pulsed e-, thin shielding: “gamma flash”
- Neutrons come later (up to tens of μs)
- MCA LiI Pulse-height spectra (with γ-flash)



SLAC SSRL

- Gamma flash with "non-equilibrium" spectra