EUROPEAN
SPALLATION
SOURCE

Radiation, shielding and tools

Günter Muhrer

www.europeanspallationsource.se

Bio: Graz and Berlin

1989 – 1994
Physics at TU Graz, Austria
Dipl. Ing
Master thesis: Electrons for brain cancer therapy

mid 1994 – mid 1995
Civil serves: paramedics at the red cross: 3418 patients

1995 – 1998
PhD at TU Graz, Austria
Thesis: Free energy formula for HTC

1993 – 1996
Austron

1997 – 1998
Hahn Meitner Institute
Moderator study for ESS

1995- early 1997
Handball coach

Bio: Los Alamos

1999-2001
PostDoc at LANSCE
Spallation physics

2001 – 2005
Staff at LANSCE
Spallation physics

2005 – 2013
LANSCE Spallation Physics Team Leader

2012 – 2013
Lujan Center deputy group leader for science

2013 Alternate EAM for the Lujan Center and DAQ Team Leader

Bio: Lund

2014 – present
Workpackage manager for physics
(WU: target physics, neutronics, materials)

2014 – present
Group Leader for target physics
(shielding, activation)

2014 – present
ESS shield design coordinator

Outline

- Radiation 101
- Rules and Sources
- Physics
- Tools
- Payoff

Radiation 101

Why do we need to shield against radiation?

- Damage to the equipment (Gy or Rad)
- Damage to the human body (Sievert or Rem)
- Damage to experimental data (noise level of the data)

Units (protection of equipment)

- Gray [Gy] and Radiation Absorbed Dose (Rad) are the two most commonly used units that quantifies the dose received by equipment.
- 1 Gy = 1 J/kg
- 1 Gy = 100 rad

Units (protection of humans)

- Sievert [Sv] and Röntgen Equivalent Man (Rem) are the two most commonly used units that quantifies the dose received by human body.
- 1 Sv = 100 rem
- Like Gy, Sv has the SI unit of J/kg, however Sv is the absorbed dose convoluted with the respective biological damage factors, which are usually published by the International Commission on Radiological Protection (ICRP)

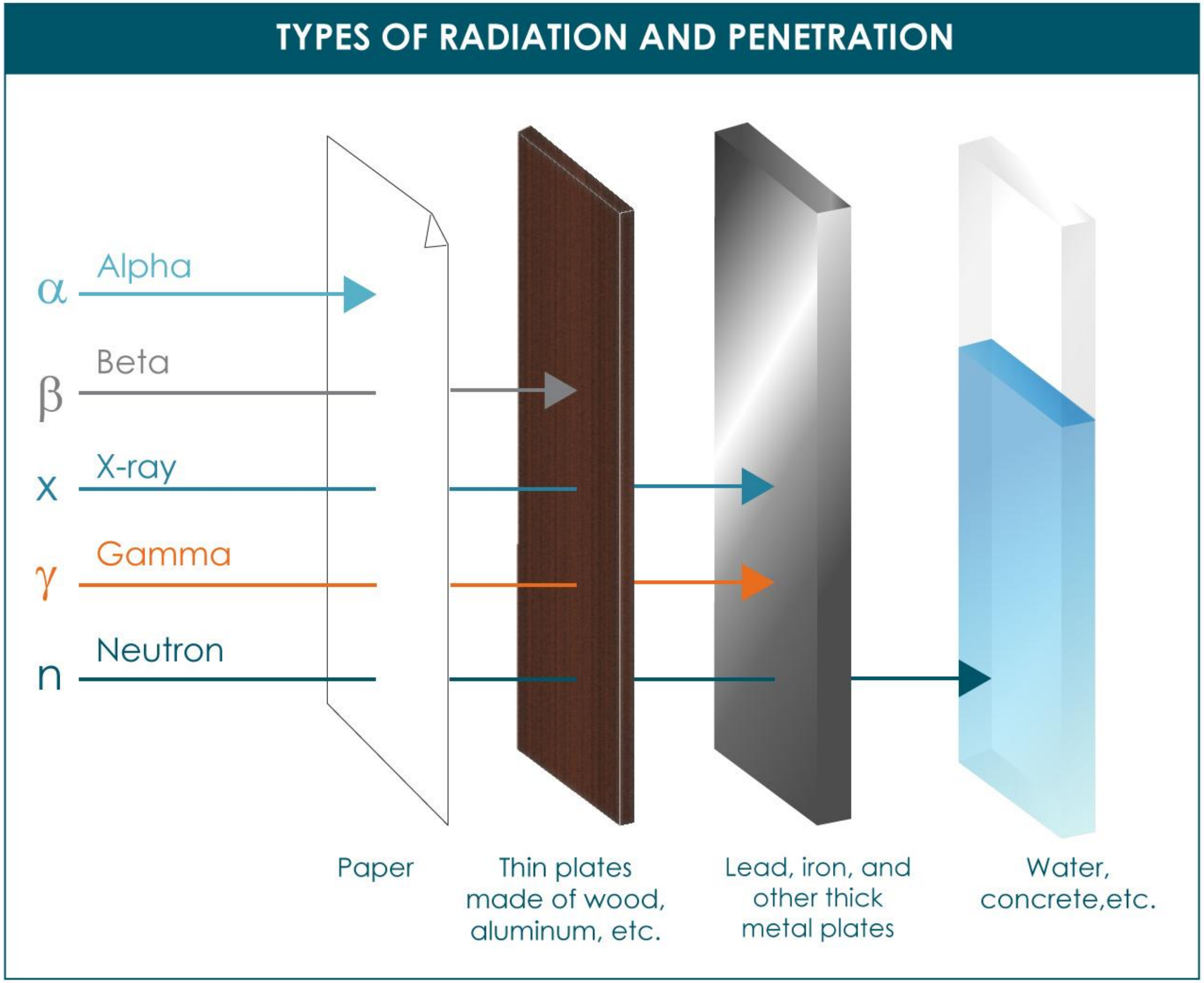
Units (protection of humans/activation)

- Becquerel [Bq] and Curie (Ci) are the two most commonly used units that quantifies activation.
- 1 Ci = $3.7*10^{10}$ Bq (activity of 1g Ra^{226})
- 1 Bq = 1 decay per second

Units (protection of data)

- The definition of the noise of an experiment will depend on the experiment.

Types of radiation 1(2)



Types of radiation 2(2)

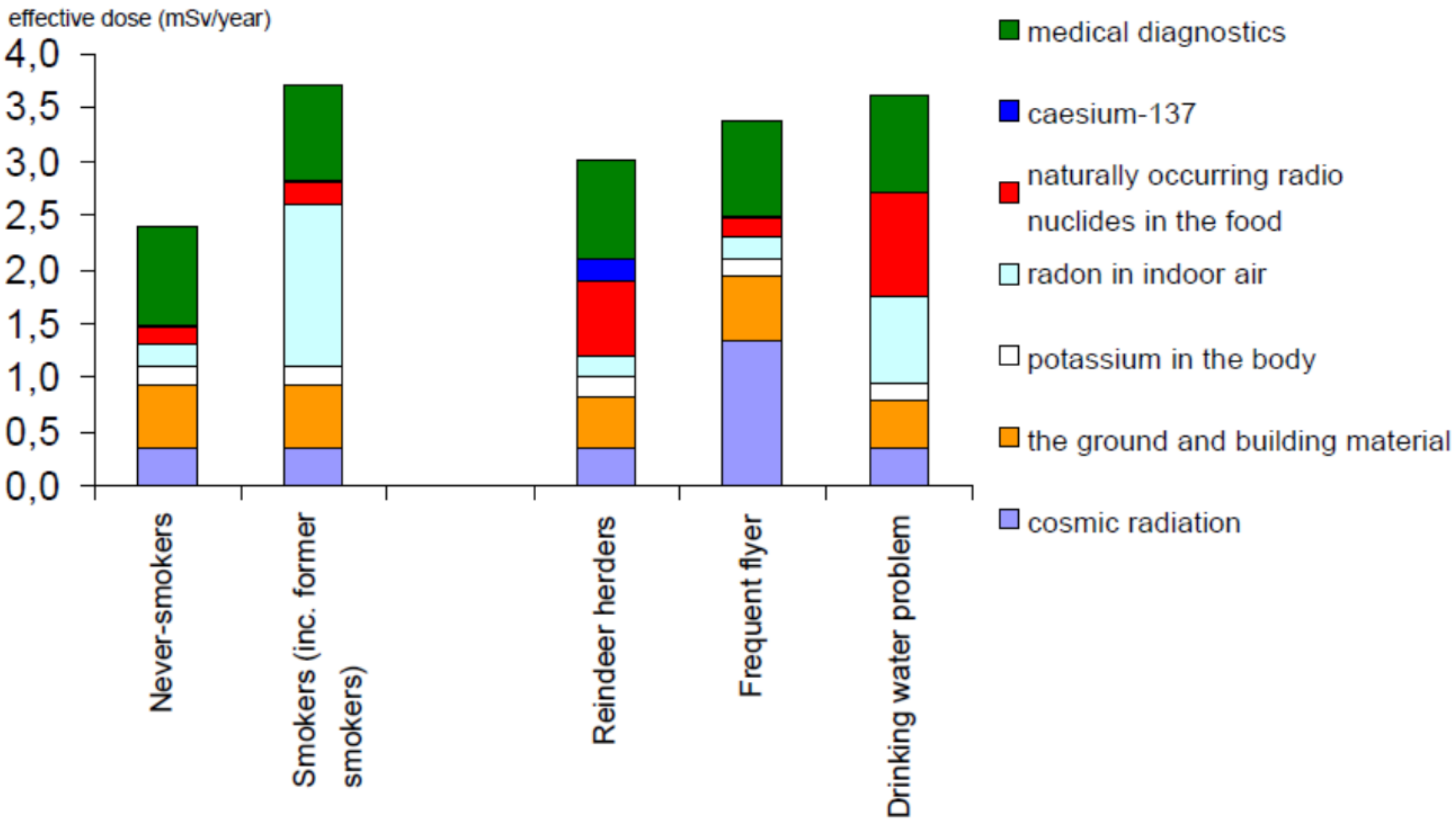
- Prompt radiation:
  - Prompt radiation is defined as radiation that is generate instantaneously once the radiation generating device is put into operation, and ceases to exist once the device is turned off.
- Decay radiation/activation:
  - Decay radiation is defined as radiation that comes from the decay on unstable isotopes. Cannot be turned off.
- Irremovable volume activation/contamination:
- Removable surface activation/contamination:
- Airborne activation/contamination:

Sources of natural radiation

Los Alamos, NM, USA

Source	mSv/year
Radon	2
Cosmic	0.28
Terrestrial	0.28
Internal	0.4
Medical X-rays	0.39
Nuclear Medical	0.14
Consumer Products	0.1
Other	0.03
Total	3.62

Dose as a function of human behavior



Dose as a function of occupation

Occupation	cause	mSv/year
DOE employees and site worker	radiaolgical work activities	0.44
medical personal	patient diagnosis/treatment	0.7
Grand Central Station workers	building materials	1.2
nuclear power plant workers	radiological work activities	7
Sweden Rad worker B	radiological work activities	6
Sweden Rad worker A	radiological work activities	20
airline flight crew members	cosmic	10
international space station	cosmic	150
flight to Mars	cosmic	500 - 1000

Dose as a function of medical investigation

Procedure	mSv
Dental X-ray per image	0.01
conventional lung investigation	0.08
mammography	0.1
conventional lower back investigation	1.5
computer tomography brain	2.2
computer tomography thorax	6.5
computer tomography abdomen	10

Rules and Sources

Protecting people: Swedish law (public and supervised areas; law will be changed soon)

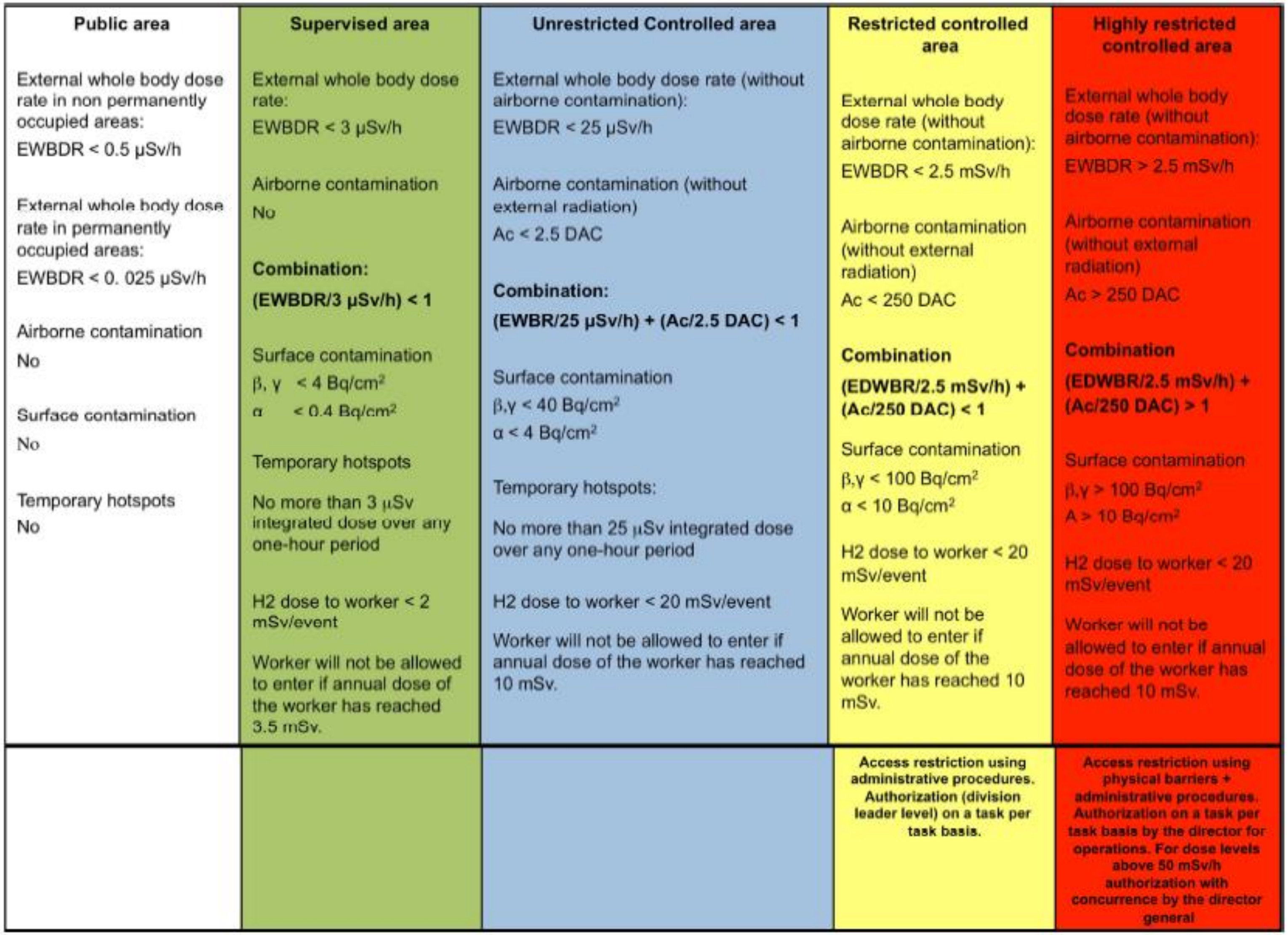
- **Public areas:** In accordance with SSM 2008:51 an area can be declared as public if the annual biological full body dose a person is expected to receive in this area from normal operation and likely accidents (H2 events) is less than 1 mSv, the annual dose to the lens/eye is less than 15 mSv, the dose to the hands, forearms, feet ankles or skin is less than 50 mSv and removable surface contamination and air contamination are indistinguishable from background.

- **Supervised areas:** An area shall be declared as supervised if at least one of the following conditions applies:
  - The expected annual biological full body dose to a person from normal operation and likely accidents, during the time the room is accessible, is between 1 mSv and 6 mSv.
  - The expected annual dose to lens or eye of a person from normal operation and likely accidents is between 15 mSv and 45 mSv.
  - The expected annual dose to a persons' hands, feet, ankles or skin form normal operation and likely accidents (H2 event), is between 50 mSv and 150 mSv.
  - Removable surface contamination is not significant from a radiological point of view.

Protecting people: Swedish law (Controlled areas; law will be changed soon)

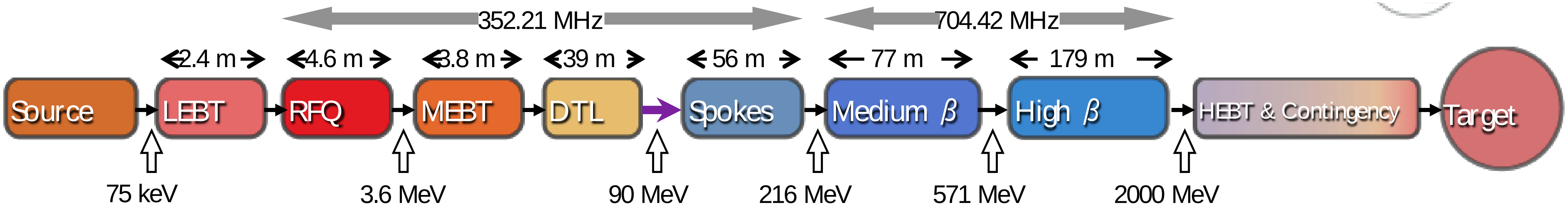
- **Controlled areas:** An area shall be declared as controlled if at least one of the following conditions applies:
  - The expected annual biological full body dose to a person from normal operation and likely accidents exceeds 6 mSv.
  - The expected annual dose to lens or eye of a person from normal operation and likely accidents exceeds 45 mSv.
  - The expected annual dose to a person's hands, feet, ankles or skin from normal operation and likely accidents exceeds 150 mSv.
  - The removable surface contamination exceeds 40 KBq/m^2 for β,γ or 4 KBq/m^2 for α.

Protecting people: Radiation zoning at ESS



Public area	Supervised area	Unrestricted Controlled area	Restricted controlled area	Highly restricted controlled area
External whole body dose rate in non permanently occupied areas: EWBDR < 0.5 µSv/h External whole body dose rate in permanently occupied areas: EWBDR < 0. 025 µSv/h Airborne contamination No Surface contamination No Temporary hotspots No	External whole body dose rate: EWBDR < 3 µSv/h Airborne contamination No **Combination:** **(EWBDR/3 µSv/h) < 1** Surface contamination β, γ < 4 Bq/cm^2 α < 0.4 Bq/cm^2 Temporary hotspots No more than 3 µSv integrated dose over any one-hour period H2 dose to worker < 2 mSv/event Worker will not be allowed to enter if annual dose of the worker has reached 3.5 mSv.	External whole body dose rate (without airborne contamination): EWBDR < 25 µSv/h Airborne contamination (without external radiation) Ac < 2.5 DAC **Combination:** **(EWBR/25 µSv/h) + (Ac/2.5 DAC) < 1** Surface contamination β,γ < 40 Bq/cm^2 α < 4 Bq/cm^2 Temporary hotspots: No more than 25 µSv integrated dose over any one-hour period H2 dose to worker < 20 mSv/event Worker will not be allowed to enter if annual dose of the worker has reached 10 mSv.	External whole body dose rate (without airborne contamination): EWBDR < 2.5 mSv/h Airborne contamination (without external radiation) Ac < 250 DAC **Combination** **(EDWBR/2.5 mSv/h) + (Ac/250 DAC) < 1** Surface contamination β,γ < 100 Bq/cm^2 α < 10 Bq/cm^2 H2 dose to worker < 20 mSv/event Worker will not be allowed to enter if annual dose of the worker has reached 10 mSv.	External whole body dose rate (without airborne contamination): EWBDR > 2.5 mSv/h Airborne contamination (without external radiation) Ac > 250 DAC **Combination** **(EDWBR/2.5 mSv/h) + (Ac/250 DAC) > 1** Surface contamination β,γ > 100 Bq/cm^2 A > 10 Bq/cm^2 H2 dose to worker < 20 mSv/event Worker will not be allowed to enter if annual dose of the worker has reached 10 mSv.
			Access restriction using administrative procedures. Authorization (division leader level) on a task per task basis.	**Access restriction using physical barriers + administrative procedures. Authorization on a task per task basis by the director for operations. For dose levels above 50 mSv/h authorization with concurrence by the director general**

ESS proton accelerator



352.21 MHz
704.42 MHz

2.4 m · 4.6 m · 3.8 m · 39 m · 56 m · 77 m · 179 m

Source → LEBT → RFQ → MEBT → DTL → Spokes → Medium β → High β → HEBT & Contingency → Target

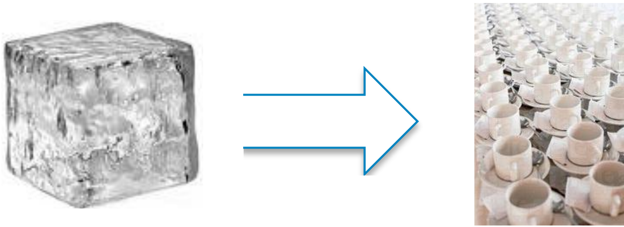
75 keV · 3.6 MeV · 90 MeV · 216 MeV · 571 MeV · 2000 MeV

Accelerating protons to almost the speed of light
in pulses hitting the target 14 times per second.

Energy per pulse equals to

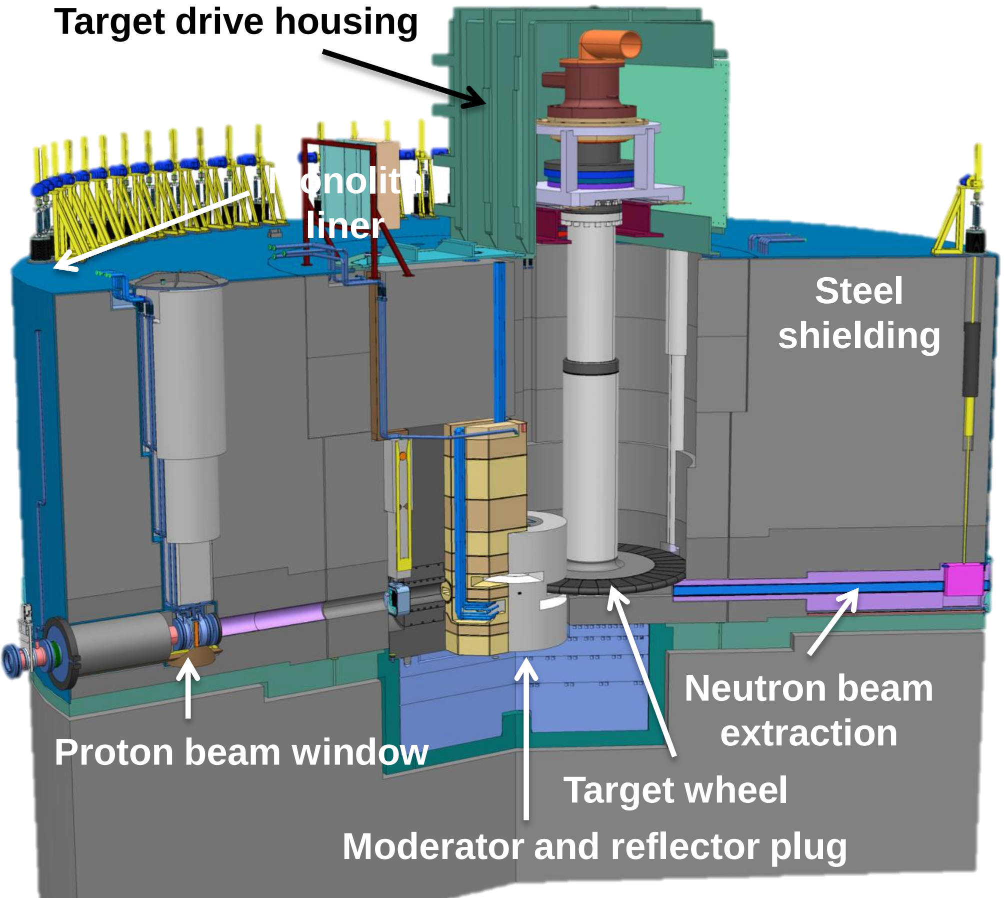
- 16lb (7,2kg) shot travelling with 1100 km/h.
- melting approx. 1 kg (1 liter) of ice …

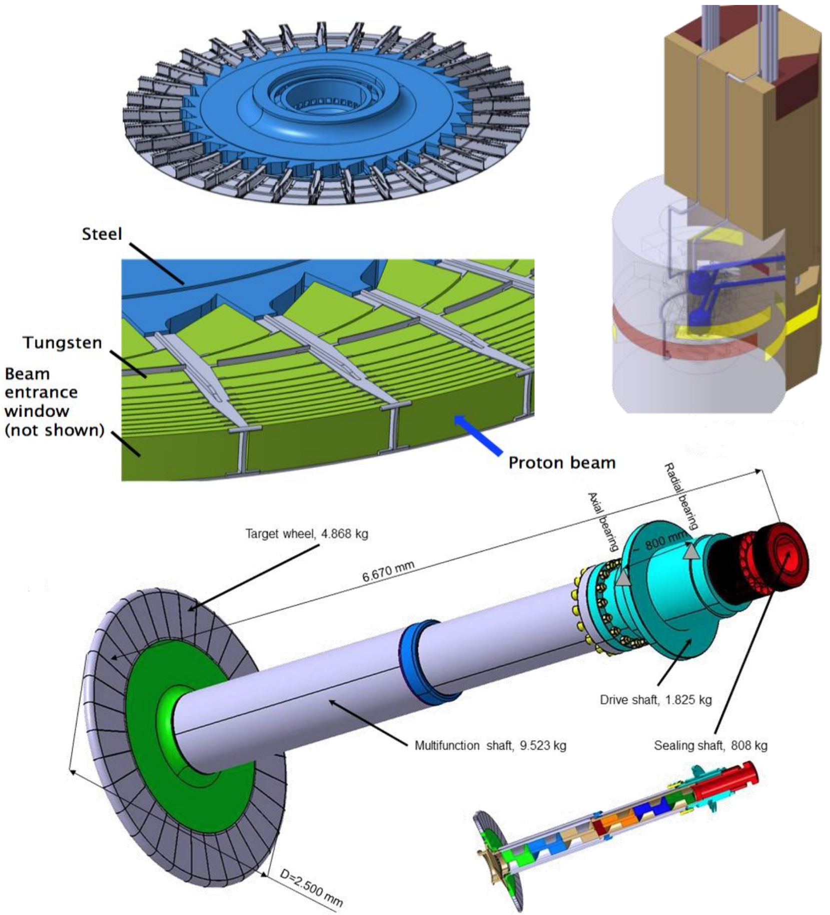
…. *and next pulse boils it.*



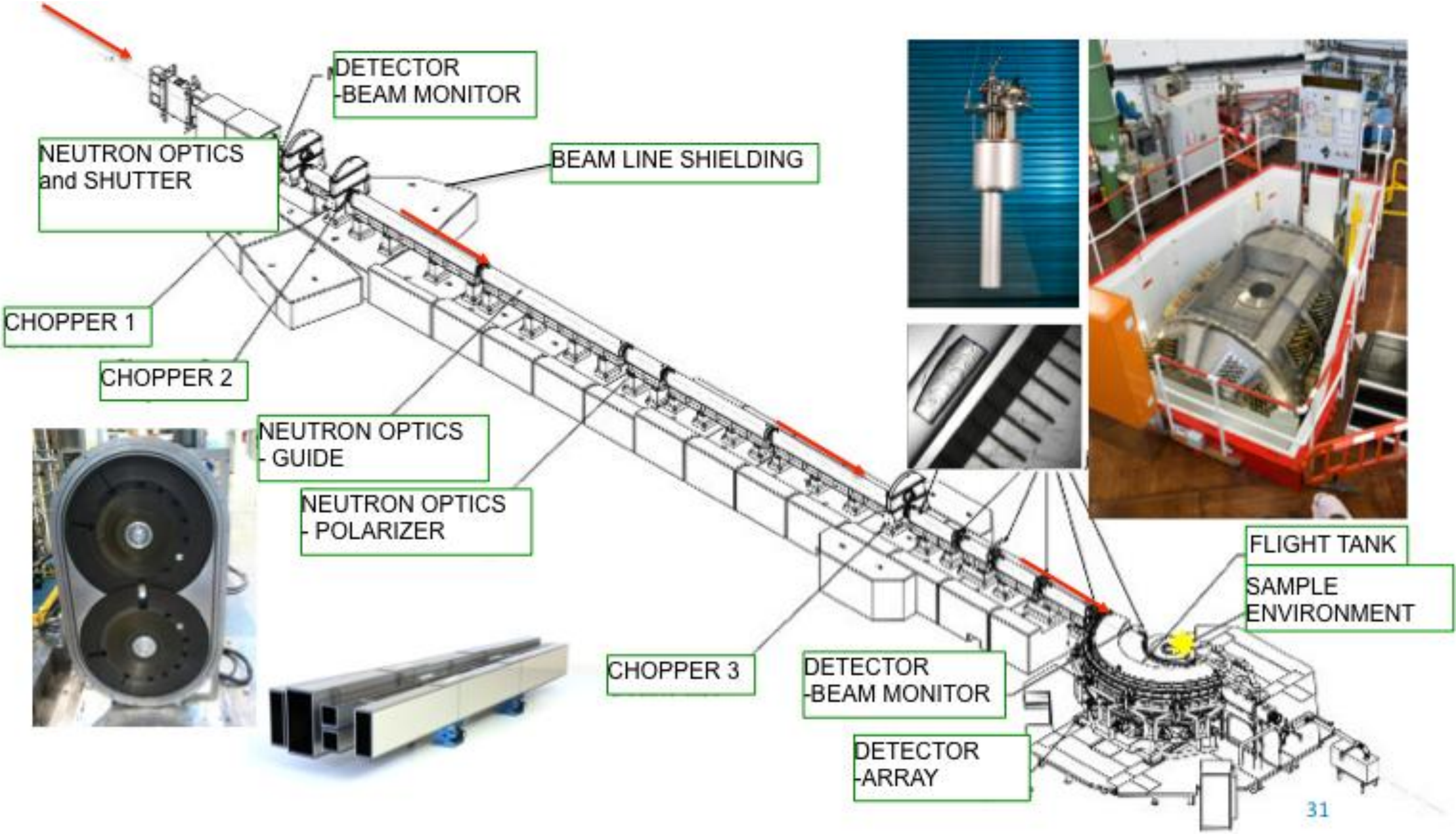
ESS Target Moderator Assembly with Monolith

Converting protons into neutrons and slowing them down.





Generic Instrument



DETECTOR
-BEAM MONITOR

NEUTRON OPTICS
and SHUTTER

BEAM LINE SHIELDING

CHOPPER 1

CHOPPER 2

NEUTRON OPTICS
- GUIDE

NEUTRON OPTICS
- POLARIZER

CHOPPER 3

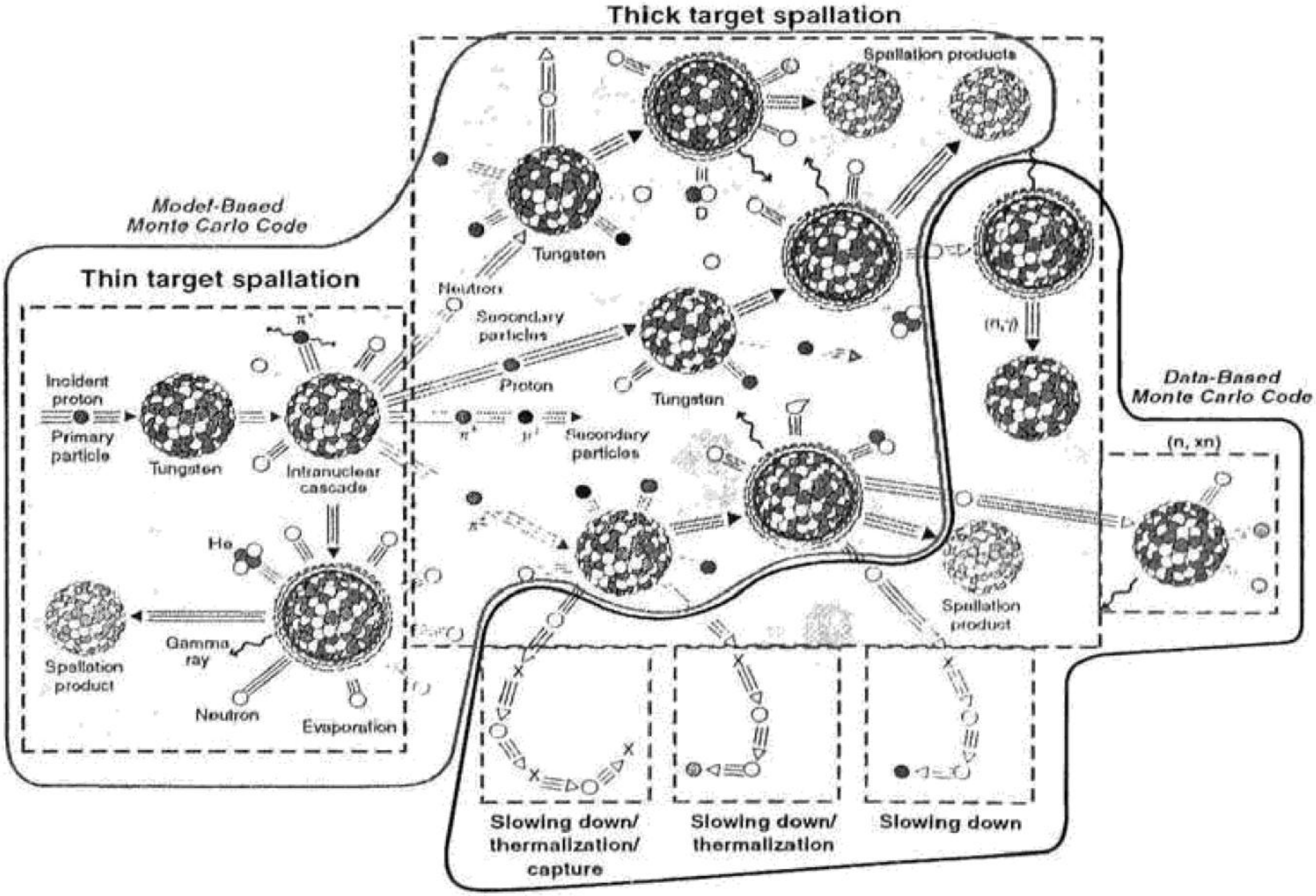
DETECTOR
-BEAM MONITOR

DETECTOR
-ARRAY

FLIGHT TANK

SAMPLE
ENVIRONMENT

Source: Spallation process



G. J. Russell et al, Fundamental Physics with Pulsed Neutrons Beams (2000) p 19

Source: Reactor versus spallation source

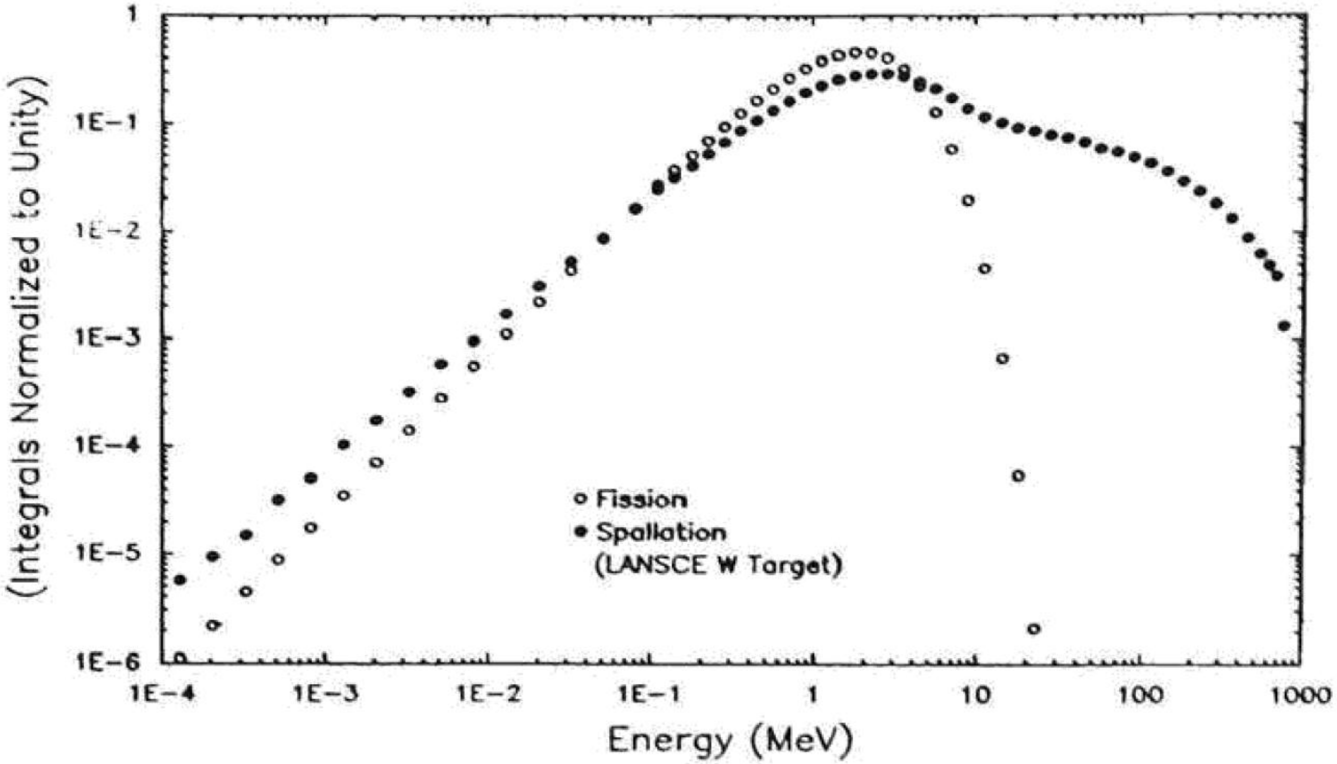


Figure 4. Spallation neutron spectrum compared to a typical neutron spectrum from thermal neutron fission of ^{235}U. The spallation spectrum is at 90 degrees from a "finite" 10-cm-diam by 30-cm-long tungsten target bombarded by 800-MeV protons.

G. J. Russell et al, Fundamental Physics with Pulsed Neutrons Beams (2000) p 19

Source: Angular dependency of the source

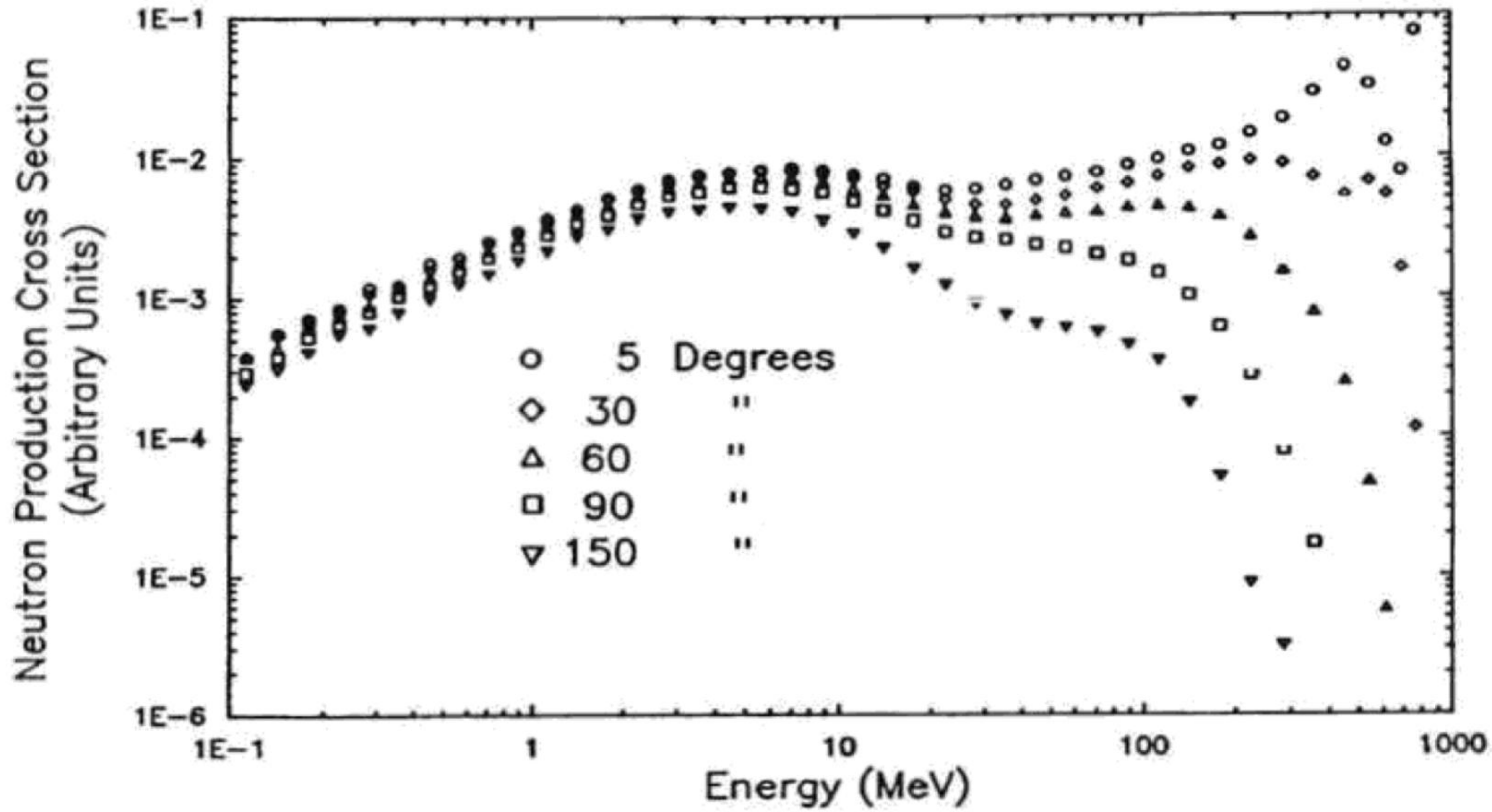
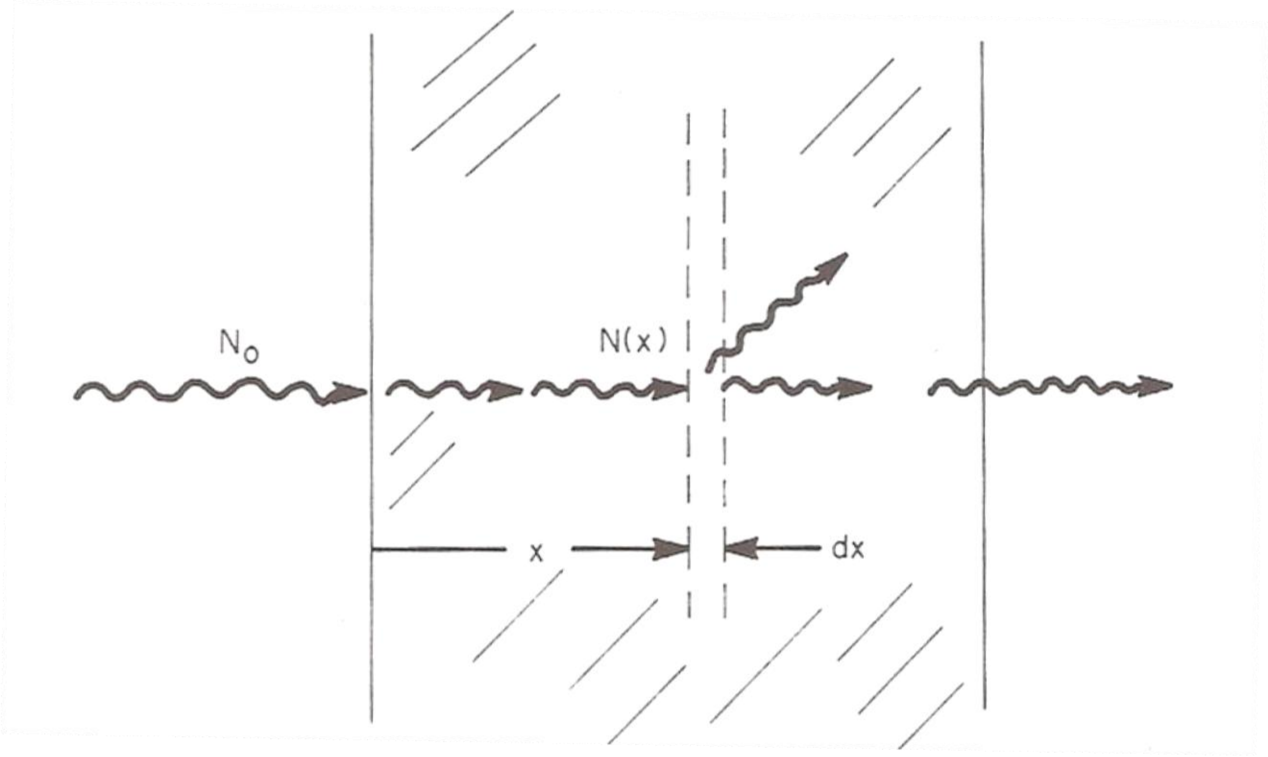


Figure 3. Neutron production from a thin iron target bombarded by 800-MeV protons.

G. J. Russell et al, Fundamental Physics with Pulsed Neutrons Beams (2000) p 19

Physics

Physics: Attenuation

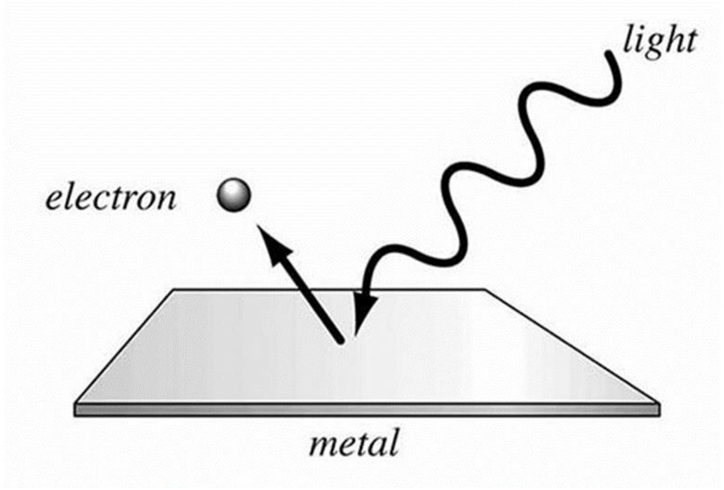


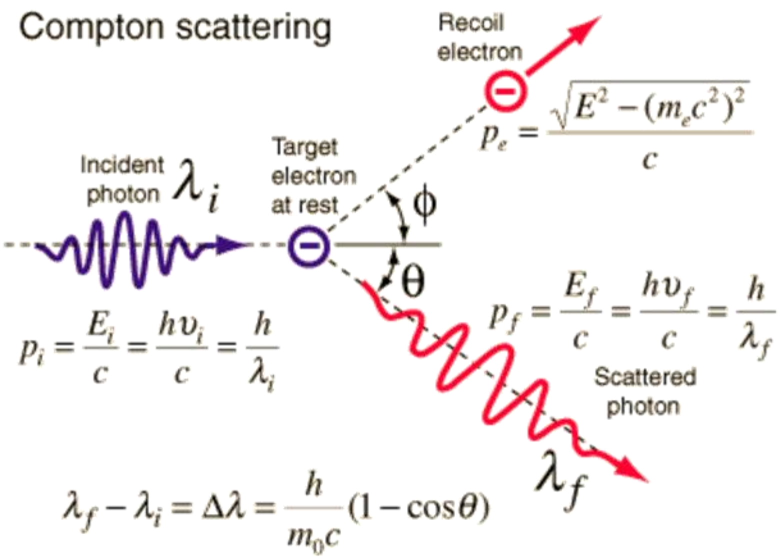
$$dN = -\mu N dx \;\Rightarrow\; N(x)=N_0 e^{-\mu x}$$

Physics: Photons

- Photoelectric effect

  During the photoelectric effect the photon will be absorbed by the matter and an electron will be emitted.





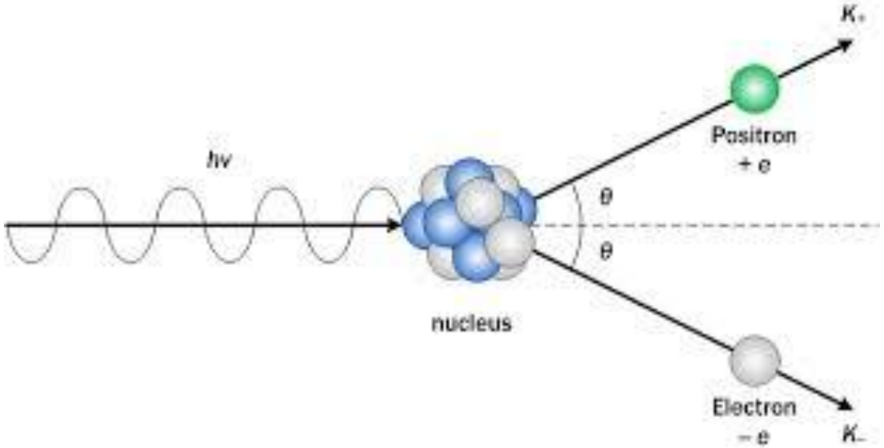
- Compton effect

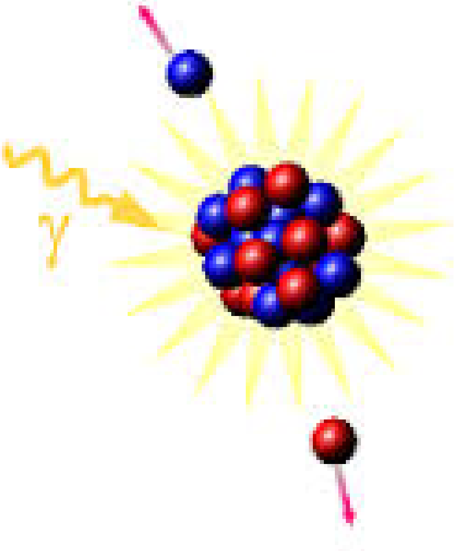
  Compton effect is the inelastic scattering of a photon on a charged particle, unusually electron. It results in a reduction of the photon energy and a momentum change of the photon (Compton scattering.) or the photon gets absorbed and a different photon with a lower energy will be emitted (Compton absorption).

Physics: Photons

- Pair production

  A photon with an energy of at least twice the electron rest mass, can be converted into a electron-positron pair.

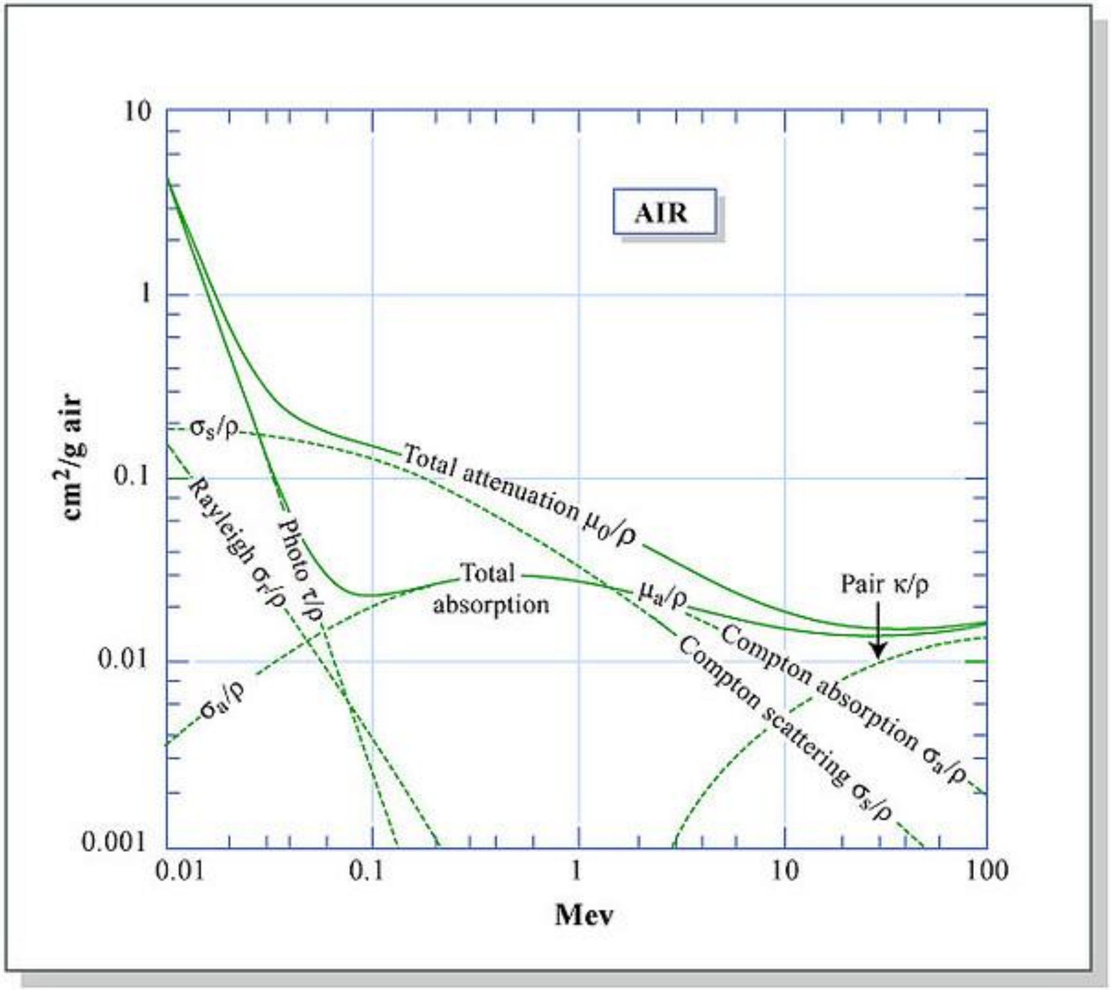




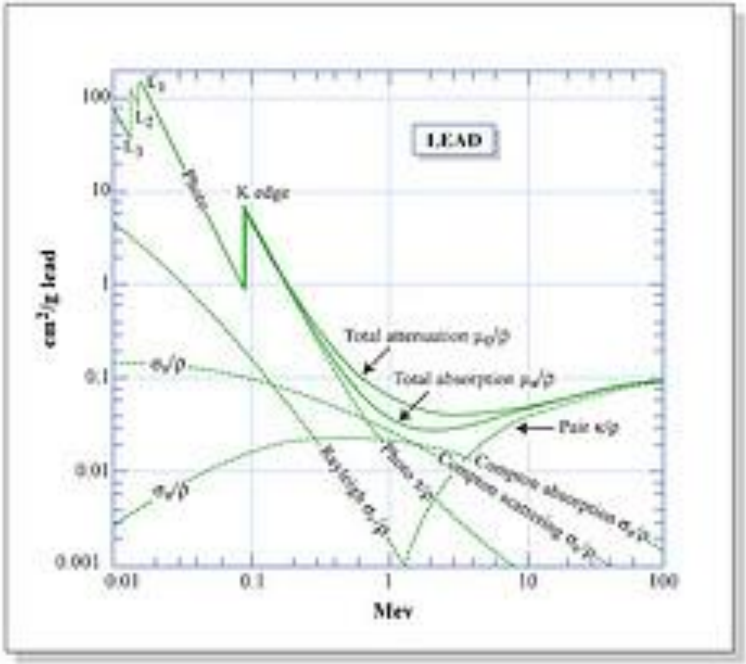
- Photonuclear reactions

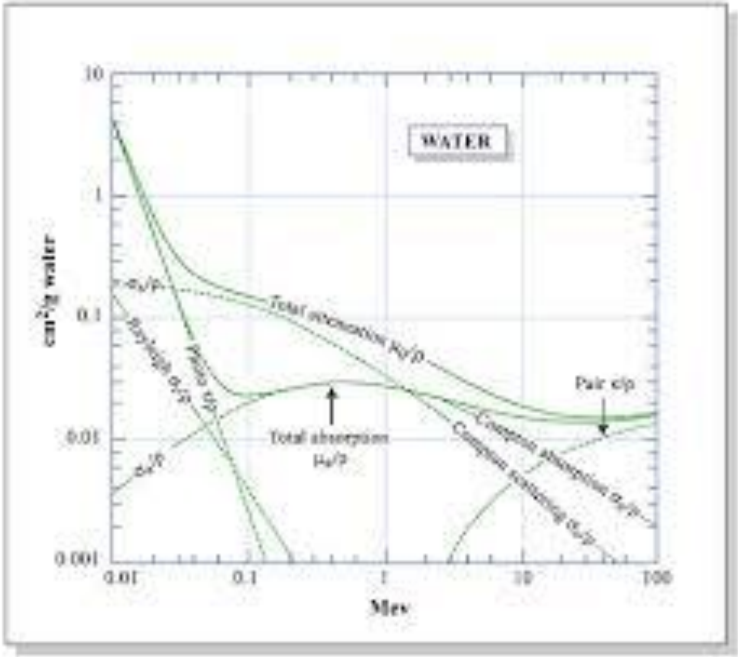
  Photons can be absorbed by an atomic nucleus and a nucleon will be emitted (e.g. (γ,n) reaction).

Photon mass attenuation factor in air



Photon mass attenuation factor in lead and water





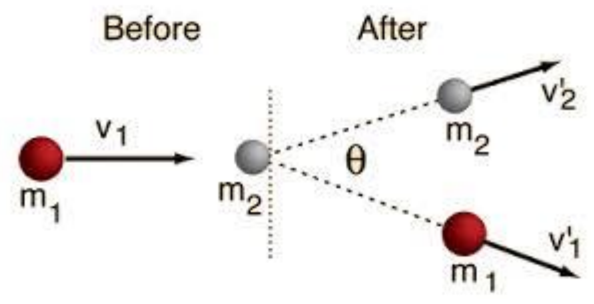
Physics: Neutrons

- Slowing down process:

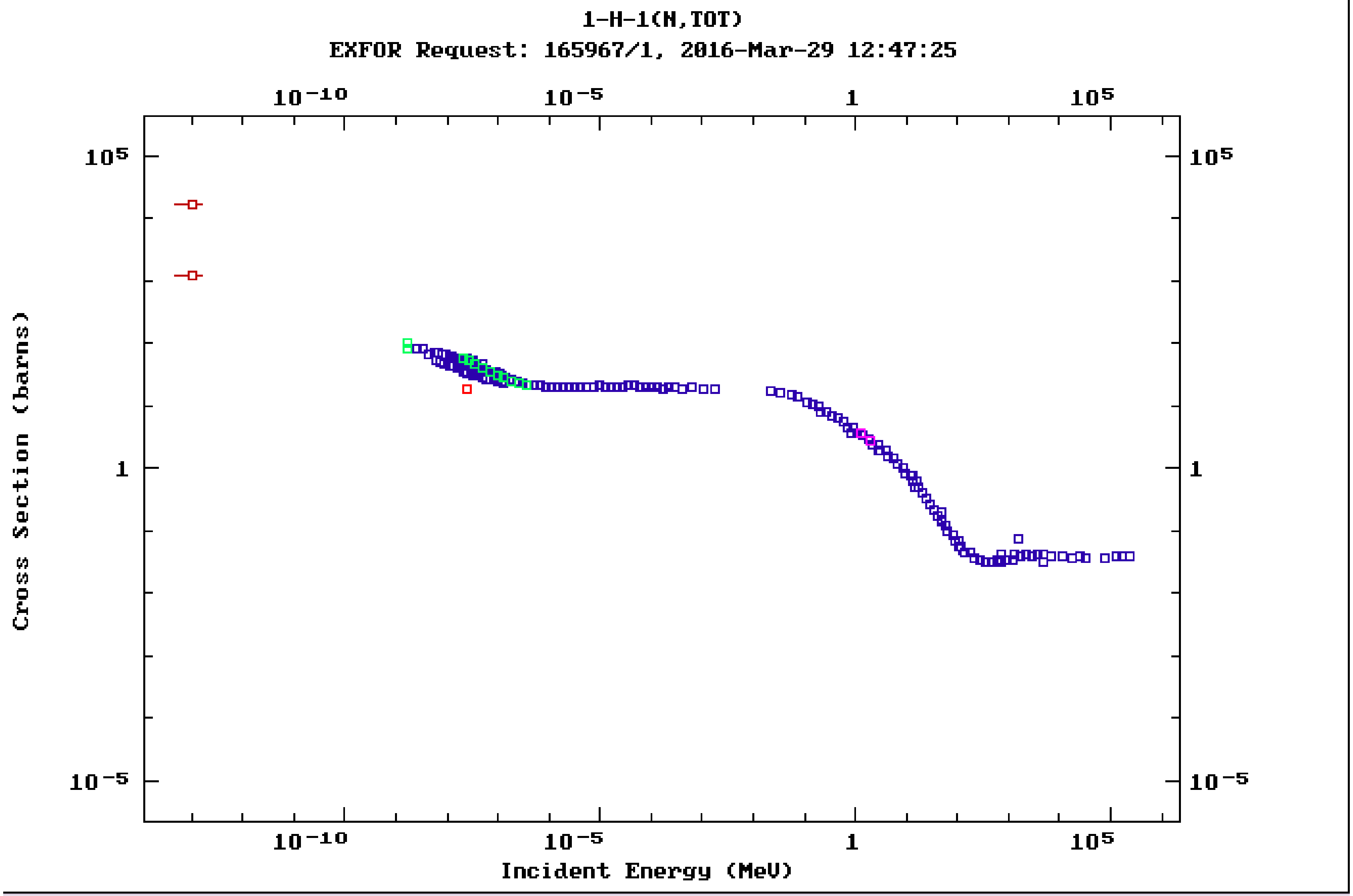
  The slowing down process of neutrons in matter can be described by the two body problem from classical mechanics.

  Nuclear physicist define this as an elastic process, because the neutron-nucleus system does not loose energy.

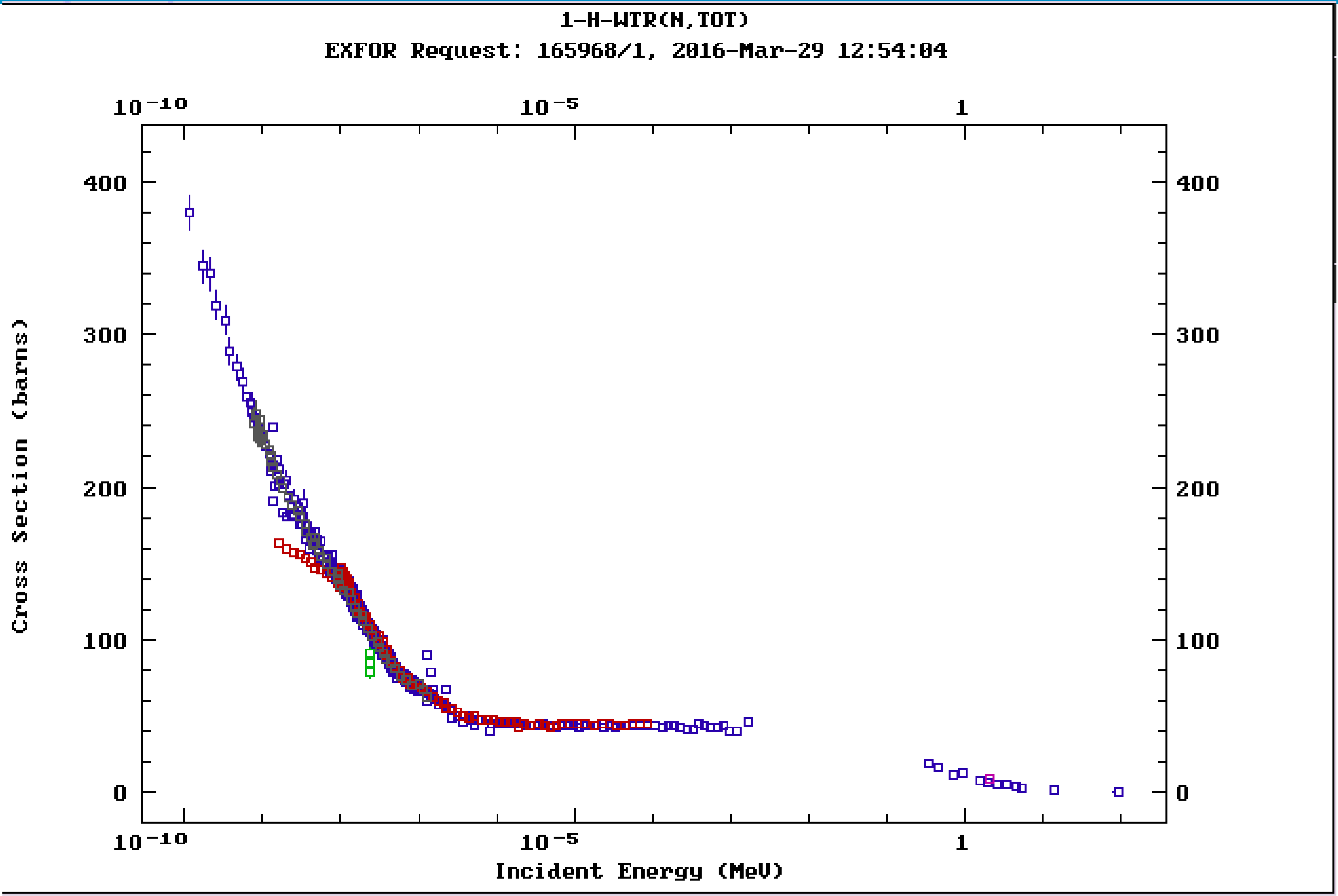
  Neutron scattering define this as an inelastic process, because the neutron looses energy.



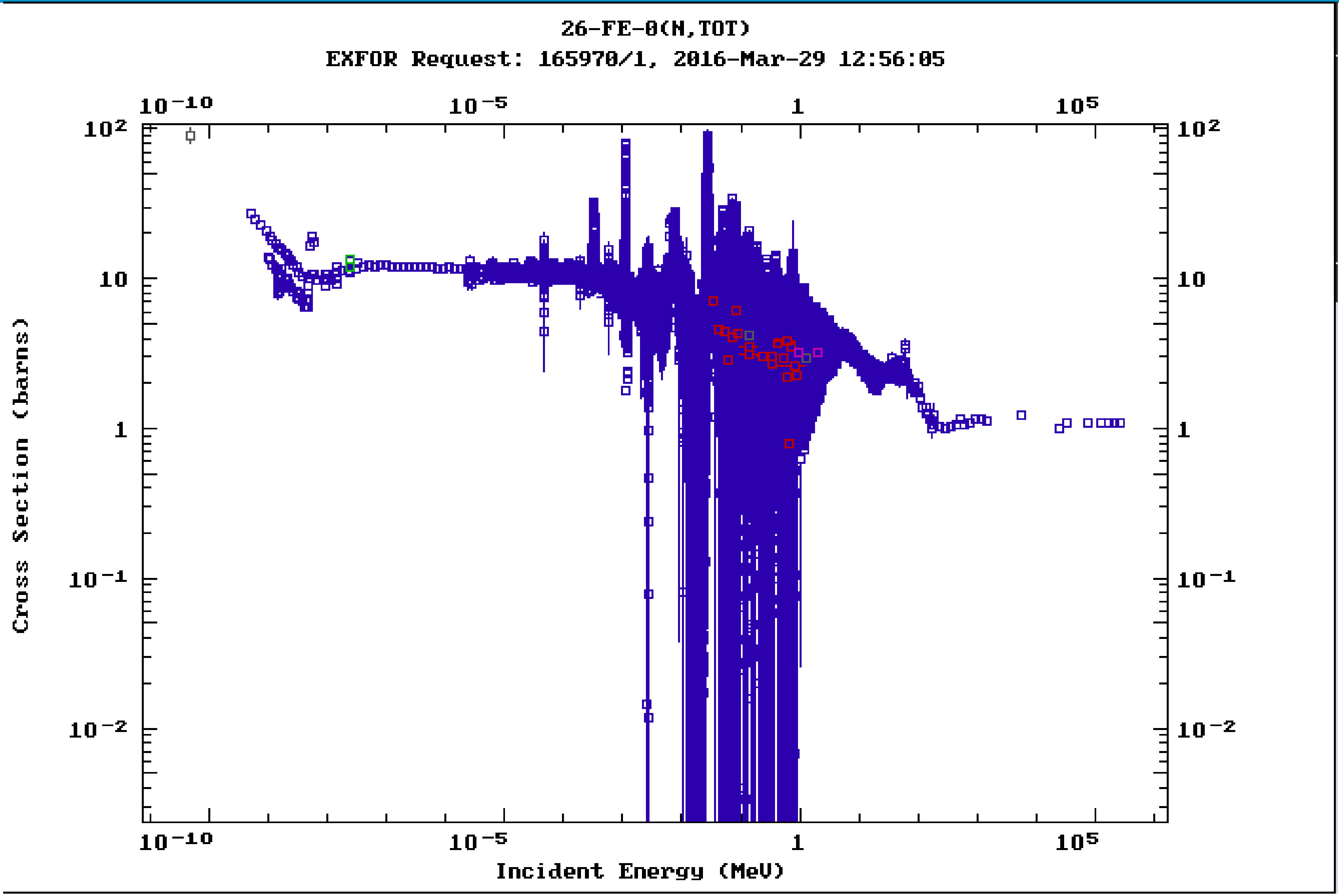
Physics: Hydrogen cross-section



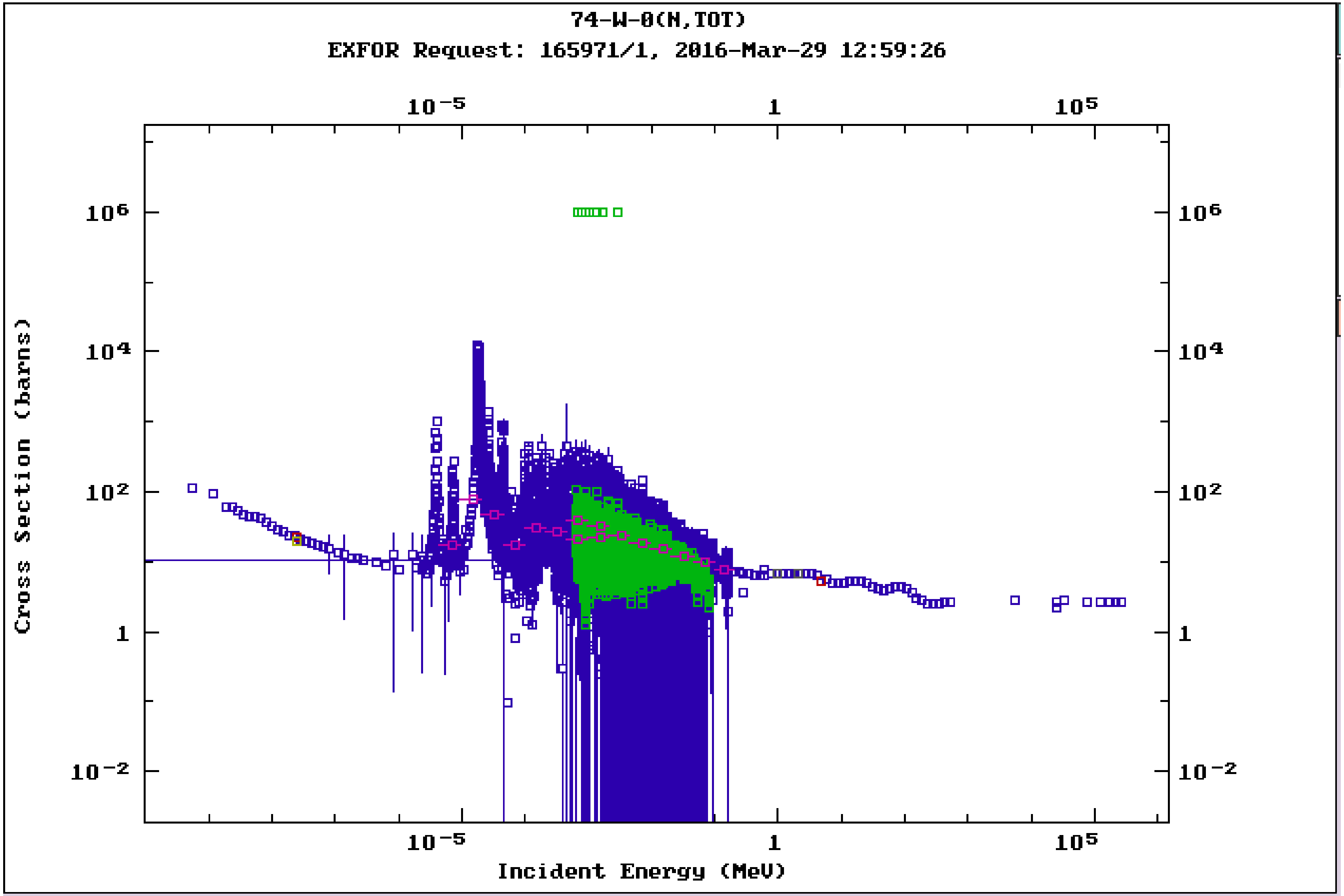
Physics: H in water cross-section



Physics: Iron cross-section



Physics: Tungsten cross-section



Physics: Neutrons absorption

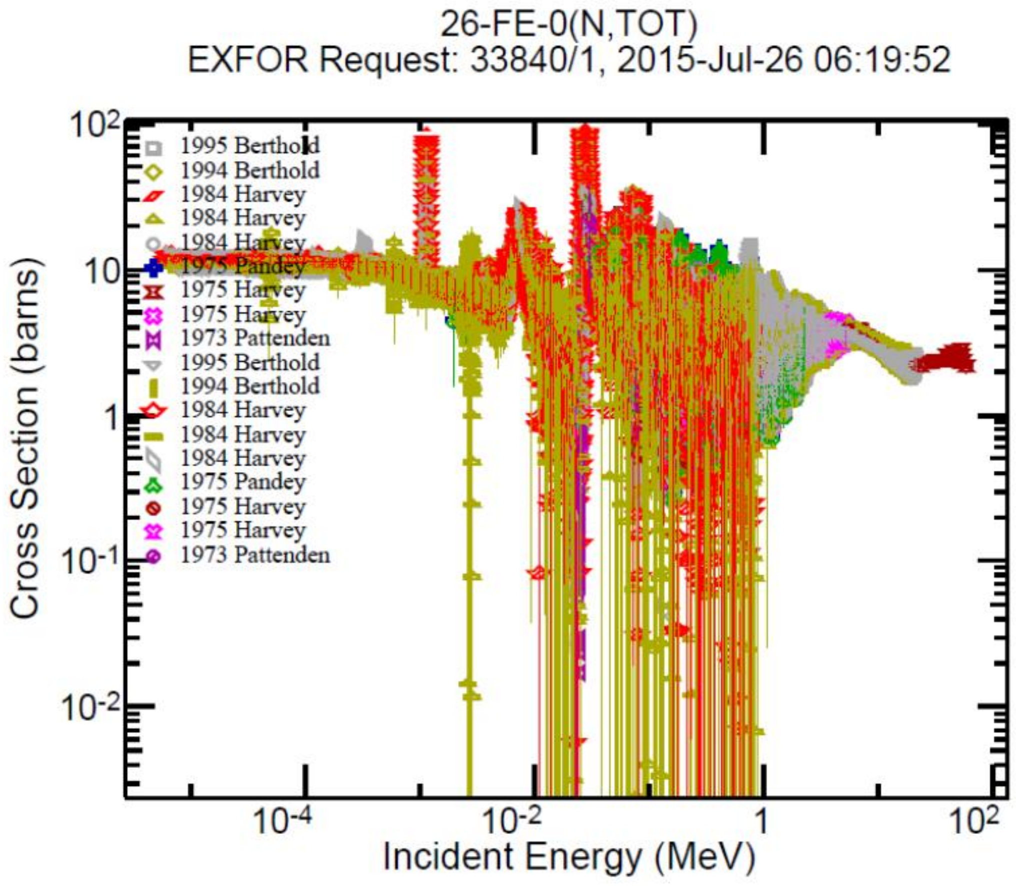
- Capture:

  This process a low energy neutron gets by a nucleus and a different particle will be emitted.

  e.g.:
  - $^{3}\mathrm{He}(n,p)^{3}\mathrm{H}$
  - $^{6}\mathrm{Li}(n,t)^{4}\mathrm{He}$
  - $^{10}\mathrm{B}(n,\alpha)^{7}\mathrm{Li}$
  - $^{14}\mathrm{N}(n,p)^{14}\mathrm{C}$
  - $^{113}\mathrm{Cd}(n,\gamma)^{114}\mathrm{Cd}$
  - $^{1}\mathrm{H}(n,\gamma)^{2}\mathrm{H}$

- Resonances:

  In this process neutron with energies of the excitation level of the nucleus get absorbed and the nucleus will be put into am excited state.



Tools

Tools

- Handbook calculations

  e.g: A.H. Sullivan: “A Guide to Radiation and Radioactivity Levels Near High Energy Particle Accelerators.” Nuclear Technology Publishing Ashford, Kent, TN23 1JW, England

- Monte Carlo Particle transport codes
  - MCNP(X)
  - FLUKA
  - PHITS
  - MARS
  - GEANT (not for safety)

- Variance reductions

- Activation: Hand calculations

- Activation Codes
  - CINDER
  - FISPACT
  - Activation Script
  - Gamma Script

Handbook: Attenuation through solid shielding

$$H = \frac{H_0 e^{-\frac{d}{l}}}{R^2}$$

Accelerator source term:

$$H_0(90^0) = 1.7 * 10^{-14} E_0^{0.8} \quad \mathrm{Sv*m^2} / p$$

Handbook: target shielding (Moyer Model)

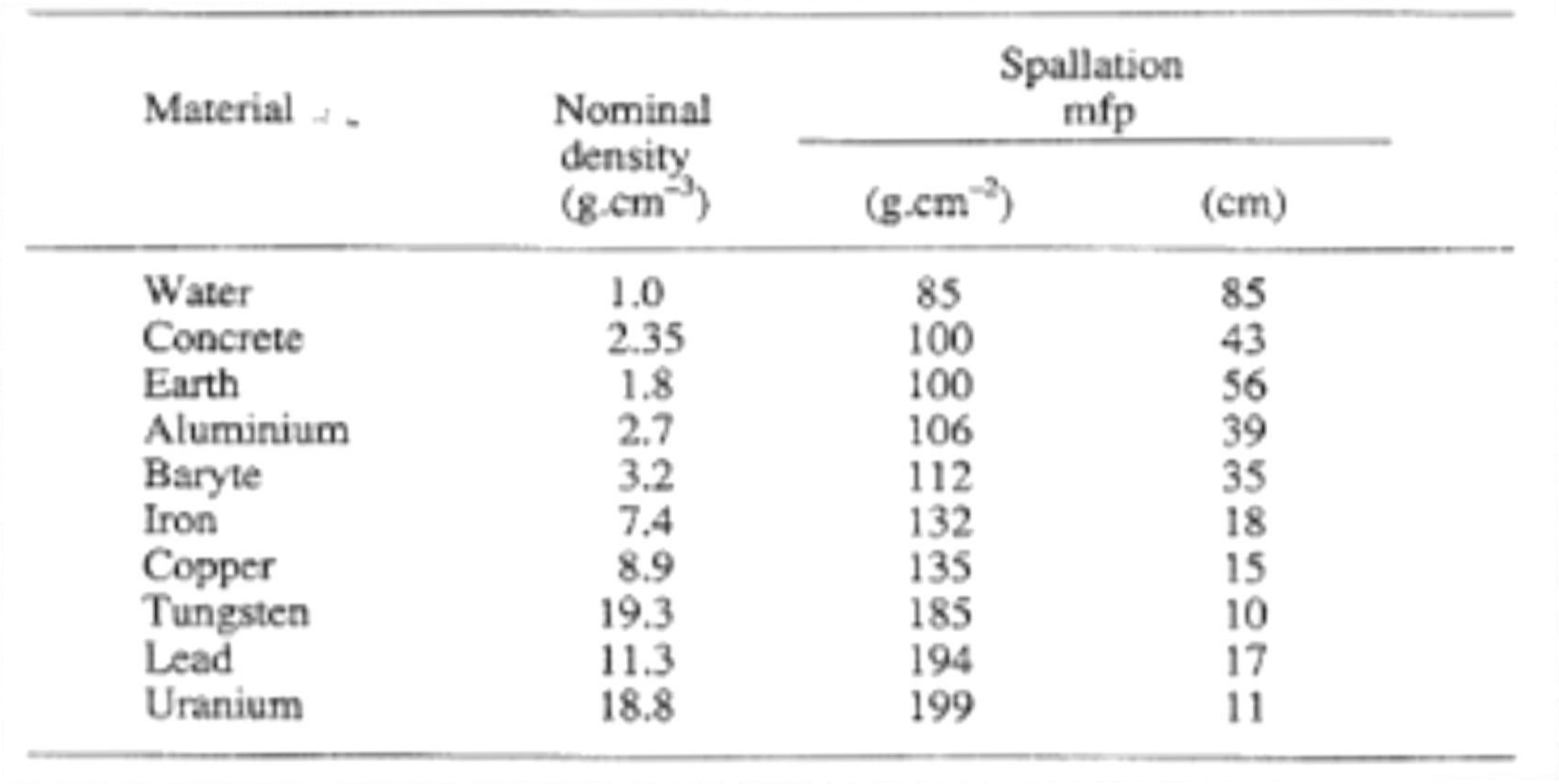
Moyer Model:

$$H=I*H_0(E_p)/r^2*e^{-\beta\theta}*e^{-d/\lambda}$$

- $H_0(E_p)=4*10^{-7}\ E_p^{0.8}\ \mathrm{Sv\ h^{-1}\ m^2\ nA^{-1}}$ = source term*
- r = distance from the spill point to the detector
- β = 2.3/radian*
- d = shielding thickness
- λ = dose attenuation length in the shielding material
- θ = angle between the proton beam and the direction from the spill to the detector
- I = proton current

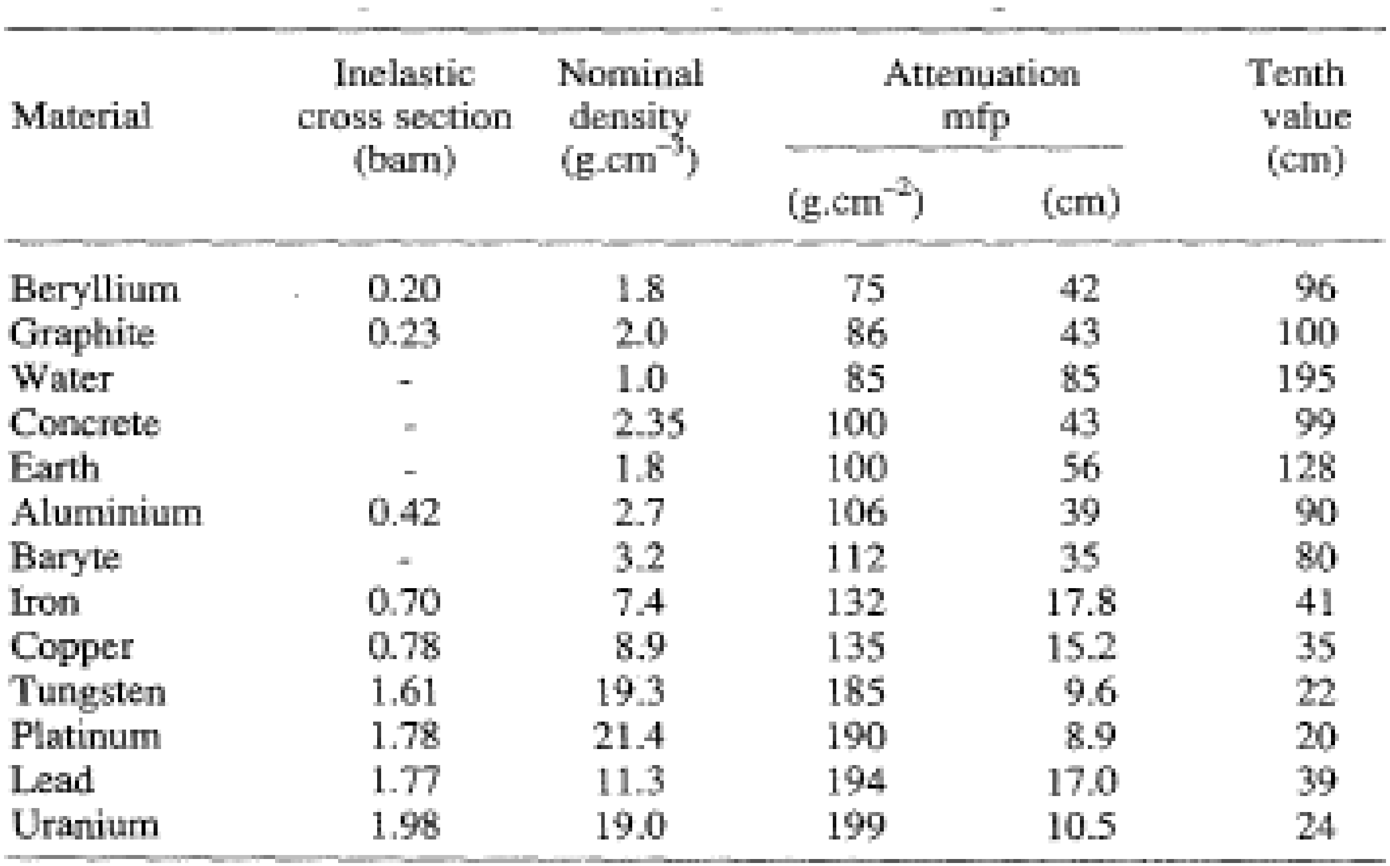
*Thomas and Thomas, Health Physics **46**, 954 (1984)

Handbook: Neutron dose attenuation lengths



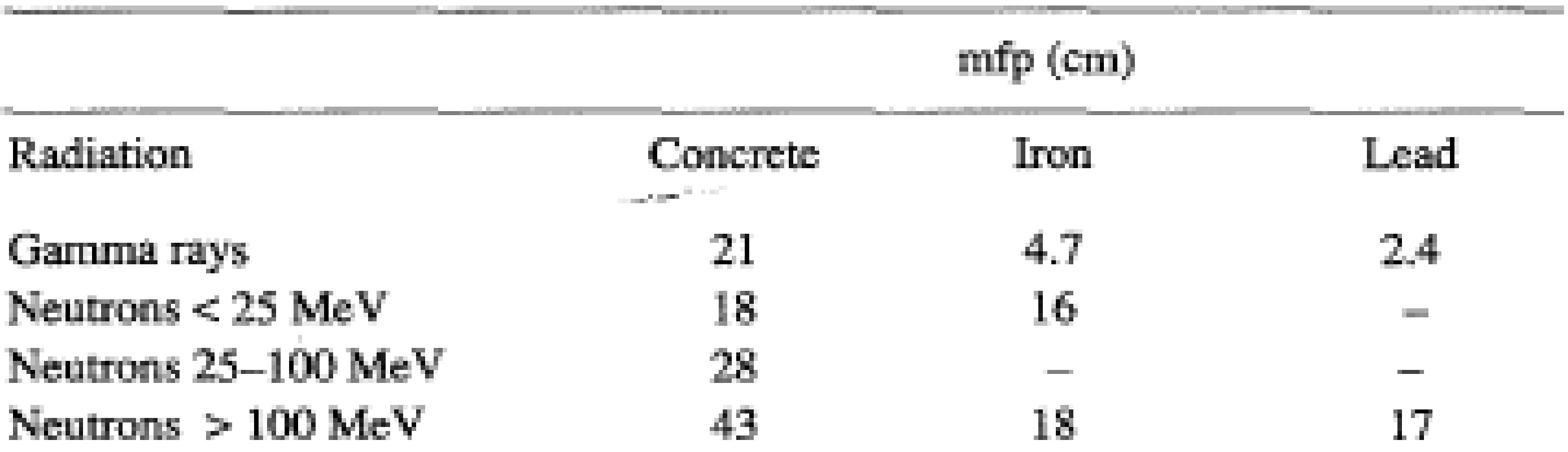
Material	Nominal density ($g.cm^{-3}$)	Spallation mfp ($g.cm^{-2}$)	Spallation mfp (cm)
Water	1.0	85	85
Concrete	2.35	100	43
Earth	1.8	100	56
Aluminium	2.7	106	39
Baryte	3.2	112	35
Iron	7.4	132	18
Copper	8.9	135	15
Tungsten	19.3	185	10
Lead	11.3	194	17
Uranium	18.8	199	11

Handbook: Neutron dose attenuation lengths and tenth layers



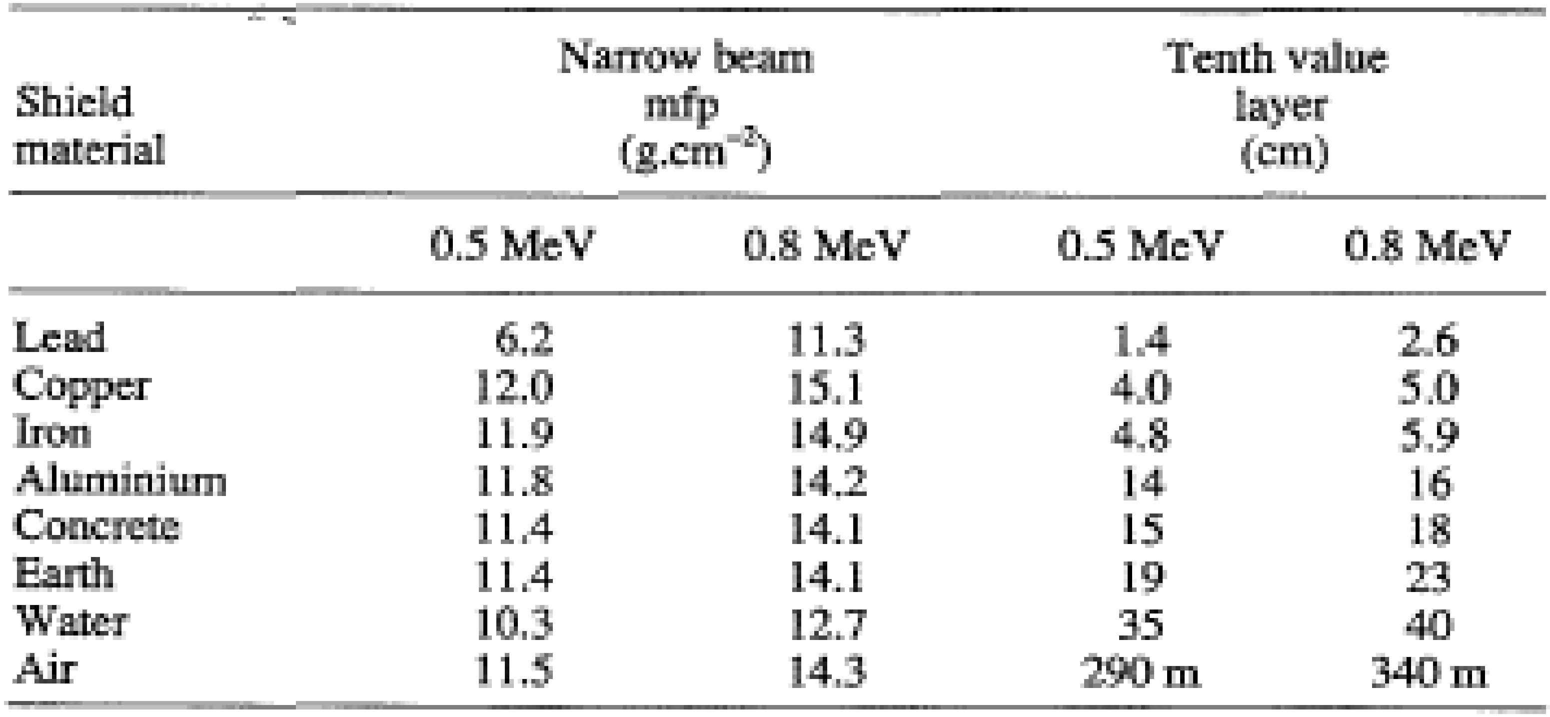
Material	Inelastic cross section (barn)	Nominal density ($g.cm^{-3}$)	Attenuation mfp ($g.cm^{-2}$)	Attenuation mfp (cm)	Tenth value (cm)
Beryllium	0.20	1.8	75	42	96
Graphite	0.23	2.0	86	43	100
Water	-	1.0	85	85	195
Concrete	-	2.35	100	43	99
Earth	-	1.8	100	56	128
Aluminium	0.42	2.7	106	39	90
Baryte	-	3.2	112	35	80
Iron	0.70	7.4	132	17.8	41
Copper	0.78	8.9	135	15.2	35
Tungsten	1.61	19.3	185	9.6	22
Platinum	1.78	21.4	190	8.9	20
Lead	1.77	11.3	194	17.0	39
Uranium	1.98	19.0	199	10.5	24

Handbook: Gamma and Neutron dose attenuation length



	mfp (cm)		
Radiation	Concrete	Iron	Lead
Gamma rays	21	4.7	2.4
Neutrons < 25 MeV	18	16	–
Neutrons 25–100 MeV	28	–	–
Neutrons > 100 MeV	43	18	17

Handbook: Gamma dose attenuation lengths



Shield material	Narrow beam mfp (g.cm^{-2})		Tenth value layer (cm)	
	0.5 MeV	0.8 MeV	0.5 MeV	0.8 MeV
Lead	6.2	11.3	1.4	2.6
Copper	12.0	15.1	4.0	5.0
Iron	11.9	14.9	4.8	5.9
Aluminium	11.8	14.2	14	16
Concrete	11.4	14.1	15	18
Earth	11.4	14.1	19	23
Water	10.3	12.7	35	40
Air	11.5	14.3	290 m	340 m

Handbook: Chicane 1(3)

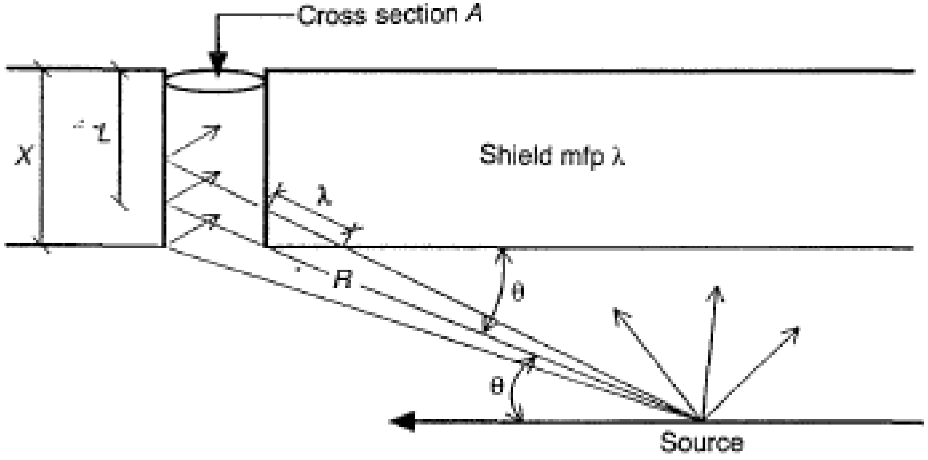
$$A_{\mathrm{eff}} = A\tan(\theta) + \lambda\sqrt{A}\sin(\theta)$$

$$L = X - A_{\mathrm{eff}}/\sqrt{A}$$

If H_m is the radiation level at the mouth of a hole, then the radiation level due to radiation scattered to a depth X into the hole is found to depend on:

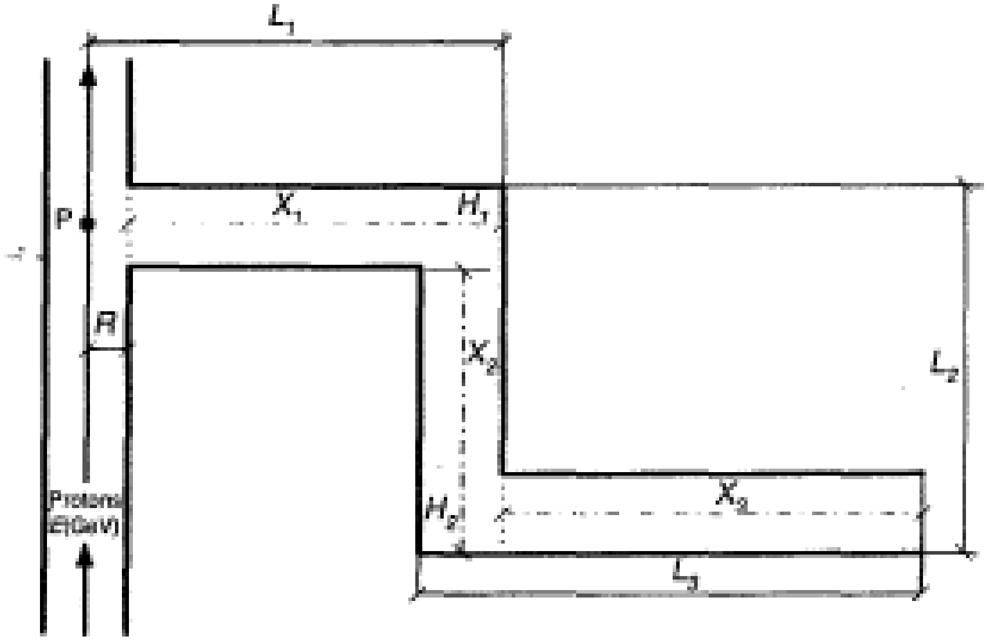
(a) the amount of radiation entering the hole,~ $A_{\mathrm{eff}} \times H_m$;
(b) ratio of the effective hole cross section to wall area ~ $\sqrt{A}/L$; and
(c) inverse square of distance the scattered radiation travels into the hole = $(1/L)^2$.

Combining these parameters gives, for the expected radiation level at a depth X into a hole, where that at the hole mouth is H_m,



$$H = H_m \cdot \frac{K.A_{\mathrm{eff}}.\sqrt{A_a}}{L^3}$$

Handbook: Chicane 2(3)



$$H_1 = H_0 / L_1^{\,2}$$

$$L_1 = R + X_1$$

$$L_n = X_n + \sqrt{A_{n-1}}$$

$$H_n = H_{(n-1)} \cdot \frac{K . A_{(n-1)} . \sqrt{A_n}}{L_n^{\,3}}$$

Handbook: Chicane 3(3)

$$H_n = H_1 \times K^{n-1} \frac{A_1}{A_n} \cdot \left(\frac{\sqrt{A_2}}{L_2} \cdot \frac{\sqrt{A_3}}{L_3} \cdots \frac{\sqrt{A_n}}{L_n} \right)^3$$

$$\frac{H_n}{H_0} = \frac{T(n,A)}{L_1^{2}(L_2.L_3 ... L_n)^3}$$

$$T(n,A) = (K \times A^{3/2})^{n-1}$$

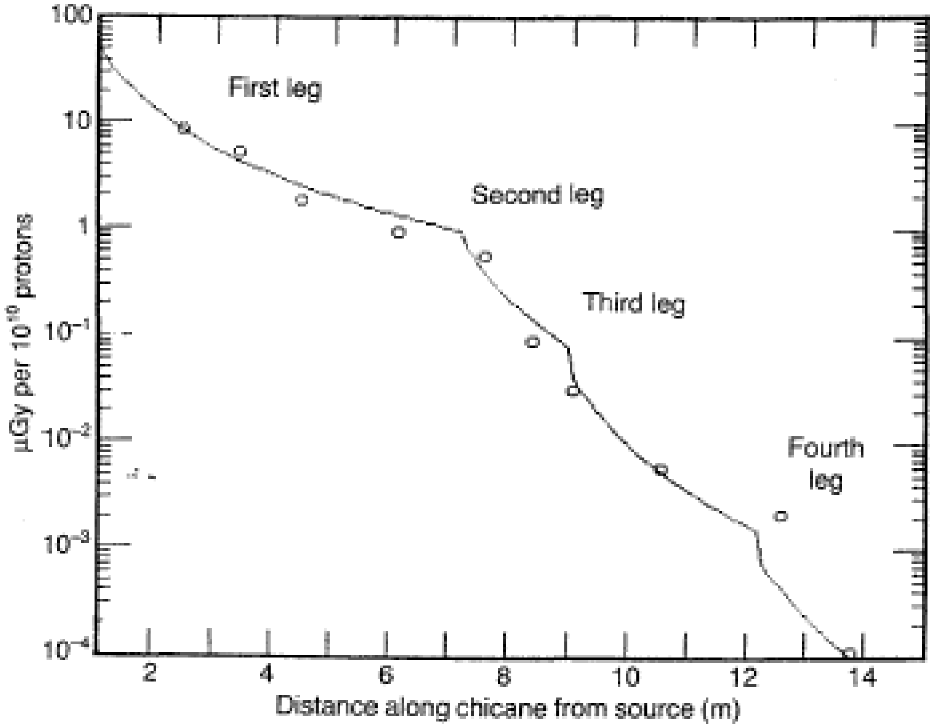
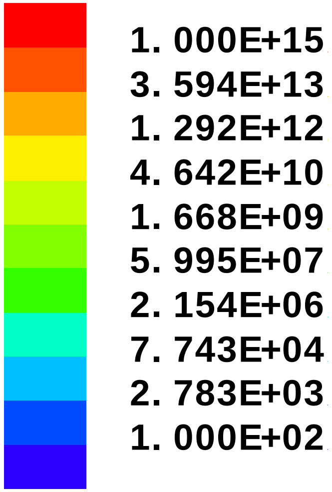


Figure 2.30. The calculated radiation level along the four legs of a chicane compared to measured data[(15)] using a 400 GeV proton beam on a 1 interaction length target opposite the entrance to the chicane. Dose equivalent given in Figure 2.21 was converted to absorbed dose assuming a constant quality factor of 3.

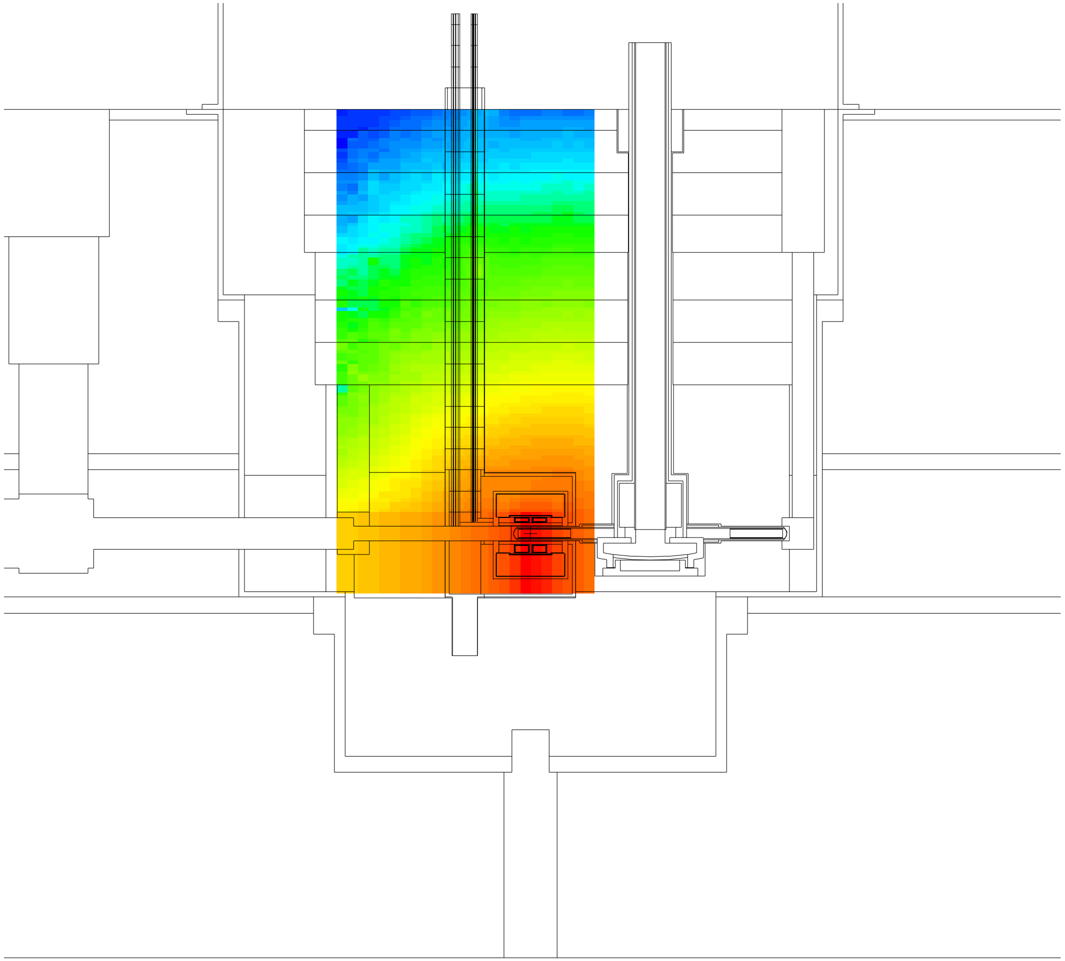
Variance reductions

- Variance reductions are very power full and absolutely essential for deep penetration problems, while very dangerous to cheat time in Monte Carlo simulations.

Variance reductions: Why?



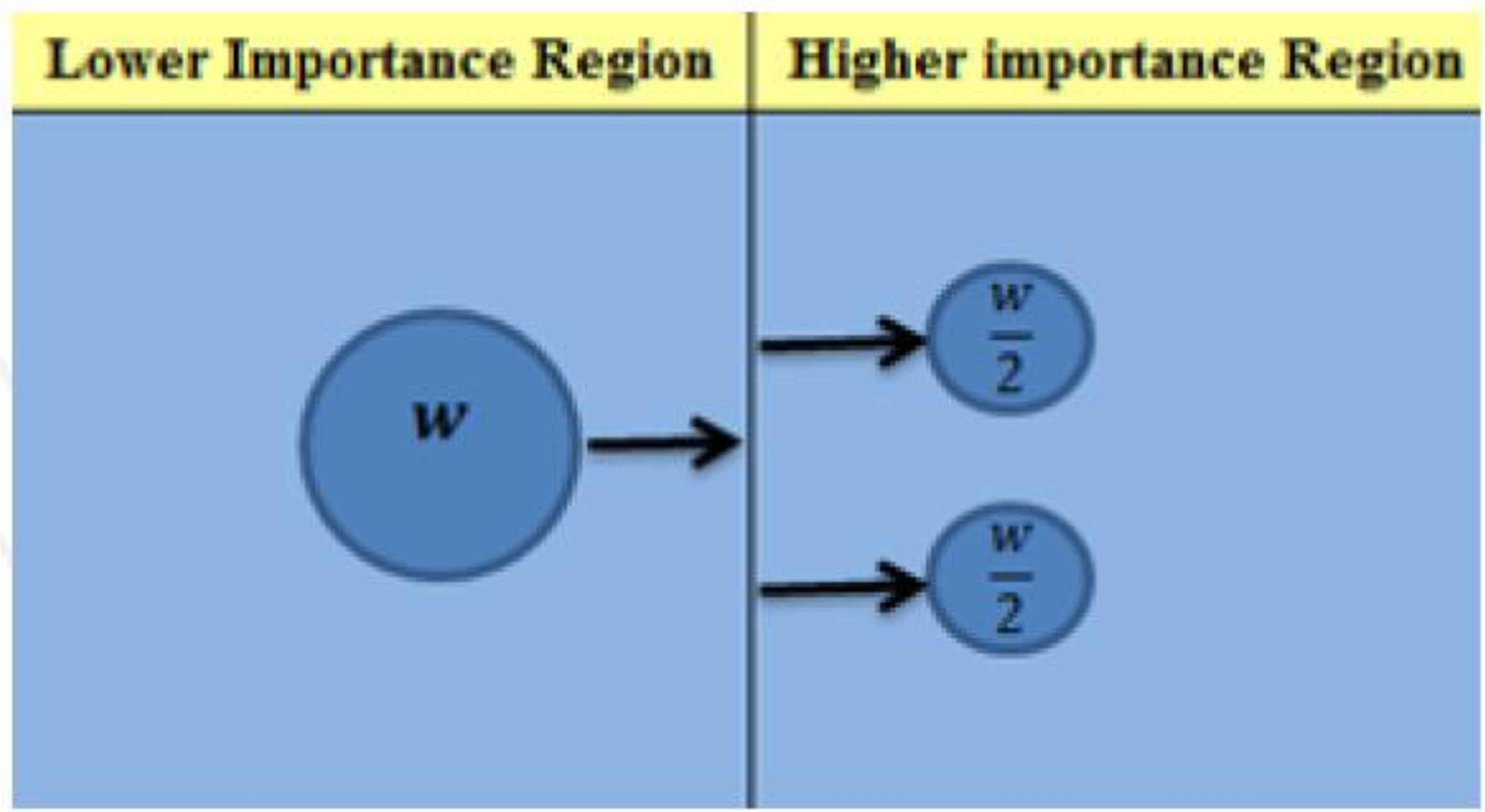
Prompt dose in μSv/h



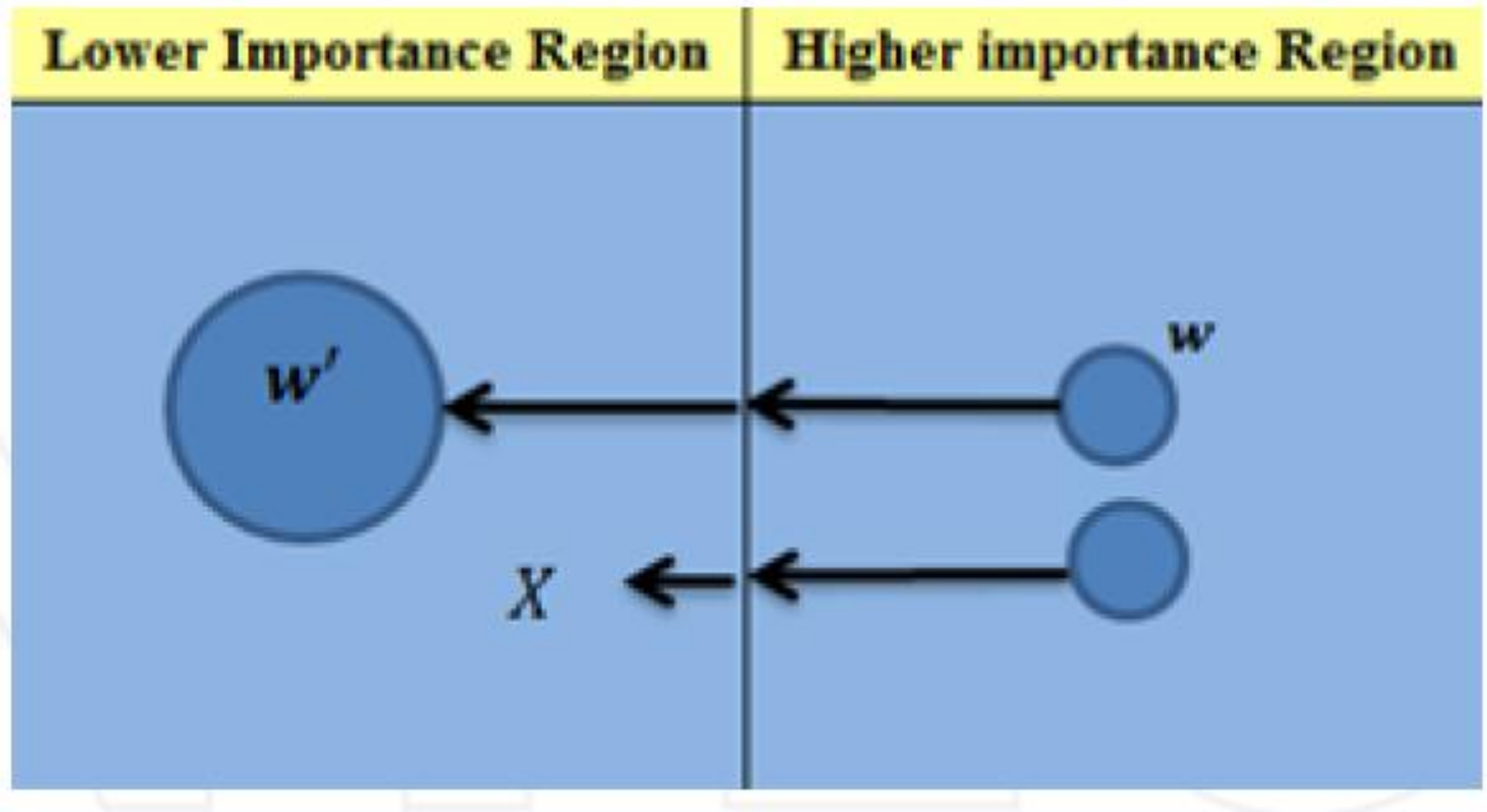
Variance reductions

- Cell importance
- DXTRAN sphere
- Forced collision
- Energy splitting
- Second particle biasing
- Weight windows

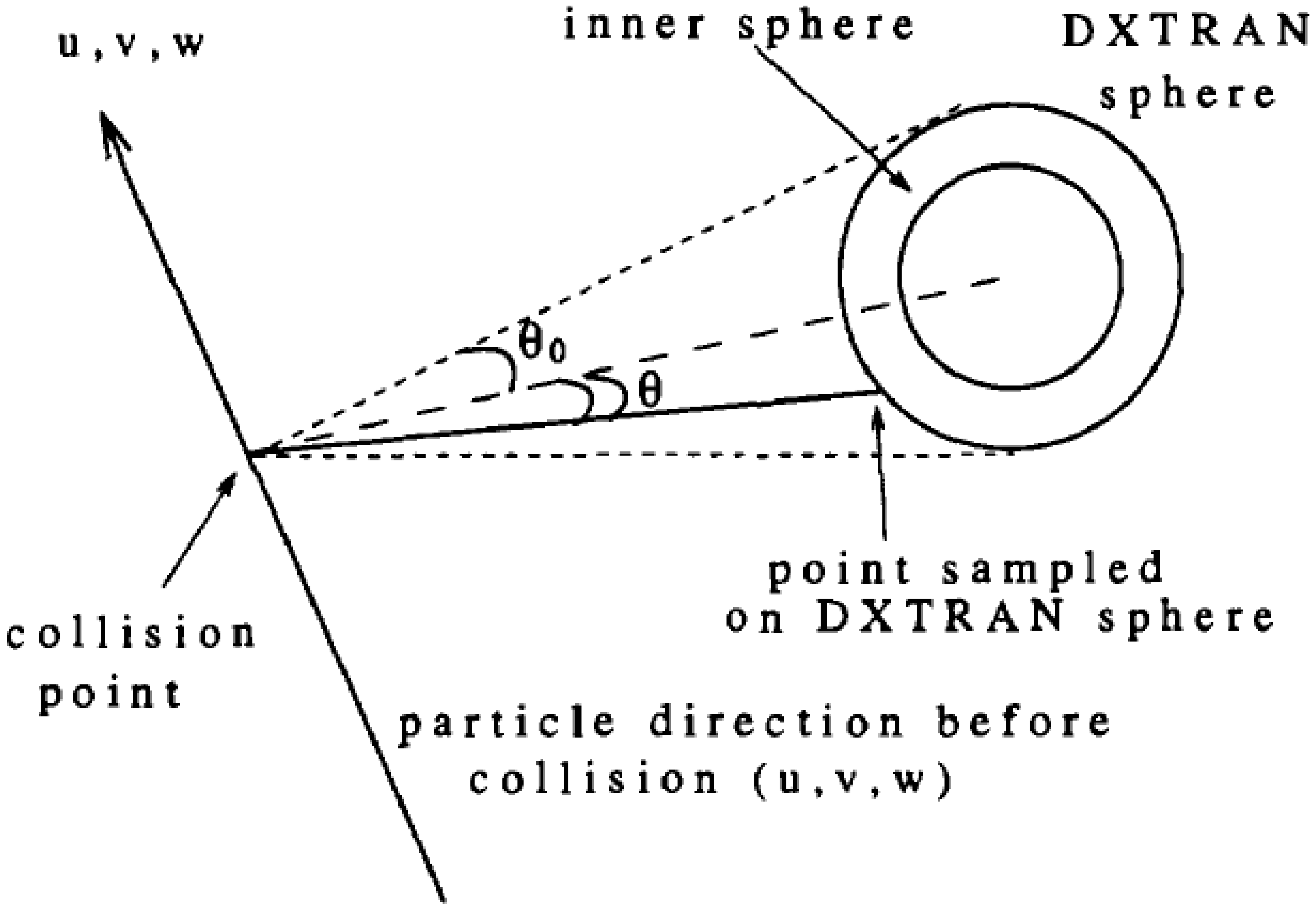
Geometry splitting



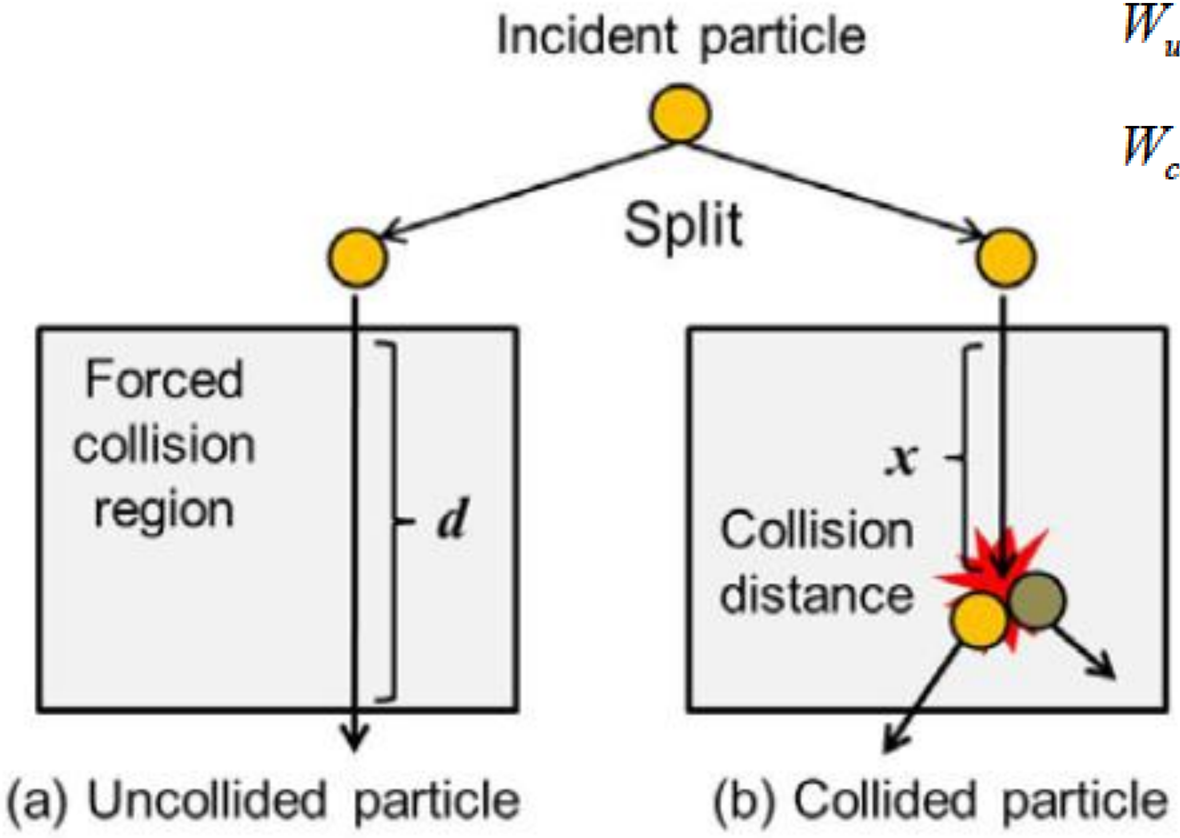
Russian roulette



Dxtran sphere



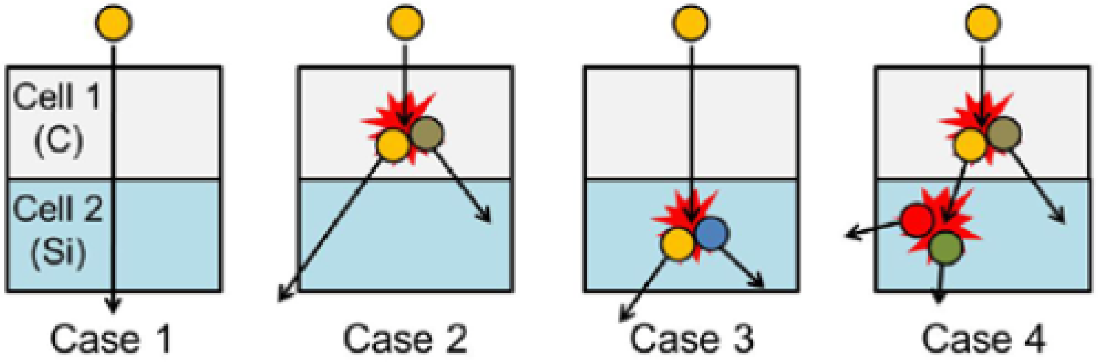
Forced collision 1(2)

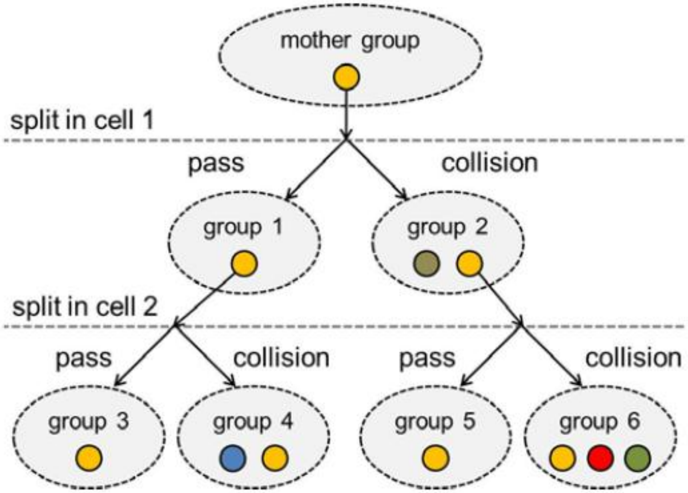


$$W_{uncoll} = W_0 \exp(-\Sigma_t d),$$

$$W_{coll} = W_0 \{1 - \exp(-\Sigma_t d)\}$$

Forced collision 2(2)





$$
\begin{aligned}
E_{mother} &= 0\,, & W_{mother} &= W_0 \\
E_1 &= 0\,, & W_1 &= W_{mother}\exp(-\Sigma_1 d_1) \\
E_2 &= e_C\,, & W_2 &= W_{mother}\left[1-\exp(-\Sigma_1 d_1)\right] \\
E_3 &= 0\,, & W_3 &= W_1\exp(-\Sigma_2 d_2) \\
E_4 &= e_{Si}\,, & W_4 &= W_1\left[1-\exp(-\Sigma_2 d_2)\right] \\
E_5 &= 0\,, & W_5 &= W_2\exp(-\Sigma_2 d_2) \\
E_6 &= e_{Al}+e_p\,, & W_6 &= W_2\left[1-\exp(-\Sigma_2 d_2)\right],
\end{aligned}
$$

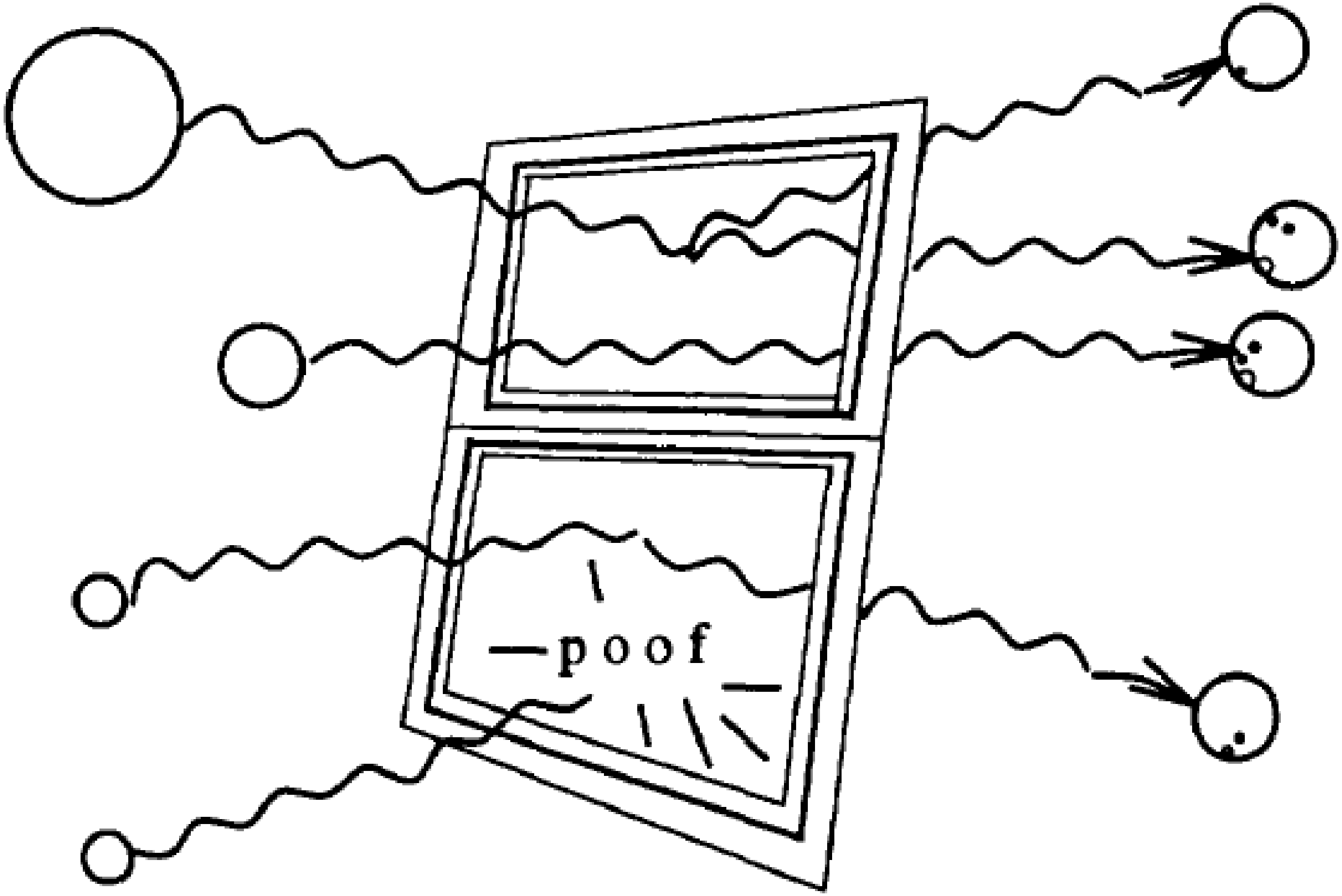
Energy splitting

- Energy splitting is like geometry splitting put in energy space.

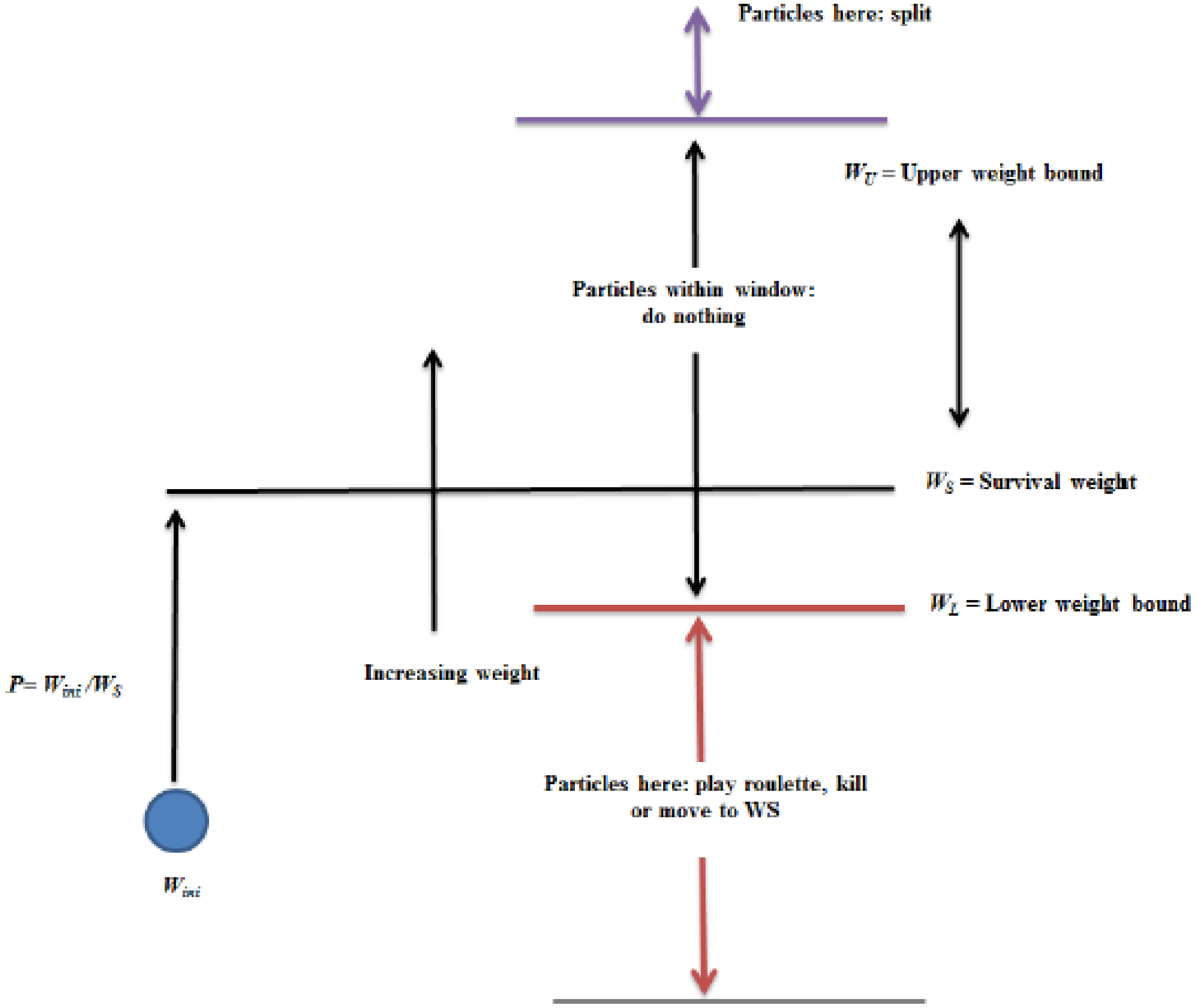
Secondary particle biasing

- Secondary particle biasing is like geometry splitting but in secondary particle space.

Weight window principle 1(2)



Weight window principle 2(2)



Particles here: split

W_U = Upper weight bound

Particles within window: do nothing

W_S = Survival weight

W_L = Lower weight bound

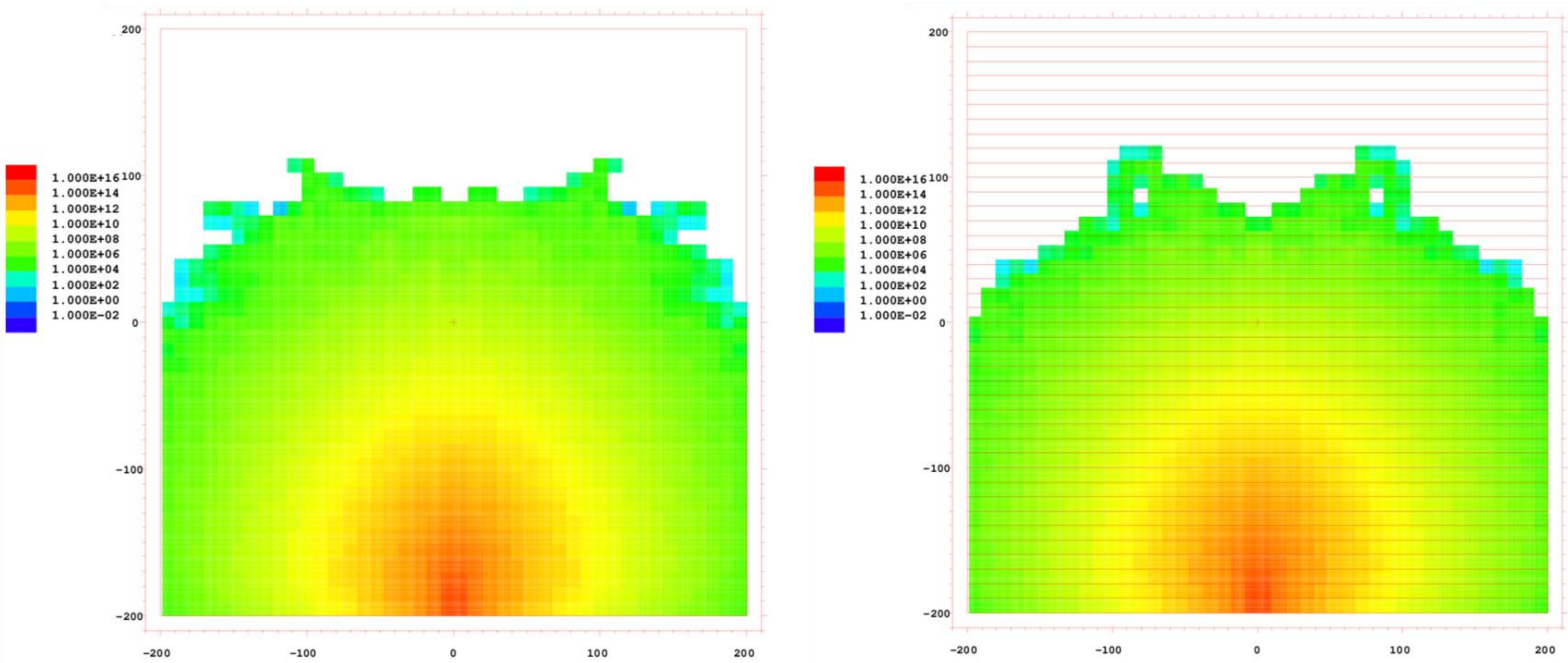
$P = W_{ini}/W_S$

Increasing weight

Particles here: play roulette, kill or move to WS

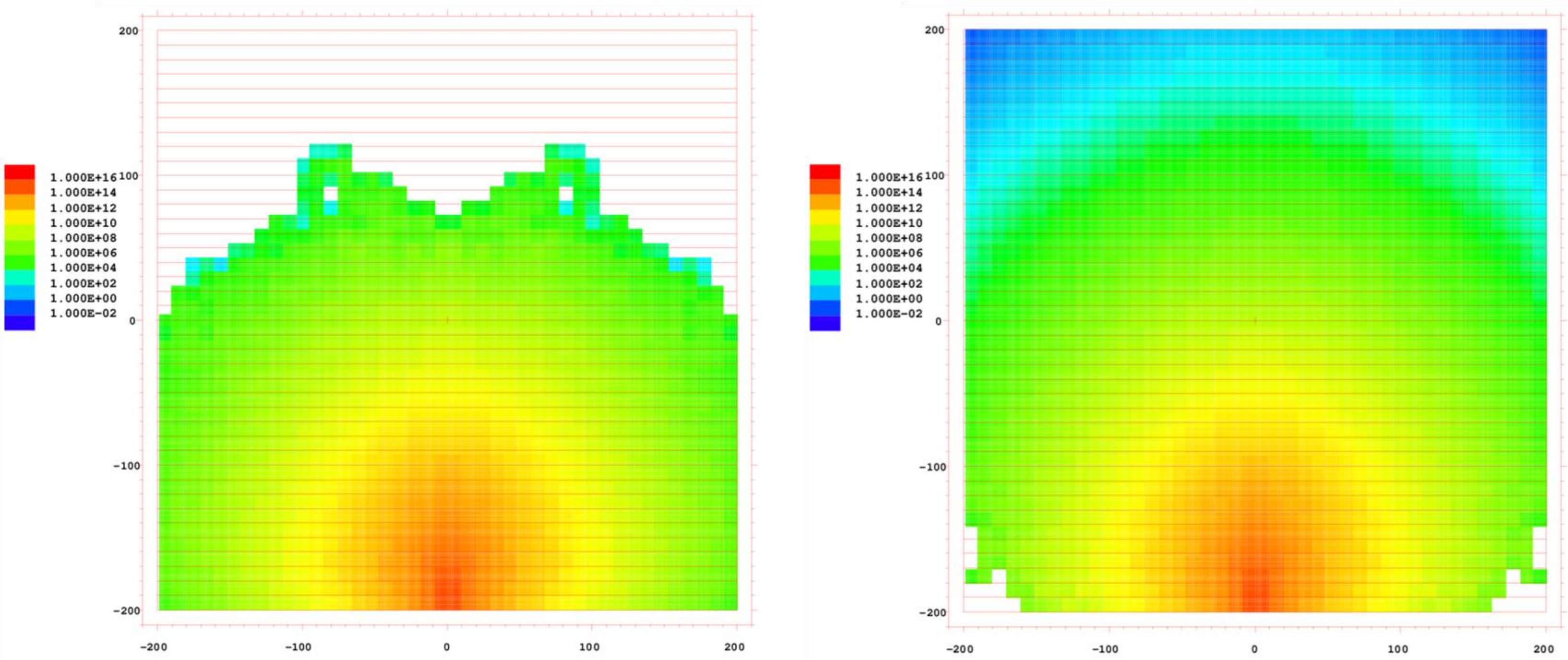
W_{ini}

Running analog/without variance reductions



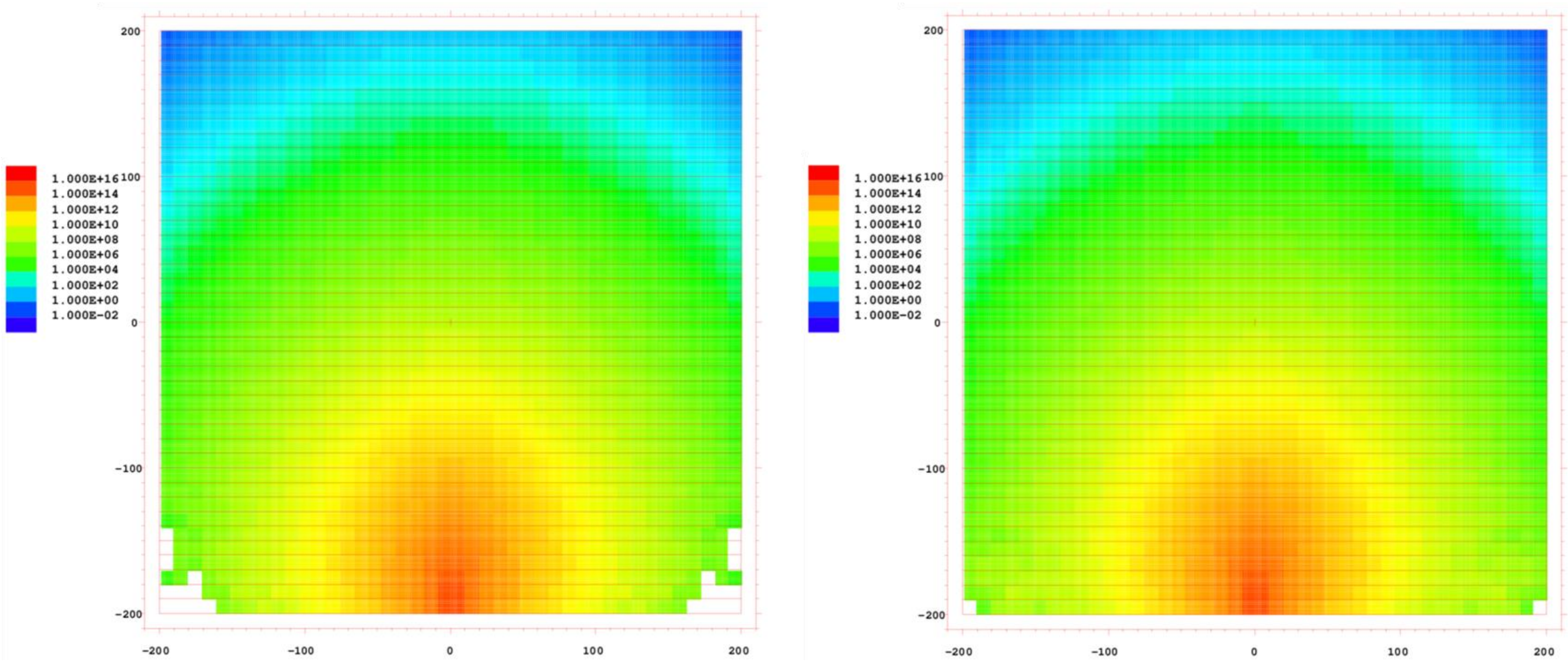
10^7 start particles (100 MeV neutrons), single processor, CPU time: left: 878 min; right 896 min, population extinct after ~2/3 - 3/4 of the problem. At least 10^{11} start particle needed to get good statistic on top => $9*10^6$ min ~ 1 week with 1000 cores

Geometry splitting versus analog



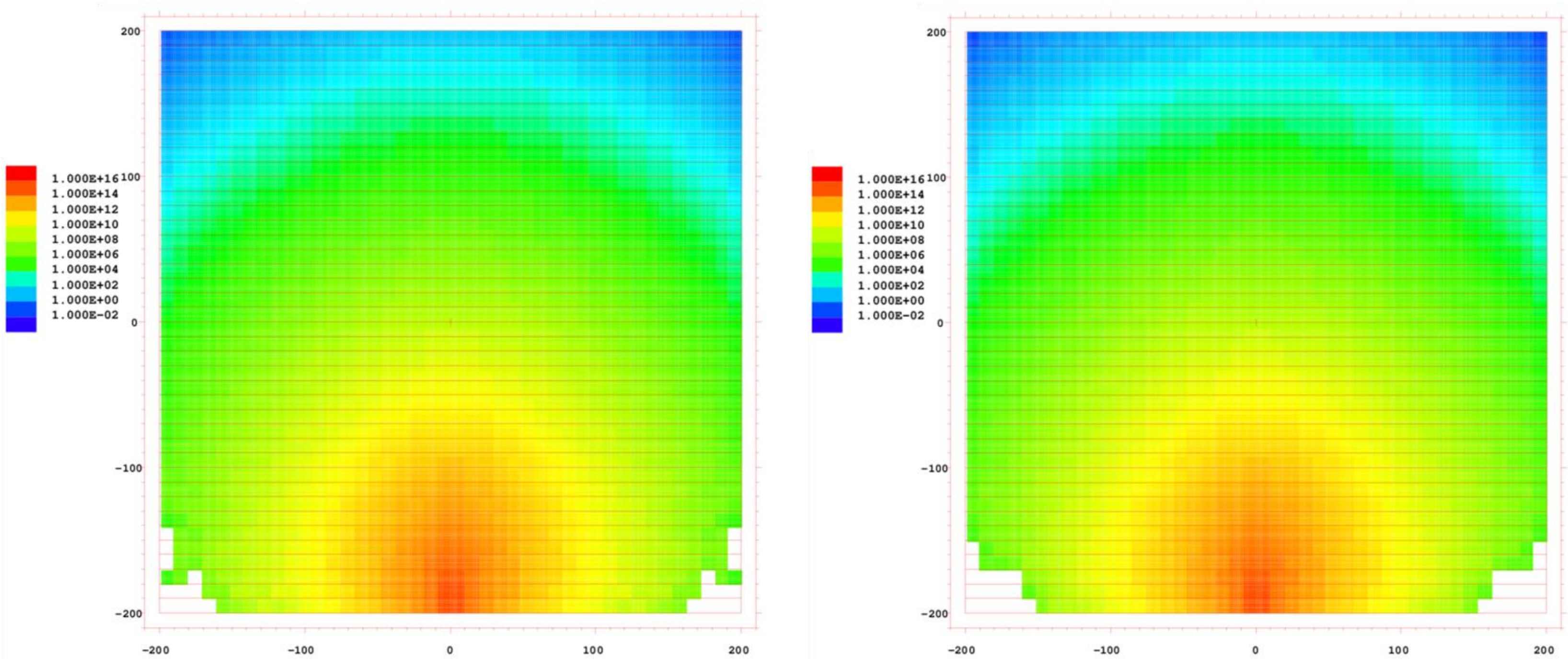
single processor, CPU time: left: 896 min; right 504 min 5-7% uncertainty on top, conversion speed difference ~ factor 20000.

Splitting with an without energy restriction



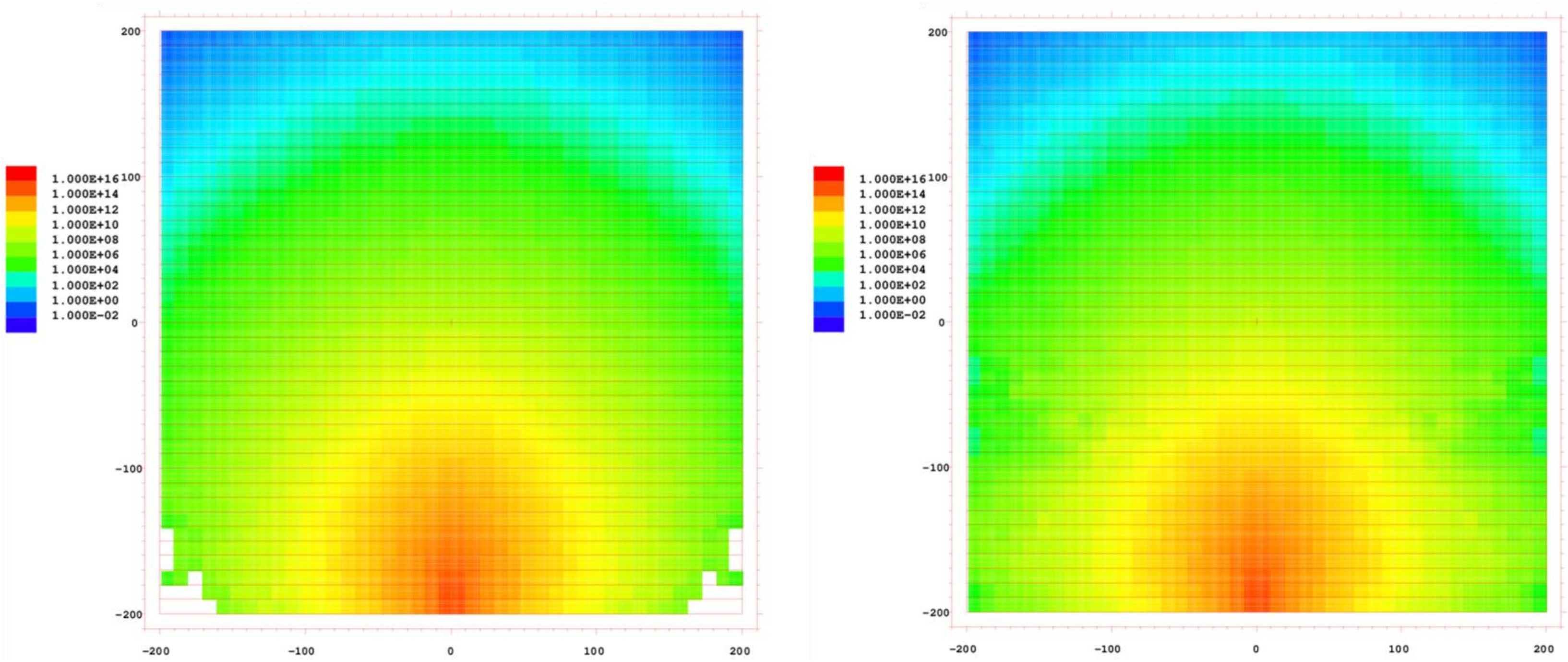
single processor, 5-7% uncertainty on top, CPU time: left: 504 min (no energy restriction); right 237 min (cut < 1MeV). Factor of 2 in speed, but tally 15-20% lower (=4cm).

Splitting versus most simple weight windows



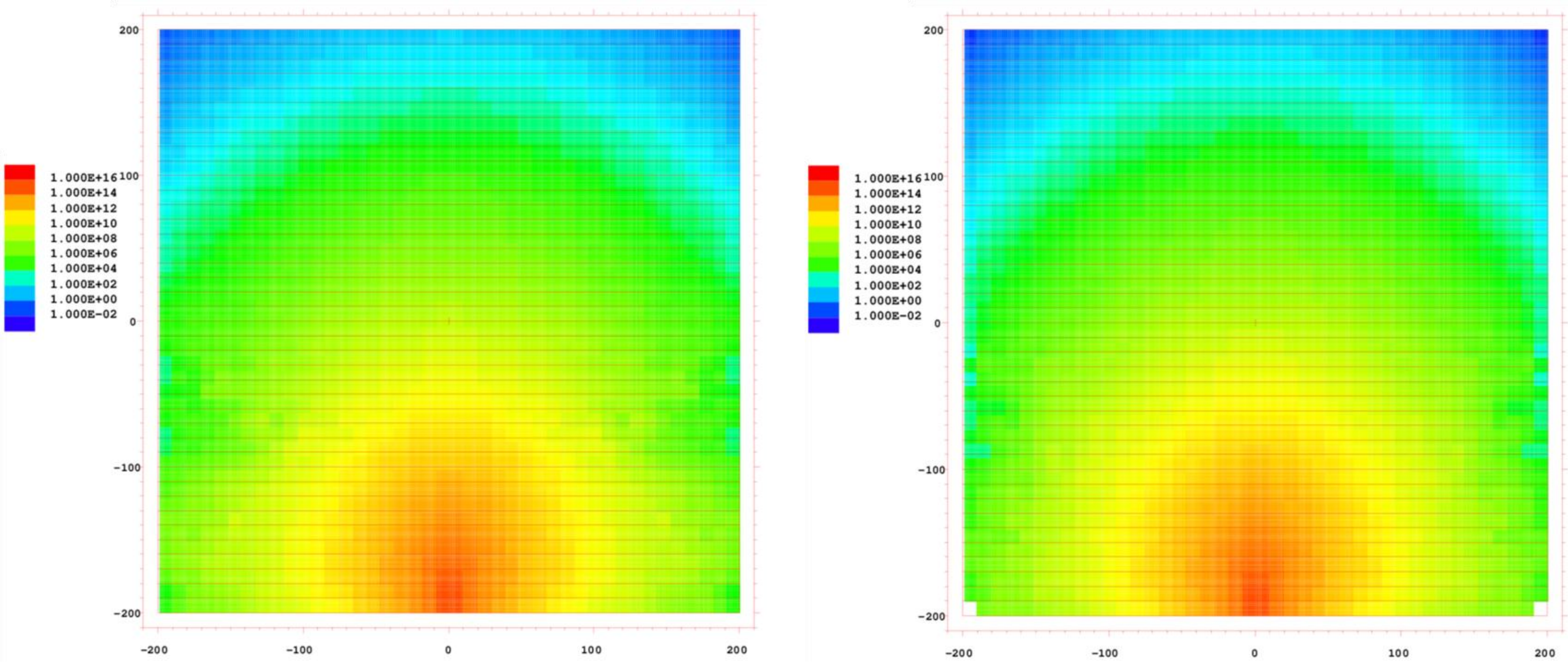
single processor, 5-7% uncertainty on top, CPU time: left: 504 min (no energy restriction); right 415 min (cell/cell importance based weight windows).

Splitting versus energy based weight windows



single processor, 5-7% uncertainty on top, CPU time: left: 504 min (no energy restriction); right 83 min (cell based weight windows with 4 energy bins). (Speed difference: factor:6; speed difference versus analog: factor: 120000 (1 hour on single processor versus 1 week on a 1000 core cluster).

Weight windows: cell versus mesh based



single processor, 5-7% uncertainty on top, CPU time, 4 energy bins: left: 83 min (cell based); right: 240 (mesh based, finer grid). (Speed difference: factor:4).

Activation

- Spallation productions
- Neutron flux induced
    - High energy neutron flux induced
    - Thermal and cold neutron absorption

Hand calculations: Production term

$$P = \Phi V \sigma_{abs} \varrho$$

- P … production term
- Φ … volume flux
- V … volume
- σ_{abs} … thermal neutron absorption cross-section
- ρ … density

Hand calculations: activation

$$A(t) = P(1 - e^{-\lambda t}) \qquad \lambda = \frac{\ln 2}{t_{1/2}}$$

- A … activation at time t
- P … production term
- λ … decay rate
- $t_{1/2}$ … half-life time

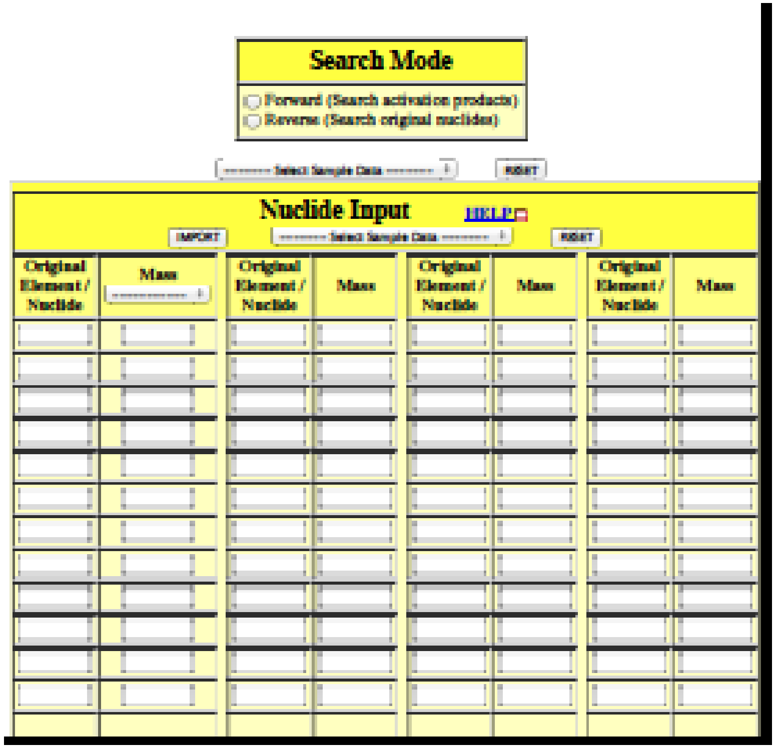
Hand calculations: inventory

$$I(t) = \frac{P}{\lambda}\left(1 - e^{-\lambda t}\right) \qquad \lambda = \frac{\ln 2}{t_{1/2}}$$

- A … inventory at time t
- P … production term
- λ … decay rate
- $t_{1/2}$ … half-life time

Activation calculator

http://www.wise-uranium.org/rnac.html

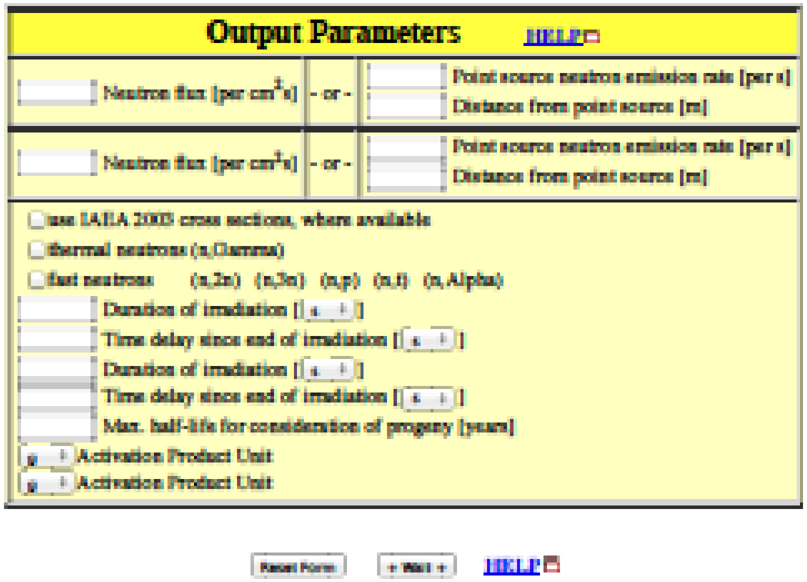


Search Mode

○ Forward (Search activation products)
○ Reverse (Search original nuclides)

Nuclide Input HELP

Original Element / Nuclide	Mass	Original Element / Nuclide	Mass	Original Element / Nuclide	Mass	Original Element / Nuclide	Mass



Output Parameters HELP

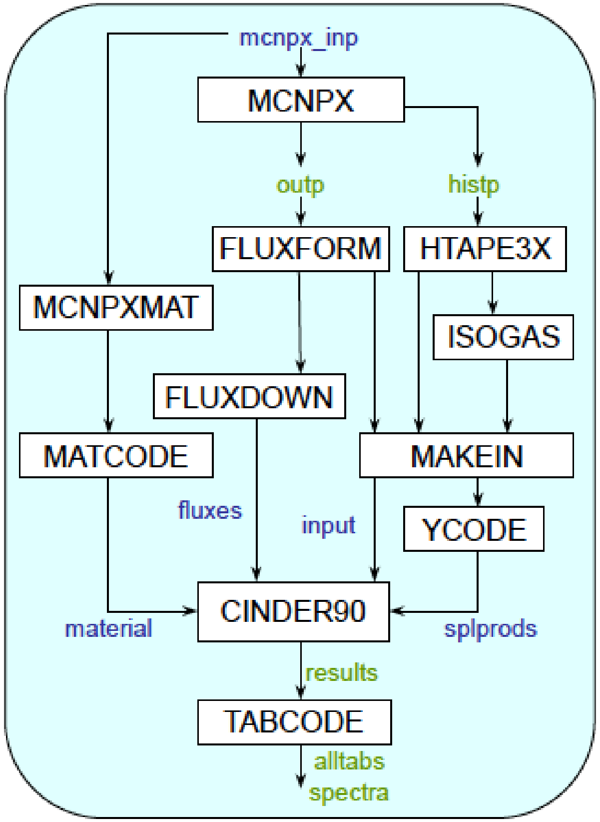
Neutron flux [per cm^{2}s] - or - Point source neutron emission rate [per s]
Distance from point source [m]

Neutron flux [per cm^{2}s] - or - Point source neutron emission rate [per s]
Distance from point source [m]

☐ use IAEA 2003 cross sections, where available
☐ thermal neutrons (n,Gamma)
☐ fast neutrons (n,2n) (n,3n) (n,p) (n,t) (n,Alpha)
Duration of irradiation [s]
Time delay since end of irradiation [s]
Duration of irradiation [s]
Time delay since end of irradiation [s]
Max. half-life for consideration of progeny [years]
g Activation Product Unit
g Activation Product Unit

Activation script

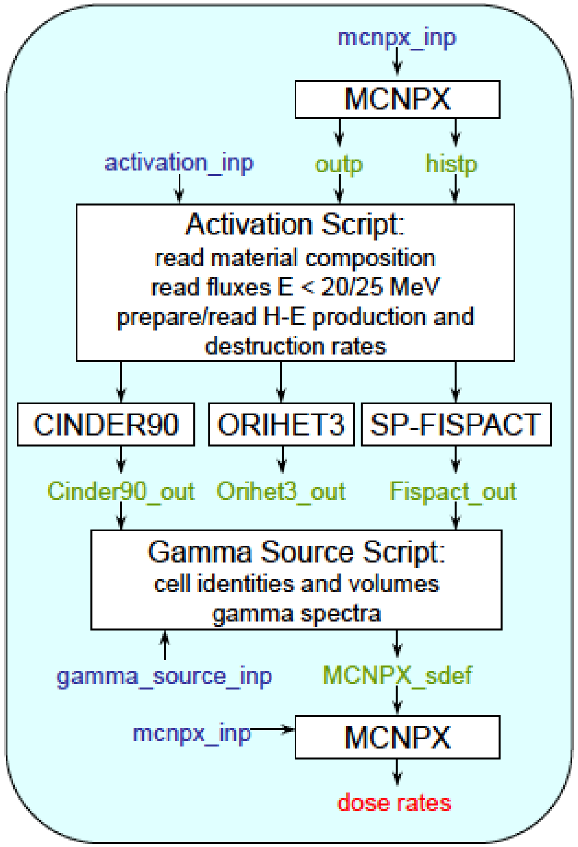
OLD



mcnpx_inp
MCNPX
outp
histp
FLUXFORM
HTAPE3X
MCNPXMAT
ISOGAS
FLUXDOWN
MATCODE
MAKEIN
fluxes
input
YCODE
material
CINDER90
splprods
results
TABCODE
alltabs
spectra

EXTRACT γ-SPECTRA
MANUALLY

NEW



mcnpx_inp
MCNPX
activation_inp
outp
histp

Activation Script:
read material composition
read fluxes E < 20/25 MeV
prepare/read H-E production and destruction rates

CINDER90
ORIHET3
SP-FISPACT
Cinder90_out
Orihet3_out
Fispact_out

Gamma Source Script:
cell identities and volumes
gamma spectra

gamma_source_inp
MCNPX_sdef
mcnpx_inp
MCNPX
dose rates

SCRIPT TO EXTRACT γ-SPECTRA
+ SDEF CARD PREPARATION

Gamma script

MAIN FEATURES

- Perl Script
- All cells treated in previous activation calculations will be considered to contribute to the γ-source that is constructed.
- Capable to extract gamma source information from CINDER90 spectra file and SP-FISPACT TAB2 file.
- Only acoount for single cell entries.
- The time step for which the source should be evaluated can be user defined.
- More than 200 cells ➔ SDEF distribution overflow ➔ source defintion is split.
- Only “regular” cells currently possible; no universes/lattices

Payoff

Metric: Background metric