Shielding and activation

Requirements and Physics

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Outline

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- Why do we need shielding?
- Definitions
- Requirements
- Physics: Source Term
- Physics: Gamma and Neutron
- Metrics
- Project management metric

Why do we need to shield against radiation?

- Damage to the human body (Sievert or Rem)
- Damage to the equipment (Gy or Rad)
- 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
- 1 Bq = 1 decay per second

Units (protection of data)

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

Where to start? Requirements

- Protecting people
  - Governmental and facility regulations
    - Dose to the worker
    - Dose to the public
- Protecting equipment (Gy or Rad)
  - Availability and reliability
- What is the source term?
- What are the performance requirements for the instrument?
- Protecting experimental data (noise level of the data)
  - Performance metric of the designed beamline
  - Performance metric of the neighboring beamlines

Protecting people: The "Safety First" thingy – Rest risk

- First step: "Ensuring safe operation is an absolute necessary requirement, but be itself not a sufficient requirement for operation.
- Rest risk: 100% perfect safety does not exist (Kurt Gödel's incompleteness theorems (1931))
- The law defines what rest risk is tolerated by the society.
- It is your job to prove that the rest risk of your operation is lower than the one tolerated by society.
    - Passive safety (one time cost at the beginning of the project)
    - Active safety features (continues maintenance cost)
    - Administrative controls (seems cheap, but high rest risk => large overhead for operation)

Protecting people: Event classes

Definition of event classes for radiation hazards

Classification	Event	Frequency/y
H1	Normal Operation	≥ 1
H2	Anticipated events	1 to 10^{-2}
H3	Unanticipated events	10^{-2} to 10^{-4}
H4A	Improbable events	10^{-4} to 10^{-6}
H4B	Events with multiple failures	$> 10^{-4}$
H5	Highly improbable events	

Protecting people: Swedish law (public and supervised areas)

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- **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)

- **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/cm² α < 0.4 Bq/cm² 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/cm² α < 4 Bq/cm² 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/cm² α < 10 Bq/cm² 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/cm² A > 10 Bq/cm² 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**

Protecting people: Allowable doses at ESS

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Event	Description	Radiation workers	Non-exposed workers	Public
H1	Normal Operation	10 mSv/y	0.05 mSv/y	0.05 mSv effective dose/y
H2	Anticipated events	20 mSv/event	0.1 mSv/event	0.1 mSv effective dose/occurrence
H3	Unanticipated events	50 mSv/event	1 mSv/event	1 mSv effective dose/occurrence
H4A	Improbable events	50 mSv/event	20 mSv/event	20 mSv effective dose/occurrence
H4B	Events with multiple failures	50 mSv/event	20 mSv/event	20 mSv effective dose/occurrence
H5	Highly improbable events	Not defined.	100 mSv/event	100 mSv effective dose/occurrence

Protecting people: Current ESS dose budgets

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Radiation Protection Design Criteria

Facility Dose Budget, to Critical Group

	Acc.	**Target**	**Instr.**	**Waste-build.**
- Maximum Direct Radiation	AA X	TA X	IA X	WA X
- Maximum Activation	AB X	TB	IB	WB
- Maximum Emission into Air	AC X	TC X	IC	WC
- Maximum Emission into Drains	AD	TD X	ID X	WD
Summary Operation and Maintenance	0.03	0.01	0.005	0.005

X = preliminary, major contributors

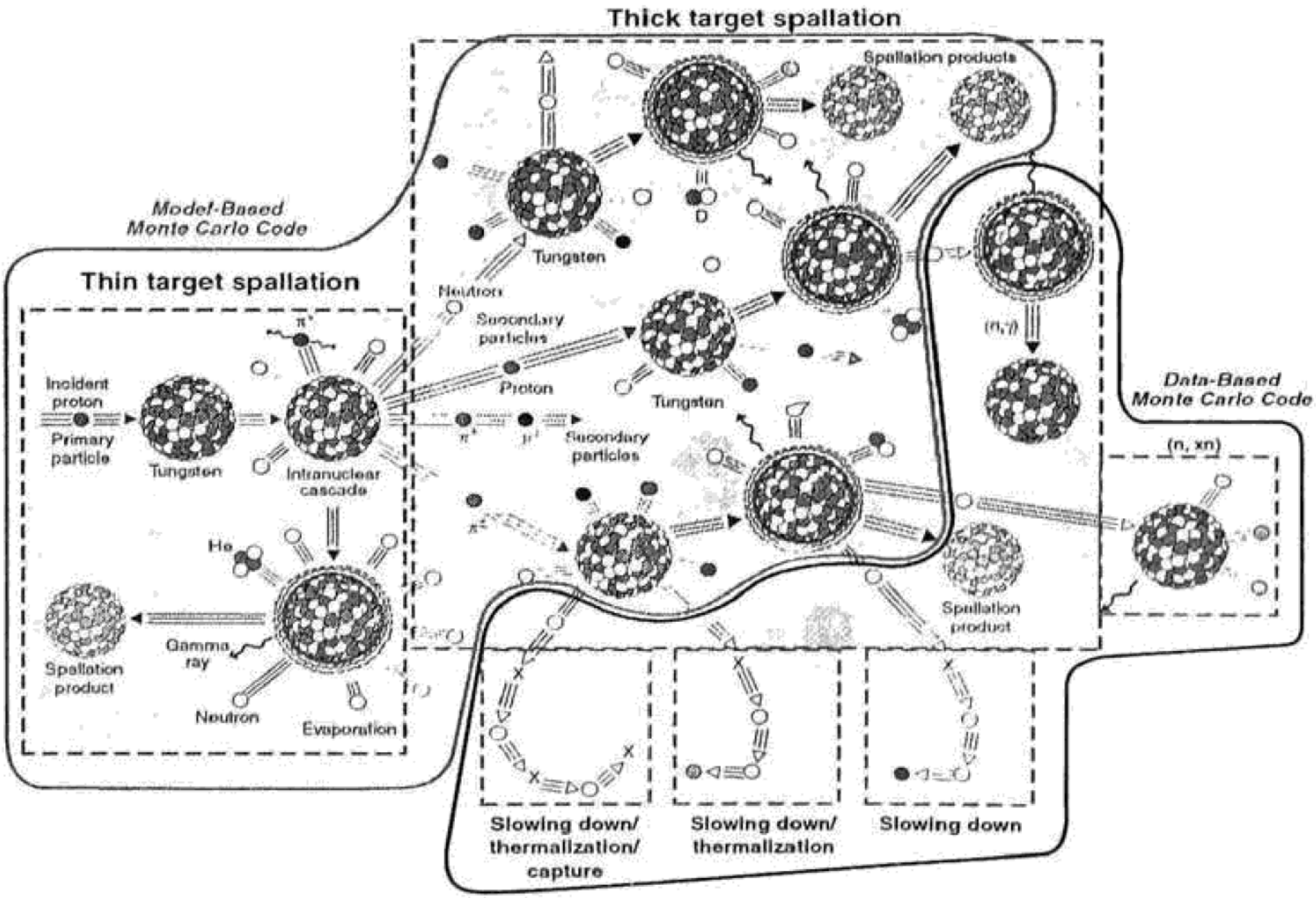
ESS Total

0.05 mSv/year **H1**

Protecting equipment

Will strongly depend on the application.

Source: Spallation process



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

Source: Reactor versus spallation source

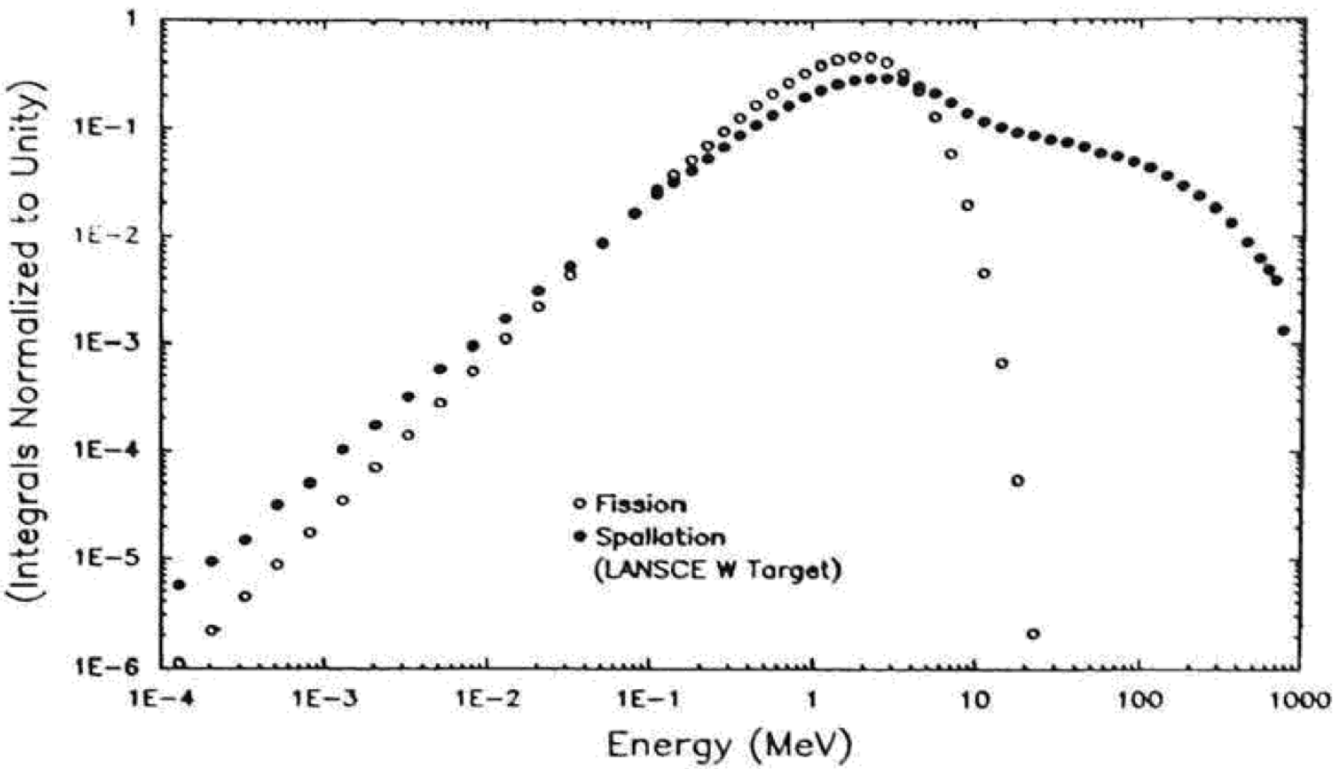


Figure 4. Spallation neutron spectrum compared to a typical neutron spectrum from thermal neutron fission of ^{235}U. The spallation spectrum is at 90 degrees from a "finite" 10-cm-diam by 30-cm-long tungsten target bombarded by 800-MeV protons.

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

Source: Angular dependency of the source

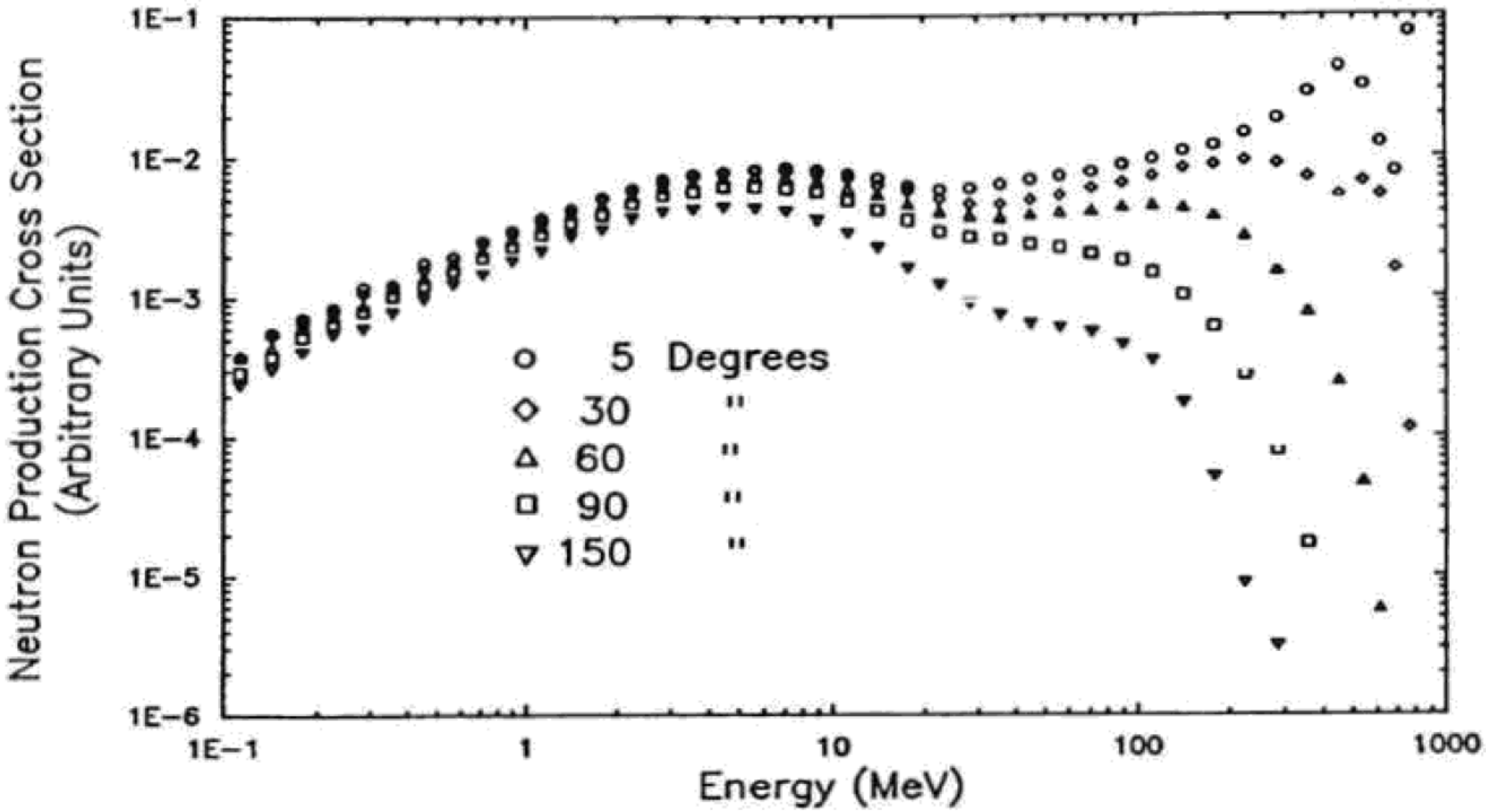
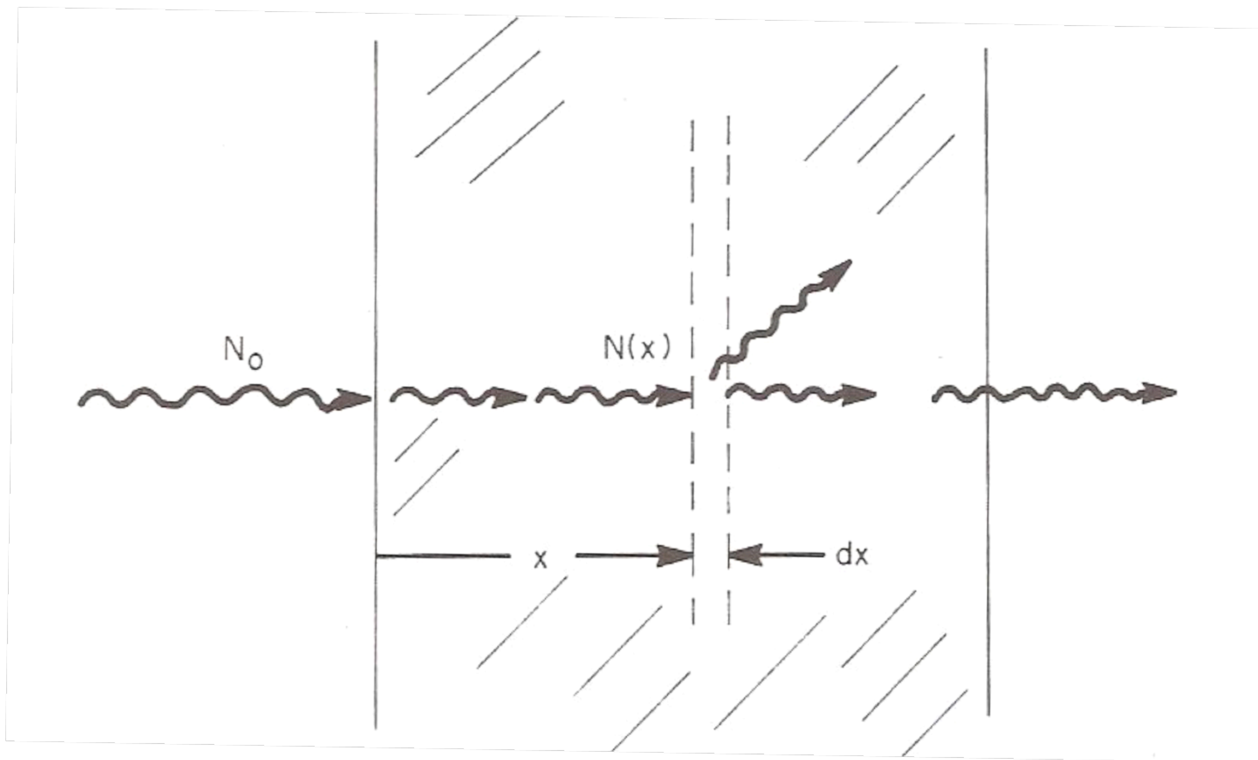


Figure 3. Neutron production from a thin iron target bombarded by 800-MeV protons.

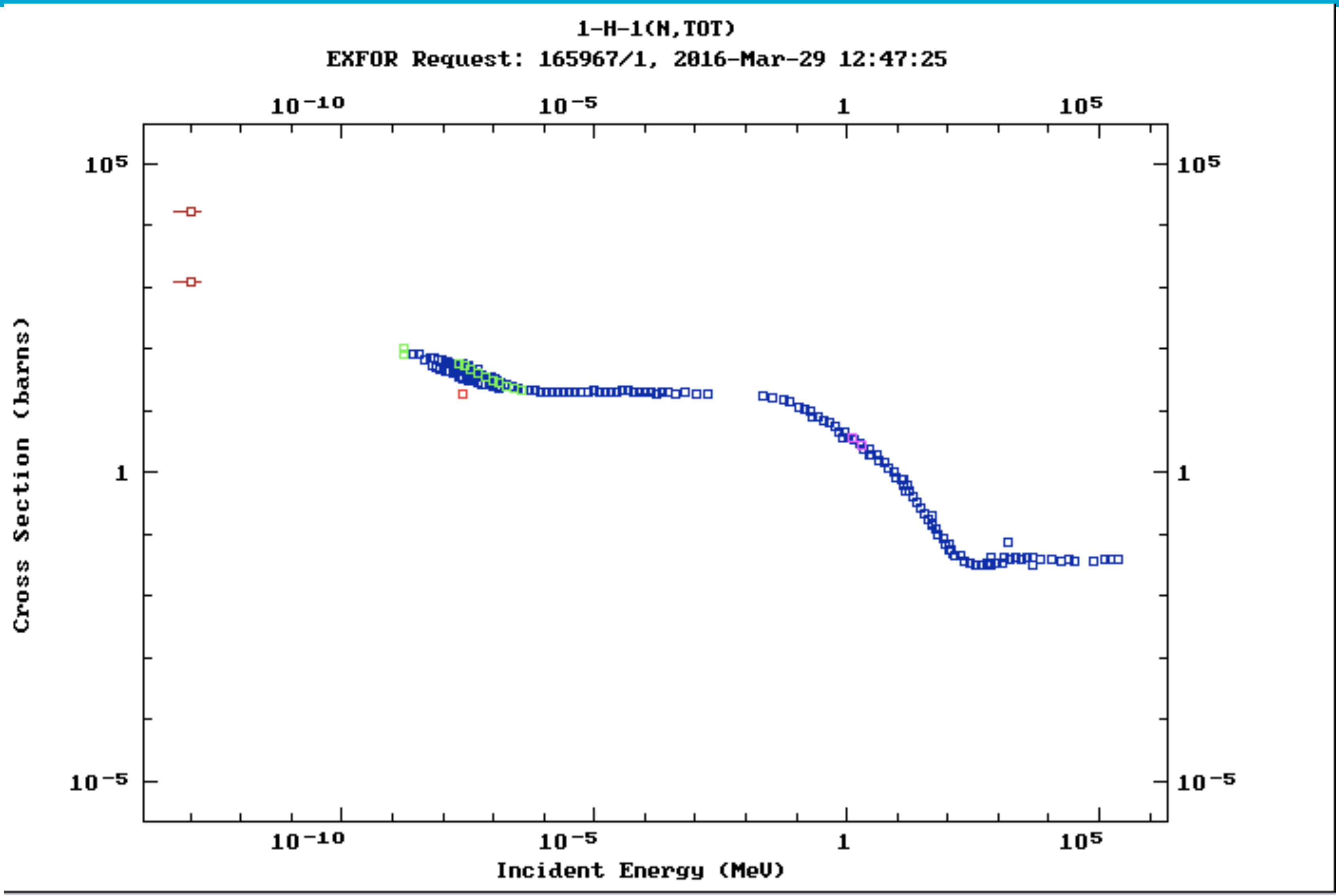
G. J. Russell et al, Fundamental Physics with Pulsed Neutrons Beams (2000) p 19

Physics: Attenuation

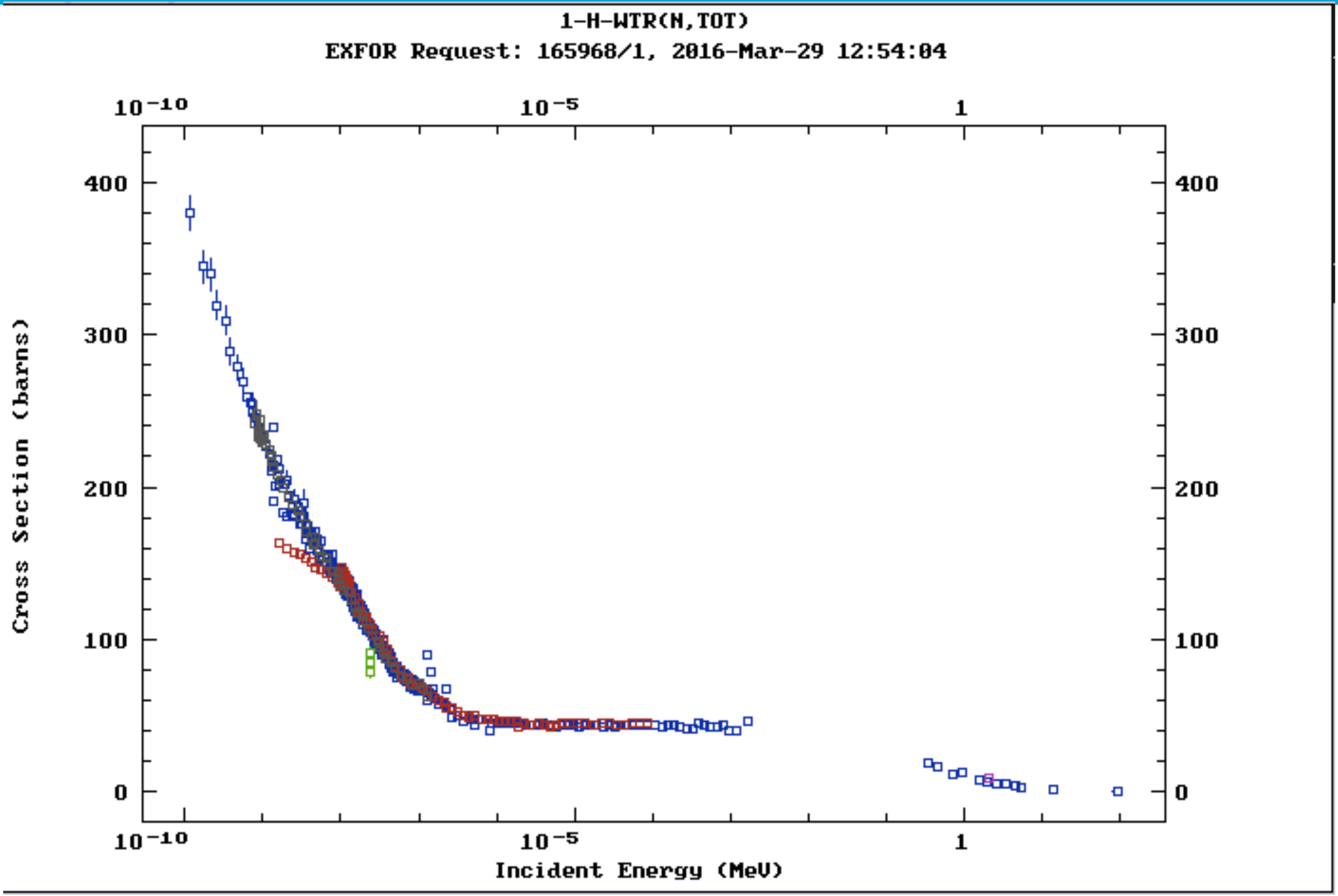


$$dN = -\mu N dx \Rightarrow N(x) = N_0 e^{-\mu x}$$

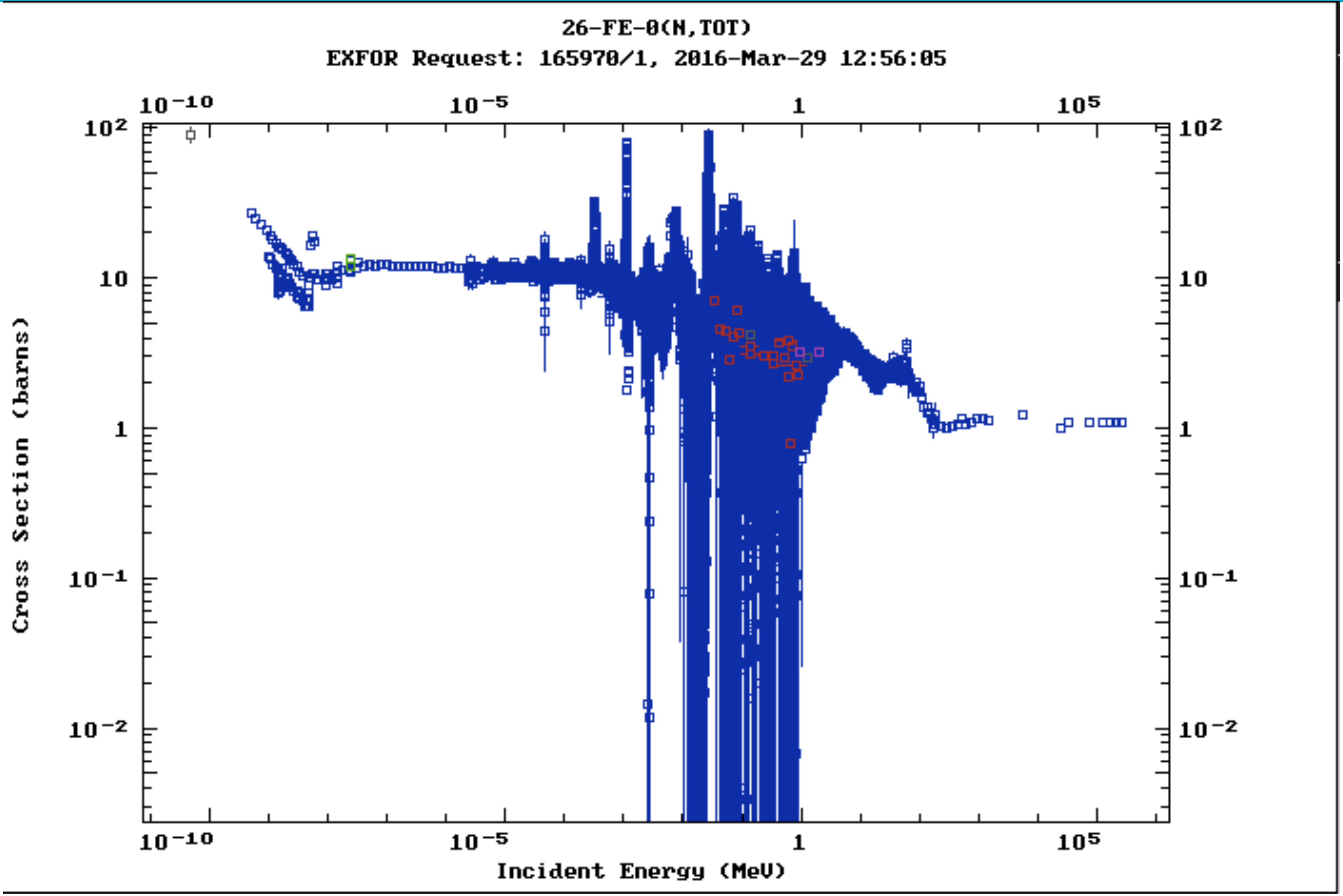
Physics: Hydrogen cross-section



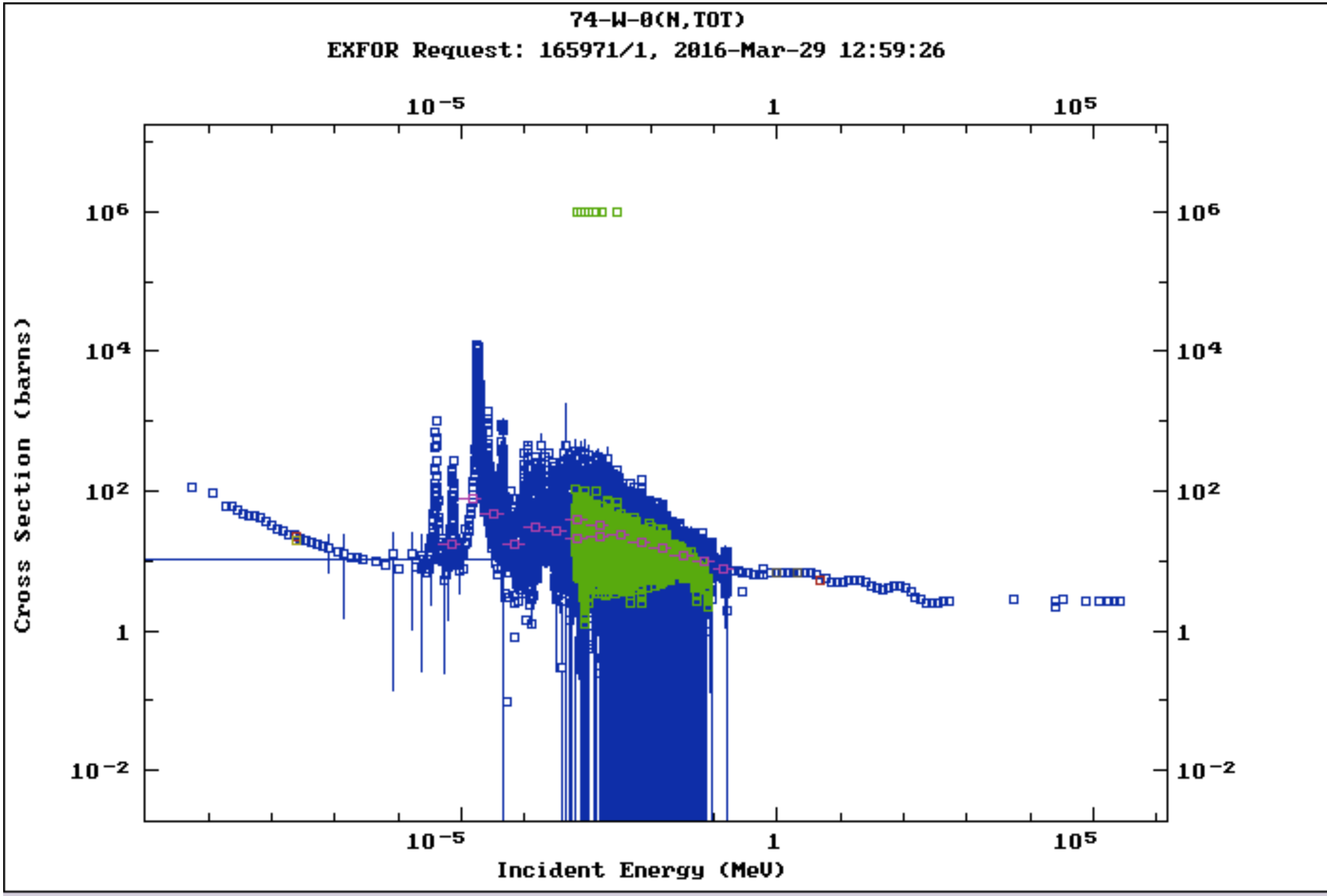
Physics: H in water cross-section



Physics: Iron cross-section



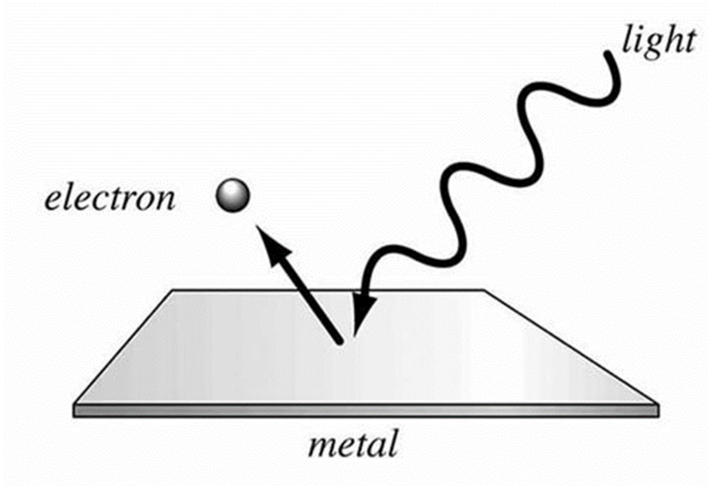
Physics: Tungsten cross-section

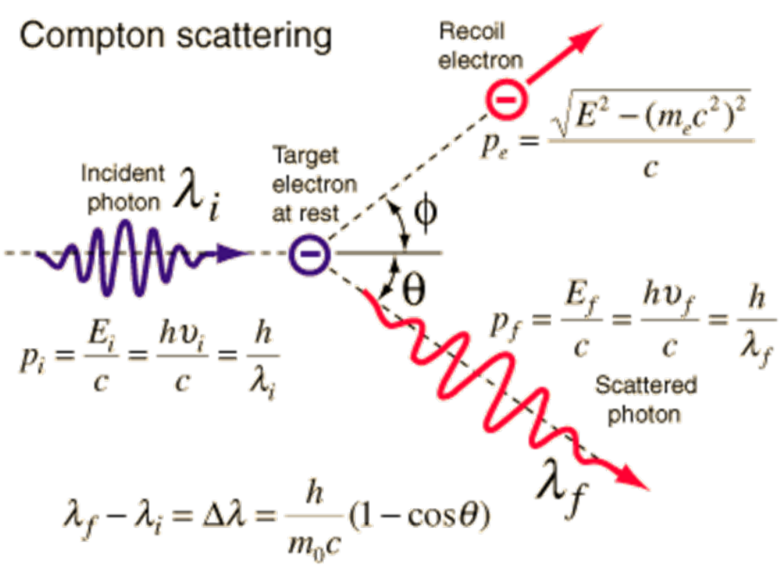


Physics: Photons

- 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

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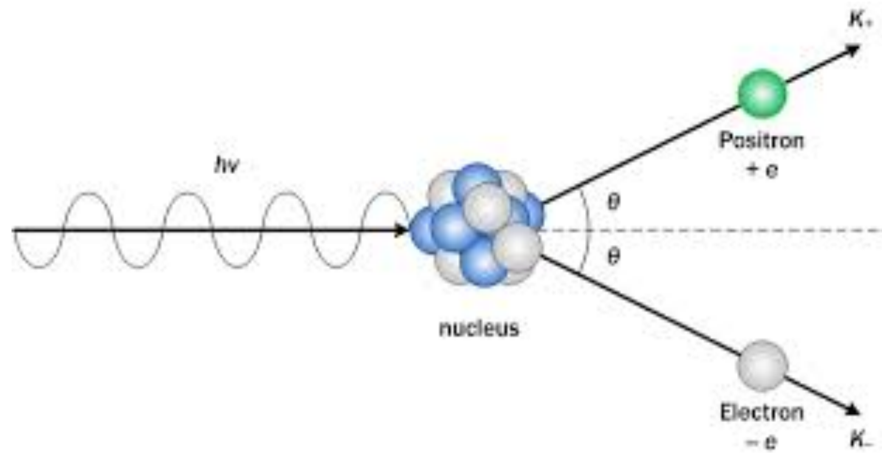
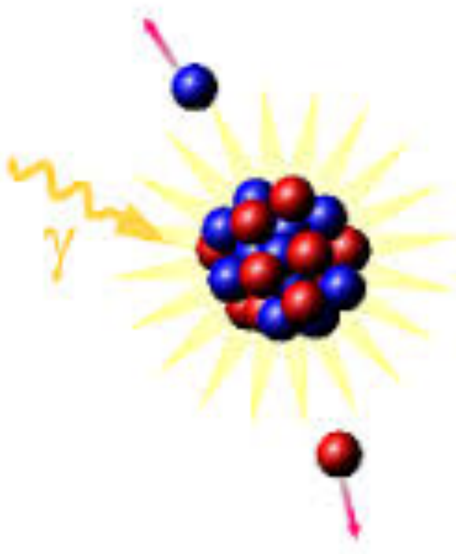
- Pair production

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

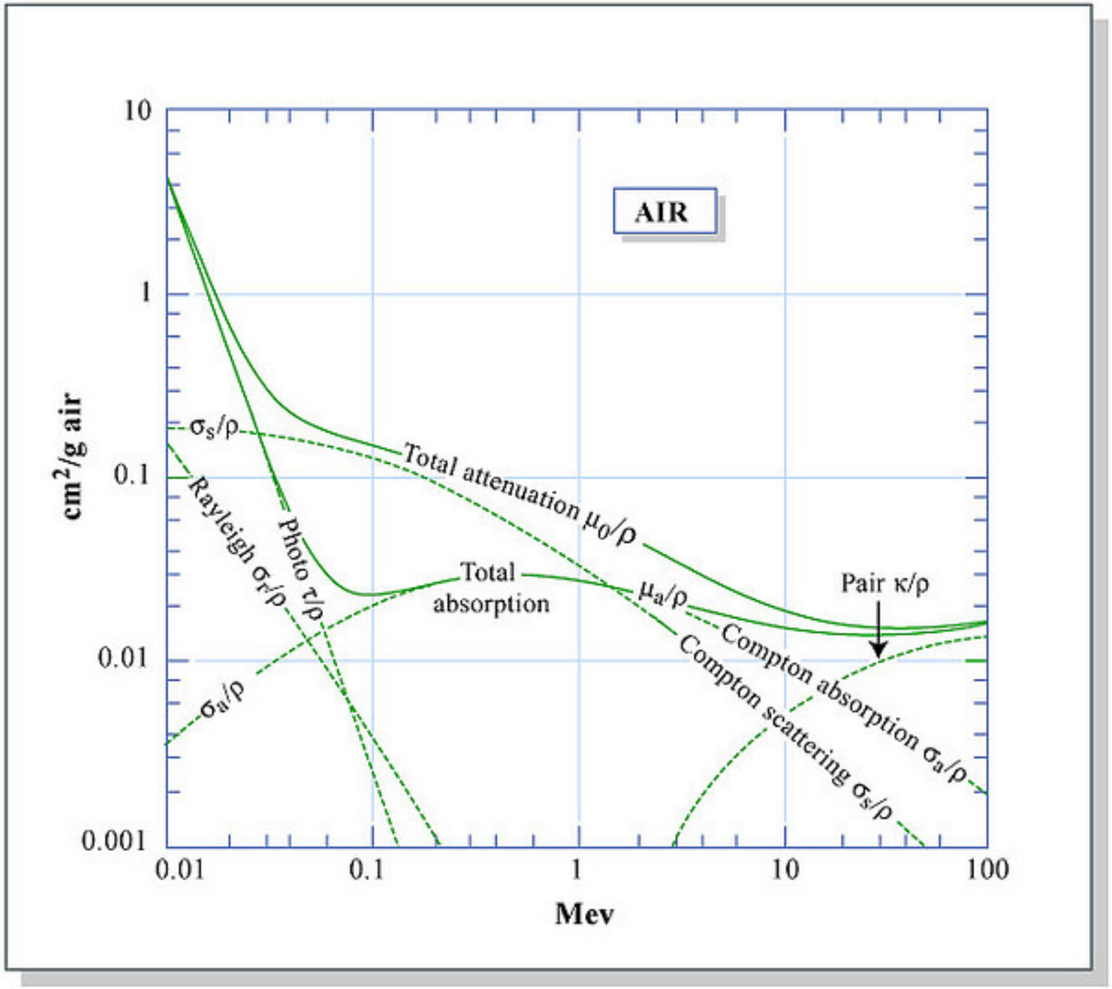




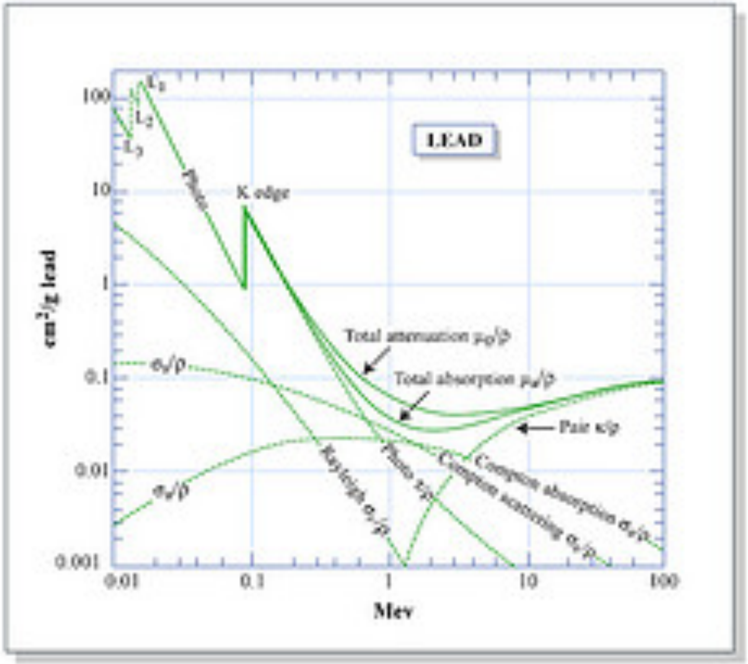
- Photonuclear reactions

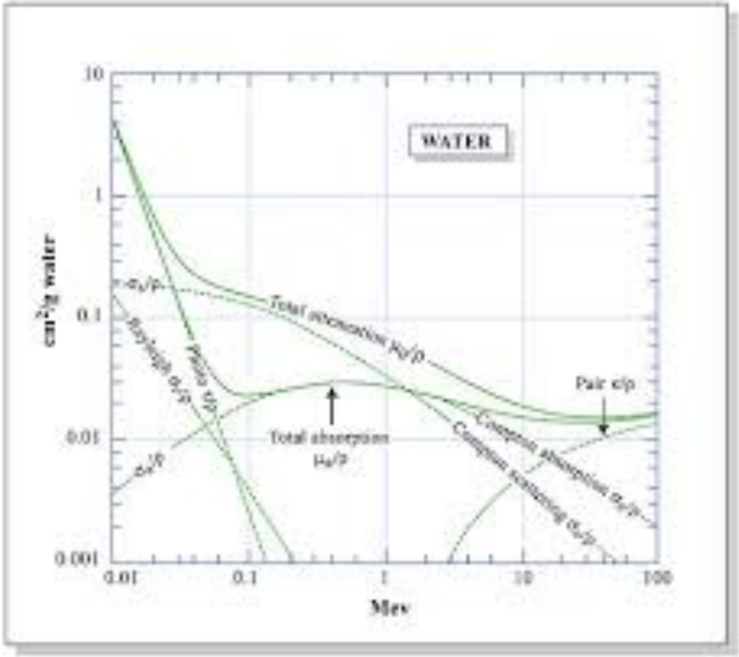
  Photons can be absorbed by an atomic nucleus and a nucleon will be emitted (e.g. (γ,n) reaction).

Photon mass attenuation factor in air



Photon mass attenuation factor in lead and water





Physics: Neutrons

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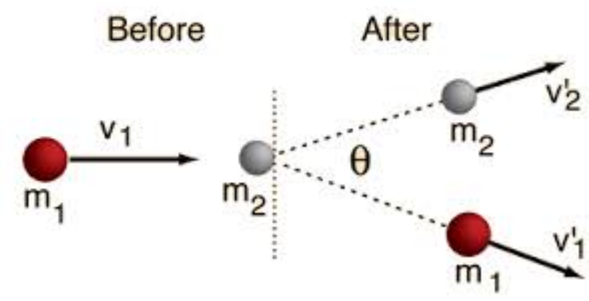
- Slowing down process:

  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: Neutrons absorption

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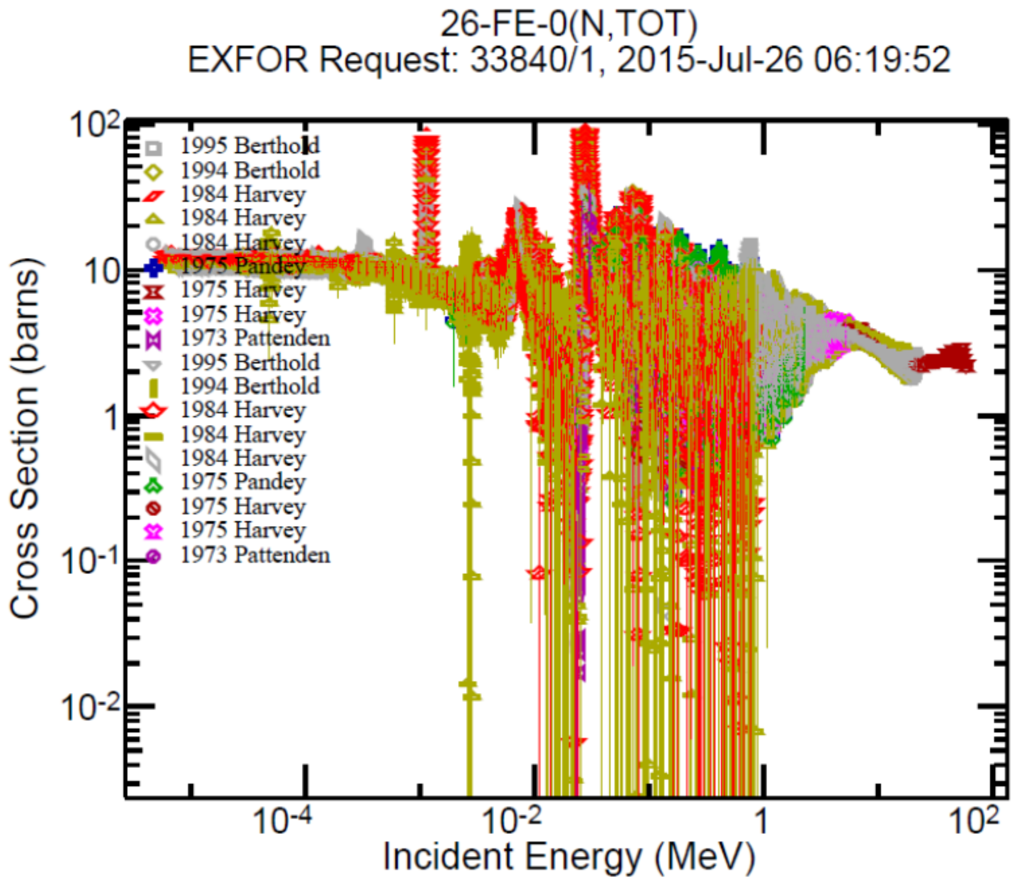
- Capture:

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

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

- 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.



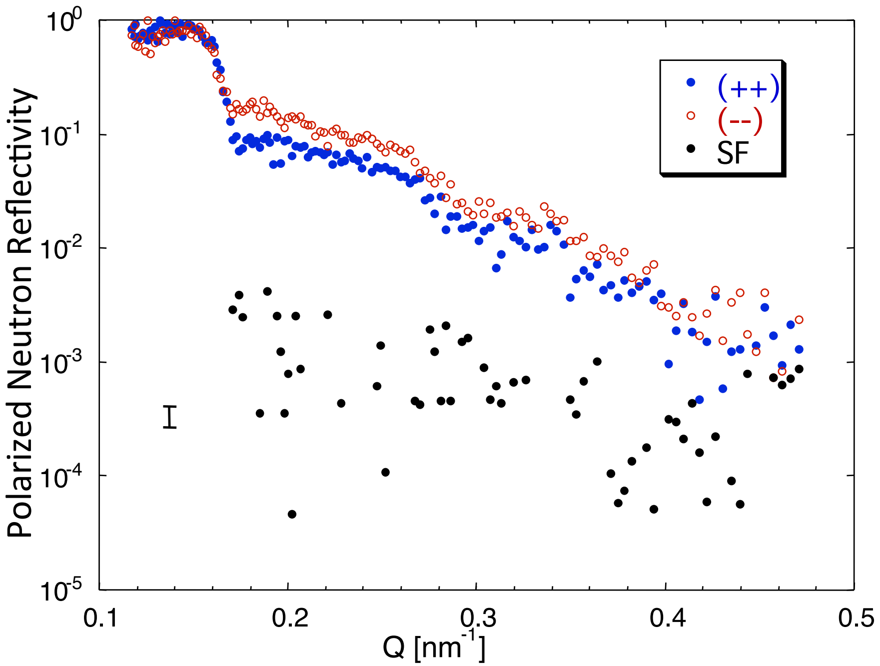
Metric: What is the metric for the performance of your instrument?

Instrument group	Flux metric	Shape metric
Small angle neutron scattering	$\max\left(\int_{1.5A}^{20A} IF(\lambda)\lambda^{2-3}d\lambda\right)$	N/A
Reflectometry	$\max\left(\int_{3A}^{15(20)A} IF(\lambda)\lambda^{4}d\lambda\right)$	N/A
Spin-Echo	$\max\left(\int_{4A}^{20A} IF(\lambda)\lambda^{2-3}d\lambda\right)$	N/A
Spectroscopy	$\max\left(\int_{1A}^{10A} PF(\lambda)\lambda^{0}d\lambda\right)$	$\min\left(\int_{1A}^{10A} \left\|\frac{dPF(\lambda)}{d\lambda}\right\| d\lambda\right)$
Nuclear (classical) diffraction	$\max\left(\int_{0.5(0.2)A}^{4A} PF(\lambda)\lambda^{0}d\lambda\right)$	$\min\left(\int_{0.5(0.2)A}^{4A} \left\|\frac{dPF(\lambda)}{d\lambda}\right\| d\lambda\right)$
Magnetic diffraction	$\max\left(\int_{1A}^{10A} PF(\lambda)\lambda^{0}d\lambda\right)$	$\min\left(\int_{1A}^{10A} \left\|\frac{dPF(\lambda)}{d\lambda}\right\| d\lambda\right)$

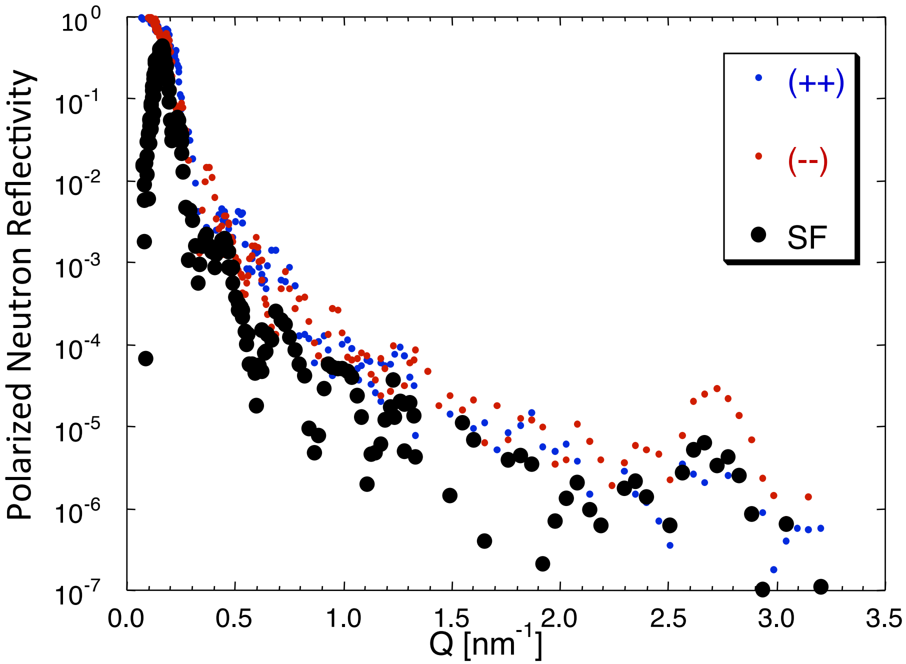
R.K. Crawford et al, Long-Pulse Neutron Instrumentation Workshop, STS04-41-TR0002, R00, At Franscatti, Italy

Metric: Background metric

P-SPEAR ('98)
24+h measurement



Asterix ('02)
19h measurement



Project management

- Performance metric
- Safety requirements
- Space constraints
- Cost
  - 1 m^3 concrete (including labor) ~ 1200 Euro
  - 1 m^3 good steel (including labor) ~ 12500 Euro
- Schedule