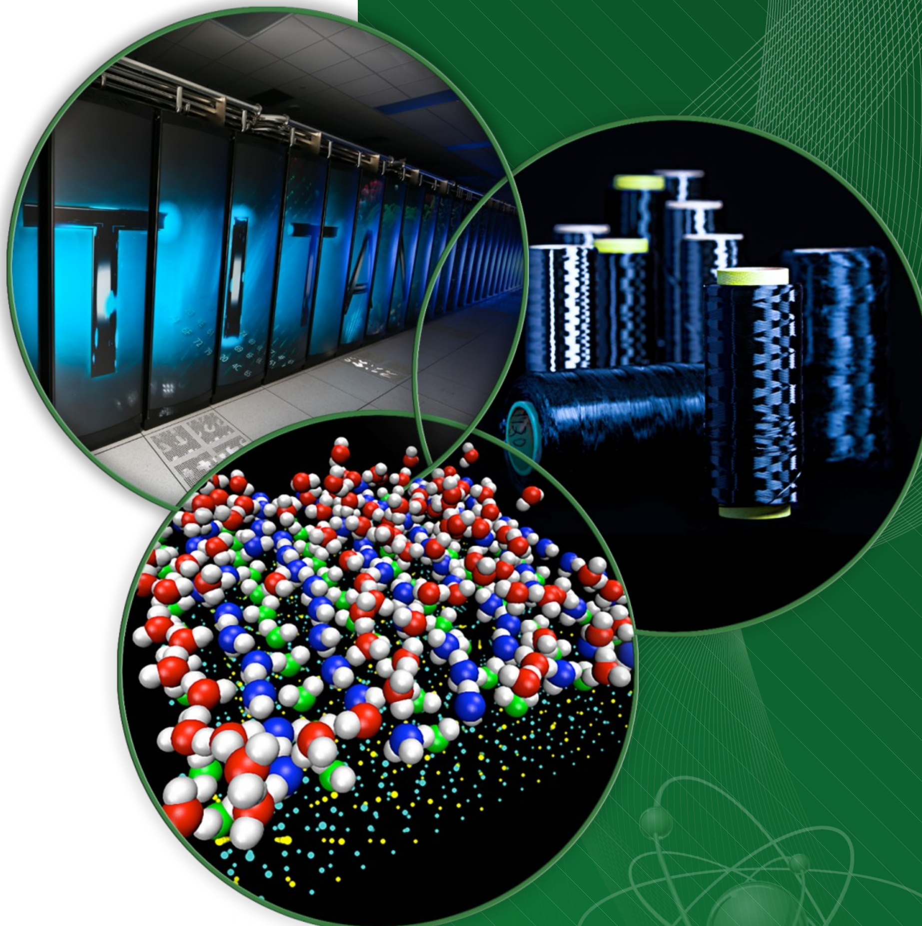
Neutron Moderation



E. B. Iverson
SNS Neutronics

2016 June 23

ORNL is managed by UT-Battelle
for the US Department of Energy

Concepts to Develop

- **Primary neutrons have <u>too much energy</u> for neutron scattering**
- **Neutron scattering needs knowledge of <u>every neutron's energy</u>**
- **<u>Time-of-flight</u> with a pulsed source requires reducing neutron energies to useful ranges without corrupting the "short-pulsed" character**
- **<u>Moderation</u> is how we reduce neutron energies to the desirable range**
- **<u>Moderators</u> moderate the neutrons and provide the neutron beams**
- **<u>Reflectors</u> send misdirected neutrons back to the moderator for another chance at being useful (and also provide additional moderation)**
- **<u>Decouplers</u> prevent long-lived populations of low-energy neutrons in the reflector from returning back to the moderator**
- **<u>Poisons</u> control the exact time-response of the moderator**

Fission Neutron Production

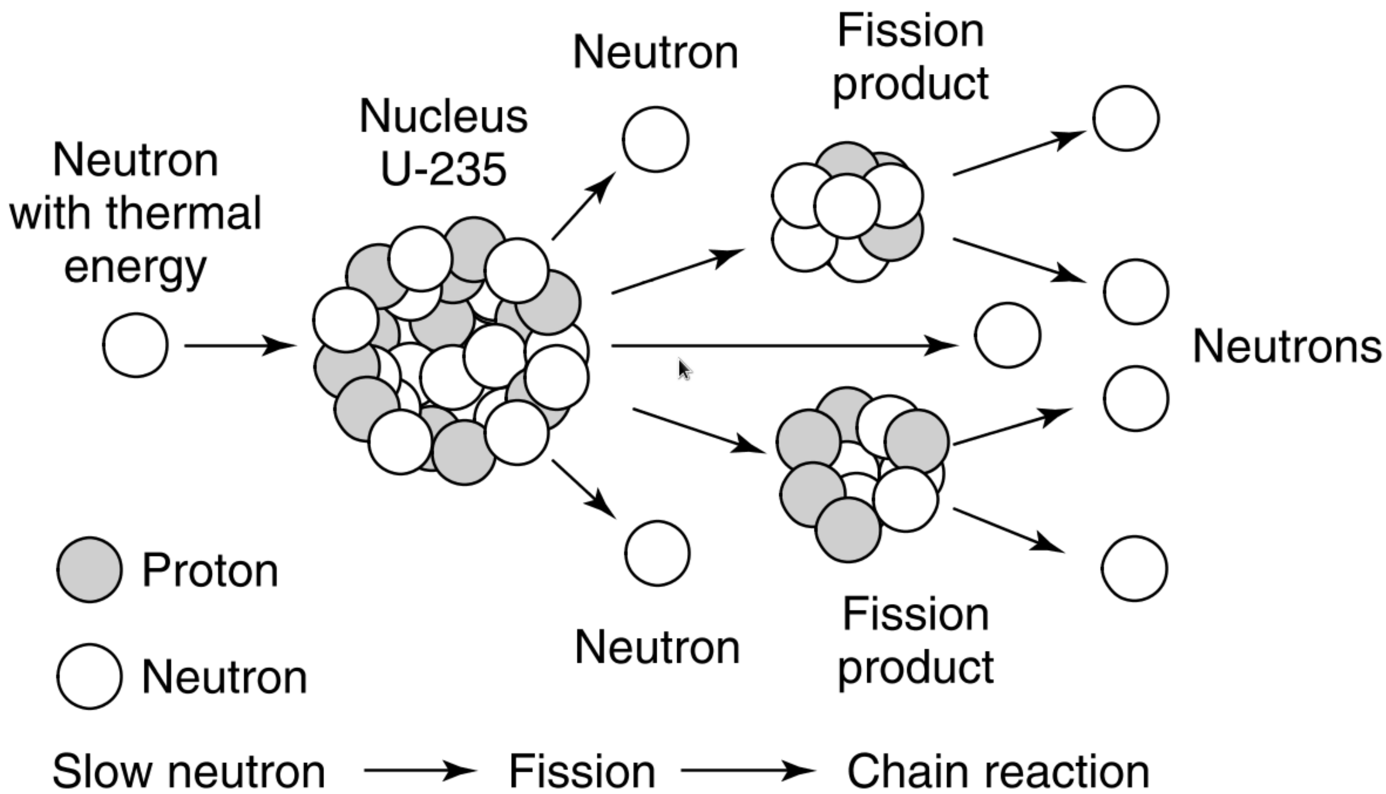


Fig. 1.10 Schematics of fission processes.

Filges, D. & Goldenbaum, *Handbook of Spallation Research*, Wiley, 2010

- **An average of 2.35 neutrons per fission reaction are emitted by excited fission product nuclei**
- **One neutron required to carry on the chain reaction**
- **1.35 available neutrons from ~200 MeV of energy to remove**

Spallation Neutron Production

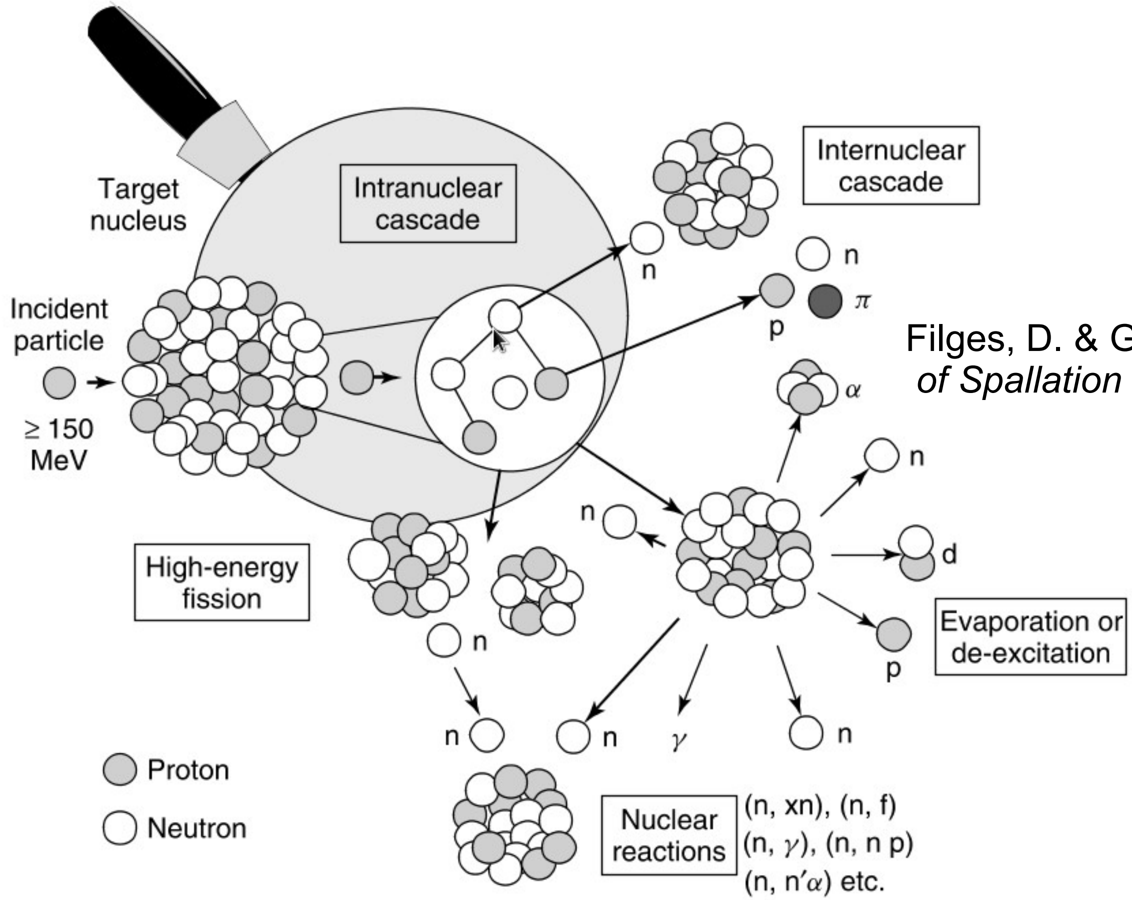


Fig. 1.12 The principal scheme of spallation.

Filges, D. & Goldenbaum, *Handbook of Spallation Research*, Wiley, 2010

- **Average of 20 – 35 neutrons per proton, depending on *A* and *E***
- **30 neutrons for 1 GeV on mercury; <35 MeV per neutron**
- **Typical target materials: uranium, tungsten, mercury, lead**

OAK RIDGE National Laboratory

Spallation Neutron Yields

Conrad, H. "Spallation – Neutrons Beyond Nuclear Fission" in *Handbook of Particle Detection and Imaging*, Springer Berlin Heidelberg, 2012, 719-757

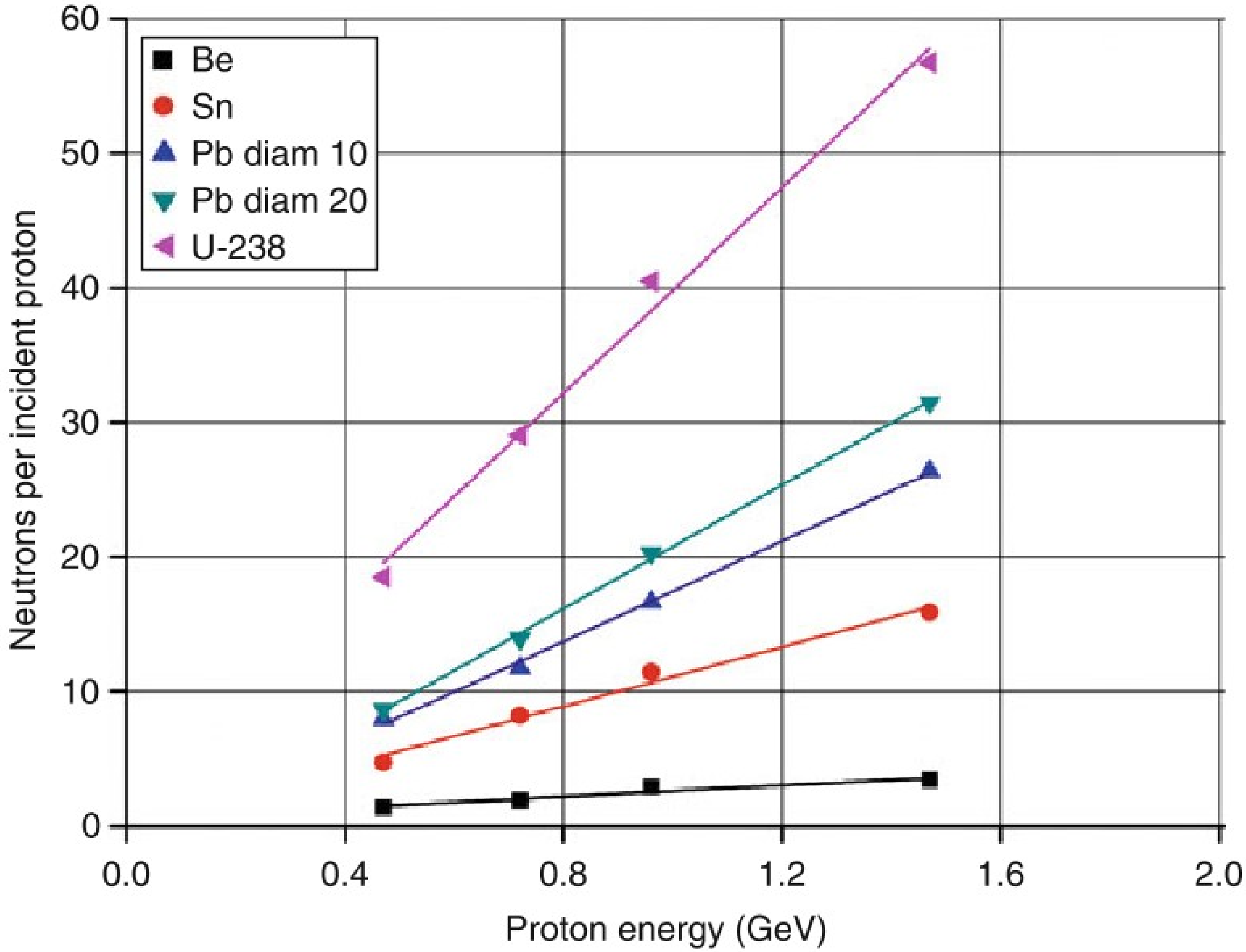
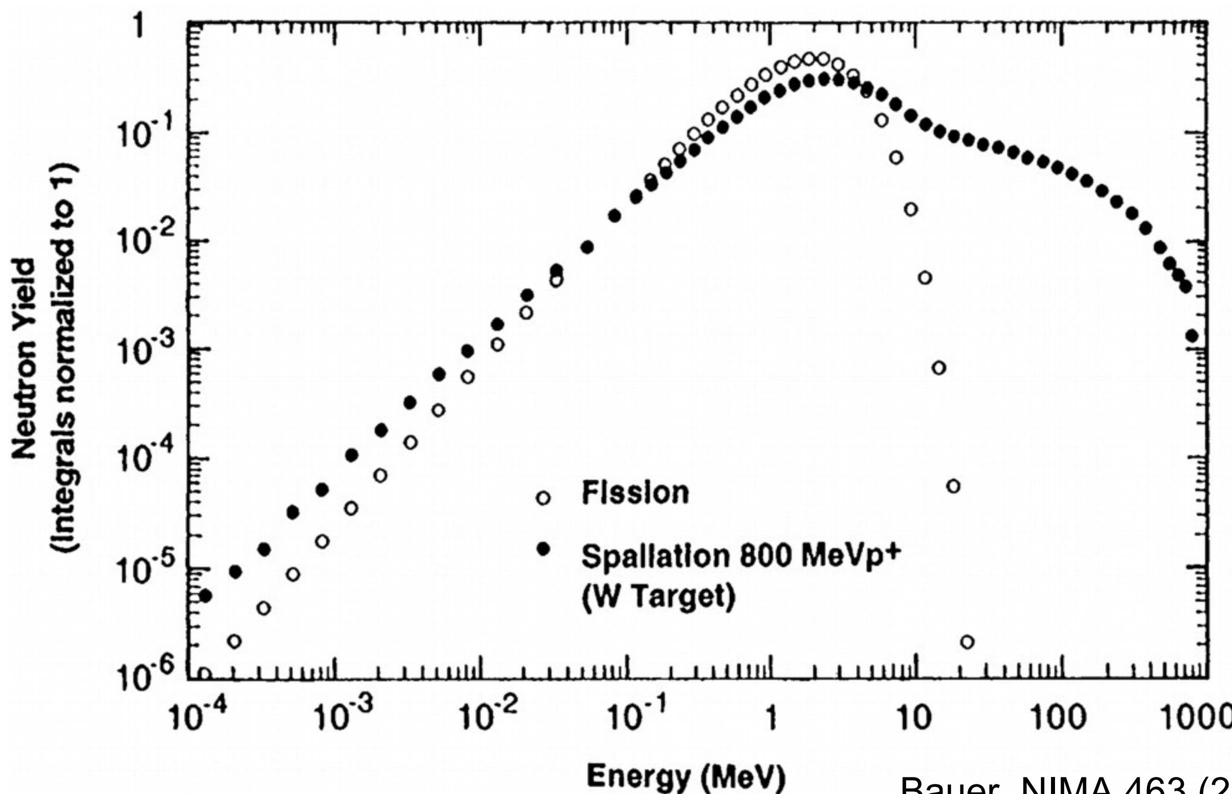


Fig. 2

Experimental fast-neutron yield *Y* for selected targets as a function of proton energy.

Primary Neutrons are Not Right…



Bauer, NIMA 463 (2001) 505–543

Fig. 3. Calculated neutron spectra for fission and for spallation in a tungsten target [1].

- **Both spallation and fission processes can be thought of as evaporating nucleons from excited nuclei – and steam is hot!**
- **Both emission spectra peak around 2 MeV, and more than 90% of both distributions lie between 0.1 and 10 MeV**

Not the Right Neutrons?

- **Primary NScD mission is neutron scattering: a technique for condensed matter research – looking at material where the interactions between atoms are important**
- **Diffraction shows structure of matter – how the atoms are arranged**
  - **Requires neutrons (or other particles) with de Broglie wavelengths similar to interatomic spacings: about 0.5 – 5 Å**
  - **Variations (SANS, reflectometry) can show much larger structures, up to micron-sized, using wavelengths of 10 – 30 Å**
- **Spectroscopy shows dynamics of matter – how the atoms move around and transfer energy, spin, etc., between themselves**
  - **Requires neutrons (or other particles) with energy comparable to molecular or crystalline excitations: 0.1 meV to 1000 meV**
- **Neutrons are good at seeing light atoms, especially hydrogen, and magnetism, and average over large volumes; they're not limited to surface effects**

Making the Neutrons Useful…

- **To do neutron scattering, we need**
  - **Neutrons between 10 eV and 0.1 meV**
  - **To know the energy of each neutron to some precision**
- **Time-of -flight techniques rely on approximation that all neutrons start out down a flight path at the same time**
- **Faster neutrons outpace slower neutrons, sorting themselves out over flight paths ranging from 2 to 200 m**
  - **The distribution in emission time must be much smaller than the flight time; tens of microseconds rather than tens of milliseconds**
  - **Difference between arrival and departure is time-of-flight, and gives velocity, which directly also gives energy and wavelength**
- **To make the neutrons "useful" for neutron scattering by time-of-flight, we remove almost all kinetic energy without destroying the starting time distribution**

Spectral Distributions

- **Individual neutrons have energy, *E***
- **Groups of neutrons have a distribution in energy; this is an energy spectrum, *f(E)*, and is intrinsically differential**
  - **The number of neutrons in *dE* about *E* is *f(E) dE***
- ***f(E)* can be a (spectral) flux, brightness, count rate, etc., and may have additional normalization (such as $\mathrm{MeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$)**
- **Some people like energy, some like wavelength; people also use velocity, wavevector, etc.**
  - **1 Å ~ 0.0818 eV ~ 3956 m/s ~ 6.28 1/Å**
- **To transform between different variables, we must keep the number of neutrons in that differential element the same!**

$$f(E)\,dE = f(\lambda)\,d\lambda = f(v)\,dv = f(k)\,dk$$

- **Generally bin in an observed variable to represent our measurement (counts in an energy bin, for example)**
  - **Expressing as "per bin" obscures important information if the bin size isn't constant – do the normalization!**

OAK RIDGE National Laboratory

Neutron Moderation

- **Neutron <u>moderation</u> is the process by which we remove about 99.99999% of the kinetic energy of the original source neutrons, bringing them to useful energies**
  - **At a short-pulsed source like SNS, we need to do this without destroying the sharp emission time distribution we need to take advantage of time-of-flight techniques**
- **<u>Slowing-Down</u> theory describes the loss of energy through repeated elastic collisions with effectively free nuclei**
  - **Loss of energy – "slowing-down" only until up-scattering is relevant**
  - **Free nuclei – "slowing-down" only runs through energies high enough that molecular / crystalline effects can be ignored**
  - **Elastic collisions – "overloaded" term; in nuclear physics / engineering, kinetic energy of the system is conserved, in neutron scattering, kinetic energy of the neutron is conserved**

Slowing-Down Theory

- **To slow neutrons down we bounce them off nuclei, turning neutron kinetic energy into recoil energy**
- **Important energy-loss parameters:**
  - **Minimum fraction left after a collision: Energy-loss ratio α**
  - **Fractional loss per collision: Mean logarithmic energy decrement ξ**
  - **Lighter nuclei require fewer collisions to slow the neutron**
- **The rate of collisions is just as important in slowing-down as amount of energy lost per collision**
  - **High macroscopic scattering cross section means collisions happen faster – comes from both microscopic cross section and number density**
- **Neutrons leak from the moderator as they slow down, forming neutron beams**

Slowing-Down in Practice

- **Energy loss per collision goes down with nuclear mass**
- **Rate of collisions goes up with higher scattering cross section**

	H_2O	Be	D_2O	C	Fe	Pb
α	-	0.64	-	0.72	0.93	0.98
ξ	0.93	0.21	0.51	0.16	0.04	0.01
Σ_s (1/cm)	1.50	0.87	0.37	0.38	0.96	0.37
Collisions to 1 eV	16	69	28	91	414	1450
Time to 1 eV (μs)	1.5	8.5	9.7	25	43	390

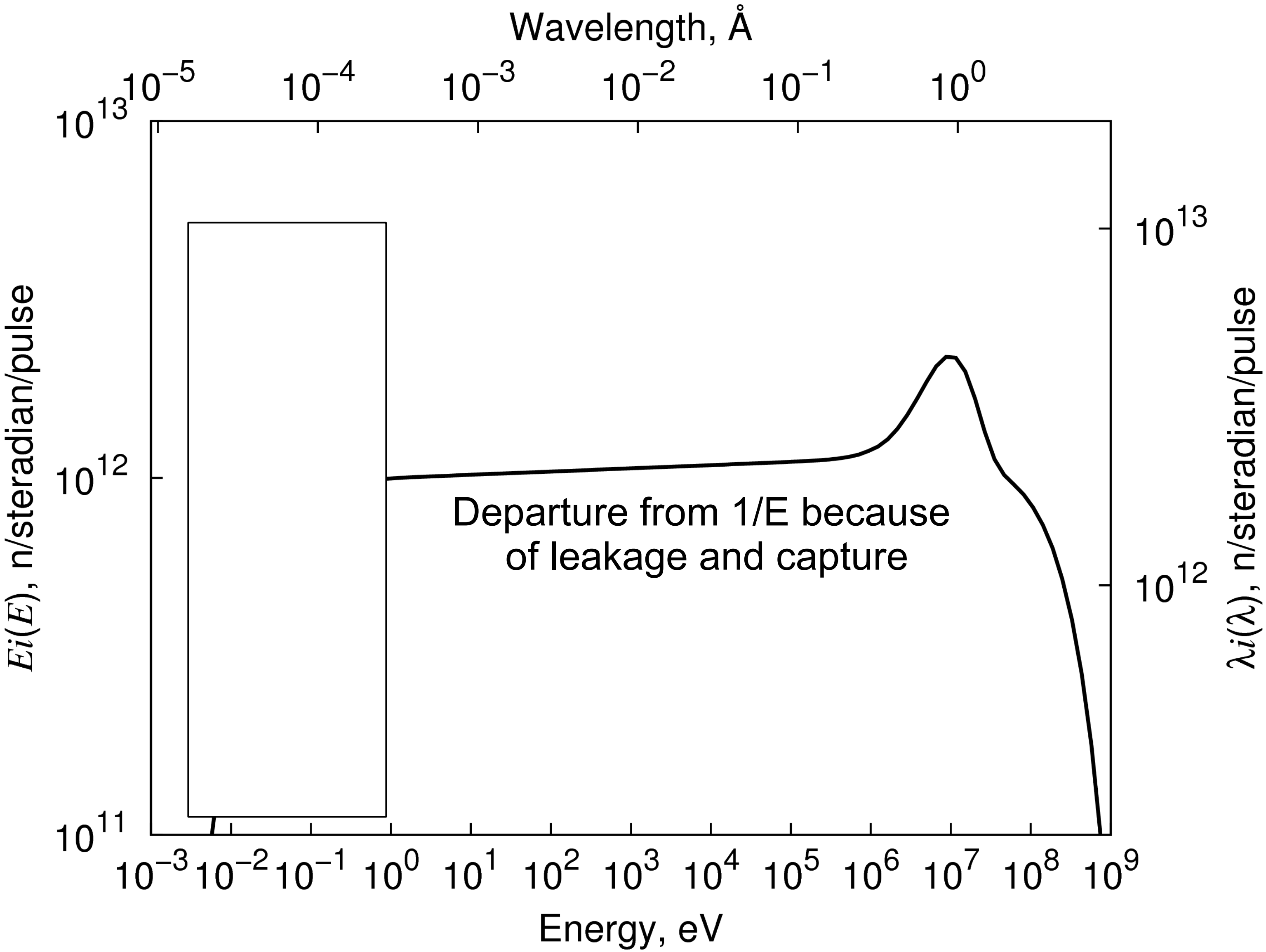
- **The quicker we slow down the neutrons, the less we corrupt the initial narrow time distribution that the accelerator guys work so hard to provide!**
- **Anything with high hydrogen density is fast, and can make a slow neutron from a single collision**
- **Water, beryllium, and heavy water are all good moderators**

Slowing-Down Units

- **Remove "about" 99.9999% of neutron energy**
  - **Nonsense: change to log-space; six orders of magnitude**
- **Neutron <u>lethargy</u> $u = -ln(E_{max}/E)$**
  - **Losing 99.9999% *E* is just gaining 13.8 lethargy units**
  - **Losing 99.999999% *E* means gaining 18.4 lethargy units**
  - **Just as crystallography makes better sense in reciprocal space, neutron physics is easier in lethargy space**
- **Some people like energy, some like wavelength; in addition to lethargy, people also use velocity, wavevector, etc.**
  - **1 Å ~ 0.0818 eV ~ 3956 m/s ~ 6.28 1/Å**
  - **Temperature is different – it applies to a distribution, not a single neutron**
- **Slowing-down leads to an (almost) *1/E* spectrum**
  - **$\varphi(E) \sim 1/E$ or $\varphi(u) = E\varphi(E) = \frac{1}{2}\lambda\varphi(\lambda) \sim constant$**

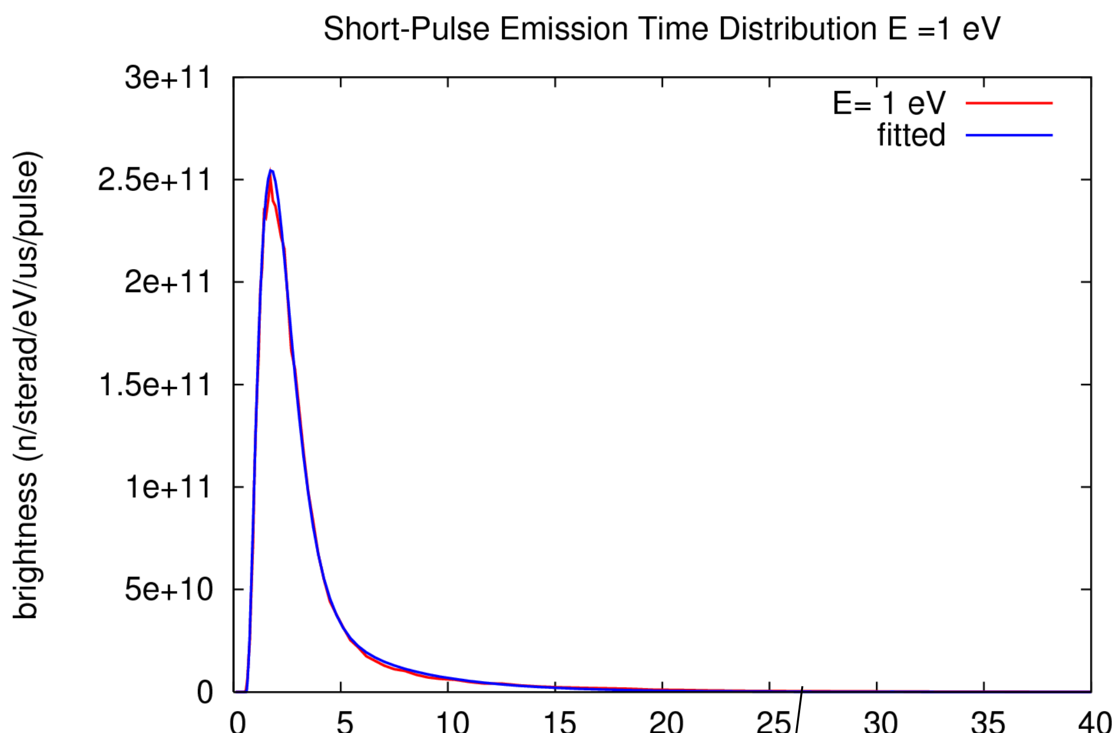
OAK RIDGE National Laboratory

Source & Slowing Down Spectrum



Slowing Down Speed

- A block of water (H_2O) next to our fast neutron source is the <u>moderator</u>, providing moderation
- For 1 eV neutron emission, we see an asymmetric distribution peaked at 1.0 μs with mean 1.5 μs and second moment 0.8 μs
- This is the <u>pulse shape</u>, or <u>emission time distribution</u>, one of the fundamental drivers of scattering instrument performance
- All time metrics for slowing down to an energy are inversely proportional to the velocity
  - e.g., peak neutron emission time is 5.3 μs/Å < 0.5 Å
  - Makes *t/λ* and *vt* useful

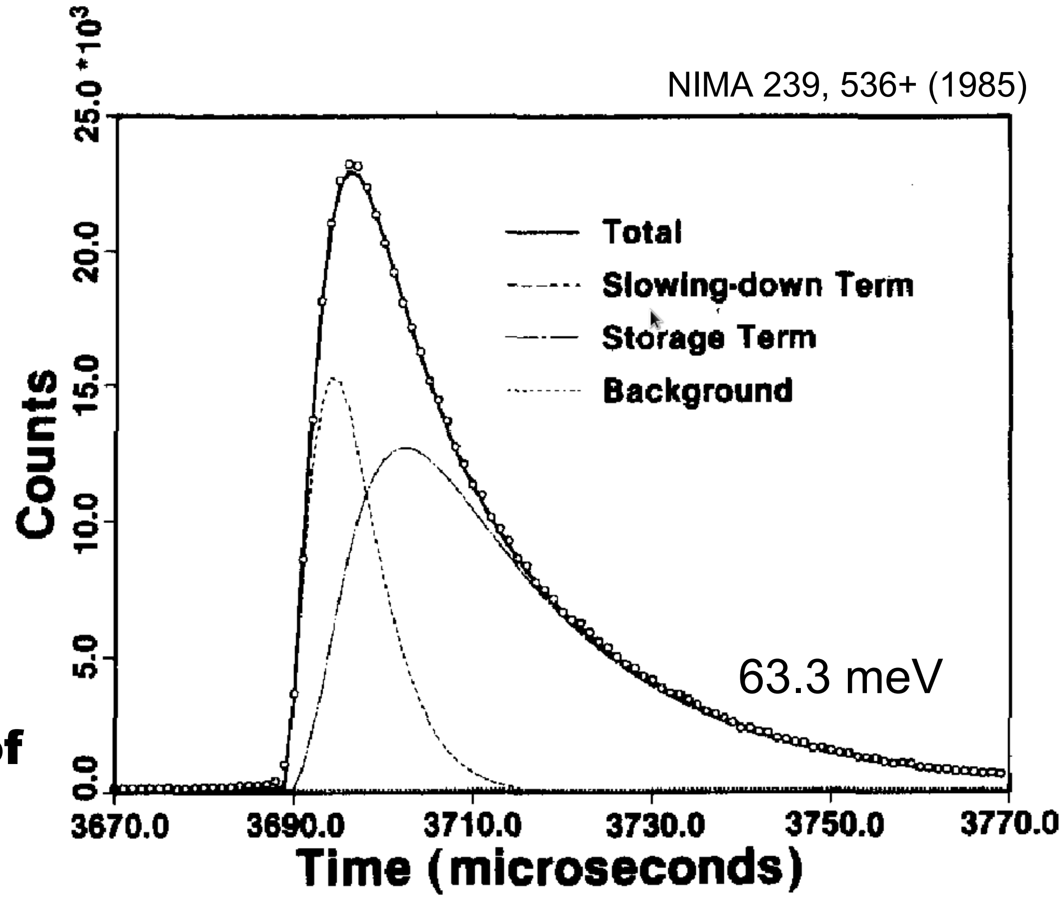


Calculated emission time distribution;
see Gallmeier, F. X. (2010), 'SNS Source Descriptions for Use with MCSTAS' (SNS-106100200-TR0195-R00), Technical report, Oak Ridge National Laboratory

Neutron Thermalization in Time

- Remove "another few 9s" in *E* (add 3-5 more lethargy units)
- Takes place with molecules, crystals, and liquids, not nuclei
- Start with the special case of thermalization
- Neutrons reach thermal equilibrium with the scattering material
- Slowing-down neutrons come out quickly
- Equilibrated population decays more slowly; all (low) energies having the same time response
- Overall emission is sum of slowing-down term and convolution of slowing-down term with exponential decay

NIMA 239, 536+ (1985)



Neutron Thermalization in Energy

- **Neutrons reach thermal equilibrium with the moderator material**
- **Neutron number density follows a Maxwell-Boltzmann distribution**
- **Characteristic temperature in emitted beam is shifted up by diffusion heating**
  - **Scattering cross section increases with decreasing energy, so higher-energy neutrons can more easily leave the moderator**
- **Neutrons are "stored" in the system as they bounce back and forth, diffusing to the surface of the moderator and escaping**

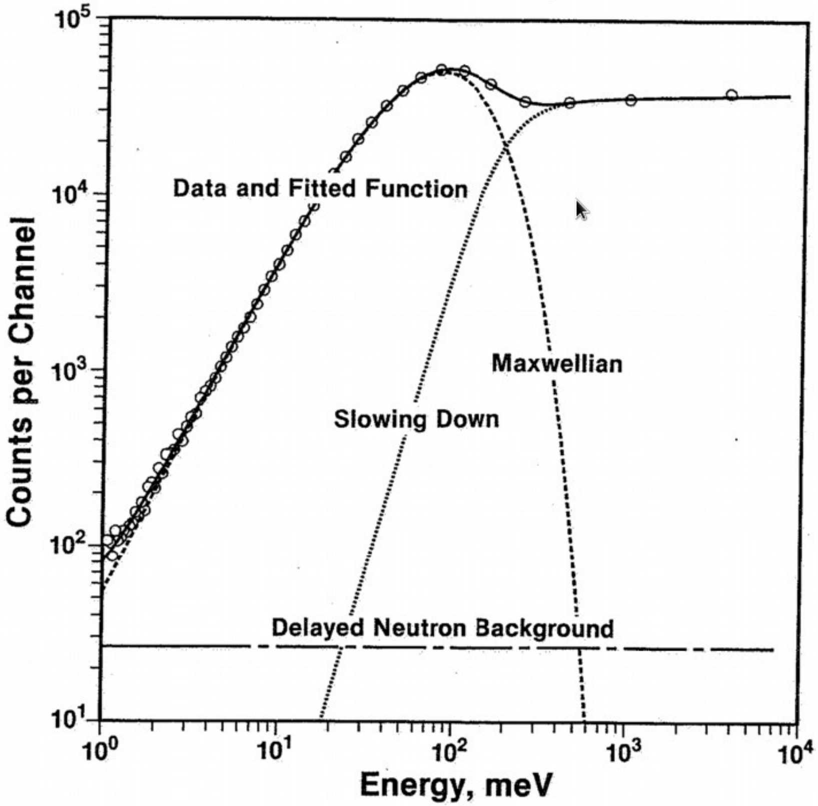
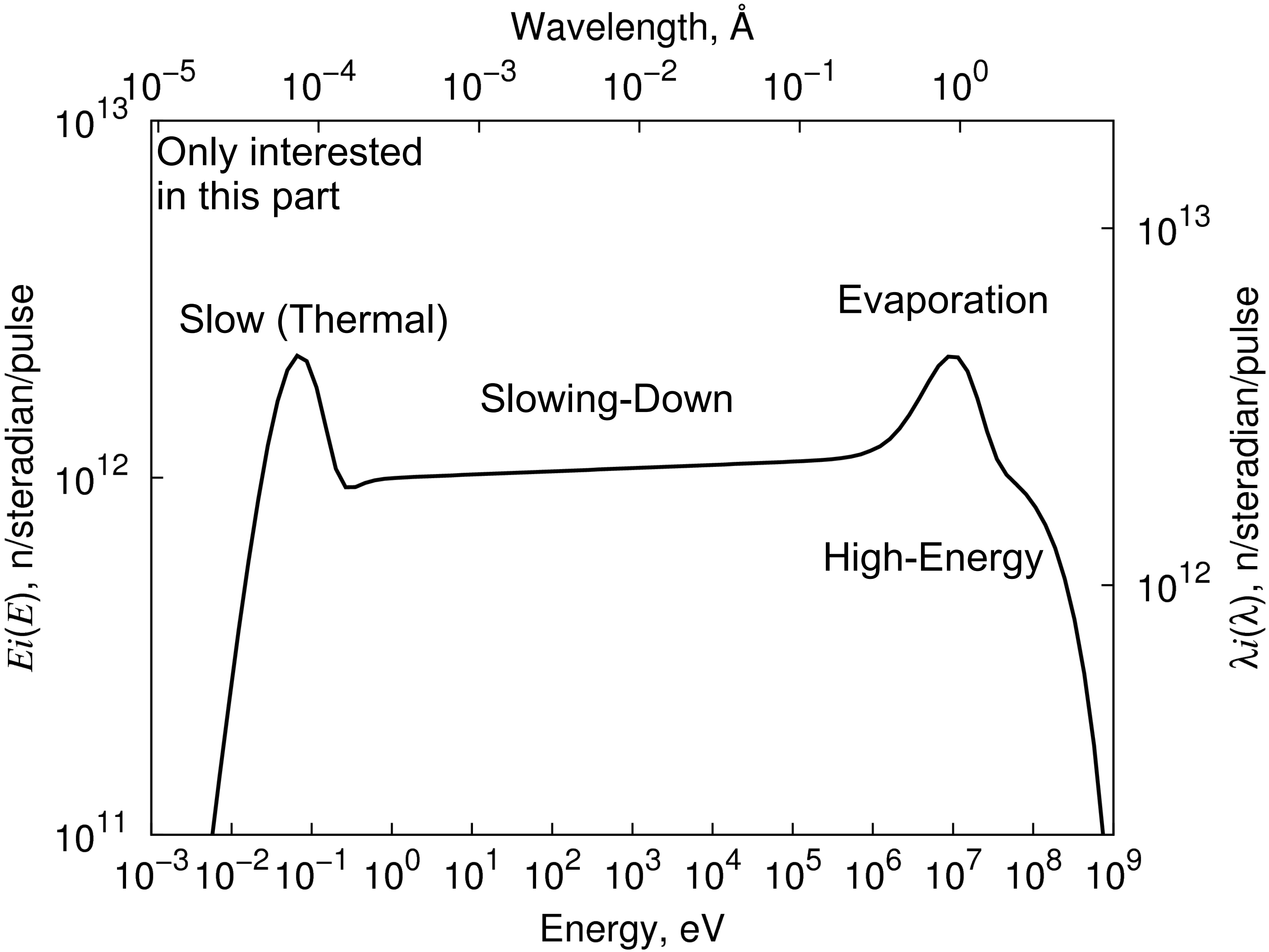


FIG. 35. The counting rate in a $1/v$ detector, proportional to the beam current per unit lethargy $Ei(E)$, for a heavily irradiated ambient-temperature polyethylene moderator. The

Carpenter, J. M. & Yelon, W. B. (1986), *Neutron scattering*, Academic Press, Inc., chapter 2. Neutron Sources, pp. 99-196.

Overall Source Spectrum



Don't Say Flux…

- **When people say flux, they usually mean:**
  - **“something proportional to the rate of Good Neutrons”**
  - **Not meaningful without energy, area, divergence, etc.**
- **Formal definition of flux is rate of neutrons of all energies passing through a sphere of unit cross sectional area**
  - **Velocity-weighted integral of number density in said sphere**
    - $\varphi = \int v\, n(v)\, dv = \int \varphi(v)\, dv$
    - **For a beam, this is the same as the rate per unit area across the beam**
    - **Even using spectral flux, still missing a divergence range**
- **Consider instead the instantaneous spectral <u>brightness</u>; *n/cm²/ster/eV/s* – it is a completely differential quantity, and fully specifies the phase space density of neutrons**
  - **Just like the proton phase space density discussed earlier**
  - **As a thermodynamically conserved quantity, it can only be increased by doing work on the system (like moderation)**

OAK RIDGE National Laboratory

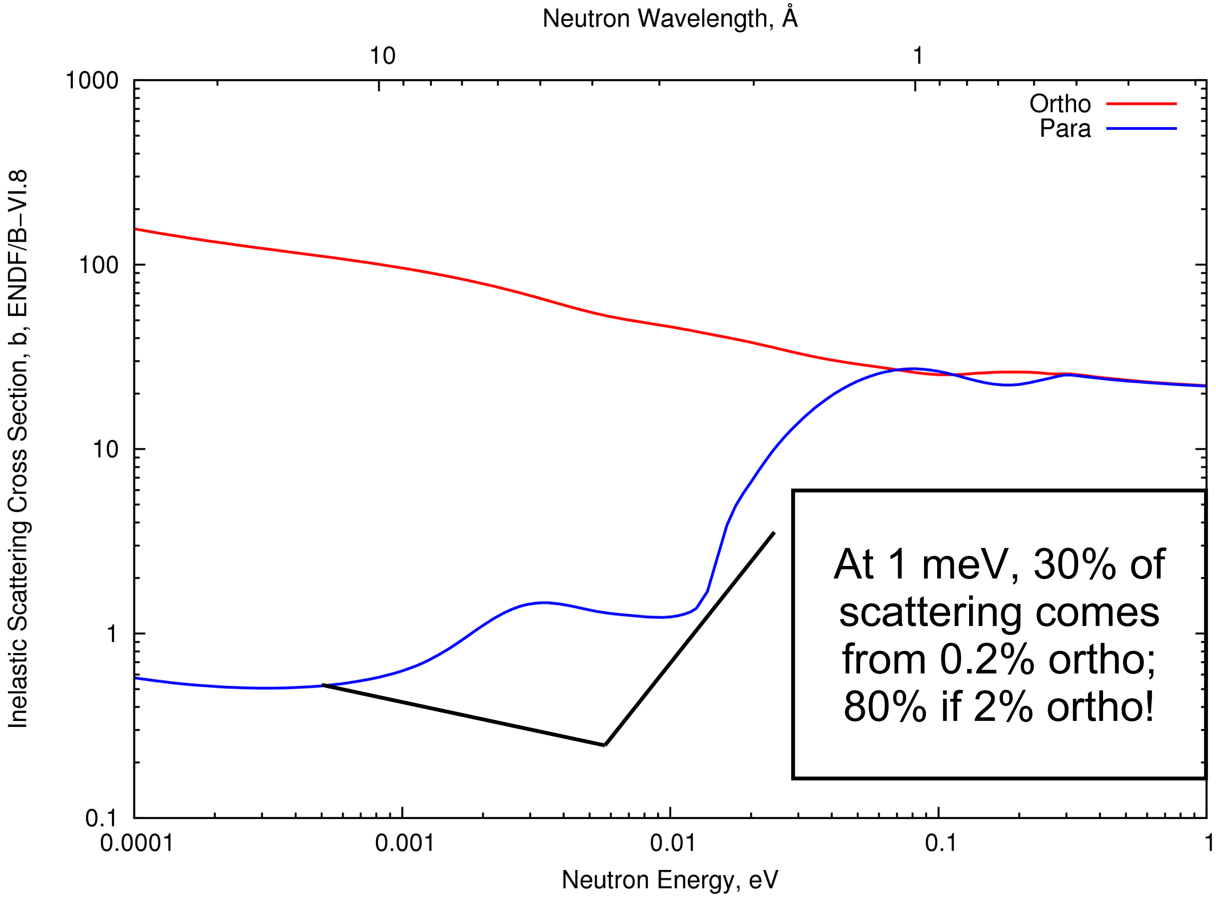
Maxwellian Distributions and Units

- **Maxwellian distribution (energy spectrum) has characteristic temperature *T*, corresponding to a peak energy $E_T = k_B T$**
  - **Transform to wavelength spectrum; $\varphi(\lambda) = \varphi(E)\, dE/d\lambda$ and you find that it peaks at the wavelength corresponding to energy 5/2 $k_B T$**
  - **The energy peak, velocity peak, and wavelength peak all happen at different values**
  - **The neutron having mean energy isn't the same as the neutron having mean wavelength**
- **Maxwellian distributions do make it easy to predict trends**
  - **Reducing spectral temperature by 1% increases low-energy spectral intensity by 2%**
  - **Low-*E* spectra goes as *1/E***
  - **Long-λ spectra goes as $1/\lambda^5$**
- **Maxwellian spectra from moderator changed by guides…**

Moderator Size and Poisoning

- **As a moderator gets bigger, the slowing-down process doesn't change much, but the thermalization process does:**
  - **The Maxwellian temperature remains same**
  - **The Maxwellian scale factor goes up**
  - **The emission time distribution grows wider, and the exponential tail slower**
- **We add <u>poison</u> to limit the volume participating in the thermalization process even in a larger moderator**
  - **A 50 mm thick moderator poisoned at 25 mm has higher intensity with the same pulse width as a 25 mm moderator**
- **The best poisons are gadolinium, cadmium, etc., with cut-off style absorption cross section**
- **Water with 25 mm poisoning has 35 μs FWHM below 20 meV**
- **“Infinite” water around target stores neutrons for a long time; FWHM around 300 – 500 μs – won't work for all applications**
- **At SNS, poison burn-up limits the life of some components**

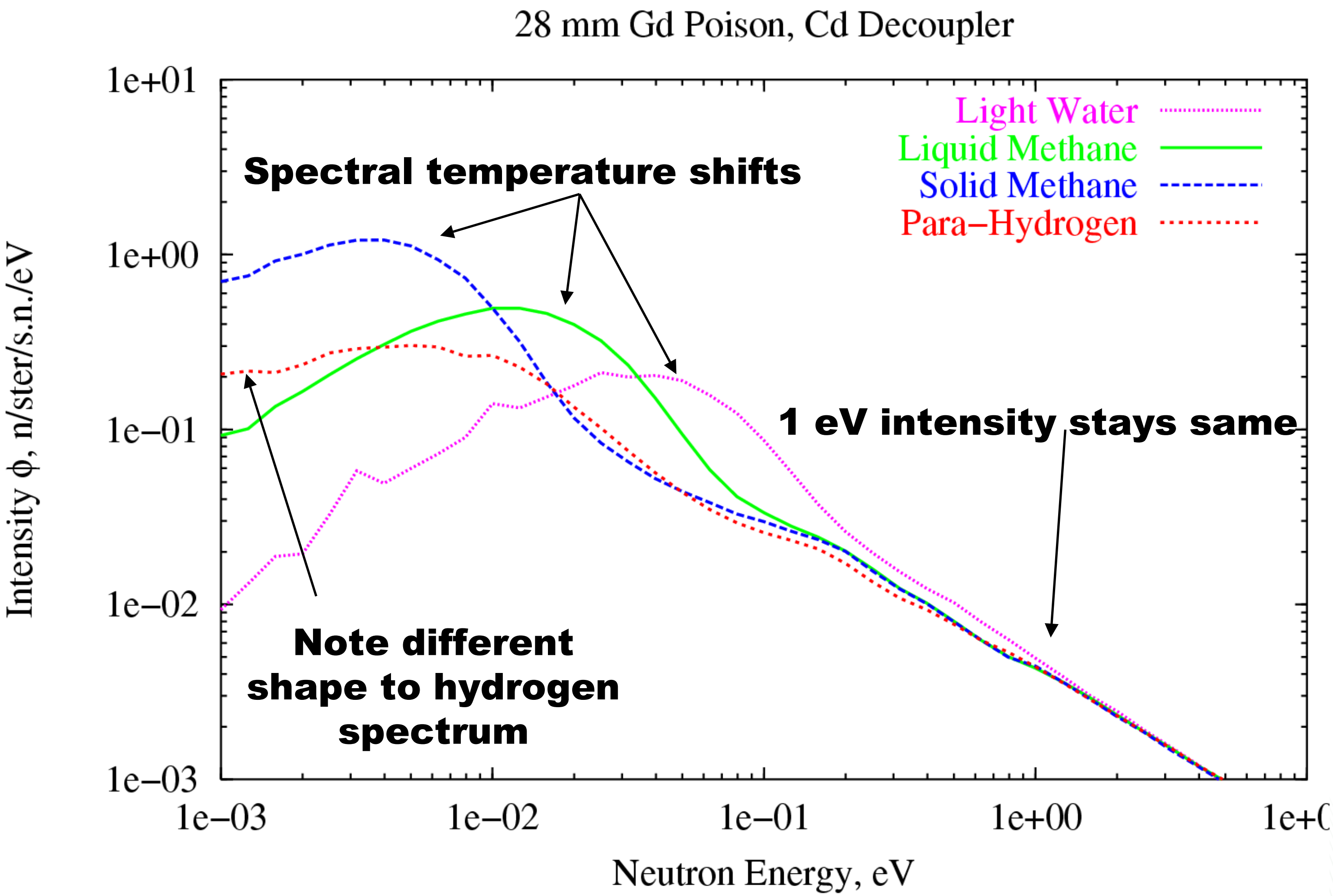
Non-Thermalizing Moderators



- **But most moderators at SNS are NOT thermalizing moderators**
- **Parahydrogen lets neutrons leak out without thermalizing**
- **One example of a LEAKAGE moderator**

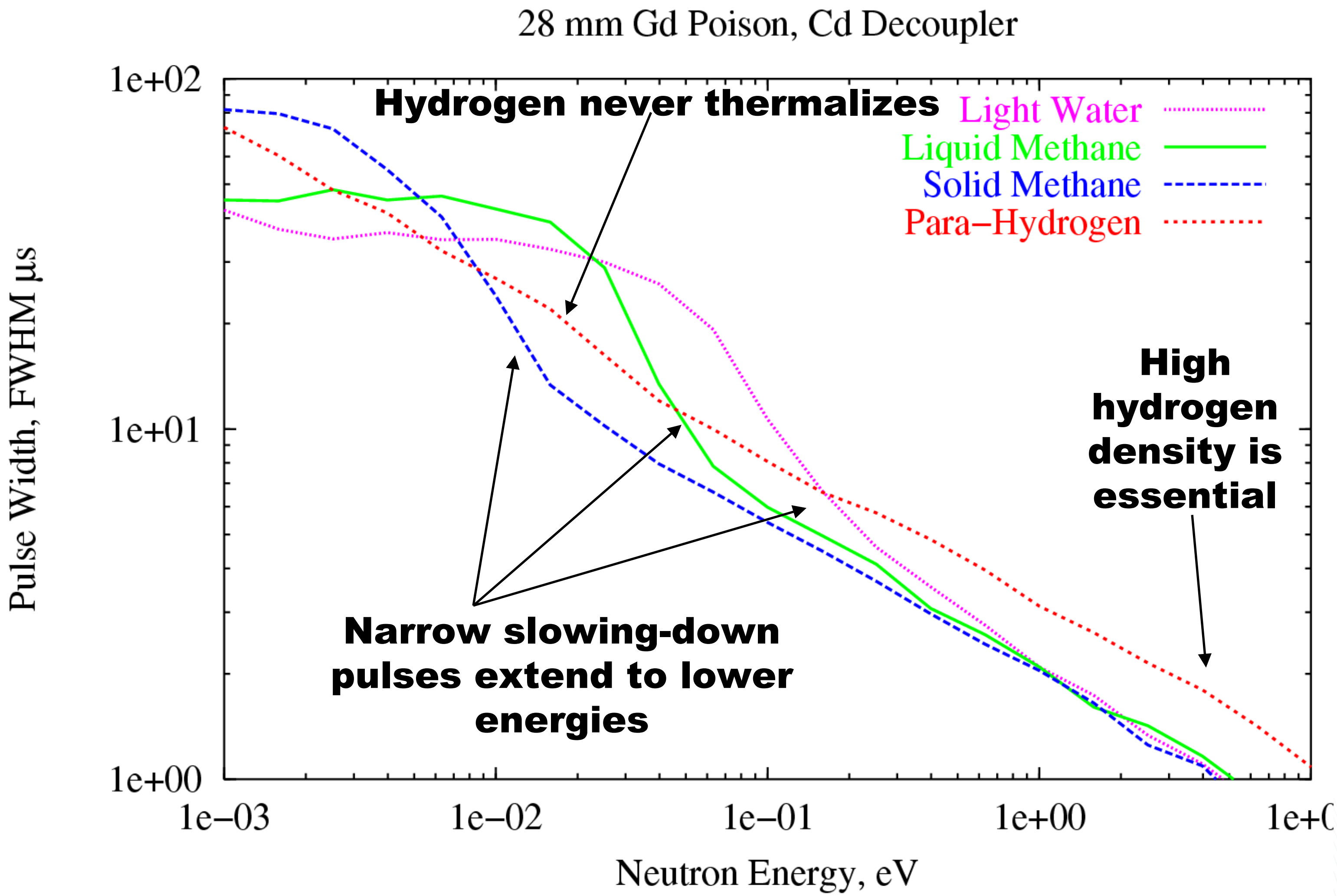
OAK RIDGE National Laboratory

Cold Moderators – More at Low Energies



Changing from 300 K to 20 K increases 1 meV intensities by factor 80

Cold Moderators Extend Sharp Pulses



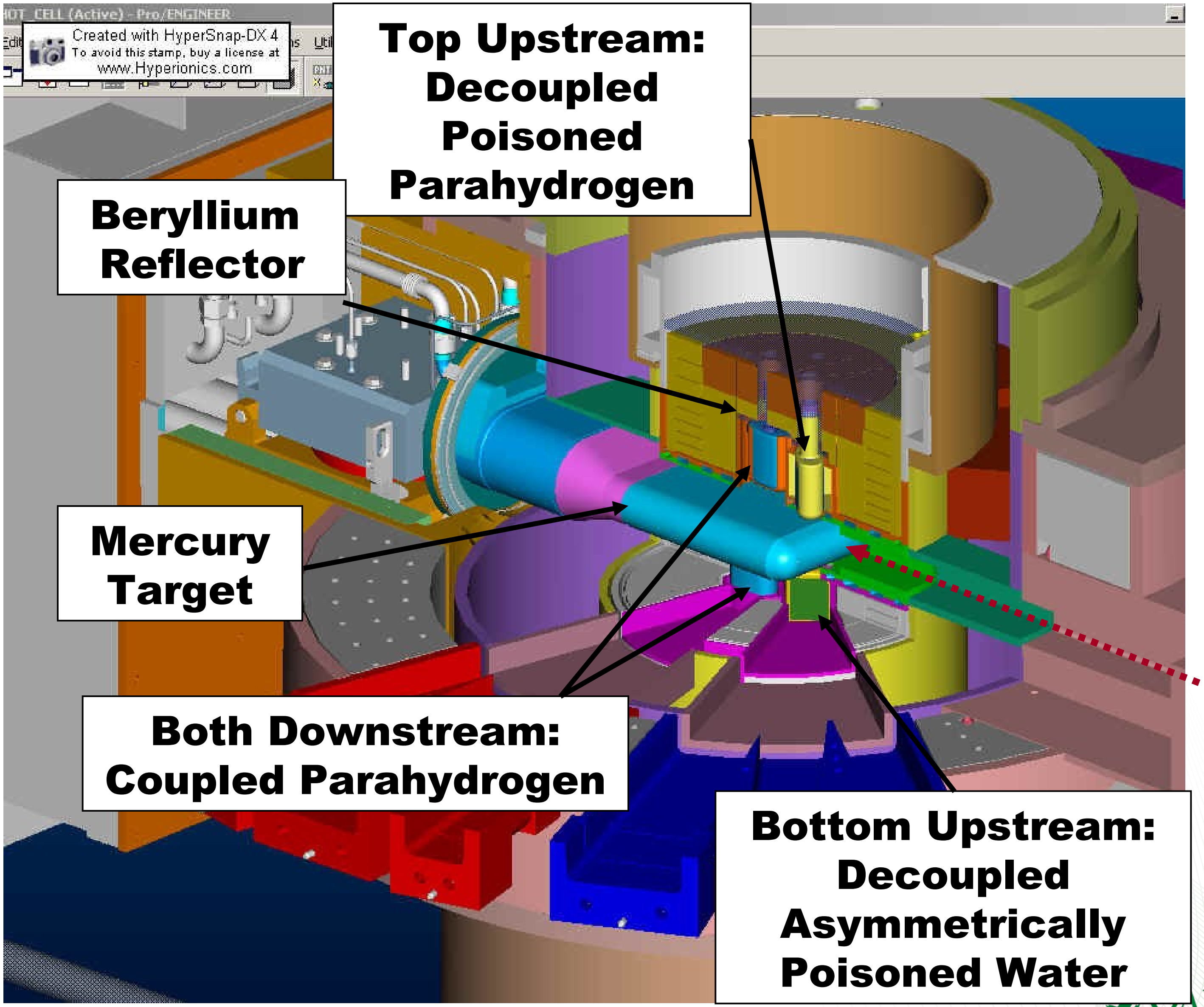
Intensity / FWHM² at 20 meV is best for coldest moderator, where the pulse width is still in slowing-down behavior, even though it's 5x less intensity

OAK RIDGE National Laboratory

Reflectors and Decoupling

- **Moderator so far:**
  - **Light water block 100 mm by 120 mm by 50 mm**
  - **Poisoned at 25 mm out of 50 mm**
- **No other material allowed; thermalization in shielding / room extends pulse widths by orders of magnitude**
  - **Not practical – we need shielding**
  - **Not efficient – most neutrons miss the moderator**
- **A <u>reflector</u> surrounds the moderator and the target:**
  - **Returns neutrons that miss the moderator or leave in the wrong direction to get another chance**
  - **Provides moderation**
- **Can be decoupled from moderators to prevent long-lived slow neutrons from corrupting pulse shapes**
  - **Decoupling happens in energy, even though needed in time**

The Target-Moderator-Reflector Assembly



OAK RIDGE
National Laboratory

Detailed Performance Calculations

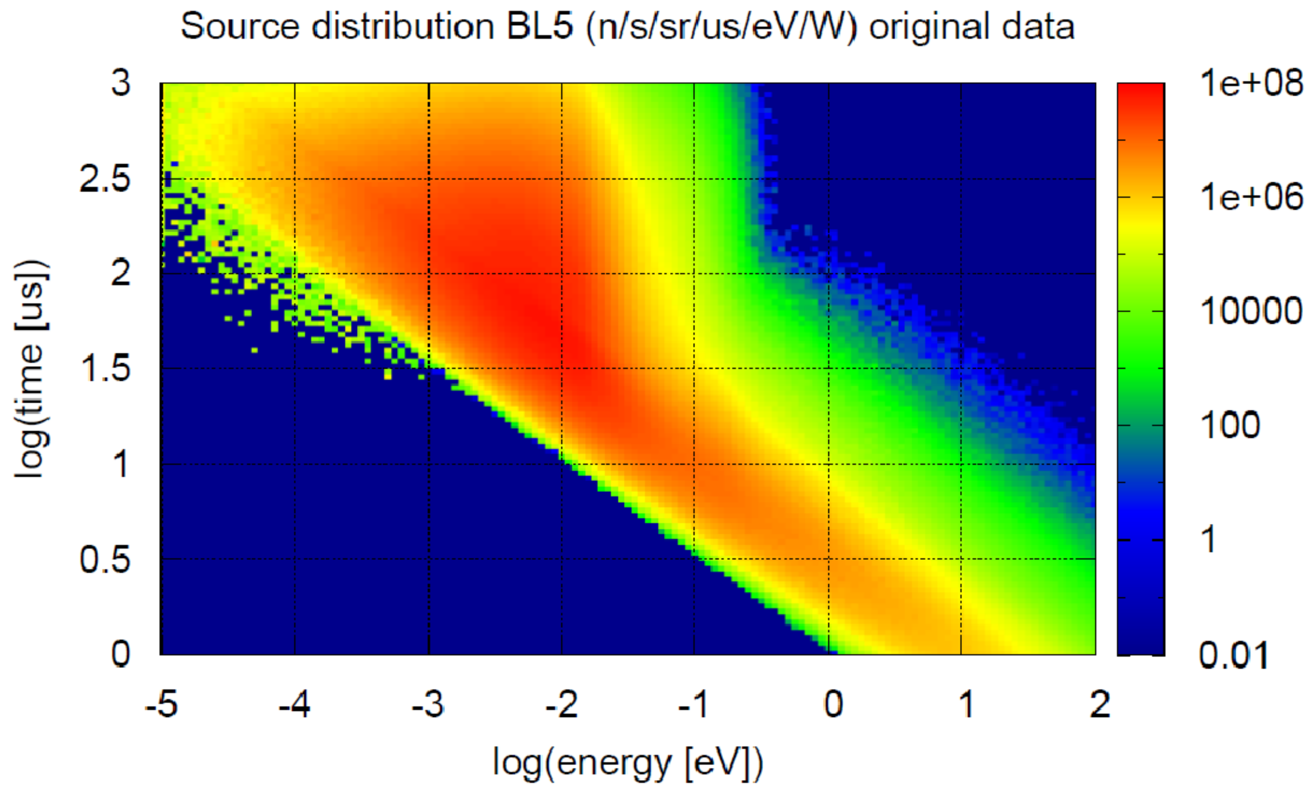


Fig. 12: Short-pulse emission time distributions for the coupled top downstream SNS hydrogen moderator on linear (at top) and logarithmic (at bottom) scale as simulated by Wei Lu with MCNPX [2].

Gallmeier, F. X. "SNS Source Descriptions for Use with MCSTAS," SNS-106100200-TR0195-R00, Oak Ridge National Laboratory, 2010

Neutronics team uses MCNPX to simulate detailed pulse shapes and spectra for SNS moderators to be used for instrument design, as well as shielding calculations, activation, radiation damage, and energy deposition estimates

OAK RIDGE National Laboratory

Ideas to Take Away

- Primary neutrons have too much energy for neutron scattering
- Neutron scattering needs knowledge of every neutron's energy
- Time-of-flight with a pulsed source requires reducing neutron energies to useful ranges without corrupting the “short-pulsed” character
- Moderation is how we reduce neutron energies to the desirable range
- Moderators moderate the neutrons and provide the neutron beams
- Reflectors send misdirected neutrons back to the moderator for another chance at being useful (and also provide additional moderation)
- Decouplers prevent long-lived populations of low-energy neutrons in the reflector from returning back to the moderator
- Poisons control the exact time-response of the moderator

OAK RIDGE National Laboratory

Further Reading

Bauer, G. S. (2001), 'Physics and technology of spallation neutron sources', *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **463**(3), 505--543.

Carpenter, J. M. (1977), 'Pulsed spallation neutron sources for slow neutron scattering', *Nuclear Instruments and Methods* **145**(1), 91--113.

Carpenter, J. M. & Loong, C.-K. (2015), *Elements of Slow Neutron Scattering*, Cambridge University Press.

Conrad, H. (2012), Spallation - Neutrons Beyond Nuclear Fission, *in* Claus Grupen & Irène Buvat, ed., 'Handbook of Particle Detection and Imaging', Springer Berlin Heidelberg, , pp. 719--757.

Filges, D. & Goldenbaum, F. (2010), *Handbook of Spallation Research*, Wiley-VCH Verlag GmbH & Co. KGaA.

Watanabe, N. (2003), 'Neutronics of pulsed spallation neutron sources', *Reports on Progress in Physics* **66**(3), 339--381.

Willis, B. T. M. & Carlile, C. J. (2013), *Experimental Neutron Scattering*, Oxford University Press.

Windsor, C. G. (1981), *Pulsed neutron scattering*, Taylor & Francis, Ltd..

OAK RIDGE
National Laboratory