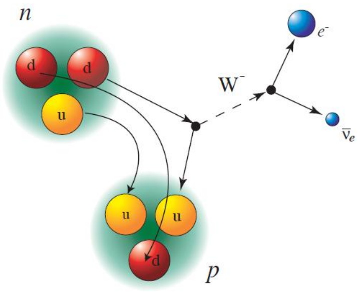
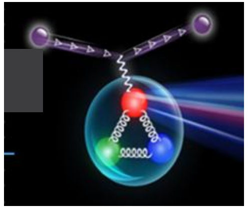
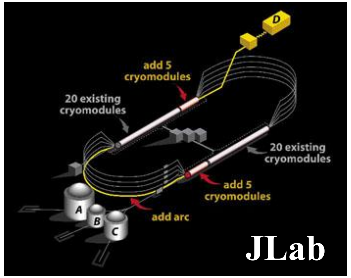
Neutrons and Where to Find them
(Fundamental Symmetries)

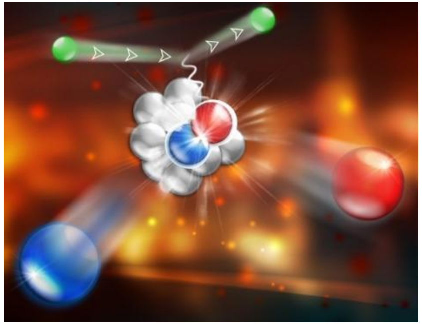
Nadia Fomin – HUGS 2025



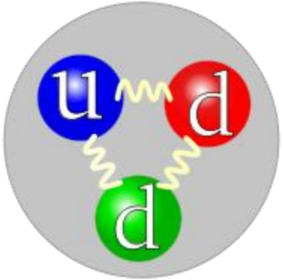


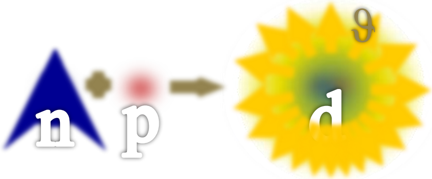


- Short-range nucleon-nucleon behavior
- Nuclear medium effects

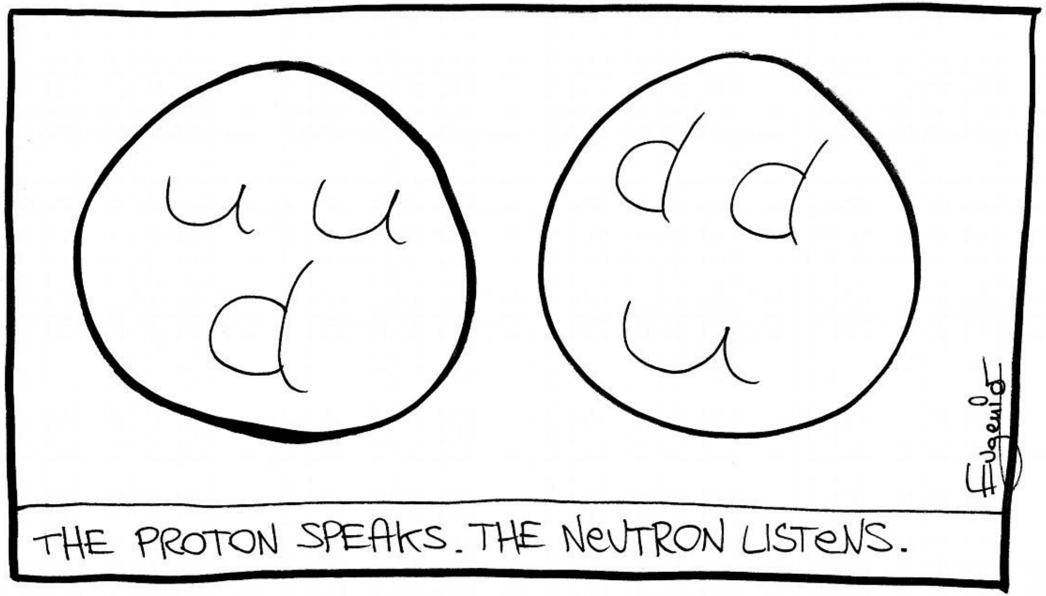


Fundamental Neutron Physics





What is neutron physics ?



Research which uses “low energy” neutrons from nuclear reactors and accelerator-driven spallation sources to address questions in nuclear, particle, and astrophysics

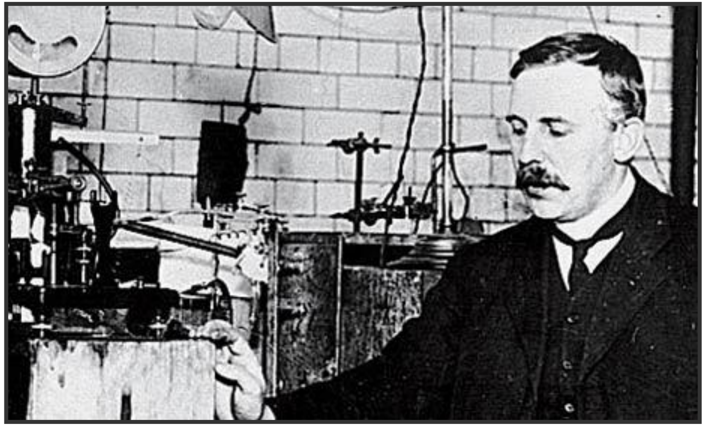
Why so neutral and unstable?

- Rutherford (1920) observed that atomic mass differs from atomic number and that electromagnetism would not bind a group of positively charged protons.
- Suggested the existence of a heavy neutral particle that was a tightly bound combination of an electron and proton, meaning:

$$M_n < M_p + M_e$$

Under some circumstances…… it may be possible for an electron to combine much more closely with the H nucleus, forming a kind of neutral doublet. Such an atom would have very novel properties. Its external field would be practically zero, and in consequence it should be able to move freely through matter..."

Bakerian Lecture, 1920



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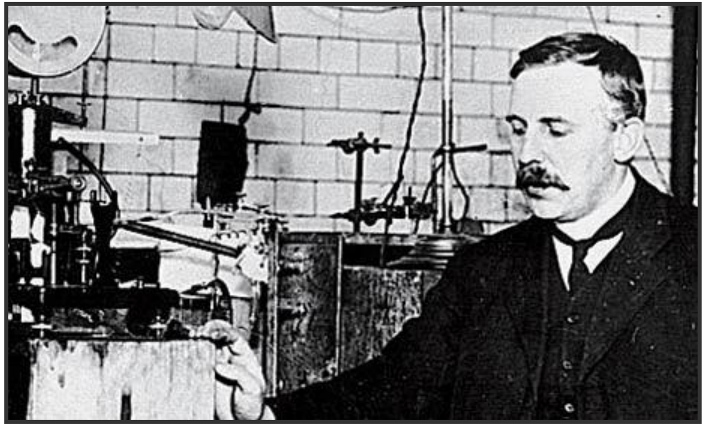


If true, would be impossible for the neutron to spontaneously decay into a proton and electron

A neutral radiation

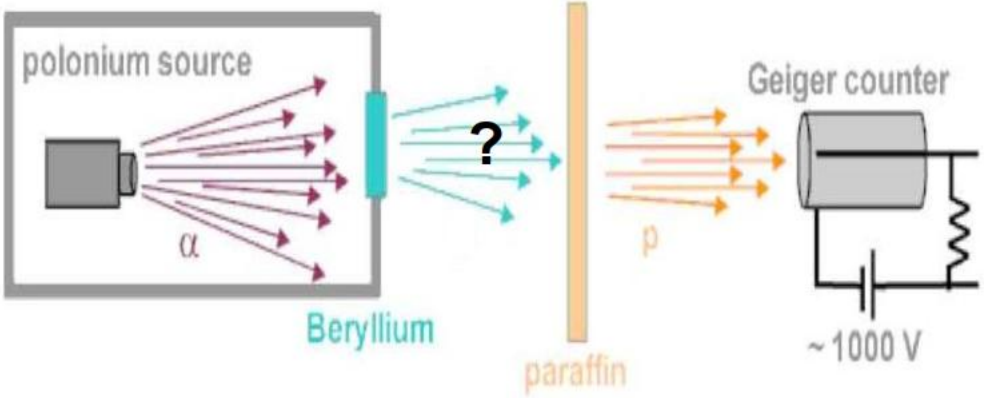
Walter Bothe

1930 *Bothe and Becker discover a penetrating, neutral radiation when alpha particles hit a Be target.*

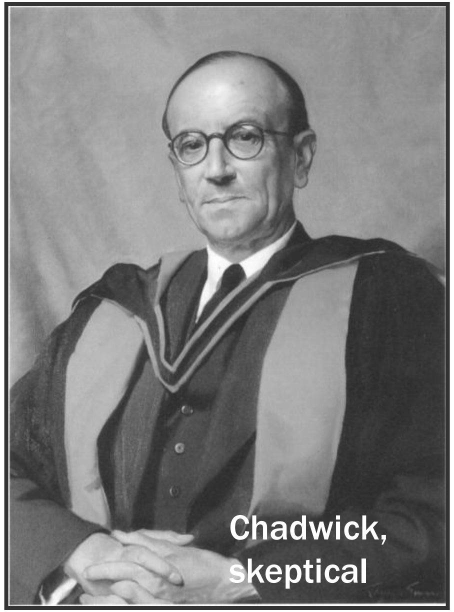
$$\alpha + {}^{9}Be \rightarrow {}^{12}C + n$$

1931 *Mme Curie shows that they are not gamma rays and they have sufficient momentum to eject p's from paraffin.*

Irene Curie



Idea of neutron as an elementary particle was met with skepticism

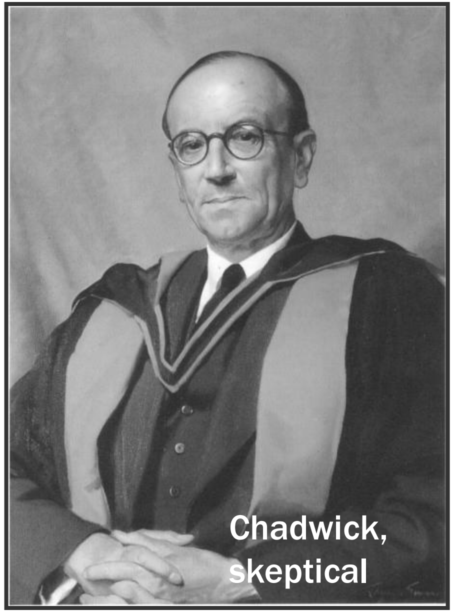


"It is, of course, possible to suppose that the neutron may be an elementary particle. This view has little to recommend it at present."

-Chadwick, 1932 Proc. Roy. Soc., A ***136*** *692*

(same year as he discovered the neutron)

Idea of neutron as an elementary particle was met with skepticism



Chadwick replaced the paraffin with a variety of other targets and measured the recoil energies of the ejected particles → was able to solve for the mass of the mystery neutron particle

Said it must be "Rutheford's Neutron"

1933: Bainbridge makes precision measurement of the atomic masses of the proton and the neutron using a mass spectrograph

1934: Chadwich and Goldhaber make the first "precision" measurement of the neutron mass via photo-disassociation of the deuteron

1935: M_n=1.0090 amu

M_H=1.00081 amu

$$M_n > M_p + M_e$$

First serious suggestion of neutron decay

1948: Observation of neutron decay by Snell and Miller

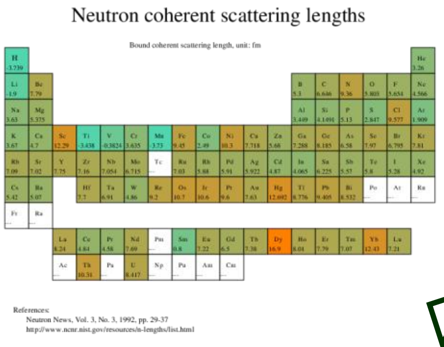
PHYSICAL REVIEW VOLUME 74, NUMBER 9 NOVEMBER 1, 1948

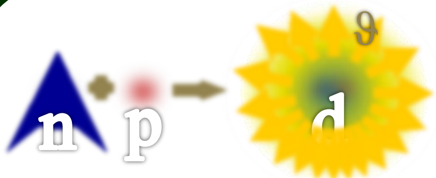
Proceedings of the American Physical Society

Minutes of the Meeting at Washington, April 29 to May 1, 1948

F12. On the Radioactive Decay of the Neutron. ARTHUR H. SNELL AND L. C. MILLER, *Clinton National Laboratories.*—A collimated beam of neutrons, three inches in diameter, emerges from the nuclear reactor and passes axially through a thin-walled, aluminum, evacuated cylindrical tank. A transverse magnetic field behind the thin entrance window cleans the beam of secondary electrons. Inside the vacuum, axially arranged, an open-sided cylindrical electrode is held at +4000 volts with respect to ground. Opposite the open side a smoothed graphite plate is held at −4400 volts. The field between these electrodes accelerates and focuses protons which may result from decay of neutrons, so that they pass through a $2\frac{7}{8}\times 1\frac{5}{8}$ inch aperture in the center of the graphite plate, and strike the first dynode of a secondary electron multiplier. The first dynode is specially enlarged so as to cover the aperture. Readings are taken (1) with and without a thin B^{10} shutter in the neutron beam; (2) with and without a thin foil over the multiplier aperture; (3) with and without the accelerating voltage. In a total counting rate of about 300 per min., about 100 are sensitive to operations (1), (2), and (3). In the absence of the accelerating field or with the foil (2) in, operation (1) does not change the counting rate. Assuming all of the 100 c.p.m. to be due to decay protons, preliminary estimates of the collecting and counting efficiency (10 percent) and of the number of neutrons in the sample (4×10^4) give for the neutron a half-life of about 30 minutes. It is at present much safer however to say that the neutron half-life must exceed 15 minutes. Coincidences are presently being sought between the disintegration betas and the collected protons.

Strong Force

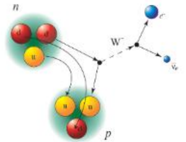


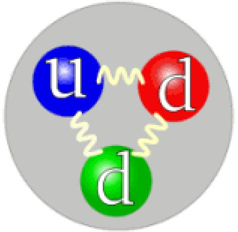


Weak Force

-neutron beta decay

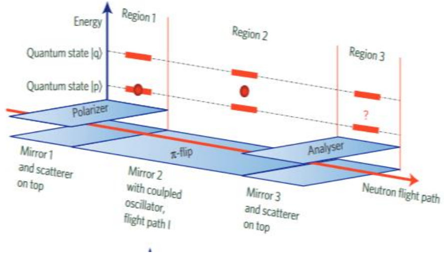
-hadronic weak interaction



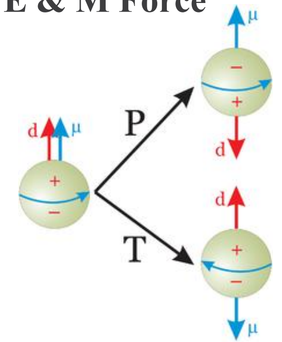


Neutron

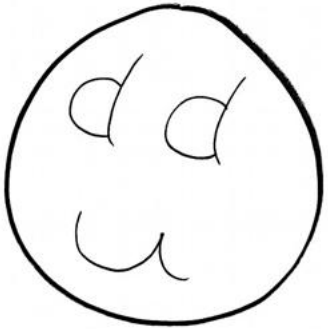
Gravity



E & M Force



Neutron Properties



Electric charge: q_n=0, electrically neutral [$q_n<10^{-22}$e]

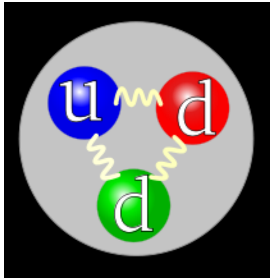
Size: r_n~10^{-5}Angstrom=1 Fermi [area~ 10^{-25} cm^2=0.1 "barn"]

Internal Structure: quarks [ddu, m_d~ m_u~few MeV] + gluons

Spin: s_n= 1/2 [Fermi statistics]

Magnetic Dipole Moment: μ_n/μ_p = -0.68497935(17)

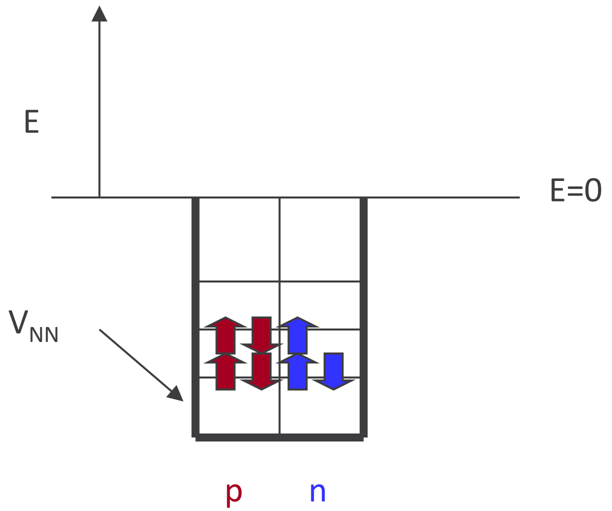
Electric Dipole Moment: zero[$d_n < 10^{-26}$ e-cm]

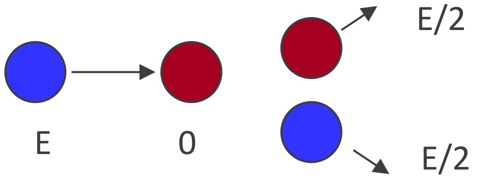


Mass: m_n=939.566 MeV [$m_n > m_p + m_e$, neutrons can decay]

Lifetime: τ_n=880ish (depends on whom you ask)

Neutrons are hard to get





Neutrons are bound in nuclei, need several MeV for liberation

We want $E \sim kT \sim 25\ meV$ (room temperature)

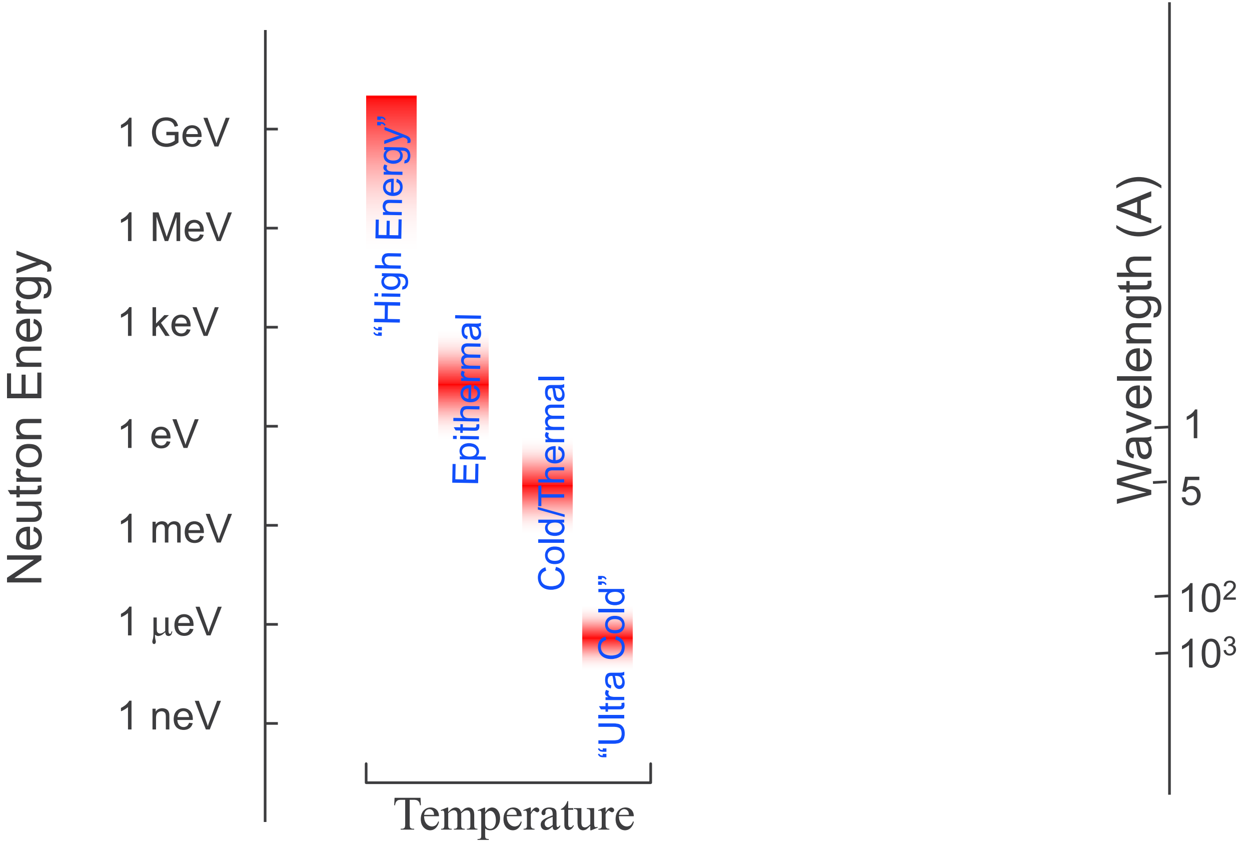
How to slow down a heavy neutral particle with $M_n = M_p$? Lots of collisions…

For N collisions

$$\left(\frac{1}{2}\right)^N = \frac{1\ MeV}{25\ meV}$$

Neutrons are unstable when free → they can't be accumulated easily

Neutron Energies and Applications



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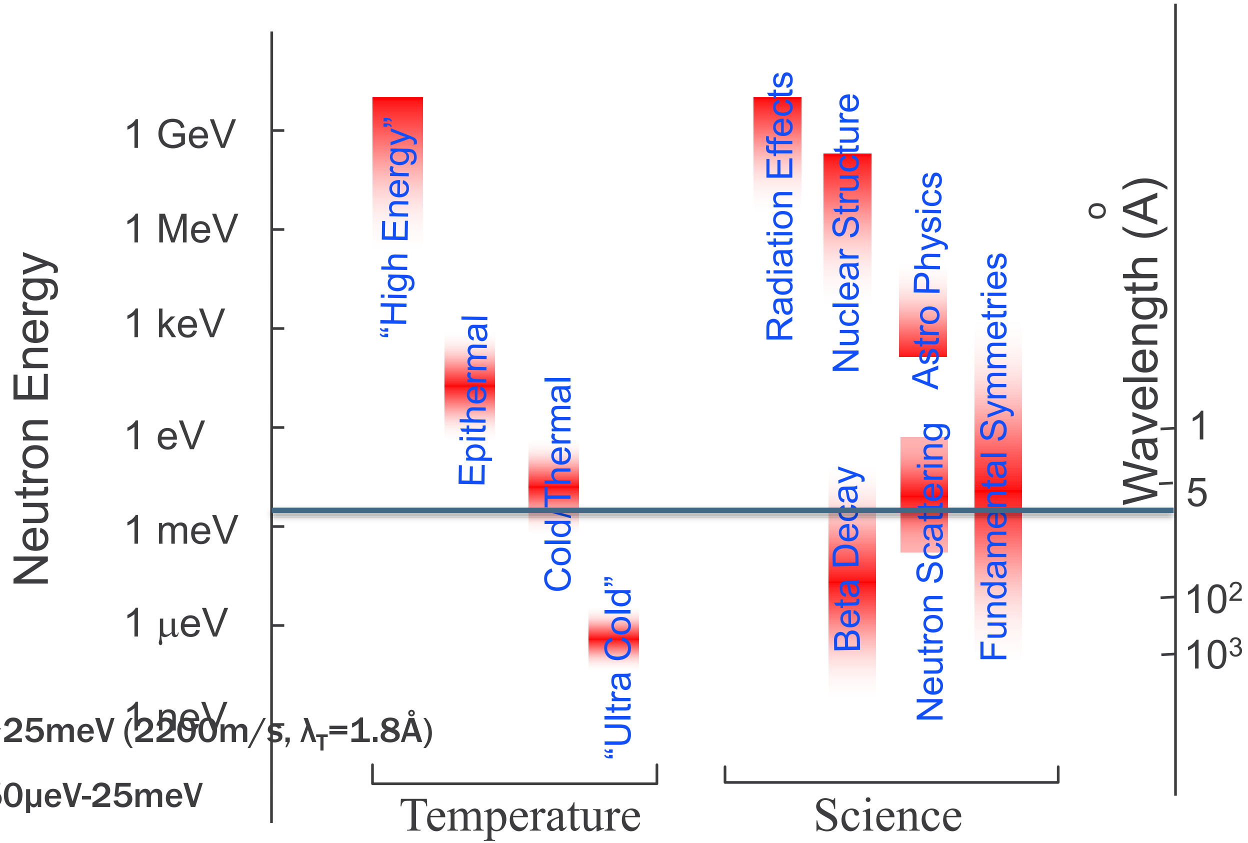
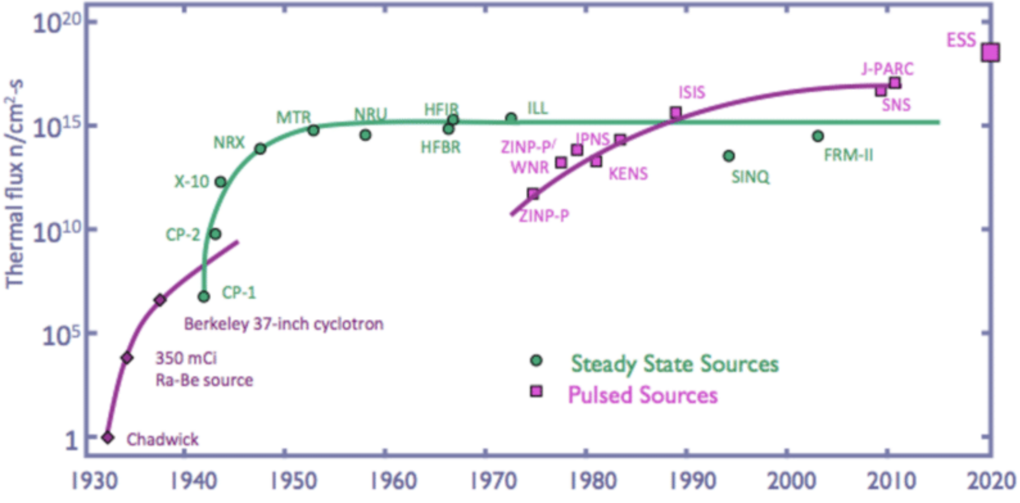
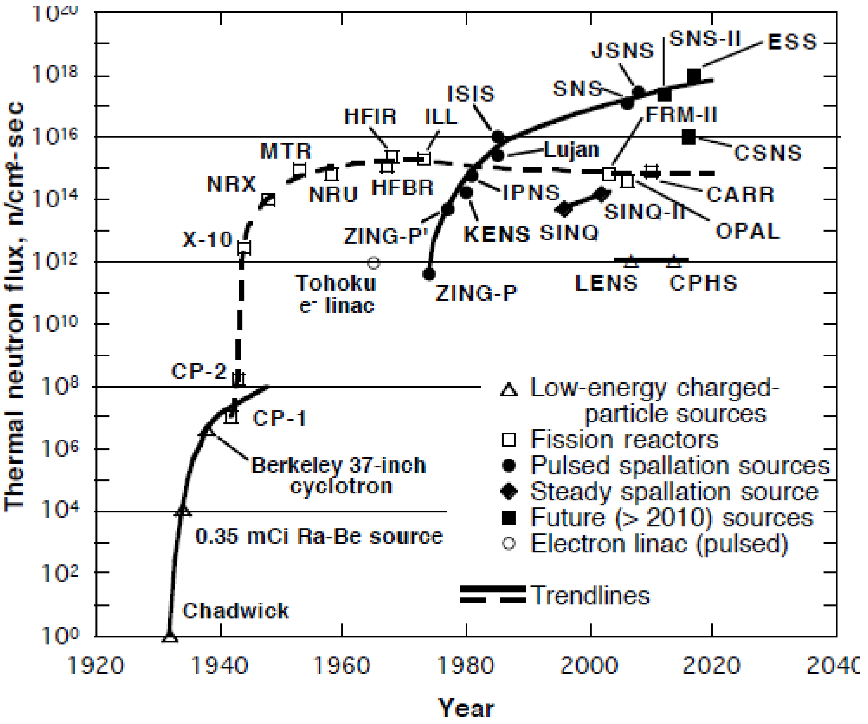


- Thermal ~25meV (2200m/s, λ_T=1.8Å)
- Cold 50μeV-25meV
- Very cold $2x10^{-7}$ - $5x10^{-5}$ eV
- Ultra cold <$2x10^{-7}$eV

Neutron Sources
2 plots – same story





<u>Modern high-flux sources:</u>

- Accelerator based (pulsed)
- Fission based

Where are the Neutron Facilities?

Where are the Neutron Facilities?

Europe

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- **Berlin Neutron Scattering Center**, Helmholtz-Zentrum Berlin, Germany
- **Frank Laboratory of Neutron Physics**, Joint Institute of Nuclear Research, Dubna, Russia
- **FRM-II Research Reactor**, Garching, Germany
- **Institut Laue Langevin**, Grenoble, France
- **ISIS Pulsed Neutron and Muon Facility**, Rutherford-Appleton Laboratory, Oxfordshire, UK
- **JEEP-II Reactor**, IFE, Kjeller, Norway
- **Laboratoire Léon Brillouin**, Saclay, France
- **Ljubljana TRIGA MARK II Research Reactor**, J. Stefan Institute, Slovenia
- **Nuclear Physics Institute (ASCR)**, Rez nr Prague, Czech Republic
- **Reactor Institute Delft**, Delft University of Technology, Netherlands
- **St. Petersburg Nuclear Physics Institute**, Gatchina, Russia
- **Swiss Spallation Neutron Source (SINQ)**, Villigen Switzerland

North and South America

- **Centro Atomico Bariloche**, Rio Negro, Argentina
- **Canadian Neutron Beam Centre**, Chalk River, Ontario, Canada
- **High Flux Isotope Reactor (HFIR)**, Oak Ridge National Laboratory, Tennessee, USA
- **Los Alamos Neutron Science Center (LANSCE)**, New Mexico, USA
- **Low Energy Neutron Source (LENS)**, Indiana University Cyclotron Facility, USA
- **McMaster Nuclear Reactor**, Hamilton, Ontario, Canada
- **MIT Nuclear Reactor Laboratory**, Massachusetts, USA
- **NIST Center for Neutron Research**, Gaithersburg, Maryland, USA
- **Peruvian Institute of Nuclear Energy (IPEN)**, Lima, Peru
- **Spallation Neutron Source**, Oak Ridge National Laboratory, Tennessee, USA
- **University of Missouri Research Reactor**, Columbia, Missouri, USA

Planned Facilities

- **Austron Spallation Neutron Source**, Vienna, Austria
- **China Advanced Research Reactor (CARR)**, Beijing, China
- **China Spallation Neutron Source (CSNS)**, Dongwan, Guangdong, China
- **European Spallation Source (ESS)**, Lund, Sweden

Asia and Australia

- **Bragg Institute**, Australian Nuclear Science and Technology Organisation, Lucas Heights, Australia
- **High-flux Advanced Neutron Application Reactor (HANARO)**, Korea
- **Japan Atomic Energy Research Institute (JAERI)**, Tokai, Japan
- **Japan Proton Accelerator Research Complex (J-PARC)**, Tokai, Japan
- **Kyoto University Research Reactor Institute (KURRI)**, Kyoto, Japan
- **Reactor Triga Puspati (RTP)**, Malaysian Nuclear Agency, Malaysia

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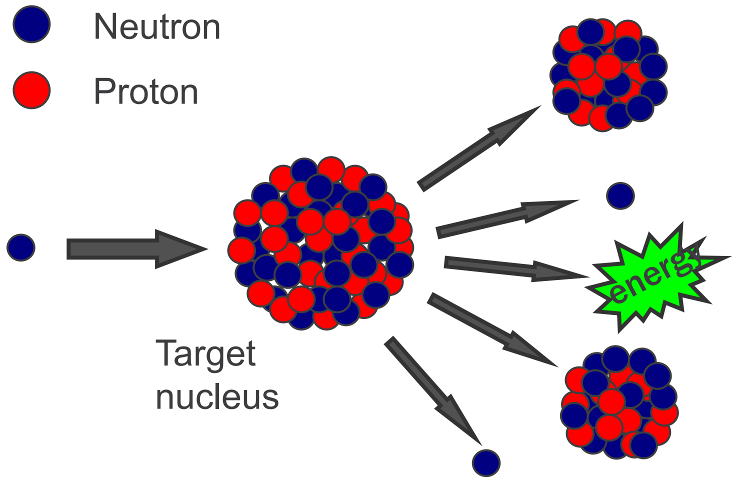
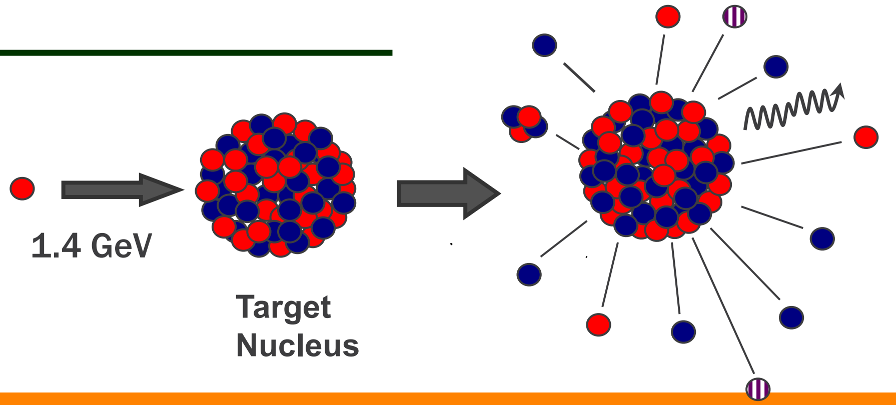
Neutrons – where do they come from



- **<u>Fission:</u>**
- Chain Reaction
- Continuous Flow
- 1-2 neutrons/fission
- ~180 MeV/n (as heat)

<u>Spallation</u>
- No chain reaction
- Pulsed operation
- 30-40 neutrons released by an incident proton
- ~30MeV/n (as heat)



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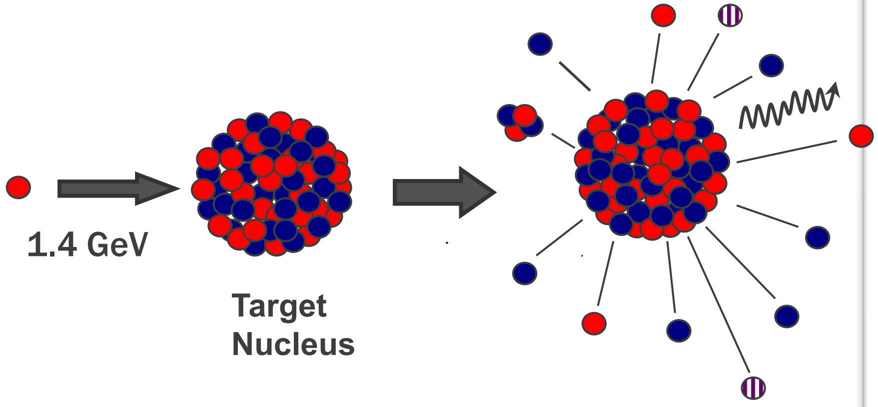
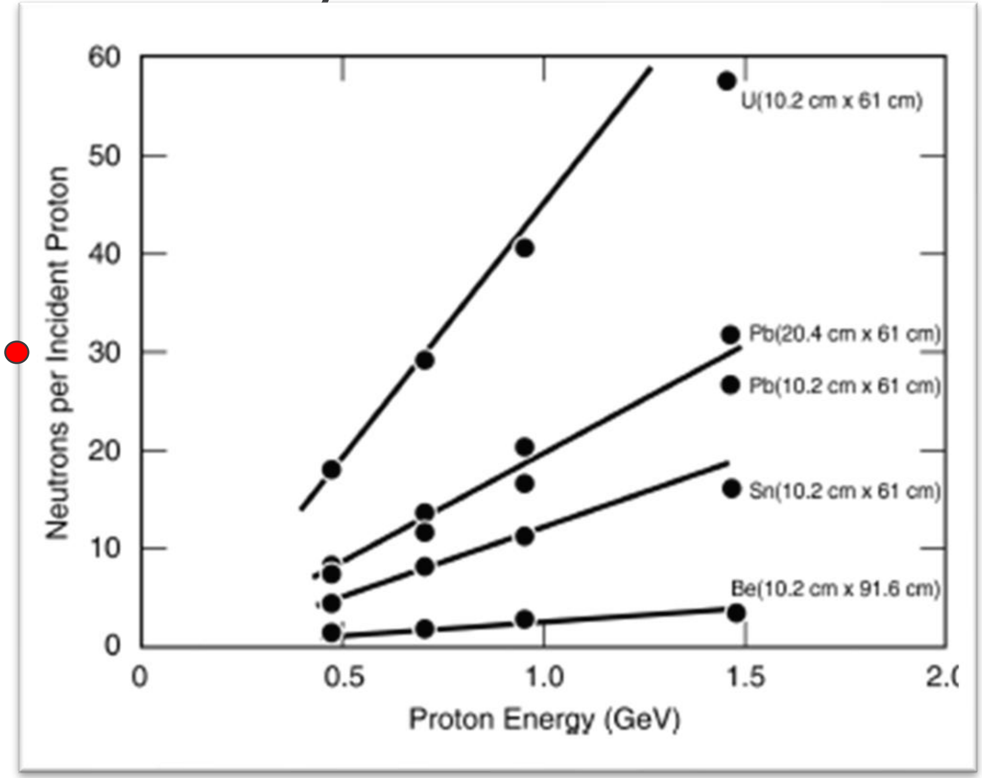




Measured Spallation Neutron Yield vs Proton Energy for Various Targets, J. Frazer et al (1965)

Why a spallation source?

Pros

- High Peak Flux
- Known time structure
- Accelerator based – no "political" stigma

Cons

- Low time averaged flux
- Not all applications exploit time structure
- Thermoelastic shock

Examples:

SNS at ORNL: 1.4 mA, 1.4 MW, 8×10^{15} n/cm^2/s peak flux

All things in moderation

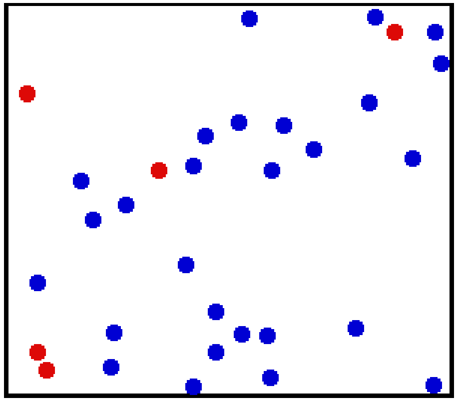
Neutrons are produced with MeV of energies

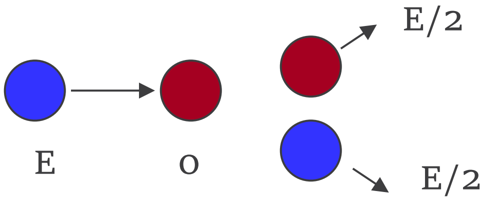
For most purposes, we'd like meV neutrons

Use collisions to slow neutrons down

→ heavy elements don't help much

→ smaller mass candidates are better





For N collisions:

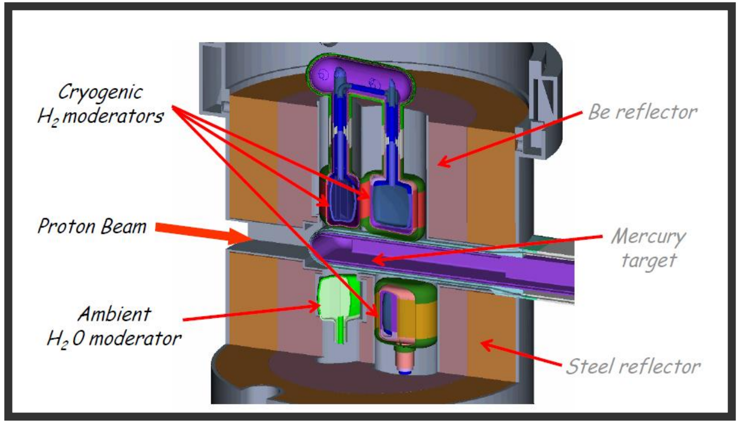
$$\left(\frac{1}{2}\right)^{N} = \frac{1\ MeV}{25\ meV}$$

Example:
Moderator at Spallation Neutron Source

Moderators embedded in reflector, usually D_2O-cooled Be

Minimal absorption

Large scattering cross-section (8b)



- Proton pulse > 1 μs
- Neutrons moderated by H
  - Several cm depth of H required to thermalize
  - 4Å neutron speed: 1cm / 10μs
  - Additional time-broadening: coupling between moderators and reflector

- Decoupling: Cd between moderator and reflector
  - Transparent above 0.3 eV

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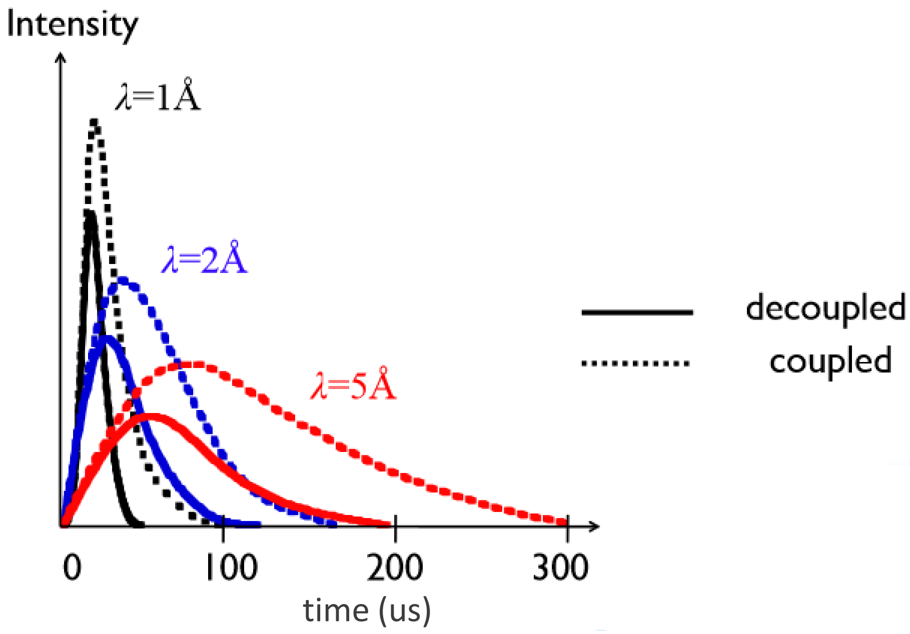

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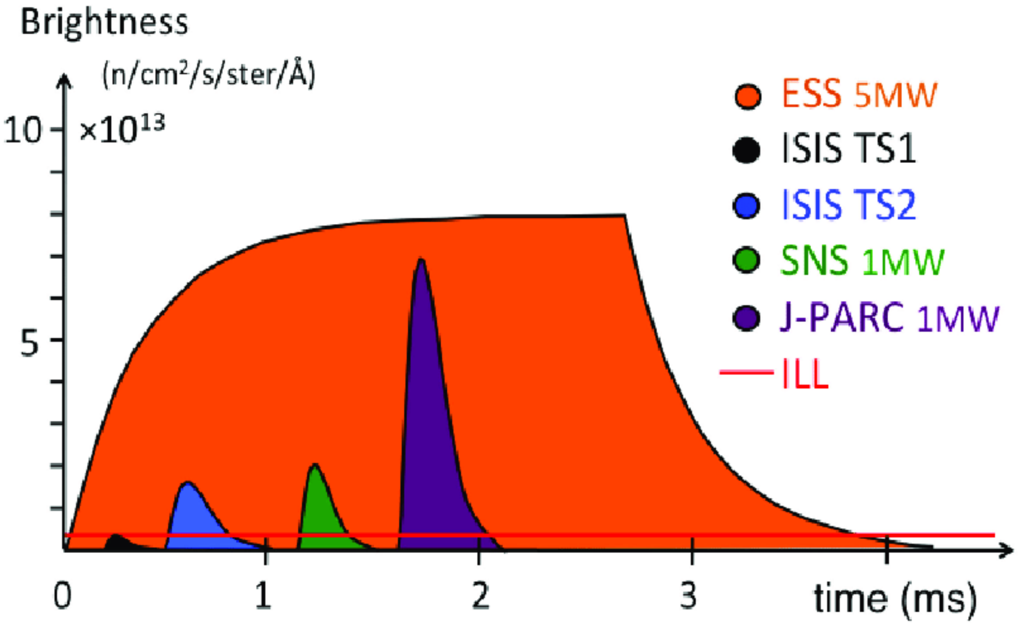
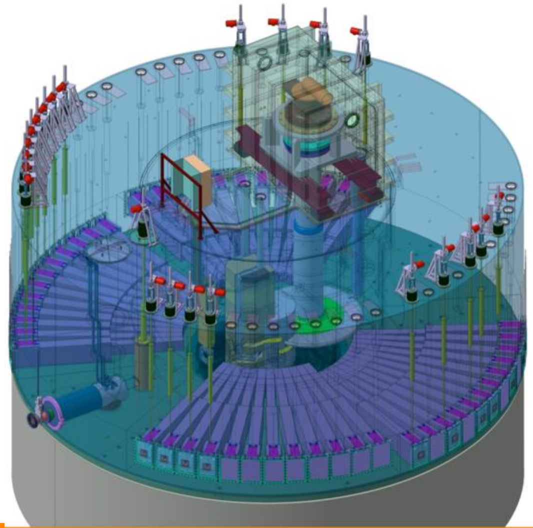
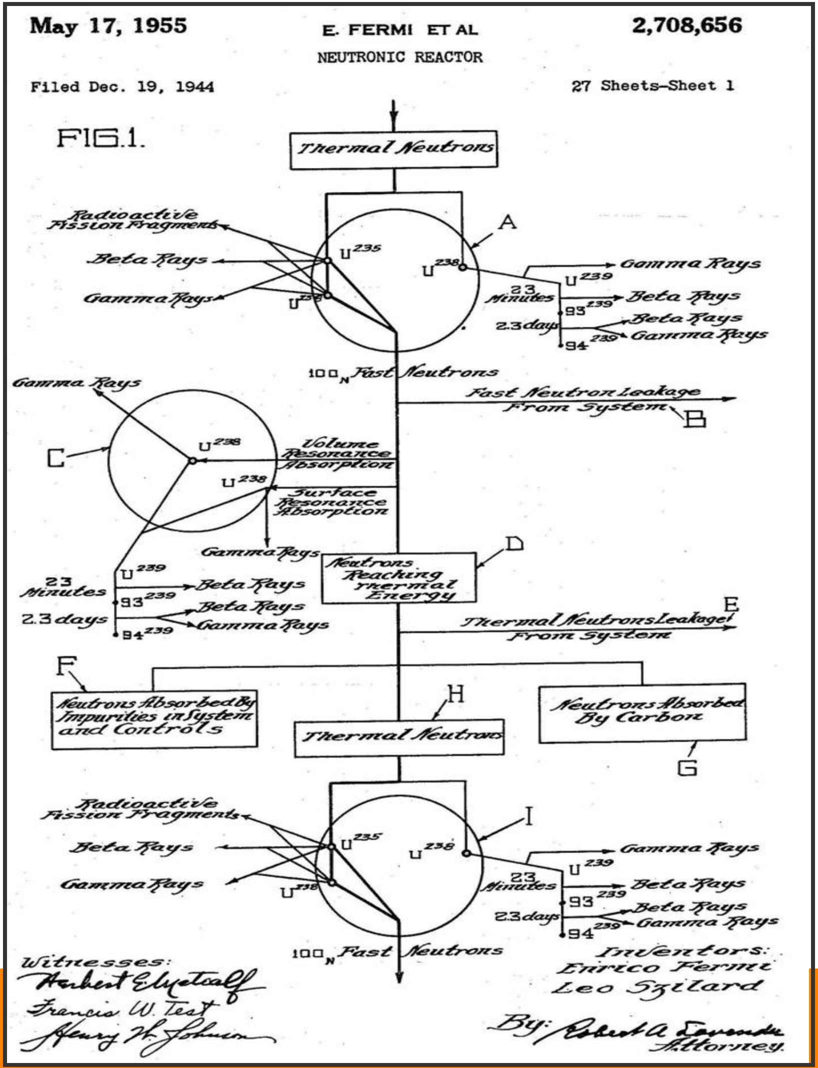
What is this slide for?

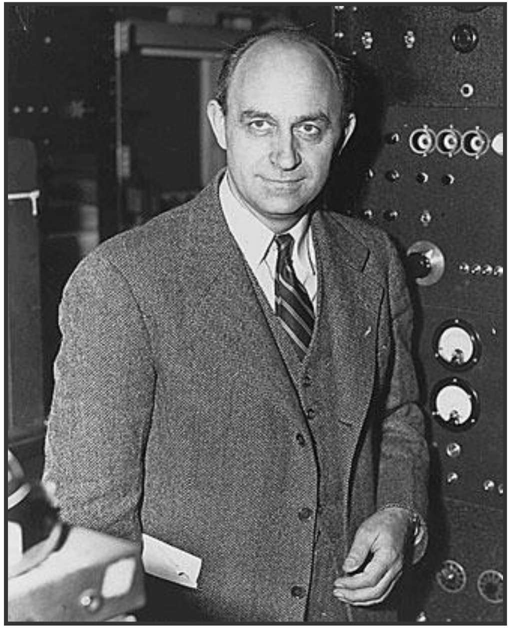




Reactors

Fermi said it best





Why a reactor?

Pros

- High time-averaged flux
- Mature technology
- Very good for cold neutrons
- Cryogenic Cold Sources
- $D_2$0 Moderation and cooling

Cons

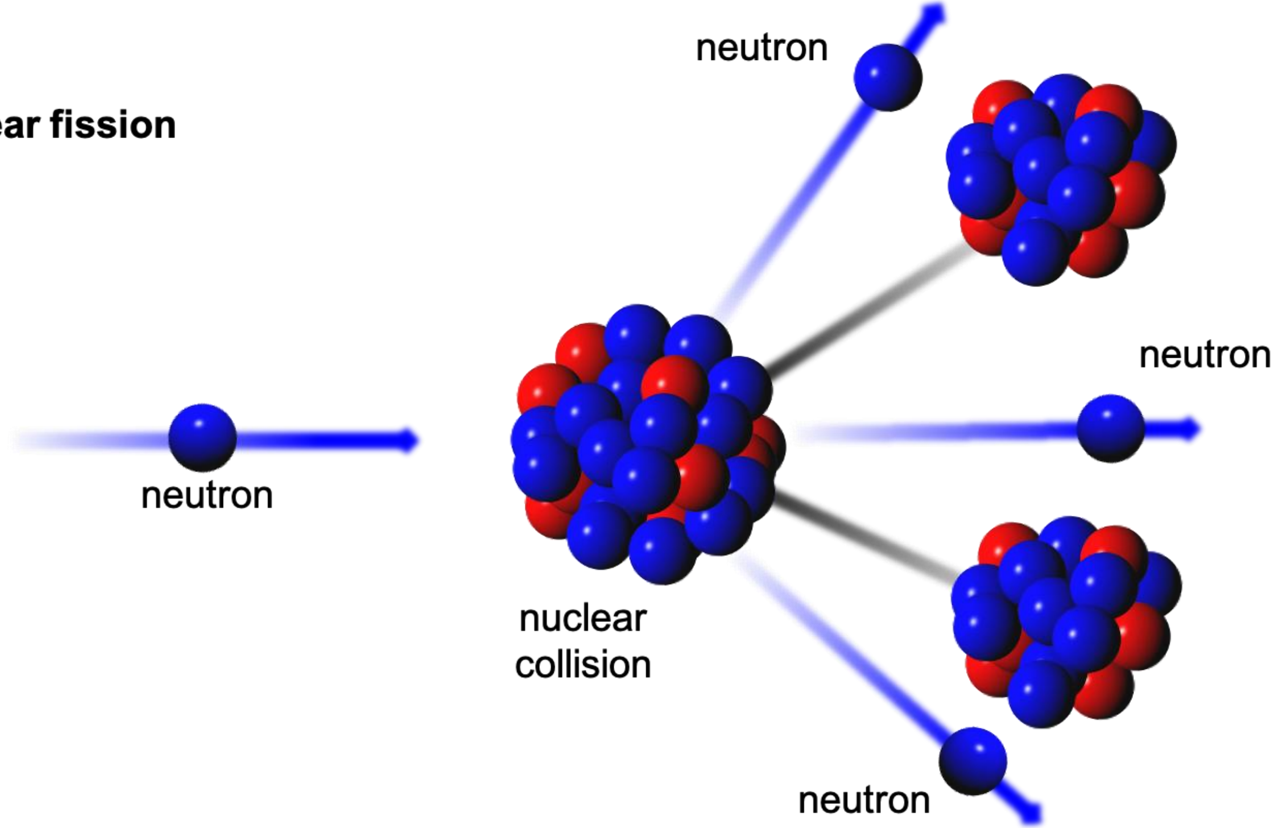
- Licensing
- No time structure

Examples:

FRM-2 at Munich (~1x10^{15} n/cm^2/s)
HFR at ILL (~1.5x10^{15} n/cm^2/s)
HFIR at ORNL (~1.5x10^{15} n/cm^2/s)

Major limitation → Ability to remove heat from the core at 100MW

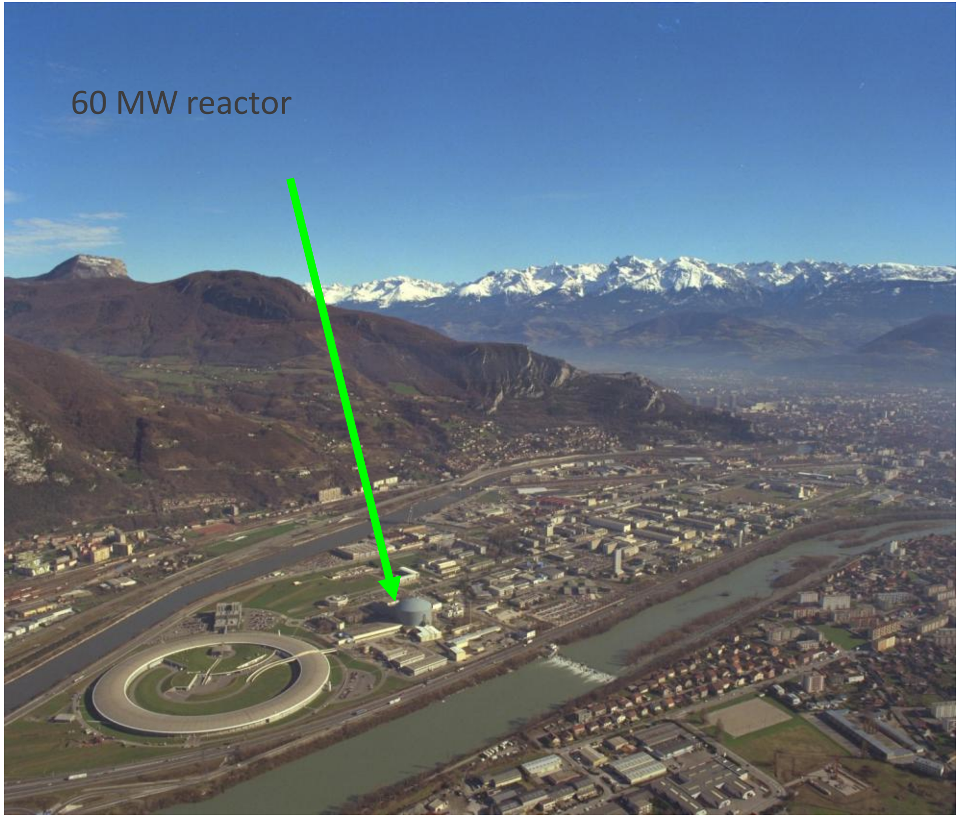
Nuclear fission



Graphite Reactor at ORNL (1943-1966)

- Designed and built in 10 months
- went into operation on November 4, 1943
- 1,248 horizontal diamond-shaped channels in which rows of cylindrical uranium slugs formed long rods

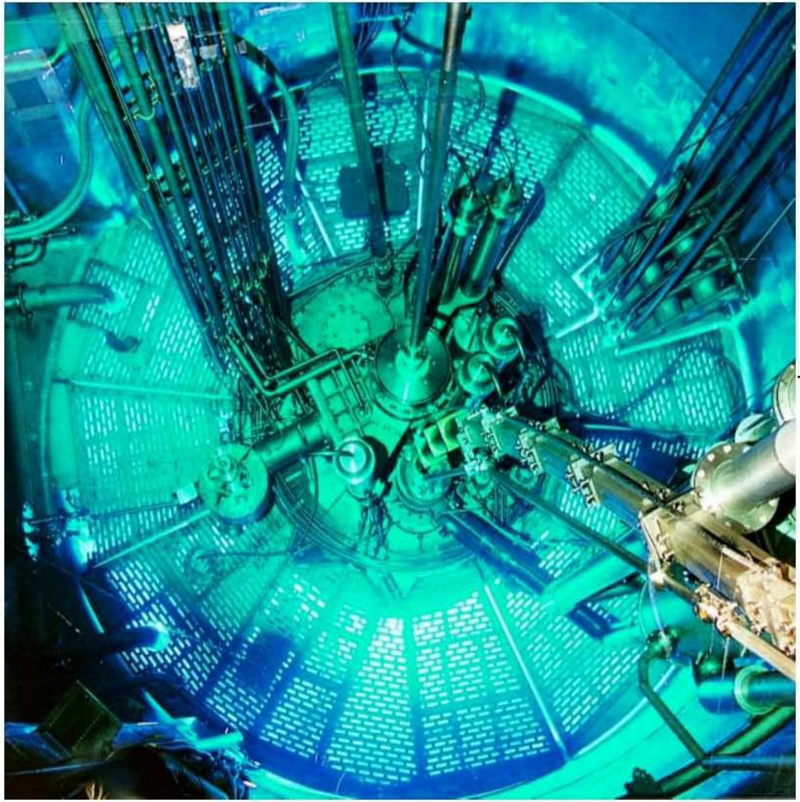
Institute Laue Langevin, Grenoble, France

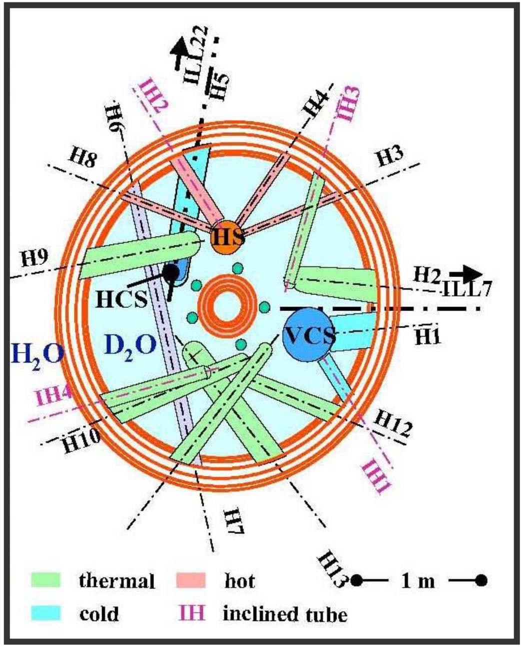


World's most intense source of neutrons for scientific research since 1973

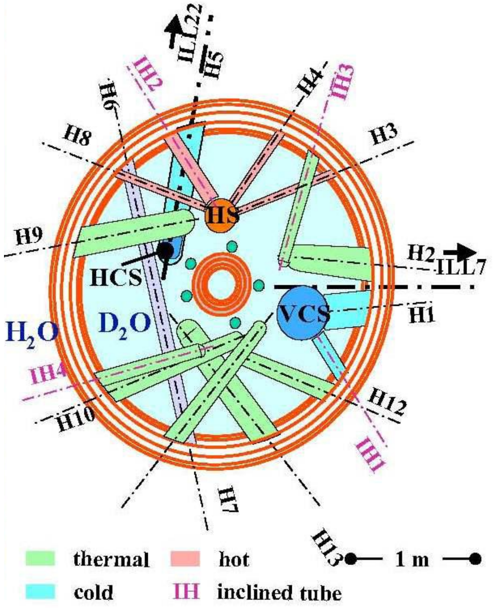
France, UK, Germany are founding members

High flux neutron reactor at ILL – 57 MW

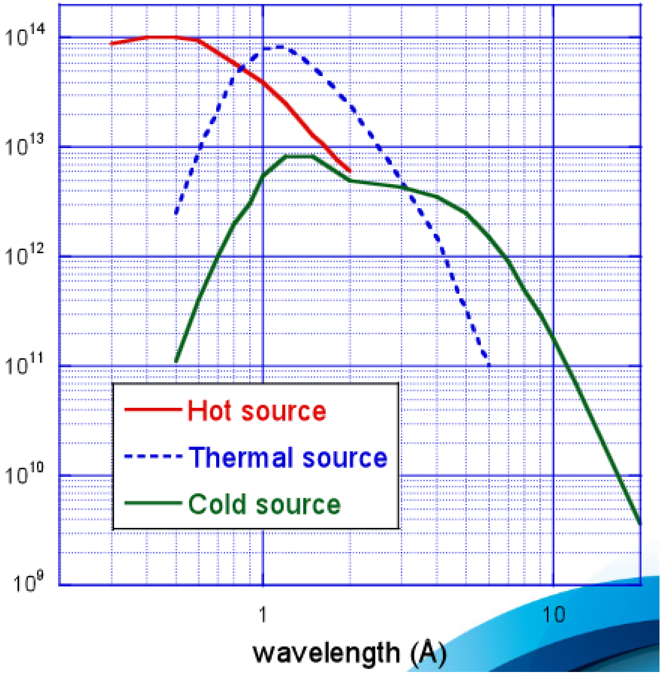




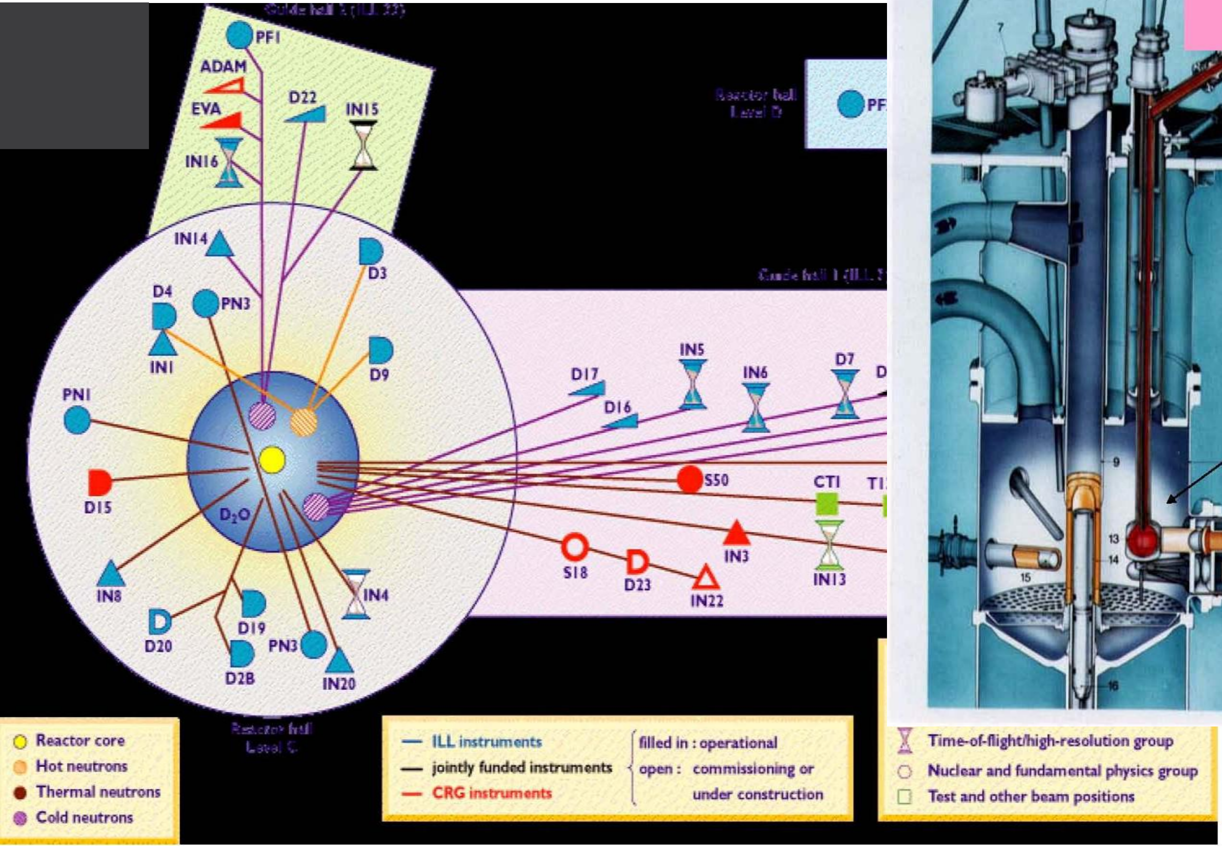
High flux neutron reactor at ILL – 57 MW

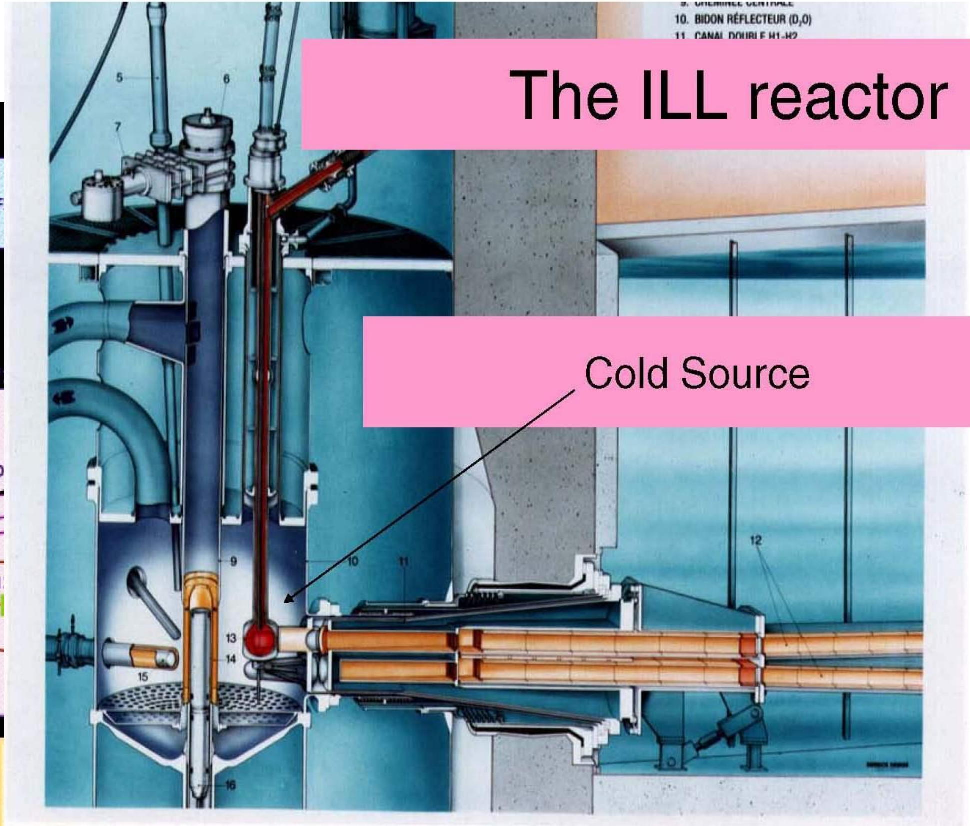


	cold	thermal	hot
moderator	liquid D_2	Liquid D_2O	graphite
moderator temperature	20K	300K	2000K
neutron wavelength	3→20Å	1→3Å	0.3→1Å
sample lengthscale	1Å→100 nm	0.3→5Å	0.1→2Å
sample timescale	1kHz→1 THz	0.1→10 THz	1→100 THz

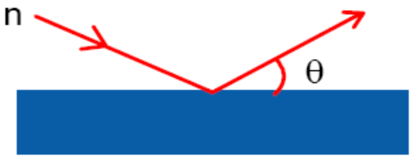


The ILL reactor



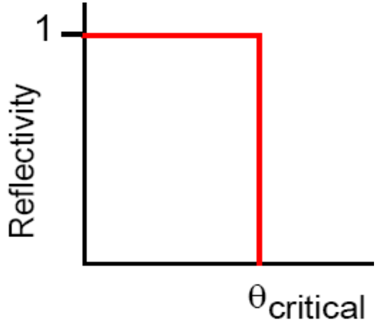


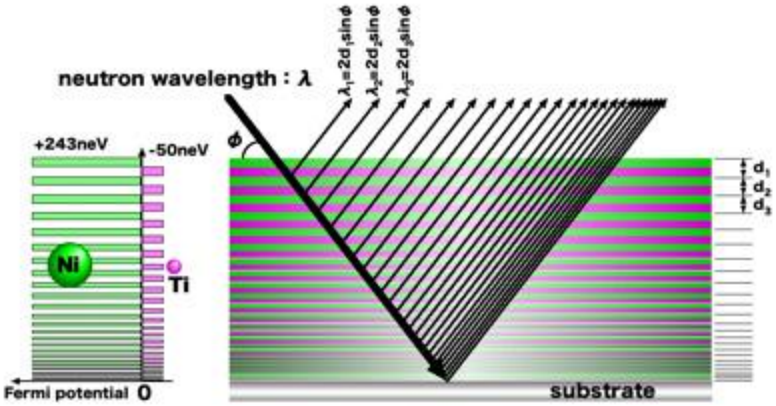
Transporting Cold Neutrons

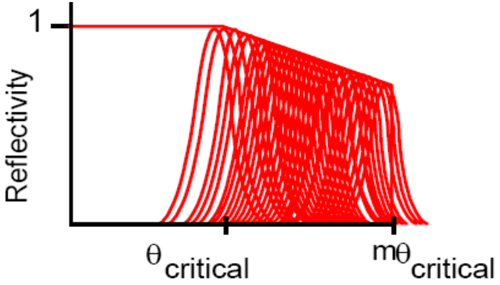


$$\cos\theta_c = n$$

$$n = \sqrt{1 - \frac{V_{eff}}{E}}$$

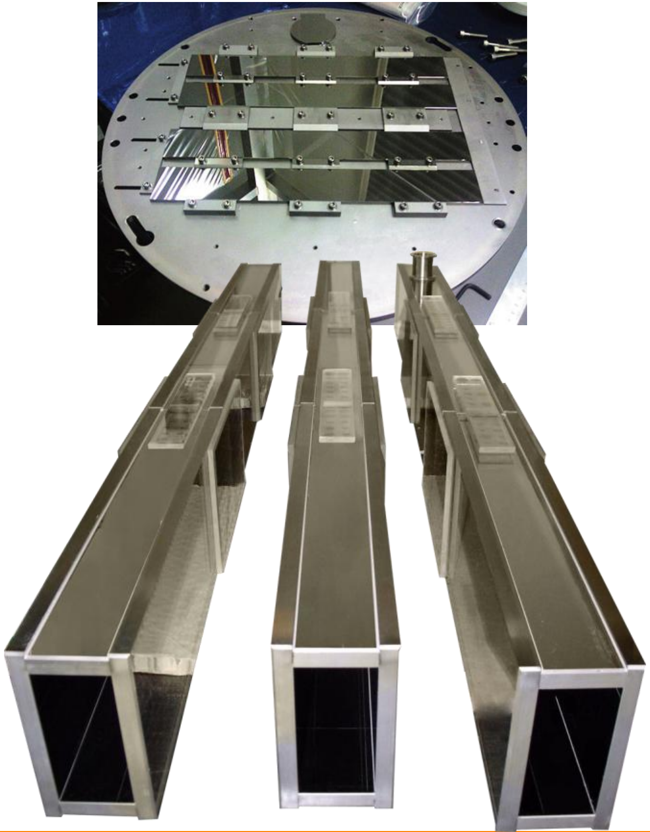




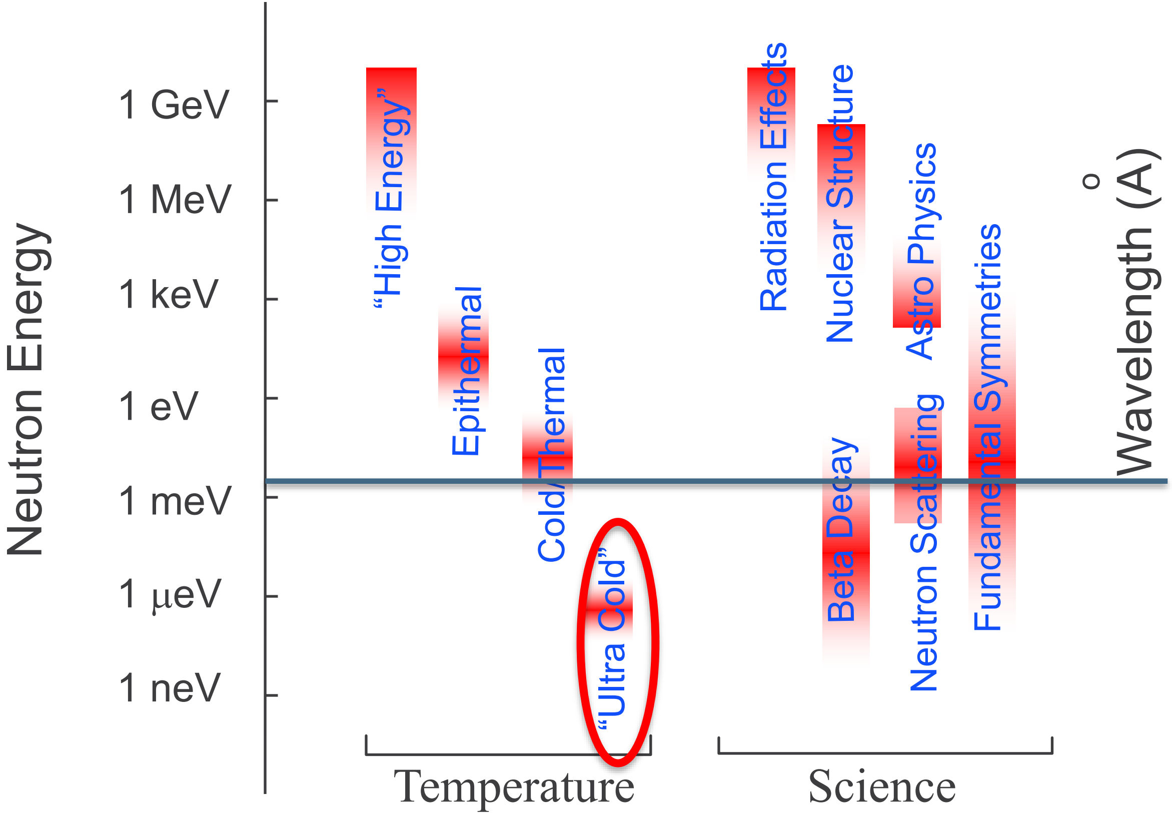


Multi-layers in a super-mirror act as a crystal; neutrons undergo Bragg diffraction. Varying layer spacing *d* allows multiple Bragg peaks, thus extending the critical angle.

Transporting Cold Neutrons



The slowest and coldest of neutrons



Why UCNs?

- Neutrons that can be confined in a material or magnetic bottle
  - K.E. $\lesssim$ 300 neV, T $\lesssim$ 4 mK
- Vital for fundamental neutron physics experiments
  - Lifetime measurements
  - nEDM
  - Neutron beta decay correlations
  - Bound states in earth's gravitational field
- Exist in in sufficient density (~10^3 UCN/cm^3) in the low energy tail of cold neutrons from cold moderator coupled to a powerful reactor
  - Difficulty in extraction without significant loss

Slide courtesy of T. Ito (LANL)

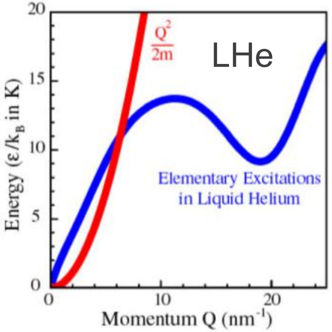
Superthermal process

- No thermal equilibrium between the neutron “gas” and the scattering system
- Neutrons lose energy by creating photons in the “converter” (down-scattering)
- “Up-scattering” is suppressed by the Boltzmann factor

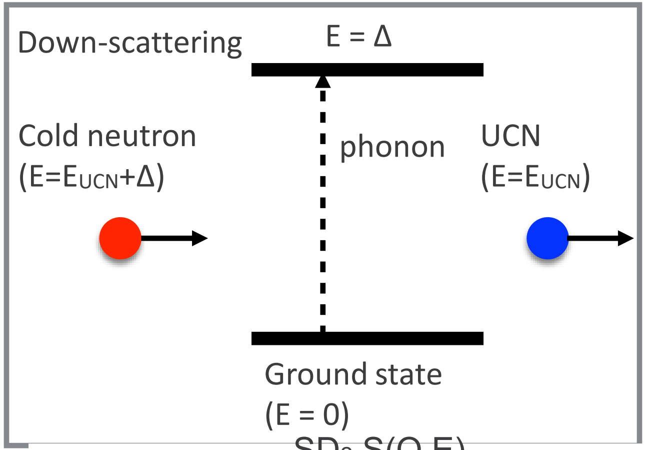
$$\sigma_{up} = \frac{E_{UCN} + \Delta}{E_{UCN}} e^{-\frac{\Delta}{kT}} \sigma_{down}$$

$$\Rightarrow \text{For } \Delta \gg kT \gg E_{UCN},\ \sigma_{up} \ll \sigma_{down}$$

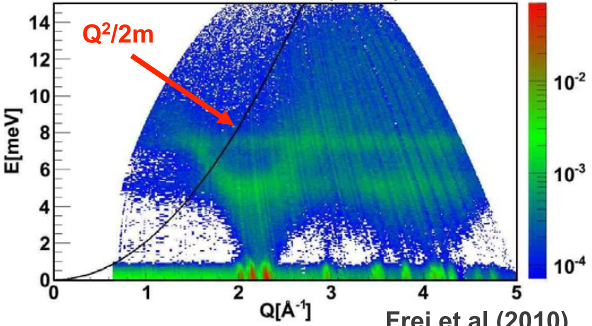
- Two commonly used converter materials:
  - LHe
  - SD2



Golub and Pendlebury (1975)



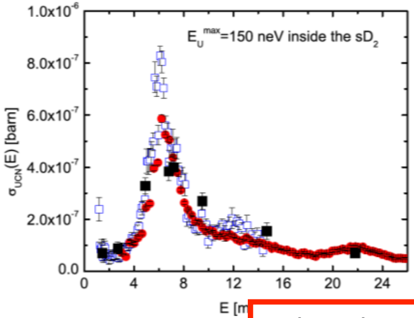
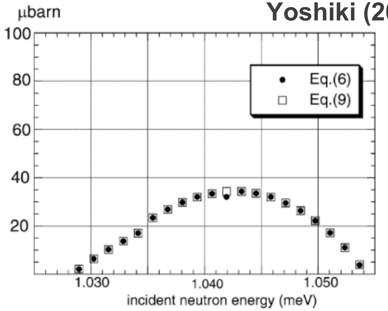
SD_2 S(Q,E)



Frei et al (2010)

Slide courtesy of T. Ito (LANL)

SD_2 vs LHe

	SD_2	LHe
UCN production	Frei et al (2010) 	Yoshiki (2003) 
	$\int\sigma(SD_2)dE \sim 10 \times \int\sigma(LHe)dE$	
Up scattering	$\tau_{abs} \sim$ 150 ms at 5 K	$\tau_{up} \sim T^7$, and ~1000 s at 0.7 K (multiphonon process)
Nuclear absorption	$\tau_{abs} \sim$ 150 ms	0
Other losses	• Absorption by H contamination (τ_{abs}~150 ms at 0.2% HD) • Up-scattering by para-D2 (τ_{up}~150 ms at 1.0% para)	Absorption by ^3He (τ_{abs}~500 s at $X=10^{-10}$)

Slide courtesy of T. Ito (LANL)

THE UNIVERSITY OF TENNESSEE KNOXVILLE

Superthermal converter UCN Sources

Neutron source

- ❑ Reactor
- ❑ Spallation

→

Moderator (thermal/cold)

- ❑ Graphite
- ❑ Beryllium
- ❑ Polyethylene
- ❑ Methane
- ❑ LH_2
- ❑ SH_2
- ❑ D_2O
- ❑ SD_2

→

Superthermal converter

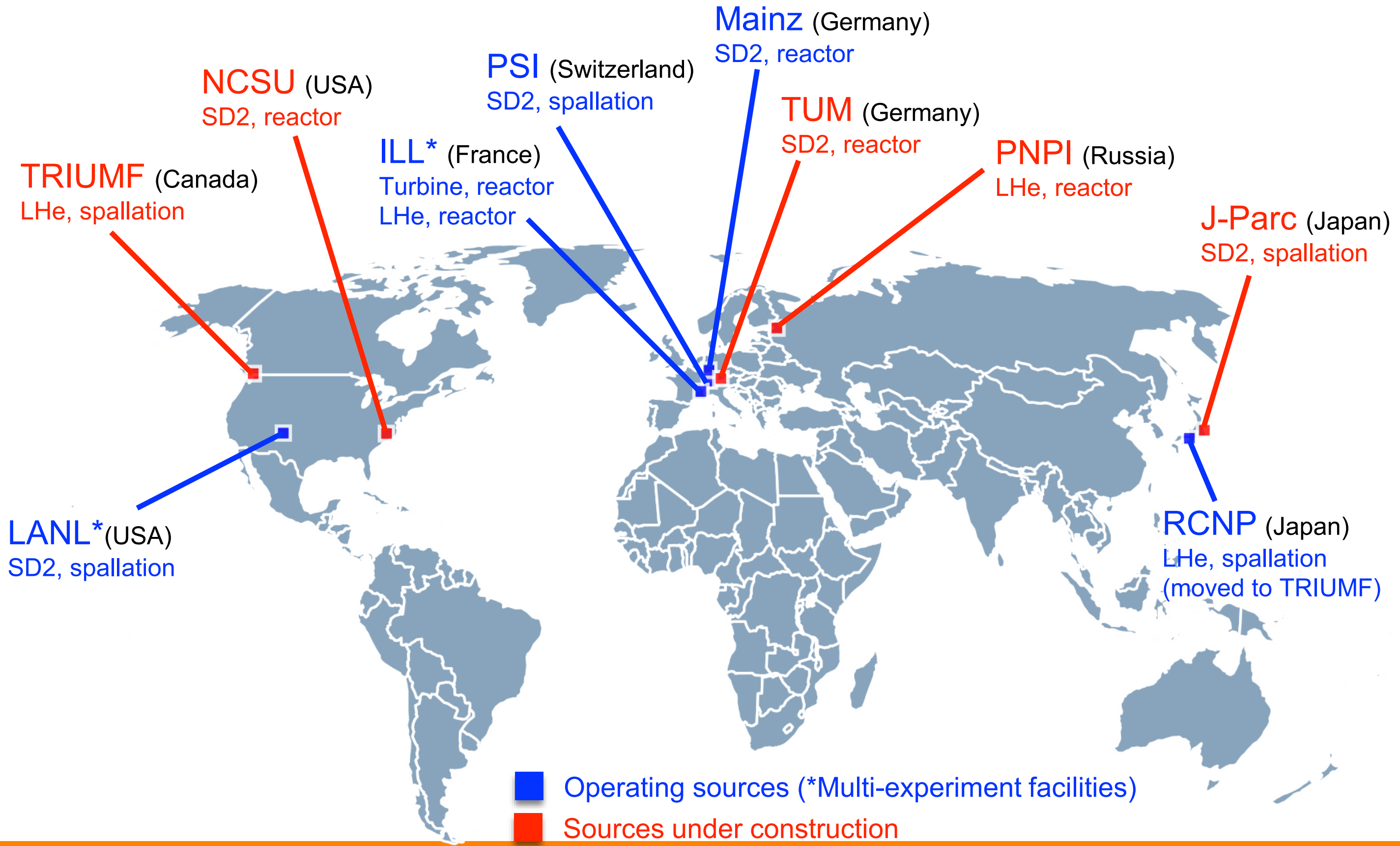
- ❑ LHe
- ❑ SD_2

It is important to optimize the entire system:

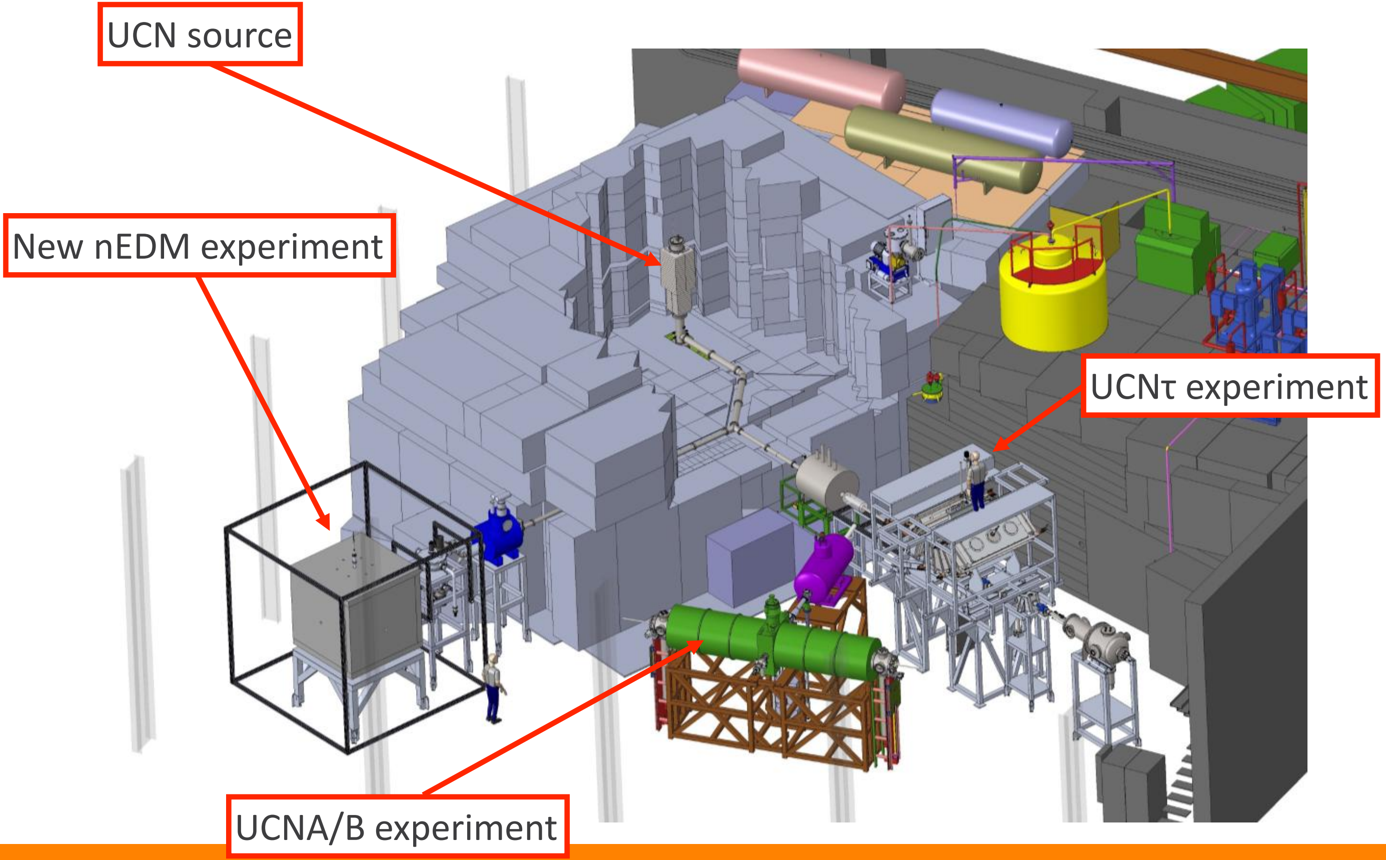
- Spectrum of the cold neutrons
- Coupling of the cold moderator to the UCN converter.

Slide courtesy of T. Ito (LANL)

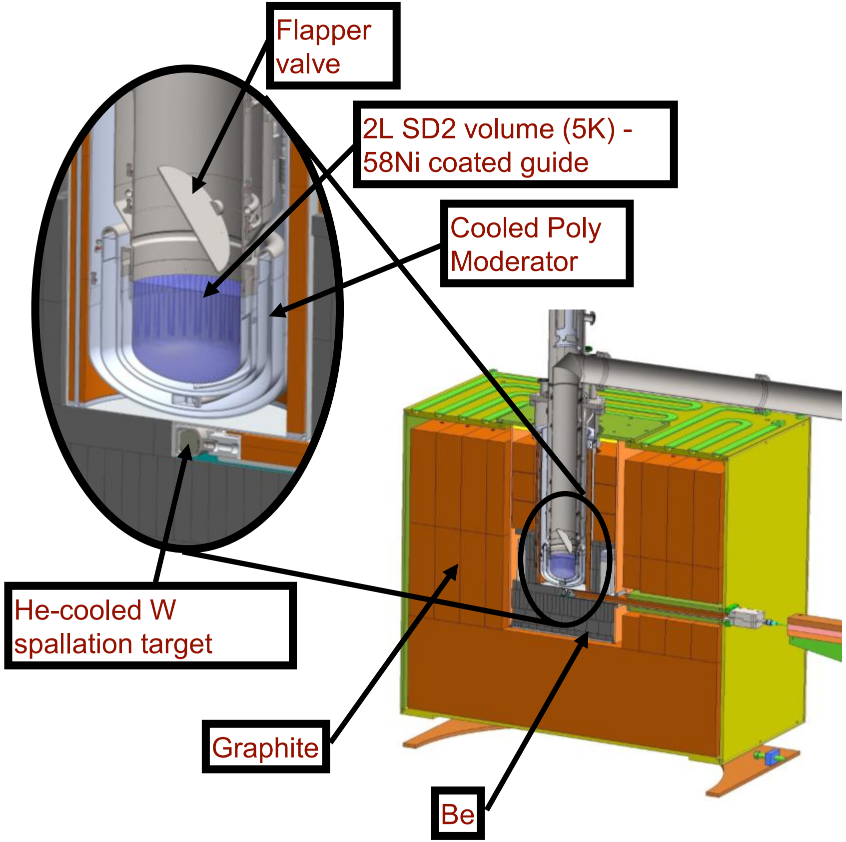
UCN sources around the world



LANL UCN Facility



LANL UCN Source



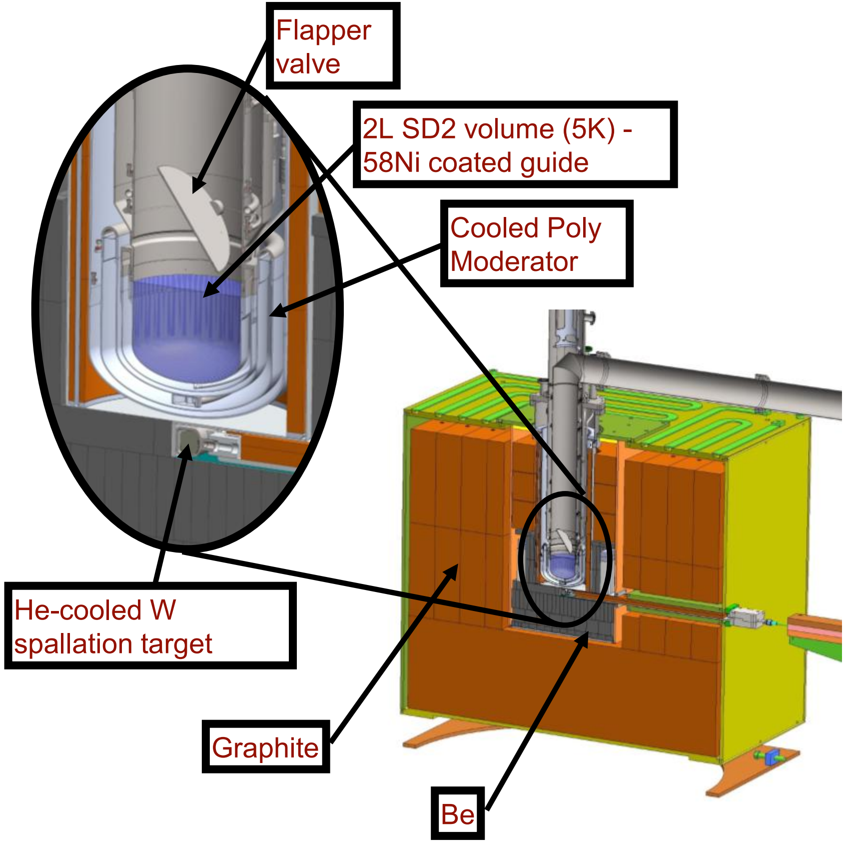
Spallation neutrons from W target ~ 2 MeV

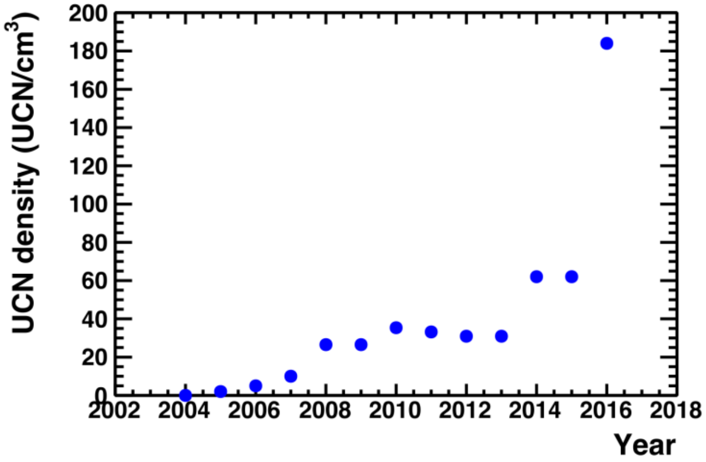
Thermal neutrons in Be and graphite moderator ~ 25 meV

Cold neutrons in polyethylene cold moderator ~ 6 meV

Ultracold neutrons in SD2 converter ~ 100 neV

LANL UCN Source





Summary

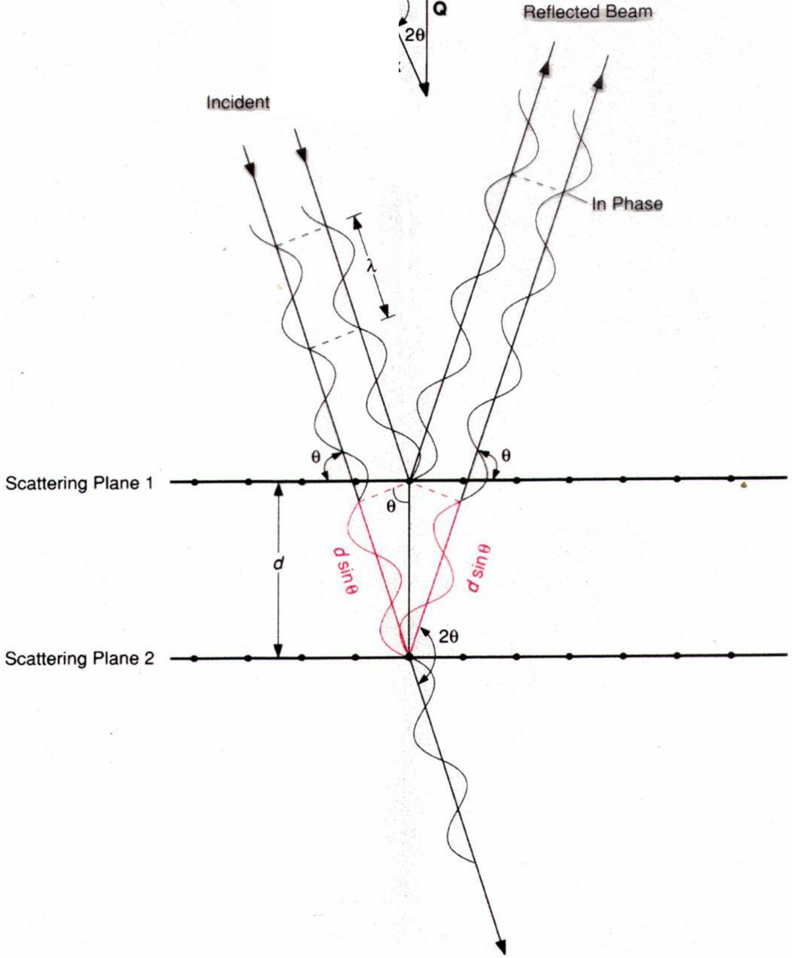
- Choice of neutron source (Accelerator or Rector)
- Choice of energy/wavelength range
- What do we do with them?

Next → Watch Neutrons Die!

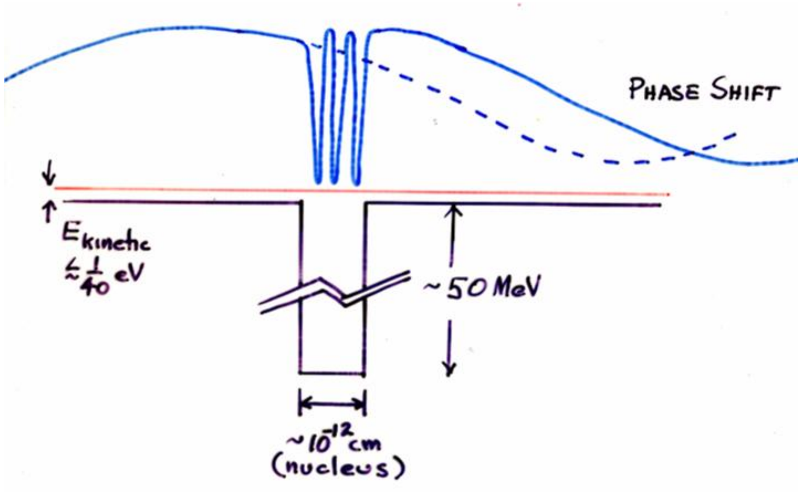
Unused Slides

Bragg Diffraction

$$n\lambda = 2d \sin\theta$$



Coherent ("Optical") Interaction Between Neutrons and Matter



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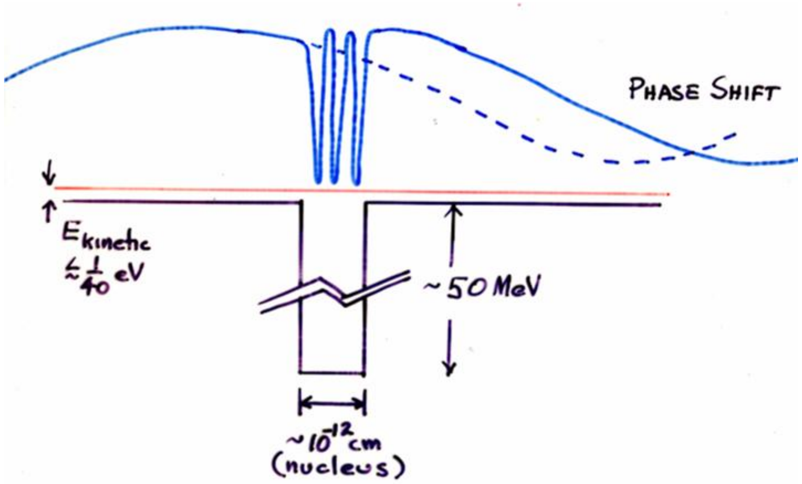
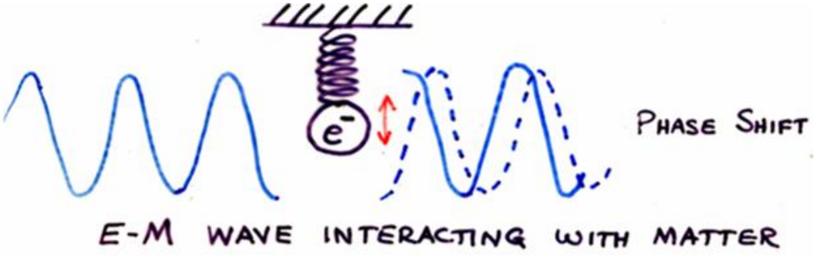
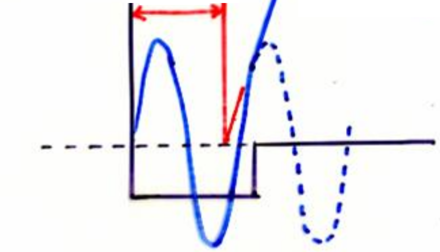


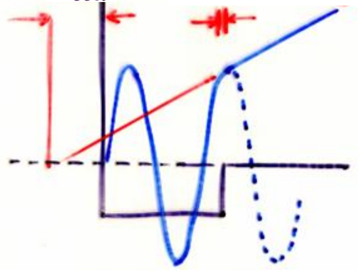


Phase shift leads to Index of Refraction

At low energies, S-wave scattering dominates, phase shift is usually related to a coherent scattering length $b_{coherent}$

$$\cot(\delta) = \frac{-1}{kb_{coh}} \Rightarrow b_{coh} \approx \frac{\delta}{k}$$





For most nuclear well depths and well sizes, it is unlikely to obtain a positive coherent scattering length:

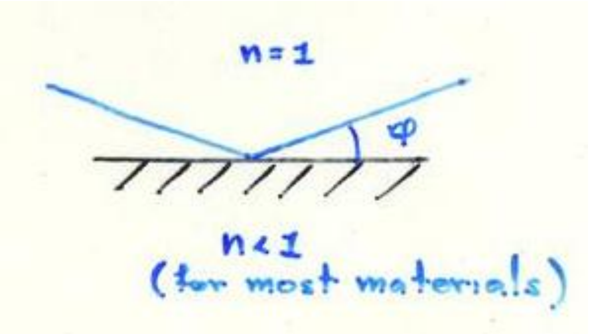
$$n = \sqrt{1 - \frac{N\lambda^2 b_{coh}}{\pi}}$$

*Index of refraction is therefore <1 for most nuclei **

**In the vicinity of A=50 (V,Ti,Mn) nuclear sizes are such that $b_{coh}<1$ and thus n>1*

Neutron Index of Refraction

$$n^2 = 1 - \frac{\lambda^2 N b_{coh}}{2\pi} \longrightarrow \cos\varphi_{crit} = n$$



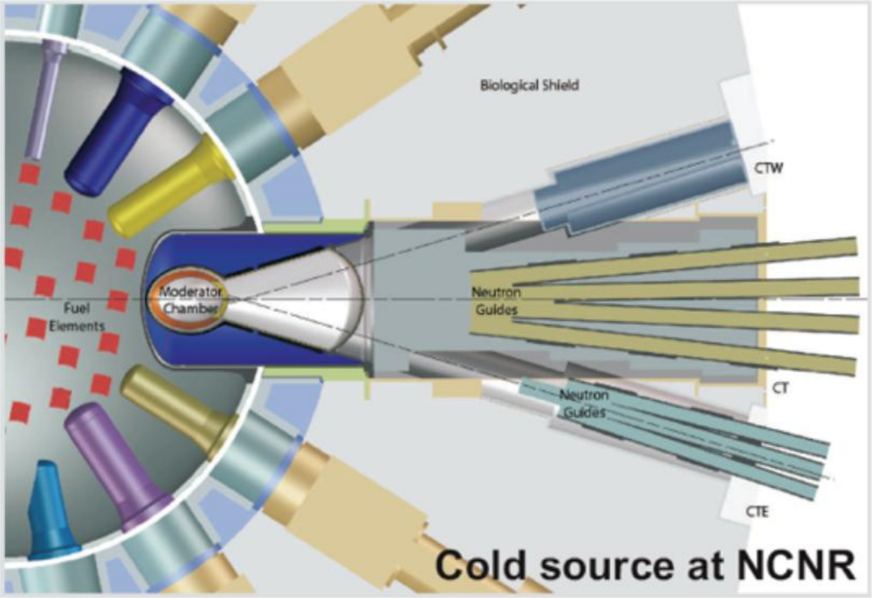
For sufficiently large neutron wavelength, λ *, n=0 and cos* θ_{crit} = $90°$

This implies that neutrons will be reflected at all angles
and can be confined in a "bottle"

These are known as "Ultracold Neutrons."

NCNR – NIST Center for Neutron Research

NCNR – NIST Center for Neutron Research

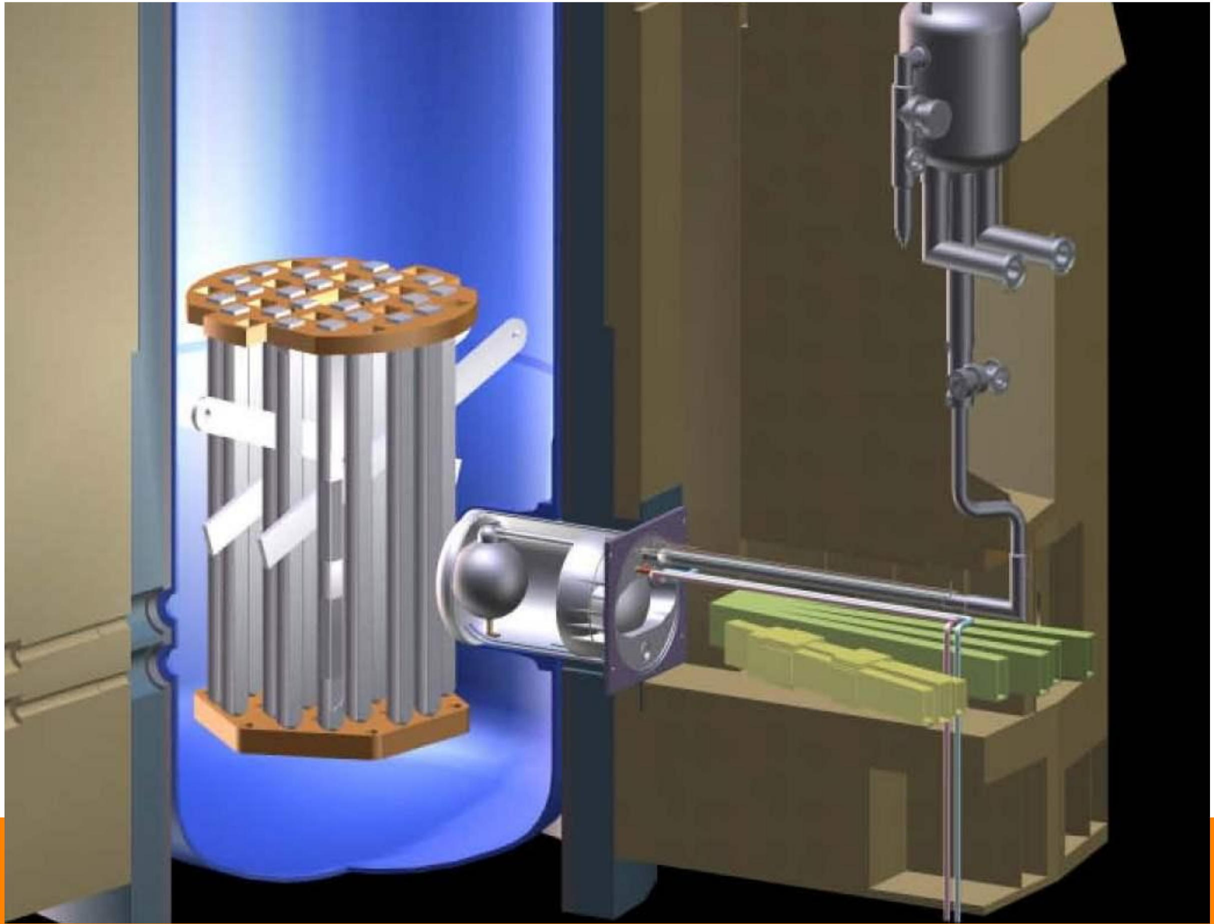


Neutrons partially thermalize in a cold source

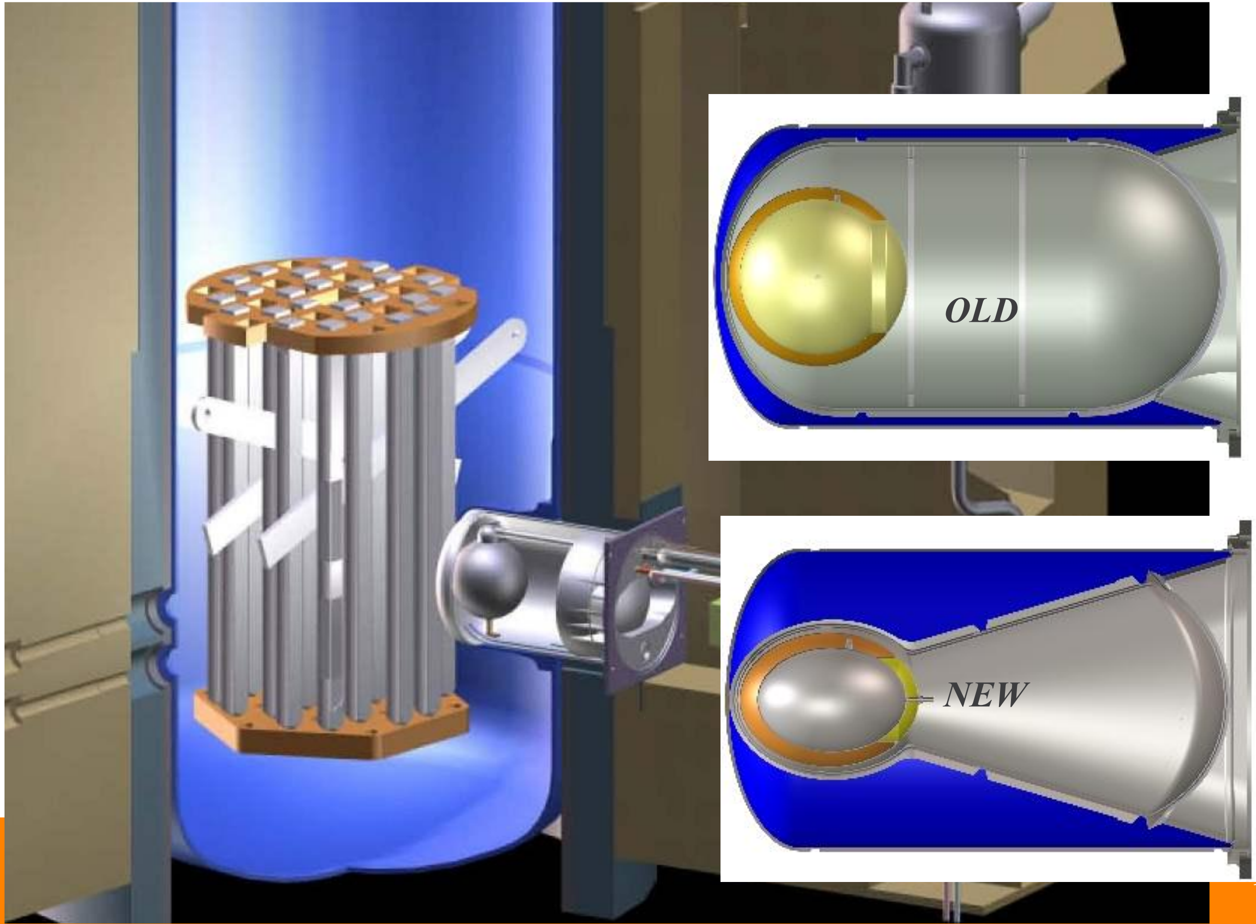
- NCNR, liquid hydrogen (eff. 20K)
- Slow neutrons have larger probability of decaying in the detector

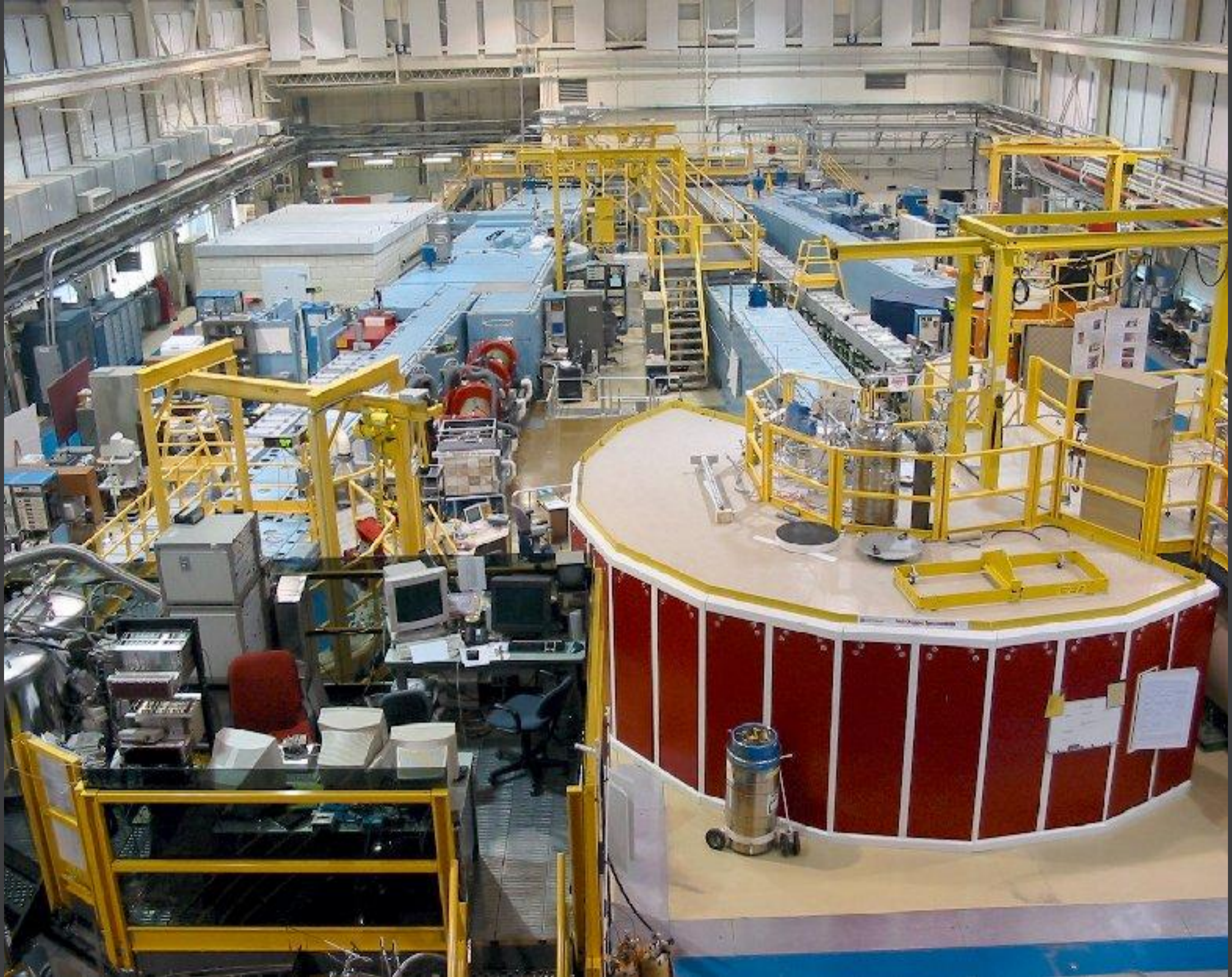
- neutron temp ≈ 40 K
- neutron energy ≈ 3.4 meV
- neutron velocity ≈ 800 m/s
- neutron flux (typ. ≈ 10^9 cm^2 s^{-1})

NCNR – NIST Center for Neutron Research



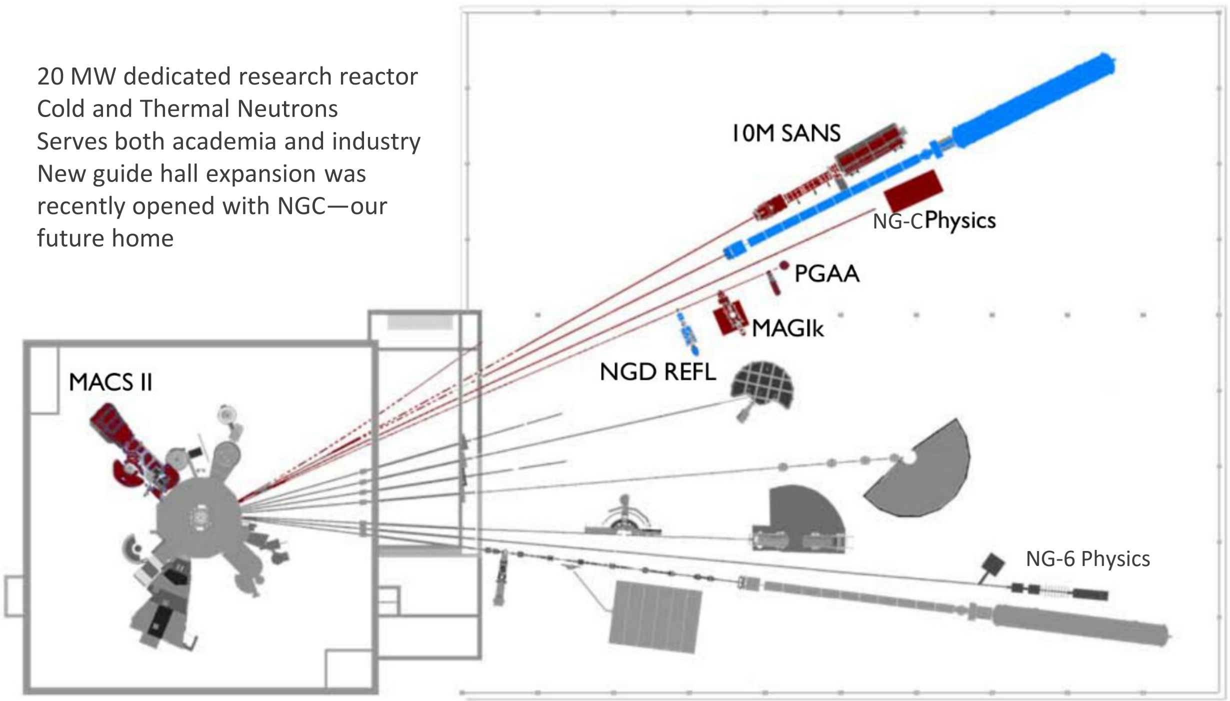
NCNR – NIST Center for Neutron Research



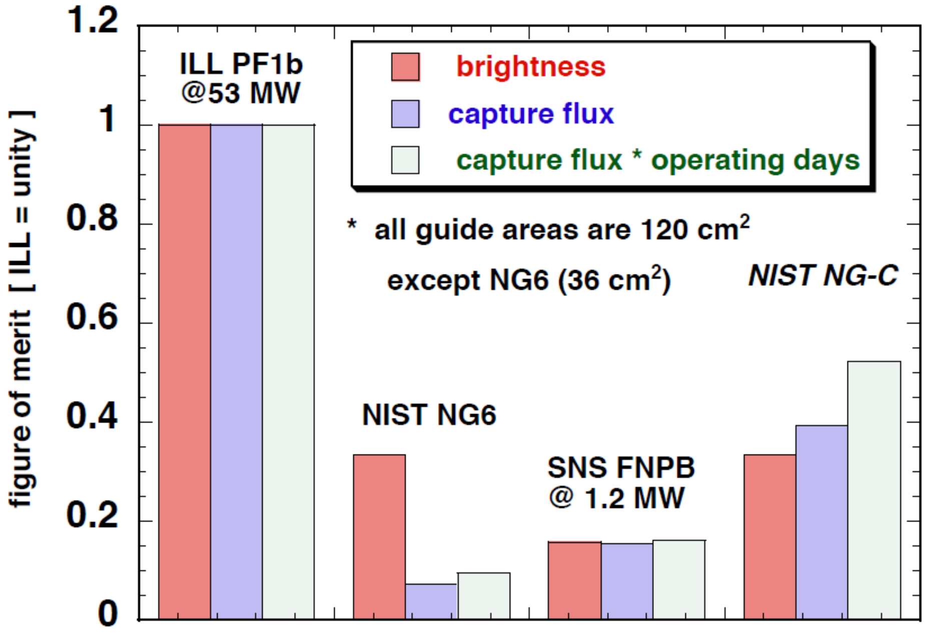


NCNR – NIST Center for Neutron Research

20 MW dedicated research reactor
Cold and Thermal Neutrons
Serves both academia and industry
New guide hall expansion was recently opened with NGC—our future home



NCNR – NIST Center for Neutron Research



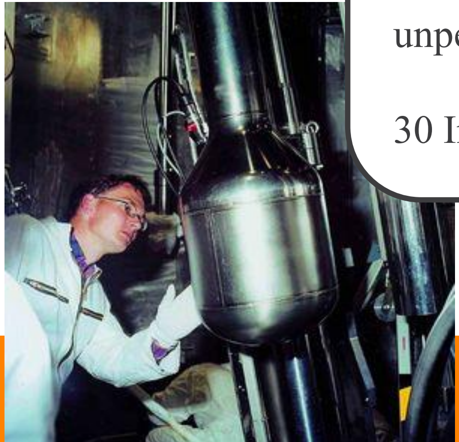
plot courtesy T. Gentile

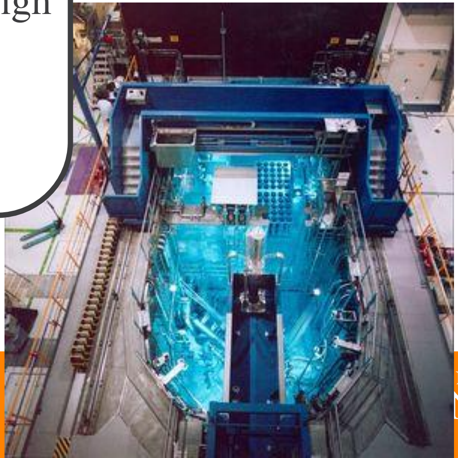
FRM-II: A 20 MW reactor

Compact core containing an uranium silicide-aluminum dispersion fuel

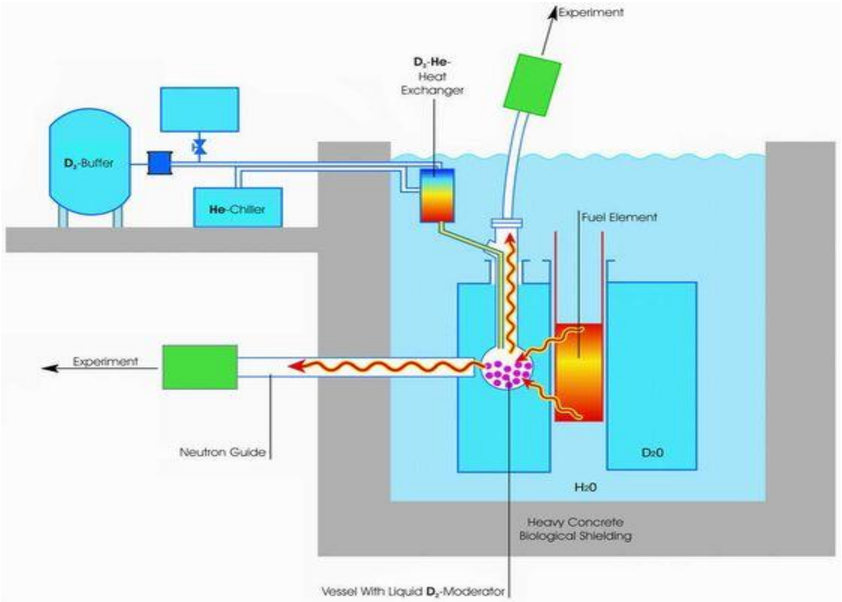
The neutron source provides a very high unperturbed thermal peak flux

30 Instruments available to users





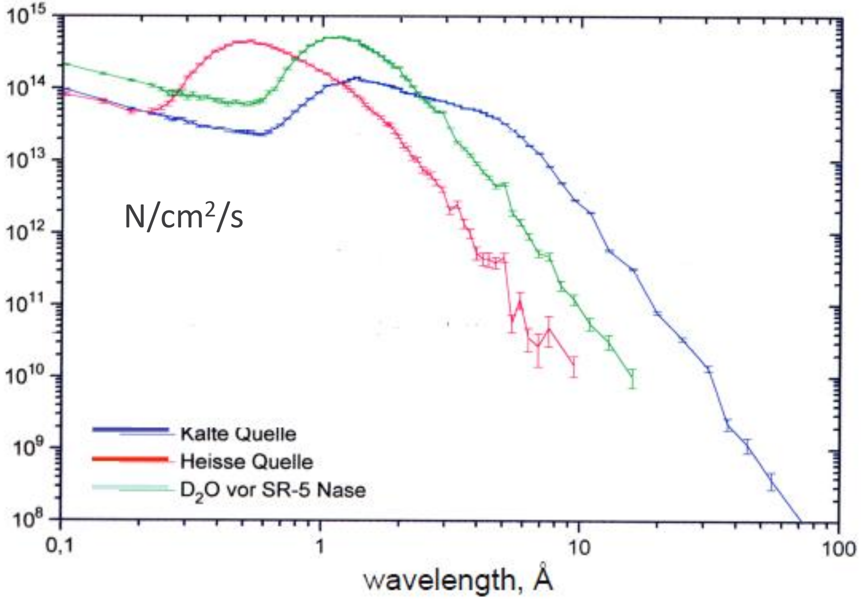
FRM-II: The Cold Source



16 L of liquid deuterium at 25K

19/32 Instruments use only cold neutrons

FRM-II: The Cold Source

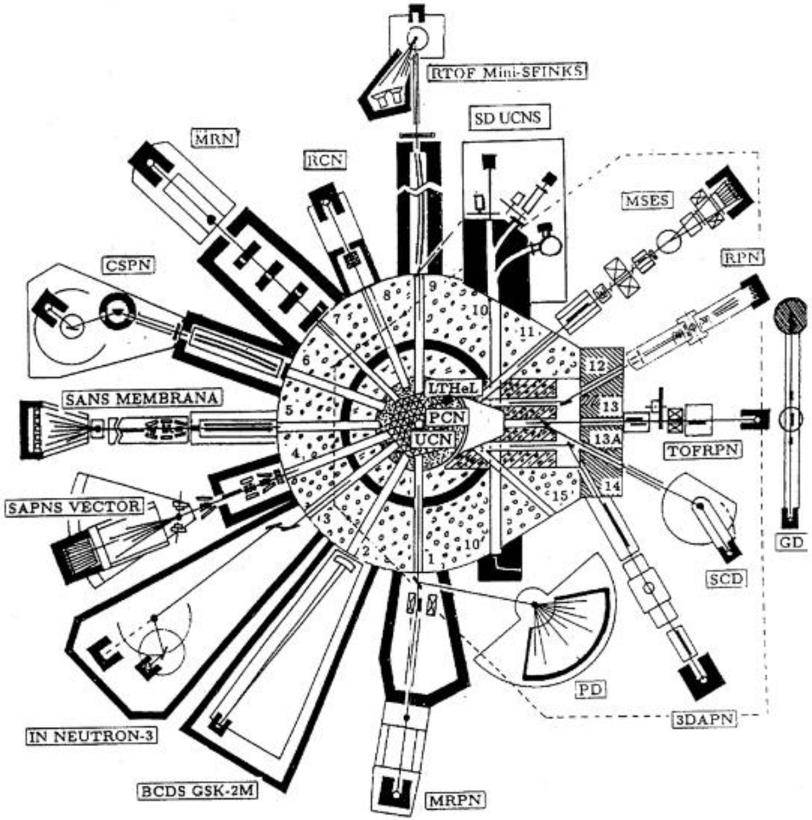


PNPI (Reactor formerly known as LNPI)

In December 1959, the research reactor WWR-M was put into operation

Basic characteristics:
Power: 18 MW
Thermal neutron flux: $4x10^{14}$ n/cm2/s
Horizontal experimental channels: 17
Vertical experimental channels used for isotope production: 18
Operational time per year: 3000 hours
Neutron instruments for users: 16

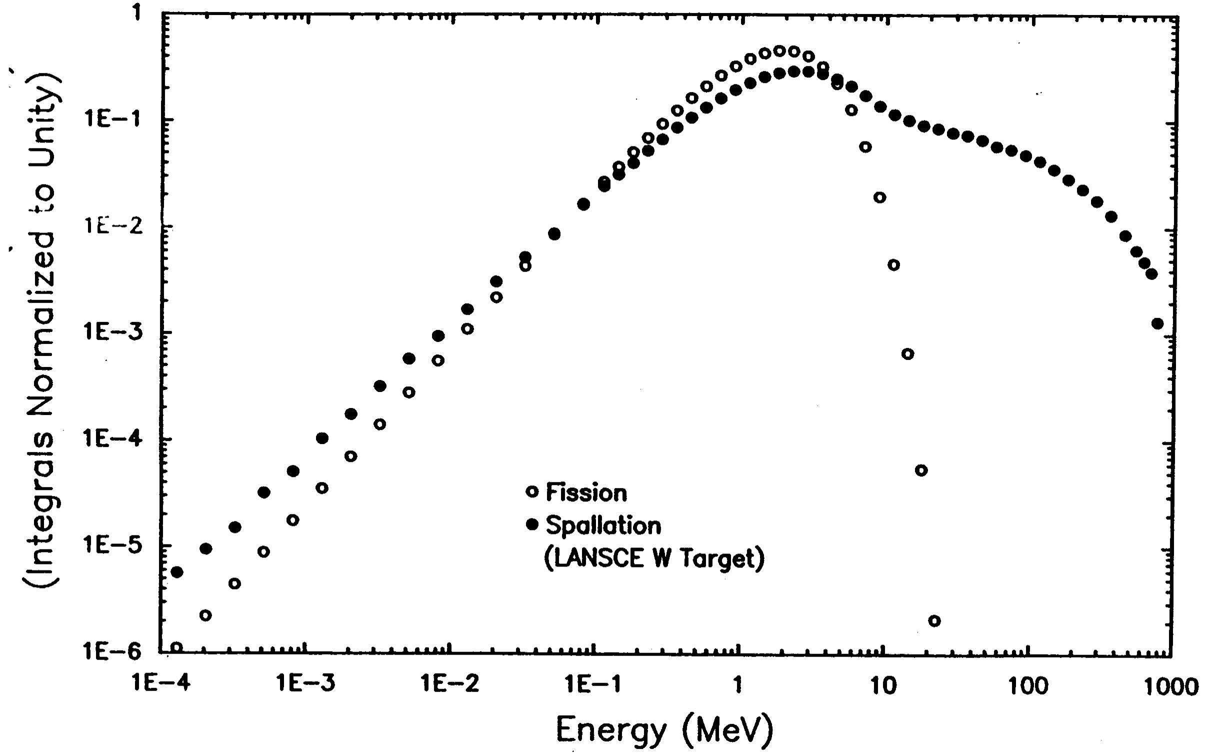
PNPI (Reactor formerly known as LNPI)



Spallation Sources

(endorsed by Captain Picard)

Different Spectra

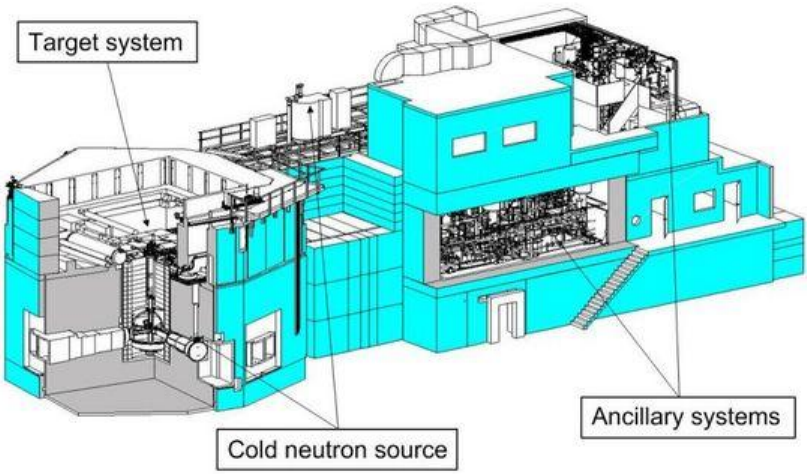


(Courtesy of Gary Russell)

SINQ at PSI -- 10^{14} n/cm^2/s

First CW neutron source in the world

SINQ at PSI



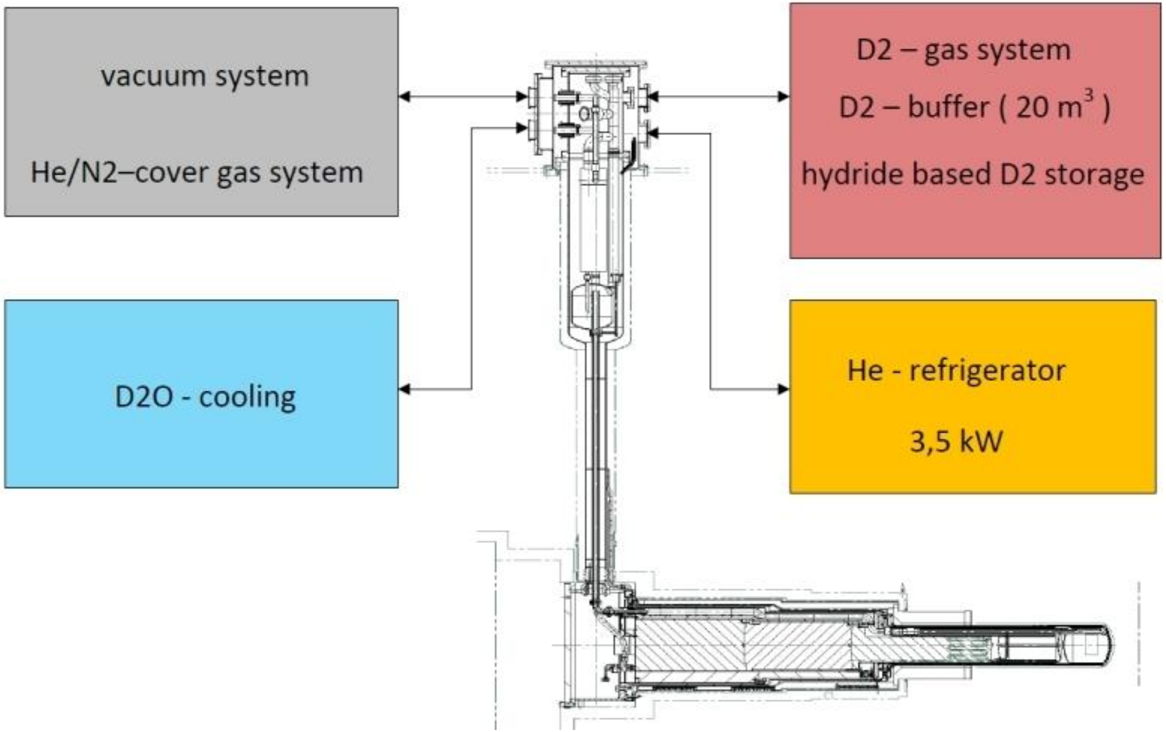
Target: lead rods

Proton beam of 590 MeV and upto 2.3 mA

Heavy metal target, situated in the center tube of the heavy water moderator tank.

The vertical proton beam injection allows a maximum number of horizontal beam tubes and neutron guides to the SINQ-instruments.

SINQ at PSI – Cold Neutron Source



20L of liquid deuterium at 25K inside the moderator tank

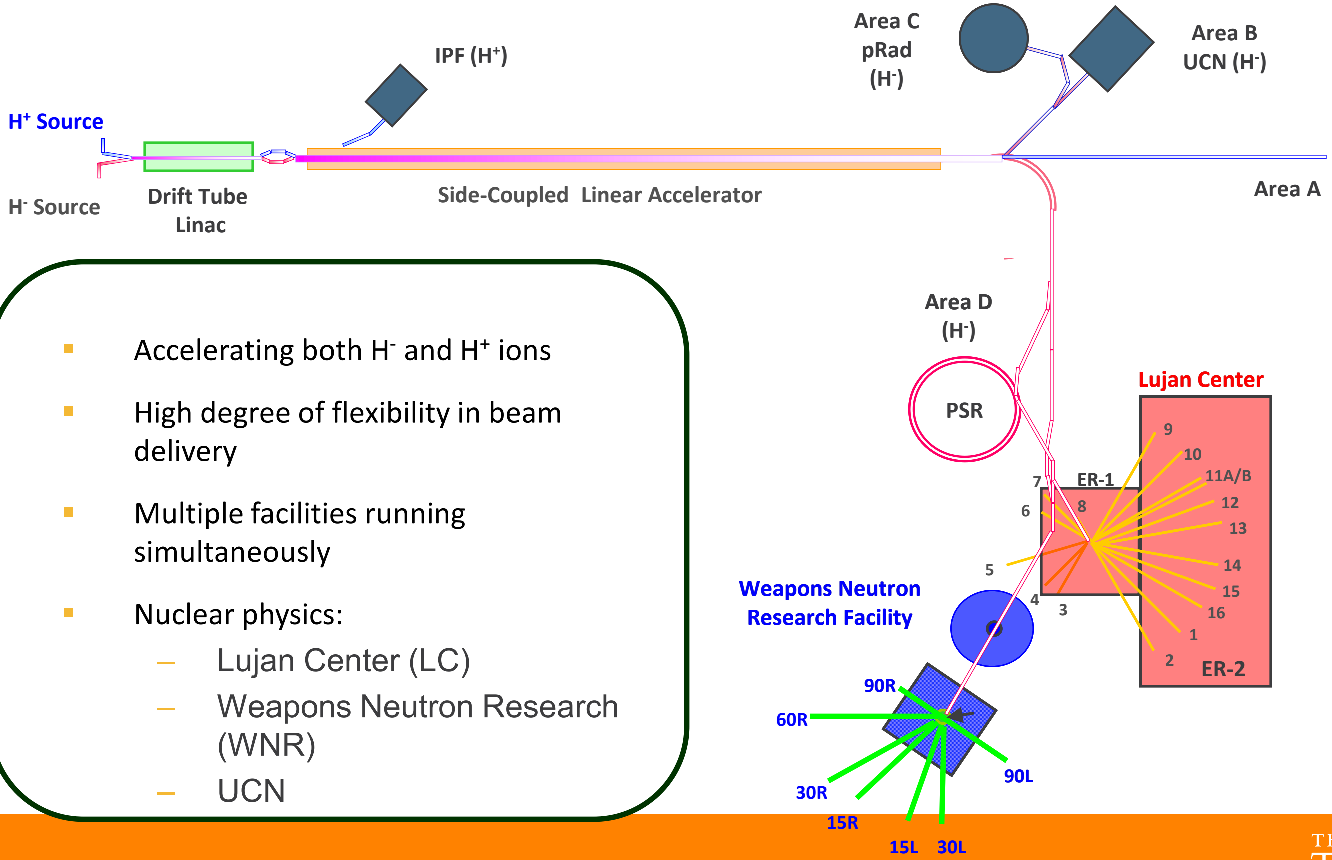
LANSCE: flyover

- Los Alamos Neutron Science CEnter
- Lujan Center
- WNR facility

- **Ultra Cold Neutron source**
- **Proton RADiography**
- **Isotope Production Facility**

Powerful proton LINAC driving multiple target stations simultaneously

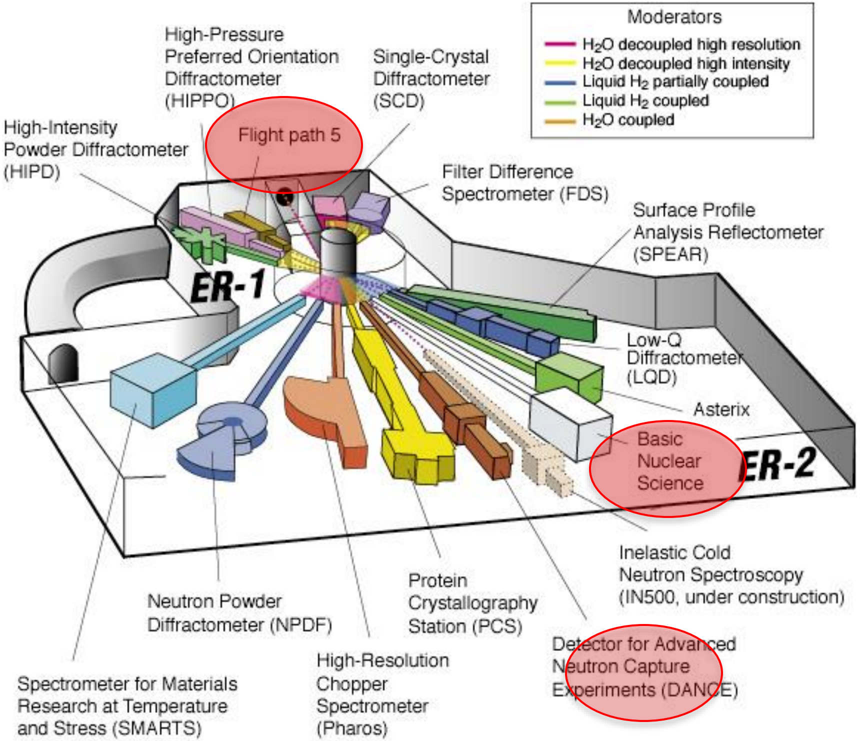
LANSCE: facilities



- Accelerating both H^- and H^+ ions
- High degree of flexibility in beam delivery
- Multiple facilities running simultaneously
- Nuclear physics:
  - Lujan Center (LC)
  - Weapons Neutron Research (WNR)
  - UCN

Lujan Center

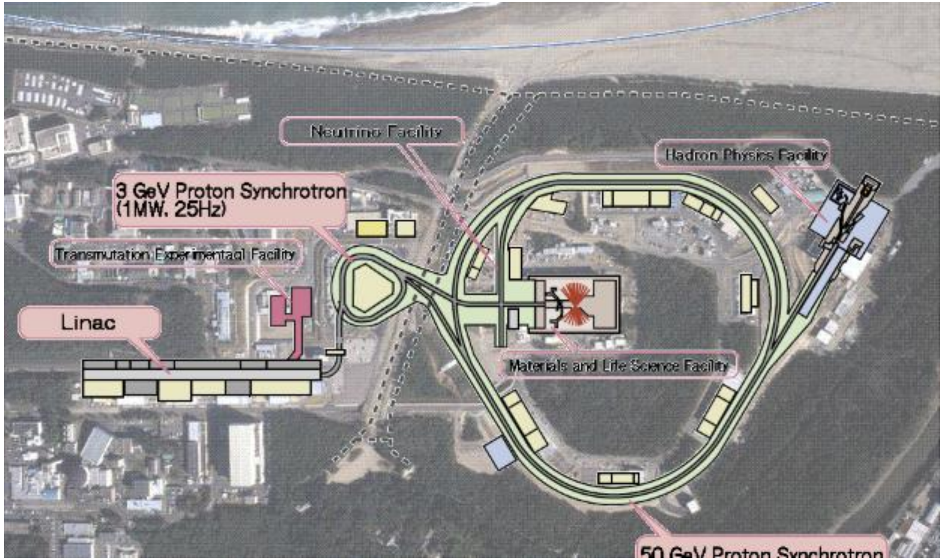
- 6 moderators (4+2)
- 16 neutron FPs
- Optimized for neutron scattering experiments
- Average 100 μA proton beam current
- Nuclear Physics FPs:
    - FP-5: Fission experiments, radiography
    - FP-12: general purpose
    - FP-14: DANCE (Detector for Advanced Neutron Capture Experiments)



J-PARC

(100kW in 2010, 1MW in 2014)

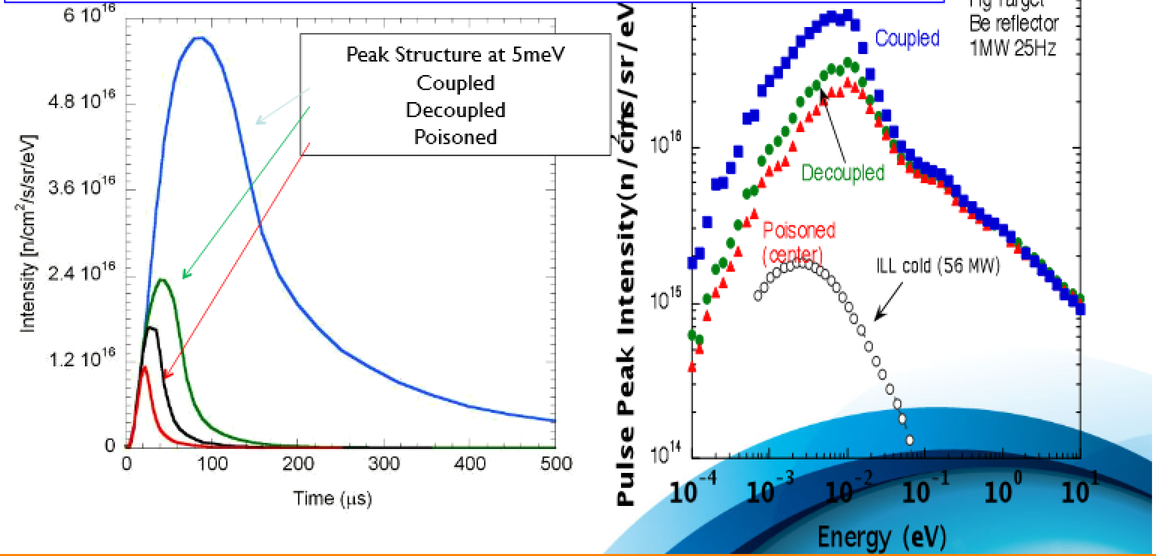
J-PARC



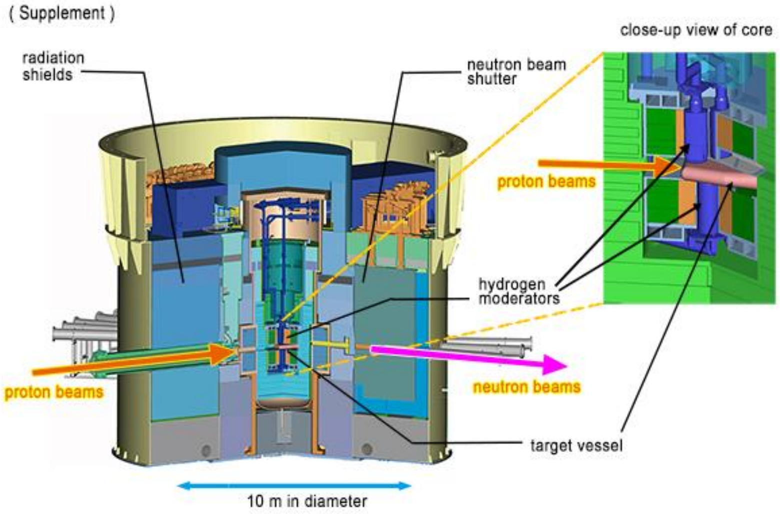
(100kW in 2010, 1MW in 2014)

J-PARC

Time Averaged Intensity (for CM) :1/4 of ILL Cold source
Pulse Peak Intensity (for CM) : ~100 of ILL Cold source

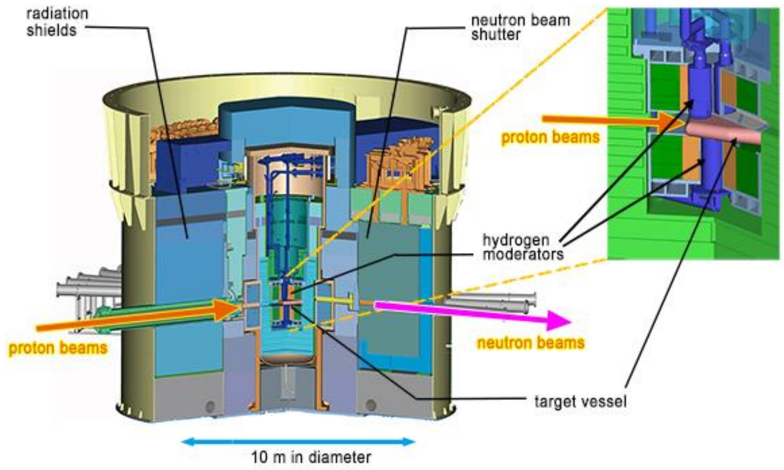


J-PARC



Cross-sectional view of pulsed neutron source in J-PARC

J-PARC



PARC

J-PARC won world record of neutron beam intensity!

○ J-PARC raised proton beam power to 300 kW on November 22, 2012 and started operation for user programs with high-intensity pulsed neutron beams.

○ The neutron beams were examined and analyzed in detail and the number of neutrons turned out to be 6.5×10^{13} per pulse. We proudly announce that J-PARC provide the strongest pulsed neutron beams in the world.

○ The world strongest pulsed neutron beams must bring breakthroughs to the cutting edge of materials science and life science. Their application to industries would be also promoted extensively, such as high functional materials or new medicines.

neutron facility	# of neutrons per pulse
J-PARC (Japan)	6.5×10^{13}
SNS (USA)	5.3×10^{13}
ISIS (UK)	4.9×10^{13}

J-PARC – Fundamental Neutron Physics

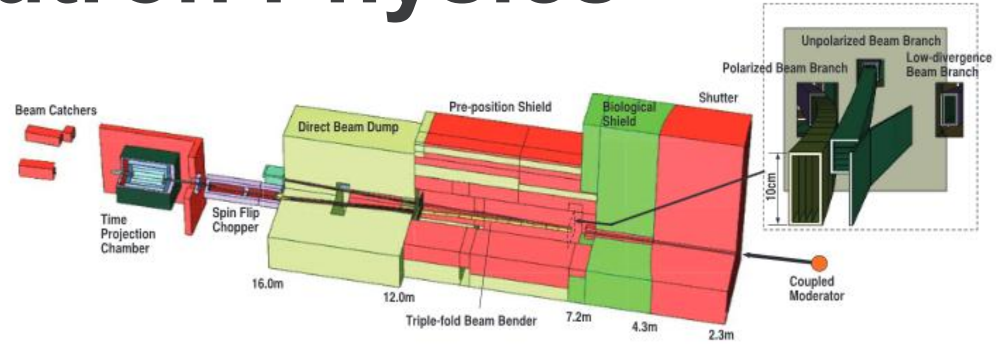
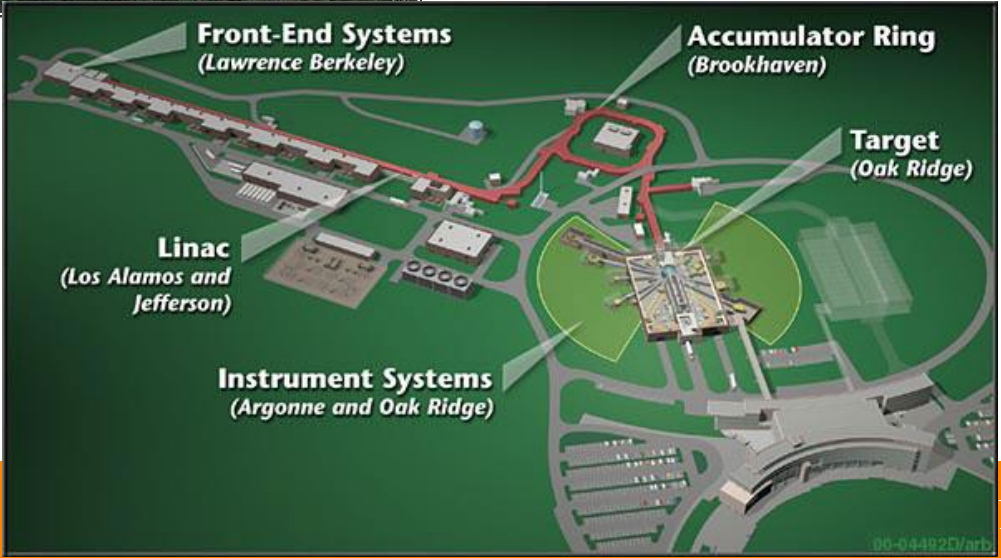


Fig. 1. Schematic view of the configuration of the NOP beamline for the study of neutron optics and fundamental physics at the beam port BL05.

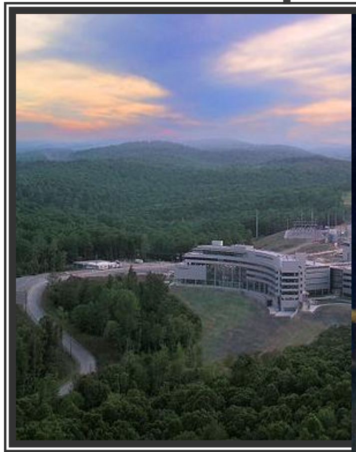
Type of Moderator	Number of Beam Ports	Time-integrated Thermal Neutron Flux	Peak Neutron Flux at 10 meV	Pulse Width in FWHM at 10 meV
	-	[n/s · cm^2] #	[n/eV · s · cm^2] #	[μs]
Coupled Moderator	11	4.6 x 10^8	6.0 x 10^{12}	92
Decoupled Moderator	6	0.95 x 10^8	3.0 x 10^{12}	33
Poisoned Moderator (Thicker Side)	3	0.65 x 10^8	2.4 x 10^{12}	22
Poisoned Moderator (Thinner Side)	3	0.38 x 10^8	1.4 x 10^{12}	14

Spallation Neutron Source at ORNL

- 1.4 GeV protons, 60Hz
- Hg Spallation target → neutrons
- H_2 moderator
- 17 m SM guide, curved



Spallation Neutron Source at ORNL



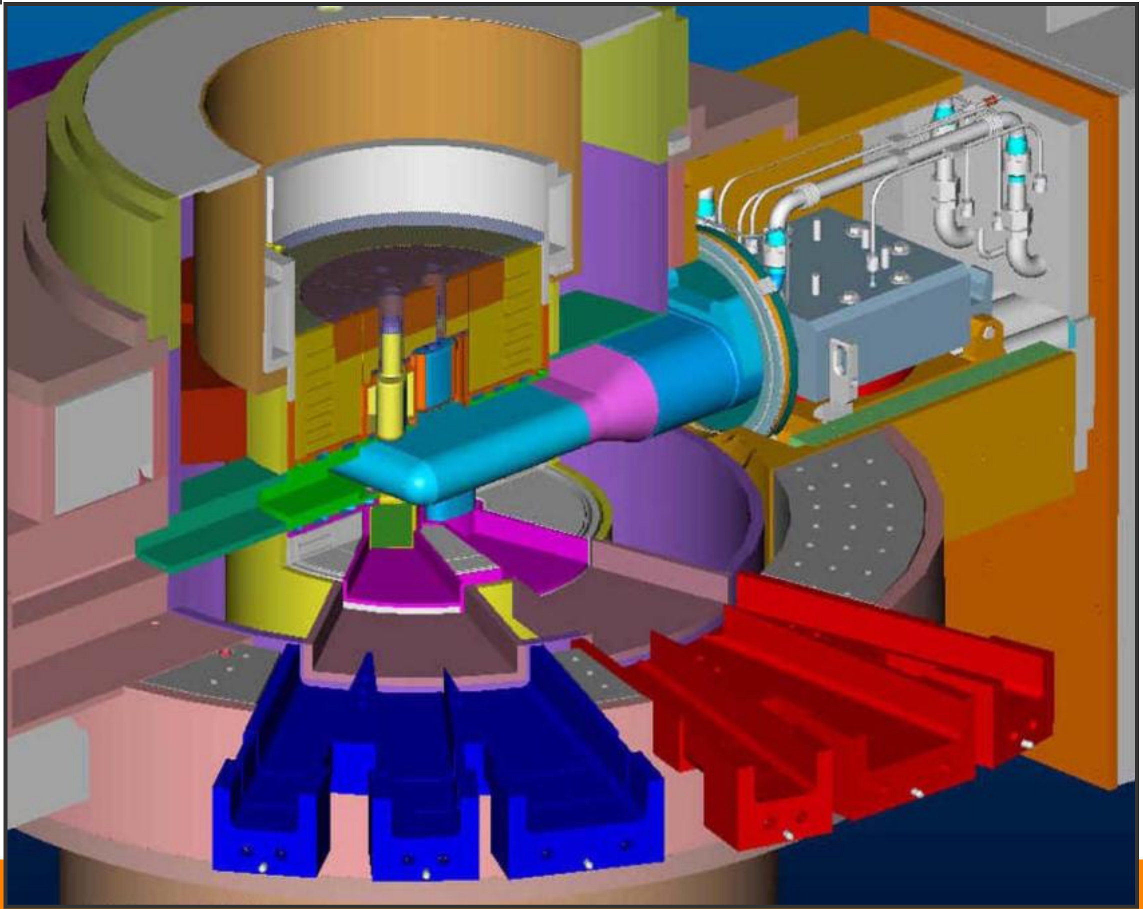
…ons, 60Hz

…n target → neutrons

…r

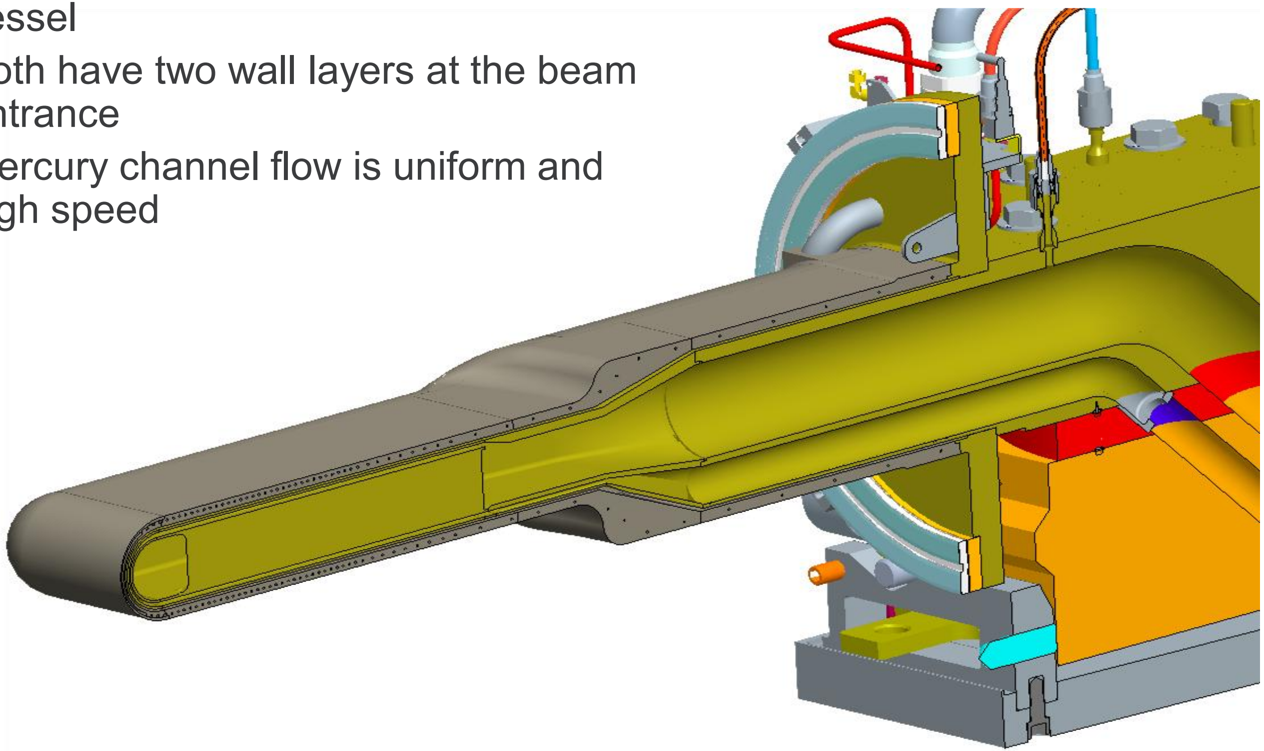
…ide, curved

Spallation Neutron Source



Original SNS Target Module Design

- Water cooled shroud surrounds mercury vessel
- Both have two wall layers at the beam entrance
- Mercury channel flow is uniform and high speed



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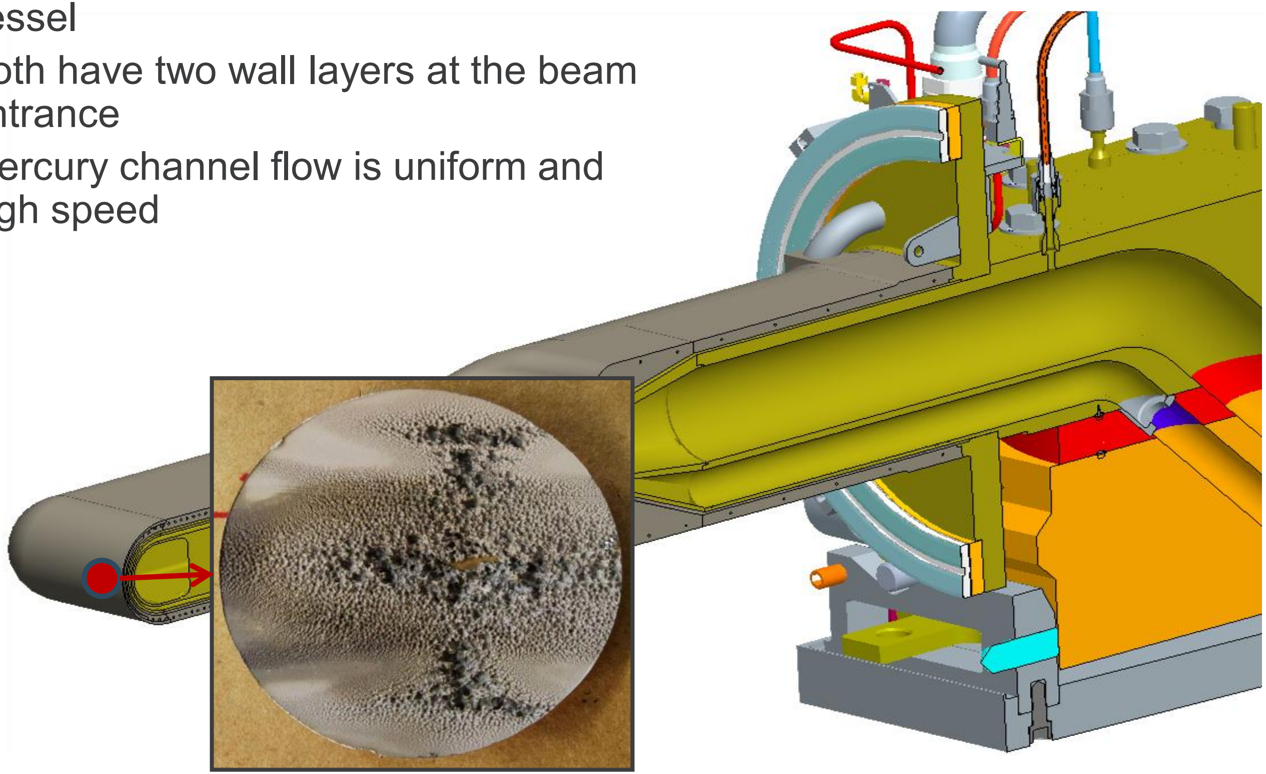
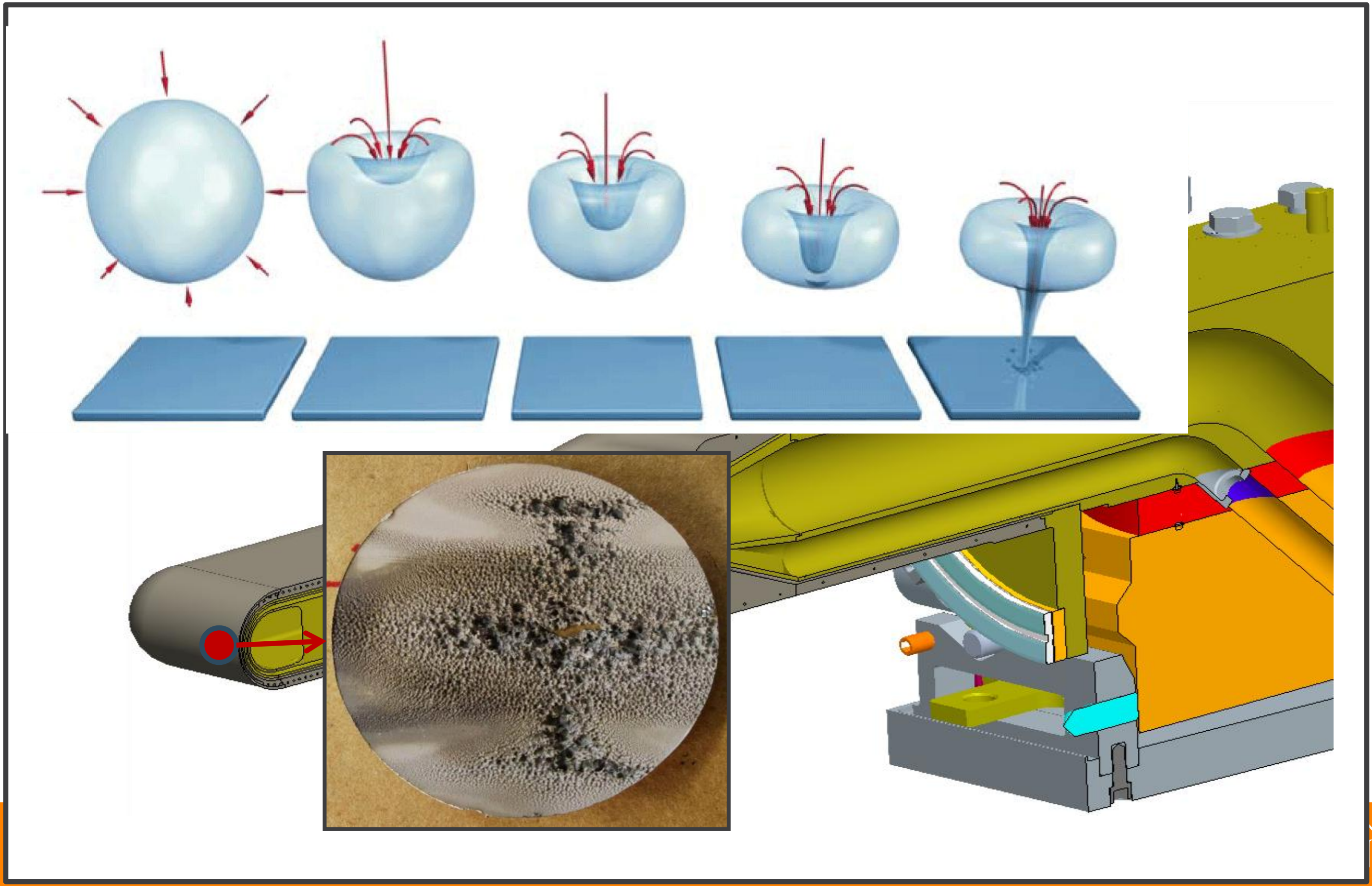


Original SNS Target Module Design



New and Improved SNS Target Module Design

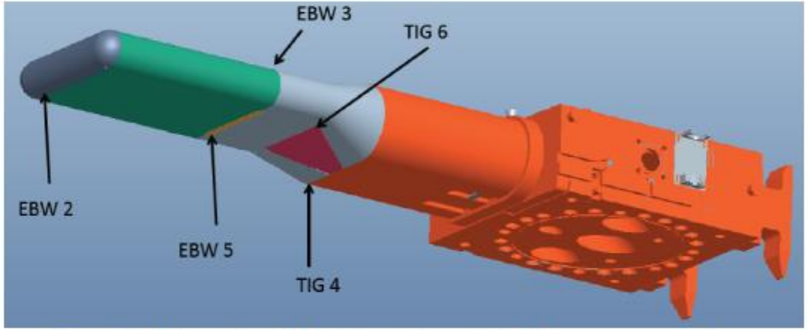


Figure 1: External weld joints on the original mercury vessel

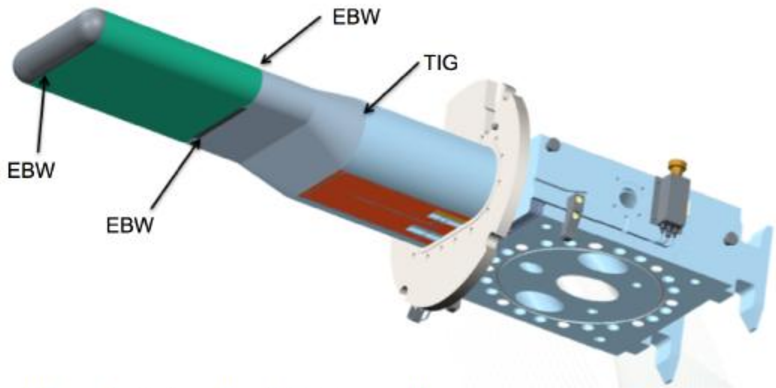
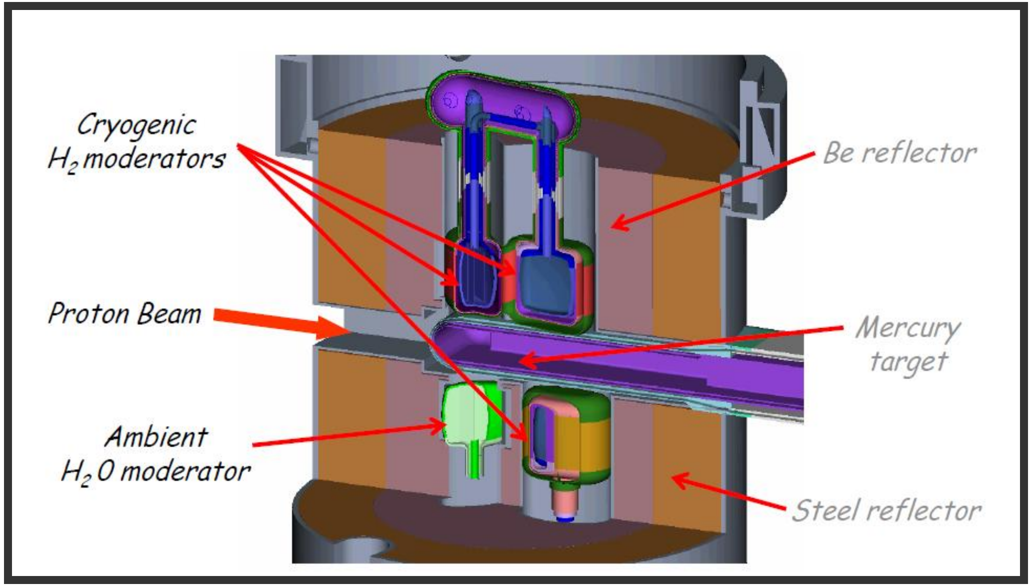


Figure 2: External weld joints on all new mercury vessels

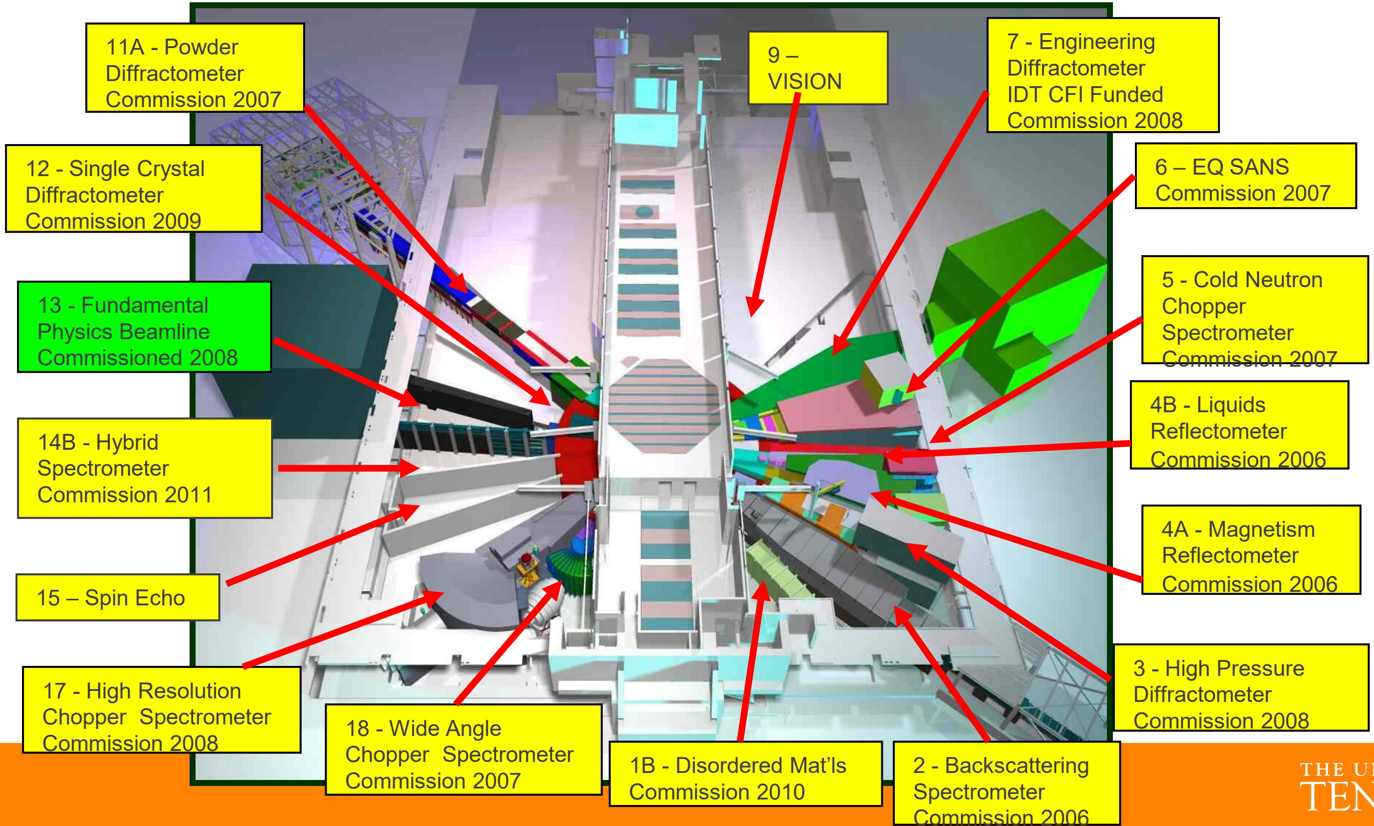
A closer look at the Mercury Target



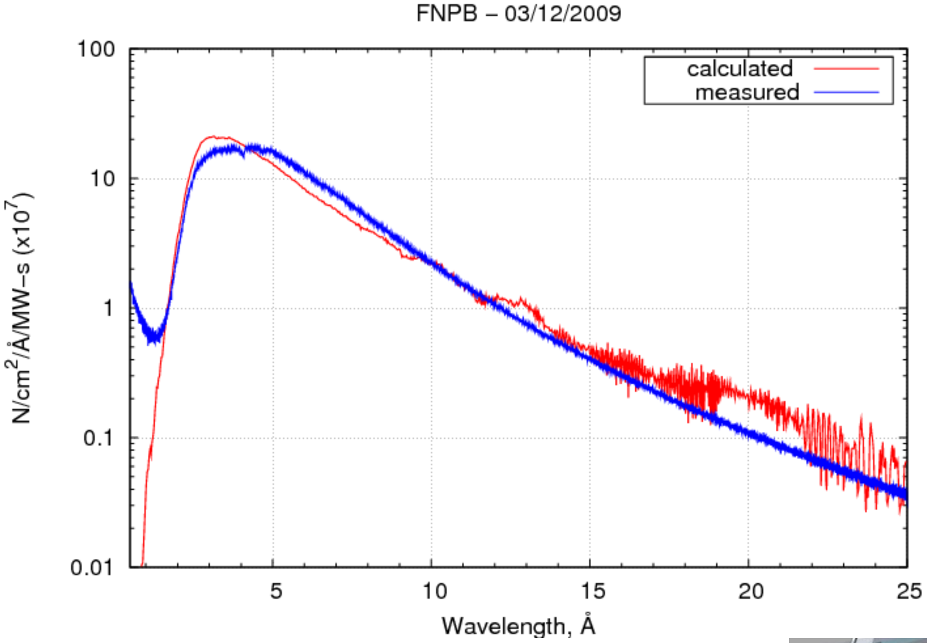
- **Thermal** ~25meV (2200m/s, λ_T=1.8Å)
- **Cold** 50μeV-25meV
- **Very cold** $2x10^{-7}$ - $5x10^{-5}$ eV
- **Ultra cold** <$2x10^{-7}$eV

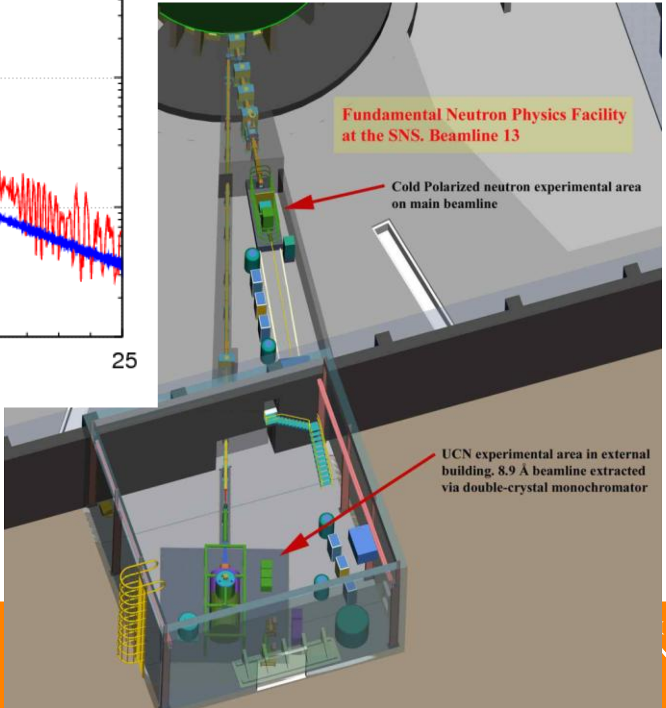
Spallation Neutron Source at ORNL

Reached 1.4 MW of power – September, 2013



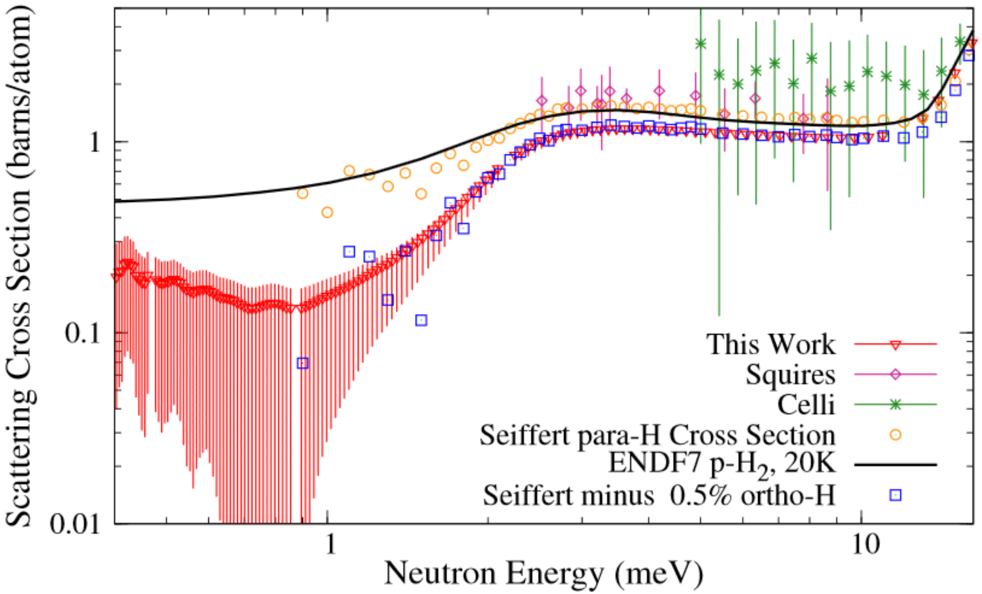
FnPB at the SNS (at ORNL)





New measurement of the scattering cross section of slow neutrons on liquid parahydrogen from neutron transmission

K. B. Grammer,[1,*] R. Alarcon,[2] L. Barrón-Palos,[3] D. Blyth,[2] J. D. Bowman,[4] J. Calarco,[5] C. Crawford,[6] K. Craycraft,[1,6] D. Evans,[7] N. Fomin,[1] J. Fry,[8] M. Gericke,[9] R. C. Gillis,[8] G. L. Greene,[1,4] J. Hamblen,[10] C. Hayes,[1] S. Kucuker,[1] R. Mahurin,[11,9] M. Maldonado-Velázquez,[3] E. Martin,[6] M. McCrea,[9] P. E. Mueller,[4] M. Musgrave,[1] H. Nann,[8] S. I. Penttilä,[4] W. M. Snow,[8] Z. Tang,[12,8] and W. S. Wilburn[12]



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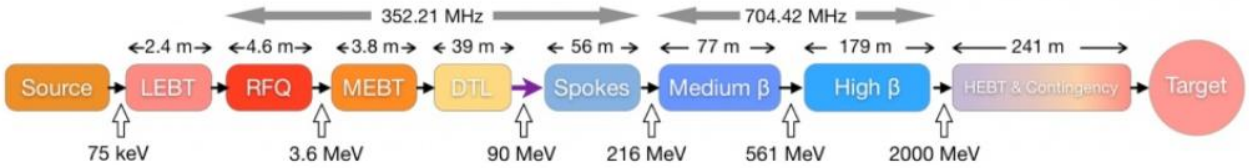
In the future: ESS

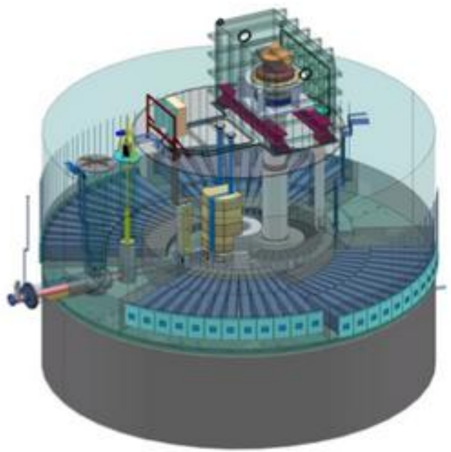


- Long pulse -- 2.86 ms proton pulse at 2 GeV at repetition rateof 14 Hz
- 5 MW of average beam power

Target - an 11-tonne helium-cooled tungsten wheel

The moderators

- 2 liquid-hydrogen moderators (2.5 L each)
- Water pre-moderators of comparable volume. Inner beryllium reflector



In the future: second SNS target station

Long pulse structure – no need for ring