Fundamental Neutron Physics II

Neutron Sources and Neutron Beams

Fundamental Neutron Physics III

Neutron Beta Decay

Geoffrey Greene
University of Tennessee / Oak Ridge National Laboratory

Introduction to Neutron Sources

Early neutron sources were based on simple nuclear processes:

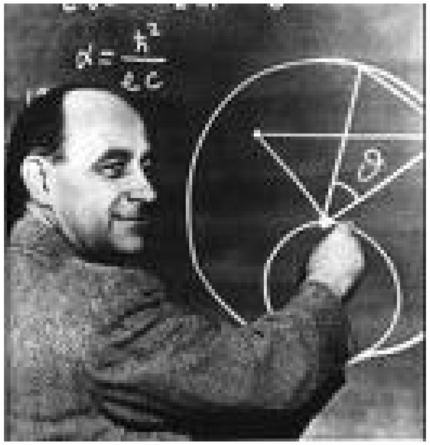
$$\alpha + {}^{9}Be \rightarrow {}^{12}C + n$$

Such sources are still used ("Pu-Be") but are limited in intensity.

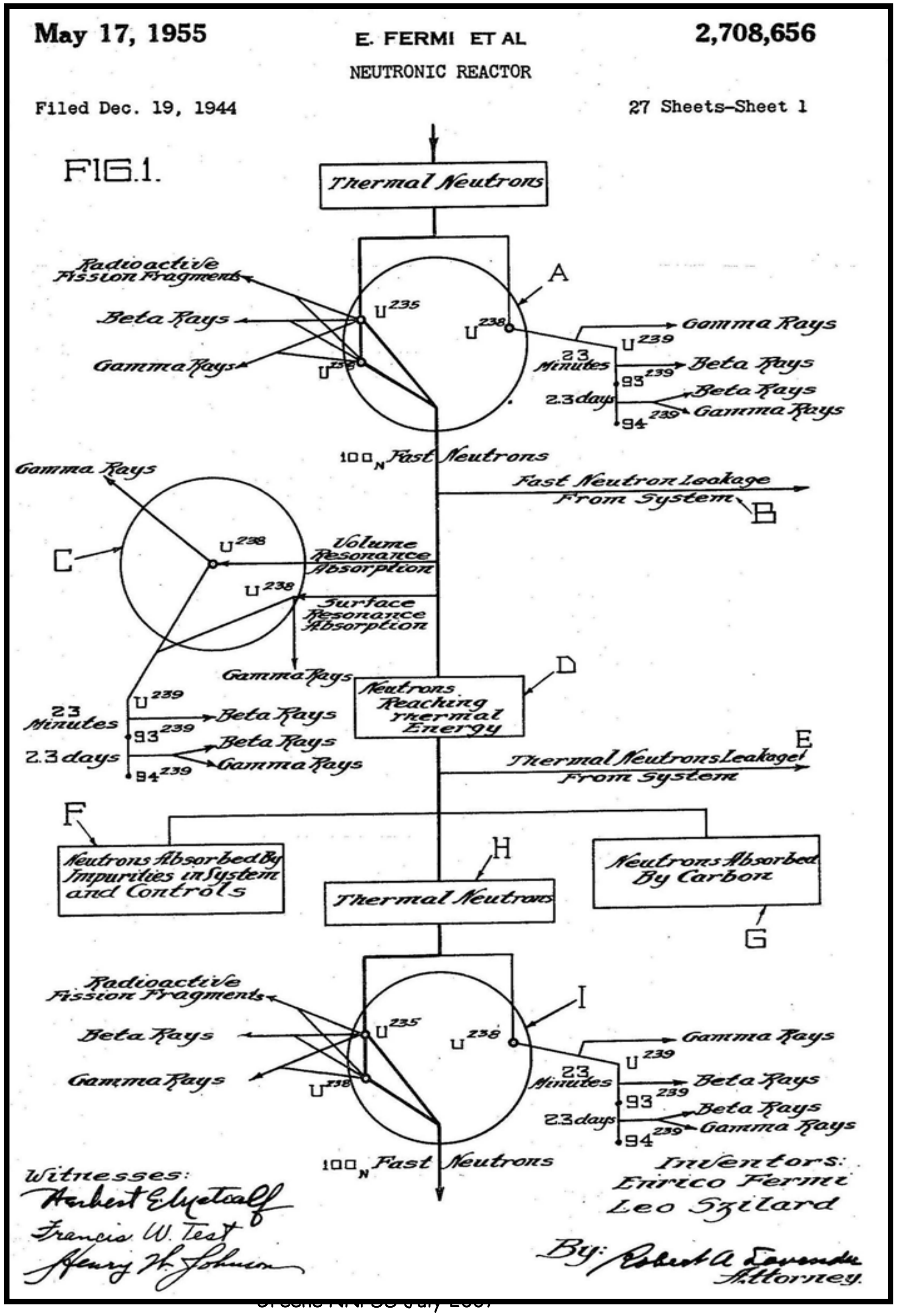
Modern neutron research is based at sources of two types:

1. **High Flux Fission Reactor**
2. **Accelerator "Spallation" Sources**

The Fission Reactor



Enrico Fermi



May 17, 1955 E. FERMI ET AL **2,708,656**

NEUTRONIC REACTOR

Filed Dec. 19, 1944 27 Sheets-Sheet 1

FIG.1.

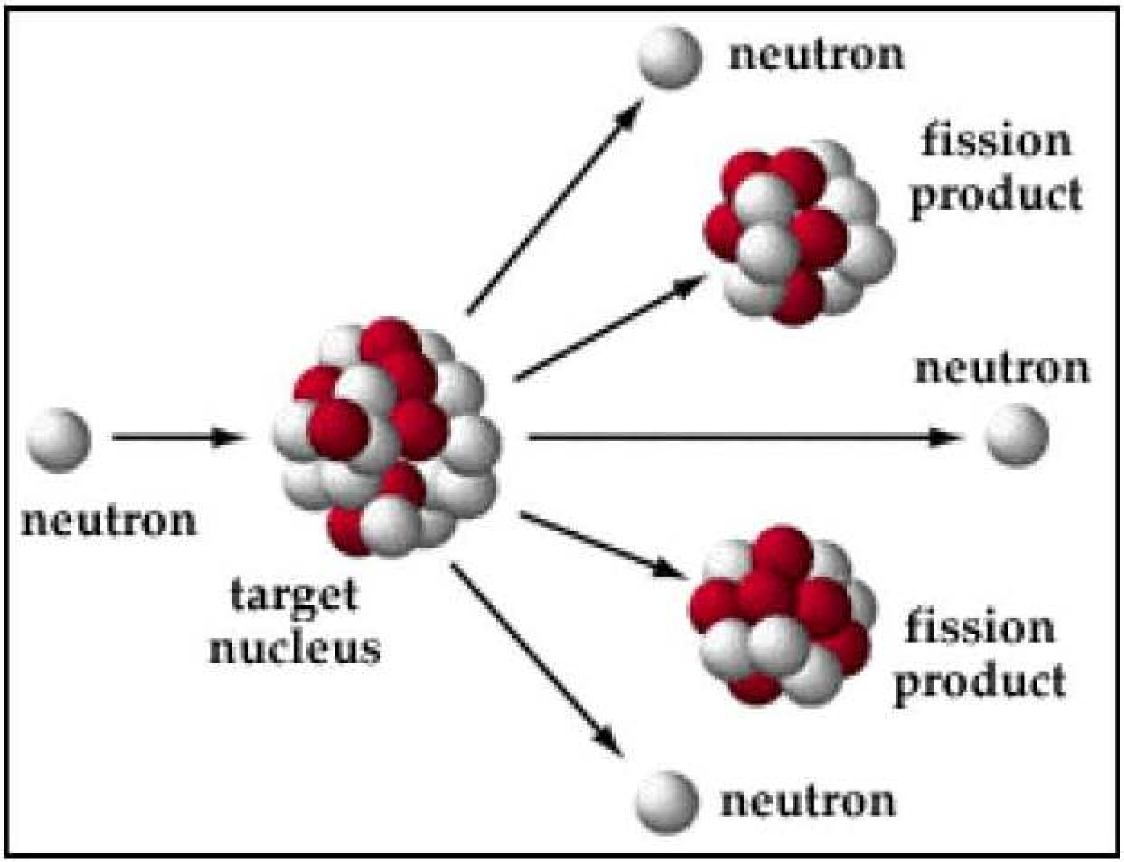
Witnesses:
Herbert E. Metcalf
Francis W. Test
Henry W. Johnson

Inventors:
Enrico Fermi
Leo Szilard

By: Robert A. Lavender
Attorney.

Leo Szilard

Each Fission Event Produces ~200Mev and ~1.5 "Useful" Neutrons



Nuclear Fission

Some Essential Features of a High Flux Reactor

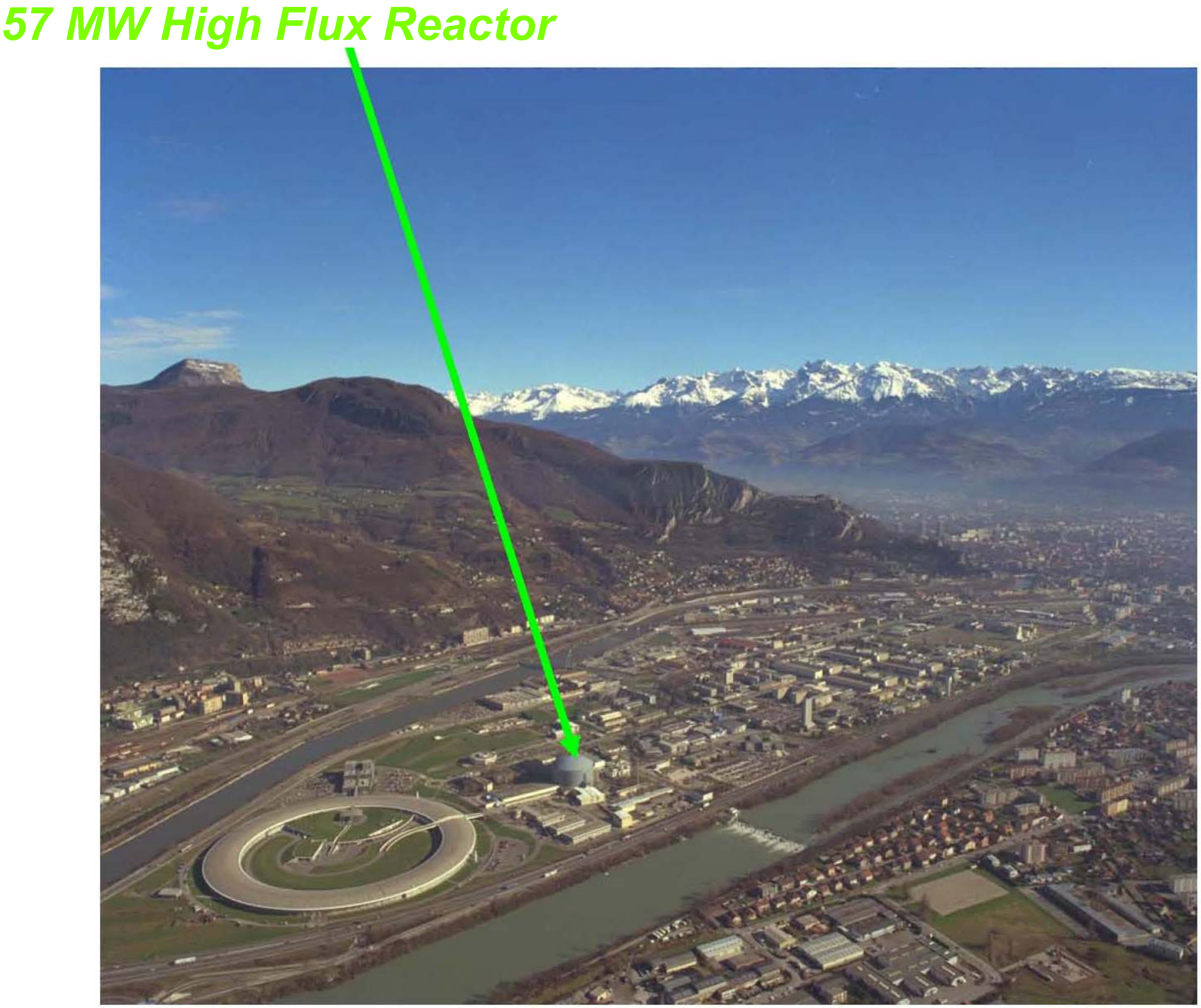
Figure of Merit is the Peak Neutron Flux at the Core $n/cm^2/s$

Key Design Features:

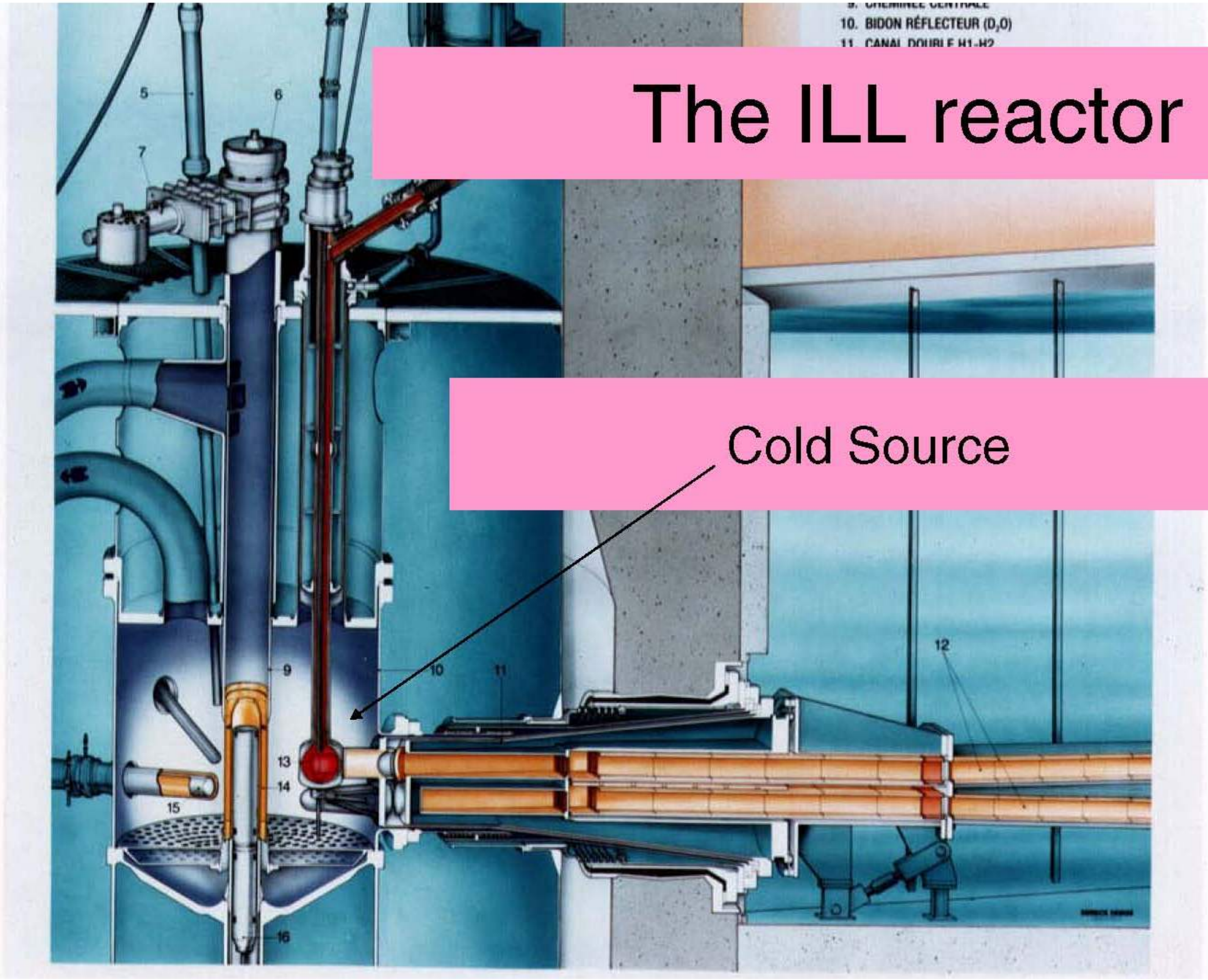
1. ***High Power Density***
2. ***Compact Core***
3. ***Highly Enriched Fuel***
4. ***D_2O Moderation and Cooling***
5. ***Cryogenic Cold Source(s)***

Ultimate engineering limitation is ability to remove heat from the compact core at ~100MW

The Institute Laue Langevin, Grenoble

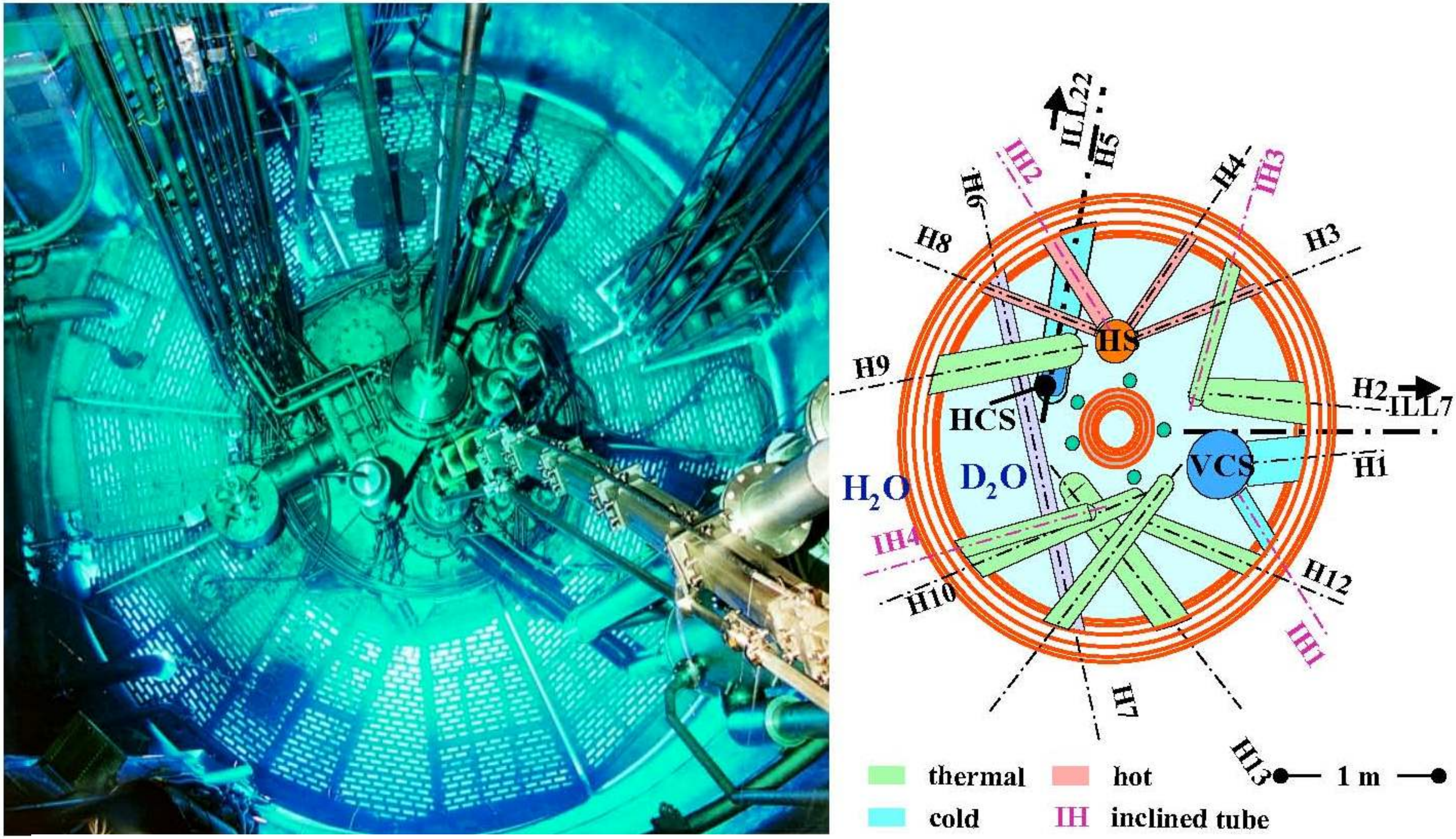


The ILL reactor



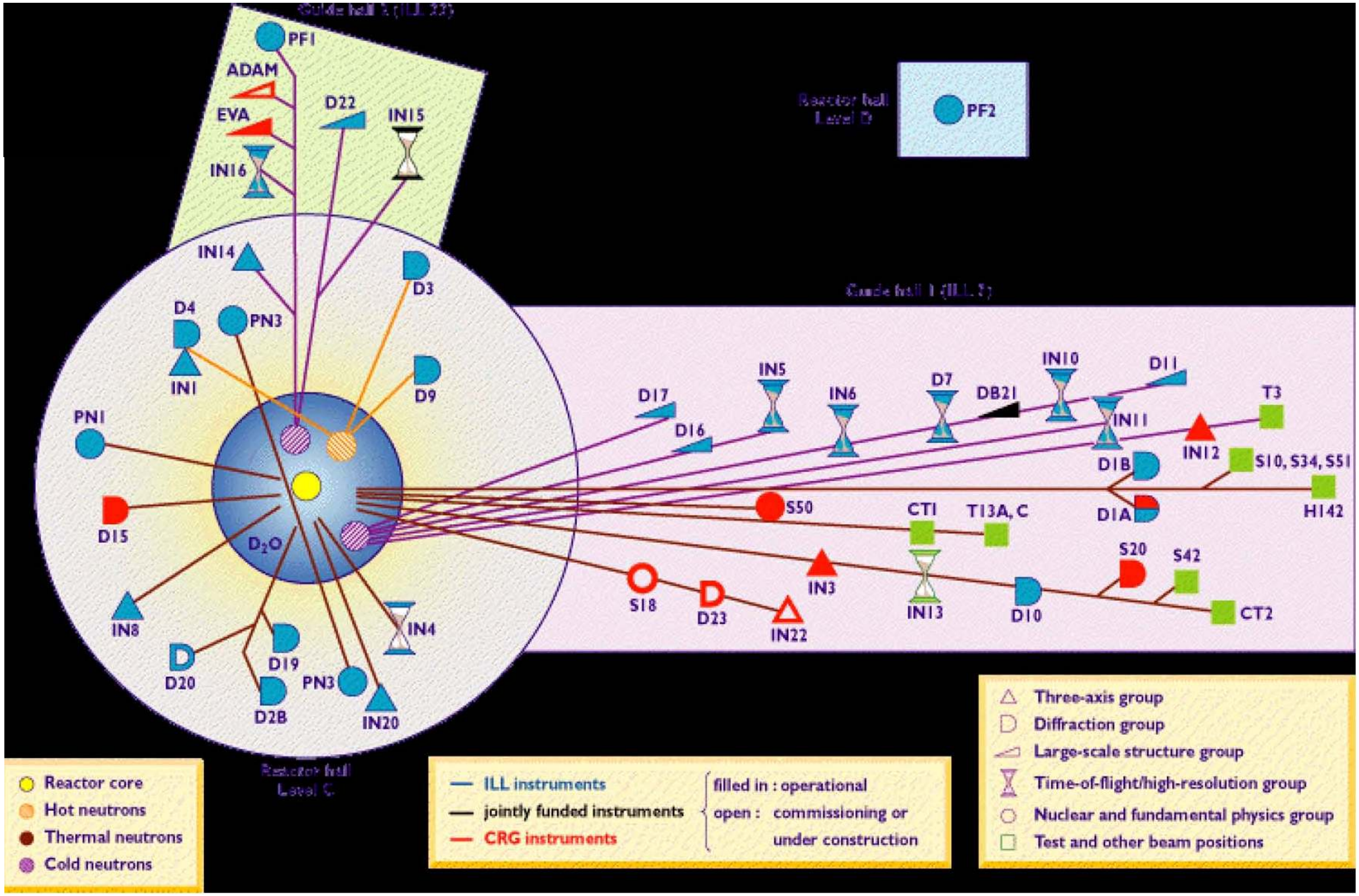
Cold Source

Most Neutron Sources Have Multiple Moderators



The High Flux neutron Source at the ILL

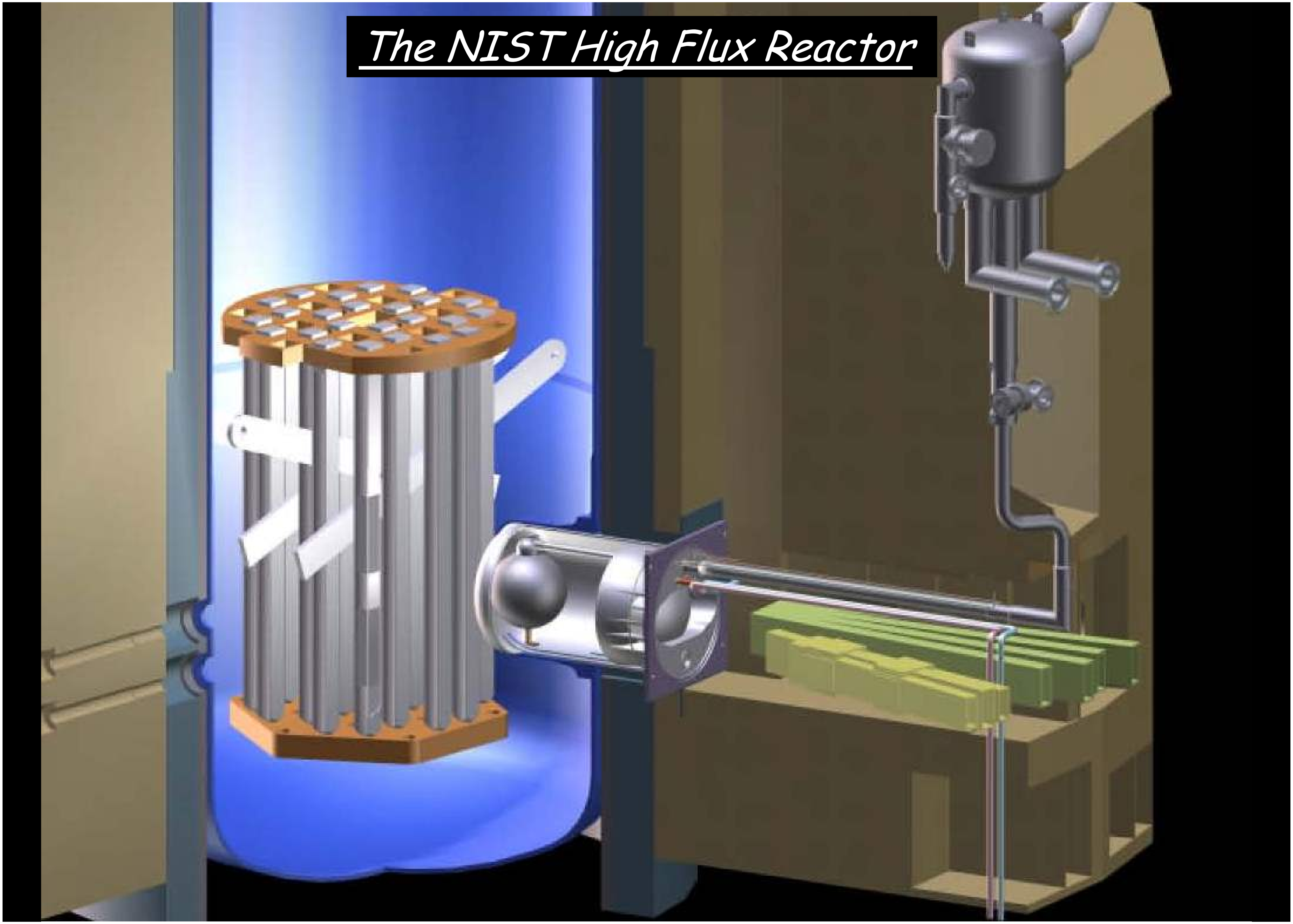
A Neutron Source Can Serve Many Neutron Instruments



Instrument Layout at the Institut Laue Langevin

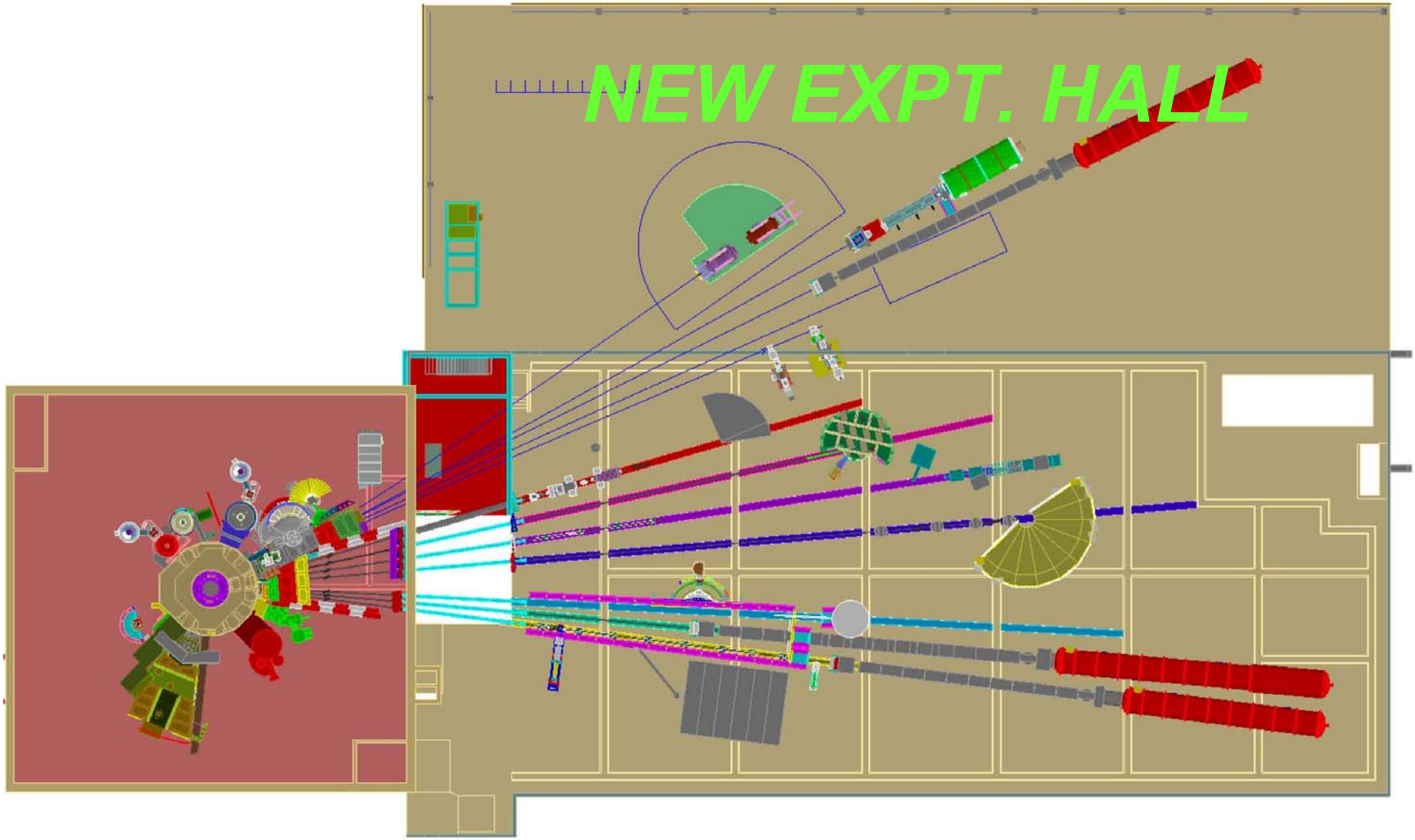
The Guide Hall at the ILL Houses ~30 Neutron Spectrometers

The NIST High Flux Reactor



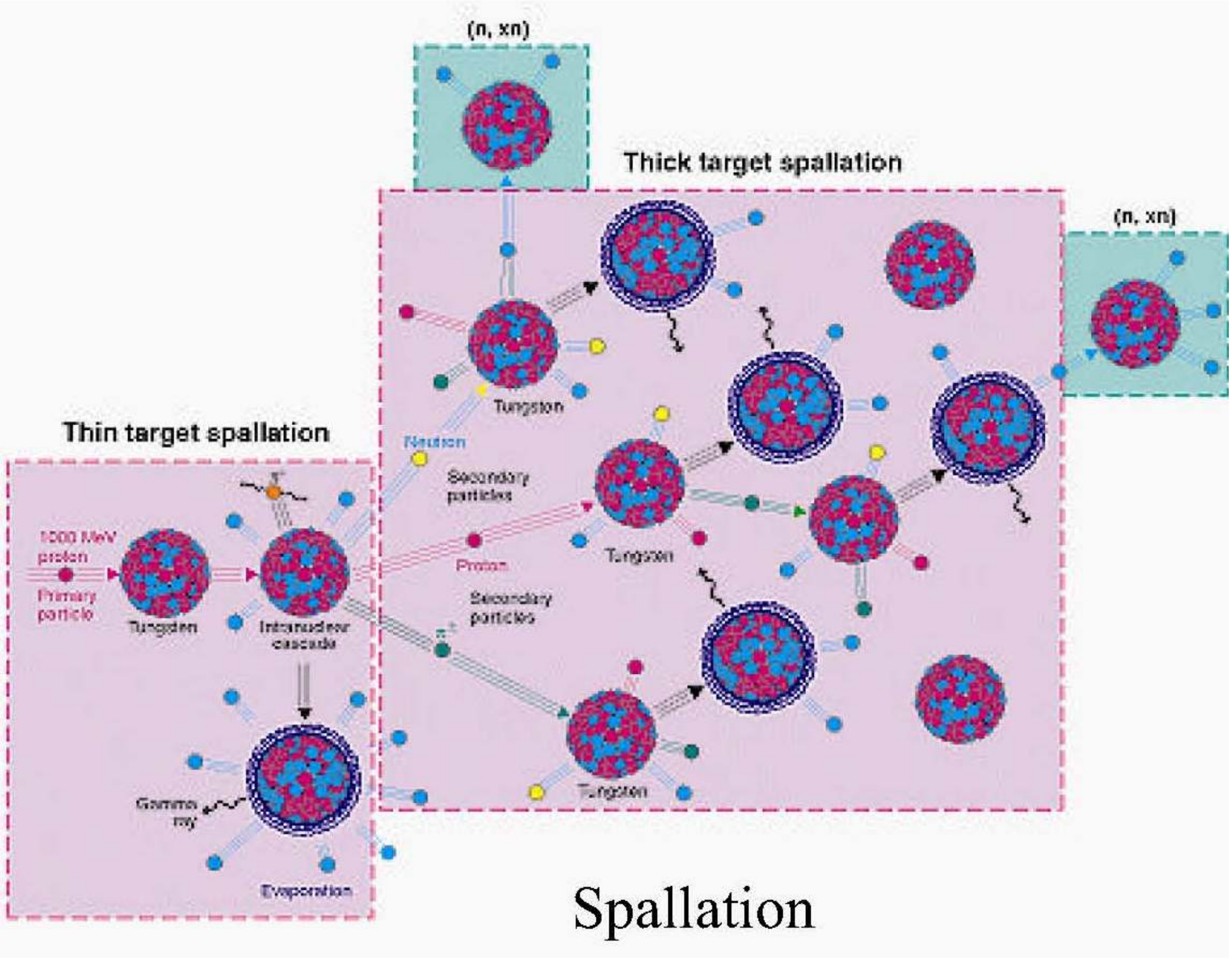
The NIST Cold Neutron research Center

The NIST Cold Neutron research Center

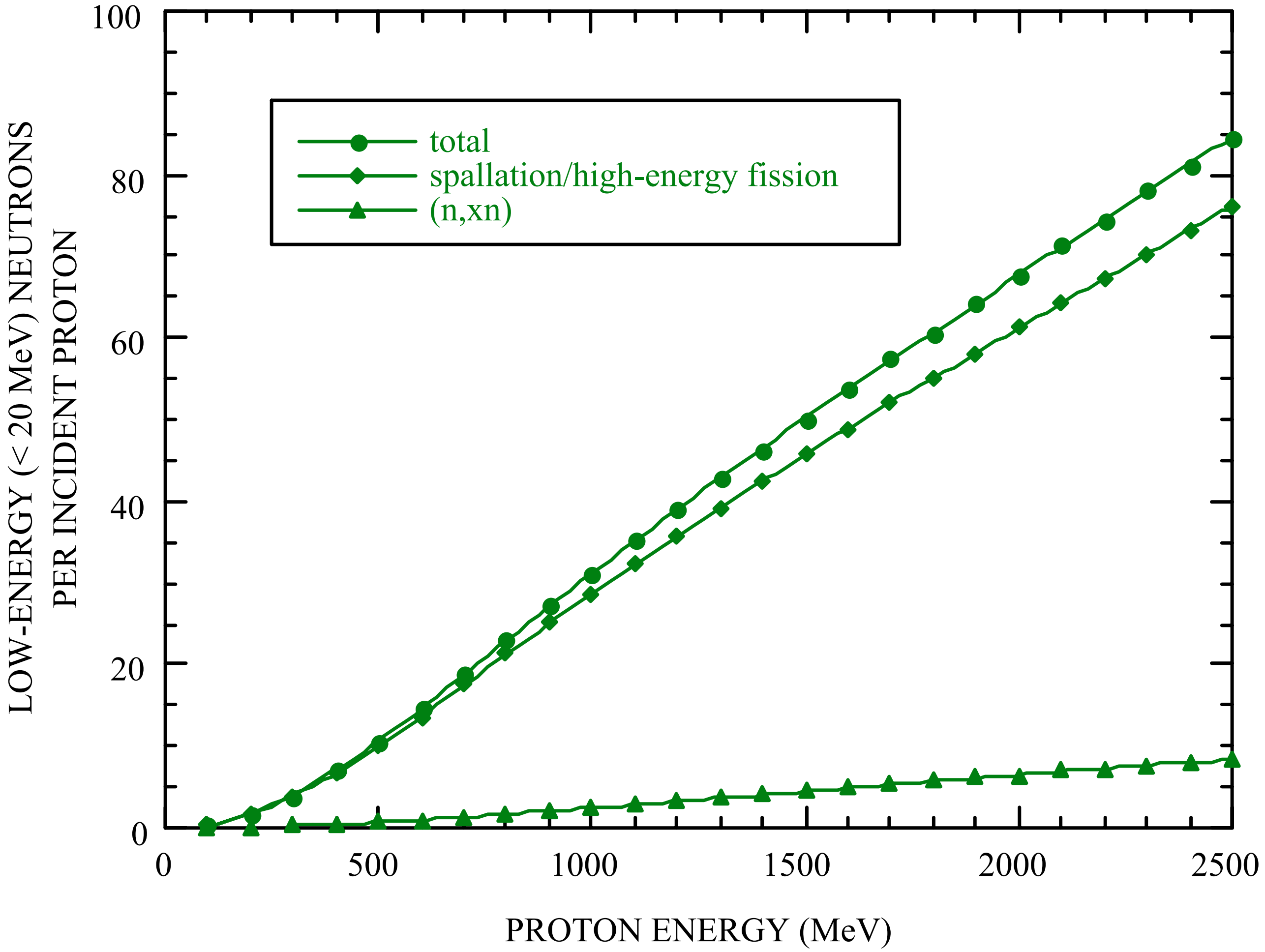


Spallation Sources

At ~1.4 GeV, Each Incident Proton Produce ~40 "Useful" Neutrons



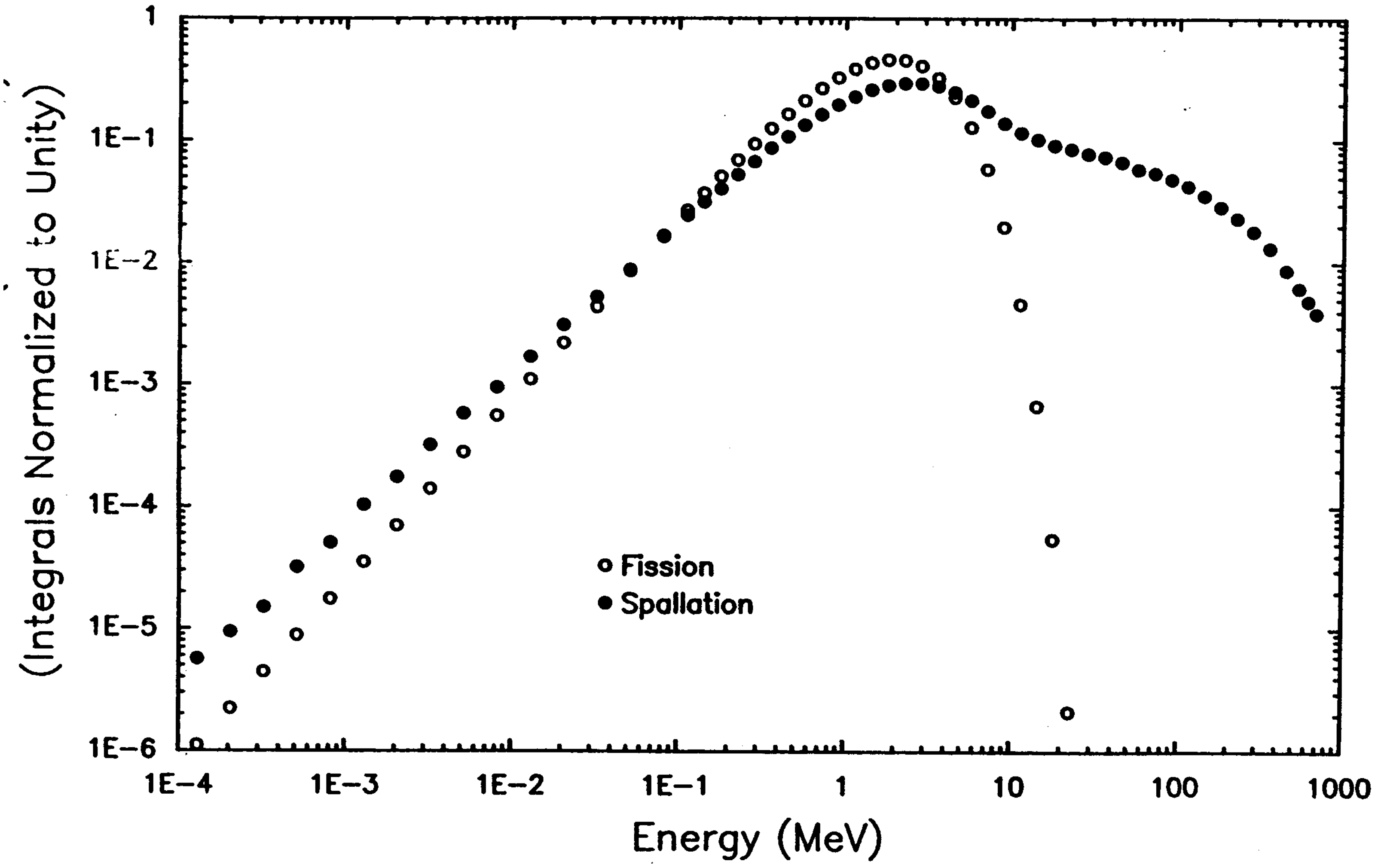
Neutron Production is Roughly Proportional to Power



NOTE: Spallation gives ~x10 more neutrons per MW

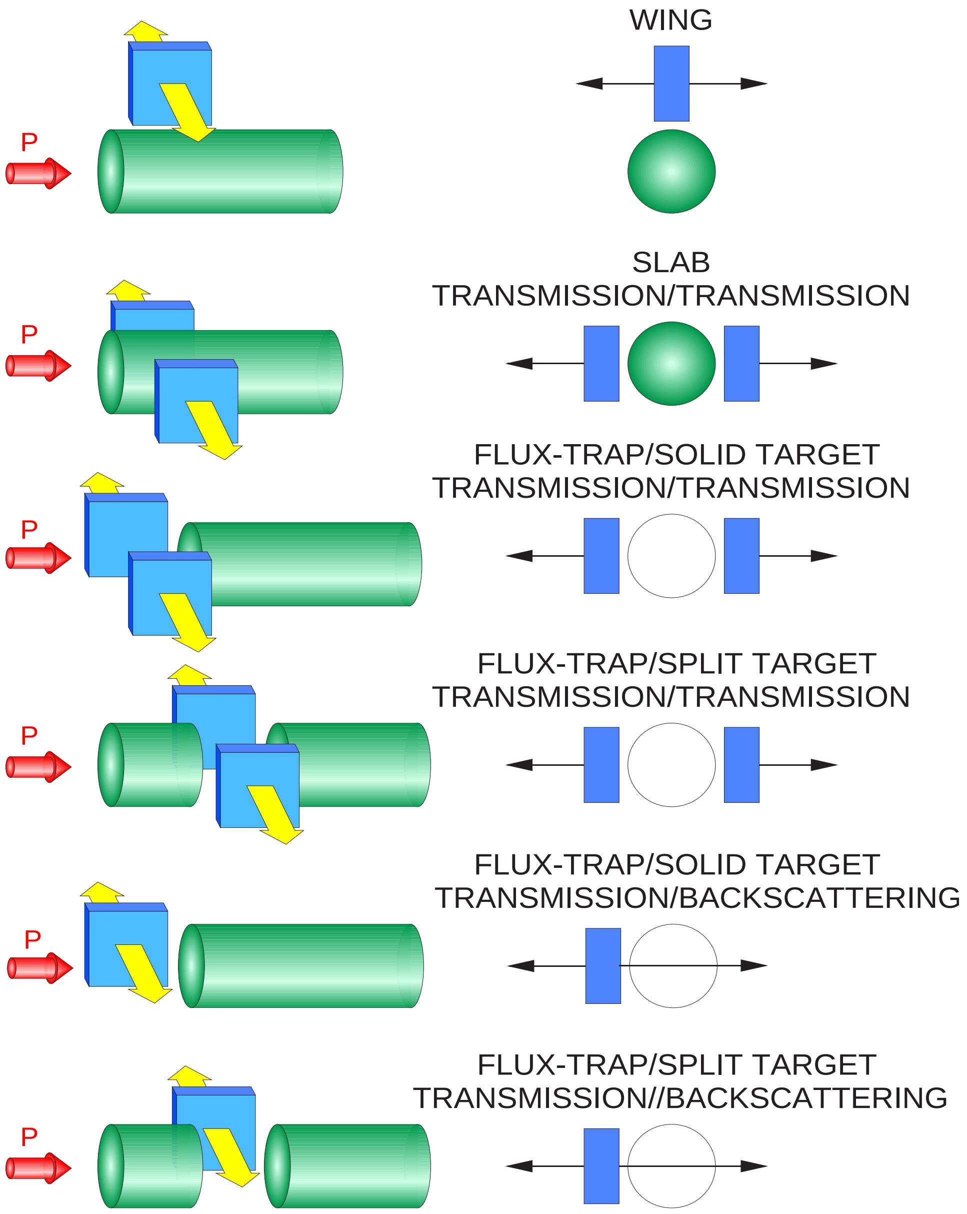
(Courtesy,Gary Russell)

The Spallation Neutron Spectrum is Broad



(Courtesy,Gary Russell)

Moderators are Engineered for Specific Neutronic Performance



WING

SLAB
TRANSMISSION/TRANSMISSION

FLUX-TRAP/SOLID TARGET
TRANSMISSION/TRANSMISSION

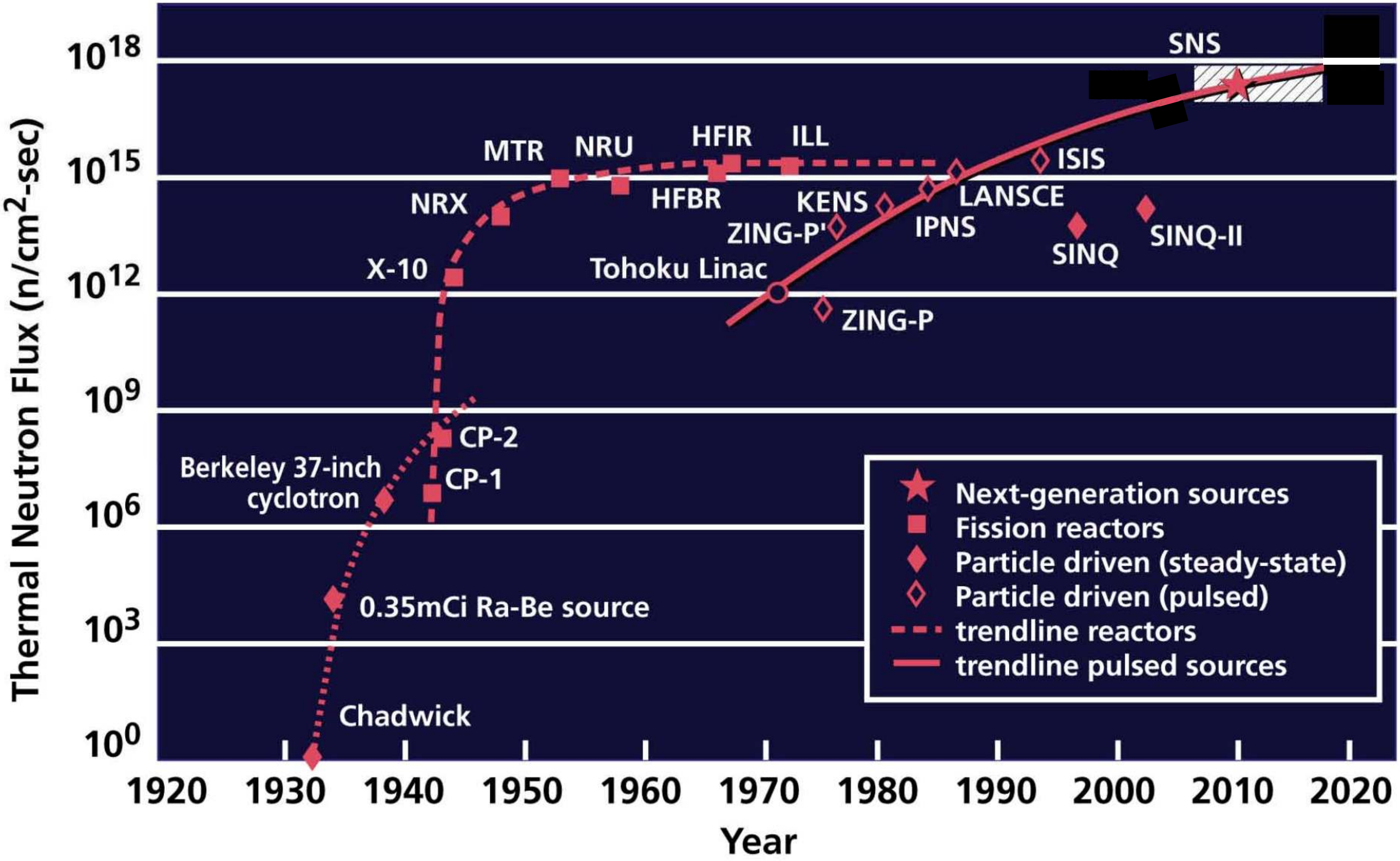
FLUX-TRAP/SPLIT TARGET
TRANSMISSION/TRANSMISSION

FLUX-TRAP/SOLID TARGET
TRANSMISSION/BACKSCATTERING

FLUX-TRAP/SPLIT TARGET
TRANSMISSION//BACKSCATTERING

(Courtesy,Gary Russell)

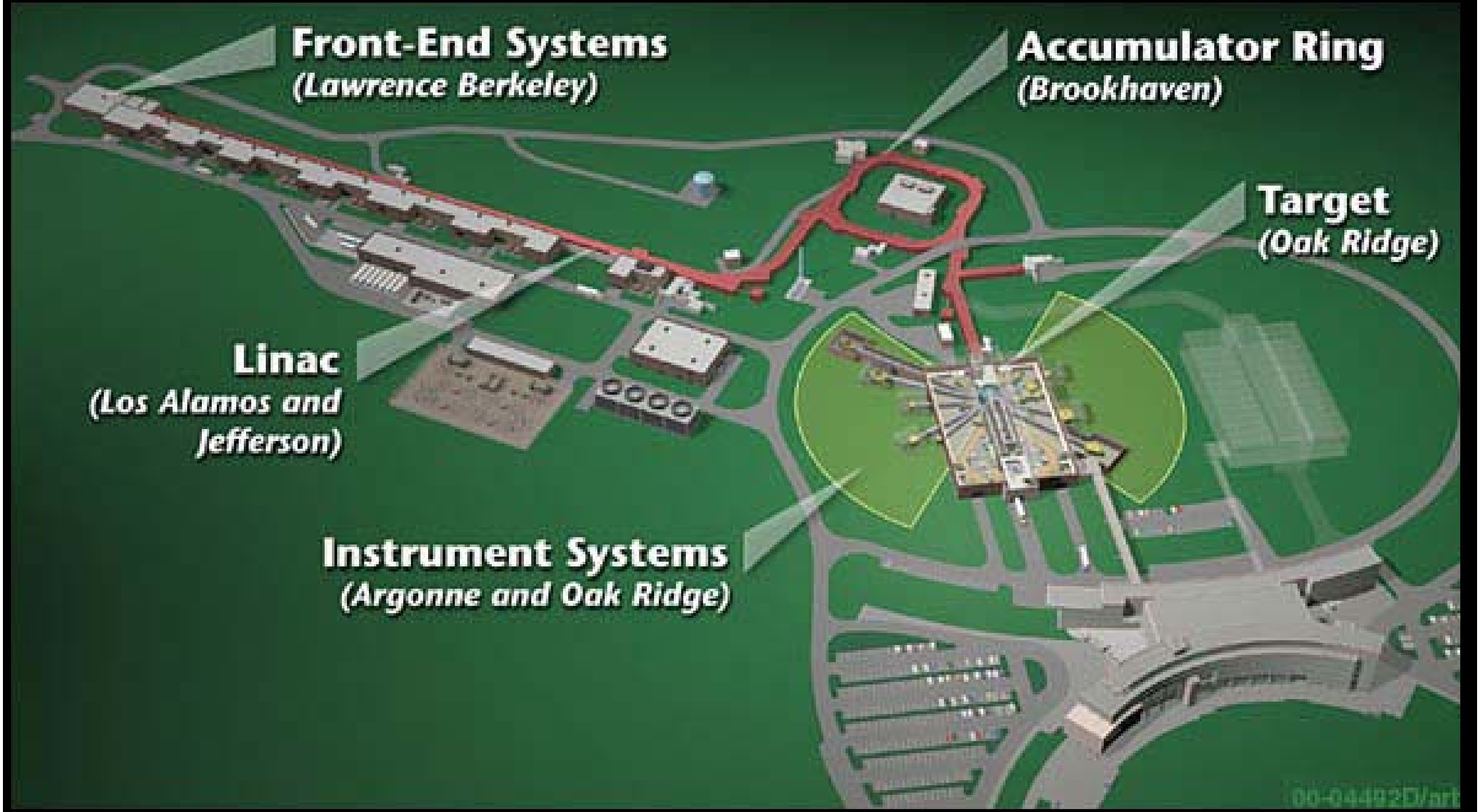
Neutron Source Intensities Have Increased by Nearly 18 Orders of Magnitude* Since Chadwick



(Updated from *Neutron Scattering*, K. Skold and D. L. Price: eds., Academic Press, 1986)

The Spallation Neutron Source


SNS-03671-2005



Front-End Systems
(Lawrence Berkeley)

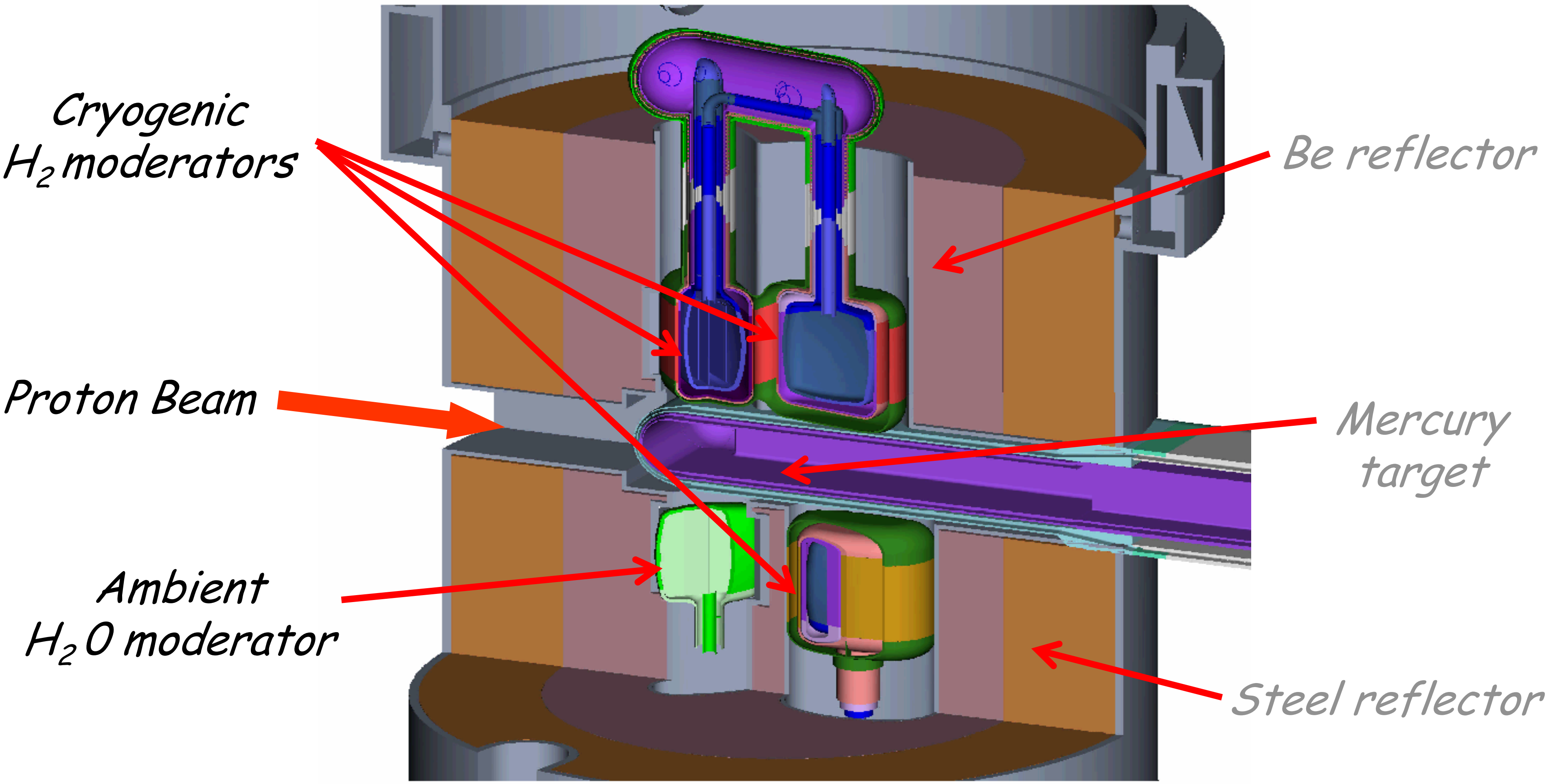
Accumulator Ring
(Brookhaven)

Target
(Oak Ridge)

Linac
(Los Alamos and
Jefferson)

Instrument Systems
(Argonne and Oak Ridge)

Target, Reflectors, and Moderators


Cryogenic H_2 moderators

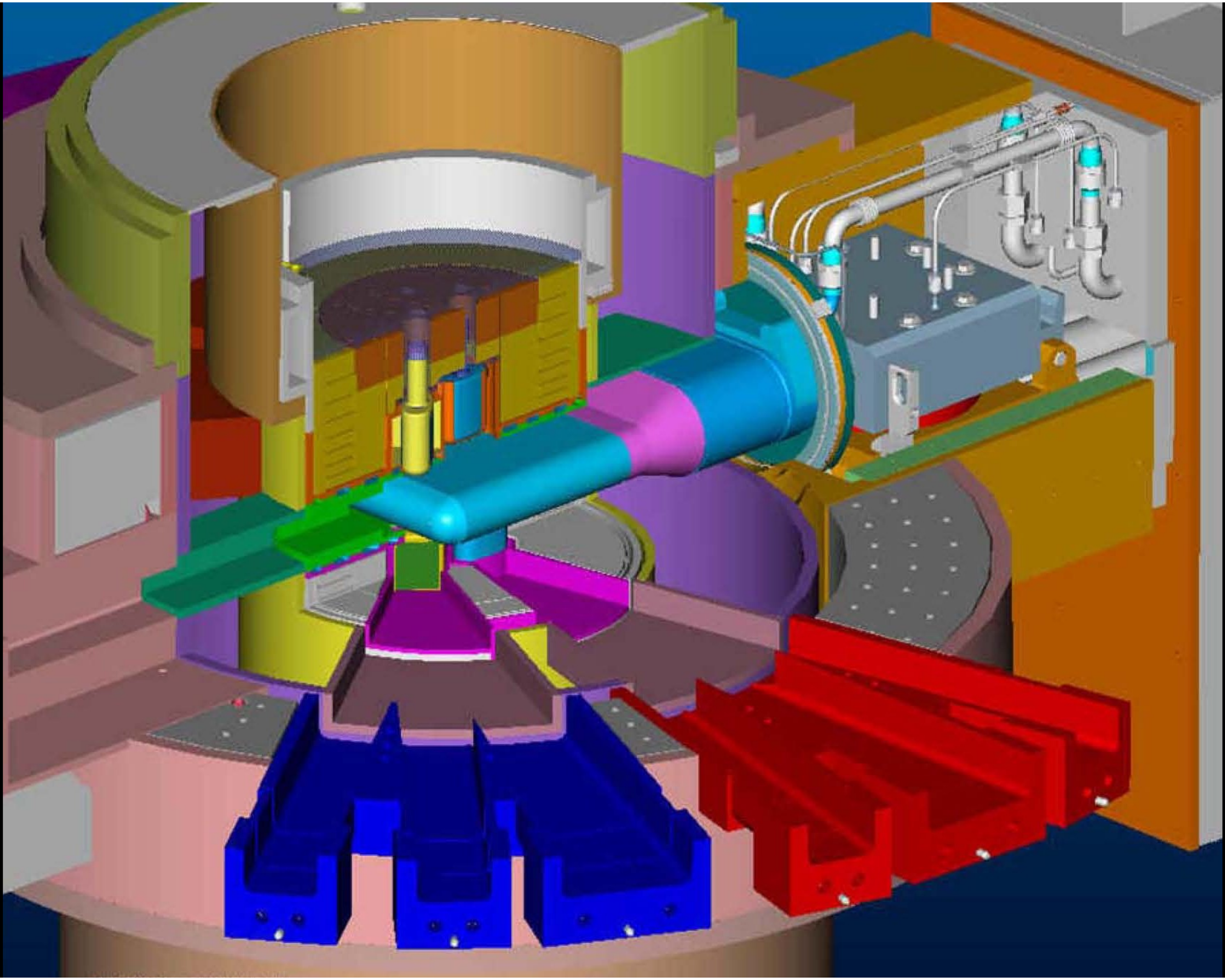
Proton Beam

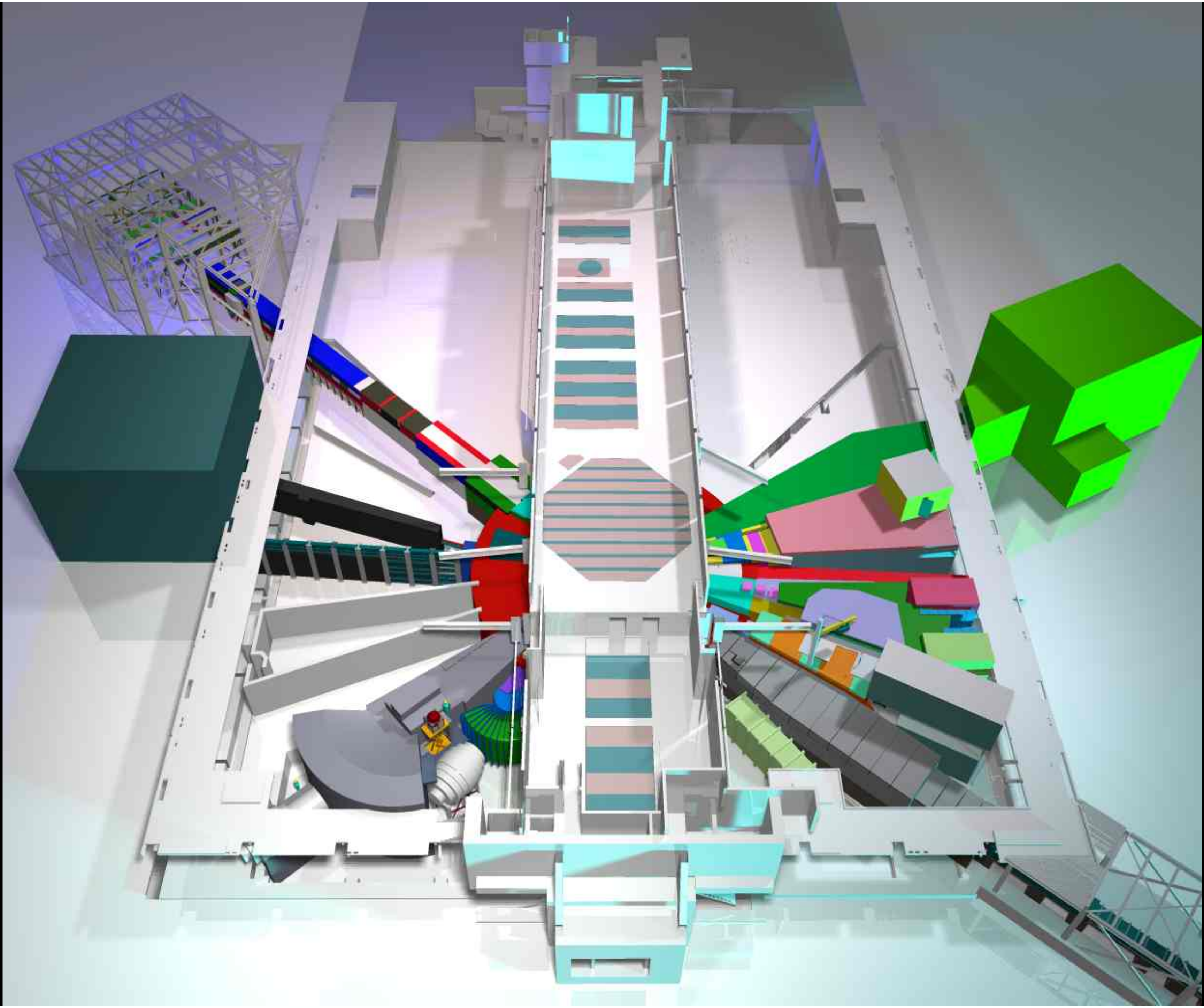
Ambient H_2O moderator

Be reflector

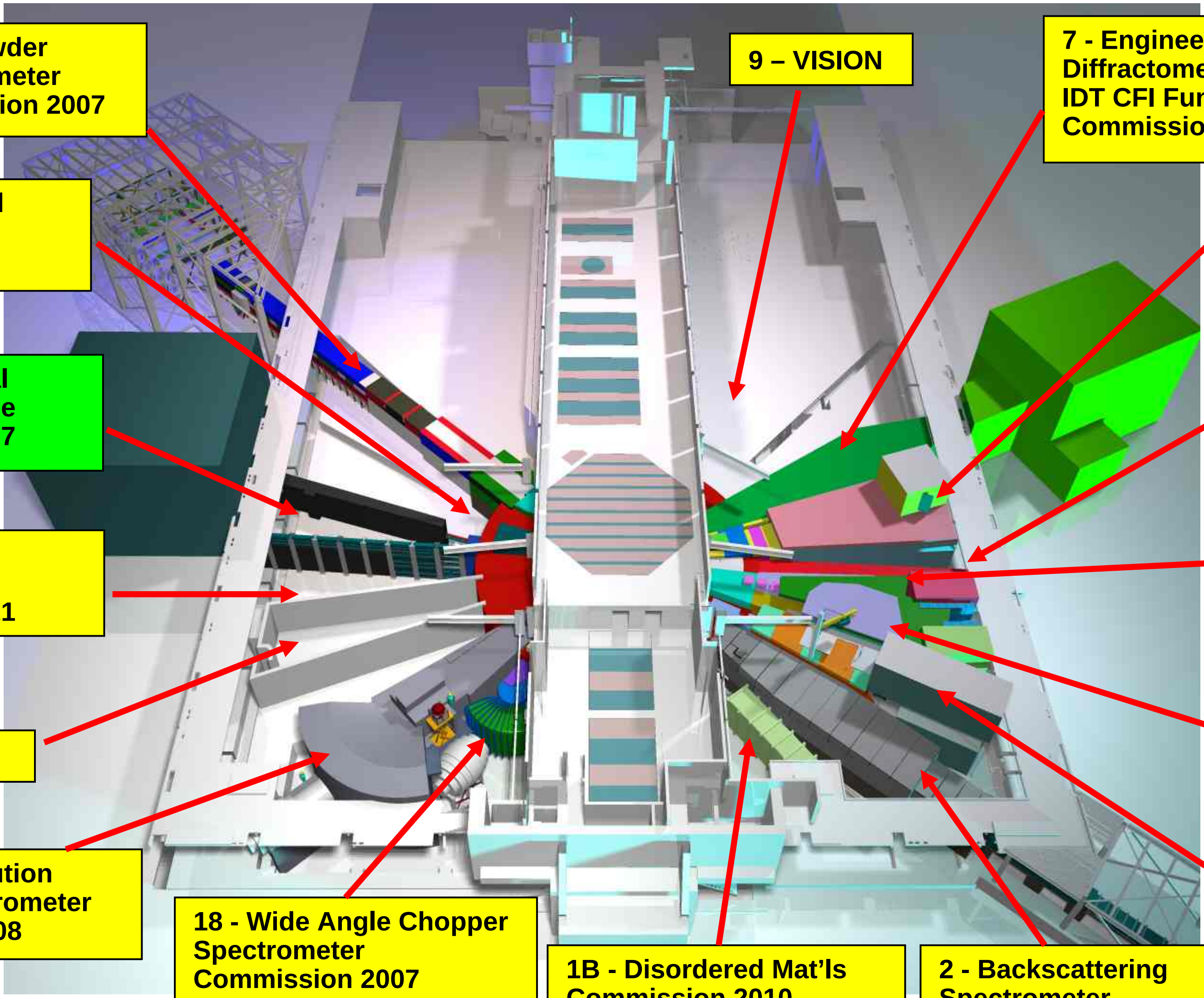
Mercury target

Steel reflector





Beamline 13 Has Been Allocated for Nuclear Physics



11A - Powder Diffractometer Commission 2007

12 - Single Crystal Diffractometer Commission 2009

13 - Fundamental Physics Beamline Commission 2007

14B - Hybrid Spectrometer Commission 2011

15 – Spin Echo

17 - High Resolution Chopper Spectrometer Commission 2008

18 - Wide Angle Chopper Spectrometer Commission 2007

1B - Disordered Mat'ls Commission 2010

2 - Backscattering Spectrometer Commission 2006

9 – VISION

7 - Engineering Diffractometer IDT CFI Funded Commission 2008

6 - SANS Commission 2007

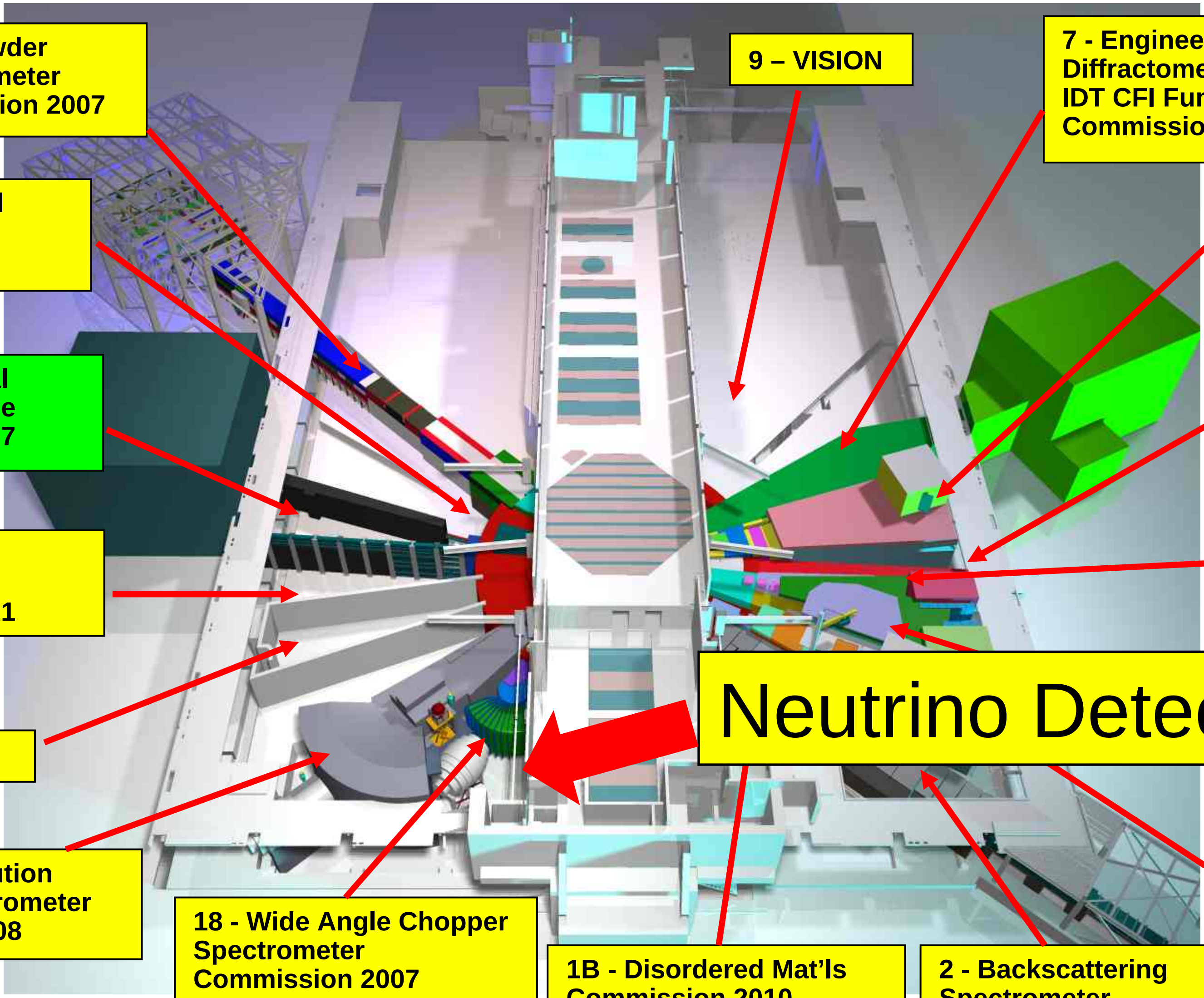
5 - Cold Neutron Chopper Spectrometer Commission 2007

4B - Liquids Reflectometer Commission 2006

4A - Magnetism Reflectometer Commission 2006

3 - High Pressure Diffractometer Commission 2008

Beamline 13 Has Been Allocated for Nuclear Physics



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1B - Disordered Mat'ls Commission 2010

2 - Backscattering Spectrometer Commission 2006

3 - High Pressure Diffractometer Commission 2008

Neutrino Detector Here

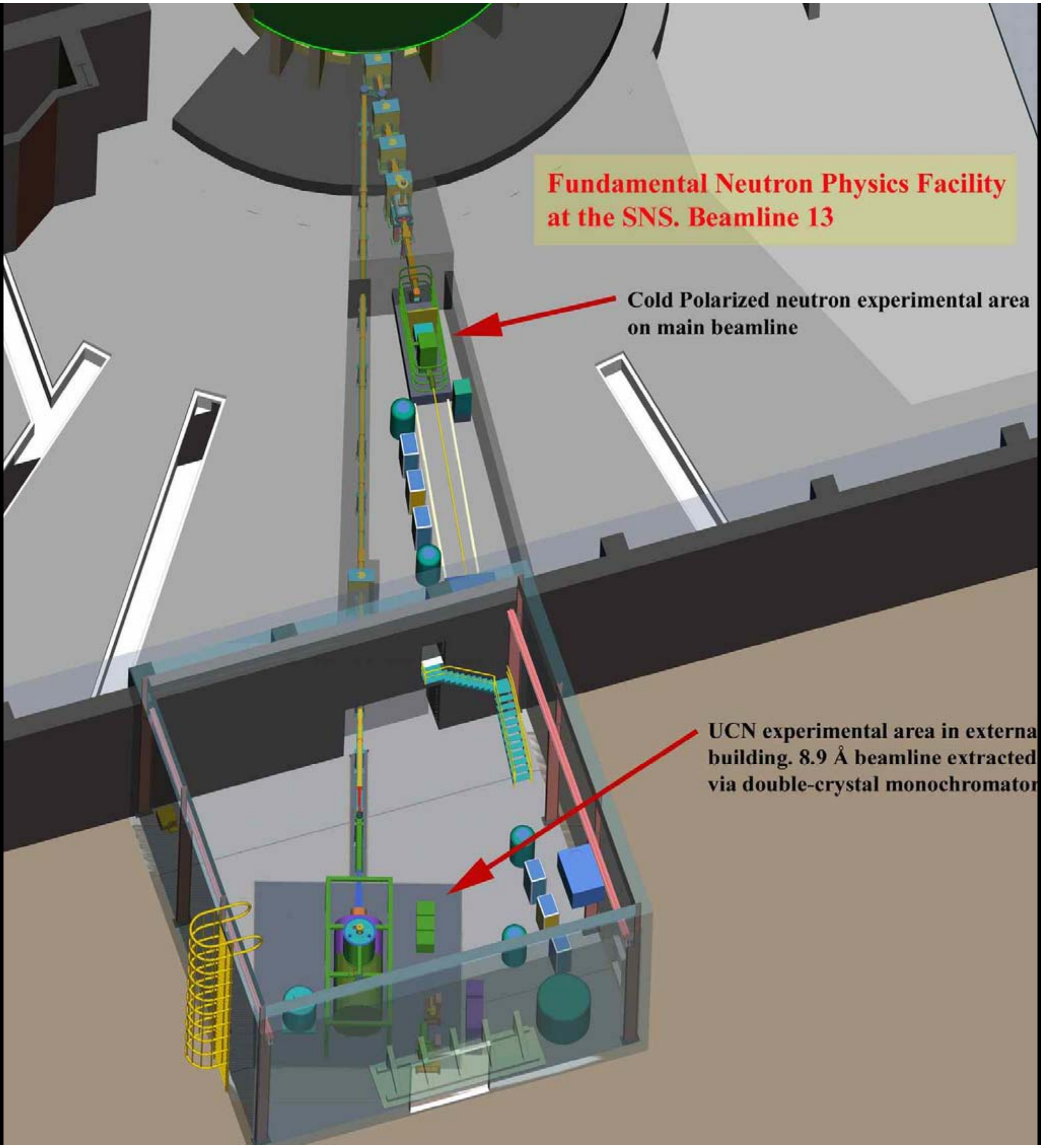
4B - Liquids Reflectometer Commission 2006

5 - Cold Neutron Chopper Spectrometer Commission 2007

6 - SANS Commission 2007

7 - Engineering Diffractometer IDT CFI Funded Commission 2008

9 – VISION



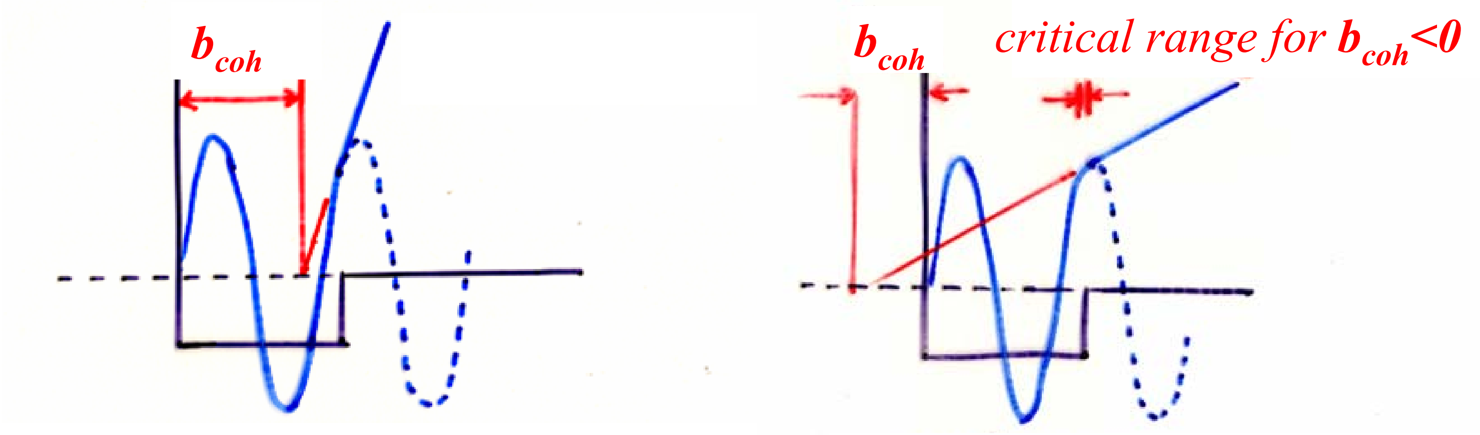
Fundamental Neutron Physics Facility at the SNS. Beamline 13

Cold Polarized neutron experimental area
on main beamline

UCN experimental area in externa
building. 8.9 Å beamline extracted
via double-crystal monochromato

Neutron Guides

At low energies S-wave scattering dominates, phase shift is given by $\cot(\delta) = \frac{-1}{kb_{coh}}$



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

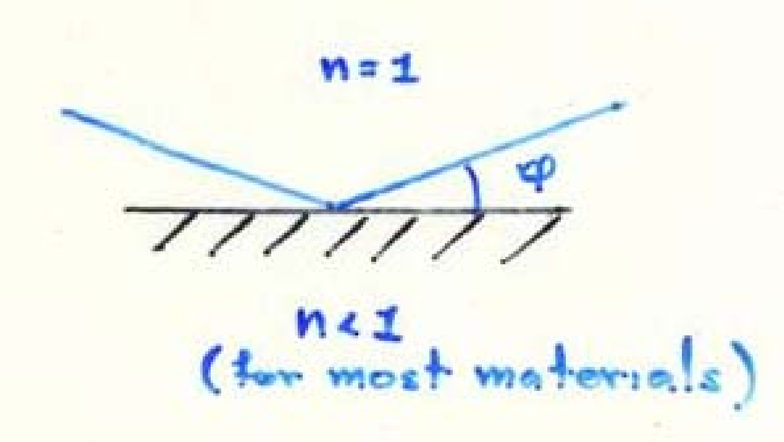
$$\boxed{n = \sqrt{1 - \frac{N\lambda^2 b_{coh}}{\pi}}}$$

*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 Reflection from Matter

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



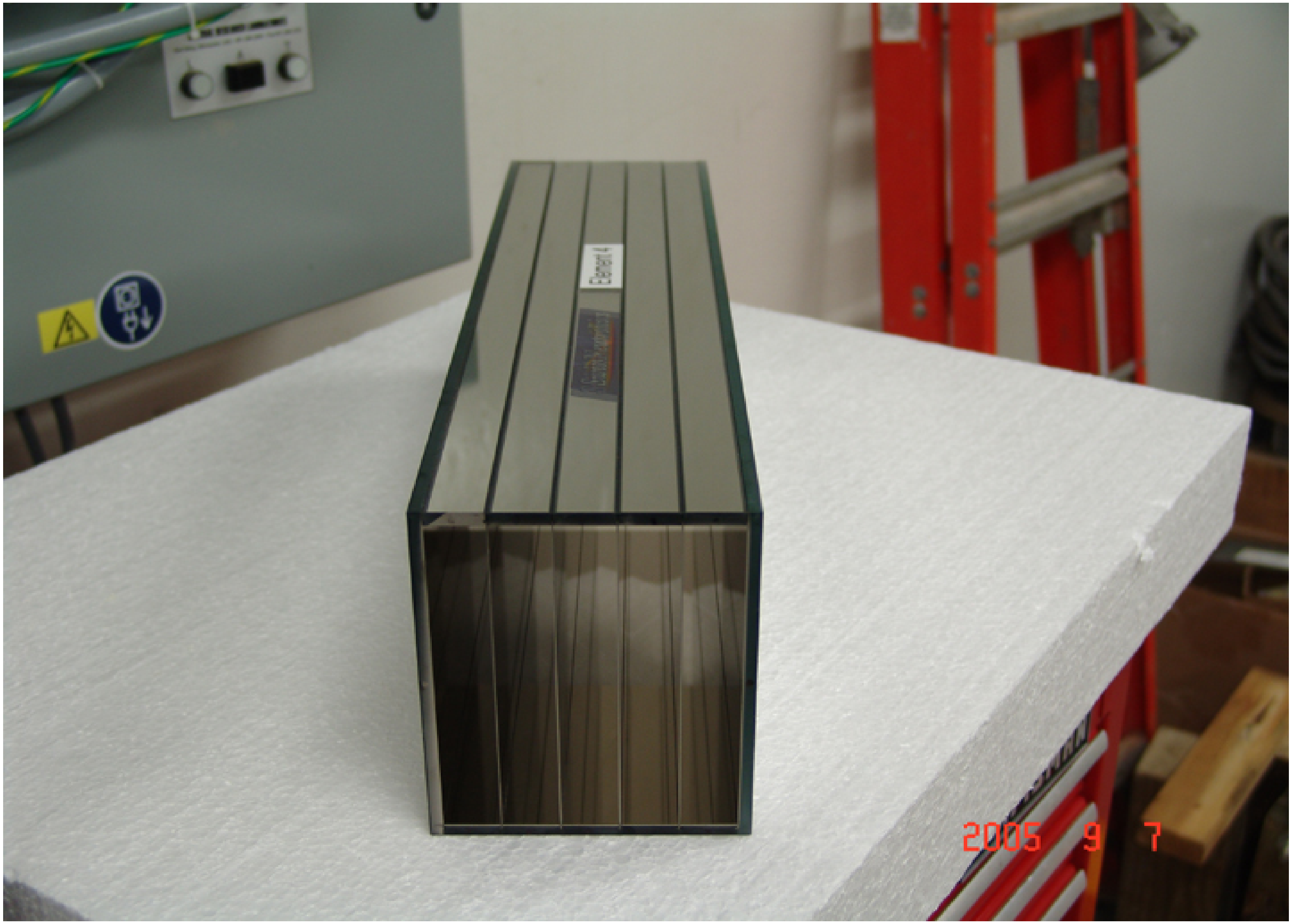
Neutrons will undergo complete "external" reflection from a polished surface for most materials

Ni or ^{58}Ni are particularly useful as a neutron mirror material

$$\theta_{crit}(Ni) \approx 1.7x10^{-3} / \lambda(Angstrom)$$

For most neutron beams this means $\theta_{crit} \le 10^{-2}$

Guide Section from SNS



Neutron Guides can be used to Focus Neutron Beams

Photo: Swiss Neutronics

Large Cross Section Guides are Commercially Available

Prototype Guide for SNS Ultracold Beam

Neutron Guide Installation at LANSCE

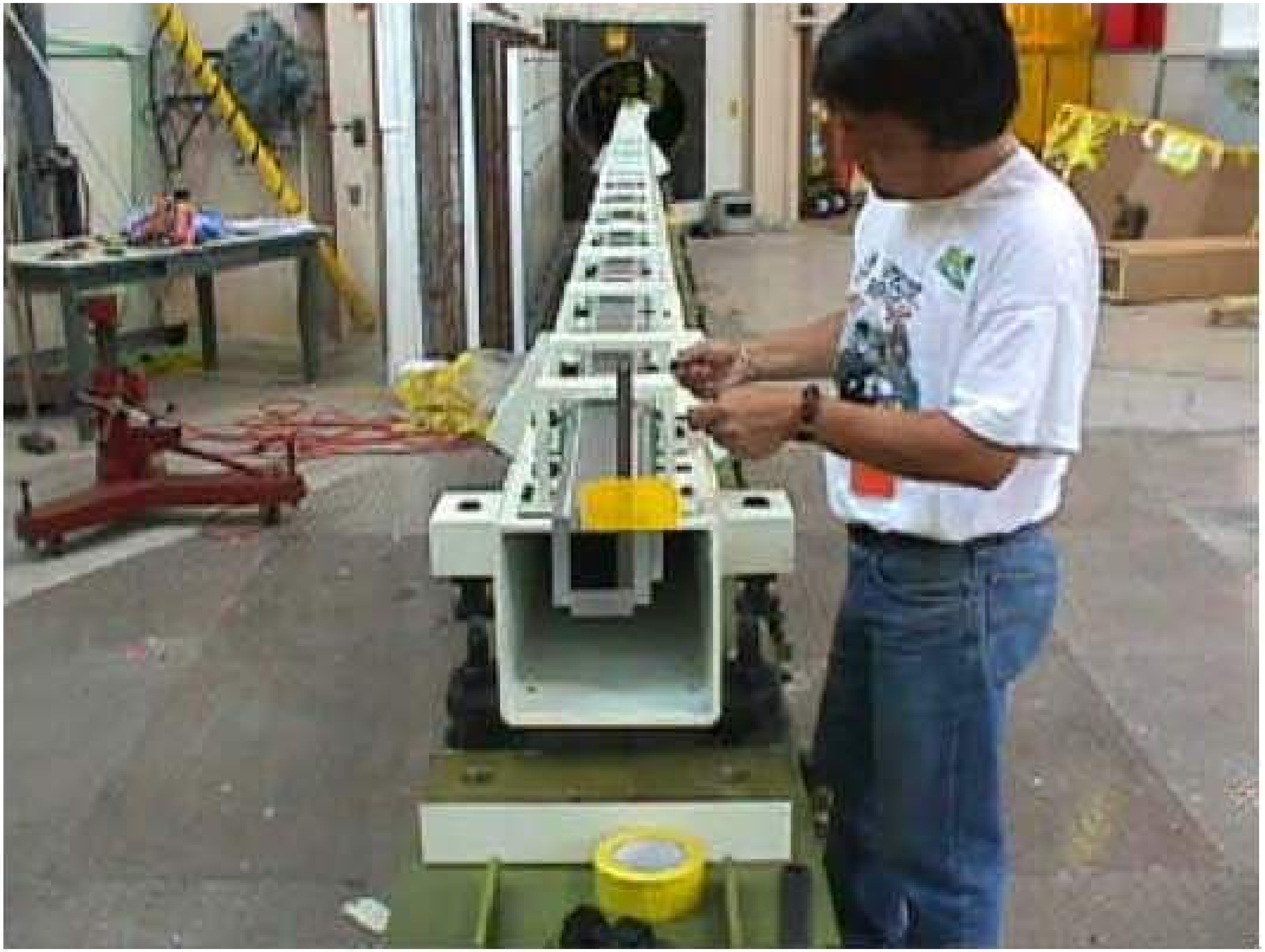


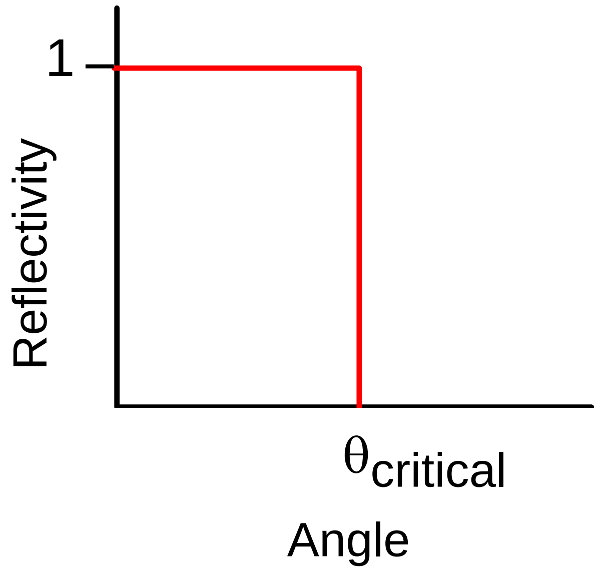
Photo: LANSCE

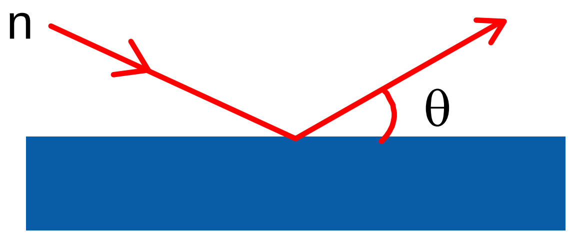
A Single Moderator can Feed Multiple Neutron Guides

Photo: Institut Laue Langevin

Reflectivity of Neutron Mirror

A Simple Neutron Mirror has Nearly Unit Reflectivity Up to a Maximum Critical Angle

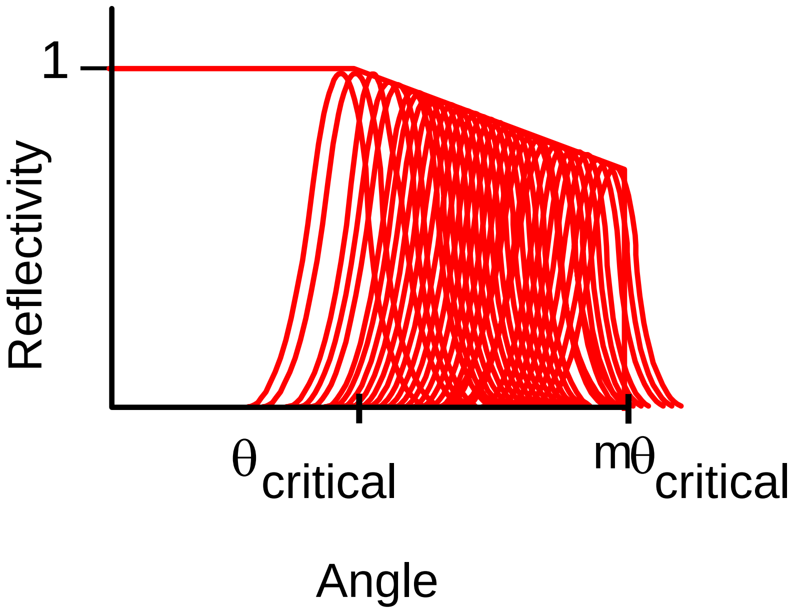


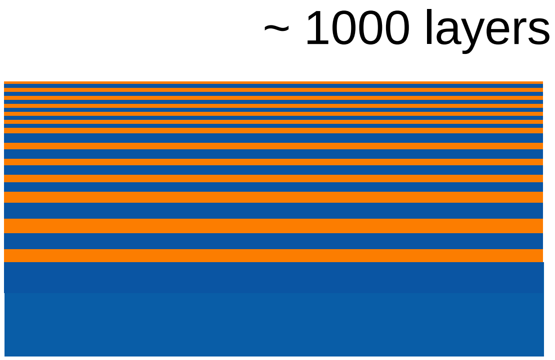


$\Theta_{critical} \cong 2\ \mathrm{mR/Å}$ for $^{58}\mathrm{Ni}$

The "Supermirror" Extends the "Effective" $\theta_{critical}$

Commercial Supermirror Neutron Guides
are Available With m ≈ 3 - 4

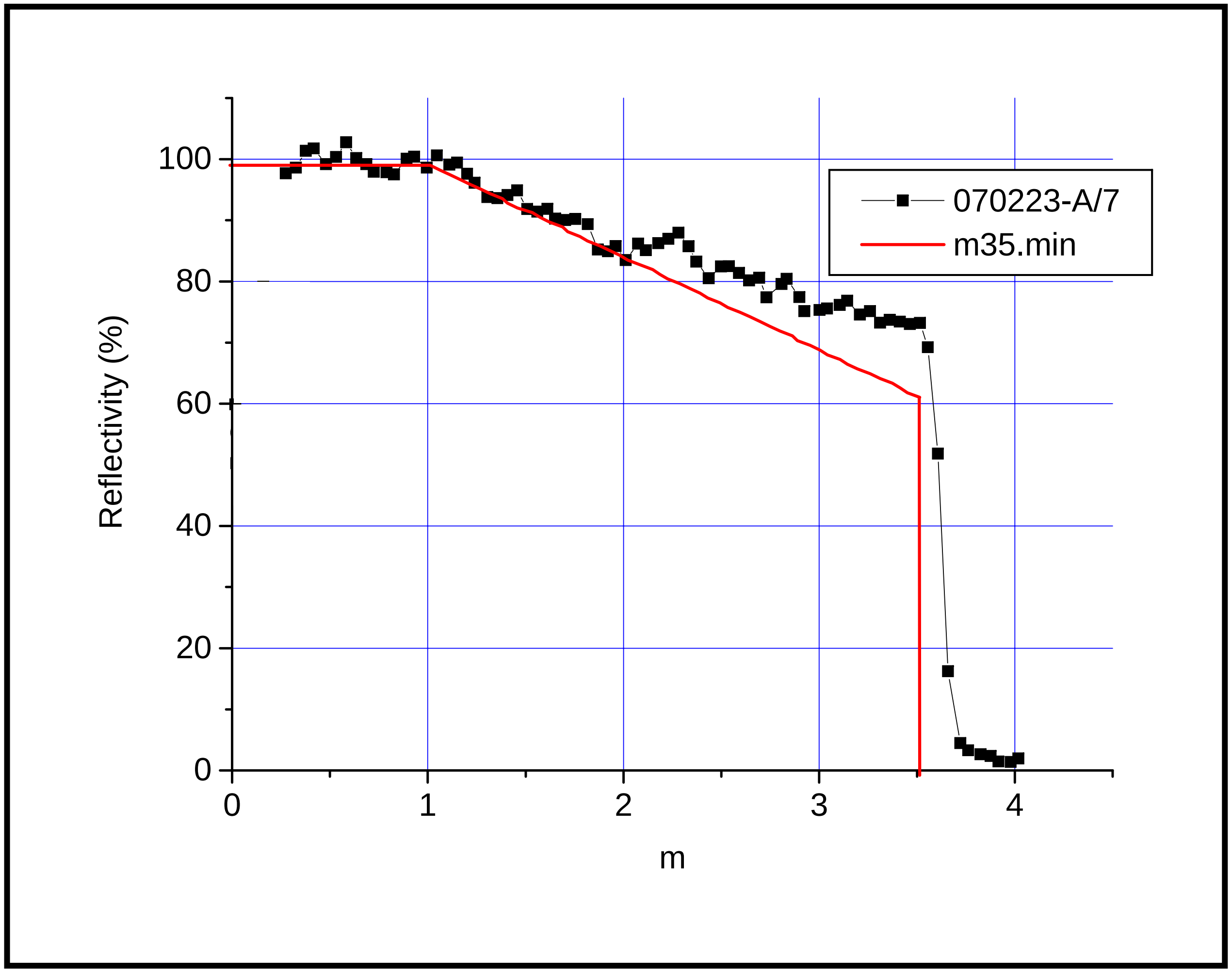




NOTE: Flux scales as Square of Critical Angle

Commercial Supermirrors are available with m~4

Note that the number of layers scales as ~m^4



Data: Mirrotron

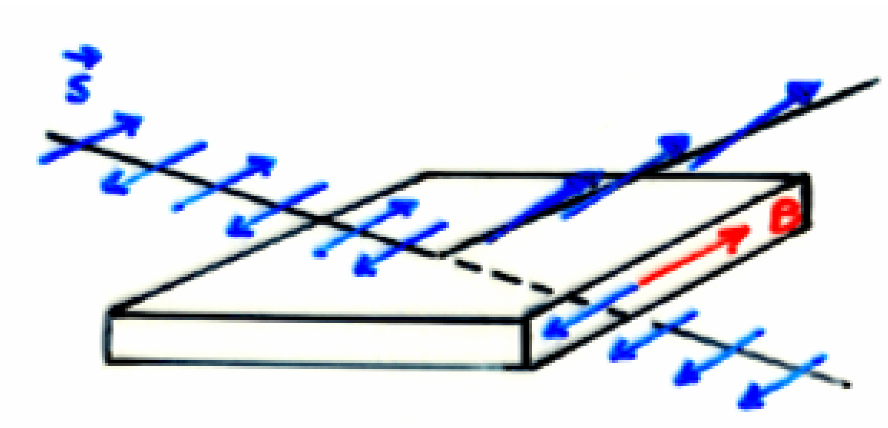
Neutron Polarization

Neutron Polarization by Mirror Reflection

For a magnetic material, the index of refraction includes
an additional spin dependent term:

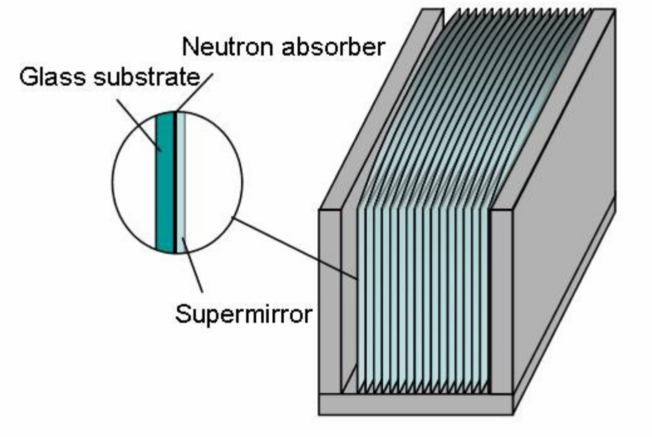
$$n = \sqrt{1 - \left(\frac{Nb_{coh}}{\pi} \pm \frac{\mu B}{2\pi^2 \hbar^2} \right) \lambda^2}$$

For a judicious selection of material (~60% Fe-40% Co at saturation works quite well) it is possible to have $n=1$ for one state and $n<1$ for the other.



The reflected (or transmitted beam from such a mirror will be polarized)

Mirror Polarizers are Usually Configured as Multi-Channel “Benders”



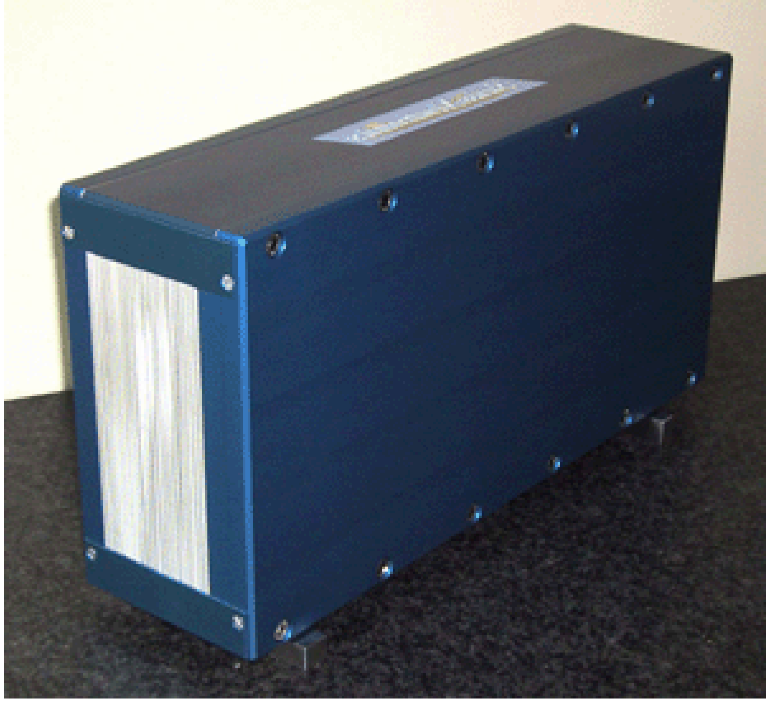


Photo: Swiss Neutronics

Some Advantages of Magnetic Supermirror Reflection Polarizers:

High Polarization ~99%
Simple to Use
Commercially Available
Highly Reliable

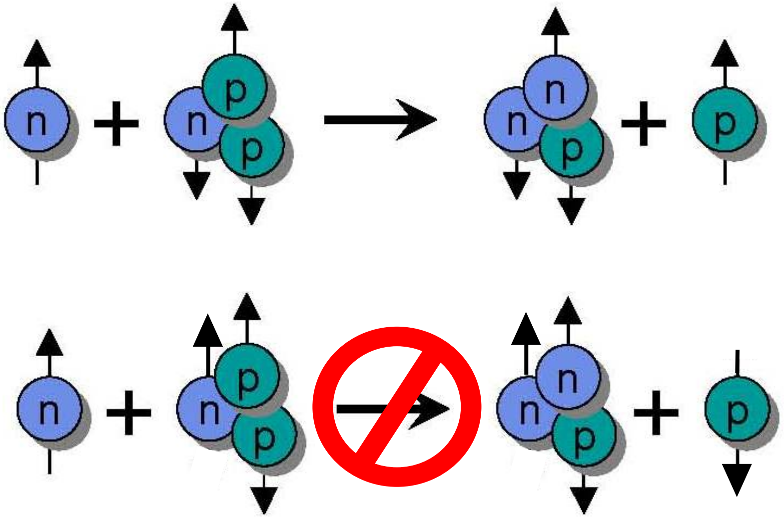
Some Disadvantages of Magnetic Supermirror Reflection Polarizers:

Challenging to Accurately Determine Polarization
Limited Range of Neutron Energies
Beam is Deflected

Photo: Swiss Neutronics

Spin Polarized ^{3}He Works as a Neutron Spin Filter

$$\boxed{n + {}^3He \rightarrow {}^3H + p}$$



$\sigma_{J=0} = 5300$ barn at v_0=2200 m/s

$\sigma_{J=1} \approx 0$

For low energy neutron there is essentially NO capture in the triplet state

An un-polarized neutron beam incident on a Polarized ^{3}He Target yields a polarized neutron beam.

Accurate Absolute Determination of Polarization

Neutron polarization depends upon thickness of cell, pressure in cell, 3He polarization, etc. which are hard to measure to high accuracy

$$P_n = \tanh\left(\sigma^{\uparrow\downarrow} \rho_{He} d P_{He} \big/ 2 \right)$$

However, the neutron transmission depends on the same parameters:

$$T_n = \cosh\left(\sigma^{\uparrow\downarrow} \rho_{He} d P_{He} \big/ 2 \right)$$

The application of a few hyperbolic trigonometric identities provides a greatly simplified relation for the neutron polarization that is based only on (relatively) easy to measure neutron transmission:

$$P_n = \sqrt{1 - T_0^2 \big/ T^2}$$

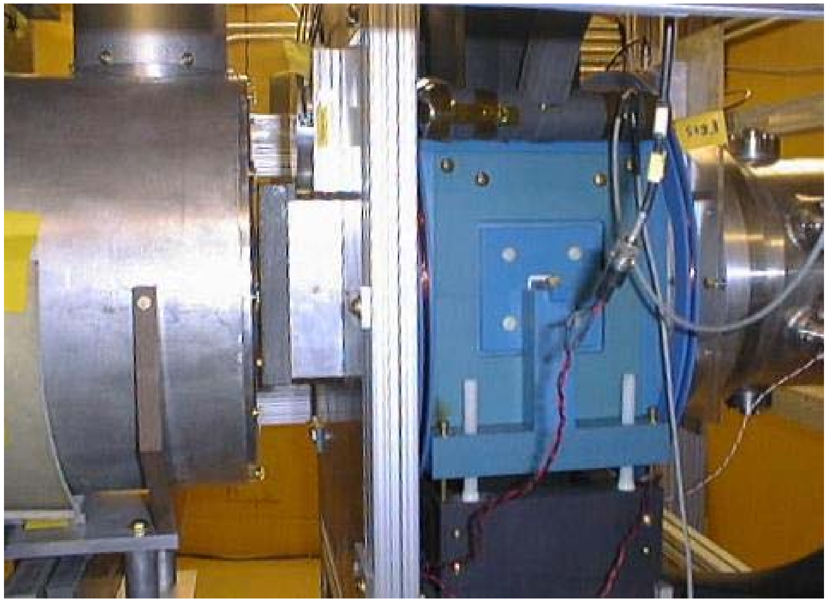
Where T_0 *is the transmission through the cell when unpolarized and* T *is the transmission when the cell is polarized.*

*Greene, Thompson, Dewey, NIM **356**, 177, (1995)*

^{3}He Neutron Polarizer for n+p → d + γ Experiment

3He Optical Pumping Cell

3He Cell in Oven



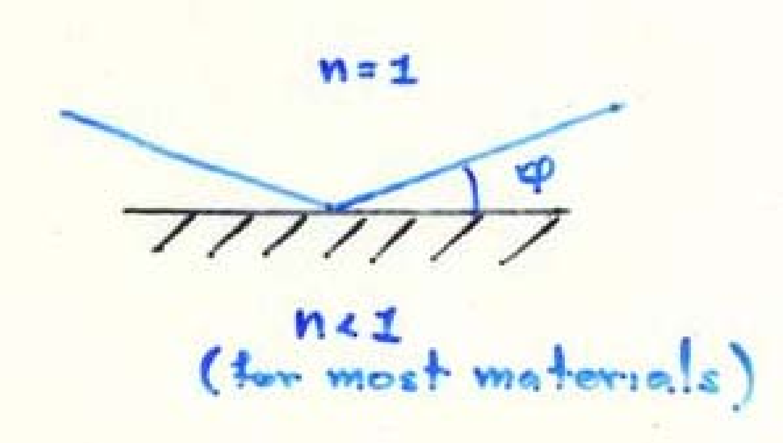
Polarizer System on Beamline at LANSCE

Ultra Cold Neutrons

*see Golub, Richardson, Lamoreaux, Ultracold Neutrons

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 $\cos\varphi_{crit}$ =90°

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

These are known as "Ultracold Neutrons."

Ultracold Neutron Energies are Very Low

The Fermi "Pseudo-Potential" the most advantageous materials is ~ 100 neV

This corresponds to a:

Neutron Velocity	≈ 500 m/s
Neutron Wavelength	≈ 500 Å
Magnetic Moment Interaction	$\mu_n \cdot B \approx 100$ neV for B~1Tesla
Gravitational Interaction	$m_n g h \approx 100$ neV for h~1 m

Ultracold Neutron can be trapped in material, magnetic, or gravitational bottles

"A Thermal" Source of UCN*

In thermal equilibrium: $\rho(v)dv = \frac{2\Phi_0}{\alpha}\frac{v^2}{\alpha^2}e^{-v^2/\alpha^2}\frac{dv}{\alpha}$

$\alpha \equiv \sqrt{2k_BT_n/m}$ Φ_0 *is total thermal flux*

For a maximum UCN energy V: $\rho_{UCN} = \frac{2}{3}\frac{\Phi_0}{\alpha}\left(\frac{V}{k_BT_n}\right)^{3/2}$

For $T \sim 300k$, $\alpha \sim 2.2x10^5$ cm/s, and $V \sim 250$ neV: $\boxed{\rho_{UCN} = 10^{-13}\Phi_0 cm^{-3}}$

The most intense neutron sources in the world (HFIR at ORNL or ILL) have $\Phi_0 \sim 10^{15}$ n/cm^2/s So:

$$\boxed{\rho_{UCN} \approx 100cm^{-3}}$$

*see Golub, Richardson, Lamoreaux, *Ultracold Neutrons*

Limits to Thermal UCN Production

In thermal equilibrium: $\rho_{UCN} = \frac{2}{3}\frac{\Phi_0}{\alpha}\left(\frac{V}{k_B T_n}\right)^{3/2}$

Increase the Flux Φ_0:

Reactors are at the practical limit of heat transfer.
Only practical hope would be a 10-20 MW Spallation Source.

Lower the temperature T_n (also reduces α):

Practical limit for true moderator is about 20k which gives a density increase of ~x20

Practical Thermal Source Limit for UCN production:

$$\boxed{\rho_{UCN} \approx 2 \cdot 10^3\, cm^{-3}}$$

Limits to Thermal UCN Production

In thermal equilibrium: $$\rho_{UCN} = \frac{2}{3}\frac{\Phi_0}{\alpha}\left(\frac{V}{k_B T_n}\right)^{3/2}$$

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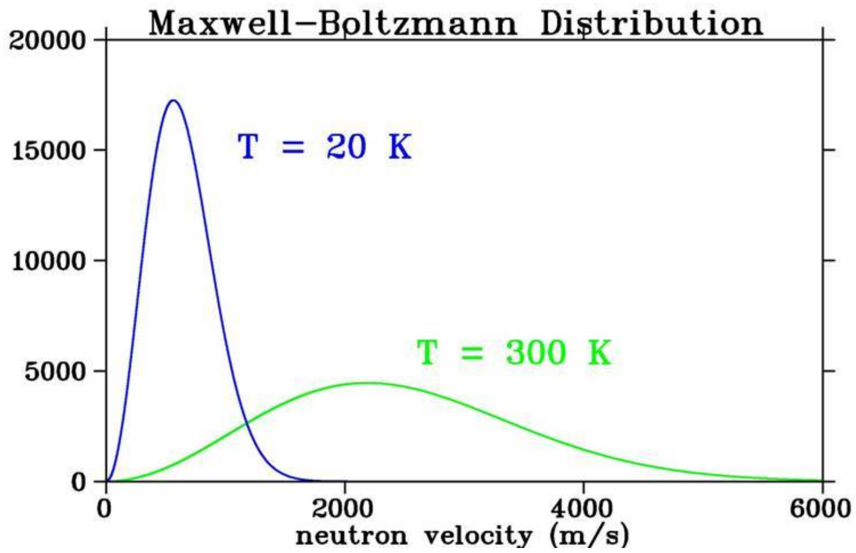
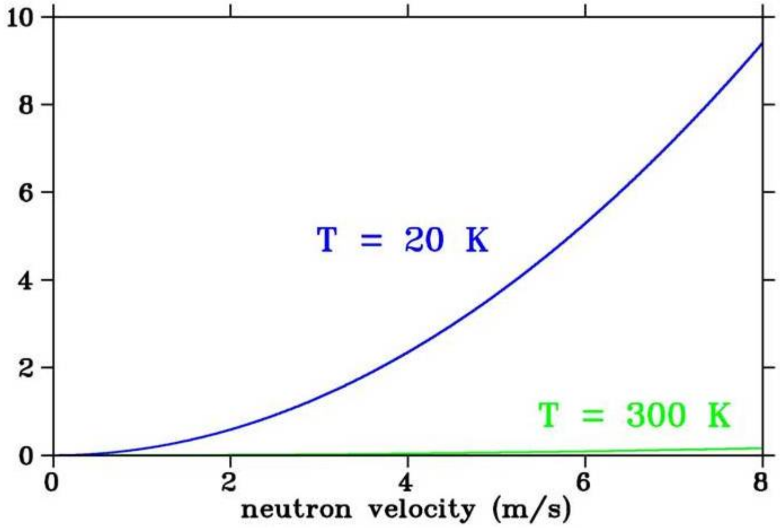
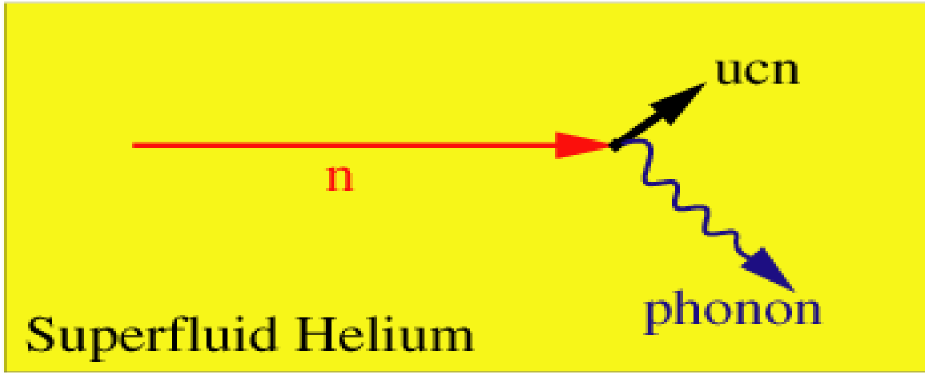


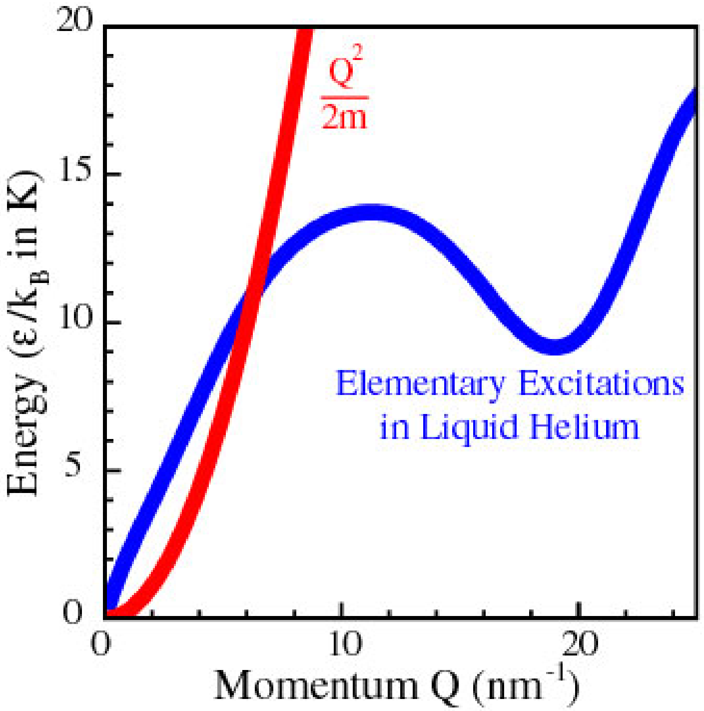


Practical limit for true moderator is about 20k which gives a density increase of ~x20

Practical Thermal Source Limit for UCN production: $\boxed{\rho_{UCN} \approx 2\cdot10^3\,cm^{-3}}$

Super Thermal Source of UCN





- *Neutrons of energy E ≈ 0.95 meV (11 k or 0.89 nm) can scatter in liquid helium to near rest by emission of a single phonon.*
- *Upscattering by absorption of an 11 k phonon is a UCN loss mechanism. But population of 11 K phonons is suppressed by a large Boltzman Factor: ~ $e^{-11/T}$ where T~200 mk*

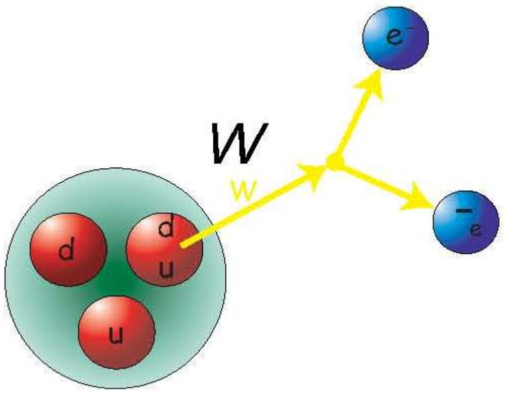
Golub and Pendlebury (1977)

Fundamental Neutron Physics III

Neutron Beta Decay

Geoffrey Greene
University of Tennessee / Oak Ridge National Laboratory

Neutron Beta Decay



Historical Digression

1934 ***Chadwick and Goldhaber make the first "precision" measurement of the neutron mass by looking at the photo-disassociation of the deuteron***

$$h\nu + {}_1D^2 \rightarrow {}_1H^2 + {}_1n^0$$

Using 2.62MeV gammas from Thorium and determining the recoil energy of the protons they we re able to determine*:

$$M_n = 1.0080 \pm 0.0005$$

$$\boldsymbol{M_n > M_p + M_e}$$

It is energetically possible for a neutron to decay to e + p

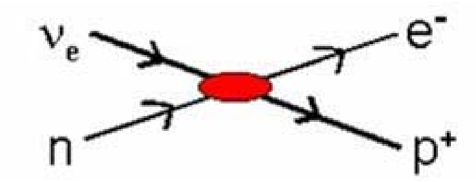
****Chadwick and Goldhaber, Nature, 134 237 (1934)***

Wolfgang Pauli

Enrico Fermi

1930 Pauli proposes the "neutrino" to explain apparent energy and angular momentum non-conservation in beta decay

1934 Fermi takes the neutrino idea seriously and develops his theory of beta decay



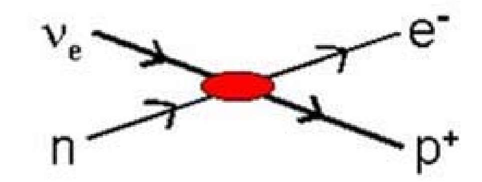
1935 The β decay of the neutron is predicted by Chadwick and Goldhaber based on their observation that $M_n > M_p + M_e$. Based on this ΔM, the neutron lifetime is estimated at ~½ hr.

1948 Snell and Miller observe neutron decay at Oak Ridge

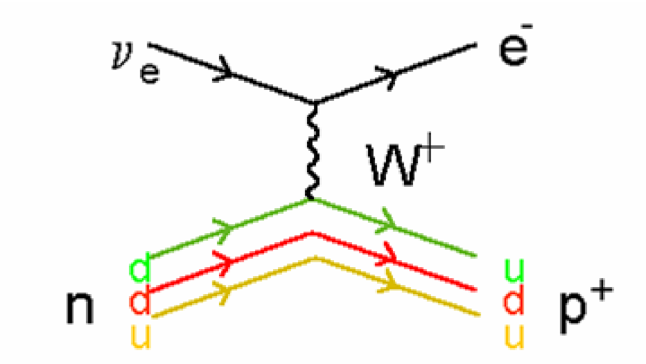
1951 Robson makes the first "measurement" of the neutron lifetime

$$n \rightarrow p^{+} + e^{-} + \overline{\nu}_e$$

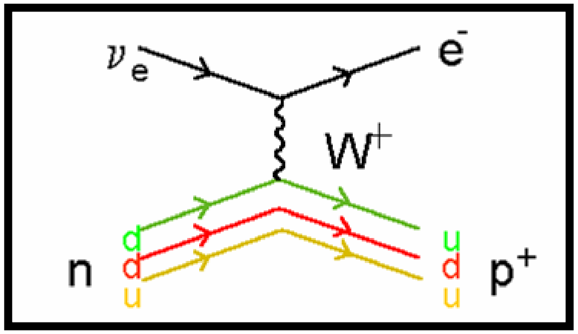
Fermi's View of Neutron Decay:



Modern View of Neutron Decay:



Processes with the same Feynman Diagram as Neutron Decay



Primordial element formation	$n + e^+ \longleftrightarrow p + \bar{\nu}_e$
	$p + e^- \longleftrightarrow n + \nu_e$
	$n \longrightarrow p + e^- + \bar{\nu}_e$
Solar cycle	$p + p \longrightarrow {}^2H + e^+ + \nu_e$
	$p + p + e^- \longrightarrow {}^2H + \nu_e$ etc.
Neutron star formation	$p + e^- \longrightarrow n + \nu_e$
Pion decay	$\pi^- \longrightarrow \pi^0 + e^- + \bar{\nu}_e$
Neutrino detectors	$\nu_e + p \longrightarrow e^+ + n$
Neutrino forward scattering	$\nu_e + n \longrightarrow e^- + p$ etc.

After D. Dubbers

Introduction to Big-Bang Nucleosynthesis

The "Later" Big Bang

Time Since Big Bang	Temp	
0.01s	**10^{11}K**	**Era of Nuclear Physics**

At this temperature, only familiar "nuclear physics" particles are present, the density is well below nuclear densities, and only well understood processes are relevant.

Neutrons and Protons are in thermal equilibrium through the processes:

$$\nu_e + n \leftrightarrow p^+ + e^-$$

$$e^+ + n \leftrightarrow p^+ + \bar{\nu}_e$$

$$\boxed{\frac{N_n}{N_p} = e^{-(m_n - m_p)/kT}}$$

The "Later" Big Bang

Time Since Big Bang	Temp	
1s	**10^{10}K**	**Neutrinos "decouple"**

Neutrino cross-sections are highly energy dependent and at this energy they become so small that neutrino scattering is insignificant. Thermal equilibrium between neutron and protons is no longer maintained.

$$\frac{N_n}{N_p} \approx 1/3$$

If nothing else happened ALL the neutrons would decay via

$$n \rightarrow p^+ + e^- + \overline{\nu}$$

and the universe would be end up with only protons (Hydrogen)

Big Bang Nucleosynthesis

Time Since Big Bang	Temp	
3 min	**10^9K**	**Nucleosynthesis Begins**

Nuclei are now stable against photo disassociation e.g.

$$n + p \rightarrow d + \gamma$$

and nuclei are quickly formed. The Universe is now ~87% protons & 13% neutrons

3½ min	**10^8K**	**Nucleosynthesis Ends**

Neutrons are all "used up" making ^{4}He and the Universe is now has ~80% H and ~20% He.

Some of the Reactions in Big Bang Nucleosynthesis

$$\begin{array}{lcl} \boxed{\begin{array}{l} n \rightarrow p + e + \overline{\nu} \\ p + n \rightarrow d + \gamma \end{array}} & \begin{array}{c} \Rightarrow \\ \Rightarrow \end{array} & \begin{array}{l} N_n = N_0 e^{-t/\tau_n} \\ \textit{Disassociation Energy 2.2MeV} \end{array} \end{array}$$

$$p + D \rightarrow {}^3He + \gamma$$

$$D + D \rightarrow {}^3He + n$$

$$D + D \rightarrow T + p$$

$$D + T \rightarrow {}^4He + n$$

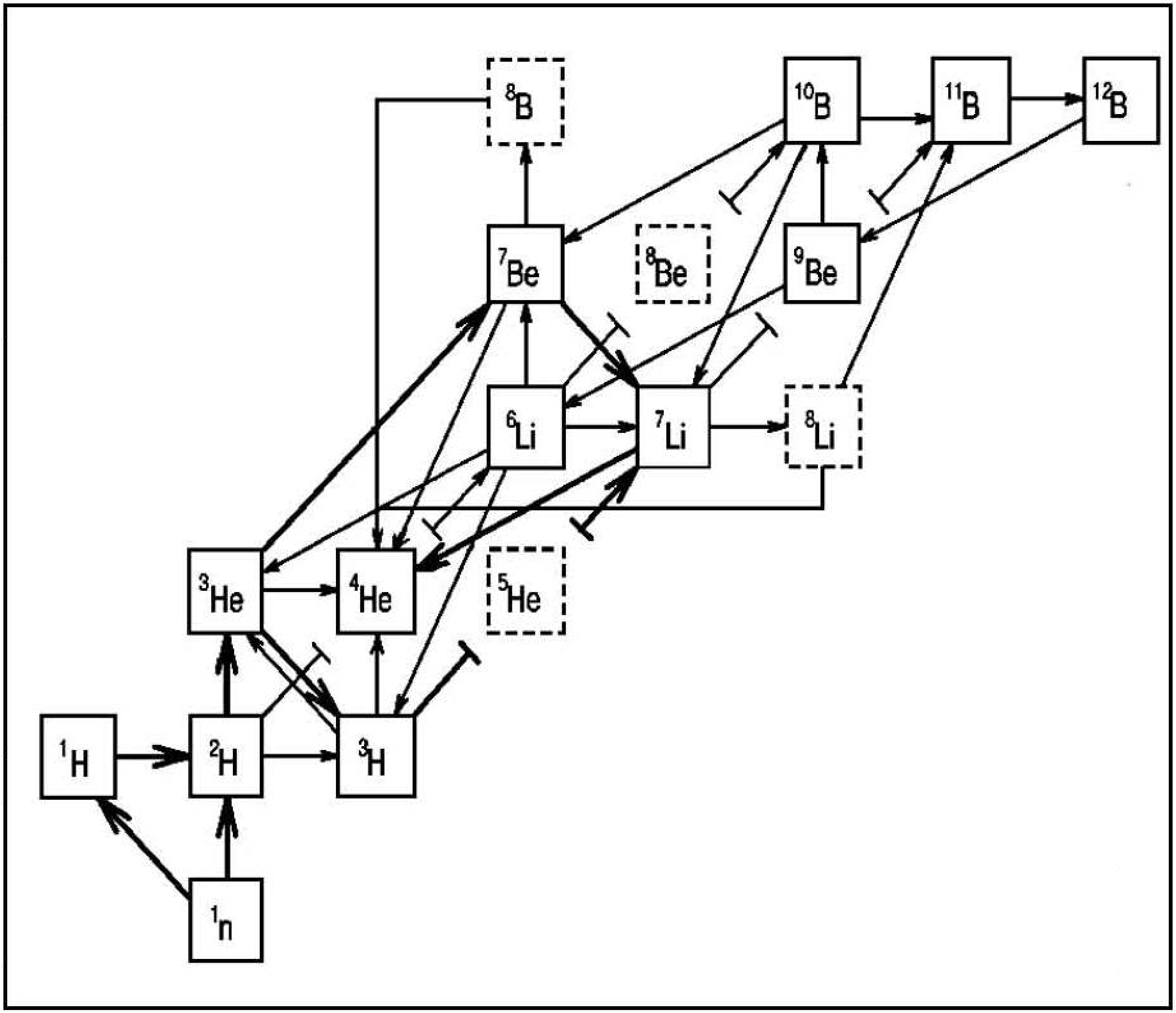
$$D + {}^3He \rightarrow He + p$$

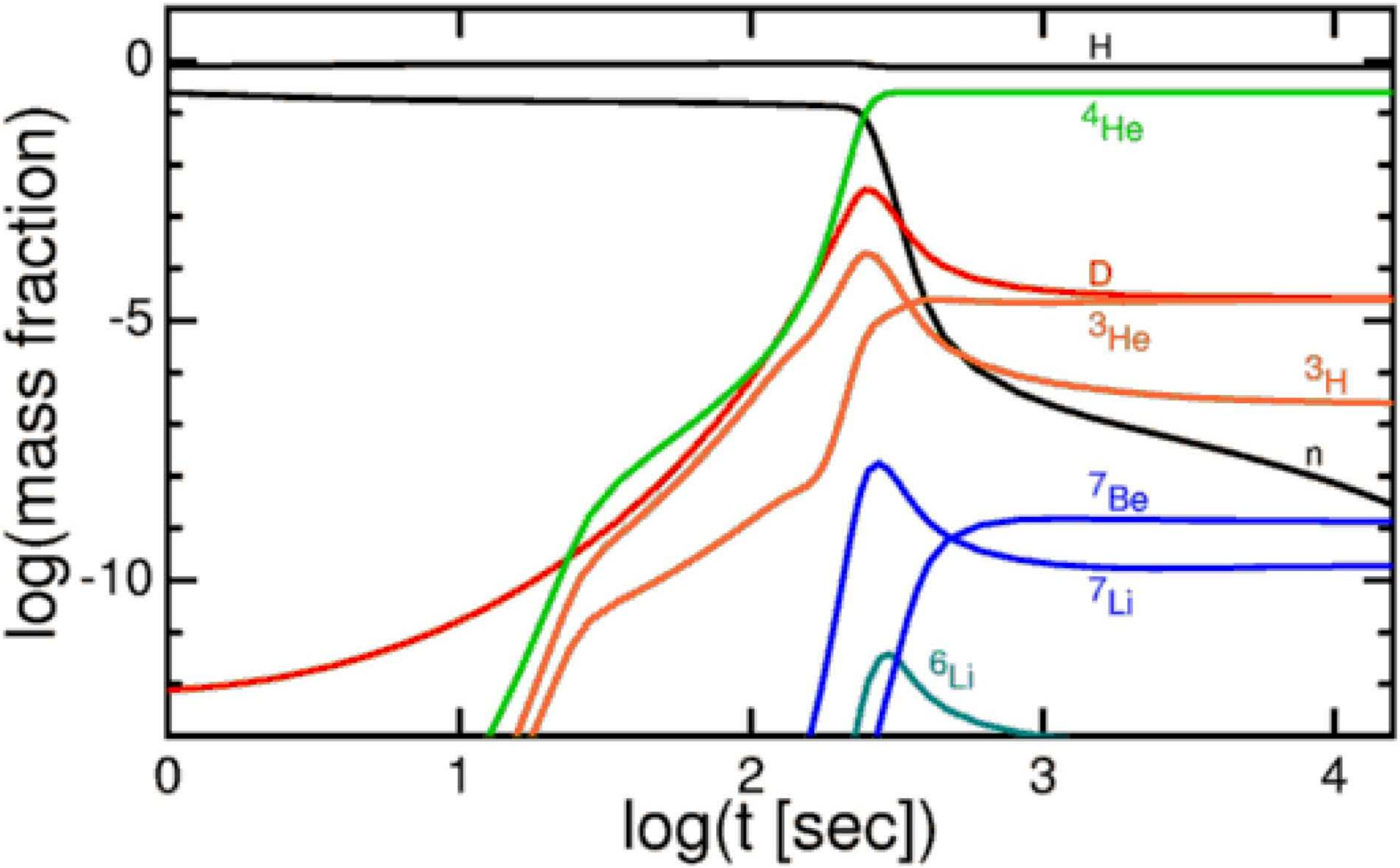
$${}^3He + {}^3He \rightarrow {}^4He + 2p$$

....

..

Some of the Reactions in Big Bang Nucleosynthesis





Burles et al. 1999

The Cosmic He/H Ratio Depends upon three quantities:

1) The Cooling rate of the Universe

Given by the heat capacity of the Universe
Determined mainly by the number of “light particles” (m ≤ 1 MeV)
Includes photons, electrons (positrons), neutrinos (x3)

2) The Rate at which Neutrons are decaying

The neutron lifetime

3) The rate at which nuclear interactions occur

Determined by the the logarithm of the density of nucleons (baryons)*

**Because of expansion, the “absolute” baryon density is decreasing with time so the density is scaled as the ratio of matter to photons.*

The Parameters of Big Bang Nucleosynthesis

$$\boxed{Y_p} = 0.264 + 0.023 \log \boxed{\eta_{10}} + 0.018\left(\boxed{\tau_n} - 10.28\right)$$

Cosmic Helium Abundance

Cosmic Baryon Density

Neutron Lifetime in Minutes

We can "invert" this line of reasoning. If we measure the Helium Abundance and the Neutron Lifetime, we can determine the density of "ordinary" matter in the universe.

$$\log \boxed{\eta_{10}} = \left[0.264 - \boxed{Y_P} + 0.018(\boxed{\tau_n} - 10.28)\right] / 0.023$$

Cosmic Baryon Density

Cosmic Helium Abundance

Neutron Lifetime in Minutes

A Brief Digression on the Mass of the Universe

From Big Bang Nucleosynthesis, we conclude that, averaged over the entire universe today, after expansion, there are a few protons per cubic meter.

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Compared to What?

A Scale for the Density of the Universe

- From red-shift observations we know that the Universe is in a state of (nearly) uniform expansion.
- If the density of the Universe is sufficiently high, this expansion will come to a stop and a universal collapse will ensue.
- If the density of the Universe is sufficiently low, it will expand forever.
- The critical density of the universe is given by the Hubble constant H, and the Gravitational constant G

$$\rho_{critical} = \frac{3}{8\pi}\frac{H^2}{G}$$

- We define:

$$\Omega = \rho / \rho_{critical}$$

A Lower Limit for Ω

By simply counting the number of visible stars and galaxies we find

$$\boxed{0.005 \leq \Omega_{total}}$$

From extremely simple reasoning we have:

$$\boxed{0.005 \leq \Omega_{total} \leq 2.5}$$

Ω is NOT necessarily constant over time

If $\Omega > 1$ at any time, Then Ω will continue to grow larger with time.

If $\Omega < 1$ at any time, Then Ω will tend toward zero with time.

Only if $\Omega = 1$ EXACTLY, will it stay constant for all time

We observe that Ω is NOW not too far from 1 $(0.01 < \Omega < 2.5)$. Thus:

Ω was EXTREMELY close to 1 early in the big bang ($|\Omega-1| \leq 10^{-16}$)

This raises the "Fine Tuning" question:

If Ω is very nearly equal to 1, is it exactly 1?

For a many compelling reasons ("fine tuning", inflation, microwave background,…),We strongly believe that

$$\boxed{\Omega_{Total} = 1}$$

Big Bang Nucleosynthesis provides a determination of the Cosmic Baryon Density: $\Omega_B \equiv \dfrac{\rho_{Baryon}}{\rho_{critical}}$

$$\boxed{\Omega_B = (3.3 \pm 0.7)\%}$$

BBN

This can be compared with the determination from the Cosmic Microwave Background:

$$\boxed{\Omega_B = (2.3 \pm 0.1)\%}$$

CMB

The largest uncertainty to the nuclear theory of Big Bang nucleosynthesis is the experimental value of the neutron lifetime.