P-odd/T-odd Tests using Polarized Neutron Optics

Mike Snow

Indiana University/CEEM

IU Center for Spacetime Symmetries

Polarized neutron optics tests of T invariance: summary of the key points

Statistical reach at MW-class spallation neutron sources

How to prove that systematics are under control?

T violation in Neutron Optics

- T – odd term in FORWARD scattering amplitude (a null test, like EDMs) with polarized n beam and polarized nuclear target
- P-odd/T-odd (most interesting) $\vec{\sigma_n} \cdot (\vec{k_n} \times \vec{I})$
- Amplified on select P-wave epithermal neutron resonances by ~5-6 orders of magnitude
- Estimates of stat sensitivity at SNS/JSNS look very interesting:

Existing technology/sources->$\Delta\sigma_{PT}/\Delta\sigma_P$~1E-5

- The nuclei of interest, resonance energies, and P-odd asymmetry amplifications are measured

Nucleus	Resonance Energy	PV asymmetry
^{131}Xe	3.2 eV	0.043
^{139}La	0.748 eV	0.096
^{81}Br	0.88 eV	0.02

So why has this experiment never been done?

How to design experiment that can realize “null test” theorem?

How to get enough polarized eV neutrons on resonance?

How best to characterize/eliminate “non-optical” systematic effects?

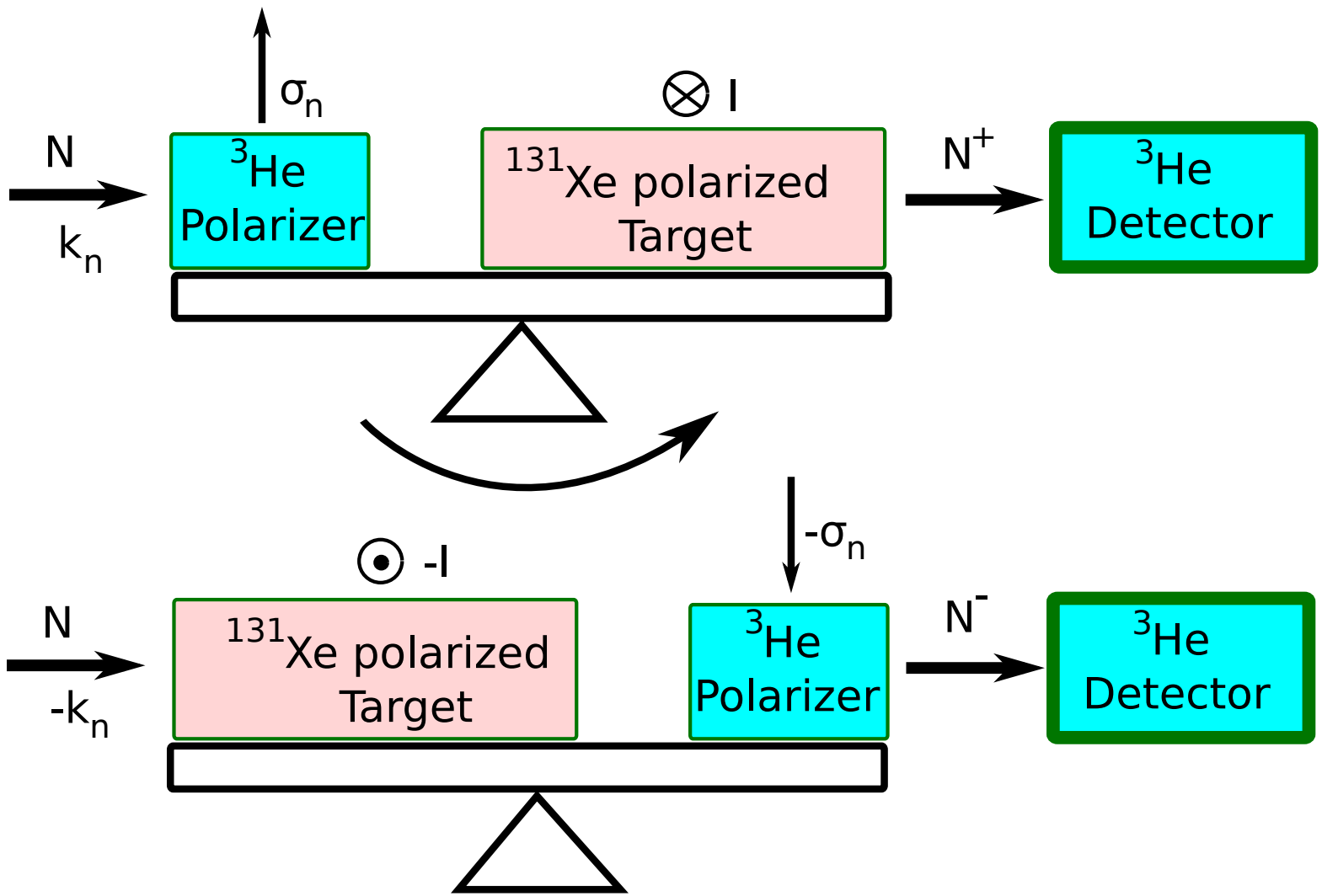
Russian/Japanese/US groups looked into it in ~1990s:
“death by a thousand cuts”

Now the situation is greatly improved

“Motion-Reversed” Experiment (sys error free in the n optics limit)

$$f = f_0 + f_1 \vec{\sigma_n} \cdot \vec{I} + f_2 \vec{\sigma_n} \cdot k_n + f_3 \vec{\sigma_n} \cdot (\vec{k_n} \times \vec{I})$$

Want $f_3 << f_1, f_2$



Bowman/Gudkov, arXiv:1407.7004

Experiment Components

- Intense Epithermal (~eV) neutron beam
- Polarized eV neutrons
- Polarized nuclear target
- Ability to flip $\vec{k_n}, \vec{\sigma_n}, \vec{I}$ and B (mechanical rotation of apparatus, B shielding)
- Current mode eV neutron detector

So who has ever done a precision polarized neutron experiment on a rotating platform?

Norman Ramsey

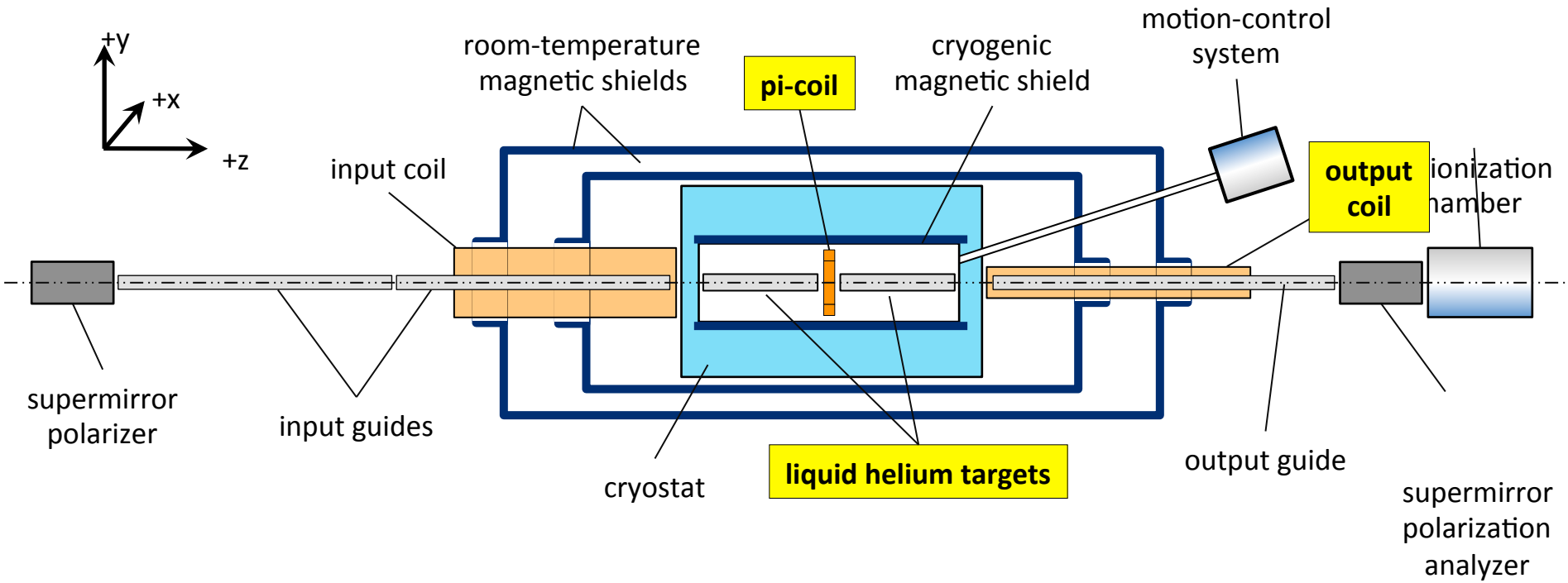
Neutron EDM experiment at ORNL in ~1970's (before UCNs)

Apparatus was periodically rotated on a navy surplus gun turrett

What is the most sensitive polarized neutron transmission experiment conducted with a “slow” flip to isolate an asymmetry?

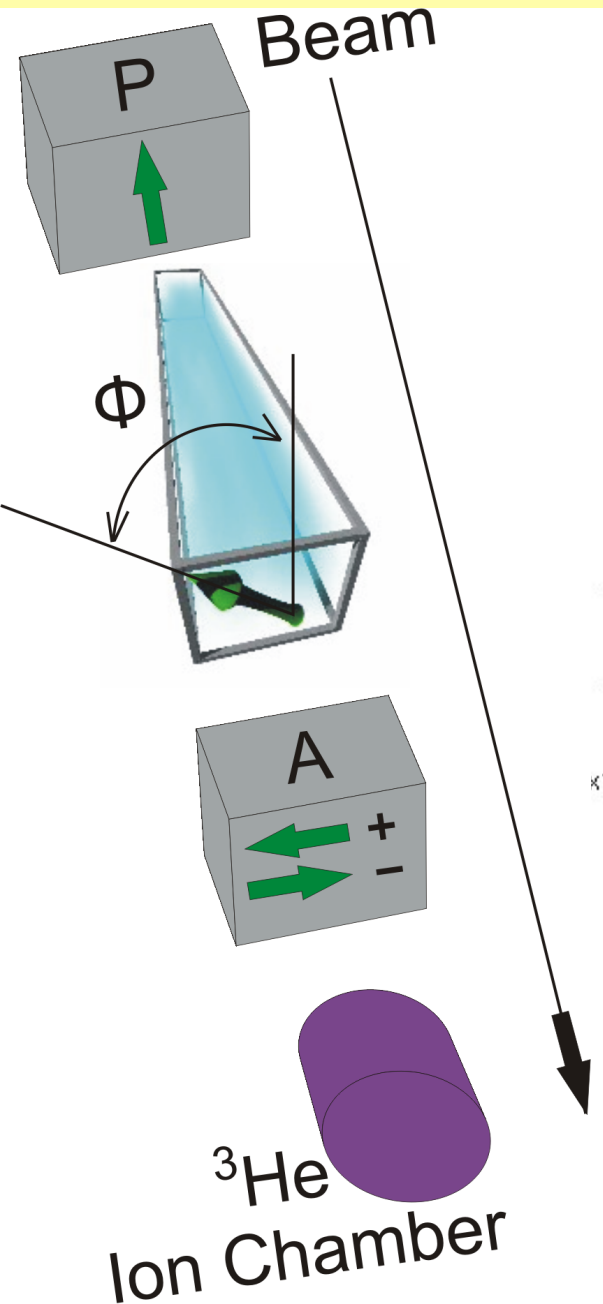
Parity Violation in Neutron Spin Rotation

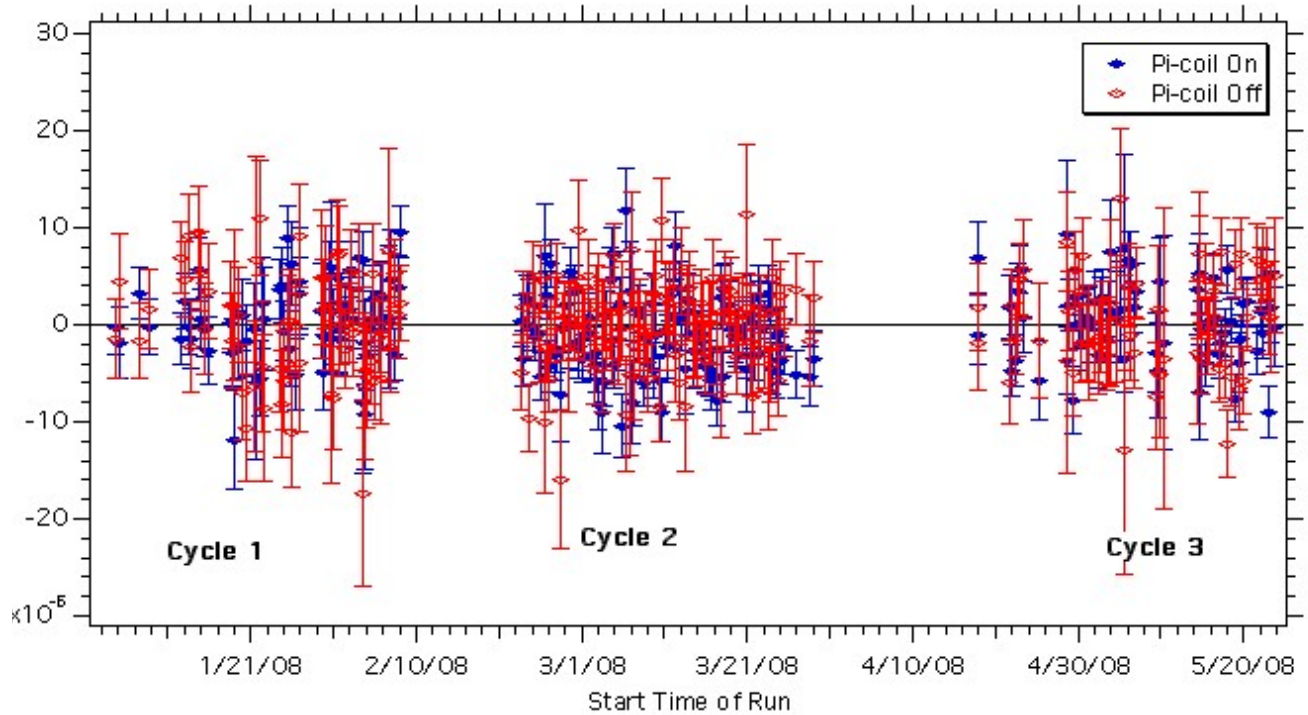
Apparatus measures the horizontal component of neutron spin generated in the liquid target starting from a vertically-polarized beam



Moving liquid helium before and after an internal precession coil was the “flip” needed to isolate the parity-odd amplitude. This took a couple of minutes

Neutron Spin Rotation in n+4He



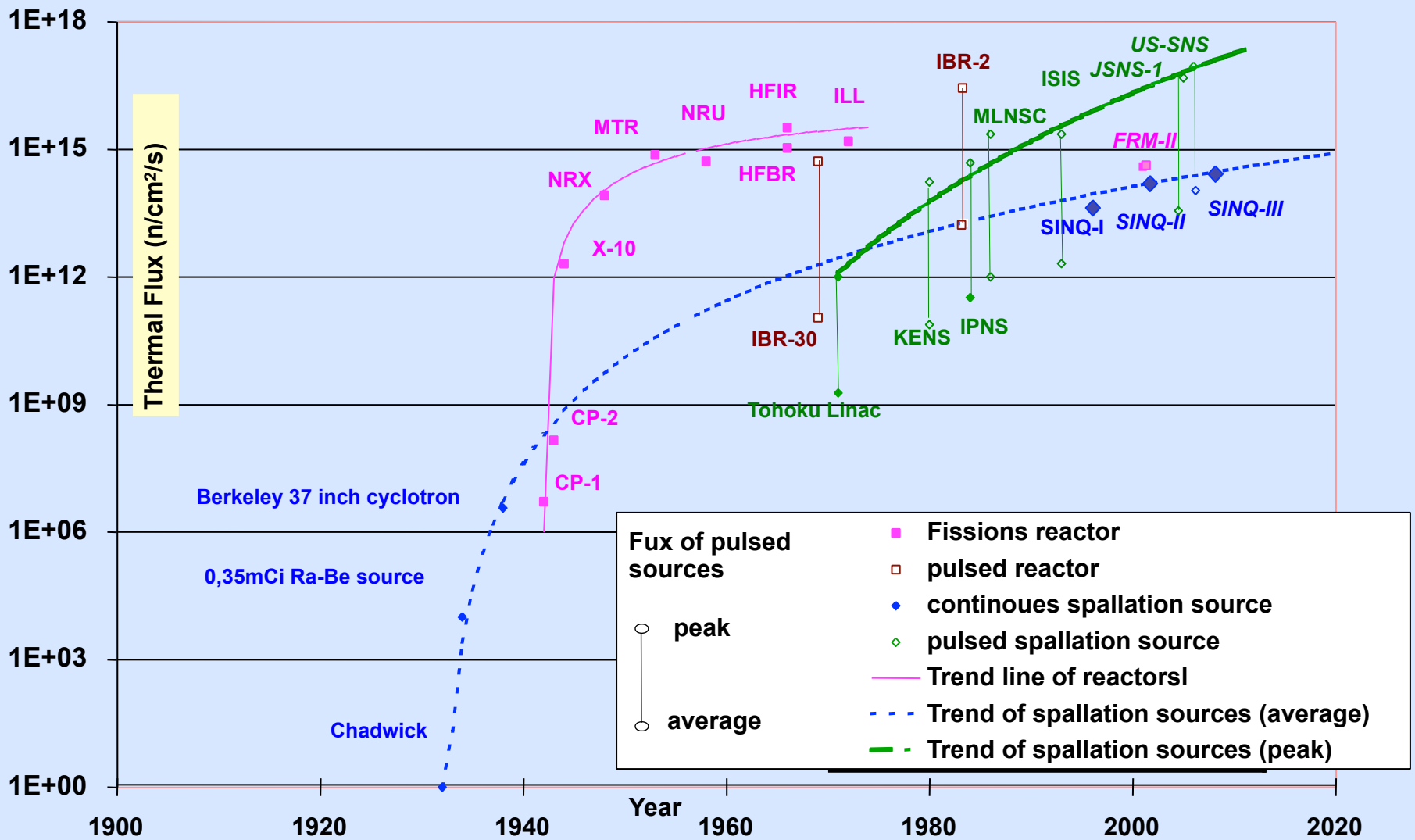


Transversely polarized neutrons corkscrew due to weak interaction

ϕ_{PNC}= [+1.7 ± 9.1 (stat) ±1.4 (sys)] x 10^{-7} rad/m

W. M. Snow et al., Phys. Rev. C83, 022501(R) (2011).

Neutron source flux with time. Only within last decade do we have ~MW-class short-pulsed spallation sources



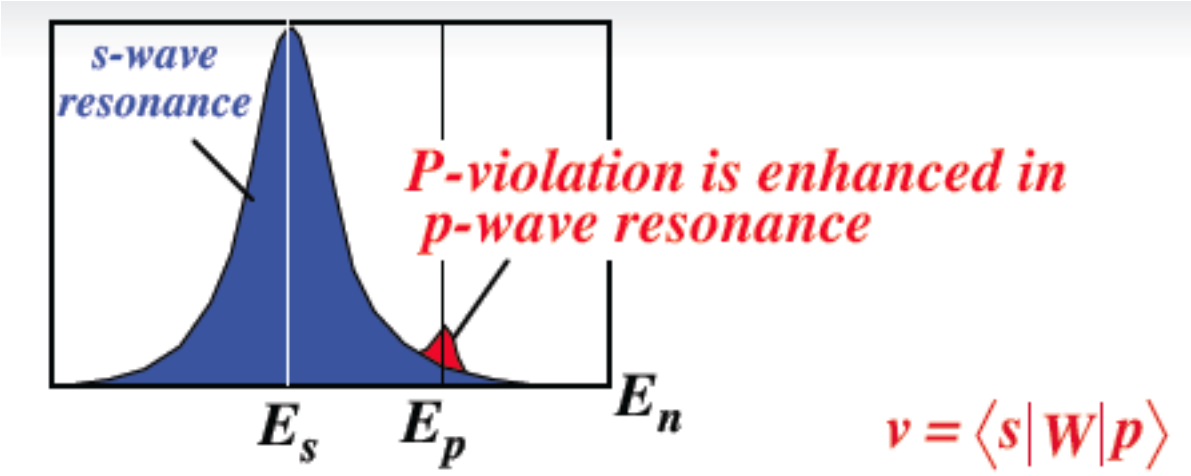
R. Eichler, PSI

The Spallation Neutron Source

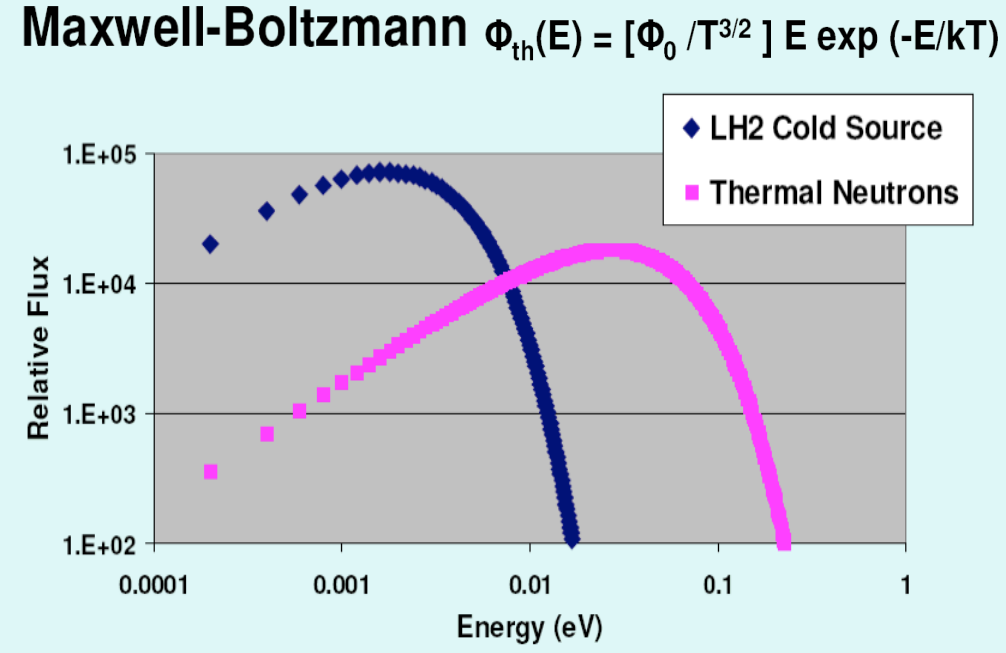
SNS Site Overlay

- $1.4B--1GeV protons at 1.4 MW, started in 2007.
- Short (~1 usec) pulse– mainly for high TOF resolution

Why is a "short-pulsed" spallation neutron source important?



$$v = \langle s | W | p \rangle$$



(from Hiro's talk)

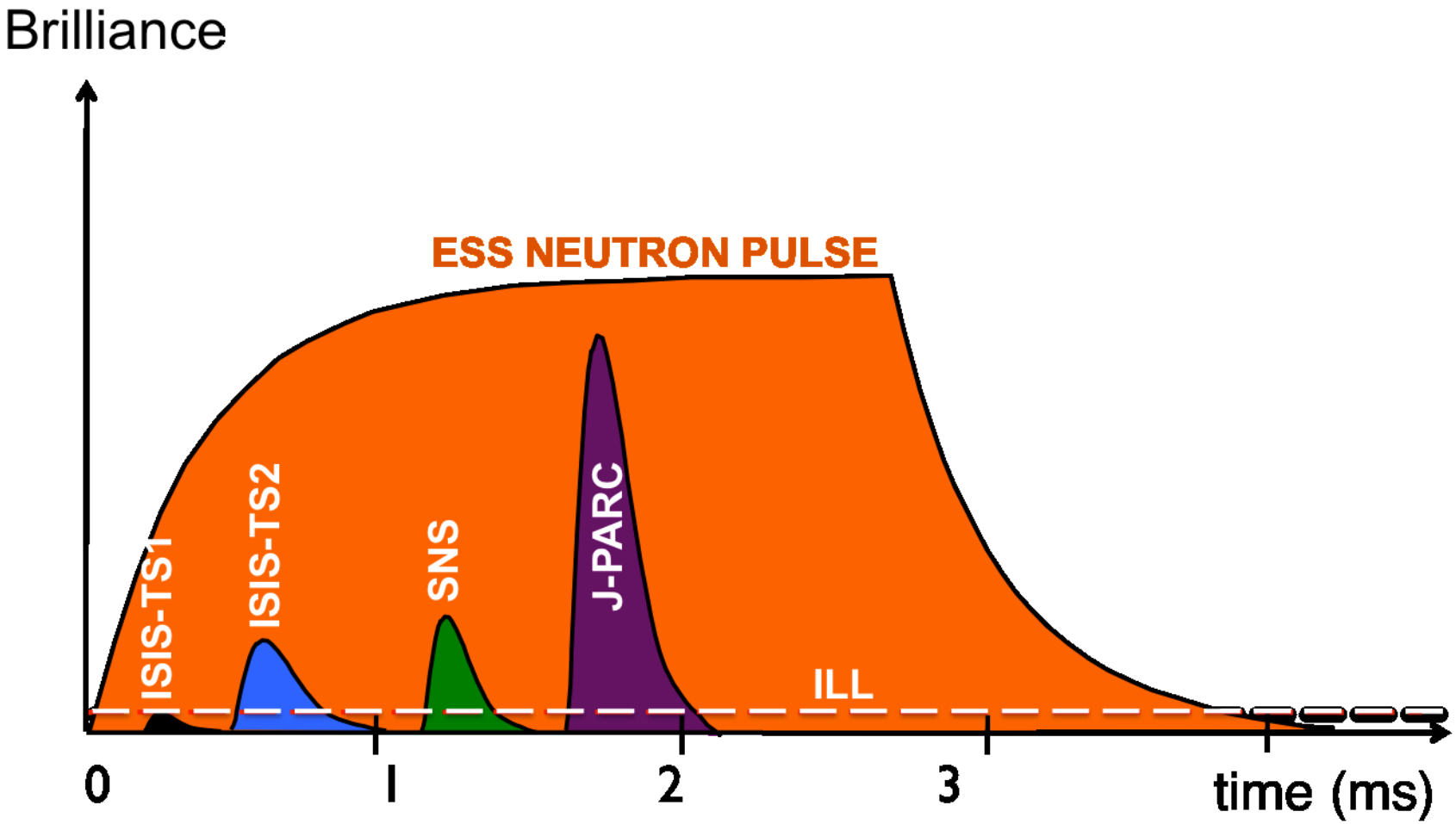
resonance energy ~eV, resonance width ~meVs

Short pulse-> resonance can be resolved using neutron time-of-flight

The rest of the neutrons in the beam can be used to characterize possible systematic effects !

>~10^4 more of these "off-resonance" neutrons

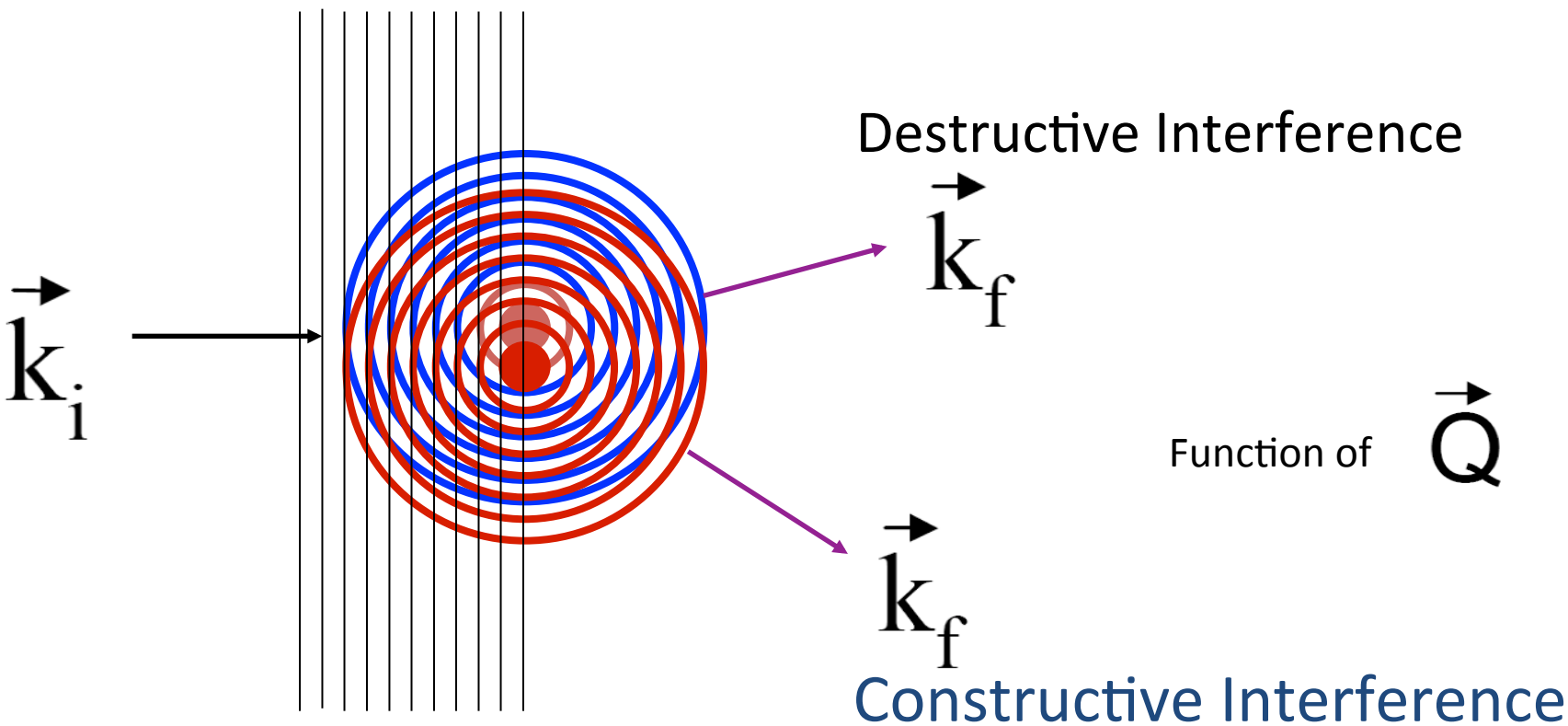
ESS Slow Neutron Peak Brilliance (from website)



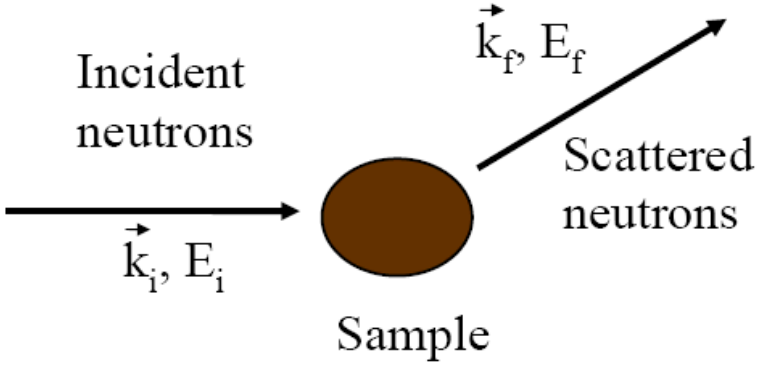
Pulsed, but wide pulse (~msec) optimized completely for meV neutrons, not eV neutrons

Scattering Function S($\vec{Q}$,ω)

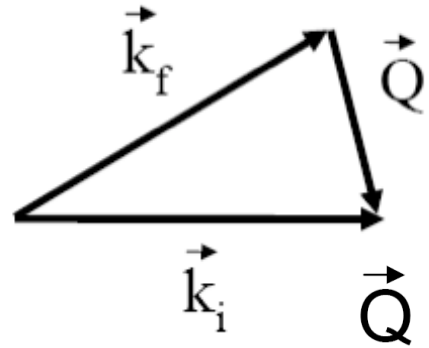
- Depends only on structure and dynamics of atoms in sample
- The scattering from each individual atom is a spherical wave
- The scattering from a collection of atoms is a huge sum of waves from each atom, with constructive and destructive interference giving information on space and time arrangement of the atoms



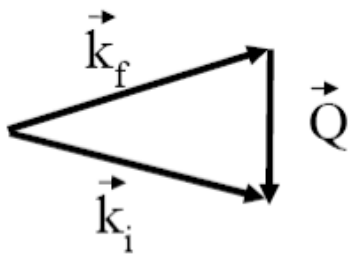
Elastic vs. Inelastic Scattering



Scattering triangle:

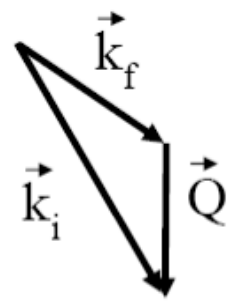


$$\vec{Q} = \vec{k}_i - \vec{k}_f$$

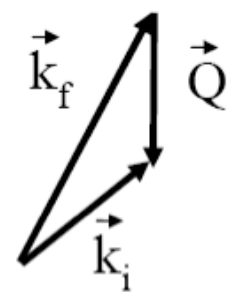


$k_i = k_f$
$\omega = 0$

Elastic scattering



$k_i > k_f$
$\omega > 0$



$k_i < k_f$
$\omega < 0$

Inelastic scattering

Probes structures by interference of neutrons scattered from them

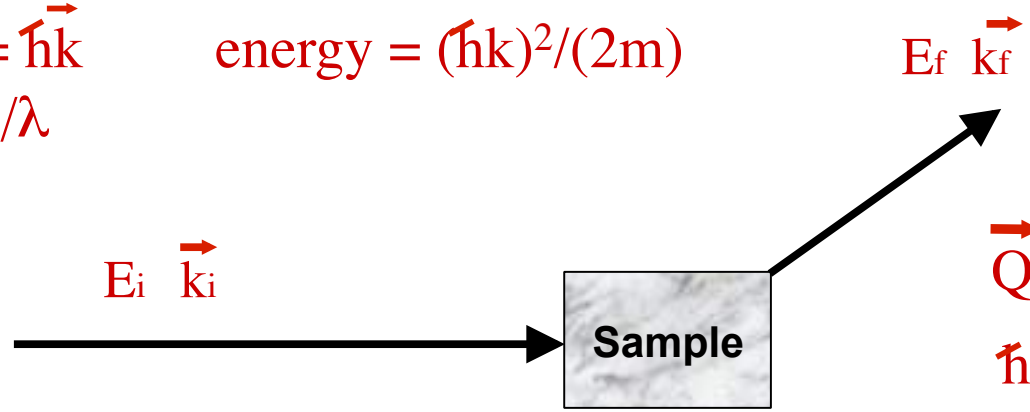
Probes dynamics: energy transferred from excitations in the sample

Use neutron scattering to evaulate any in-beam nonforward scatttering systematics!

momentum = $\hbar\vec{k}$

$k=2\pi/\lambda$

energy = $(\hbar k)^2/(2m)$



$\vec{Q} = \vec{k}_i - \vec{k}_f$

$\hbar\omega = E_i - E_f$

At eV neutron energy: neutron momenta are large, q is small if it stays inside the beam

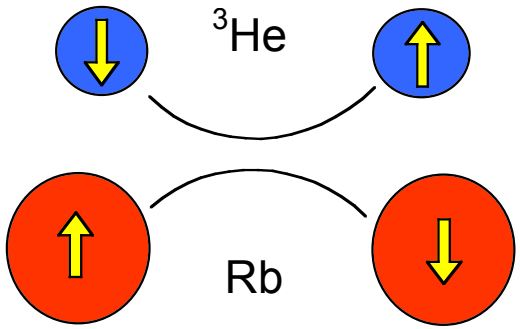
At meV neutron energy: neutron momenta are smaller, q is the same for any nonforward mode-> the scattering angle will increase and this neutron will appear out of beam

With a downstream neutron detector: can MEASURE any nonforward events present In the eV beam using the (much more intense) meV neutrons that come later in time!

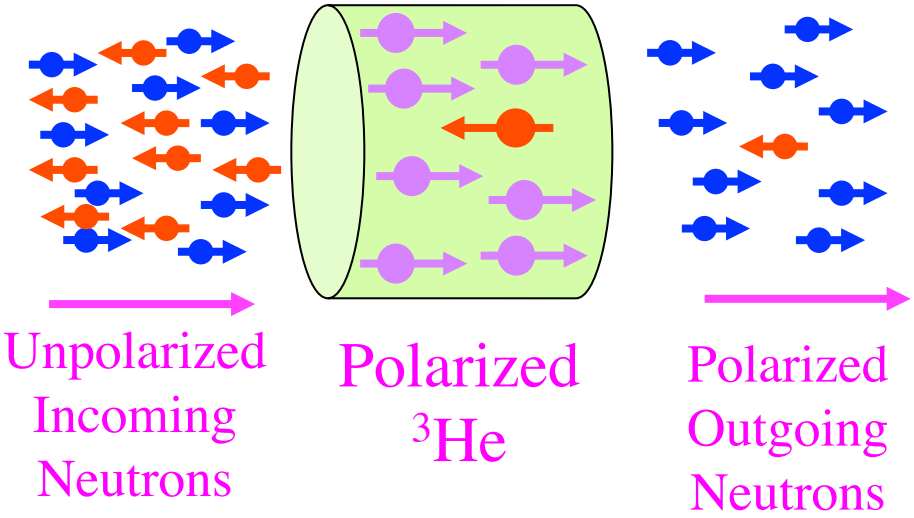
ALSO: for transverse neutron spin, P-even left-right asymmetries are very small at eV neutron energies (<~1E-3)->left/right beam motion effects negligible

Polarized ^{3}He Neutron Spin Filters

(Indiana, Hamilton, NIST, Wisconsin)



Laser-polarized Rb⇒3He nucleus



Uniform polarized neutron beam phase space from absorption in polarized 3He gas

R&D funded by DOE materials science for ~15 years

Educated the people now implementing this technology

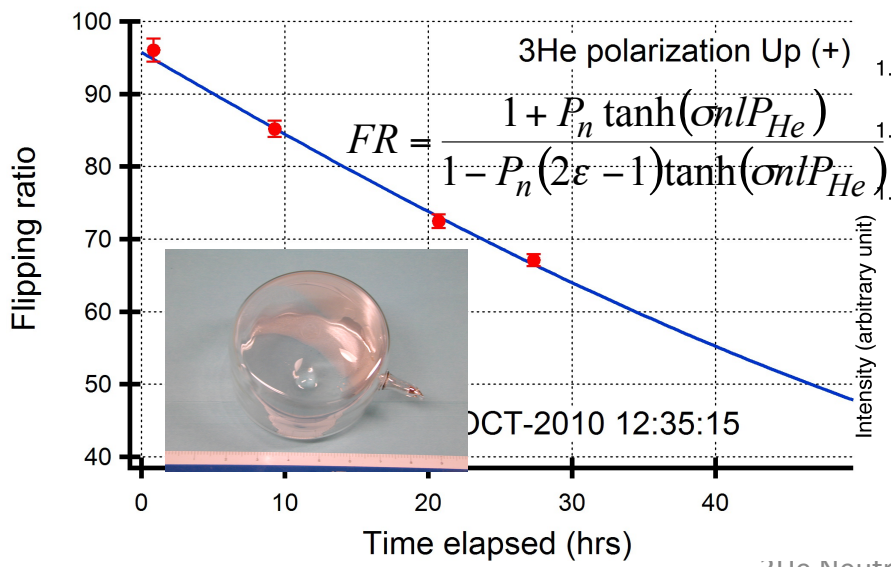
> 80% ^{3}He polarization for neutron spin fiters

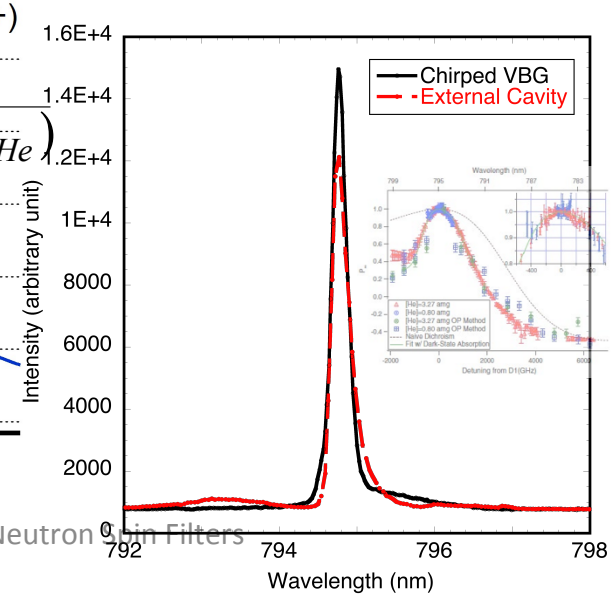
Cell name	D	V, cm^3	T_{up}, h	T_1, h	X	P_{He}	nl, bar-cm	instrument
Burgundy	4	895	4.76	NA	NA	0.853±0.012	8.507±0.060	ANDR
Maverick	4	615	4.33	NA	NA	0.821±0.011	8.878±0.060	ANDR
Burgundy	4	895	6.61	203	0.140	0.851±0.007	8.507±0.071	NG6A
Maverick	4	615	5.76	208	0.177	0.826±0.007	8.878±0.071	NG6A
Syrah	6.2	790	4.03	NA	NA	0.835±0.023	13.16±0.16	BT-7 TAS

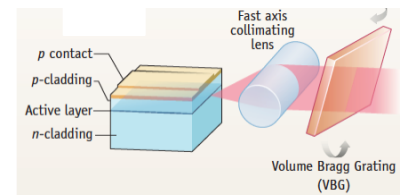
2010

2012

Confirmed with pol. n's

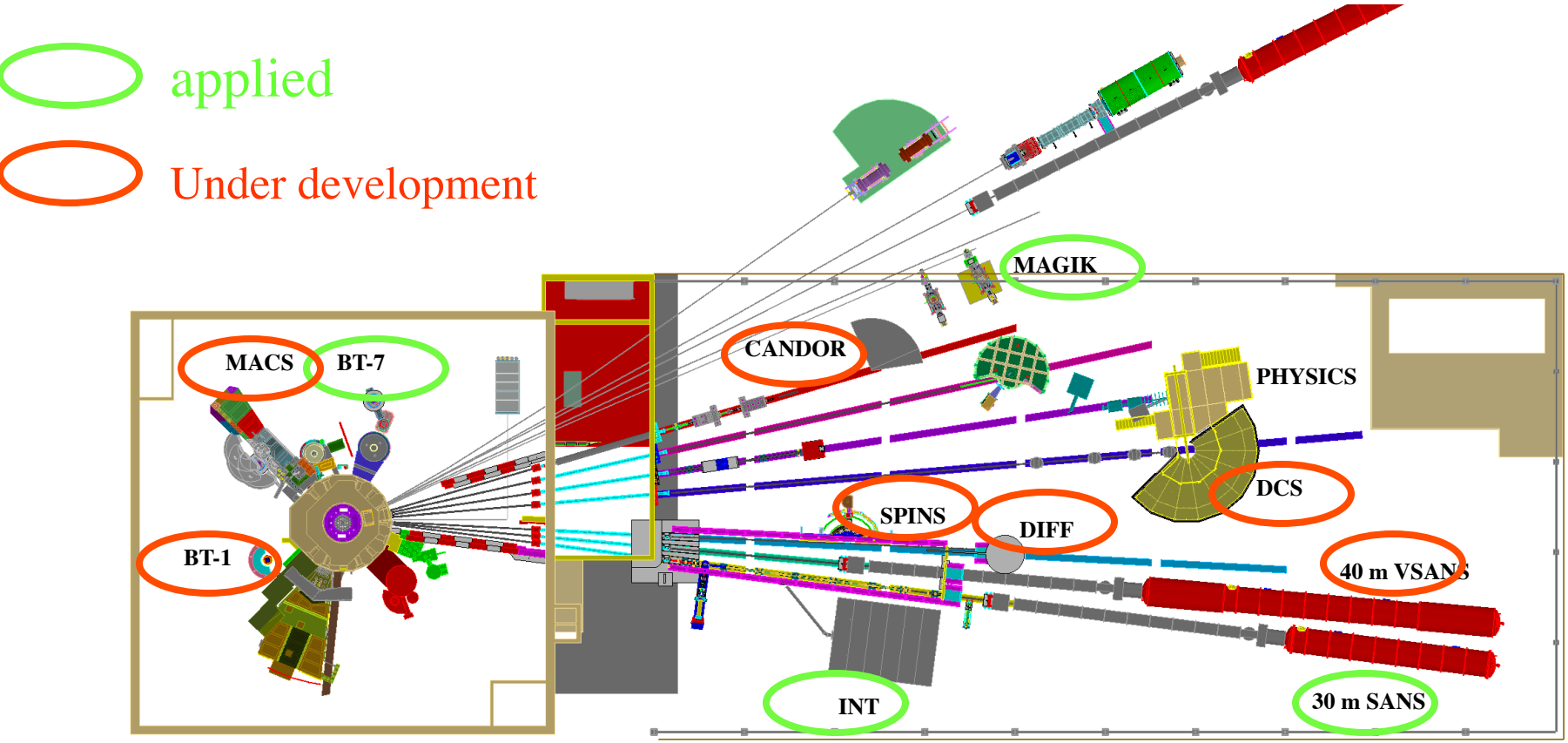






Volume Bragg gratings are bulk slabs of photosensitive glass that contains Bragg planes with varying indices of refraction. They work as a frequency-selective feedback element. Chirped VBGs indicate variable grating periods

^{3}He NSF applications at the NCNR (W. Chen)

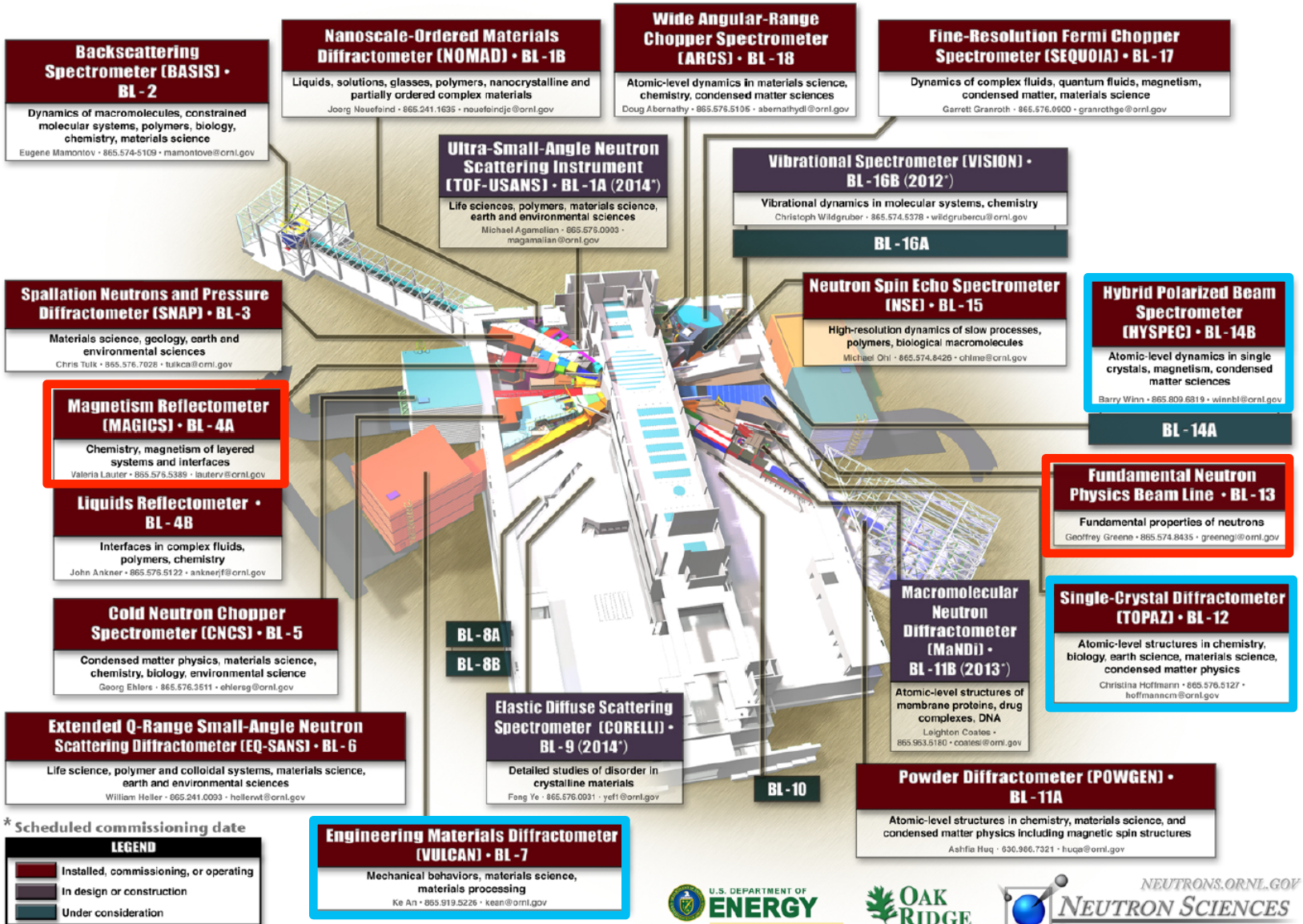


- **Polarized 3He neutron spin filters becoming "routine" at neutron scattering facilities**

3He Operational Under development & construction (T. Tong)

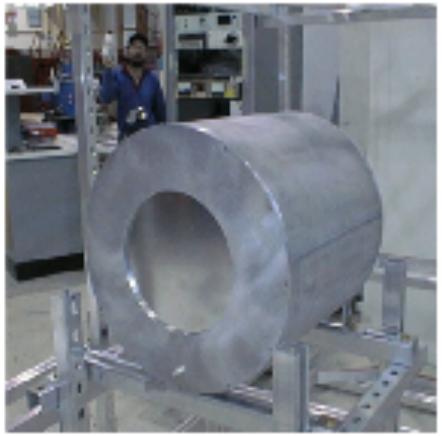
Spallation Neutron Source at Oak Ridge National Laboratory

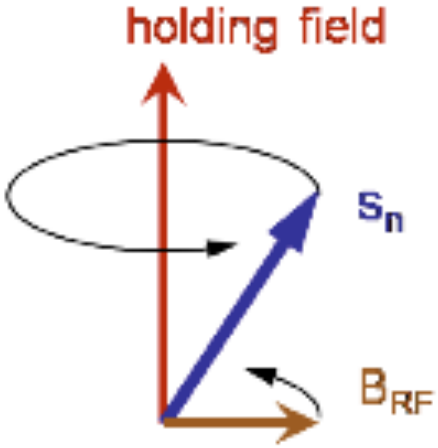
The world's most intense pulsed, accelerator-based neutron source



Polarized neutron RF spin flipper at Pulsed Neutron Source

- RF field oscillating along the beam at Larmor frequency of neutron in the holding field
- Precession angle $\theta = \pi\gamma|\overrightarrow{B}_{rf}|\Delta t$ so we can ramp the amplitude to 1/tof to spin flip all neutrons
- Dump the current into a dummy load when spin flipper is off to avoid false signal
- spin flipper efficiency of ~99%





Polarized beam phase space unchanged! Can be chosen on a pulse-by-pulse basis

Other Neutron Facilities can Characterize Polarized Target Systematics

ILL and FRM “hot” neutron sources (~2000K graphite “heaters” in reactor)

Possess eV neutrons, polarized 3He neutron polarizers, cryogenics,…

Designed to measure magnetic structure/dynamics

We can use it to torture our polarized target

Polarized neutron imaging of internal magnetic fields now in operation

measure the internal magnetic fields/polarization of target

Conclusions

On-resonance T violation in epithermal neutron resonances can now be measured with interesting sensitivity

MW-class, short-pulsed spallation neutron sources (SNS, JPARC) are beautiful sources to use for the experiment: neutron time-of-flight can be used to great advantage to characterize possible systematic errors, especially to “dig out” any non-forward scattering in the transmitted beam

Individual components/operation modes for the experiment have been realized: hardest part is the polarized target