Parity-Violating Neutron Spin Rotation Measurements at NIST

ISINN-21

Alushta, UK May 20-25, 2013

Neutron Spin Rotation (NSR) Collaboration

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Florida State University[14]
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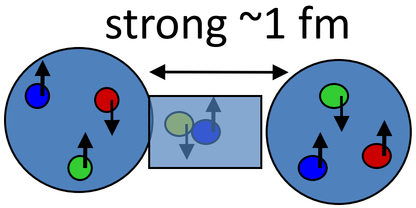
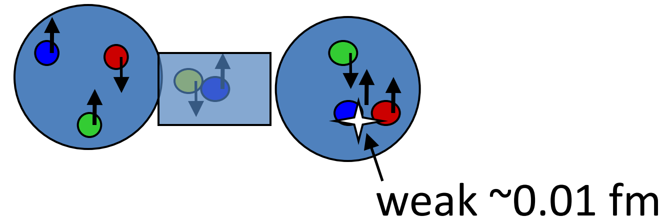
Support: NSF, NIST, DOE, CONACYT, BARC

N-N Weak Interaction





- HWI mediated by $W^{\pm}$ and Z^{o} but

  short range (~0.01 fm) << size of nucleon (~1 fm)

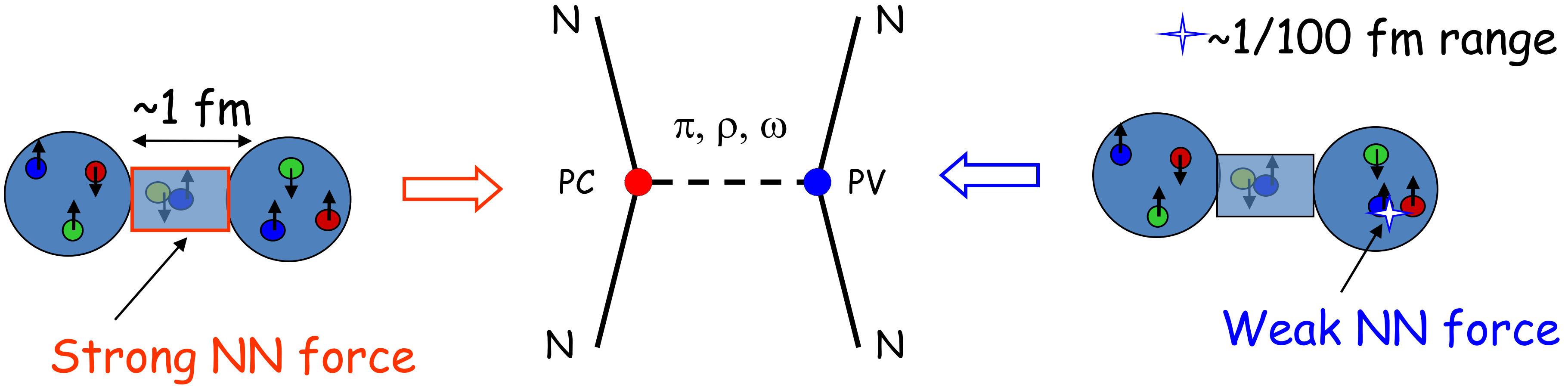
…yet responsible for parity violating effects in

N-N interactions, nuclear decay, atomic structure, anapole moments

- Weak/strong ~10^{-6}

  Use parity violation to isolate Weak contribution

Meson Exchange



- DDH model – exchange of 3 lightest mesons, leads to six coupling constants

$$f_\pi , h_\rho^0 , h_\rho^1 , h_\rho^2 , h_\omega^0 , h_\omega^1$$

- Different experiments sensitive to different linear combinations

Parity Violating Spin Rotation

- Acquired phase shift is a function of index of refraction

$$\phi = \mathrm{Re}(n) k_o z$$

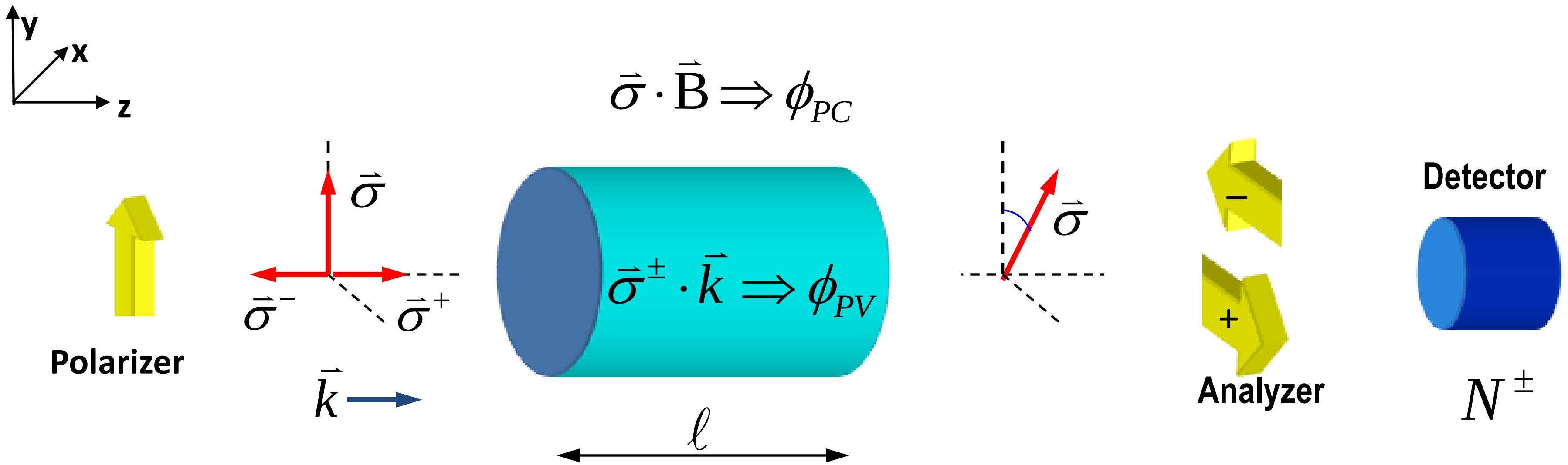
- Index of refraction depends on forward scattering amplitude, which includes PNC term (polarized neutrons, unpolarized target)

$$n = 1 + \left(\frac{2\pi}{k^2} \right) \rho \left[f_{PC} + f_{PNC} \left(\vec{\sigma}_n \cdot \vec{k}_n \right) \right]$$

- Two helicity states acquire different phases → rotation angle.

$$\phi_{PNC} = \phi_+ - \phi_- = 4\pi\rho z f_{PNC}$$

ϕ_{PNC} for Transversely Polarized Neutrons

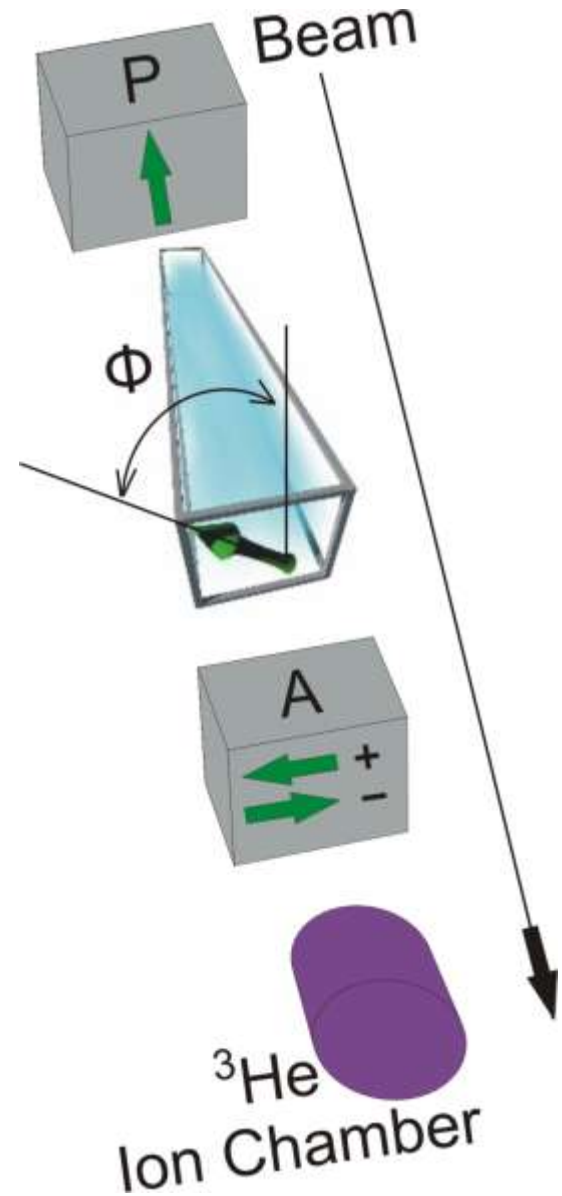


$$\sin(\phi_{PNC}) = \frac{1}{PA}\frac{N^+ - N^-}{N^+ + N^-}$$

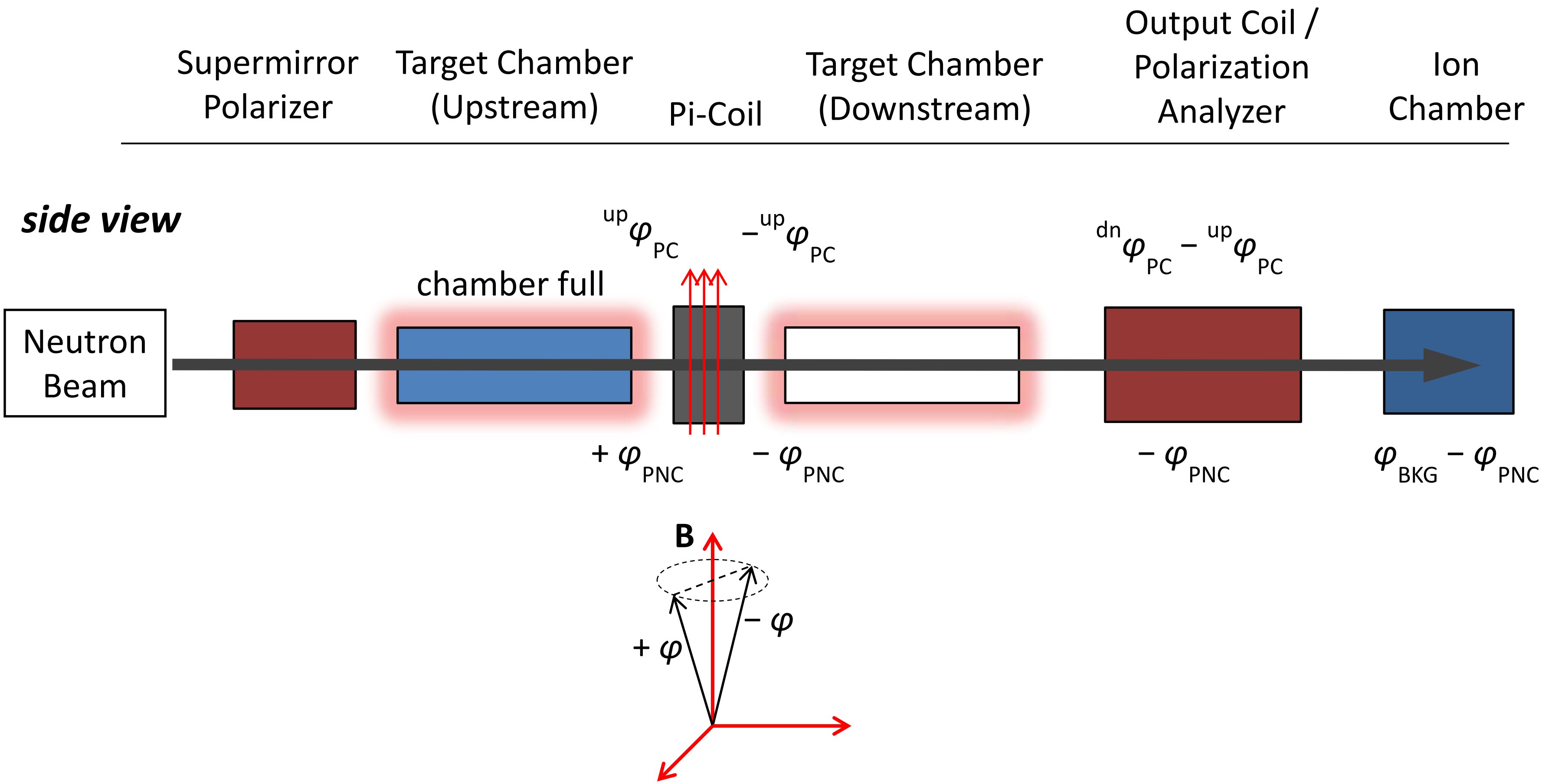
- Expected Size:

$$\frac{d\phi_{PNC}}{dz} \sim 10^{-7} \text{ to } 10^{-6} \; (\text{rad/m})$$

- Experimental challenge
  - Reducing $\vec{\sigma} \cdot \vec{\mathrm{B}} \Rightarrow \phi_{PC}$
  - effectively canceling what is left
  - controlling noise
  - controlling other systematics



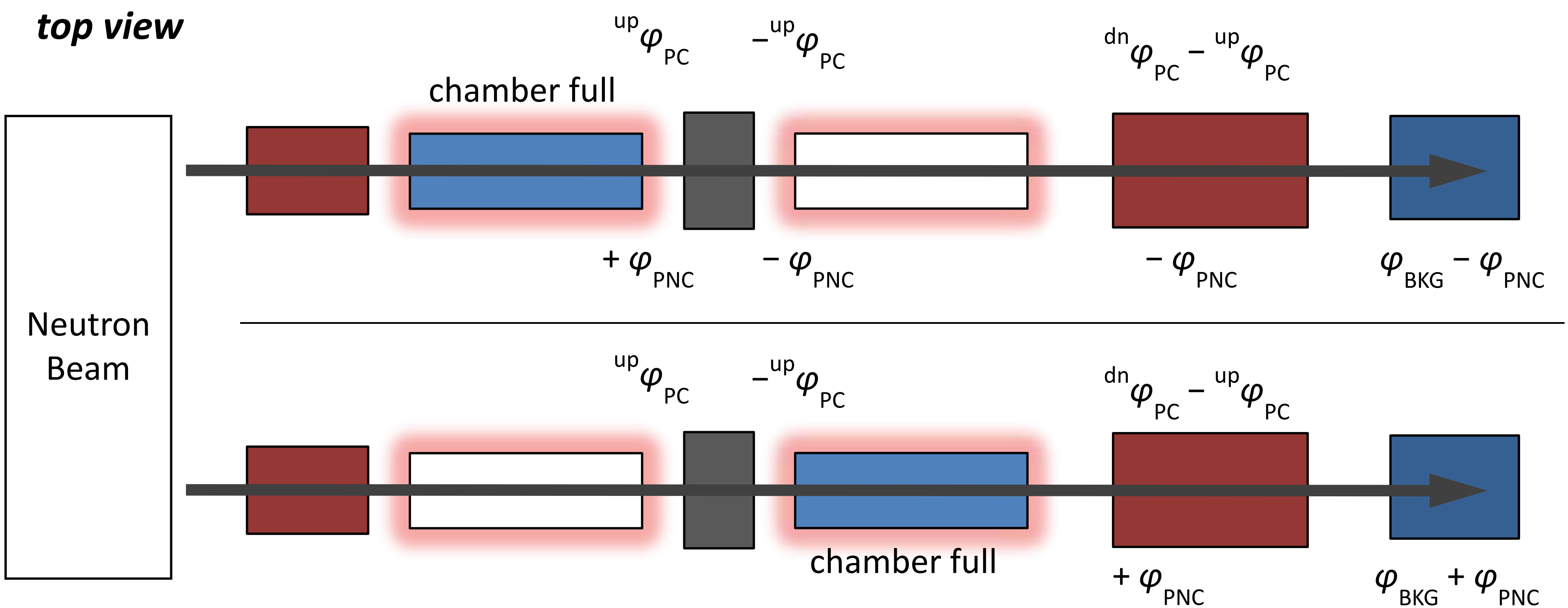
Canceling ϕ_{PC}



- Vertical field of "Pi-coil" reverses rotation angle
- Detector sensitive to $\varphi_{BKG} - \varphi_{PNC}$
- $\varphi_{BKG} = {}^{dn}\varphi_{PC} - {}^{up}\varphi_{PC} \sim 0$

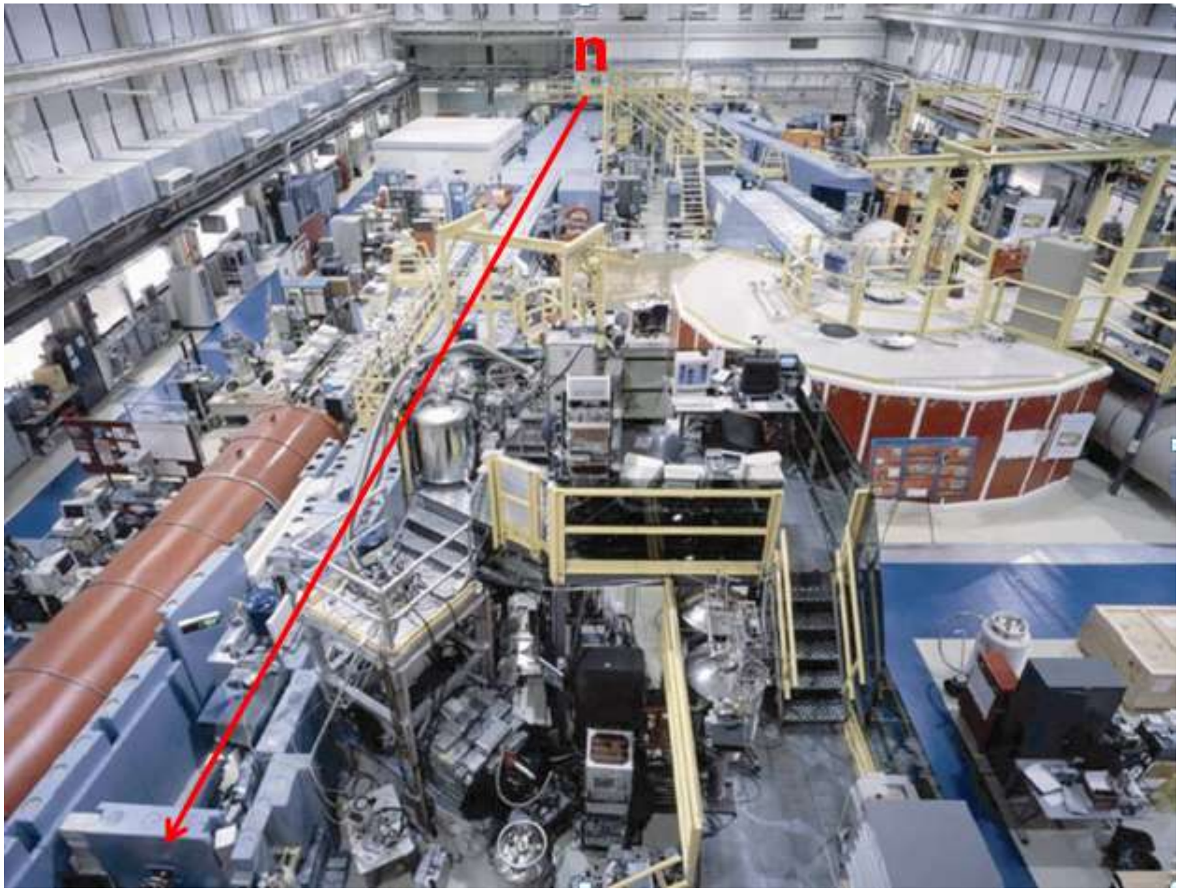
Canceling ϕ_{PC} – Side-by-side experiments

Supermirror Polarizer | Target Chamber (Upstream) | Pi-Coil | Target Chamber (Downstream) | Output Coil / Polarization Analyzer | Ion Chamber



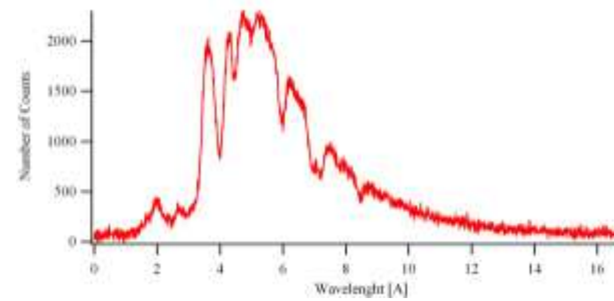
- $\varphi_{BKG} = {}^{dn}\varphi_{PC} - {}^{up}\varphi_{PC}$ is insensitive to target location
- Change target locations
- Double subtraction isolates ϕ_{PNC} and reduces effects of reactor fluctuations

Cold Neutron Guide hall at NCNR



^{58}Ni guide θ_c=2.1 mrad/A (m=1.2)

NG-6 Polychromatic beam



Reactor **20 MW**
(fission neutrons)

↓ Moderation D_2O

Thermal neutrons

↓ Moderation LH

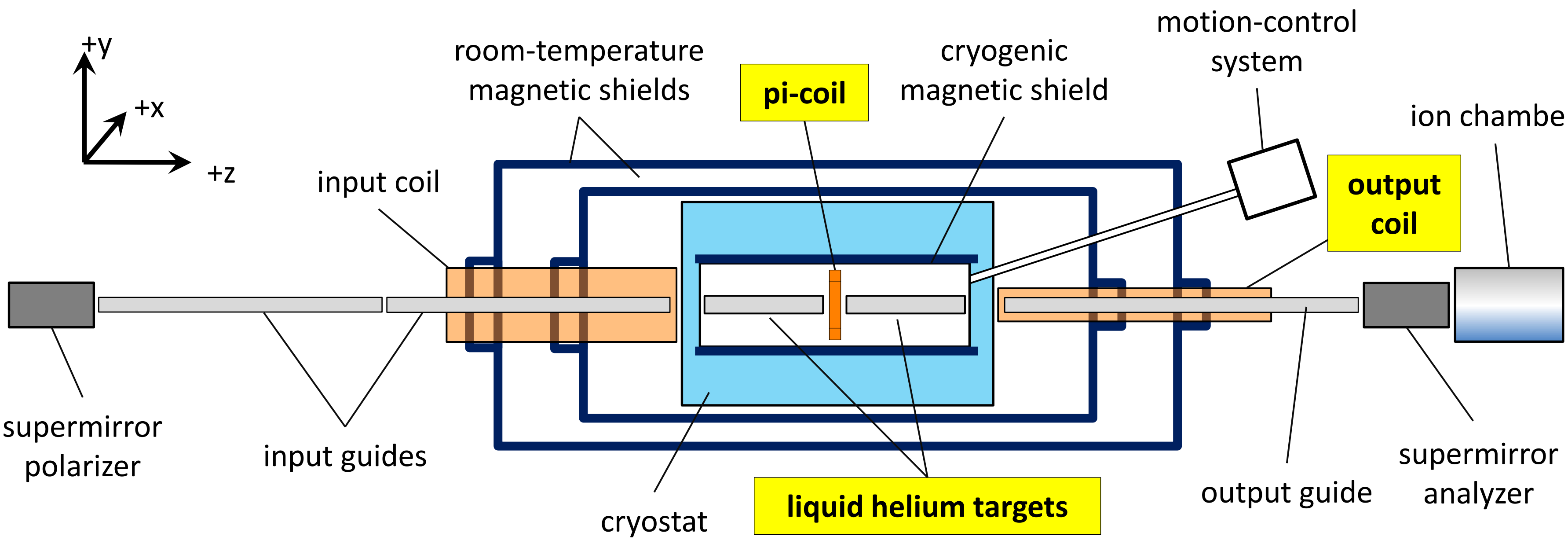
Cold neutrons T=20K

Main measurement – 3 reactor cycles January – May 2008,
Systematic studies – 1 reactor cycle June 2008.

slide courtesy A. Micherdzinska

Spin Rotation Apparatus

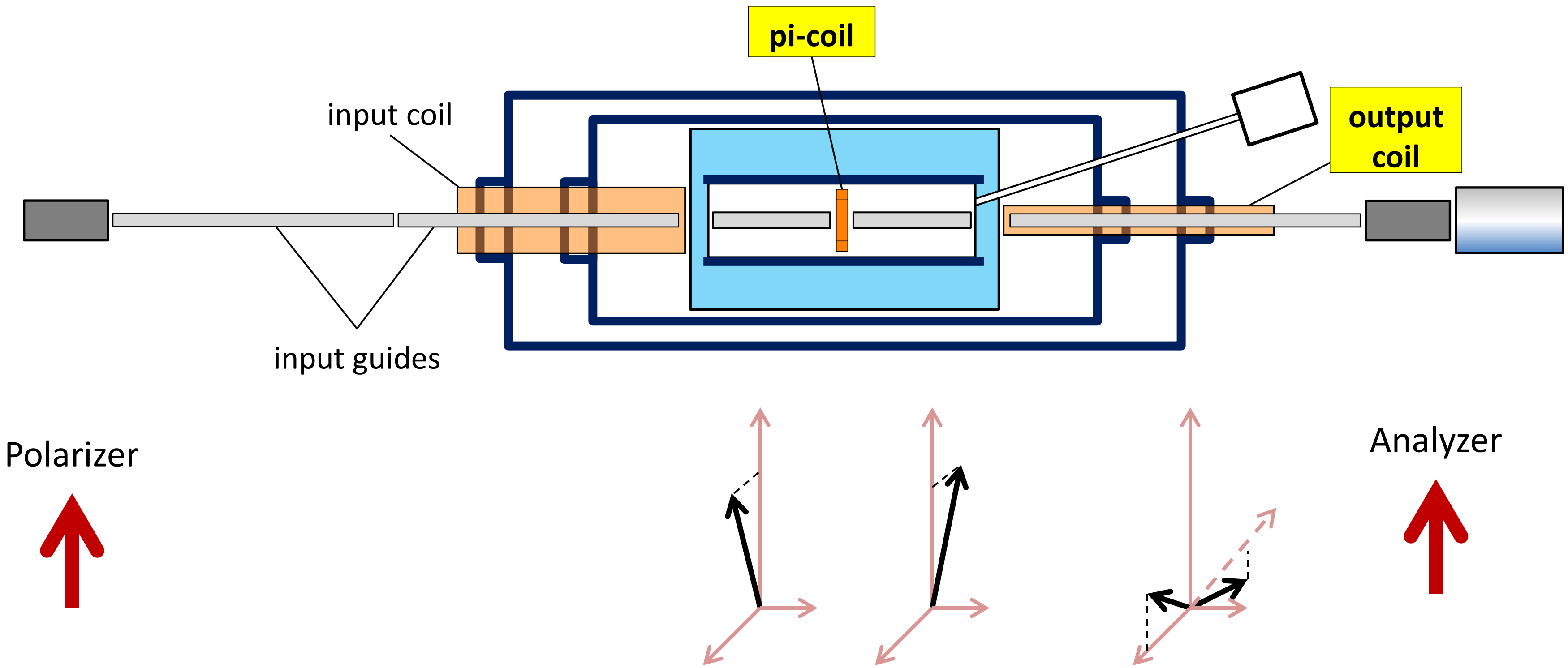
Measures the horizontal component of neutron spin for a vertically-polarized beam



- 100microGauss in target region
- float glass waveguides θ_c=1.2mrad/Å (m=0.68)
- Be filter -> spectrum above 4Å limits under rotation by pi-coil

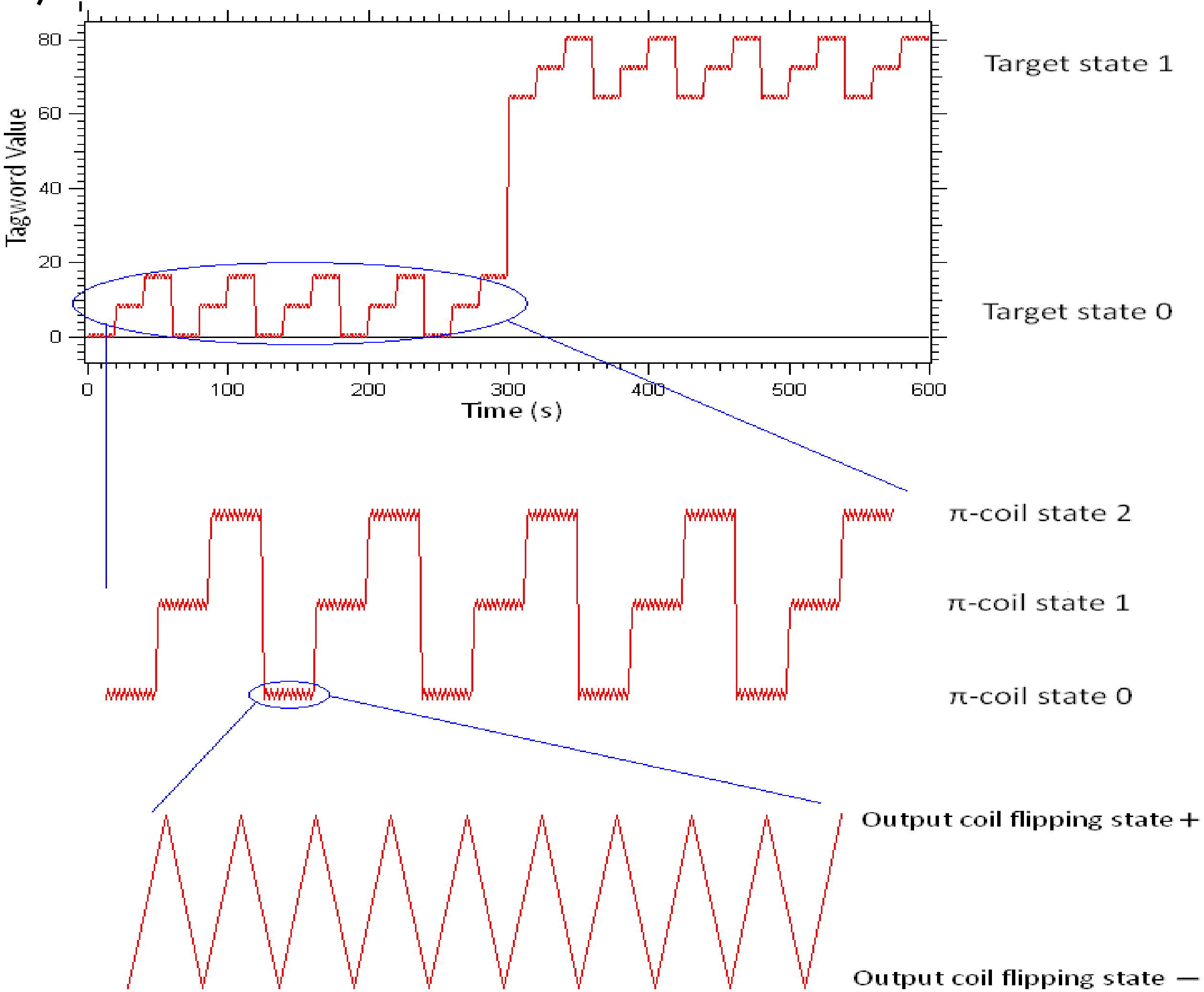
Rotation Angle Asymmetry

$$\sin(\phi_{PNC}) = \frac{1}{PA}\frac{N^{+} - N^{-}}{N^{+} + N^{-}}$$



- Output coil rotates vertical spin by +90º or -90º (1 Hz)
- Vertical super-mirror analyzer analyzes component due to rotation

Data sequence

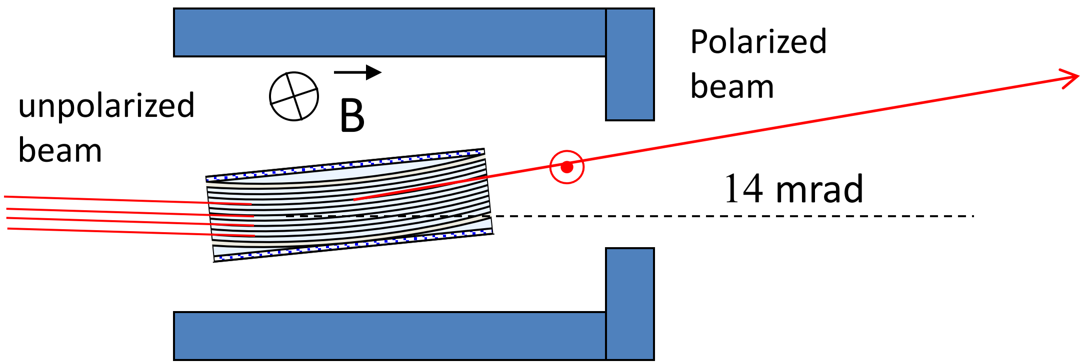


A spin rotation angle is determined from each pair of output coil states (+, −).

Reversing the π-coil current cancels any neutron spin rotations from stray fields outside the coil.

Π-coil (−, 0, +) state is repeated five times to form a 300-s target sequence. The liquid helium is then drained and filled in the complementary state in 300–350 s, and the previous sequence is repeated to form a target cycle.

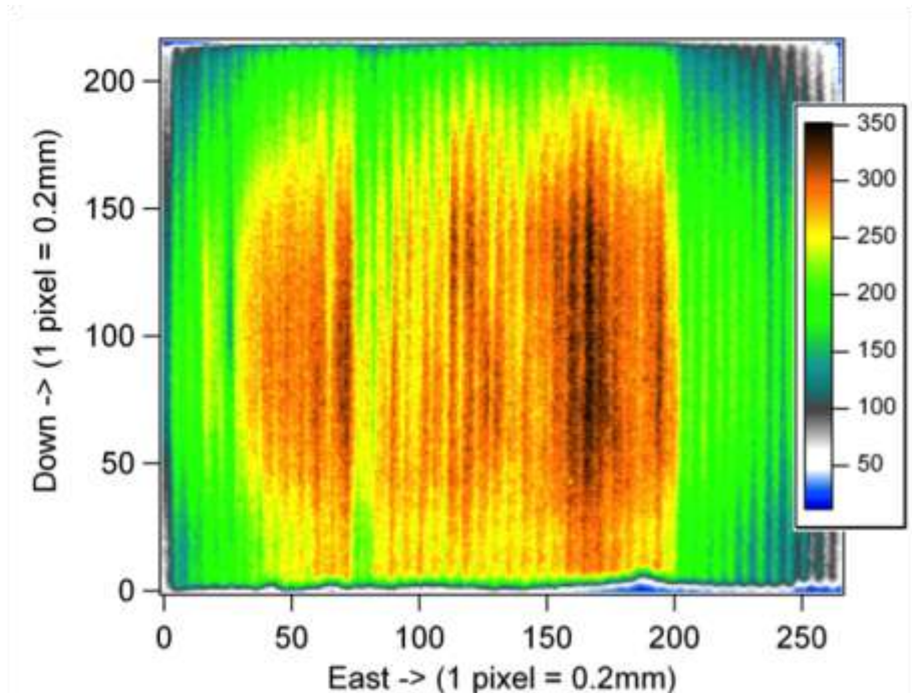
Polarizing Super Mirror



$$n = 1 - \left[\frac{2\pi\rho\hbar^2 a}{p^2} \pm \frac{\mu(B-H)m}{p^2}\right] \equiv 1 - \frac{\theta_{c\pm}^2}{2}$$

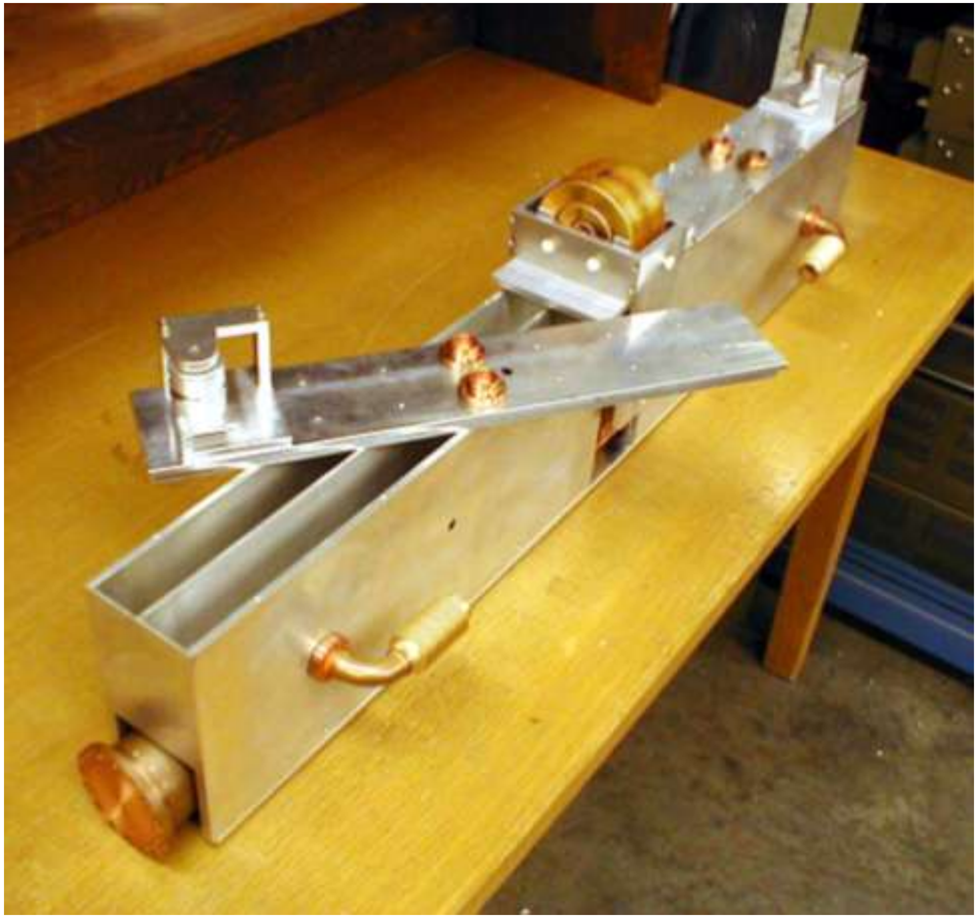
- spin-dependent scattering from magnetized mirrors
- Alternating layers of magnetic surface (cobalt) and absorptive layer (titanium and gadolinium); 1mm separation; Placed in 300 G permanent box.
- Typical polarization: 98%; transmission: 25%

4.5cmX5.5cm



slide courtesy A. Micherdzinska

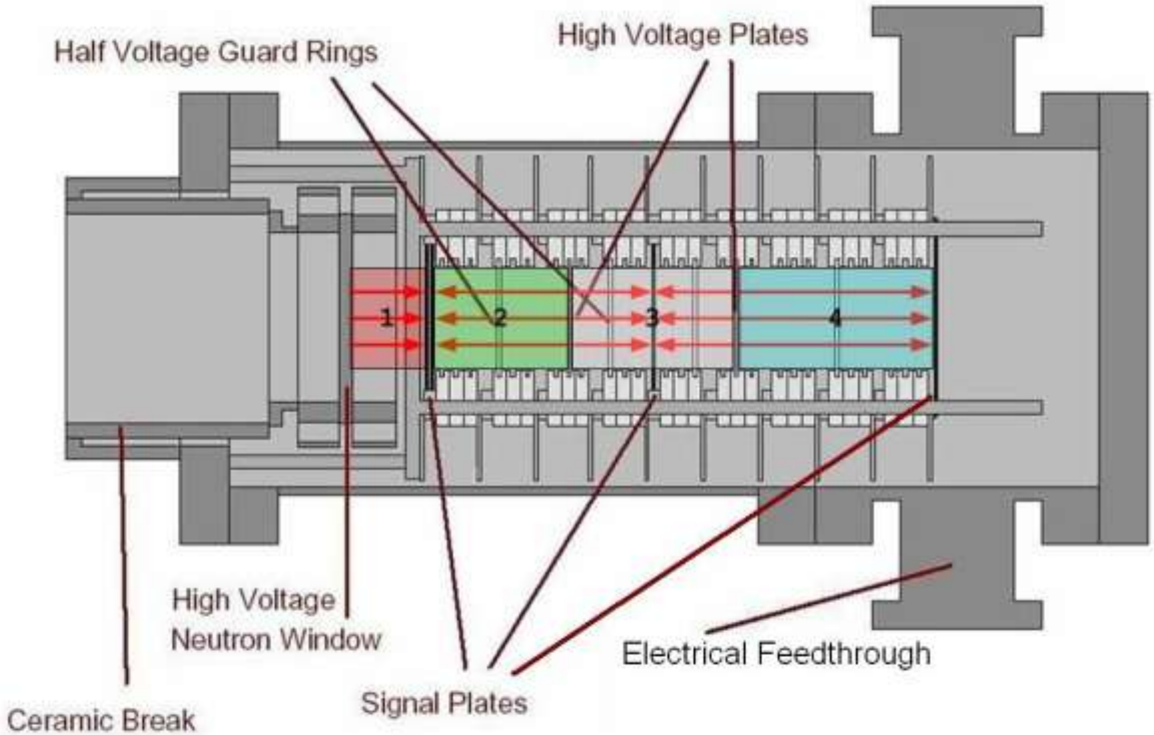
Target Chamber

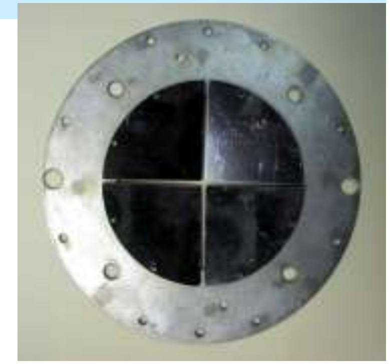


pi-coil

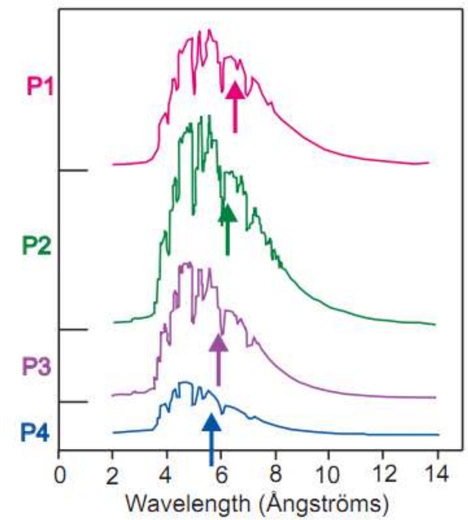
Separate Left and Right chambers upstream and downstream of pi-coil
C.D. Bass NIM A **612** (2009) 69-82

Segmented ^{3}He ionization chamber





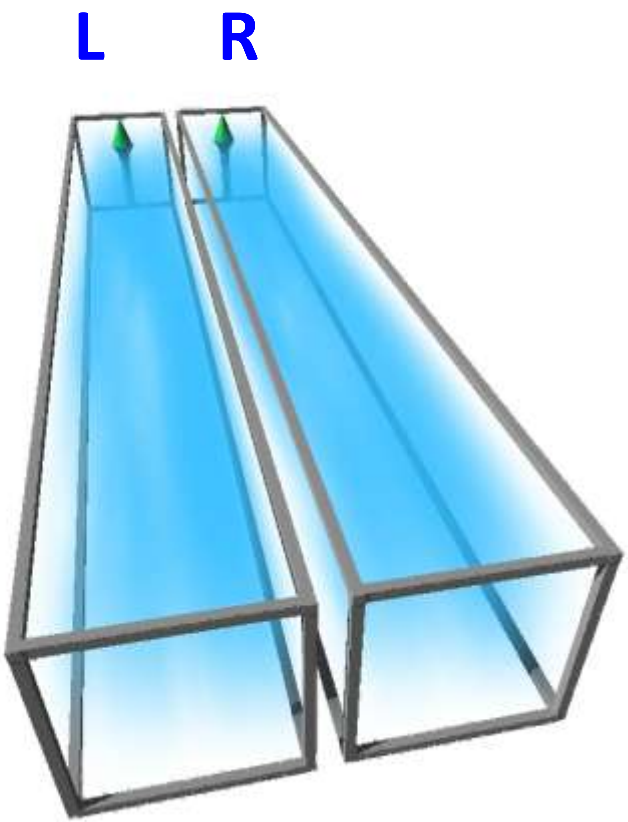
charge collection plates are divided into 4 quadrants (3" diam) separated L/R and U/D beam

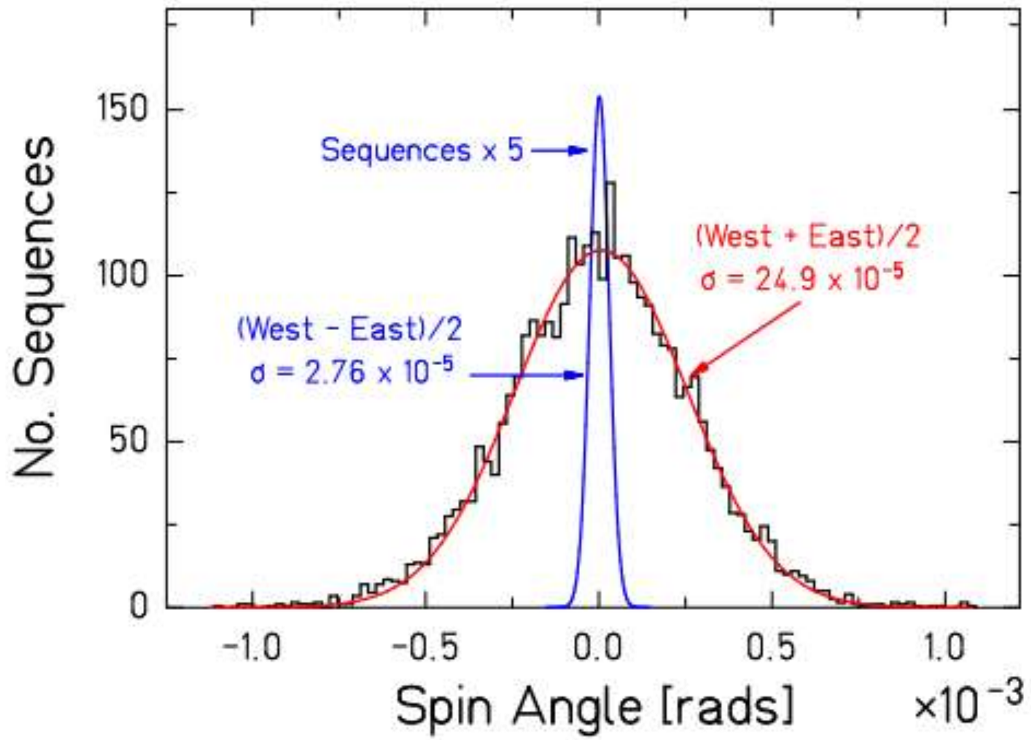


- ^{3}He and Ar gas mixture
- Neutrons detected through $n + {}^3He \rightarrow {}^3H + {}^1H$
- High voltage and grounded charge-collecting plates produce a current proportional to the neutron flux
- 4 Detection Regions along beam axis - velocity separation (1/*v* absorption)

S.D.Penn *et al.* [NIM A457 332-37 (2001)]

Reactor Noise Suppression





$$\phi_0 = \frac{L - R}{2}$$

- Large noise from beam intensity fluctuations is suppressed

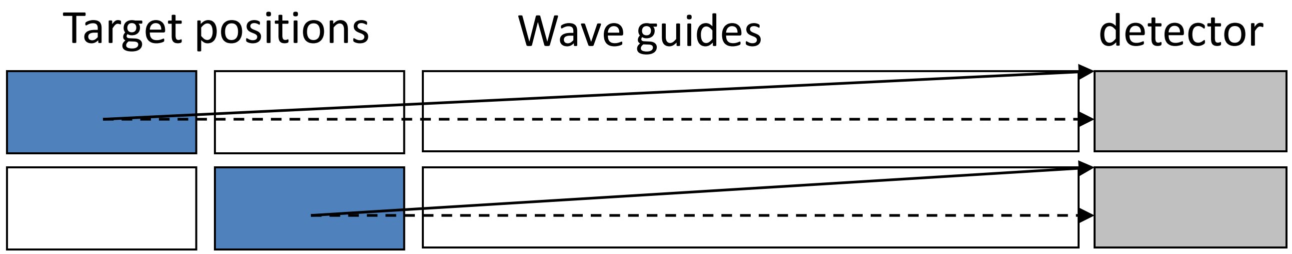
- Width of LEFT-RIGHT difference of spin rotation angles is consistent with √N neutron counting statistics noise to ~10% accuracy

Systematic Effects

Diamagnetism of LHe	*ΔB/B ≈ 6E-8*	2E-9 rad/m	Calculated
Optical potential of LHe	*~ 10 neV*	3E-9 rad/m	
Shift in neutron energy spectrum	*Δ L ≈ 0.01 mm*	8E-9 rad/m	
Small angle scattering		2E-8 rad/m	
Change in neutron paths due to refraction/reflection		3E-10 rad/m	
Polarimeter nonuniformity		1E-8 rad/m	
B amplification		< 4E-8 rad/m	Measured
B gradient amplification		< 3E-8 rad/m	
PA/target nonuniformity		< 6E-8 rad/m	
TOTAL estimated systematic effect		1.4E-7 rad/m	

Simulations used to investigate small angle scattering and B-field gradients

Small-angle scattering

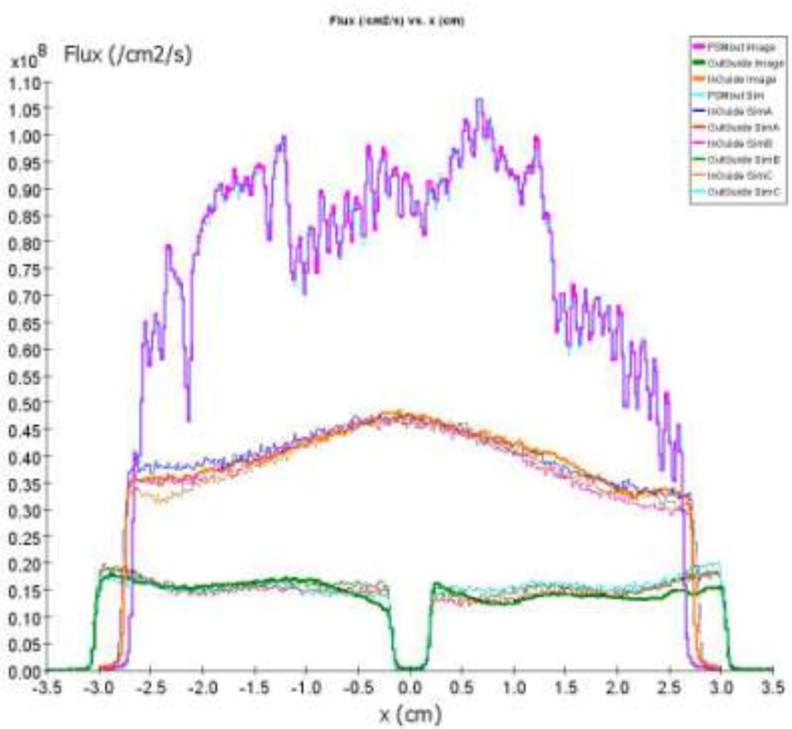


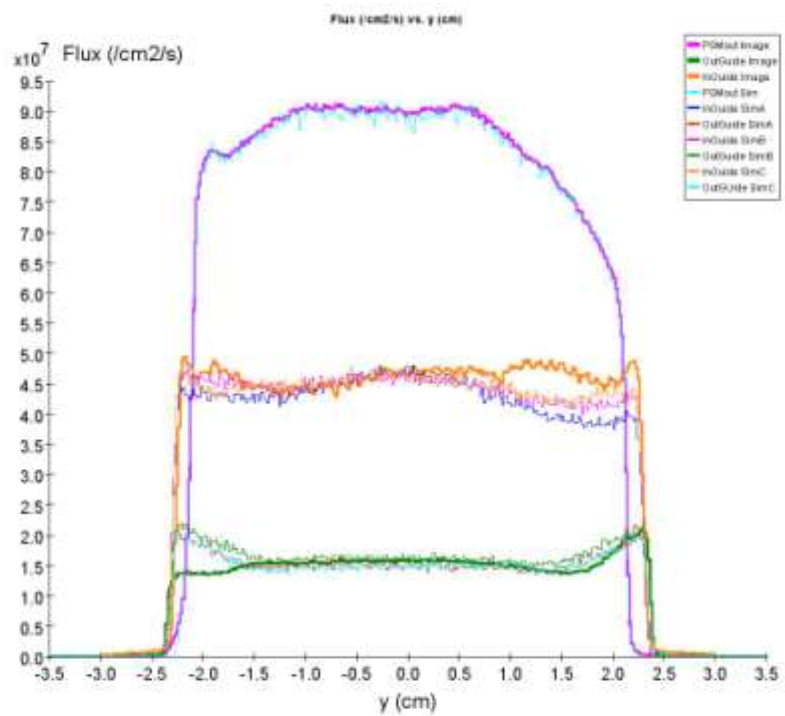
- Upstream-downstream subtraction is incomplete
  - Energy loss for scattered neutrons + different paths in target region (up stream scatters travel farther at lower energy)
  - path length of scattered neutrons is different (up stream scatters spend longer time in target region)
  - different detector solid angles from target positions (fewer scattered neutron reach detector from up target)

Simulations

- Monte-Carlo neutron transport
  - Phase space of polarizing super mirror as input
  - allow reflections from waveguides, scattering from Al windows, air gaps
  - small angle scattering in liquid He target
  - calculate PC rotation
  - study effect of target position, alignment, B-field gradients, changes in energy and path length

$$\varphi = \gamma_n \frac{B\ell}{v}$$





Systematic Effects

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B gradient amplification		< 3E-8 rad/m	
PA/target nonuniformity		< 6E-8 rad/m	
TOTAL estimated systematic effect		1.4E-7 rad/m	

Results

- Artificially high magnetic field 10mG

$(-0.9 \pm 2.2) \times 10^{-6}$ rad-meas $(-1.7 \pm 0.6) \times 10^{-6}$ rad-sim

implies <4x10^{-8} rad/m systematic

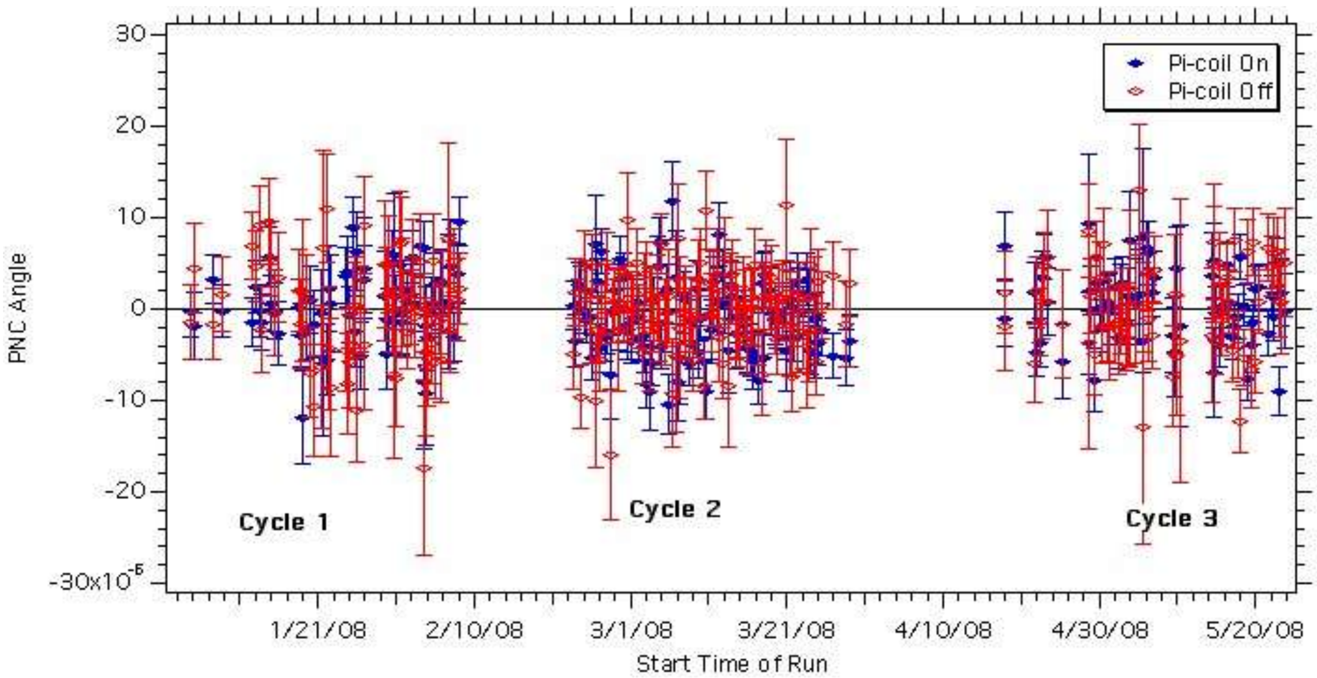
- Artificially high magnetic gradient +7mG to -7mG

$(-2.0 \pm 3.1) \times 10^{-6}$ rad-meas $(-0.7 \pm 2.7) \times 10^{-6}$ rad-sim

implies <3x10^{-8} rad/m systematic

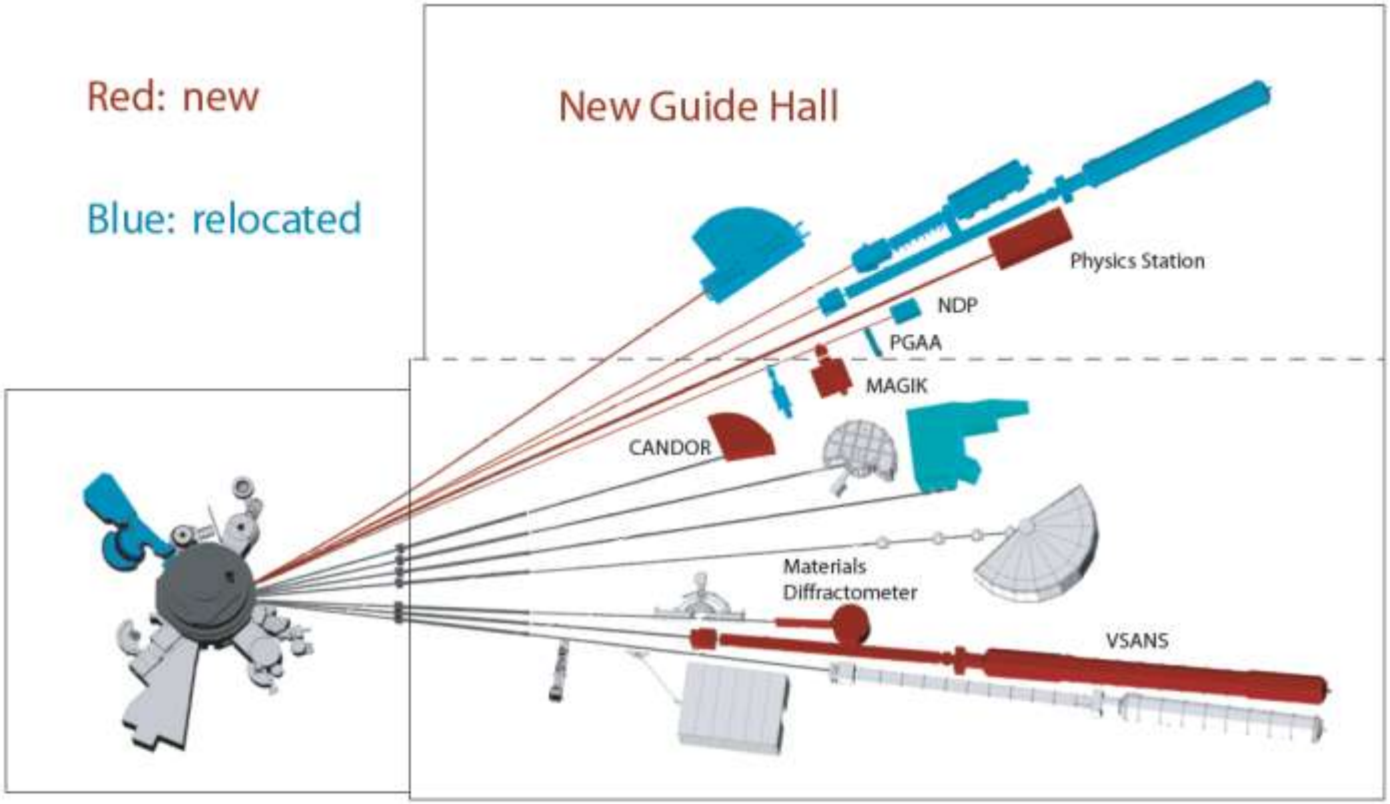
Results

- pi-coil ON runs measure φ_{PNC}
- pi-coil OFF runs should be zero if no systematics



$$\frac{d\phi}{dz} = \left(+1.7 \pm 9.1(stat.) \pm 1.4(sys.)\right) \times 10^{-7} \text{ rad/m}$$

NIST Guide Hall Expansion Project



NGC beam – larger area, higher flux, more divergent beam

~X20 increase in polarized slow neutron flux in spin rotation apparatus(!)

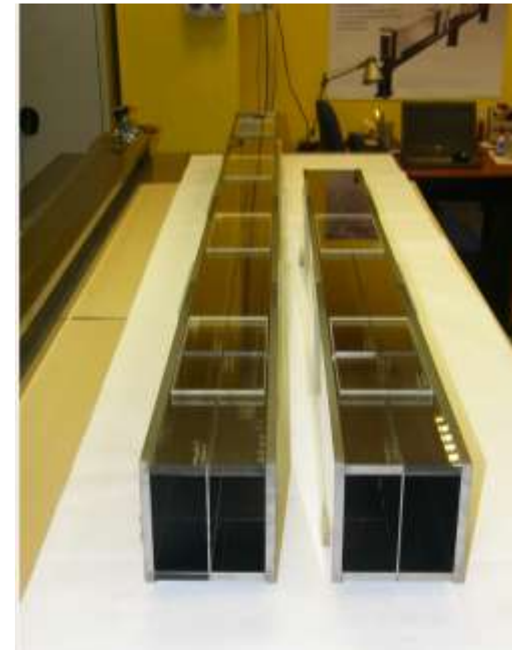
Spin rotation stat precision of <2E-7 rad/m in a 5 week cycle is possible

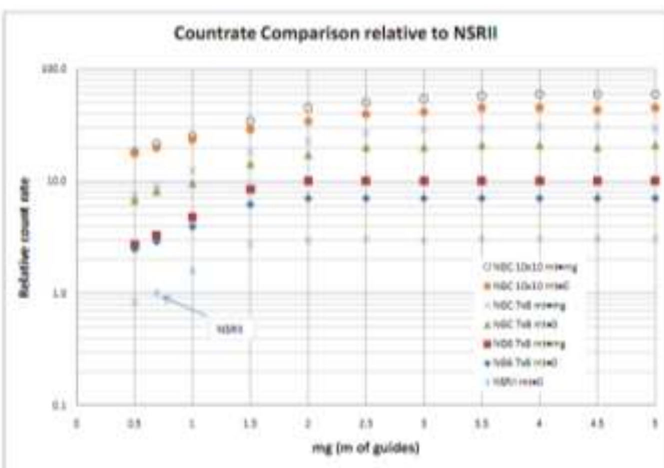
slide courtesy M. Snow

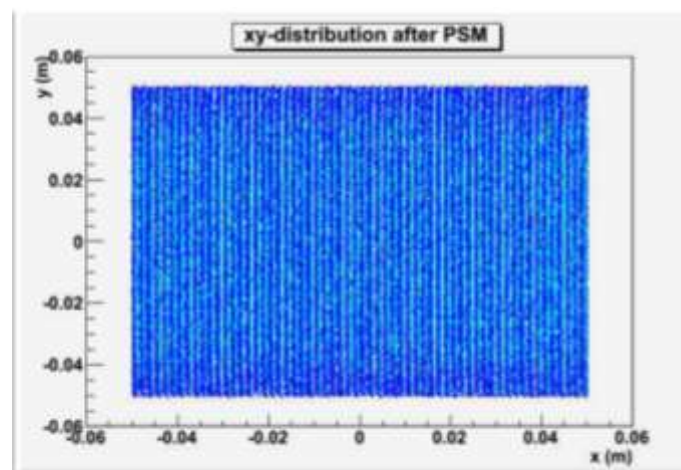
Apparatus Improvements

- New 10cmX10cm supermirror polarizer/analyzer pair *(on order)*

  61 vanes with Fe/Si supermirror (m=2.5)
- Non-magnetic Supermirror (m=2) waveguides
- Enlarged target chambers, ion chamber
- Decreased heat load and He re-liquidification to reduced down time
- Improved liquid He pumping

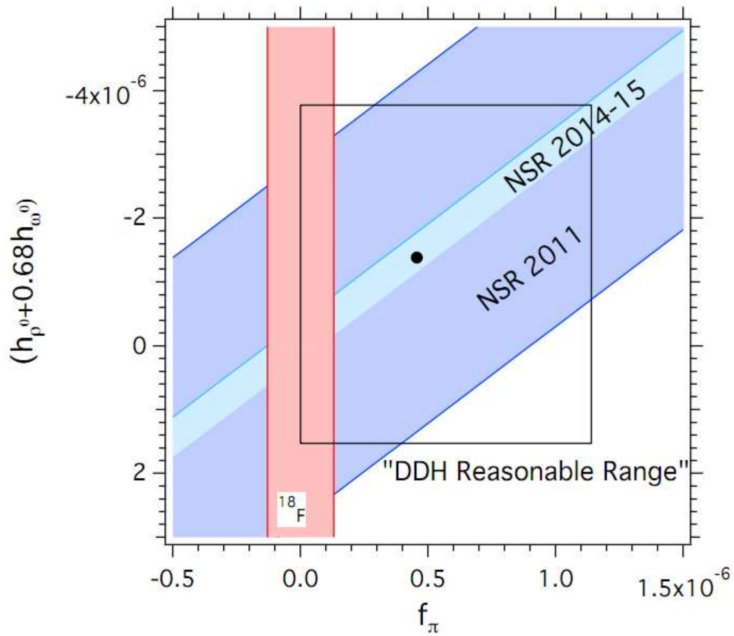




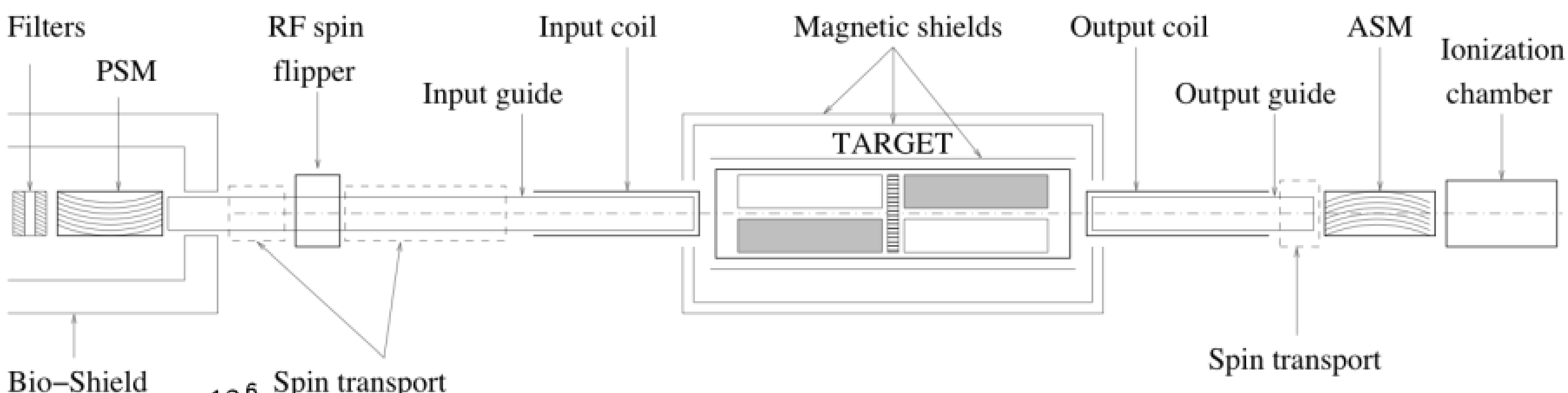


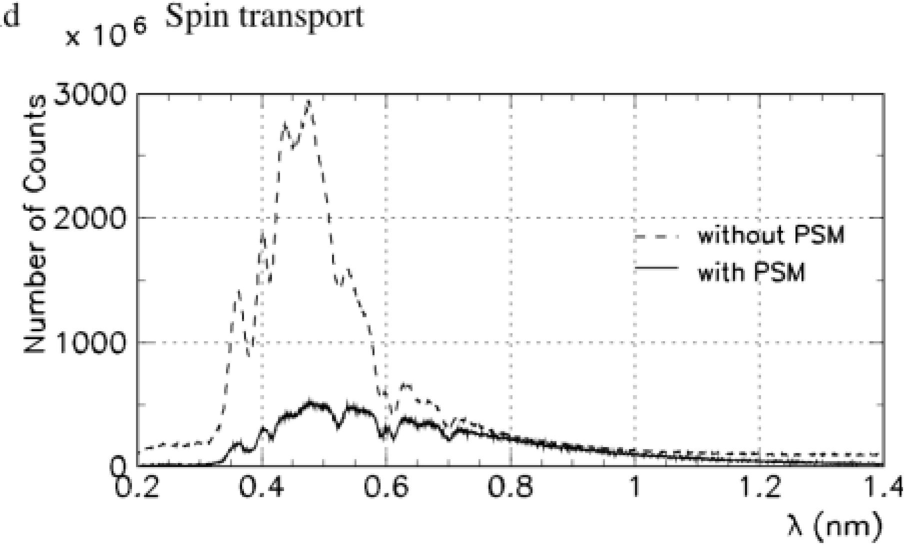
Conclusions

- In addition to helping constrain hadronic weak coupling constants, recent analysis demonstrates that the result also places the most stringent limit to date on new parity-odd long-range sub-eV interactions (WISPs) *Phys. Rev. Lett. 110, 082003 (2013)*
- Upcoming experiment on new NGC beam at NIST promises to improve precision to the 2×10^{-7} rad/m level.



Before real measurement we need to understand beam
and apparatus behavior – systematic check of beam and apparatus behavior





- Beam intensity distribution as I(λ) / chopper – TOF, ionisation chamber

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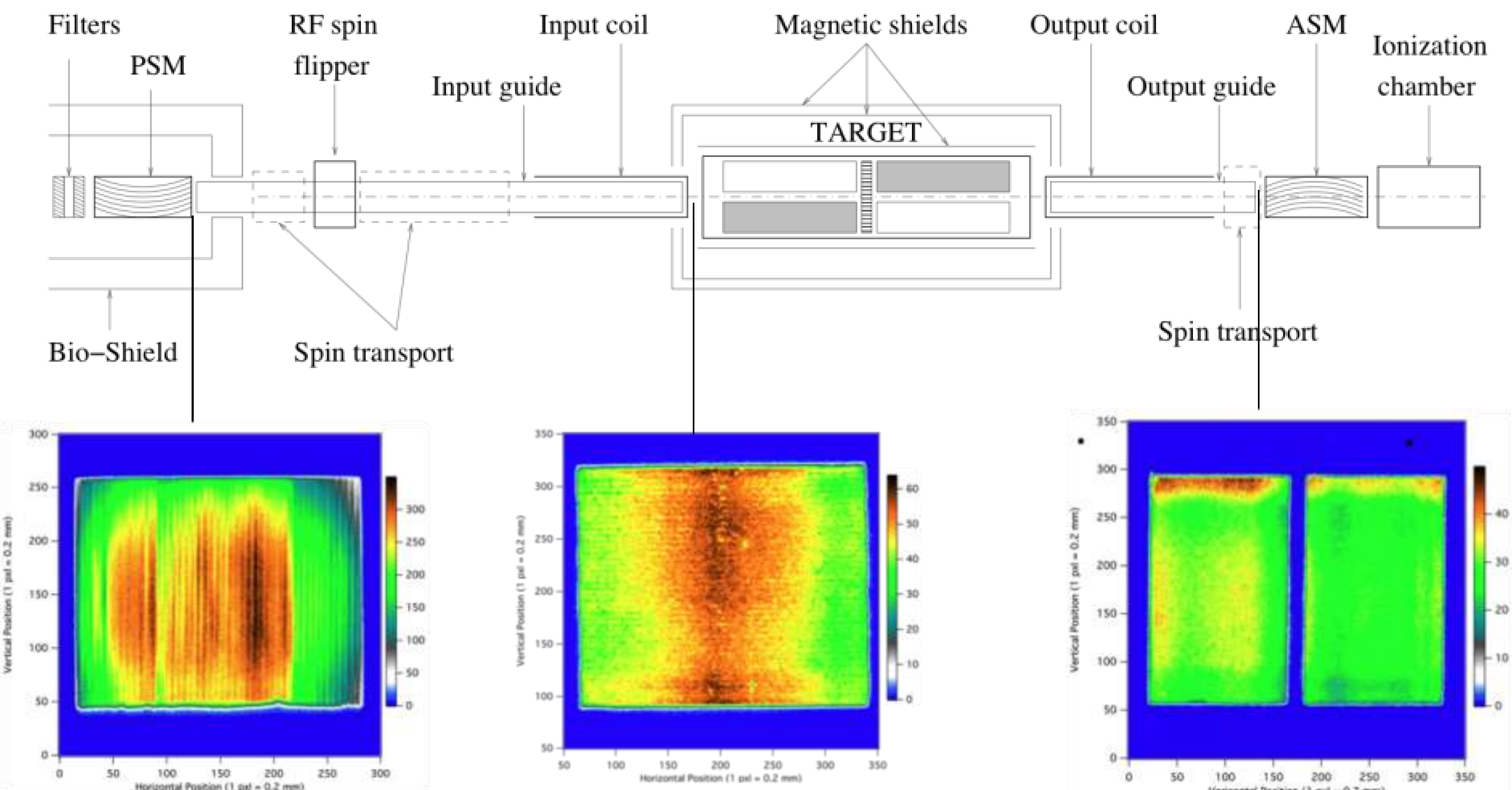
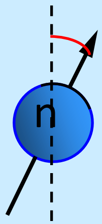


- Beam intensity distribution as I(x,y) / image plate



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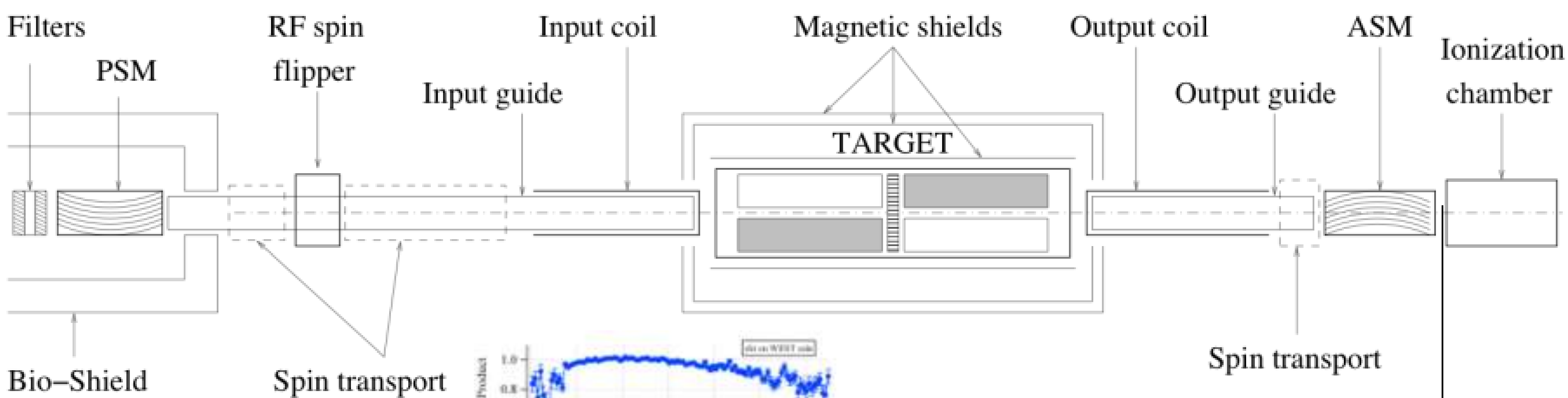
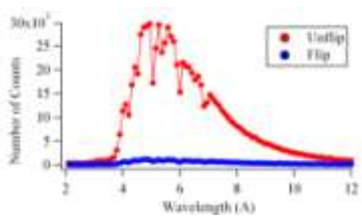
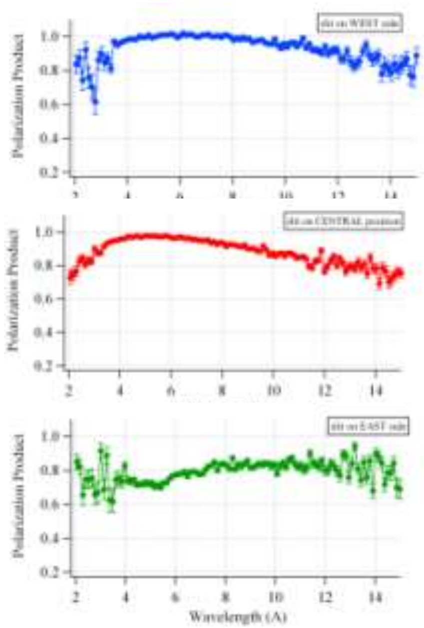
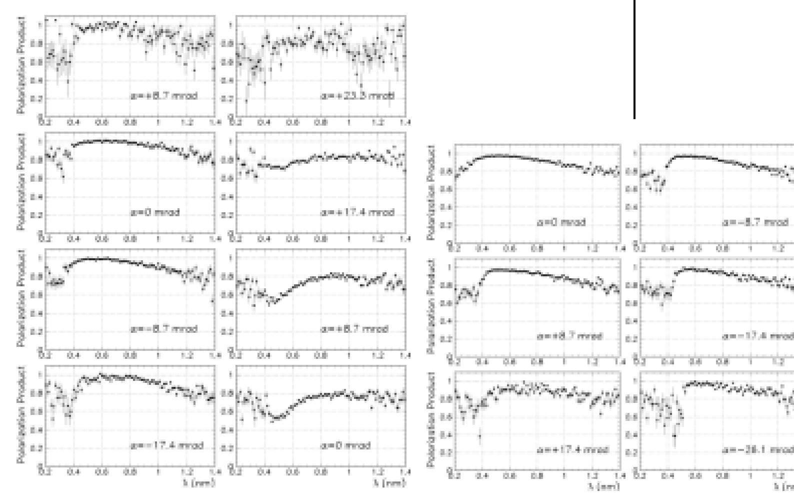




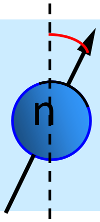




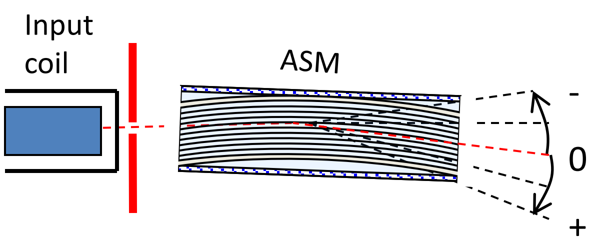
PA=(U-F)/(sU+F)

U- Unflip; F- flip
s – spin-flip efficiency
(s=0.95 ± 0.05)

- Polarization product (PA) as a f(λ) /PSM, ASM, chopper – TOF

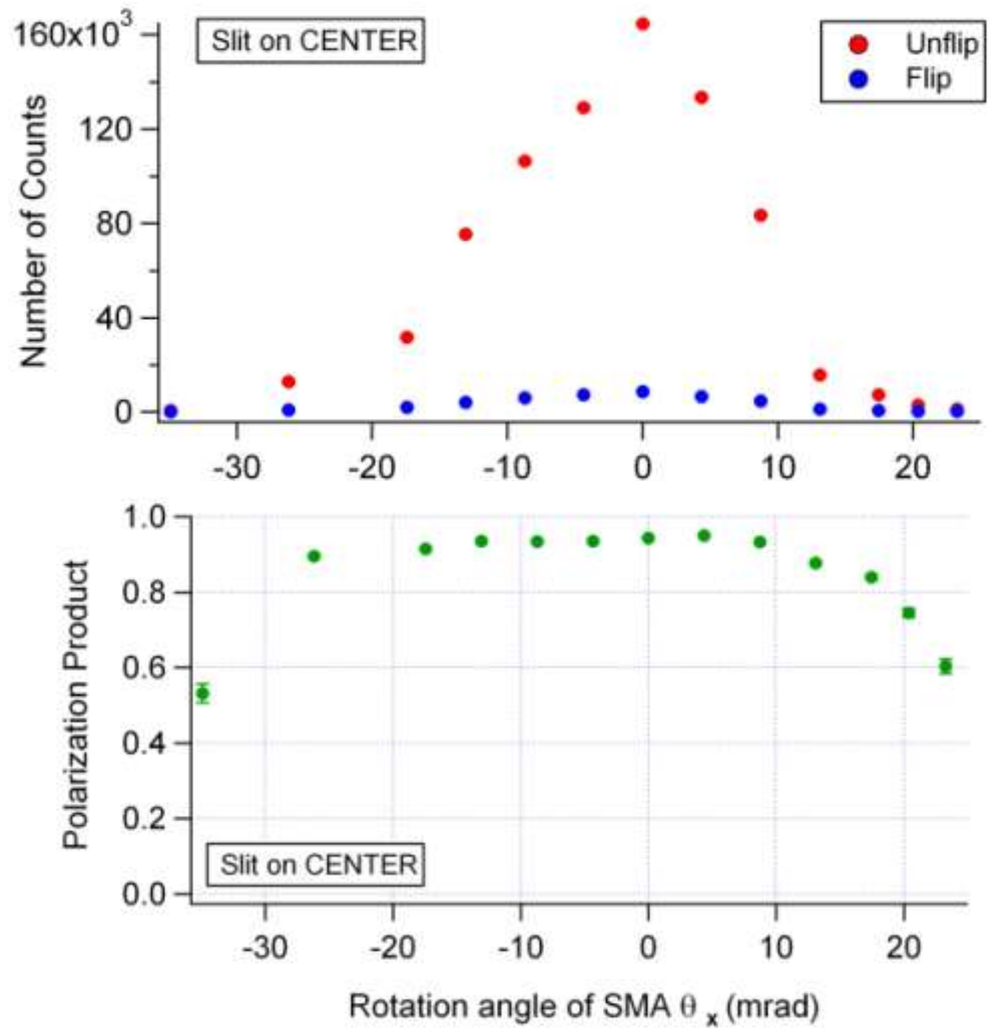


PA as a function of angle



For 5mm slit in the
CENTRAL position

PA does not change with angle



Small Angle Scattering in liquid ^{4}He

- cross section ~ Dynamic structure factor $S(q,\omega)$

$$\frac{d^2\sigma}{dE d\Omega} = b^2 \frac{k}{k_o} S(q,\omega)$$

- for q<0.1 (1/Å), $S(q,\omega)$ found from hydrodynamic properties of liquid
- Measured $\sigma(E)$ used to determine if scattering takes place

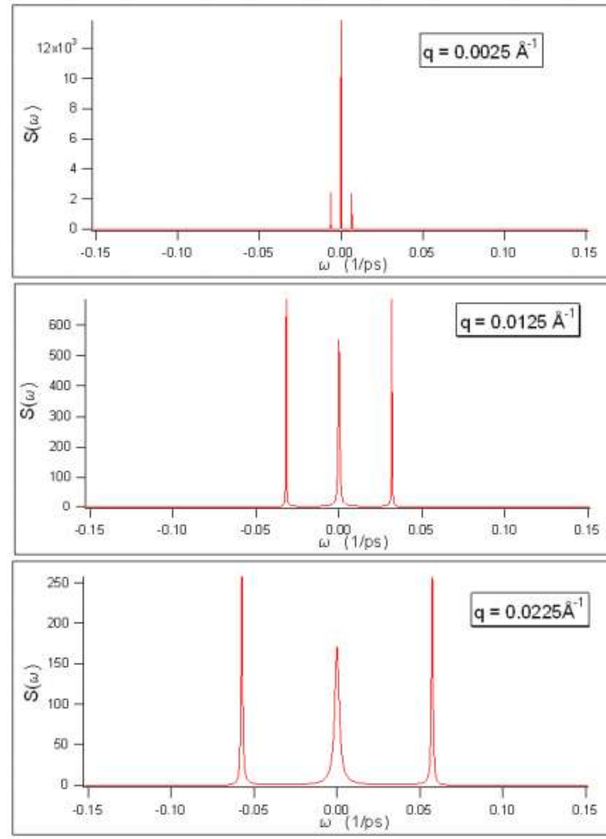
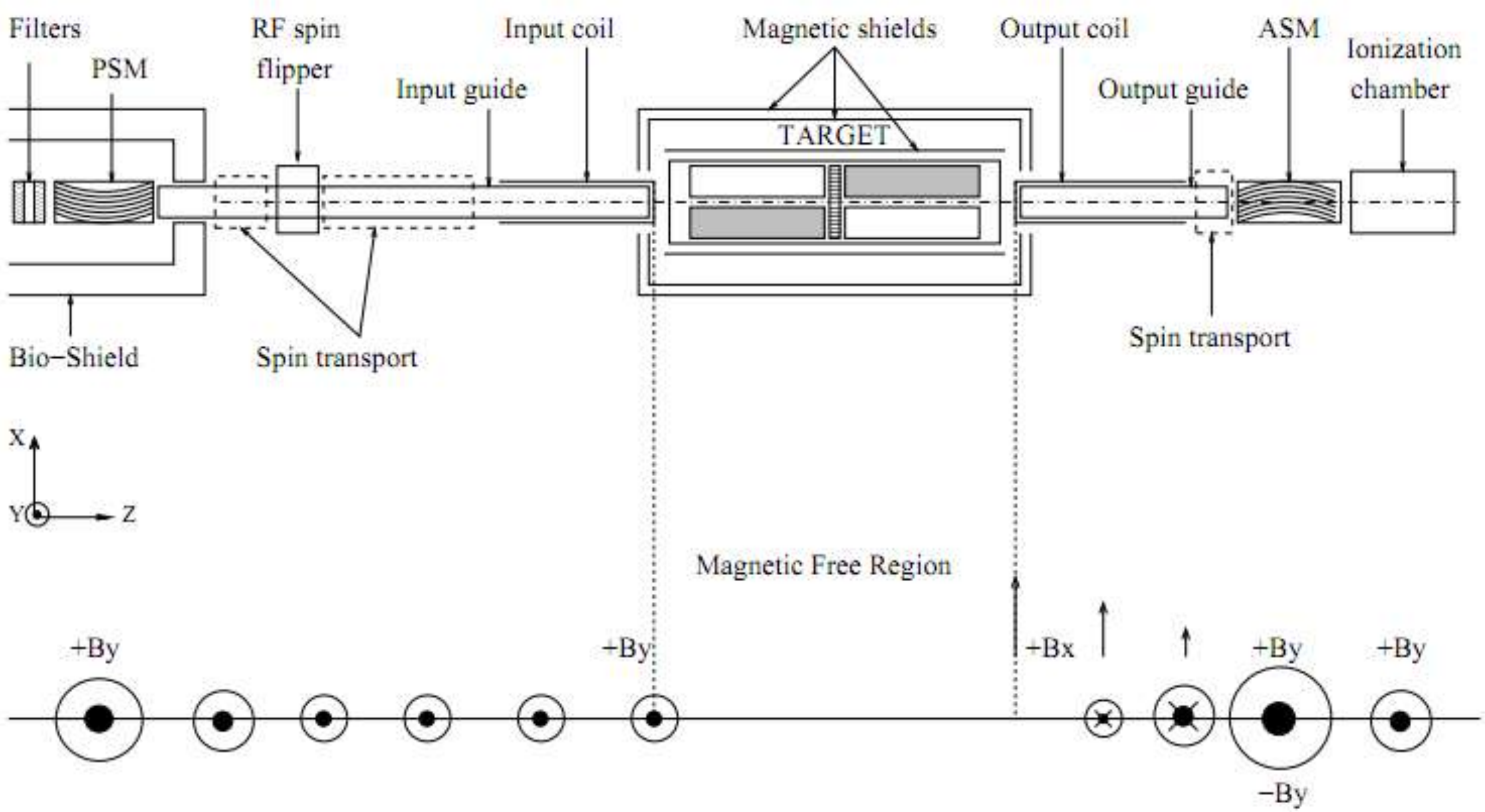
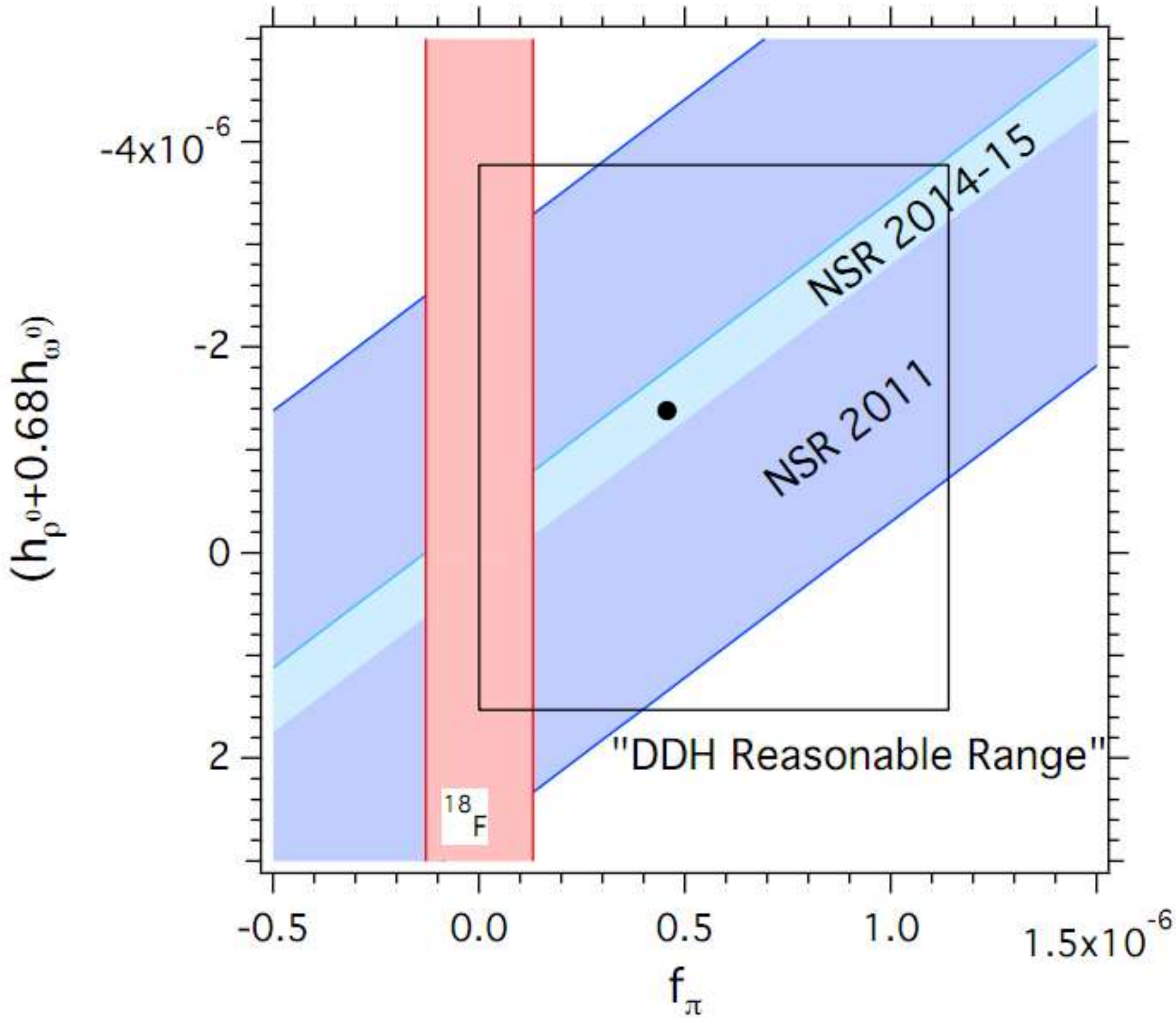


FIG. 11: $S(\omega)$ plots at various q values.

- Central peak from quasi-elastic scattering from diffusive motion of liquid
- side peaks from single phonon scattering


Filters
PSM
RF spin
flipper
Input guide
Input coil
Magnetic shields
TARGET
Output coil
Output guide
ASM
Ionization
chamber
Bio−Shield
Spin transport
Spin transport
X
Y
Z
Magnetic Free Region
+By
+By
+Bx
+By
+By
−By



-4x10^-6
-2
0
2
(h_ρ^0+0.68h_ω^0)
-0.5
0.0
0.5
1.0
1.5x10^-6
f_π
NSR 2014-15
NSR 2011
"DDH Reasonable Range"
18F

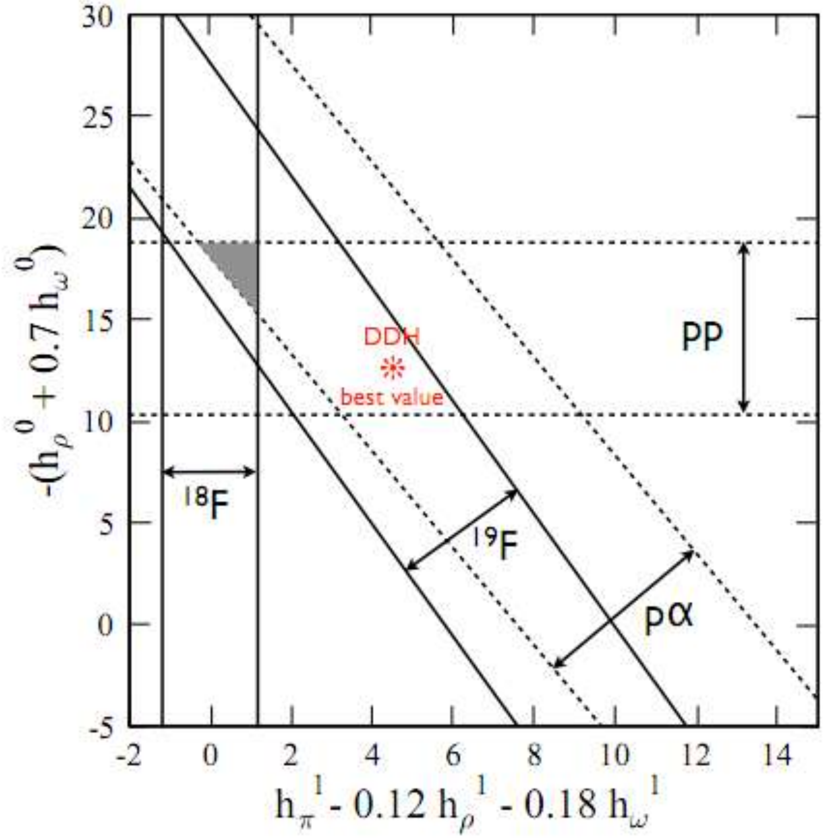
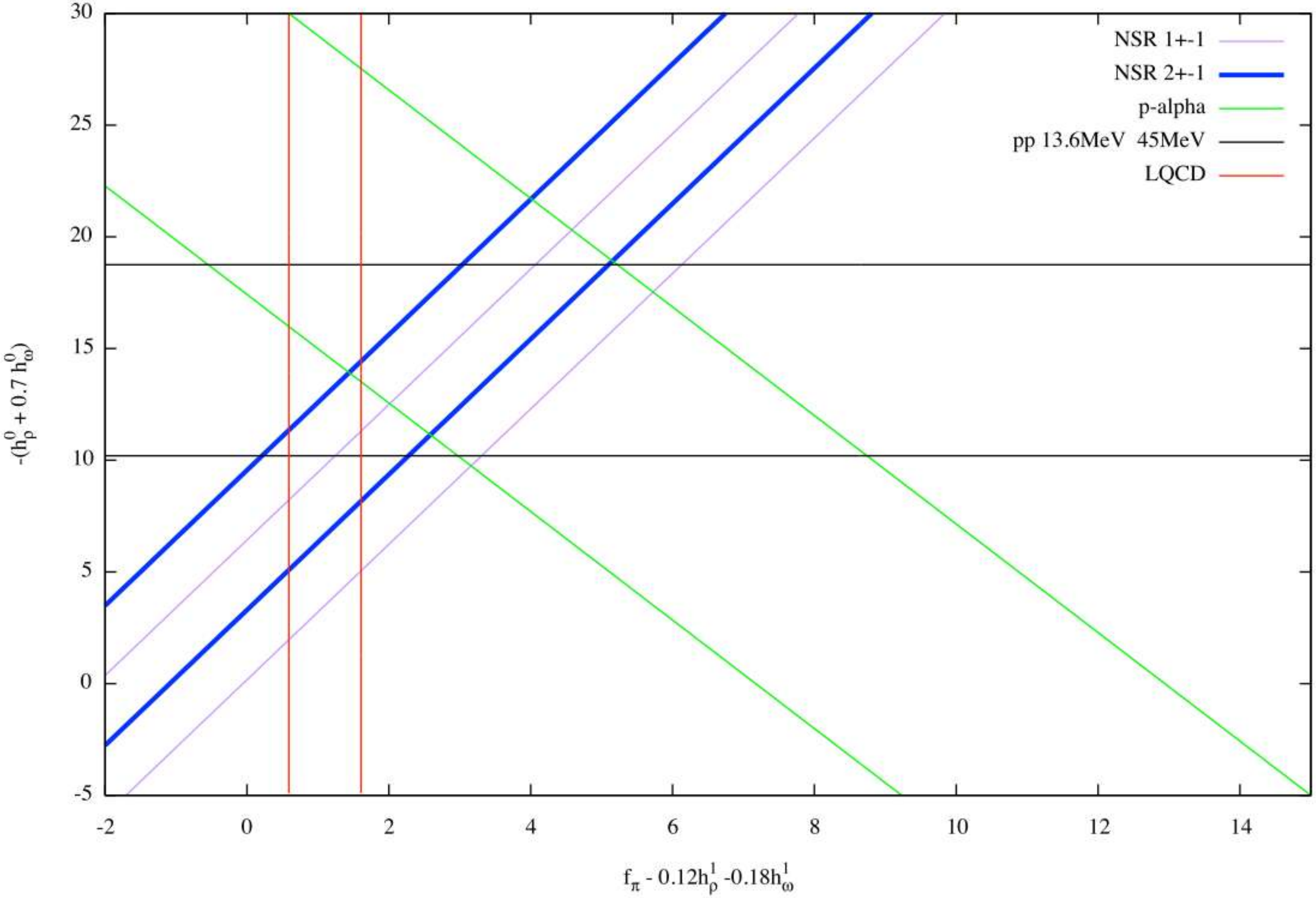


Figure 1: Experimental constraints on linear combinations of isoscalar and isovector DDH couplings (in units of 10^{-7}), taken from the 2001 work of [37], displaying bounds from four experiments where it is believed that theoretical analysis uncertainties are under reasonable control: pp, pα, ^{18}F, and ^{19}F. The small shaded triangle is consistent with all four experiments. The DDH best value point is also shown. Later we show that the data on $\vec{p}+p$ subsequently obtained at TRIUMF [13] and the analysis of Ref. [54] have a significant impact on this plot.

Haxton and Holstein, arXiv:1303.4132v2 [nucl-th] 21 Mar 2013



NSR 1+-1
NSR 2+-1
p-alpha
pp 13.6MeV 45MeV
LQCD
30
25
20
15
10
5
0
-5
-2
0
2
4
6
8
10
12
14
$-(h_\rho^0 + 0.7\, h_\omega^0)$
f_π - $0.12h_\rho^1$ -$0.18h_\omega^1$