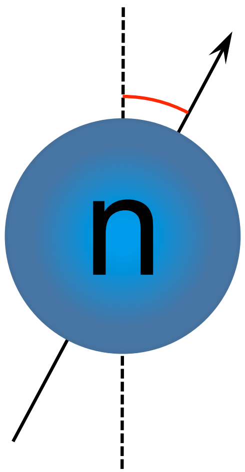
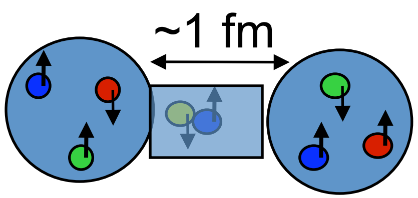
PNC Polarized Neutron Spin Rotation in Liquid Helium

for the NSR Collaboration



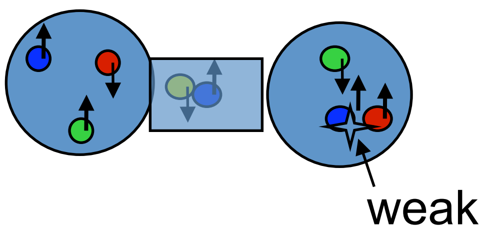
J. Nico, NIST
Hadronic Parity Nonconservation Workshop
KITP, UC - Santa Barbara
March 15-16, 2018

Nucleon-Nucleon Weak Interaction



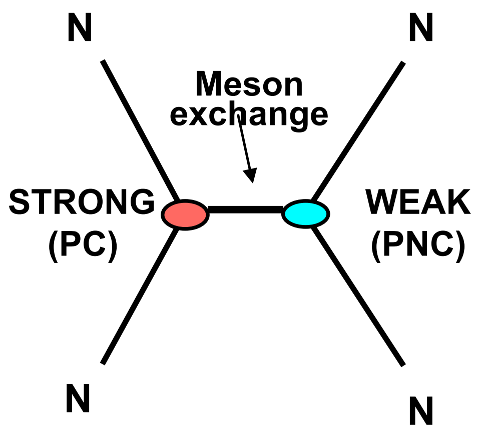
• NN repulsive core -> 1 fm range for the strong force.

• QCD has vector quark-gluon couplings that conserve parity (PC).



• Weak interaction has a much smaller range (~1/100 fm).

• Weak interaction violates parity (PNC).



Use parity violation to isolate the weak force contribution to the NN interaction.

$$\left(\frac{e^2}{M_W^2}\right) / \left(\frac{g^2}{M_\pi^2}\right) \sim 10^{-6}$$

Hadronic Weak Interaction

➢ The weak interaction among quarks is a fundamental part of the Standard Model, but the hadronic weak interaction (HWI) between nucleons remains one of the most poorly-understood areas.

➢ It has proven difficult both experimentally and theoretically to test the fundamental nucleon-nucleon weak interaction. The problem is the non-perturbative nature of QCD at low energies.

➢ Heavy nuclei have large parity non-conserving (PNC) asymmetries, but the dynamics are complicated and the interpretation depends on nuclear models. One must investigate PNC effects in light nuclei.

More recently...

➢ Much recent theoretical activity in pionless EFT and large N_{c}.

➢ One can carry out measurements and calculations in few body systems (npdg, n-^{3}He, p-^{4}He, and n-^{4}He).

➢ Advances in experimental techniques and facilities make possible measurement of small asymmetries in few-body systems.

$\bar{n}$ + ^{4}He Spin Rotation: Theoretical Expectations

Existing calculations:

➢ DDH "reasonable range"

$$\phi_{PNC}(\bar{n},{}^4\mathrm{He}) \sim 1 \times 10^{-6} \mathrm{rad/m}$$

Desplanques, Donoghue, and Holstein, *Ann., Phys.* **124**, 449 (1980)

➢ Dmitriev et al. calculation

$$\begin{aligned}\phi_{PNC} &= -(0.97 f_\pi + 0.22 h_\omega^0 - 0.22 h_\omega^1 + 0.32 h_\rho^0 - 0.11 h_\rho^1)\,\mathrm{rad/m} \\ &= (0.1 \pm 1.5) \times 10^{-6}\,\mathrm{rad/m}\end{aligned}$$

Dmitriev et al., *Phys. Lett.* **125**, 1 (1983)

➢ Nuclear PNC phenomenology

$$\phi_{PNC}(\bar{n},{}^4\mathrm{He}) = (6 \pm 2) \times 10^{-7} \mathrm{rad/m}$$

Desplanques, *Phys. Rep.* **297**, 1 (1998)

➢ EFT calculation

$$\phi_{PNC}(\bar{n},{}^4\mathrm{He}) = (0.85 \lambda_s^{nn} - 0.43 \lambda_s^{np} + 0.95 \lambda_t - 1.89 \rho_t)\,\mathrm{rad/m}$$

Zhu et al., *Nucl. Phys. A* **748**, 435 (2005)

New Theoretical Directions

➢ System is simple enough that P-odd spin rotation can be related to weak NN amplitudes. GFMC is possible (*Carlson, Wiringa, Nollett, Schiavilla, Pieper,...*)

➢ Pionless EFT (Grießhammer, Schindler, Springer, Vanasse…Phillips, Samart, Schat….)

S. Gardner, W.C. Haxton, B.R. Holstein, arXiv:1704.02617v1 (2017)

Observable	Exp. Status	LO Expectation	LO LEC Dependence
$A_p(\vec{n} + {}^3\mathrm{He} \to {}^3\mathrm{H}+\mathrm{p})$	ongoing	-1.8×10^{-8}	$-\Lambda_0^+ + 0.227\Lambda_2^{{}^1S_0-{}^3P_0}$
$A_\gamma(\vec{n} + \mathrm{d} \to \mathrm{t} + \gamma)$	8×10^{-6} (see text) [58]	7.3×10^{-7}	$\Lambda_0^+ + 0.44\Lambda_2^{{}^1S_0-{}^3P_0}$
$P_\gamma(\mathrm{n} + \mathrm{p} \to \mathrm{d} + \gamma)$	$(1.8 \pm 1.8) \times 10^{-7}$ [57]	1.4×10^{-7}	$\Lambda_0^+ + 1.27\Lambda_2^{{}^1S_0-{}^3P_0}$
$\frac{d\phi^n}{dz}\big\vert_{\mathrm{parahydrogen}}$	none	9.4×10^{-7} rad/m	$\Lambda_0^+ + 2.7\Lambda_2^{{}^1S_0-{}^3P_0}$
$\frac{d\phi^n}{dz}\big\vert_{{}^4\mathrm{He}}$	$(1.7 \pm 9.1 \pm 1.4) \times 10^{-7}$ [56]	6.8×10^{-7} rad/m	Λ_0^+
$A_L(\vec{p} + \mathrm{d})$	$(-3.5 \pm 8.5) \times 10^{-8}$ [43]	-4.6×10^{-8}	$-\Lambda_0^+$

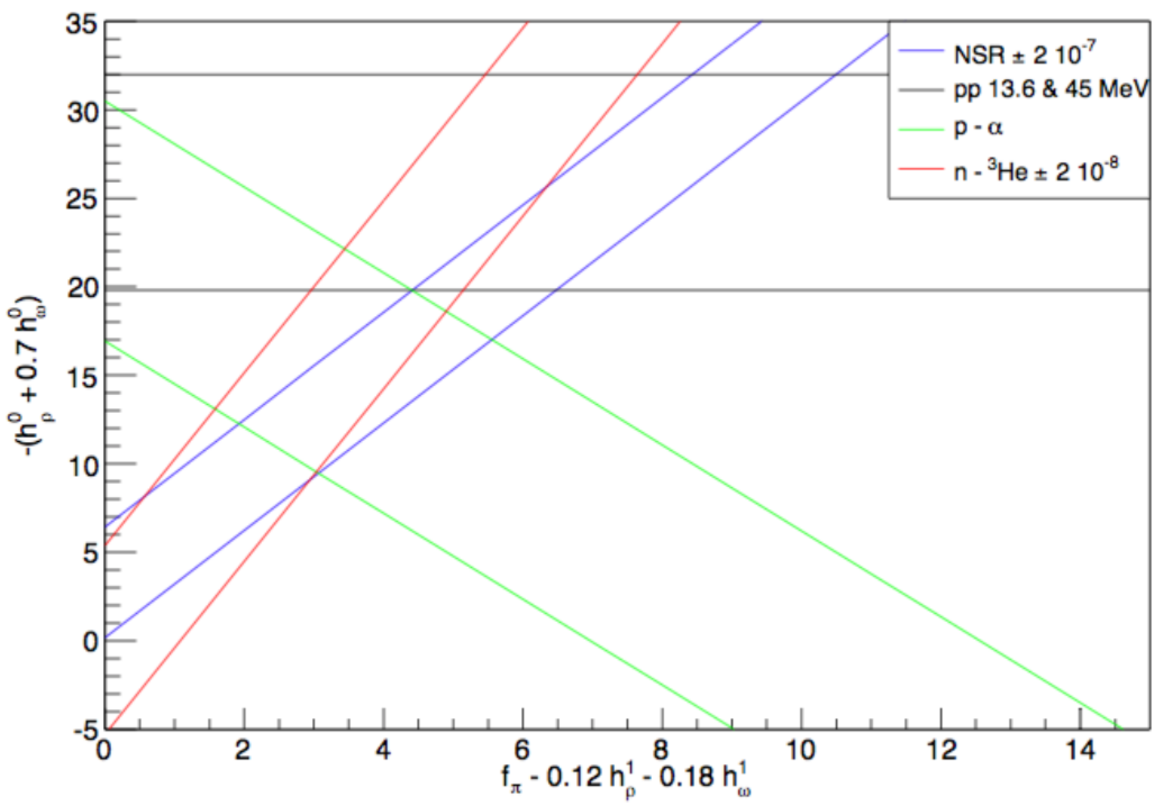
➢ No dependence on the isotensor component, making it distinct from other observables.

➢ Dependence only on LO LEC (Λ_0) with a relatively large expectation, makes it accessible to spin rotation with several sigma significance.

Why $\overline{n}$- ^{4}He Spin Rotation?

➢ Linear combination of NN weak amplitudes in n-^{4}He spin rotation is roughly orthogonal to existing constraints from past measurements with protons (p-^{4}He) and anapole moments. Addition of n-^{4}He gives stronger constraints.

➢ n-^{4}He and n-^{3}He both measure approximately the same linear combination of weak amplitudes, providing a strong check. However, there is no dependence on the isotensor component in n-^{4}He, an important distinction between the two experiments.



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➢ n-^{4}He dependence on only the LO LEC has a relatively large expectation valve, within experimental spitting distance.

➢ An experiment on NG-C at NIST is feasible in the range of 1-2 x 10^{-7}, which could a measurement several sigma from prediction. This would be a quantitative test of the theory and a definitive observation of PNC in spin rotation.

➢ This experimental development has yielded an extremely sensitive neutron polarimeter. Forward scattering amplitude of neutron in matter is sensitive to all neutron-matter interactions.

PNC Observable in the $\overline{n}$ + ^{4}He System

➢ Cold neutrons (average wavelength 0.5 nm) traversing helium can be described by wave propagation in a medium with index of diffraction *n*, analogous to light.

$$n = 1 + \left(\frac{2\pi}{k^2}\right)\rho f(0)$$

➢ Express forward scattering in terms of parity-conserving (PC) and parity-violating (PNC) parts

$$f(0) = f_{PC} + f_{PNC}(\vec{\sigma} \cdot \vec{k})$$

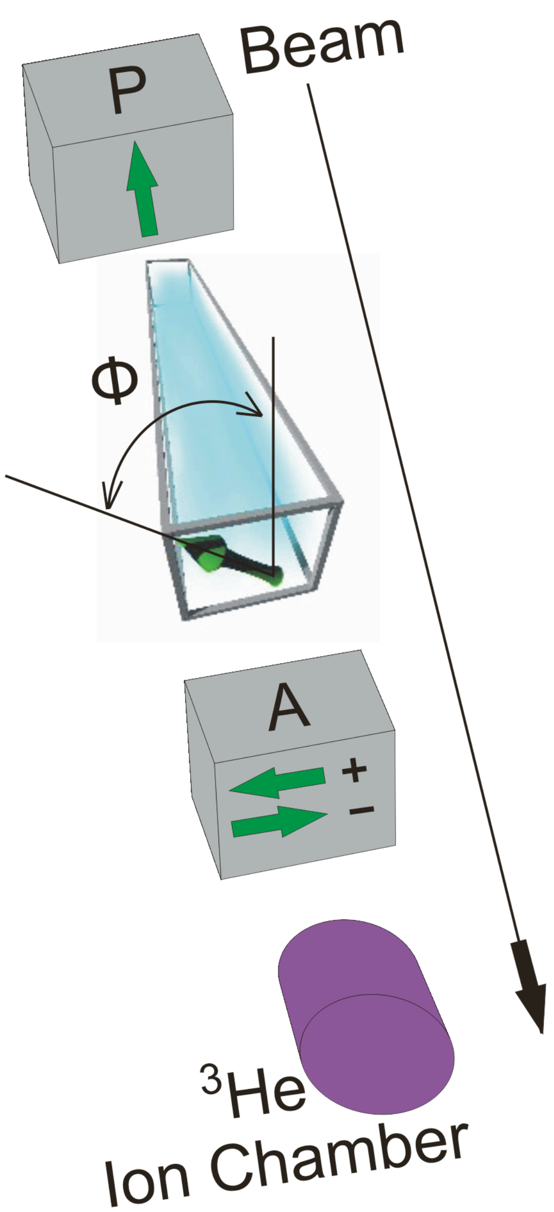
➢ As the neutron propagates along the z-axis, it accumulates a phase

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

➢ In the helicity basis, the accumulated phase of the two states are different

$$\phi_{\pm} = \phi_{PC} \pm \phi_{PNC} \qquad \phi_{PNC} = 2\pi\rho z f_{PNC}$$

Measurement Principle



➢ It's a *very* small angle measurement $O(10^{-7})$ rad.

➢ Target is placed between a crossed (supermirror) polarizer-analyzer pair (analyzing power *PA*).

➢ Output field is rotated every second, and neutrons are counted in a ^{3}He ion chamber.

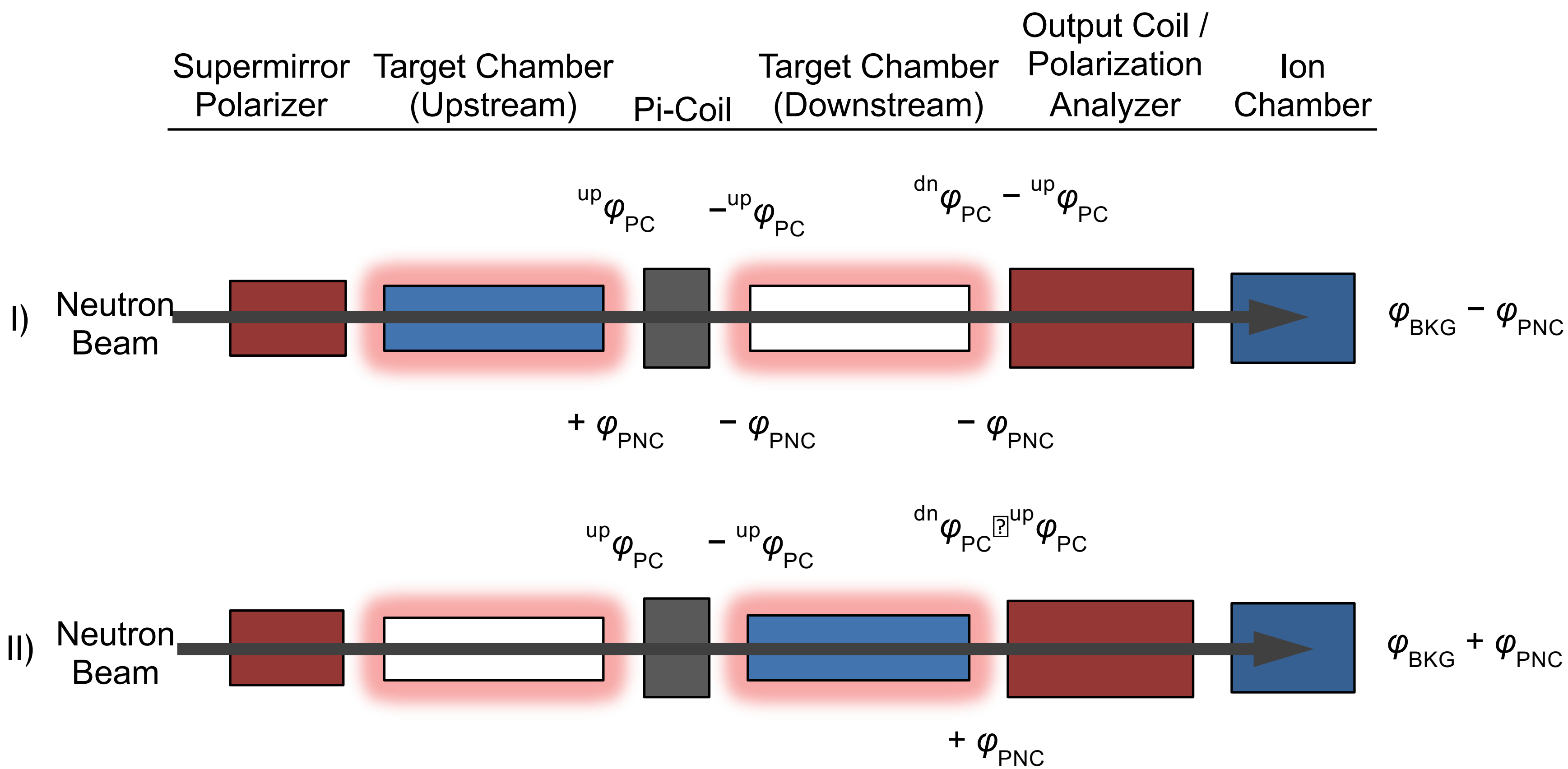
$$sin\phi = \frac{1}{PA}\frac{N_+ - N_-}{N_+ + N_-}$$

Two critical issues:

➢ Beam fluctuations exist at O(1%).

➢ Difficult to shield below 100 μG. Rotation angle from this field is about 3 orders of magnetic greater than ϕ_{PCN}.

Measurement Principle

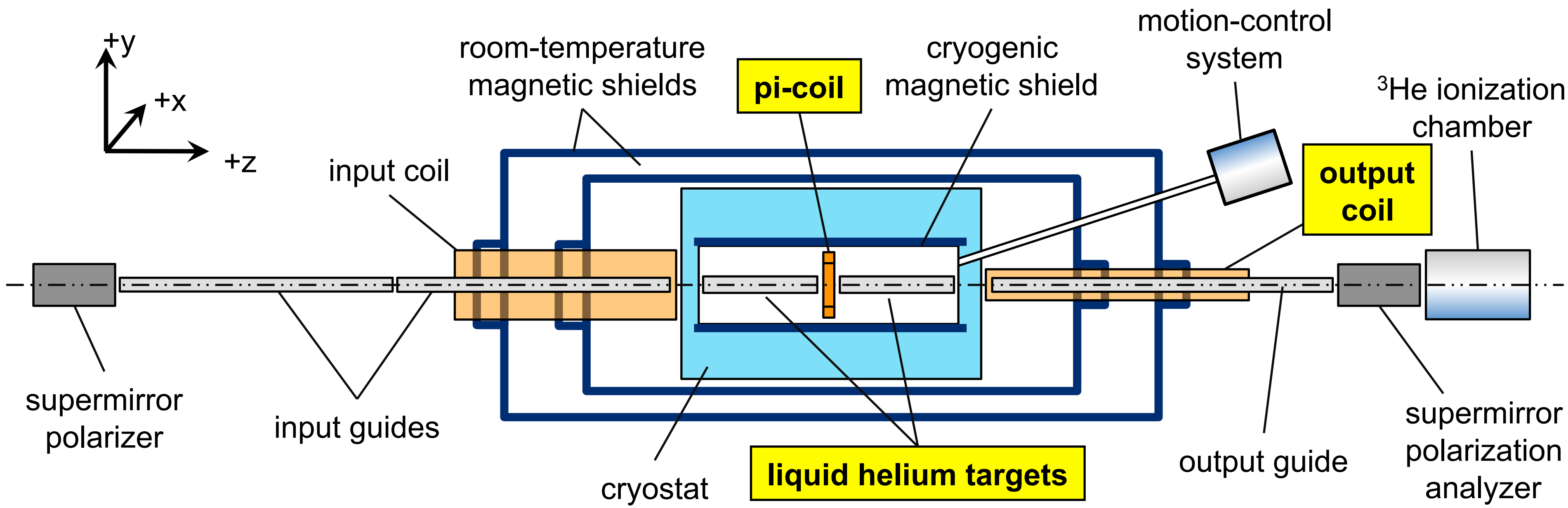


$$(N_I - N_{II})_{T1} - (N_I - N_{II})_{T2} = 4\,\varphi_{PNC}$$

if $\int_I \vec{B}\cdot\vec{d\ell} - \int_{II} \vec{B}\cdot\vec{d\ell}$ is stable during target motion

B. Heckel, *NBS SP* **711**, 90 (1986)

Spin Rotation Apparatus (Polarimeter)

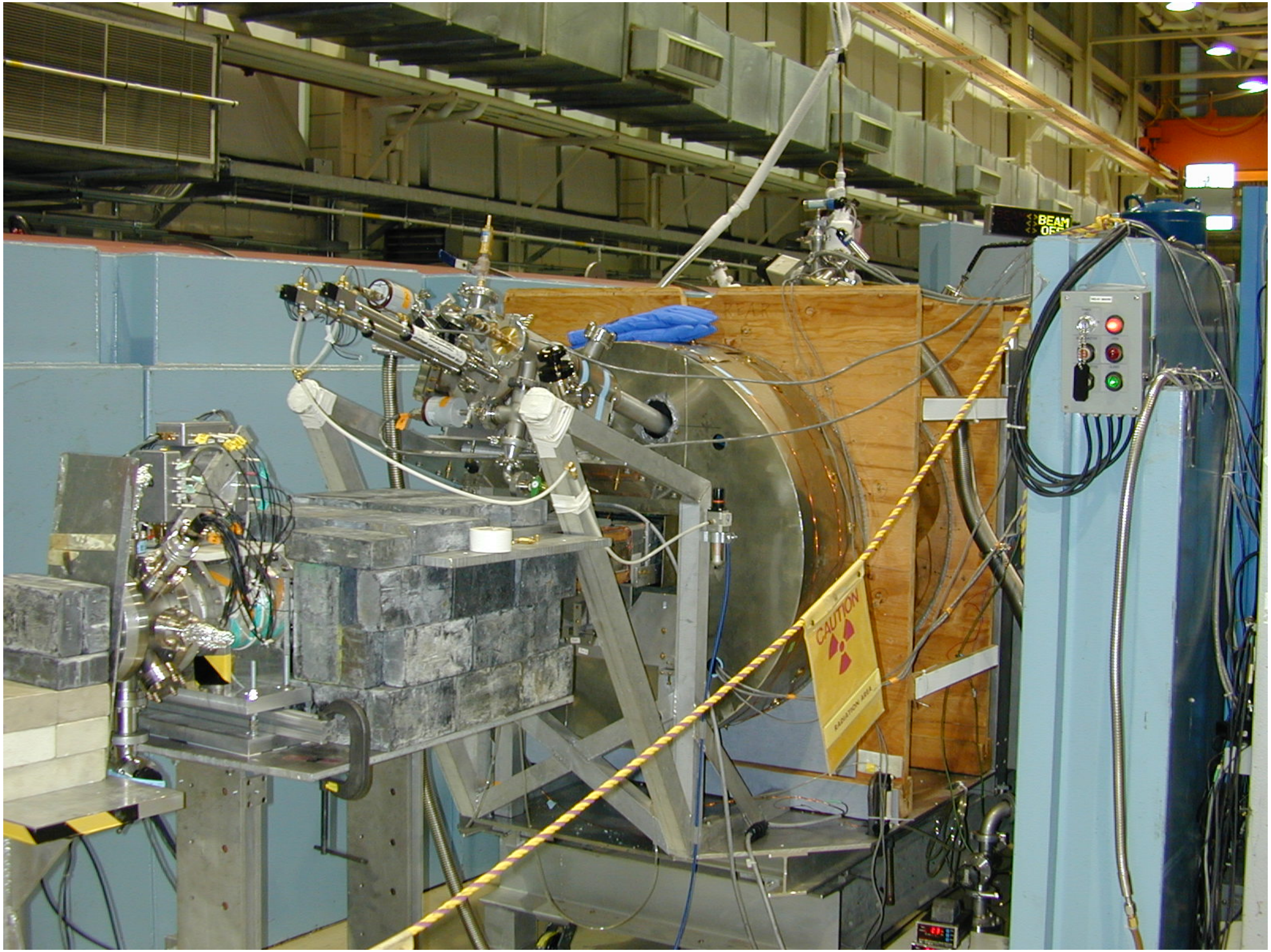


Measure the horizontal component of a vertically polarized neutron beam.

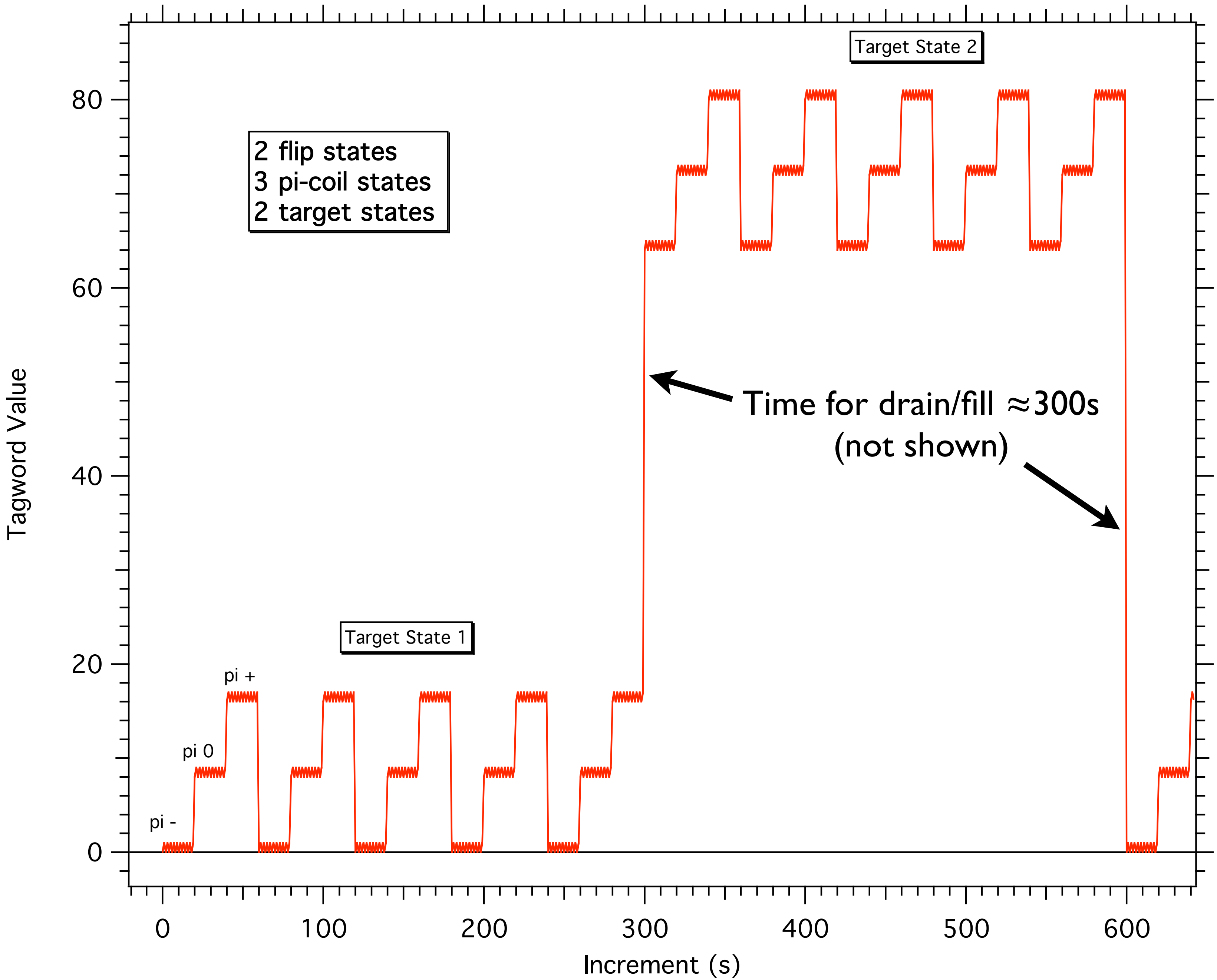
NSR-2 Apparatus on NG-6 Beamline at NIST

NIST Center for Neutron Research - 20 MW research reactor
Gaithersburg, MD campus

NSR-2 Apparatus on NG-6 Beamline at NIST



DAQ Control Sequence



Analysis

➢ Define an asymmetry:

$$A_P^T(D) = \frac{N^+(D,T,P) - N^-(D,T,P)}{N^+(D,T,P) + N^-(D,T,P)}$$

• D signifies a part of the detector (W for the west side and E for the east side).

• T is the target state, T0 or T1.

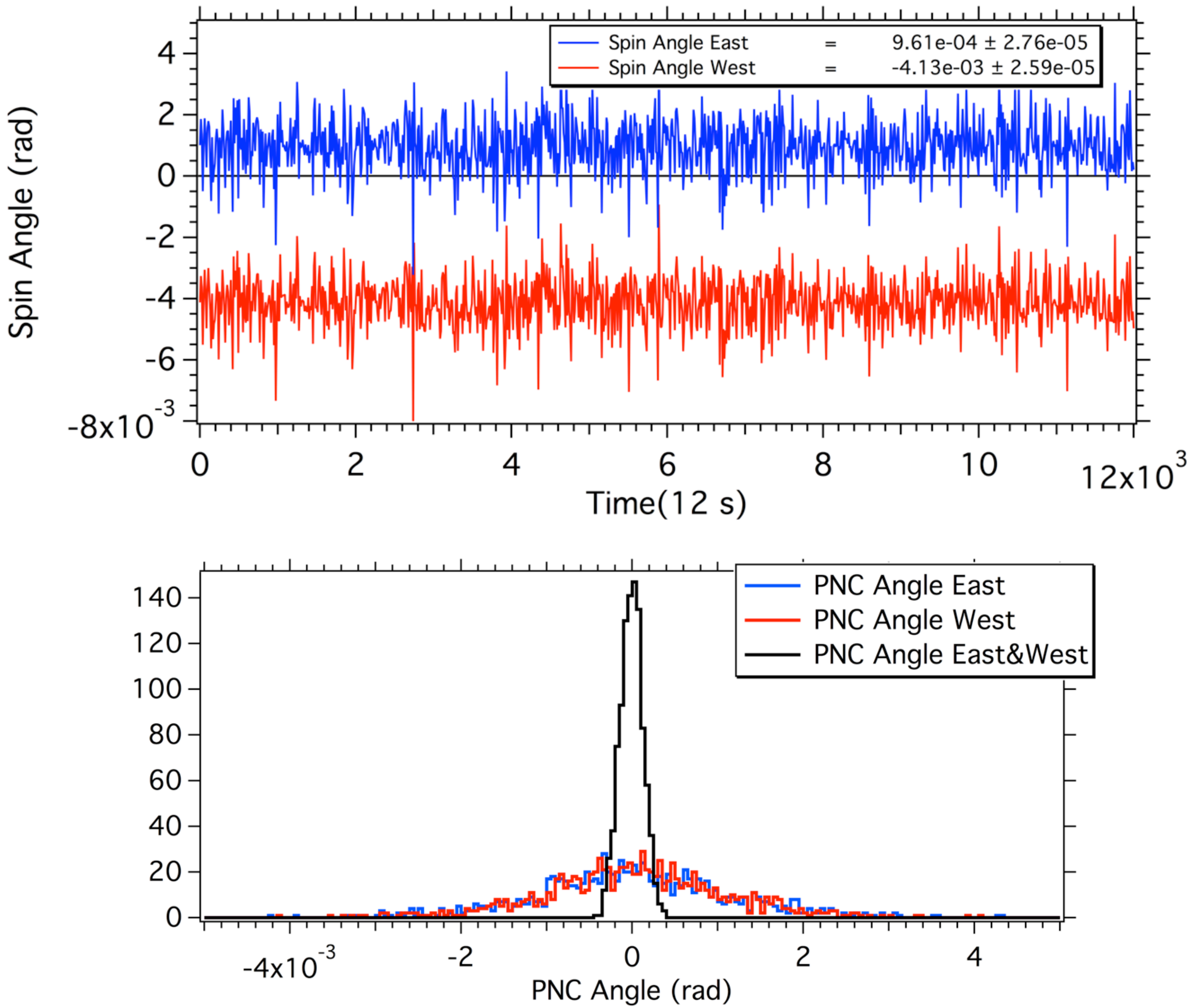
• P is the π-coil state P0, P1, or P2 (P1 is the off state).

➢ Define the rotation angles. For example:

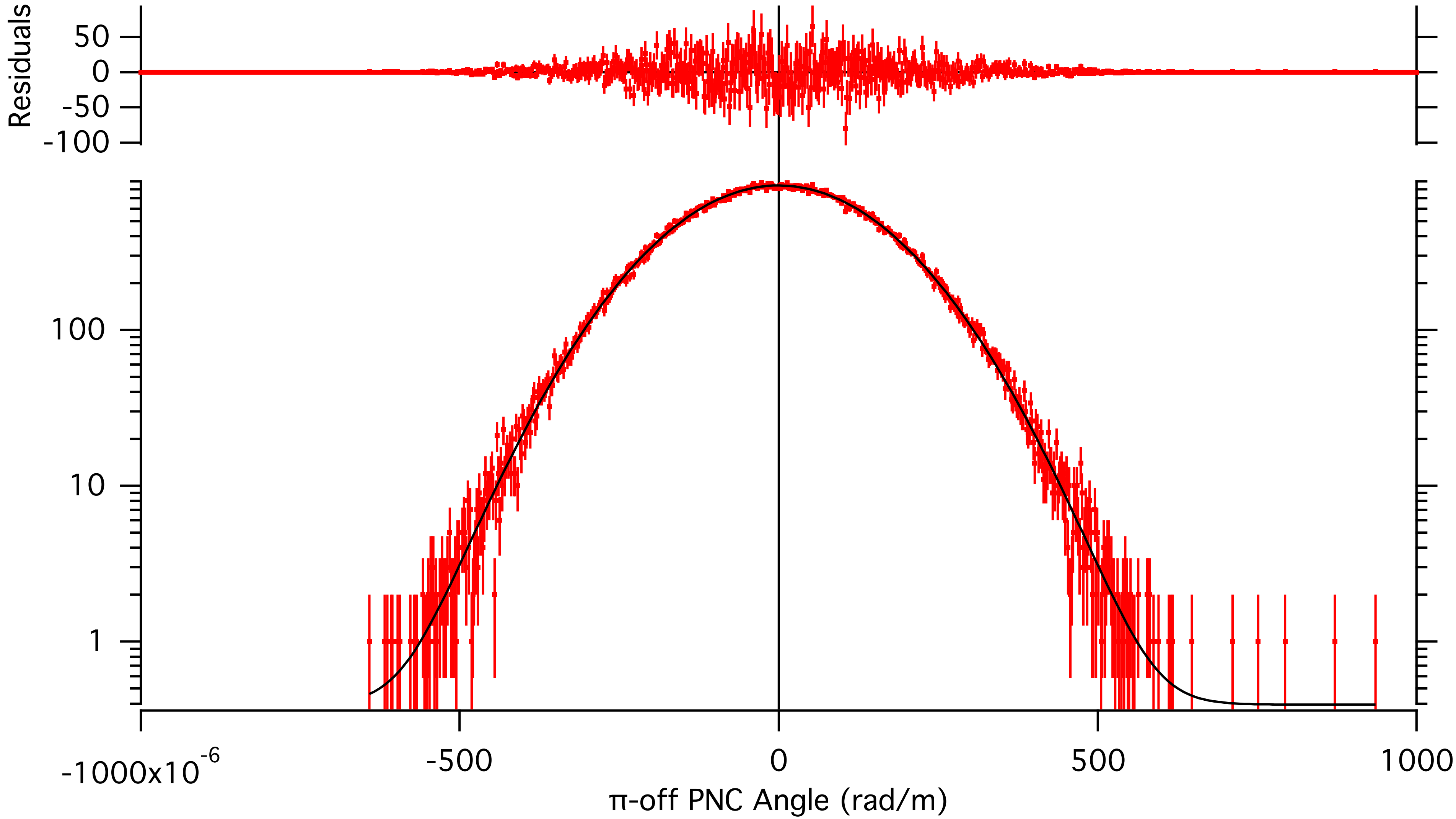
$$\text{Spin Angle} = \left(A_{P0}^{T0}(W) + A_{P0}^{T1}(W) + A_{P2}^{T0}(W) + A_{P2}^{T1}(W)\right)/4$$

$$\text{PNC Angle} = \left(A_{P0}^{T0}(W) - A_{P0}^{T1}(W) + A_{P2}^{T0}(W) - A_{P2}^{T1}(W)\right)/4$$

Common Mode Noise

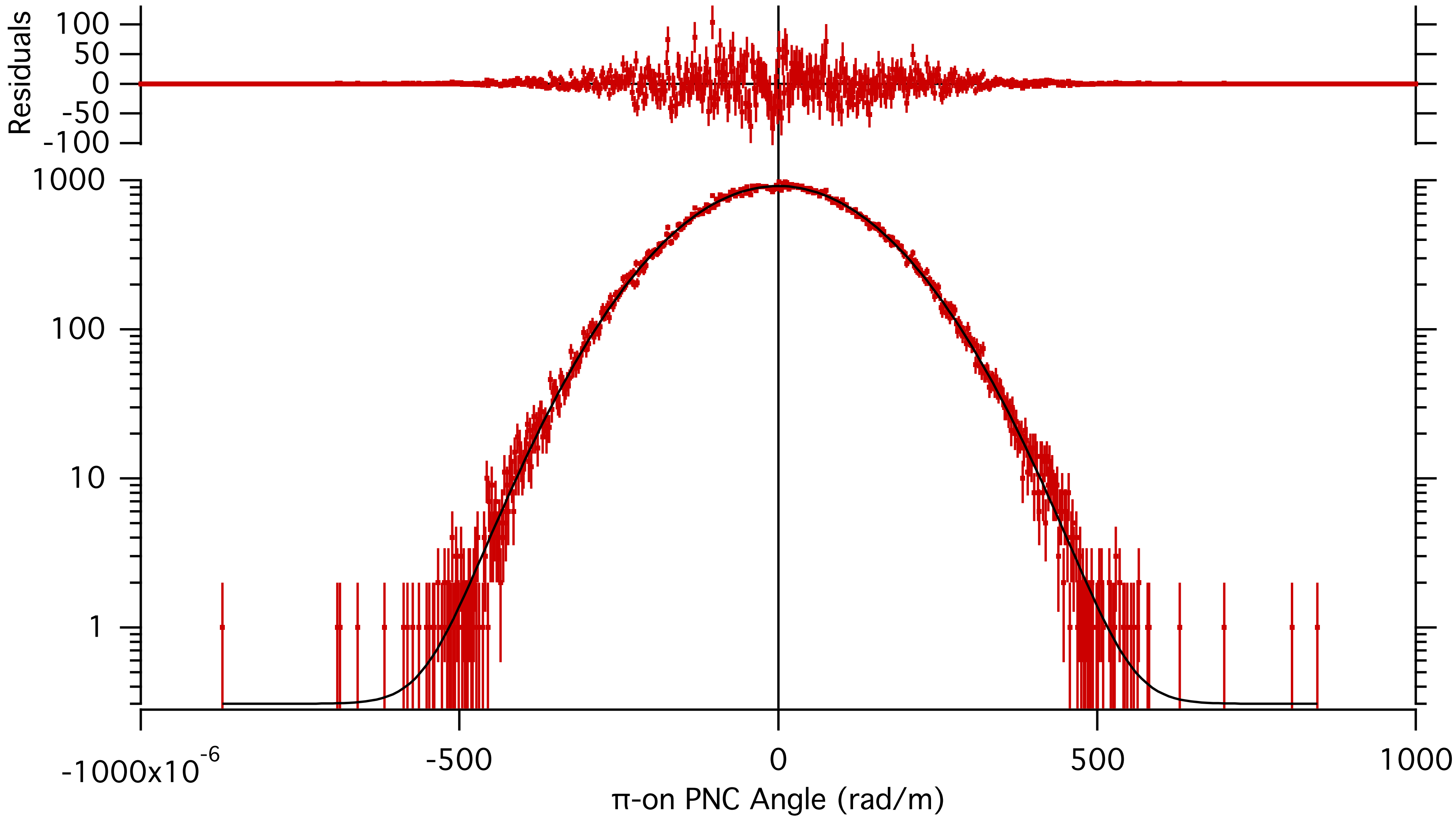


Results: π-coil Off

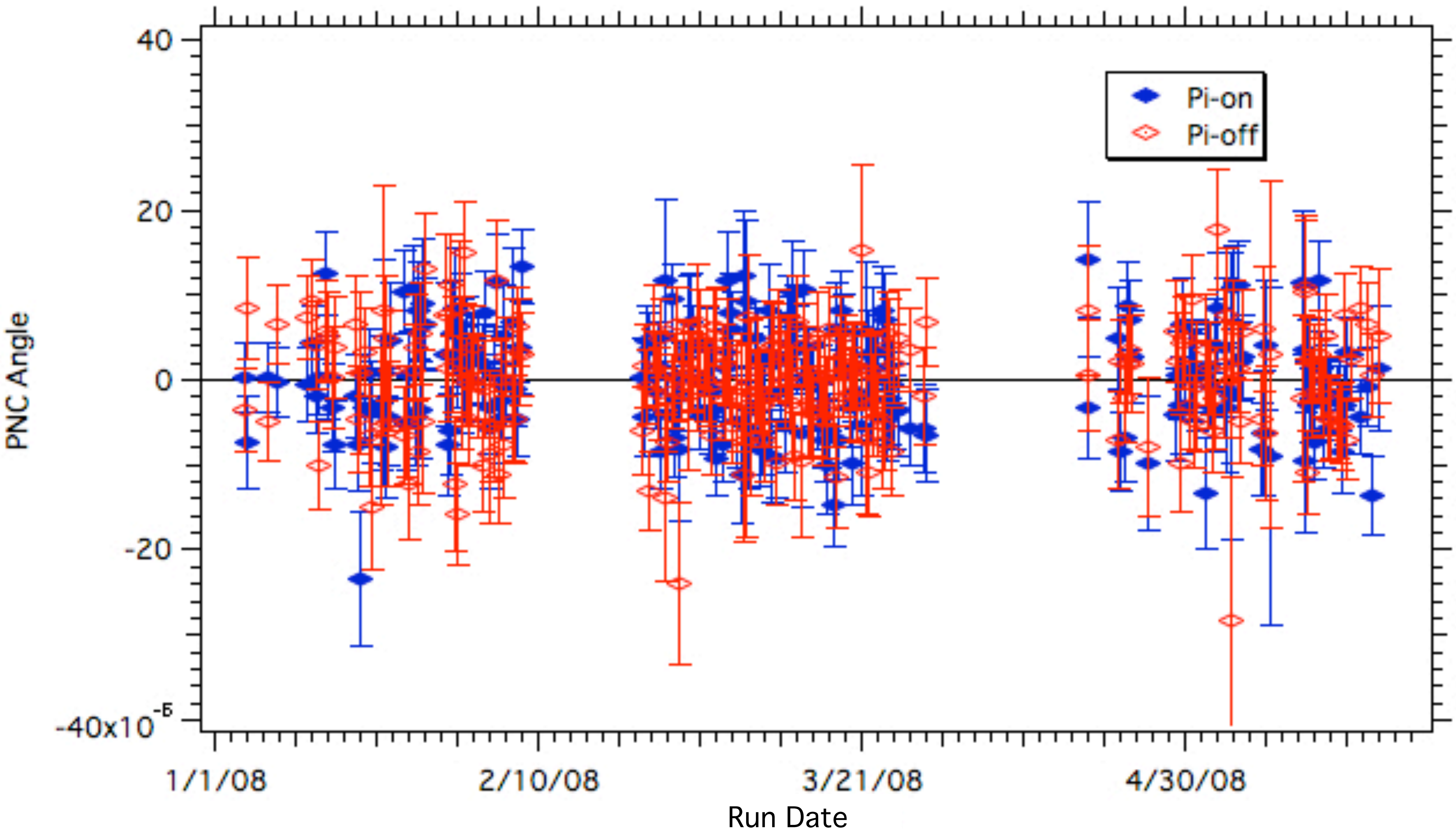


$$\phi_{PC} = (-1.2 \pm 10.0) \times 10^{-7} \mathrm{rad/m}$$

Results: π-coil On



Results: Run-by-Run



Systematics and Result

Table 1: A list of sources for potential systematic effects and estimates for the uncertainties. The values for the uncertainties originate from either a calculation or are the result of a direct measurement that places an upper bound on the effect.

Source	Uncertainty (rad/m)	Method
liquid ^{4}He diamagnetism:	2×10^{-9}	calc.
liquid ^{4}He optical potential:	3×10^{-9}	calc.
neutron E spectrum shift:	8×10^{-9}	calc.
neutron refraction/reflection:	3×10^{-10}	calc.
nonforward scattering:	2×10^{-8}	calc.
polarimeter nonuniformity:	1×10^{-8}	meas.
B amplification:	$< 4\times10^{-8}$	meas.
B gradient amplification:	$< 3\times10^{-8}$	meas.
PA/target nonuniformity:	$< 6\times10^{-8}$	meas.
Total (from measurements)	1.4×10^{-7}	

$$\frac{d\phi_{PNC}}{dz} = [+1.7 \pm 9.1(stat) \pm 1.4(sys)] \times 10^{-7}\,\mathrm{rad/m}$$

Neutron Spin Rotation (NSR-2) Collaboration

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NSF PHY-0100348
NSF PHY-0457219

THE GEORGE WASHINGTON UNIVERSITY WASHINGTON DC

Gettysburg COLLEGE

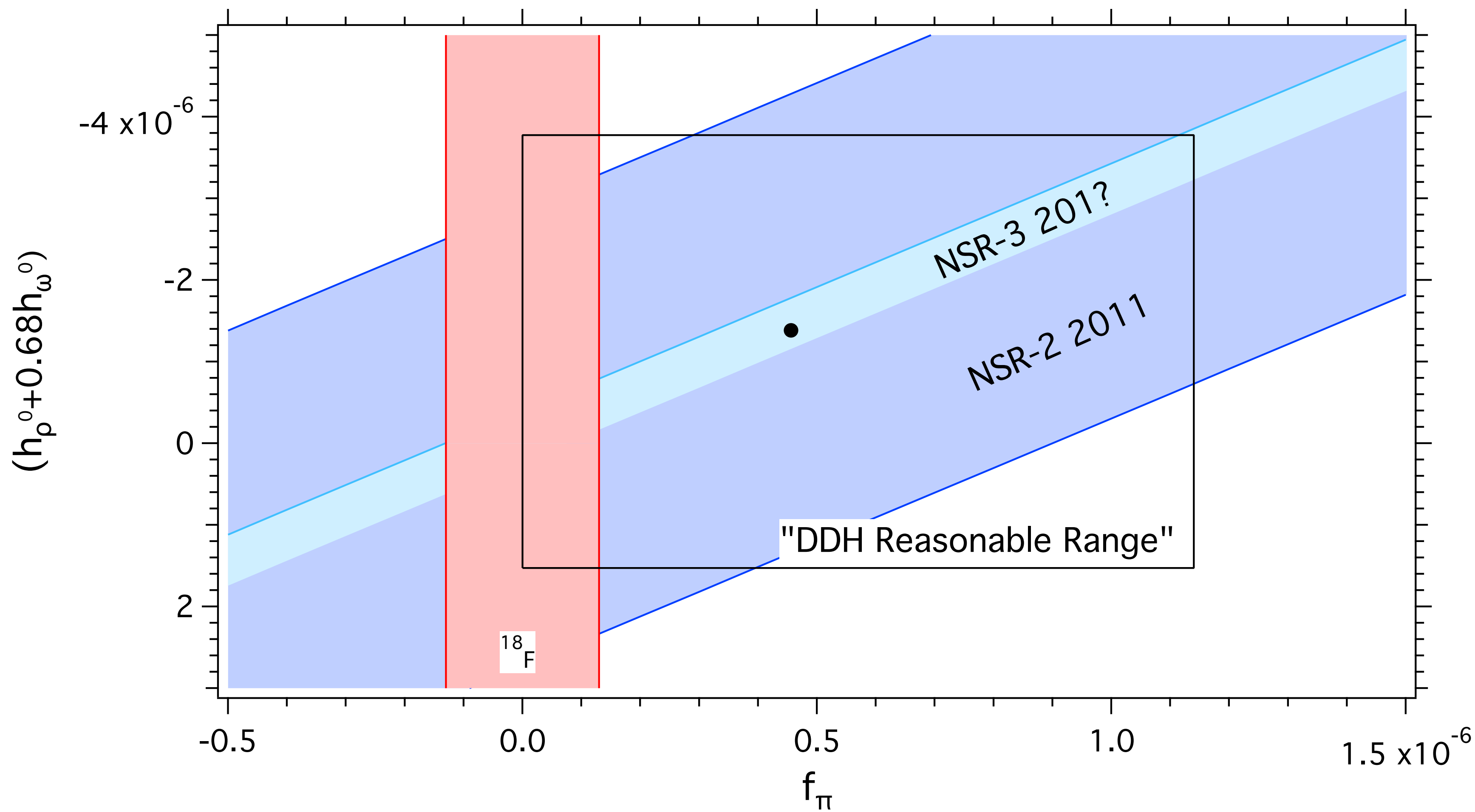
NIST
United States Department of Commerce
National Institute of Standards and Technology

NORTH CAROLINA CENTRAL UNIVERSITY FOUNDED 1910

U.S. DEPARTMENT OF ENERGY

NSR-2 Result

➢ No observation of PNC rotation, but the result limits the range of theoretical/phenomenological predictions.



Toward an improved NSR-3 measurement

Goal: $\frac{d\phi_{PNC}}{dz} \leq 2 \times 10^{-7}\,\mathrm{rad/m}$

Statistical Improvement

- Counting statistics → Expect x40 more polarized neutron flux through apparatus from
  1) NIST NCNR expansion and NG-C
  2) Increasing apparatus acceptance

- Low duty factor →
  1) Reduce heat load
  2) Reduce fill/drain times

Systematic Improvement

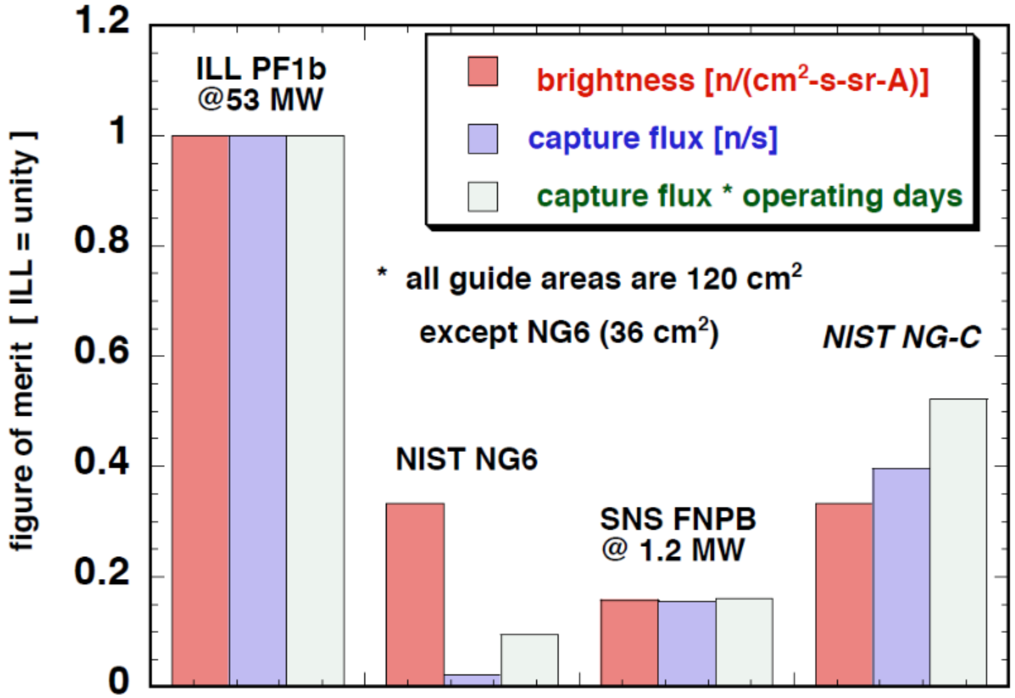
- Reduce B field in target region →
  1) Goal of 10 μG using additional passive shielding and active trimming.

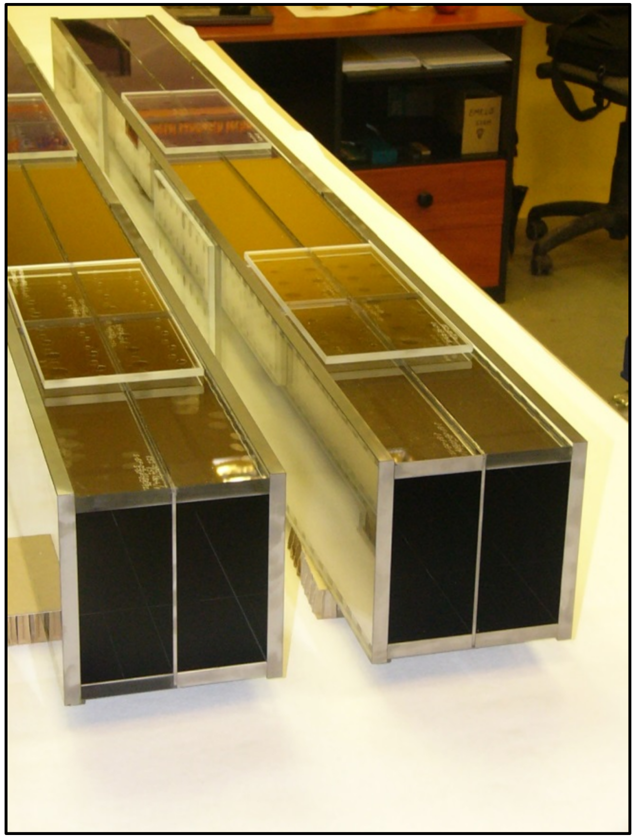
- Improve PA →
  1) Procure new supermirror polarizers with better reflectivity characteristics.
  2) Characterize east-west beams
  3) More frequent *PA* measurements

Statistics - more neutrons

NG-C: High-flux cold beam for fundamental neutron physics experiments at NIST.

- Ballistic guide; 11 cm x 11 cm at output
- Curved guide (no line-of-sight to reactor)
- Thermal capture fluence rate ≈ $8x10^9/cm^2/s$

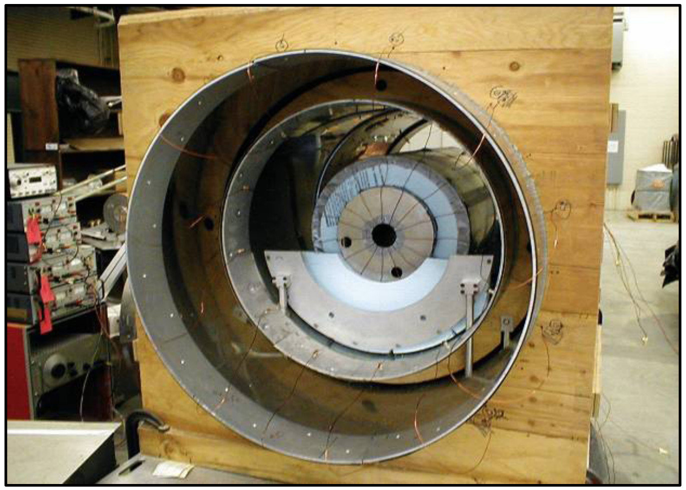




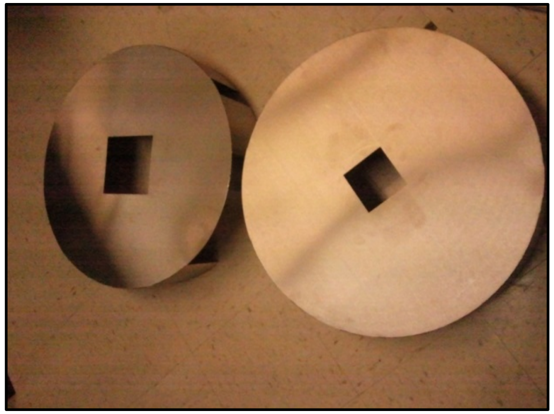
Supermirror guides:

- 10 cm x 10 cm input and output guides
- m = 2, better match with NG-C phase space

Magnetic field - Improve shielding



Three mu-metal shields
(one inside vacuum canister, two outside)

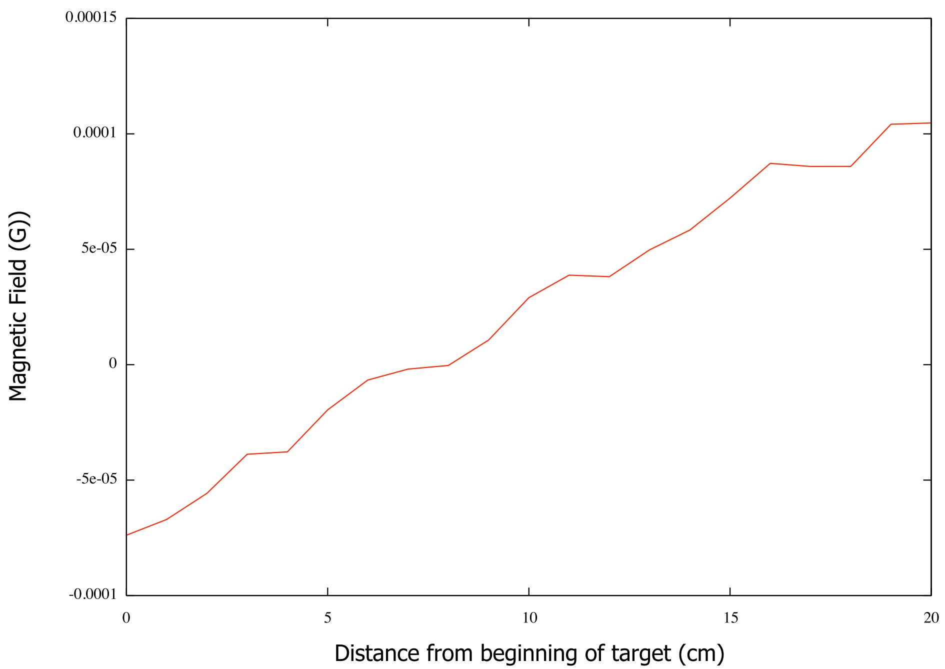


Endcaps for innermost shield

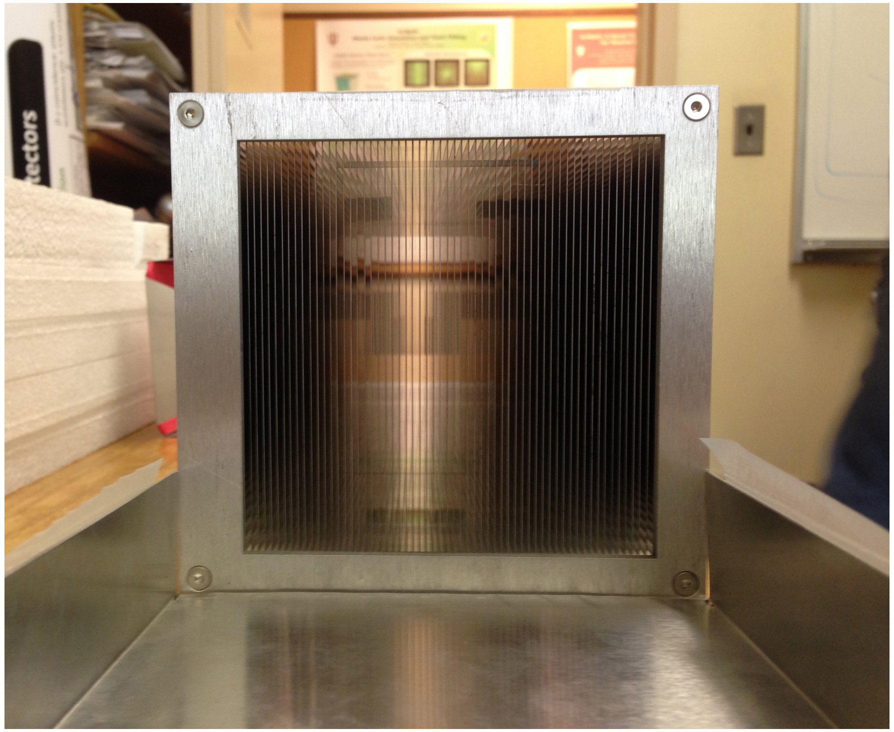
Improve passive and active shielding

- Degaussing capability
- Internal magnetometry
- Trim coils
- Active cancelation field

Demonstrate B-field suppression to < 10μG in the target region, x10 improvement over NSR-2

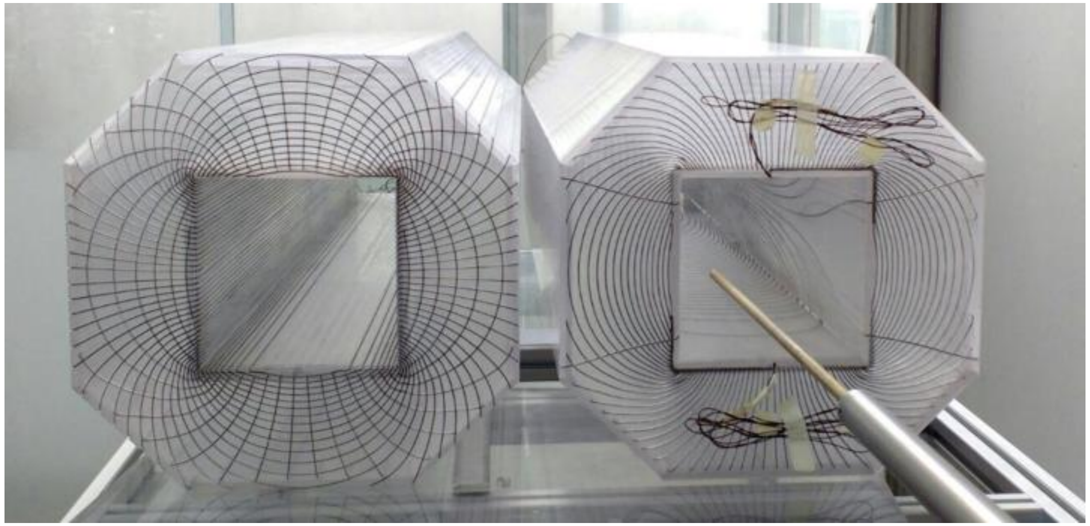


Polarization Product PA



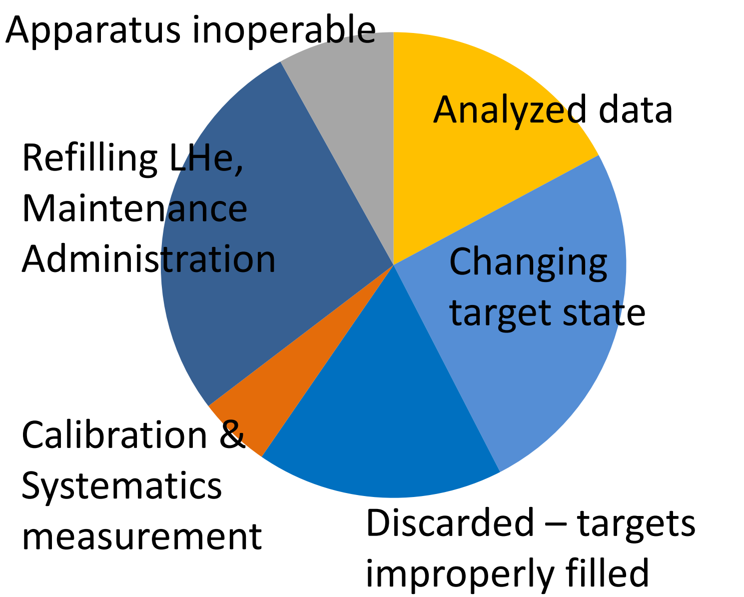
Supermirror polarizer/analyzer pair:
- Two new 10 cm x 10 cm polarizers
- m = 2.5; polarization ≈ 90%
- Better uniformity

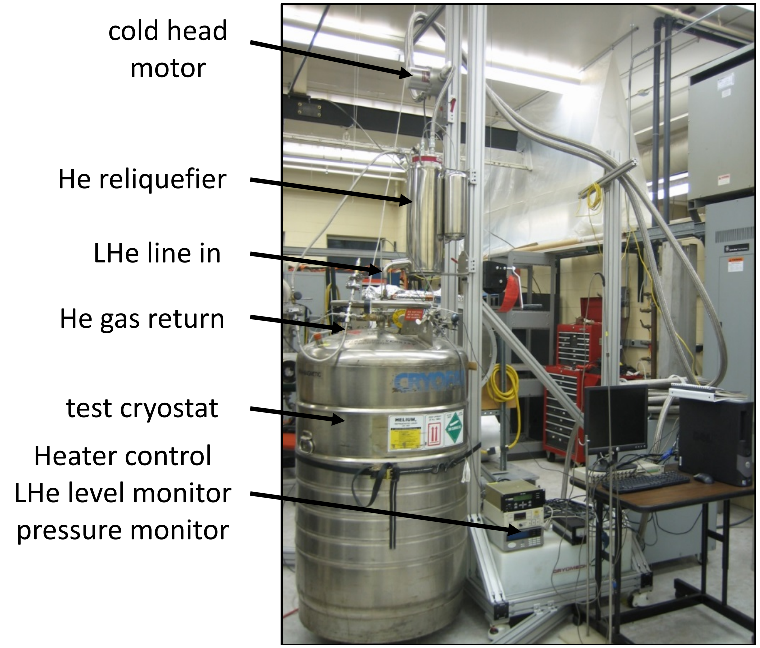
Input and Output Coils
- Accommodate larger guides
- Improved uniformity and efficiency of the spin transport



Duty Factor - Improve Cryogenics

120 NSR-II "Reactor On" days

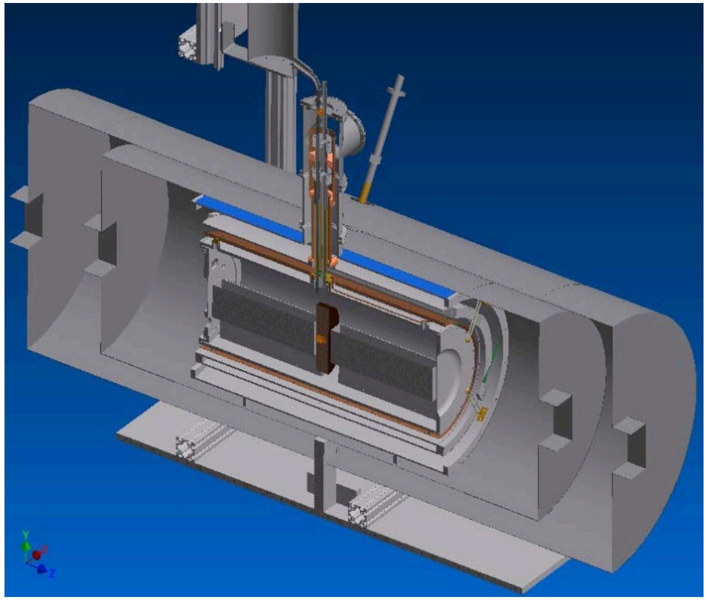




Cryomech pulse-tube reliquefier

- Tested for 3 months of continuous operation
- Observed liquefaction rate from warm gas of 12L/day
- Automated operation capable of handling ~550 mW heat load

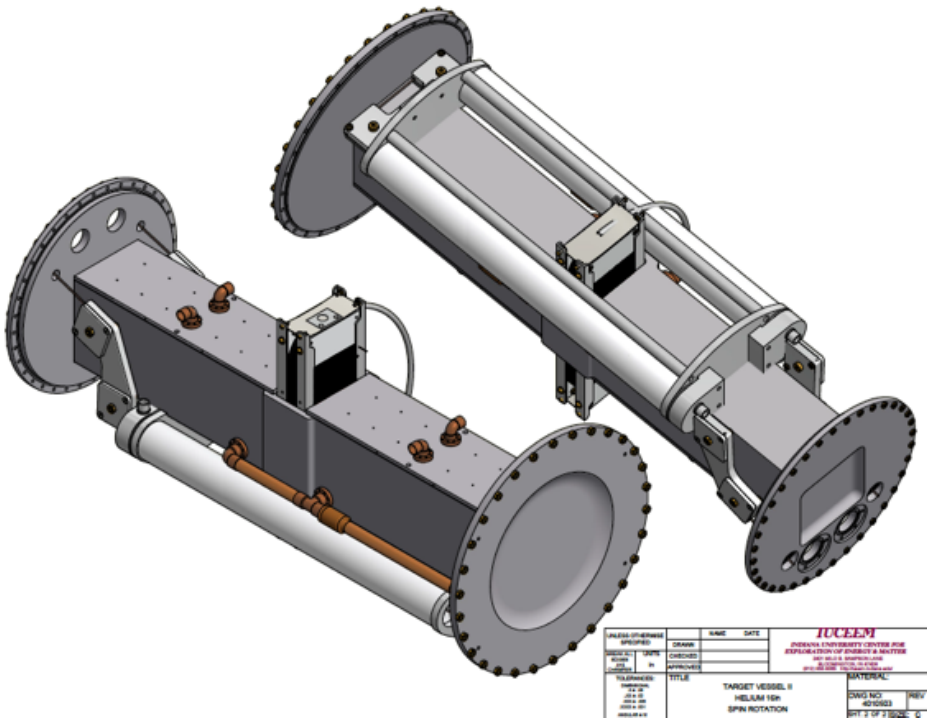
•Improved cryogenic design for reduced heat load, simpler assembly/disassembly, and more robust operation
•He re-liquefier removes necessity of LHe fills
•R&D on new LHe pump to reduce target change time

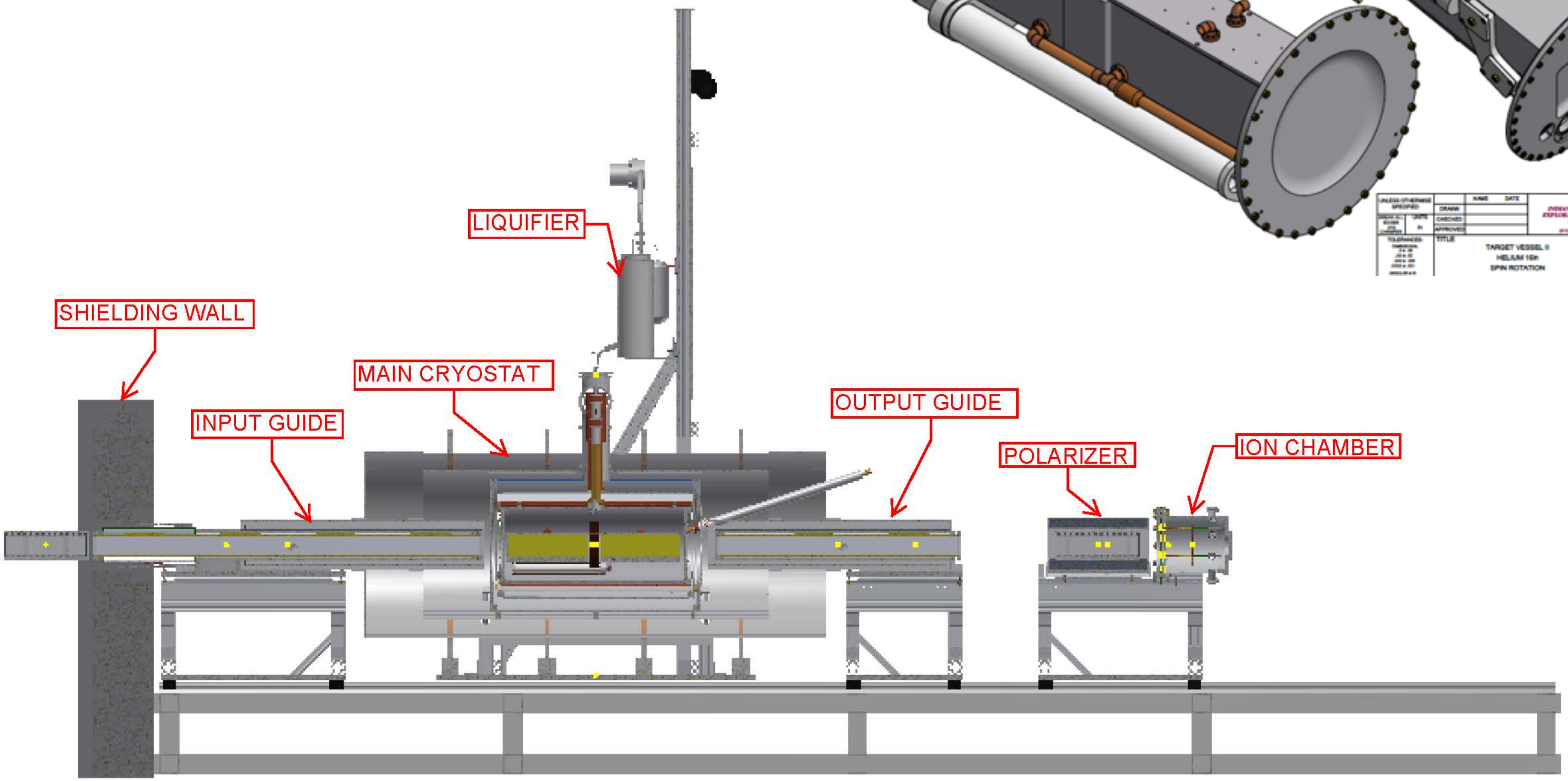


Duty Factor - Improve Cryogenics

Titanium bellows pump design:

tested for ~600,000 cycles in liquid nitrogen

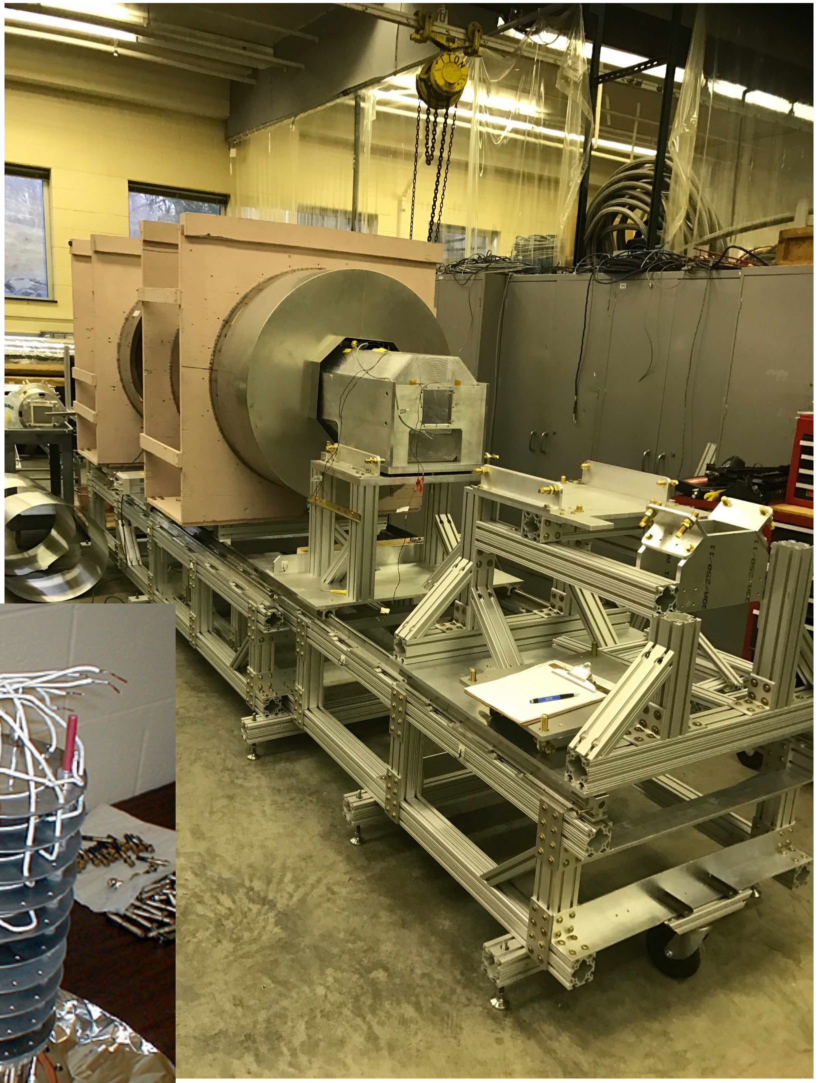


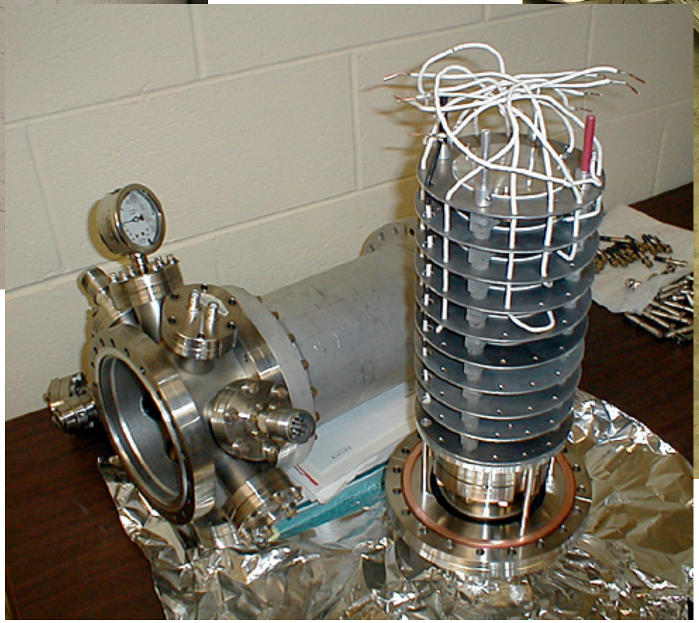


Other improvements

4-Chamber LHe Target

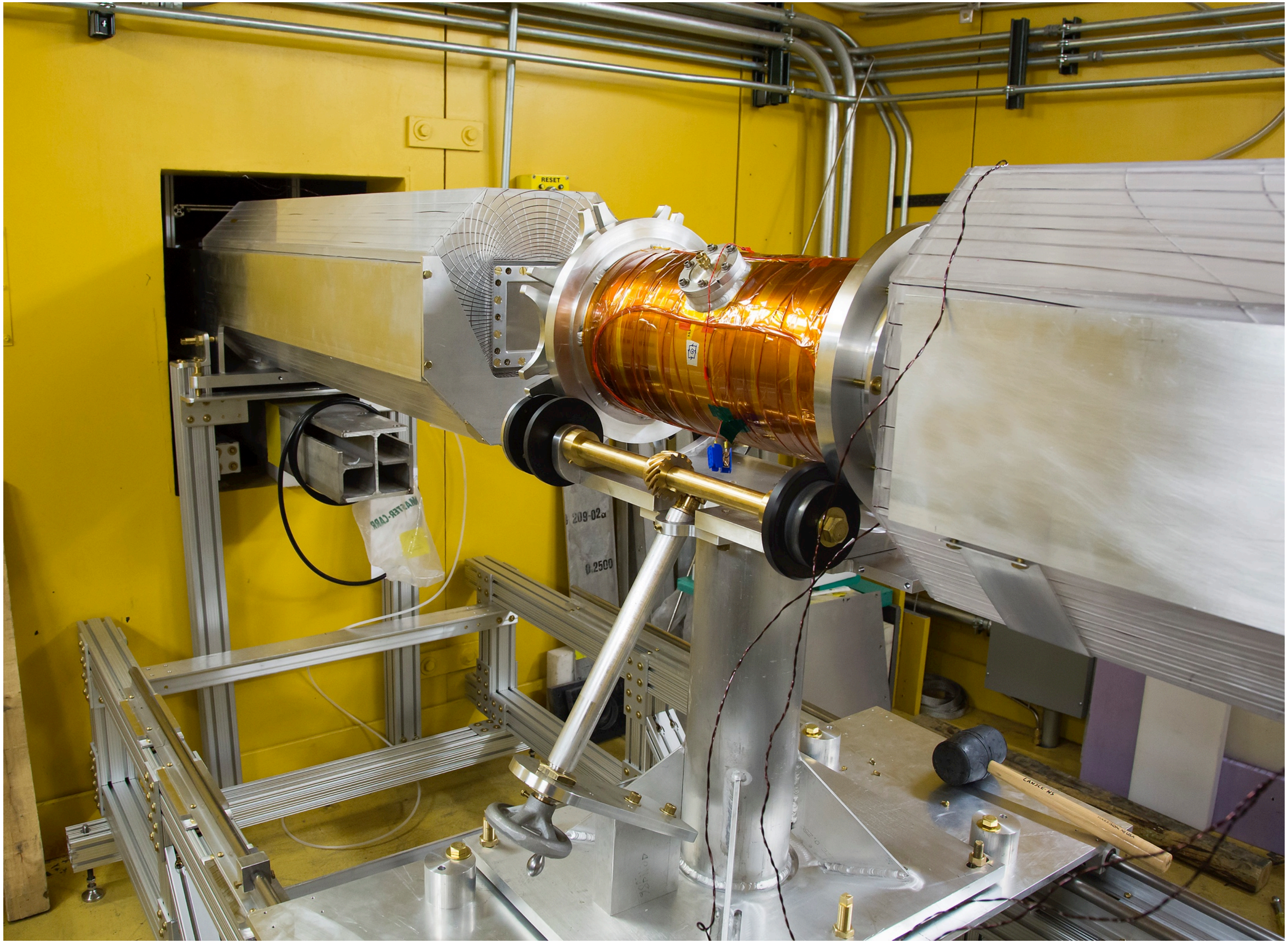
Shielding





He-3 Ion Chamber

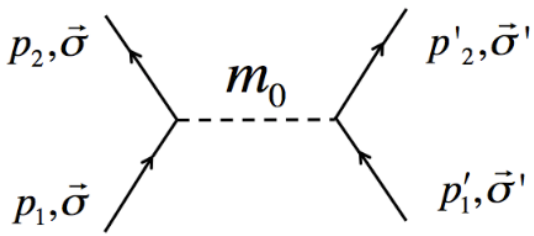
NSRf5 Apparatus at LANSCE FP12



Why NSRf5 Apparatus at LANSCE FP12?

$$\mathcal{L} = \overline{\psi}\left(g_V \gamma^\mu + g_A \gamma^\mu \gamma^5\right)\psi X_\mu$$

→ Generic interaction between fermions with a light spin-1 particle arising in a number of Beyond the Standard Model Theories from, e.g., spontaneous breaking of new symmetries.

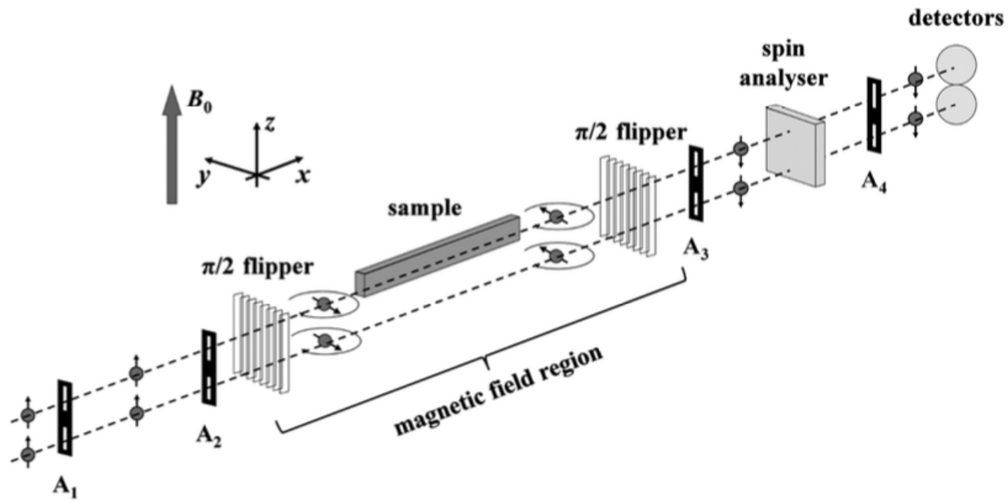


16 independent rotationally invariant low-energy potentials.

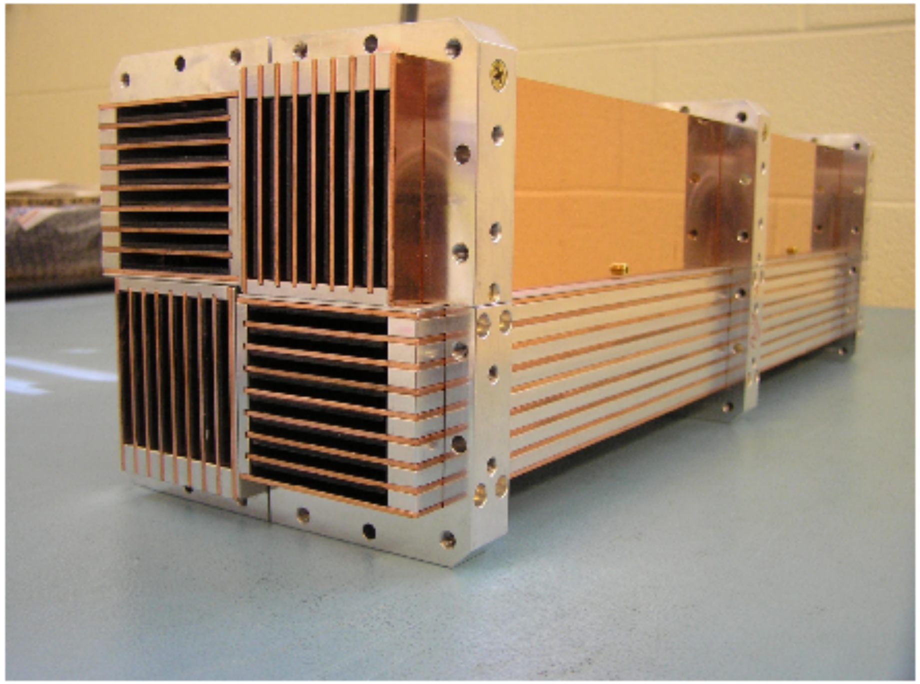
for example...

$$V_{AA} \propto g_A^2\, \vec{\sigma}\cdot(\vec{v}\times\hat{r})\left(\frac{1}{\lambda}+\frac{1}{r}\right)\frac{e^{-r/\lambda}}{r}$$

B. Dobrescu and I. Mocioiu, J. High Energy Physics. 11, 005 (2006)



F. Piegsa and G. Pignol, PRL 108, 181801 (2012)



NSRf5 Apparatus at LANSCE FP12

A Search for Possible Long Range Spin Dependent Interactions of the Neutron From Exotic Vector Boson Exchange

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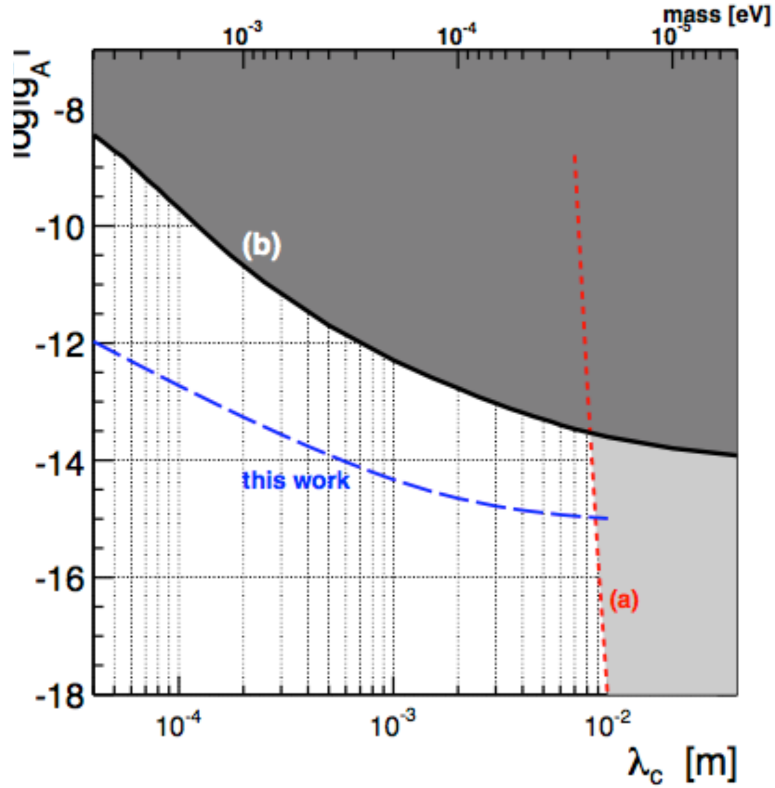


Figure 3: g_A^2 as a function of interaction length λ_c from our experiment (dashed-blue) compared with constraints from a neutron measurement using Ramsey spectroscopy (a) [22] and from K-^{3}He comagnetometry (b) [36]. The final g_A^2 limit includes both statistical and systematic uncertainties.

Submitted to PLB

Summary

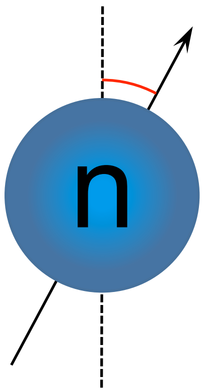
➢ The NSR-2 collaboration completed an experiment limiting spin rotation in LHe at the level of 9×10^{-7} rad/m. The experiment was statistics limited.

➢ Significant recent theoretical work. Prediction a relatively large size for the neutron spin rotation of ≈ 7×10^{-7} rad/m without sensitivity to the isotensor component of the NN weak interaction.

➢ A substantially improved apparatus was used to make significantly improvement in limits on spin-dependent fifth forces using a room temperature target.

➢ The NSR-3 collaboration has an apparatus nearing readiness for an n-^{4}He spin rotation measurement at the level 1×10^{-7} rad/m.

The critical path items are the LHe pump, LHe target, and radiation shielding.



➢ The goal is to be ready for beam in 2019.

NRS-3 Collaboration

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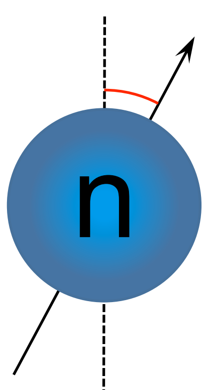

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If we listen very carefully…

…the neutrons have a lot to tell us.

Thanks for contributions from L. Barron-Palos, C. Haddock, M. Sarsour, M. Snow.