Parity-Odd Neutron Spin Rotation

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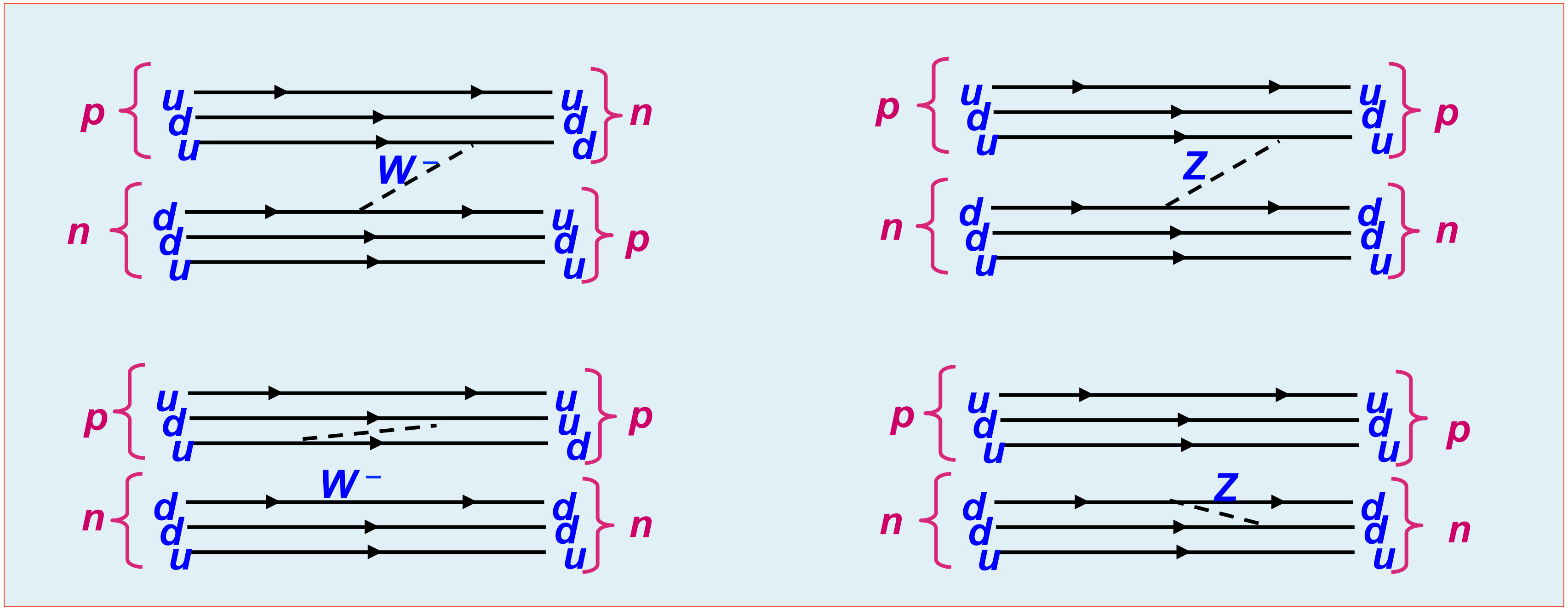
Theoretical background
Previous neutron spin rotation measurement in liquid helium
Preparations for new experiment: $<2 \times 10^{-7}$ rad/m sensitivity goal
Experimental bounds on meV-mass Z' boson exchange
Other possible NN weak experiments/conclusions

NN Weak Interaction: the nucleons are the “problem”

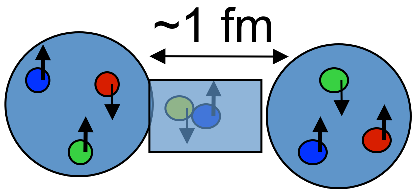
In the Standard Model, the structure of the quark-quark weak interaction is known from the electroweak sector. However, strong QCD confines color and breaks chiral symmetry, thereby strongly correlating the quarks in both the *initial* and *final* nucleon ground states.



Two aspects of the qq weak interaction make it useful as an interesting probe of QCD:

(1) Since it is weak, it probes the nucleons in their ground states without exciting them.
(2) Since it is short-ranged compared with the size of the nucleon, NN weak amplitudes should be first-order sensitive to quark-quark correlation effects in the nucleon.

N- N Weak Interaction: Size and Mechanism

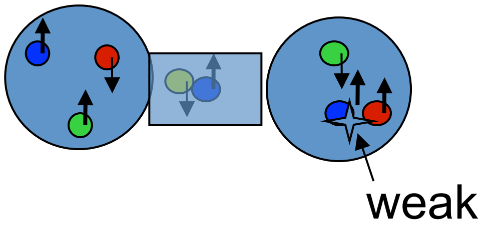


NN repulsive core → 1 fm range for NN strong force

$|N\rangle = |qqq\rangle + |qqqq\bar{q}\rangle + \cdots$ = valence + sea quarks + gluons + …

interacts through NN strong force, mediated by mesons $|m\rangle = |q\bar{q}\rangle + |q\bar{q}q\bar{q}\rangle + \cdots$

QCD possesses only vector quark-gluon couplings → conserves parity



Both W and Z exchange possess
much smaller range [~1/100 fm]

Relative strength of weak / strong amplitudes: $\frac{e^2}{M_W^2} / \frac{g^2}{m_\pi^2} \approx 10^{-7}$

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

NN strong interaction at low energy largely dictated by QCD chiral symmetry.
Can be parametrized by effective field theory methods.

qq Weak → NN Weak: What can we learn about QCD?

(1) ΔS=1 nonleptonic weak interactions show large QCD effects

ΔI=1/2 rule/hyperon decays, not close to simple estimates from flavor symmetries. Must be some nontrivial QCD dynamics. Is this problem specific to the strange quark, or is it a general feature of nonleptonic weak interactions of light quarks?

Look at I dependence of ΔS=0 nonleptonic weak interactions (u,d quarks)

NN weak interaction is one of the few experimentally feasible systems

(2) NN weak interactions are a new arena to apply effective field theories.

$1/N_c$ expansion+EFT predicts I dependence of NN weak amplitudes.

(3) NN weak interactions provide a new opportunity to exercise lattice gauge theory in a challenging but doable system.

Now there is real hope to calculate the ΔI=2 NN weak amplitude on the lattice (a "computational frontier" of the Standard Model).

(4) NN weak interaction is a "test case" for our ability to trace symmetry-violating effects across strong interaction scales

How to use EDM/0ββ constraints in nucleons/nuclei to constrain T-odd physics?

Let's understand the P-odd physics, where we know the operators from the SM

q-q Weak Interaction: Isospin Dependence

At energies below the W± and Zº mass, the q-q weak interaction can be written in a current-current form, with contributions from charged currents and neutral currents.

$$M_{CC} = \frac{g^2}{2M_W^2} J^{\dagger}_{\mu,CC} J^{\mu}_{CC} \qquad M_{NC} = \frac{g^2}{\cos^2\theta_W M_Z^2} J^{\dagger}_{\mu,NC} J^{\mu}_{NC}$$

$$J^{\mu}_{CC} = \bar{u}\frac{1}{2}\gamma^{\mu}(1-\gamma^5)\begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}\begin{pmatrix} d \\ s \end{pmatrix}; J^{\mu}_{NC} = \sum_{q=u,d} \bar{q}\frac{1}{2}\gamma^{\mu}(c_V^q - c_A^q\gamma^5)q$$

Looks like neutral currents dominate Δ I=1

Between electroweak scale and QCD scale one can perturbatively calculate RG evolution of the 4-quark operators. Done at LO (Dai91) and for Δ I=1 at NLO (Tiburzi 2012)

possible isospin changes from q-q weak interactions	
	Δ I
charged current	0, 2 : (~V^2_{ud}) 1 : (~V^2_{us})
neutral current	0, 1, 2

NN Weak Interaction:
5 Independent Elastic Scattering Amplitudes at Low Energy

Using isospin symmetry applied to NN elastic scattering we get the usual Pauli-allowed L,S,J combinations:

I_{tot} = 1 *(isospin-S)*:

Space-S (even L) ⊗ spin-A (S_{tot} = 0) ⇒ $^1S_0$, $^1D_2$, $^1G_4$, …

or Space-A (odd L) ⊗ spin-S (S_{tot} = 1) ⇒ $^3P_{0,1,2}$, $^3F_{2,3,4}$, …

I_{tot} = 0 *(isospin-A)*:

Space-A (odd L) ⊗ spin-A (S_{tot} = 0) ⇒ $^1P_1$, $^1F_3$, …

Space-S (even L) ⊗ spin-S (S_{tot} = 1) ⇒ $^3S_1$, $^3D_{1,2,3}$, $^3G_{3,4,5}$, …

$^{(2S+1)}L_J$ notation, with L=0,1,2,3,4,… denoted as S,P,D, F,G,…

If we use energies low enough that **only *S*-waves are important for strong interaction,** parity violation is dominated by ***S- P interference***,

Then we have 5 independent NN parity-violating transition amplitudes:

$^3S_1 \Leftrightarrow {}^1P_1(\Delta I=0,\ np)$; $^3S_1 \Leftrightarrow {}^3P_1(\Delta I=1,\ np)$; $^1S_0 \Leftrightarrow {}^3P_0(\Delta I=0,1,2;\ nn,pp,np)$

Theoretical Approaches to NN Weak Interactions

- Kinematic: 5 S→P transition amplitudes in elastic NN scattering (*Danilov*)

- QCD effective field theory: χ perturbation theory, incorporates low energy symmetries of QCD (Kaplan, Savage, Wise, *Liu, Holstein, Musolf, Zhu, Phillips, Springer, Schindler, de Vries, Meissner,…)*

- Dynamical models: meson exchange model for NN weak interaction

(effect of qq weak interactions parametrized by ~6 couplings), QCD sum rules, Skyrme models, chiral quark models, ADS/CFT-based models (*Desplanques, Donoghue, Holstein, Meissner, Hwang, Gazit,…)*

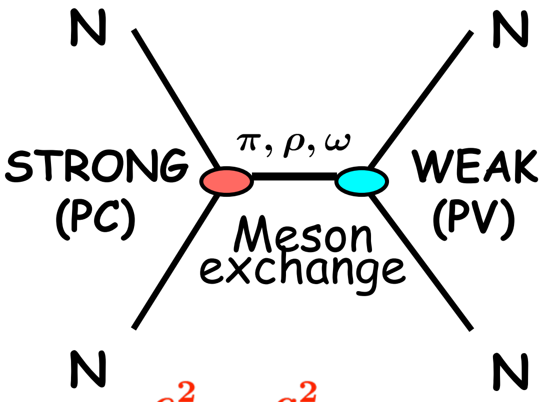
- Standard Model; lattice gauge theory: a target for exoscale computing (*Beane & Savage, Wasem, Walker-Loud,…*)

Strong NN amplitudes are now well-enough known to relate parity violation measurements in few body systems to the weak NN interaction (*Pieper, Wiringa, Nollett, Schiavilla, Carlson, Paris, Kievsky, Viviani,*…).

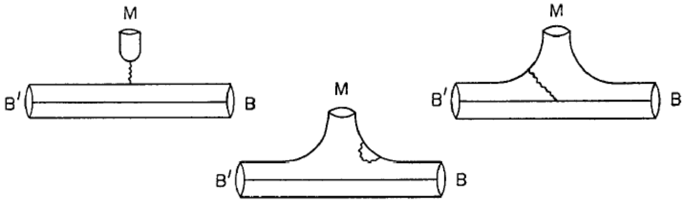
P-odd NNN interactions should be small compared to P-odd NN interactions (Schindler)

DDH Potential

PV meson exchange



$$\frac{e^2}{M_W^2} \Big/ \frac{g^2}{m_\pi^2} \approx 10^{-7}$$



Desplanques, Donoghue, Holstein,
Annals of Physics 124, 449 (1980)

1. ***DDH model*** – uses valence quarks to calculate effective PV meson-nucleon coupling directly from SM via 6 weak meson coupling constants

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

P-odd observables can be written as linear combinations of these couplings

$$A = a_\pi^1 f_\pi^1 + a_\rho^0 h_\rho^0 + a_\rho^1 h_\rho^1 + a_\rho^2 h_\rho^2 + a_\omega^0 h_\omega^0 + a_\omega^1 h_\omega^1$$

	np A_γ	nD A_γ	n^{3}He A_p	np ϕ	nα ϕ	pp A_z	pα A_z
f_π	-0.11	0.92	-0.18	-3.12	-0.97		-0.34
h_ρ^0		-0.50	-0.14	-0. 23	-0.32	0.08	0.14
h_ρ^1	-0.001	0.10	0.027		0.11	0.08	0.05
h_ρ^2		0.05	0.0012	-0.25		0.03	
h_ω^0		-0.16	-0.13	-0. 23	-0.22	-0.07	0.06
h_ω^1	-0.003	-0.002	0.05		0.22	0.07	0.06

Adelberger, Haxton, A.R.N.P.S. **35,** 501 (1985)

Five parity-violating EFT$_{\not{\pi}}$ low-energy constants

$$
\begin{aligned}
\mathcal{L}_{PV} = -\Big[& \mathcal{C}^{({}^3S_1-{}^1P_1)} \left(N^T\sigma_2\,\vec{\sigma}\tau_2 N\right)^\dagger \cdot \left(N^T\sigma_2\tau_2 i\overleftrightarrow{D} N\right) \\
& + \mathcal{C}^{({}^1S_0-{}^3P_0)}_{(\Delta I=0)} \left(N^T\sigma_2\tau_2\vec{\tau} N\right)^\dagger \left(N^T\sigma_2\,\vec{\sigma}\cdot\tau_2\vec{\tau} i\overleftrightarrow{D} N\right) \\
& + \mathcal{C}^{({}^1S_0-{}^3P_0)}_{(\Delta I=1)}\ \epsilon^{3ab} \left(N^T\sigma_2\tau_2\tau^a N\right)^\dagger \left(N^T\sigma_2\,\vec{\sigma}\cdot\tau_2\tau^b \overleftrightarrow{D} N\right) \\
& + \mathcal{C}^{({}^1S_0-{}^3P_0)}_{(\Delta I=2)}\ \mathcal{I}^{ab} \left(N^T\sigma_2\tau_2\tau^a N\right)^\dagger \left(N^T\sigma_2\,\vec{\sigma}\cdot\tau_2\tau^b i\overleftrightarrow{D} N\right) \\
& + \mathcal{C}^{({}^3S_1-{}^3P_1)}\ \epsilon^{ijk} \left(N^T\sigma_2\sigma^i\tau_2 N\right)^\dagger \left(N^T\sigma_2\sigma^k\tau_2\tau_3\overleftrightarrow{D}^j N\right)\Big] + h.c.
\end{aligned}
$$

Schindler/RPS NPA 846 (2010) 51

cf. Danilov parameters, Zhu et al. NPA 748 (2005) 435,
Girlanda PRC 77 (2008) 067001.

R. Springer

Pionless EFT Potential for Weak NN

$$
\begin{aligned}
V_{\mathrm{LO}}^{\mathrm{PNC}}(\boldsymbol{r}) = {}& \Lambda_0^{{}^1\mathrm{S}_0-{}^3\mathrm{P}_0}\left(\frac{1}{i}\frac{\overleftrightarrow{\nabla}_A}{2m_N}\frac{\delta^3(\boldsymbol{r})}{m_\rho^2}\cdot(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2)-\frac{1}{i}\frac{\overleftrightarrow{\nabla}_S}{2m_N}\frac{\delta^3(\boldsymbol{r})}{m_\rho^2}\cdot i(\boldsymbol{\sigma}_1\times\boldsymbol{\sigma}_2)\right)\\
&+\Lambda_0^{{}^3\mathrm{S}_1-{}^1\mathrm{P}_1}\left(\frac{1}{i}\frac{\overleftrightarrow{\nabla}_A}{2m_N}\frac{\delta^3(\boldsymbol{r})}{m_\rho^2}\cdot(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2)+\frac{1}{i}\frac{\overleftrightarrow{\nabla}_S}{2m_N}\frac{\delta^3(\boldsymbol{r})}{m_\rho^2}\cdot i(\boldsymbol{\sigma}_1\times\boldsymbol{\sigma}_2)\right)\\
&+\Lambda_1^{{}^1\mathrm{S}_0-{}^3\mathrm{P}_0}\left(\frac{1}{i}\frac{\overleftrightarrow{\nabla}_A}{2m_N}\frac{\delta^3(\boldsymbol{r})}{m_\rho^2}\cdot(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2)(\tau_{1z}+\tau_{2z})\right)\\
&+\Lambda_1^{{}^3\mathrm{S}_1-{}^3\mathrm{P}_1}\left(\frac{1}{i}\frac{\overleftrightarrow{\nabla}_A}{2m_N}\frac{\delta^3(\boldsymbol{r})}{m_\rho^2}\cdot(\boldsymbol{\sigma}_1+\boldsymbol{\sigma}_2)(\tau_{1z}-\tau_{2z})\right)\\
&+\Lambda_2^{{}^1\mathrm{S}_0-{}^3\mathrm{P}_0}\left(\frac{1}{i}\frac{\overleftrightarrow{\nabla}_A}{2m_N}\frac{\delta^3(\boldsymbol{r})}{m_\rho^2}\cdot(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2)(\boldsymbol{\tau}_1\otimes\boldsymbol{\tau}_2)_{20}\right),
\end{aligned}
$$

Danilov, Zhu et al, Girlanda et al, Schindler/Springer

Large N_c for Weak NN in DDH and Pionless EFT

$$\mathcal{C}^{(^3S_1-^1P_1)} \sim N_c$$

$$\mathcal{C}^{(^1S_0-^3P_0)}_{(\Delta I=0)} \sim N_c$$

$$\mathcal{C}^{(^1S_0-^3P_0)}_{(\Delta I=2)} \sim N_c\,[\sin^2\theta_W]$$

$$\mathcal{C}^{(^1S_0-^3P_0)}_{(\Delta I=1)} \sim N_c^0 \sin^2\theta_W$$

$$\mathcal{C}^{(^3S_1-^3P_1)} \sim N_c^0 \sin^2\theta_W$$

Imply a hierarchy of NN weak amplitudes.

Predict parity violation amplitude measured in NPDGamma small compared to other NN weak amplitudes.

D.R. Phillips, D. Samart, C. Schat, PRL 114 (2015)
M.R. Schindler, R.P. Springer, J. Vanasse, PRC 93 (2016)

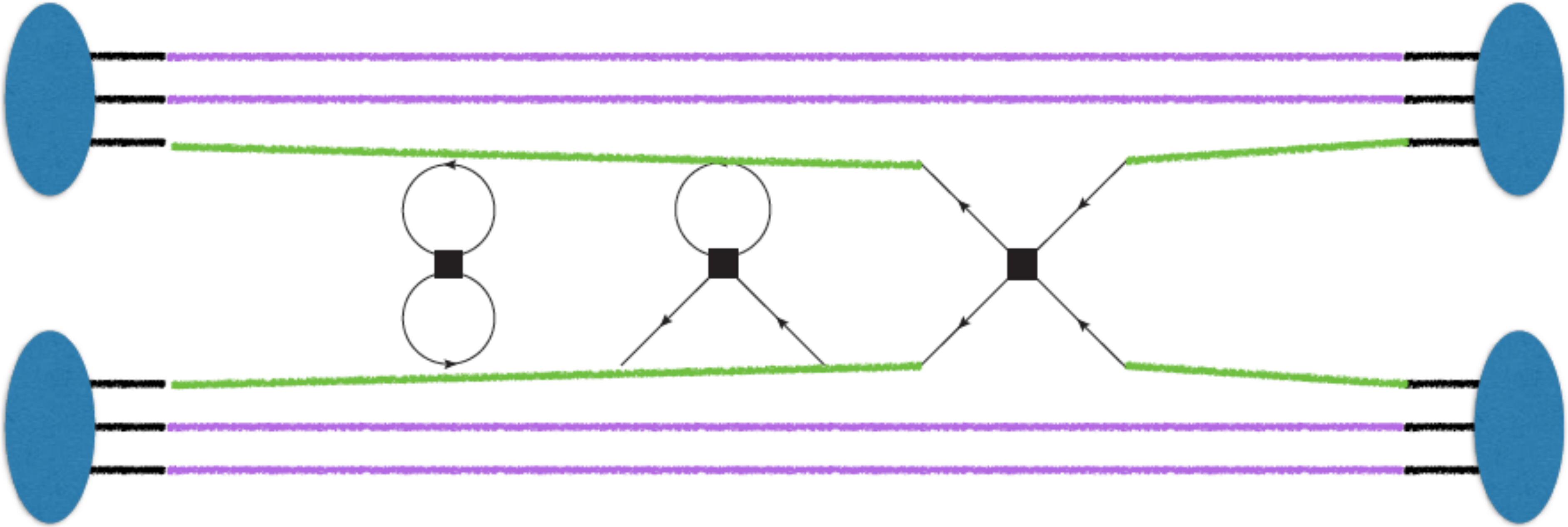
Large-N_c scaling of weak meson-nucleon couplings

$$h_\rho^0 \sim \sqrt{N_c} \qquad h_\rho^2 \sim \sqrt{N_c}\,[\sin^2\theta_W]$$

$$h_\rho^{1\prime} \lesssim \sqrt{N_c}\sin^2\theta_W \qquad h_\omega^1 \sim \sqrt{N_c}\sin^2\theta_W$$

$$h_\rho^1 \lesssim \frac{1}{\sqrt{N_c}}\sin^2\theta_W \qquad h_\pi^1 \lesssim \frac{1}{\sqrt{N_c}}\sin^2\theta_W \qquad h_\omega^0 \sim \frac{1}{\sqrt{N_c}}$$

LQCD Challenges for Parity Nonconservation



ΔI=0,1,2

- The “disconnected” quark loops are numerically more expensive, and stochastically noisier
- LQCD calculations can project onto definite ΔI

The ΔI=2 P-odd 4-quark operator is the easiest one to calculate on the lattice. Cal-Lat +collaborators plan to perform the calculation.

A. Walker-Loud

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

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

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

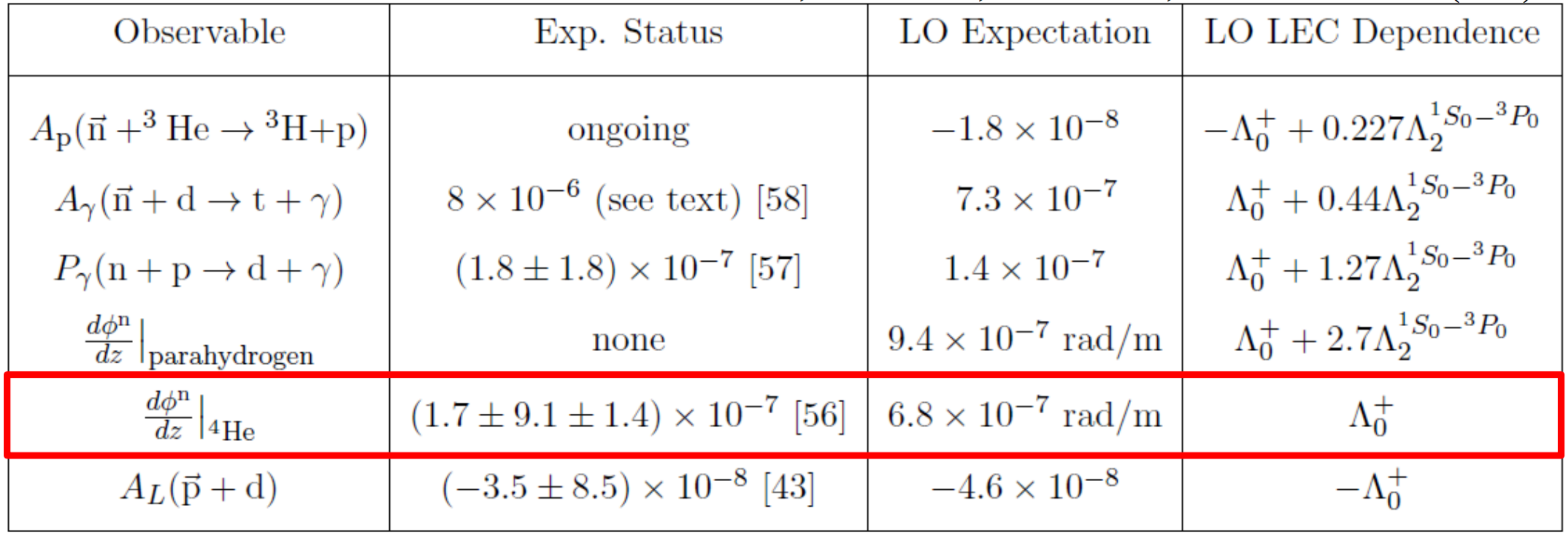
$$\phi_{PNC}(\bar{n},{}^4\,\mathrm{He}) = (0.85\lambda^{nn}_s - 0.43\lambda^{np}_s + 0.95\lambda_t - 1.89\rho_t)\ \mathrm{rad/m}$$

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

Large N_c Implications for n+4He Spin Rotation

- 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}	$\Lambda_0^+ + 0.44\Lambda_2^{{}^1S_0-{}^3P_0}$
$P_\gamma(\mathrm{n}+\mathrm{p}\to\mathrm{d}+\gamma)$	$(1.8\pm1.8)\times10^{-7}$ [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	$\Lambda_0^+ + 2.7\Lambda_2^{{}^1S_0-{}^3P_0}$
$\frac{d\phi^n}{dz}\Big\vert_{{}^4\mathrm{He}}$	$(1.7\pm9.1\pm1.4)\times10^{-7}$ [56]	6.8×10^{-7} rad/m	Λ_0^+
$A_L(\vec{p}+\mathrm{d})$	$(-3.5\pm8.5)\times10^{-8}$ [43]	-4.6×10^{-8}	$-\Lambda_0^+$

Dependence on one leading-order LEC (Λ_0^+) in large N_c estimation

Relatively large expected value, should be measurable in an experiment at NIST

P-odd Rotary Power in the n + ^{4}He System

➢ Forward transmission of cold neutrons can be described using neutron optics with index of refraction *n*

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

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

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

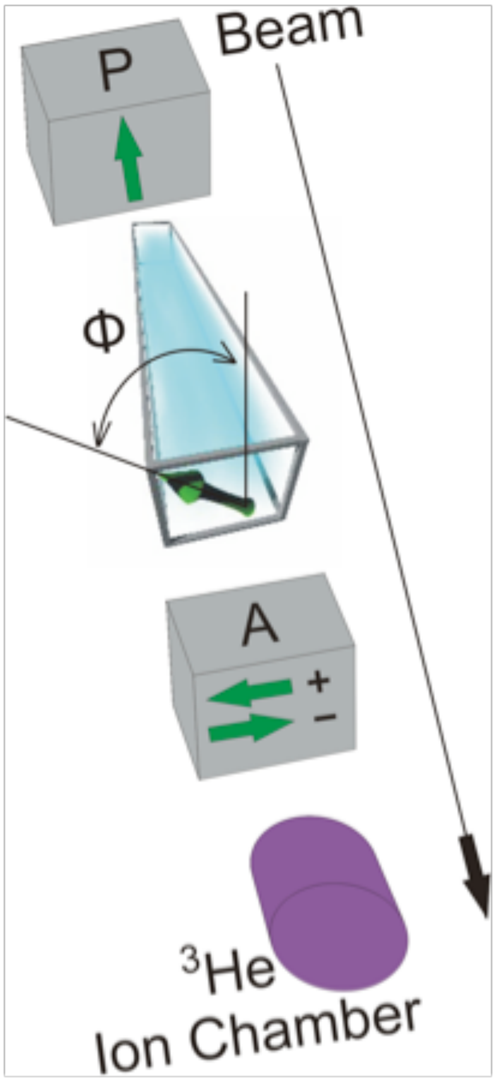
➢ As the neutron propagates along z, it accumulates a phase

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

➢ For a transversely polarized beam, the phases of the two helicity states are different

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

Measurement Principle



We need an angle measurement of $O(10^{-7})$ rad.

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

PA sign is flipped every second, neutrons are detected in a ^{3}He ion chamber operated in current mode

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

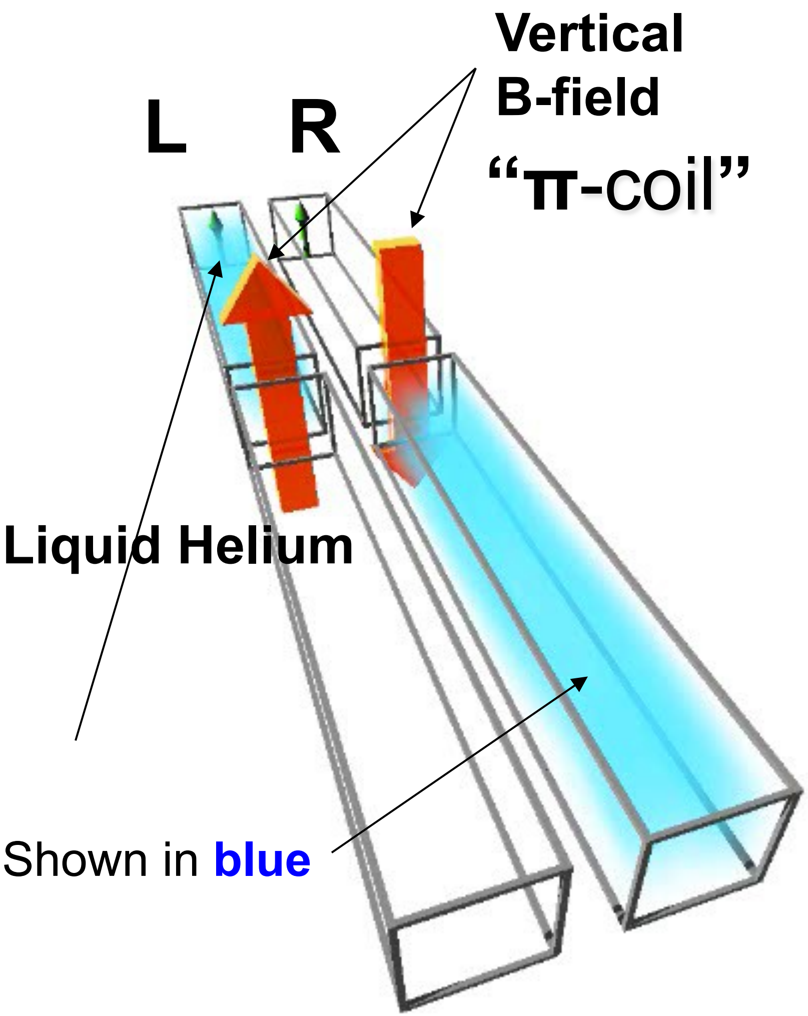
Two critical issues:

Beam intensity fluctuations threaten statistical error.

Hard to shield B below 10 μG with big holes. Rotation angle from this field is about 3 orders of magnetic greater than ϕ_{PNC} error.

What to do? Split the beam and oscillate the liquid

Isolating the PV signal



L R

Vertical B-field

"π-coil"

Liquid Helium

Shown in **blue**

The left and right chambers are each divided in two as shown

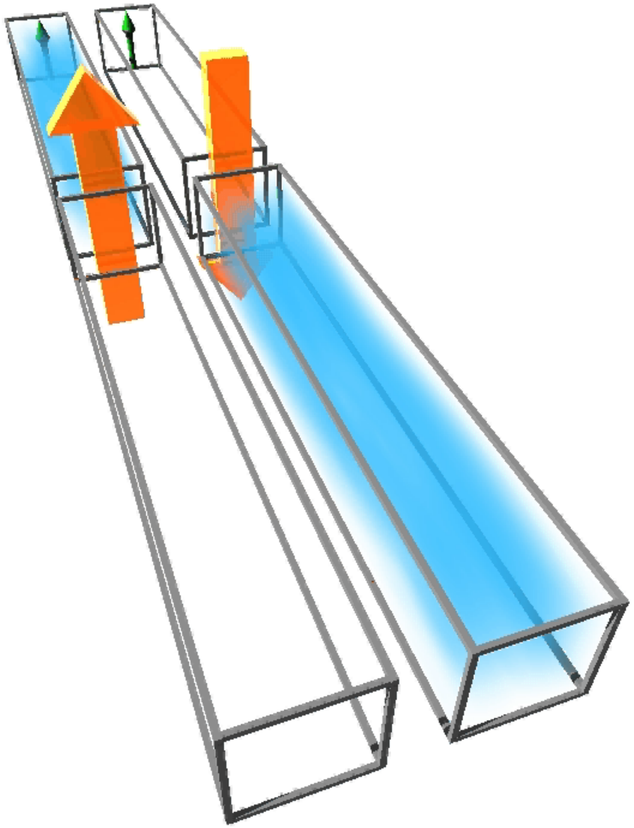
- 2 target positions separated by vertical solenoid ("pi-coil")
- pi-coil tuned to precess neutrons about vertical field by 180° for the average neutron energy in the beam

PV Spin Angle
changes sign for
target position due to pi-coil

PC Spin Angle
is B-field dependent for each target
but is cancelled out due to the left/
right chambers

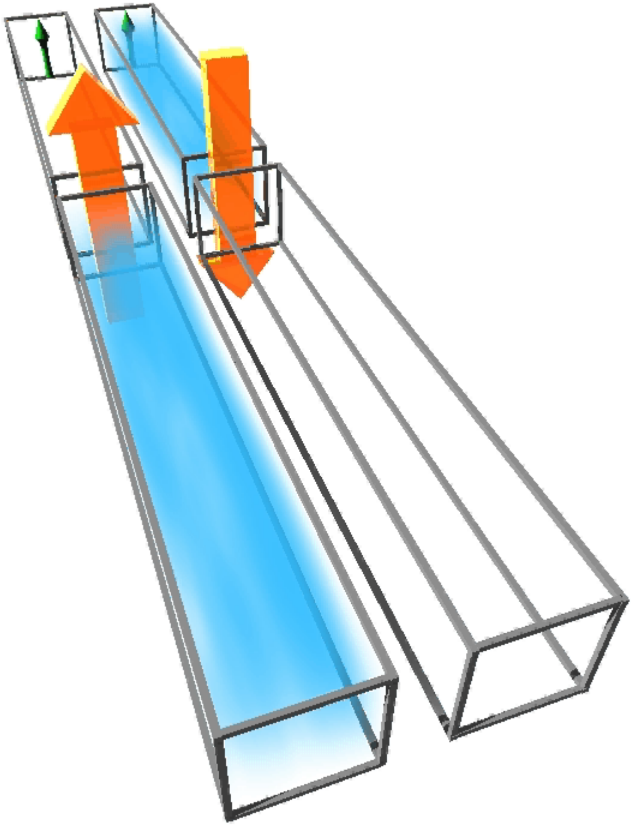
Divide and Conquer

Target state **A**



$$\phi_A = \frac{(-L) - R}{2}$$

Target state **B**



$$\phi_B = \frac{L - (-R)}{2}$$

Neutron Spin Rotation (NSR-2) Collaboration

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B.R. Heckel[5], J.C. Horton[3], C.R. Huffer[3], D. Luo[3], D.M. Markoff[6],
A.M. Micherdzinska[7], H.P. Mumm[1], J.S. Nico[1], A.K. Opper[4], E. Sharapov[8],
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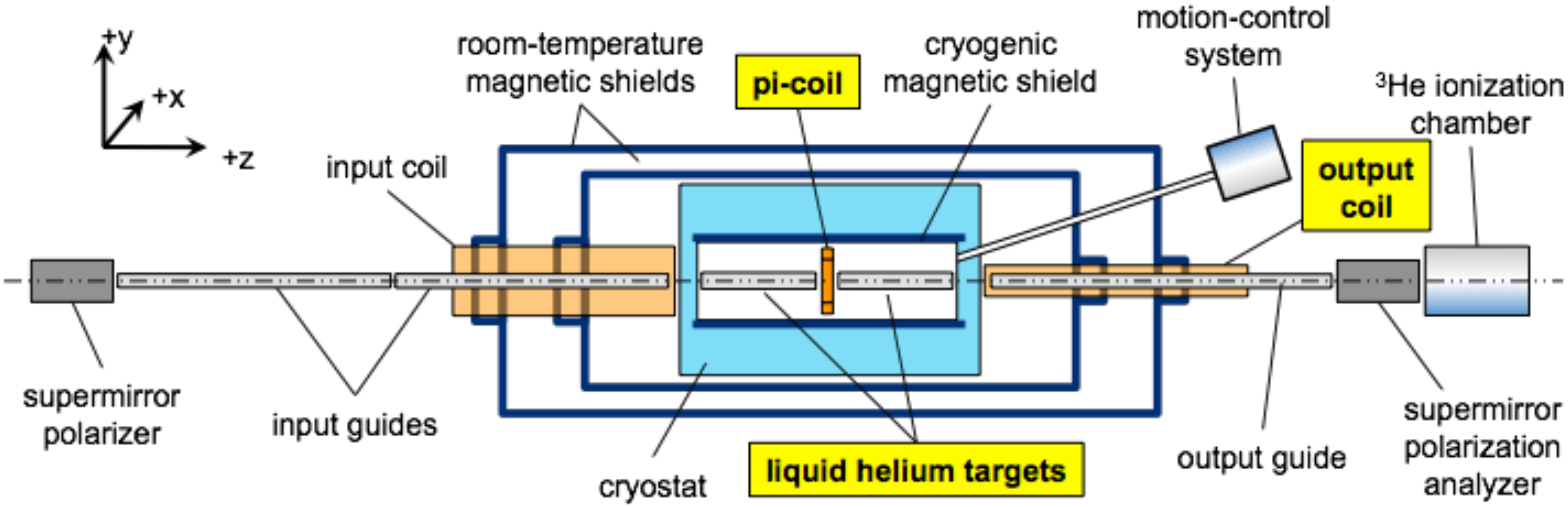
NSF PHY-0100348
NSF PHY-0457219

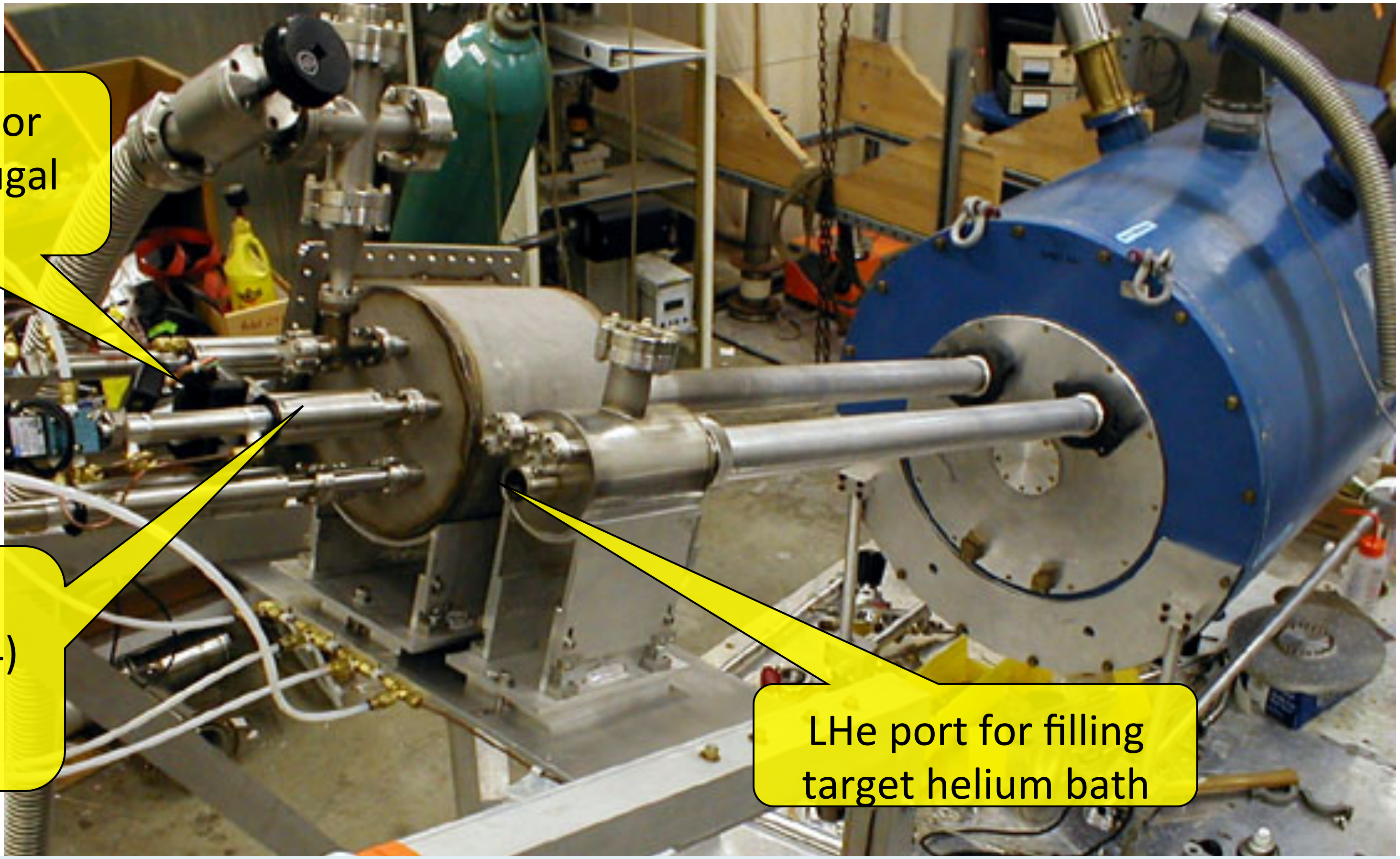
Spin Rotation Apparatus (Polarimeter)



Measures the horizontal component of a transversely polarized slow neutron beam.

W. M. Snow et al., **A slow neutron polarimeter for the measurement of parity-odd neutron rotary power**, Rev. Sci. Inst. **86**, 055101 (2015).

Liquid Helium Cryostat and Motion Control



Stepper motor turns centrifugal pump

Pneumatic actuators (x4) raise/lower drainpipes

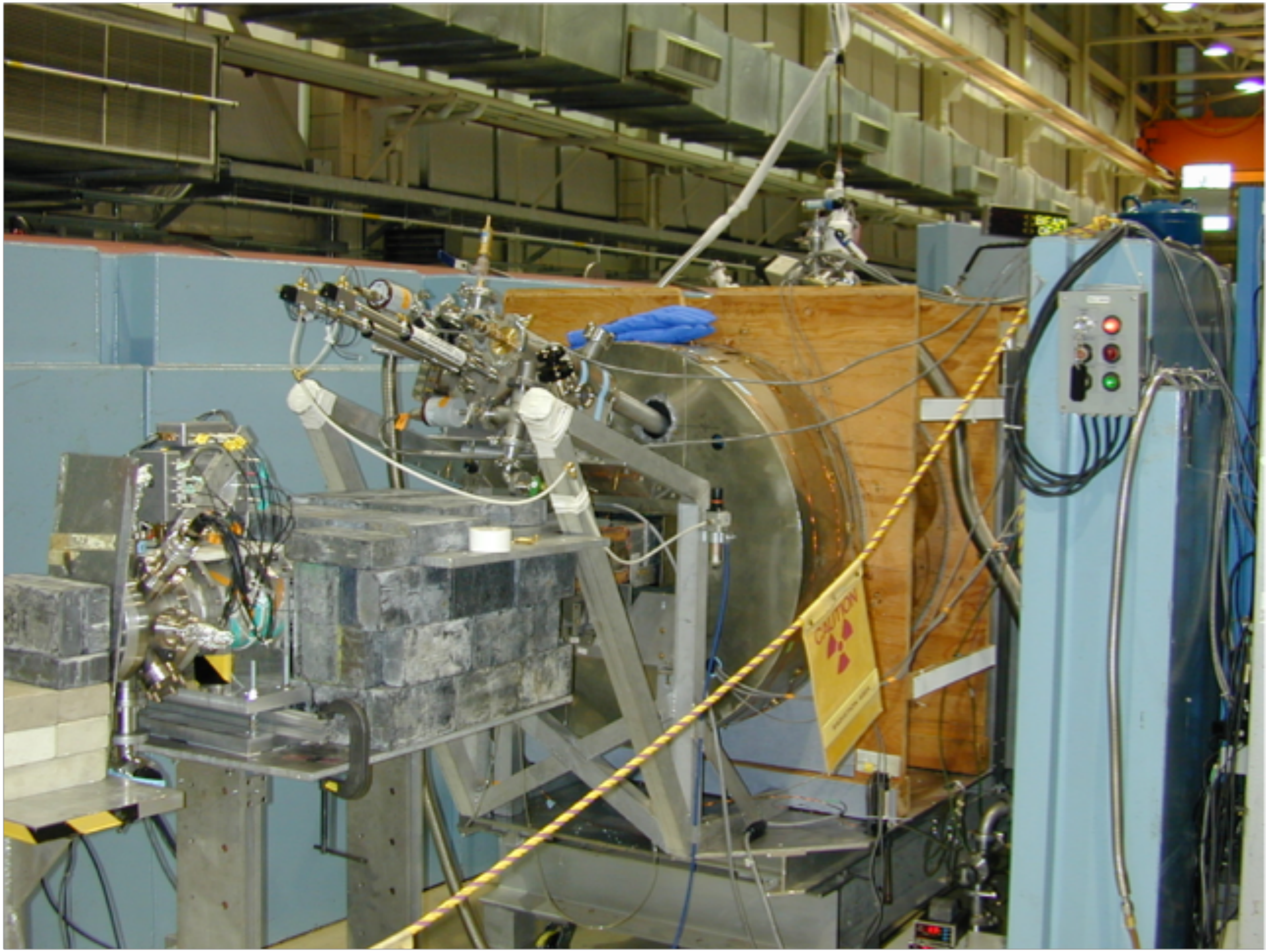
LHe port for filling target helium bath

- Nonmagnetic movement of liquid helium.

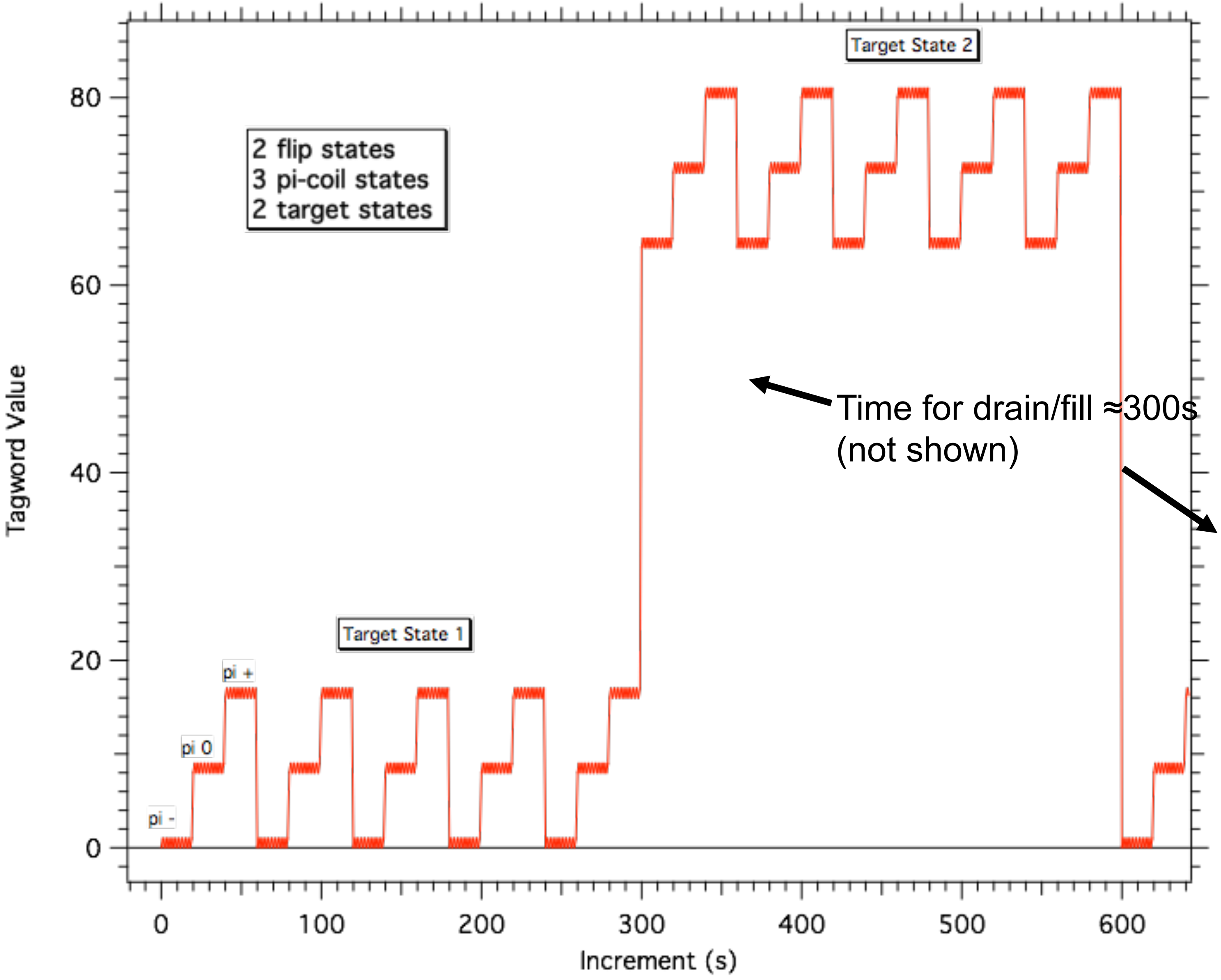
•Cryogenic target of 4K helium, volume~10 liters

C. D. Bass et al, Nucl. Inst. Meth. A612, 69-82 (2009).

NSR-2 Apparatus on NG-6 Beamline at NIST



DAQ Control Sequence



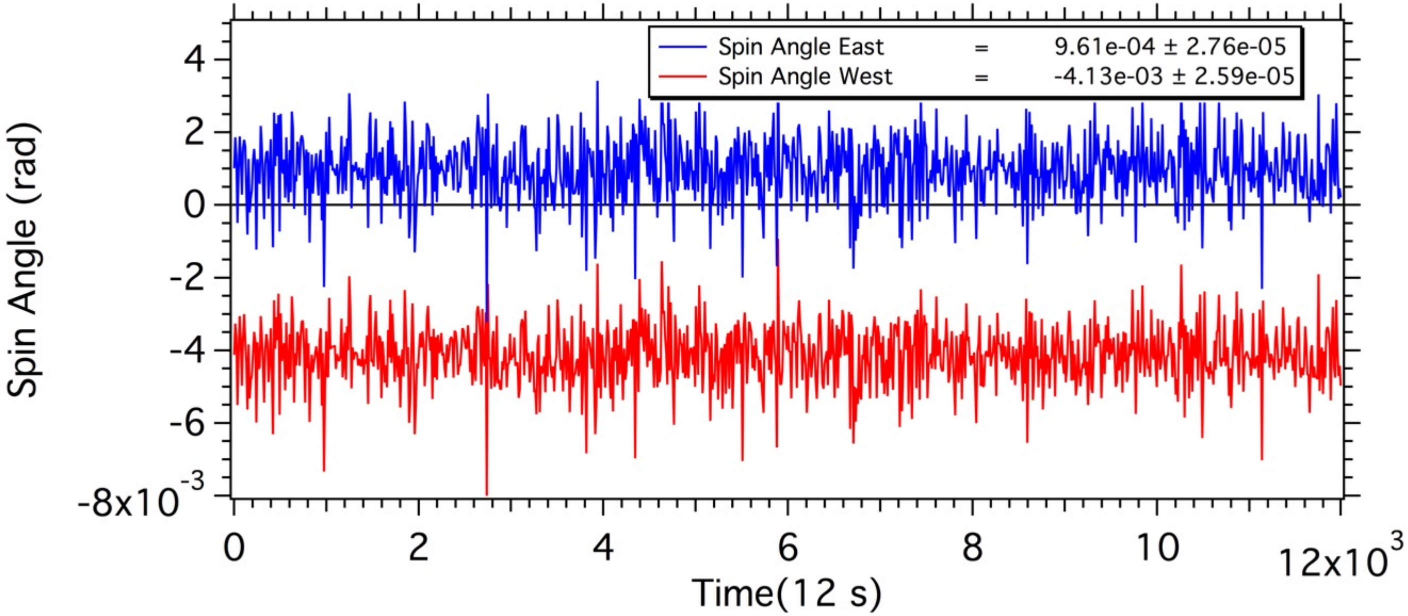
Time for drain/fill ≈300s (not shown)

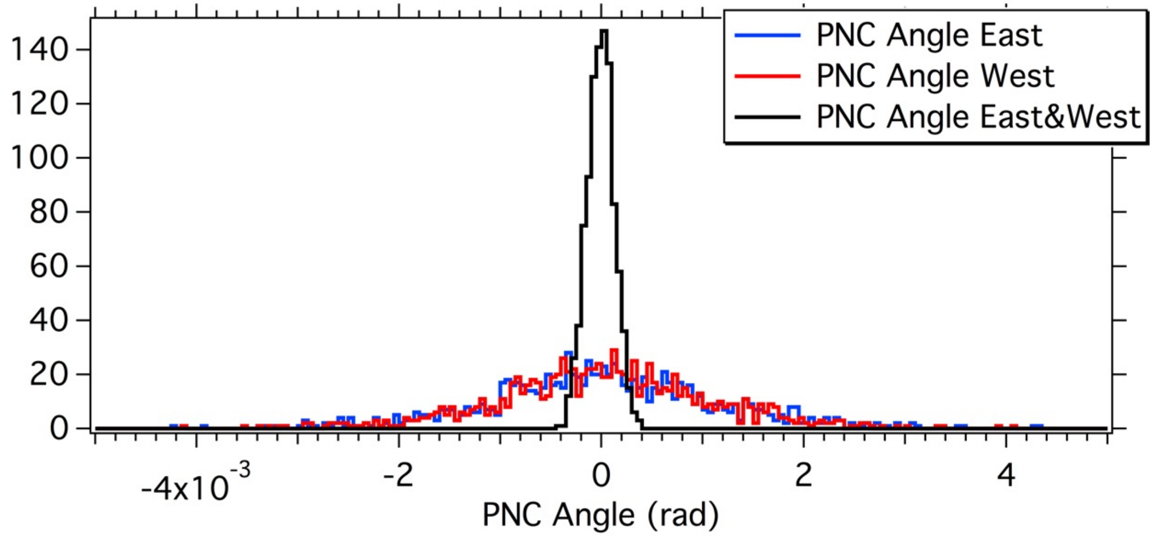
Analyzer direction oscillates at 1 Hz

pi-coil off states constrain systematic Errors

Systematics amplified by applying B fields in target

Common Mode Rotation Angle Noise

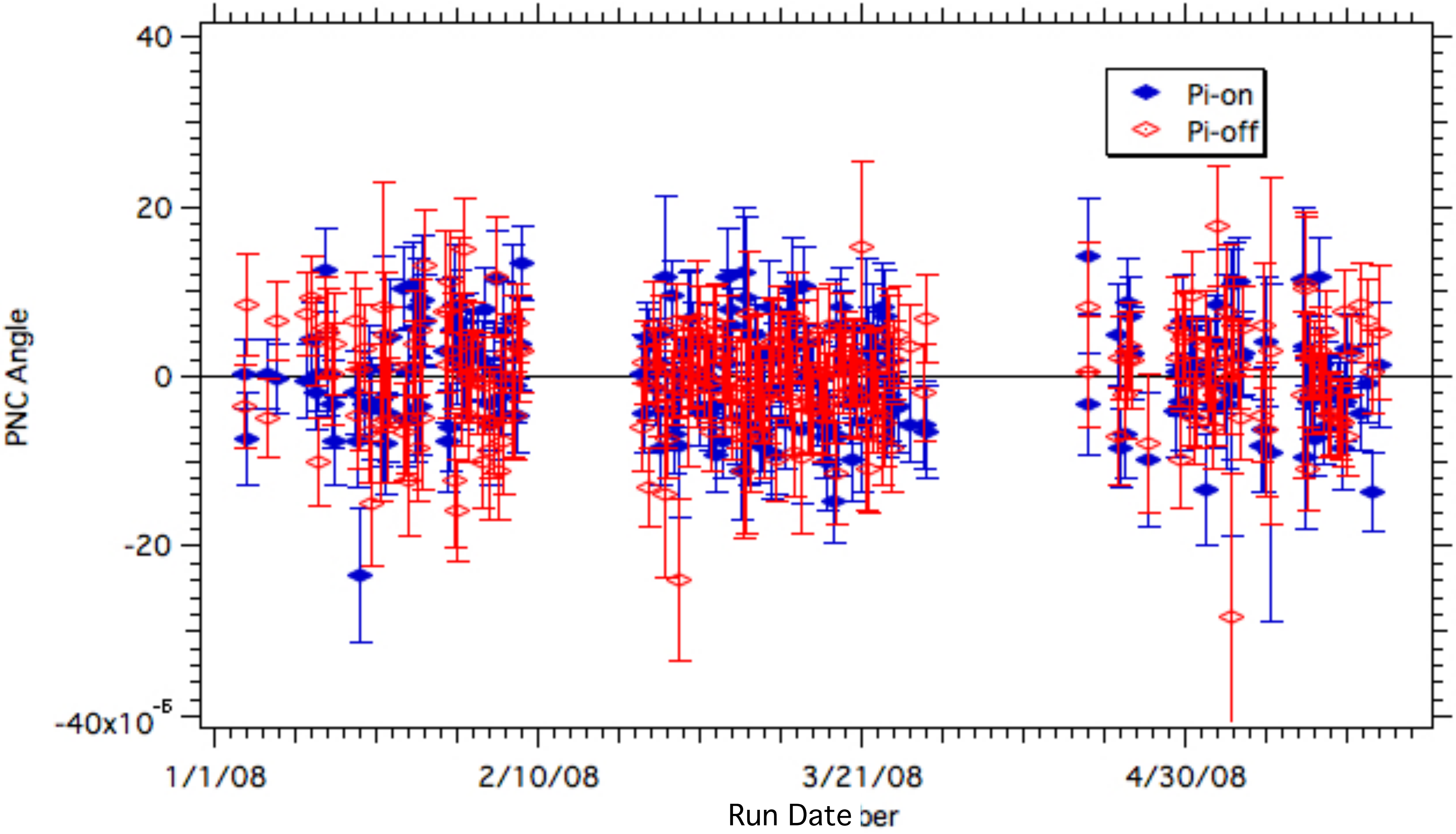




Noise is ~1.1√N

Left/right beam division works to suppress common-mode beam intensity noise. The rest is ion chamber noise and B field noise

Results: Run-by-Run



Systematics and Result

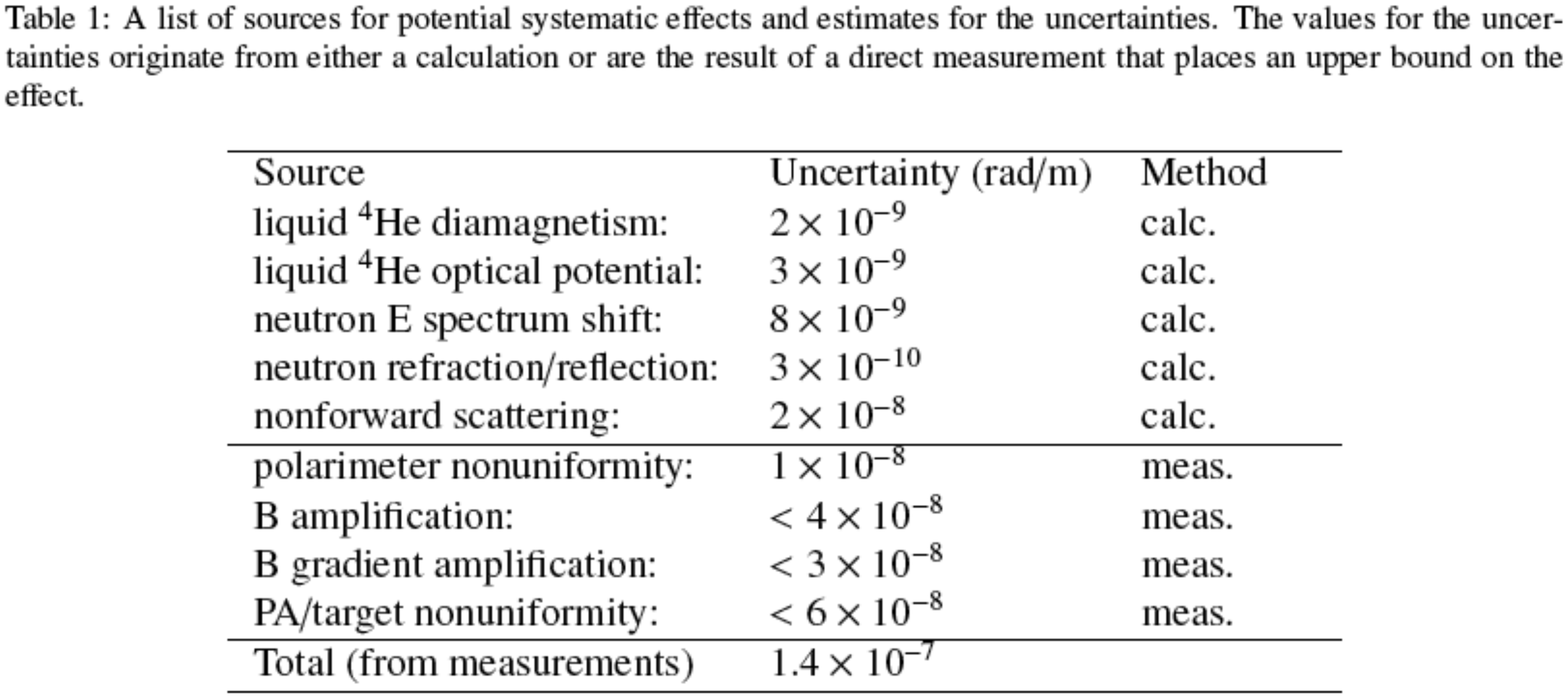


Table 1: A list of sources for potential systematic effects and estimates for the uncertainties. The values for the uncertainties originate from either a calculation or are the result of a direct measurement that places an upper bound on the effect.

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}	

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

W.M. Snow et al., *PRC* **83**, 022501(R) (2011)

Toward an improved NSR-3 measurement

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
should give another factor of 4 in stats

Systematic Improvement

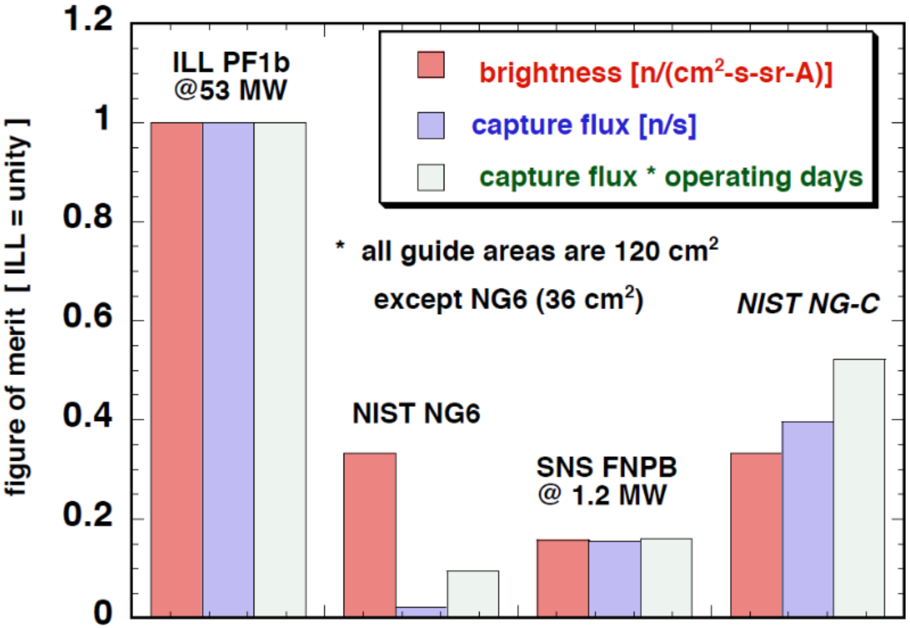
➢ Reduce B field in target region →
1) Goal of 10 μG using additional passive shielding and active trimming.

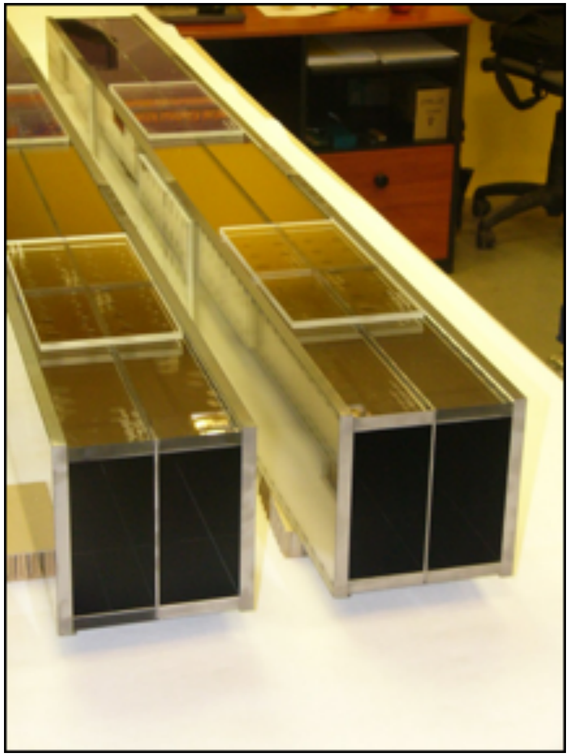
➢ Improve PA →
1) New supermirror polarizers with better reflectivity characteristics.
2) Characterize east-west beams
3) More frequent *PA* measurements

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 ≈ $8\times10^9/\text{cm}^2/\text{s}$

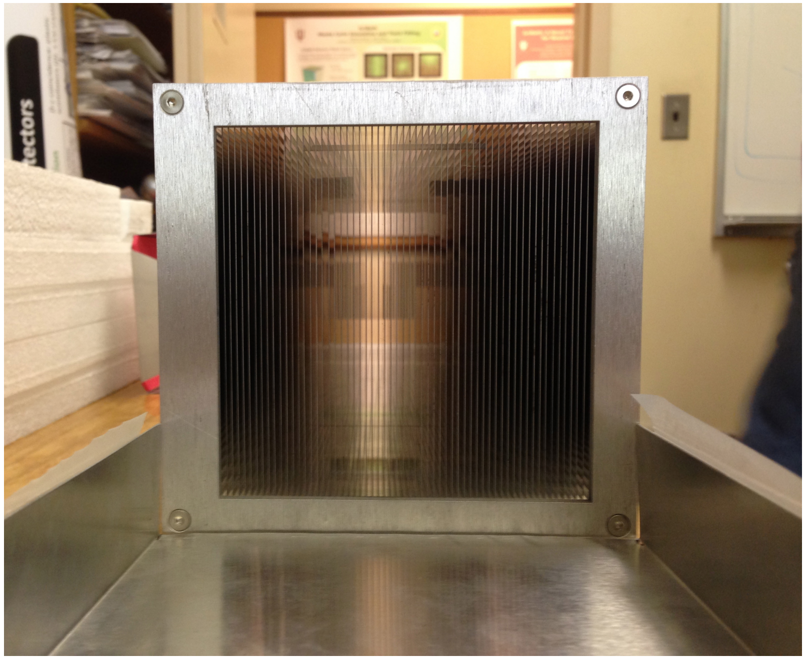




Nonmagnetic Supermirror guides:

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

Polarization Product PA

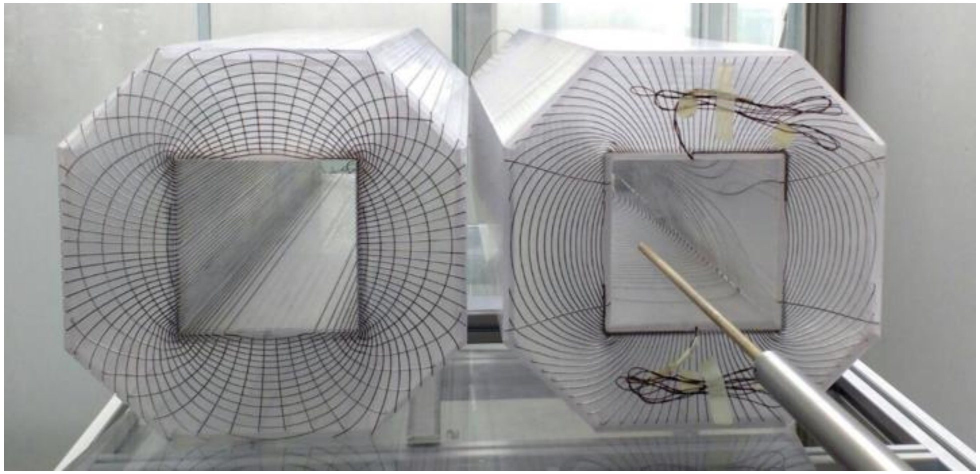


New Supermirror polarizer/analyzer pair:

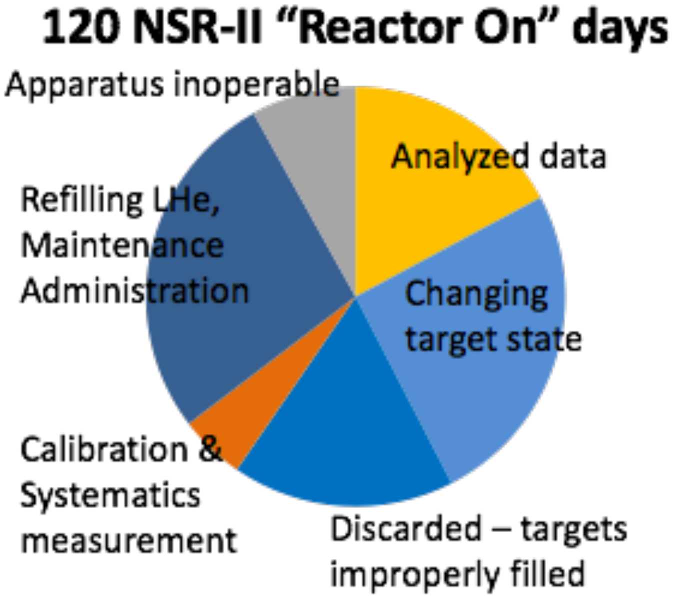
- Two new 10 cm x 10 cm polarizers
- m = 2.5; polarization ≈ 90%
- Better uniformity

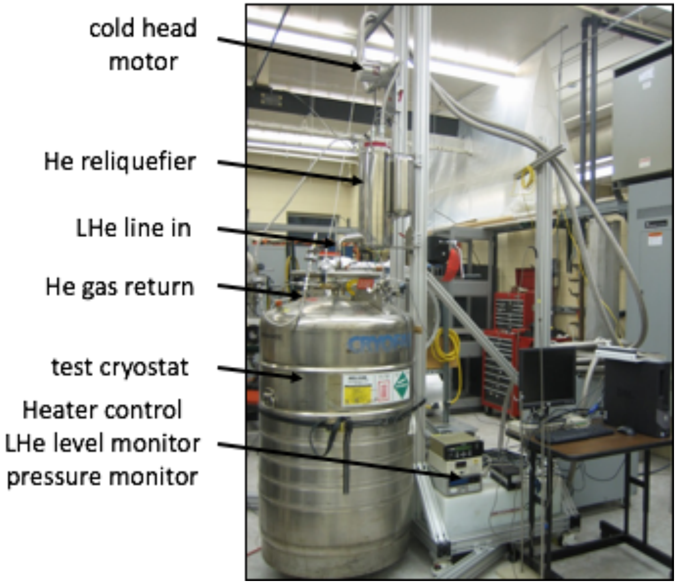
New Input and Output Coils

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



Duty Factor - Improve Cryogenics



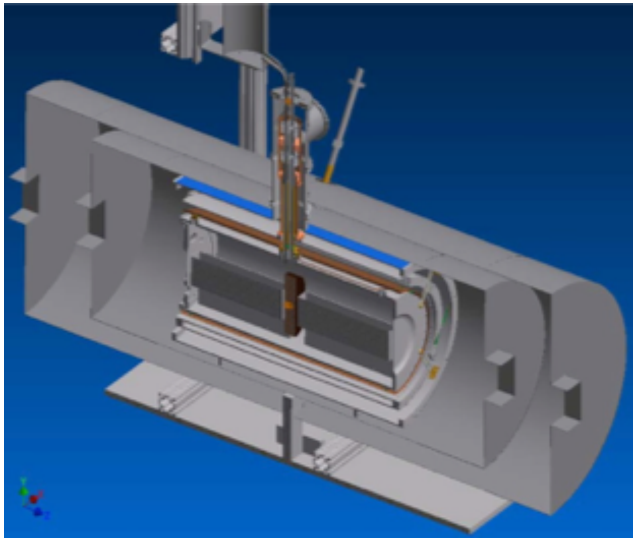


Cryomech pulse-tube reliquefier

- 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 reliquefier removes necessity of LHe fills

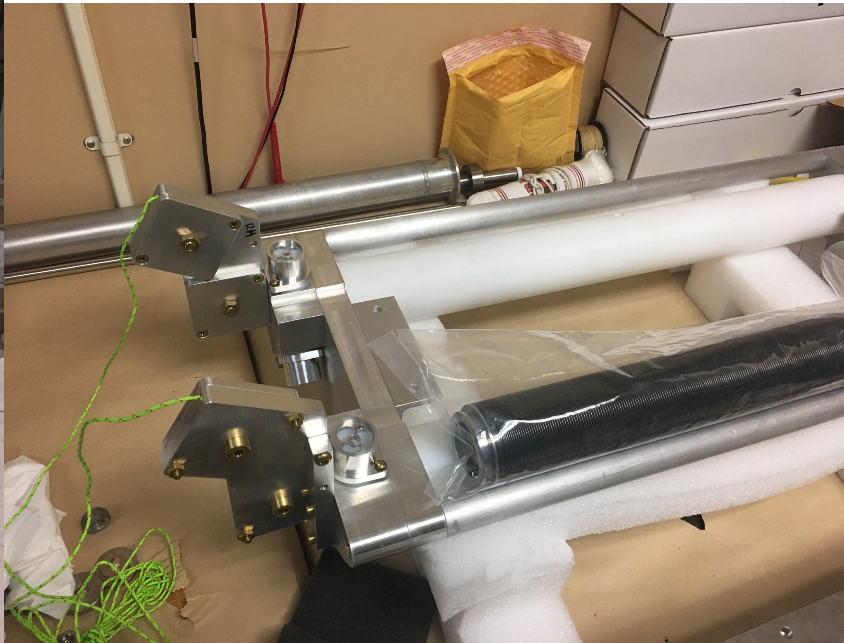


Pump and Target

Nonmagnetic Titanium bellows pump design

Tested for ~600,000 cycles in liquid nitrogen

Suggestion of S Van Sciver, FSU



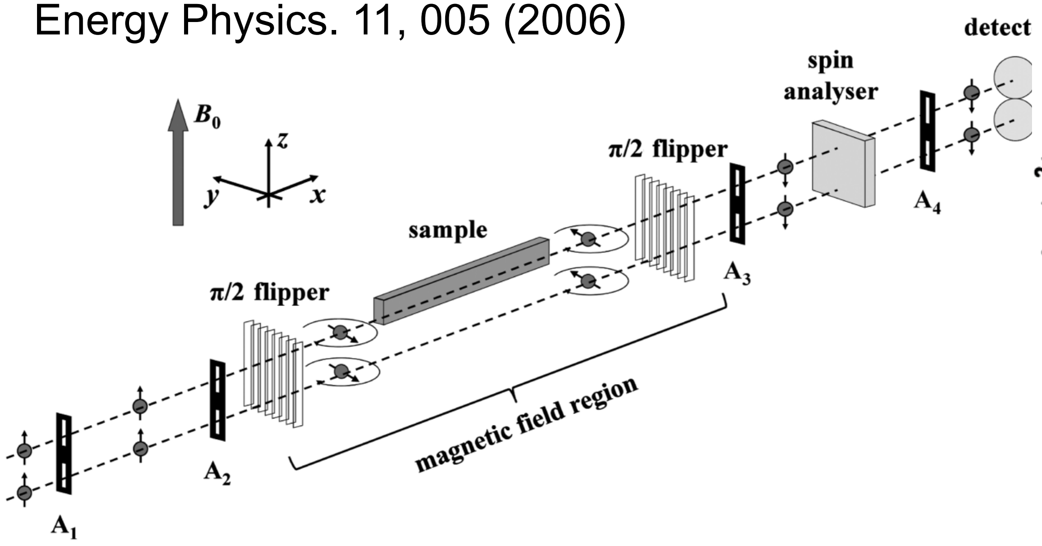
A Spin-1 Boson Axial Coupling Search

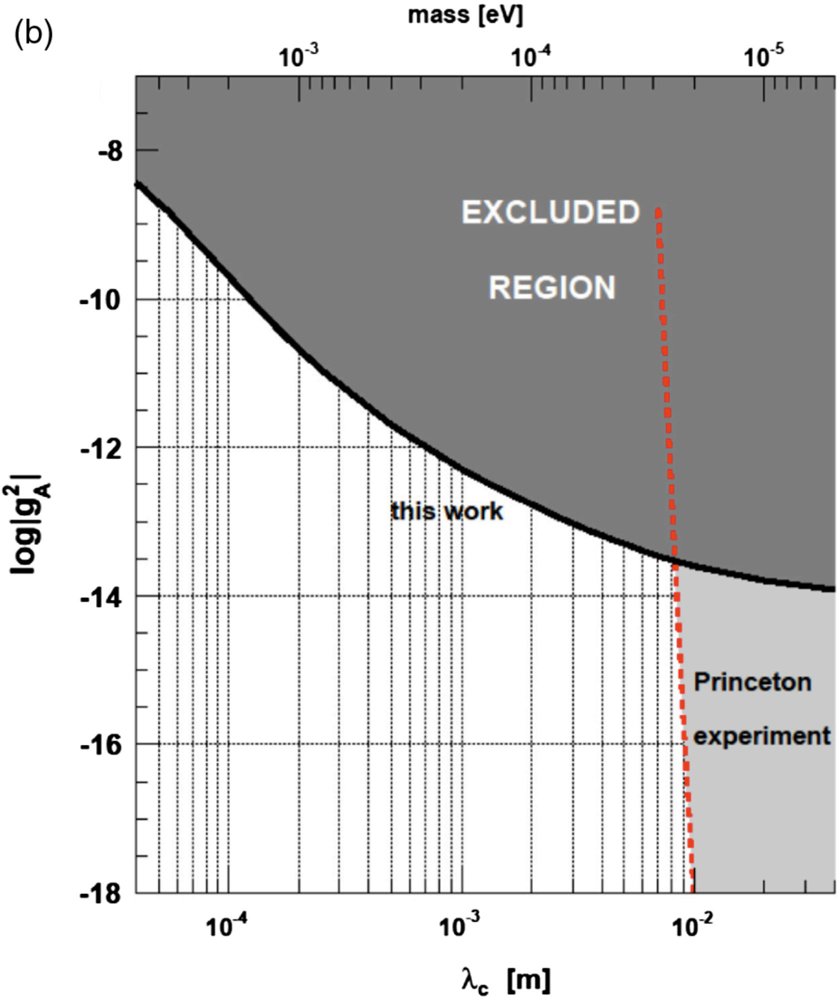
We searched for a beyond-Standard-Model VERY light (~meV) spin-1 boson by passing polarized neutrons near one side of a nonmagnetic mass and looking for an induced rotation of the polarization direction.

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

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

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



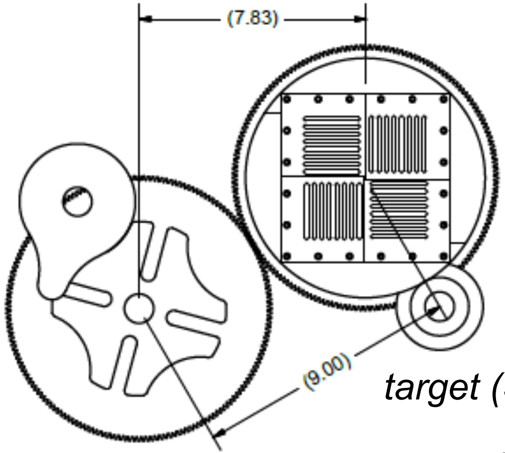


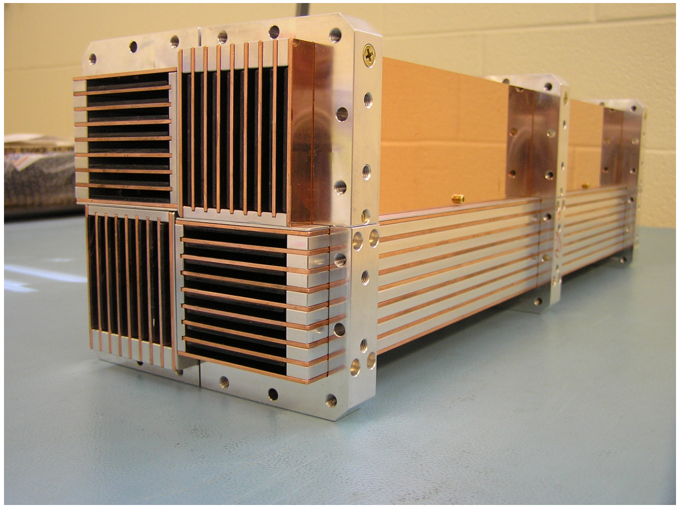
F. Piegsa and G. Pignol, PRL 108, 181801 (2012)

Spin-1 Boson Neutron Axial Coupling Search at LANSCE

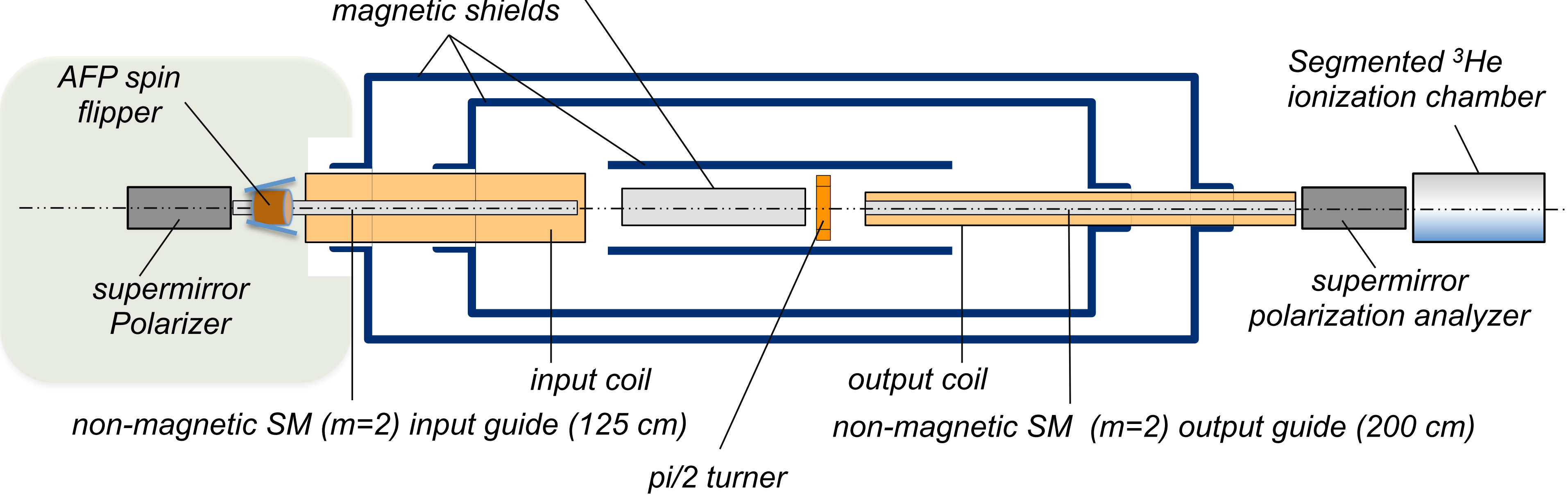
Geneva Mechanism:

Rotate the target by increments of 90°



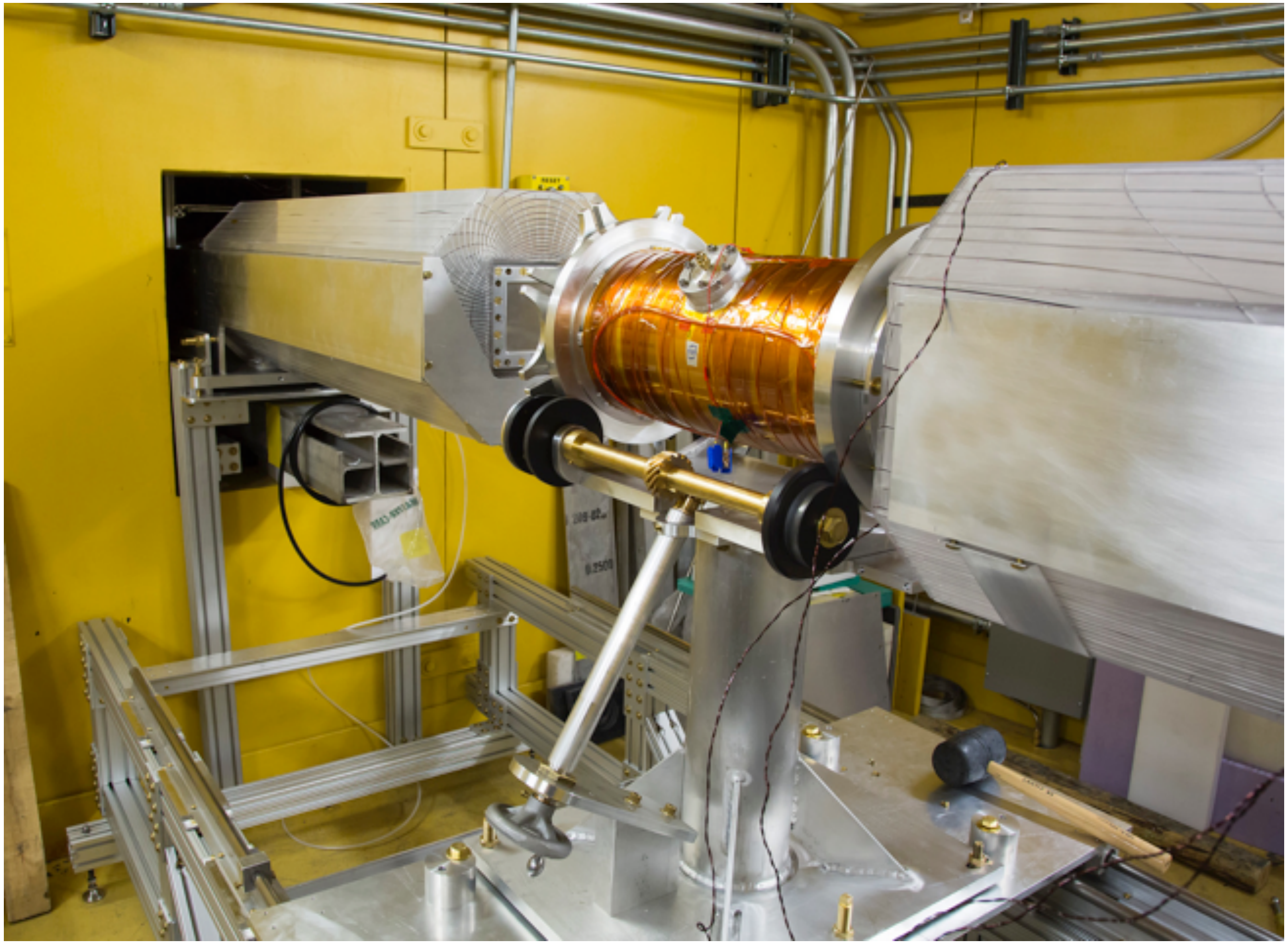


Plates of different nucleon density N are assembled so that the polarized neutrons traveling between the gaps will always see a nucleon density gradient.

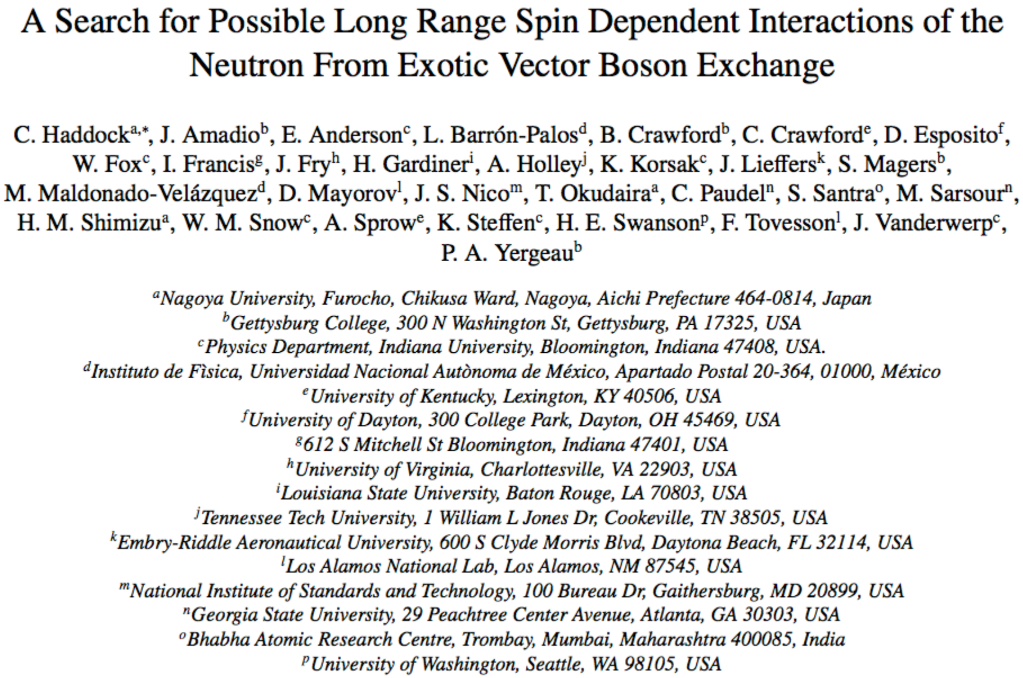


NSRf5 Apparatus at LANSCE FP12

View inside FP12 cave showing input/output supermirror guides and coils and target vacuum chamber. Neutron supermirror polarizer/analyzer, ion chamber, magnetic shielding not shown.



NSRf5 Apparatus at LANSCE FP12



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

C. Haddock[a,*], J. Amadio[b], E. Anderson[c], L. Barrón-Palos[d], B. Crawford[b], C. Crawford[e], D. Esposito[f], W. Fox[c], I. Francis[g], J. Fry[h], H. Gardiner[i], A. Holley[j], K. Korsak[c], J. Lieffers[k], S. Magers[b], M. Maldonado-Velázquez[d], D. Mayorov[l], J. S. Nico[m], T. Okudaira[a], C. Paudel[n], S. Santra[o], M. Sarsour[n], H. M. Shimizu[a], W. M. Snow[c], A. Sprow[e], K. Steffen[c], H. E. Swanson[p], F. Tovesson[l], J. Vanderwerp[c], P. A. Yergeau[b]

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[o]Bhabha Atomic Research Centre, Trombay, Mumbai, Maharashtra 400085, India
[p]University of Washington, Seattle, WA 98105, USA

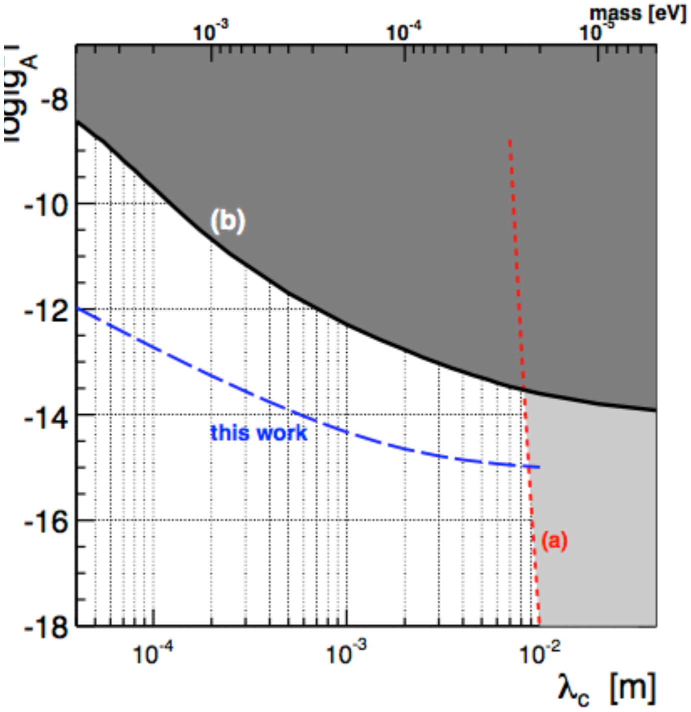


Figure 3: g_A^2 as a function of interaction length λ_c from our experiment (dashed-blue) compared with constraints from a neutron measurement using Ramsey spectroscopy (a) [22] and from K-^{3}He comagnetometry (b) [36]. The final g_A^2 limit includes both statistical and systematic uncertainties.

Submitted to PLB

Previous limits improved by ~3 orders of magnitude.

Summary: n+4He spin rotation

➢ 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. 1.4×10^{-7} rad/m systematic error.

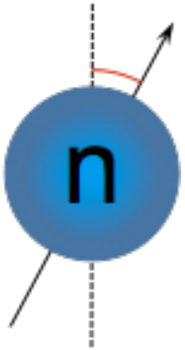
➢ Recent theoretical work suggests a relatively large size for the neutron spin rotation of $\approx 7 \times 10^{-7}$ rad/m.

➢ 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 of $<2 \times 10^{-7}$ rad/m with negligible systematic error

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

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



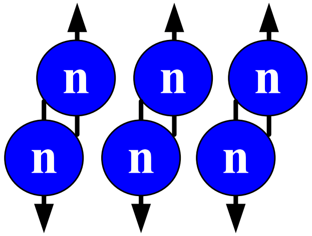
NPDγ Status

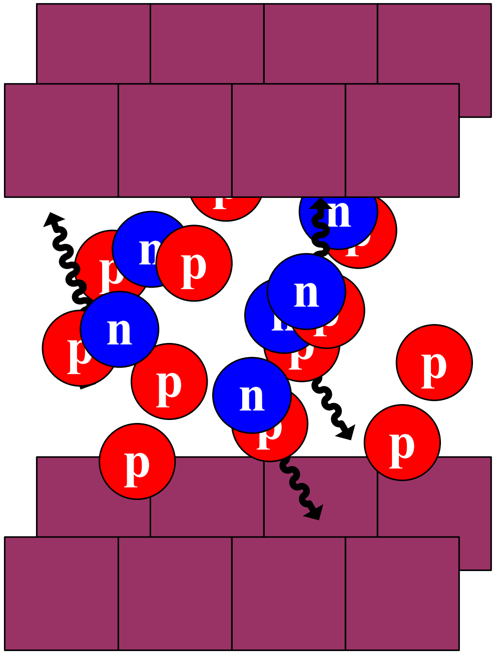
$$A_\gamma(t)P_n\cos\theta=\frac{U_\uparrow-D_\uparrow-(U_\downarrow-D_\downarrow)}{U_\uparrow+D_\uparrow+U_\downarrow+D_\downarrow}$$

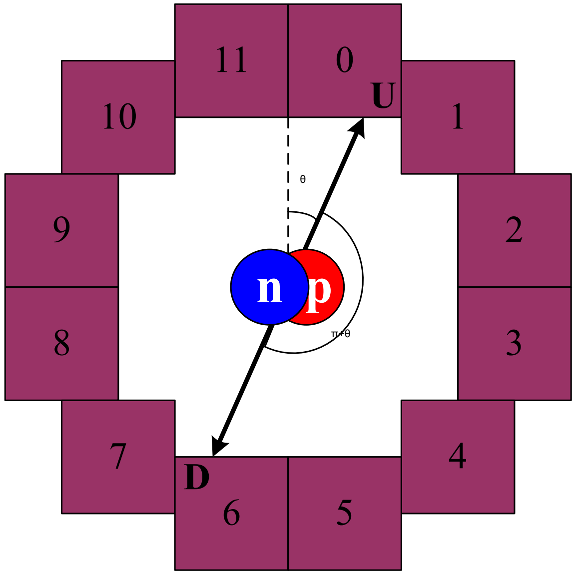
$$A_\gamma=-0.107f_\pi^1-0.001h_\rho^1-0.004h_\omega^1$$

$$\boxed{A_\gamma^{\vec{n}p}\approx\tilde{C}^{3S1->3P1}}$$ Pionless EFT

$$\boxed{A_\gamma^{\vec{n}p}\approx-0.27\tilde{C}_6^\pi-0.09m_\mathrm{N}\rho_\mathrm{t}}$$ Hybrid EFT

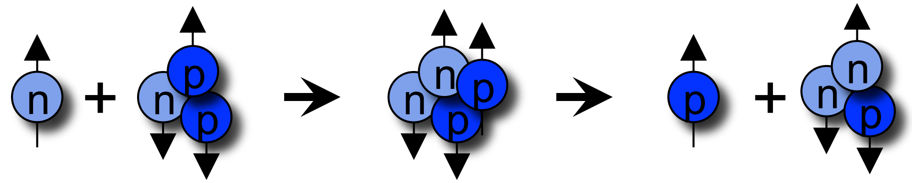




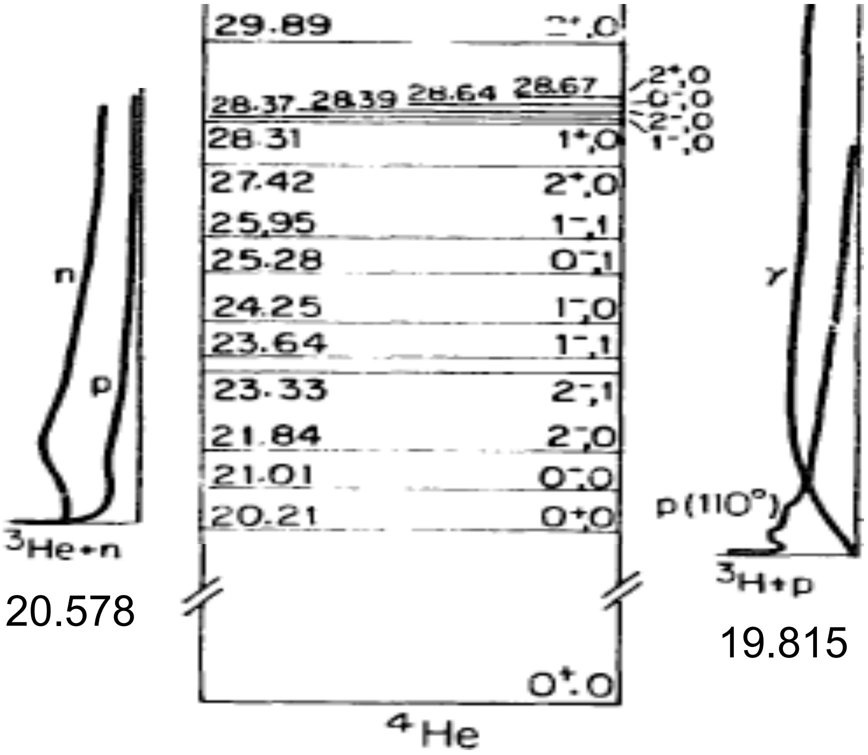


- Prelim. Result (from thesis of D. Blyth): A_γ =(-3.0 +/- 1.4) x 10^{-8} , negligible sys. error
- Submitted to PRL
- Result to be presented at CIPANP

n-^{3}He PV asymmetry at SNS



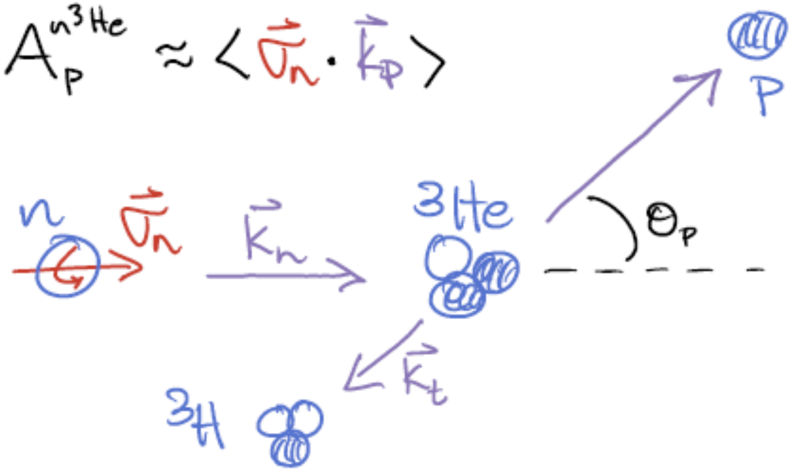
$$\vec{\mathrm{n}} + {}^3\mathrm{He} \rightarrow \mathrm{p} + \mathrm{t} + 764\ \mathrm{keV}$$



Tilley, Weller, Hale, Nucl. Phys. A541, 1 (1992)

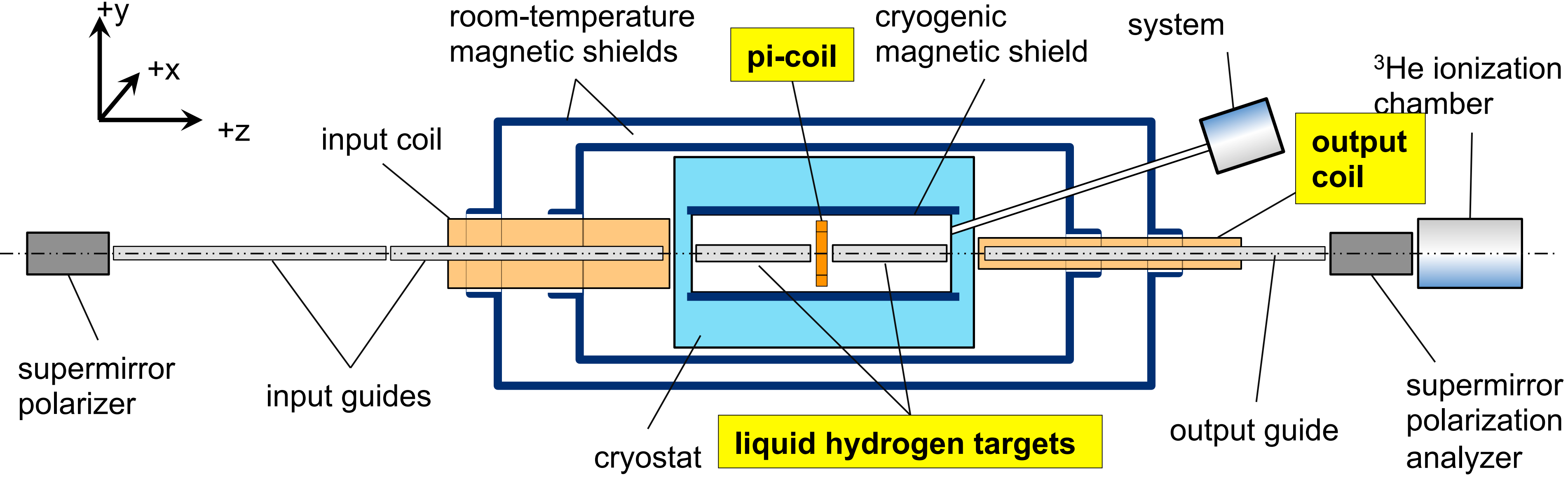
PV observables:

$$A_P^{n^3He} \approx \langle \vec{\sigma}_n \cdot \vec{k}_P \rangle$$



- Sensitive to isoscalar couplings (ΔI=0) of the hadronic weak interaction
- GOAL: measure asymmetry to ~2 x 10^{-8}
- A=(1 +/-1 [stat]) x 10^{-8} (L. Kabir, PhD thesis, U Kentucky, shown by M. Gericke at KITP workshop)

What about Liquid Hydrogen Spin Rotation?



+y
+x
+z
room-temperature magnetic shields
pi-coil
cryogenic magnetic shield
motion-control system
^{3}He ionization chamber
input coil
output coil
supermirror polarizer
input guides
cryostat
liquid hydrogen targets
output guide
supermirror polarization analyzer

2-body system: very nice from pionless EFT point of view, some sensitivity to ΔI=2 amplitude

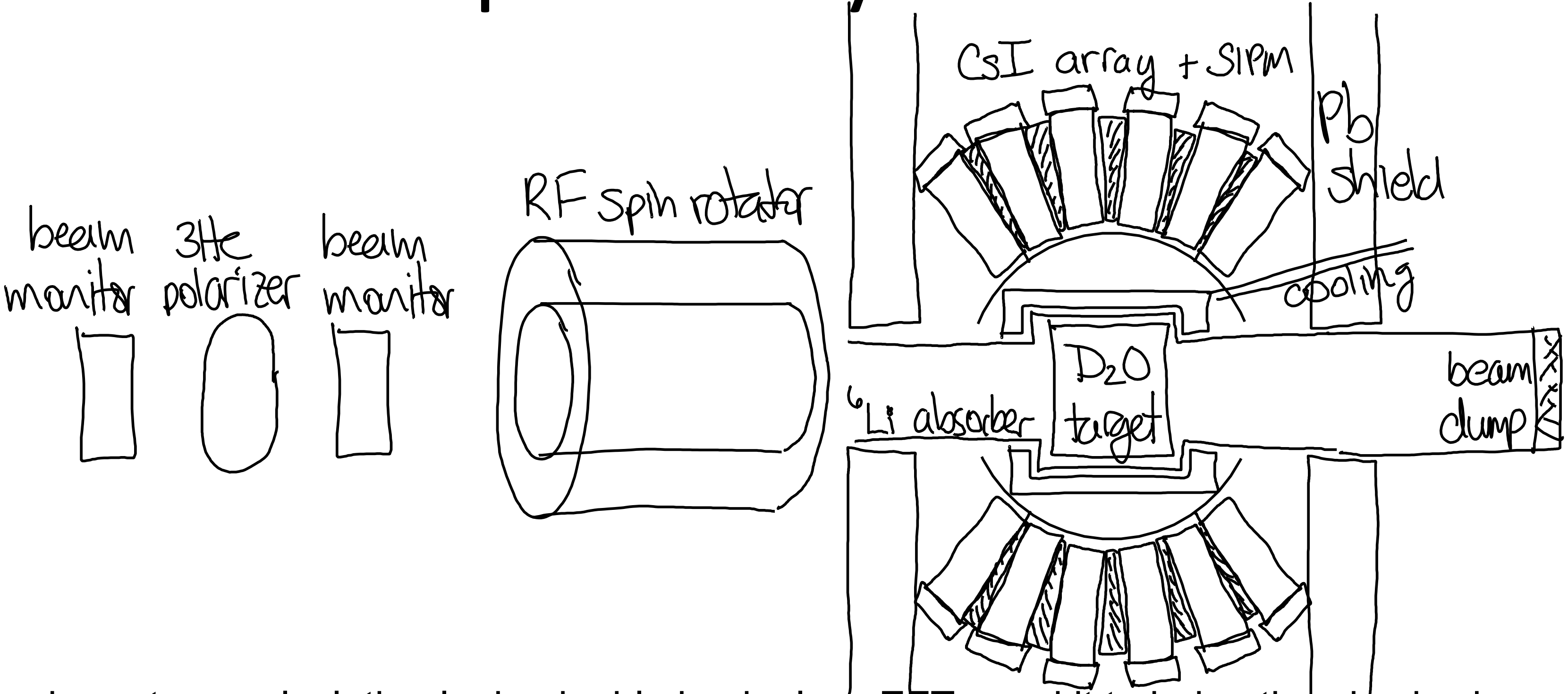
PV spin rotation angle estimated to be “large” (1 E-6 rad/m) using $1/N_c$

Can use same components as for the helium spin rotation apparatus except for the cryogenic target

Target length is shorter than for 4K helium by ~factor of 2, more small angle scattering systematics

With NIST cold source upgrade and longer running time: 1E-7 rad/m statistical error is possible

NDTG possibility at NIST NG-C



3-body system: calculation looks doable in pionless EFT, need it to judge the physics impact (new calculations by Gudkov et al and others exist)

PV asymmetry should be “large” (~10E-6)

~1E-7 statistical error on asymmetry looks possible at NIST NG-C (needs checking)

Some work done on preservation of n polarization on D capture in D2O

Many of the hardware components are in-hand/inexpensive

Would need a large double-cell 3He neutron spin filter: possible (see Jlab cells)

Comments on other neutron HPV experiments

Final results from NPDGamma and n-3He PV experiments.

There are enough neutrons to do more HPNC experiments

Best beam for this in the short-term is NIST NG-C

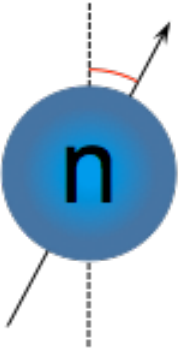
Three experiments appear within reach statistically at NG-C:

(1) n-4He spin rotation (under construction)
(2) NDTGamma (proposed at the KITP2018 workshop)
(3) n-p spin rotation (active parahydrogen target is a challenge)

Circular polarization in n-p capture ("Lobashev experiment"): could see ΔI=2 piece calculable on lattice: can we find a thermal beam?

If/when ESS beam is constructed, can get ~X5 more polarized cold neutrons for this physics

NRS-3 Collaboration



E. Anderson[1], L. Barron-Palos[2], B.E. Crawford[3], C. Crawford[4], W. Fox[1], J. Fry[1], C. Haddock[1], B.R. Heckel[5], A. T. Holley[6], S.F. Hoogerheide[7], K. Korsak[1], M. Maldonado-Velazquez[2], H.P. Mumm[7], J.S. Nico[7], S. Penn[8], S. Santra[9], M. Sarsour[10], W.M. Snow[1], K. Steffen[1], H.E. Swanson[5], J. Vanderwerp[1]

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