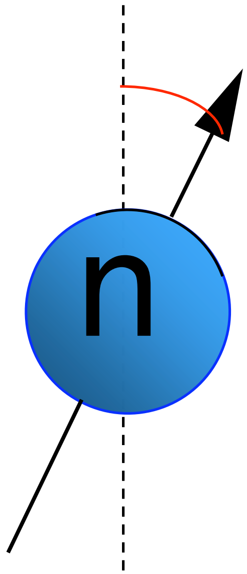

Parity-odd Neutron Spin Rotation and the NN weak interaction

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Indiana University/IUCF
PAVI09

Theory outline of weak NN interaction
What is parity-odd neutron spin rotation?
n+4He experiment @NIST: analysis nearing completion
Future possibilities for 4He, H, D P-odd spin rotation

N-4He Spin Rotation Collaboration

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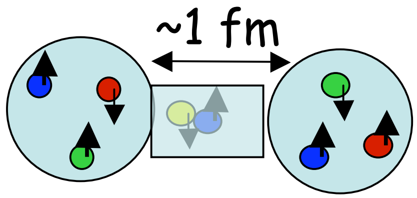
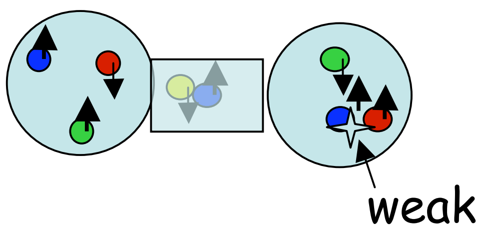
North Carolina State University / TUNL [5]
North Carolina Central University [6]
National Institute of Standards and Technology (NIST) [7]
Joint Institute for Nuclear Research, Dubna, Russia [8]
Al-Farabi Khazakh National University [9]

The Weak NN Interaction on one slide



NN repulsive core (from Pauli principle applied to quarks)->1 fm range for strong NN

$|N\rangle=|qqq\rangle+|qqq\bar{q}q\rangle+\ldots$=valence+sea quarks+gluons+…
interacts through strong NN force, mediated by mesons $|m\rangle=|q\bar{q}\rangle+\ldots$
Interactions have long (~1 fm) range, <u>QCD conserves parity</u>



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

If the quarks are close, the weak interaction can act, which violates parity at a length scale small compared to that set by Λ_{QCD}

Relative weak/strong amplitudes: $\sim[e^2/m^2_W]/[g^2/m^2_\pi]\sim10^{-6}$

Quark-quark weak interaction induces NN weak interaction

<u>Visible using parity violation</u>

<u>q-q weak interaction: an “inside-out” probe of QCD ground state</u>

Weak qq-> Weak NN: what can we learn?

Δs=1 nonleptonic weak interactions [ΔI=1/2 rule, hyperon decays not (completely) understood, data not close to simple estimates from flavor symmetries]

Question: is this problem specific to the strange quark, or is it a general feature in the nonleptonic weak interactions of light quarks? [For nontrivial q-q dynamics answer should be yes.]

To answer, we must look at Δs=0 nonleptonic weak interactions (u,d quarks) [this sector also sees q-q neutral weak currents]

Any such process is dominated by strong interaction->must measure ~1E-6 PV effects at low E

Weak NN interaction is one of the few experimentally feasible systems where this is possible

SM Structure of qq Weak Interaction

- At low energies L_{weak} takes a current-current form involving charged and neutral weak currents with $\Delta I = 0, 1/2, 1$

$$L = \frac{G_F}{\sqrt{2}}(J_W^\dagger J_W + J_Z^\dagger J_Z) + h.c. \quad J_W = \cos\theta_c J_W^1 + \sin\theta_c J_W^{1/2} \qquad J_z = J_Z^0 + J_Z^1$$

$$L = \frac{G_F}{\sqrt{2}}[\cos^2\theta_c (J_W^1)^\dagger J_W^1 + \sin^2\theta_c (J_W^{1/2})^\dagger J_W^{1/2} + (J_Z^0)^\dagger J_Z^0 + (J_Z^1)^\dagger J_Z^1 + (J_Z^0)^\dagger J_Z^1 + (J_Z^1)^\dagger J_Z^0] + h.c.$$

$$\Delta I = 0, 2 \qquad \Delta I = 1 \qquad \Delta I = 0, 1, 2$$

- Charged currents in ΔI=1 weak NN processes are Cabbibo-suppressed at tree level

- QCD renormalization of terms in L_{weak} is known to modify relative size of operators between electroweak scale and QCD scale

NN Weak Interaction: 5 Independent Amplitudes at Low Energy

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

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

Space-$\mathcal{S}$ (even L) ⊗ spin-$\mathcal{A}$ (S_{tot} = 0) ⇒ $^1S_0$, $^1D_2$, $^1G_4$, …
or Space-$\mathcal{A}$ (odd L) ⊗ spin-$\mathcal{S}$ (S_{tot} = 1) ⇒ $^3P_{0,1,2}$, $^3F_{2,3,4}$, …

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

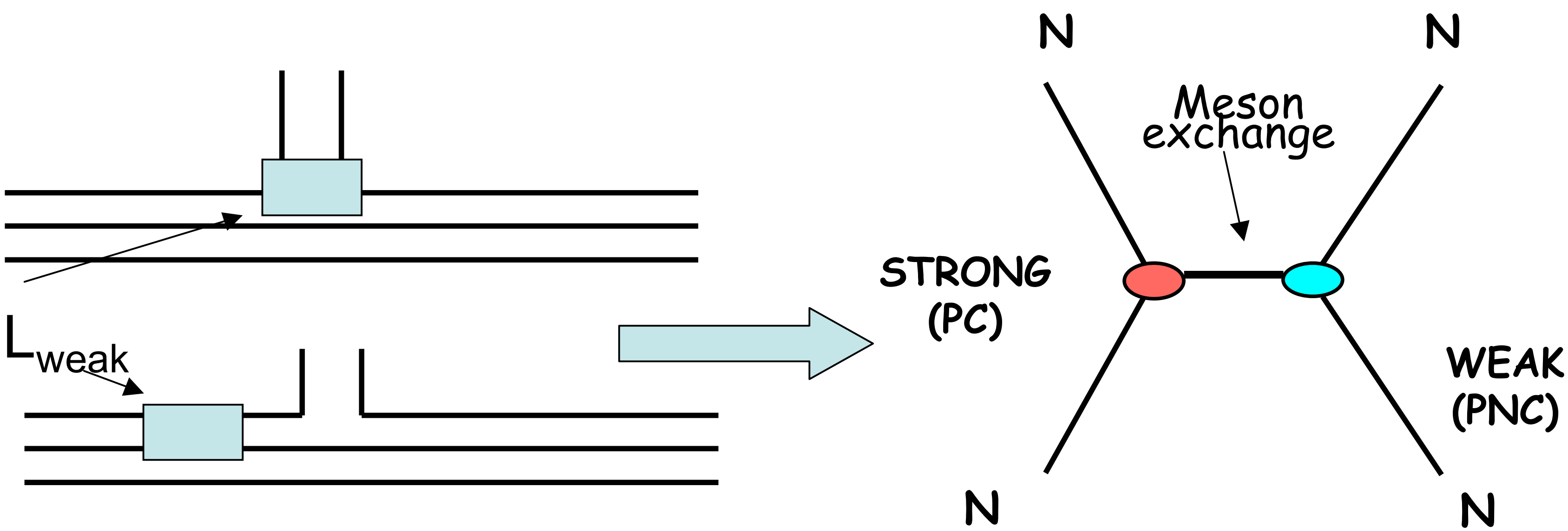
Space-$\mathcal{A}$ (odd L) ⊗ spin-$\mathcal{A}$ (S_{tot} = 0) ⇒ $^1P_1$, $^1F_3$, …
Space-$\mathcal{S}$ (even L) ⊗ spin-$\mathcal{S}$ (S_{tot} = 1) ⇒ $^3S_1$, $^3D_{1,2,3}$, $^3G_{3,4,5}$, …

$^{(2S+1)}L_J$ 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 and only source for P waves is from weak interaction, we have 5 independent NN parity-violating 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)

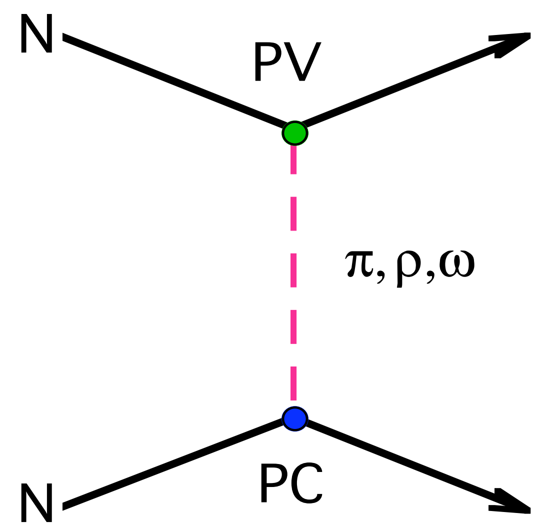
Different Theoretical Approaches to weak NN interaction



- Kinematic: 5 S->P transition amplitudes in elastic NN scattering [Danilov]
- QCD effective field theory: χ perturbation theory [Liu, Holstein, Musolf, et al, incorporates chiral symmetry of QCD]
- Dynamical model: meson exchange model for weak NN [effect of qq weak interactions parametrized by ~6 couplings, Desplanques, Donoghue, Holstein,…]+ QCD model calculations
- Standard Model [need QCD in strong interaction regime, lattice+EFT extrapolation (Beane&Savage)]

Meson Exchange Model (DDH) and other QCD Models

assumes π, ρ, and ω exchange dominate the low energy PNC NN potential as they do for strong NN



Weak meson-nucleon couplings $f_\pi, h_\rho^0, h_\rho^1, h_\rho^2, h_\omega^0, h_\omega^1$ to be determined by experiment

f_π calculated/estimated to be (x E-7)

~5	χPT+strange quarks (Kaplan/Savage 93)
4.6	quark model (DDH)
3	QCD sum rules (Henley/Hwang/Kisslinger 98)
0.8-1.3	SU(3) chiral soliton model (Meissner/Weigel 99)
3.4	QCD sum rules (Lobov02)
	chiral quark/instanton model (Lee/Hyun/Lee/Kim)
	ADS/CFT model (Gazit/Lee)

NN χPT coefficients and quantum numbers (Liu07)

Partial wave transition	$I \leftrightarrow I'$	ΔI	n-n	n-p	p-p	EFT coupling
$^3S_1 \leftrightarrow {}^3P_1$	$0 \leftrightarrow 1$	1		√		$m\rho_t$
$^3S_1 \leftrightarrow {}^1P_1$	$0 \leftrightarrow 0$	0		√		$m\lambda_t$
$^1S_0 \leftrightarrow {}^3P_0$	$1 \leftrightarrow 1$	0	√	√	√	$m\lambda_s^{nn}$
$^1S_0 \leftrightarrow {}^3P_0$	$1 \leftrightarrow 1$	1	√		√	$m\lambda_s^{np}$
$^1S_0 \leftrightarrow {}^3P_0$	$1 \leftrightarrow 1$	2	√	√	√	$m\lambda_s^{pp}$
$^3S_1 \leftrightarrow {}^3P_1$	$0 \leftrightarrow 1$	1		√		$C^\pi [\sim f_\pi]$

First 5 couplings are allowed s->p transition amplitudes in NN elastic scattering in "pionless" EFT limit (same as Danilov parameters)

Last coupling is long-range part of weak pion exchange [in DDH$\sim f_\pi$]

NN χPT coefficients and observables (Liu07)

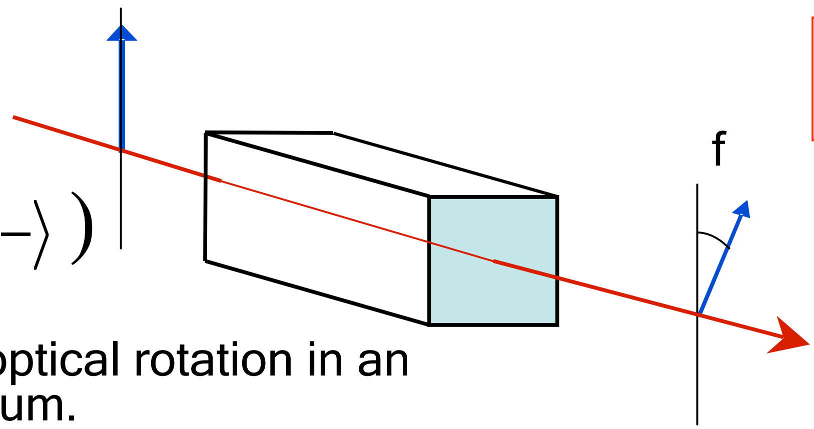
EFT coupling (partial wave mixing)	np A_γ	np P_γ	nD A_γ	nα ϕ	np ϕ	pp A_z	pα A_z
$m\rho_t\,(^3S_1 - {}^3P_1)$	-0.09	0	1.4	-2.7	1.4	0	-1.07
$m\lambda_t\,(^3S_1 - {}^1P_1)$	0	0.7	1.2	1.3	-0.6	0	-0.54
$m\lambda_s^{nn}\,(^1S_0 - {}^3P_0)$	0	0	0.6	1.2	0	0	-0.48
$m\lambda_s^{np}\,(^1S_0 - {}^3P_0)$	0	-0.16	0.5	0.6	2.5	0	-0.24
$m\lambda_s^{pp}\,(^1S_0 - {}^3P_0)$	0	0	0	0	0	-0.45, -0.78	0
$C^\pi\,(^3S_1 - {}^3P_1)[\sim f_\pi]$	-0.3	0	0	0	0.3	0	0
experiment (10^{-7})	0.6 ±2.1	1.8 ±1.8	42 ±38	8 ±14		-0.93, -1.57 ±0.2	-3.3 ±0.9

Column gives relation between PV observable and weak couplings in EFT with pion
Needs calculations of PV in few body systems (NN done, others in progress)

A Parity-Violating Observable: Neutron Spin Rotation

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

$$|\uparrow\rangle_i = \frac{1}{\sqrt{2}}\left(|+\rangle + |-\rangle\right)$$



- Analogous to optical rotation in an "handed" medium.

- Transversely-polarized neutrons corkscrew due to the NN weak interaction

- ***PV Spin Angle*** is independent of incident neutron energy in cold neutron regime, d ϕ_{PV}/dx ~ 10^{-6} rad/m based on dimensional analysis

- dϕ_{PC}/dx (due to B field) can be much larger than dϕ_{PV}/dx, and is v_n dependent

Refractive index dependent on neutron helicity

$$\frac{1}{\sqrt{2}}\left(e^{-i(\phi_{PC}+\phi_{PV})}|z\rangle + e^{-i(\phi_{PC}-\phi_{PV})}|-z\rangle\right)$$

$$\phi_{PV} = \varphi_+ - \varphi_- = 2\pi l \rho f_{PV}$$

Theoretical Expectations for 4He Spin Rotation

$$\phi_{PV}\left(\vec{n}, {}^{4}\mathrm{He}\right) = -\left(0.97 f_{\pi} + 0.22 h_{\omega}^{0} - 0.22 h_{\omega}^{1} + 0.32 h_{\rho}^{0} - 0.11 h_{\rho}^{1} - 0.02 h_{\rho}^{\prime 1}\right) \mathrm{rad/m}$$

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

Using "best values" and "reasonable range" values for DDH couplings:

$$\varphi_{PV}\left(\vec{n}, {}^{4}\mathrm{He}\right) = -\left(0.1 \pm 1.5\right) \times 10^{-6} \ \mathrm{rad/m}$$

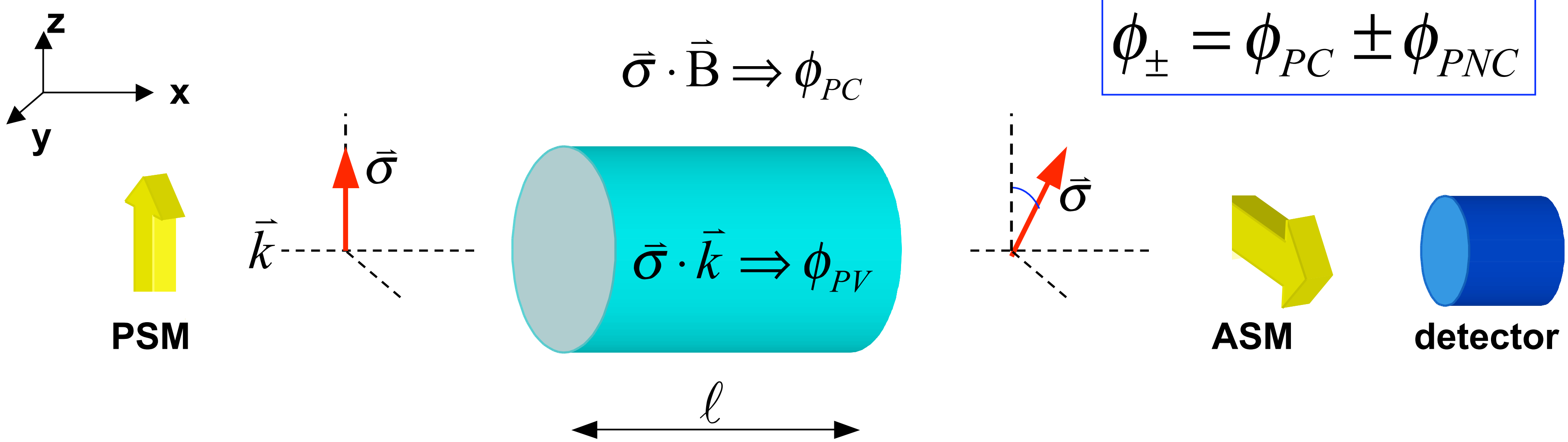
In terms of new EFT couplings Zhu *et al*. Nucl. Phys. A **748** 435-498 (2005)

$$\phi_{\mathrm{PV}}(n\, {}^{4}\mathrm{He}) = (1.2 \lambda_{s}^{nn} + 0.6 \lambda_{s}^{np} + 1.3 \lambda_{t} - 2.7 \rho_{t})\, m_{n}$$

ϕ = (8 ± 14 (stat) ± 2 (sys)) ´10-7 rad/m is existing (unpublished) experimental limit (D. Markoff, PhD thesis U Washington)

PV Neutron Spin Rotation Measurement

$$\phi_{\pm} = \phi_{PC} \pm \phi_{PNC}$$



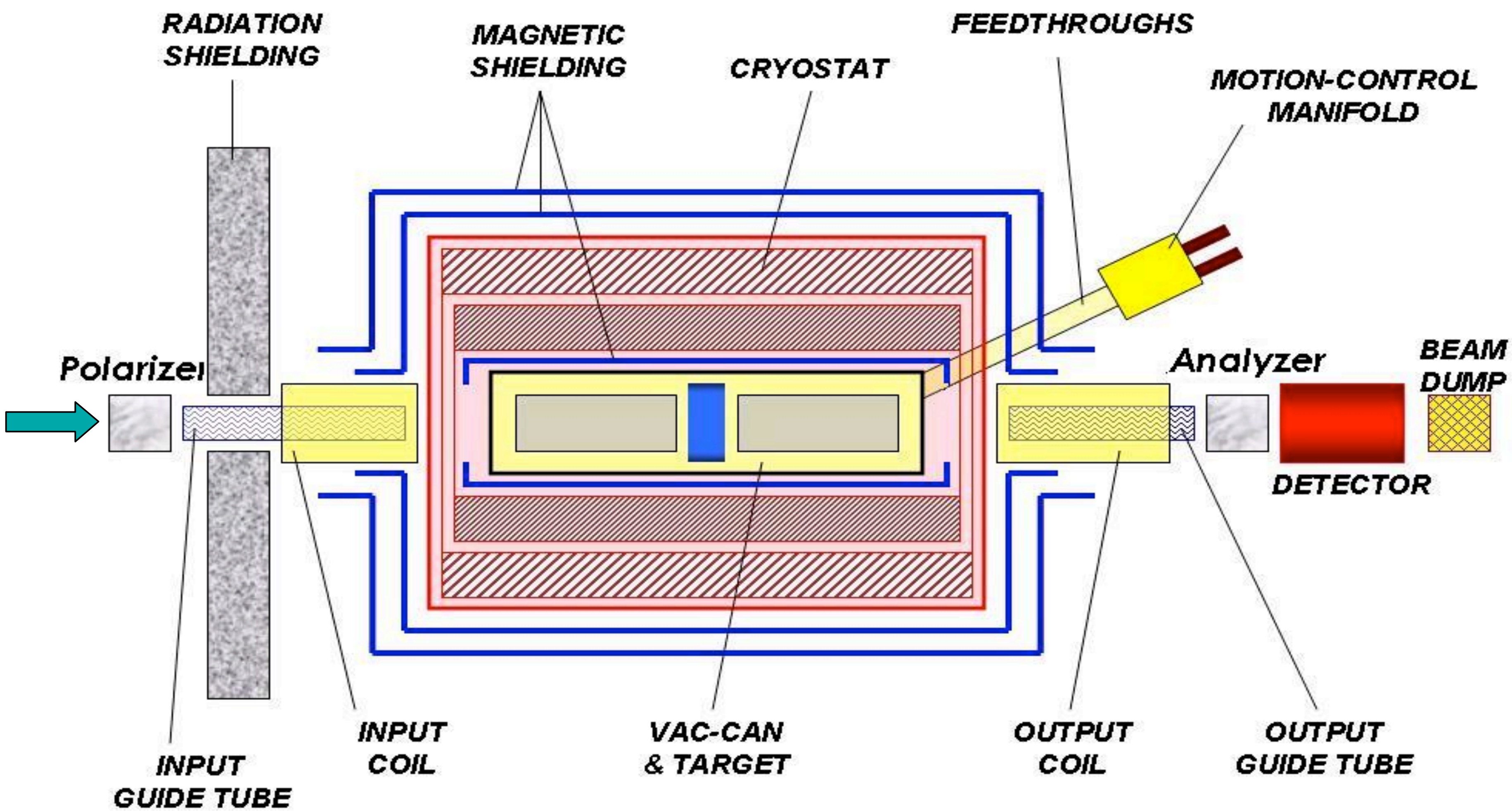
$$\phi_{PNC} = \varphi_{+} - \varphi_{-} = 2\pi \rho z f_{PNC}$$

- PV rotation angle / unit length ($d\phi_{PV}/dx$) approaches a finite limit for zero neutron energy:

  $d\phi_{PV}/dx \sim 10^{-6}$ rad/m inlight nuclei (H,D,^{4}He)
- $d\phi_{PC}/dx$ (due to B field) is much larger than $d\phi_{PV}/dx$, and is v_n dependent:

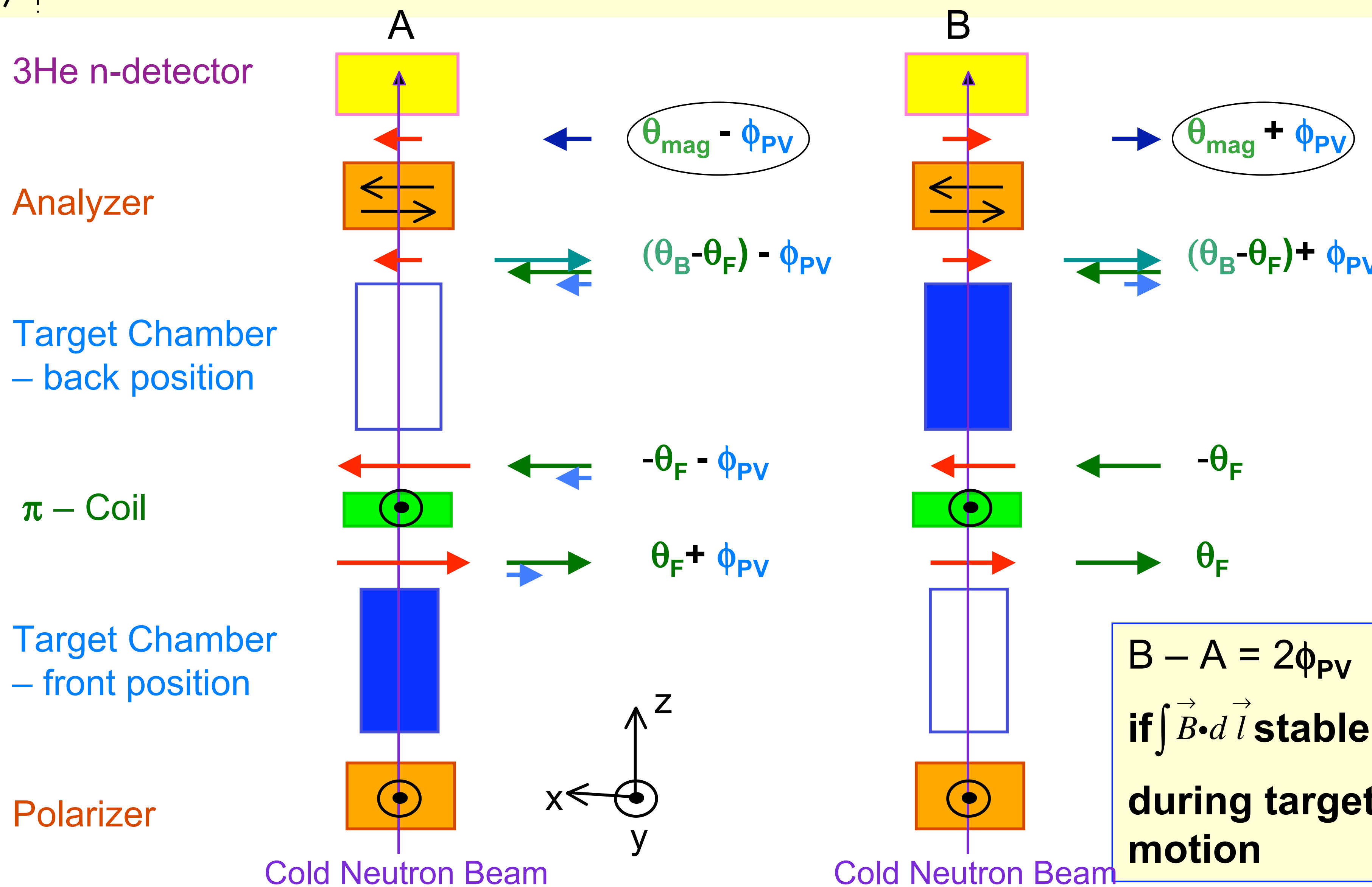
Spin rotation of polarized meV neutrons in B field of Earth is larger than PV rotation by 6 orders of magnitude

Cross section of Spin Rotation Apparatus



Step 1 to isolate PV spin rotation: shielding reduces B by $\sim 10^4$

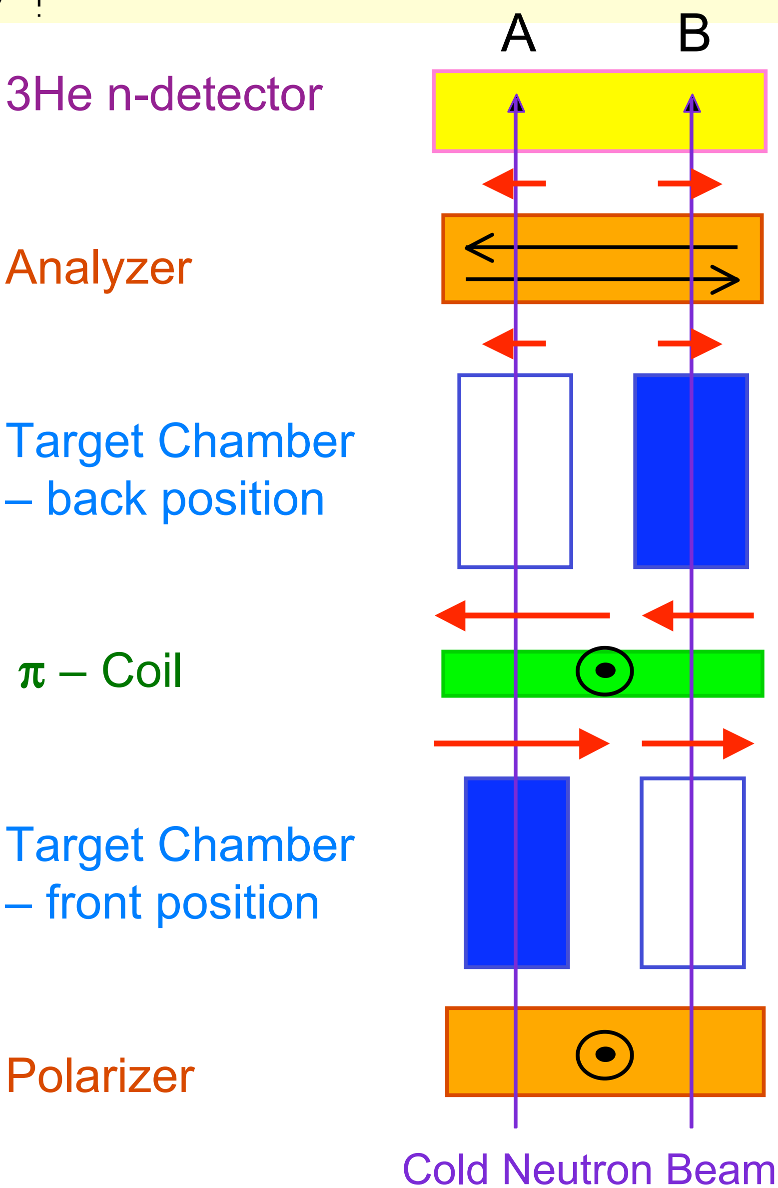
Target design: Oscillation of PV Signal

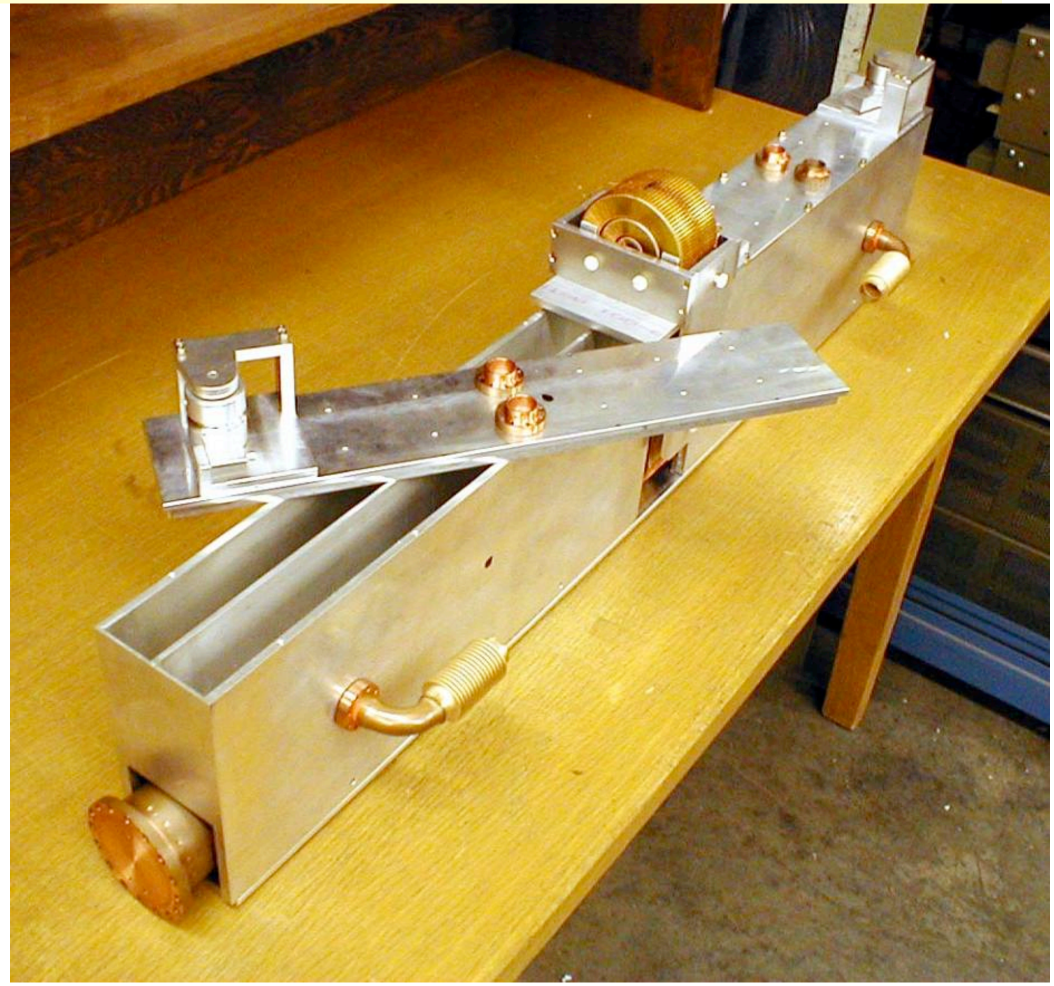


$B - A = 2\phi_{PV}$

if $\int \vec{B}\cdot d\vec{l}$ stable during target motion

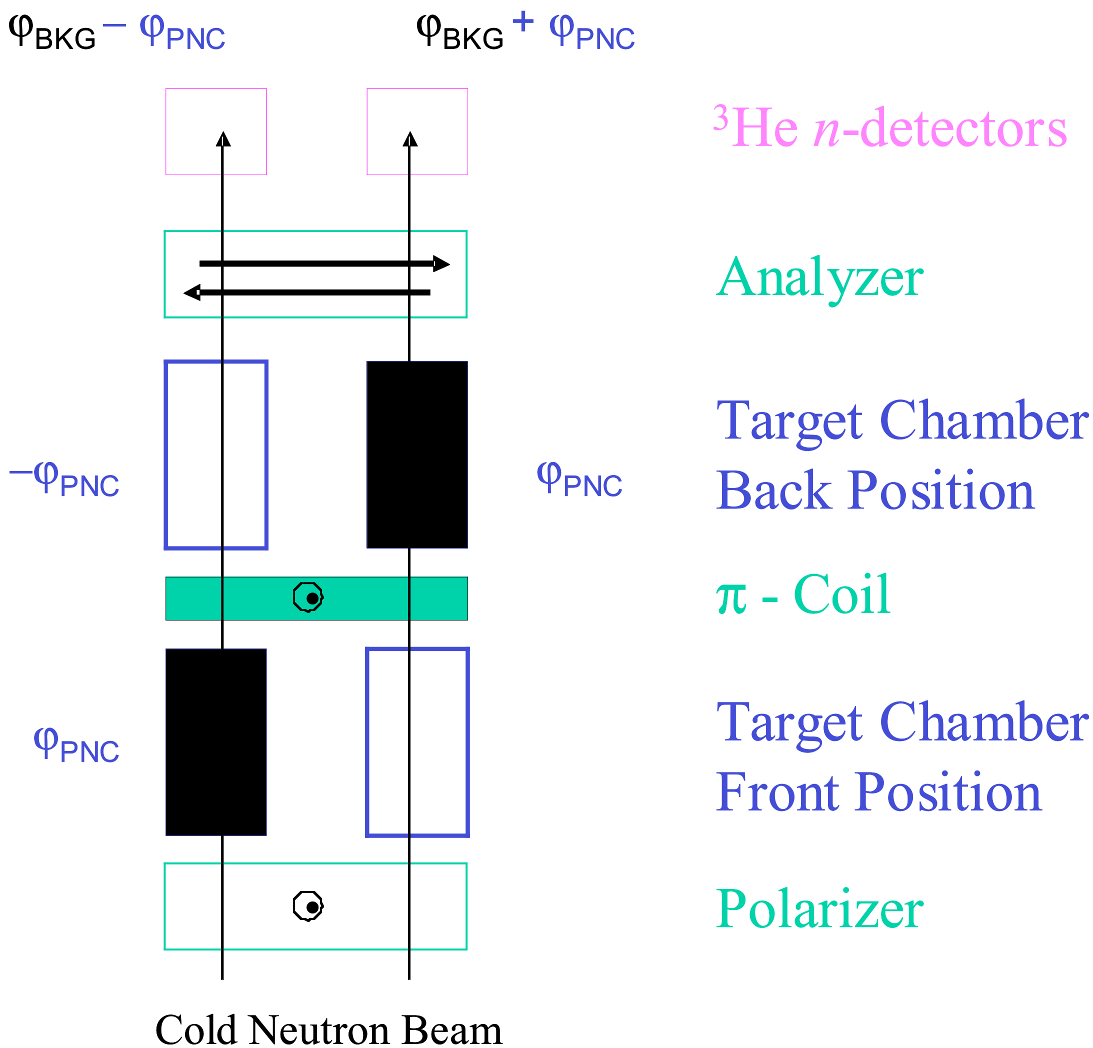
Target design: Beam Noise Suppression





$[B - A]_1 - [B - A]_2 = 4\phi_{PV}$ **if** $\int_B [\vec{B} \cdot d\vec{l}\,] - \int_A [\vec{B} \cdot d\vec{l}\,]$ **stable during target motion**

Signal Modulation/ Noise Suppression



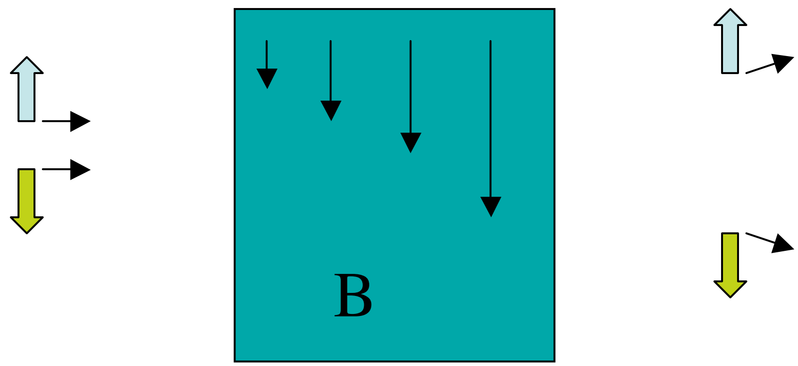
Motion of liquid isolates P-odd signal

Beam split into two parallel beams for common-mode noise reduction

Analyzer direction switched at known frequency

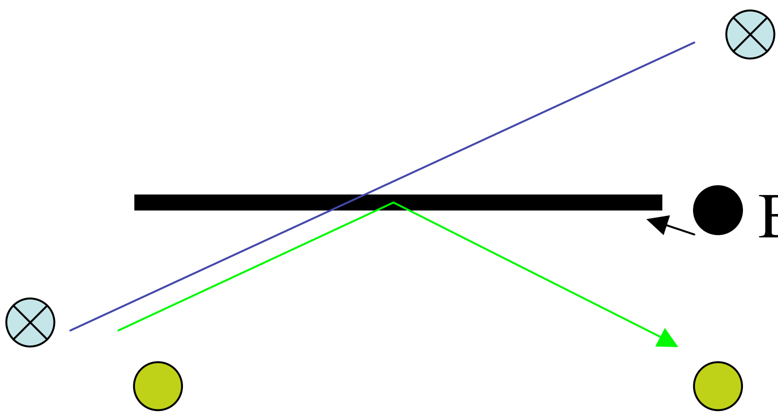
$$\sin\varphi = \frac{N_{+} - N_{-}}{N_{+} + N_{-}}$$

How can neutrons be polarized?



B gradients (Stern-Gerlach, sextupole magnets) electromagnetic

$F=(\mu \bullet \nabla)B$

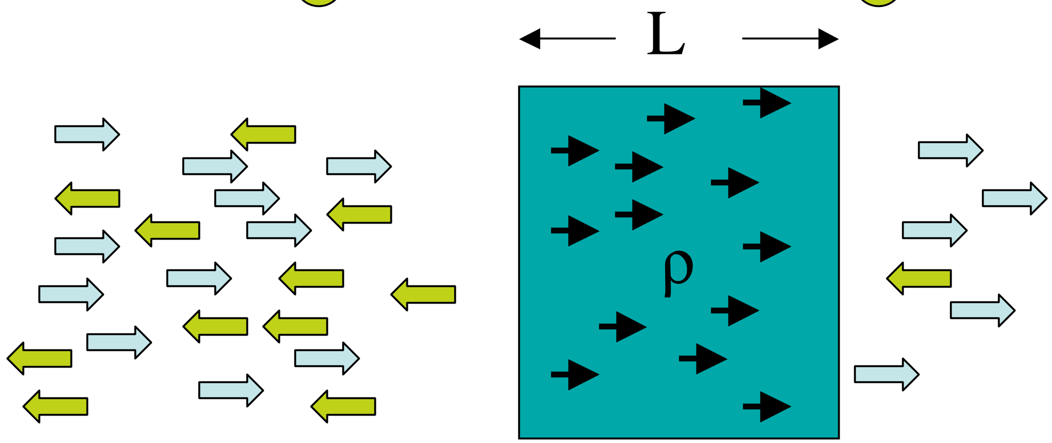


Reflection from magnetic mirror: electromagnetic+ strong

$f\pm=a(strong)\ +/-\ a(EM)$

with $|a(strong)|=|a(EM)|$

$\Rightarrow f+=2a,\ f-=0$

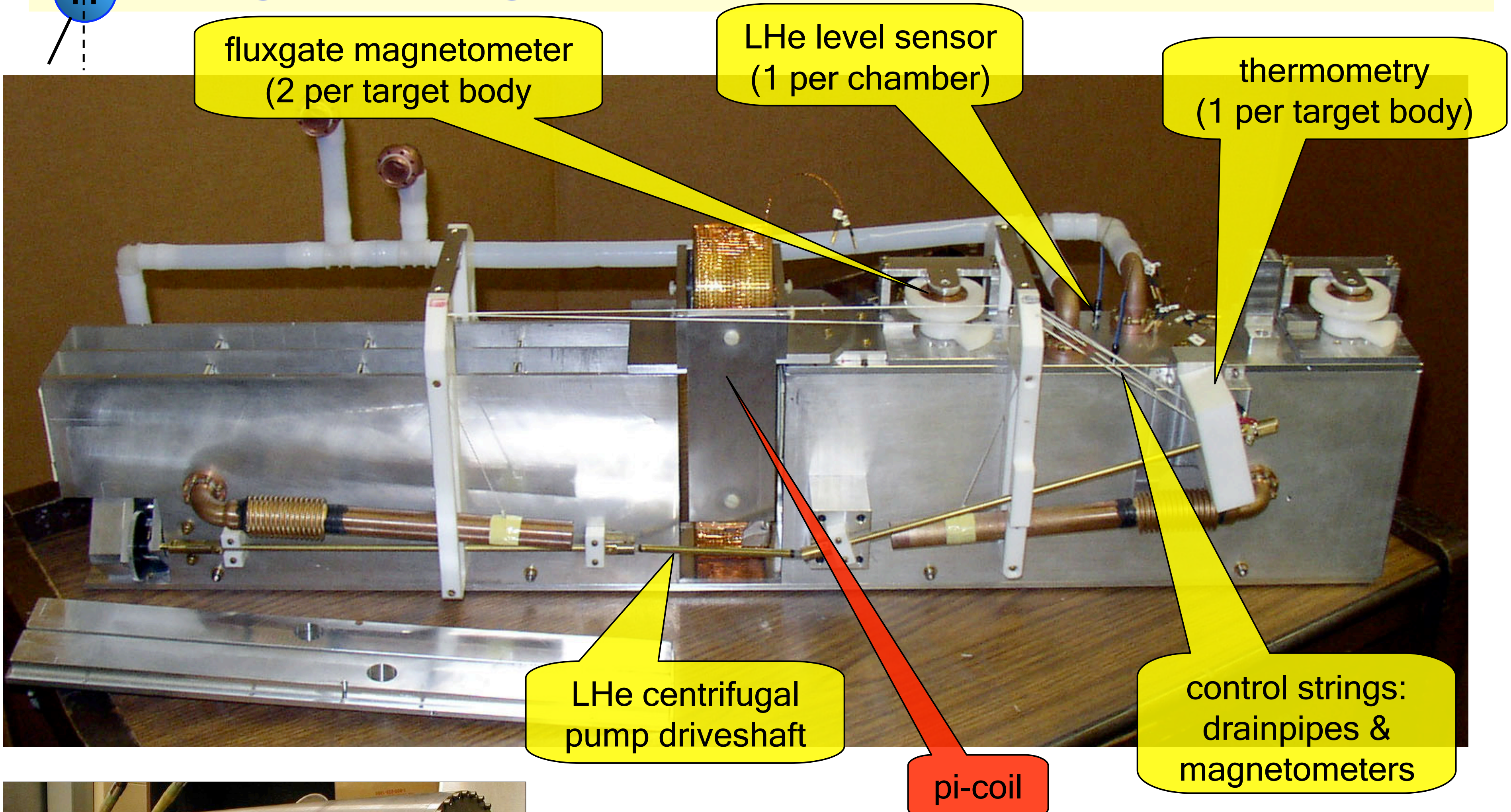


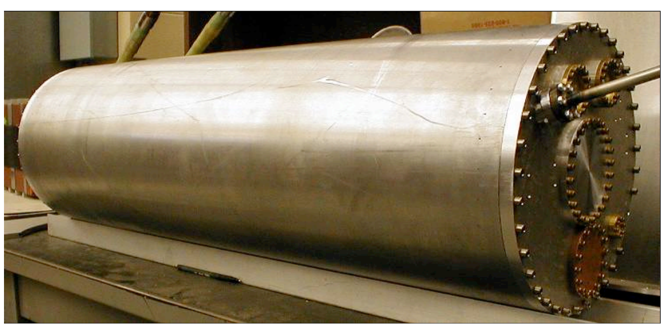
Transmission through polarized nuclei: strong

$\sigma+\neq\sigma- \Rightarrow T+\neq T-$

Spin Filter:$T_{\pm}=\exp[-\rho\sigma_{\pm}L]$

Target Design: Sensors & Motion Control

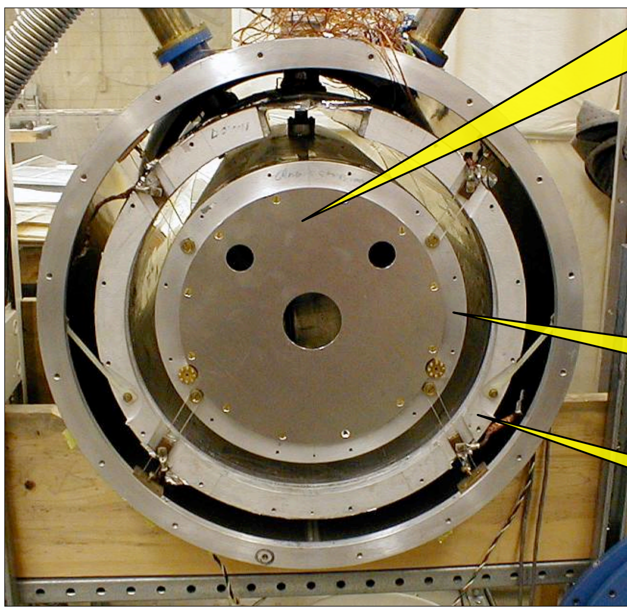


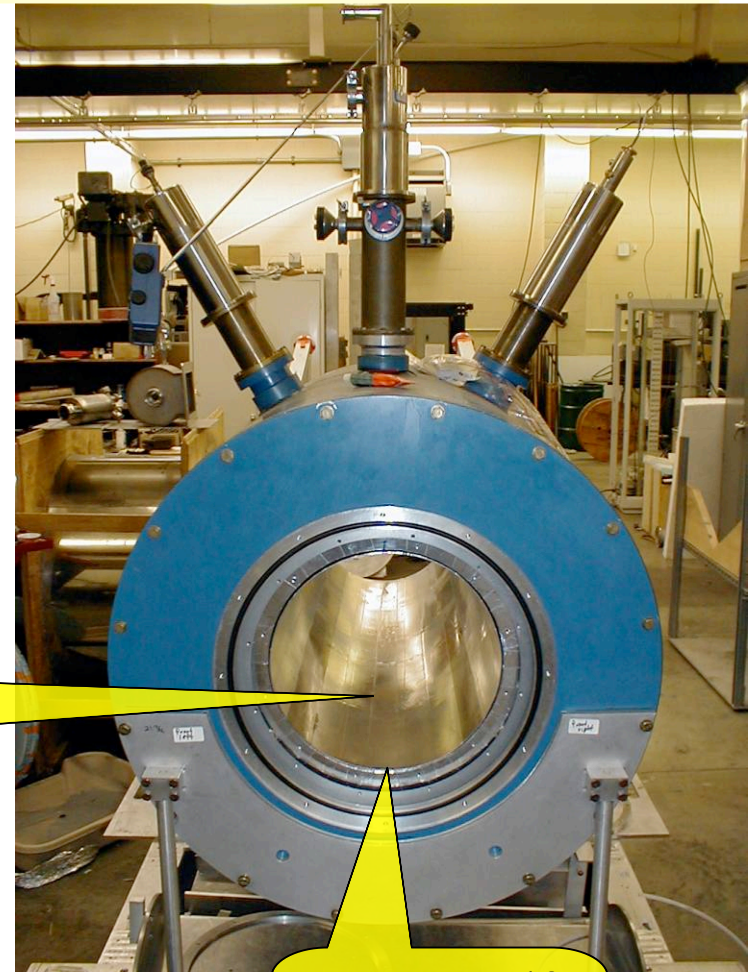


Target/pump immersed in a pool of liquid helium below n beam inside this cylinder

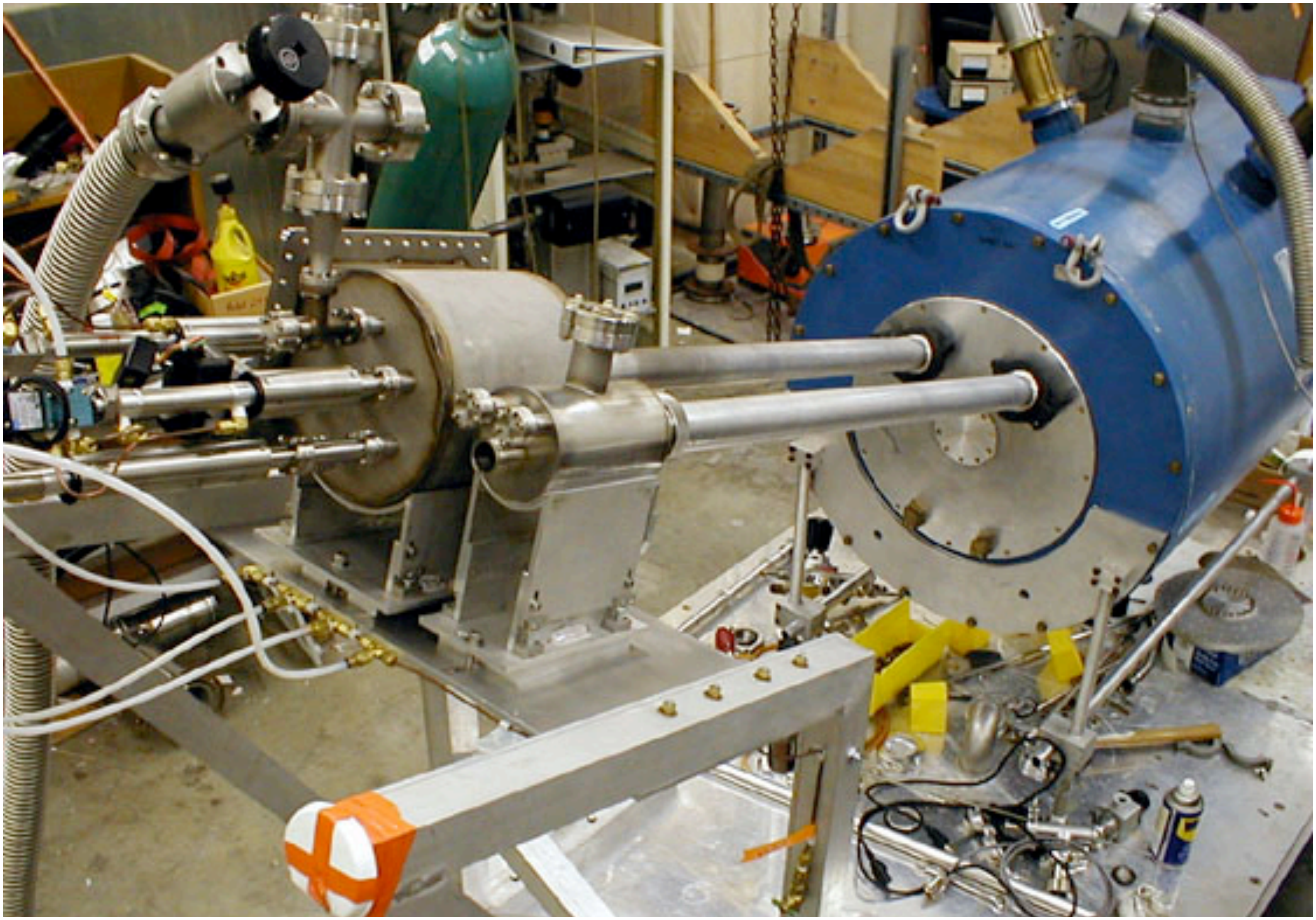
Nonmagnetic Cryostat

- Oxford horizontal, cold-bore cryostat
  - built from *non-magnetic* materials
  - consists of two coaxial annular vessels housed within a cylindrical main vacuum vessel



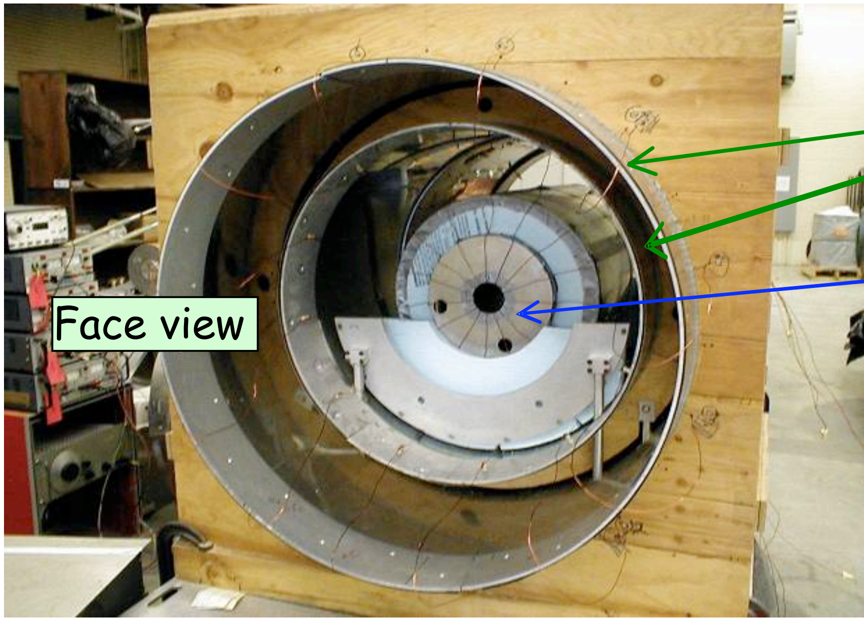


Liquid Helium Motion Control System



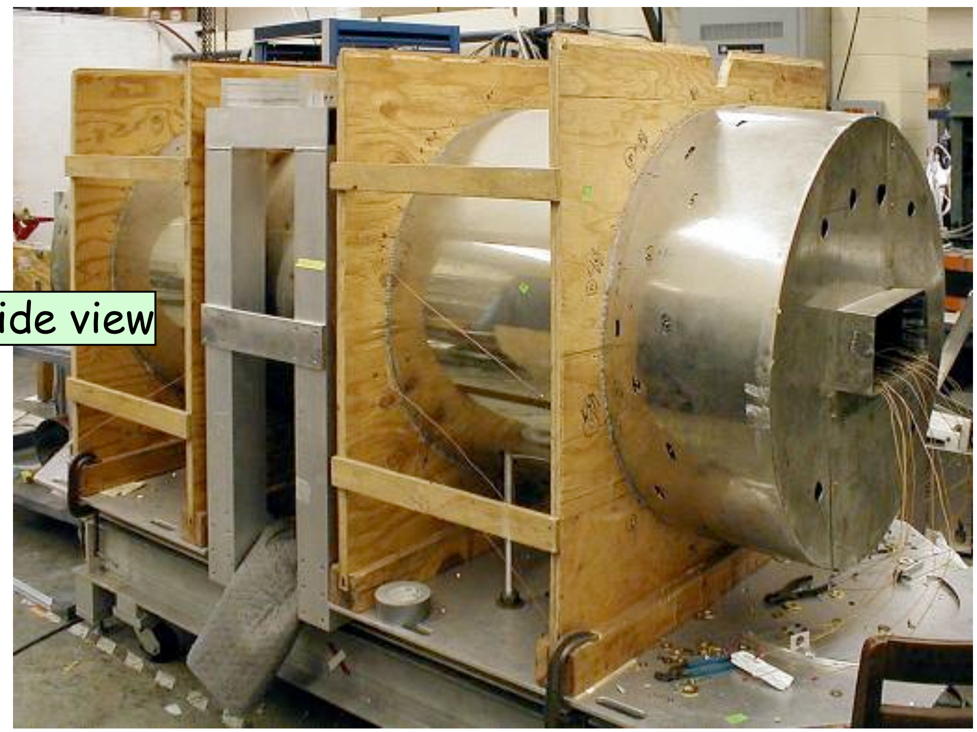
Nonmagnetic cryostat: target feedthroughs and liquid motion control system

Magnetic shielding

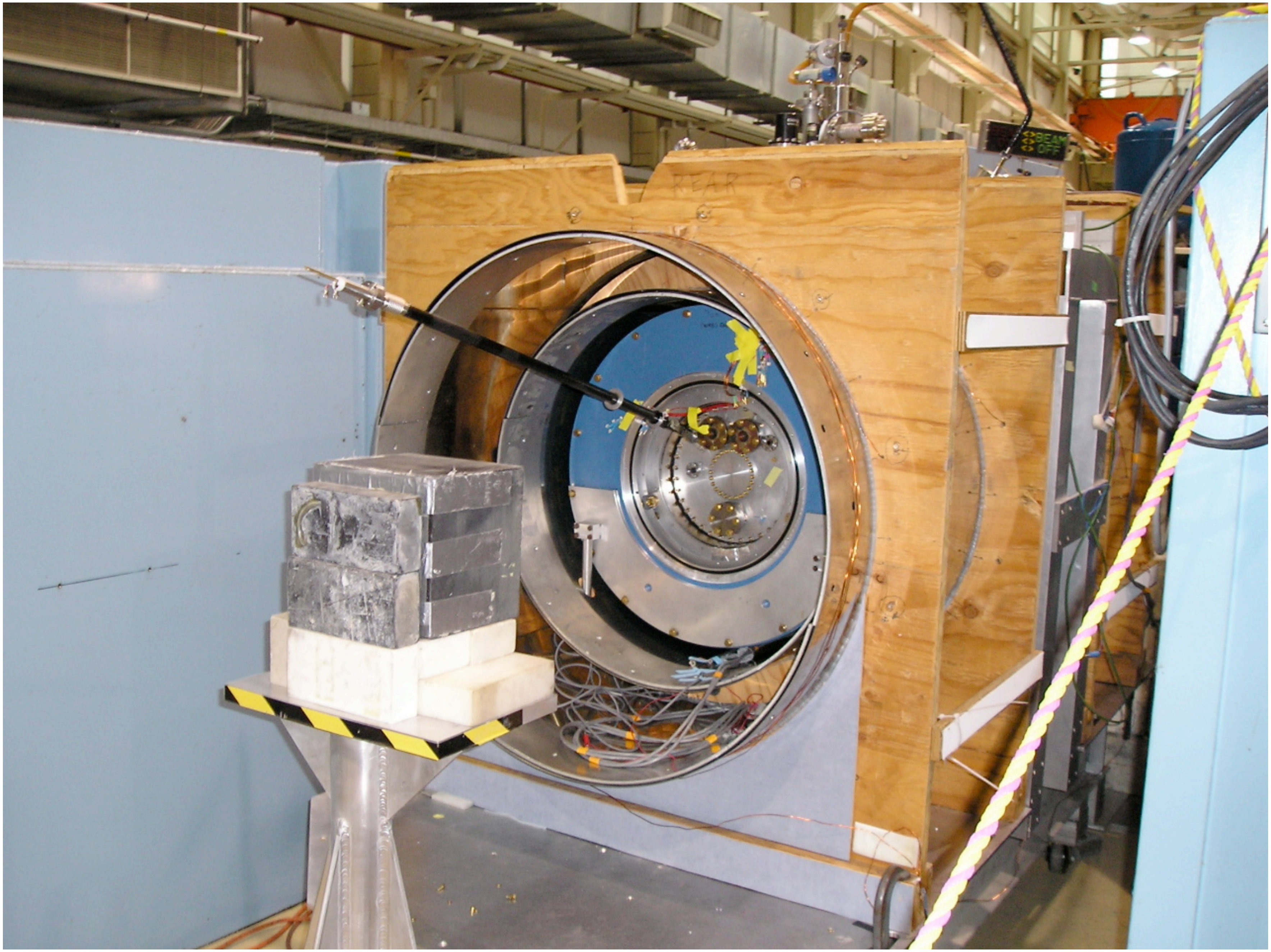


2 outer
CO-NETIC AA shield

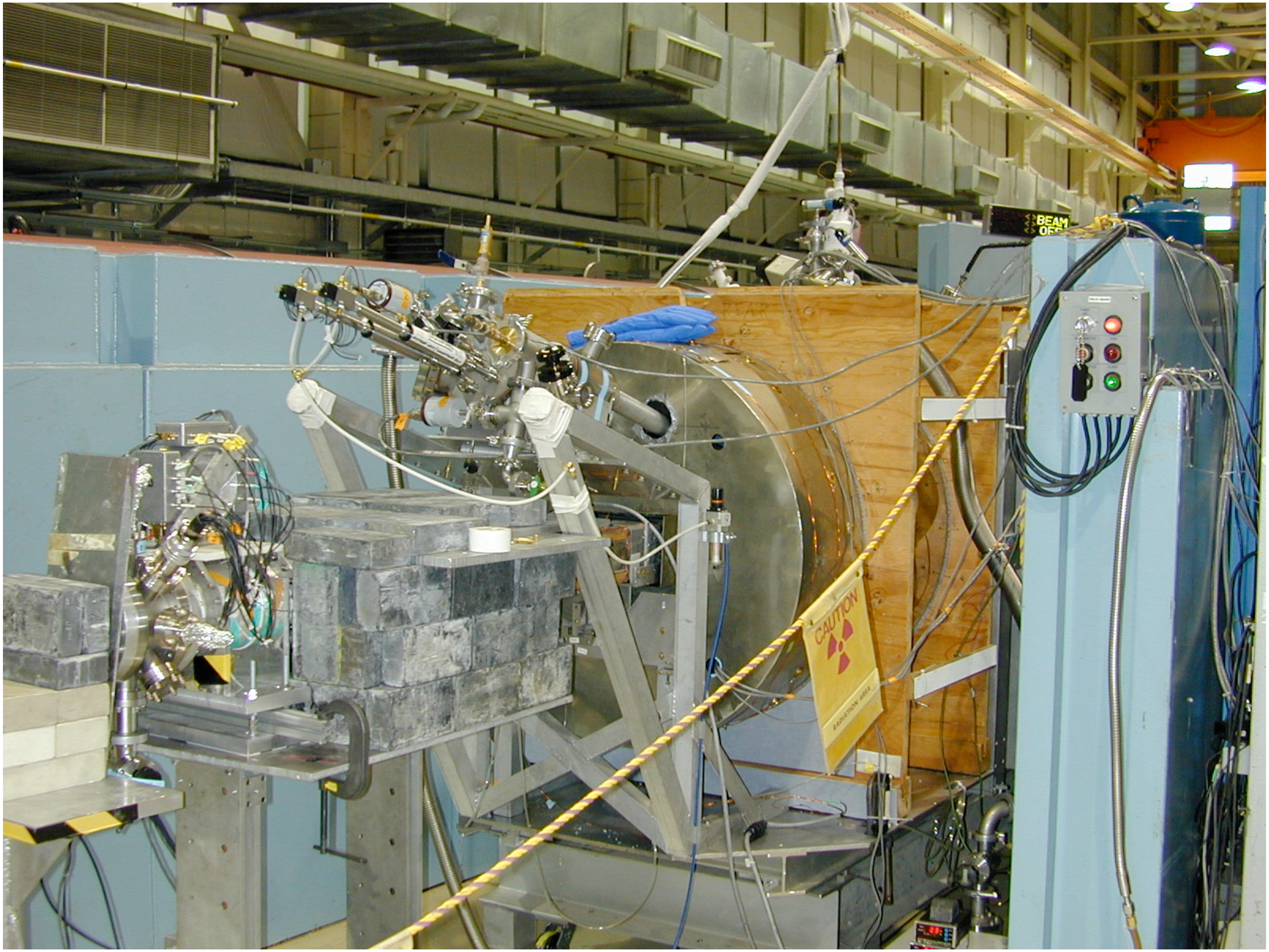
1 inner
CRYOPERM-10 shield



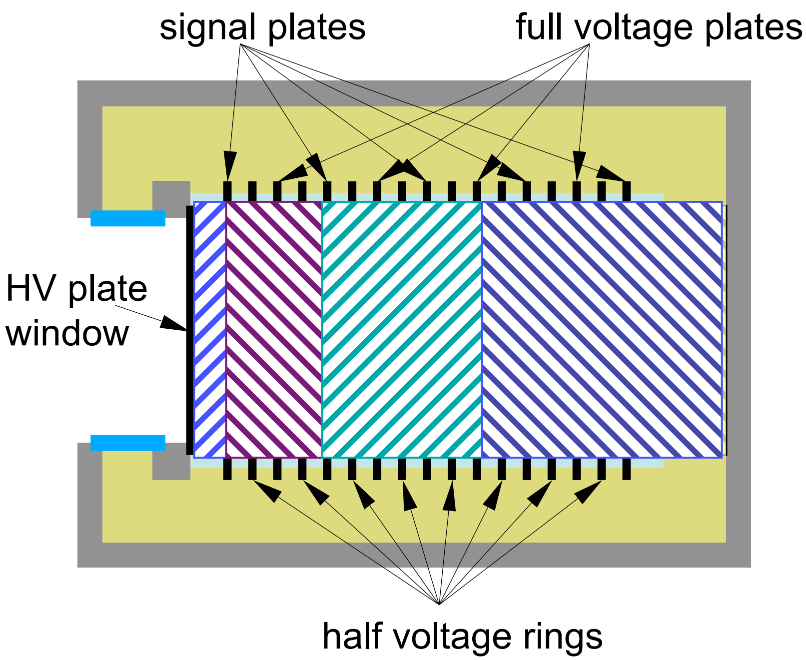
Cryostat and Target in B Shielding on Beamline

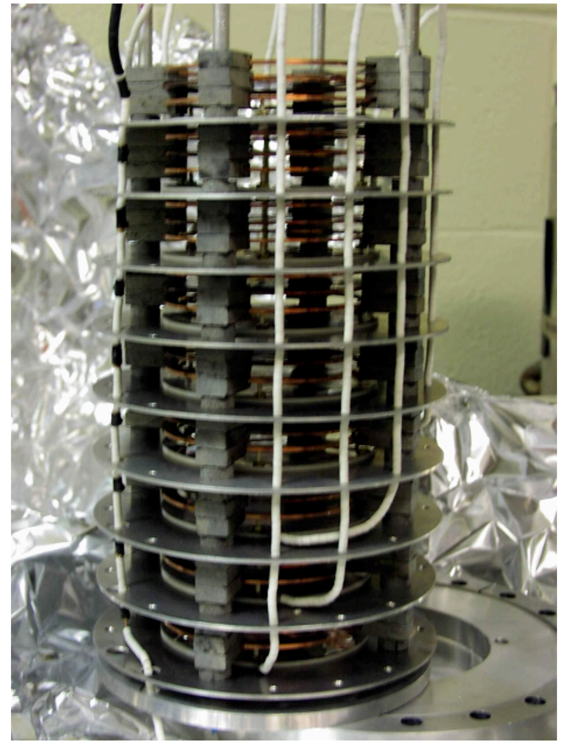


N-4He Spin Rotation Apparatus at NIST

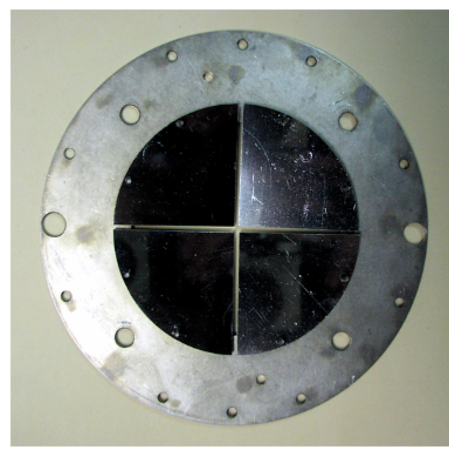


Segmented ^{3}He ionization chamber





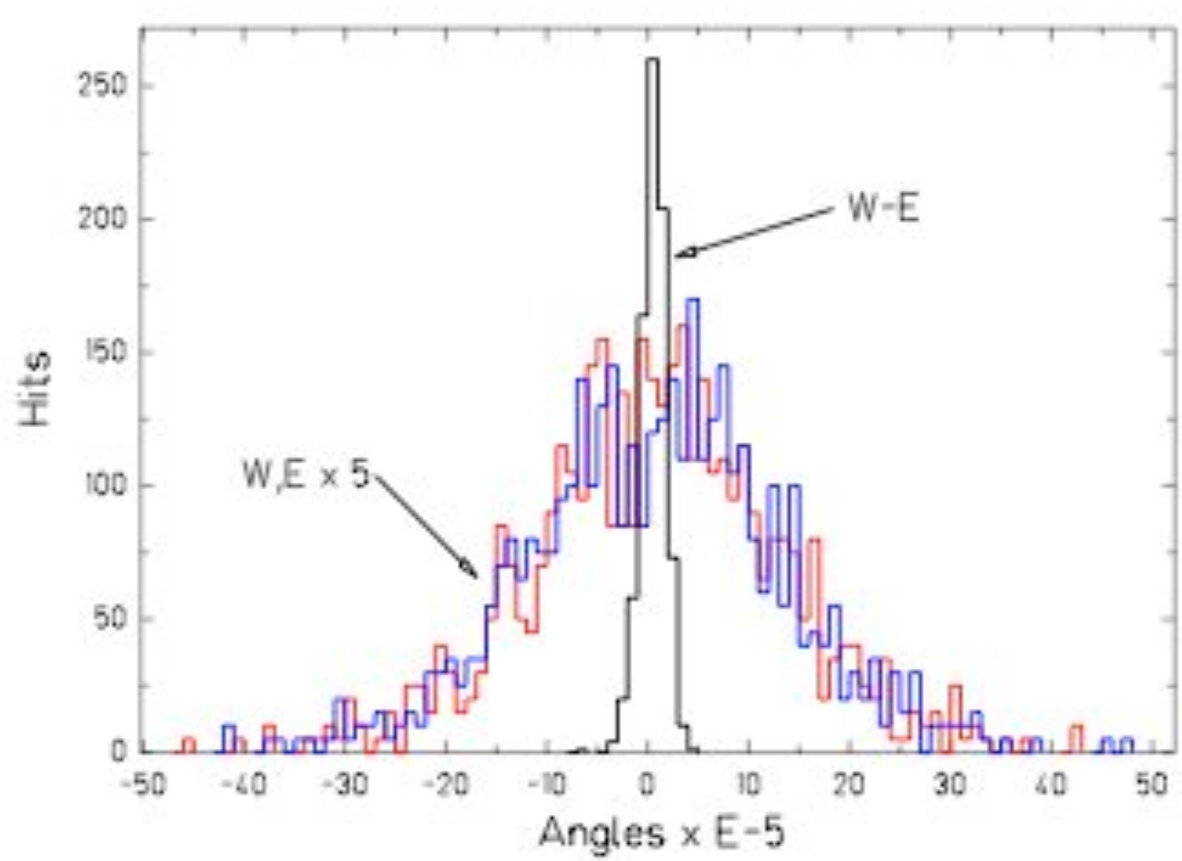
- ^{3}He and Ar gas mixture
- Neutrons detected through $n + {}^3He \rightarrow {}^3H + {}^1H$
- High voltage and grounded charge-collecting plates produce a current proportional to the neutron flux
- 4 Detection Regions along beam axis - velocity separation (1/*v* absorption)



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

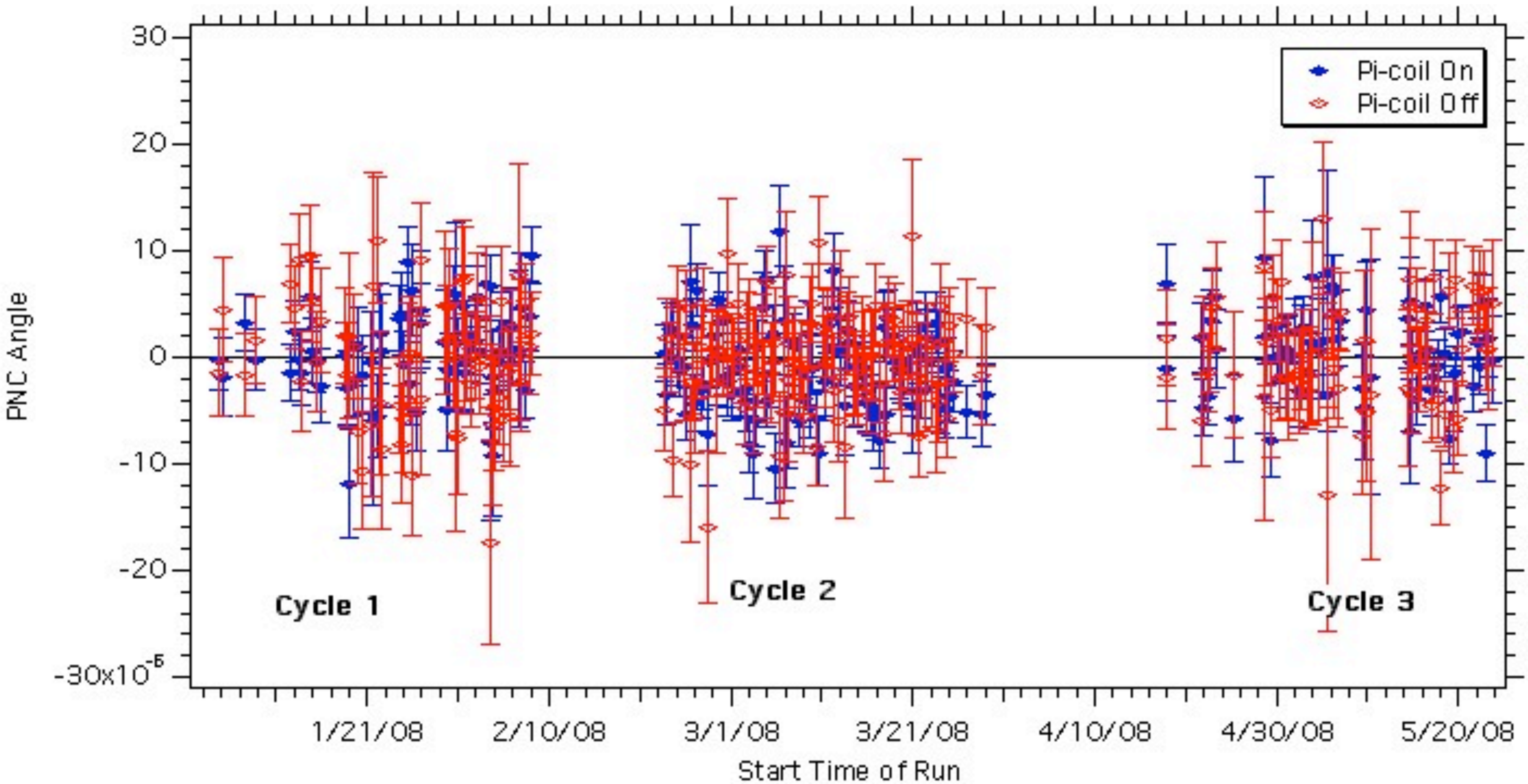
S.D.Penn *et al*. [NIM A457 332-37 (2001)]

Reduction of Common Mode Noise from Reactor Fluctuations: 4He Target

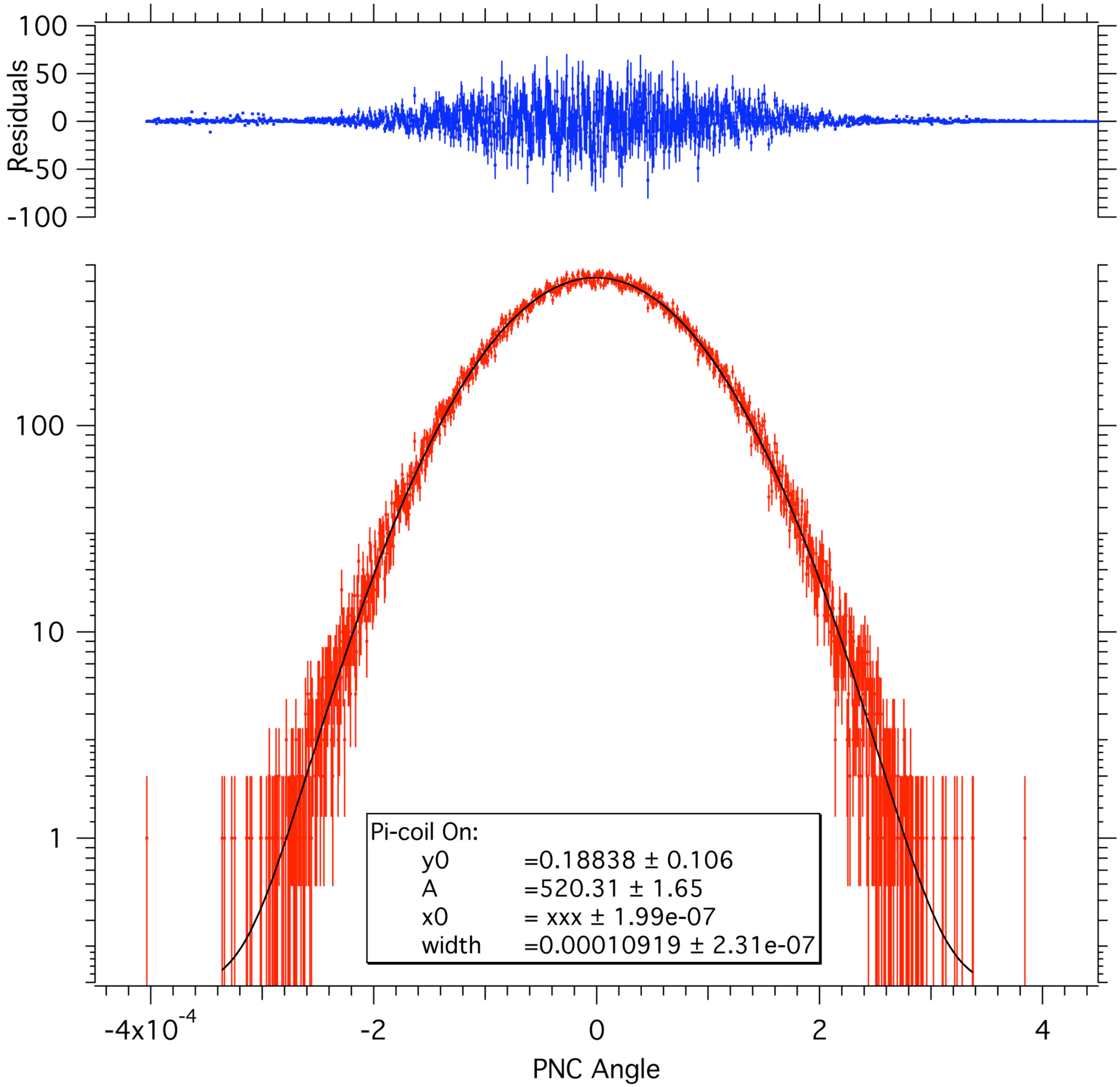


Large noise from beam intensity fluctuations is suppressed
Width of W-E difference of spin rotation angles is $\sim\sqrt{N}$

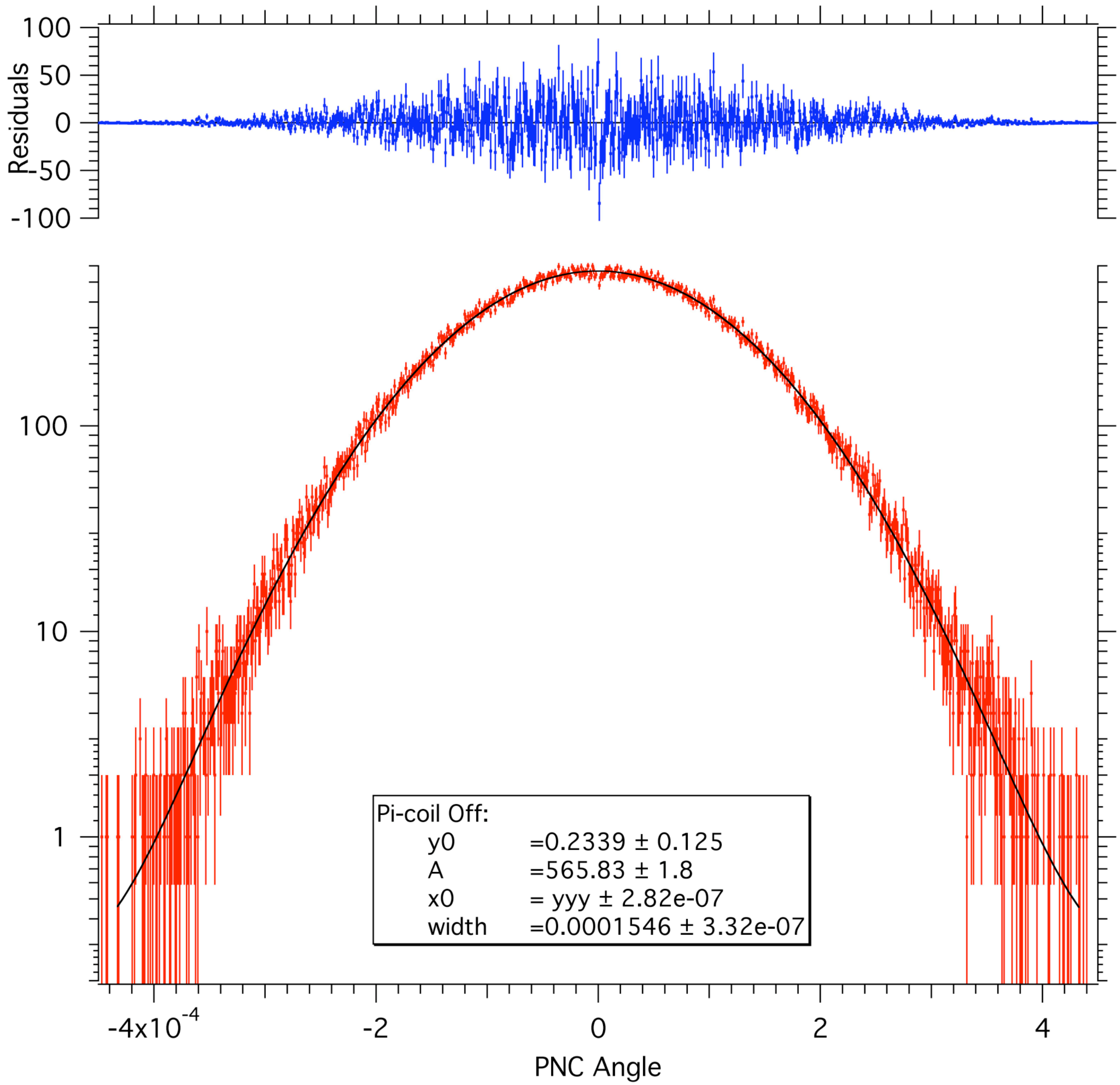
4He Spin Rotation data from NIST vs cycle



Distribution of Raw Asymmetries, pi-coil on



Distribution of Raw Asymmetries, Pi-coil off



For pi-coil off, no oscillation of PV signal, asymmetry should be zero

Width larger by factor of sqrt(2) as expected from +,-,0 pi-coil sequence

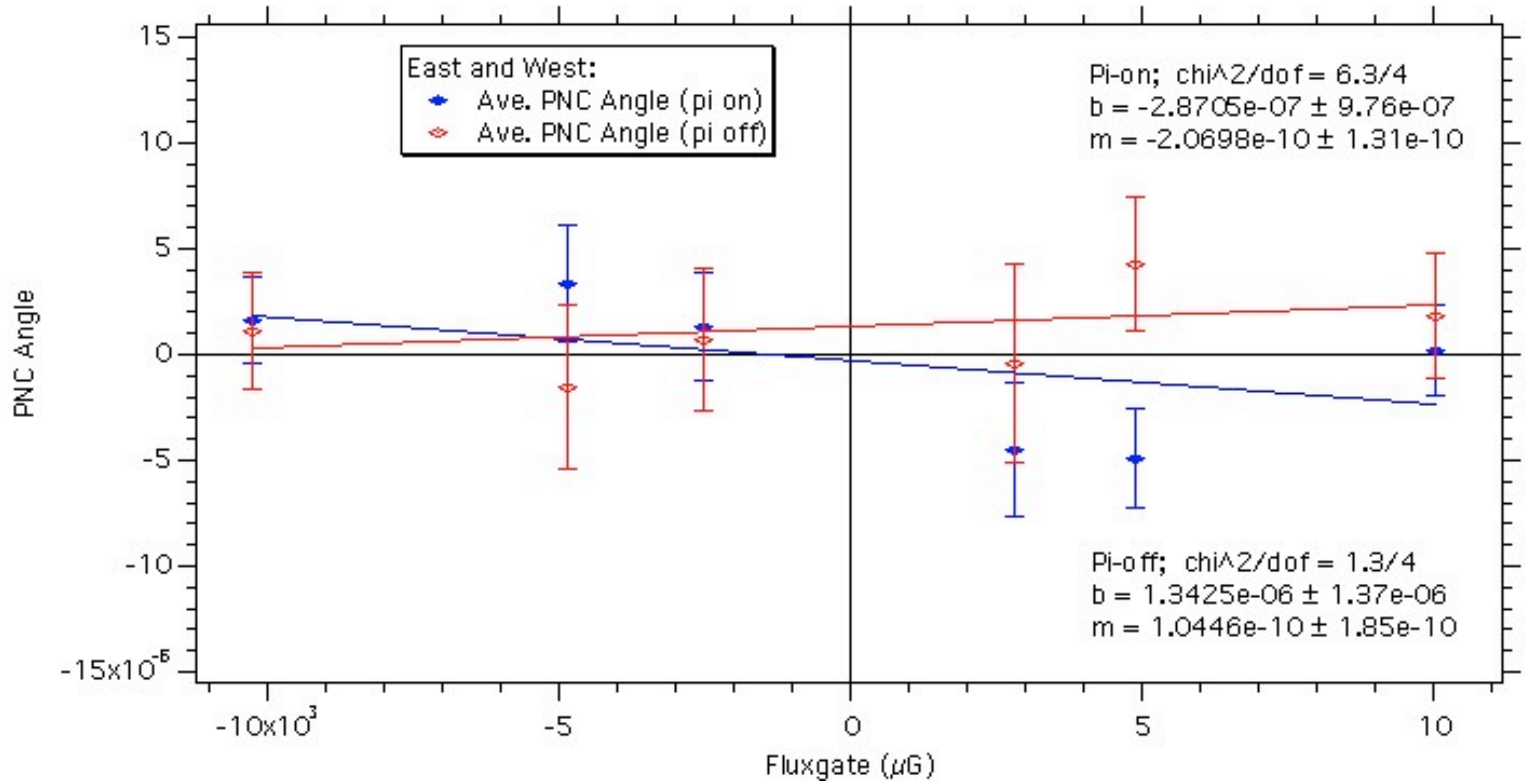
Upper Bounds on 4He Systematic Effects

Background rotations cancel if liquid motion does not change spin rotation from internal B fields

- Measurement noise above $\sqrt{N}$
  - reactor noise (use right-left chambers to suppress common-mode noise)
  - *ion chamber current-mode measurement method*

- Systematics associated with residual B-fields (100 μG level)
  - Diamagnetism of liquid helium → $\Delta B/B \approx 6E\text{-}8$ → 2E-9 rad/m
  - Optical potential of liquid helium → ~ 10 neV → 2E-8 rad/m
  - Shift in neutron energy spectrum → $\Delta L \approx 0.01$ mm → 4E-8 rad/m
  - *Small angle scattering* → <5E-8 rad/m
  - *Change in neutron paths due to refraction* → <5E-8 rad/m
  - *Change in neutron phase space from target reflections* → <5E-8 rad/m
  - *Phase space non-uniformity in analyzing power of ASM* → <4E-8 rad/m
  - *Time-dependence of internal magnetic field IN PROGRESS*
  - *Time-dependence of density fluctuations IN PROGRESS*

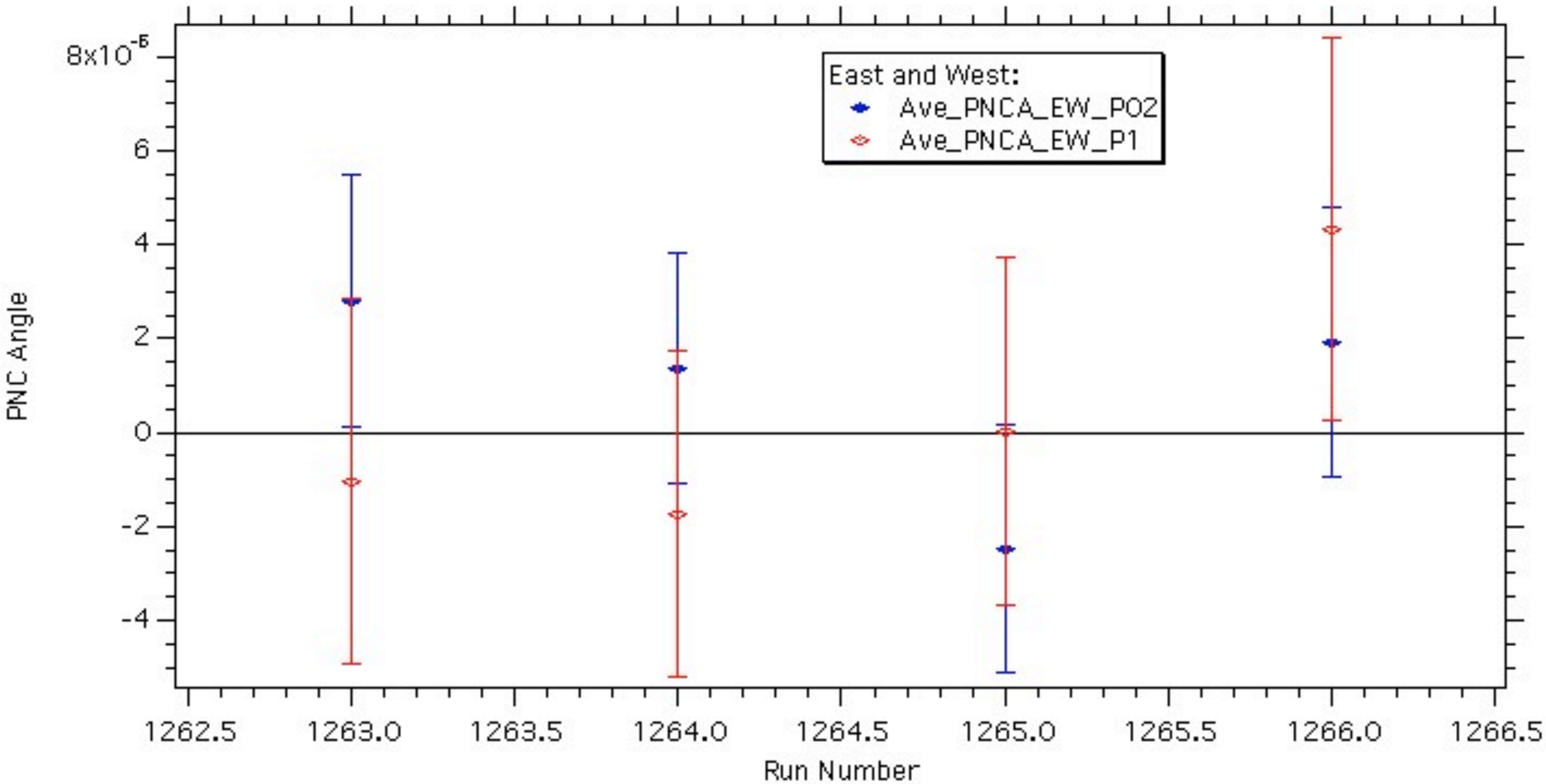
Systematics from Internal B Field



Generate internal B larger than expt. conditions by 2 orders of magnitude

Limit on systematic <5E-8 rad/m

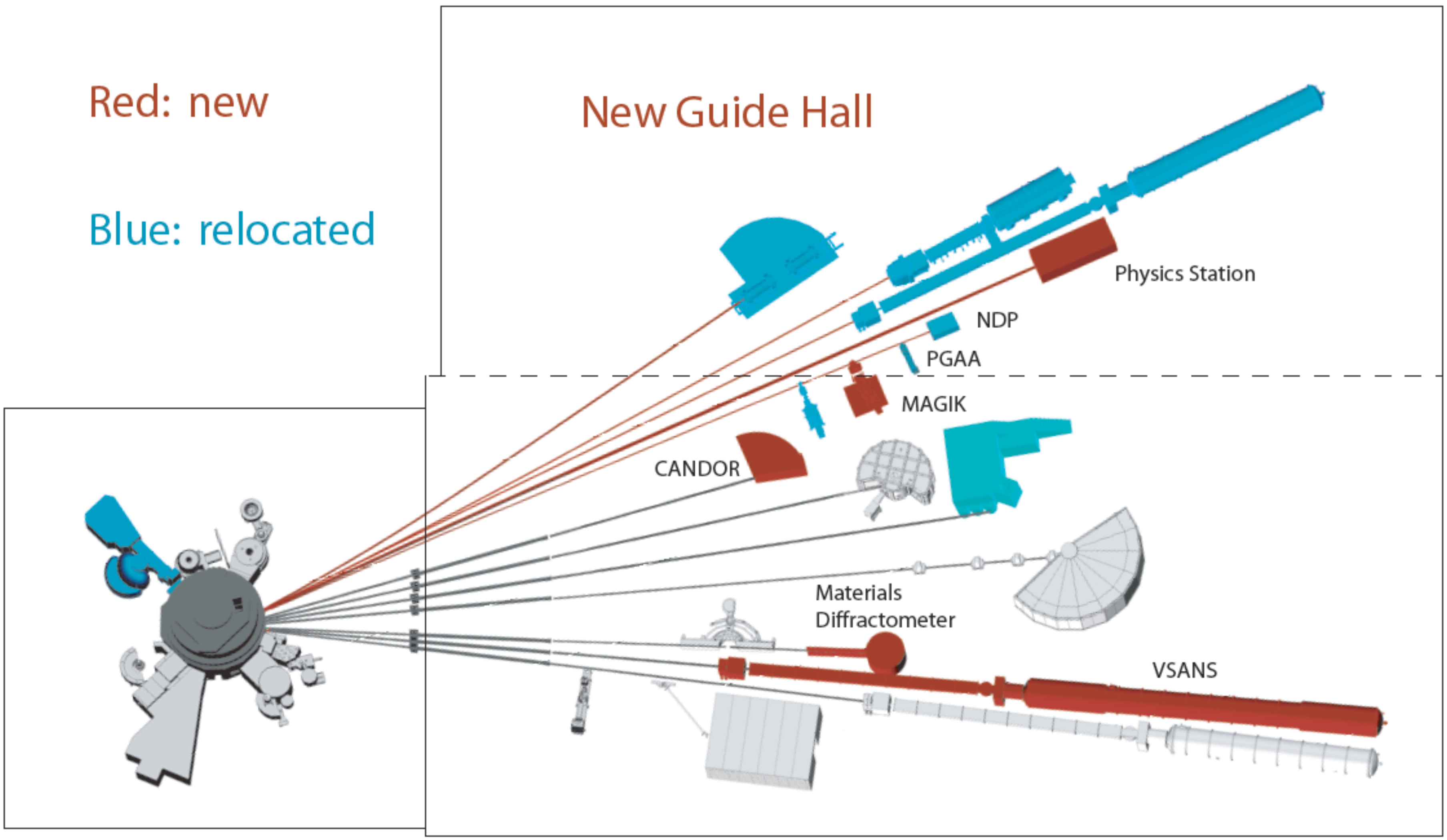
Systematics from Internal B Field Gradient



Generate internal gradient larger than expt. conditions by >2 orders of magnitude

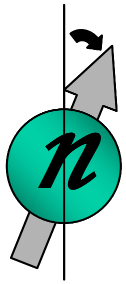
Limit on systematic <4E-8 rad/m

More neutrons soon: NIST Guide Hall Expansion Project



X20 increase in polarized slow neutron flux(!) done~late 2010

Spin rotation statistical precision of 1E-7 rad/5 week cycle possible



Neutron Spin Rotation in Few-Body Systems: Expected size of Effects

φ($n\alpha$) ***liquid helium***

DDH range gives ~± 1.5E-6 rad/m L~0.5m-><u>7E-7 rad</u>

φ(np) ***parahydrogen***

calculations in DDH framework (Schiavilla et al) gives ~5E-7 rad/m for DDH best values. L~20 cm -><u>1E-7 rad</u>

φ(nD) ***orthodeuterium***

calculations in DDH framework(Schiavilla et al) give ~5E-6 rad/m for the DDH best value, larger than n-p by an order of magnitude, dominated by weak pion exchange. L~5 cm -><u>2.5E-7 rad</u>

Conclusions

Our result (analysis nearing completion) will be the most sensitive neutron spin rotation measurement performed to date.

With NIST upgrade, can reach 1E-7 rad statistical accuracy/5 week cycle in n-p, n-D, and n-4He neutron spin rotation

In combination with SNS measurements in inelastic processes (NPDGamma, NDTGamma, n-3He), make real progress in NN weak interaction

Continued work in effective field theory description of weak NN interaction is in progress