Hadronic parity violation measurements with neutrons

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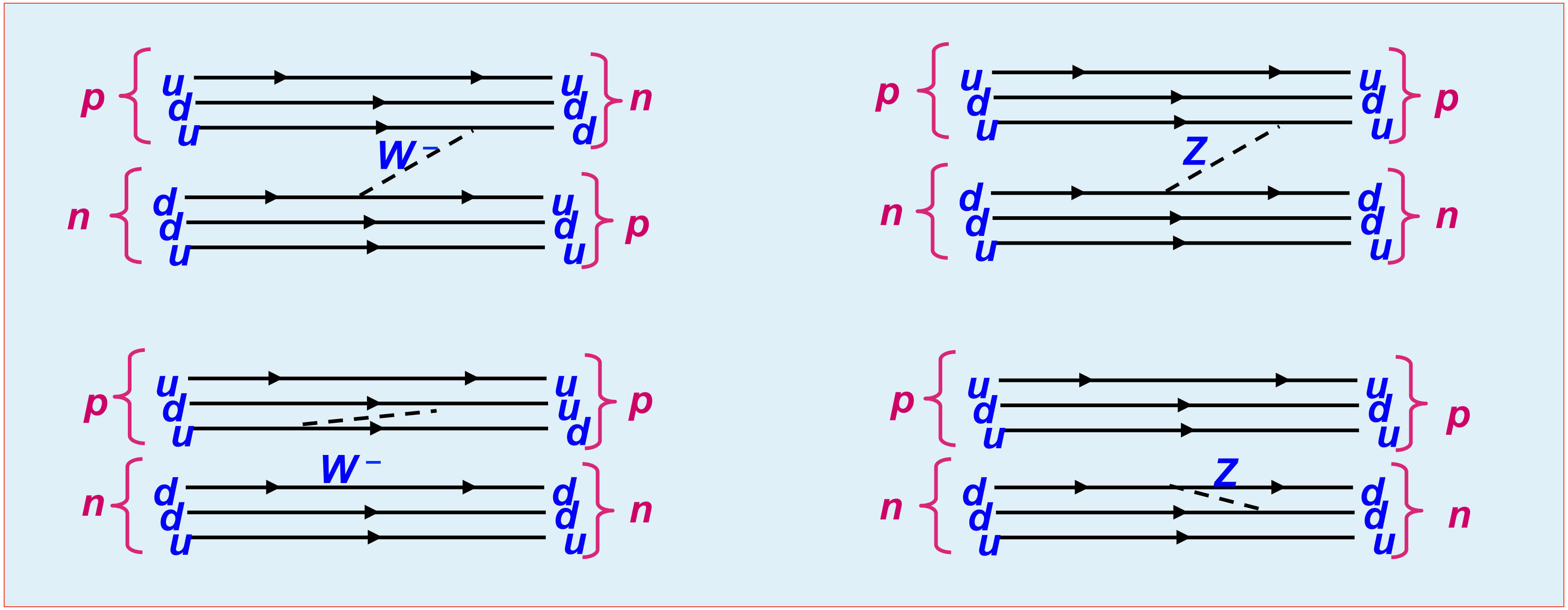
1. Theoretical background/present experimental status
2. Neutron experiment in progress: NPDGamma
3. Proposed neutron experiments:(a) n+3He, (b) n+4He
4. Experimental bounds on “long-range” neutron parity violation

NN Weak Interaction: the nucleons are the “problem”

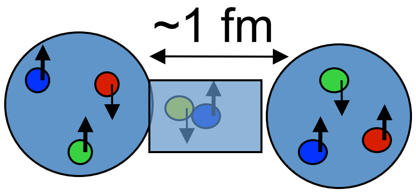
In the Standard Model, the structure of the quark-quark weak interaction is known from the electroweak sector.

However, strong QCD confines color and breaks chiral symmetry by correlating the quarks in both the *initial* and *final* nucleon ground states. The dynamical mechanisms which do this in QCD are not yet understood.



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 correlations in the nucleon.

N- N Weak Interaction: Size and Mechanism

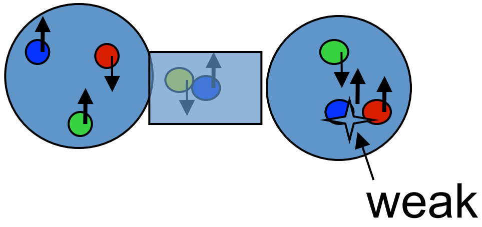


NN repulsive core → 1 fm range for NN strong force

$|N\rangle = |qqq\rangle + |qqqq\bar{q}\rangle + \cdots$ = 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: $\left(\frac{e^2}{m_W{}^2}\right)/\left(\frac{g^2}{m_\pi{}^2}\right) \approx 10^{-6}$

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?

Δs=1 nonleptonic weak interactions: a decades-old problem

ΔI=1/2 rule, hyperon decays not (completely) understood,
data not close to simple estimates from flavor symmetries.

Must be some nontrivial QCD dynamics, but what?

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. Already some hints for this from PV measurements in light nuclei like 18F)

To answer : *Look at Δs=0 nonleptonic weak interactions (u,d quarks)*

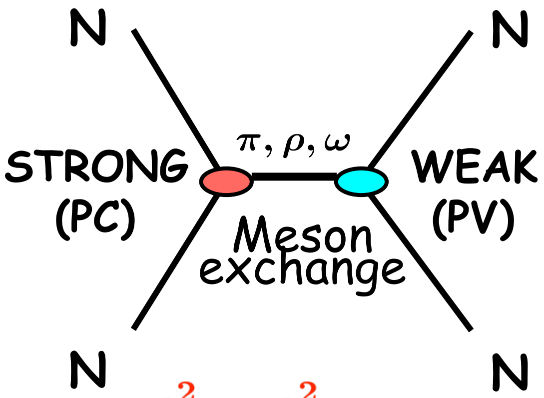
NN weak interaction is one of the few experimentally feasible systems where this is possible

Applications to other systems:

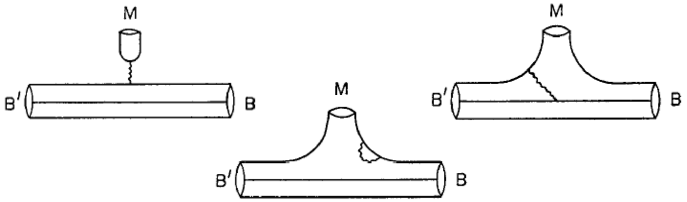
Atomic parity violation (anapole moments)
Parity violation in nuclei
Parity violation in electron scattering

DDH Potential

PV meson exchange



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



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_r^0		-0.50	-0.14	-0. 23	-0.32	0.08	0.14
h_r^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

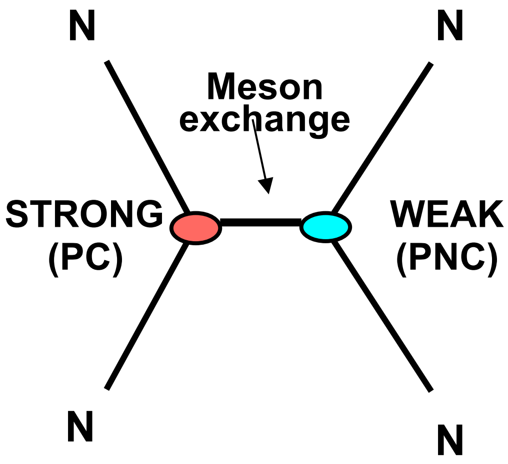
Adelberger, Haxton, A.R.N.P.S. **35,** 501 (1985)

Meson Exchange/NN Weak Effective Field Theories

Meson exchange model: exchange of light mesons (*π, ρ, ω*) with one strong interaction vertex and one weak interaction vertex (Desplanques, Donoghue, Holstein 1980)

Effective Field Theory approach: most general formulation for NN weak interaction consistent with QCD symmetries (Zhu et al 2005)

Pionless EFT (equivalent to 5 S-P transition amplitudes). Calculations in progress (Phillips, Schindler, Springer 2009, Springer,Schindler 2013)



Partial wave transition	I ⇔ I'	ΔI	n-n	n-p	p-p	Hybrid EFT coupling	Pionless EFT coupling	Exchanged Meson
$^3S_1 \Leftrightarrow {}^3P_1$	0 ⇔ 1	1		✓		$m\rho_t$, C^π [~ f_π]	$C\,(^3S_1 - {}^3P_1)$	$\pi^\pm$, ρ, ω°
$^3S_1 \Leftrightarrow {}^1P_1$	0 ⇔ 0	0		✓		$m\lambda_t$	$C(^3S_1 - {}^1P_1)$	ρ, ω°
$^1S_0 \Leftrightarrow {}^3P_0$	1 ⇔ 1	0	✓	✓	✓	$m\lambda_s^{nn}$	$C\,(^1S_0 - {}^3P_{0,} \Delta I=0)$	ρ, ω°
$^1S_0 \Leftrightarrow {}^3P_0$	1 ⇔ 1	1	✓		✓	$m\lambda_s^{np}$	$C\,(^1S_0 - {}^3P_0, \Delta I=1)$	ρ, ω°
$^1S_0 \Leftrightarrow {}^3P_0$	1 ⇔ 1	2	✓	✓	✓	$m\lambda_s^{pp}$	$C(^1S_0 - {}^3P_0, \Delta I=2)$	ρ

Existing HPV data

- p-p scat. 15, 45 MeV A_z^{pp}
- p-α scat. 46 MeV A_z^{pp}
- p-p scat. 220 MeV A_z^{pp}
- n+p→d+γ circ. pol. P_γ^d
- n+p→d+γ asym. A_γ^d
- n-α spin rot. $d\phi^{n\alpha}/dz$

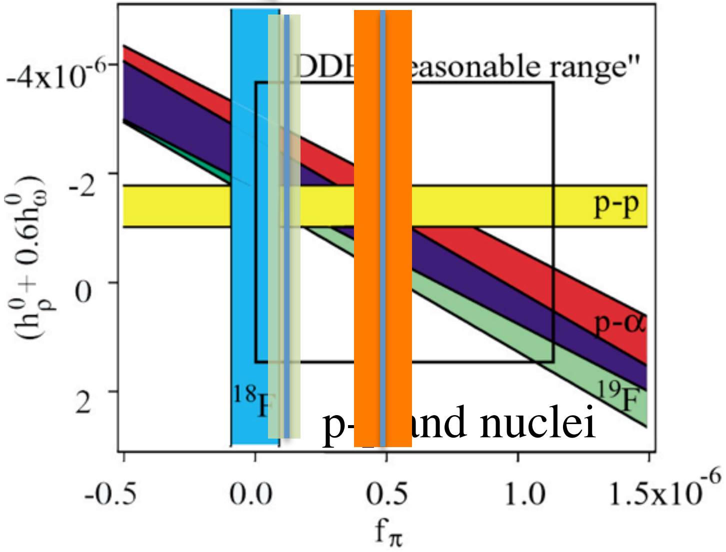
- ^{18}F asym. $\Delta I = 1$
- ^{19}F, ^{41}K, ^{175}Lu, ^{181}Ta asym.
- ^{21}Ne (even-odd)
- ^{133}Cs, ^{205}Tl anapole moment

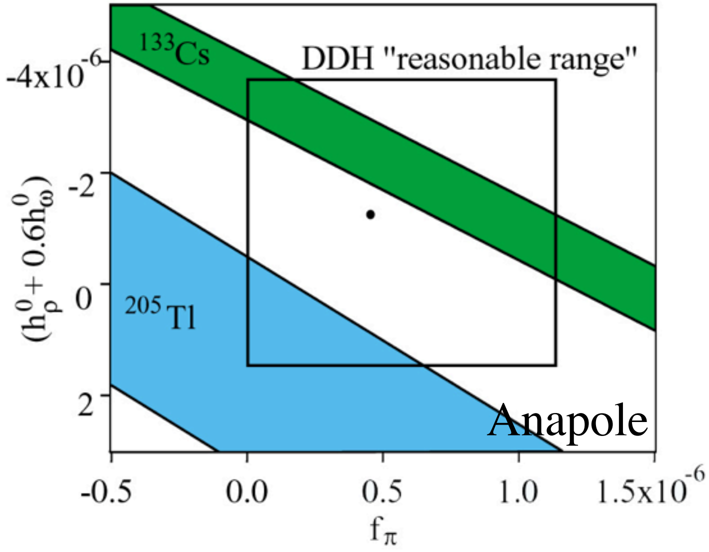
GOAL – resolve coupling constants from few-body PV experiments only

Wasem, Phys. Rev. C **85** (2012) 022501

1st Lattice QCD result

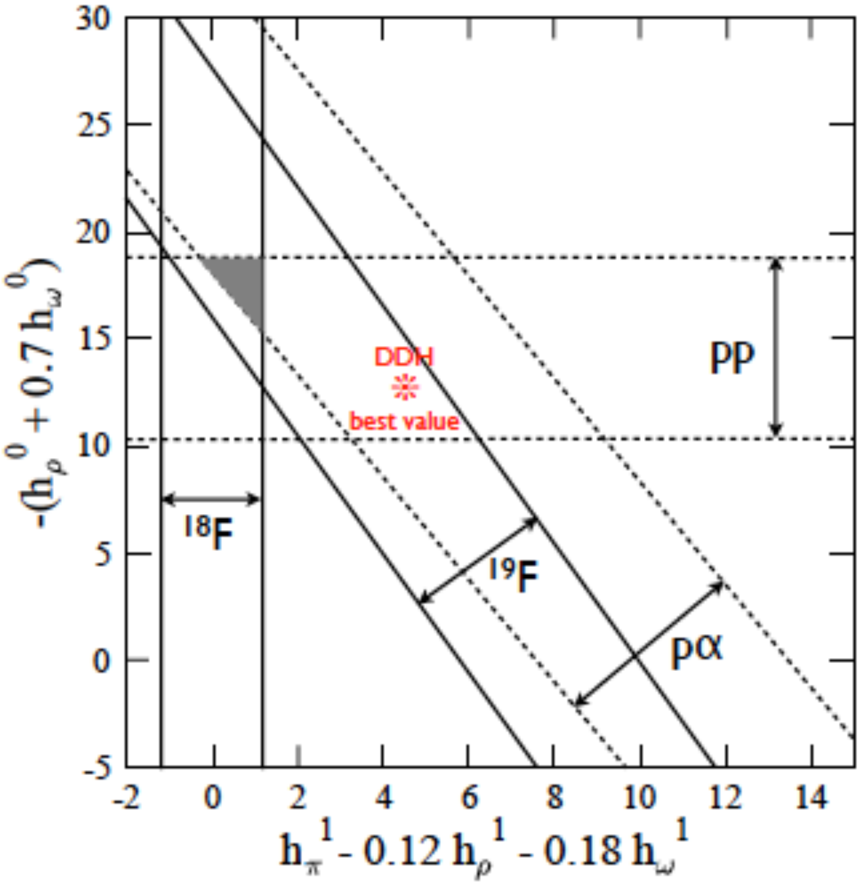
NPDGamma



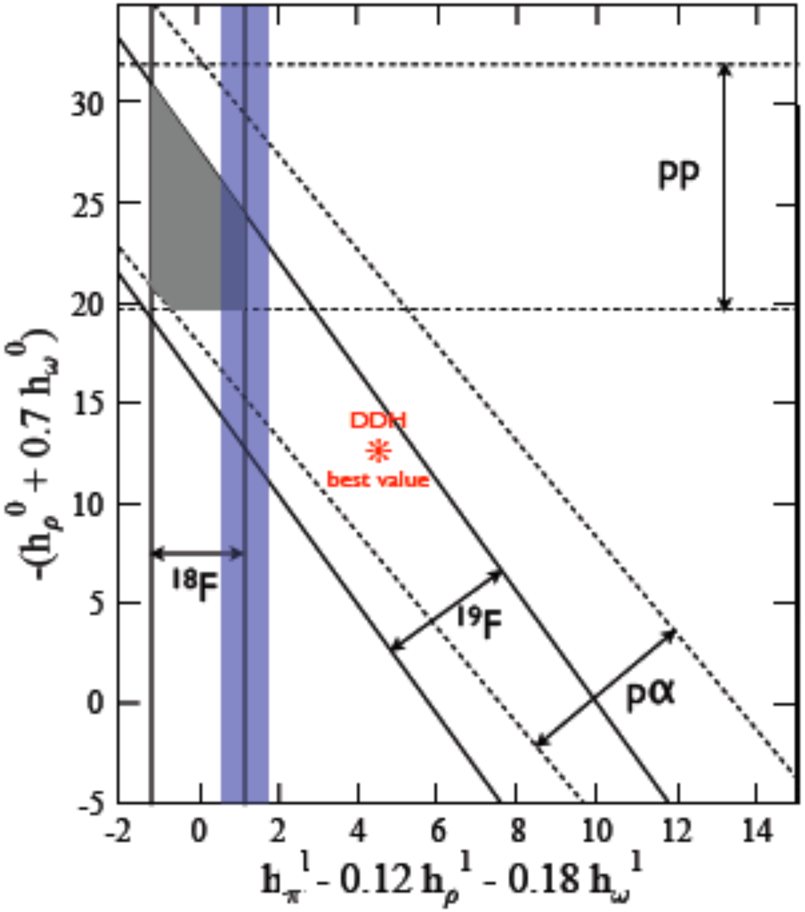


Haxton and Holstein 2013: reanalysis of pp parity violation

Corrected pp analysis for treatment of strong NN couplings
Result: isoscalar linear combination goes up by ~50%

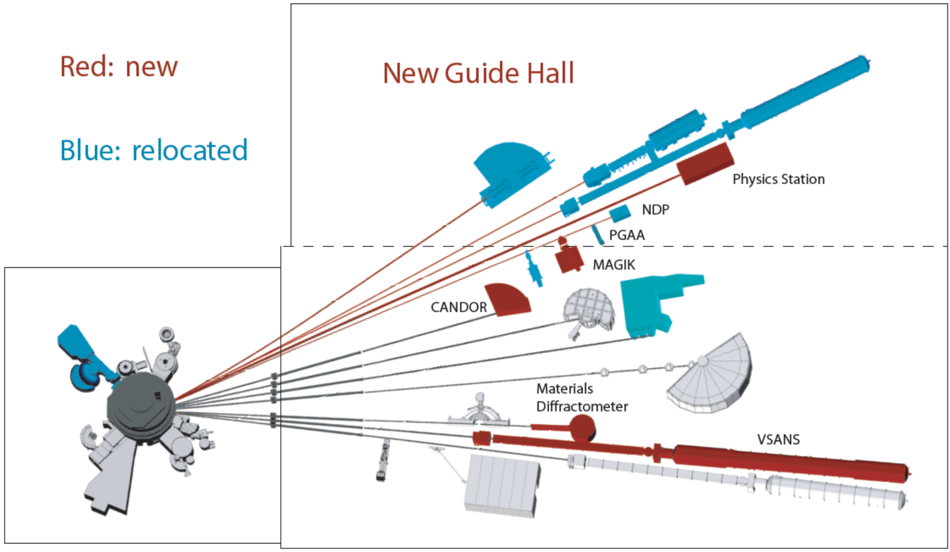


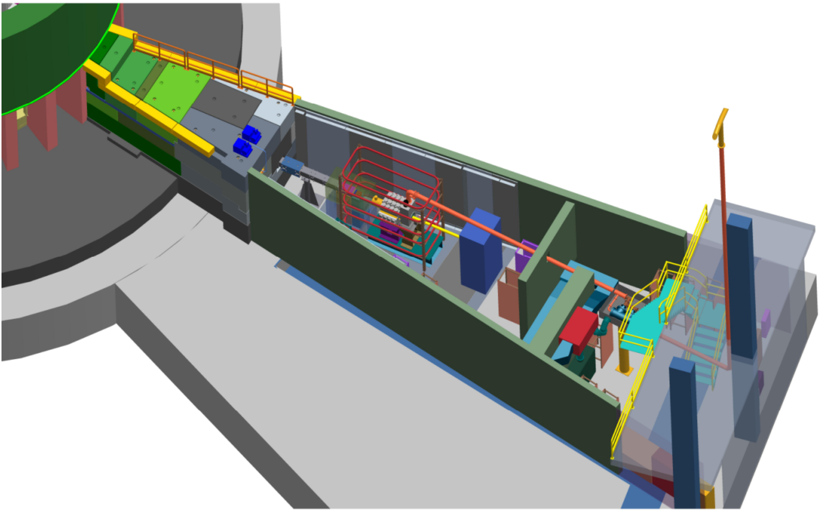
Haxton/Wieman ~2001



Haxton/Holstein 2013

Nuclear/Particle/Astrophysics with Slow Neutrons: New Beams in US

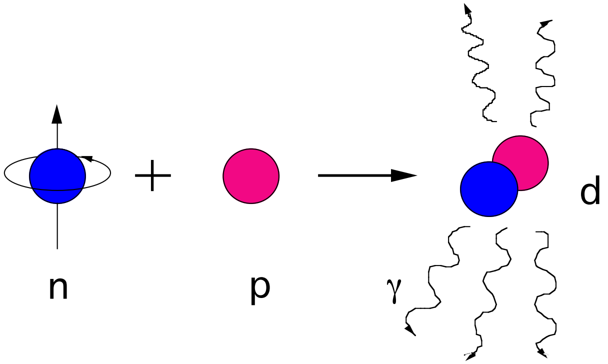




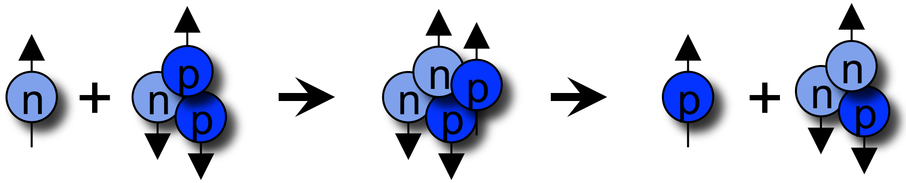
NIST Center for Neutron Research
Gaithersburg MD
Most intense reactor-based US
slow neutron source
new beam #2 intensity in the world in 2014.

Spallation Neutron Source
Oak Ridge National Lab (TN)
Most intense short pulsed spallation
neutron source in the US.
Now in operation

P-odd Observables: n-p, n-3He, and n-4He

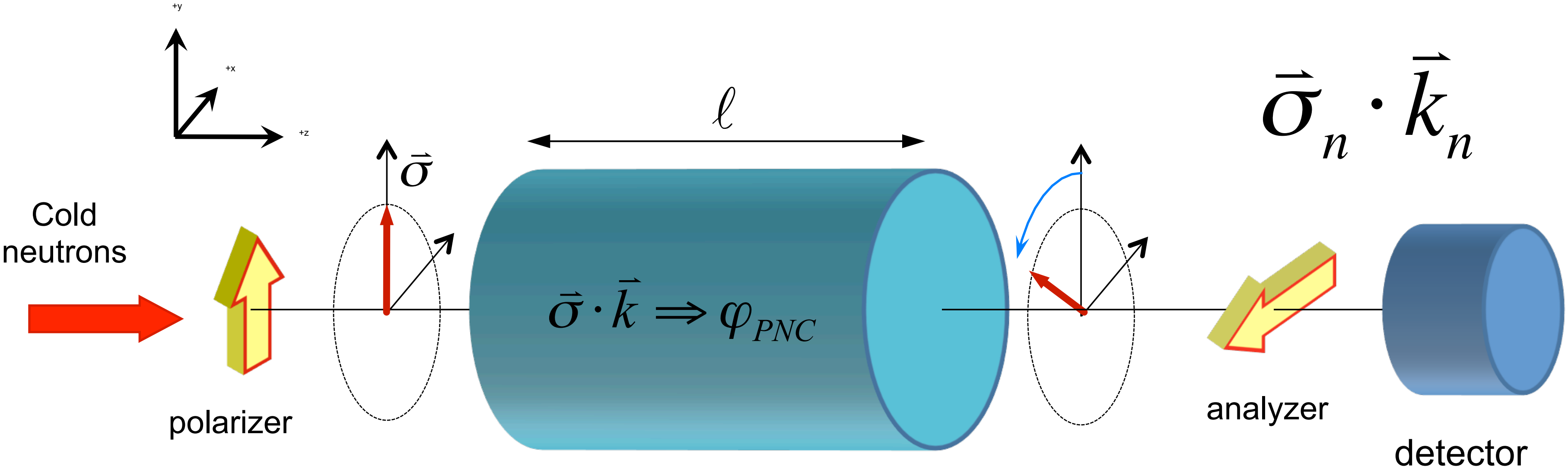


$$\vec{\sigma}_n \cdot \vec{k}_\gamma$$



$$\vec{\sigma}_n \cdot \vec{k}_p$$

$$\vec{\sigma}_n \cdot \vec{k}_n$$



The NPDGamma collaboration

P. Alonzi[3], R. Alacron[1], R. Allen[4], S. Balascuta[1], L. Barron-Palos[2], S. Baeßler[3,4], A. Barzilov[25], D. Blyth[1], J.D. Bowman[4], M. Bychkov[3], J.R. Calarco[9], R.D. Carlini[5], W.C. Chen[6], T.E. Chupp[7], S. Covrig[9], C. Crawford[8], M. Dabaghyan[9], N. Fomin[10], S.J. Freedman[13], E. Frlež[3], J. Fry[11], T.R. Gentile[6], M.T. Gericke[14] R.C. Gillis[11], K. Grammer[12], G.L. Greene[4,12], J. Hamblen[26], F. W. Hersman[9], T. Ino[15], G.L. Jones[16], S. Kucucker[12], B. Lauss[17], W. Lee[18], M. Leuschner[11], W. Losowski[11], E. Martin[8], R. Mahurin[14], M. McCrea[14], Y. Masuda[15], J. Mei[11], G.S. Mitchell[19], P. Mueller[4], S. Muto[15], M. Musgrave[12], H. Nann[11], I. Novikov[25], S. Page[14], D.Počanic[3], S.I. Penttila[4], D. Ramsay[14,20], A. Salas Bacci[10], S. Santra[21], P.-N. Seo[3], E. Sharapov[23], M. Sharma[7], T. Smith[24], W.M. Snow[11], Z. Tang[11], W.S. Wilburn[10] , V. Yuan[10]

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[16]Hamilton College
[17]Paul Scherrer Institute, Switzerland
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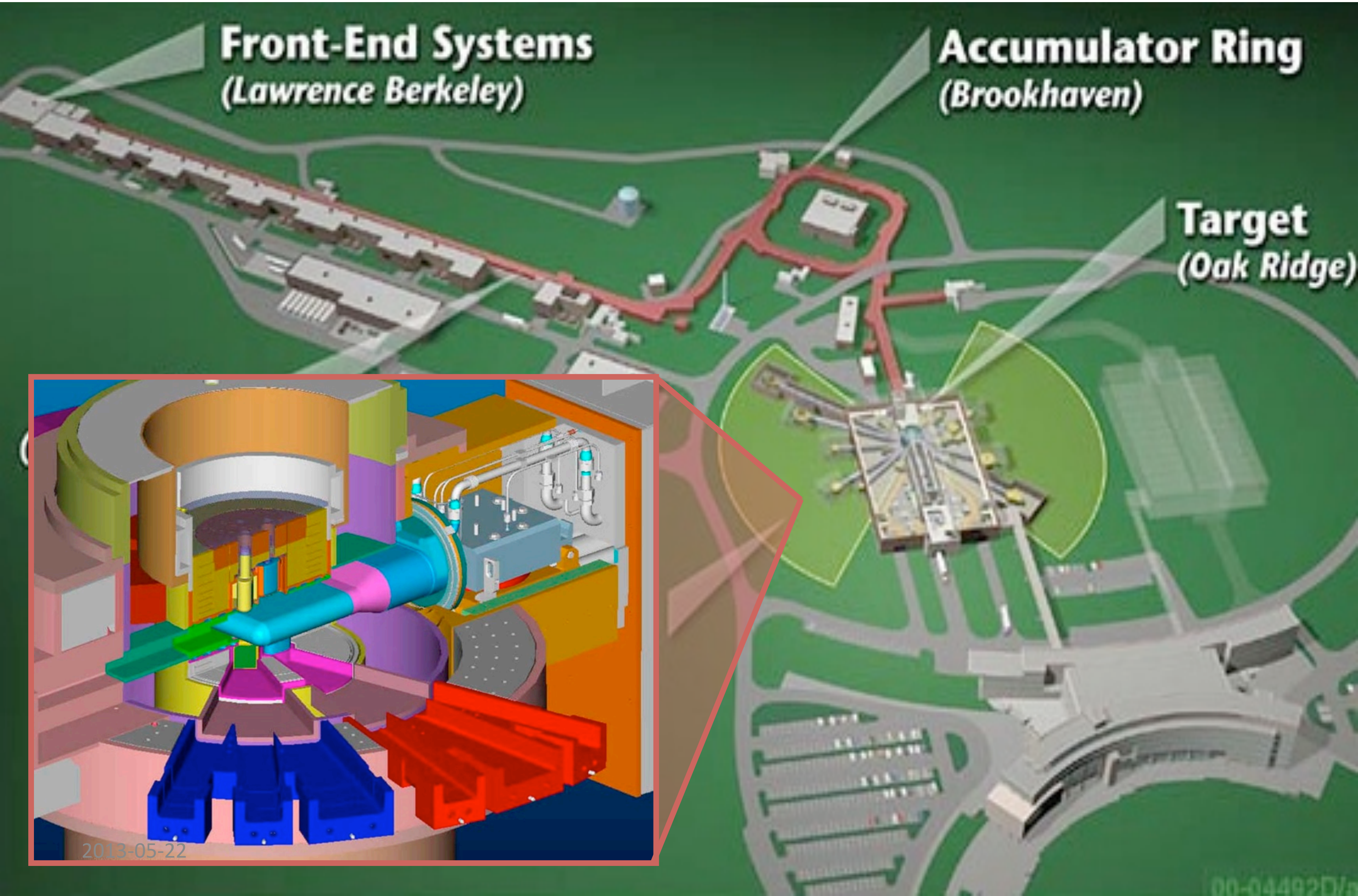
Spallation Neutron Source (SNS)

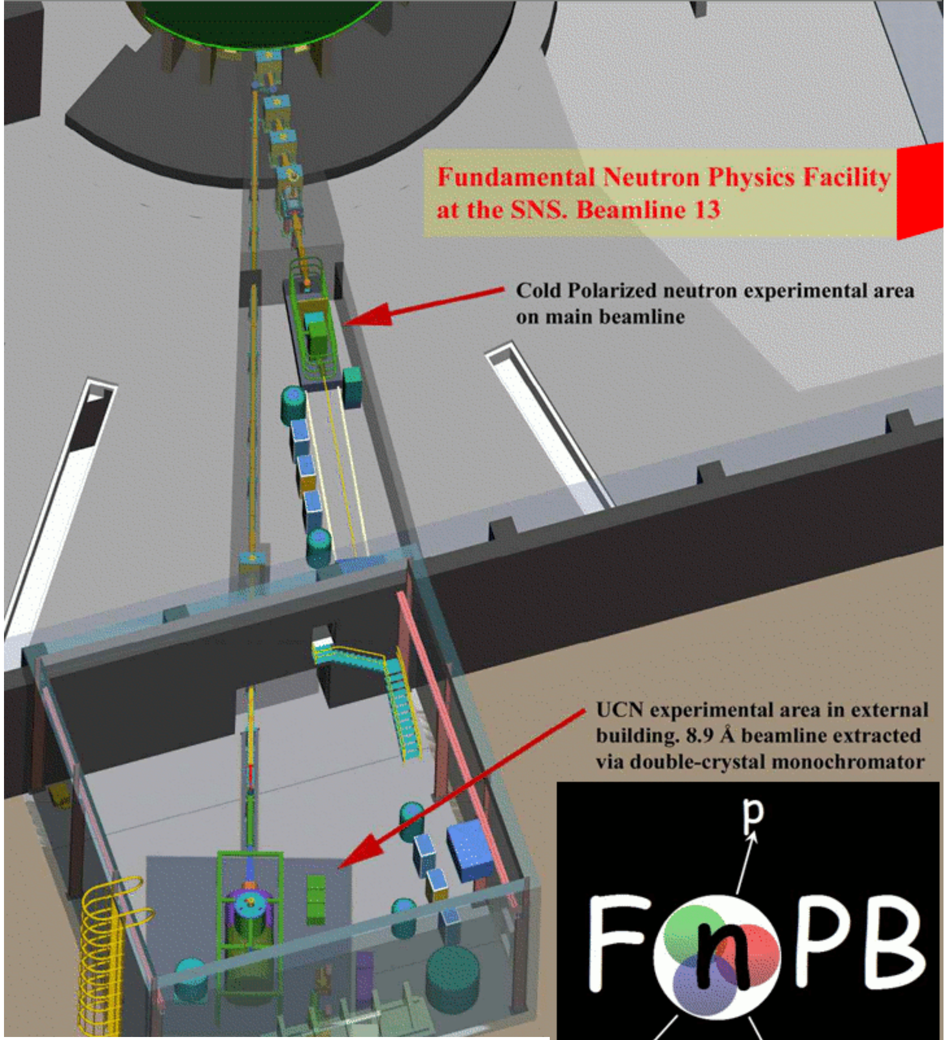
Spallation Neutron Source



2013-05-22

The Fundamental Neutron Physics Beam (FnPB) at SNS

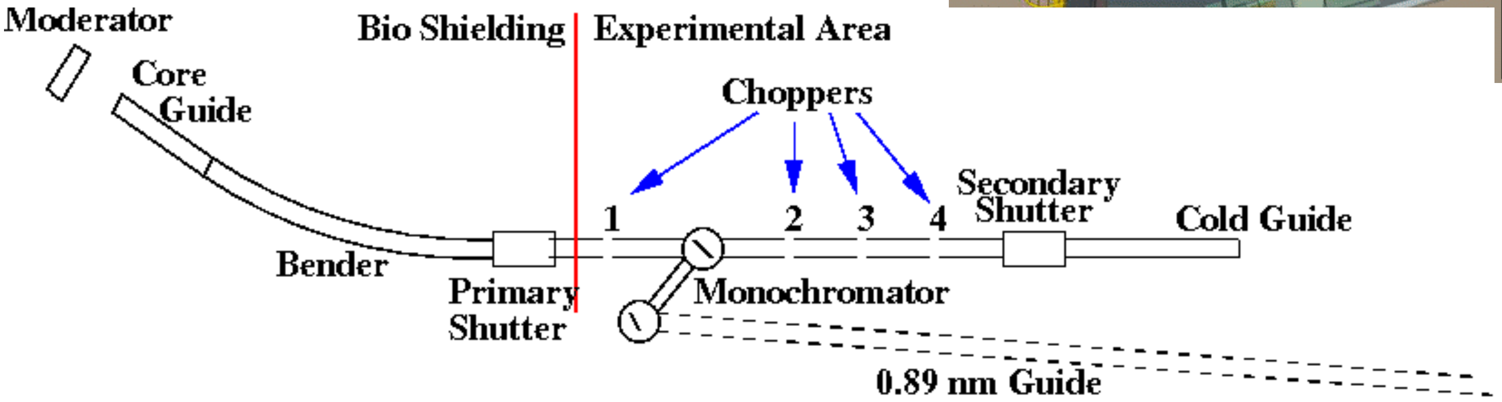
- LH2 moderator
- 15 m long guide ~ 18 m to experiment
- one polyenergetic cold beam line
- one monoenergetic (0.89 nm) beam line
- 4 frame overlap choppers
- 60 Hz pulse repetition



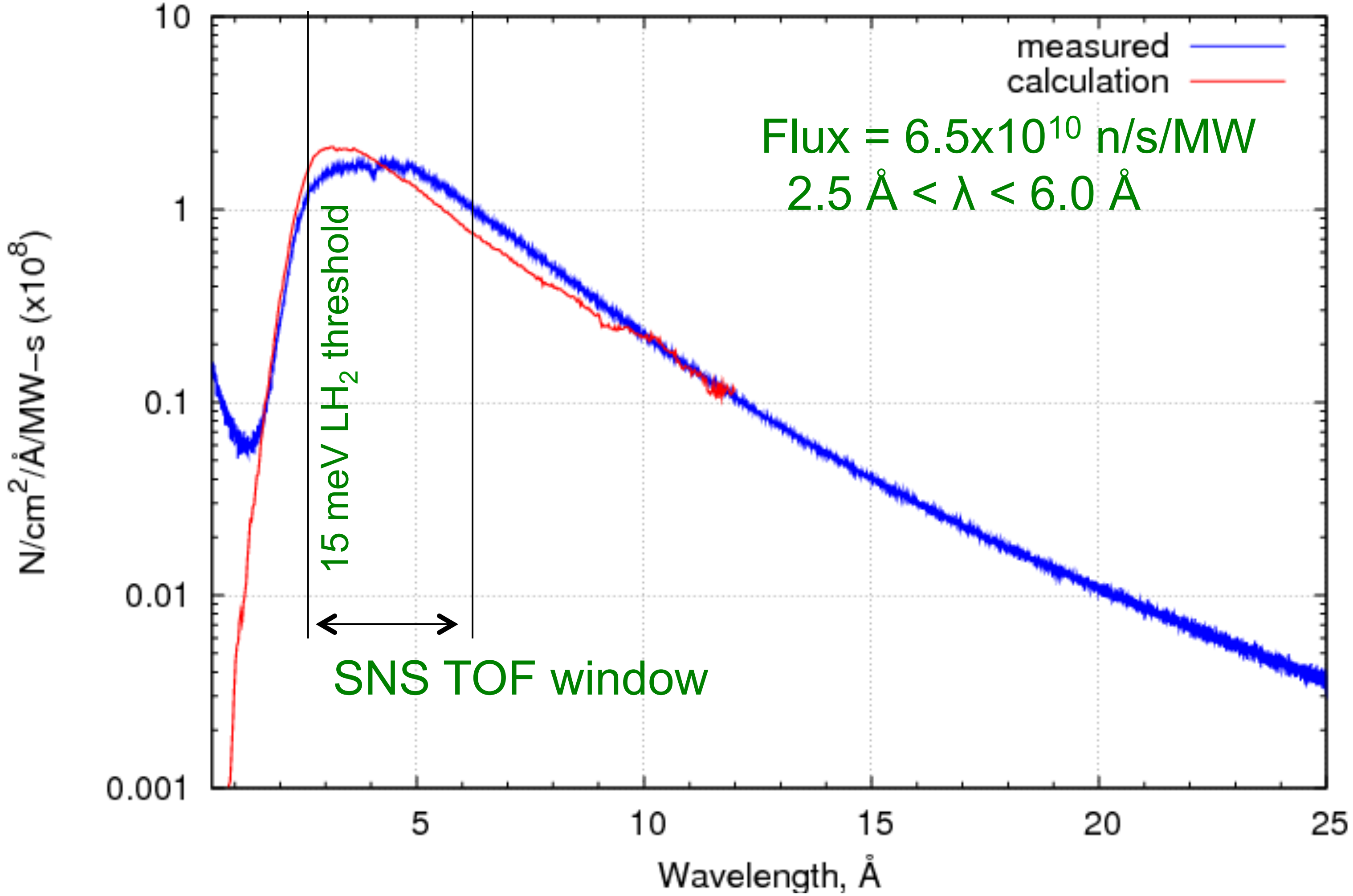
Fundamental Neutron Physics Facility at the SNS. Beamline 13

Cold Polarized neutron experimental area on main beamline

UCN experimental area in external building. 8.9 Å beamline extracted via double-crystal monochromator



Neutron Brightness at the SNS FnPB



Flux = 6.5x10^{10} n/s/MW
2.5 Å < λ < 6.0 Å

15 meV LH_2 threshold

SNS TOF window

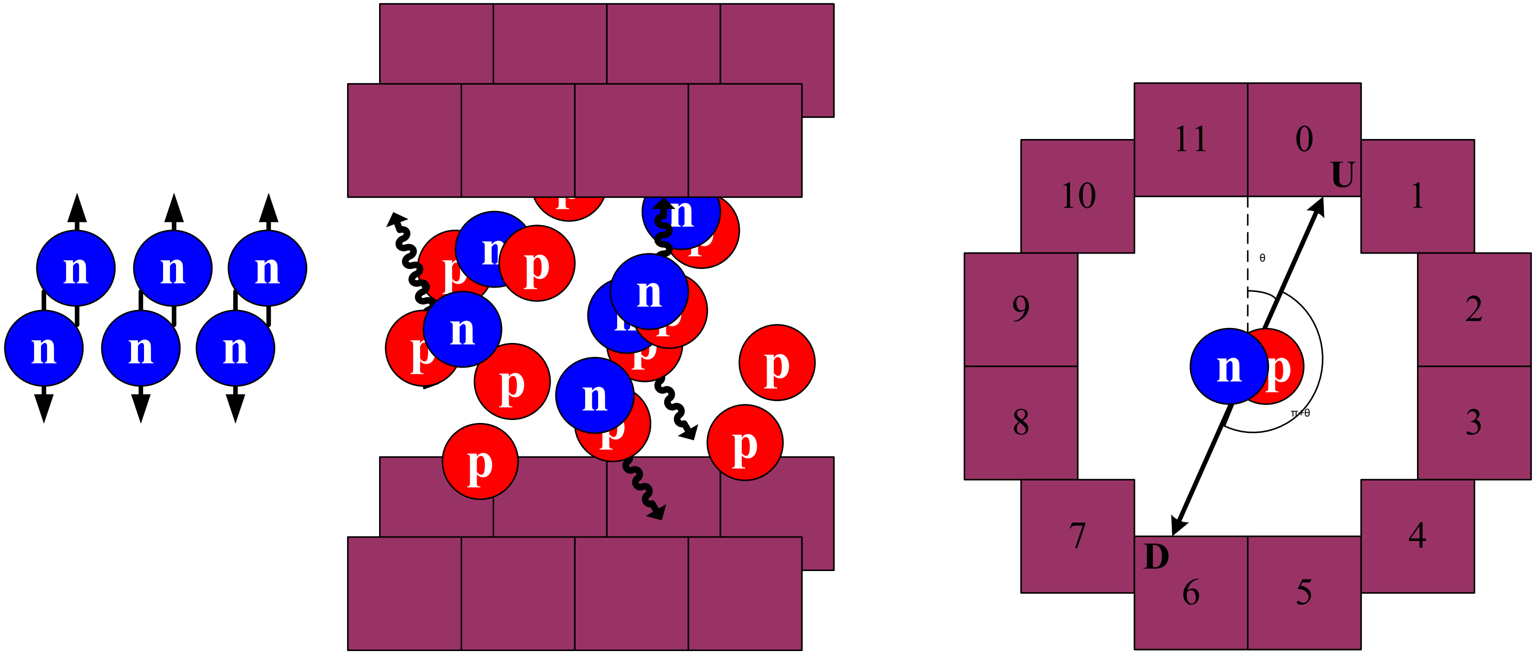
NPDγ: A Gamma-ray Asymmetry Measurement

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

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

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

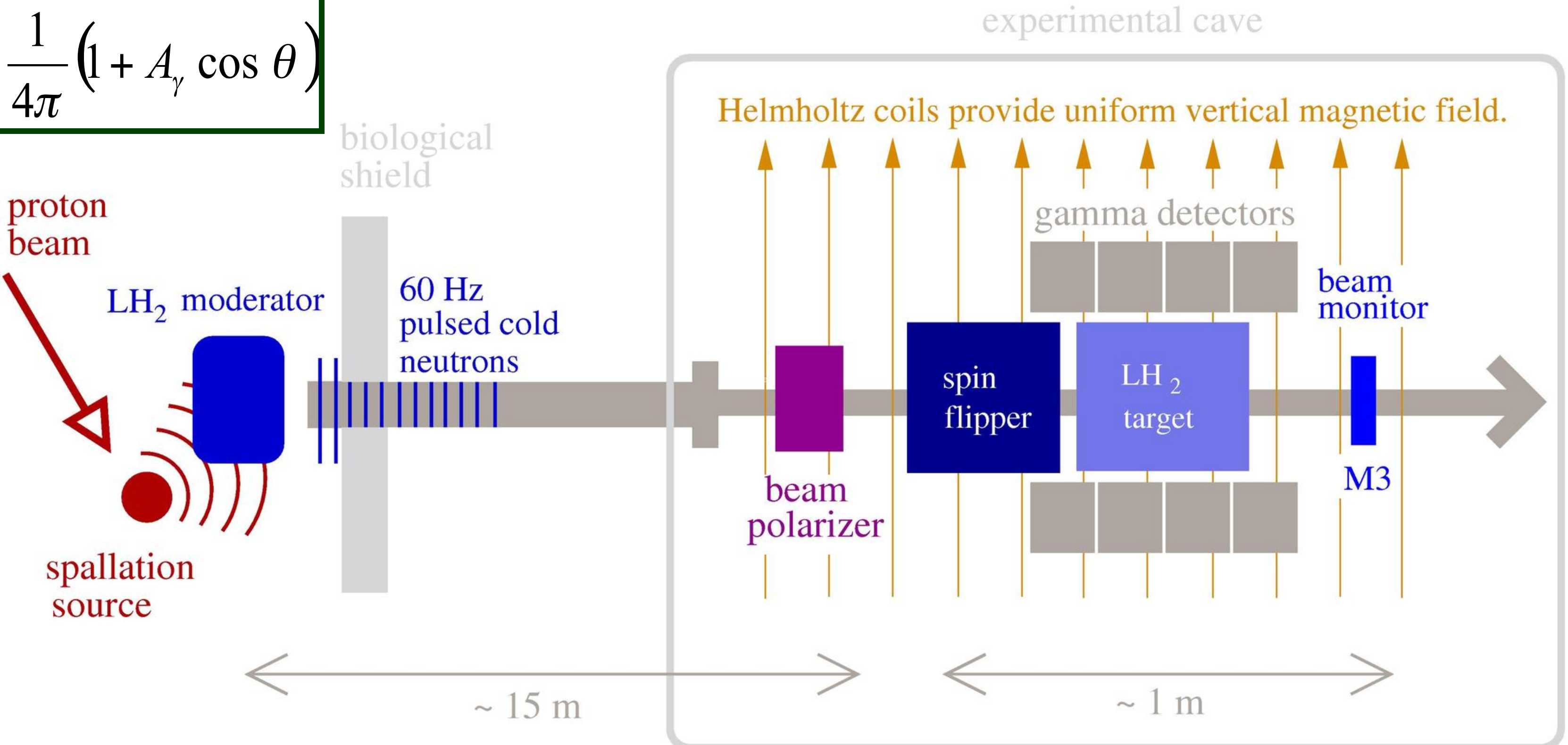
$$\boxed{A_\gamma^{\vec{n}p} \approx -0.27\tilde{C}_6^{\pi} - 0.09 m_{\mathrm{N}} \rho_{\mathrm{t}}}$$ Hybrid EFT



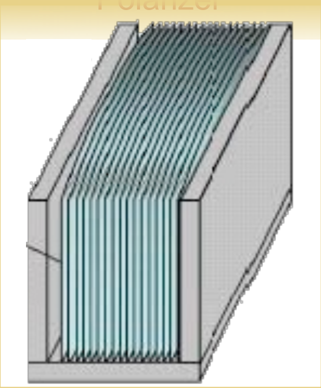
- Reverse the polarization pulse-by-pulse according to the sequence ↑↓↓↑↓↑↑↓ to cancel linear and quadratic time-dependent gain drifts
- Analyze opposite detector pairs to extract asymmetry as a function of θ
- Goals for gamma asymmetry: ~ $1\text{x}10^{-8}$ statistical error, ~ 10^{-9} systematic error.

PV Gamma Asymmetry Apparatus Concept

$$\boxed{\frac{d\sigma}{d\Omega} \propto \frac{1}{4\pi}\left(1 + A_\gamma \cos\theta\right)}$$



Supermirror Polarizer



Beam Monitors

RF Spin Rotator

LH_2 Target

Gamma Detectors

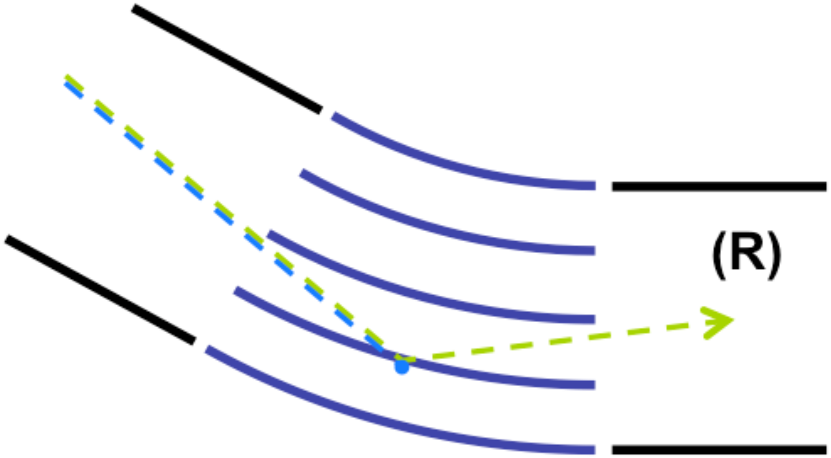
NPDGamma Apparatus at SNS

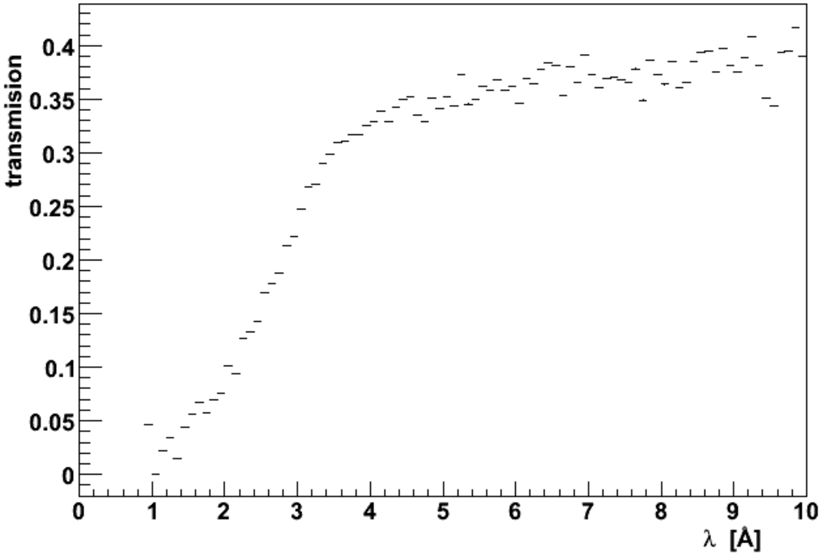
FnPB supermirror polarizer

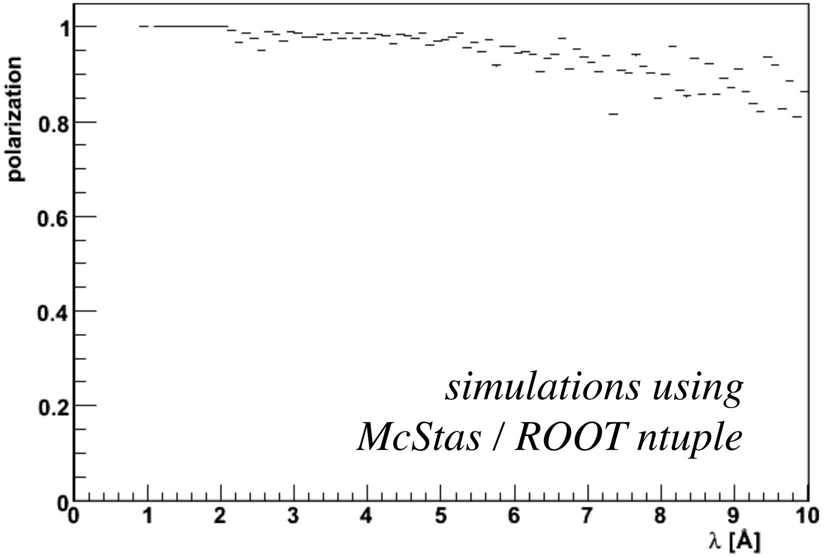
Fe/Si on boron float glass, no Gd

m = 3.0 critical angle
n = 45 channels
r = 9.6 m radius of curvature
l = 40 cm length
d = 0.3mm vane thickness

T=25.8% transmission
P=95.3% polarization
N=2.2x10^{10} n/s output flux (chopped)





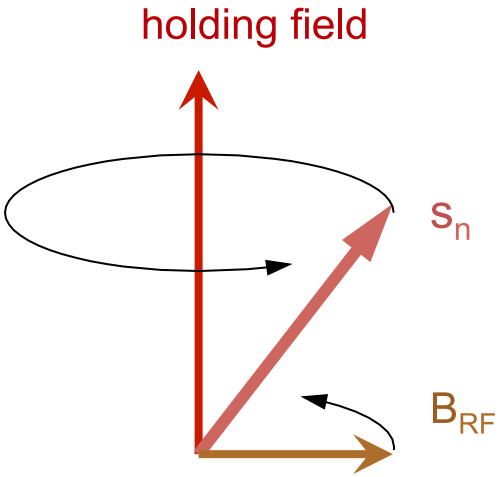


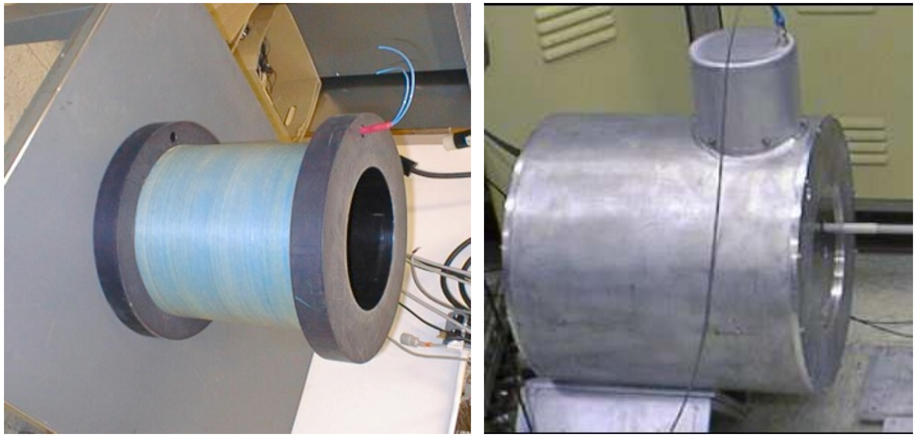
simulations using
McStas / ROOT ntuple

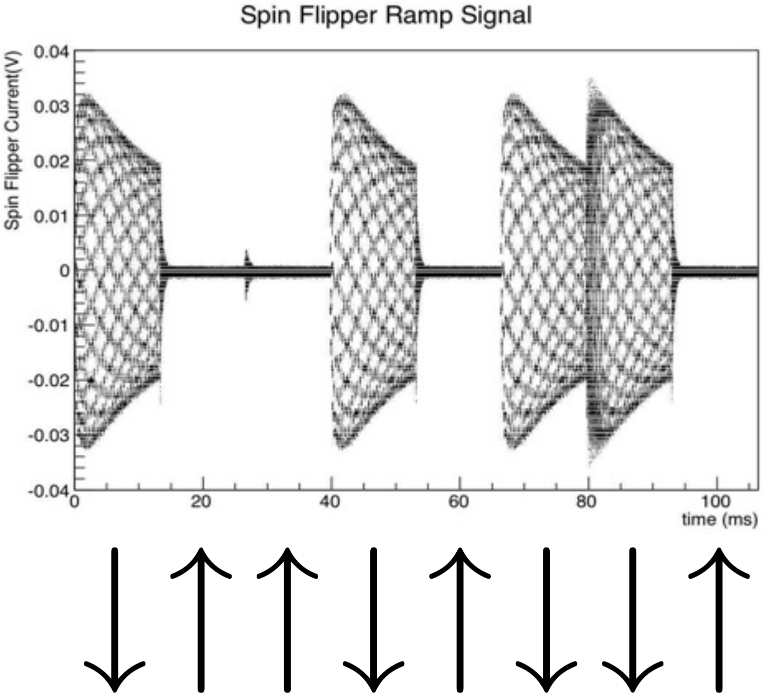
S. Balascuta *et al.,* Nucl. Instr. Meth. **A671** 137 (2012)

RF neutron spin rotator

- Resonant RF spin rotator,
  - 1/t RF amplitude tuned to velocity of neutrons
  - Affects spin only – NOT velocity! (neutron absorbs RF)
- essential to reduce instrumental systematics
  - spin sequence: ↑↓↓↑ ↓↑↑↓ cancels drift to 2nd order
  - danger: must isolate fields from detector
  - false asymmetries: additive & multiplicave

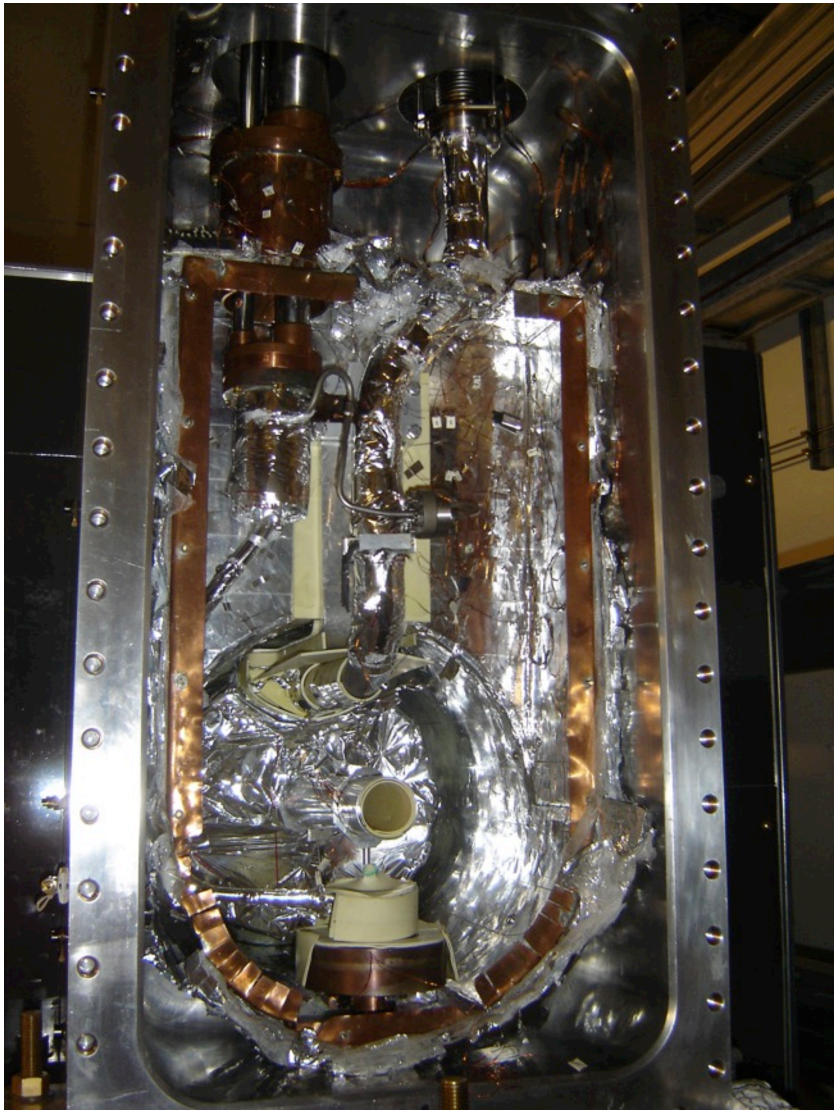






P. Neo-Seo, *et al.* Phys. Rev.
ST Accel. Beams **11** 084701 (2008)

16L liquid parahydrogen target

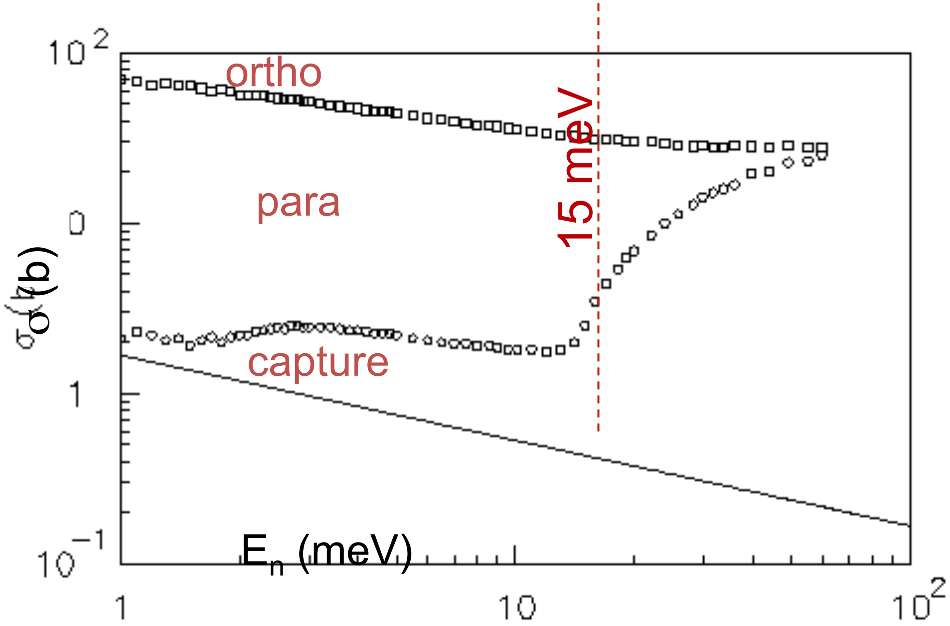


- 30 cm long → 1 interaction length
- 99.97% para → 1% depolarization
- Improvements: pressure-stamped vessel, thinner windows

para-H_2

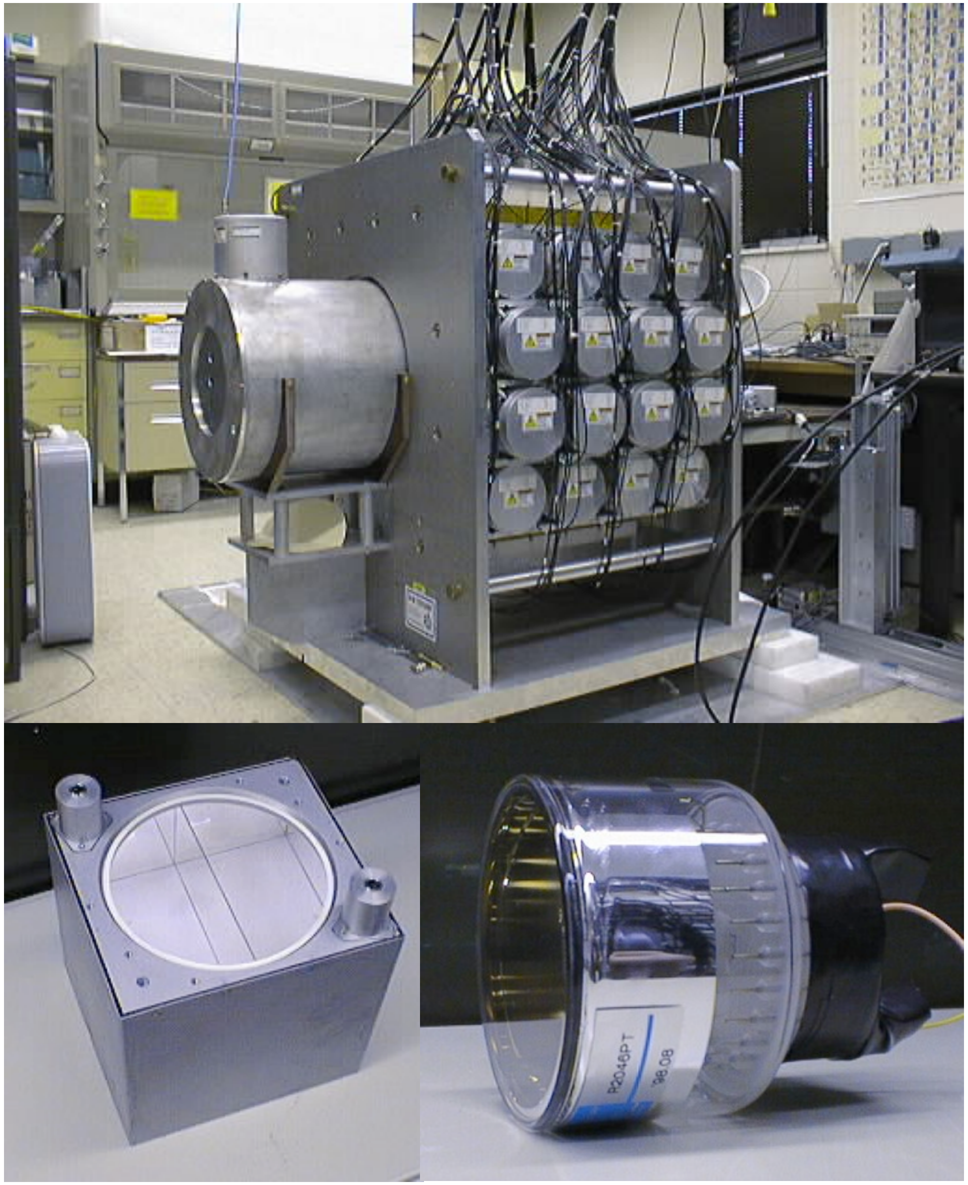
ΔE = 15 meV

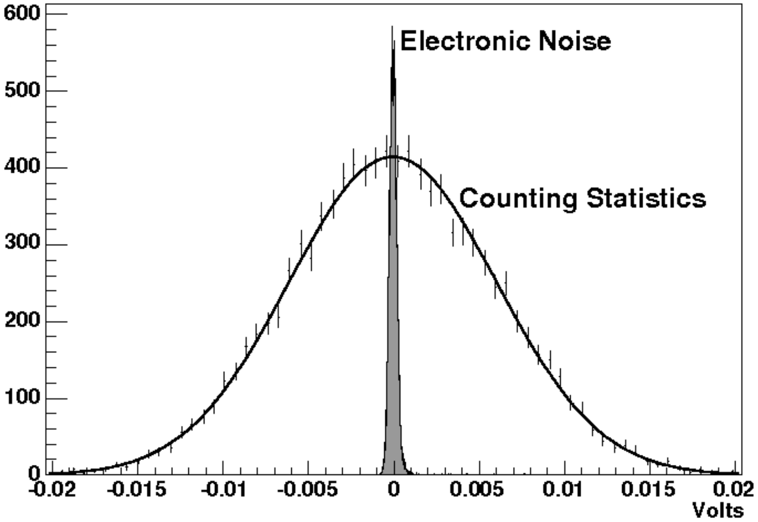
ortho-H_2



CsI(Tl) Detector Array

- 4 rings of 12 detectors each
    - 15 x 15 x 15 cm^3 each
- VPD's insensitive to B field
- detection efficiency: 95%
- current-mode operation
    - 5 x 10^8 gamma rate
    - counting statistics limited



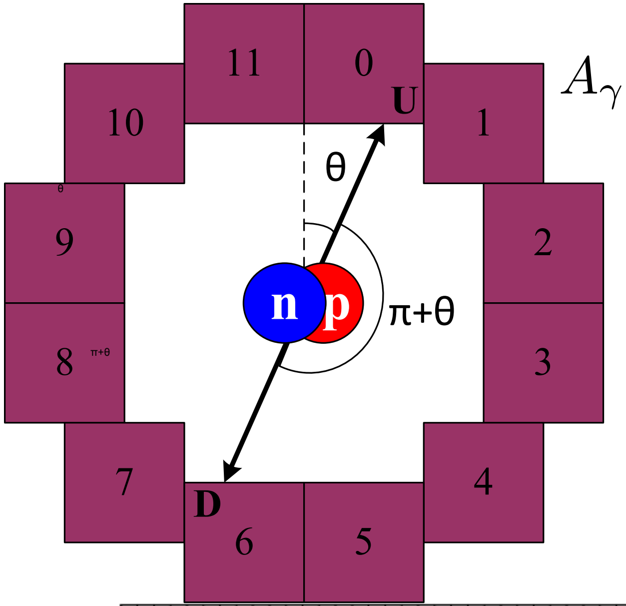


Signal/Systematic Errors

Reaction	Correlation	Pattern	PV?	TOF	Size
n+p→d+γ	$S_n . k_\gamma$	U-D	Yes	t^o	$1x10^{-8}$
n+p→n+p (scattering shift)	$K'_n . S_n \times k_n$	L-R	No	t^{-1}	$3x10^{-10}$
n+p→d+γ (Csoto & Gibson)	$K'_\gamma . S_n \times k_n$	L-R	No	t^{-2}	$2x10^{-11}$
n+p→d+γ (magnetized iron)	$S_\gamma . S_n$	U-D	No	t^o	$1x10^{-12}$
n→p+e+ν_e (beta decay)	$S_n . k_e$	U-D	Yes	t^o	$3x10^{-11}$
n+d→t+γ (D_2 contamination)	$S_n . k_\gamma$	U-D	Yes	t^o	$1x10^{-10}$
n+p→n+p (Mott-Schwinger)	$K'_n . S_n \times k_n$	L-R	No	$t^{-2.8}$	$1x10^{-10}$
n+^{6}Li→α+t (Li-shield)	$S_n . K'_n$	U-D	Yes	t^o	$2x10^{-11}$
$(\mu_n.\nabla)B$ (Stern-Gerlach)	$(S_n . \nabla)B$	U-D	No	t^1	$1x10^{-10}$
n+A→A+1+e+ν_e	$S_n . k_e$	U-D	Yes	Varies	$<10^{-10}$

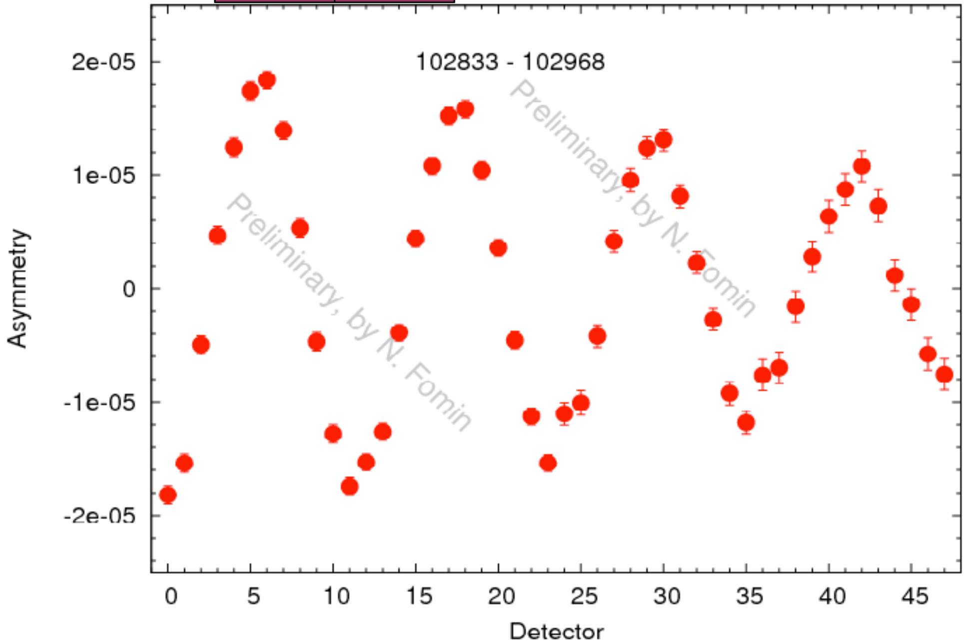
Under analysis: asymmetry from polarized n capture in aluminum

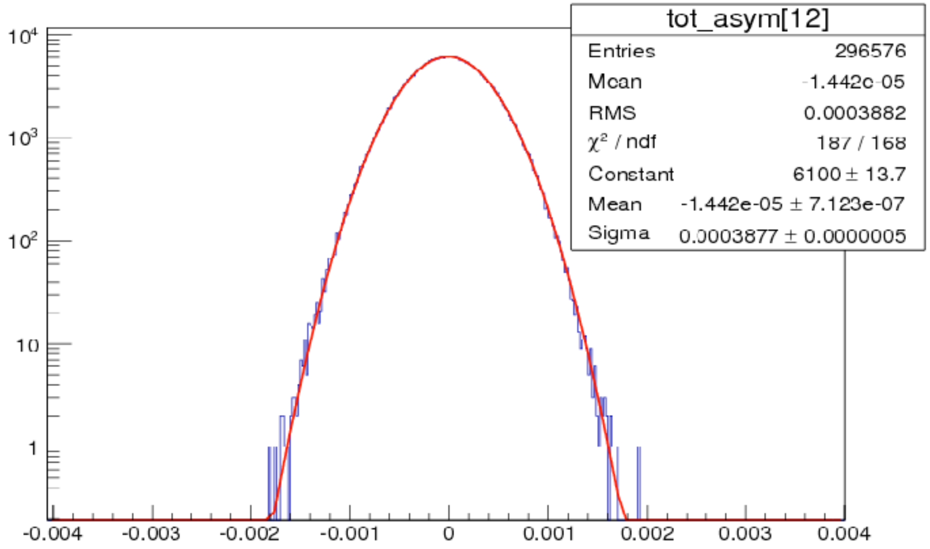
PV asymmetry in 35Cl



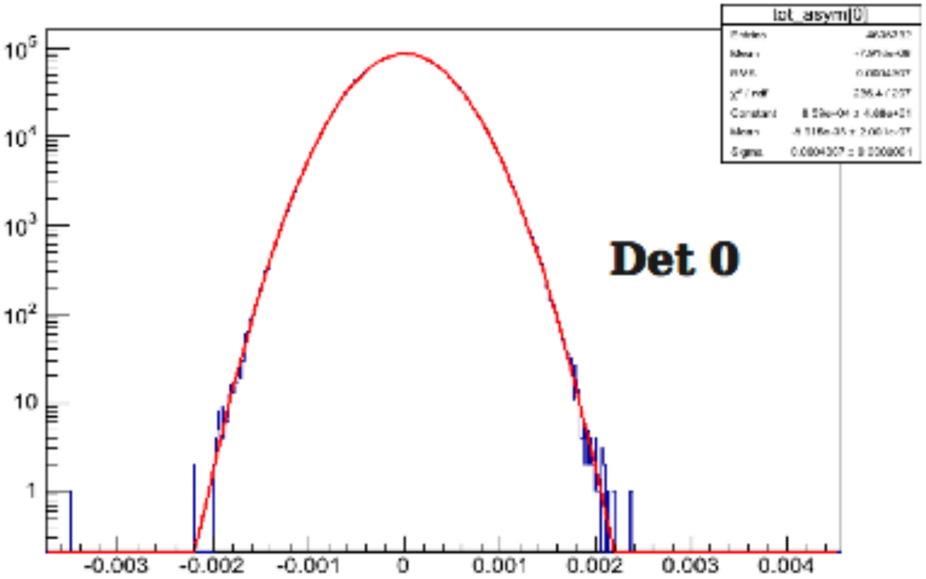
$$A_\gamma P_N cos(\theta) = \frac{[N(\theta) - N(\theta+\pi)]_\uparrow - [N(\theta) - N(\theta+\pi)]_\downarrow}{[N(\theta) - N(\theta+\pi)]_\uparrow + [N(\theta) - N(\theta+\pi)]_\downarrow}$$

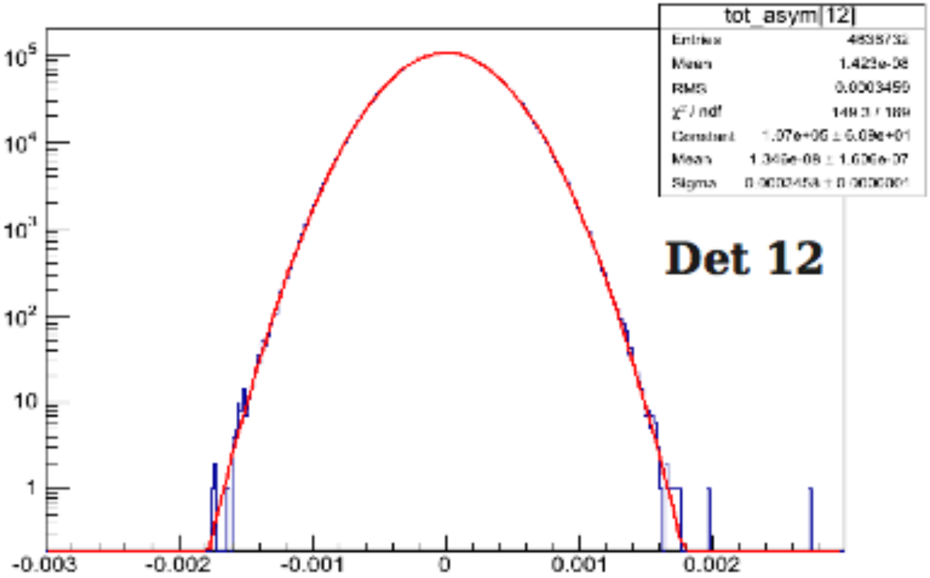
Measurement	Asymmetry (x10^{-6})
LANL	-29.1 ± 6.7
Leningrad	-27.8 ± 4.9
ILL	-21.2 ± 1.72
SNS (Current result)	-25.9 ± 0.6

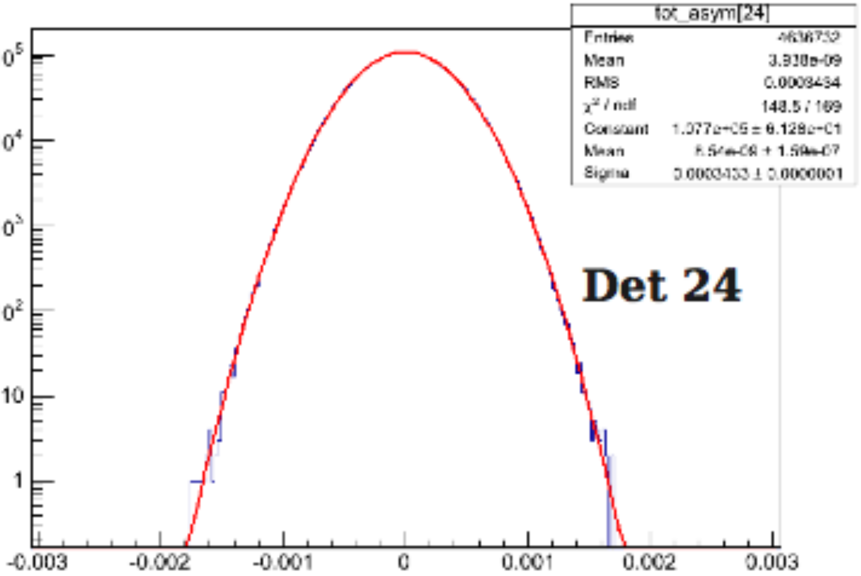


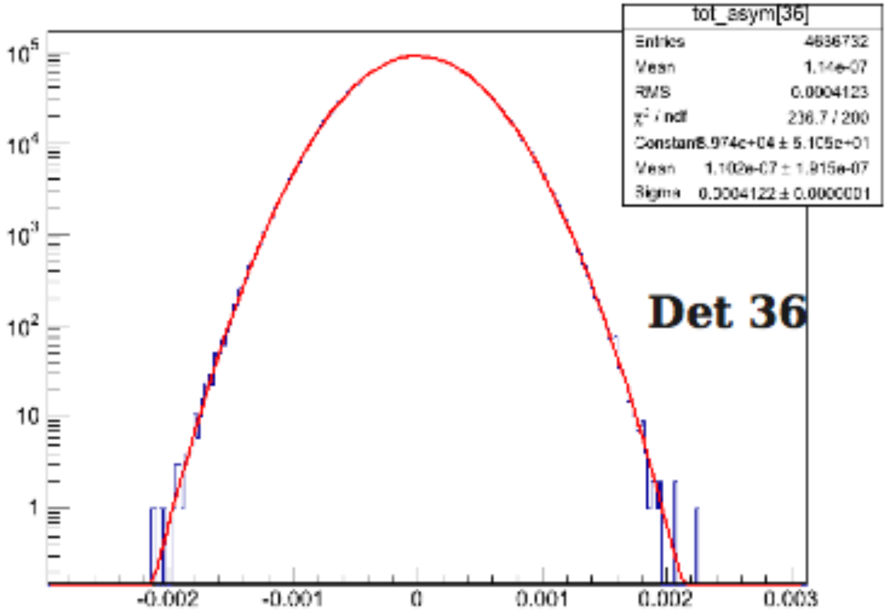


H1 Asymmetries, after cuts

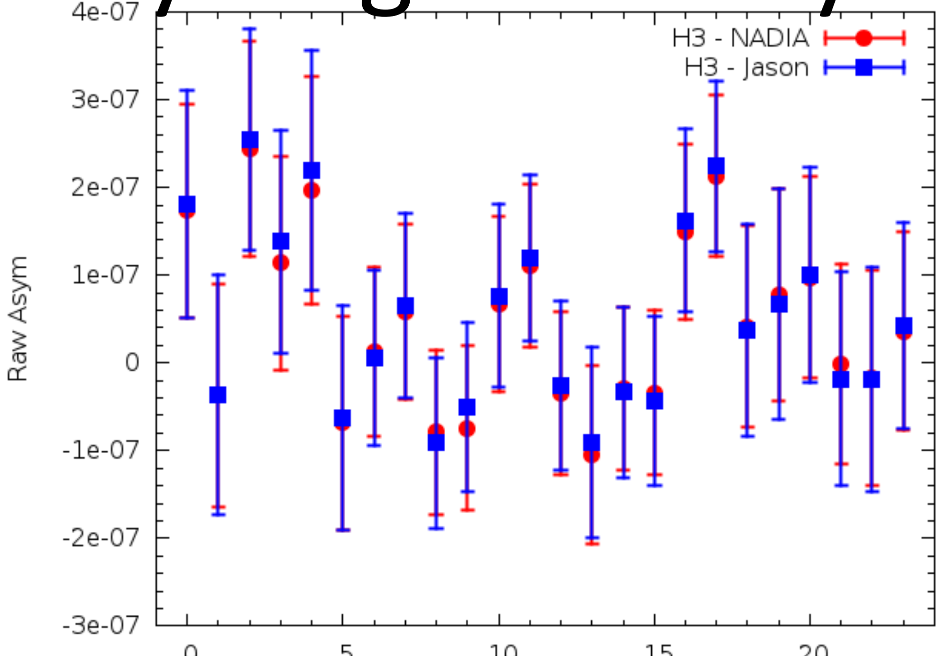


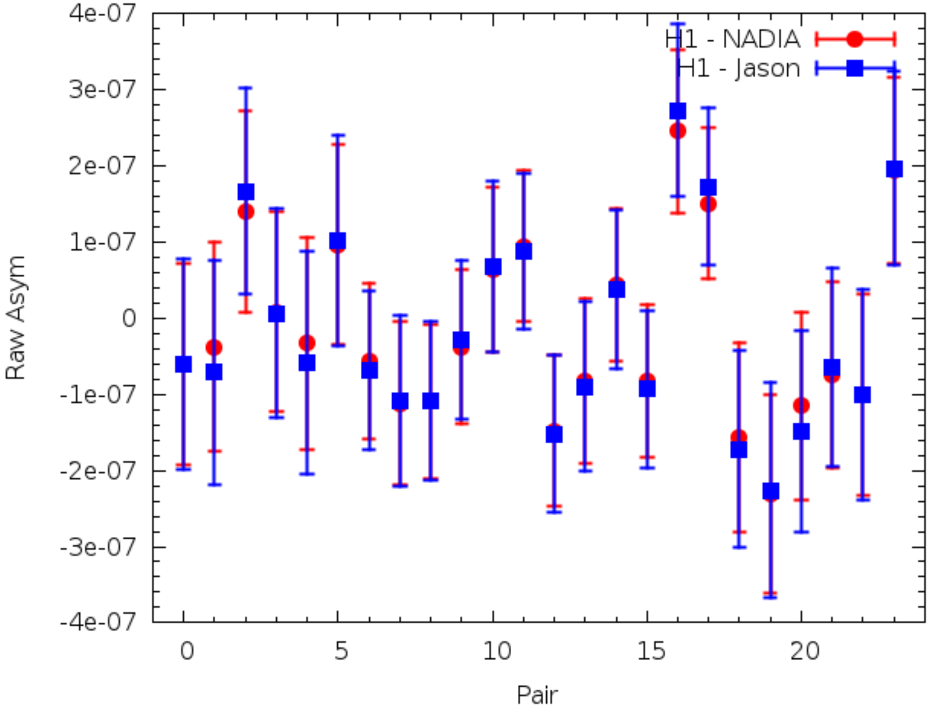


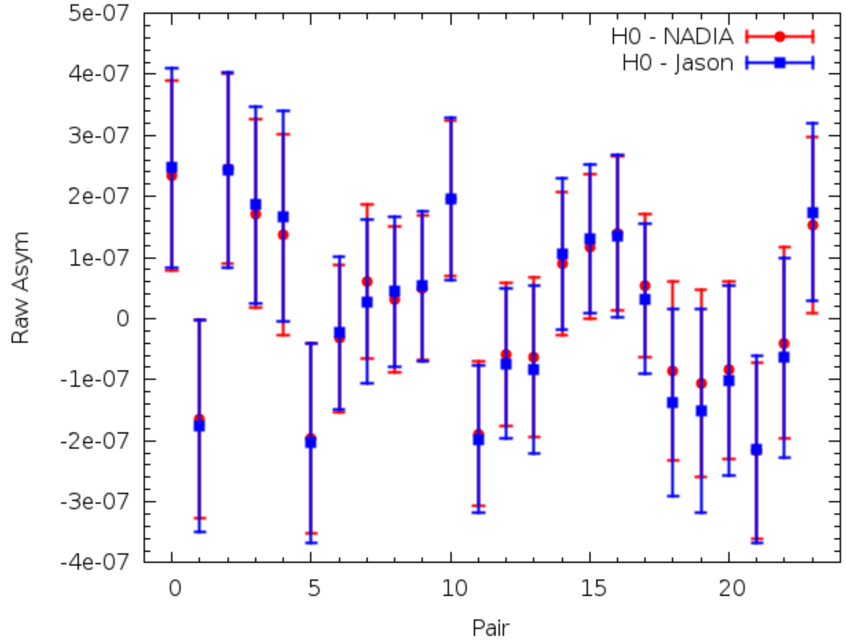




Hydrogen: Analyses of Different Runs





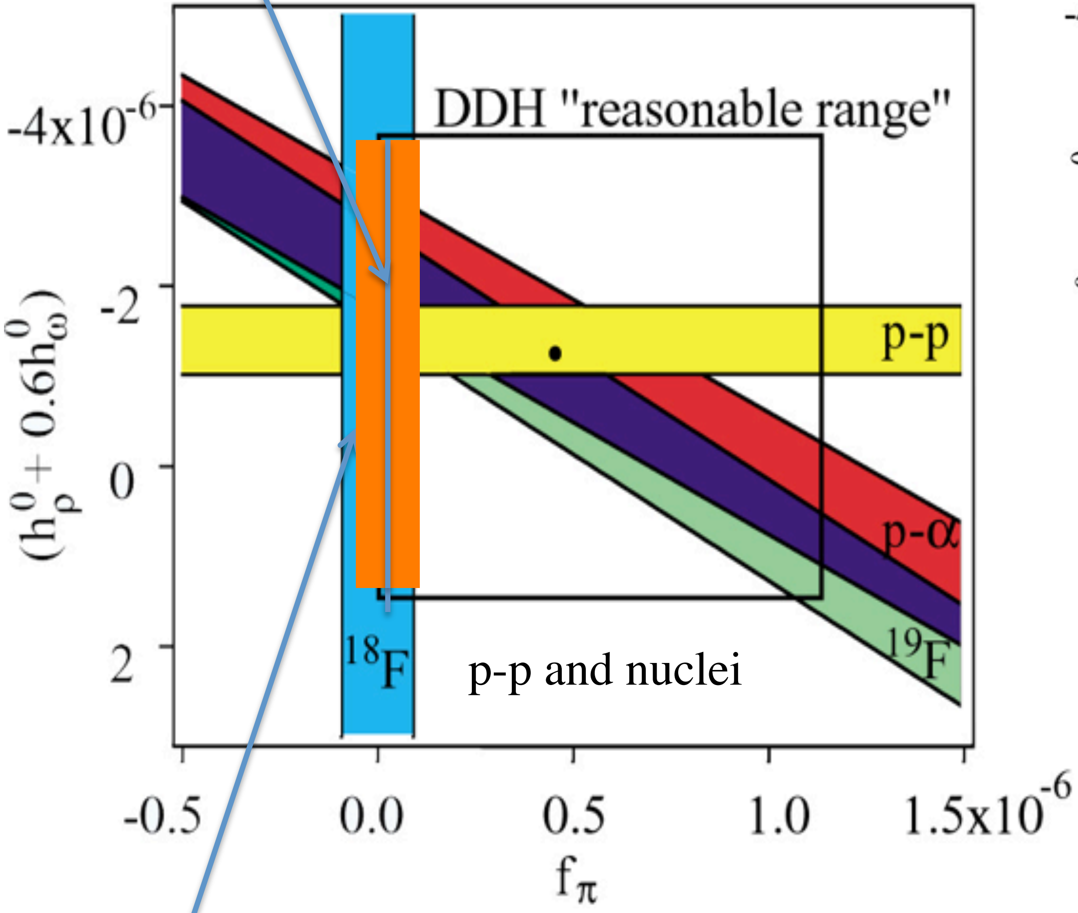


Preliminary result:
asymmetry consistent with zero
statistical error ~13 ppb
negligible systematic error

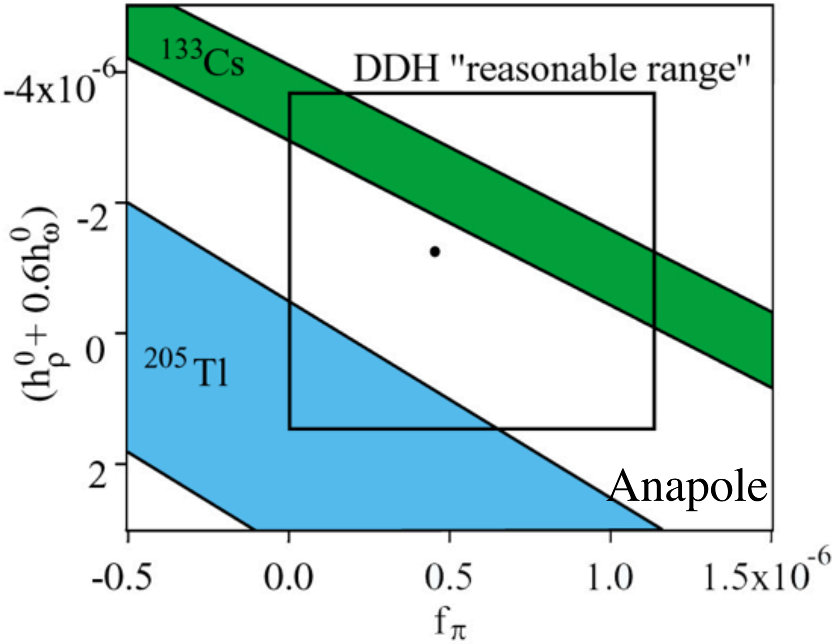
Conclusion: f-pi is very small

Prelim: NPDGamma result: what does it mean?

NPDGamma prelim. result



Wasem, Phys. Rev. C **85** (2012) 022501
1st Lattice QCD result



No weak pion coupling!

Isoscalar/isovector NN weak ~10 (like another ΔI=1/2 rule!)

A new problem in nonperturbative QCD

Also consistent with ILL results (V. A. Vesna et al, Phys.Rev.C77:035501 (2008))

n-3He and n-4He Parity Violation: ~orthogonal to p-4He

The PV longitudinal analyzing power in *p*-^{4}He scattering at 40 MeV has been measured:

$$A_L(p,4He) = [-3.3 +/- 0.9] \times 10^{-7}$$

Lang et al. PRC ***34*** *1545 (1986)*

It was calculated in the DDH framework:

$$A_L\left(p,{}^4\mathrm{He}\right) = -\left(0.34 f_\pi - 0.06 h_\omega^0 - 0.06 h_\omega^1 - 0.14 h_\rho^0 - 0.05 h_\rho^1\right)$$

The calculation for the *n*-^{4}He spin rotation (*isospin mirror system*):

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

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

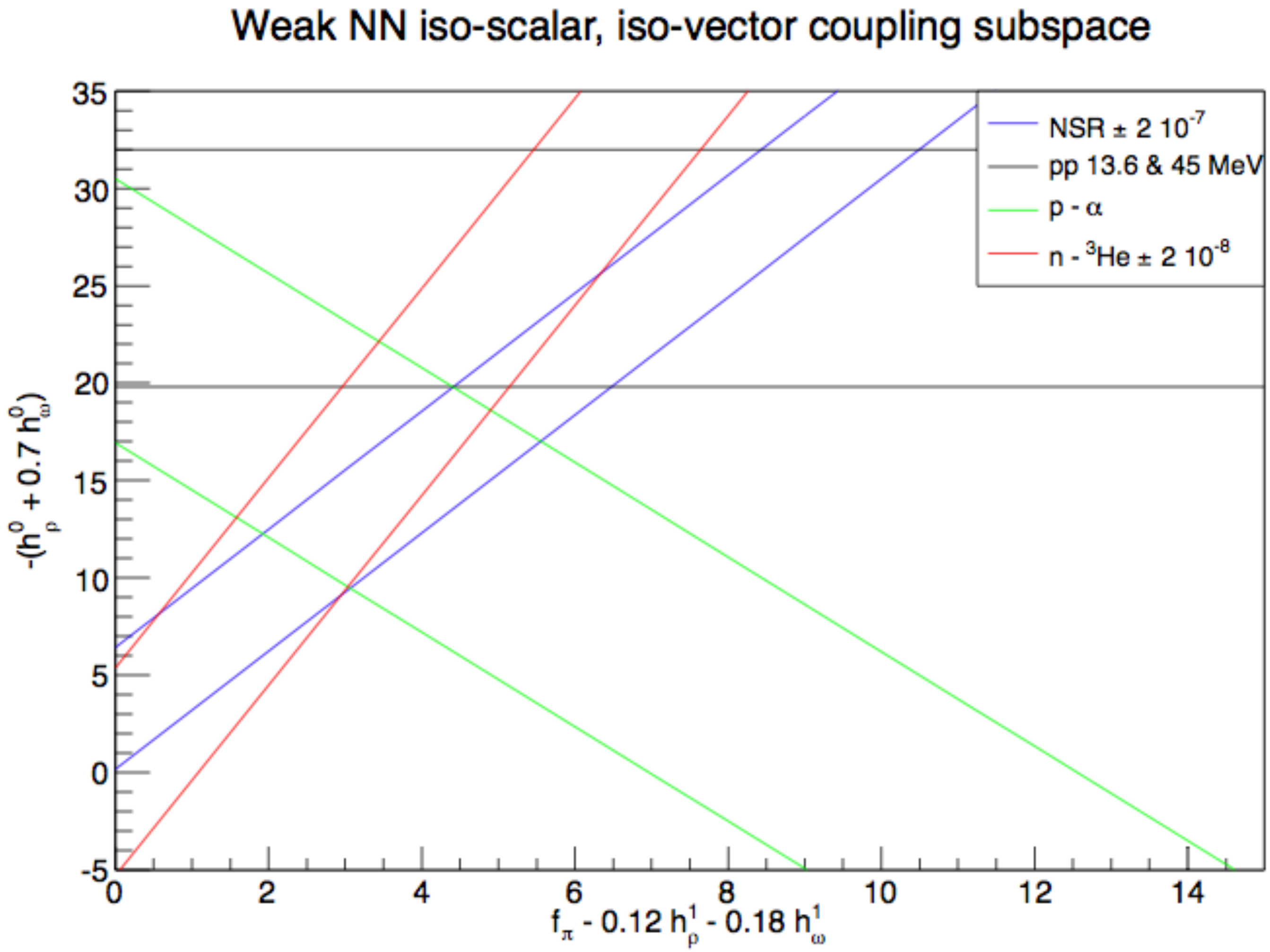
The calculation for the *n*-^{3}He correlation:

$$A_{PV}\left(\vec{n},{}^3\mathrm{He}\right) = \left(-.19 f_\pi - .023 h_\omega^0 - .038 h_\rho^0 + .023 h_\rho^1 + .05 h_\omega^1\right)$$

Vivani et al. PRC ***82*** *044001 (2010)*

These expressions are proportional (up to signs of coefficients) from isospin. Also n-3He and n-4He observables constrain a similar linear combination of amplitudes. This makes n-3He/*n*-^{4}He and *p*-^{4}He combination more powerful in constraining weak NN

Constraints from n-3He and n-4He experiments



The n3He Collaboration

- Spokespersons

D. Bowman, M. Gericke, C. Crawford

- Local Project Manager

S. Penttila

- Project Engineer

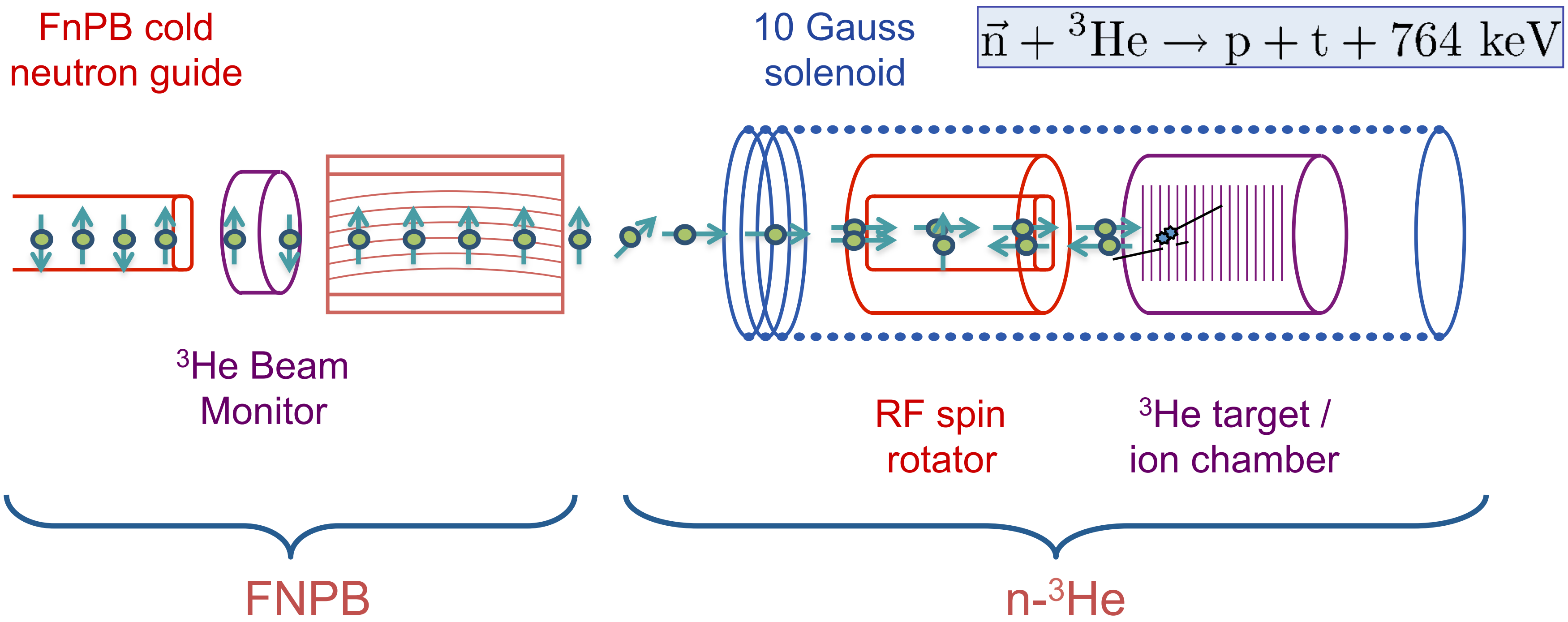
Jack Thomison

- Work Subpackage Leaders

G. Greene	Neutronics
L. Barrón	Solenoid
C. Crawford	Spin rotator
M. Gericke	Target / detector
D. Bowman	Preamplifiers
C. Crawford	Data acquisition
N. Fomin	Online analysis
J. Hamblen	Integration
D. Bowman	Commissioning

Institution	Researcher	Category	2014 Effort
Duke University, Triangle Universities Nuclear Laboratory			
	Pil-Neo Seo	Research Staff	10
Istituto Nazionale di Fisica Nucleare, Sezione di Pisa			
	Michele Viviani	Research Staff	15
Oak Ridge National Laboratory			
	Seppo Pentillä	Research Staff	70
	David Bowman	Research Staff	70
	Paul Mueller	Research Staff	50
	Jack Thomison	Engineer	50
	Vince Cianciolo	Research Staff	10
University of Kentucky			
	Chris Crawford	Faculty	50
	Kabir Latiful	Grad Student	100
Western Kentucky University			
	Ivan Novikov	Faculty	70
University of Manitoba			
	Michael Gericke	Faculty	50
	Mark McCrea	Grad Student	70
	Carlos Olguin	Grad Student	100
Universidad Nacional Autónoma de México			
	Libertad Baron	Faculty	50
	Andrés Ramírez Morales	Grad Student	100
University of New Hampshire			
	John Calarco	Faculty	50
University of South Carolina			
	Vladimir Gudkov	Faculty	5
	Matthias Schindler	Faculty	5
Univeristy of Tennessee			
`	Geoff Greene	Faculty	30
	Nadia Fomin	Faculty	30
	Irakli Garishvili	Postdoc	50
	Chris Hayes	Grad Student	100
	Chris Coppola	Grad Stduent	100
Univeristy of Tennessee at Chattanooga			
`	Josh Hamblen	Faculty	75
	Caleb Wickersham	Undergraduate	100
University of Virginia			
	S. Baessler	Faculty	10

Experimental Setup



FnPB cold neutron guide

10 Gauss solenoid

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

^{3}He Beam Monitor

RF spin rotator

^{3}He target / ion chamber

FNPB

n-^{3}He

- Measure PV spin asymmetry to 2×10^{-8}
- Longitudinal holding field – suppressing PC nuclear asymmetry:

  ($1.7 \times 10^{-6} \propto s_n \bullet k_n \times k_p$ (Hale) suppressed by two small angles
- RF spin flipper – negligible spin-dependence of neutron velocity
- ^{3}He ion chamber – both target and detector

NSR Collaboration

Indiana University/CEEM

E. Anderson, W. Fox, J. Fry, C. Haddock, A. T. Holley, W. M. Snow

Universidad Nacional Autónoma de México Instituto de Física

L. Barrón Palos, M. Maldonado-Velázquez

Le Moyne College

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B. E. Crawford, R. Malone

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C. Crawford, A. Sprow

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Bhabha Atomic Research Centre

Prakash Chandra Rout, S. Santra

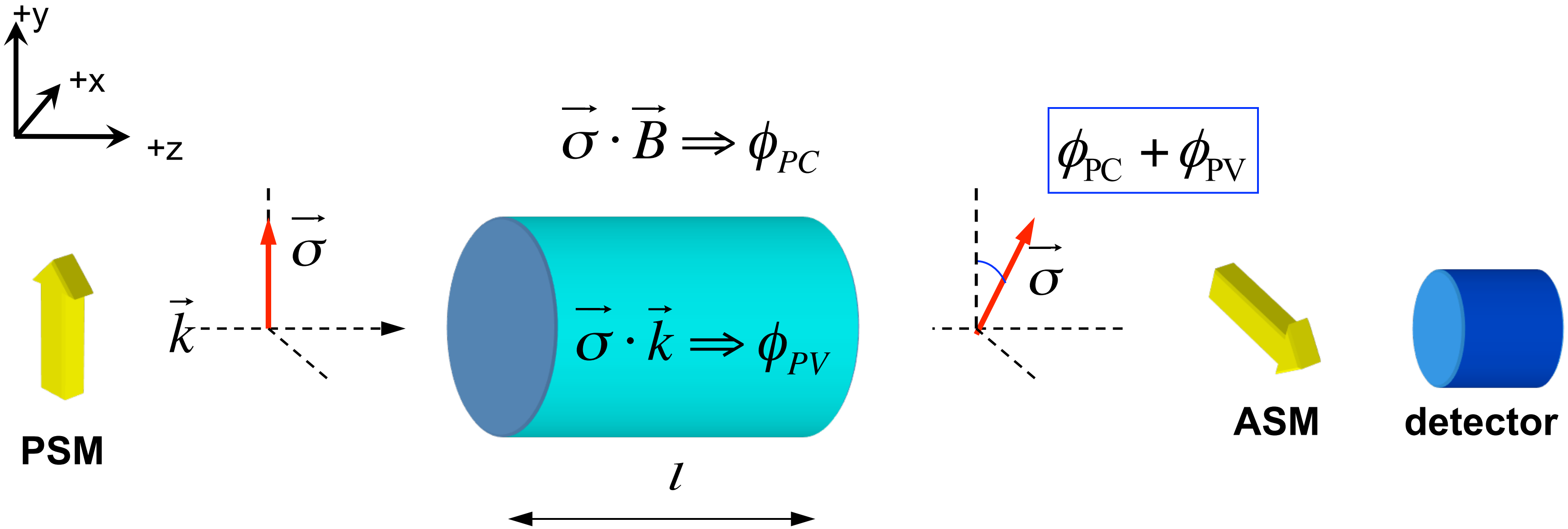
Georgia State University

Churamani Paudel, M. G. Sarsour

Florida State University

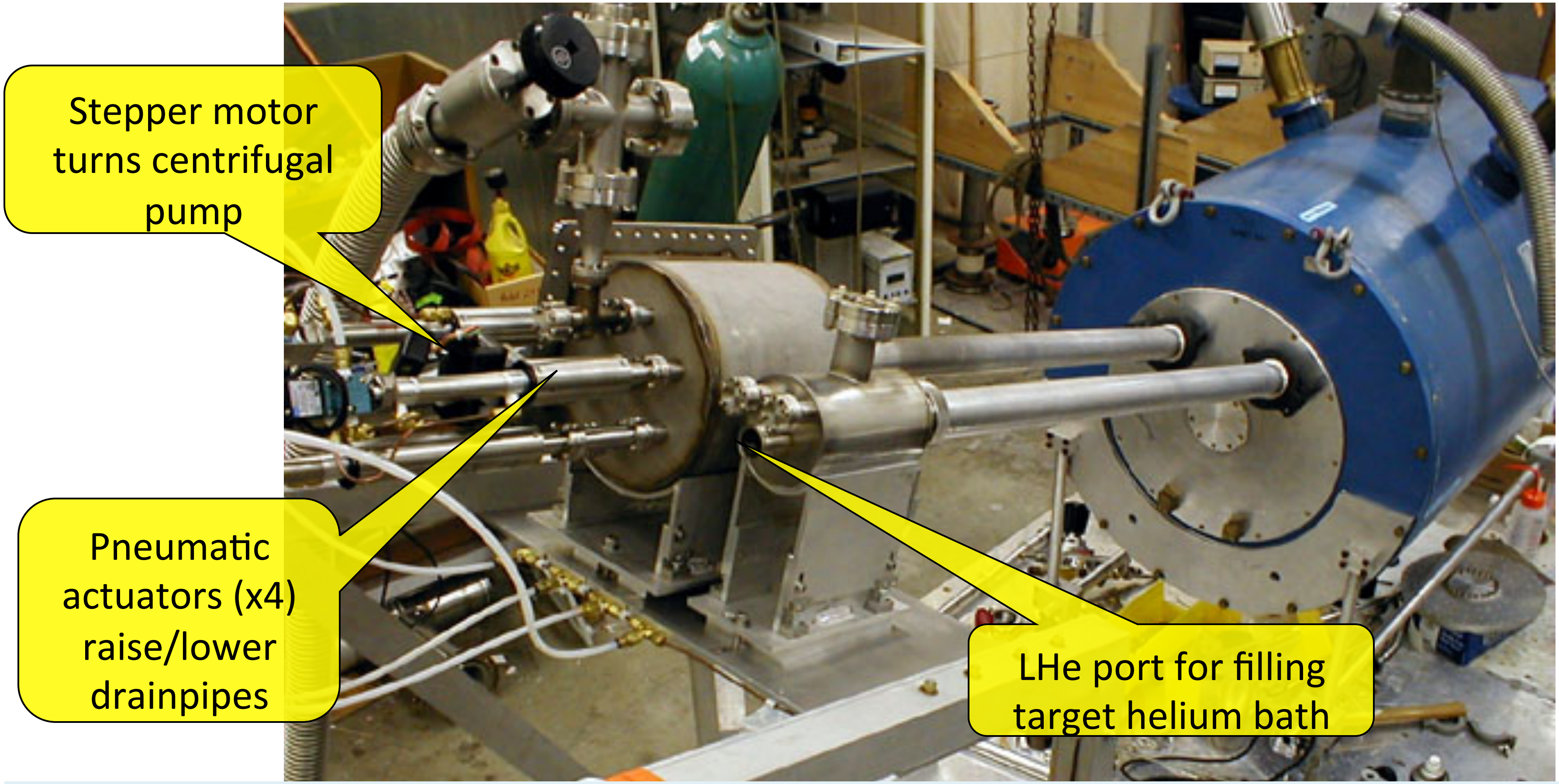
S. van Sciver

Experimental Overview



- Cold neutrons are polarized in the y direction traveling in the z direction
- They interact with the ^{4}He over a length l
- The neutron spin gains $\phi_{\mathrm{PC}}+\phi_{\mathrm{PV}}$ and passes through the supermirror analyzer where the neutrons are detected
- Accumulated phase differences between opposite helicity states causes transversely-polarized neutrons to corkscrew as they propagate through target

Liquid Helium Cryostat and Motion Control

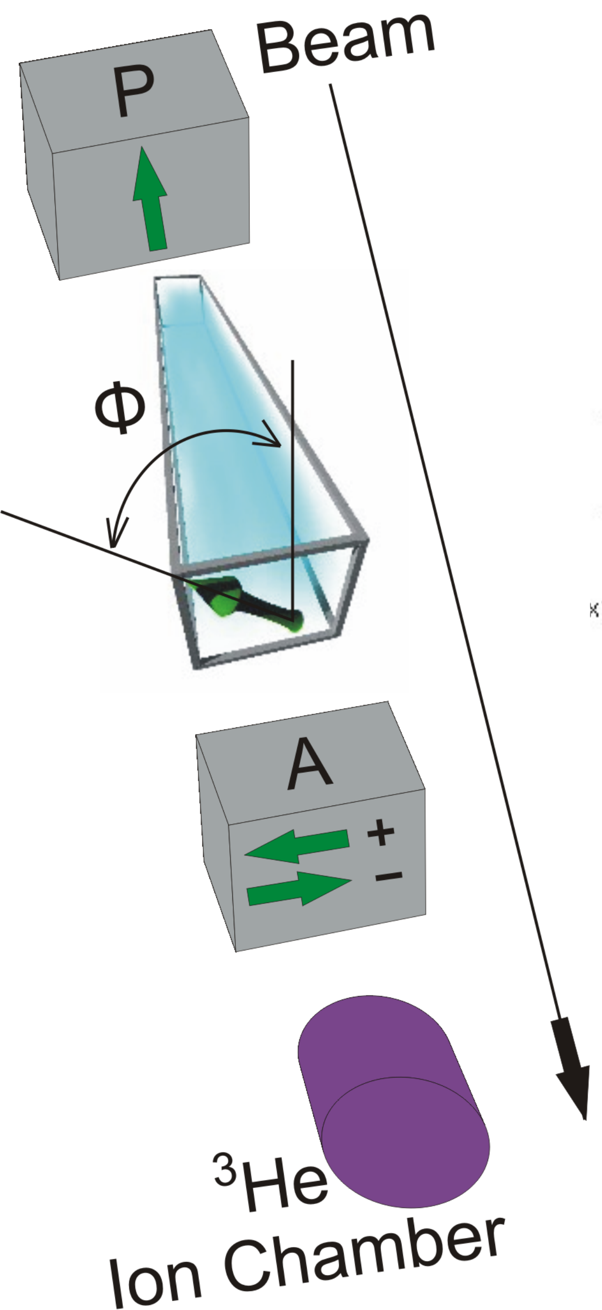


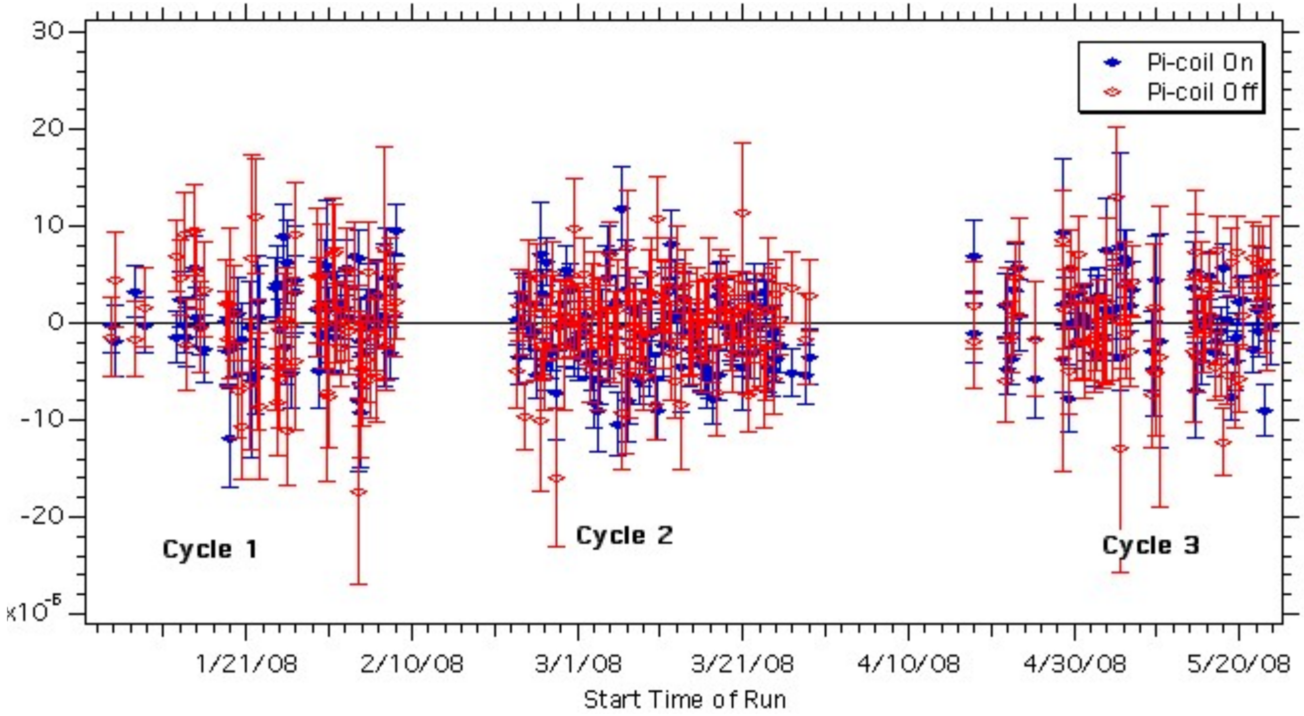
- Nonmagnetic movement of liquid helium.

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

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

Neutron Spin Rotation in n+4He





Transversely polarized neutrons corkscrew due to weak interaction

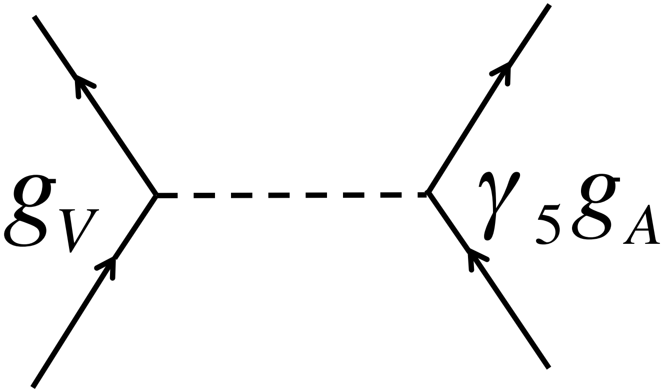
ϕ_{PNC}= [+1.7 ± 9.1 (stat) ±1.4 (sys)] x 10^{-7} rad/m

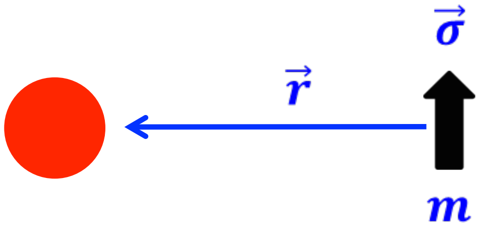
W. M. Snow et al., Phys. Rev. C83, 022501(R) (2011).

PLAN: experiment to be repeated at NIST, ~1 x 10^{-7} rad/m goal

Example of a nonstandard P-odd interaction from spin 1 boson exchange:

[Dobrescu/Mocioiu 06, general construction of interaction between nonrelativistic fermions]

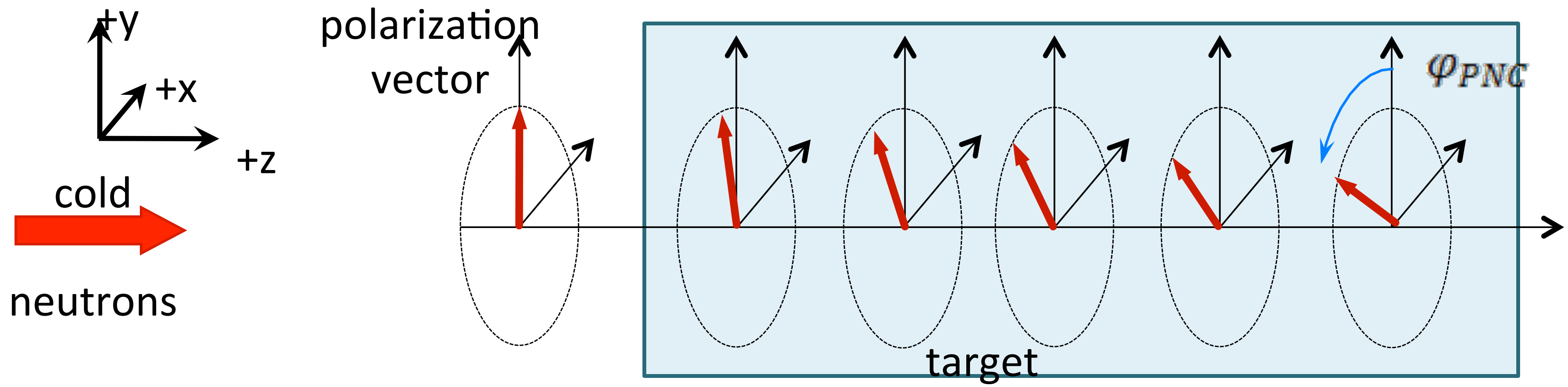




$$V(\vec{\sigma},\vec{r},\vec{v}) = \frac{\hbar}{8\pi mc^2} g_A g_V \vec{\sigma} \bullet \vec{v} \frac{1}{r} e^{-\frac{r}{\lambda}}$$

- Induces an interaction between polarized and unpolarized matter
- Violates P symmetry
- Not very well constrained over “mesoscopic” ranges(millimeters to microns)
- Best investigated using a beam of polarized particles

Neutron Spin Rotation:
A Parity-Odd Observable in Neutron Optics



$$f(0) = f_{strong} + f_{P-odd}(\vec{\sigma}\cdot\vec{p})$$

$$f_{P-odd} = g_A g_V \lambda^2$$

Forward scattering amplitude of neutron in matter sensitive to all neutron-matter interactions

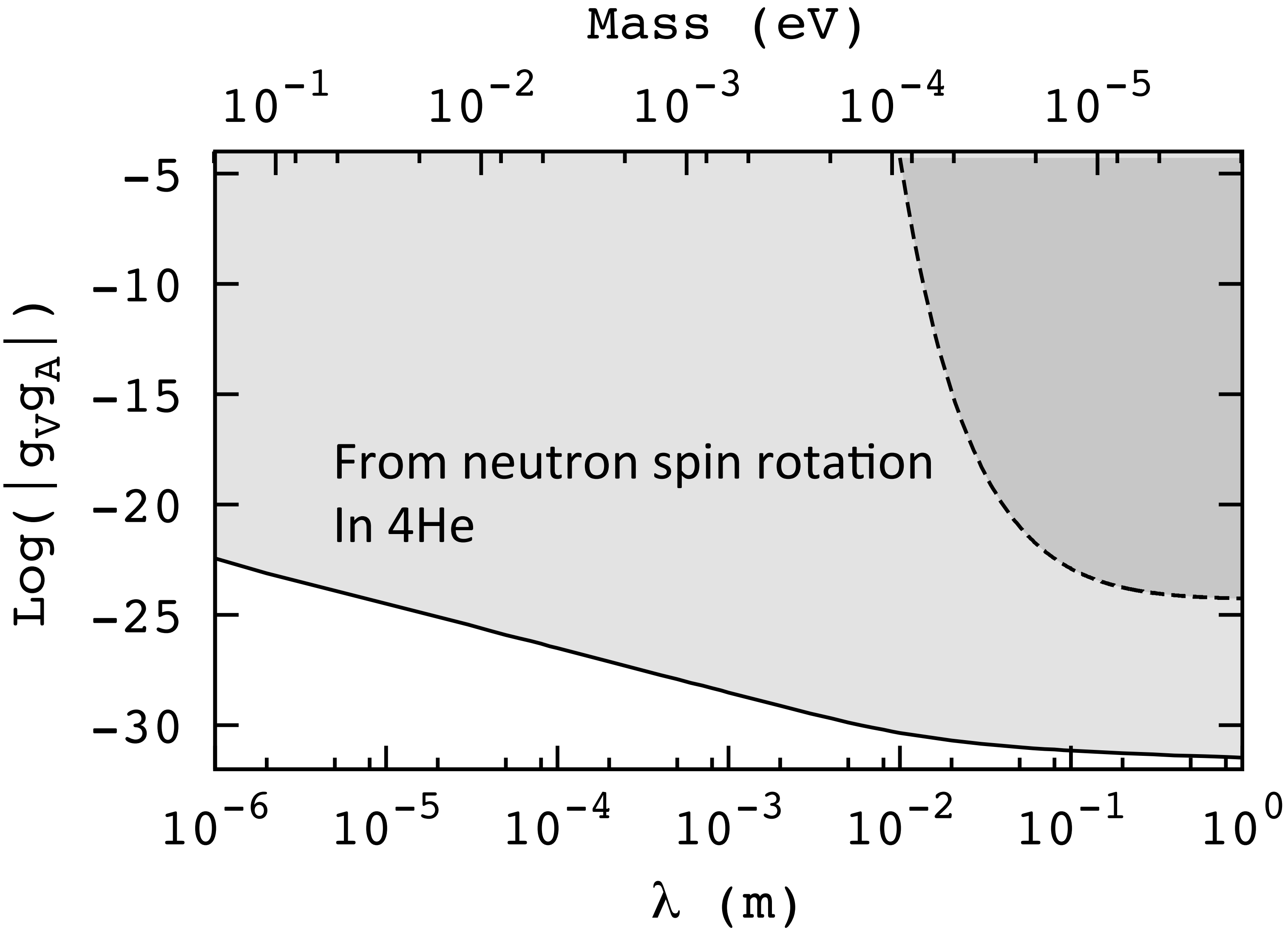
$$\phi_{\pm} = \phi_{strong} \pm \phi_{P-odd}$$

Parity violation gives helicity-dependent phase shift and therefore rotation of plane of polarization vector

$$\frac{d\phi_{P-odd}}{dL} = 4 g_A g_V \rho \lambda^2$$

An upper bound on $f_{P\text{-odd}}$ places a constraint on possible new P-odd interactions between nucleons over a broad set of distance scales

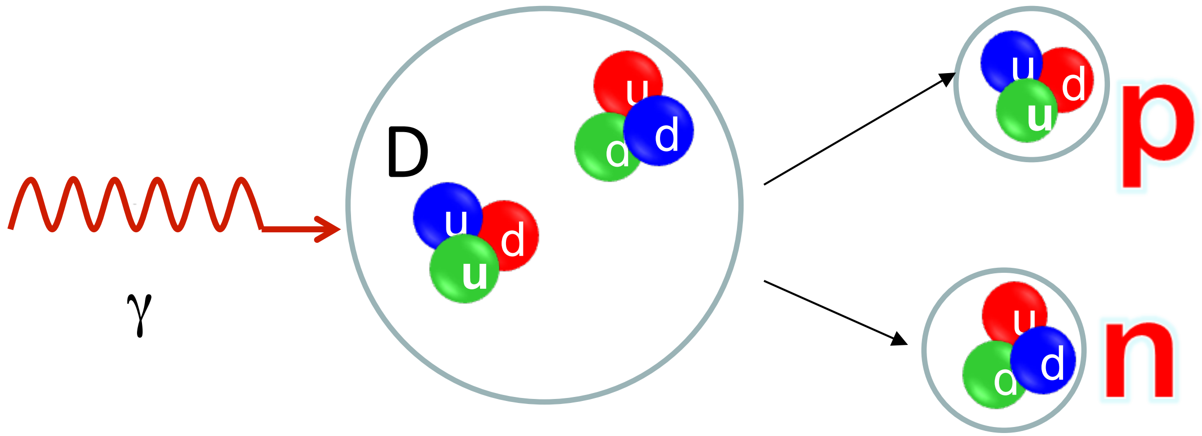
Constraints on exotic V-A interactions



H. Yan, and W. M. Snow, PRL 110, 082003 (2013).

Also: much stronger constraints now above ~1 cm from Eot_Wash+
other data [E. G. Adelberger and T. A. Wagner, PRD 88, 031101 (2013)]

Parity Violation in deuteron photodisintegration



Parity violation leads to helicity dependence of photodisintegration cross section

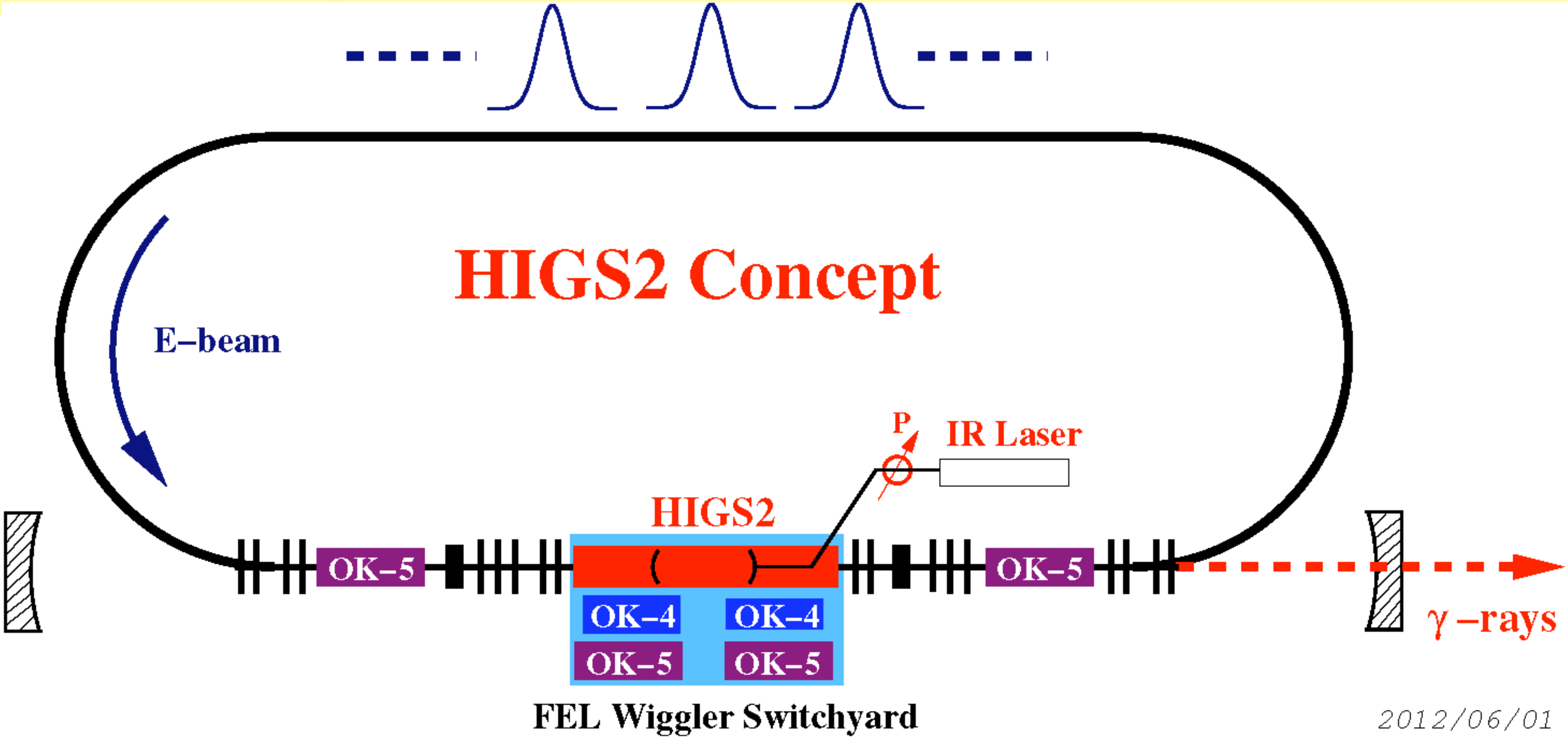
The neutron can escape the target and its intensity can be detected in current mode

Signal is helicity dependence of neutron current from target

Detect also scattered and transmitted gammas for normalization/systematics effect suppression

Need to observe >~10^{16} γs to be sensitive to a 1E-8 asymmetry.

Parity Violation Experiments at HiGS2?



~10^{11} to 10^{12} polarized γ/sec (X100 increase in polarized gamma flux relative to HiGS1.)

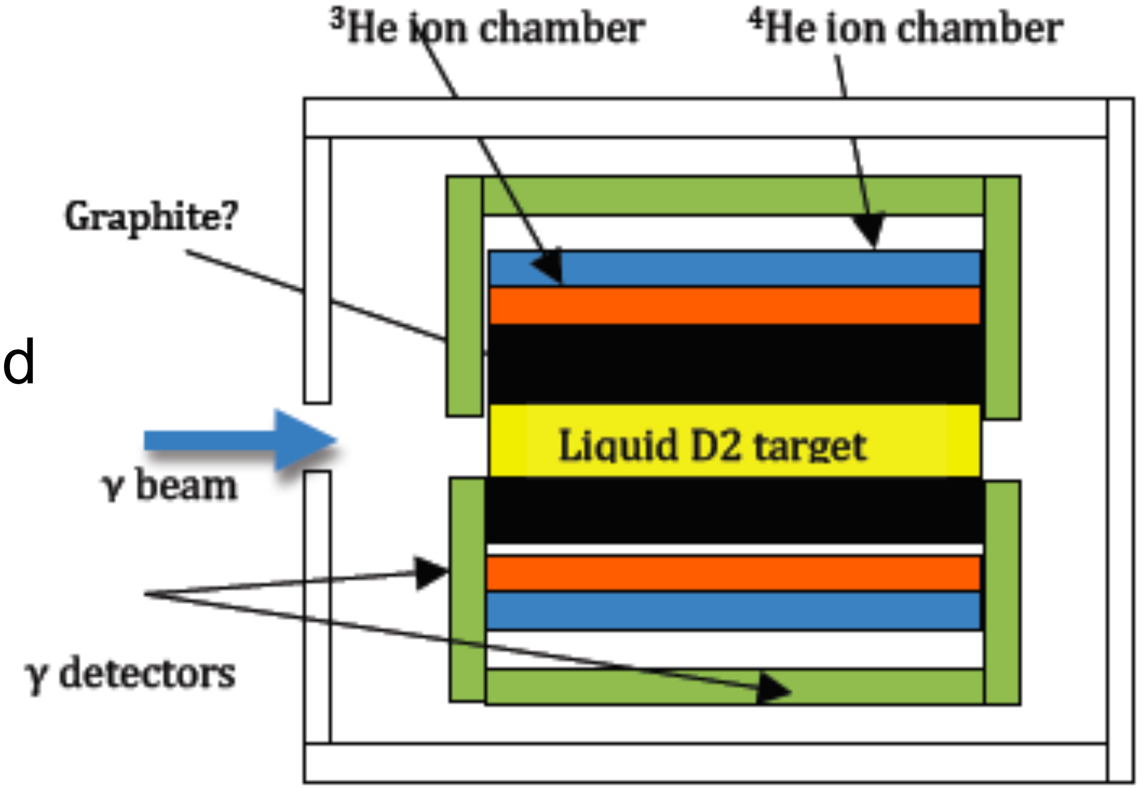
Circularly polarized gammas (>~90%), fast (~100 Hz) gamma helicity reversal possible

Controlled beam phase space: ~1% energy resolution on gamma energy (2-12 MeV)

These are attractive features in principle for parity violation experiments

Concept of P-odd Deuteron Photodisintegration Expt.

Circularly-polarized
γ beam
from HiGS2



The neutron can be moderated in the liquid deuterium target, escape with low energy (~10 meV), and be detected efficiently in current mode in a 3He/4He ion chamber

The transmitted and scattered γs can be measured using current-mode γ detectors located behind the 3He/4He ion chamber

Cylindrical symmetry of detector array to help suppress possible systematic errors

NN parity violation: experiment summary

NPDGamma: preliminary result: ~13 ppb error on P-odd asymmetry, consistent with zero

->f-pi is very small, new problem in nonperturbative QCD established

n-3He P-odd asymmetry measurement: apparatus on beam at SNS

n-4He P-odd spin rotation: limit on exotic P-odd interactions of the neutron, future measurement at NIST

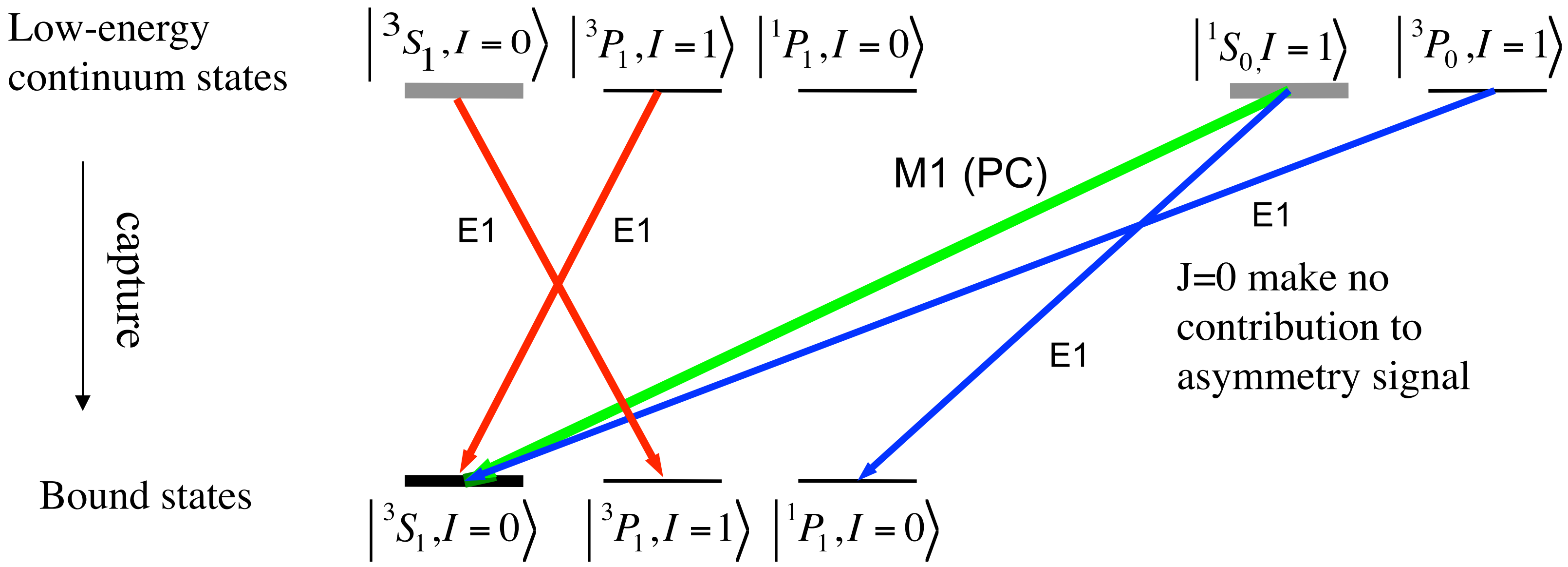
~both orthogonal to already-measured p-4He in isoscalar/isovector
NN weak amplitude space

Status:

n-3He parity violation experiment at SNS: start of installation now
n-4He parity violation experiment at NIST: planned for NIST NG-C

γ-D P-odd photodisintegration: long-term possibility for HiGS2

Simple Level Diagram of *n-p* System



J=0 make no contribution to asymmetry signal

$\dot{n} + p \rightarrow d + \gamma$ is primarily sensitive to the $\Delta I = 1$ component of the weak interaction

- Weak interaction mixes in *P* waves to the singlet and triplet *S*-waves in initial and final states.
- Parity conserving transition is $M1$.
- Parity violation arises from mixing in *P* states and interference of the $E1$ transitions.
- A_γ is coming from ${}^3S_1$ - ${}^3P_1$ mixing and interference of $E1$-$M1$ transitions in $\Delta I = 1$ channel.

Mixing amplitudes:

$\langle {}^3S_1 | V_W | {}^3P_1 \rangle ; \Delta I = 1$

$\langle {}^3S_1 | V_W | {}^1P_1 \rangle ; \Delta I = 0$

$\langle {}^1S_0 | V_W | {}^3P_0 \rangle ; \Delta I = 2$

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:

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

Parity-odd Nonrelativistic Potentials between Fermions

$$\mathcal{V}_{9,10} = -\frac{1}{2m\,r^2}\,(\vec{\sigma} \pm \vec{\sigma}\,') \cdot \hat{\vec{r}} \left(1 - r\frac{d}{dr}\right) y(r) \ ,$$

$$\mathcal{V}_{11} = -\frac{1}{m\,r^2}\,(\vec{\sigma} \times \vec{\sigma}\,') \cdot \hat{\vec{r}} \left(1 - r\frac{d}{dr}\right) y(r) \ ,$$

$$\mathcal{V}_{12,13} = \frac{1}{2r}\,(\vec{\sigma} \pm \vec{\sigma}\,') \cdot \vec{v}\; y(r) \ ,$$

$$\mathcal{V}_{14} = \frac{1}{r}\,(\vec{\sigma} \times \vec{\sigma}\,') \cdot \vec{v}\; y(r) \ ,$$

$$\mathcal{V}_{15} = -\frac{3}{2m^2\,r^3}\left\{ \left[\vec{\sigma} \cdot \left(\vec{v} \times \hat{\vec{r}}\right)\right] \left(\vec{\sigma}\,' \cdot \hat{\vec{r}}\right) + \left(\vec{\sigma} \cdot \hat{\vec{r}}\right) \left[\vec{\sigma}\,' \cdot \left(\vec{v} \times \hat{\vec{r}}\right)\right] \right\}$$

$$\times \left(1 - r\frac{d}{dr} + \frac{1}{3}r^2\frac{d^2}{dr^2}\right) y(r) \ ,$$

$$\mathcal{V}_{16} = -\frac{1}{2m\,r^2}\left\{ \left[\vec{\sigma} \cdot \left(\vec{v} \times \hat{\vec{r}}\right)\right] (\vec{\sigma}\,' \cdot \vec{v}) + (\vec{\sigma} \cdot \vec{v}) \left[\vec{\sigma}\,' \cdot \left(\vec{v} \times \hat{\vec{r}}\right)\right] \right\} \left(1 - r\frac{d}{dr}\right) y(r)$$

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

Comparison with (*p*,^{4}He) PV in EFT

In terms of pionless EFT couplings:

$$\phi_{\mathrm{PV}}(n\,{}^4\mathrm{He}) = (0.85\lambda_s^{nn} - 0.43\lambda_s^{np} + 0.95\lambda_t - 1.89\rho_t) = (1.7 +/- 8.3)\times 10^{-7}$$

$$A_L(p\,{}^4\mathrm{He}) = -0.48\lambda_s^{pp} - 0.24\lambda_s^{np} - 0.54\lambda_t - 1.07\rho_t) = -(3.3 +/- 0.9)\times 10^{-7}$$

$$A_L(pp, 13MeV) = -0.48\lambda_s^{pp} = -(0.9 +/- 0.2)\times 10^{-7}$$

*Eversheim et al, Phys Lett B **256** 11 (1991)*

$$P_\gamma(np) = 0.63\lambda_t - 0.16\lambda_s^{np} = (1.8 +/- 1.8)\times 10^{-7}$$

npDγ

The same constraint expressed in terms of the Danilov parameters :

$$1.95\lambda_t + 0.85\lambda_s^{nn} = (6.0 +/- 8.3)\times 10^{-7}$$

Hadronic Parity Violation Theory?

There is no quantitative theory for NN parity violation.

The reason why there is no theory is because such a theory would need to understand subnucleon-range quark-quark correlation effects and their long-range manifestation in a two nucleon system. We have no such understanding at present.

From all of our previous experience with strongly interacting many-body systems, we know that it is very important to understand the ground state of the theory and build excitations upon it. In QCD the first part is equivalent to understanding the mechanism of confinement and chiral symmetry breaking.

If the (strongly interacting) ground state is not boring it is typically highly correlated. The QCD ground state is not boring.

Lattice gauge theory? There is hope…

What to do in the meantime? Classify

$(n,{}^4\text{He})$ and $(p,{}^4\text{He})$ PV Theory

n-^{4}He spin rotation has been calculated in DDH framework

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

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

The PV longitudinal analyzing power in *p*-^{4}He scattering at 40 MeV (*isospin mirror system!*) has been measured:

$$A_L(p,4He) = [-3.3 + / - 0.9] \times 10^{-7}$$

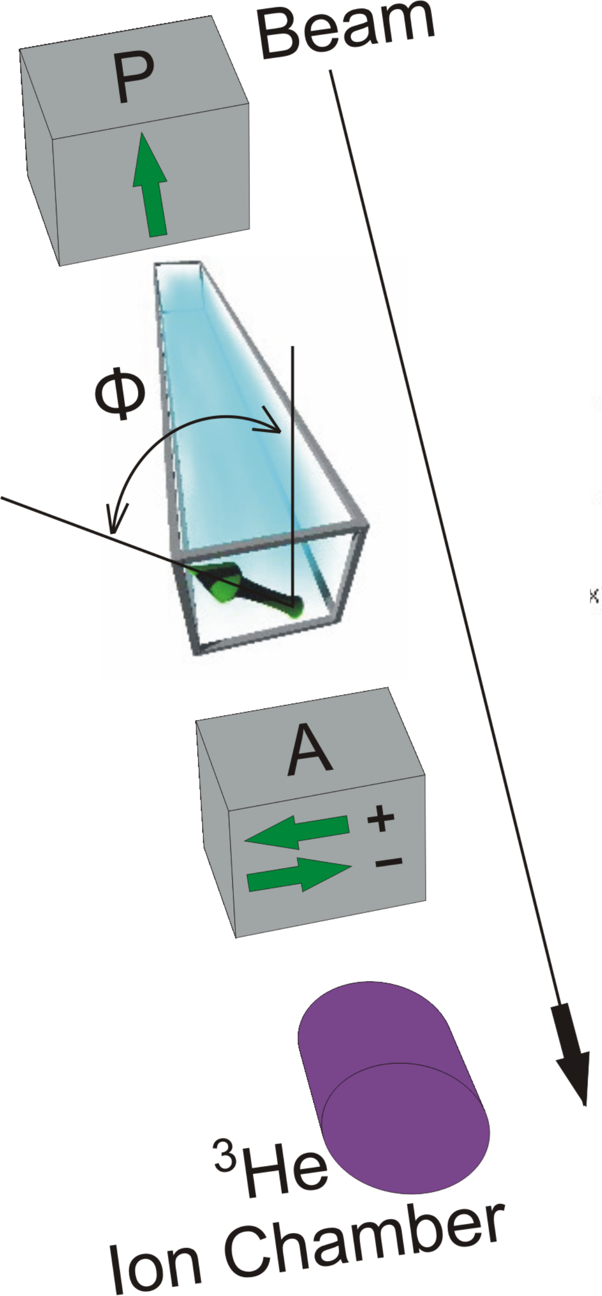
It was also calculated in the DDH framework:

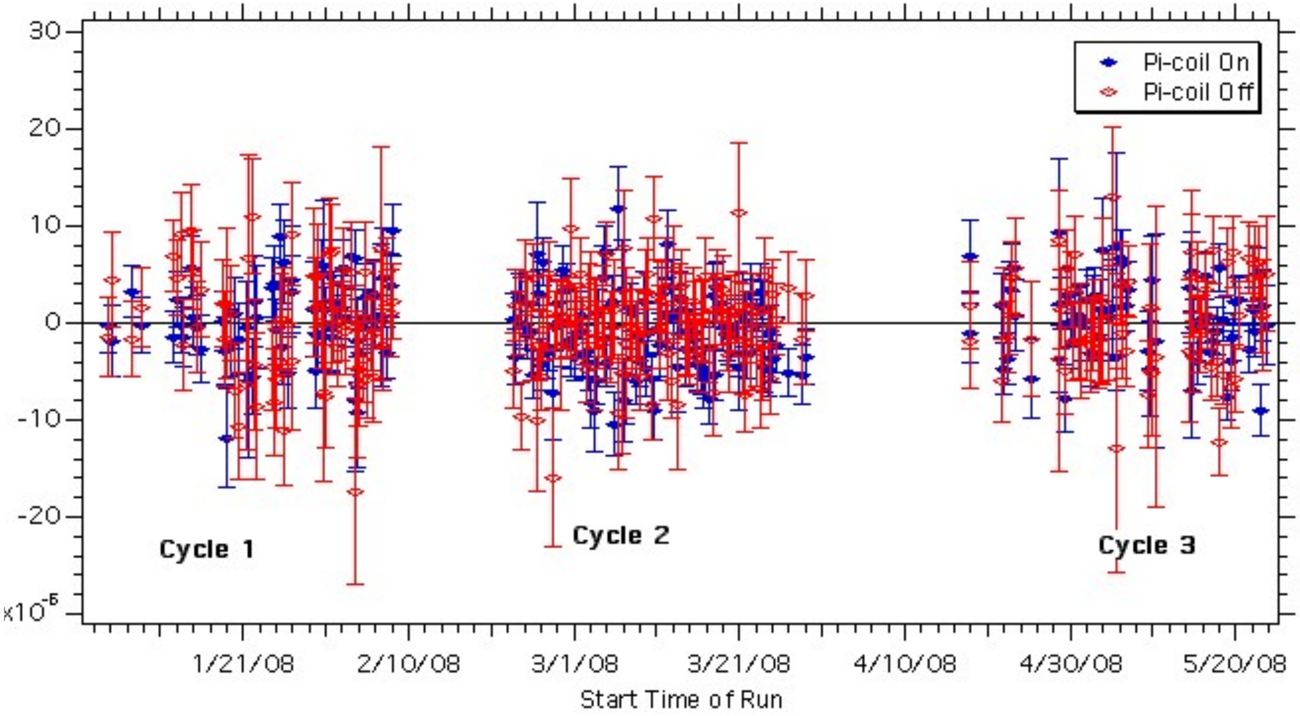
$$A_L\left(p,{}^{4}\text{He}\right) = -\left(0.34 f_\pi - 0.06 h_\omega^0 - 0.06 h_\omega^1 - 0.14 h_\rho^0 - 0.05 h_\rho^1\right)$$

Lang et al. PRC ***34*** *1545 (1986)*

Calculations are old and in DDH framework; need GFMC methods/conversion to EFT
Can EFT treatment even be applied to *p*-^{4}He? Is 40 MeV too high?
New calculations in progress (*Carlson, Wiringa, Nollett, Schiavilla, Pieper*)

Neutron Spin Rotation in n+4He





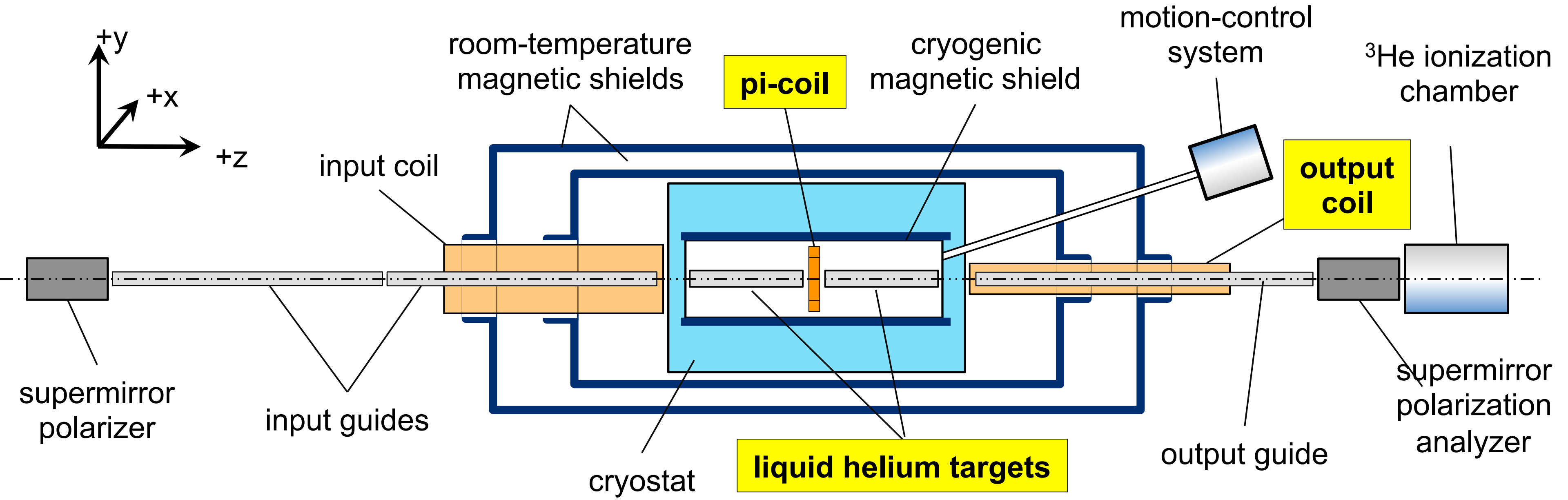
Transversely polarized neutrons corkscrew due to parity violation

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

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

Sets upper bound on any P-odd neutron coupling to protons, neutrons, electrons in 4He

Apparatus Improvements



If we stay with 5 cm x 5 cm beam, can reuse B shields, target, cryostat, ion chamber, motion control, and (maybe) coils

Pi-coil: measure/reconstruct?
Input/output guides: glass->supermirrors (IU $$$ exists)
New polarizer/analyzer (NIST?)
Target motion improved
Change location of cryo shield (IU $$$ exists)
Continuous liquid helium fill of cryostat/target (IU $$$ exists)
Better B shielding/compensation

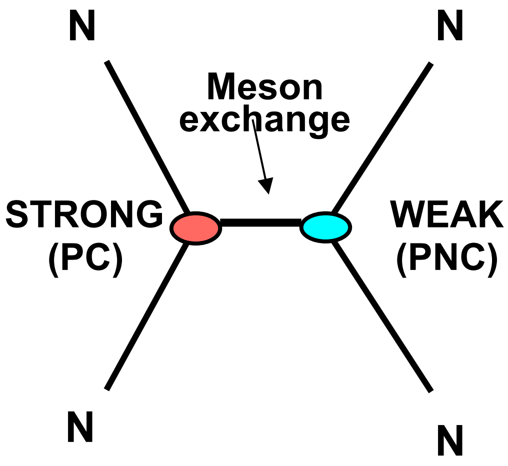
Chris will discuss

Meson Exchange Model of NN weak interaction

Based on the meson exchange model that successfully describes the low-E *NN strong interaction*

An exchange of light mesons (π, ρ, ω) with one strong interaction vertex and one weak interaction vertex

Effect of qq weak interactions parameterized by couplings :



Partial wave transition	ΔI	*n-n*	*n-p*	*p-p*	Exchanged Meson	Nucleon-Meson Weak Coupling
$^3S_1 \Leftrightarrow {}^3P_1$	1		✓		$\pi^\pm, \rho, \omega^\circ$	$f_\pi, h_\rho^1, h_\omega^1$
$^3S_1 \Leftrightarrow {}^1P_1$	0		✓		ρ, ω°	h_ρ^0, h_ω^0
$^1S_0 \Leftrightarrow {}^3P_0$	0	✓	✓	✓	ρ, ω°	h_ρ^0, h_ω^0
$^1S_0 \Leftrightarrow {}^3P_0$	1	✓		✓	ρ, ω°	h_ρ^1, h_ω^1
$^1S_0 \Leftrightarrow {}^3P_0$	2	✓	✓	✓	ρ	h_ρ^2

NN Weak Effective Field Theories

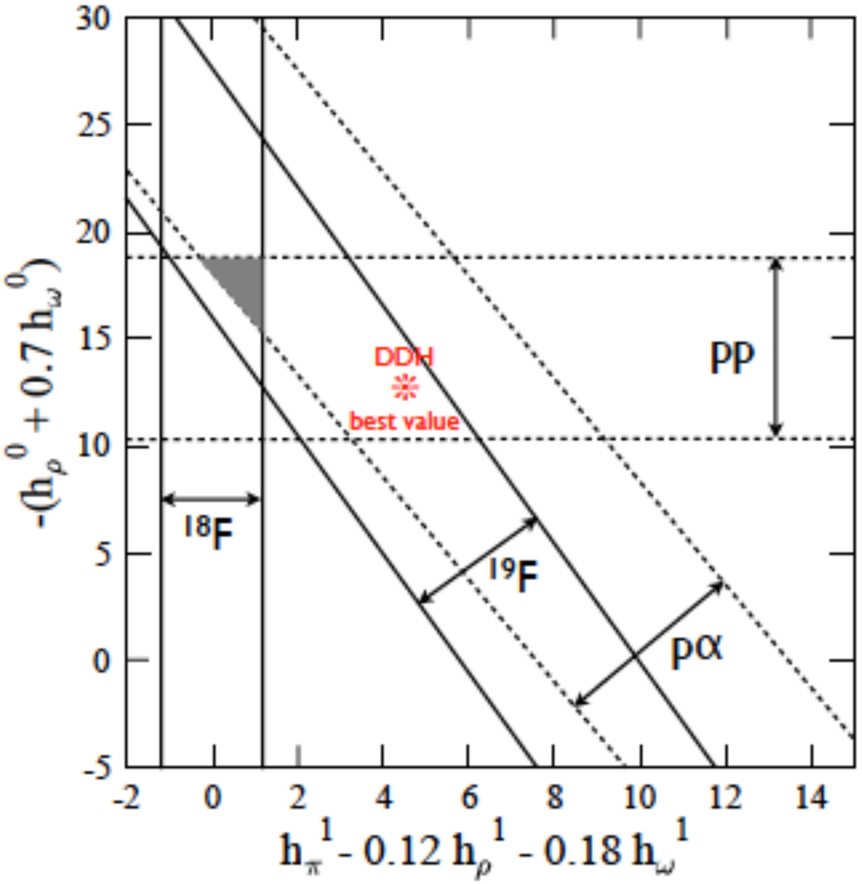
- Effective Field Theory approach: most general formulation for NN weak interaction consistent with QCD symmetries (Zhu et al 05)

- Can treat both strong and weak NN interaction consistently. “Pionless” (5 couplings) and “pionful” (6 couplings) versions available. Calculations in the NN system are in progress (Phillips, Schindler, Springer 09, Schindler, Springer arXiv:1305.4190)

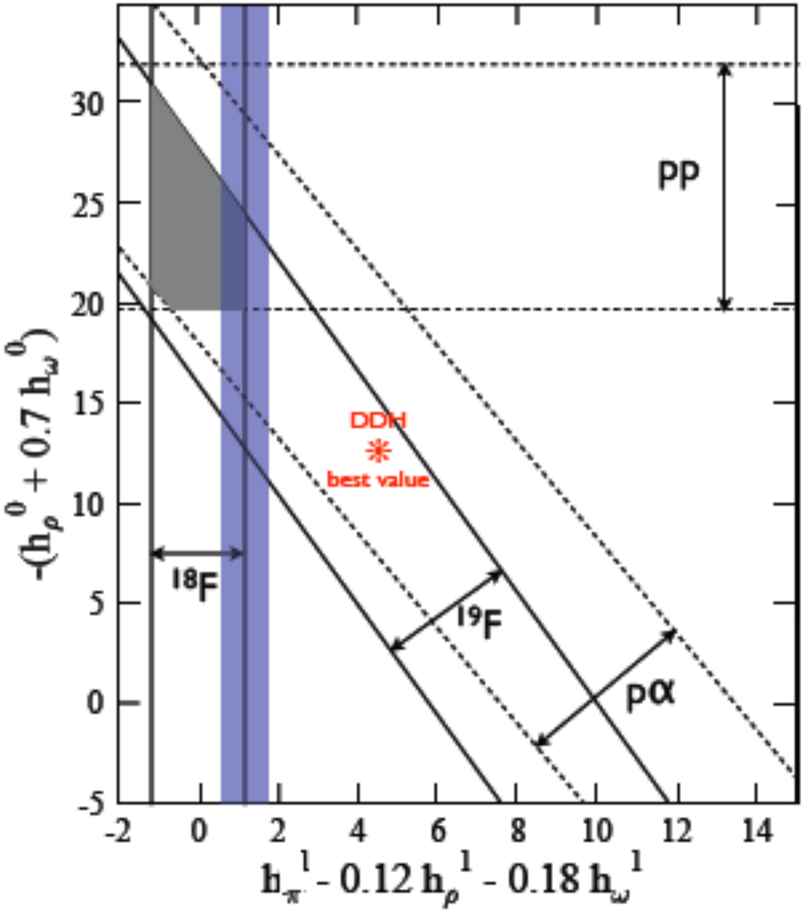
Partial wave transition	I ⇔ I’	ΔI	n-n	n-p	p-p	Hybrid EFT coupling	Pionless EFT coupling
$^3S_1 \Leftrightarrow {}^3P_1$	0 ⇔ 1	1		✓		$m\rho_t$,C^π [~ f_π]	$C\,({}^3S_1 - {}^3P_1)$
$^3S_1 \Leftrightarrow {}^1P_1$	0 ⇔ 0	0		✓		$m\lambda_t$	$C({}^3S_1 - {}^1P_1)$
$^1S_0 \Leftrightarrow {}^3P_0$	1 ⇔ 1	0	✓	✓	✓	$m\lambda_s^{nn}$	$C\,({}^1S_0 - {}^3P_{0,} \Delta I=0)$
$^1S_0 \Leftrightarrow {}^3P_0$	1 ⇔ 1	1	✓		✓	$m\lambda_s^{np}$	$C\,({}^1S_0 - {}^3P_0, \Delta I=1)$
$^1S_0 \Leftrightarrow {}^3P_0$	1 ⇔ 1	2	✓	✓	✓	$m\lambda_s^{pp}$	$C({}^1S_0 - {}^3P_0, \Delta I=2)$

Haxton and Holstein 2013: reanalysis of pp parity violation

Corrected pp analysis for inconsistent treatment of strong NN couplings
Result: isoscalar linear combination goes up by ~50%



Haxton/Wieman ~2001



Haxton/Holstein 2013

NN Weak Pionless EFT coefficients and observables

Five constants in the pionless EFT (equivalent to 5 S-P transition amplitudes). NN observables calculated, few body systems in progress (Phillips, Schindler, Springer 09)

$$A_L^{nn} = \frac{8M}{\pi} p \left(\mathcal{C}^{(\Delta I=0)}_{(^1S_0-^3P_0)} - \mathcal{C}^{(\Delta I=1)}_{(^1S_0-^3P_0)} + \mathcal{C}^{(\Delta I=2)}_{(^1S_0-^3P_0)} \right) \left(\frac{1}{a^{^1S_0}} - \mu \right)$$

$$A_L^{pp} = \frac{8M}{\pi} p \left(\mathcal{C}^{(\Delta I=0)}_{(^1S_0-^3P_0)} + \mathcal{C}^{(\Delta I=1)}_{(^1S_0-^3P_0)} + \mathcal{C}^{(\Delta I=2)}_{(^1S_0-^3P_0)} \right) \left(\frac{1}{a^{^1S_0}} - \mu \right)$$

$$A_L^{np} = \frac{8M}{\pi} p \frac{\frac{d\sigma^{(^1S_0)}}{d\Omega}}{\frac{d\sigma^{(^1S_0)}}{d\Omega} + 3\frac{d\sigma^{(^3S_1)}}{d\Omega}} \left(\mathcal{C}^{(\Delta I=0)}_{(^1S_0-^3P_0)} - 2\mathcal{C}^{(\Delta I=2)}_{(^1S_0-^3P_0)} \right) \left(\frac{1}{a^{(^1S_0)}} - \mu \right)$$

$$+ \frac{8M}{\pi} p \frac{\frac{d\sigma^{(^3S_1)}}{d\Omega}}{\frac{d\sigma^{(^1S_0)}}{d\Omega} + 3\frac{d\sigma^{(^3S_1)}}{d\Omega}} \left(\mathcal{C}_{(^3S_1-^1P_1)} - 2\mathcal{C}_{(^3S_1-^3P_1)} \right) \left(\frac{1}{a^{(^3S_1)}} - \mu \right)$$

Schlinder/Springer, arXiv: 1305.4190

Nonzero experimental results are pp A_z and pα A_z . $^1S_0 \Leftrightarrow {}^3P_0$ partial wave determined

NN Weak Pionless EFT coefficients and observables

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$$+ \frac{8M}{\pi} p \frac{\frac{d\sigma^{({}^3S_1)}}{d\Omega}}{\frac{d\sigma^{({}^1S_0)}}{d\Omega} + 3\frac{d\sigma^{({}^3S_1)}}{d\Omega}} \left(\mathcal{C}_{({}^3S_1 - {}^1P_1)} - 2\mathcal{C}_{({}^3S_1 - {}^3P_1)} \right) \left(\frac{1}{a^{({}^3S_1)}} - \mu \right)$$

Schlinder/Springer, arXiv: 1305.4190

Nonzero experimental results are pp A_z and pα A_z . ${}^1S_0 \Leftrightarrow {}^3P_0$ partial wave determined

Hadronic Weak Interaction Models

1. ***DDH model*** – uses valence quarks to calculate effective PV meson-nucleon coupling directly from SM via 7 weak meson coupling constants

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

$f_\pi \sim 4.5\text{x}10^{-7}$ DDH best guess

- Observables can be written as their combinations

$$A_\gamma \approx -0.11 f_\pi^1$$

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

Meson exchange

2. Lattice QCD [J. Wasem, PRC (2012)]

- Result: $f_\pi = (1.1 \pm 0.5) \times 10^{-7}$

3. *Effective Field Theory* (hybrid and pure) – model-independent

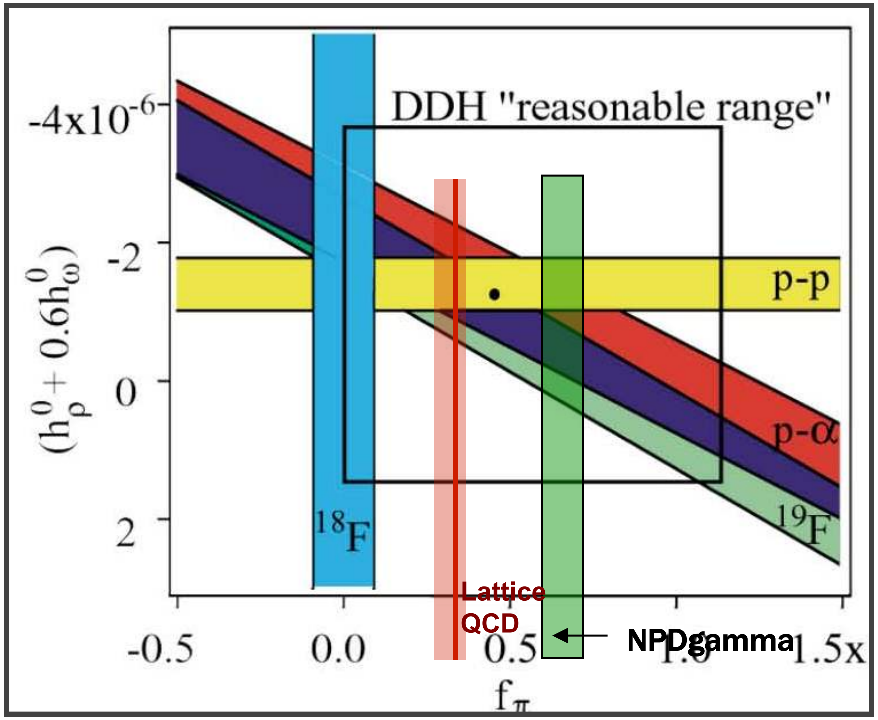
- connect to 5 parity-odd S-P NN amplitudes

$$A_\gamma^{\vec{n}p} \approx -0.27 \tilde{C}_6^\pi - 0.09 m_N \rho_t$$

hybrid

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

pionless



NN Weak Interaction: Isospin Dependence

The quark-quark weak interaction at energies below the W and Z mass can be written in a current-current form, with contributions from charged and neutral currents

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

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

Possible isospin changes from qq weak interactions:

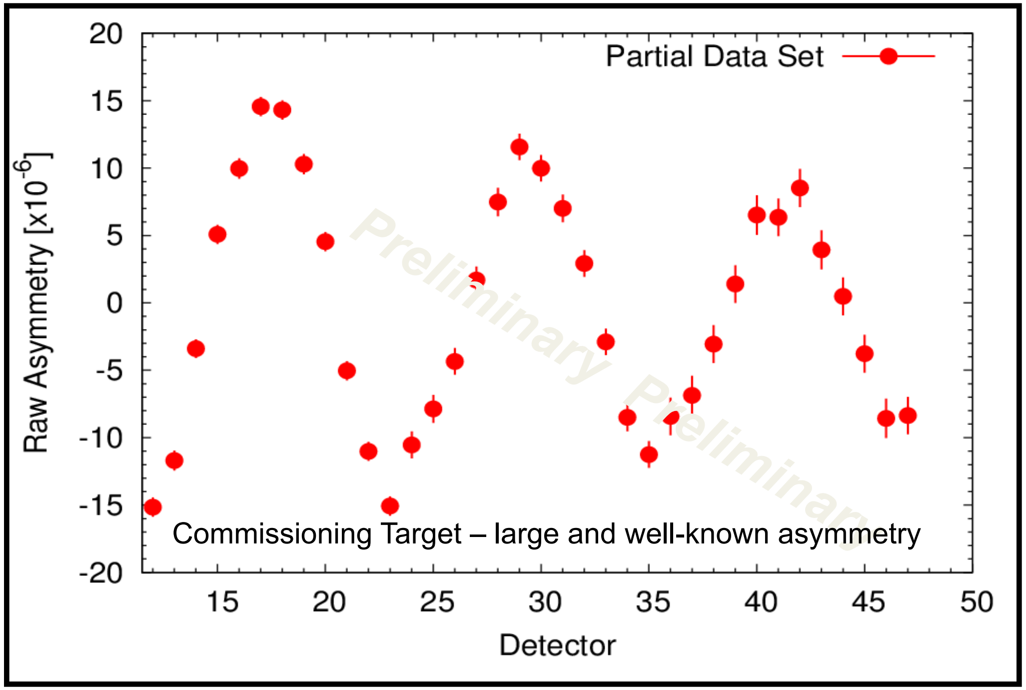
Charged current: ΔI=0,2 (~ V^2_{ud}), ΔI=1 (~ V^2_{us})

Neutral current: ΔI=0,1,2.

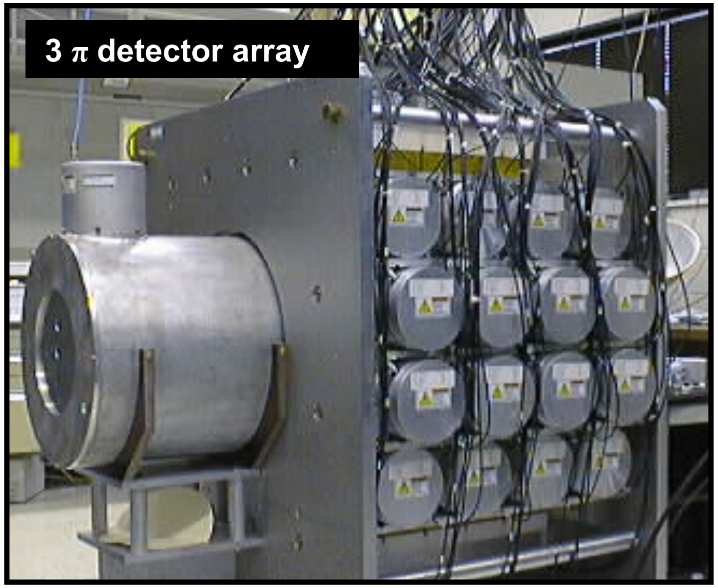
The ΔI=1 terms comes only from the quark-quark neutral currents in the absence of strange quarks due to small size of V_{us}

These terms are about the same size, so any large differences in different isospin channels presumably would come from QCD dynamics.

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)



Ability of apparatus to measure parity violation confirmed using n capture on 35Cl (possesses ~20 ppm P-odd asymmetry)

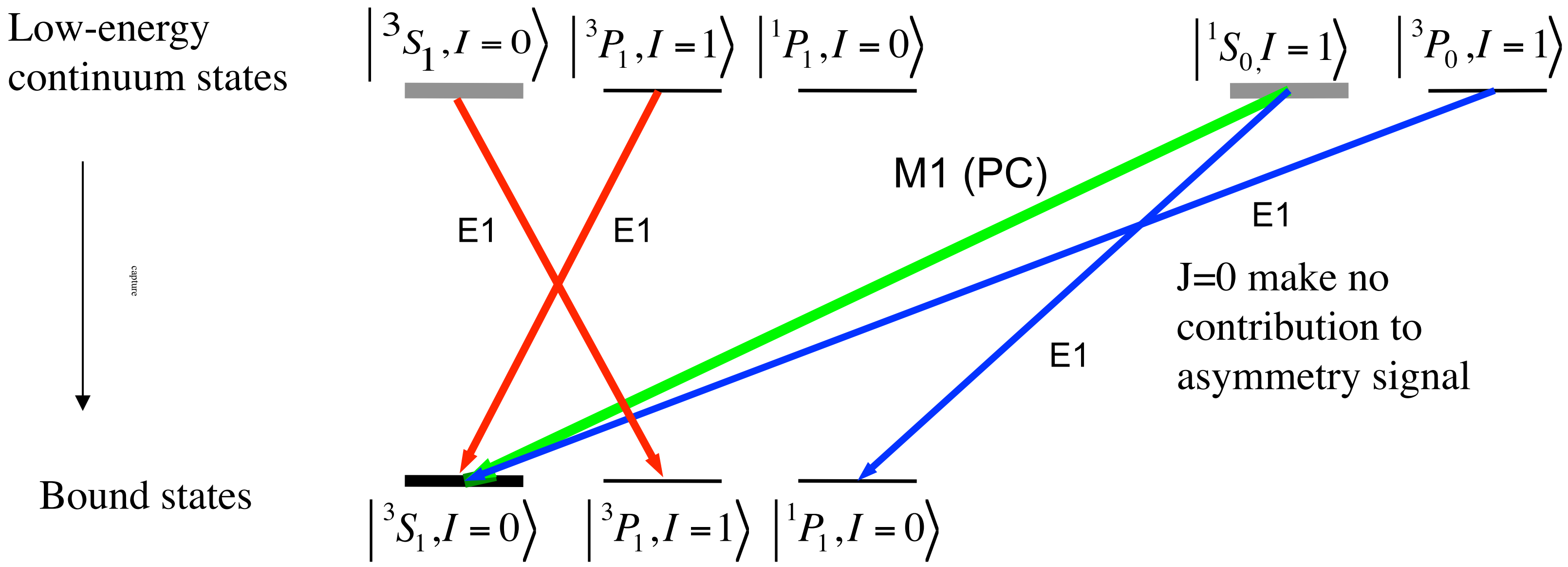


CsI gamma array operated in current mode

Systematic errors bounded from several auxiliary measurements at LANSCE and SNS

Need to measure and correct for possible aluminum P-odd asymmetry

Simple Level Diagram of *n-p* System



Low-energy continuum states

$\left|{}^3S_1, I=0\right\rangle$ $\left|{}^3P_1, I=1\right\rangle$ $\left|{}^1P_1, I=0\right\rangle$ $\left|{}^1S_0, I=1\right\rangle$ $\left|{}^3P_0, I=1\right\rangle$

capture

E1

E1

M1 (PC)

E1

E1

J=0 make no contribution to asymmetry signal

Bound states

$\left|{}^3S_1, I=0\right\rangle$ $\left|{}^3P_1, I=1\right\rangle$ $\left|{}^1P_1, I=0\right\rangle$

$\dot{n}+p\rightarrow d+\gamma$ is primarily sensitive to the $\Delta I=1$ component of the weak interaction

- Weak interaction mixes in *P* waves to the singlet and triplet *S*-waves in initial and final states.
- Parity conserving transition is *M*1.
- Parity violation arises from mixing in *P* states and interference of the *E*1 transitions.
- A_γ is coming from ${}^3S_1$ - ${}^3P_1$ mixing and interference of *E*1-*M*1 transitions in $\Delta I=1$ channel.

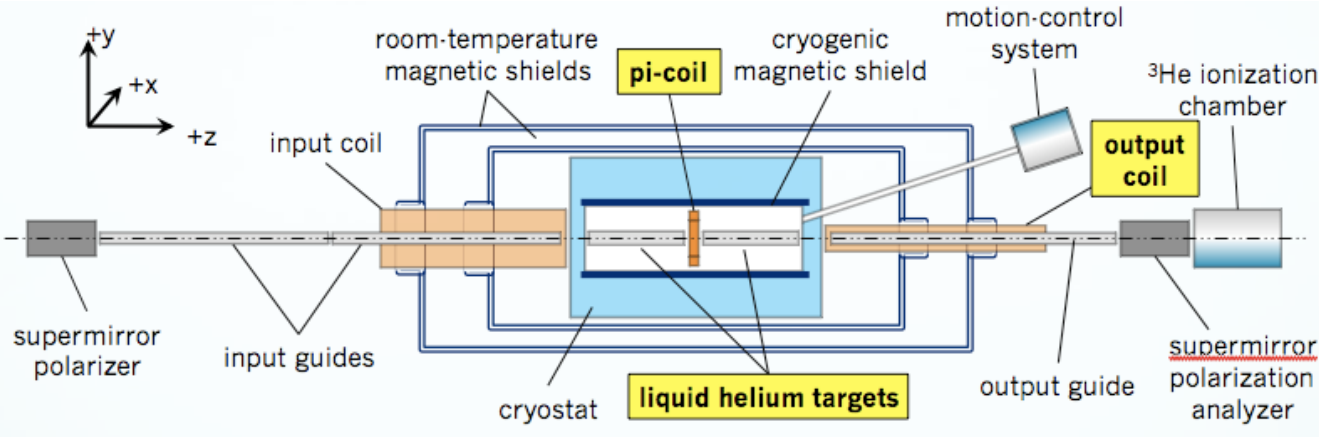
Mixing amplitudes:

$\left\langle {}^3S_1 \middle| V_W \middle| {}^3P_1 \right\rangle; \Delta I=1$

$\left\langle {}^3S_1 \middle| V_W \middle| {}^1P_1 \right\rangle; \Delta I=0$

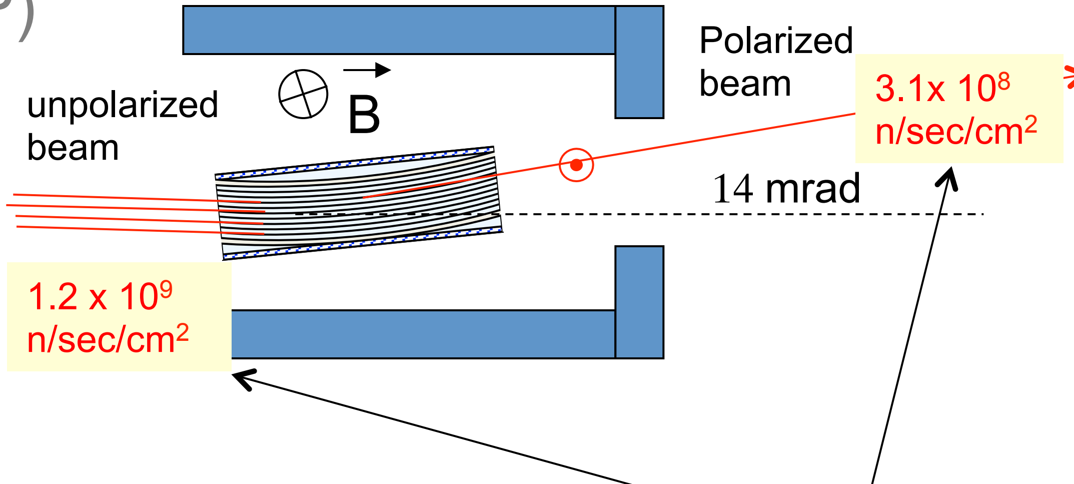
$\left\langle {}^1S_0 \middle| V_W \middle| {}^3P_0 \right\rangle; \Delta I=2$

Polarimeter

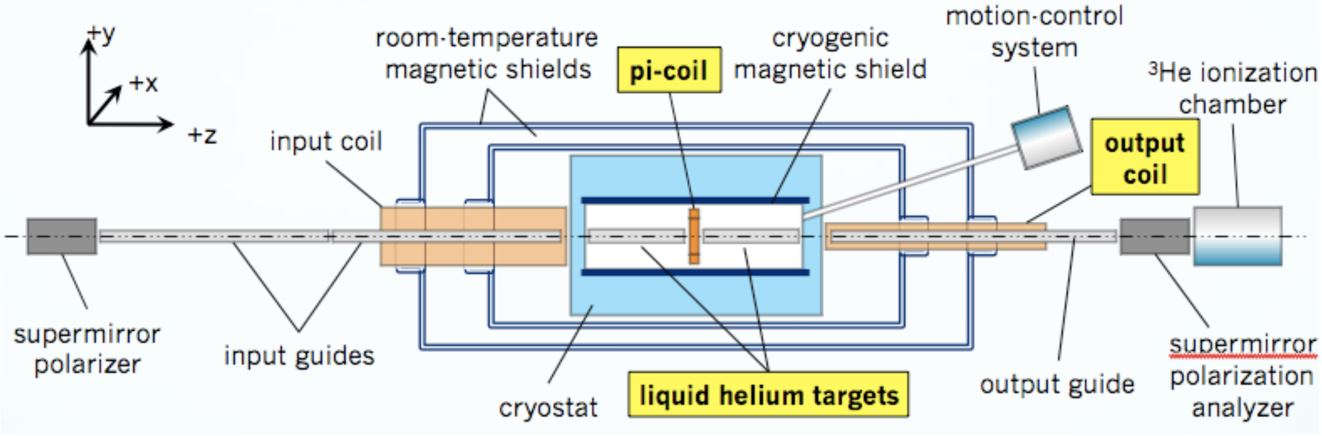


Supermirror polarizer (SMP)

- Neutrons initially travel through a vertically aligned SMP and get polarized in the y direction
- Neutrons with magnetic moments parallel to the magnetic field are reflected, while all others are absorbed by the gadolinium
- Previous: bender supermirror polarizes through spin-dependent magnetized mirrors
- Next: …



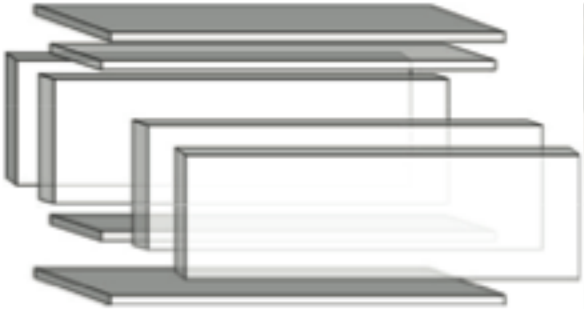
Polarimeter

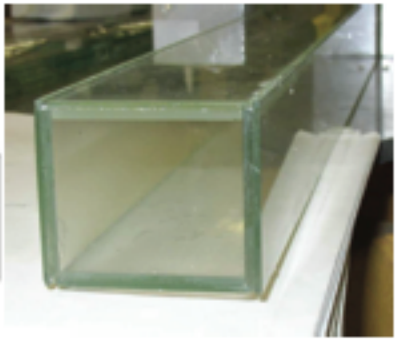


Input and Output guides

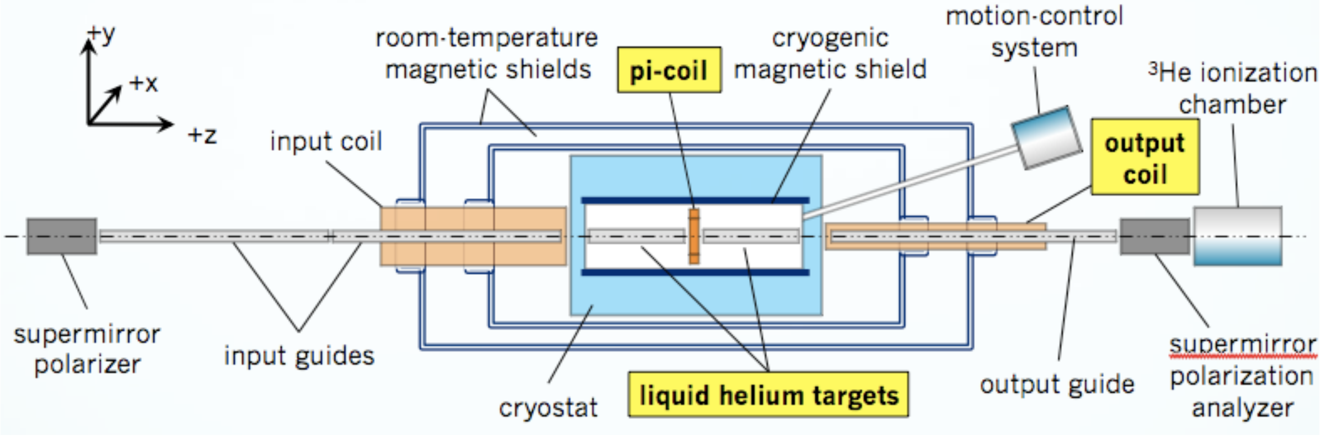
Beam passes through input guide

- Previous: ^{6}LiF glass collimators in previous experiment
- Next: new supermirror guides





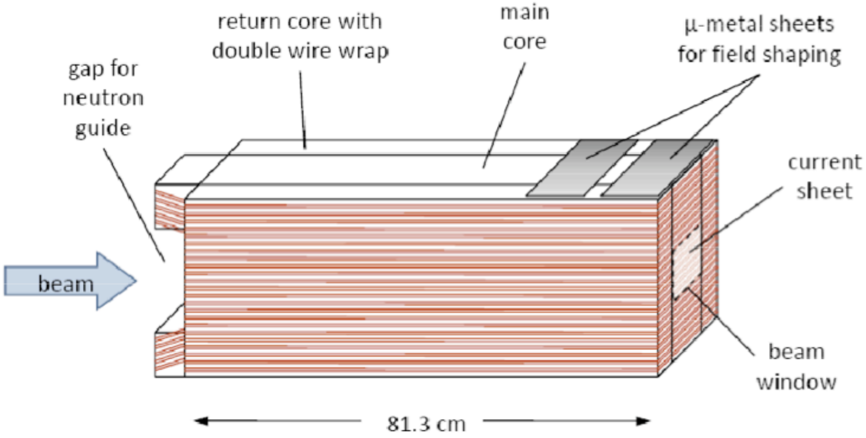
Polarimeter



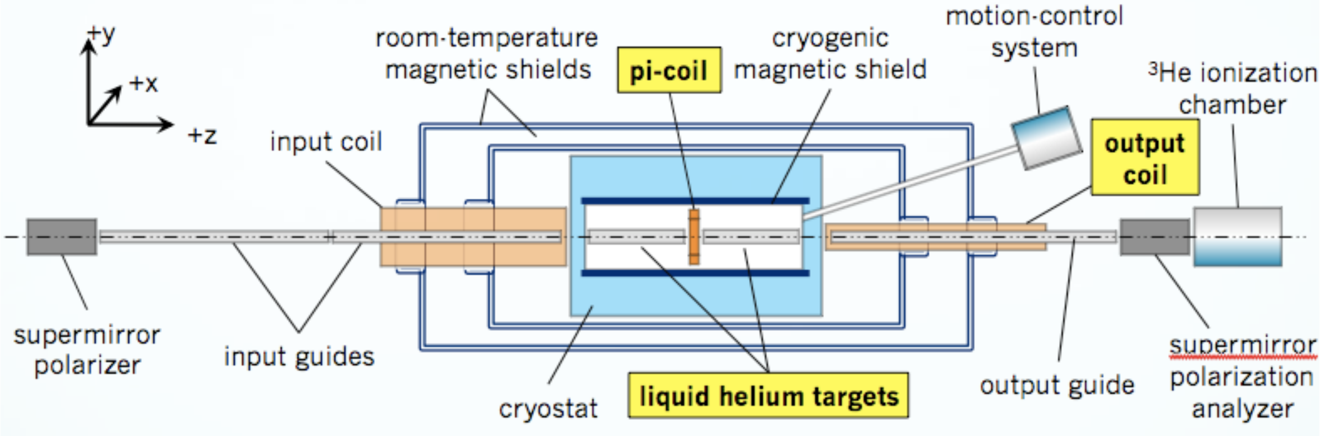
Input coil

To preserve the polarization from the SMP, the input coil matches the field produced by the SMP 2m downstream. A 5G vertical field maintains the polarization

- Previous: wrapped at UW
- Next: need to be re-made and simulations are in the works



Polarimeter

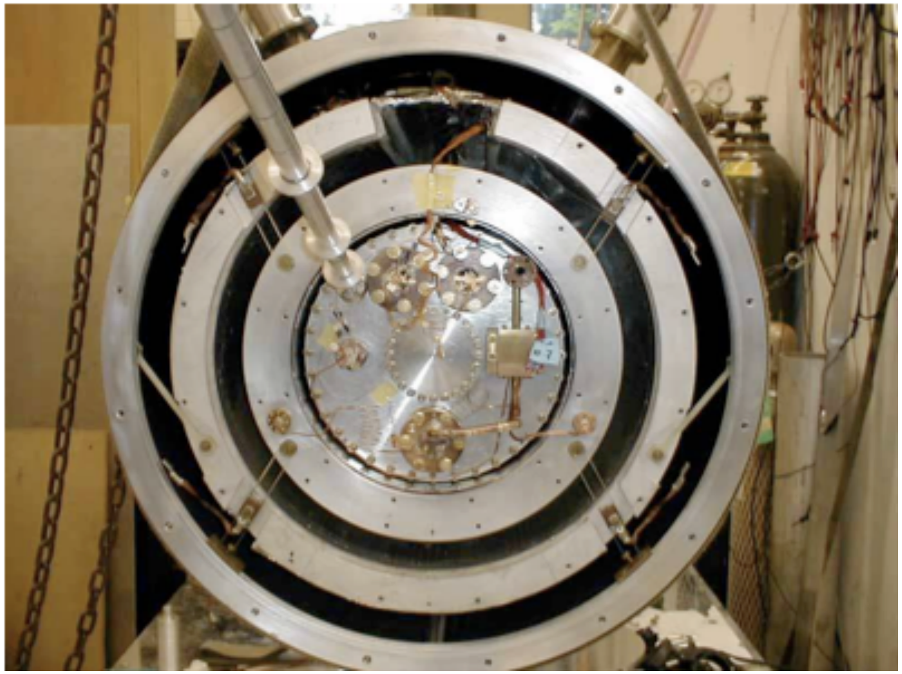


Cryostat

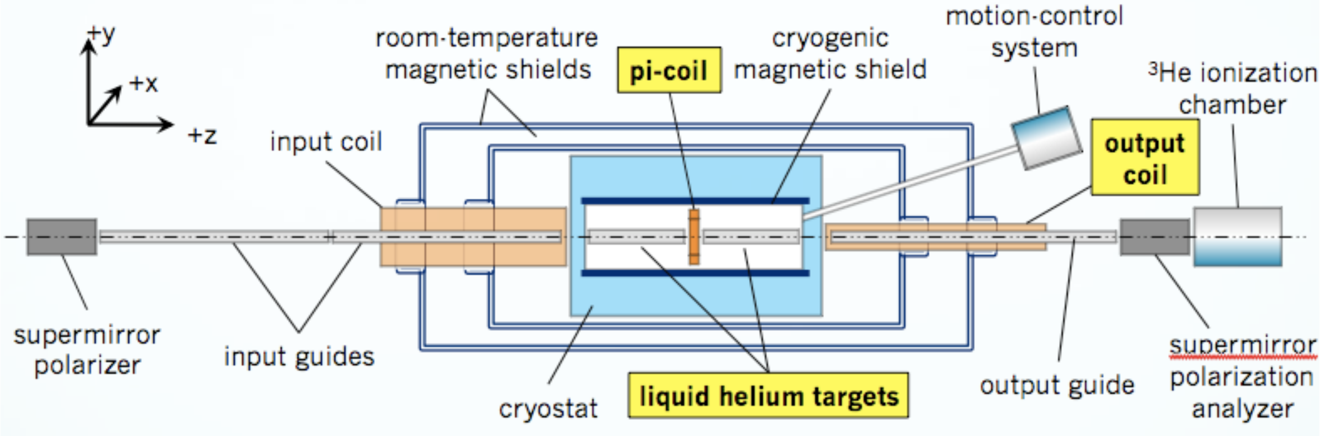
Both the 4K-volume and the 77K-volume are suspended by G10 straps. Cryogenic wiring is routed from the target insert to electrical feedthroughs at the top of the cryostat.

- 77K volume can hold 50L of N
- 4K volume can hold 30L of He

Next: we will implement a He reliquifier to cut down refill times



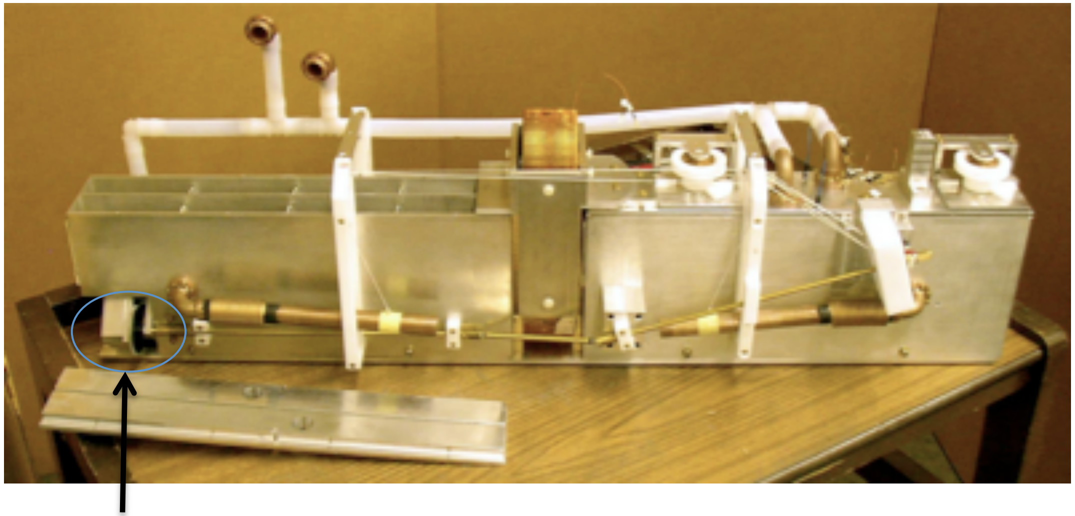
Polarimeter



Liquid ^{4}He targets

Mean free path of neutrons passing through LHe determines the thickness of the target: for 5Å neurons at 4K, l~1m.

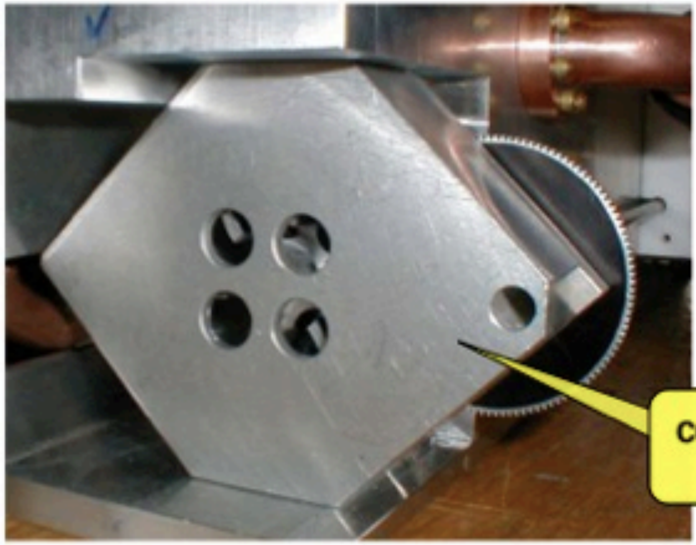
Next: plan to remake the target to accommodate the larger beam and better pumping system

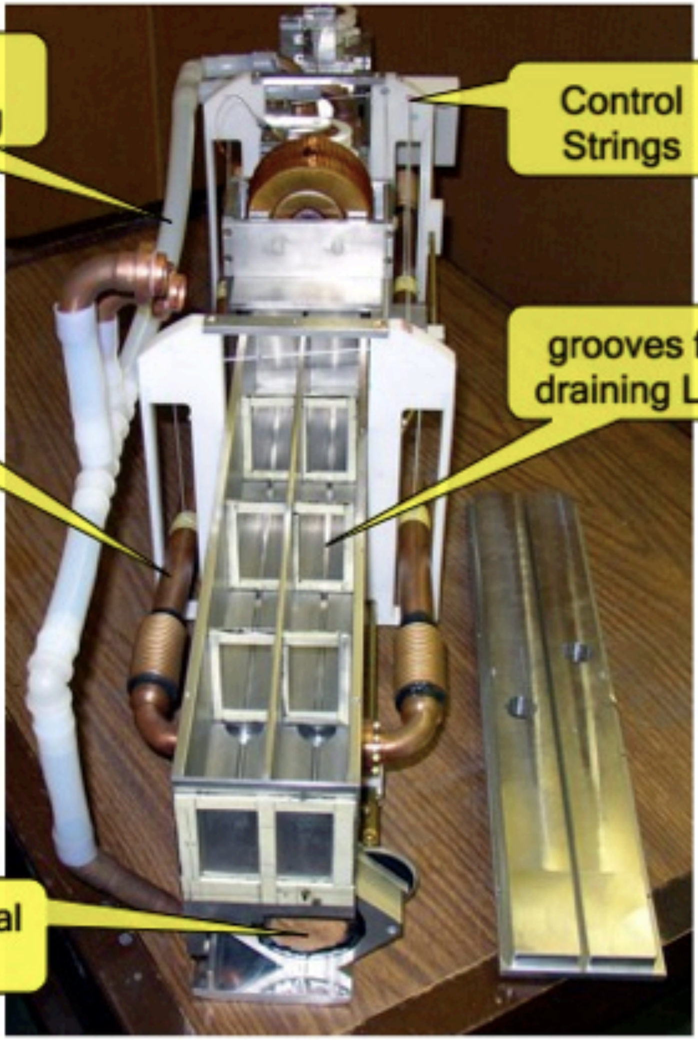


The current pump takes minutes to fill the chamber. We plan on improving the pump system.

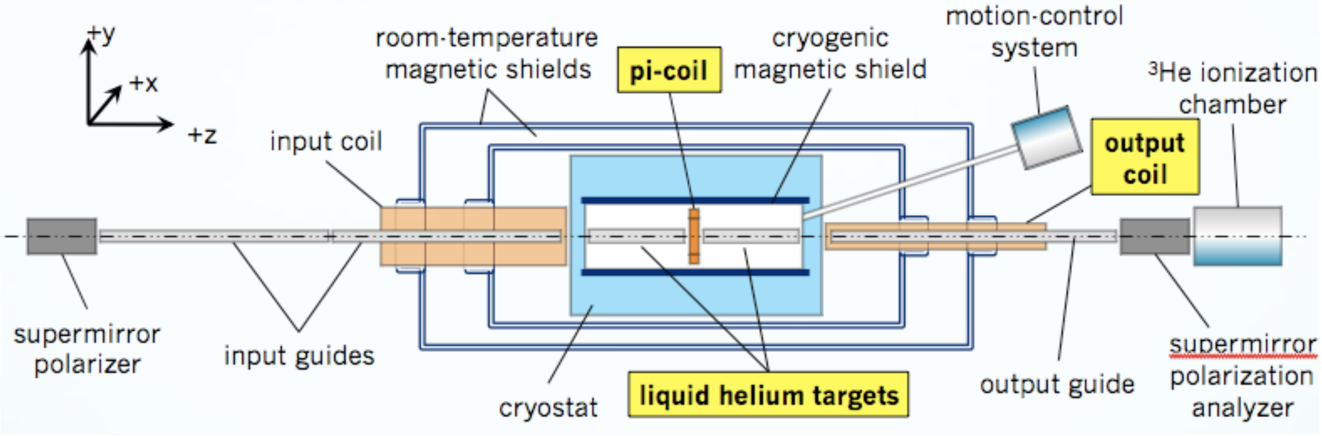
Pump and drain system

- Target fill: 570 s
- Target drain: 30 s





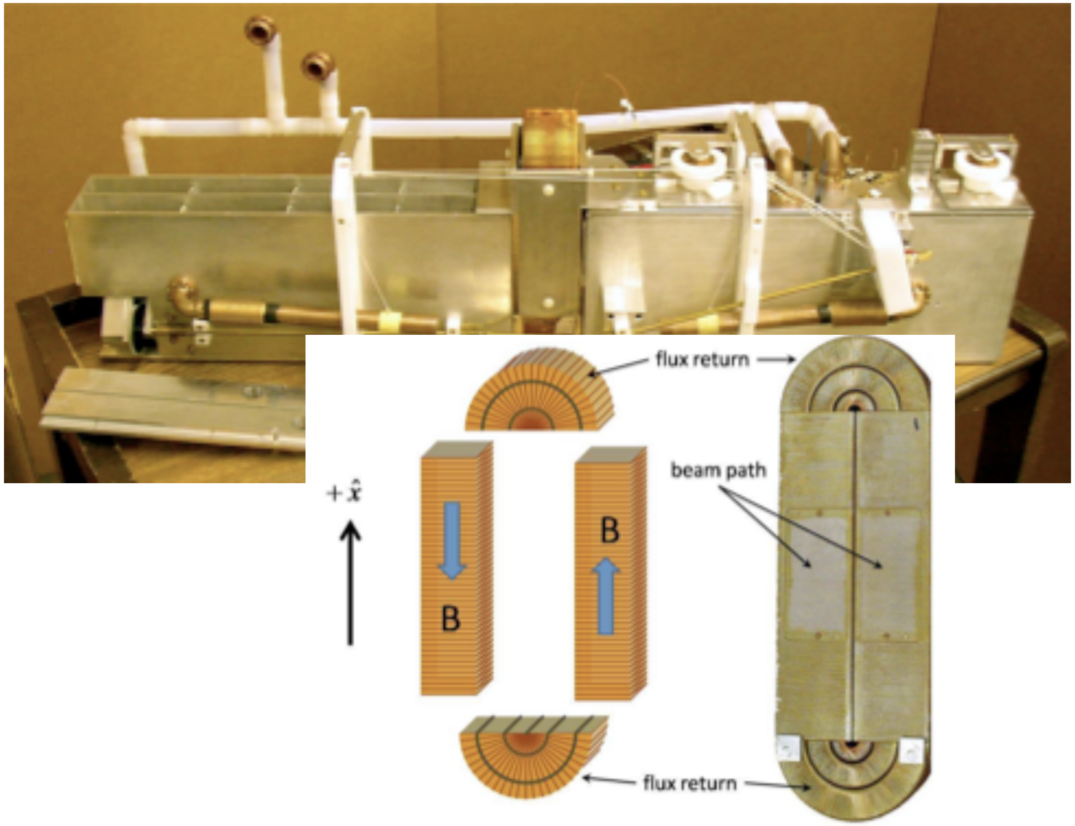
Polarimeter



Pi-coil

Generates a vertical internal field that that precesses the transverse component of the average wavelength neutron spin by 180° about the vertical axis

Next: need to remake to accommodate the larger beam



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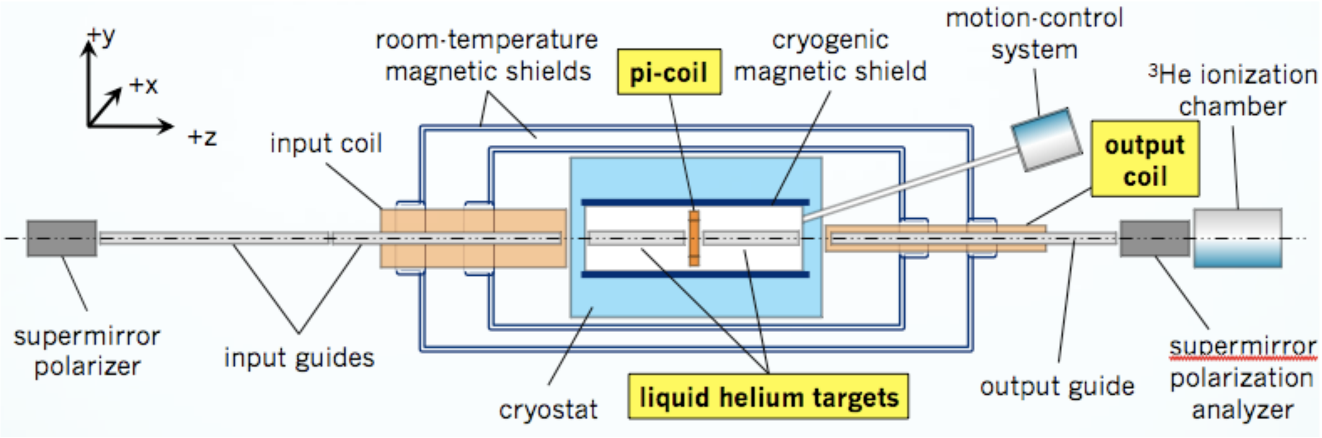
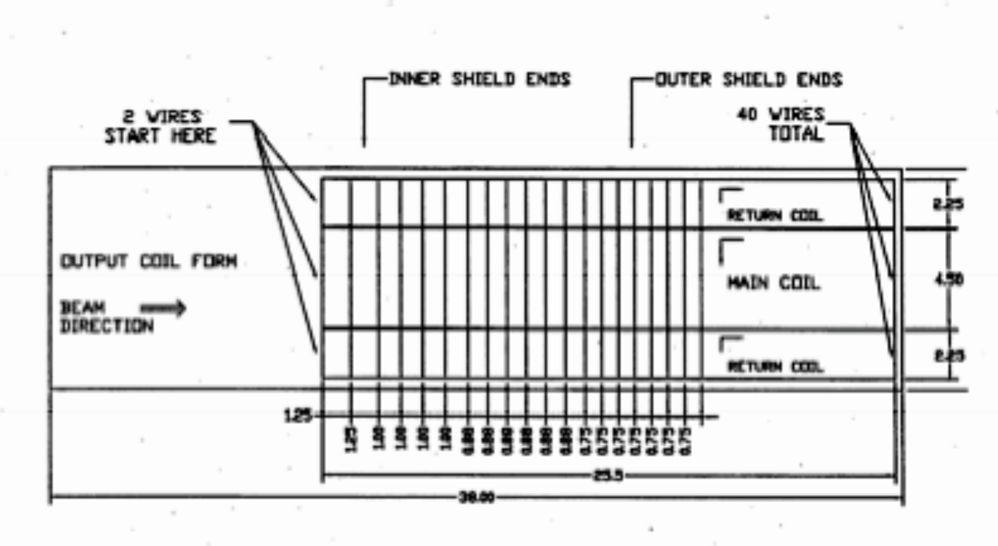


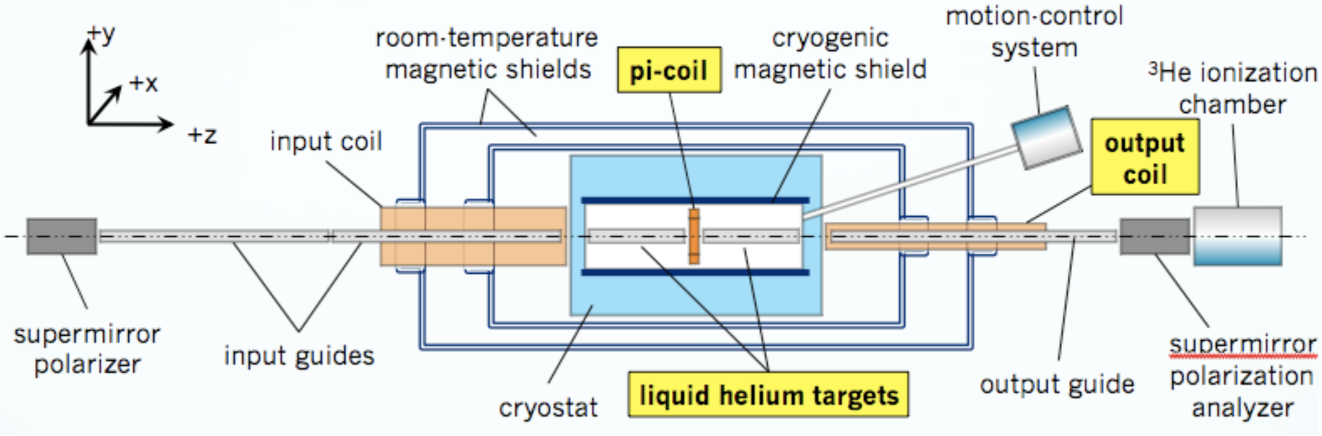
Output coil

- Same design as the input coil but has an additional surrounding spin rotator coil
- Additional coil has increasing winding density such that when combined with the main field, the neutron spin is rotated π/2.
- The current can modulate the sign of the field to adiabatically rotate the spin by ±π/2



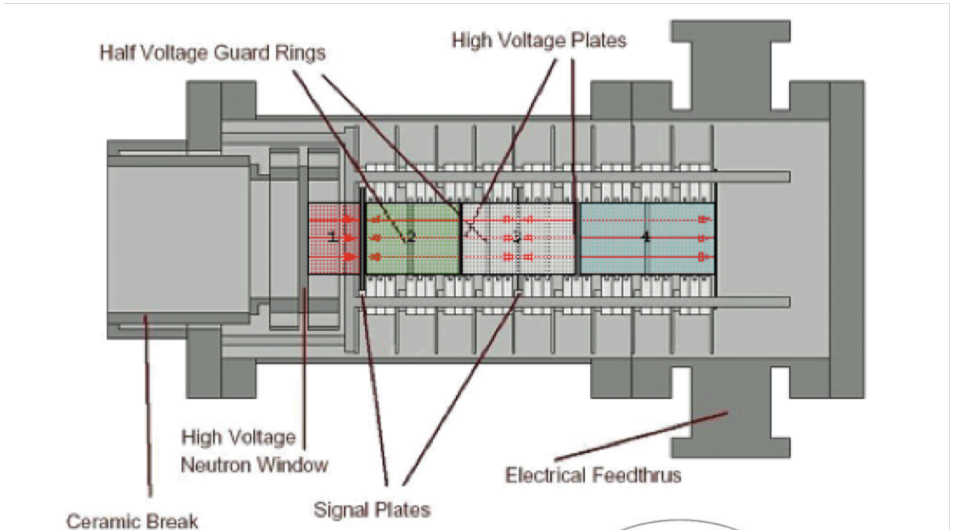
Next: need to be re-made and simulations are in the works

Polarimeter

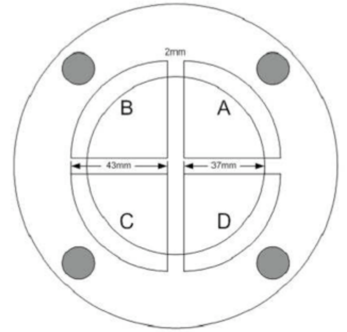


^{3}He ion chamber

- The neutrons interact with the helium and produce charged particles that ionize the gas and get detected on voltage plates.
- There are four collection plates along the detector for energy (wavelength) resolution and each plate is separated into four quadrants so that the left and right sub beams can be independently be monitored

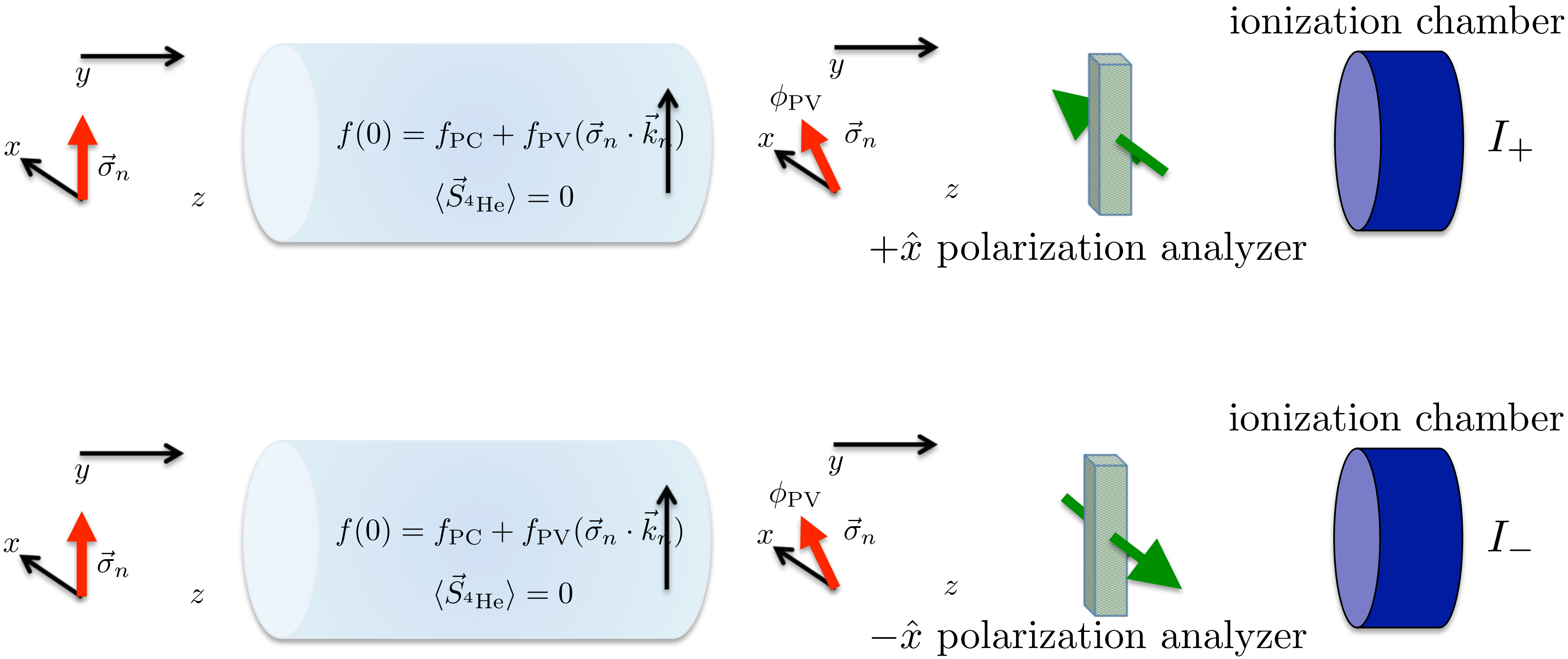


$$n + {}^3He \rightarrow {}^3H + p + 764 keV$$



3He absorption cross section is ~1/v

PV Spin Rotation Measurement Technique

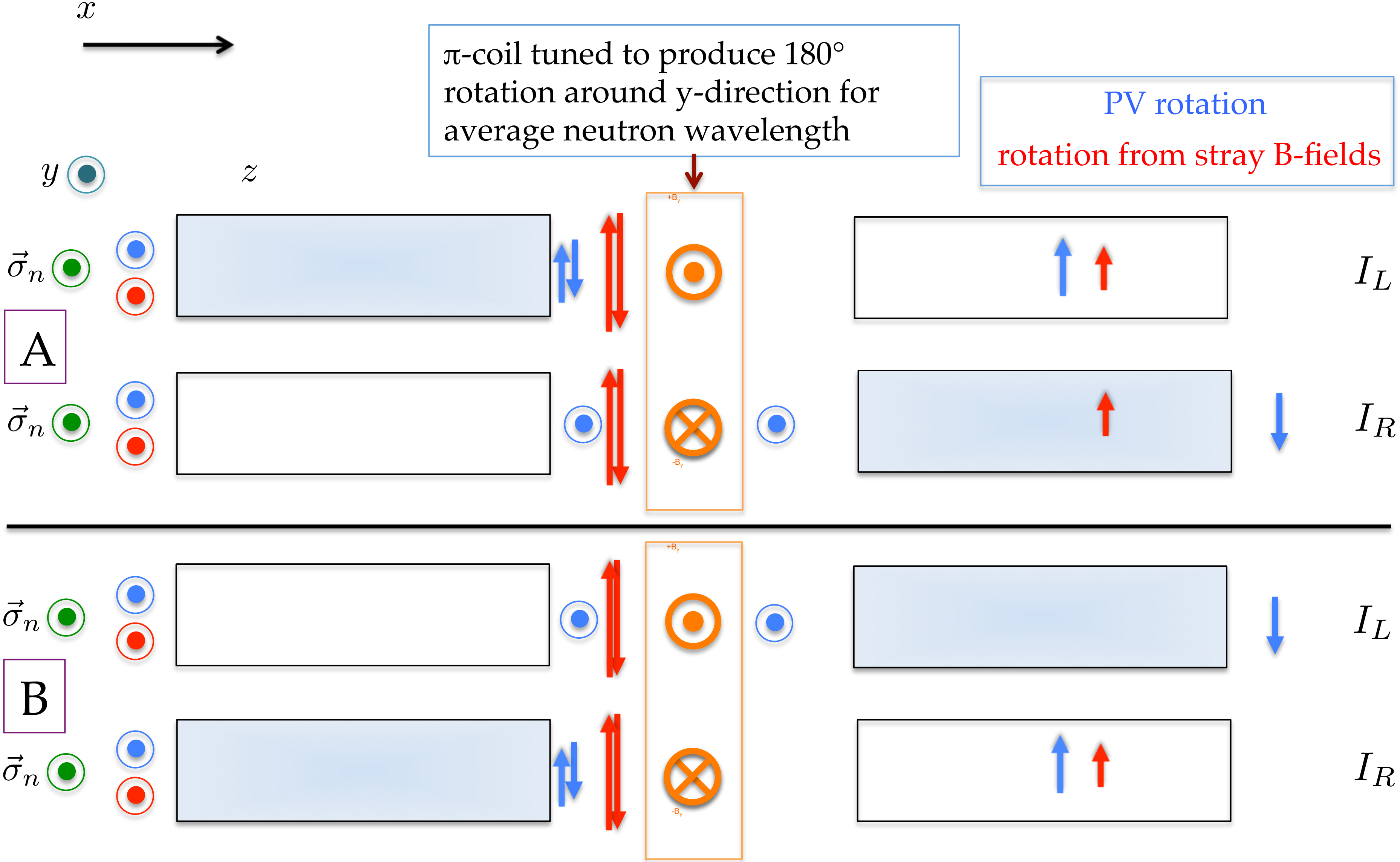


Two measurements produce a spin rotation angle

$$PA \sin\phi = \frac{I_+ - I_-}{I_+ + I_-}$$

PV rotation ~10^{-7} rad/m, but earth's field would produce a rotation ~10 rad/m!

PV Spin Rotation Measurement Technique



π-coil tuned to produce 180° rotation around y-direction for average neutron wavelength

PV rotation

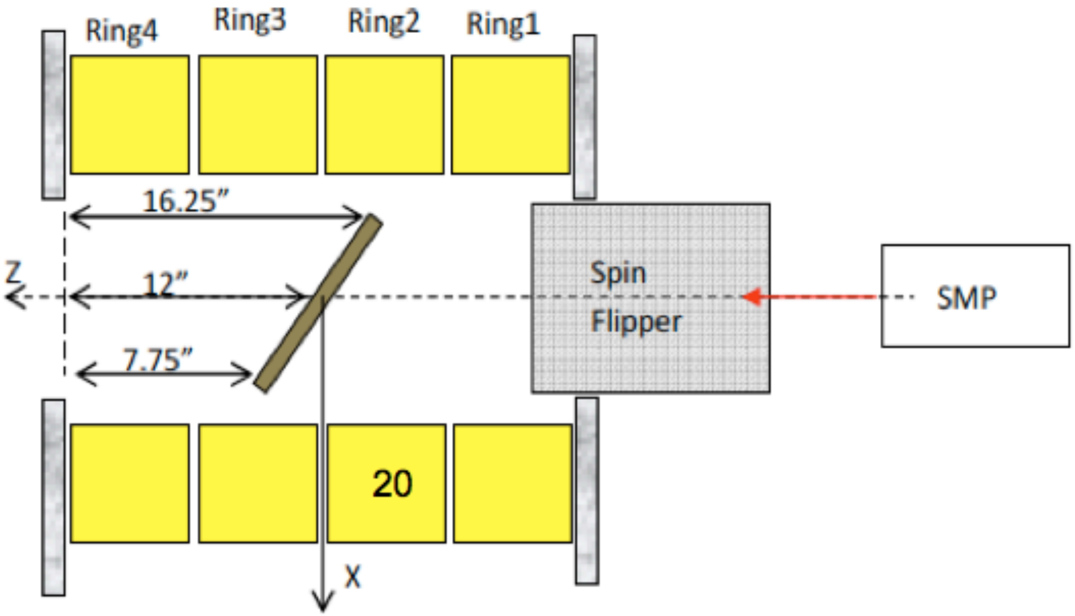
rotation from stray B-fields

Spin rotation from stray fields as well as left/right field asymmetries cancel

$$(\phi_L - \phi_R)_A - (\phi_L - \phi_R)_B = 4\phi_{\rm PV}$$

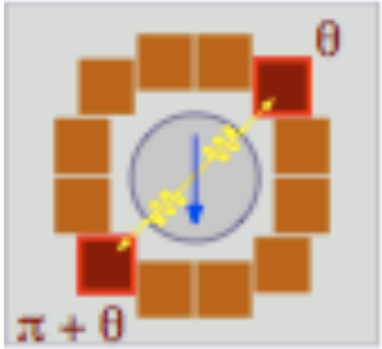
beam intensity

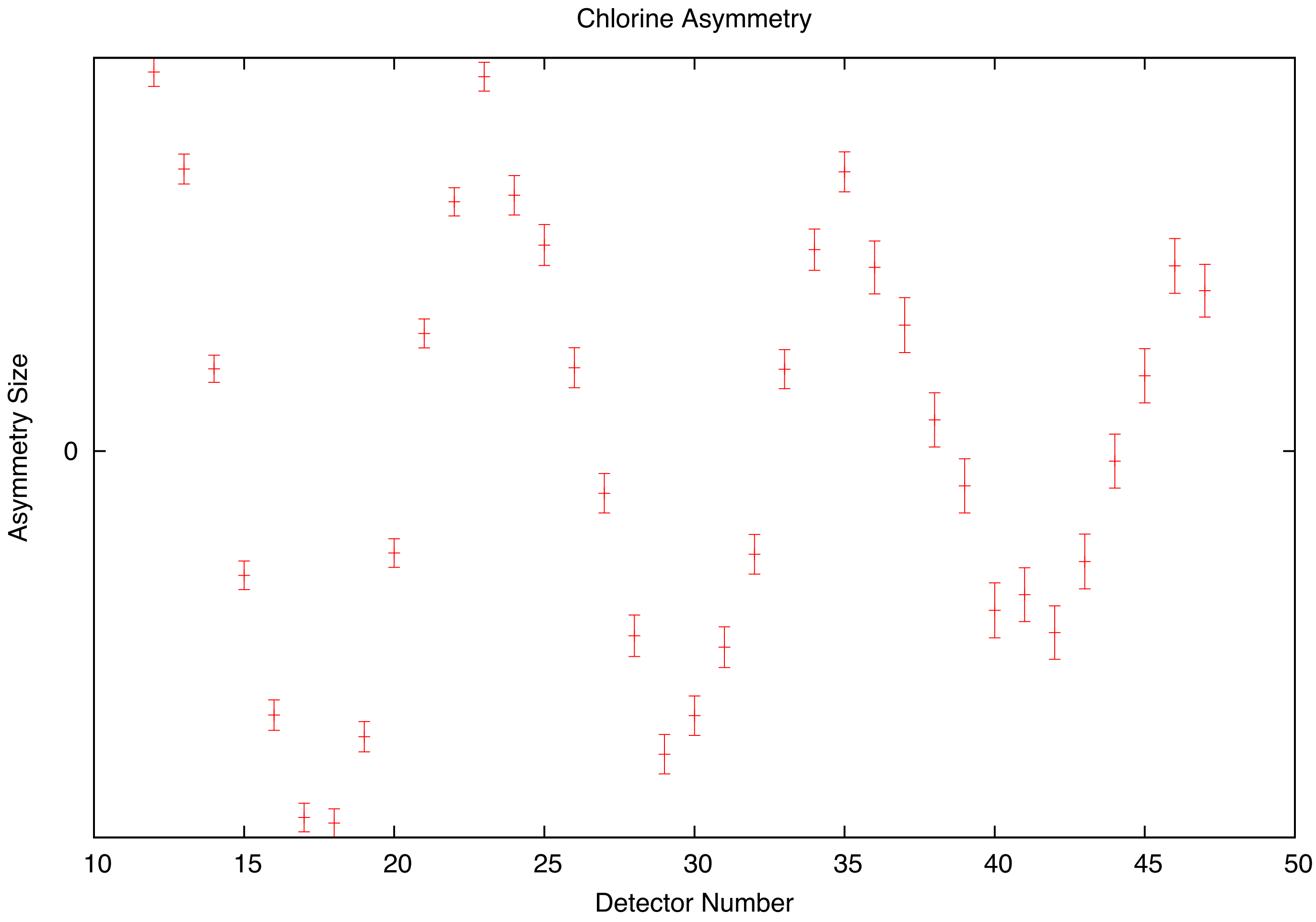
- it gives us a sanity check on the statistical error
- measurement of intensity done by inserting a boron plate into the center of the detector array.
- then the signal size is compared to a known Cs source



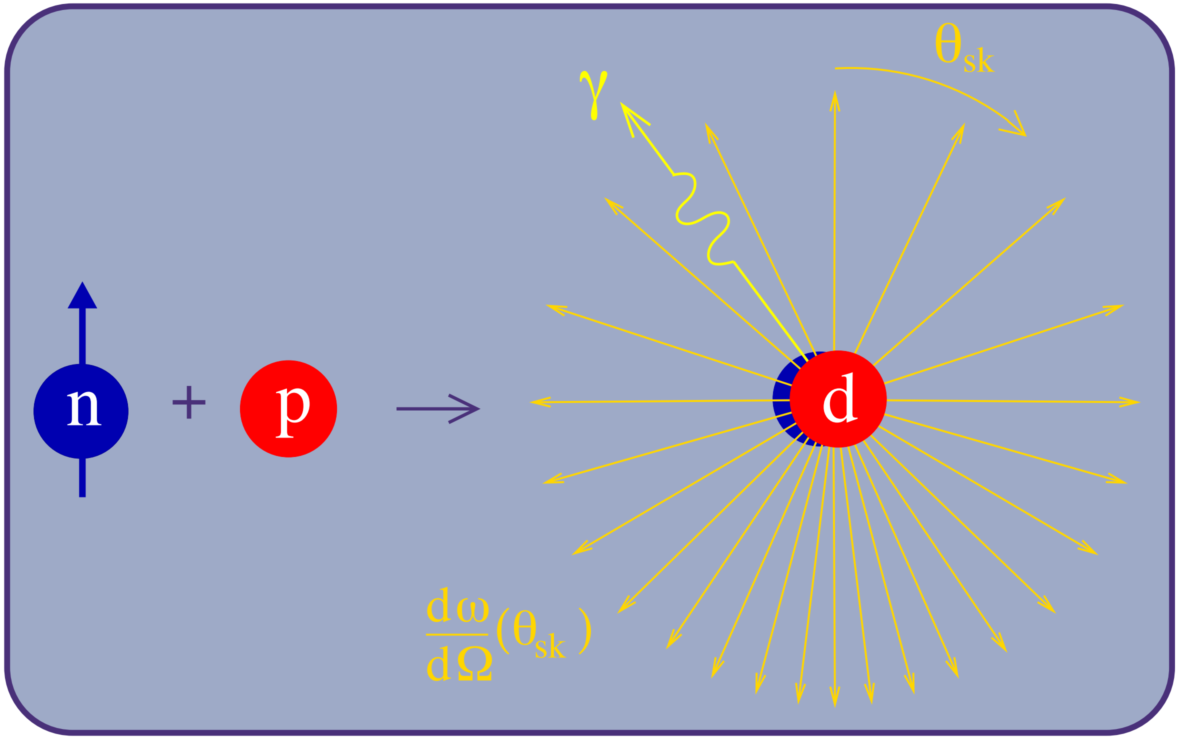
Chlorine Asymmetry

$$A_\gamma P_N cos(\theta) = \frac{[N(\theta) - N(\theta + \pi)]_\uparrow - [N(\theta) - N(\theta + \pi)]_\downarrow}{[N(\theta) - N(\theta + \pi)]_\uparrow + [N(\theta) - N(\theta + \pi)]_\downarrow}$$





NPDγ Experiment

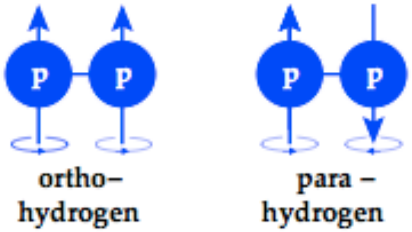


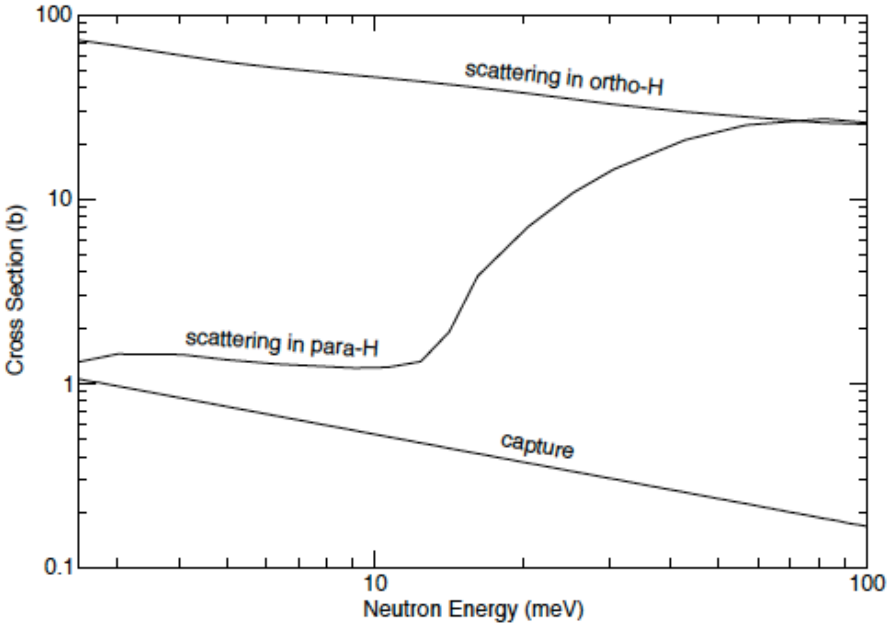
$$\frac{d\sigma}{d\Omega} \propto 1 + A_{\gamma} cos(\theta_{sk})$$

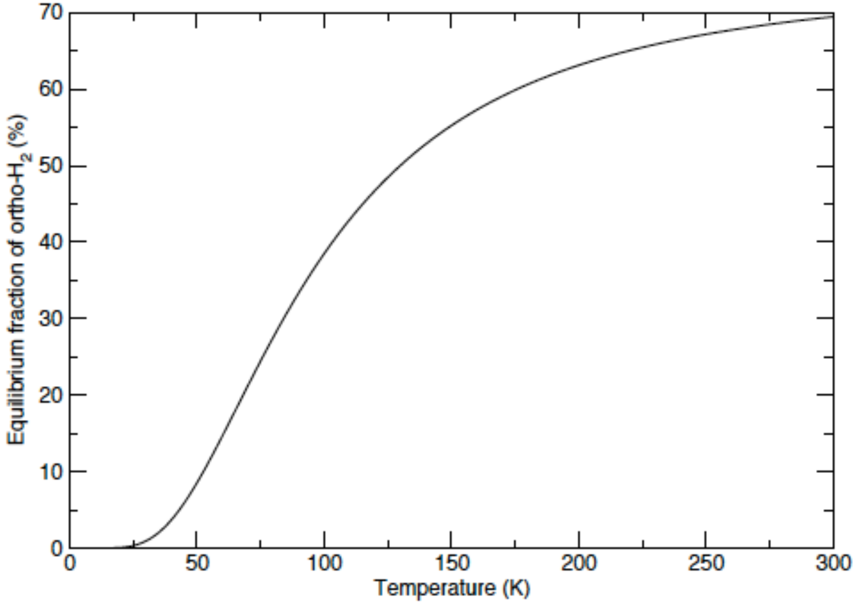
$$cos(\theta_{sk}) = \frac{\overrightarrow{s}_{n} \cdot \overrightarrow{k}_{\gamma}}{|\overrightarrow{s}_{n}||\overrightarrow{k}_{\gamma}|}$$

Ortho to Para Converter

- Two nuclear spin states for LH2 with ΔE = 15 meV
- Ortho-H2 has high incoherent scattering cross section
- Use catalyst to convert ortho into para
- Can monitor OP conversion rate by looking at beam flux after target

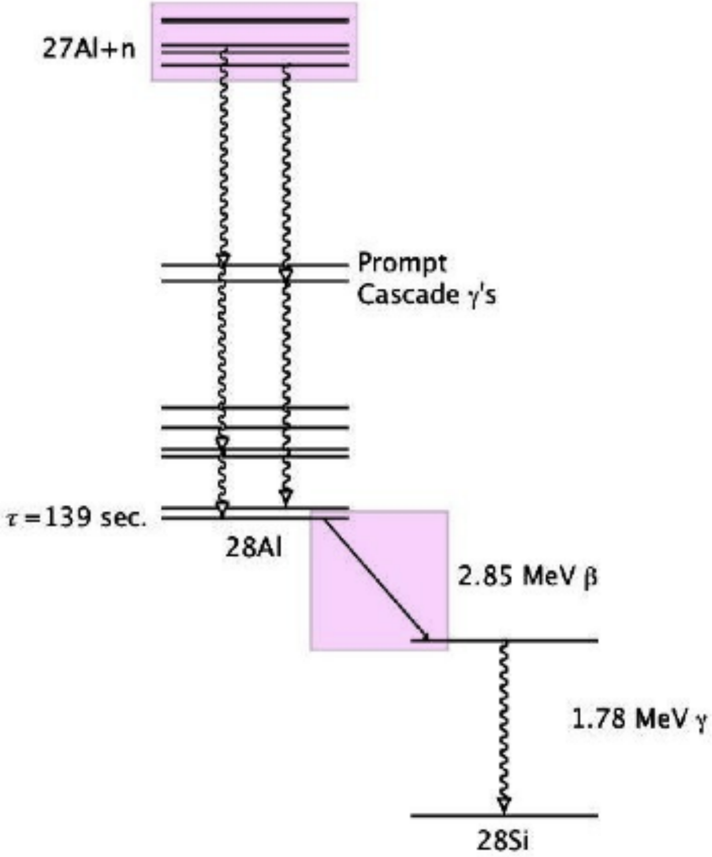




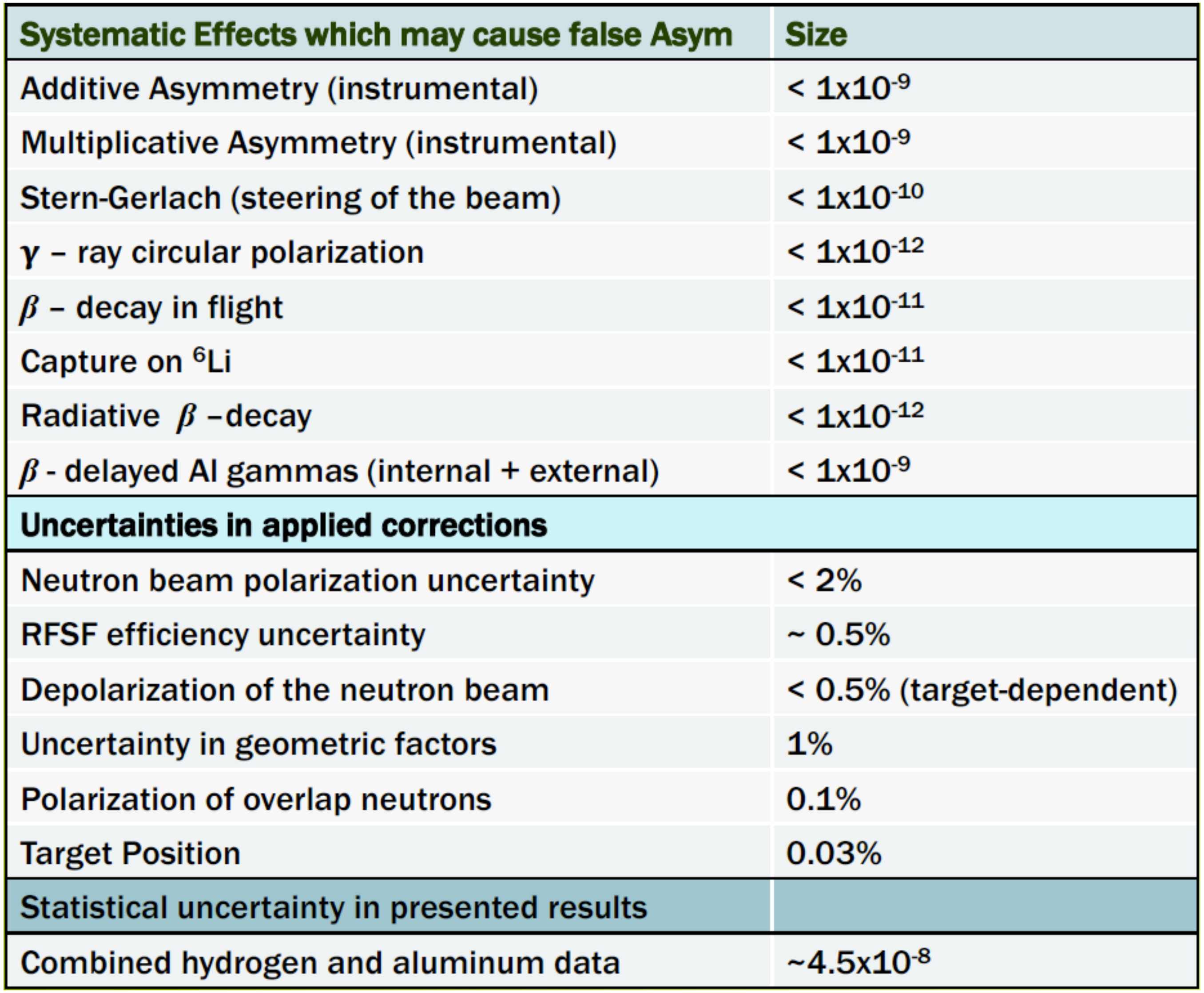


Determining Aluminum background from decay

- Aluminum is essential in our target construction
- must determine aluminum background from neutron capture from Al.
- Includes both prompt and beta decay gammas
- we can fit the aluminum decay after beam off to relate back to prompt yield

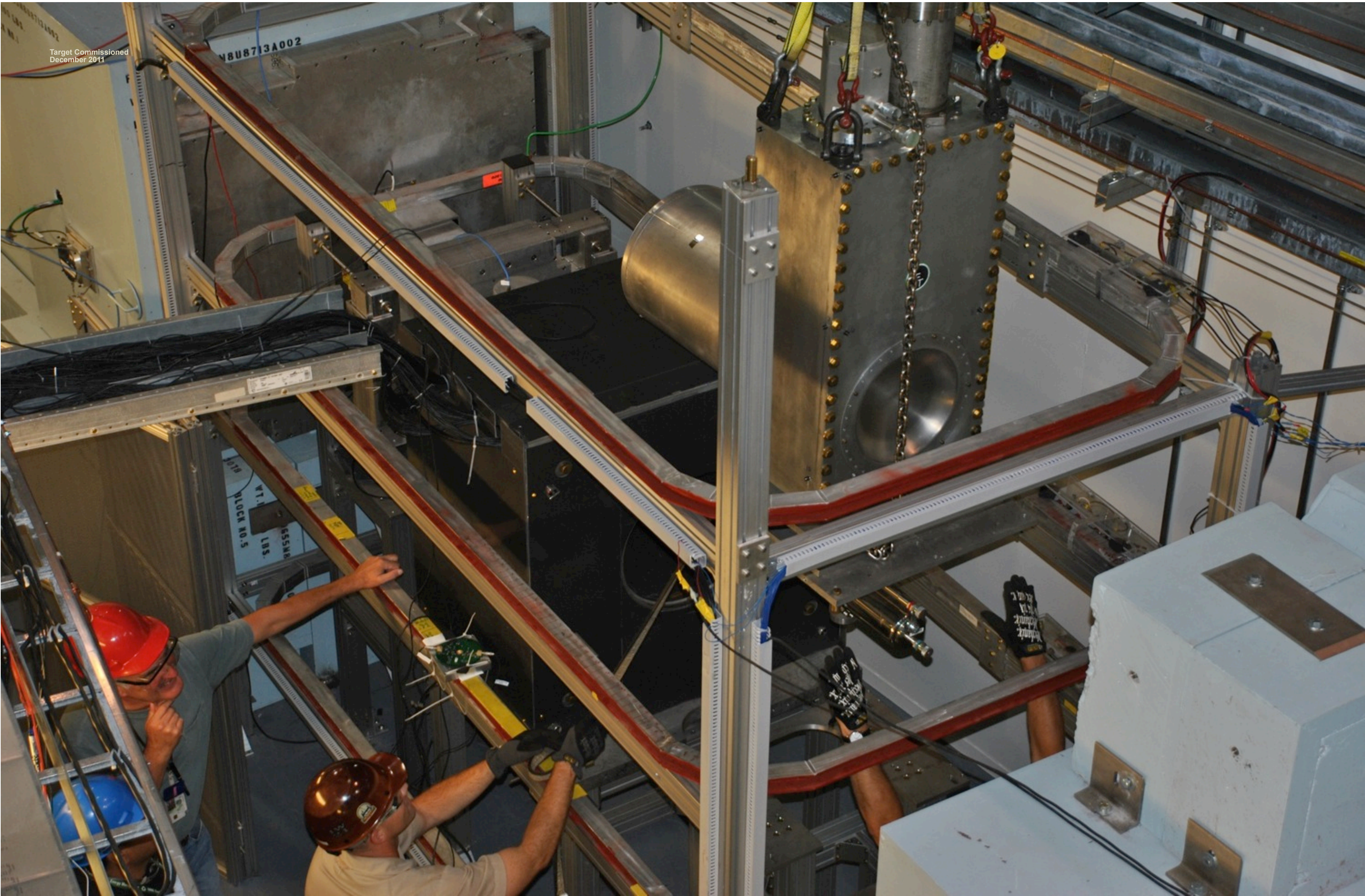


Systematic & Statistical Uncertainties



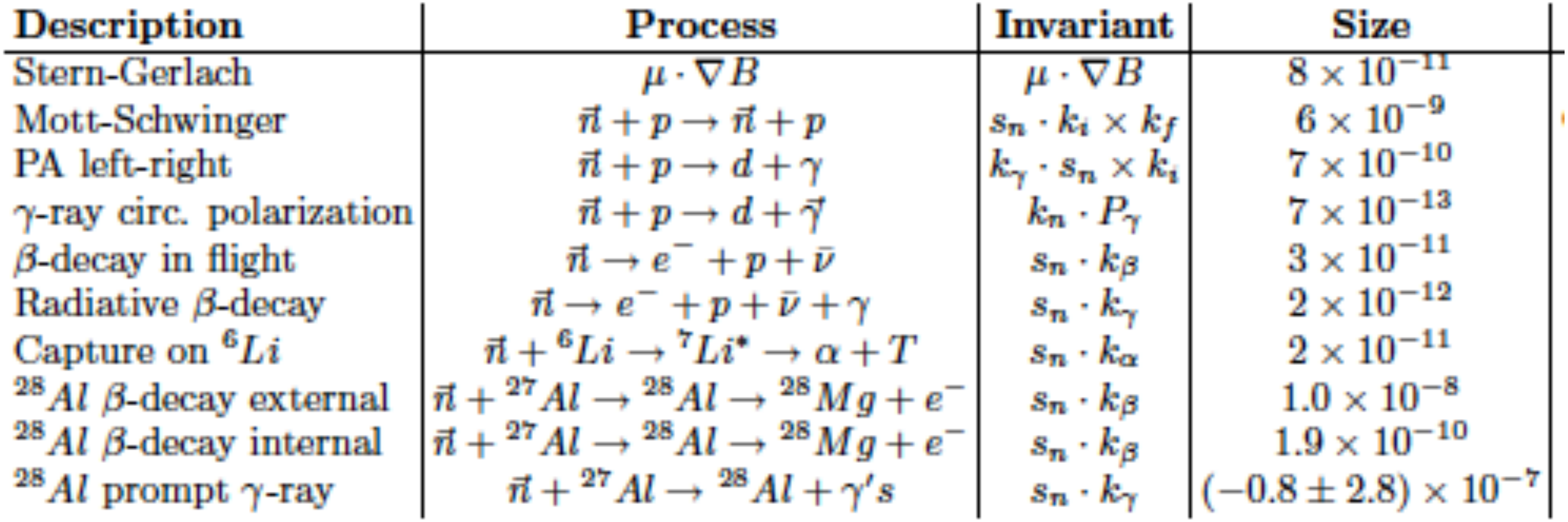
Systematic Effects which may cause false Asym	**Size**
Additive Asymmetry (instrumental)	$< 1x10^{-9}$
Multiplicative Asymmetry (instrumental)	$< 1x10^{-9}$
Stern-Gerlach (steering of the beam)	$< 1x10^{-10}$
γ – ray circular polarization	$< 1x10^{-12}$
β – decay in flight	$< 1x10^{-11}$
Capture on ^{6}Li	$< 1x10^{-11}$
Radiative β –decay	$< 1x10^{-12}$
β - delayed Al gammas (internal + external)	$< 1x10^{-9}$
Uncertainties in applied corrections	
Neutron beam polarization uncertainty	< 2%
RFSF efficiency uncertainty	~ 0.5%
Depolarization of the neutron beam	< 0.5% (target-dependent)
Uncertainty in geometric factors	1%
Polarization of overlap neutrons	0.1%
Target Position	0.03%
Statistical uncertainty in presented results	
Combined hydrogen and aluminum data	$\sim4.5x10^{-8}$

Installation of the LH_2 target on the FnPB

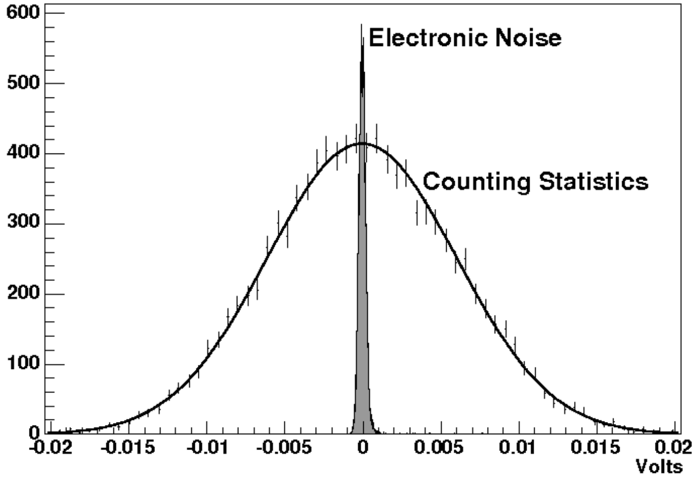


Target Commissioned
December 2011

Systematic effects



Description	Process	Invariant	Size
Stern-Gerlach	$\mu \cdot \nabla B$	$\mu \cdot \nabla B$	8×10^{-11}
Mott-Schwinger	$\vec{n} + p \to \vec{n} + p$	$s_n \cdot k_i \times k_f$	6×10^{-9}
PA left-right	$\vec{n} + p \to d + \gamma$	$k_\gamma \cdot s_n \times k_i$	7×10^{-10}
γ-ray circ. polarization	$\vec{n} + p \to d + \vec{\gamma}$	$k_n \cdot P_\gamma$	7×10^{-13}
β-decay in flight	$\vec{n} \to e^- + p + \bar{\nu}$	$s_n \cdot k_\beta$	3×10^{-11}
Radiative β-decay	$\vec{n} \to e^- + p + \bar{\nu} + \gamma$	$s_n \cdot k_\gamma$	2×10^{-12}
Capture on ^6Li	$\vec{n} + {}^6Li \to {}^7Li^* \to \alpha + T$	$s_n \cdot k_\alpha$	2×10^{-11}
^{28}Al β-decay external	$\vec{n} + {}^{27}Al \to {}^{28}Al \to {}^{28}Mg + e^-$	$s_n \cdot k_\beta$	1.0×10^{-8}
^{28}Al β-decay internal	$\vec{n} + {}^{27}Al \to {}^{28}Al \to {}^{28}Mg + e^-$	$s_n \cdot k_\beta$	1.9×10^{-10}
^{28}Al prompt γ-ray	$\vec{n} + {}^{27}Al \to {}^{28}Al + \gamma's$	$s_n \cdot k_\gamma$	$(-0.8 \pm 2.8) \times 10^{-7}$



Search of CP violation

- In CPT conserving limit,

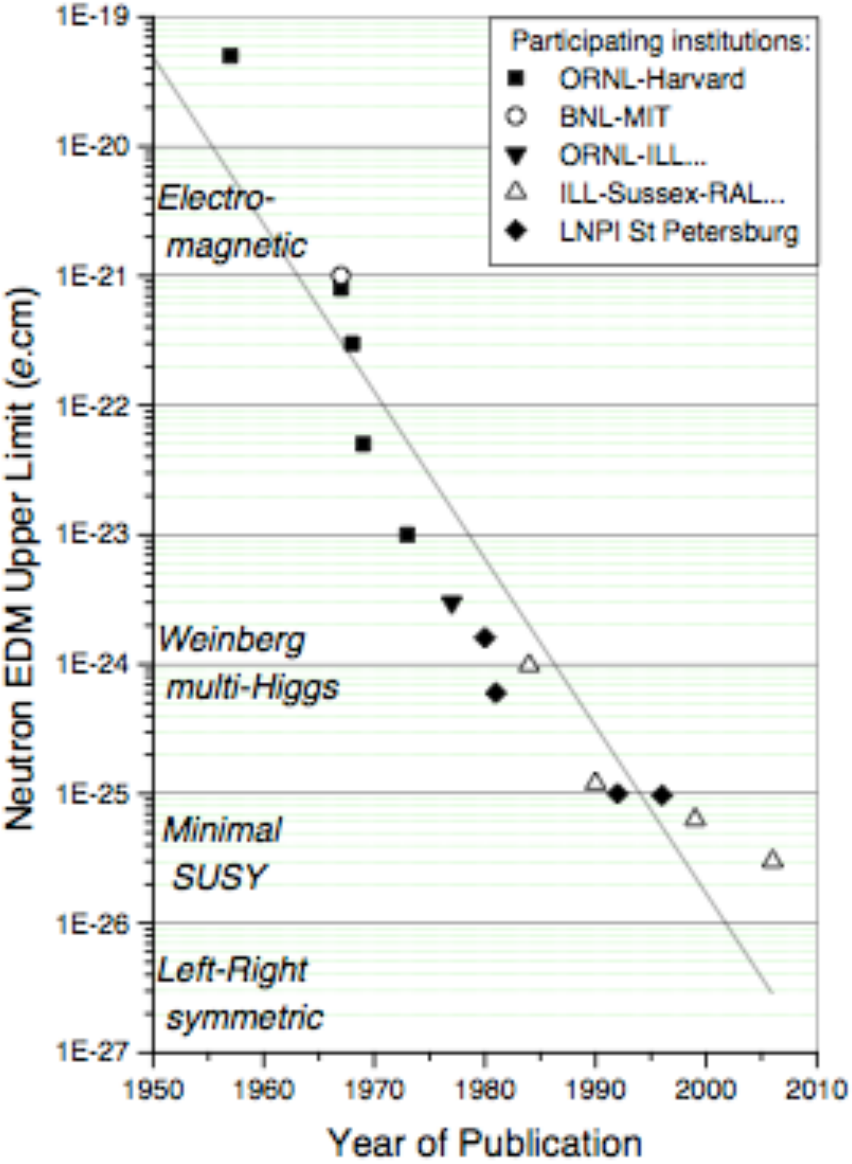
  $$\not{T} \rightarrow \not{CP}$$

- Electric Dipole Moment violates T

  $$H = 2\mu \cdot B \pm 2d \cdot E$$

- neutron EDM
  - search for Beyond SM particles
  - current limit

    $$3 \times 10^{-26} e \cdot cm$$



T violation in Nuclei

- measures transmission of neutrons T – odd observable

  $$\vec{\sigma_n} \cdot (\vec{k_n} \times \vec{I})$$

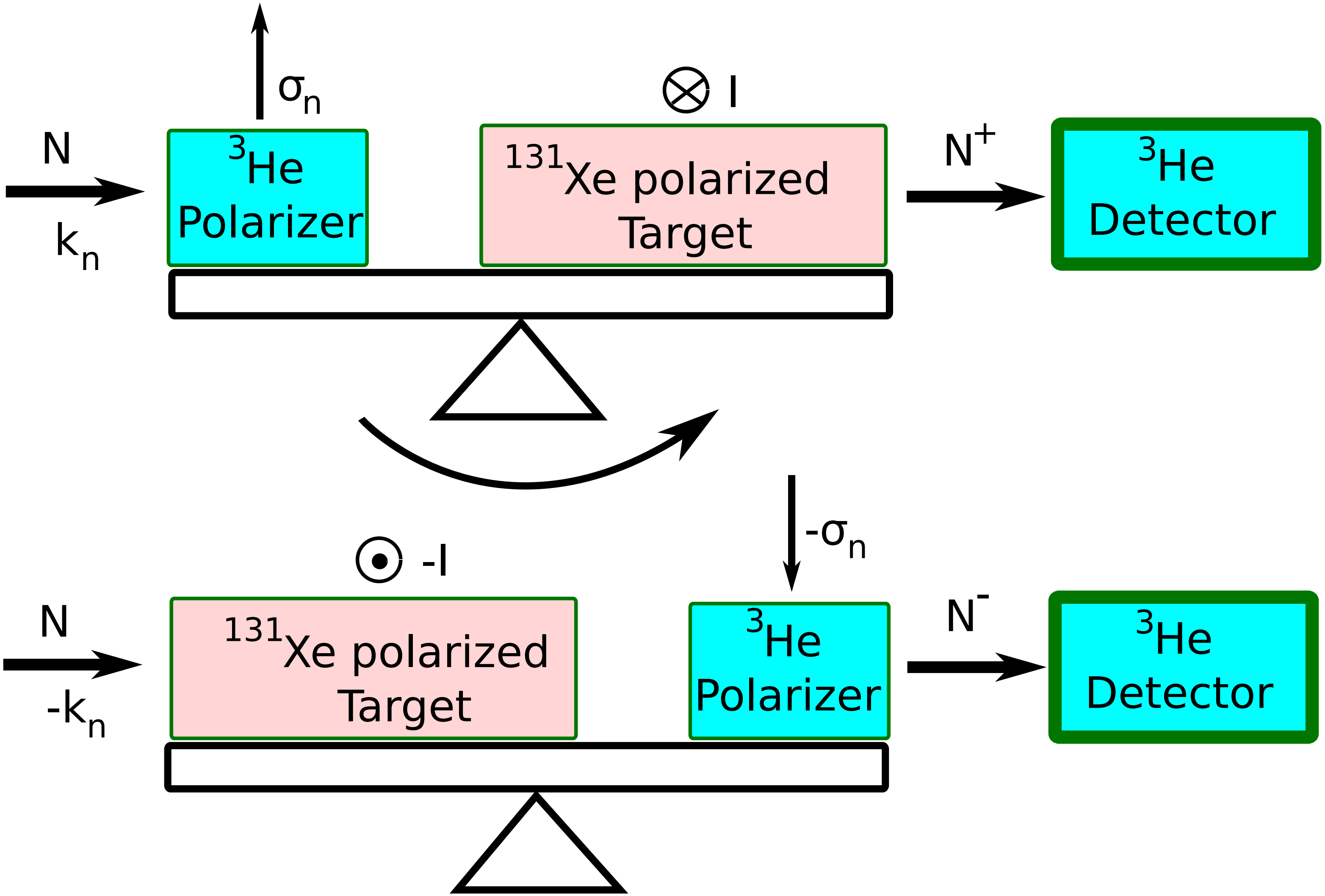
- P-odd and T-odd
- receives an enhancement from large P-odd asymmetry
- sensitivity of experiments recorded as

$$\lambda_{PT} = \frac{\delta\sigma_{PT}}{\delta\sigma_P}$$

	Resonance	PV
^{131}Xe	3.2 eV	0.043
^{139}La	0.748 eV	0.096

Model	λ_{PT}
CKM δ phase	$\lesssim 10^{-10}$
Left-right symmetry	$\lesssim 4 \times 10^{-3}$
Horizontal symmetry	$\lesssim 10^{-5}$
Charged Higgs bosons	$\lesssim 2 \times 10^{-6}$
Neutral Higgs bosons	$\lesssim 3 \times 10^{-4}$
θ QCD	$\lesssim 5 \times 10^{-5}$
nEDM (single-loop)	$\lesssim 4 \times 10^{-3}$
Atomic EDM (^{199}Hg)	$\lesssim 2 \times 10^{-3}$

Experiment Setup



Experimental Sensitivity

	^{131}Xe	^{139}La
Neutron Flux	1.9×10^{7}	-
Counting Stat	9×10^{-8}	-
Neutron Pol	0.7	-
Target Pol	0.04	0.3
PV	0.04	0.1
Sig/Back	0.04 (50% enrich.)	0.08
λ sensitivity	2×10^{-3}	5.4×10^{-5}

Outlook for NN Weak Interaction Theory+Experiment

Only one NN weak EFT coupling is determined from existing experiments from p-p

Asymmetry measurement in n+p->D+gamma will fix a second NN weak EFT coupling($^3S_1 \Leftrightarrow {}^3P_1\ \Delta I=1$)

Asymmetry in n+p->D+gamma/weak isovector NN coupling a goal for lattice gauge theory/exoscale computing

Beams at NIST and SNS can be used to see parity violation in spin rotation experiments [~1E-7 rad/m statistical accuracy in n-^{4}He] and in inelastic asymmetries and analyzing powers [~1E-8 in n+p->D+gamma and n+3He->3H+p]

Theoretical work is needed to extend weak NN calculations to few nucleon systems (n-D, n-3He, n-^{4}He, p-^{4}He), investigate region of EFT validity, and make use of existing data in p-4He and experiments planned in n-3He and n-4He

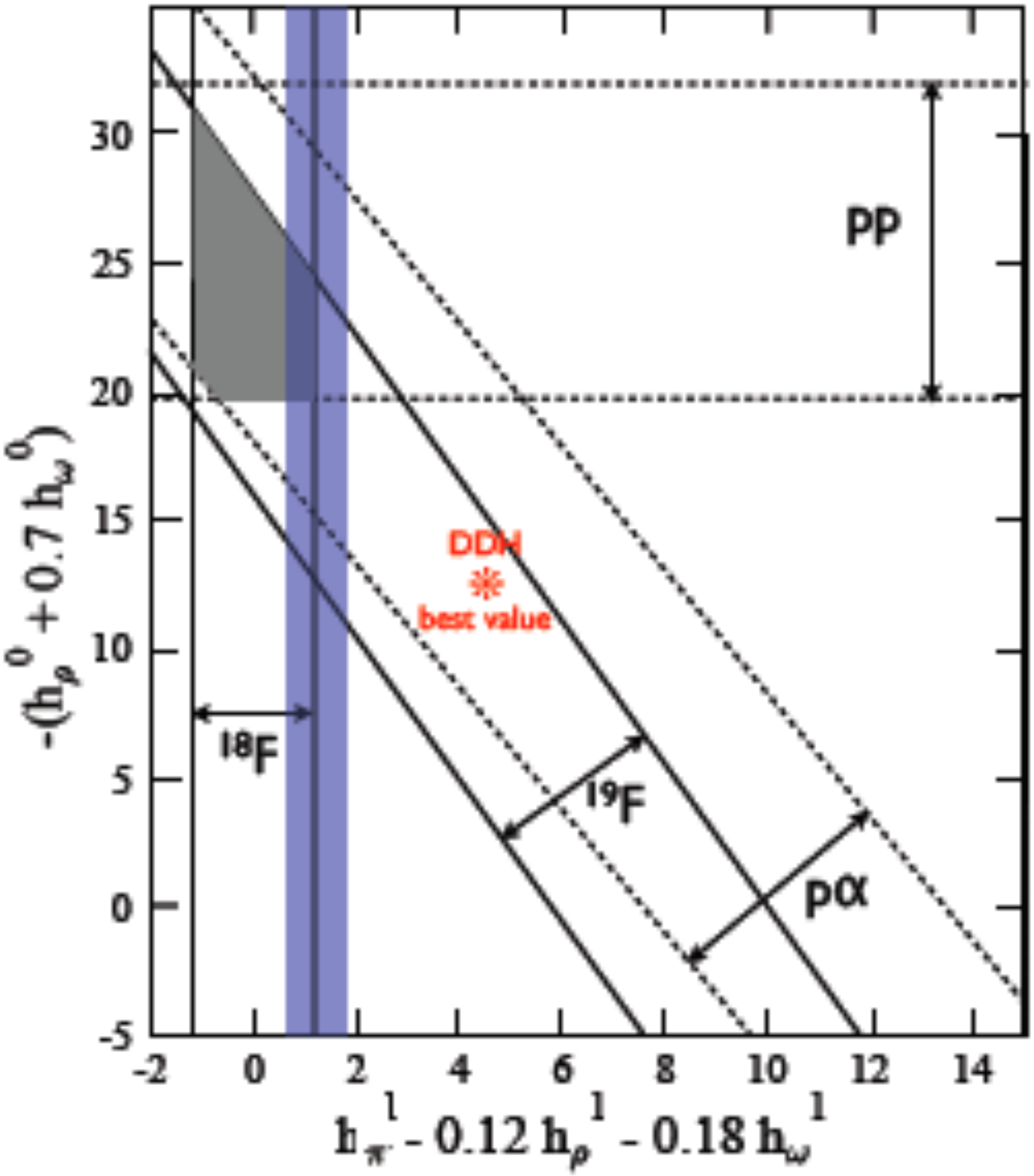
NN weak coupling constraints in DDH

Many experiments constrain a similar linear combination of isoscalar and isovector NN weak amplitudes

Within DDH model: experiments imply larger isoscalar NN PV and smaller isovector NN PV relative to expectations

New theory development: first lattice gauge theory calculation of isovector parity violation from pions Result: h_{π}=(1.1 +/- 0.5)x 10^{-7}

Wasem, arXiv:1108.1151
Haxton/Holstein, arXiv:1303.4132



Background Sub. & Geometry Factors

$$A_{\gamma}^{np} = \frac{A_{raw}}{P_n \epsilon_{sf} C_d} - F_{BG}\frac{A_{Al}}{P_n^{Al}\epsilon_{sf}^{Al} C_d^{Al}}$$

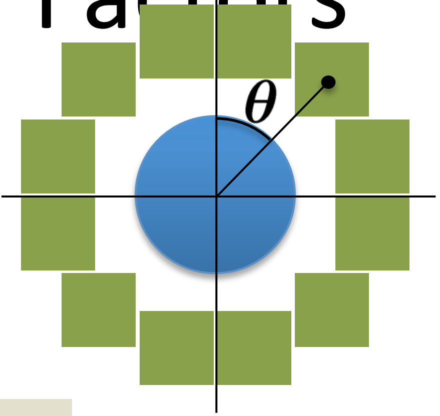
Aluminum asymmetry

neutron pol.

RFSF eff.

target depol.

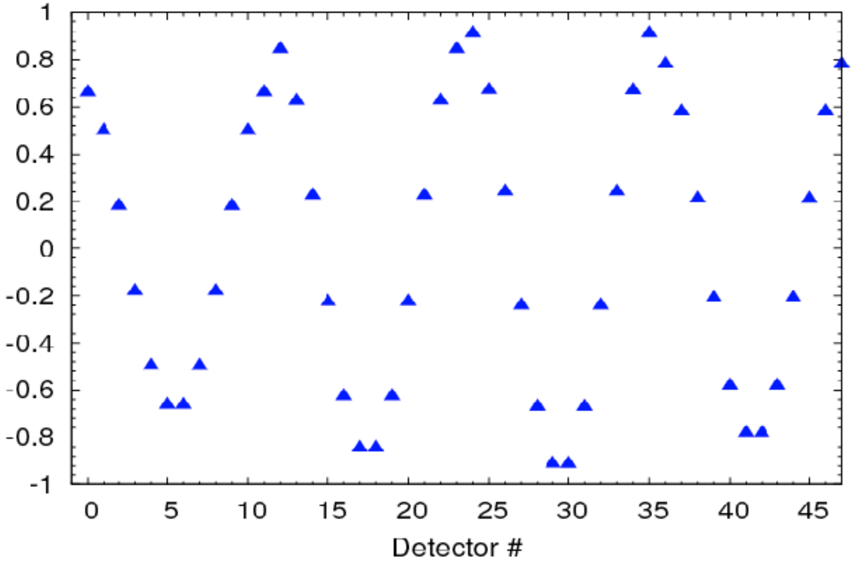
Aluminum background

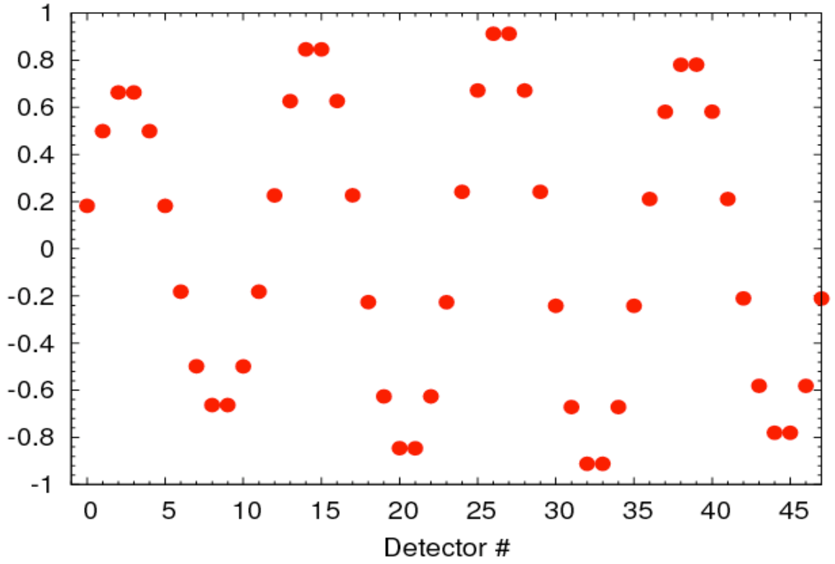


UP-DOWN

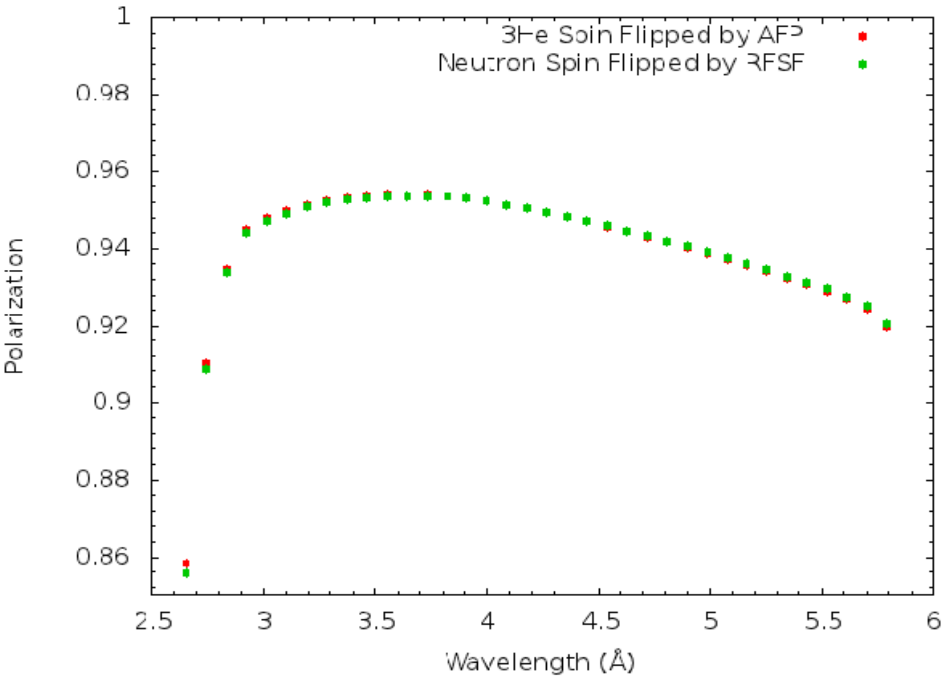
LEFT-RIGHT

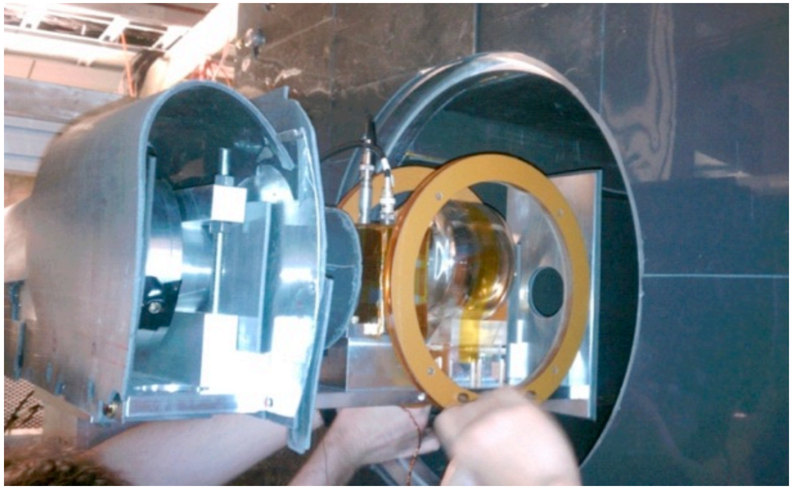
$$A_{raw} = A_{\gamma}^{PV} \underbrace{G_{UD}}_{\langle s_n \cdot k_\gamma = \cos\theta \rangle} + A_{\gamma}^{PC} \underbrace{G_{LR}}_{\langle s_n \cdot k_n \times k_\gamma = \sin\theta \rangle} + A_{offset}$$

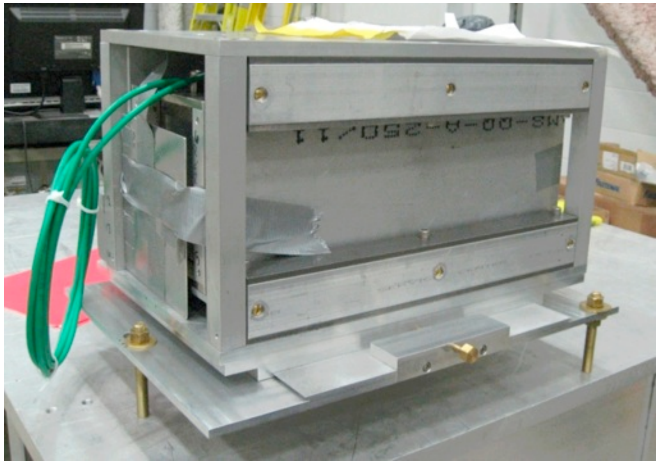


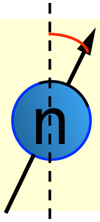


Polarimetry – ^{3}He spin filter









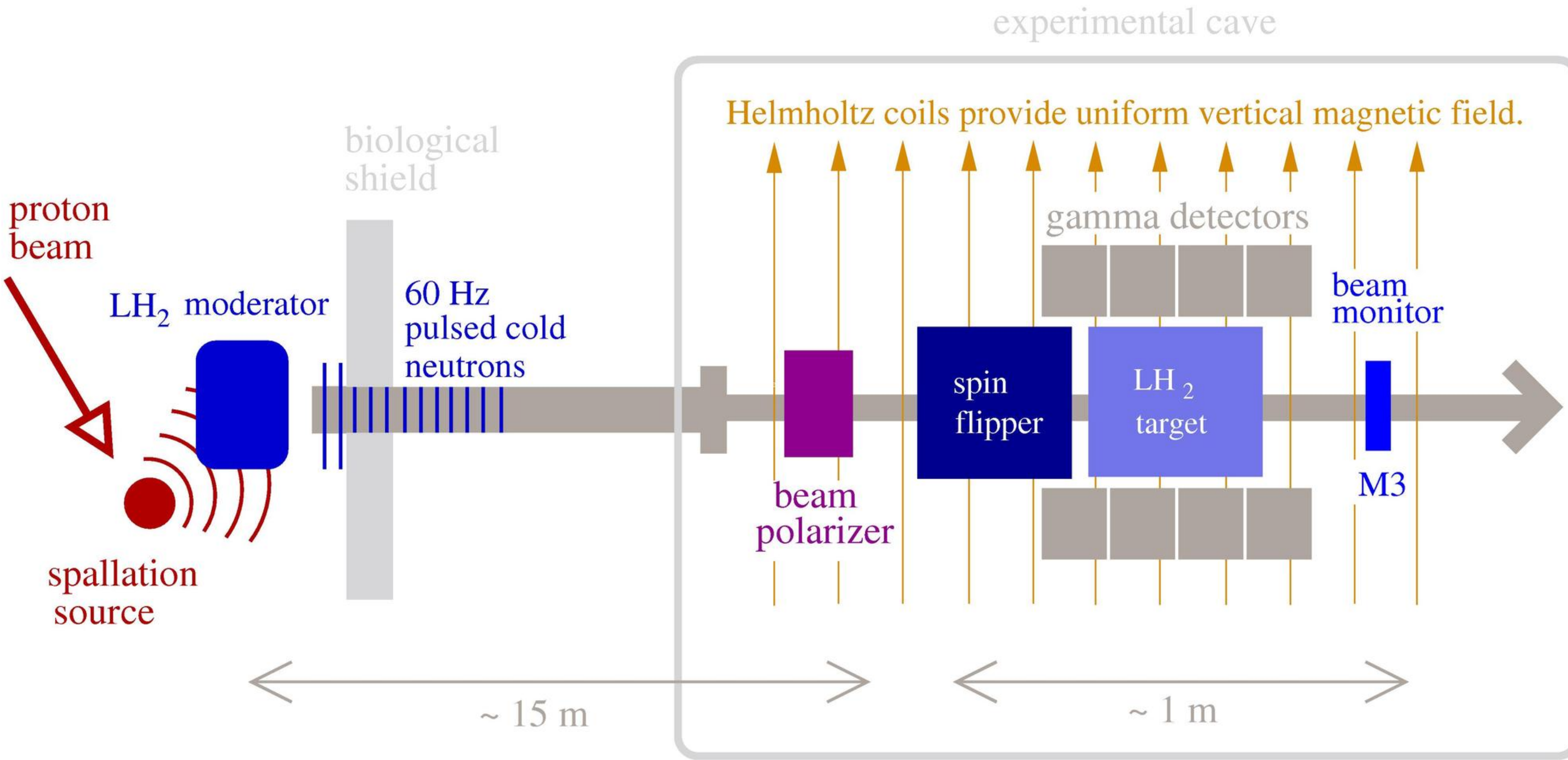
n-^{4}He Spin Rotation Collaboration

C.D. Bass[7], B.E. Crawford[2], J.M. Dawkins[1], T.D. Bass[1], K. Gan[3],
B.R. Heckel[4], J.C. Horton[1], C.R. Huffer[1], P.R. Huffman[5], D. Luo[1], D.M. Markoff[6],
A.M. Micherdzinska[3], H.P. Mumm[7], J.S. Nico[7], A.K. Opper[3], E. Sharapov[8],
M.G. Sarsour[1], W.M. Snow[1], H.E. Swanson[4], V. Zhumabekova[9]

Indiana University / IUCF [1]
Gettysburg College [2]
The George Washington University [3]
University of Washington [4]
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]

NSF PHY-0457219, NSF PHY-0758018
DOE

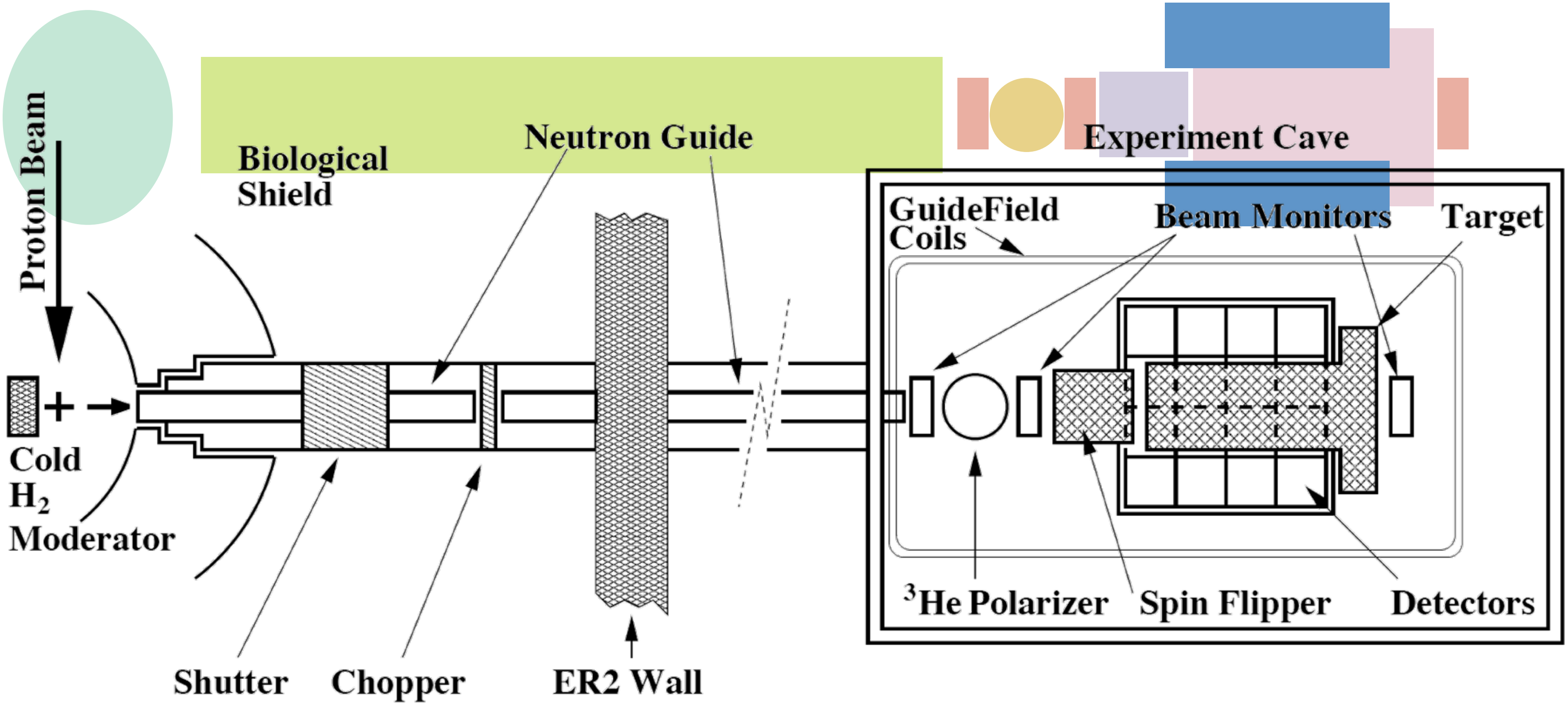
PV Gamma Asymmetry Apparatus



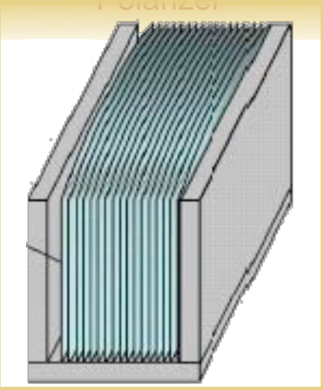
- A_γ – P-odd asymmetry in the gammas emitted from polarized slow neutron capture on protons.
- Pulsed neutron source (important for control of systematic errors)
- Liquid parahydrogen target, current mode CsI array
- Goal at SNS: 1×10^{-8} for A_γ in $n+p \to D+\gamma$

$$\frac{d\sigma}{d\Omega} \propto \frac{1}{4\pi}\left(1 + A_\gamma \cos\theta\right)$$

Experimental Layout



Supermirror Polarizer



Beam Monitors

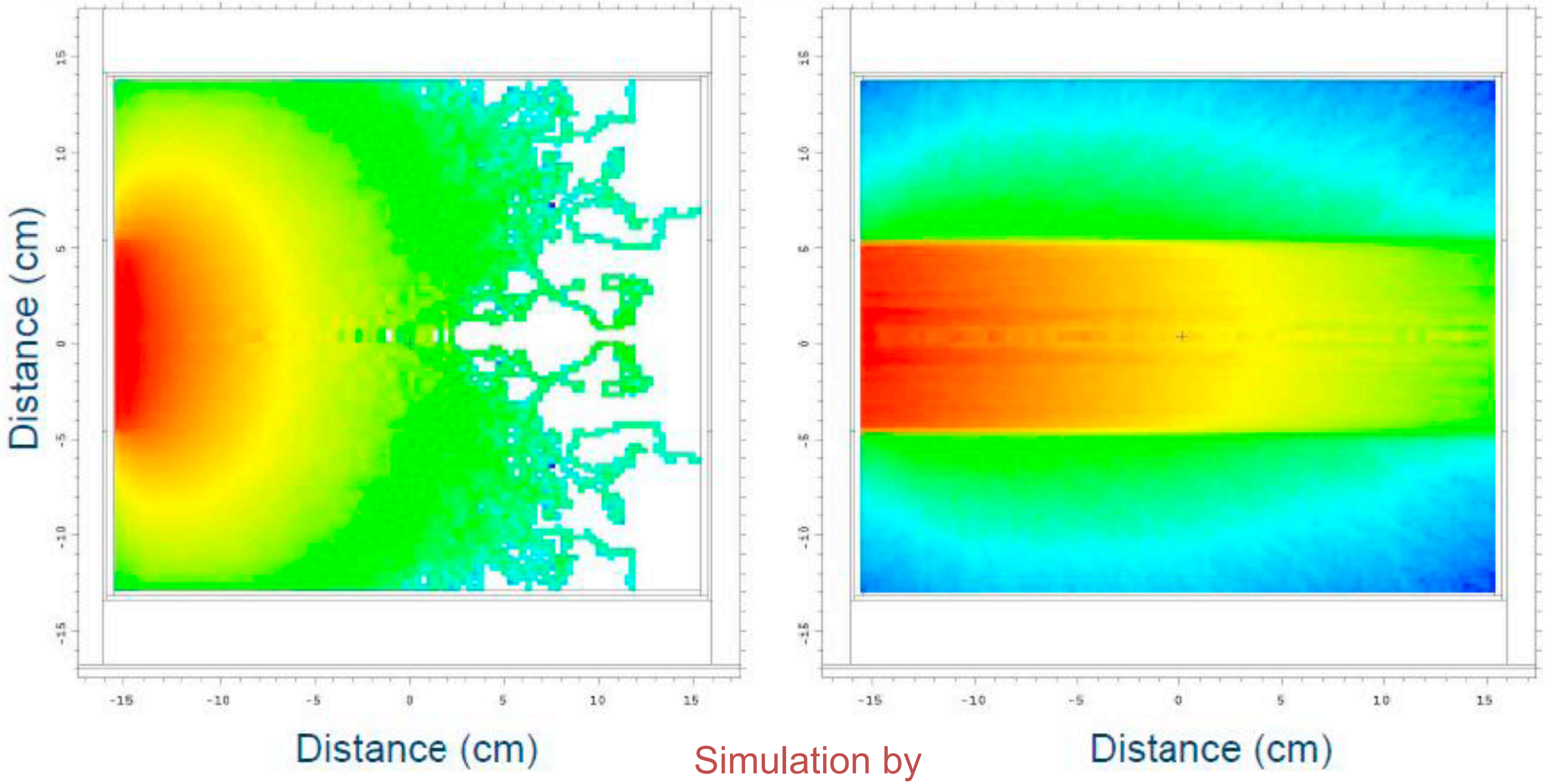
RF Spin Rotator

LH_2 Target

Gamma Detectors

Ortho vs. Para H_2 neutron scattering

MCNP calculation of neutron beam intensity in liquid hydrogen target



Pure Ortho - H_2

Simulation by
Kyle Grammer

Pure Para - H_2

L. Barron-Palos *et al.,* Nucl. Instr. Meth. **A671** 137 (2012)

n^3He Calculations

- Full four-body calculation of strong scattering wave functions
- Evaluation of the weak matrix elements in terms of the DDH potential (Work in progress on calculation of EFT low energy coefficients)

$$\boxed{A_p^{\vec{n},{}^3He}(th.) \approx (-9.4 \rightarrow 2.5) \times 10^{-8}}$$

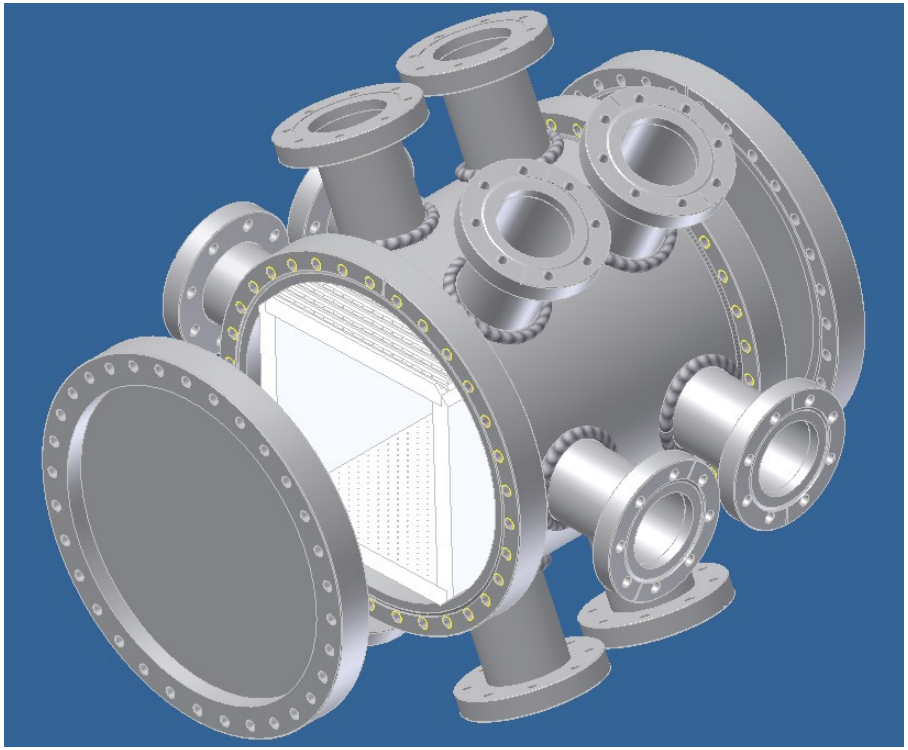
DDH Weak Coupling	(A^p_Z) $n^3He \rightarrow tp$
a_π^1	-0.189
a_ρ^0	-0.036
a_ρ^1	0.019
a_ρ^2	-0.0006
a_ω^0	-0.0334
a_ω^1	0.0413

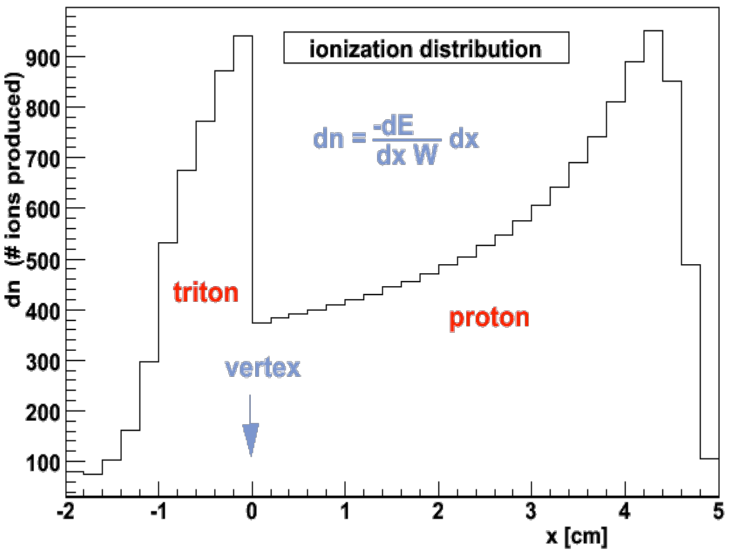
M. Viviani, R. Schiavilla, Phys. Rev. C. 82 044001 (2010)
L. Girlanda et al. Phys. Rev. Lett. 105 232502 (2010)

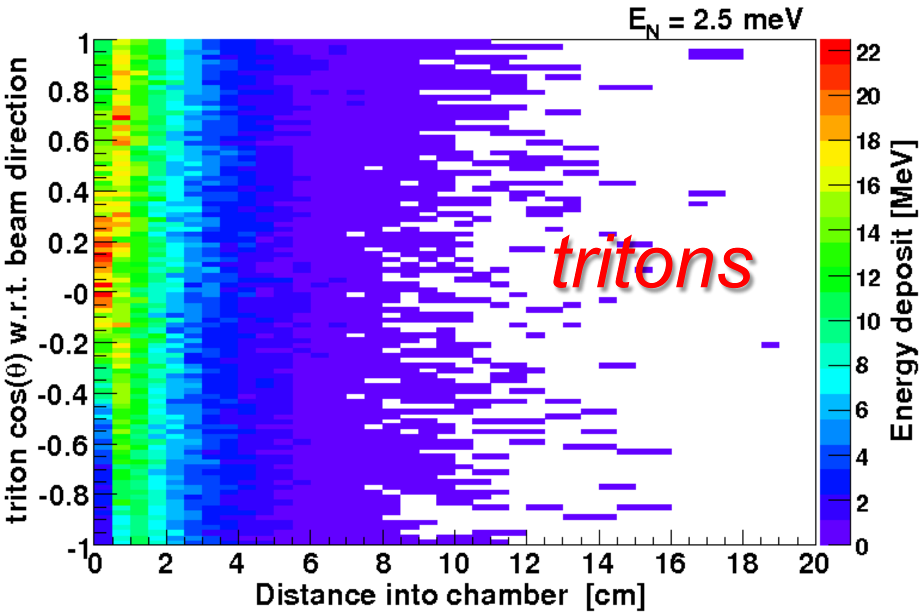
- *MC simulations of sensitivity to proton asymmetry*
  - *including wire correlations*
  - $\delta A_{ph} = \frac{1}{\sqrt{N} P_{_N}} \sqrt{\sigma_{_D}^2 + \sigma_{coll}^2}$

$$\boxed{\sigma_d \simeq 6}$$

- *tests at LANSCE FP12*
  - *fission chamber flux calibration*
  - *prototype drift chamber R&D*
  - *new beam monitors for SNS*







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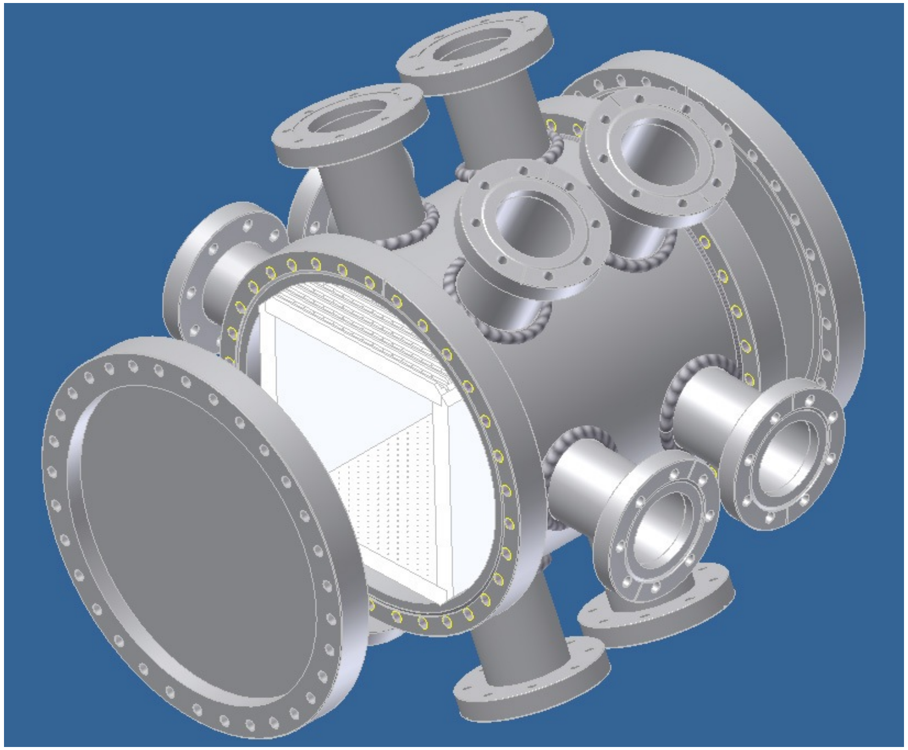
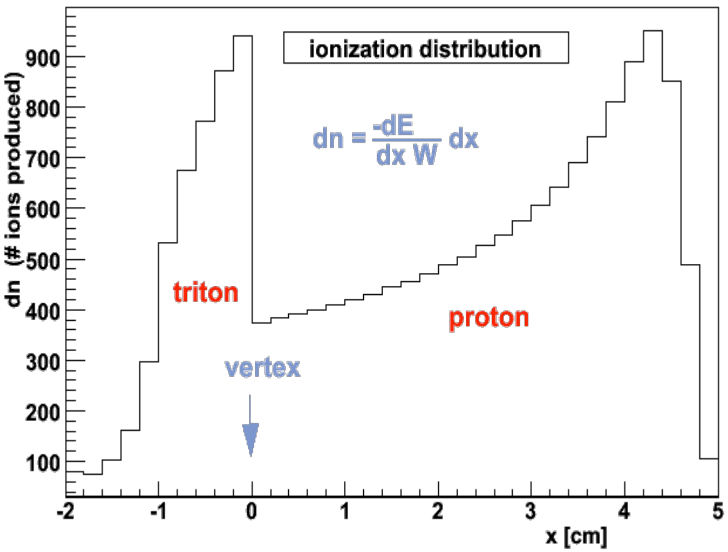
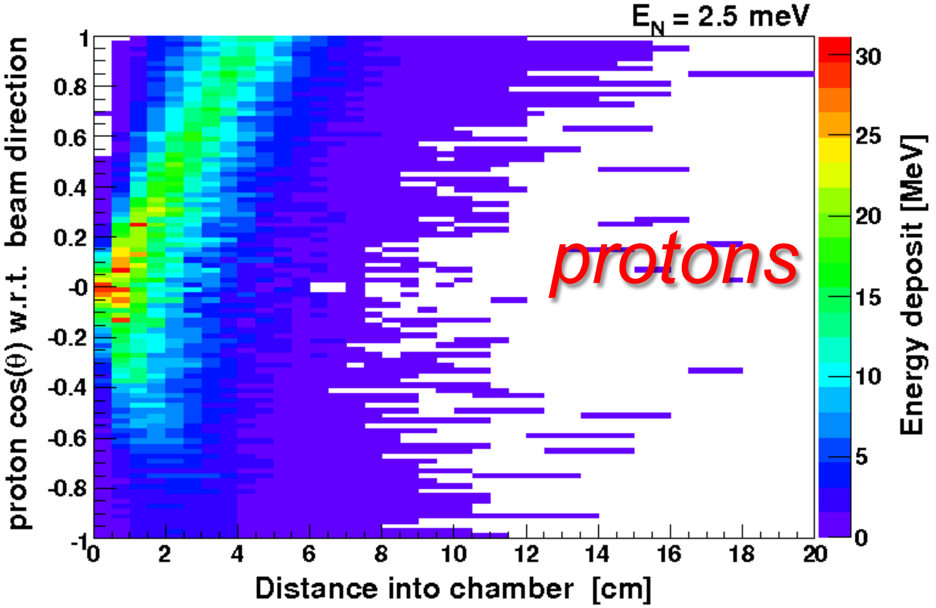




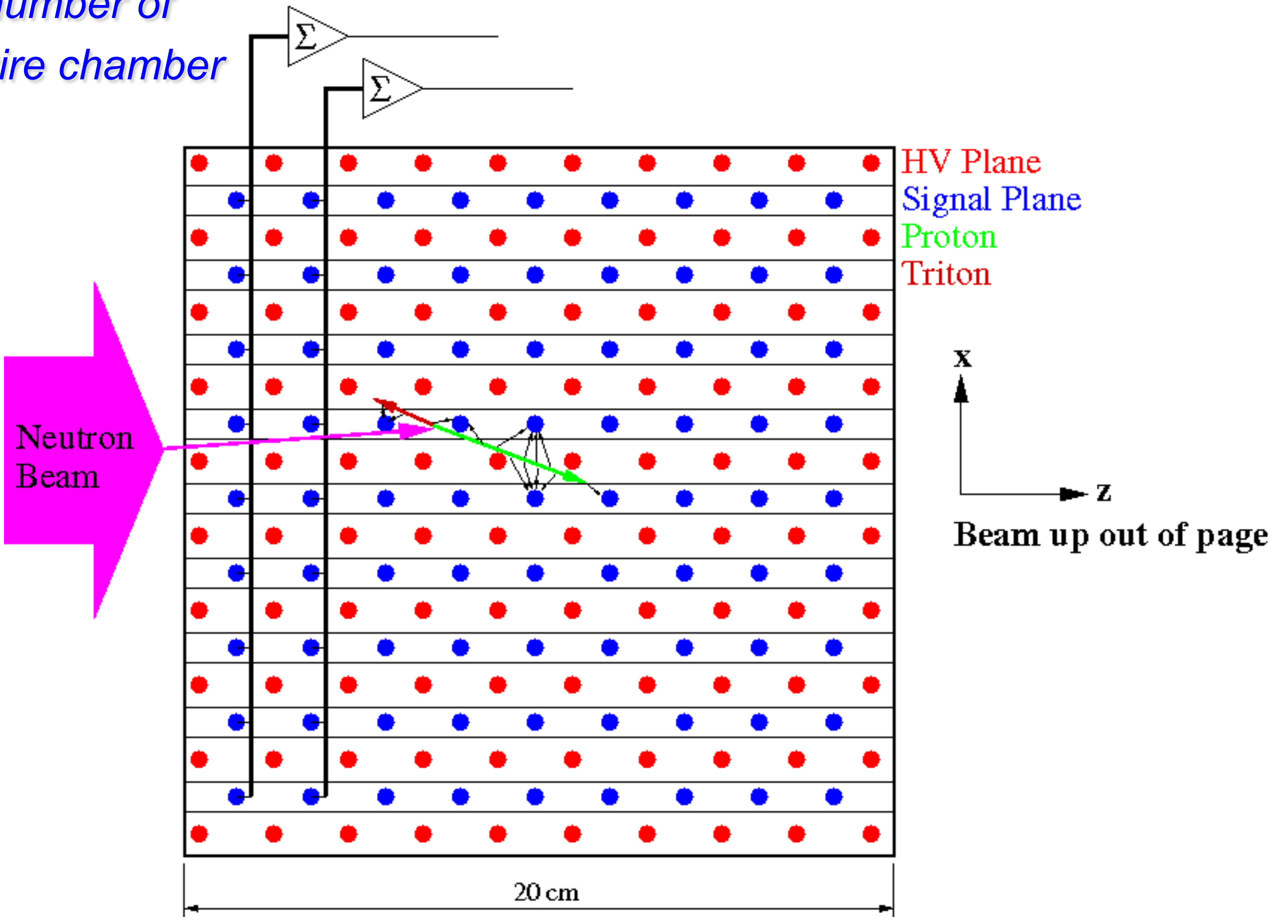


N-^{3}He Asymmetry: Principle of Measurement

- *Measure the asymmetry in the number of forward going protons in a ^{3}He wire chamber as a function of neutron spin*

- *wire chamber is both target and detector*
- *wires run vertical or horizontal*

- *no crossed wire: keep the field simple to avoid electron multiplication (non-linearities)*



$$\boxed{\vec{n} + {}^{3}\mathrm{He} \rightarrow {}^{3}\mathrm{H} + p}$$

q-q Weak Interaction: Isospin Dependence

At energies below the W± and Z° 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) $\otimes$ spin-A (S_{tot} = 0) $\Rightarrow$ $^1S_0$, $^1D_2$, $^1G_4$, …

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

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

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

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

$\}$ ***$^{(2S+1)}L_J$ 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 Interaction

- 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,…)*
- Dynamical models: meson exchange model for NN weak interaction

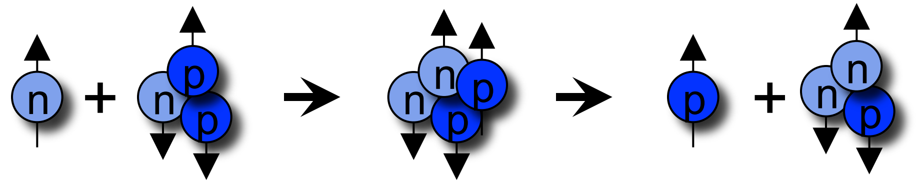
(effect of qq weak interactions parametrized by ~6 couplings), QCD sum rules, Skyrme models, chiral quark models, ADS/CFT-based models (*Desplanques, Donoghue, Holstein, Meissner, Hwang, Gazit,…)*

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

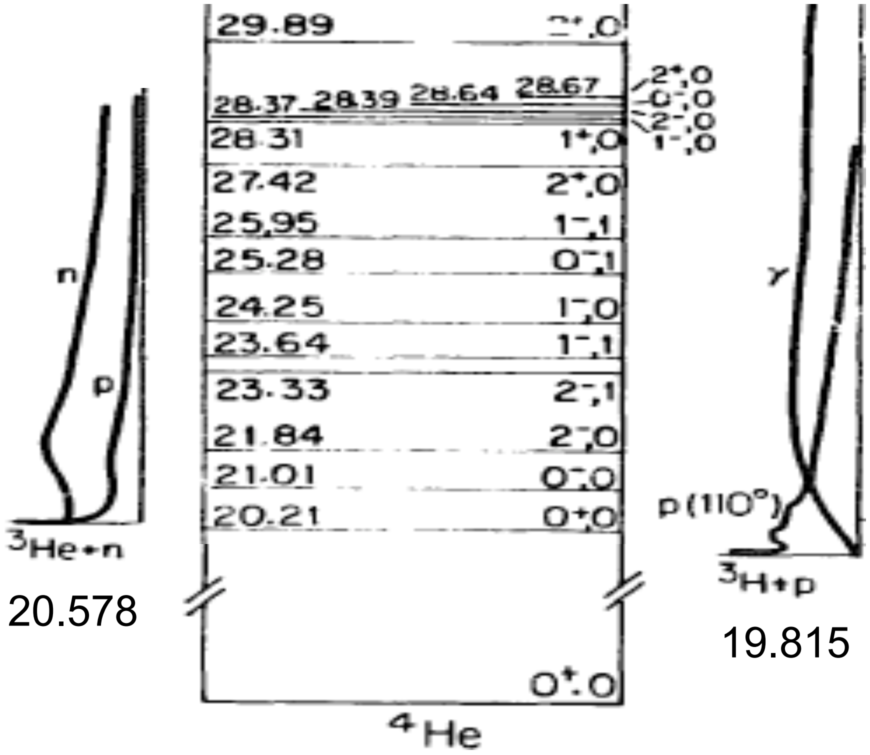
Strong NN amplitudes are now well-enough known to relate parity violation measurements in few body systems to the weak NN interaction (Pieper, Wiringa, Nollett, Schiavilla, Carlson, Paris, Kievsky, Viviani…).

It is also known that, as expected, P-odd NNN interactions are small compared to P-odd NN interactions (Schindler)

n-^{3}He PV asymmetry at SNS



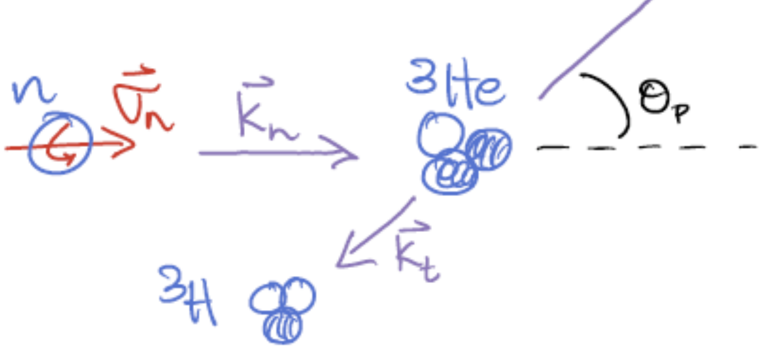
$$\vec{n} + {}^3\mathrm{He} \rightarrow \mathrm{p} + \mathrm{t} + 764\ \mathrm{keV}$$



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
- Complementary to NPDGamma (ΔI=1)
- "large" asymmetry predicted from DDH best values: $A = 1.15 \times 10^{-7}$ (Viviani, et al., PRC 82, 044001 (2010),)
- GOAL: measure asymmetry to ~2×10^{-8}

Asymmetry Measurement – Statistics

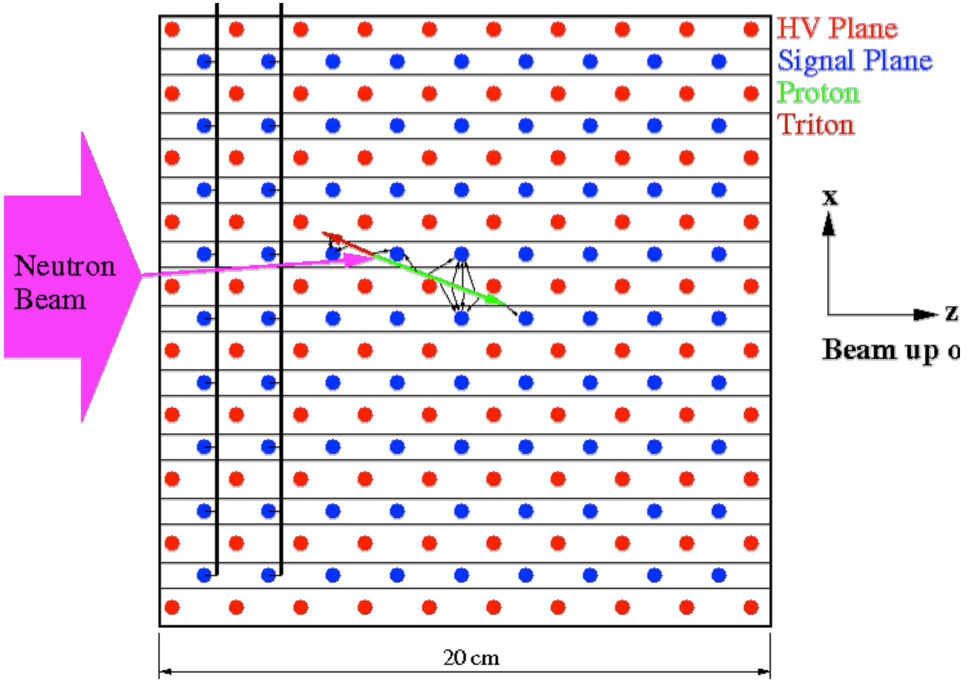
- PV Physics asymmetry is extracted from weighted average of single-wire spin asymmetries

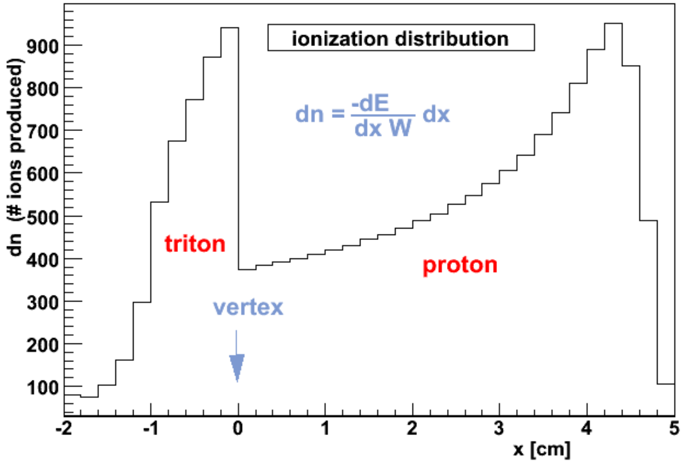
- Two Monte Carlo simulations:
  1. a code based on GEANT4
  2. a stand-alone code including wire correlations

$$\delta A = \frac{\sigma_d}{P\sqrt{N}} = 1.6 \times 10^{-8}$$

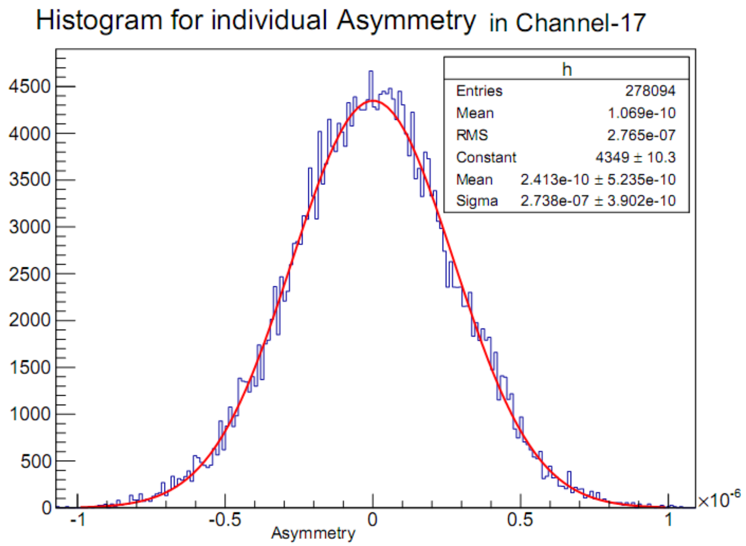
$N = 1.5\times10^{10}$ n/s flux (chopped)
$\times 10^{7}$ s (116 days)
$P = 96.2\%$ neutron polarization
$\sigma_d = 6$ detector inefficiency

- 15% measurement in 1 beam cycle (without contingency), assuming $A_z = 1.15 \times 10^{-7}$



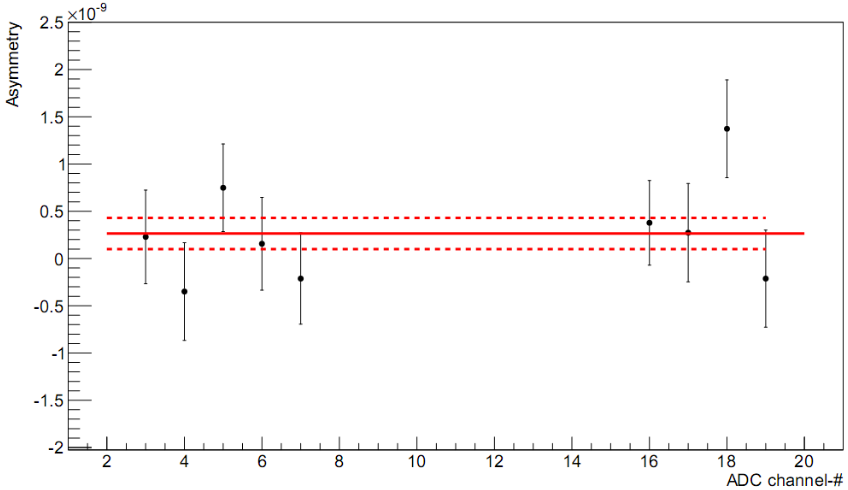


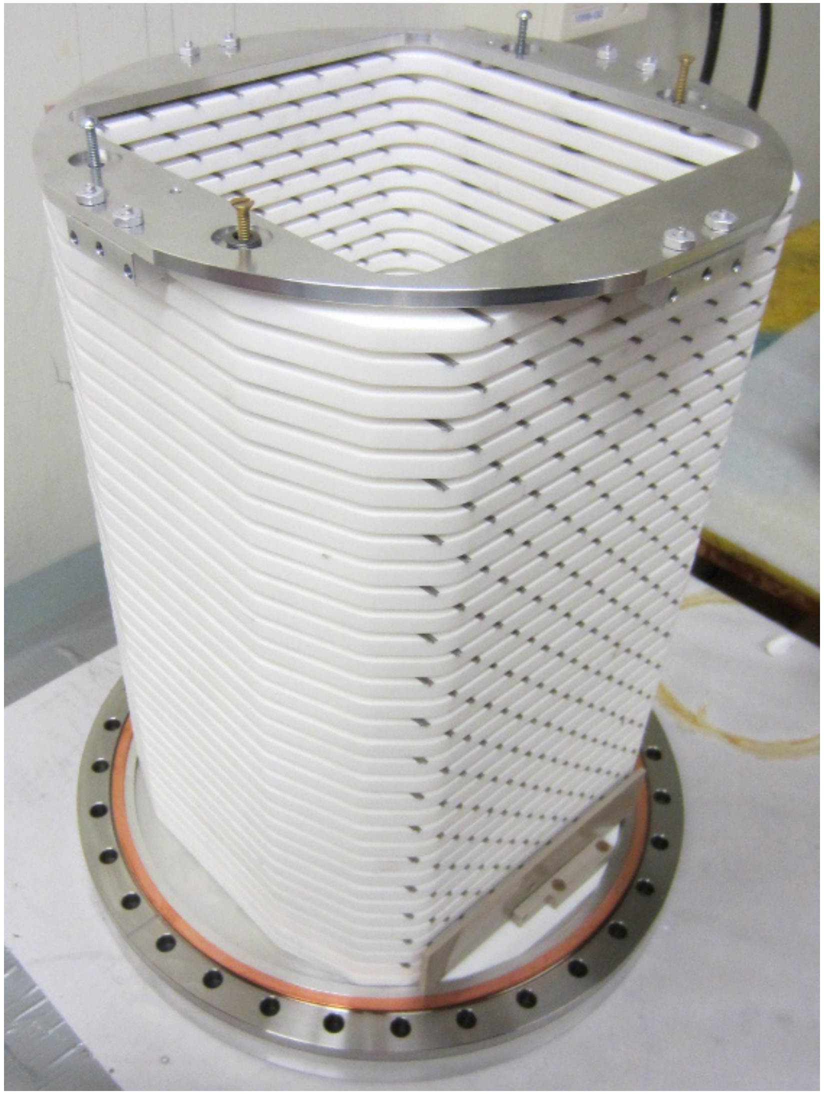
Target / Detector (Wire frame stack)



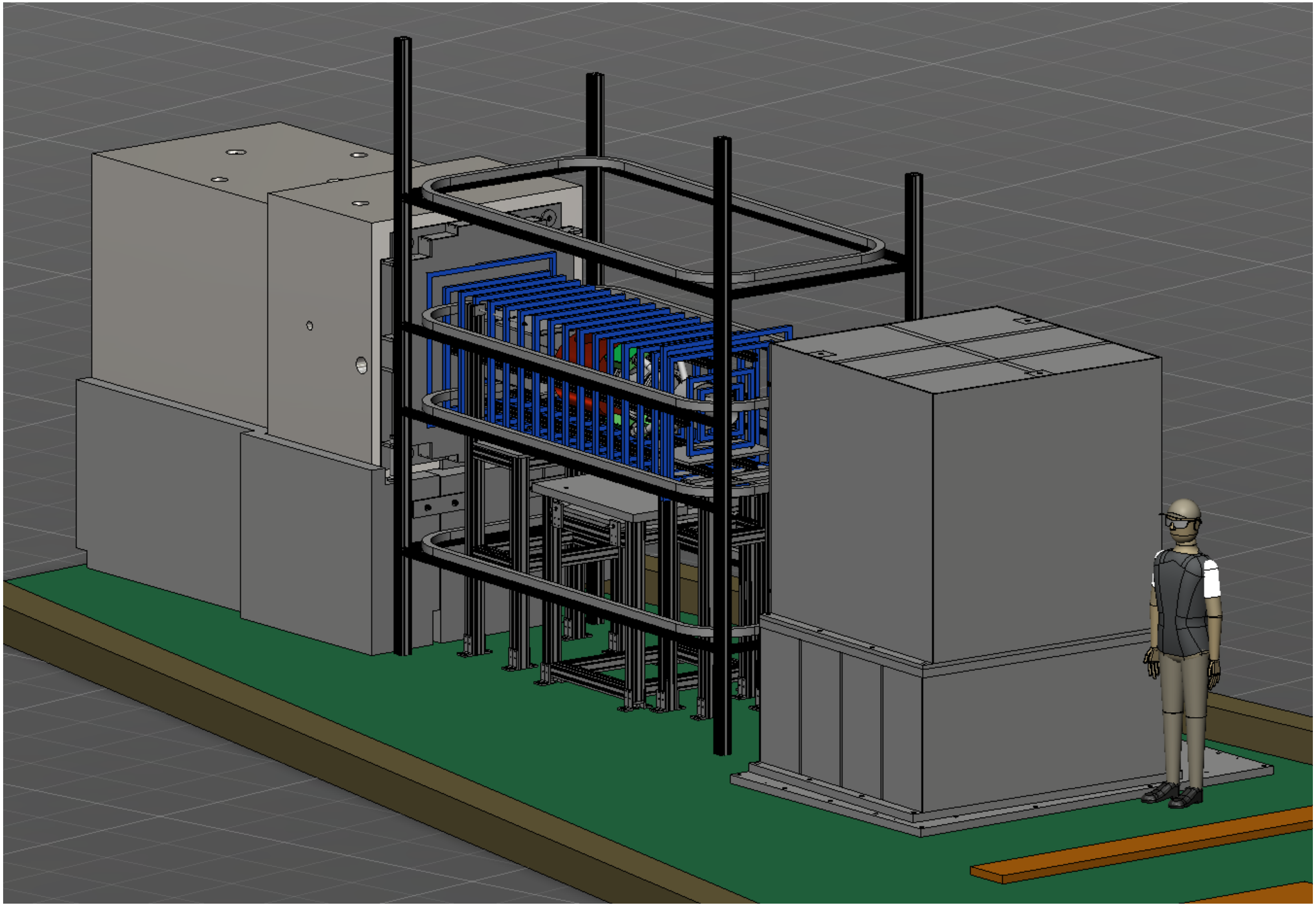
Data taken for 5 hours

$A = (2.64 \pm 1.64) \times 10^{-10}$

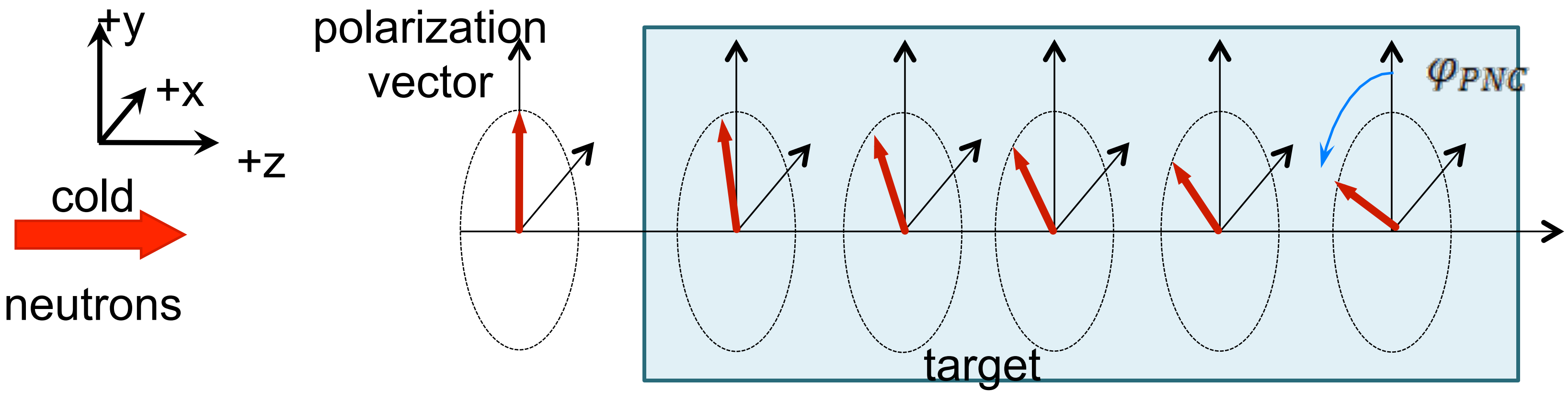




Experimental Setup



A Parity-Violating Observable: Neutron Spin Rotation



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

neutron index of refraction in target dependent on incident neutron helicity

transversely-polarized neutrons corkscrew due to the NN weak interaction

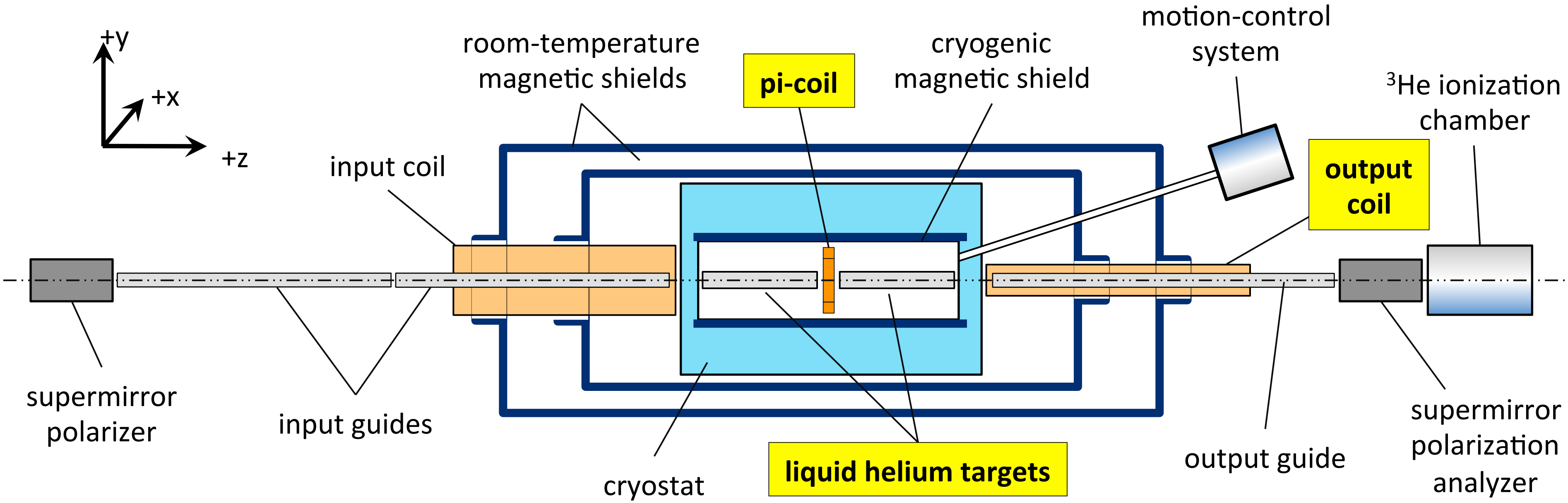
$$|+y\rangle = \frac{1}{\sqrt{2}}\left(|+z\rangle + |-z\rangle\right) \quad \Rightarrow \quad \frac{1}{\sqrt{2}}\left(e^{-i(\phi_{PC}+\phi_{PNC})}|+z\rangle + e^{-i(\phi_{PC}-\phi_{PNC})}|-z\rangle\right)$$

PNC spin rotation angle is independent of incident neutron energy

$$\varphi_{PNC} = \phi_{+} - \phi_{-} = 2\phi_{PNC} = 4\pi l \rho f_{PNC}$$

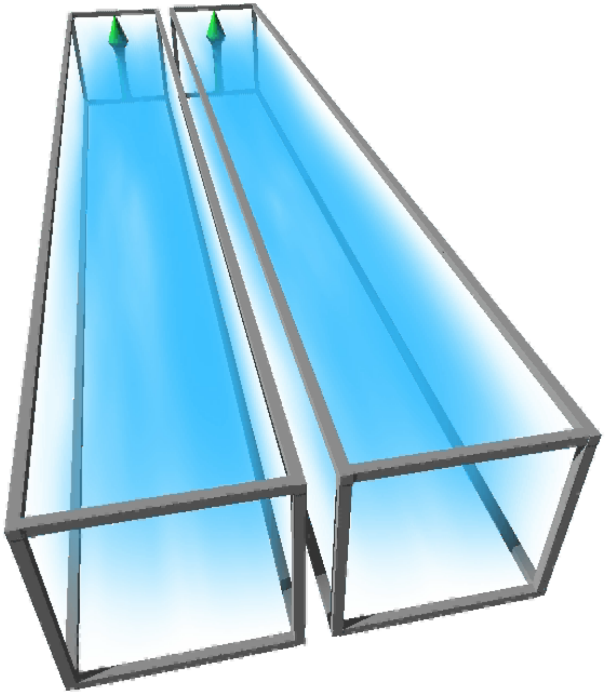
Parity Violation in Neutron Spin Rotation

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



$$|\uparrow>=\frac{1}{\sqrt{2}}(|+>+|->)\rightarrow\frac{1}{\sqrt{2}}(e^{i\phi_+}|+>+e^{i\phi_-}|->)$$

Measurement Issues



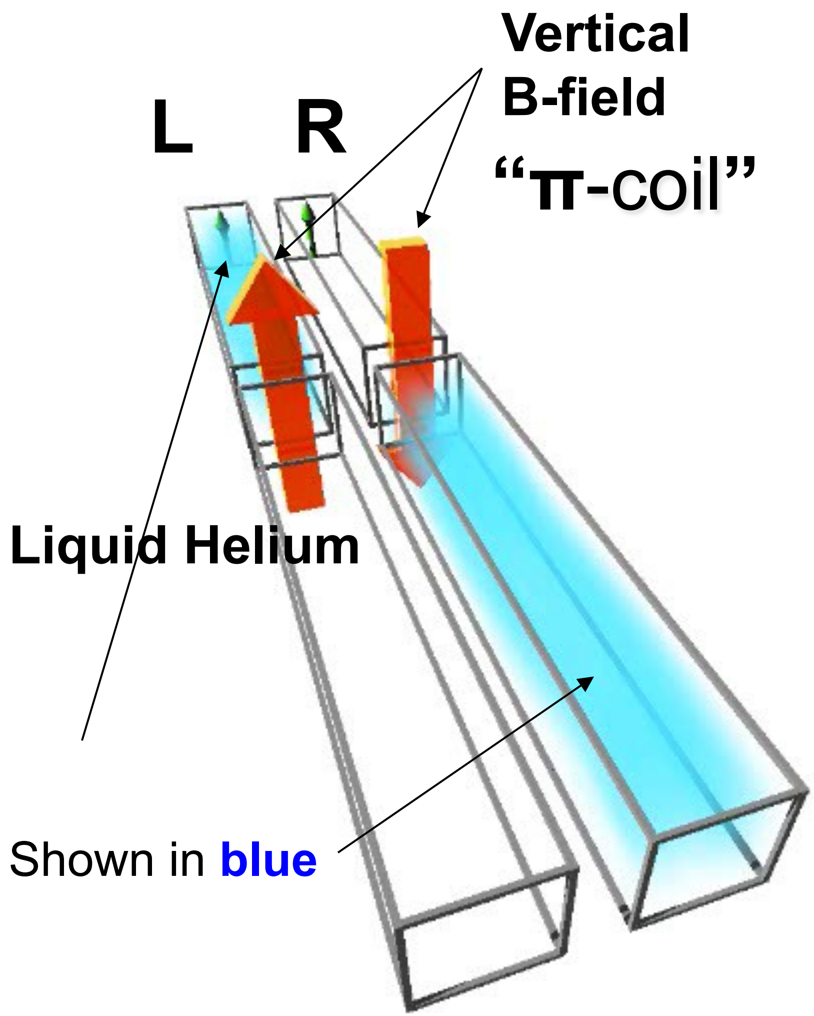
1) Reactor noise fluctuation when measuring N+ and N-

2) The angle is very small

$$\frac{d\phi_{PV}}{dz} \sim 10^{-7}\, rad / m$$

3) It's difficult to reduce background magnetic fields below 10µG. A background precession angle from a 10µG field along z is about 3 orders of magnitude greater than the PV signal.

Isolating the PV signal



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

2 target positions separated by vertical solenoid ("pi-coil")

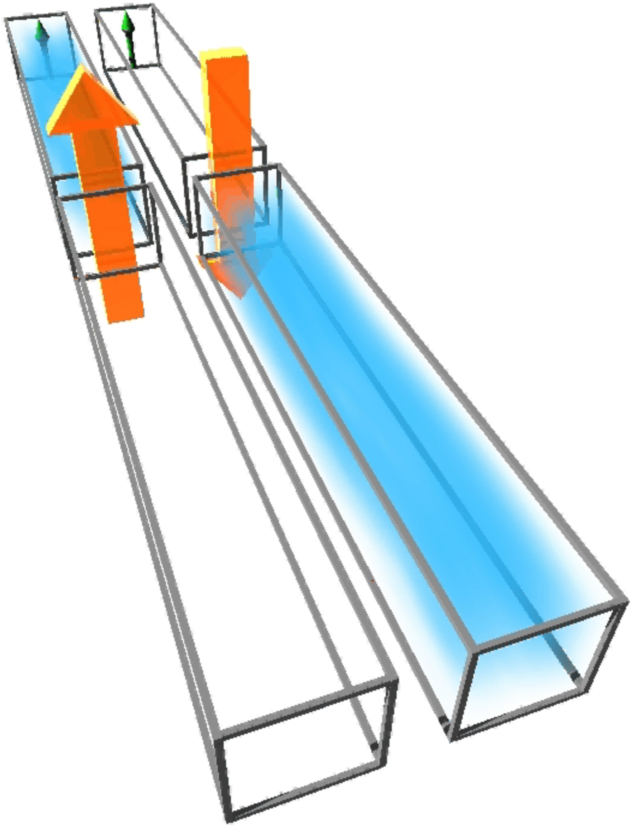
- pi-coil tuned to precess neutrons about vertical field by 180° for the average wavelength

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

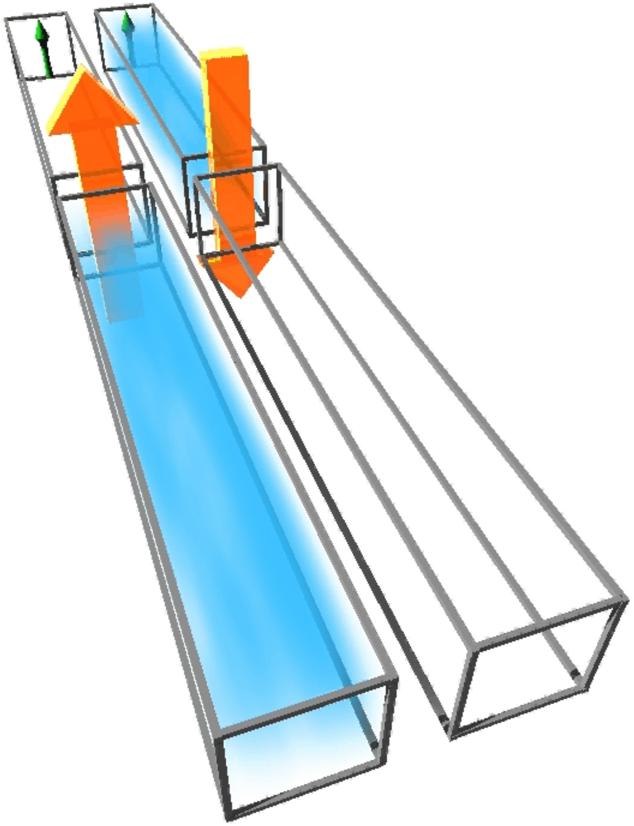
Divide and Conquer

Target state **A**



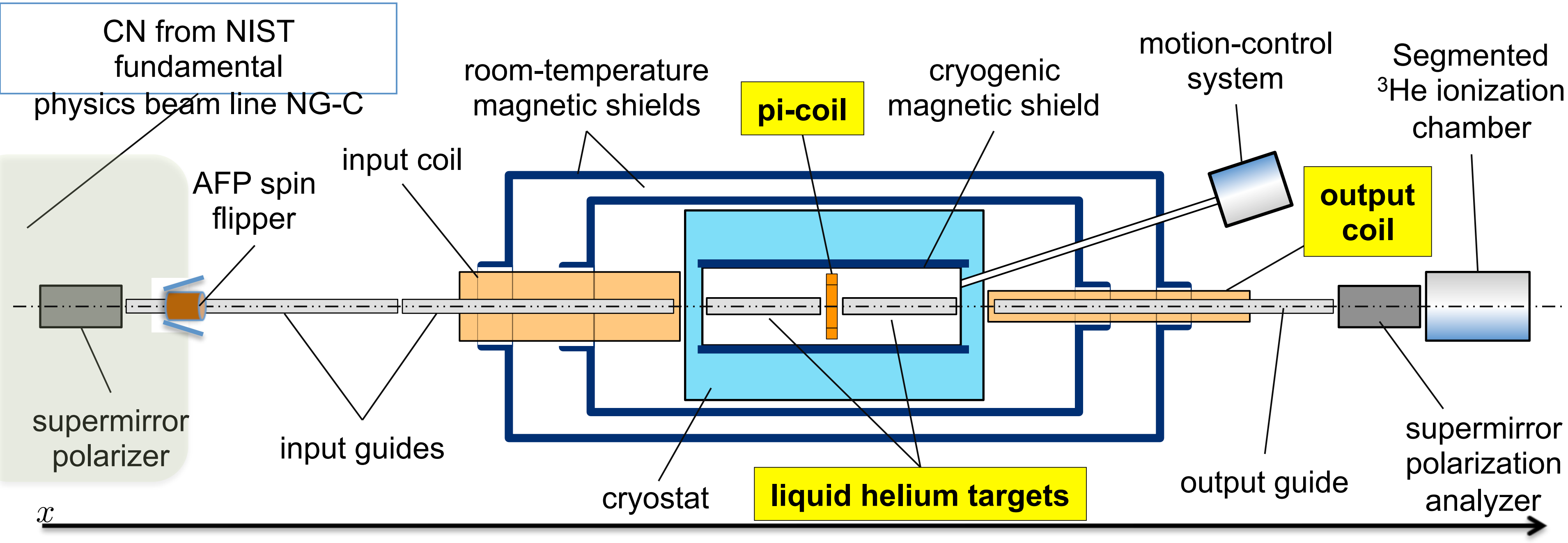
$$\phi_A = \frac{(-L) - R}{2}$$

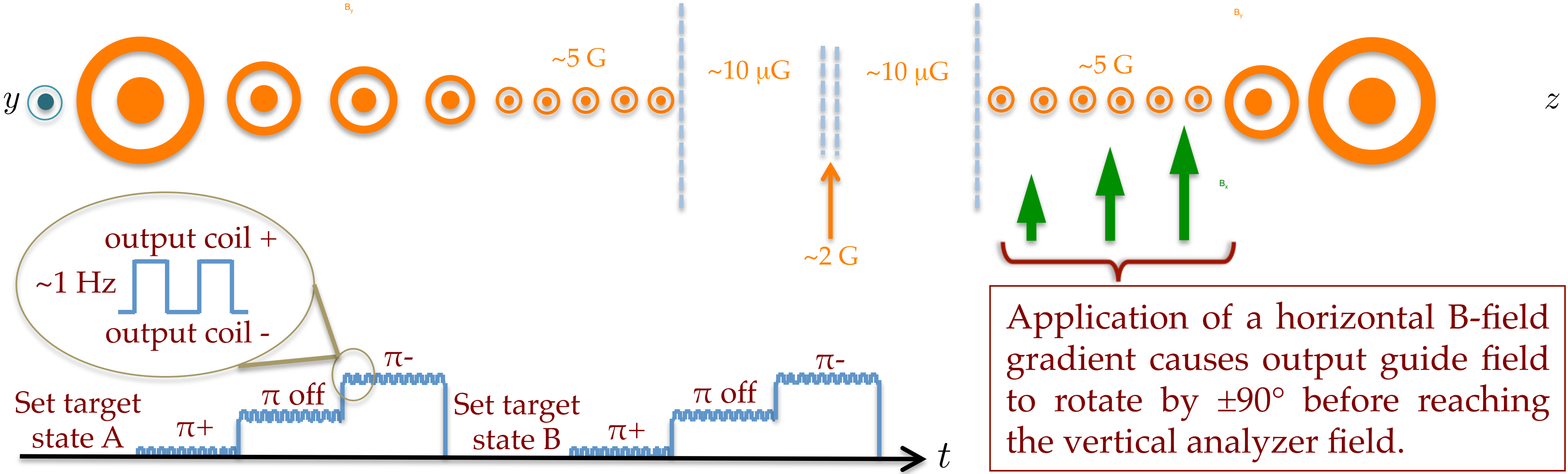
Target state **B**



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

The Neutron Spin Rotation Experiment





Application of a horizontal B-field gradient causes output guide field to rotate by ±90° before reaching the vertical analyzer field.

New interactions with ranges from millimeters to microns… "Who ordered that?"

1. Weakly-coupled, long-range interactions are a generic consequence of spontaneously broken continuous symmetries (Goldstone theorem)
2. Specific theoretical ideas (axions, extra dimensions for gravity) imply new interactions at ~mm-μm scales
3. Dimensional analysis: dark energy->100 microns

Not so many precision experiments have been conducted to search for new interactions over "mesoscopic" ranges, esp. spin-dependent ones

Comptes Rendus Physique 12, 755-778 (2011)
J. Jaeckel and A. Ringwald, Ann. Rev. Nucl. Part. Sci. **60, 405 (2010).**

Spin-dependent macroscopic interactions between nonrelativistic fermions meditated by light bosons

$$\mathcal{O}_1 = 1 \ ,$$

$$\mathcal{O}_2 = \vec{\sigma} \cdot \vec{\sigma}' \ ,$$

$$\mathcal{O}_3 = \frac{1}{m^2} (\vec{\sigma} \cdot \vec{q}) \ (\vec{\sigma}' \cdot \vec{q}) \ ,$$

$$\mathcal{O}_{4,5} = \frac{i}{2m^2} (\vec{\sigma} \pm \vec{\sigma}') \cdot \left(\vec{P} \times \vec{q}\right) \ ,$$

$$\mathcal{O}_{6,7} = \frac{i}{2m^2} \left[\left(\vec{\sigma} \cdot \vec{P}\right) \ (\vec{\sigma}' \cdot \vec{q}) \pm (\vec{\sigma} \cdot \vec{q}) \ \left(\vec{\sigma}' \cdot \vec{P}\right)\right] \ ,$$

$$\mathcal{O}_8 = \frac{1}{m^2} \left(\vec{\sigma} \cdot \vec{P}\right) \ \left(\vec{\sigma}' \cdot \vec{P}\right) \ .$$

$$\mathcal{O}_{9,10} = \frac{i}{2m} (\vec{\sigma} \pm \vec{\sigma}') \cdot \vec{q} \ ,$$

$$\mathcal{O}_{11} = \frac{i}{m} (\vec{\sigma} \times \vec{\sigma}') \cdot \vec{q} \ ,$$

$$\mathcal{O}_{12,13} = \frac{1}{2m} (\vec{\sigma} \pm \vec{\sigma}') \cdot \vec{P} \ ,$$

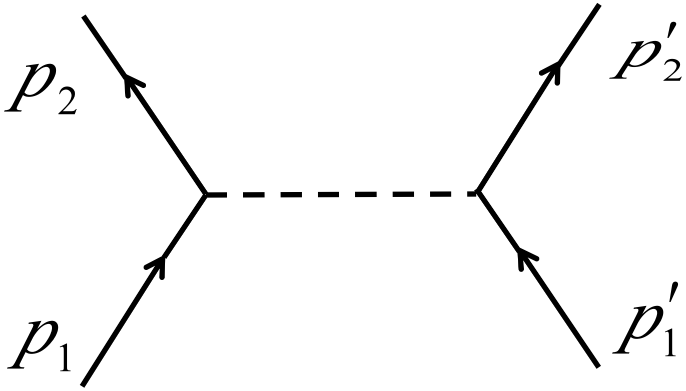
$$\mathcal{O}_{14} = \frac{1}{m} (\vec{\sigma} \times \vec{\sigma}') \cdot \vec{P} \ ,$$

$$\mathcal{O}_{15} = \frac{1}{2m^3} \left\{ \left[\vec{\sigma} \cdot \left(\vec{P} \times \vec{q}\right)\right] (\vec{\sigma}' \cdot \vec{q}) + (\vec{\sigma} \cdot \vec{q}) \left[\vec{\sigma}' \cdot \left(\vec{P} \times \vec{q}\right)\right] \right\}$$

$$\mathcal{O}_{16} = \frac{i}{2m^3} \left\{ \left[\vec{\sigma} \cdot \left(\vec{P} \times \vec{q}\right)\right] \left(\vec{\sigma}' \cdot \vec{P}\right) + \left(\vec{\sigma} \cdot \vec{P}\right) \left[\vec{\sigma}' \cdot \left(\vec{P} \times \vec{q}\right)\right] \right\} \ .$$

$$\vec{q} \equiv \vec{p}_2 - \vec{p}_1$$

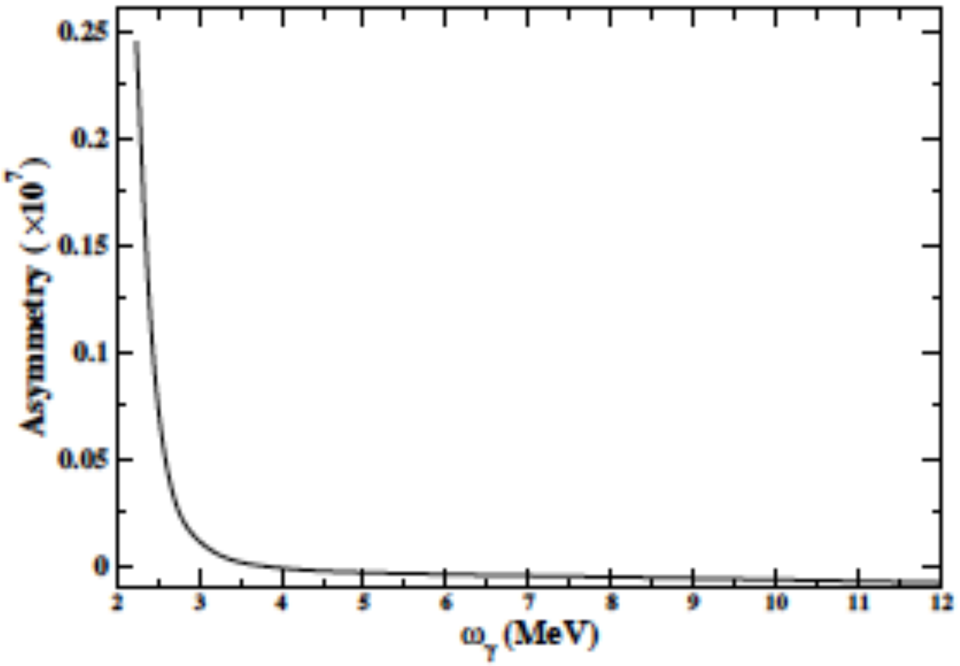
$$\vec{P} \equiv \frac{1}{2} (\vec{p}_1 + \vec{p}_2) \ .$$



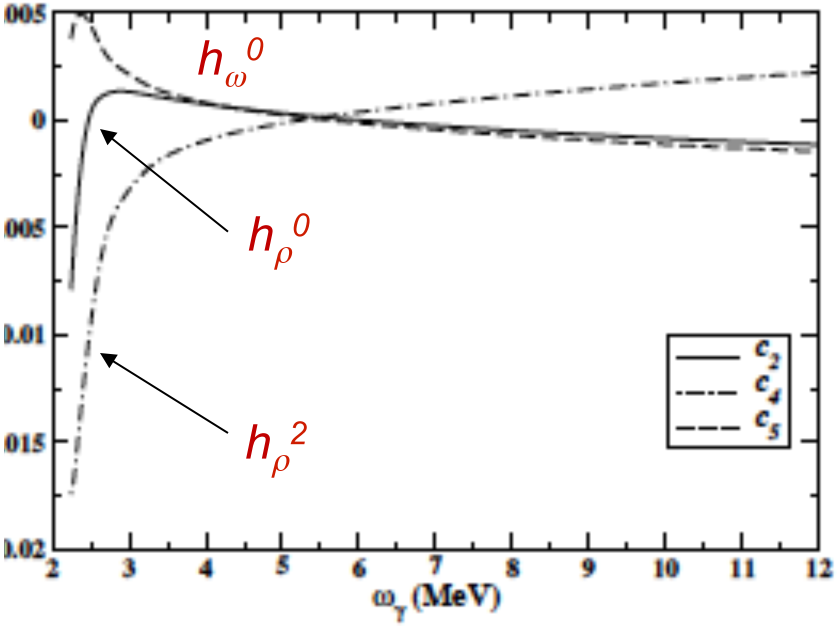
- 16 independent scalars can be formed: 8 P-even, 8 P-odd
- 15/16 depend on spin
- Traditional "fifth force" searches constrain O_1

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

PV D Photodisintegration in DDH and EFT



PV asymmetry in DDH model



Relative contributions of h_ρ^0, h_ω^0, *and* h_ρ^2 with gamma energy

$$A_\gamma \text{ (threshold)} = -8.44\, h_\rho^0 + 3.63\, h_\omega^0 - 17.6\, h_\rho^2$$

The only known P-odd NN observable which is sensitive to $\Delta I=2$ NN parity violation

$\Delta I=2$ NN parity violation might be calculable in lattice gauge theory

Liu/Hyun/Desplanques, arXiv:0403009