Experimental Tests of Hadronic Parity Violation

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Outline

Motivation

PV and the hadronic weak interaction

Shi-Lin Zhu, et al. , Nuclear Physics A 748 (2005) 435–498
M.J. Ramsey Musolf and S. Page, Annu. Rev. Nucl. Part. Sci. (2006). 56:1–52
C.-P. Liu, Nuclear Physics Phys. Rev. C 75, 065501 (2007)
M. Viviani Phys. Rev. C. 82, 044001 (2010)

Meson Exchange Picture

EFT and Hadronic PV

The experimental program

Parity violating processes between nucleons are used as a tool to study the hadronic weak interaction (HWI) as well as how it is modified by the strong interactions from the simple Standard Model prediction.

Two (common) ways to study HWI:

1. *Flavor changing $\Delta S=1$ hyperon and meson decay*
   - *Decay amplitudes, asymmetries, ...*
2. *Flavor conserving $\Delta S=0$ PV interactions at low energy*
   - *Mostly asymmetries, analyzing power, rotation angles*

Flavor changing decay of mesons and hyperons:

- Much theoretical progress from EFT, χPT, heavy quark EFT
- Structure of operators from effective Lagrangians incorporate the symmetries of QCD

In hyperon decay:

- Unresolved $\Delta I = \frac{1}{2}$ rule puzzle
- Anomalously large PV asymmetries in hyperon radiative decays
- Etc.

Goals of ΔS=0 HWI studies:

1. Answer how the symmetries of QCD characterize the HWI in strongly interacting systems

   The HWI is just a residual effect of the q-q weak interaction for which the range is set by the mass of the Z,W bosons which is much smaller than the size of nucleons, as determined by QCD dynamics

   → HWI probes short range qq correlations

2. Shed light on the puzzles in the ΔS=1 sector of the HWI

PV electron scattering and new physics ...

$$A_{LR}(\vec{e},p) = \frac{d\sigma_L - d\sigma_R}{d\sigma_L + d\sigma_R} = k(A_{Q^p_W} + A_{H,V} + A_{H,A})$$

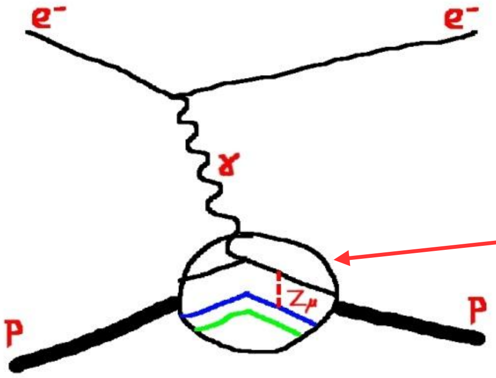
$$A_{Q^p_W} = Q^2 Q^p_W$$

Quantity of interest = -0.288 ppm

$$A_{H,V} = Q^n_W \frac{\epsilon G_E^{p,\gamma} G_E^{n,\gamma} + \tau G_M^{p,\gamma} G_M^{n,\gamma}}{\epsilon \left(G_E^{p,\gamma}\right)^2 + \tau \left(G_M^{p,\gamma}\right)^2} + Q^s_W \frac{\epsilon G_E^{p,\gamma} G_E^{s} + \tau G_M^{p,\gamma} G_M^{s}}{\epsilon \left(G_E^{p,\gamma}\right)^2 + \tau \left(G_M^{p,\gamma}\right)^2}$$

$$A_{H,A} = Q^e_W \frac{\epsilon' G_A^{p,Z} G_M^{p,\gamma}}{\epsilon \left(G_E^{p,\gamma}\right)^2 + \tau \left(G_M^{p,\gamma}\right)^2}$$

$G_A^{p,Z}$



Axial form factor due to q-q weak interaction related to NN experimental results

Hadronic structure: Must know hadronic wave function or measured form-factors

ΔS=0 HWI studies:

The ΔS=0 HWI can only be isolated experimentally via PV observables, to isolate the weak interaction from the much larger EM and strong interactions.

$$\frac{g_W^2}{\alpha M_W^2} \approx 10^{-4}$$

Weak e-N scale

$$\frac{g_W^2}{M_W^2} \cdot \frac{M_\pi^2}{g_{\pi NN}^2} \approx 10^{-7}$$

Weak N-N scale

Very challenging !

$\Delta S=0$ HWI studies:

So people started to look for nuclear many-body (large A) systems for which there exists some fortuitous enhancement of the size of the observable:

→ coming from nearly degenerate opposite parity state mixing and interference with the much larger parity allowed transition in nuclear excited states.

e.g. TRIPLE collaboration:
parity violation in compound nuclei from neutron-nucleus resonant scattering with longitudinal cross section asymmetries of order 10^{-3}–10^{-1} (up to 10^{6} enhancement)

G.E. Mitchell *et al.* Phys. Rep. 354, 157 (2001)

But you can get the weak spreading width (weak mixing amplitude) from statistical analysis of this data:

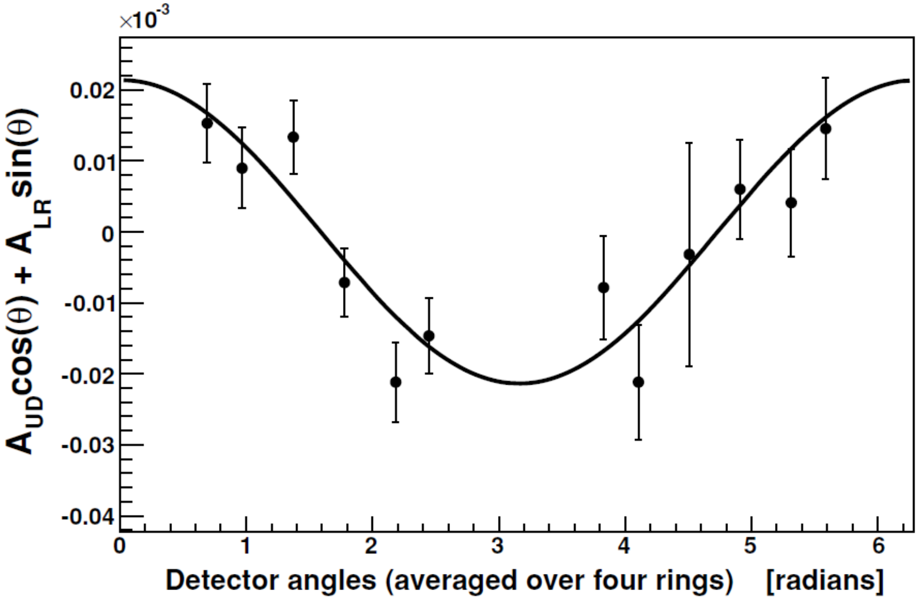
$$\longrightarrow \quad \Gamma_W = 1.8^{+0.4}_{-0.3} \times 10^{-7}\ eV$$

$$\left(\frac{\langle \psi_f | W | \psi_i \rangle}{\Delta E} \approx \sqrt{\frac{\Gamma_W}{2\pi D}} \right)$$

Can also have large(r) asymmetries from neutron radiative capture (here Cl):

M.T. Gericke *et al.* Phys. Rev. C 74, 065503 (2006)

$$A_\gamma = (-19 \pm 2) \times 10^{-6} \text{ and } A_{LR} = (-1 \pm 2) \times 10^{-6}$$



n-capture on Chlorine (CCl_4)

ΔS=0 HWI studies:

However, many-body systems are hard to deal with when it comes to interpretation of the results (wave functions).

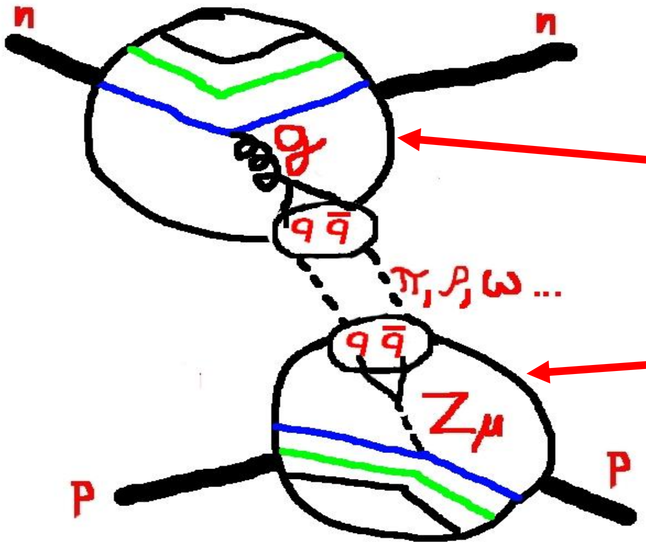
There is no transparent connection to SM.

→ So back to few body systems

- No nuclear structure physics
- Low nucleon momentum ($\leq$ ~40 MeV) allows for EFT momentum expansion
- But no enhancement of asymmetries

→ Need simpler systems

The Nucleon-Nucleon Weak Interaction Meson Exchange "Traditional" Picture



$$H_{PC} = i g_{\pi NN} \int d^3x \overline{\psi}_i(x) \gamma^5 \psi_j(x) \left(\vec{\tau} \cdot \vec{\phi}(x)\right)$$

$$H_{PNC} = \frac{h_\pi^1}{\sqrt{2}} \int d^3x' \overline{\psi}_i(x') \psi_j(x') \left(\vec{\tau} \times \vec{\phi}(x')\right)$$

Solutions to the Lippmann-Schwinger equation - Essentially the first order term in a Born series:

$$\langle f | V_{PNC} | i \rangle = \langle N_f N_f | H_{PC} \frac{1}{E_0 - H_0 + i\varepsilon} H_{PNC} | N_i N_i \rangle \longrightarrow \boxed{\frac{i g_{\pi NN} h_\pi^1}{\sqrt{32} M} \left[\vec{\tau}_1 \times \vec{\tau}_2\right]_z \left[\vec{\sigma}_1 + \vec{\sigma}_2\right] \cdot \left[\vec{p}, \frac{e^{-mr}}{4\pi r}\right]}$$

Weak π-Nucleon Coupling (ρ,ω not shown)

Meson exchange picture cont.

$$\left\langle N_f N_f \left| H_{PC} \frac{1}{E_0 - H_0 + i\varepsilon} H_{PNC} \right| N_i N_i \right\rangle$$

$$= \sum_{I} \int \frac{d^3k}{(2\pi)^3} \left\langle N_f \left| S \right| N_i\ , \pi_I(k) \right\rangle \frac{1}{\omega_k} \left\langle N_f\ , \pi_I(k) \left| S \right| N_i \right\rangle$$

Meson exchange picture cont.

$$\langle N_f N_f | H_{PC} \frac{1}{E_0 - H_0 + i\varepsilon} H_{PNC} | N_i N_i \rangle$$

$$= \sum_{I} \int \frac{d^3k}{(2\pi)^3} \langle N_f | S | N_i , \pi_I(k) \rangle \frac{1}{\omega_k} \underline{\langle N_f , \pi_I(k) | S | N_i \rangle}$$

Relationship to quark degrees of freedom:

$$S = \frac{i}{2} \int dt_1 \int dt_2 \int dt_3 \left\{ H_W^I(t_1) H_W^I(t_2) H_S^I(t_3) \right\}$$

$$H_W^I = \int d^3x \left[\frac{g}{2\sqrt{2}} \left(J_C^{\mu^*} W_\mu + J_C^{\mu} W_\mu^* \right) + \frac{g}{4\cos\theta_W} J_N^{\mu} Z_\mu \right]$$

$$H_S^I = -\int d^3x \int d^3y \int dt_y \left[J_S f(x,y) \delta(t_x - t_y) \right]$$

Meson exchange picture cont.

$$\left\langle N_f N_f \middle| H_{PC} \frac{1}{E_0 - H_0 + i\varepsilon} H_{PNC} \middle| N_i N_i \right\rangle$$

$$= \sum_{I} \int \frac{d^3k}{(2\pi)^3} \left\langle N_f \middle| S \middle| N_i , \pi_I(k) \right\rangle \frac{1}{\omega_k} \underline{\left\langle N_f , \pi_I(k) \middle| S \middle| N_i \right\rangle}$$

Relationship to quark degrees of freedom:

$$\xcancel{S = \frac{i}{2} \int dt_1 \int dt_2 \int dt_3 \left\{ H_W^I(t_1) H_W^I(t_2) H_S^I(t_3) \right\}}$$

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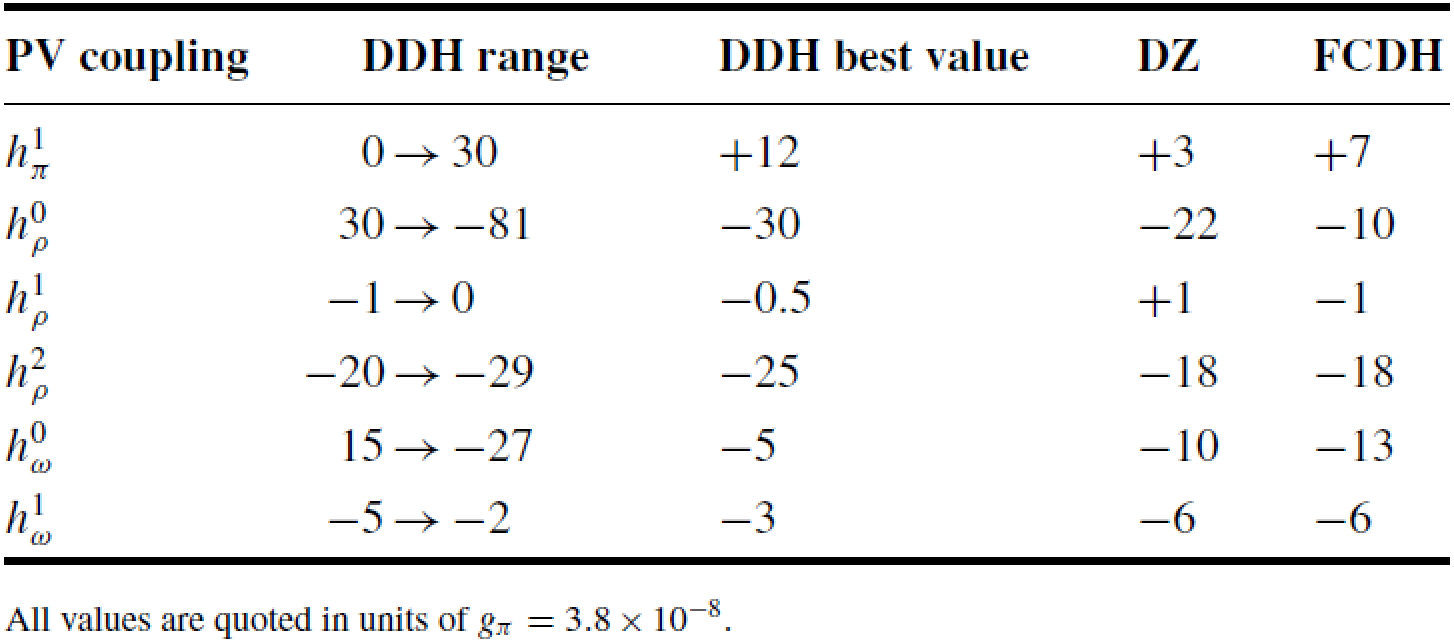
$$\xcancel{H_S^I = -\int d^3x \int d^3y \int dt_y \left[J_S f(x,y) \delta\left(t_x - t_y\right) \right]}$$

DDH use SU(6), quark model, and measured hyperon decay amplitudes instead !

DDH Model – Benchmark

B. Desplanques, J.F. Donoghue, B.R. Holstein, Annals of Physics 124:449-495 (1980)

Arrive at 7 weak meson-nucleon couplings:



PV coupling	DDH range	DDH best value	DZ	FCDH
h_π^1	$0 \rightarrow 30$	$+12$	$+3$	$+7$
h_ρ^0	$30 \rightarrow -81$	-30	-22	-10
h_ρ^1	$-1 \rightarrow 0$	-0.5	$+1$	-1
h_ρ^2	$-20 \rightarrow -29$	-25	-18	-18
h_ω^0	$15 \rightarrow -27$	-5	-10	-13
h_ω^1	$-5 \rightarrow -2$	-3	-6	-6

All values are quoted in units of $g_\pi = 3.8 \times 10^{-8}$.

DZ: Dubovik VM, Zenkin SV. *Ann. Phys.* 172:100 (1986)

FCDH: Feldman GB, Crawford GA, Dubach J,Holstein BR. *Phys. Rev. C 43:863 (1991)*

DDH Model – Benchmark

In general, a measured PV NN observable can be expanded in terms of these:

$$O_{PV} = a_\pi^1 h_\pi^1 + a_\rho^0 h_\rho^0 + a_\rho^1 h_\rho^1 + a_\rho^2 h_\rho^2 + a_\omega^0 h_\omega^0 + a_\omega^1 h_\omega^1$$

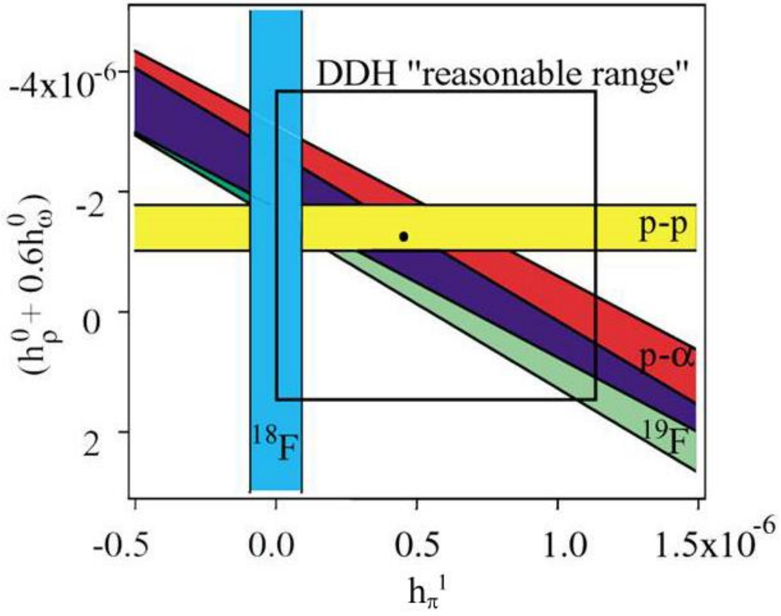
E. G. Adelberger and W. C. Haxton, Ann. Rev. Nucl. Part. Sci. 35, 501 (1985).

DDH Weak Coupling	(A_γ) $np \to d\gamma$	(A_γ) $nd \to t\gamma$	(ϕ_{PV}) n-p (μrad/m)	(ϕ_{PV}) n-α (μrad/m)	$\left(\frac{\Delta\sigma}{\sigma}\right)$ p-p	$\left(\frac{\Delta\sigma}{\sigma}\right)$ p-α	(A^p_Z) $n^3He \to tp$
a_π^1	-0.107	-0.92	-3.12	-0.97	0	-0.340	-0.189
a_ρ^0	0	-0.50	-0.23	-0.32	0.079	0.140	-0.036
a_ρ^1	-0.001	0.103	0	0.11	0.079	0.047	0.019
a_ρ^2	0	0.053	-0.25	0	0.032	0	-0.0006
a_ω^0	0	-0.160	-0.23	-0.22	-0.073	0.059	-0.0334
a_ω^1	0.003	0.002	0	0.22	0.073	0.059	0.0413

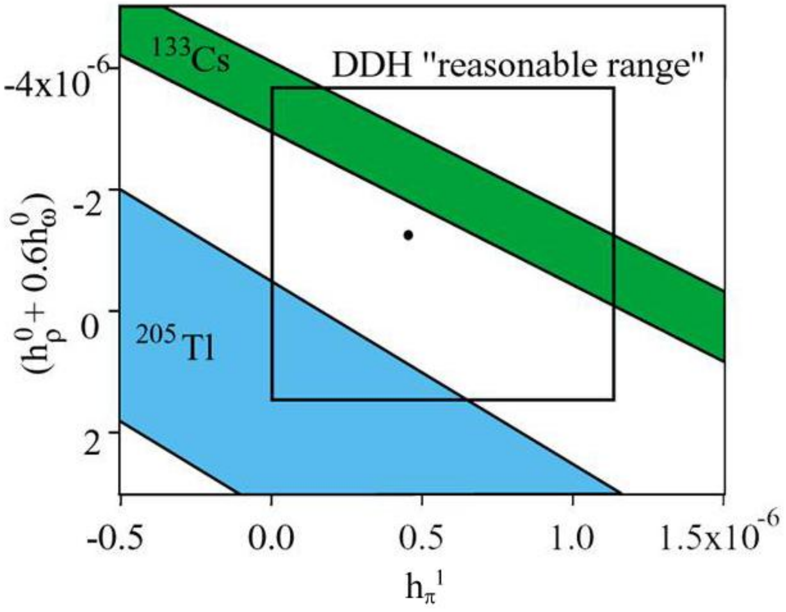
Viviani *et al.* Phys. Rev. C 82 044001

Experimental results generally agree with the DDH ranges, but:

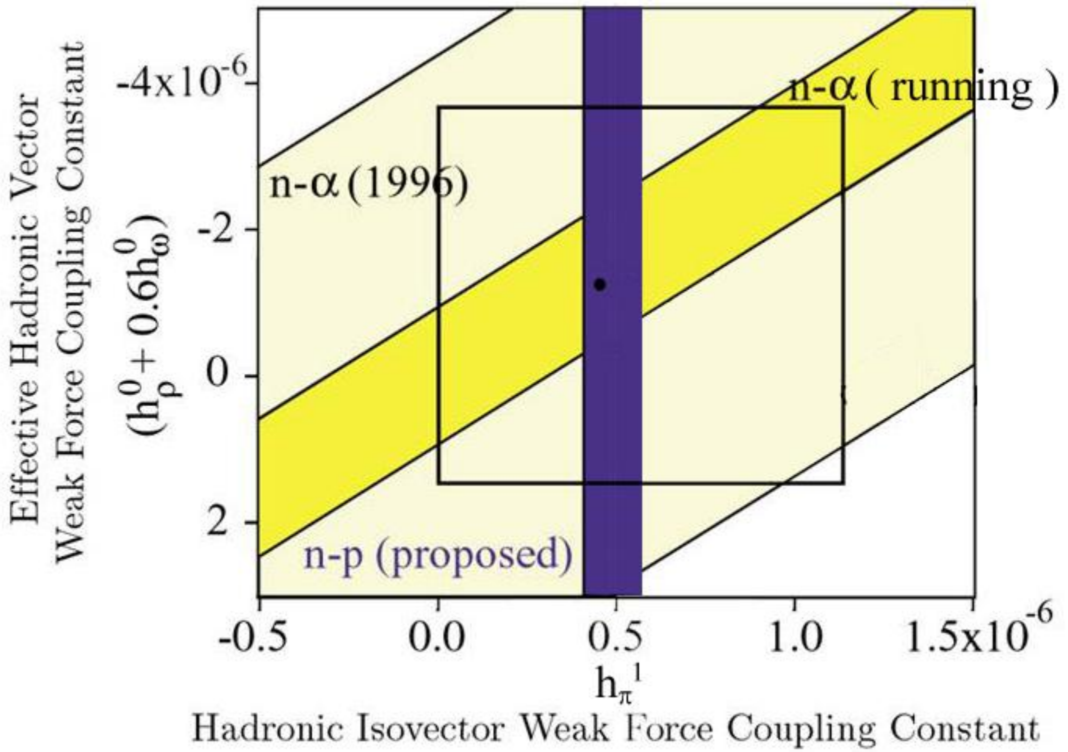
- *Uncertainties are large*
- *Some experimental results produce conflicting values for coupling constants (e.g. Values for h_π^1 from ^{18}F and ^{133}Cs differ by several σ)*



p-p scat. 15, 45 MeV A_z^{pp}
p-p scat. 221 MeV A_z^{pp}
p-α scat. 46 MeV A_z^{pp}

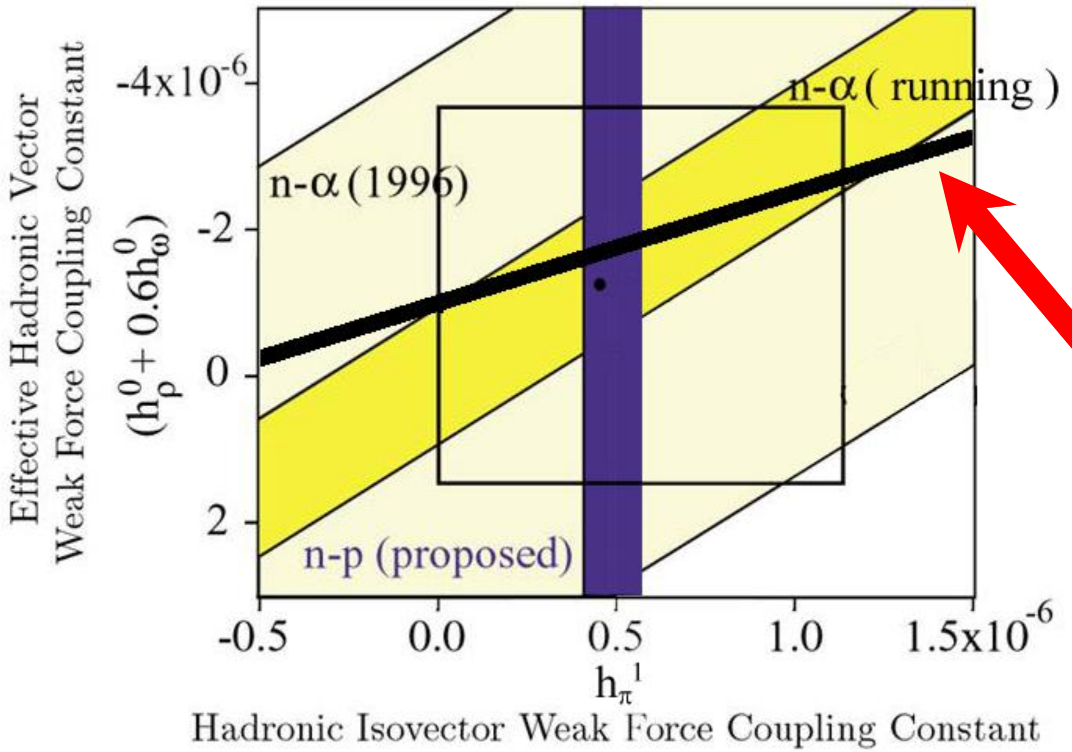


^{133}Cs, ^{205}Tl anapole moments



$n+p \rightarrow d+\gamma$ A_γ^d
n-α spin rot. $d\phi^{n\alpha}/dz$

Unfortunately , the connection between the PV observables and the SM is essentially unknown.

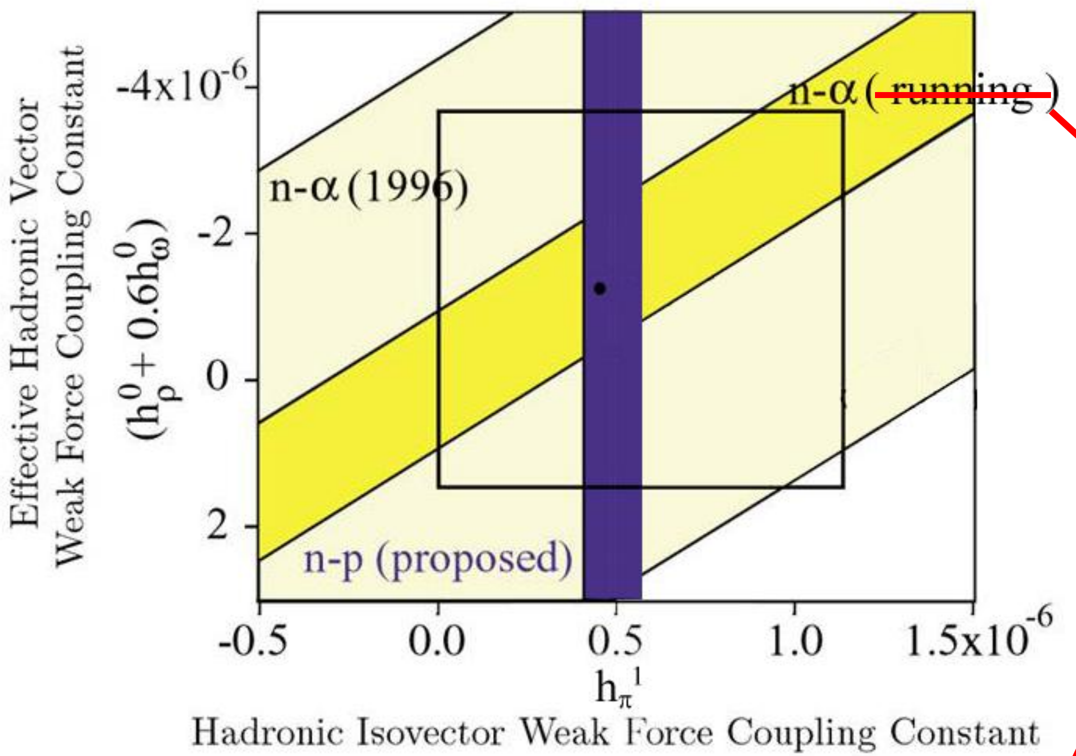


with n^{3}He (preliminary)

n+p→d+γ A_γ^d

n-α spin rot. dφ$^{n\alpha}$/dz

Unfortunately , the connection between the PV observables and the SM is essentially unknown.



Completed

n-α spin rot. $d\phi^{n\alpha}/dz = [+1.7 \pm 9.1(\text{stat.}) \pm 1.4(\text{sys.})] \times 10^{-7}$ rad/m

W. M. Snow *et al.* Phys. Rev. C 83, 022501(R) (2011)

EFT Calculations

Write down 12 possible general P violating and CP conserving current-current terms with all isospin changes up to ΔI=2:

$$O_1 = \frac{g_1}{\Lambda_\chi^2}\overline{\psi}_N 1 \gamma_\mu \psi_N \overline{\psi}_N 1 \gamma^\mu \gamma_5 \psi_N \qquad O_2 = \frac{g_2}{\Lambda_\chi^2}\overline{\psi}_N 1 \gamma_\mu \psi_N \overline{\psi}_N \tau_3 \gamma^\mu \gamma_5 \psi_N$$

$$\tilde{O}_1 = \frac{\tilde{g}_1}{\Lambda_\chi^3}\overline{\psi}_N 1 i\sigma_{\mu\nu} q^\nu \gamma_\mu \psi_N \overline{\psi}_N \tau_3 \gamma^\mu \gamma_5 \psi_N \quad \bullet\bullet\bullet$$

etc…

The NN contact potentials are expressed in terms of 12 parameters, but no mesons:

$$C_{1-5} = \frac{\Lambda_\chi}{2m_N} g_{1-5} \quad , \quad \tilde{C}_{1-5} = \tilde{g}_{1-5} + \frac{\Lambda_\chi}{2m_N} g_{1-5}$$

$$C_6 = \tilde{g}_6 - \frac{\Lambda_\chi}{2m_N} g_6$$

Shi-Lin Zhu, et al. , Nuclear Physics A 748 (2005) 435–498

Appropriate linear combinations of these produce the 5 Danilov coupling constants to be determined by experiment:

$$\lambda_t \propto (C_1 - 3C_3) - (\tilde{C}_1 - 3\tilde{C}_3)$$

$$\lambda_s^0 \propto (C_1 + C_3) + (\tilde{C}_1 + \tilde{C}_3) \qquad {}^3S_1 \rightarrow {}^1P_1 \quad I = 0$$

$$\lambda_s^1 \propto (C_2 + C_4) + (\tilde{C}_2 + \tilde{C}_4) \qquad {}^1S_0 \rightarrow {}^3P_0 \quad I = 1$$

$$\lambda_s^2 \propto -\sqrt{\frac{8}{3}}(C_5 + \tilde{C}_5)$$

$$\rho_t \propto \frac{1}{2}(C_2 - C_4) + C_6 \qquad {}^3S_1 \rightarrow {}^3P_1 \quad I = 1 \rightarrow 0$$

$$\lambda_s^{pp} = \lambda_s^0 + \lambda_s^1 + \frac{1}{\sqrt{6}}\lambda_s^2$$

$$\lambda_s^{np} = \lambda_s^0 - \frac{2}{\sqrt{6}}\lambda_s^2$$

$$\lambda_s^{nn} = \lambda_s^0 - \lambda_s^1 + \frac{1}{\sqrt{6}}\lambda_s^2$$

Shi-Lin Zhu, et al. , Nuclear Physics A 748 (2005) 435-498

EFT Calculations (in short)

The ΔS=0 HWI can be parameterized in terms of 5 (10 with pions) low energy phenomenological constants.

At very low momenta (≤ ~50 MeV) the constants essentially reduce to the 5 Danilov parameters:

→ $\lambda_s^{0,1,2}, \; \lambda_t, \; \rho_t$

originally determined from NN scattering theory (Born approximation) write down simplest S-P amplitudes with PV and CP cons. amplitudes in addition to singlet and triplet strong …

At higher momentum include explicit pions: $h^{1}_{\pi NN}, \; k^{1a}_{\pi NN}, \; \tilde{C}_{\pi}, \; \tilde{C}_{2\pi}$

Experimental Program

We need at least 8 few body experiments to completely determine the EFT parameters.

Some have already been done:

Longitudinal Asymmetries in p-p scattering:

$$A_L^{pp}(13.6\ MeV) = -(0.93 \pm 0.20 \pm 0.05)\times 10^{-7} = \boxed{-0.48\lambda_s^{pp} m_N}$$

Bonn: P.D. Evershiem *et al.* Phys. Lett. 256 (1991) 11

$$A_L^{pp}(45\ MeV) = -(1.5 \pm 0.22)\times 10^{-7} = \boxed{-0.82\lambda_s^{pp} m_N}$$

PSI:
S. Kistryn *et al.* Phys. Lett. 58 (1987) 1616
R. Balzer *et al. Phys. Rev. C. 30 (1984) 1409*

Experimental Program

The TRIUMF 220 MeV pp experiment

$$A_L^{pp}(221\ MeV) = -(0.84 \pm 0.29 \pm 0.17) \times 10^{-7} \propto h_\omega^0 + h_\omega^1 \equiv h_\omega^{PP}$$

TRIUMF: A.R. Berdoz *et al.* Phys. Rev. C 68 034004 (2003)

Of order Q^3 in EFT (no calculation yet ?)

Longitudinal Asymmetry in p-α scattering:

$$A_L^{p\alpha}(46\ MeV) = -(3.3 \pm 0.9) \times 10^{-7} = \boxed{\left[-0.48\left(\lambda_s^{pp} + \frac{1}{2}\lambda_s^{np}\right) - 0.107\left(\rho_t + \frac{1}{2}\lambda_t\right)\right] m_N}$$

Bonn: J. Lang *et al.* Phys. Rev. Lett. 54 (1985) 170

Experimental Program

New experiments:

- **Longitudinal asymmetry in proton-deuteron scattering:**
  - **p-d :**

$$A_L^{pd}(15\ MeV) = \boxed{\left(-0.21\rho_t - 0.07\lambda_s^{pp} - 0.13\lambda_t + 0.04\lambda_s^{np}\right)m_N}$$

Experimental Program

New experiments (or repeats):

- Neutron capture:
  - Circ. Polarization:

$$P_\gamma = \boxed{\left(0.63\lambda_t - 0.16\lambda_s^{np}\right) m_N}$$

Very challenging!

  - Gamma Asymmetry in np radiative capture:

$$A_\gamma = \boxed{-0.107\,\rho_t\, m_N}$$

LANSCE completed - SNS Running

  - Gamma Asymmetry in nd radiative capture:

$$A_\gamma = \boxed{\left(1.42\rho_t + 0.59\lambda_s^{nn} + 1.18\lambda_t + 0.51\lambda_s^{np}\right) m_N}$$

Hard, SNS planned

  - Proton Asymmetry in n^3He capture

$$A_Z^p = (?)\, m_N$$

Relatively easy, SNS approved ~2013

Experimental Program

New experiments (or repeats):

- Neutron spin rotation:
  - In helium:

$$\frac{d\phi^{n\alpha}}{dz} = \boxed{\left[1.2\left(\lambda_s^{nn} + \frac{1}{2}\lambda_s^{np}\right) - 2.68\left(\rho_t - \frac{1}{2}\lambda_t\right)\right] m_N} \left[\frac{rad}{m}\right]$$

W.M. Snow *et al*, Completed (NIST)

  - In hydrogen LH2

$$\frac{d\phi^{np}}{dz} = \boxed{\left[0.45\lambda_s^{nn} + 1.28\lambda_s^{np} + 0.45\lambda_s^{pp} + 1.26\rho_t - 0.63\lambda_t\right] m_N} \left[\frac{rad}{m}\right]$$

SNS planned

Hadronic Parity Violation with Cold Neutrons

Two experiments (at the SNS):

NPDGamma:

Transversely polarized cold neutrons on hydrogen – looks for a directional asymmetry in the number of γ-rays, after decay: $n + p \rightarrow d + \gamma$

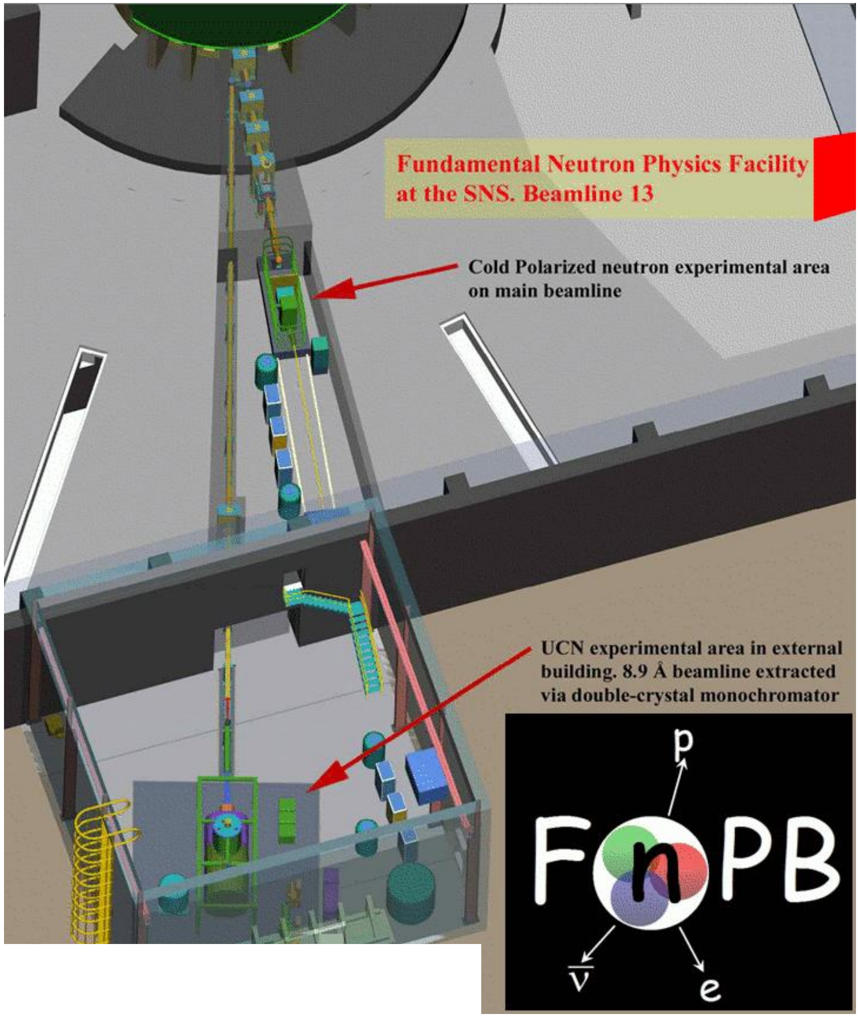
n3He:

Longitudinally polarized cold neutrons on helium 3 – looks for a directional asymmetry in the number of protons after breakup: $n + {}^3He \rightarrow t + p$

Spallation Neutron Source (SNS)

The Fundamental Neutron Physics Beam (FnPB)

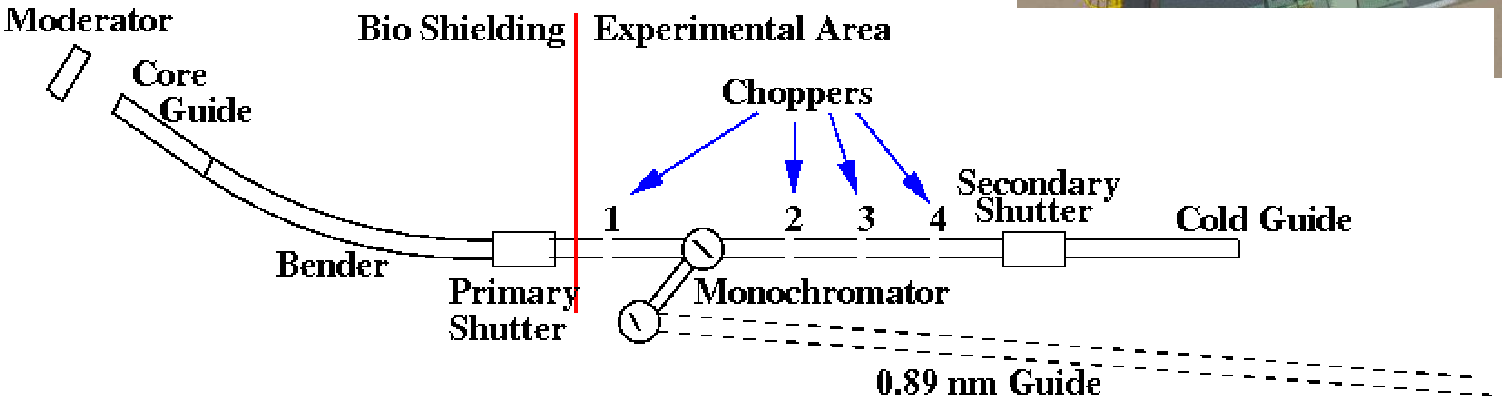
- LH2 moderator
- 15 m long guide ~ 18 m to experiment
- one polyenergetic cold beam line
- one monoenergetic (0.89 nm) beam line
- ~ 40 m to nEDM UCN source
- 4 frame overlap choppers
- 60 Hz pulse repetition



Fundamental Neutron Physics Facility at the SNS. Beamline 13

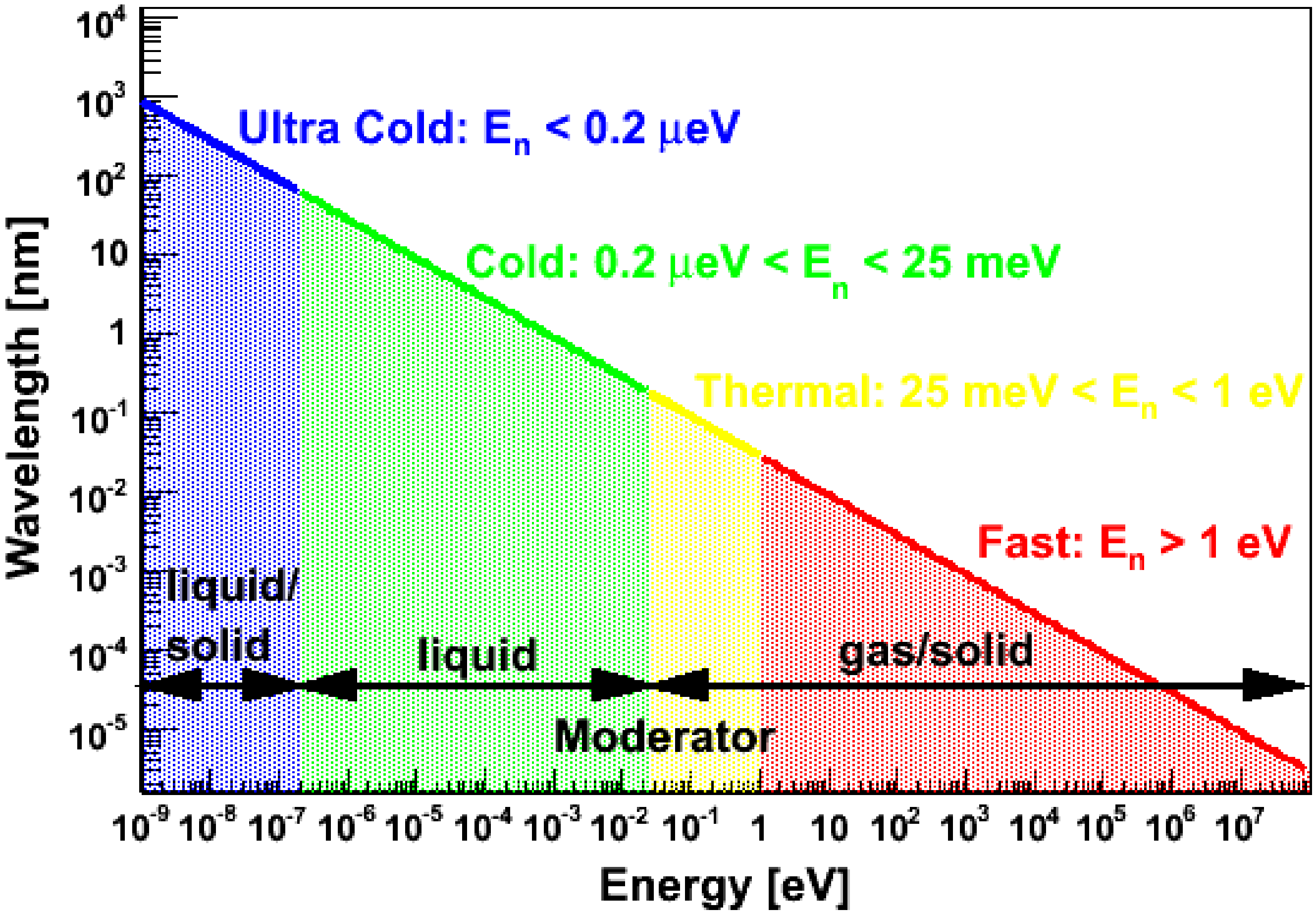
Cold Polarized neutron experimental area on main beamline

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



The Neutron Energy Scale

$$\lambda \approx \frac{29}{\sqrt{E_k}}\ fm$$



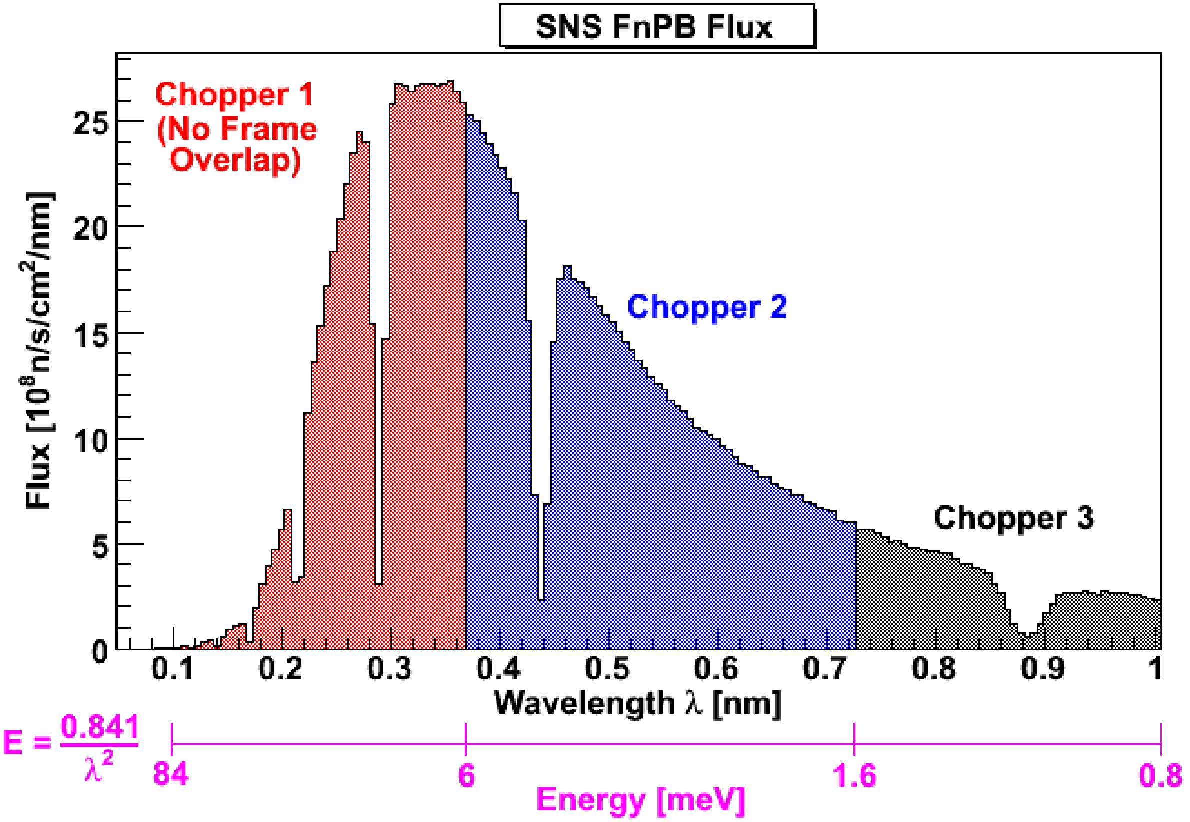
$$E_k = \frac{\hbar^2 k^2}{2M_n} = k_B T \quad , \quad k = 43.4\sqrt{E_k[MeV]}\ \ MeV/c$$

SNS Beam Properties

- total ~ 1.1×10^{11} neutrons/second

- 4.1×10^{10} n/s , 5.4×10^{10} n/s, 1.1×10^{10} n/s for three example regions with no frame overlap

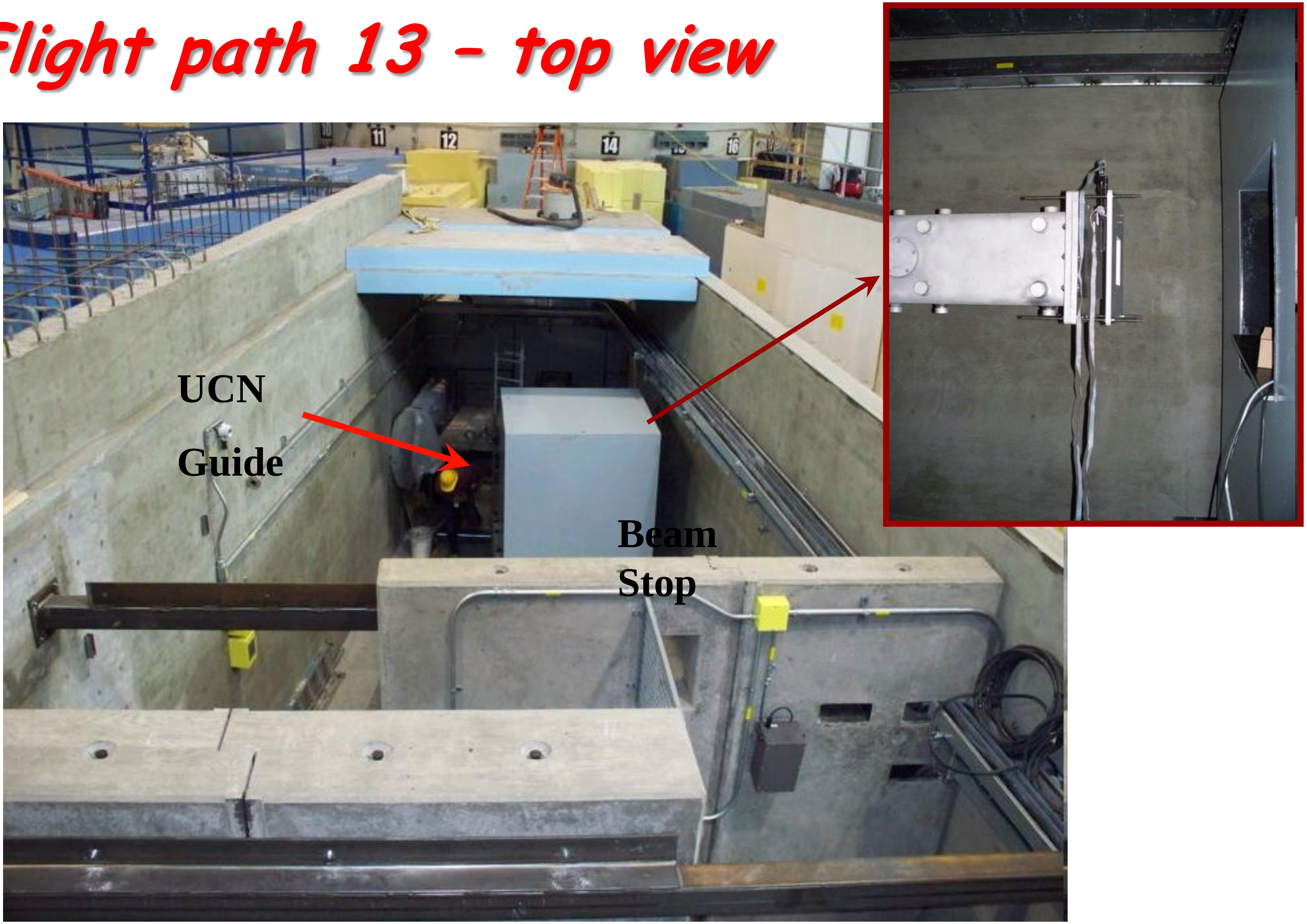
- 4 choppers required for various experimental conditions
  - → eliminate overlap with slower neutrons from previous pulses
  - → accommodate extraction of 0.89 nm beam
  - → avoid potential background problems from leakage of fast neutrons
  - → neutrons above 4.0 nm are not necessarily caught by this chopper arrangement (these come ~180 ms after pulse onset (> 10 frames later) intensity down by 4 orders of magnitude




DeSHAZO

Cold Beamline - Realized

Flight path 13 – top view



The NPDGamma Collaboration

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University of New Hampshire,
Oak Ridge National Laboratory,
University of California-Berkeley,
Hamilton College,
KEK National Laboratory, Japan
University of Virginia,
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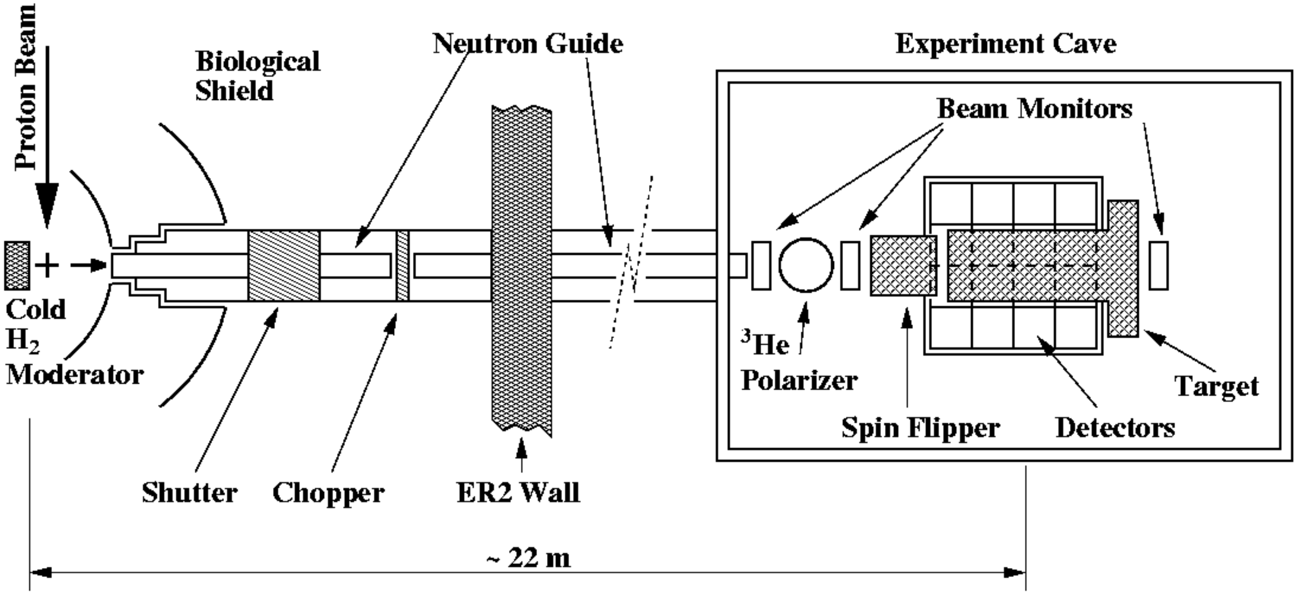
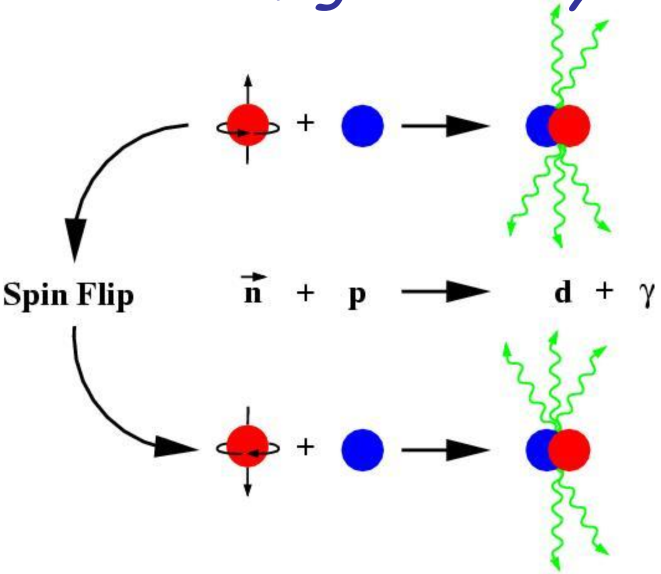
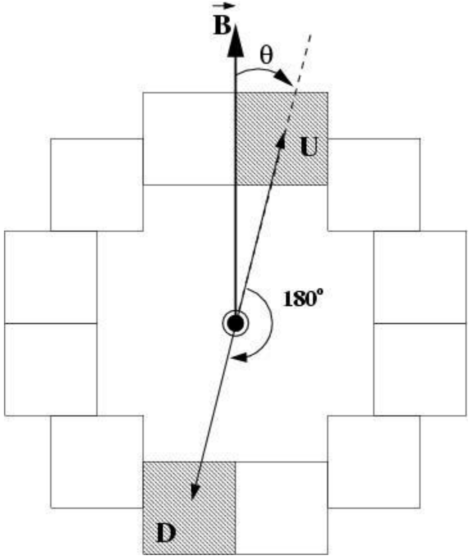


The NPDGamma Observable / Theory

The main NPDGamma observable is the up-down asymmetry in the angular distribution of gamma rays with respect to the neutron spin direction:





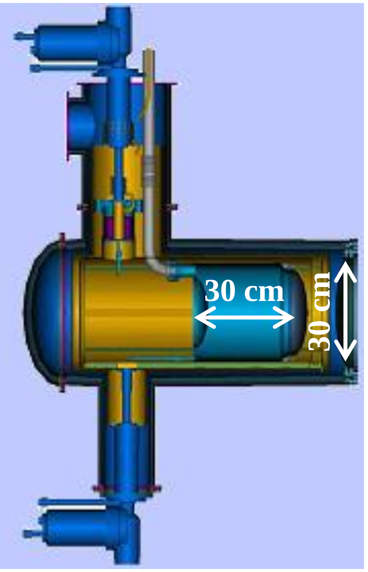
$$\boxed{\frac{d\sigma}{d\Omega} \propto \frac{1}{4\pi}\left(1 + A_\gamma \cos\theta\right)}$$

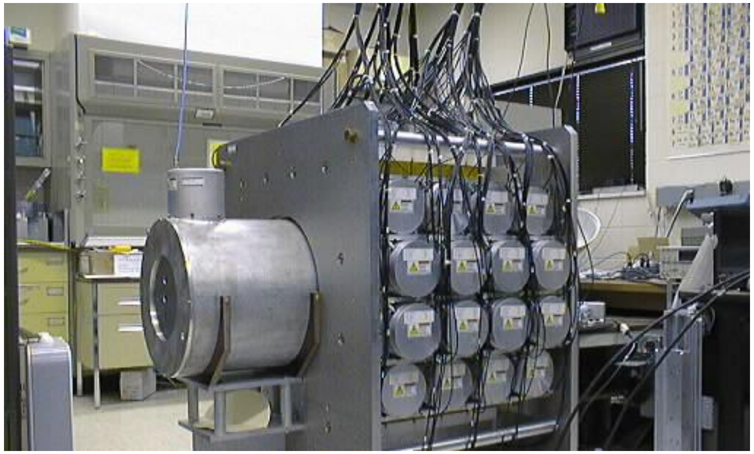
$$\boxed{A_{raw} = \left(P_n F_n D_n G\right) A_\gamma \cos\theta = \frac{1}{2}\left(\frac{\sigma_U^{\uparrow} - \sigma_D^{\uparrow}}{\sigma_U^{\uparrow} + \sigma_D^{\uparrow}} + \frac{\sigma_U^{\downarrow} - \sigma_D^{\downarrow}}{\sigma_U^{\downarrow} + \sigma_D^{\downarrow}}\right)}$$

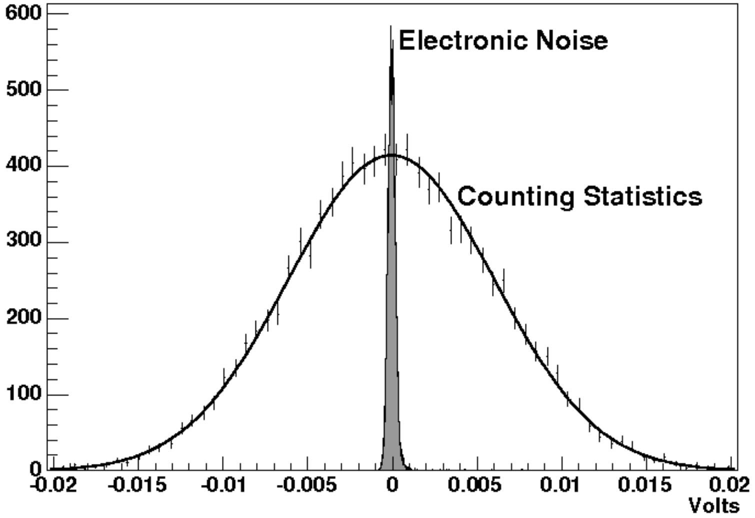
DDH: $\boxed{A_\gamma = -0.107\, h_\pi^{\Delta I=1} \approx -0.107 \times 12 \times g_\pi = -5 \times 10^{-8}}$

EFT: $\boxed{A_\gamma = -0.107\, m_N \rho_t = -5 \times 10^{-8}}$

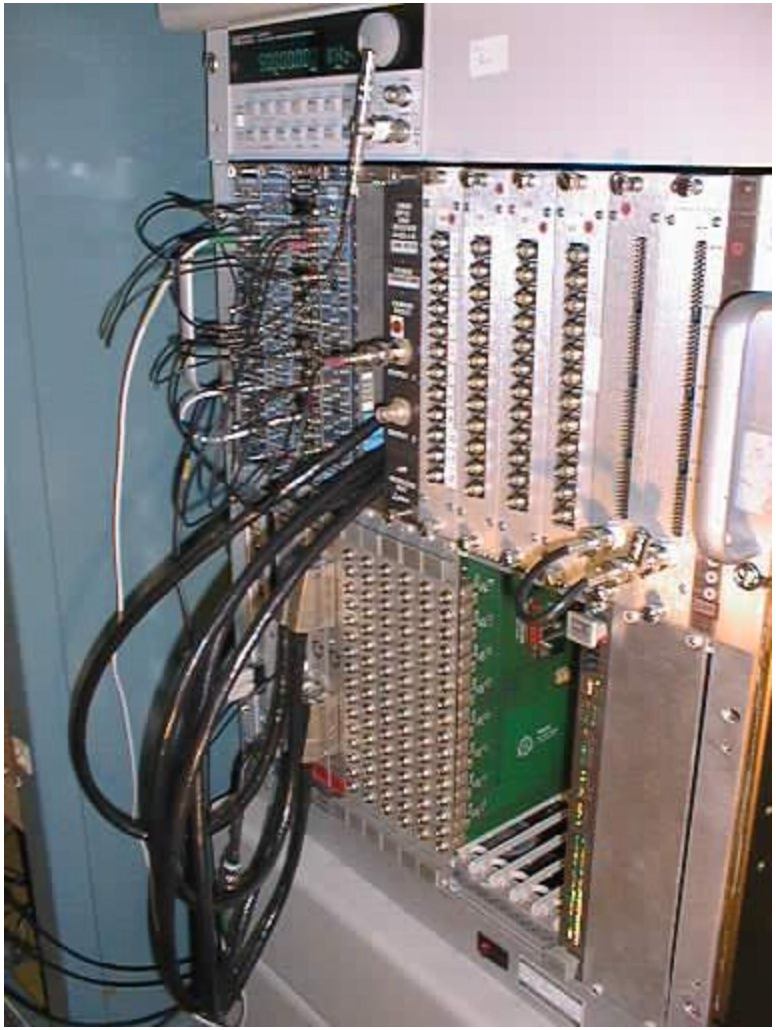
LH$_2$ target and CsI detector array





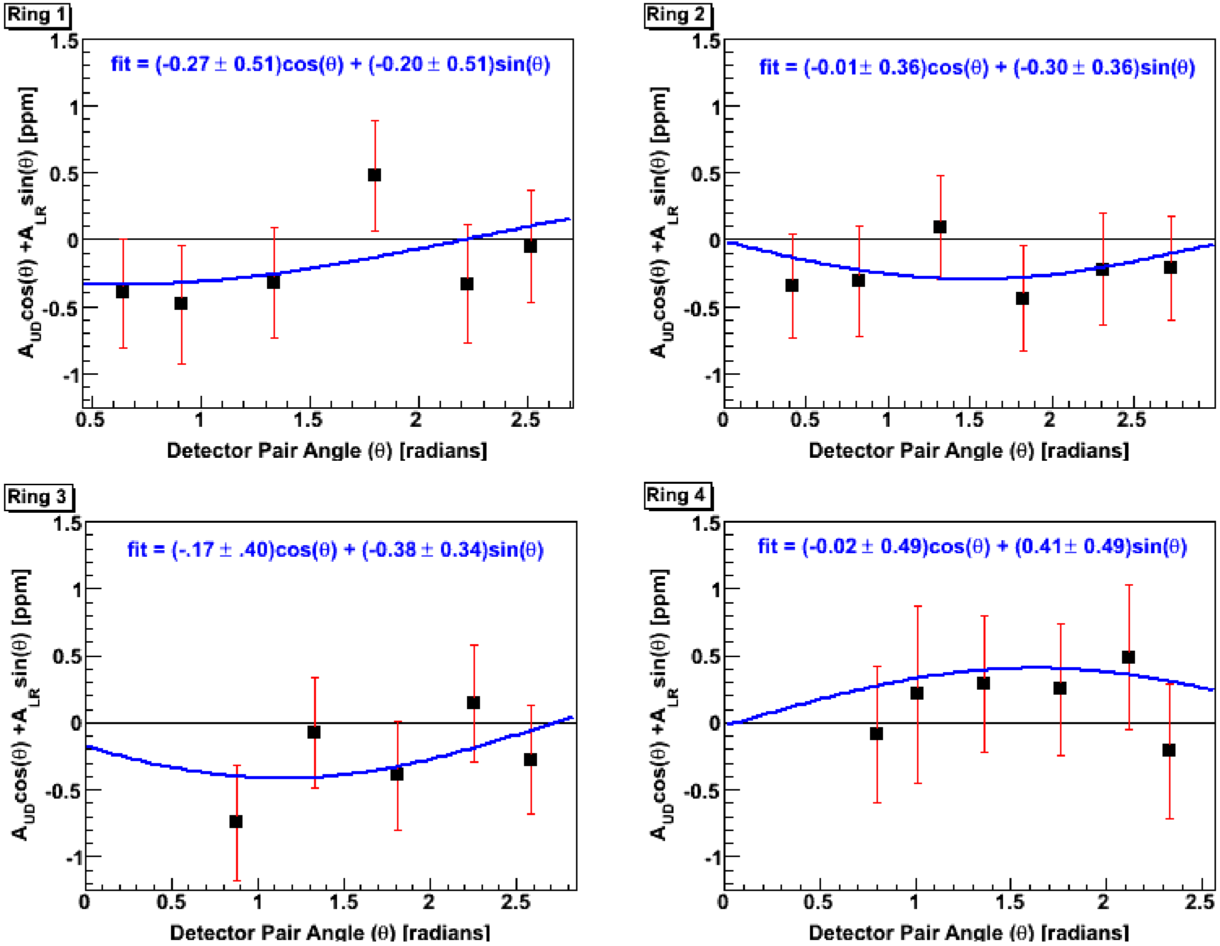


- 3π acceptance low noise detectors
- 20L vessel of liquid para-hydrogen
- γ-rate ~100MHz (single detector) - Current-mode experiment



NPDGamma has successfully taken 48 days of continuous production data in 2006 – now on par with the best previous measurement – is currently taking data at the SNS.

2006 Hydrogen Results:

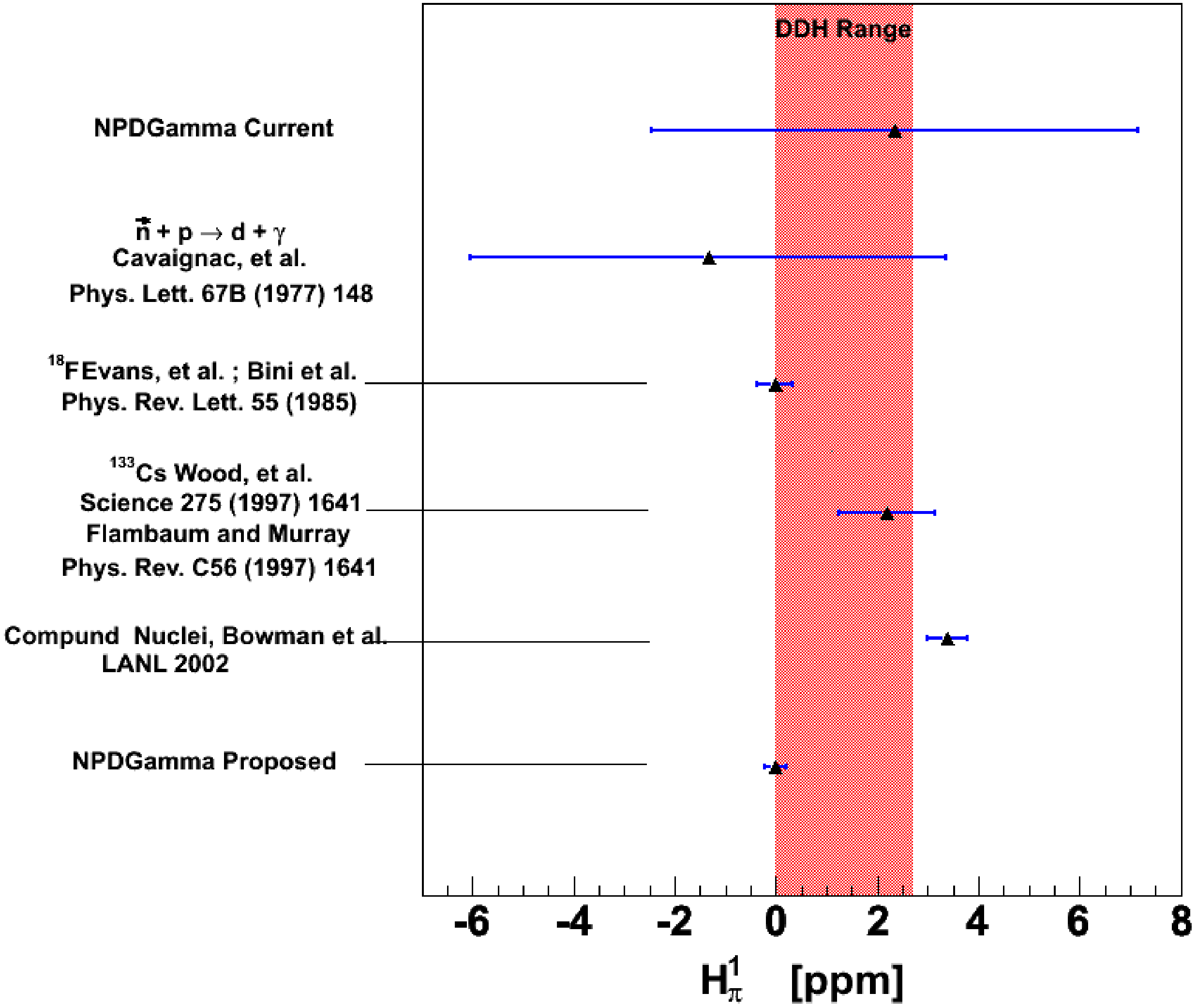


Total statistical error:

$$A_{\gamma,UD} = (-1.1 \pm 2.1)\times 10^{-7} \qquad A_{\gamma,LR} = (-1.9 \pm 2.0)\times 10^{-7}$$

Total systematic error: a (very) conservative 10% mostly due to pol.

Preliminary Hydrogen Results:



What's new for the SNS run

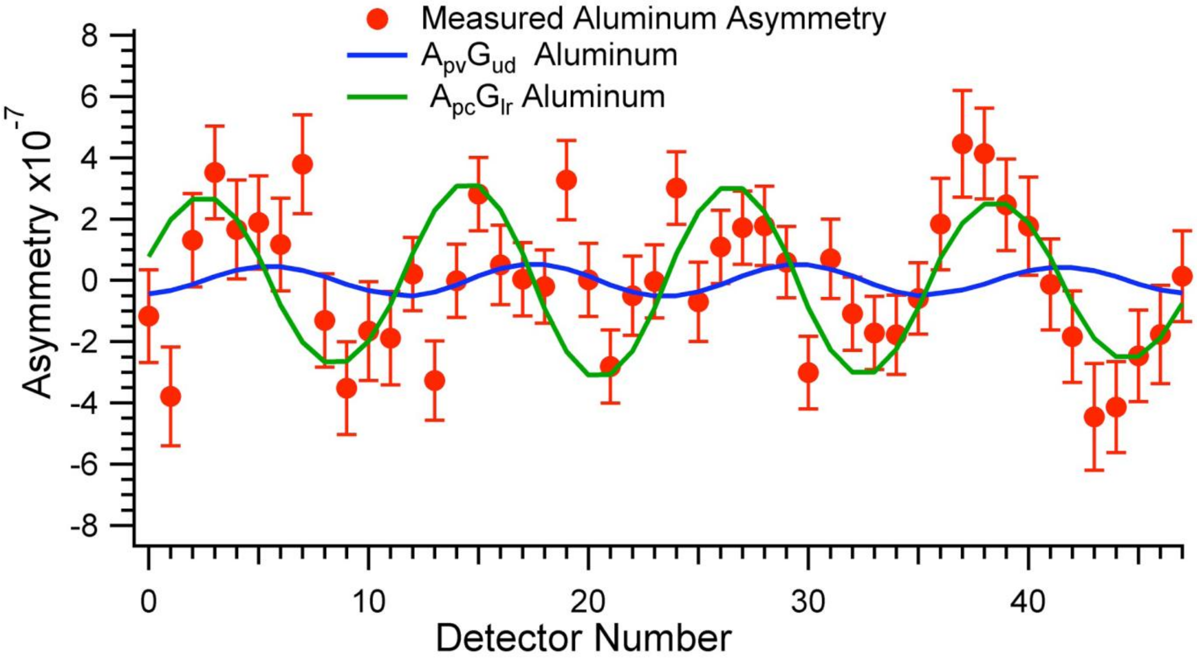
- Supermirror Polarizer replaces the ^{3}He Polarizer (x4.1)
- Higher moderator brightness (x12) => more cold/slow neutrons
- New LH2 target – thinner windows, smaller background contribution

Predicted size -5×10^{-8} - NPDGamma will make a 20% measurement, most precise so far

- Installation began in July 2009
- Production Hydrogen Data: Started December 2011

Some *Preliminary* Results from the SNS run

^{27}Al PV (up-down) and PC (left-right) Asymmetries



Current LH2 sensitivity at ~ 5×10^{-8} in 6 days of continuous running.

BUT: Backgrounds, systematics, …

→ 150 days estimated to get to *1×10^{-8}*

The Parity Violating Longitudinal Asymmetry in Polarized Cold Neutron Capture on Helium 3

n^3He

J.D. Bowman, S.I. Penttilä	Oak Ridge National Laboratory
R. Carlini	Jefferson National Laboratory
M. Gericke, S.A. Page, M. McCrea	
	University of Manitoba
C. Crawford	University of Kentucky
V. Gudkov	University of South Carolina
J. Martin	University of Winnipeg
C. Gillis	Indiana University
C .Gould	NC State University
P-N. Seyo	Duke
P. Alacorn, T. Balascuta	Arizona State University
S. Baessler	University of Virginia
M. Viviani	INFN, Sezione di Pisa
Anna Hayes, Gerry Hale,	
and Andi Klein	Los Alamos National Laboratory

n^3He Principle of Measurement

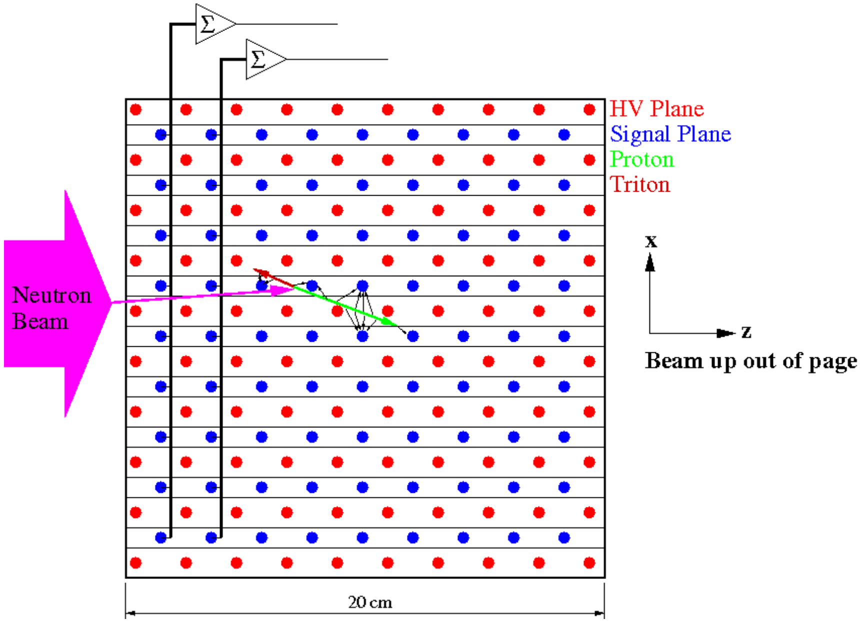
Measure the asymmetry in the number of forward going protons in a ^{3}He wire chamber as a function of neutron spin:

$\vec{\sigma}_n \cdot \vec{k}_T$ Directional PV asymmetry in the number of tritons

$\vec{\sigma}_n \cdot \vec{k}_p$ Directional PV asymmetry in the number of protons

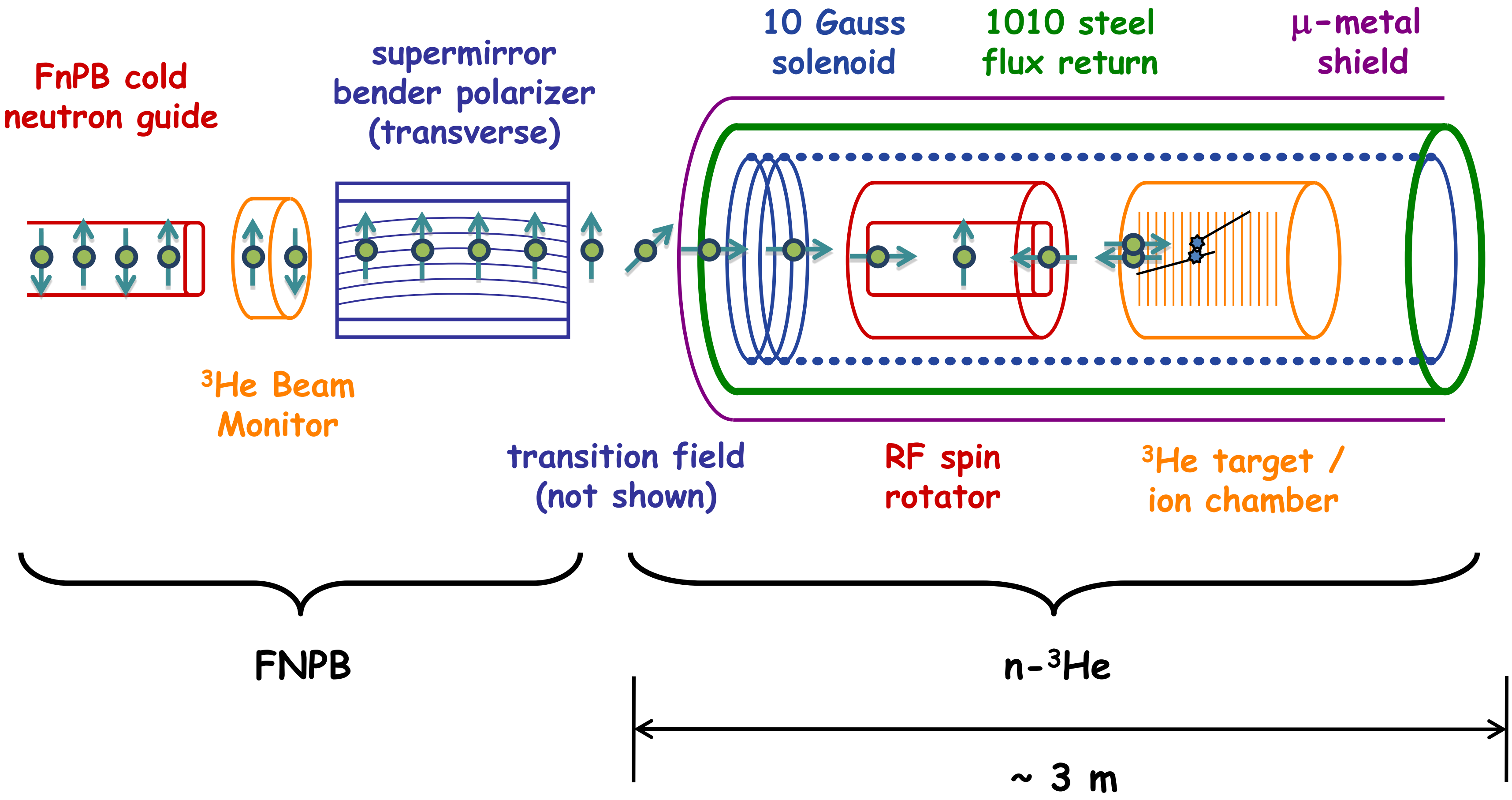
(much larger track length)

- 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)



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

Experimental Setup



FnPB cold neutron guide

supermirror bender polarizer (transverse)

10 Gauss solenoid

1010 steel flux return

μ-metal shield

^{3}He Beam Monitor

transition field (not shown)

RF spin rotator

^{3}He target / ion chamber

FNPB

n-^{3}He

~ 3 m

- *longitudinal holding field – suppressed PC asymmetry*
- *RF spin flipper – negligible spin-dependent neutron velocity*
- *^{3}He ion chamber – both target and detector*

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)

DDH Weak Coupling	(A^p_z) $n^3He \to tp$
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

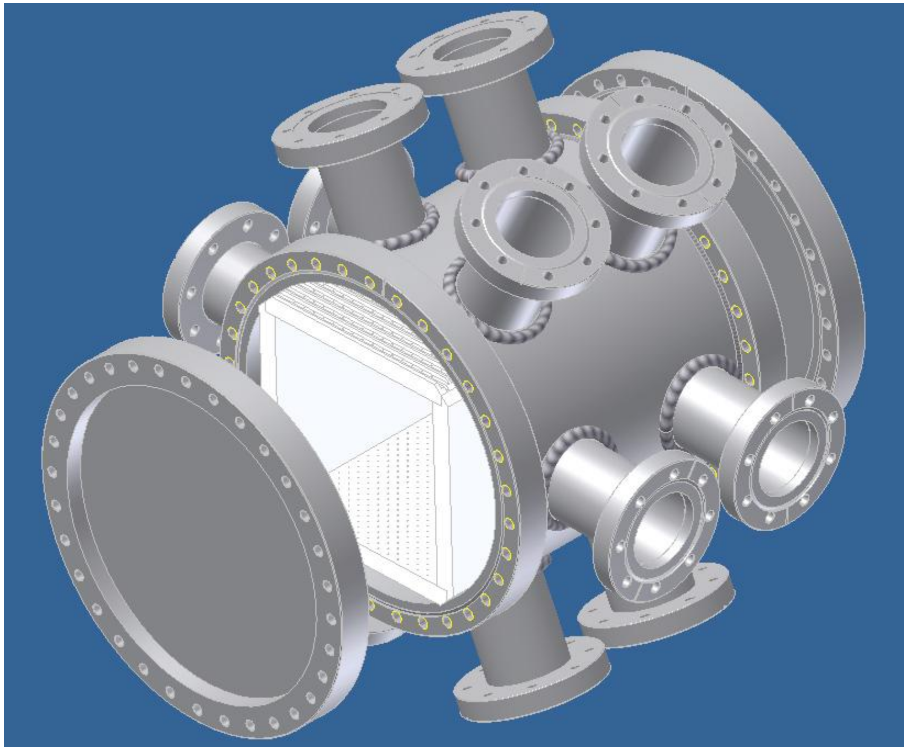
$$\boxed{A_p^{\vec{n},{}^3He}(th.) \approx (-9.4 \to 2.5)\times 10^{-8}}$$

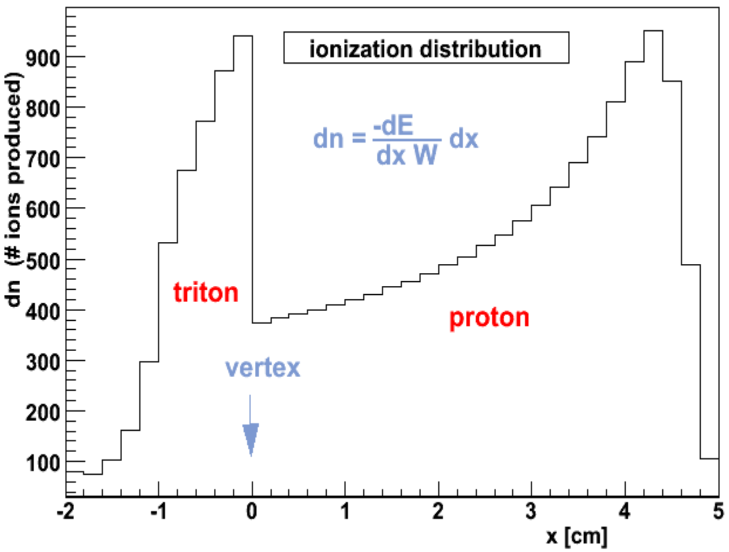
M. Viviani, R. Schiavilla, Phys. Rev. C. 82 044001 (2010)
L. Girlanda et al. Phys. Rev. Lett. 105 232502 (2010)

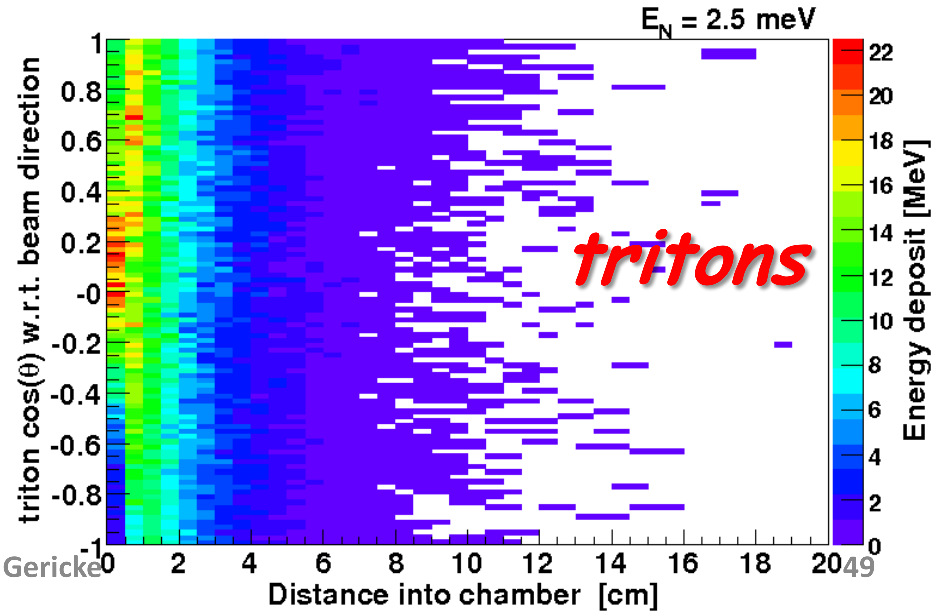
- ***MC simulations of sensitivity to proton asymmetry***
  - ***including wire correlations***
  - $$\delta A_{ph} = \frac{1}{\sqrt{N}P_N}\sqrt{\sigma_D^2 + \sigma_{coll}^2}$$

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

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







tritons

- ***MC simulations of sensitivity to proton asymmetry***
  - ***including wire correlations***
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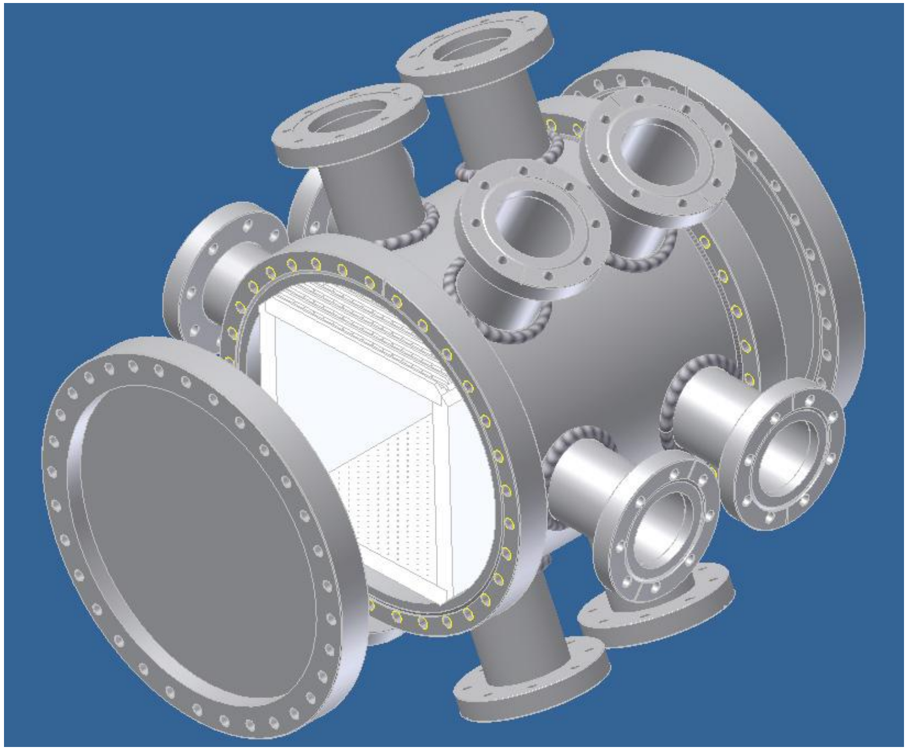
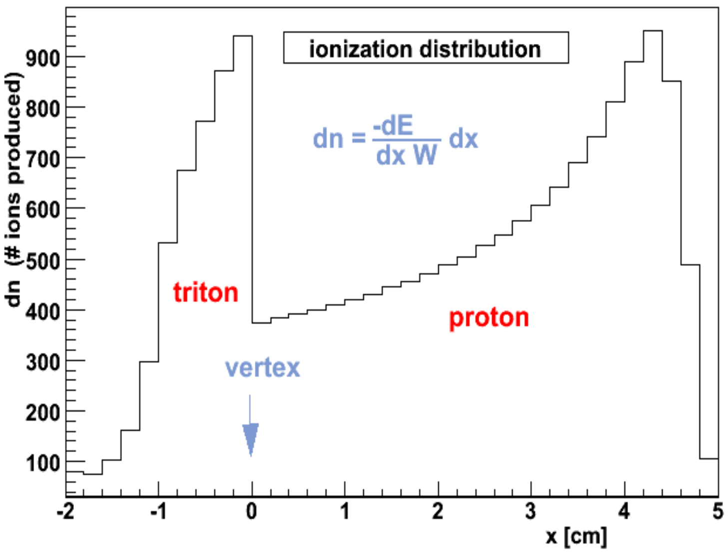
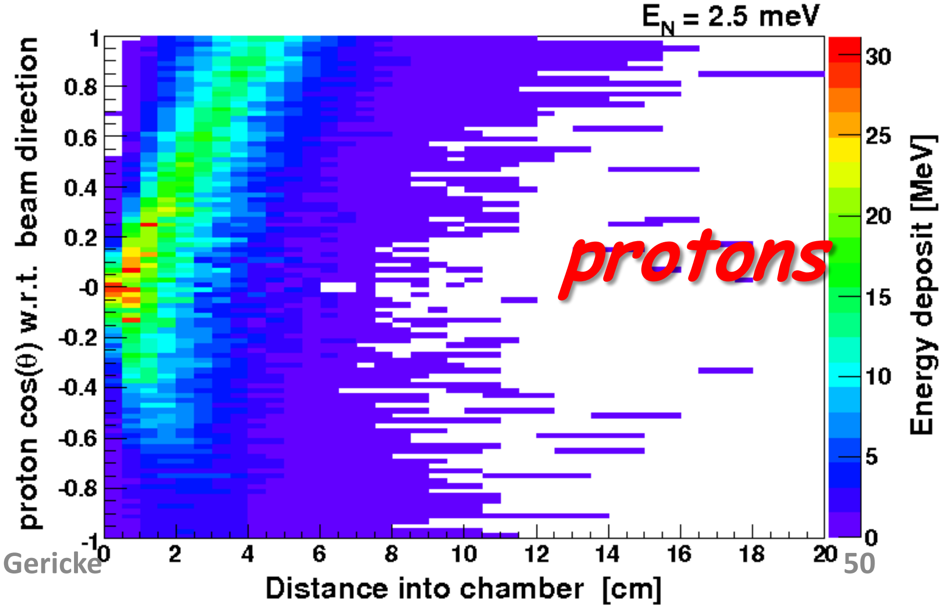
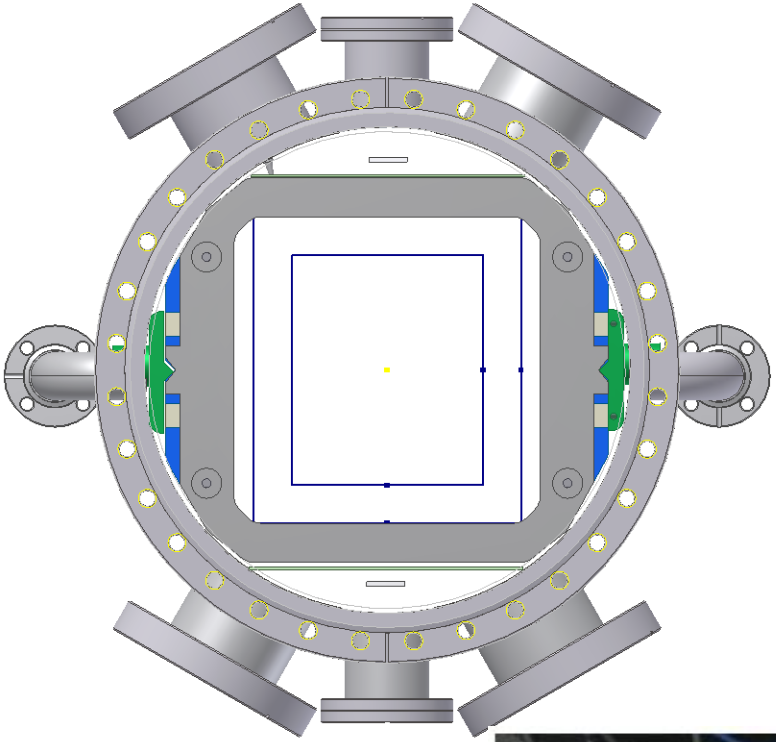








Chamber design finished in 2010

Delivered to U. of Manitoba Fall of 2010.

The chamber has:
- 4 data ports for up to 200 readout channels.
- 2 HV ports
- 2 gas inlets/outlets
- 12 inch conflat aluminum windows (0.9 mm thick).

Chamber made completely from aluminum except for the knife edges.

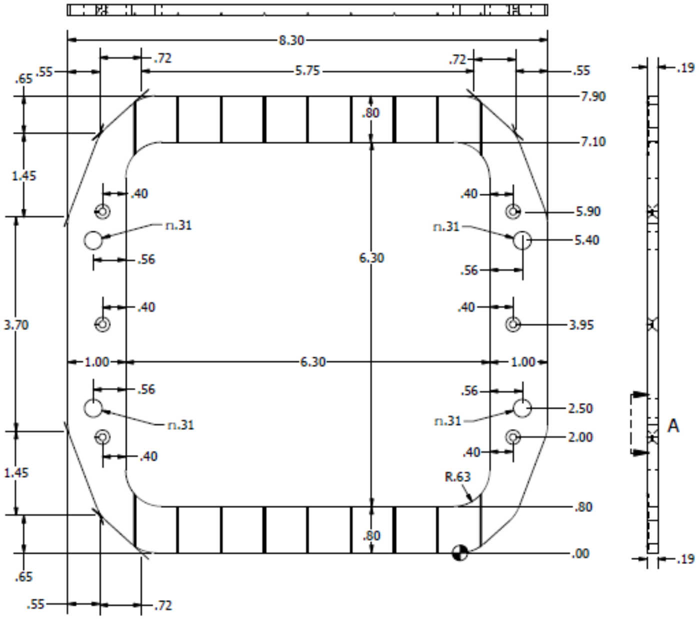
Chamber frame design finished in 2012

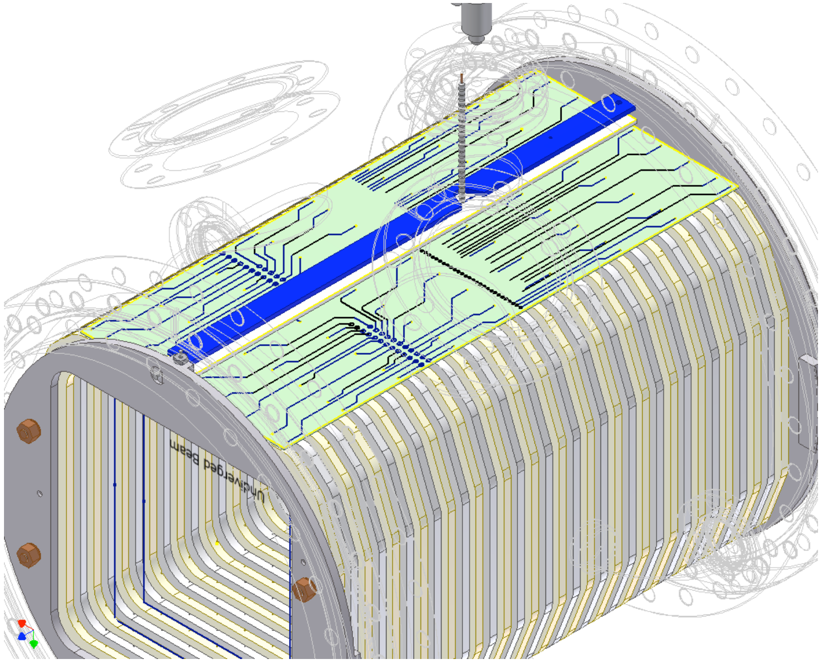
Up to 25 macor signal frames with 8 signal wires per frame.

Platinum-Gold thick film wire solder pads on macor.

In the process of getting quotes ...

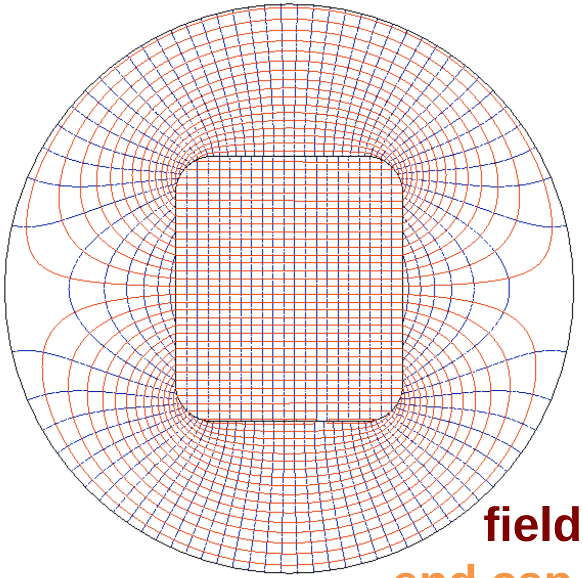
Assembly to finish by spring 2013.

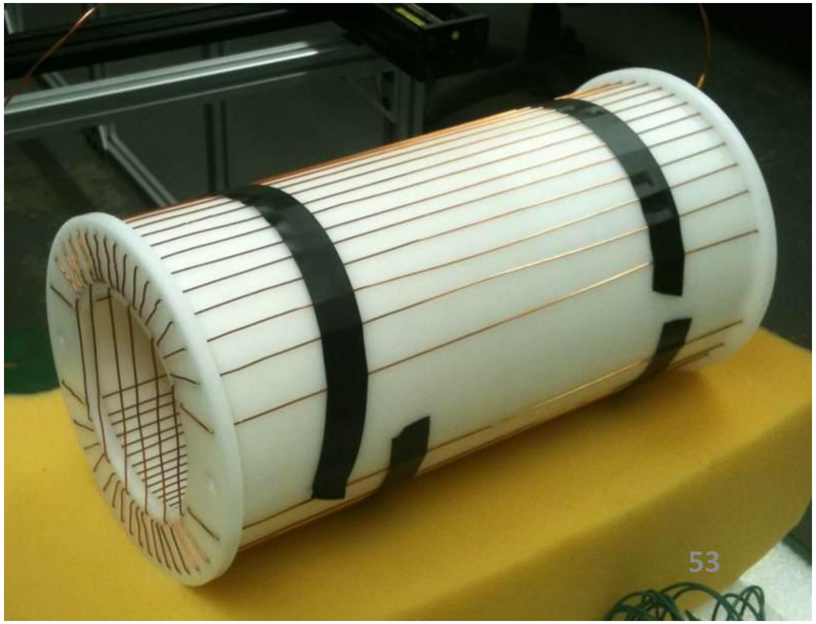




Transverse RF spin rotator

- Resonant RF spin rotator
  - P-N Seo et al., Phys. Rev. S.T. Accel. Beam **11**, 084701 (2008)
- Properties suitable for n-^{3}He expt.
  - Transverse horizontal RF B-field
  - Longitudinal or transverse flipping
  - No fringe field - 100% efficiency
  - Doesn’t affect neutron velocity
  - Compact geometry
  - Matched to the driver electronics of the NPDGamma spin flipper
- Construction
  - Development in parallel with similar design for nEDM neutron guide field
  - Few-winding prototype built at Uky currently being tested
  - Full size RFSF to be built this year





Status/Schedule

- *n-^{3}He experiment approved by the FnPB PRAC, 2008-01-07*
  - *first measurement of PV in the n-^{3}He reaction*
  - *Potentially large asymmetry ~10^{-7}*
  - *proposed measurement accuracy* $\boxed{\delta A = 1.0 \times 10^{-8}}$
- *recent progress in experimental design*
  - *full 4-body calculation of PV observable*
  - *R&D projects on target/detector design at LANL*
  - *new spin flipper design permitting compact / less expensive layout*
  - *preliminary holding field design*
- *leverage existing hardware / technology*
  - *major components based on similar NPDGamma instrumentation*
  - *can reuse NPDGamma electronics / power supplies*
- *FnPB infrastructure*
  - *no safety hazards, no LH_2 target, new power or cooling requirements*
  - *minimal modification of FnPB cave – stand for n-^{3}He solenoid*
  - *technician support for readiness review preparation, setup of experiment*
- *Tentative Schedule*
  - *2012-2013 Finsih Construction*
  - *Mid 2013 Installation*
  - *Late 2013 Run*

NPDGamma EFT Relevance

Systematic study of the NN weak interaction described in terms of a model independent theory appropriate at the low energy scale.

NN weak interaction effects enter into nucleon structure (needed for standard model tests) and atomic parity violation measurements.

5 EFT parameters : $(\lambda_t, \lambda_s^{I=0,1,2}, \rho_t)$

Correspond to: $^3S_1(I = 0) \leftrightarrow {}^1P_1(I = 0)$

$$^1S_0(I = 0,1,2) \leftrightarrow {}^3P_0(I = 0,1,2)$$

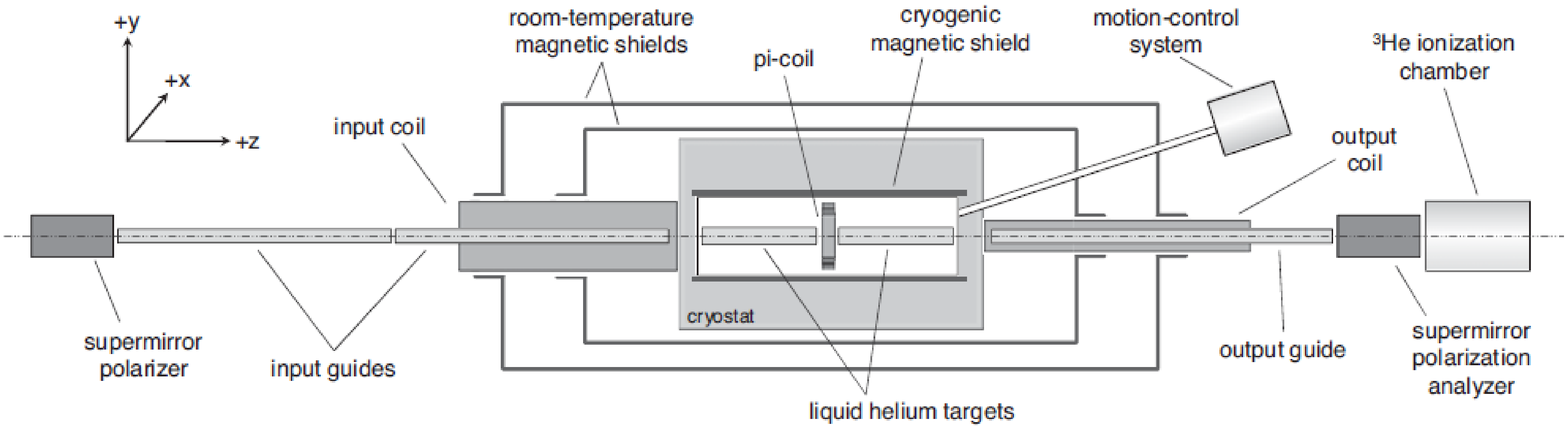
$$\boxed{^3S_1(I = 0) \leftrightarrow {}^3P_1(I = 1)}$$

NPDGamma asymmetry relation to EFT constant: $\boxed{A_\gamma^{\vec{n},p}(th.) = -0.107\, m_N \rho_t = -5\times10^{-8}}$

C.-P. Liu, Nuclear Physics Phys. Rev. C 75, 065501 (2007)

n^4He Spin Rotation

NIST Experiment:



- Vertically polarized neutrons
- Enter liquid helium target with four chambers
- Neutrons rotate in helium in a spin dependent way
- Neutrons are rotated in the x-y plane after acquiring the PV rotation
- Neutrons are analyzed in another supermirror polarizer
- Transmitted neutrons are detected in the ion chamber

$$\frac{N_+ - N_-}{N_+ + N_-} = \langle P A \sin\phi \rangle$$

Do the unexpected observations in the ΔS=1 sector come from a dynamical strange quark or some other process ?

→ ***Look at the ΔS=0 sector***

Standard Model:

$$\mathcal{L}_W^{INT} = -\frac{g}{2\sqrt{2}}\left(J_C^{\mu\dagger} W_\mu + J_c^\mu W_\mu^\dagger\right) - \frac{g}{4\cos\theta_w} J_N^\mu Z_\mu$$

Charged currents:

$$\begin{aligned} J_C^\mu &= \overline{\psi}_d \gamma^\mu (1-\gamma_5)\psi_u \cos\theta_c + \overline{\psi}_s \gamma^\mu (1-\gamma_5)\psi_u \sin\theta_c \\ &\quad -\overline{\psi}_d \gamma^\mu (1-\gamma_5)\psi_c \sin\theta_c + \overline{\psi}_s \gamma^\mu (1-\gamma_5)\psi_c \cos\theta_c \end{aligned}$$

Neutral currents:

$$\begin{aligned} J_N^\mu &= \overline{\psi}_u \gamma^\mu \left(1 - \frac{8}{3}\sin^2\theta_w - \gamma_5\right)\psi_u + \overline{\psi}_c \gamma^\mu \left(1 - \frac{8}{3}\sin^2\theta_w - \gamma_5\right)\psi_c \\ &\quad -\overline{\psi}_d \gamma^\mu \left(1 - \frac{4}{3}\sin^2\theta_w - \gamma_5\right)\psi_d - \overline{\psi}_s \gamma^\mu \left(1 - \frac{4}{3}\sin^2\theta_w - \gamma_5\right)\psi_s \end{aligned}$$

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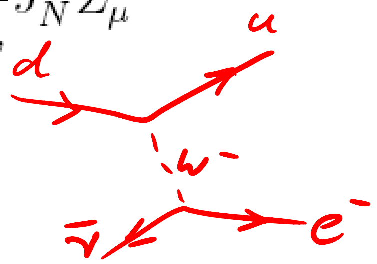


Charged currents:

beta decay =>

$$\begin{aligned} J_C^\mu &= \overline{\psi}_d\gamma^\mu(1-\gamma_5)\psi_u\cos\theta_c + \overline{\psi}_s\gamma^\mu(1-\gamma_5)\psi_u\sin\theta_c \\ &\quad -\overline{\psi}_d\gamma^\mu(1-\gamma_5)\psi_c\sin\theta_c + \overline{\psi}_s\gamma^\mu(1-\gamma_5)\psi_c\cos\theta_c \end{aligned}$$

$\Delta S = \pm 1$

Neutral currents:

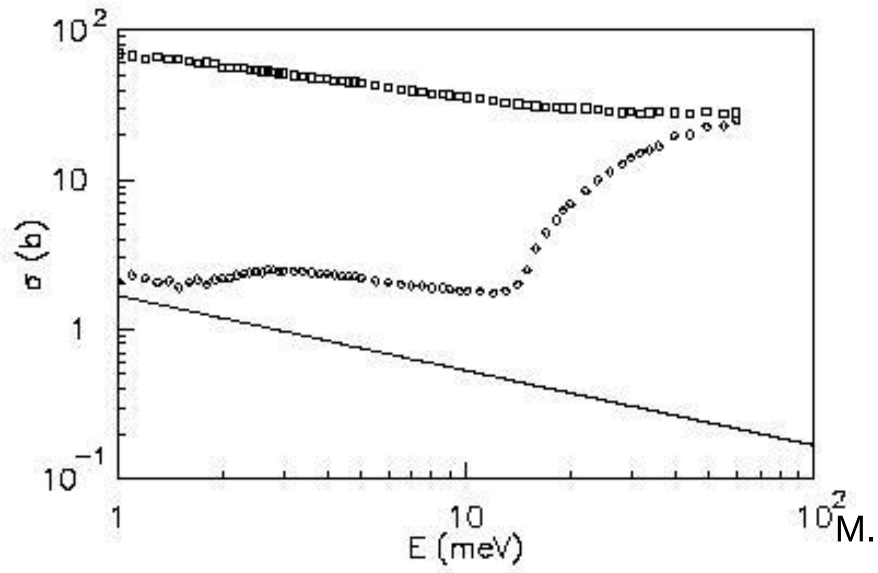
$$\begin{aligned} J_N^\mu &= \overline{\psi}_u\gamma^\mu\left(1-\frac{8}{3}\sin^2\theta_w-\gamma_5\right)\psi_u + \overline{\psi}_c\gamma^\mu\left(1-\frac{8}{3}\sin^2\theta_w-\gamma_5\right)\psi_c \\ &\quad -\overline{\psi}_d\gamma^\mu\left(1-\frac{4}{3}\sin^2\theta_w-\gamma_5\right)\psi_d - \overline{\psi}_s\gamma^\mu\left(1-\frac{4}{3}\sin^2\theta_w-\gamma_5\right)\psi_s \end{aligned}$$

$\Delta S = 0$

Hadronic weak interaction!

Data Summary from 2006 run

Number of good runs (8.5min long)	~5000
Neutron Polarization	53±2.5%
Spin Flip Efficiency	98.8±0.5%
Para fraction in LH_2 target	99.98±0.2%
Al background	~25% (ave)
Depolarization	2%
sym	10^{-10}
	10^{-10}



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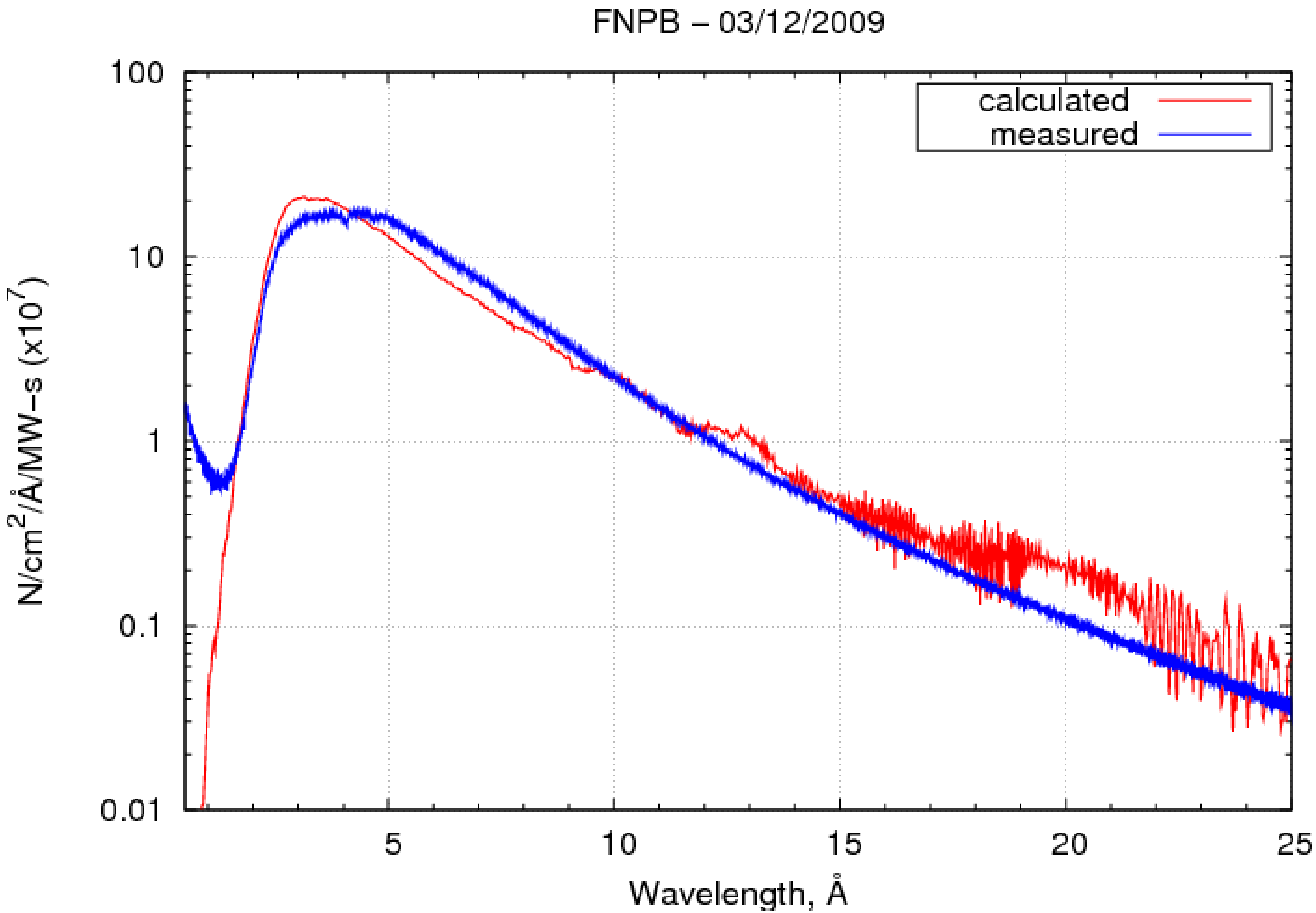
Al background	~25% (ave)
Depolarization	2%
Stern-Gerlach steering Asym	10^{-10}
γ-ray circ.pol. Asym	10^{-10}


FNPB – 03/12/2009
calculated
measured
N/cm^2/Å/MW–s (x10^7)
100
10
1
0.1
0.01
5
10
15
20
25
Wavelength, Å

The observed cross-section is the result of an electro-magnetic transition between initial and final two nucleon states.
The possible amplitudes include both parity even M1 and parity odd E1 transitions from L=1 states as a result of the weak perturbation.

$$\frac{d\sigma}{d\Omega} \propto \left|\langle\psi_f|E1|\psi_i\rangle + \langle\psi_f|M1|\psi_i\rangle\right|^2$$

$$H = H_s + V_{PNC} \qquad a = \frac{\langle\psi_1|V_{PNC}|\psi_0\rangle}{\Delta E} \qquad |\psi_{i,f}\rangle = |\psi_0\rangle + a|\psi_1\rangle$$

A measurement of the asymmetry at the 20 % level (10 ppb) will be the most precise measurement of the weak-pion nucleon coupling

$$\boxed{\frac{i g_{\pi NN} h_\pi^1}{\sqrt{32}M}\left[\vec{\tau}_1 \times \vec{\tau}_2\right]_z \left[\vec{\sigma}_1 + \vec{\sigma}_2\right] \cdot \left[\vec{p}, \frac{e^{-mr}}{4\pi r}\right]} \qquad \frac{g_{\pi NN} h_\pi^1}{\sqrt{32}} \approx 1.1 \times 10^{-6}$$

$$A_\gamma = -0.107\, h_\pi^{\Delta I=1} \approx -0.107 \times 12 \times g_\pi = \boxed{-5 \times 10^{-8}}$$