Hadronic Weak Interaction:
Parity Violation and Search of Violation of Time Reversal Invariance

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P-Division/Group ?

Content:

- Hadronic weak interaction (HWI) at low momentum transfer
  - Weak spreading width
  - Parameterization of nucleon weak interaction
  - Status of the HWI
  - Importance of NPDGamma and n-3He experiments
- Search of TRIV in transmission of neutrons through polarized matter

Discrete Symmetries; *C, P, T*

We have observed P violation and then CP violation long time ago in K^0-meson decay and lately in B-meson decay.

T- or CP- symmetry violation is the most interesting symmetry, maybe we can explain the observed ratio of baryons to photons in the universe, when we learn more about origin of the CP violation.

	$\vec{r}$	$\vec{s}$	$\vec{k}$	$\vec{I}$	$\vec{s}\cdot\vec{k}$	$\vec{s}\cdot\vec{I}$	$\vec{s}\cdot(\vec{k}\times\vec{I})$
$\hat{P}$	-	+	-	+	-	+	-
$\hat{T}$	+	-	-	-	+	+	-

Each of C, P, T symmetries are invariant in EM- and strong interaction but violated in weak. But the CPT theorem is invariant in all the interactions.

Observed Parity Violation in Compound Nuclei : nuclear parity violation

$$n + A \to A^* \to (A+1) \to \gamma$$
$$\to A + n$$

If A=100, then at E_n=100eV $\lambda \approx R$

At low neutron energies the coherent forward scattering amplitude can be written as:

$$f(0^o) = A + B\vec{s}_n \cdot \vec{I} + C\vec{s}_n \cdot \vec{k}_n + D\vec{s}_n \cdot (\vec{k}_n \times \vec{I})$$
$$= f_{PC} + f_{PV}$$

$$\omega \approx \left|f_{PC} + f_{PV}\right|^2 = \left|f_{PC}\right|^2 + 2\,\mathrm{Re}(f_{PC} f_{PV}^*) + \left|f_{PV}\right|^2$$

$$\alpha \approx \frac{\mathrm{Re}(f_{PC} f_{PV}^*)}{\left|f_{PC}\right|^2} \approx \frac{\left|f_{PV}\right|}{\left|f_{PC}\right|}$$

$$\alpha \approx G_F m_\pi^2 \approx 2 \cdot 10^{-7}$$

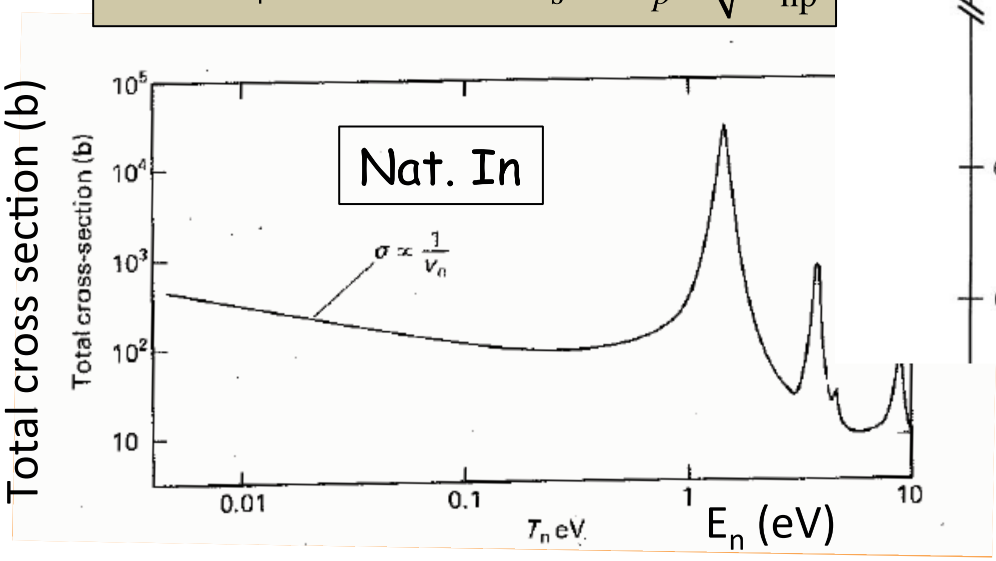
Enhanced Parity Violation Longitudinal asymmetry in Compound Nuclei

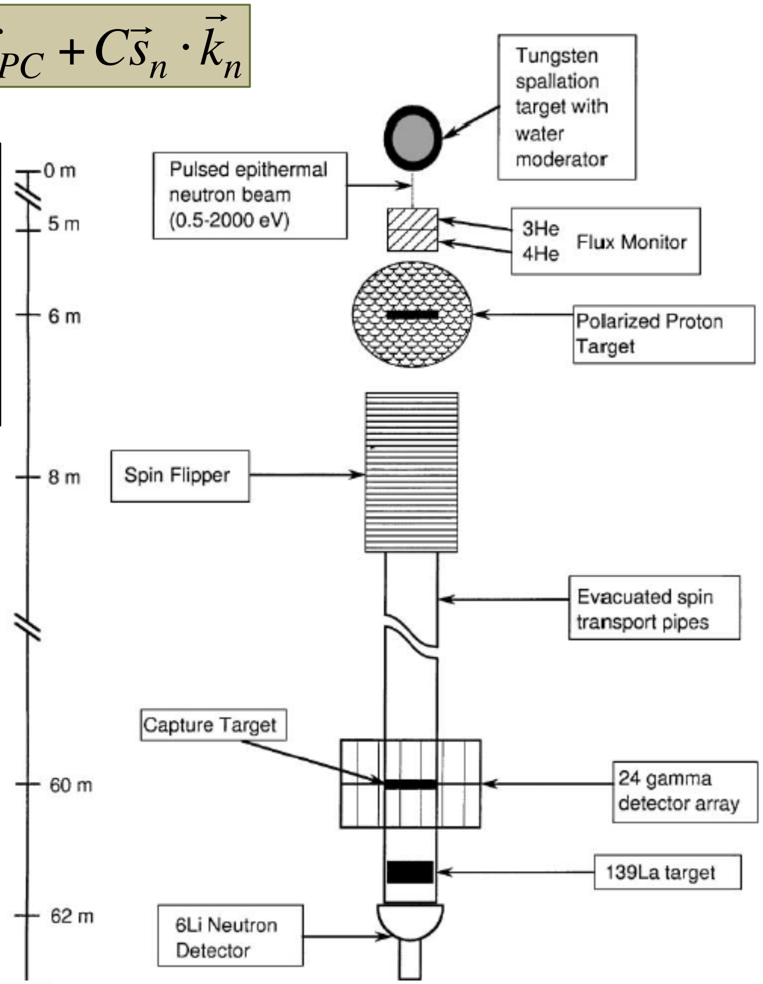
$$f(0^o) = f_{PC} + C\vec{s}_n \cdot \vec{k}_n$$

$$\varepsilon \equiv \frac{N^+ - N^-}{N^+ + N^-} = -\tanh(A_L f_n n\sigma_p) \approx -A_L f_n n\sigma_p$$

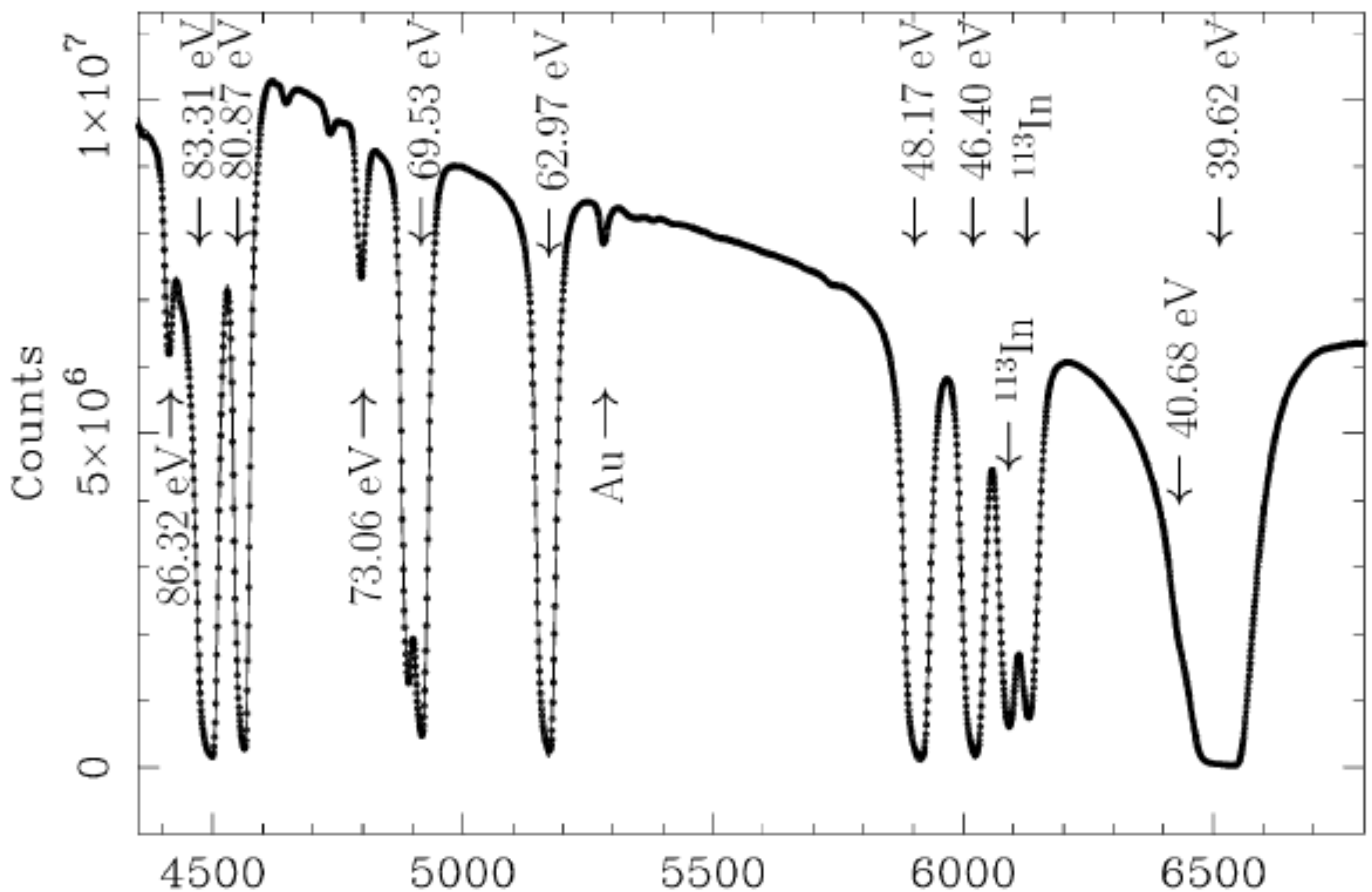
$$N^{\pm} = N\exp[-n\sigma_p(1 \pm f_n A_L)]$$

$$A_L = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = 2\sum_s \frac{V_{sp}^J}{(E_s - E_p)} \frac{\sqrt{\Gamma_{ns}}}{\sqrt{\Gamma_{np}}}$$





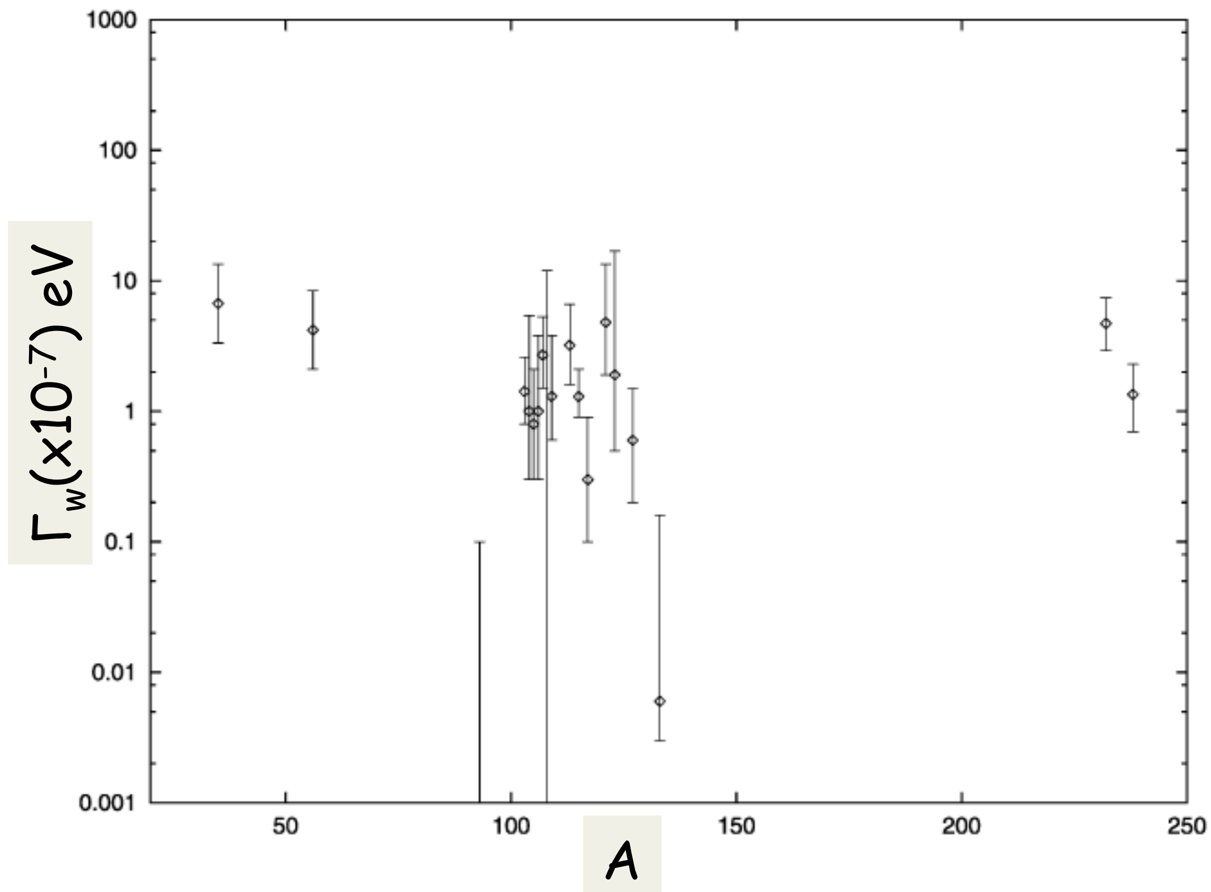
Neutron resonances in natural indium



9 statistically significant PVs observed at E_n =30eV to 1840eV

Weak Spreading Width from PVs in Compound Nuclei

18 nuclides studied and PV observed in 75 resonances



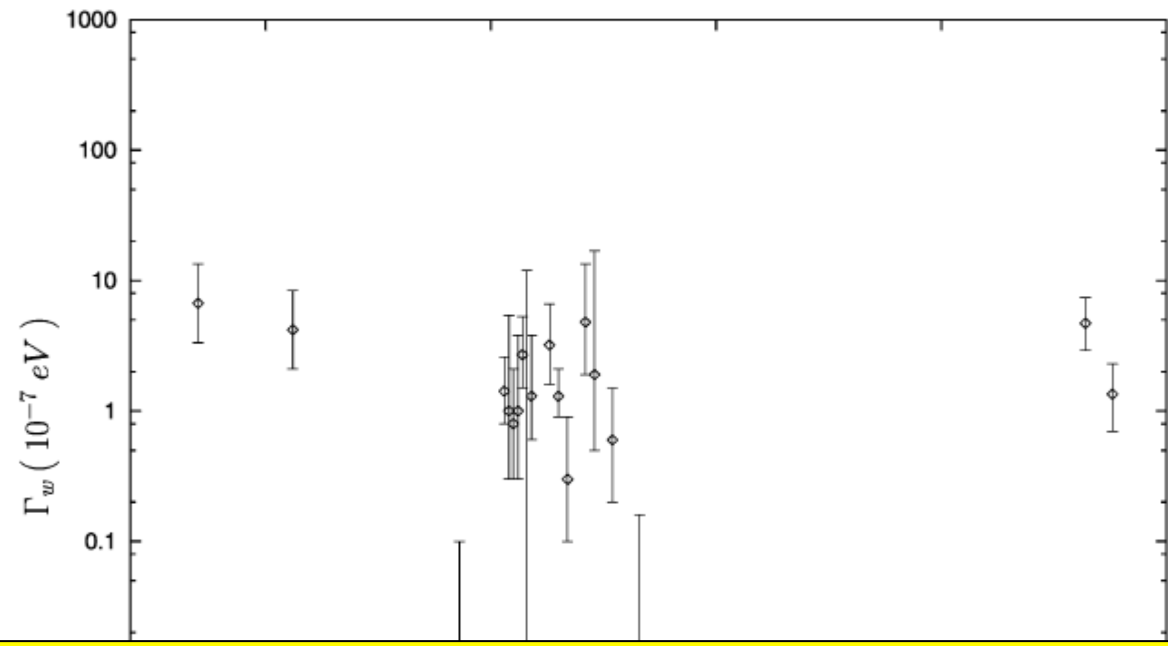
$\Gamma_W = 2\pi M_J^2 / D_J = 1.8\times10^{-7}$ eV

The largest PV is in La 9.6% at 0.748 eV

Mitchell et al. Phys.Rep.354 (2001)157

Weak Spreading Width from Compound Nuclei Results

18 nuclides studied and PV observed in 75 resonances



- Compound nuclei too complicated for extracting physics
- The nuclear system has to be simple – calculable
- But then no amplifications -> precision experiments
- Statistics requires very intense beam
- Control of systematic errors requires smart and committed collaborators
- Realization requires $$s

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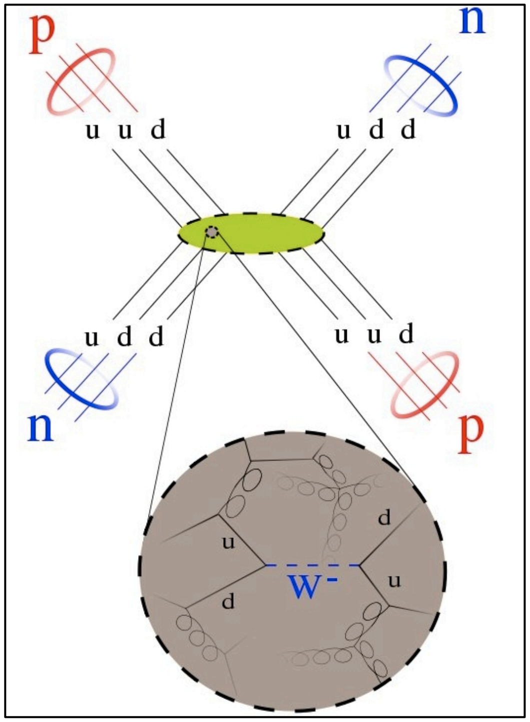
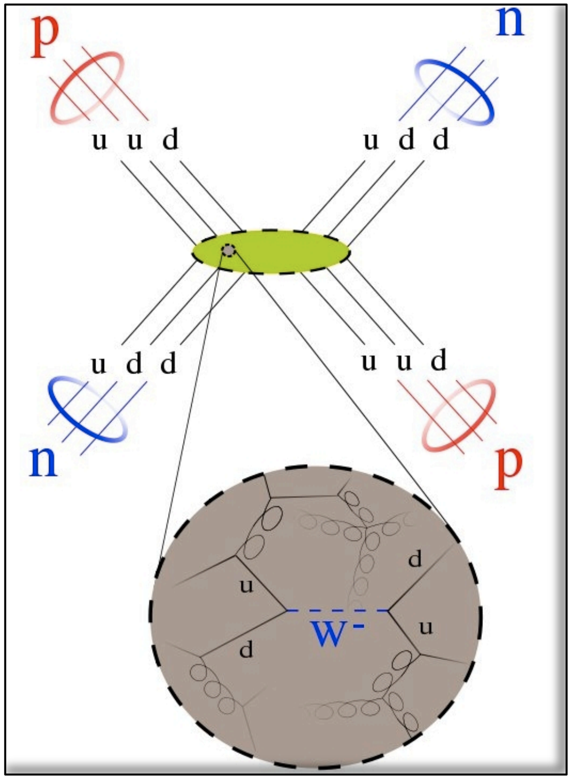
Structure of Hadronic Weak Interaction (HWI) at low energies when $\Delta S=0$

HWI between Nucleons



- Interaction length of vector bosons is 1/100 fermi.
- Interaction length of carried by mesons is about fermi.
- For pions 1.4 fermi, but ρ– and ω– mesons contribute about 10% nuclear potential.

Hadronic Weak Currents

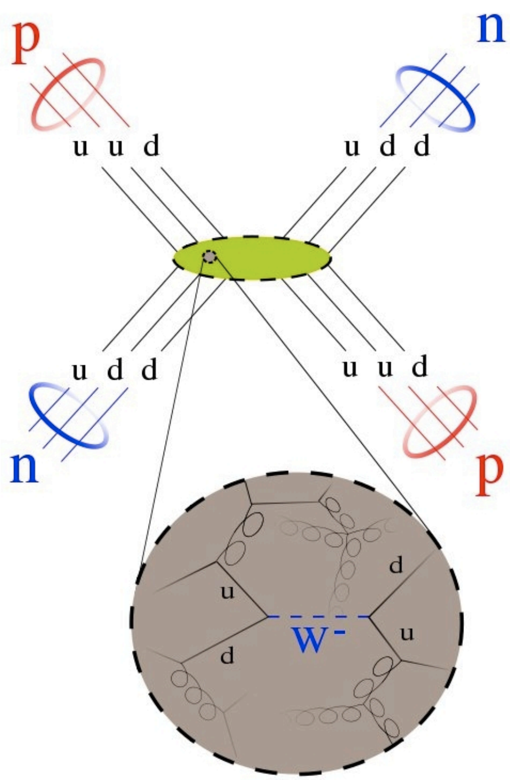


$$H_w = \frac{G_F}{\sqrt{2}}(J_c^* J_c + \frac{1}{2} J_n^* J_n)$$

$$J_\mu^c = \bar{u}\gamma_\mu(1+\gamma_5)[(\cos\theta_C)d + (\sin\theta_C)s]$$

$$J_\mu^n = \bar{u}\gamma_\mu(1+\gamma_5)u - \bar{d}\gamma_\mu(1+\gamma_5)d - \bar{s}\gamma_\mu(1+\gamma_5)s - \\ -\sin^2\theta_w J_\mu^{EM}$$

Weak Currents in Weak Interaction



$$H_w = \frac{G_F}{\sqrt{2}}\left(J_c^* J_c + \frac{1}{2} J_n^* J_n\right)$$

$$J_\mu^c = \bar{u}\gamma_\mu(1+\gamma_5)[(\cos\theta_C)d + (\sin\theta_C)s]$$

$$J_\mu^n = \bar{u}\gamma_\mu(1+\gamma_5)u - \bar{d}\gamma_\mu(1+\gamma_5)d - \bar{s}\gamma_\mu(1+\gamma_5)s - $$
$$- \sin^2\theta_W J_\mu^{EM}$$

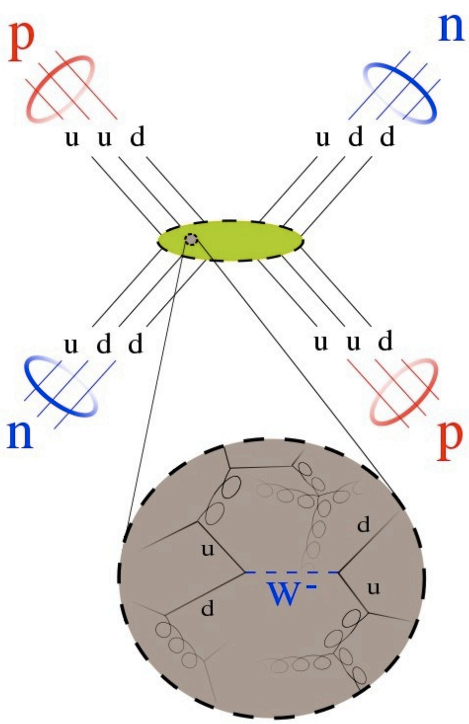
Isospin structure of weak Hamiltonian:

$$H_W^{\Delta I=2} \propto J_c^{I=1} J_c^{I=1}$$

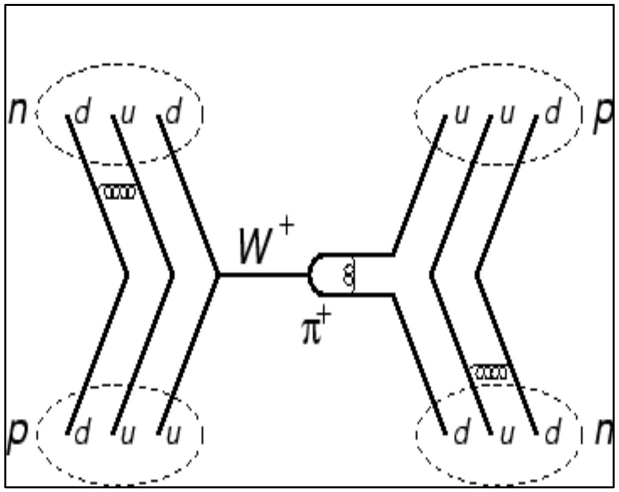
$$H_W^{\Delta I=1} \propto J_c^{I=1/2} J_c^{I=1/2} + J_n^{I=0} J_n^{I=1}, \quad J_c^{I=1/2} \propto \sin\theta_C, \ \sin^2\theta_C << 1$$

$$H_W^{\Delta I=0} \propto J_c^{I=0} J_c^{I=0} + J_n^{I=0} J_n^{I=0} + J_n^{I=1} J_n^{I=1}$$

HWI – DDH parameterization



DDH:



$$V_{PV} = \sum_{m=\pi,\rho,\omega} \sum_{\Delta I=0,1,2} h_m^{\Delta I} V_m^{\Delta I}$$

Weak NN couplings are largely unknown:

- non-perturbative regime makes calculations and
- experiments challenging.

DDH – four weak N-N couplings

- Two-body meson-exchange PV potential

$$V_{PV} = \sum_{k=\pi,\rho,\omega} \sum_{\Delta I} h_{k,\Delta I}\, Y(m_k\, r)\, Q_k(p, r, \sigma, \tau)$$

- 6 free parameters
- Really reachable 4

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

- Nuclear PV is determined by one-body potentials

$$X_N^{p\ or\ n} = \pm 5.5\, f_\pi - 1.13\, h_{\rho,0} - 0.91\, h_{\omega,0}$$

- The expressions for observables depend on the N-N PC potential used. (AV18 assumed here)

Some PV Observables within DDH Parameterization

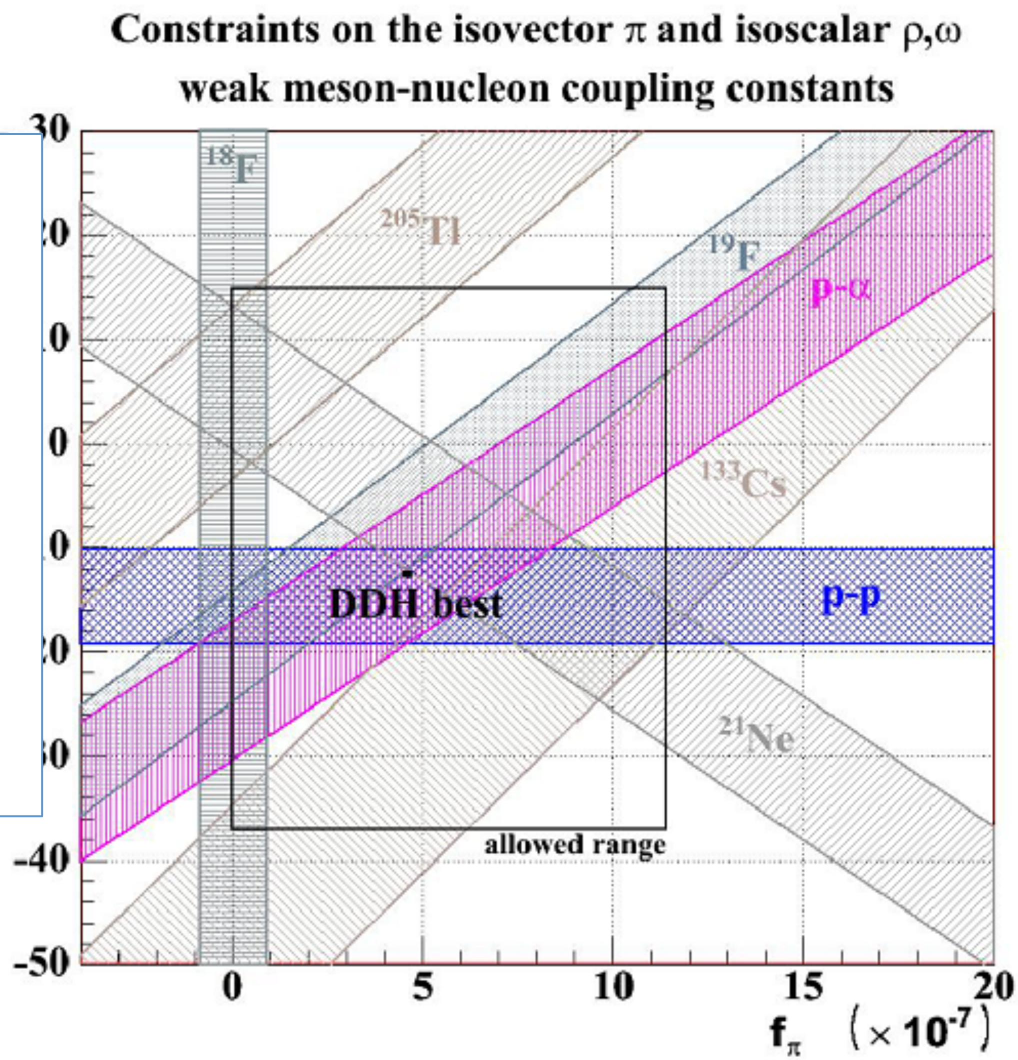
$$O = a_\pi^1 f_\pi^1 + a_\rho^0 h_\rho^0 + a_\rho^1 h_\rho^1 + a_\rho^2 h_\rho^2 + a_\omega^0 h_\omega^0 + a_\omega^1 h_\omega^1$$

	$n+p \to d+\gamma$ A_γ (ppm)	$n+d \to t+\gamma$ A_γ (ppm)	$n\text{-}p\ \varphi_{PV}$ (μrad/m)	$n\text{-}^4He\ \varphi_{PV}$ (μrad/m)	$p\text{-}p\ \Delta\sigma/\sigma$ (ppm)	$p\text{-}^4He\ \Delta\sigma/\sigma$ (ppm)
f_π	-0.107	-0.92	-3.12	-0.97		-0.340
h_ρ^0		-0.50	-0.23	-0.32	0.079	0.140
h_ρ^1	-0.001	0.103		0.11	0.079	0.047
h_ρ^2		0.053	-0.25		0.032	
h_ω^0		-0.160	-0.23	-0.22	-0.073	0.059
h_ω^1	0.003	0.002		0.22	0.073	0.059

Constraints on Weak Meson-Nucleon Isovector and Isoscalar Couplings

Observables on this plot:

- Nuclear anapole moment κ
  ^{205}Tl, ^{133}Cs
- Longitudinal analyzing power A_z
  p-p, p-α
- Photon polarization P_γ
  ^{18}F, ^{21}Ne, $\vec{\gamma}d \to pn$
- Directional gamma asymmetry A_γ
  ^{19}F, $\vec{n}p \to d\gamma$



PV Observables Sensitive to N-N Potential

By V. Gudkov:

models	DDH-best values a_n	P_γ	A_d	4-parameter fits a_n	P_γ	A_d
AV18+UIX/DDH-I	3.30	−6.38	−8.23	1.97	−2.16	−1.81
AV18/DDH-II	4.61	−8.30	−10.3	4.60	−5.18	−4.46
AV18+UIX/DDH-II	4.11	−7.30	−9.04	4.14	−4.71	−4.09
Reid/DDH-II	4.74	−8.45	−10.4	4.70	−5.25	−4.46
NijmII/DDH-II	4.71	−8.45	−10.5	4.76	−5.26	−4.41
INOY/DDH-II	9.24	−12.9	−13.8	17.5	−17.9	−13.5

Another HWI Frame Work - Effective Field Theory

- AFT is based on expansion in low-energy constants.
- Theory has f_π and five low-energy constants corresponding to S-P scattering amplitudes (so called Danilov parameters).
- EFT applies for energies < 40 MeV.
- Model independent

- NN potentials are expressed in terms of 12 parameters, whose linear combinations give us 5 low-energy coupling constants

- connecting to 5 PV S-P N-N amplitudes

$$\lambda_t, \lambda_s^{I=0,1,2}, \rho_t$$

$$^1S_0 \rightarrow {}^3P_0 \quad (\Delta I = 0,1,2)$$
$$^3S_1 \rightarrow {}^1P_1 \quad (\Delta I = 0)$$
$$^3S_1 \rightarrow {}^3P_1 \quad (\Delta I = 1)$$

and a long-range pion-nucleon coupling constant, about same as DDH f_π

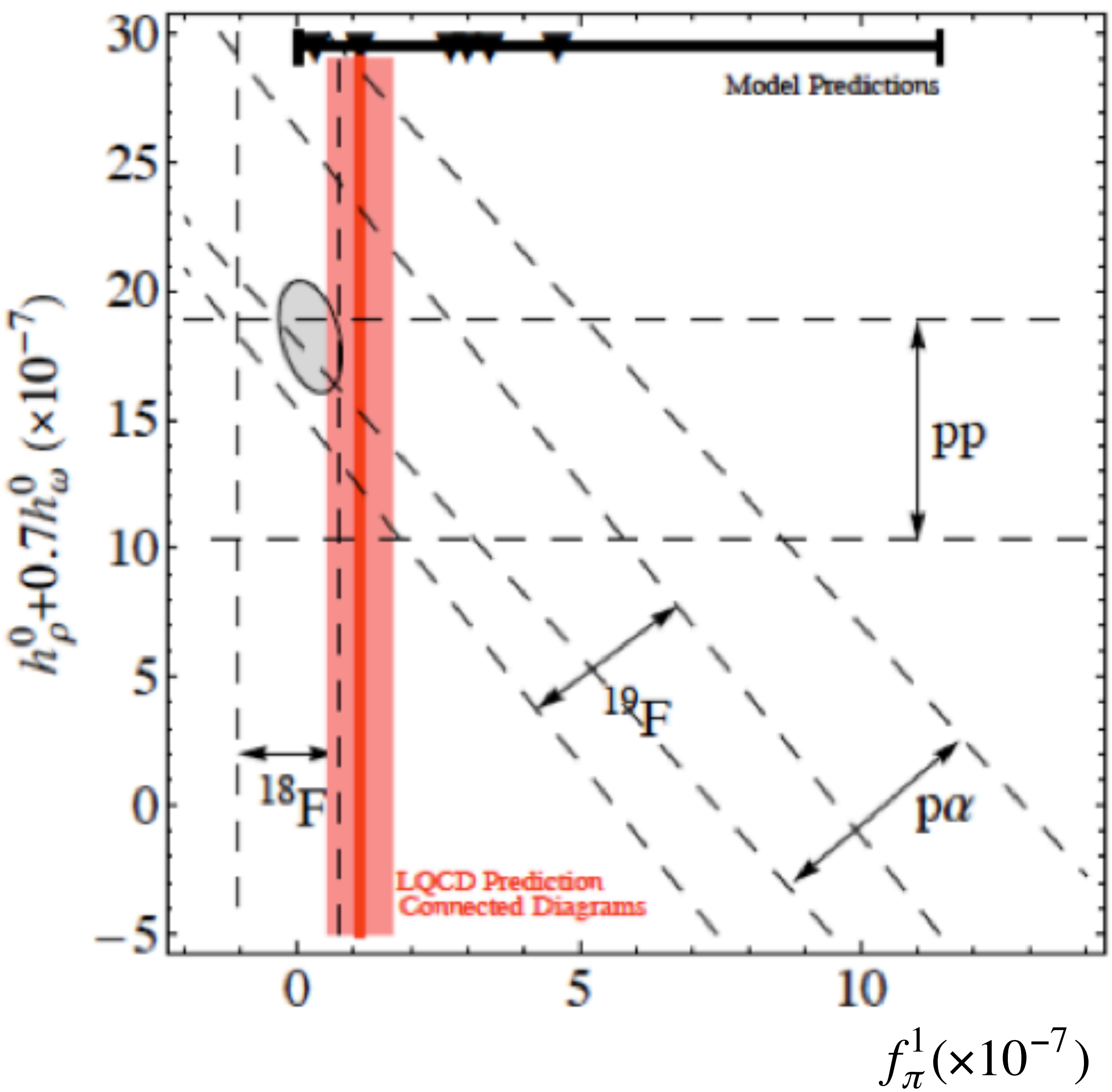
$$A_\gamma^{\vec{n}p} \approx -0.27\tilde{C}_6^\pi - 0.09 m_N \rho_t, \quad m_N \rho_t / \tilde{C}_6^\pi \approx 0.1$$

Status of Two-body Experiments

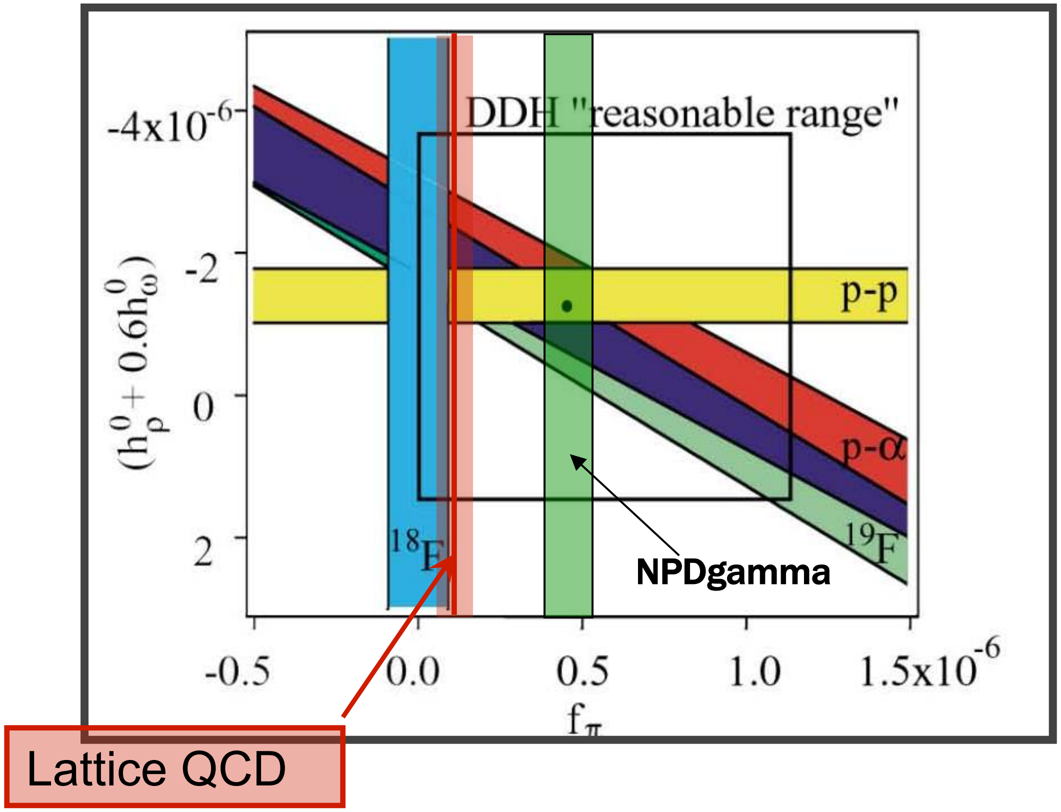
Reaction	Observable	Status
• p-p	$s_p \cdot k_p$	done
• $n+p \rightarrow d+\gamma$	$s_n \cdot k_\gamma$	running at SNS
• $d+\gamma \rightarrow n+p$	$s_\gamma \cdot k_\gamma$	FEL or intense n source
• n+p	$s_n \cdot k_n$	proposed at SNS

Status of Few-body Experiments

• $p+\alpha$	$s_p \cdot k_p$	done
• $n+\alpha \rightarrow n+\alpha$	$s_n \cdot k_n$	spin rotation - done at NIST
• $n+d \rightarrow t+\gamma$	$s_n \cdot k_\gamma$	consideration at SNS
• $n+^3He$	$s_n \cdot k_p$	will run at SNS after NPDGamma
• $n+^3He$	$s_3 \cdot k_n$	polarized 3He - consideration



Lattice QCD: Wasem et al. PRC C85(2012) $f_\pi^1 = (1.099 \pm 0.505^{+0.058}_{-0.064}) \times 10^{-7}$



- The experimental results require small f_π and large $h_{\rho,0}$ and $h_{\rho,2}$.
- For f_π only ΔI=1 contributes. The small size is a surprise since ΔI=1 contribution is Cabbibo allowed and ΔI=0 and 2 are suppressed!
  - Where are the neutral current contributions.
- The results try to tell something about the short-range correlations in the non-perturbative regime.

Nuclear PV experiments:
NPDgamma and n-3He

NPDGamma - what is the size of f_π

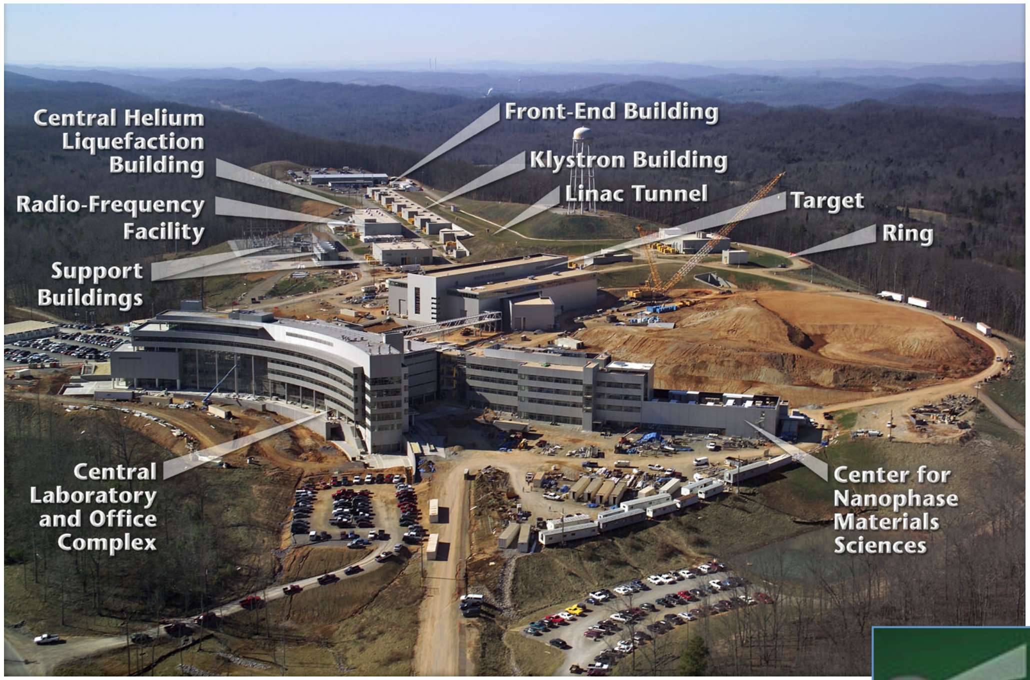
$$\vec{n} + p \rightarrow d + \gamma(2.2\mathrm{MeV})$$

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

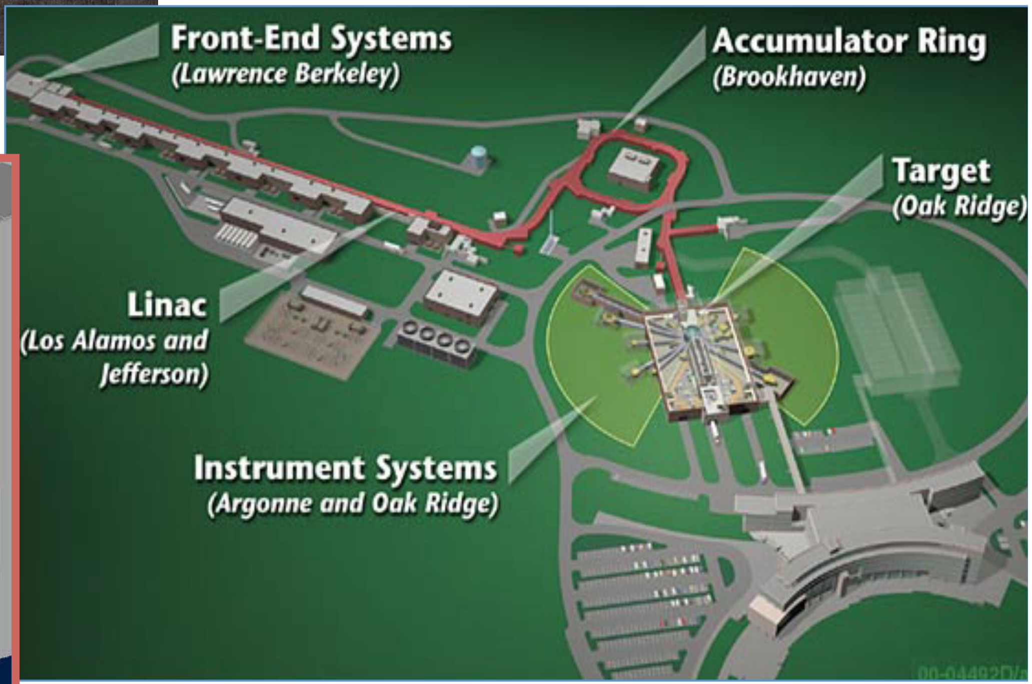
$$\theta_{sk} = \frac{\vec{s}_n \cdot \vec{k}_\gamma}{|\vec{s}_n||\vec{k}_\gamma|}$$

- Deuteron is loosely bound system.
- Long-range pions should contribute most of the weak interaction, measurement gives f_π.
- Deuteron calculable – done with DDH and EFT frame
- $A_\pi \approx - 0.1 \times f_\pi$
- Goal is to measure $A_\gamma = 1x10^{-8}$

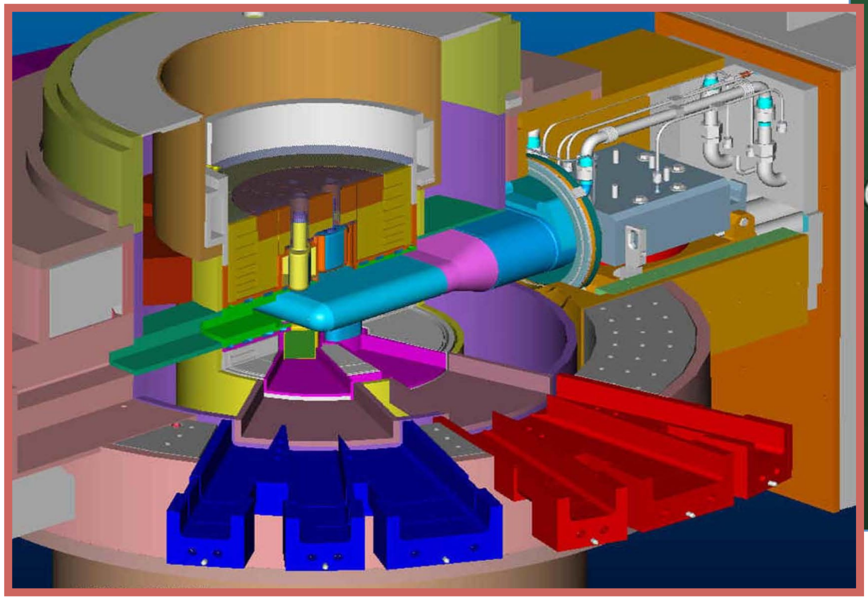
SNS



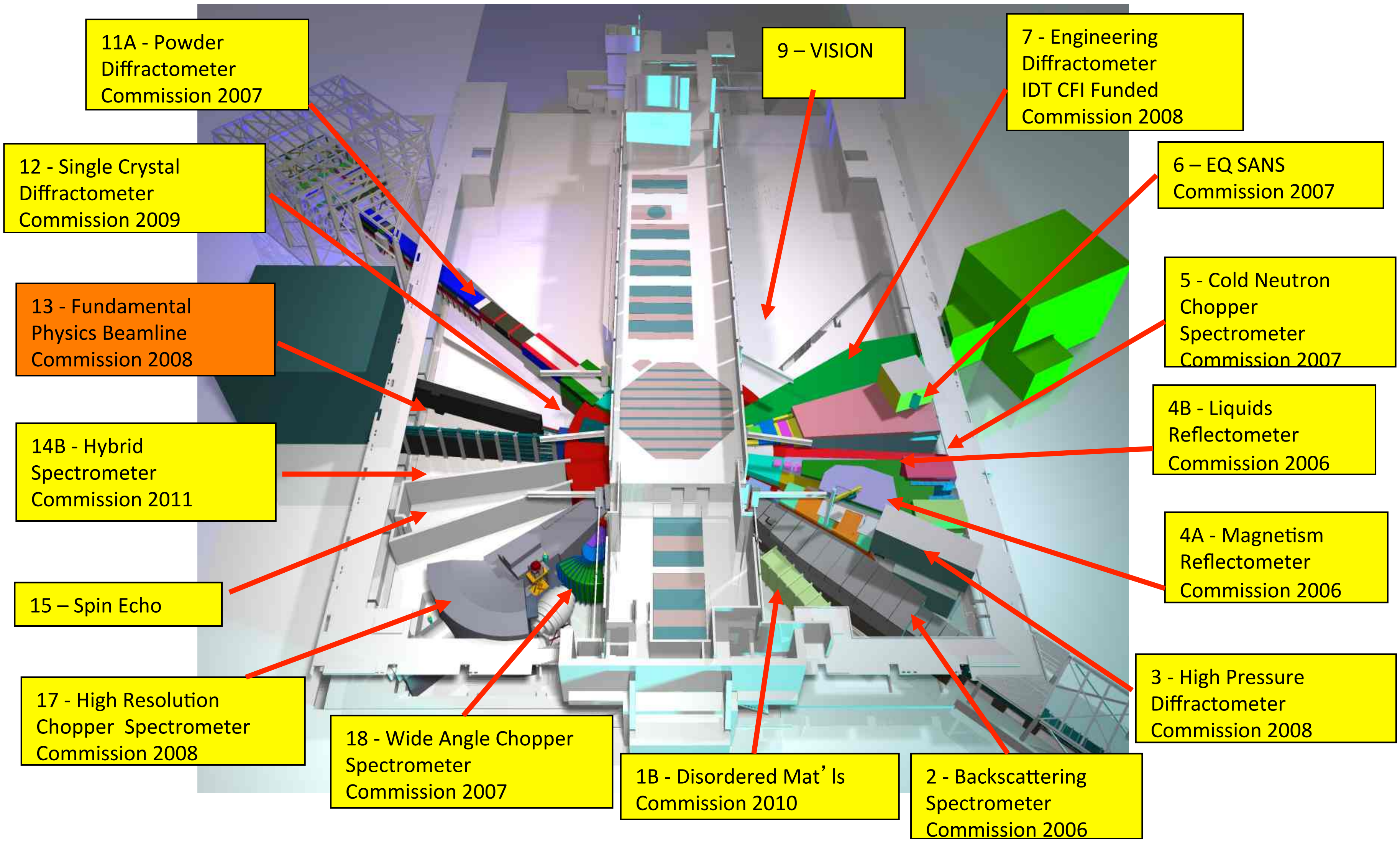
Central Helium Liquefaction Building
Front-End Building
Klystron Building
Linac Tunnel
Radio-Frequency Facility
Target
Ring
Support Buildings
Central Laboratory and Office Complex
Center for Nanophase Materials Sciences



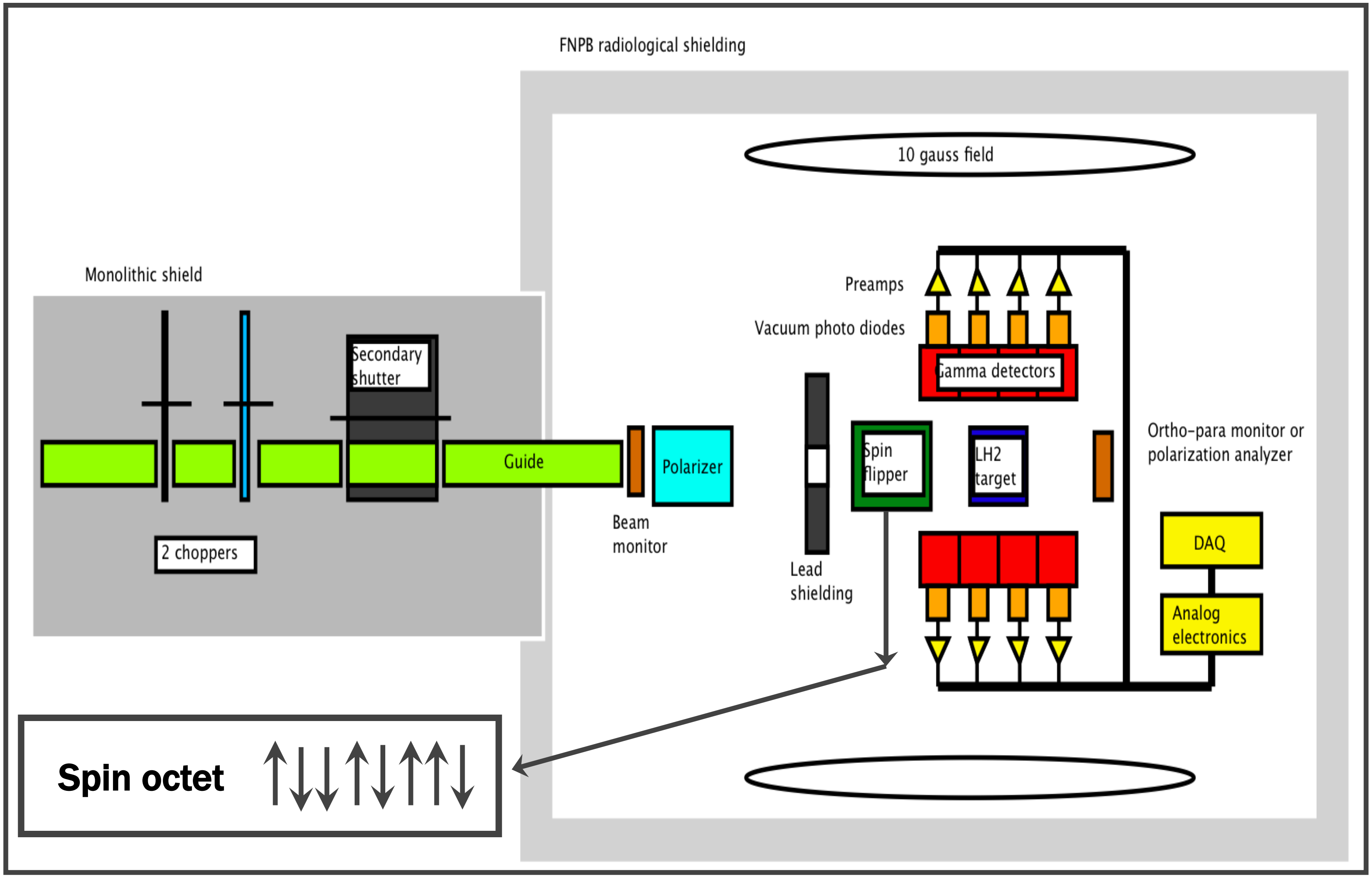
Front-End Systems
(Lawrence Berkeley)
Accumulator Ring
(Brookhaven)
Target
(Oak Ridge)
Linac
(Los Alamos and Jefferson)
Instrument Systems
(Argonne and Oak Ridge)



Spallation Neutron Source at ORNL and BL13

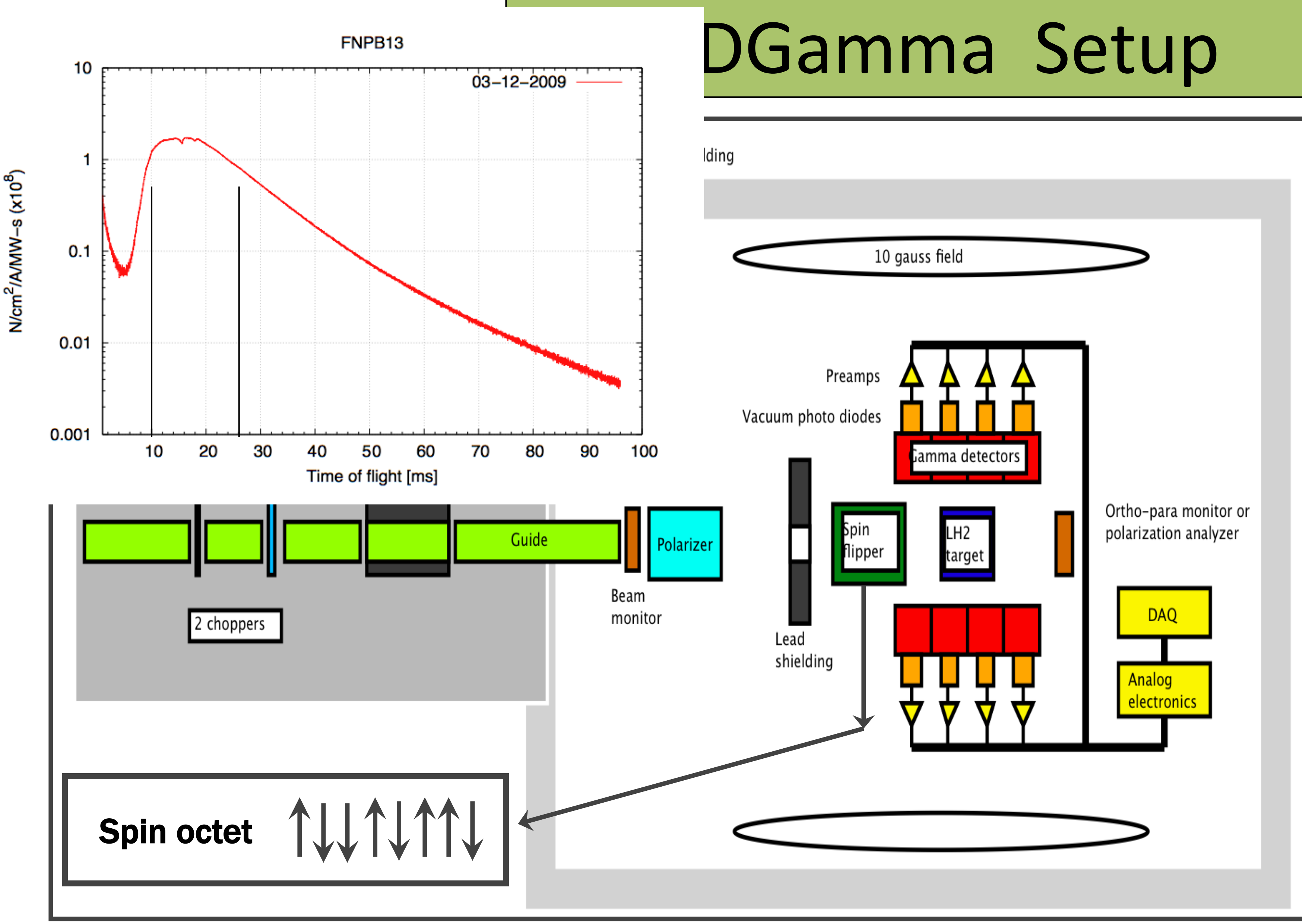


NPDGamma Setup



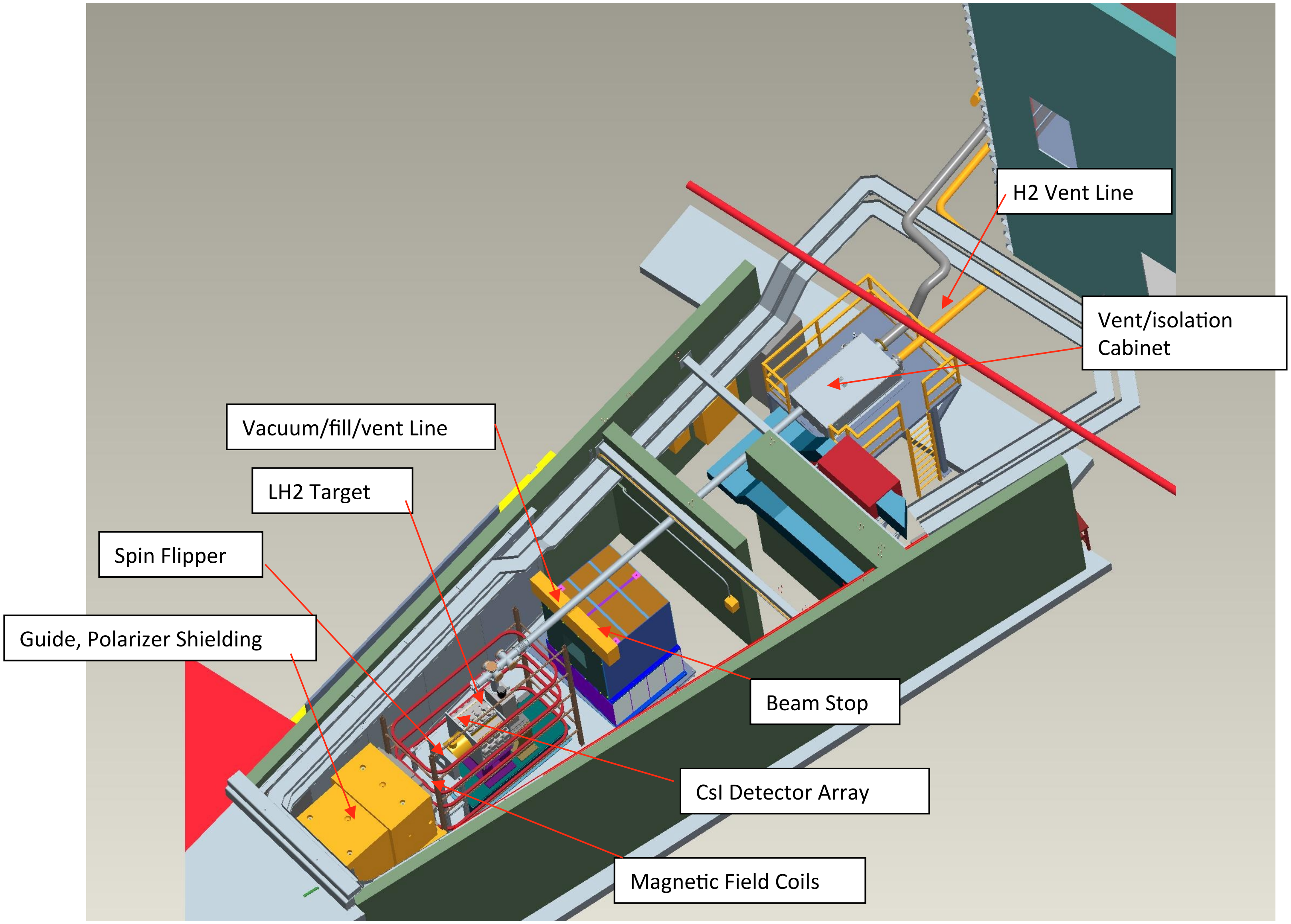
Current mode experiment

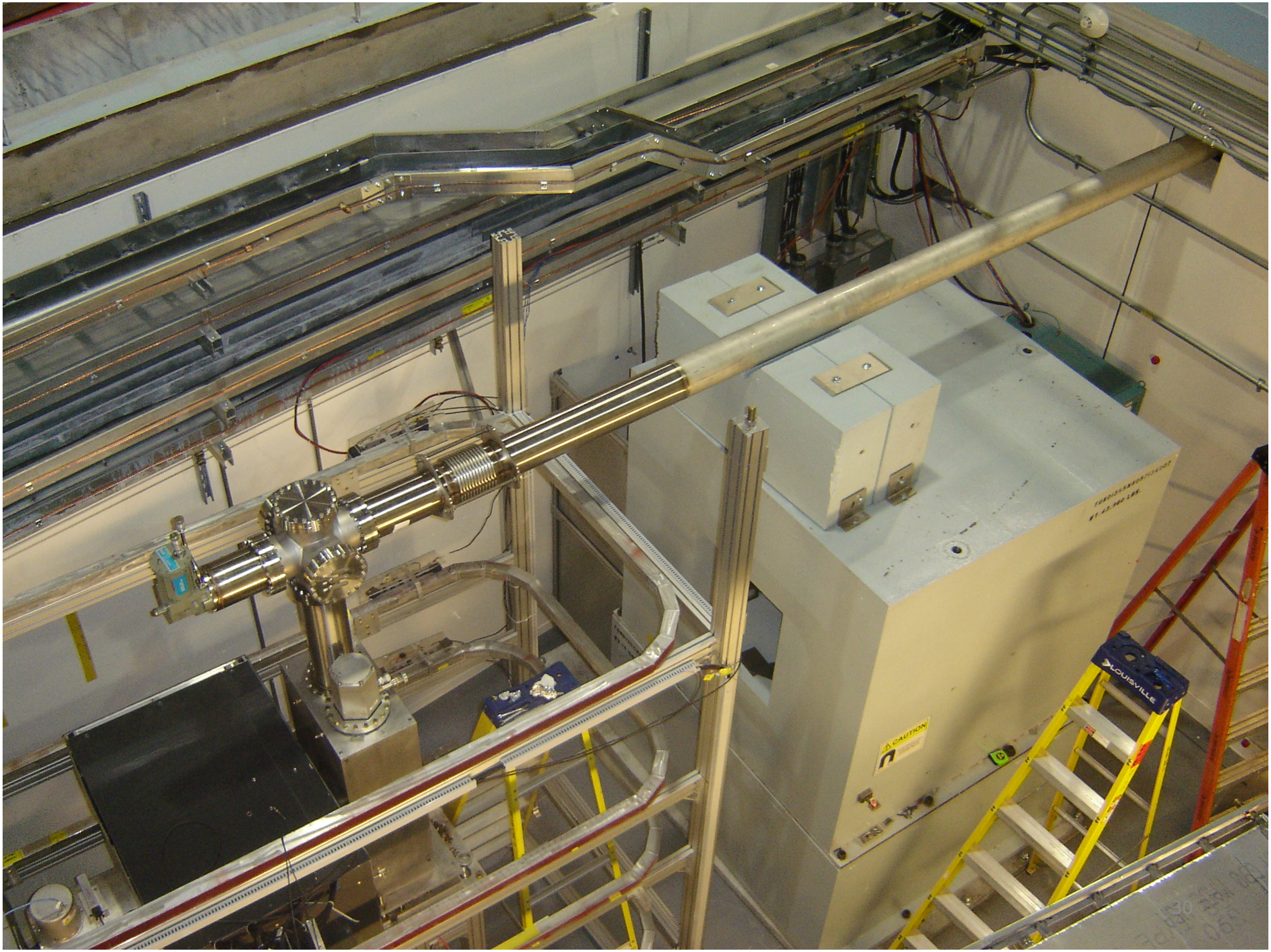
DGamma Setup



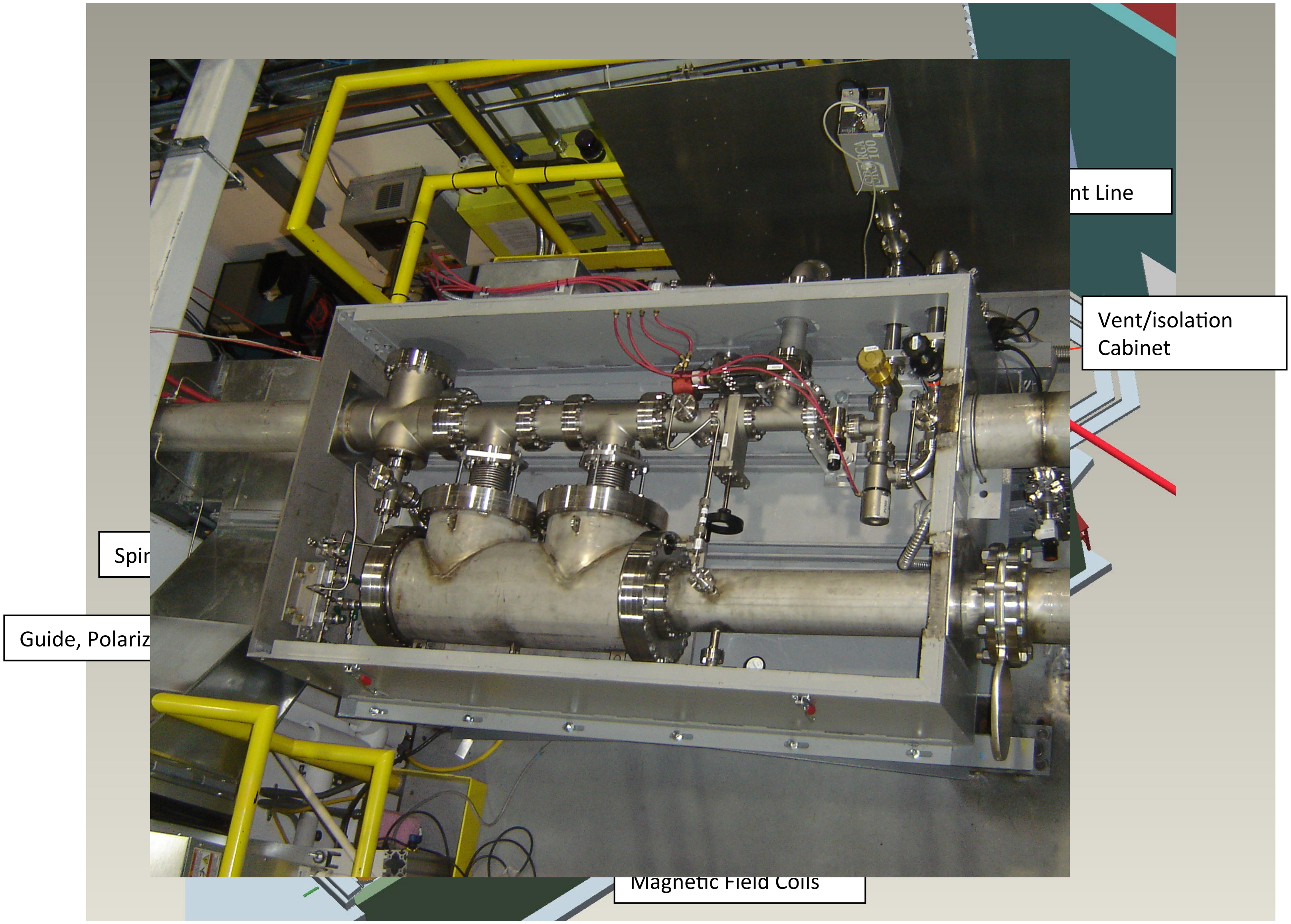
Current mode experiment

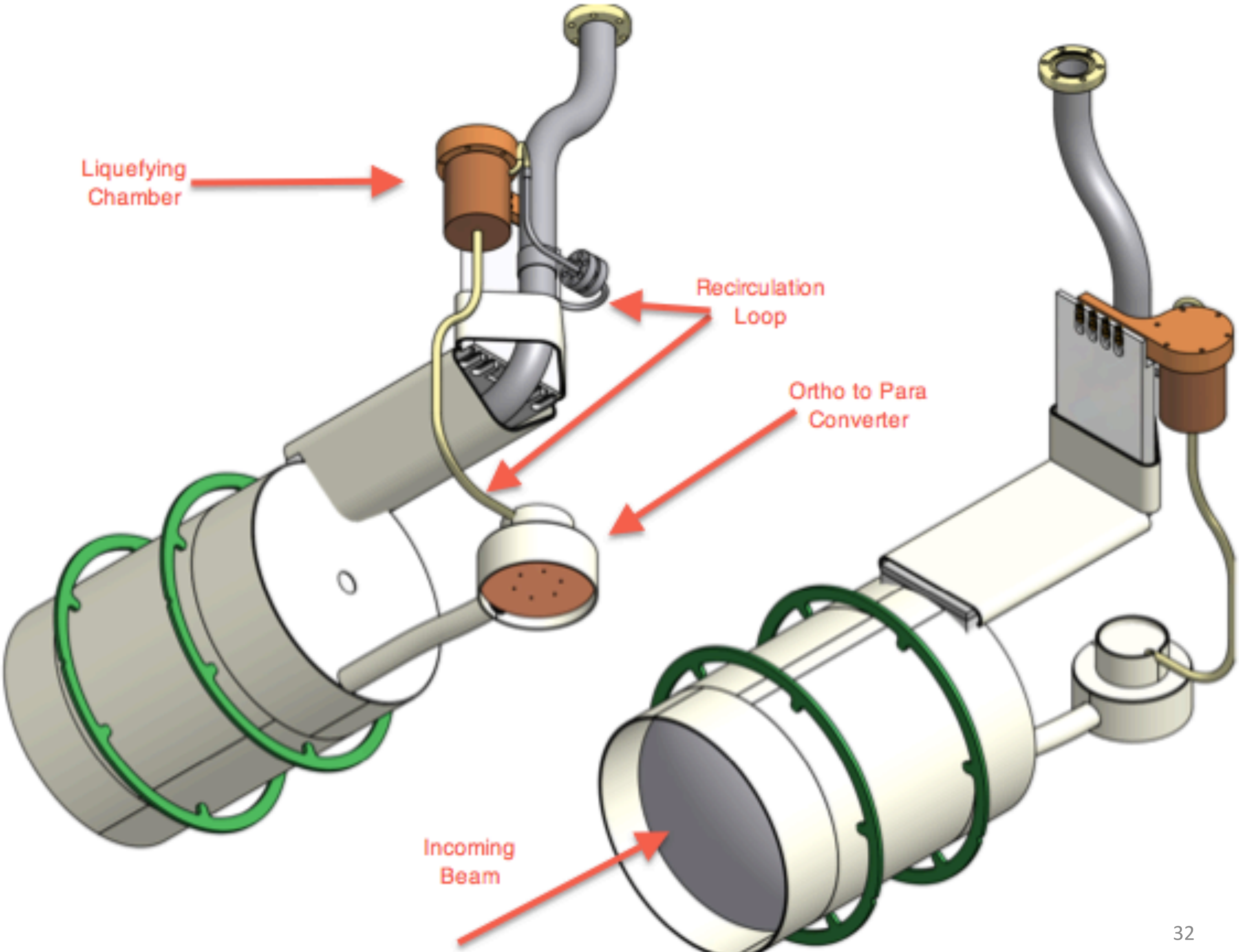
A model view of the NPDGamma



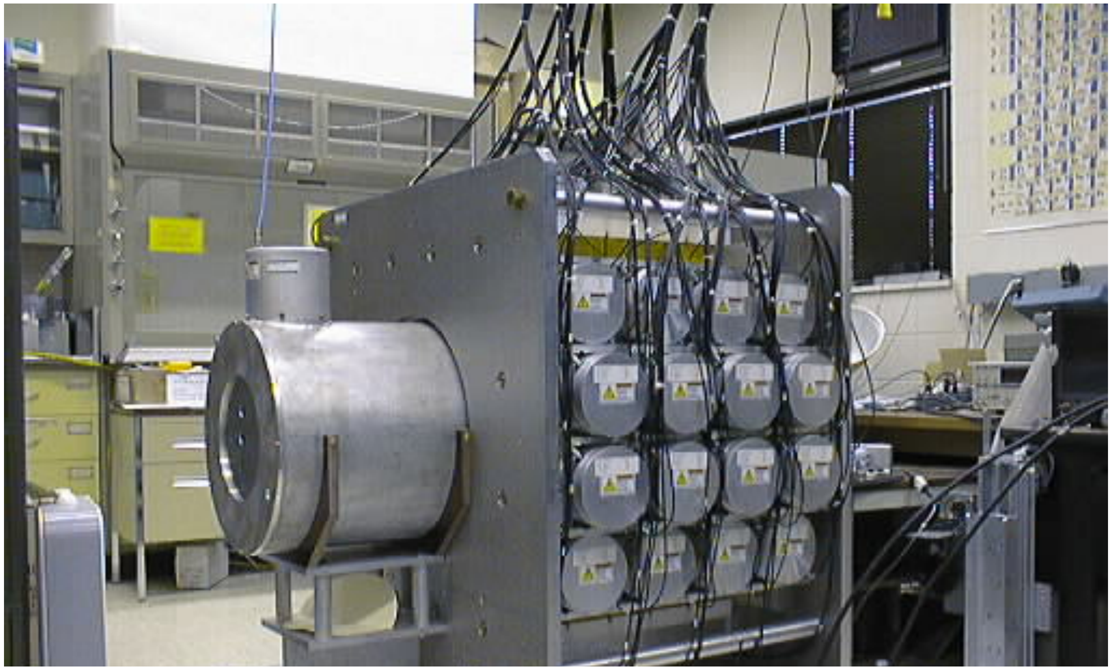

CAUTION
LOUISVILLE

A model view of the NPDGamma



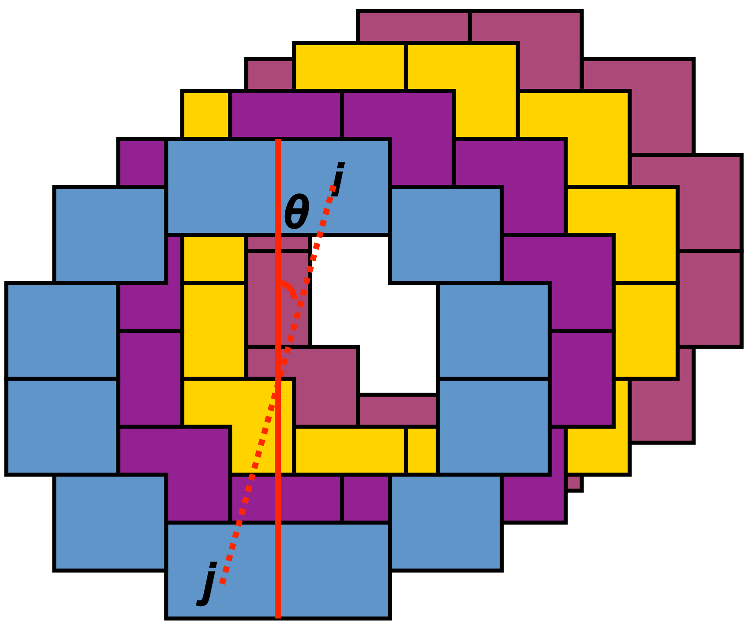


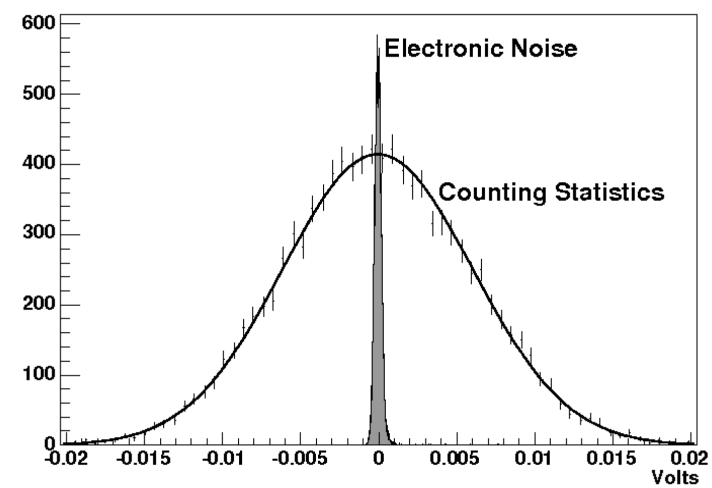
Liquefying Chamber
Recirculation Loop
Ortho to Para Converter
Incoming Beam

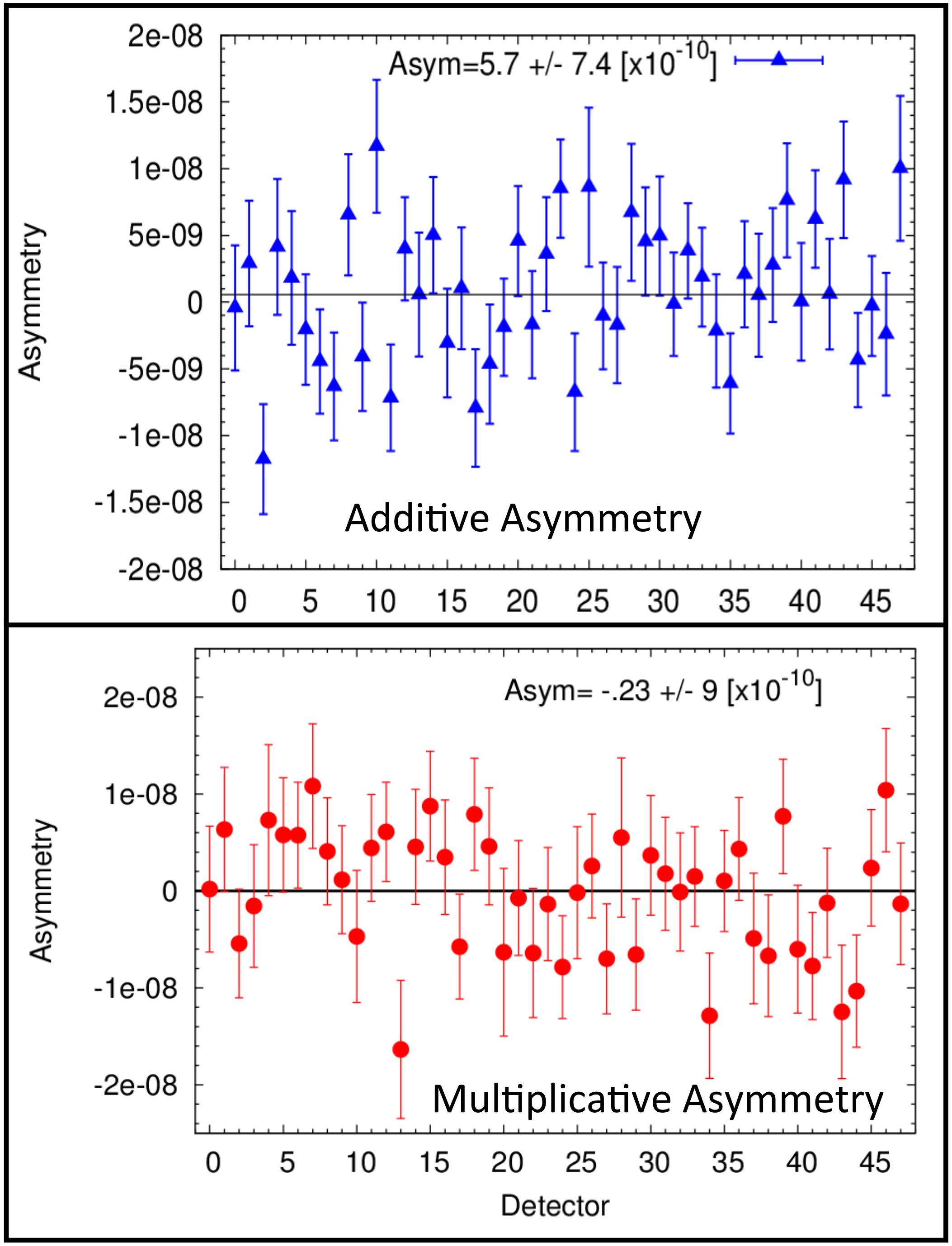


Detector - Array

- 3π acceptance
- Current-mode experiment
- γ-rate ~100 MHz (single detector)







Goal of the experiment:
$dA_\gamma = 1\times10^{-8}$

- Any instrumental asymmetries must be consistent with zero at 10^{-9} level.

NPDGamma Collaboration

R. Alracon[1], R. Allen[2], S. Balascuta[1], L. Barron-Palos[3], S. Baeßler[2,4], A. Barzilov[5], D. **Bowman**[2], M. Bychkov[4], J.R. Calarco[6], R.D. Carlini[7], W. Chen[8], T. Chupp[9], C. Crawford[10], N. Fomin[11], E. Frlez[4], W. Fox[12], M. Gericke[13], C. Gillis[12], K. Grammer[14], G. Greene[2,14], J. Hamblen[15], F. Hersman[6], G.L. Jones[16], S. Kucucker[14], B. Lauss[17], T. Tong[2], M. Maldonado-Velazquez[3], E. Martin[10], R. Mahurin[13], M. McCrea[13], Y. Masuda[18], J. Mei[12], G.S. Mitchell[20], P. Mueller[2], S. Muto[18], M. Musgrave[14], H. Nann[12], I. Novikov[21], S. Page[13], D. Pocinic[4], S. Penttila[2], A. Salas-Bacci[4], S. Santra[21], P.-N. Seo[4], E. Sharapov[22], W. Snow[12], Z. Tang[12], J.S. Waldecker[15], W. Wilburn[12]

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[10]University of Kentucky
[11]Los Alamos National Laboratory
[12]Indiana University
[13]University of Manitoba, Canada
[14]University of Tennessee
[15]University of Tennessee, Chattanooga
[16]Hamilton College
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[18]High Energy Accelerator Research Organization (KEK), Japan
[19]University of California at Davis
[20]Western Kentucky University
[21]Bhabha Atomic Research Center, India
[22]Joint Institute of Nuclear Research, Dubna, Russia

Undergrads:

Arizona:
- D. Blyth

Kentucky:
- K. Craycraft

Uva:
- D. Evans

Indiana:
- J. Fry

………

"How can I help?"

We need hydrogen target operators for the experiment

"if the US Navy can operate nuclear subs driven by teenagers, we can operate a hydrogen target"

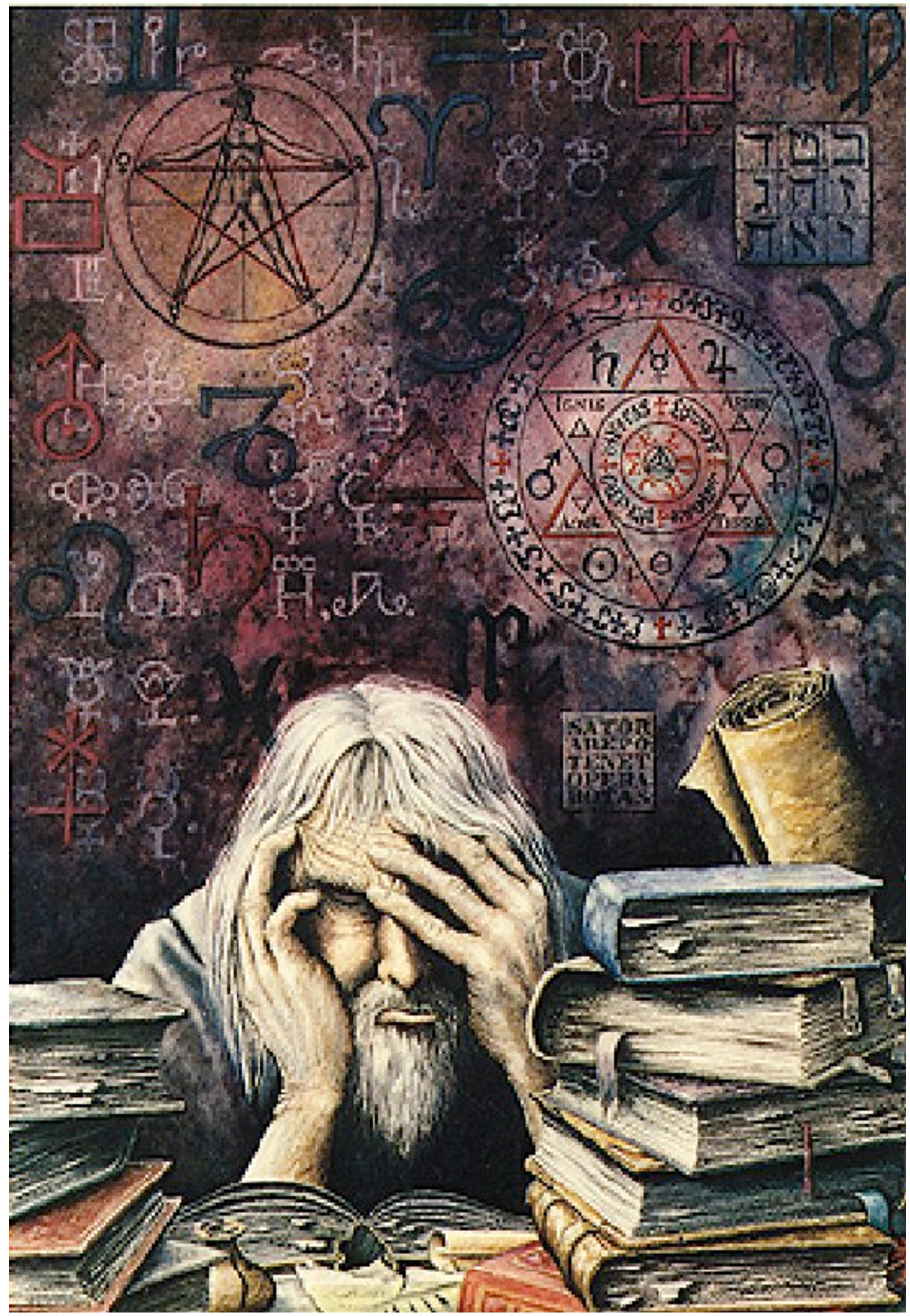
"junior" and "senior" operators will be needed

If you want to come to IU and help us in testing, you are very welcome

Today we have 32 trained and authorized LH2 tgt operators and also now we have been authorized occupy experiment only two shifts per day.

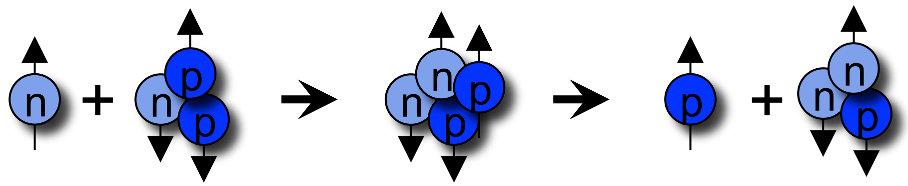
Hydrogen data runs will
last at least to the end of 2013.
Then we will have ½ year for
Systematic studies.

At present we are analyzing
Al, Cl, and hydrogen data and
the grad students are working
with their thesis.



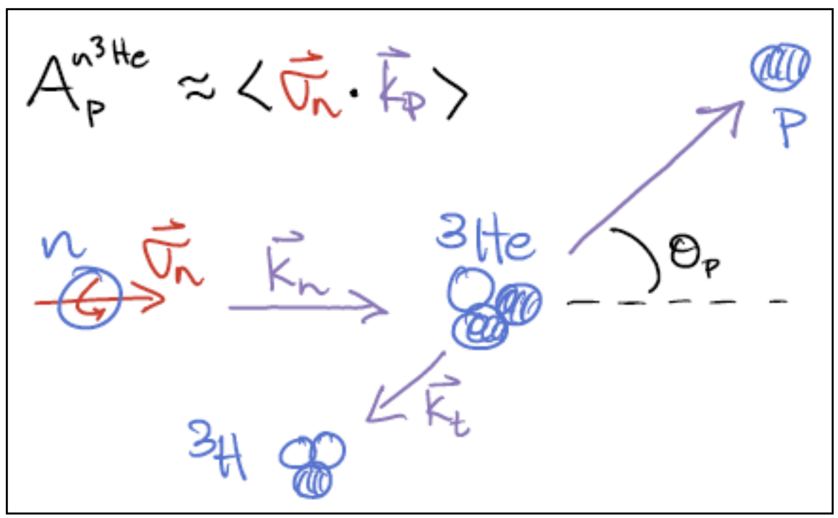
Study of PV in n-3He

PV asymmetry in n-^{3}He

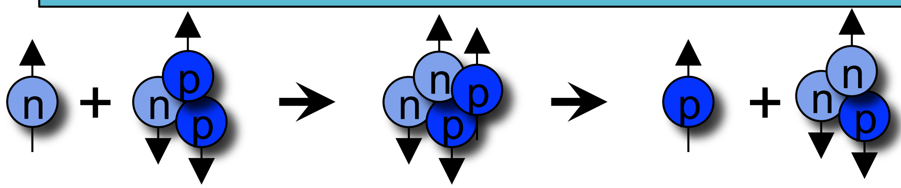


$$\vec{n} + {}^3\mathrm{He} \rightarrow \mathrm{p} + \mathrm{t} + 764\ \mathrm{keV}$$

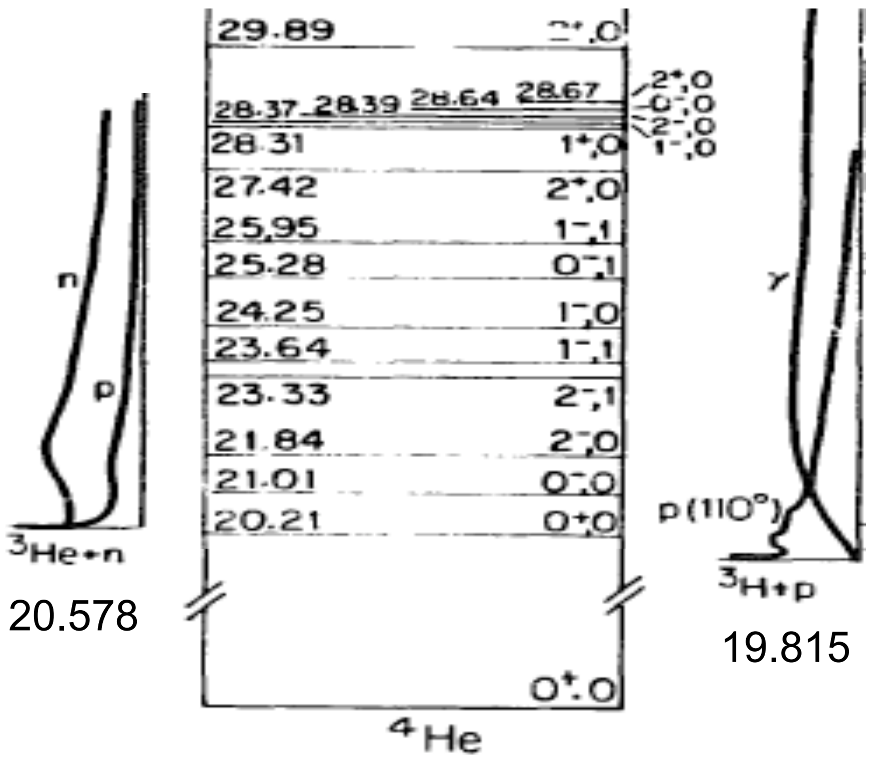
PV observables:



PV asymmetry in n-^{3}He



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



- Sensitive to isoscalar meson-nucleon couplings (I=0) of the HWI
- Complementary to NPDGamma (I=1) and p-p scattering (I=0 & 2)
- Large asymmetry $A_p = 1.15 \times 10^{-7}$ Viviani, et al., PRC 82, 044001 (2010)

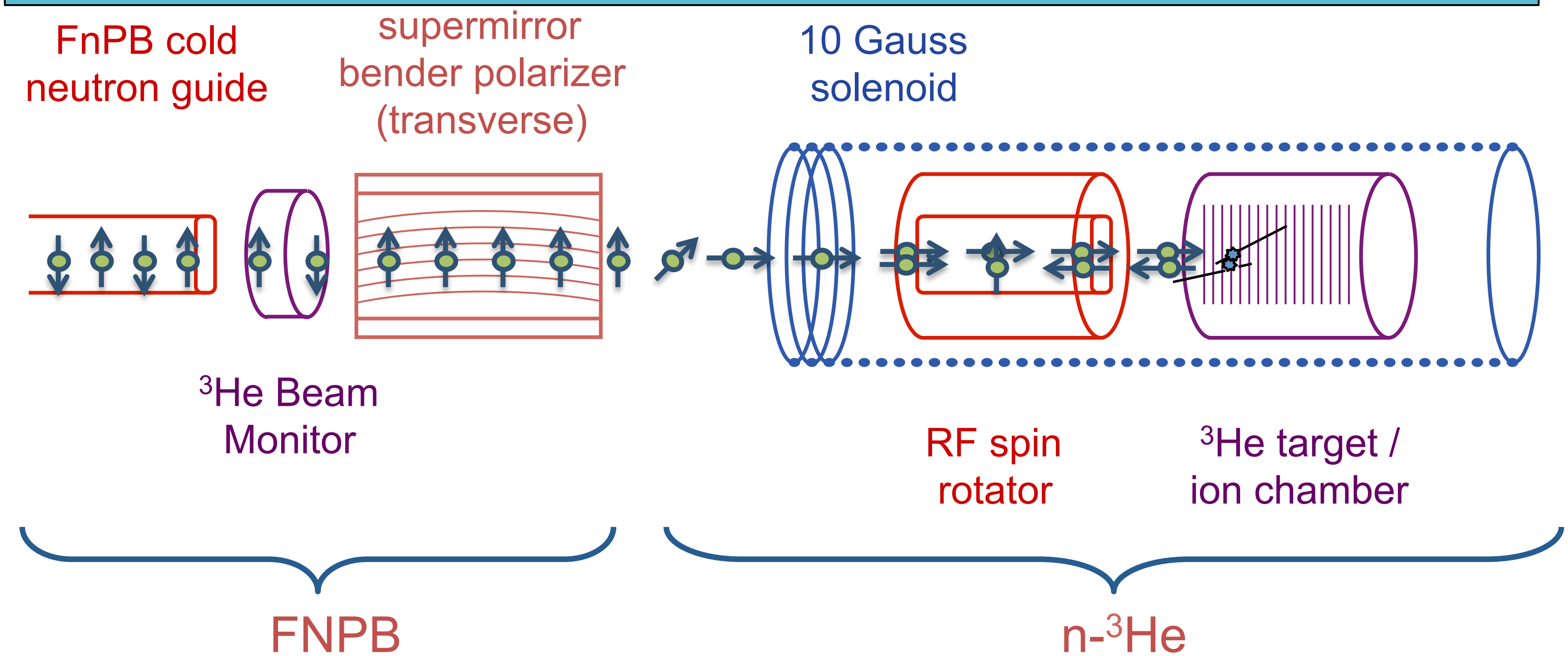
Tilley, Weller, Hale, Nucl. Phys. A541, 1 (1992)

Sensitivity matrix for few-body reactions

Observable	Exp. $[10^{-7}]$	c_π	c_ρ^0	c_ρ^1	c_ρ^2	c_ω^0	c_ω^1
X_N^p	35±2	5.5	-1.13	-4.8	0	-.91	-.77
X_N^n	(38±10)	-5.5	-1.13	-4.8	0	-.91	-.77
^{18}F	1.2±3.9[10^4]	3850.	0	0	0	0	0
A_L^{pp} (15 MeV)	-1.7±0.8	0	0.0419	0.0419	0.0171	0.0460	0.0460
A_L^{pp} (45 MeV)	-2.3±0.9	0	0.0739	0.0739	0.0302	0.0670	0.0670
A_L^{pp} (221 MeV)	0.84±.34	0	0.0391	0.0391	0.0160	0	0.
A_L^{pd}	-.35±.85	0.2307	0.0237	0.0098	0	0.0167	0.01256
$A_L^{p^4He}$	-3.3±0.9	-0.3329	0.1395	0.0474	0	0.0586	0.05859
P_γ^{np}	1.8±1.8	0	-0.0307	0	-0.0245	0.0084	0
A_γ^{np}	0.6±2.1	-0.1070	0	-0.0014	0	0	0.0042
A_γ^{nd}	78±34	0.6896	-0.3348	0.9905	0.0559	-0.2218	0.0544
$A_p^{n^3He}$	(1.14±.33)	-0.1892	-0.0364	0.0193	-0.0006	-0.0334	0.0413
$\frac{d\phi_n}{dz}$ (^{4}He)	1.7±9.1	0.97	0.32	-0.11	0	0.22	-0.22
fit – all data		-0.46±0.92	-43.3±8.8	—	37.3±12.9	13.7±9.4	—
fit – few-body		±0.64	±9.3	—	±11.4	±9.5	—
Contribution:	**1.15**	**0.087**	**1.55**	**–**	**-.002**	**-0.47**	**–**

Table 2: Sensitivities of difference PV observables to the DDH couplings. The values in parentheses are fit from the rest of the data using fitted coupling constants, displayed in the bottom section. The last line includes only present few-body measurements and the projected NPDGamma and $\vec{n}$-^{3}He errors.

Experimental setup



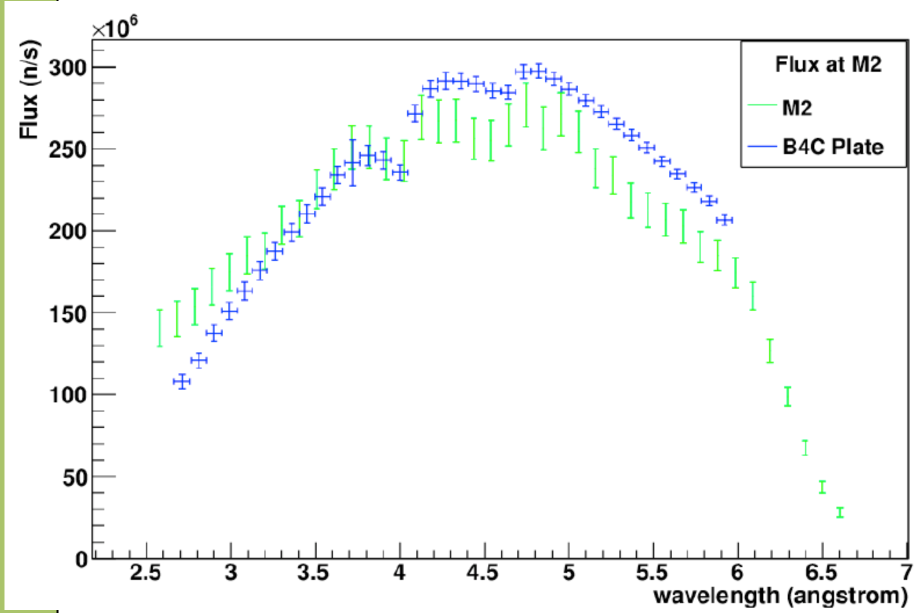
- Longitudinal holding field – suppresses PC nuclear asymmetry $s_n \cdot (k_n \times k_p)$ A=1.7x10^{-6} but suppressed by two small angles
- A novel RF spin flipper – small RF leakage
- ^{3}He ion chamber serves both target and detector

Runtime estimate for n-3He

- N = 1.5×10^{10} n/s   flux (chopped)
  x 10^7 s   (116 days)
- P = 96.2%   neutron polarization
- σ_d = 6   detector efficiency

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

- 15% measurement in one 5000 MW/h beam cycle, assuming $A_z = 1.15 \times 10^{-7}$



Systematics

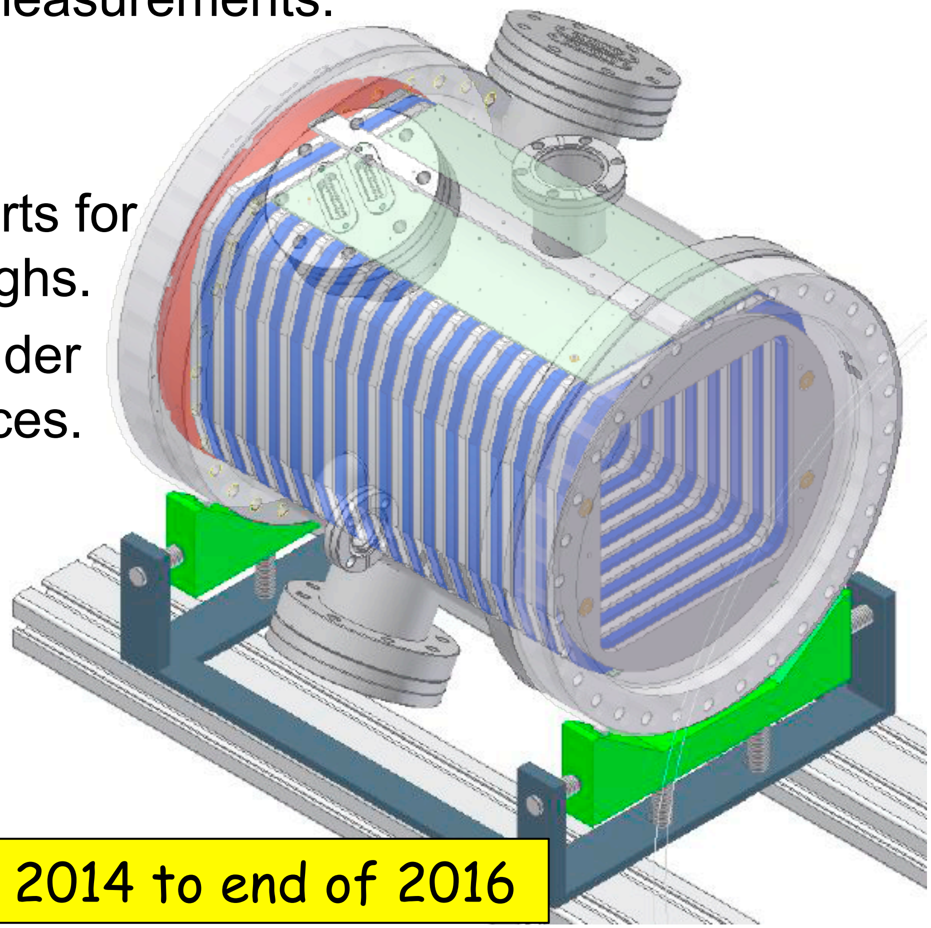
$$A_{exp} = \frac{A_b + PA}{1 + A_p PA}$$

- Beam fluctuations, polarization, RFSF efficiency:
- $k_n r \sim 10^{-5}$ small for cold neutrons
- PC asymmetries minimized with longitudinal polarization
- Alignment of field, beam, and chamber: 10 mrad achievable
- Unlike NPDG, NDTG: insensitive to gammas (only Compton electrons)

Invariant	Parity	Size	Comments
$\vec{\sigma}_n \cdot \vec{k}_p$	Odd	3×10^{-7}	Nuclear capture asymmetry
$\vec{\sigma}_n \cdot (\vec{k}_n \times \vec{k}_p)$	Even	2×10^{-10}	Nuclear capture asymmetry
	Even	6×10^{-12}	Mott-Schwinger scattering
$\vec{\sigma}_n \cdot \vec{B}$	Even	1×10^{-10}	Stern-Gerlach steering
	Even	2×10^{-11}	Boltzmann polarization of ^{3}He
	Even	4×10^{-13}	Neutron induced polarization of ^{3}He
$\vec{\sigma}_n \cdot \vec{k}_p$	Odd	1×10^{-11}	Neutron beta decay

Target Chamber Assembly Schedule

- February 2013: Have test frame finished by Hybrid Sources and verify measurements.
- March 2013: Complete feature machining at UT shop.
- April 2013: Order remaining parts for frame assembly and feedthroughs.
- June-July 2013: Completed solder pad deposition by Hybrid Sources.
- October 2013: Complete chamber assembly
- December 2013: Test with RFSF and DAQ



The N-3He will run from mid 2014 to end of 2016

Conclusions after NPDGamma and n-3He

- NPDGamma measures f_π
- f_π together with p-p result binds/confirms two-body interaction.
- n-3He will benchmark the few-body system
- The best N-N potential will be selected.
- Global fit to selected experimental results produces the four weak N-N couplings.
- Lattice QCD will support the fitting results.

Time Reversal-Invariance Violation (TRIV) in polarized neutron transmission through polarized target

- In compound nuclide T-violating observables as PV-observables are shown to have large enhancements, several orders of magnitude.
- Searches of TRIV in nuclear systems are complementary for EDM measurements.
- Recovery potential

Discrete Symmetries; C, P, T

	$\vec{r}$	$\vec{s}$	$\vec{k}$	$\vec{I}$	$\vec{s}\cdot\vec{k}$	$\vec{s}\cdot\vec{I}$	$\vec{s}\cdot(\vec{k}\times\vec{I})$	$\vec{s}_n\cdot(\vec{k}_n\times\vec{I})(\vec{k}_n\cdot\vec{I})$
$\hat{P}$	-	+	-	+	-	+	-	+
$\hat{T}$	+	-	-	-	+	+	-	-

<u>Other TRIV searches:</u>

In nuclear and neutron beta decay

- D-correlation $\vec{I}\cdot(\vec{p}_e\times\vec{p}_\nu)$ *P* even *T* odd
- R-correlations $\vec{\sigma}\cdot(\vec{I}\times\vec{p}_e)$ *P* even *T* odd
- EDMs
- …

➔ NO sign of *T* violation

Propagation of slow neutron through polarized target material

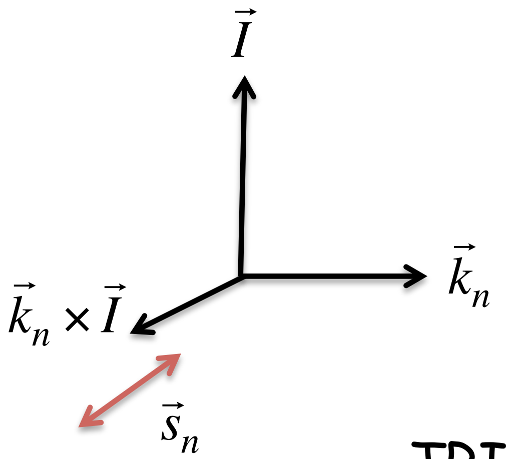
$$f(0^o) = A + B_A p_t(\vec{s}_n \cdot \vec{I}) + B_L p_t(\vec{s}_n \cdot \vec{B}) + C\vec{s}_n \cdot \vec{k}_n + Dp_t(\vec{s}_n \cdot [\vec{k}_n \times \vec{I}])$$

- *A* and B_A and B_L *are* spin independent and spin-dependent Time and Parity even strong and electromagnetic neutron-nucleus interaction.
- Re(B_A) is a pseudomagnetic field in target material.
  - spin rotation about *I*.
- Im($B_{A,L}$) absorption
- Re(*C*) is PV spin rotation about k_n
- *Im* (*C*) PV longitudinal absorption asymmetry
- ***Re(D) and Im(D) simultaneous PV- and TRIV- asymmetry***
  - **Re(D) PV spin rotation about (k_nx*I*).**

B-field is C odd, P even, T odd

No TRIV from final state interaction!

$\vec{s}_n \cdot (\vec{k}_n \times \vec{I})$ correlation



$$\Delta\sigma^{P,T} = \frac{4\pi}{k_n}\mathrm{Im}(f_\uparrow - f_\downarrow) = \frac{4\pi}{k_n}\mathrm{Im}(D)$$

$$\frac{\mathrm{d}\phi^{P,T}}{\mathrm{d}z} = \frac{2\pi N}{k_n}\mathrm{Re}(f_\uparrow - f_\downarrow) = \frac{2\pi N}{k_\mathrm{n}}\mathrm{Re}(D)$$

TRIV effects are enhanced like PV effects in neutron induced nuclear scattering

$$A^{P,T} = \frac{\sigma_\uparrow^{P,T} - \sigma_\downarrow^{P,T}}{\sigma_\uparrow^{P,T} + \sigma_\downarrow^{P,T}} = 2\sum_s \frac{V_{sp}^{P,T}}{(E_s - E_p)} \frac{\sqrt{\Gamma_{ns}}}{\sqrt{\Gamma_{ps}}}$$

At same nuclei and neutron energy

$$\lambda = \frac{V^{P,T}}{V^P} \approx \frac{g^T}{g^P},$$

where g^T and g^P are TRIV and PV nucleon-nucleon coupling constants.

Depending on used CP model λ = 10^{-2} – 10^{-10} .

Model	λ
Kobayashi – Maskawa	$\leq 10^{-10}$
Right – Left	$\leq 4\times10^{-3}$
Horizontal Symmetry	$\leq 10^{-5}$
Weinberg (charged Higgs bosons)	$\leq 2\times10^{-6}$
Weinberg (neutral Higgs bosons)	$\leq 3\times10^{-4}$
θ-term in QCD Lagrangian	$\leq 5\times10^{-5}$
Neutron EDM (one π-loop mechanism)	$\leq 4\times10^{-3}$
Atomic EDM (^{199}Hg)	$\leq 2\times10^{-3}$

PV-TRIV in n-D scattering

$\vec{s}_n \cdot (\vec{k}_n \times \vec{I})$ correlation

Including only dominant pion exchange, λ can be estimated to be

$$\lambda = \frac{\Delta\sigma^{P,T}}{\Delta\sigma^{P}} \approx (-0.47)\left(\frac{\overline{g}_\pi^{(0)}}{f_\pi^1} + 0.26\frac{\overline{g}_\pi^{(1)}}{f_\pi^1}\right)$$

The CP-odd coupling constant $\overline{g}_\pi^{(0)}$ can be related to the value of neutron EDM d_n generated via π-loop. Using the latest experimental limit on d_n,

$$\overline{g}_\pi^{(0)} < 2.5 \times 10^{-10}$$

Constant $\overline{g}_\pi^{(1)}$ can be bound using ^{199}Hg atomic EDM

$$\overline{g}_\pi^{(1)} < 0.5 \times 10^{-11}$$

and $f_\pi^1 \approx 1 \times 10^{-7}$ we have from NPDGamma.

$$\lambda < 1 \times 10^{-3}$$

TRIV in complex nuclei

$\vec{s}_n \cdot (\vec{k}_n \times \vec{I})$ correlation

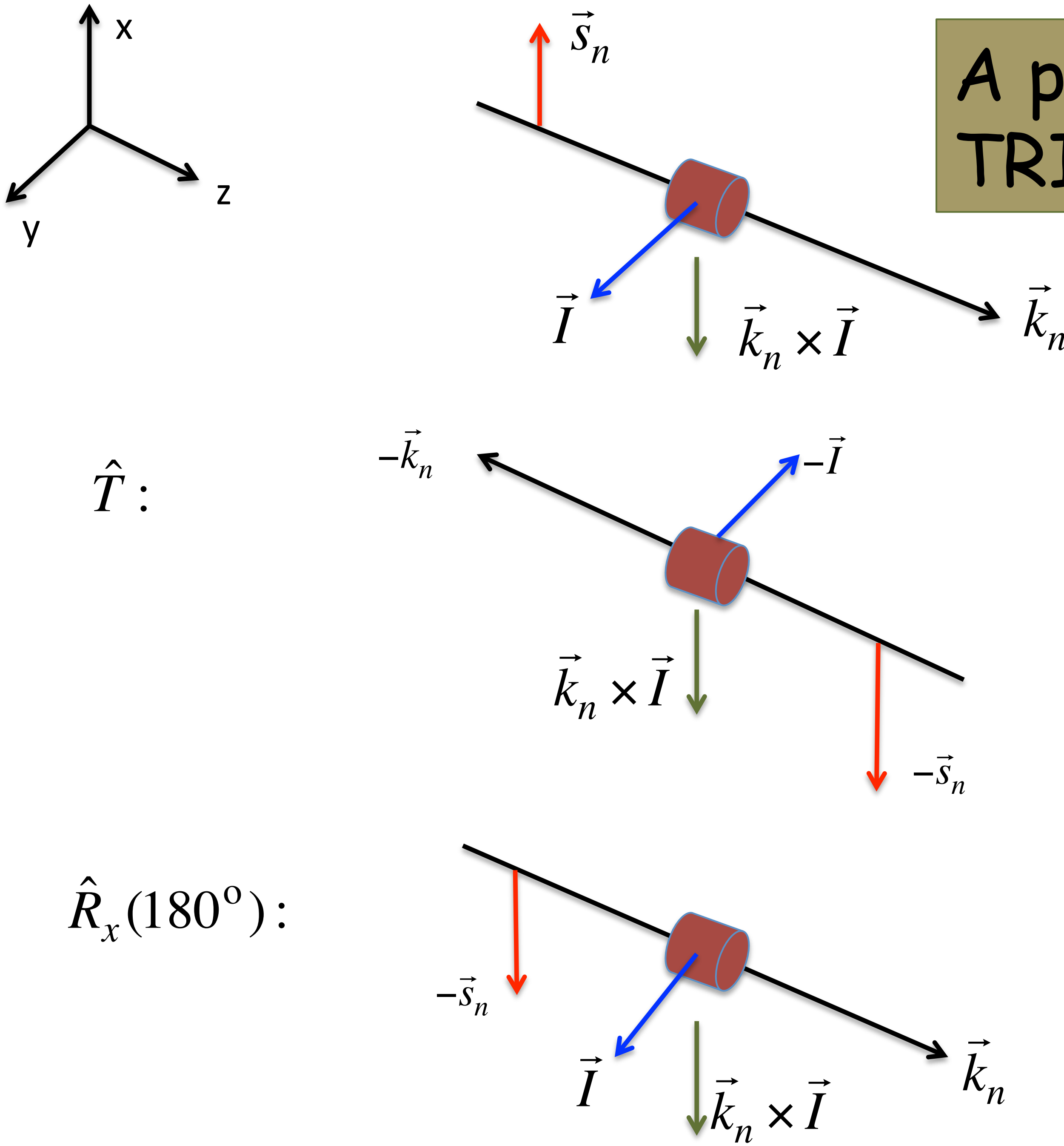
The assumption is that we can measure λ with accuracy of 10^{-5} in complex nuclei such as ^{139}La

$$\frac{\Delta\sigma^{PV}}{\sigma_{\text{total}}} = 0.09$$ at La 0.748-eV p-wave resonance.

$$\Delta\sigma^{P,T} = \lambda\Delta\sigma^{P} = 10^{-5} \times 10^{-1} = 10^{-6}$$

No experiments so far !

A principle of the TRIV experiment:



There are Practical Issues:

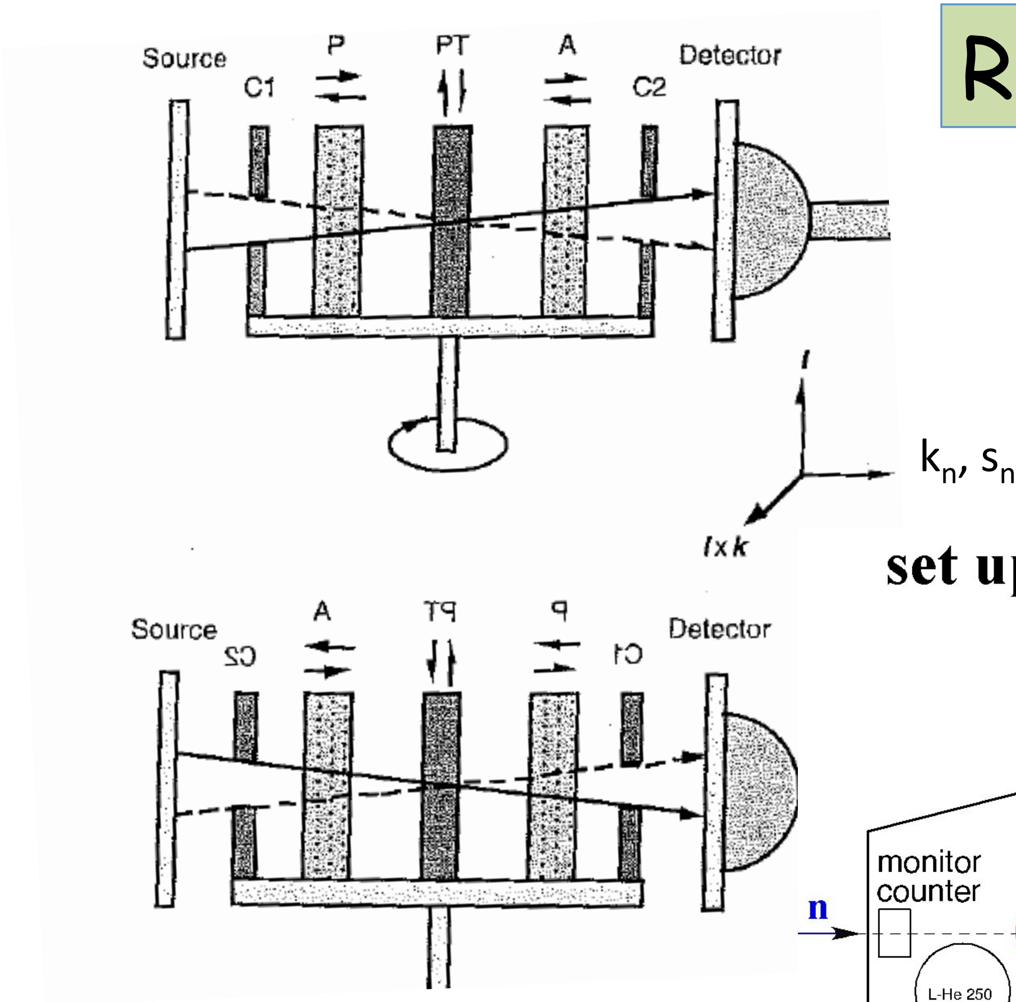
Polarized target:

- $^{139}LaAlO_3$ single crystal with 0.03% neodymium doping has been dynamically polarized at 2.5 T and 0.5 K.
- Polarization achieved 20-50% measured with neutrons.

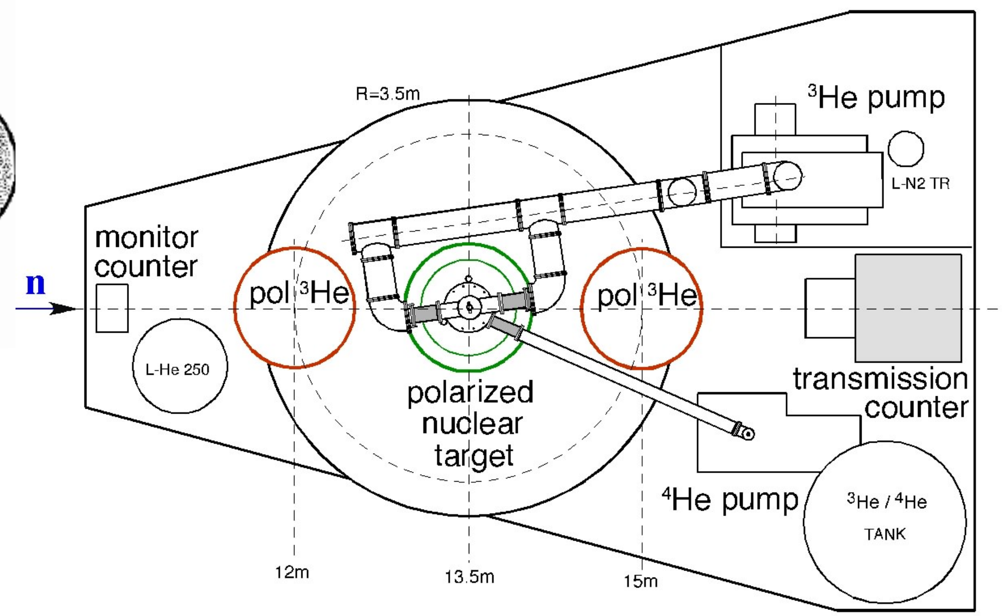
- Another possible target is ^{129}Xe or ^{131}Xe
- Advantage of Xe
  - optically polarized
  - small B-field required
  - target material is homogenous
- BUT only some neutron transmission enhancements observed around 9.5-eV and 14.4-eV s-waves.

- In a TRIV experiment polarizer and analyzer are polarized ^3He spin filters.

Rotating Table



set up for T-violation experiment



And other Problems are:

<u>About Systematics :</u>

Many sources of small systematic errors :

✓ apparatus is not linear

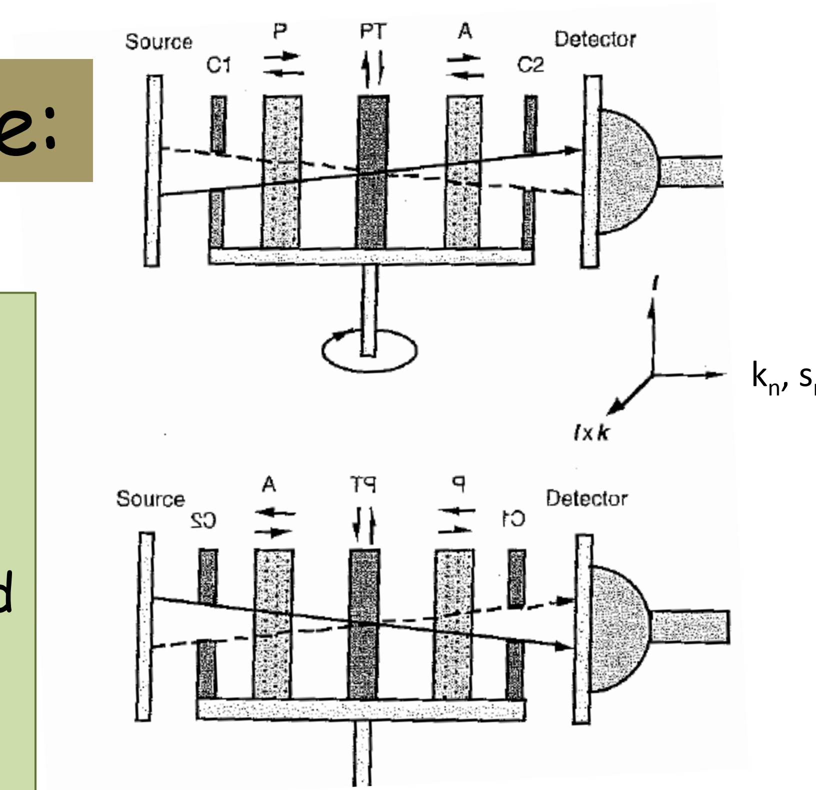
✓ analyzing powers of polarizer and analyzer are not same

✓ inhomogeneities in materials passed by neutrons

✓ rotation of neutron spin by target field (2.5T) $(\vec{s}_n \cdot \vec{B})$

✓ rotation of neutron spin due to $\vec{s}_n \cdot \vec{I}$ interaction

✓ ………



Conclusions

- Search of TRIV in neutron transmission has a recovery potential.
- Possibility to learn more about structure of weak interaction - TRIV N-N couplings at low momentum transfer
- Requires a few polarized nuclear targets : La, Xe,…
- Lately progress done in theory of TRIV in neutron – interaction
  - Theory for EDM
  - n-D calculated in DDH frame and in EFT
- But in experimental side not much progress - JPARC
- Experimental progress requires a neutron beamline with eV-range neutrons for significant feasibility and R&D effort?

Backup slides

In SM EDMs are due to CP-violation in the quark weak mixing matrix, CKM matrix

- To get EDMs at least three loops are needed
  $\Rightarrow$ In SM neutron EDM is ~ 10^{-32} e-cm

Non-Relativistic Hamiltonian

$$H = \vec{\mu} \cdot \vec{B} + \vec{d} \cdot \vec{E}$$

C-even C-even
P-even P-odd
T-even T-odd

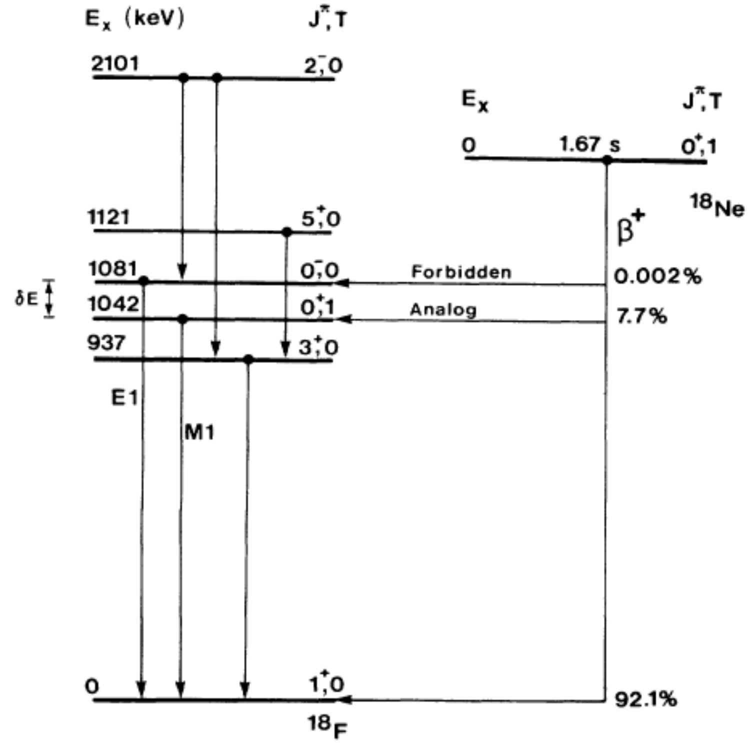
	C	P	T
$\vec{J}$	+	+	-
$\vec{\mu}$	-	+	-
$\vec{d}$	-	+	-
$\vec{B}$	-	+	-
$\vec{E}$	-	-	+

Non-zero *d* would violate P,T, and CP

^{18}F and ^{133}Cs anapole moment

1. Measurement of the circular polarization of emitted γ rays in the ^{18}F transition 0^- (1.08MeV) $\longrightarrow 1^+$(g.s)

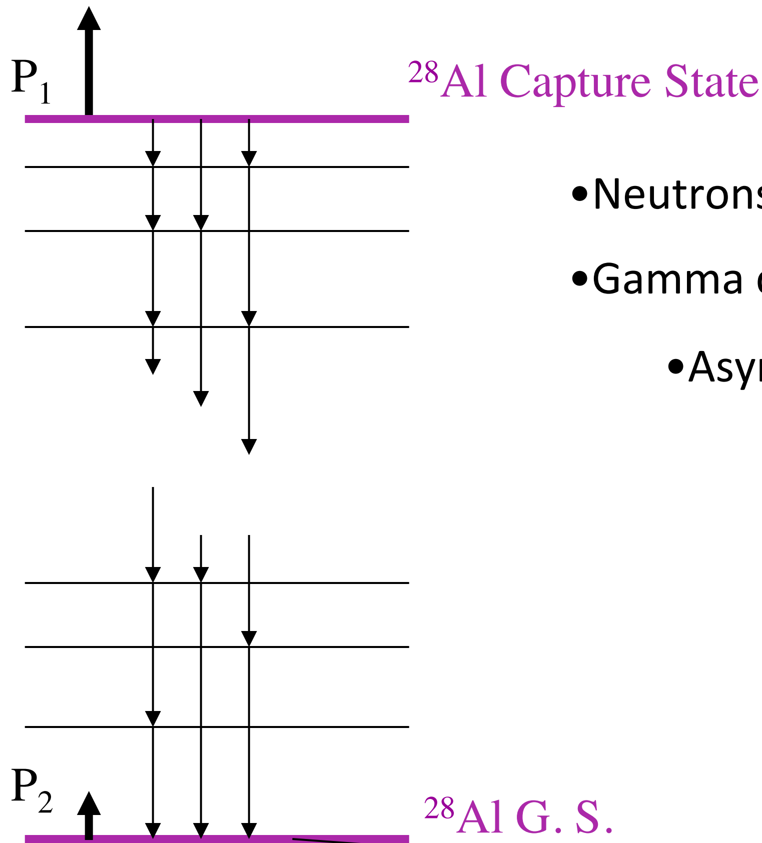
Result: $|f_\pi| \leq 1.3 \times 10^{-7}$



2. ^{133}Cs Anapole moment measurement

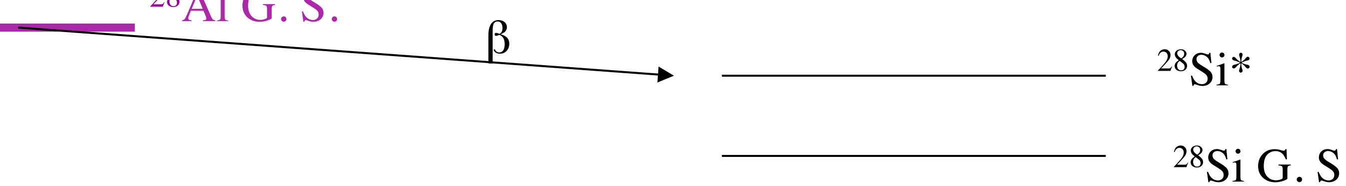
   - Atomic Spectroscopy result
   - f_π had to be separated from other effects,

Challenging Example: Capture on Aluminum



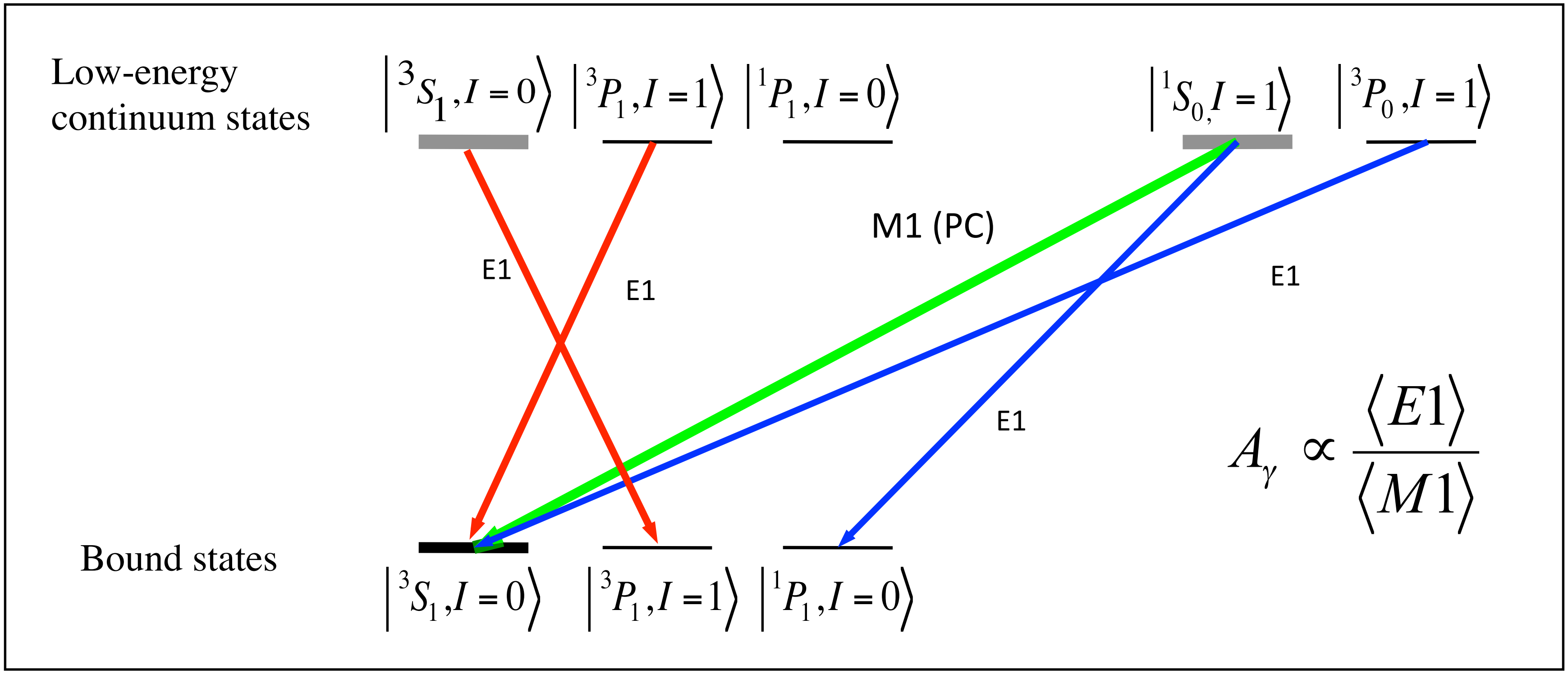
- Neutrons capture on ^{27}Al ->^{28}Al*
- Gamma cascade follows as ^{28}Al*->^{28}Al (g.s.)
  - Asymmetry correlated with σ_n

1. $P_1 \cdot k_\gamma \Rightarrow 1.3\times10^{-8}$
2. $P_2 \cdot k_\beta \Rightarrow 1\times10^{-10}$



- Fraction that capture in Aluminum – small
- Average over 8-step sequence is also small

What gives rise to parity violation in $\vec{n} + p \Rightarrow d + \gamma$?

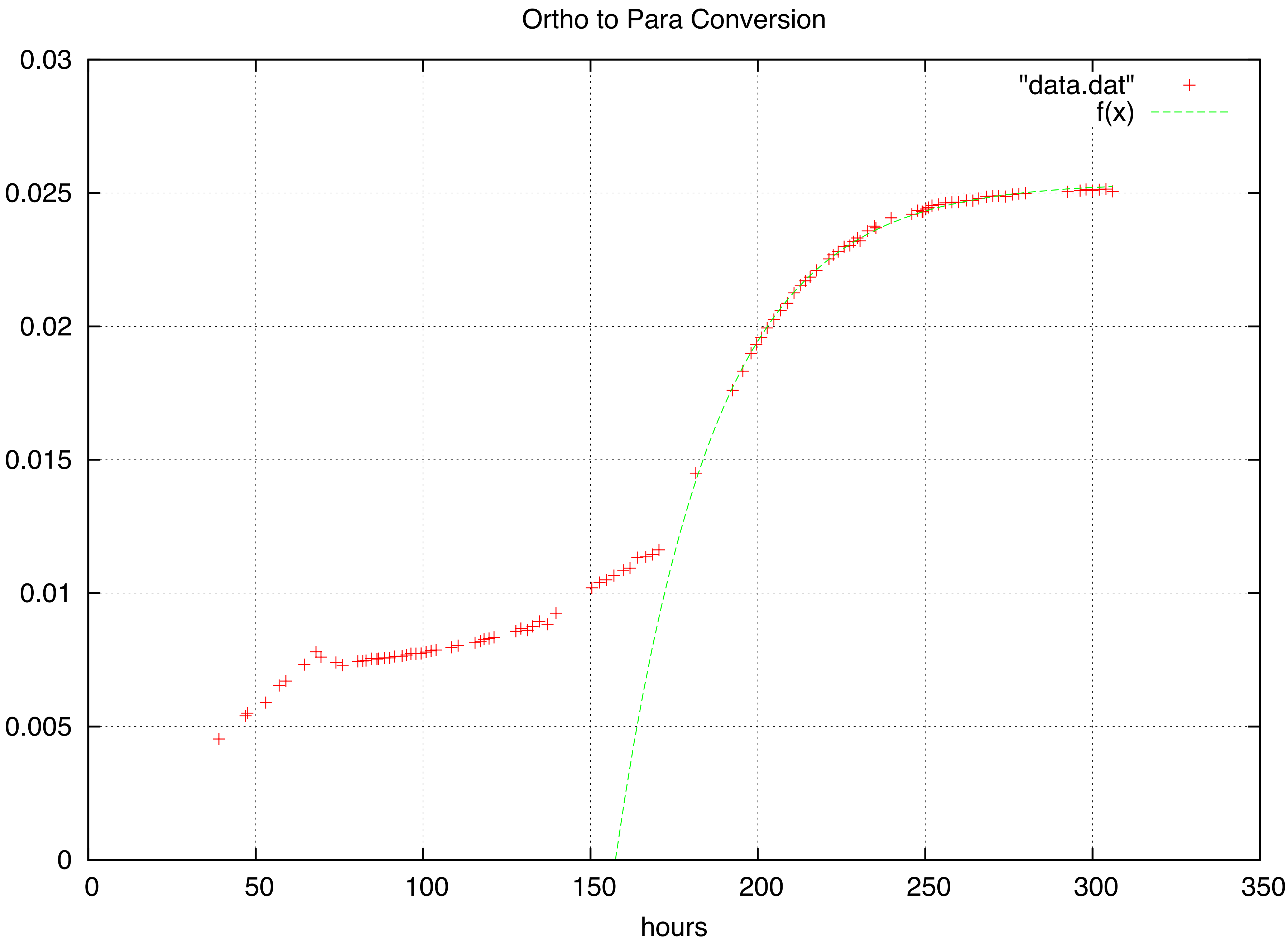


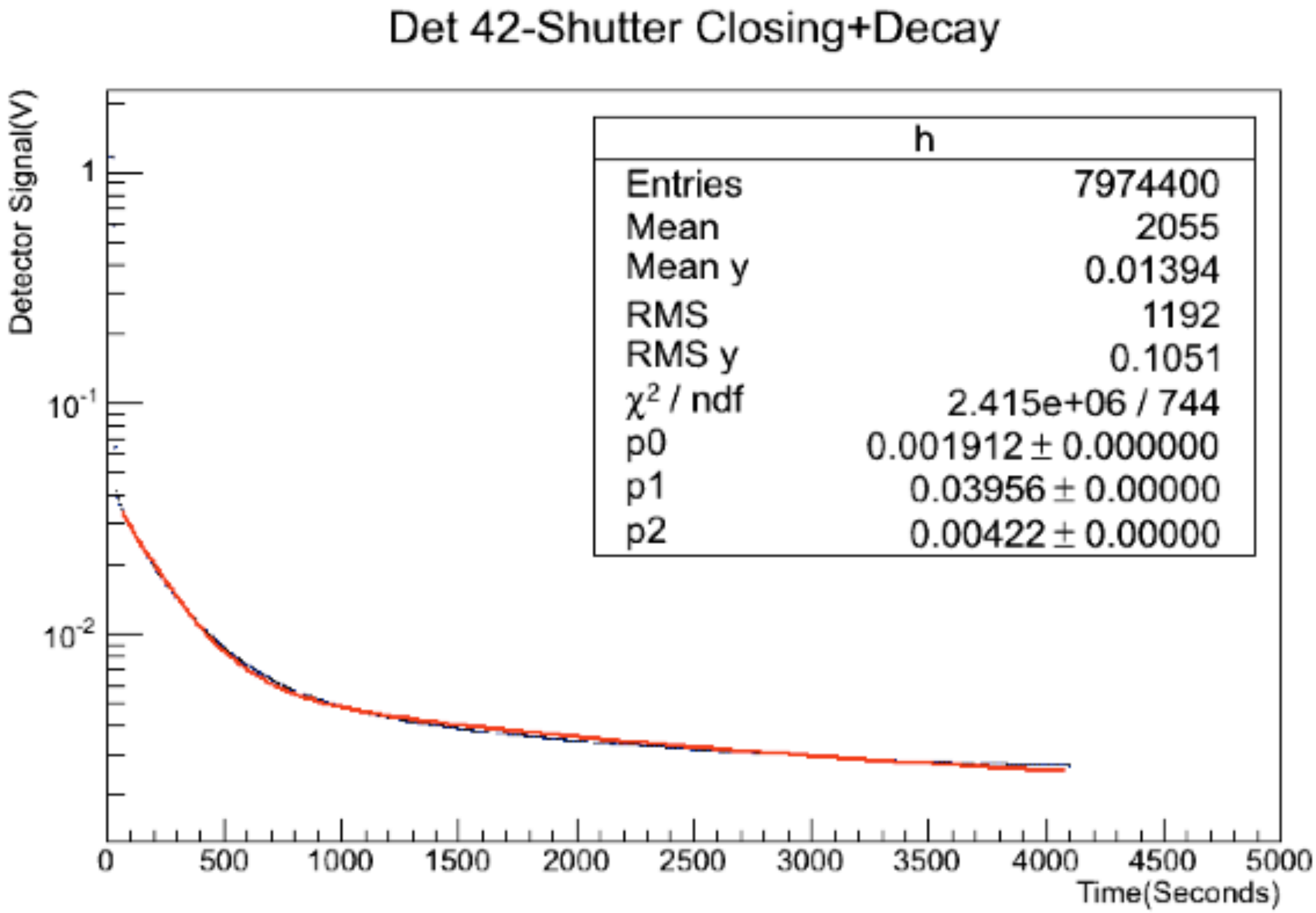
$\dot{n} + p \rightarrow d + \gamma$ is primarily sensitive to the $\Delta I = 1$ component of the weak interaction

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

$$^3S_1 \rightarrow {}^1P_1 \quad (\Delta I = 0)$$

$$^3S_1 \rightarrow {}^3P_1 \quad (\Delta I = 1)$$

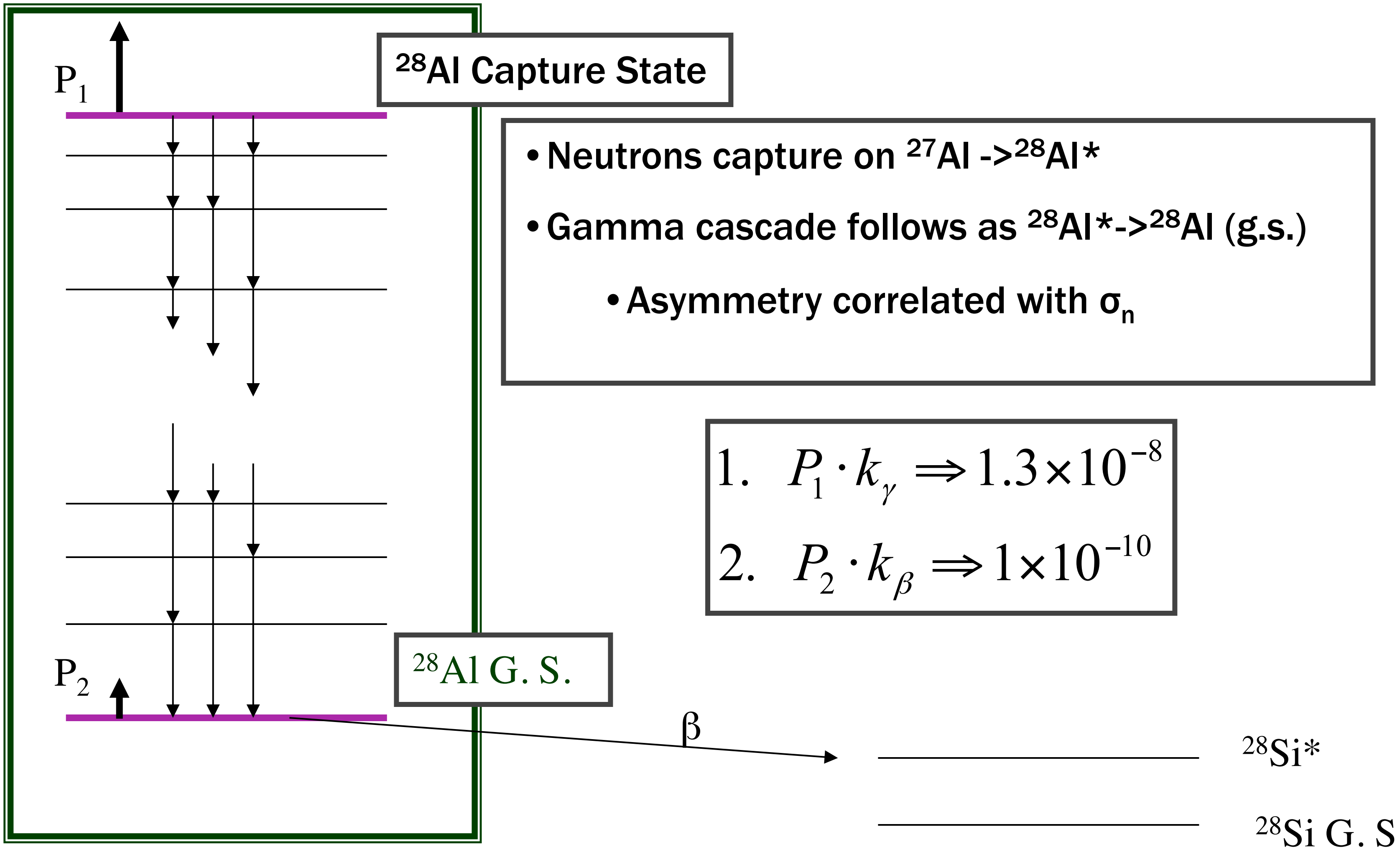

Ortho to Para Conversion
"data.dat"
f(x)
0.03
0.025
0.02
0.015
0.01
0.005
0
0
50
100
150
200
250
300
350
hours



From fit we have determined aluminum signal to be 20% for Ring 2, 16% for Ring 3, and 12% for Ring 4

courtesy of Serpil Kucuker

Capture on Aluminum



- Neutrons capture on $^{27}Al \rightarrow {}^{28}Al^*$
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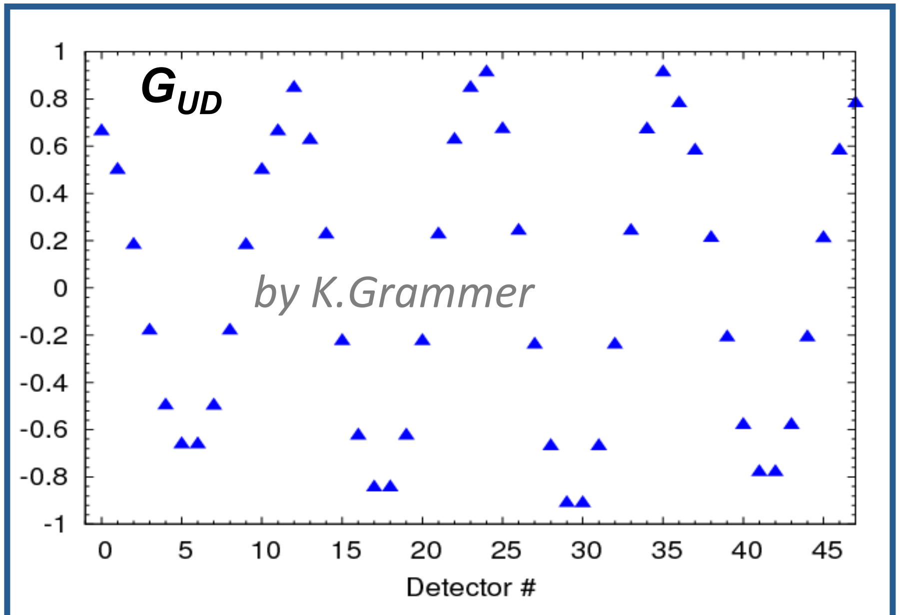
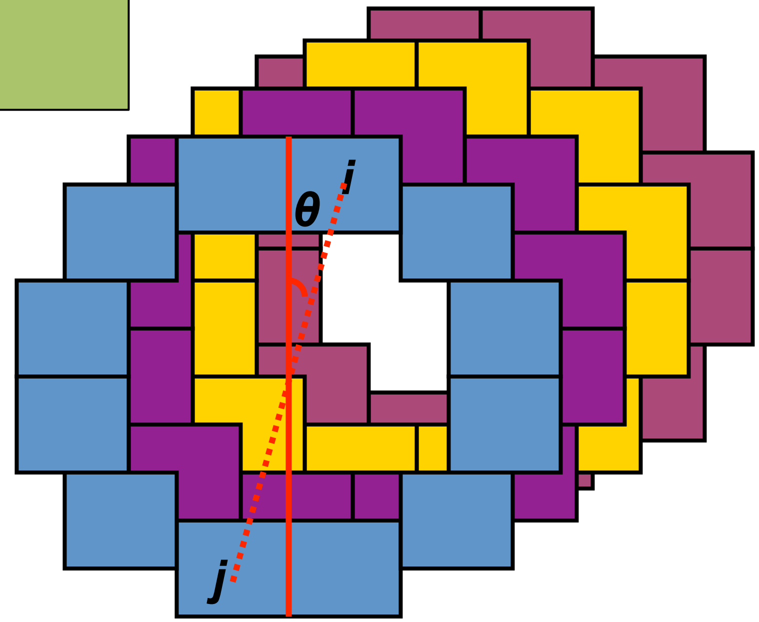
1. $P_1 \cdot k_\gamma \Rightarrow 1.3 \times 10^{-8}$
2. $P_2 \cdot k_\beta \Rightarrow 1 \times 10^{-10}$

- Fraction that capture in Aluminum – small
- Average over 8-step sequence is also small

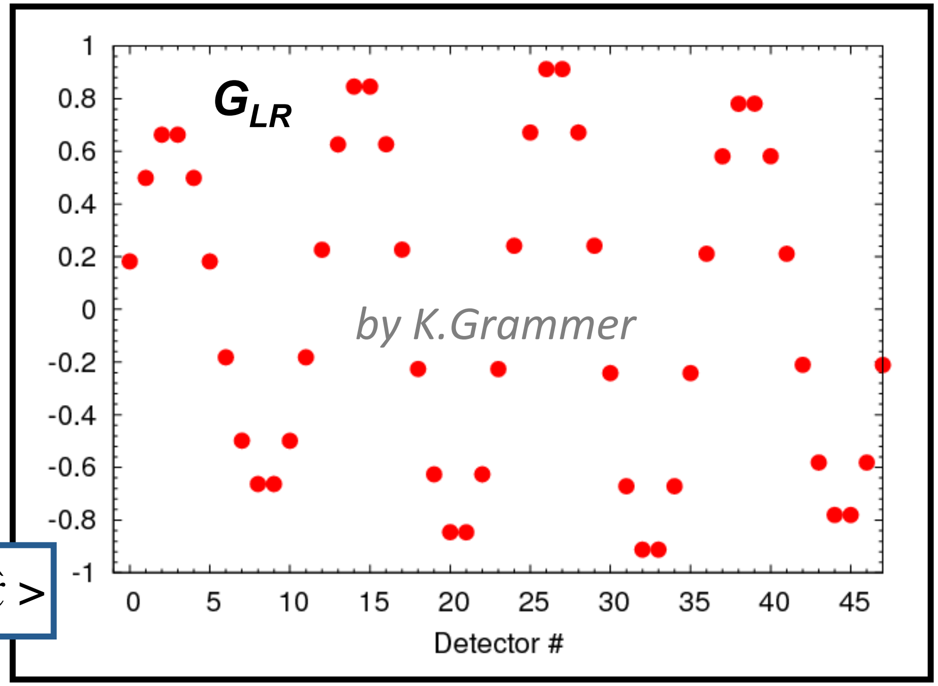
Geometrical Factors



$$G_{UD}(i) = < \hat{k}_\gamma \cdot \hat{s}_n > = < \hat{k}_\gamma \cdot \hat{y} >$$



Generated via a combination of MCNPX and measurements with a gamma source.



$$G_{LR}(i) = < \hat{k}_\gamma \cdot (\overline{s}_n \times \hat{k}_n) > = < \hat{k}_\gamma \cdot \hat{x} >$$

Improved Understanding of systematic effects

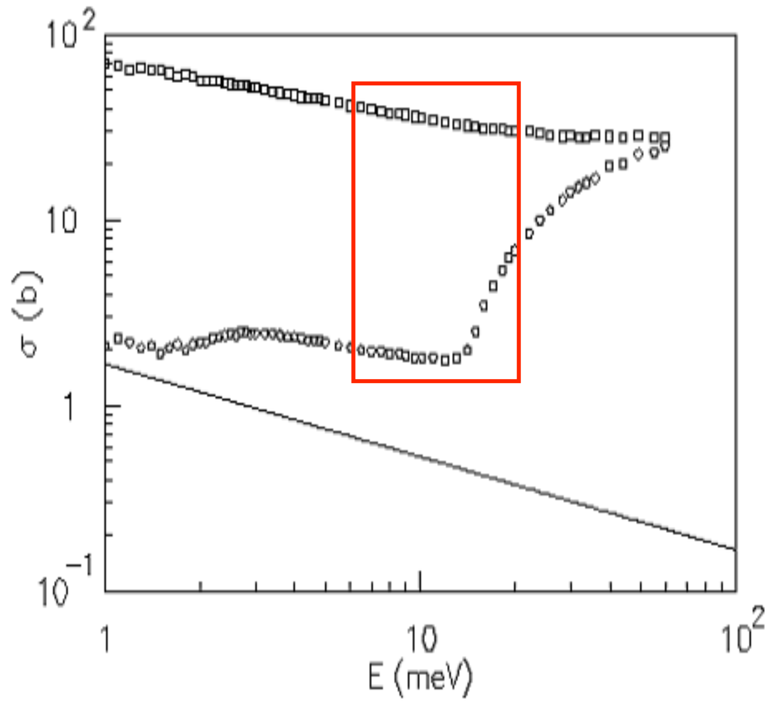
PV asymmetries

• Stern-Gerlach force	$2x10^{-11}$
• Circularly polarized γs	$9x10^{-13}$
• In-flight β decay	$1x10^{-11}$
• Capture on ^{6}Li	$2x10^{-11}$
• Al γ's	$1.3x10^{-8}$
• Al β decay	$1x10^{-10}$
Last two must be measured	

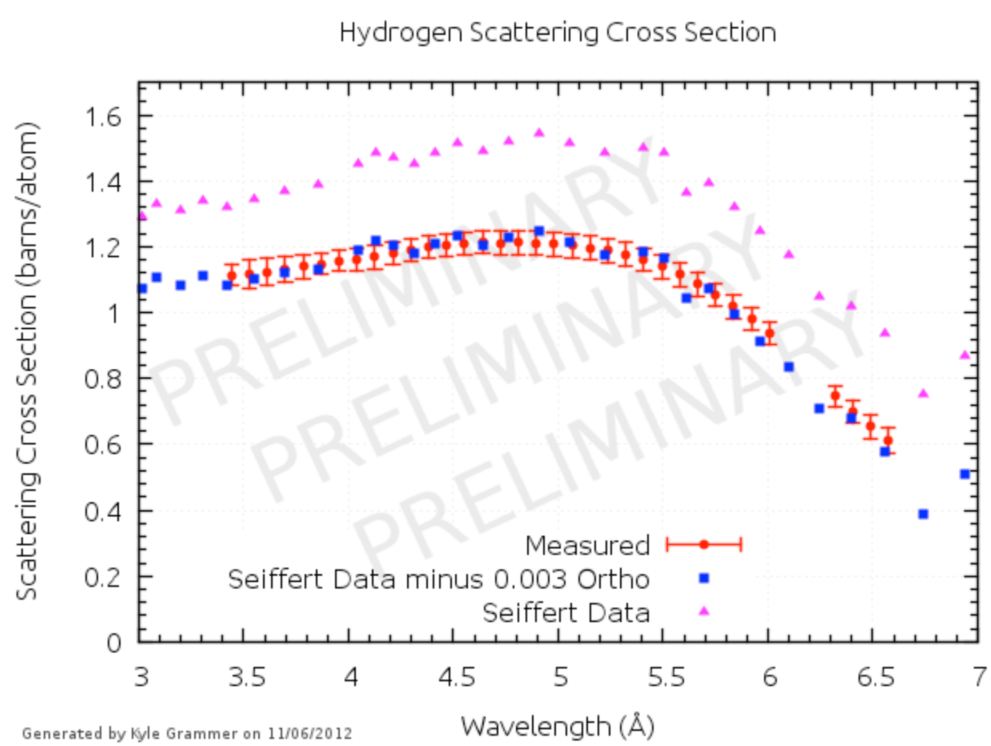
PC LR asymmetries

- **Mott-Schwinger in LH_2 (must be modeled)**
- **Parity-allowed $n+p \longrightarrow d+\gamma$** **$2x10^{-8}$**
- **Parity-allowed LR asymmetry in capture on Al=0**
- **These asymmetries can mix into the U-D channel if the detector and guide field are not aligned**

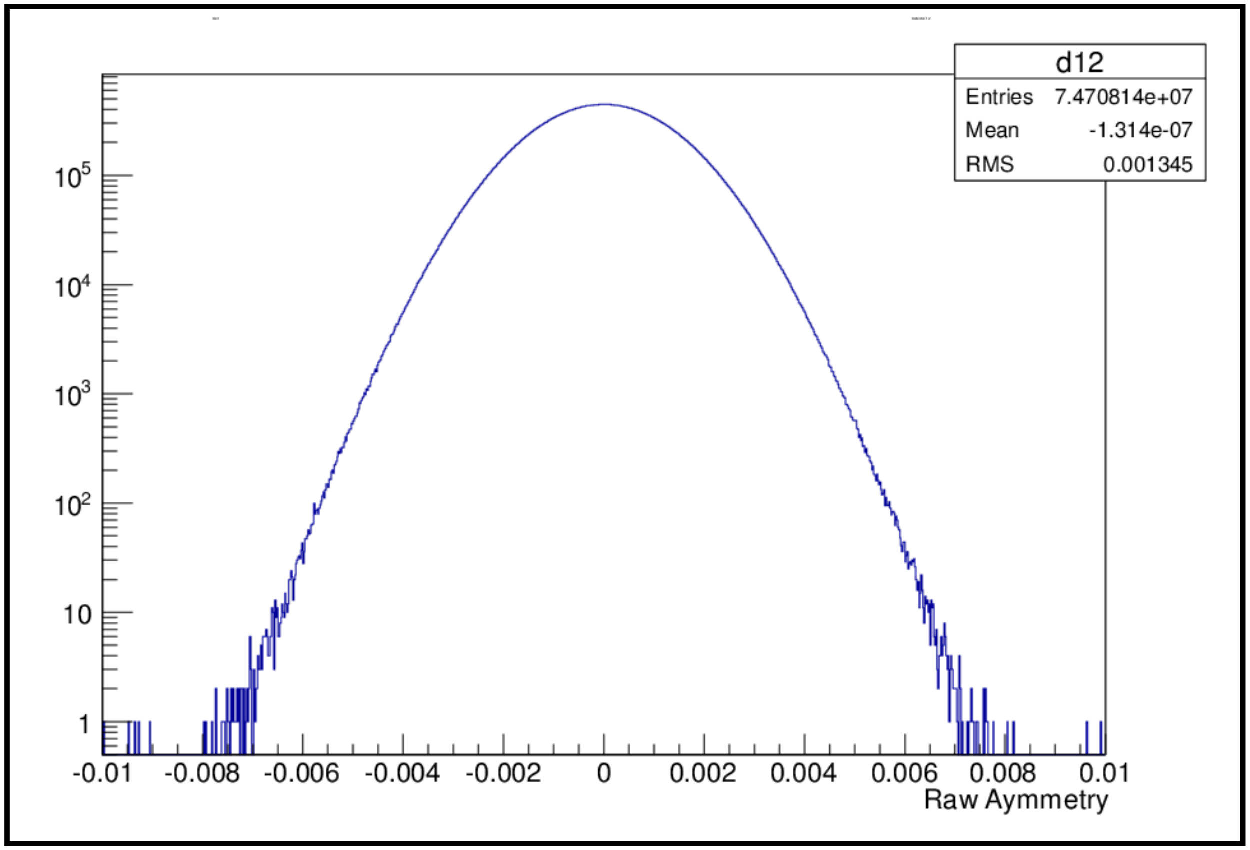
Total n-H_2 Cross Section

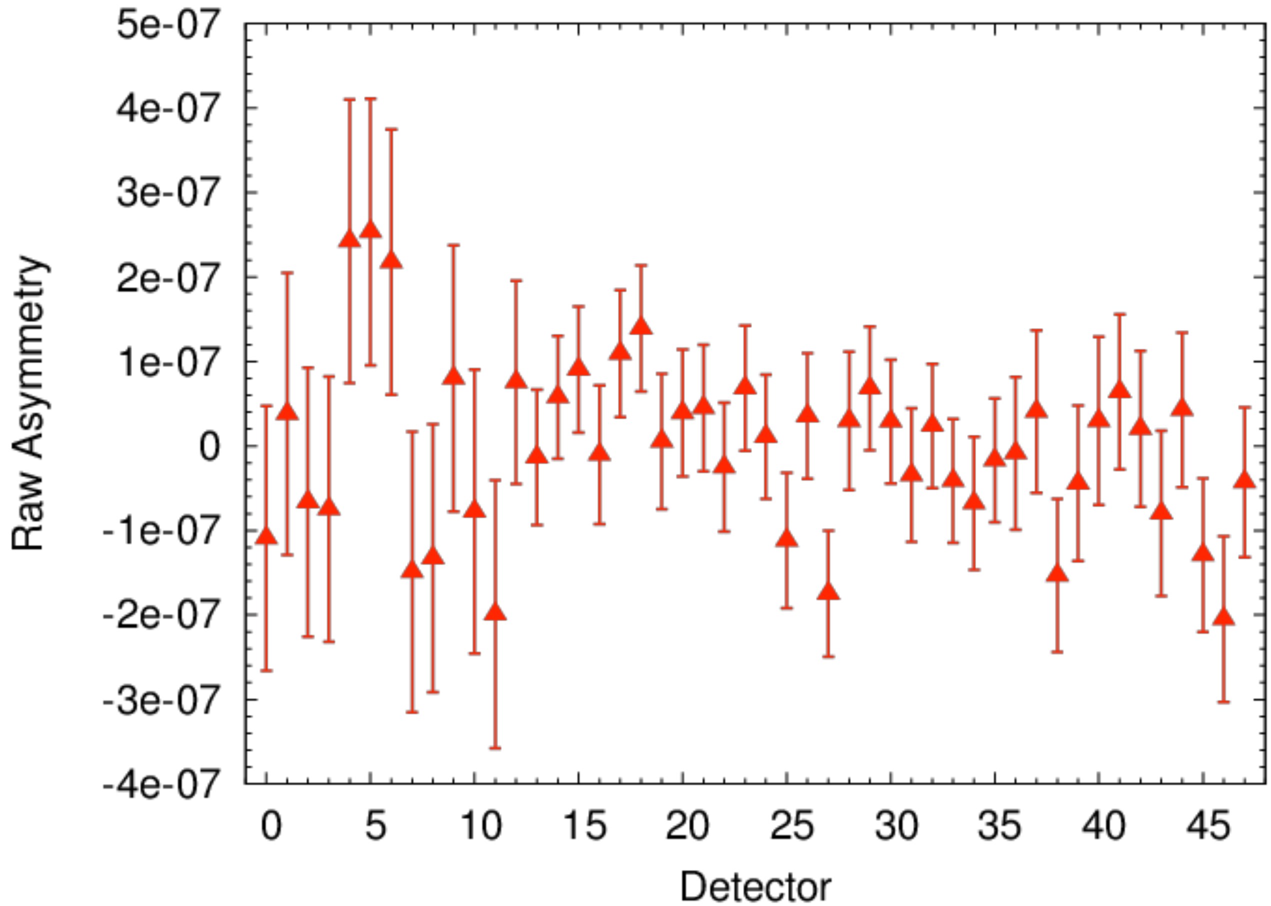


To avoid depolarization
LH_2 target has to be 99.92%
in para-hydrogen molecular state



Raw Asymmetry for Detector 12

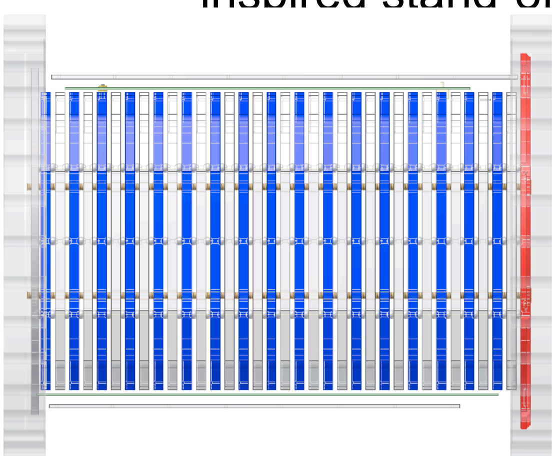


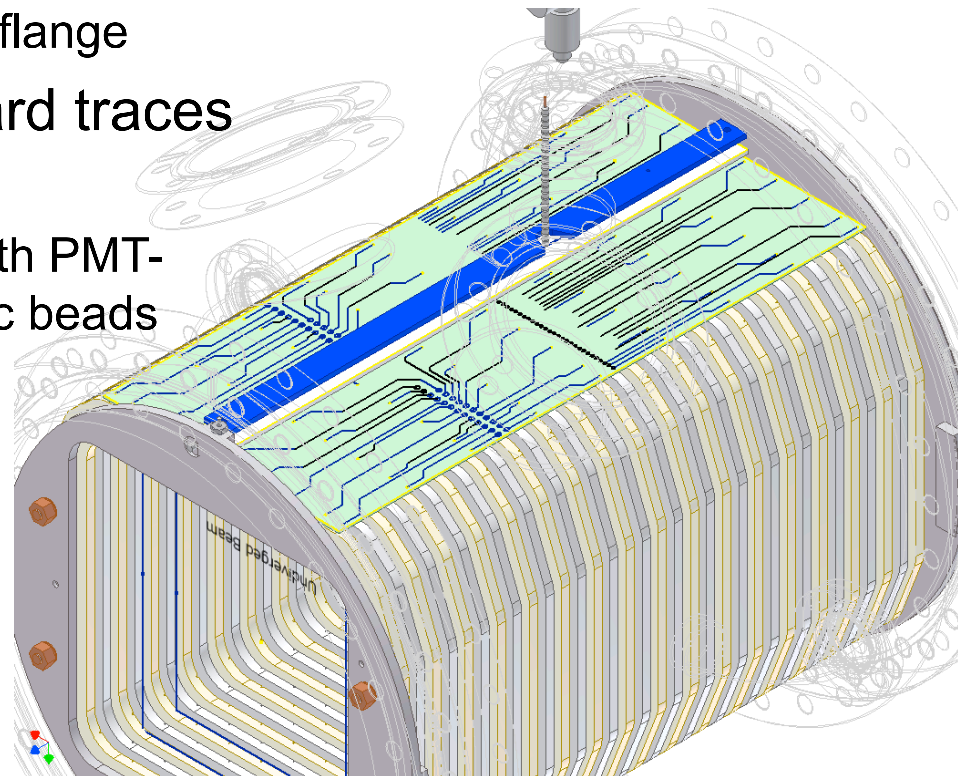


Raw Asymmetry
Detector
5e-07
4e-07
3e-07
2e-07
1e-07
0
-1e-07
-2e-07
-3e-07
-4e-07
0
5
10
15
20
25
30
35
40
45

Frame Assembly and Signal Readout

- The frame mounting structure is designed
  - pieces will be ordered in the spring
- Two options for frame mounting:
  - Mount into exit flange with threaded rods
  - Insert into existing exit window flange
- Signal readout via circuit board traces
  - Single HV connections
  - Guide wires to feedthroughs with PMT-inspired stand-offs and ceramic beads

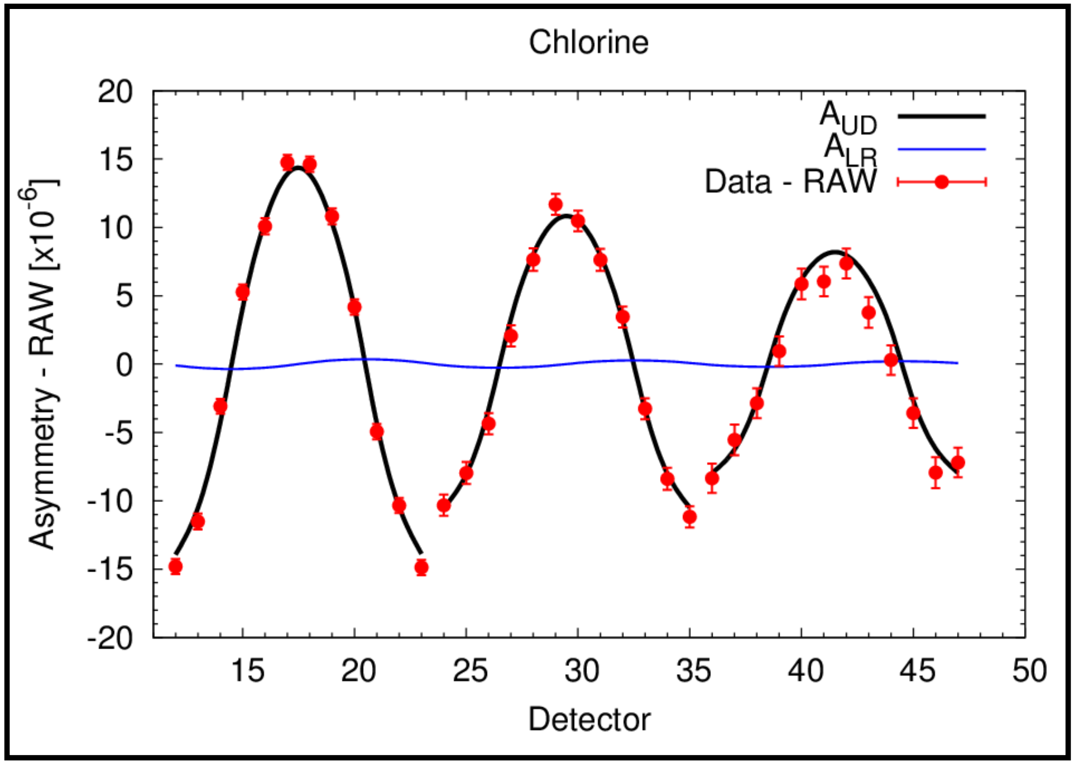




Analysis Procedure

Benchmark target: ^{35}Cl

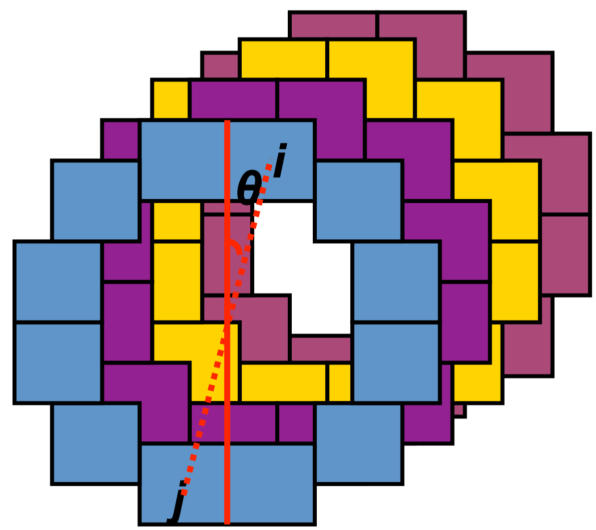
target with a large and well-known γ-asymmetry



Asymmetry for a detector pair is then given by

$$A_{\text{raw}} = A_{\text{UD}} \cdot G_{\text{UD}} + A_{\text{LR}} \cdot G_{\text{LR}}$$

- A_{UD} is extracted from a fit of A_{raw} to the geometric factors



About Systematic Uncertainties; not updated!

Name	Process	Size
Stern-Gerlach	$\mu \cdot \nabla B$	8 x 10^{-11}
Mott-Schwinger	$\vec{n} + p \to n + p$	9 x 10^{-12}
PA left-right	$\vec{n} + p \to d + \gamma$	7 x 10^{-10}
γ-ray circ. pol.	$\vec{n} + p \to d + \vec{\gamma}$	7 x 10^{-13}
N β decay	$\vec{n} \to e^{-} + p + \bar{\nu}$	3 x 10^{-11}
Capture on ^{6}Li	$n + {}^{6}Li \to \alpha + {}^{3}t$	2 x 10^{-11}
^{28}Al β decay	$\vec{n} + {}^{27}Al \to {}^{28}Al + \beta$	5 x 10^{-11}
^{28}Al prompt γ's	$\vec{n} + {}^{27}Al \to {}^{28}Al + \gamma's$	1 x 10^{-9}