Precision Measurement of Parity Violation in Polarized Cold Neutron Capture on the Proton: the N P D γ Experiment

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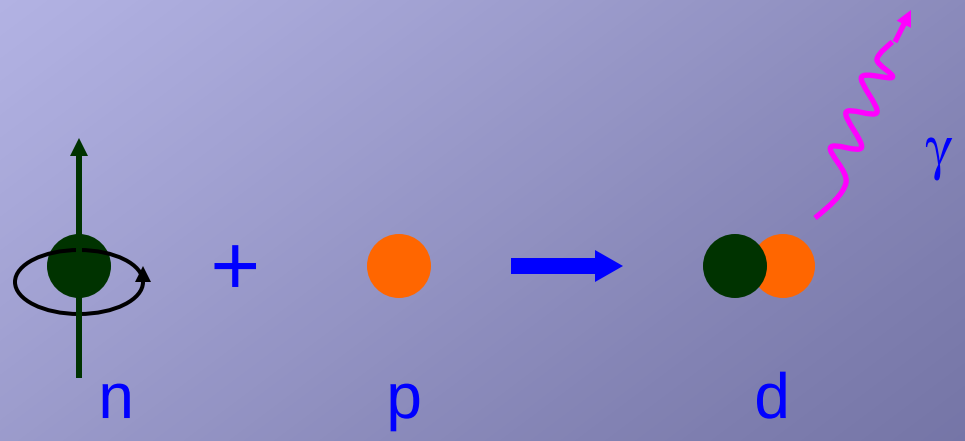

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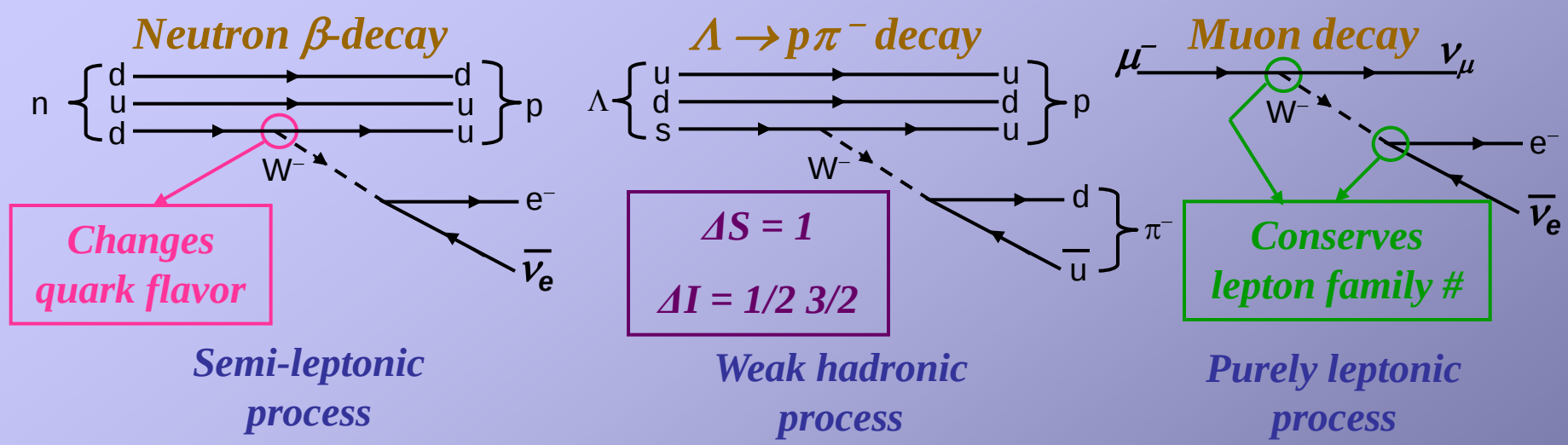
Overview

- NPDGamma Experiment motivation
- Experiment setup at LANSCE
- Experiment apparatus
- Liquid Para-hydrogen Target
- Analysis result of LH_2 target data
- Current Project status

Weak Interaction



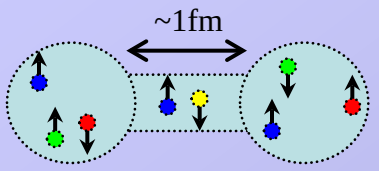
Semi-leptonic process | *Weak hadronic process* | *Purely leptonic process*

1. Parity-Violation → hadronic weak interaction isolated from the much larger effects of the strong and electromagnetic interactions (which conserve parity).
2. Heavy boson exchange ($W^{\pm}$, Z) at low momentum transfers → very short range ~0.002fm → probe quark and quark interaction and correlation at small distance.
3. Weak → not significantly perturb QCD, an "inside-out" probe of strong QCD.

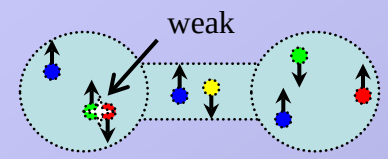
NPDGamma study the flavor-conserving nonleptonic weak interaction.

Weak qq → Weak NN

What is the weak NN interaction?



Strong NN interaction, mediated by mesons, long range ~ 1 fm



Quarks close ~ 0.001fm→ the weak interaction acts

Quark-quark weak interaction induces NN weak interaction.
Visible using parity violation.
Relative weak/strong amplitude: ~$[e^2/m^2_w]/[g^2/m^2_\pi]$ ~10^{-7}

What can we learn?

Δs = 1, nonleptonic weak interactions [ΔI = ½ rule, hyperon decays not understood] .

Q: specific to the strange quark, or a general feature in the nonleptonic weak interactions of light quarks?

To answer, must look at the $\Delta s = 0$ nonleptonic weak interactions (u, d quarks).

Weak NN interaction is one of the few experimentally feasible systems.

Theory

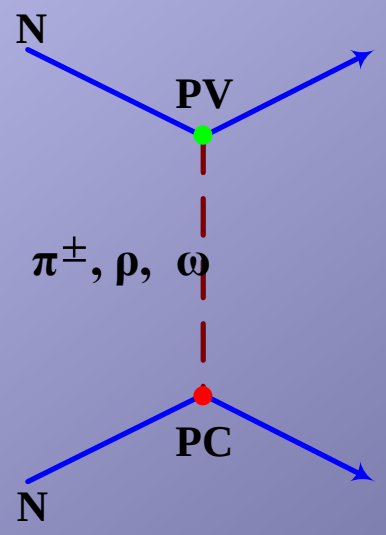
Meson Exchange Model (DDH)

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

- At low energies N-N weak interactions modeled as meson exchange with one strong PC vertex, one weak PV vertex.
- Due to hard core repulsion → n-p interaction range ~ 1.5 fm → Mesons are the appropriate degrees of freedom.
- The weak PV couplings contribute in various mixtures and a variety of observables:

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

to be determined by experiment.



Other Approaches

Recently, an **Effective Field Theory*** has been developed to calculate the NN weak interaction.

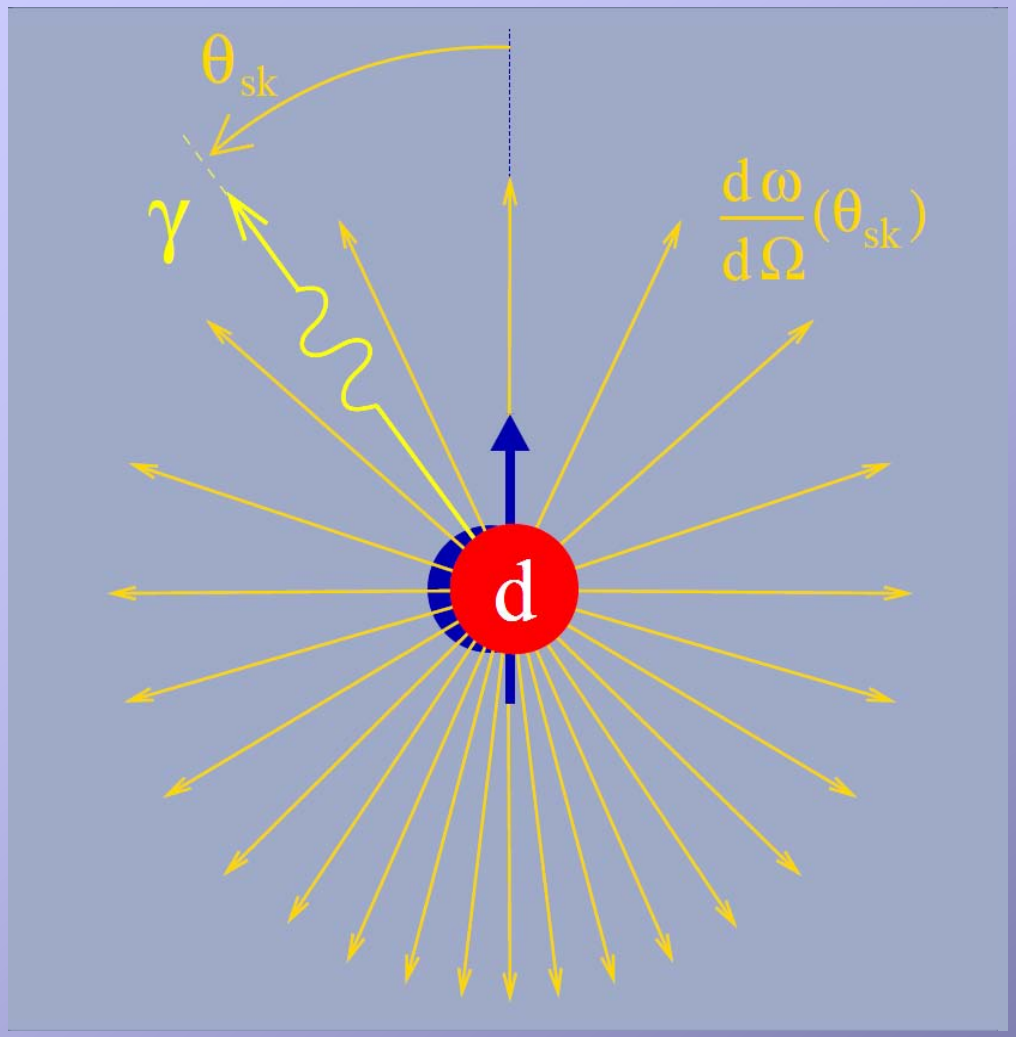
* Zhu, Maekawa, Holstein, Ramsey-Musolf, and Van Kolck, Nucl. Phys. A748, 435 (2005)

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

Very recently, the NN interactions (including weak) is included as a goal for extreme computing to calculate directly from QCD using **lattice QCD**. **

** Summary Letter Report -Nuclear Physics Workshop Jan 26-28, 2009, Washington D.C.

A Parity-violating Gamma-ray Asymmetry



Directional distribution of gamma-ray essmission in:

$$\vec{n}\,\vec{n}\,p \rightarrow d + \gamma$$

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

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

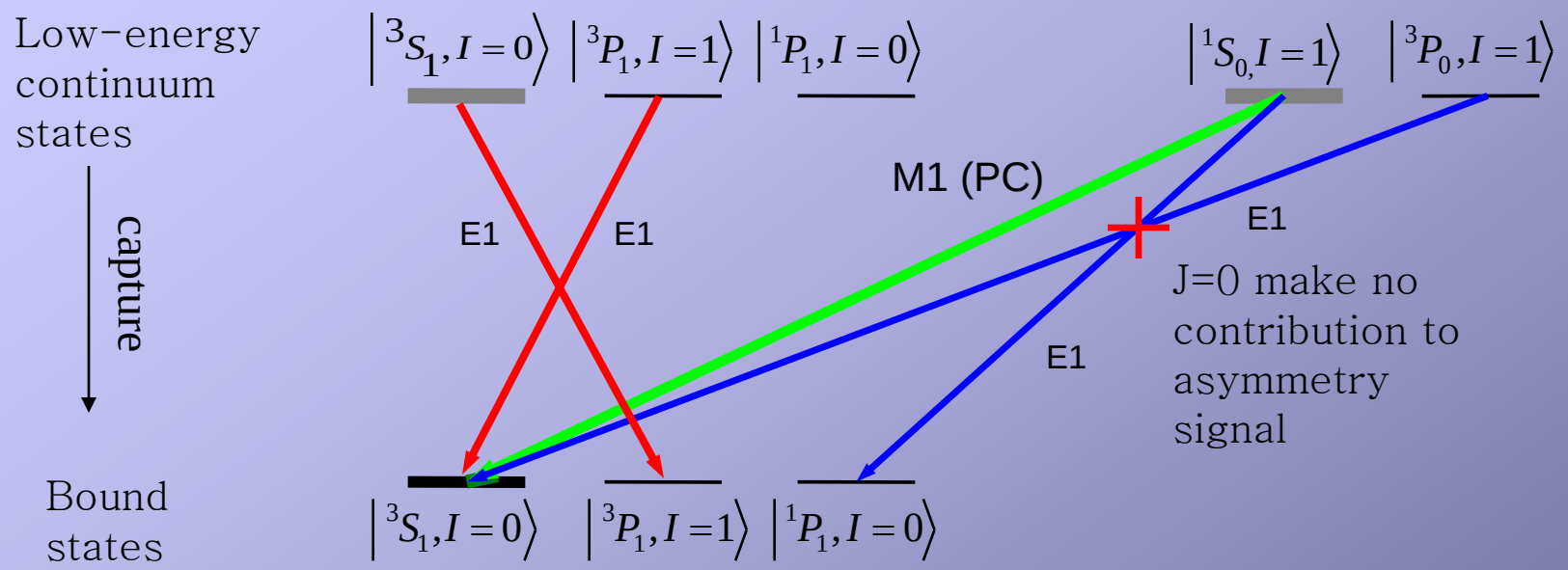
$$f_\pi^1, h_\rho^1, h_\omega^1 \sim 10^{-8}$$

is mostly isotropic but also depends on the angle θ_{sk}, between neutron spin $\vec{s}_n$ and photon momentum $\vec{k}_\gamma$.

$$\Delta s = 0, \Delta I = 1$$

A_γ is a measure of neutral current weak hadronic interaction.

Simple Level Diagram of *n-p* System



$\vec{n}\vec{p} \to d + \gamma$ 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 – $\Delta I = 1$ channel.

Mixing amplitudes:

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

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

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

Why Neutral Current?

- At low energy H_{weak} takes a current-current form with charged and neutral weak current: $H_{weak} \sim \frac{G_F}{\sqrt{2}}(J_W^+ J_W + J_W J_W^+ + J_Z^+ J_Z)$, where

  $J_W \sim \bar{u}\gamma_\mu(1+\gamma_5)d\cos\theta_c + \bar{u}\gamma_\mu(1+\gamma_5)s\sin\theta_c$;

  $J_Z \sim \bar{u}\gamma_\mu(1+\gamma_5)u + \bar{d}\gamma_\mu(1+\gamma_5)d + \bar{s}\gamma_\mu(1+\gamma_5)s - 4\sin^2\theta_W J_\mu^{EM}$;

  - J_W has ΔI = ½, 1 terms,

    ΔI = ½ currents → $H_{weak}^{\Delta I=0,\,1}$, but $H_{weak}^{\Delta I=1}$ is Cabbibo suppressed (*by* $\sin^2\theta_c$).

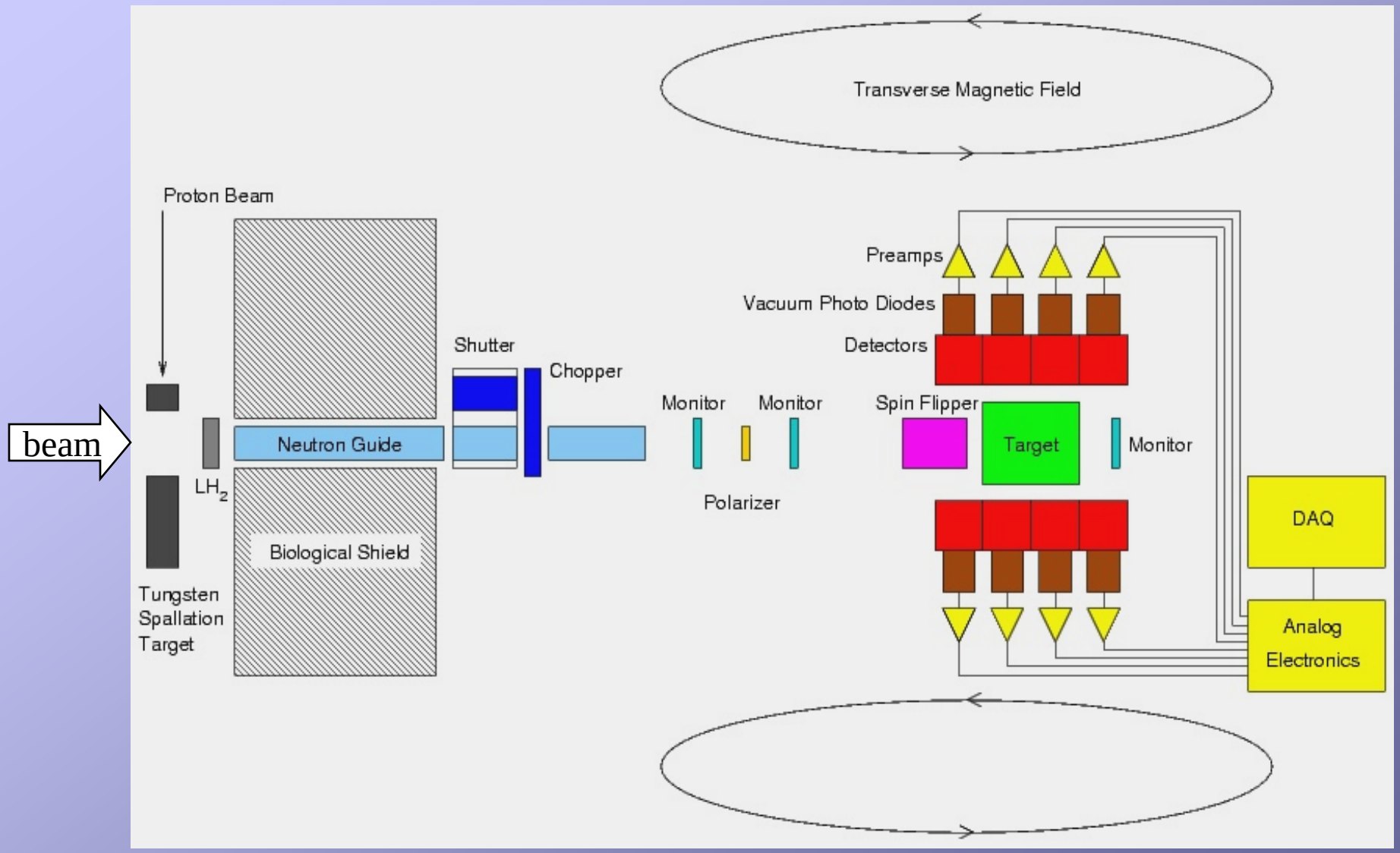
    ΔI = 1 currents → $H_{weak}^{\Delta I=0,\,1,\,2}$, but since the Hamiltonian is Hermitian, ΔI = 1 components from both $J_W{}^+ J_W$ and $J_W J_W{}^+$ have opposite sign.

  → Charged currents contribute to $H_{weak}^{\Delta I=0,\,2}$, *but not* $H_{weak}^{\Delta I=1}$.

  - J_Z has ΔI = 0, 1 terms → $H_{weak}^{\Delta I=0,\,1,\,2}$.

    Neutral current primarily contribute to $H_{weak}^{\Delta I=1}$.

n+p→d+γ Experimental Setup at LANSCE



A Gamma-ray Asymmetry Measurement

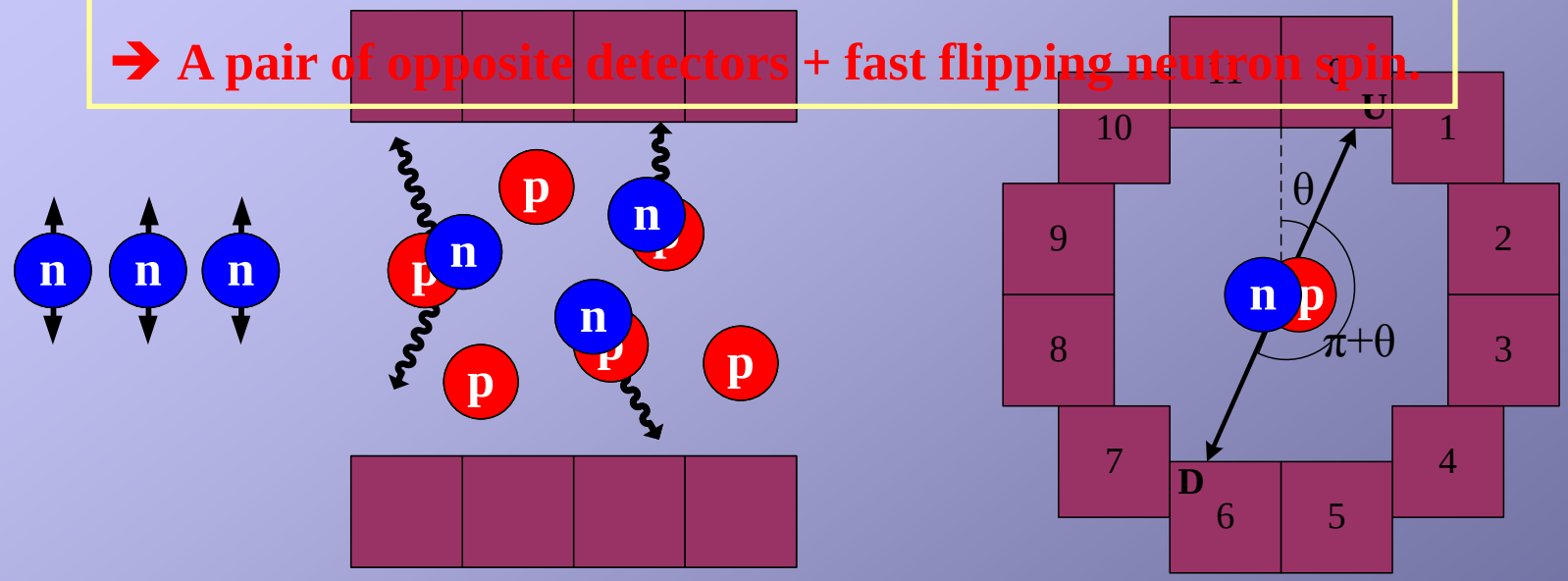
$$A_\gamma(t)P_n\cos\theta = \frac{U_\uparrow - D_\uparrow - (U_\downarrow - D_\downarrow)}{U_\uparrow + D_\uparrow + U_\downarrow + D_\downarrow} \qquad (\uparrow,\downarrow = \text{Neutron Spin})$$

P_n = *average beam polarization*

The two possibilities are precluded:

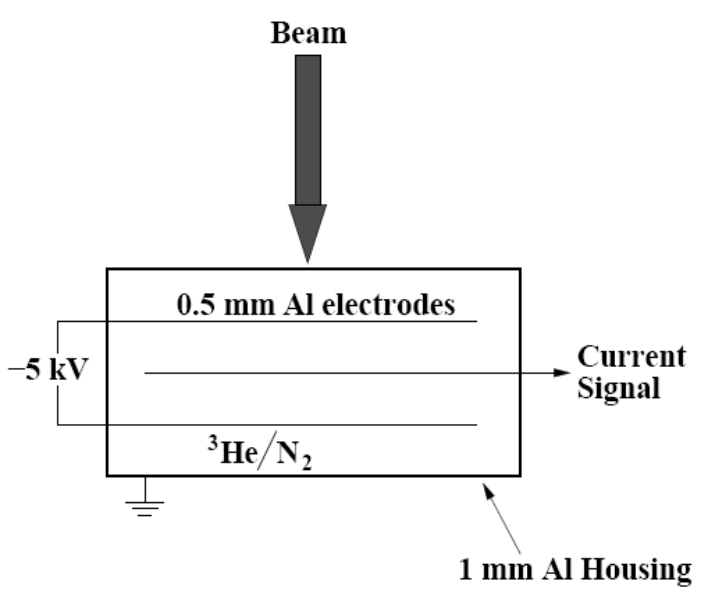
1. One detector + flip neutron spin.
2. A pair of opposite detectors + without flipping neutron spin;

➔ **A pair of opposite detectors + fast flipping neutron spin.**



- **Reverse the polarization pulse-by-pulse to compare signals in the same detector.**
- **Flip neutron spin according to the sequence ↑↓↓↑↓↑↑↓ to cancel linear and quadratic time-dependent gain drifts.**
- **Goals: ~ 10^{-8}, experiment error ~ 10^{-9}.**

Beam Monitor (Ionization Chamber)



3 beam monitors:

i) neutron flux out from the guide

ii) beam polarization

iii) depolarization, ortho/para ratio in LH_2 target, spin flipper efficiency

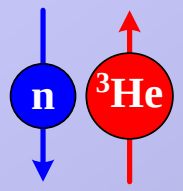
$n + {}^3He \rightarrow p + t + 765$ keV $\rightarrow$ ionizes gas mixture [(${}^3He + {}^4He$)(~.5 atm) +N_2(~.5 atm)]

Ratio of ${}^3He$ to ${}^4He$ (~3% to 100%),

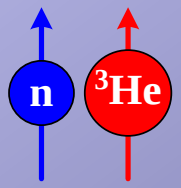
$\sigma_{abs}({}^3He) >> \sigma_{abs}({}^4He)$

Optically-Polarized ^{3}He Neutron Spin Filter

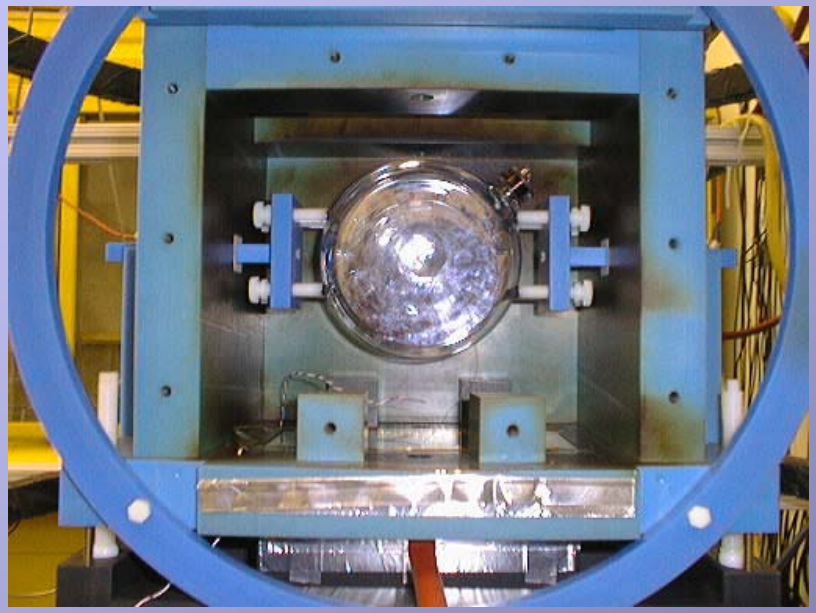
- A ^{3}He cell contains ^{3}He, Rb, and N_2.
- Rb vapor is polarized using circularly polarized laser light.
- Rb electron and ^{3}He nucleus exchange spin through the hyperfine interaction.



barns @ 10 meV

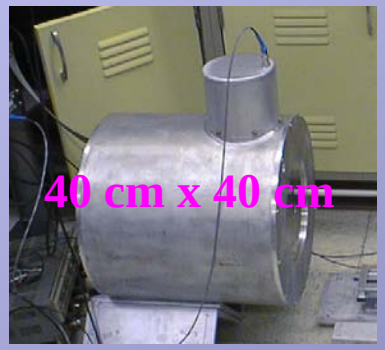


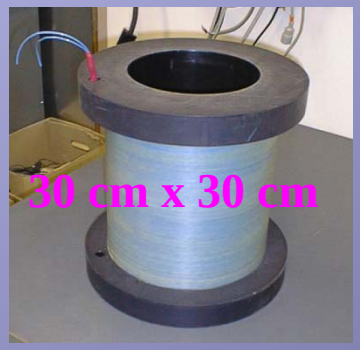
barns

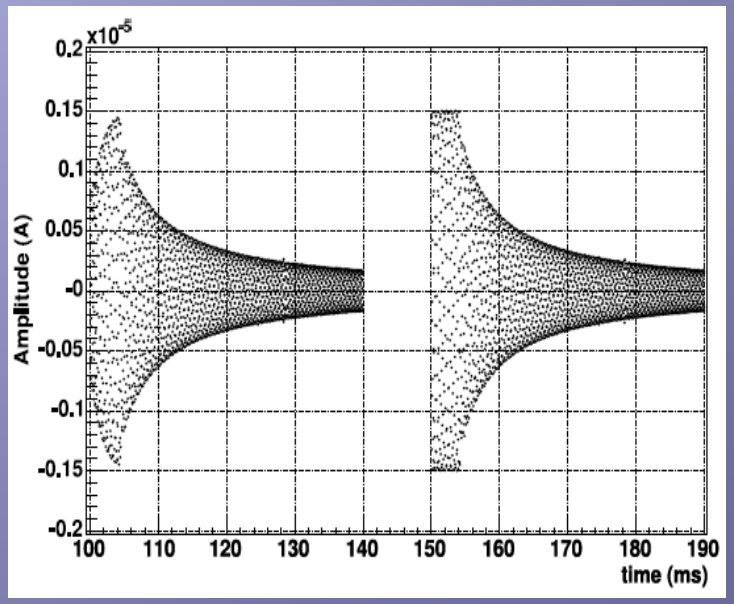


Radio Frequency Neutron Spin Flipper

- In a DC magnetic field B_o, a resonant RF magnetic field ($B_1 \cos\omega t$) is applied for a time $\tau = \pi/(\gamma B_1)$, to precess the neutron spin around B_1 by π.
- $B_1(t) \propto 1/TOF$, for reversing neutron spin in wide energy range.
- Dummy load with the same impedance as the coil to keep the load on the main power circuit constant and minimize pickup of the spin flipper on-off switching in other circuits.
- Grad. $\partial B_z / \partial z$ < 1 mgauss/cm $\Rightarrow$ no Stern-Gerlach steering force ($\mu.\nabla B$) → no false asymmetry.
- High maximum spin reversal efficiency, ~ 98.0±0.8% for 3.3 to 18.4 meV.







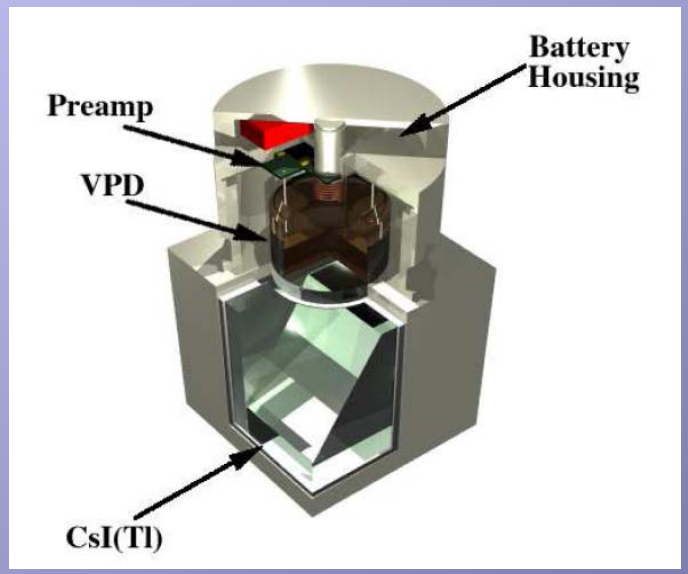
Current Mode CsI Detector Array

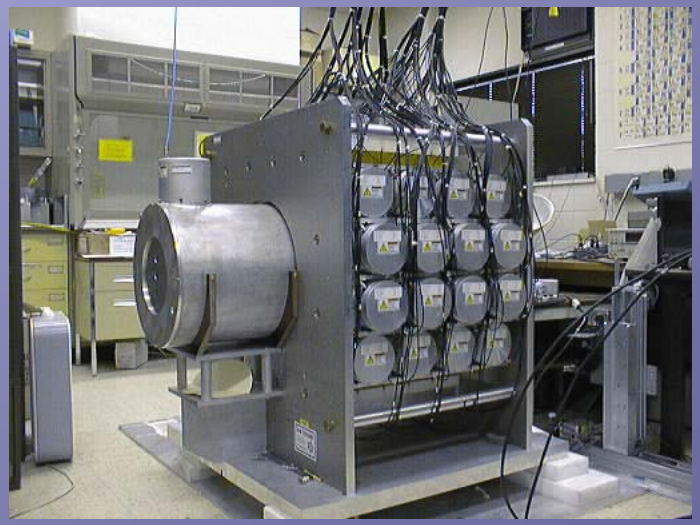
- CsI crystal
- Vacuum photodiodes (VPD)
- Low noise solid-state preamplifier.
- 152 x 152 x 152 mm^3
- The array covers a solid angle of 3π.

- Detection in current mode, pulse counting impossible. The peak γ rate into a single detector ~ 100 MHz; the decay time of the scintillation light pulse ~ 1 μs (1 MHz).

- Use sum + difference amplifier.
  (1) the average signal in a ring.
  (2) the difference in each detector from the average.

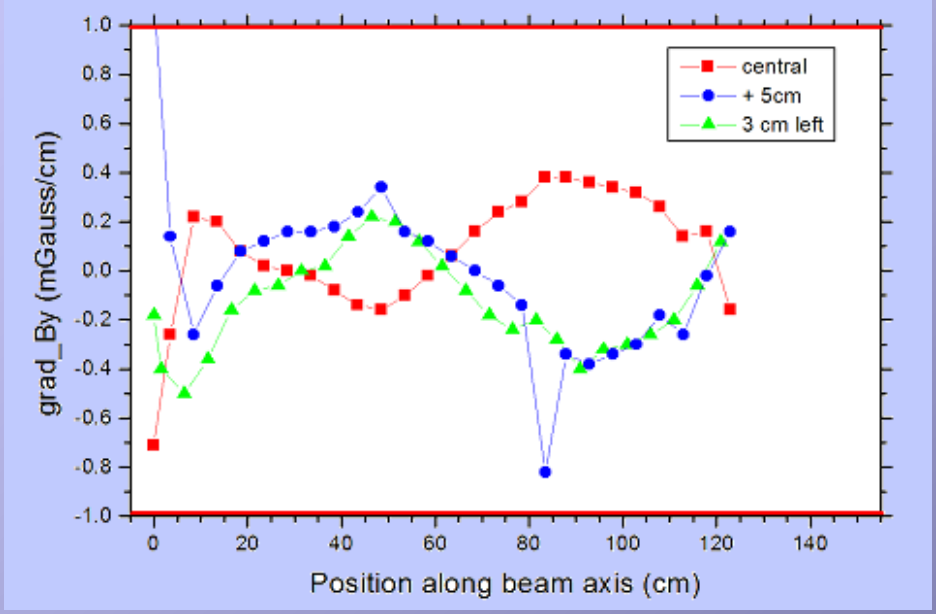
- Low noise, measurement accuracy dominated by counting statistics.





Experiment Setup Guide Field

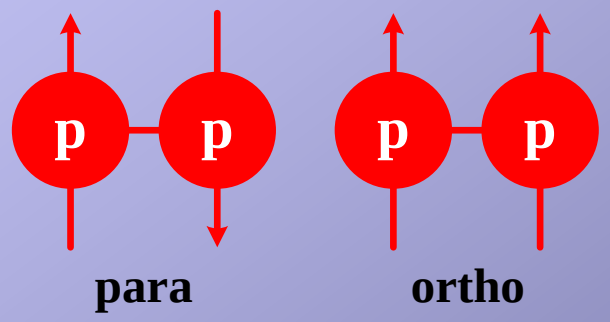
whole setup contained in 10 Gauss guide field.
To prevent Stern-Gerlach steering of neutrons:
require field gradient ≤ 1 mGauss/cm.
To prevent left-right asymmetry to produce a false up-down asymmetry:
the direction of the field respect to detector at target position has to be know with accuracy of 20 mrad.

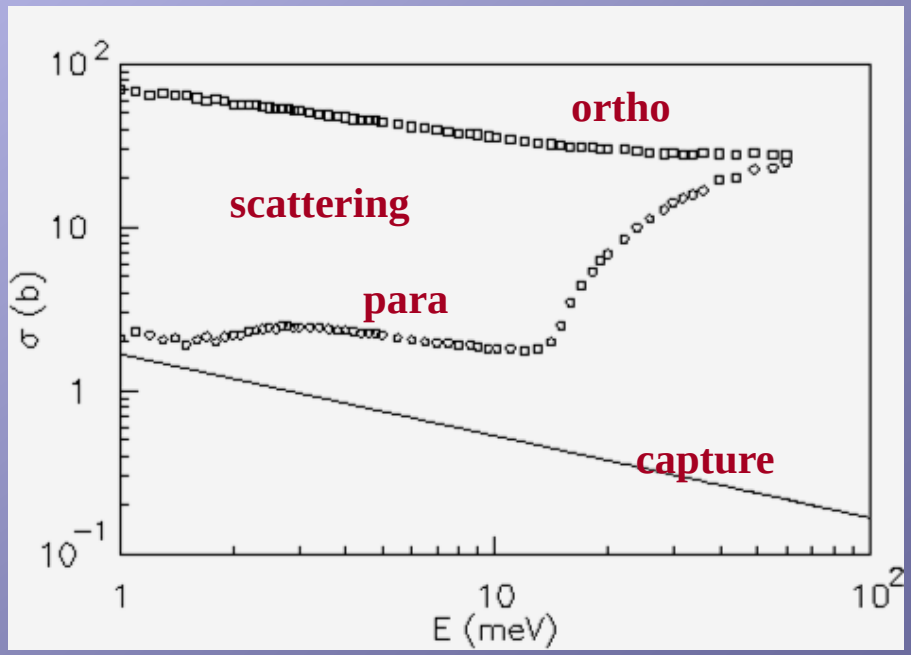


Liquid Para-hydrogen Target

Design Goal

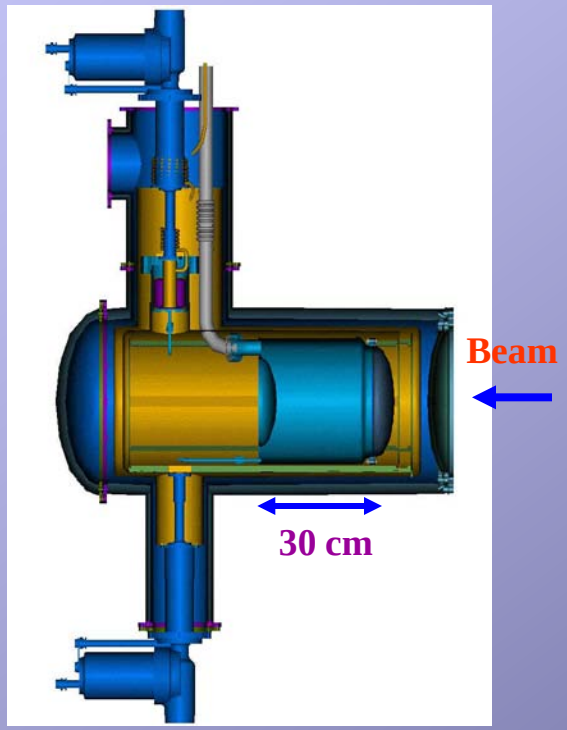
- **Target must absorb as much polarized cold neutrons as possible. Monte Carlo simulation ⇒ Target size of 30 cm diameter and 30 cm length → absorbs 60% cold n's.**
- **To prevent neutron depolarization requires para-hydrogen, cold neutron (<15meV) → Para- ⌦ Orth-H_2 & flip neutron spin at T≤17 K → 0.05% of LH_2 is in ortho state → 1% of neutrons depolarized.**



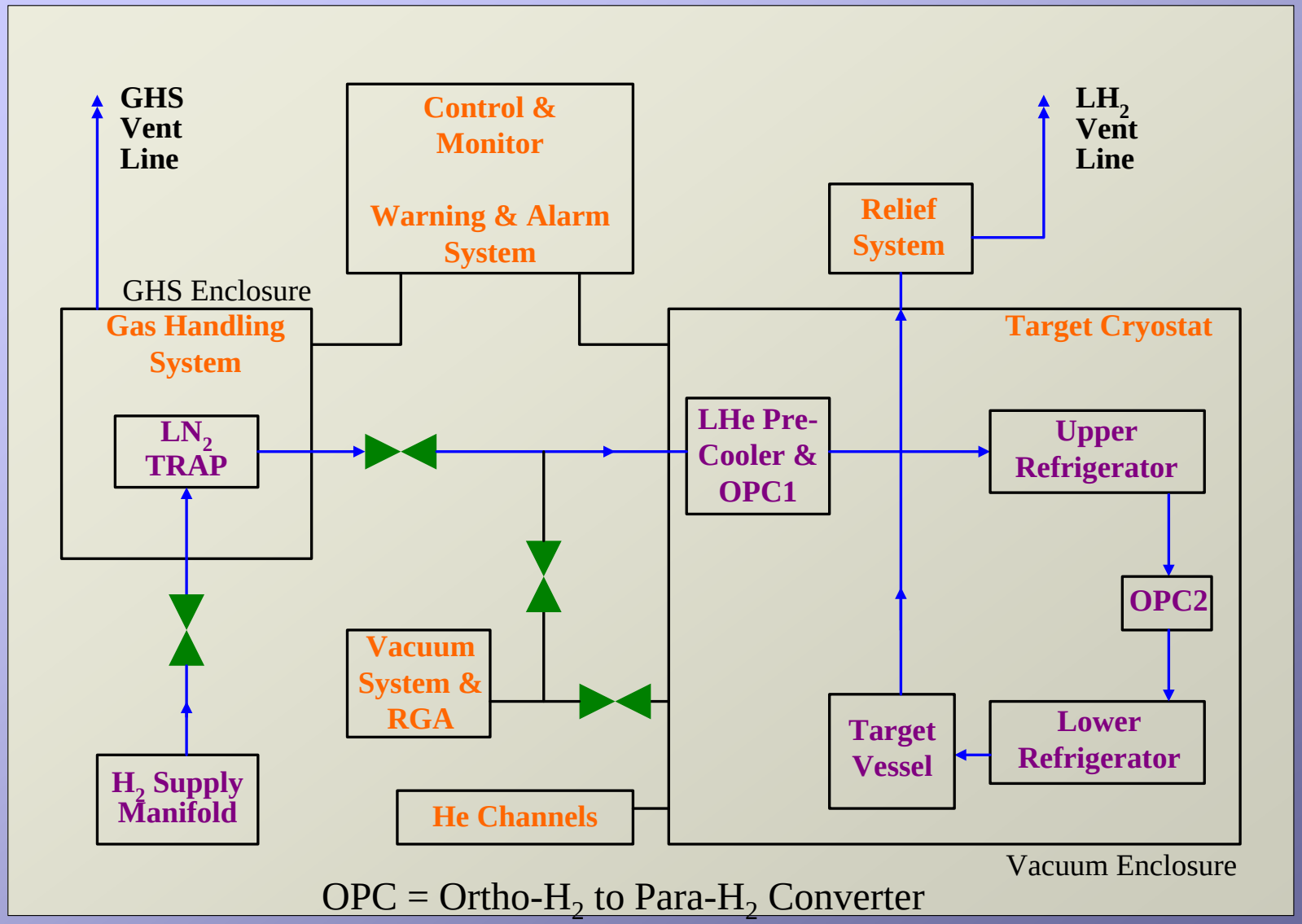


Safety Feature of the LH_2 Target

- **Triple Containment** – hydrogen has to be separated by three barriers before reaching oxygen (Air). Al target vessel (1st containment) inside an isolation vacuum (2nd containment) and then Al vacuum chamber (3rd containment).
- **Helium channels** around the joints of main vacuum chamber are used for fast detection of any leak from air to main vacuum.
- **Fast warm up of target in emergency**

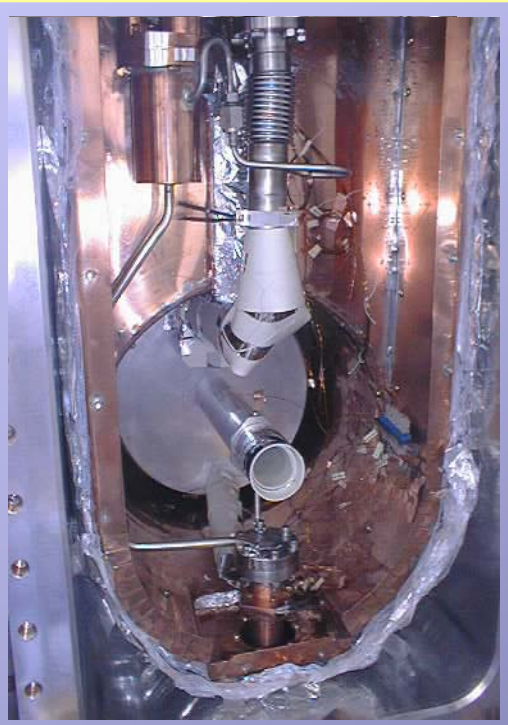


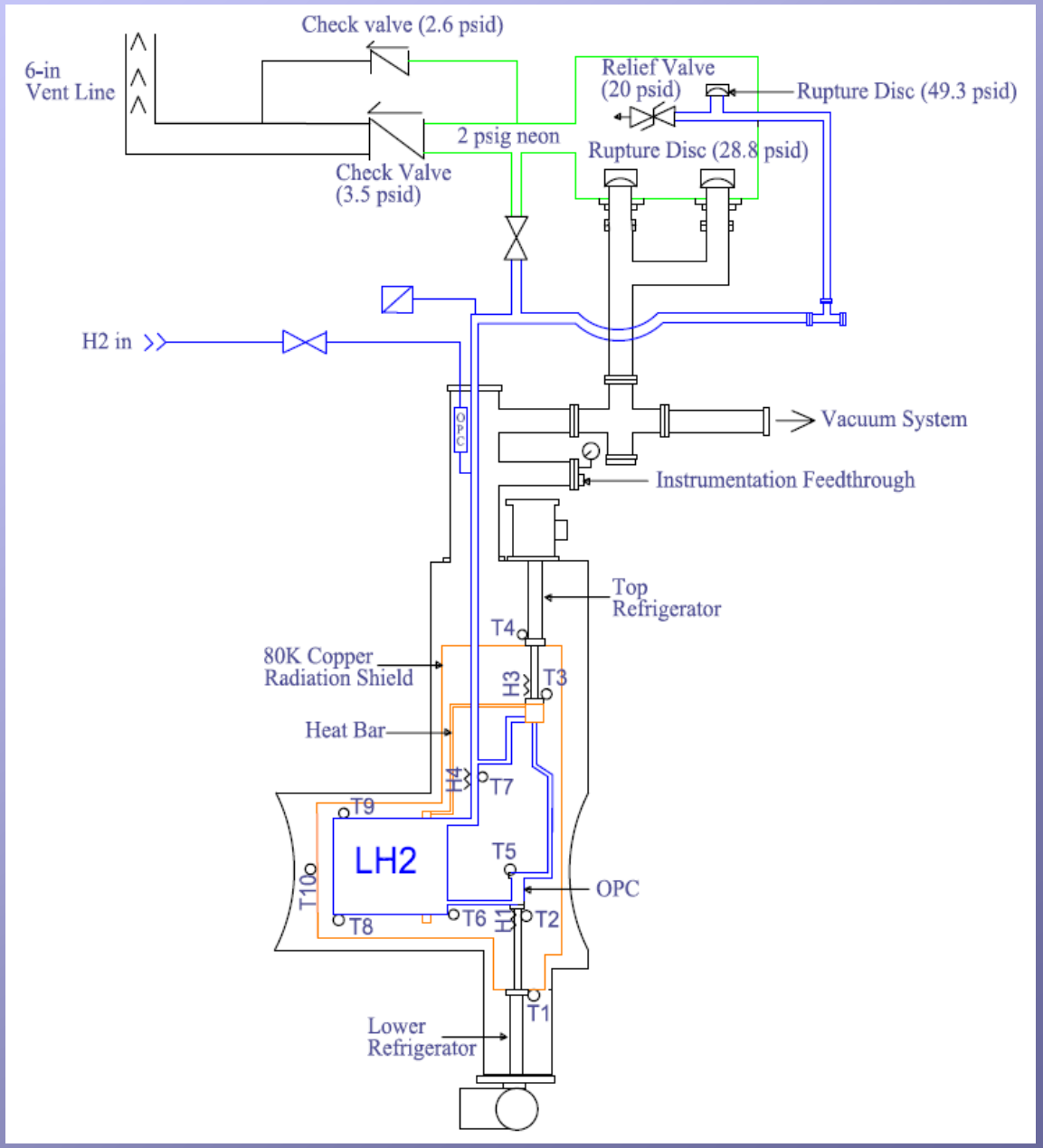
Schematic of the LH_2 Target



Al Target Cryostat

- The target vessel
- Cold heads of refrigerators
- OPCs
- Temperature sensors
- Heaters
- Radiation shield
- Hydrogen fill/vent tubing



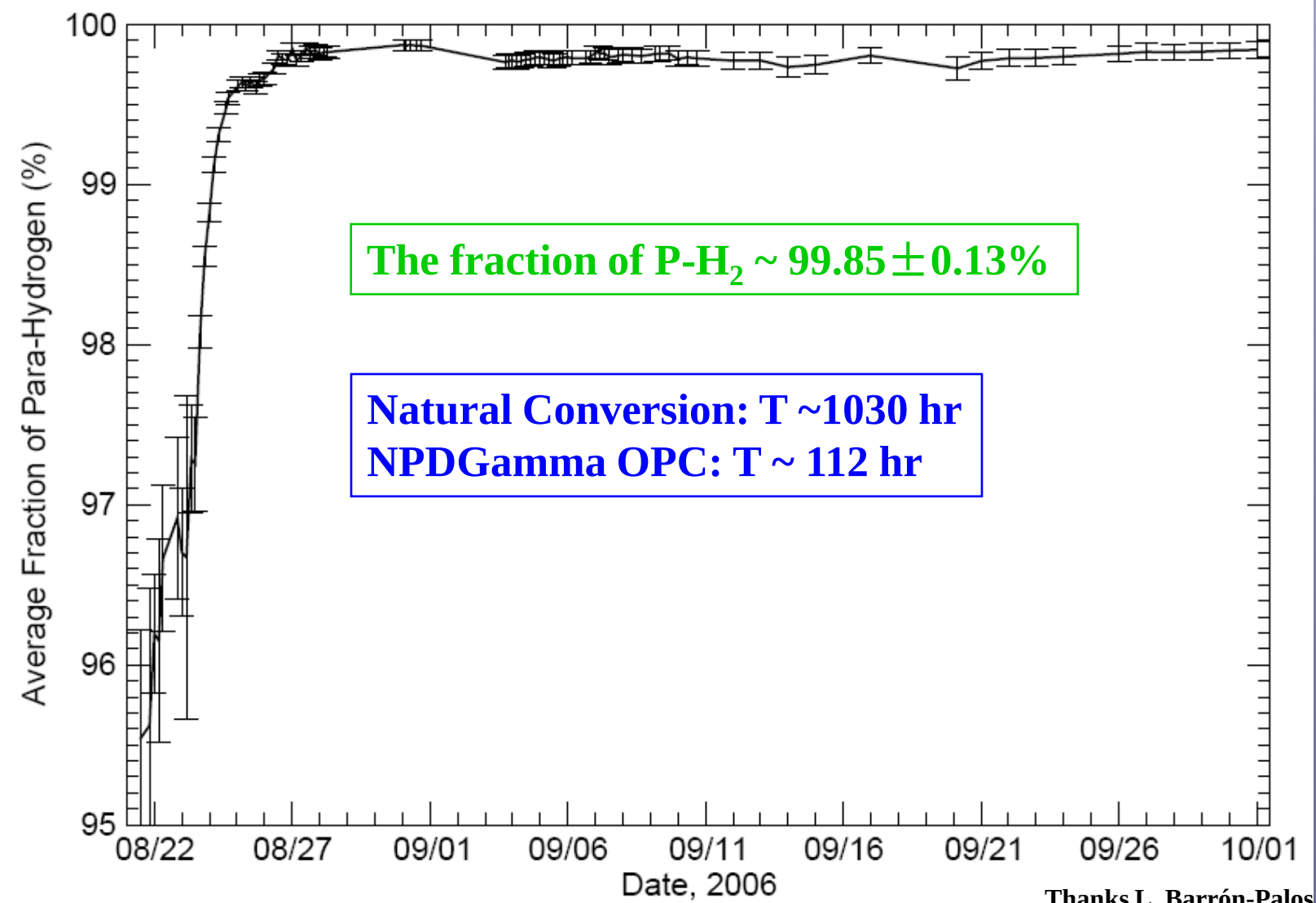


Target Vessel

- Al 6061-T6
- Two weld seams – joints of the two shaped end caps.
- ^{6}Li-rich flexible plastic neutron shield.
- Thin copper radiation sheild
- Superinsulation
- Thermally insulated support structure – two G-10 rings
- SST(304) fill/vent line – sufficiently nonmagnetic and low thermal conductivity.

Pictures of LH_2 Target at LANSCE

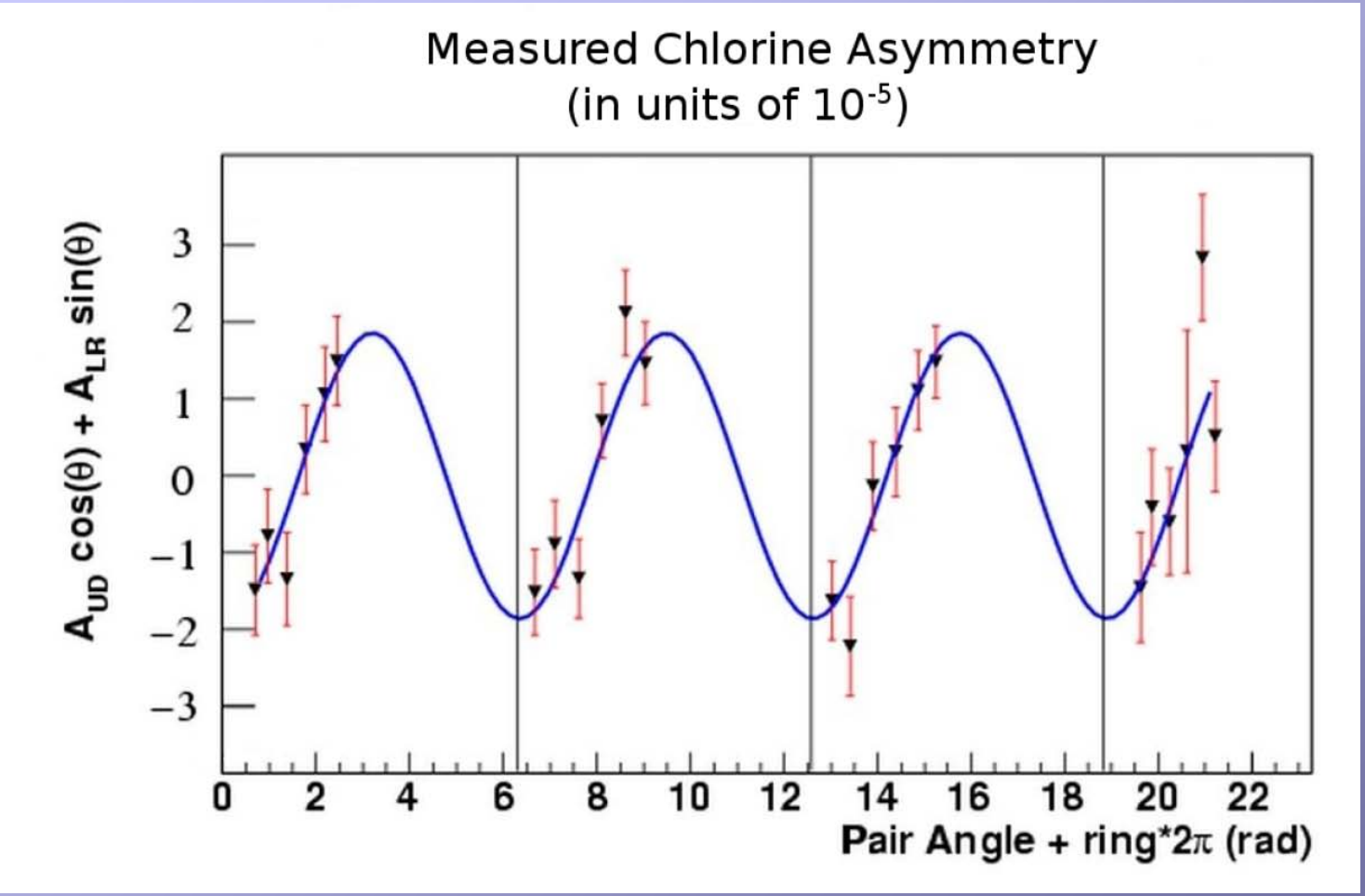
History of Para-hydrogen



Thanks L. Barrón-Palos

Some Results

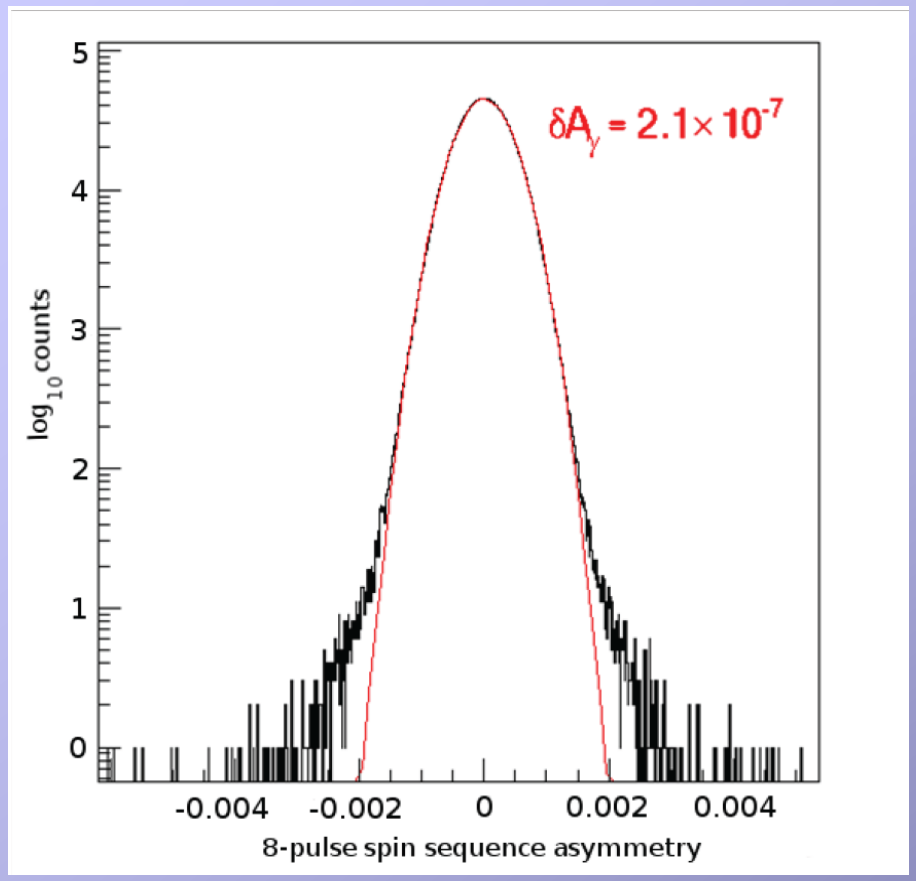
Chlorine Results



In agreement with past chlorine measurements:

- V.A. Vesna et al.. JETP Lett. 36 (1982), p. 209.
- M. Avenier et al.. Nucl. Phys. A 436 (1985), p. 83.

Experiment First-phase Run Result



	A_γ	
	Up-Down	Left-Right
Al	$(-0.02 \pm 3) \times 10^{-7}$	$(-2 \pm 3) \times 10^{-7}$
CCl_4	$(-19 \pm 2) \times 10^{-6}$	$(-1 \pm 2) \times 10^{-6}$
B_4C	$(-1 \pm 2) \times 10^{-6}$	$(-5 \pm 3) \times 10^{-6}$
Cu	$(-1 \pm 3) \times 10^{-6}$	$(0.3 \pm 3) \times 10^{-6}$
In	$(-3 \pm 2) \times 10^{-6}$	$(3 \pm 3) \times 10^{-6}$

Asymmetry results for the target materials. Stated errors are statistical only.

$\{-1.2 \pm 2.1\ (stat) \pm 0.2\ (sys)\}\times 10^{-7}$ *

* M. T. Gericke et al., to be published.

** Cavaignac,Vignon,Wilson, Phys. Lett. B, Vol. 67, Number 2 (1977) $\{0.6 \pm 2.1\}\times 10^{-7}$

Instrumental Systematic Effects

CsI Detector Array:

- Multiplicative systematic error (Gain shifts) → Magnetic field leaking into VPDs → Illuminate detectors by light emitting diodes to measure gain shift, accuracy of 0.1×10^{-8} in 1 day.
- Additive systematic error → Any electronic pickup → beam off non-zero up-down asymmetry. Accuracy of 0.1×10^{-8} in ~1 day.

RFSF:

- A spin flip pattern '↑↓↓↑↓↑↑↓' of pulse eliminates 1st & 2nd-order time-dependent detector-efficiency drifts.
- RF field is shielded by aluminum cover → skin depth ~0.5 mm.
- A change in the kinetic energy of neutron → Entry and exit static field different → Less than 0.2 μT → Less than 10^{-10}.

^{3}He Polarizer:

- Spin reversal in 3He polarizer → change in static magnetic field (~1×10^{-6} gauss) → at γ-detector, efficiency change ~ 2×10^{-11}.

Beam-dependant Systematic Errors

Reaction	Correlation	Pattern	PV?	TOF	Size
$n+p \rightarrow d+\gamma$	$S_n \cdot k_\gamma$	U-D	Yes	t^o	5×10^{-9}
$n+p \rightarrow n+p$ (scattering shift)	$K'_n \cdot S_n \times k_n$	L-R	No	t^{-1}	2×10^{-10}
$n+p \rightarrow d+\gamma$ (Csoto & Gibson)	$K'_\gamma \cdot S_n \times k_n$	L-R	No	t^{-2}	2×10^{-11}
$n+p \rightarrow d+\gamma$ (magnetized iron)	$S_\gamma \cdot S_n$	U-D	No	t^o	1×10^{-10}
$n \rightarrow p+e+\nu_e$ (beta decay)	$S_n \cdot k_e$	U-D	Yes	t^o	3×10^{-11}
$n+d \rightarrow t+\gamma$ (D_2 contamination)	$S_n \cdot k_\gamma$	U-D	Yes	t^o	1×10^{-10}
$n+p \rightarrow n+p$ (Mott-Schwinger)	$K'_n \cdot S_n \times k_n$	L-R	No	$t^{-2.8}$	1×10^{-10}
$n+{}^6Li \rightarrow \alpha+t$ (Li-shield)	$S_n \cdot K'_n$	U-D	Yes	t^o	2×10^{-11}
$(\mu_n.\nabla)B$ (Stern-Gerlach)	$(S_n \cdot \nabla)B$	U-D	No	t^1	1×10^{-10}
$n+A \rightarrow A+1+e+\nu_e$	$S_n \cdot k_e$	U-D	Yes	Varies	$<10^{-10}$

Table from: W. M. Snow et al., Fundamental Physics with Pulse Neutron Beams, World Scientific, 2001, pp. 203-213.

Experiment Modification for SNS

Related to the Target:

- Reducing the upstream main vacuum inner and outer windows. (0.12 in → 0.06 in).
- Reducing the upstream target vessel thickness.
- Larger OPC to reduce the conversion time.
- Adding one more refrigerator to reduce the cooling time.
- Adding more temperature sensors to determine the liquid hydrogen level.

Other major modification:

- ^{3}He Polarizer → Supermirror Polarizer.
- 20Hz → 60Hz

Status & Plan

- The experiment ran successfully in 2006.
- LH_2 target data have been analyzed, to be published soon.
- LH_2 target modifications are in process at IUCF.
- Beam line construction in SNS is done.
- Supermirror polarizer and B-coil have been installed.
- Take more runs on Al target to get a better limit.
- LH_2 target will be shipped to SNS and start to take data in 2010.
- Goal at SNS is $\sim 10^{-8}$

The NPDGamma Collaboration

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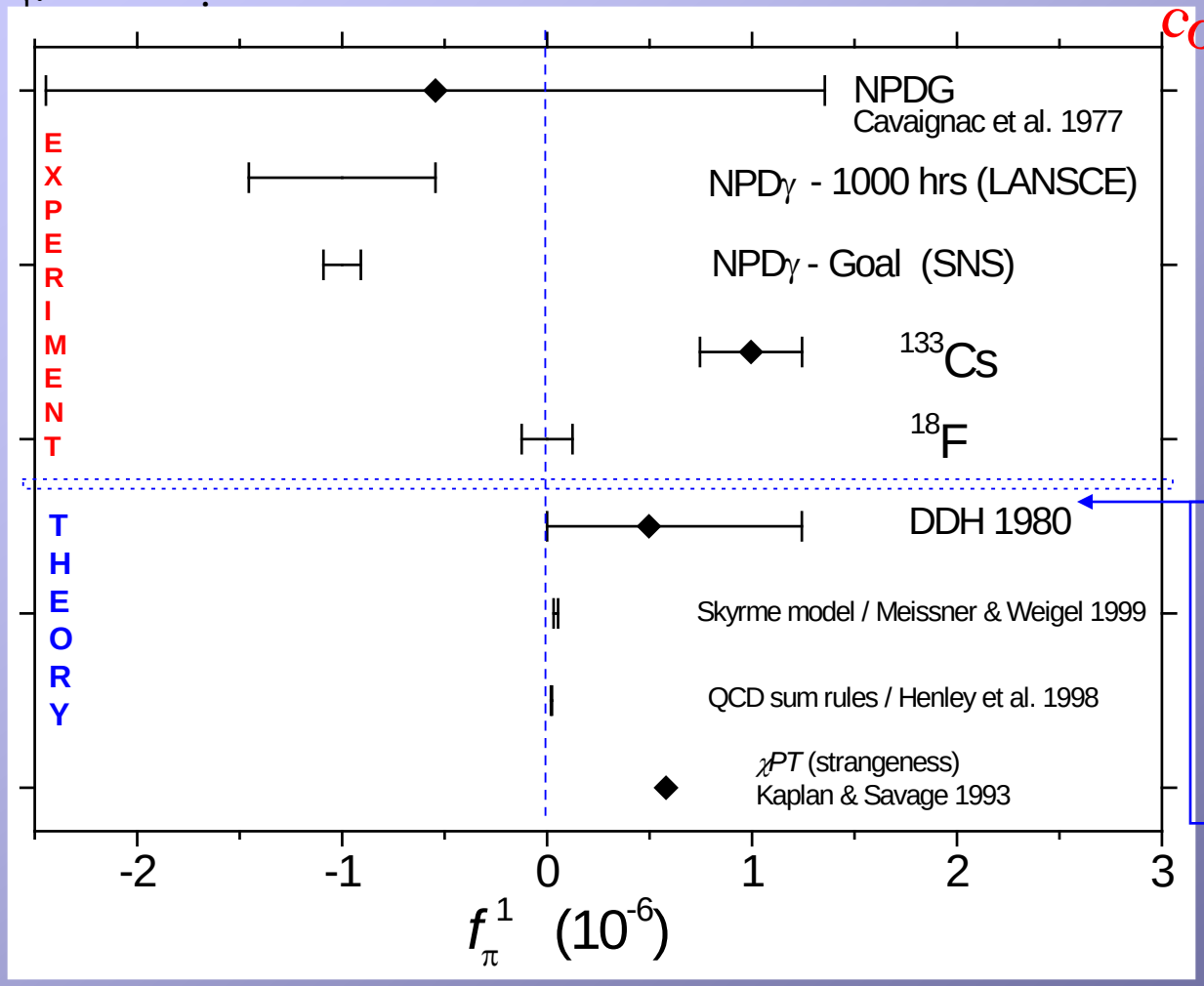
Thank You

Constraints on Weak N-N Coupling

- Previous determinations of $\sqrt{\beta_\pi^2}H_\pi^1 / g_{\pi NN}$



contradictory results

anapole moment

photon polarization

DDH Meson Exchange Currents Reasonable theoretical range 0 – 1.14 best value 0.45

Importance of a precision measurement of f_π^1?

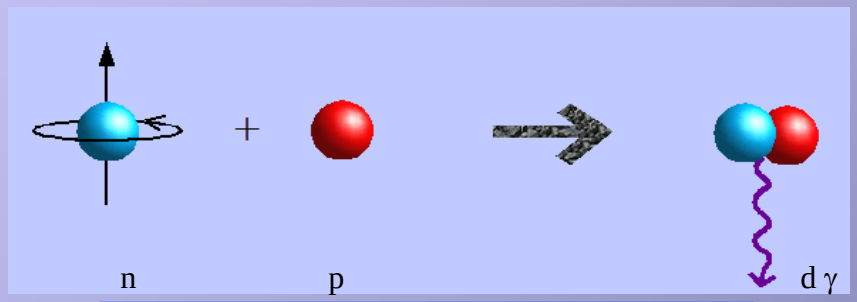
- A precision value of f_π^1 is necessary to understand and interpret the measurements of parity-violating observables in complex nuclei.
- f_π^1 is the most important weak coupling in the determination of the complete set of the couplings in the weak meson-exchange potential for a two-nucleon system.
- Interpretation of parity-violating phenomena in finite nuclei will be reduced to understanding the nuclear structure of the states involved.
- Stimulate further theoretical work to calculate f_π^1 and other weak couplings, starting from standard model description of weak interactions and a QCD description of the strong interaction.

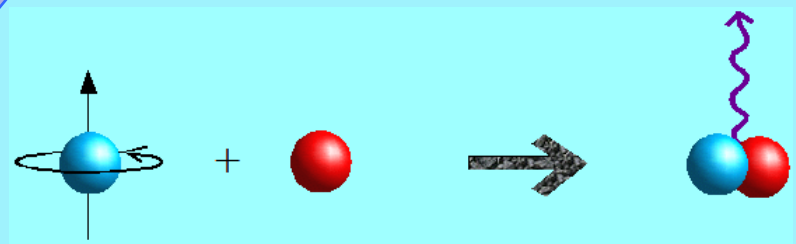
The NPDGamma Process

Study the hadronic weak interaction between spin-polarized neutrons and protons in the reaction.

$$\vec{n} + p \rightarrow d + \gamma$$

Measure A_γ, the parity-violating asymmetry in the distribution of emitted 2.2 MeV γ's.





Parity Transformation

$$\Psi(\vec{r}) \rightarrow \Psi(-\vec{r})$$

up/down γ rates differ

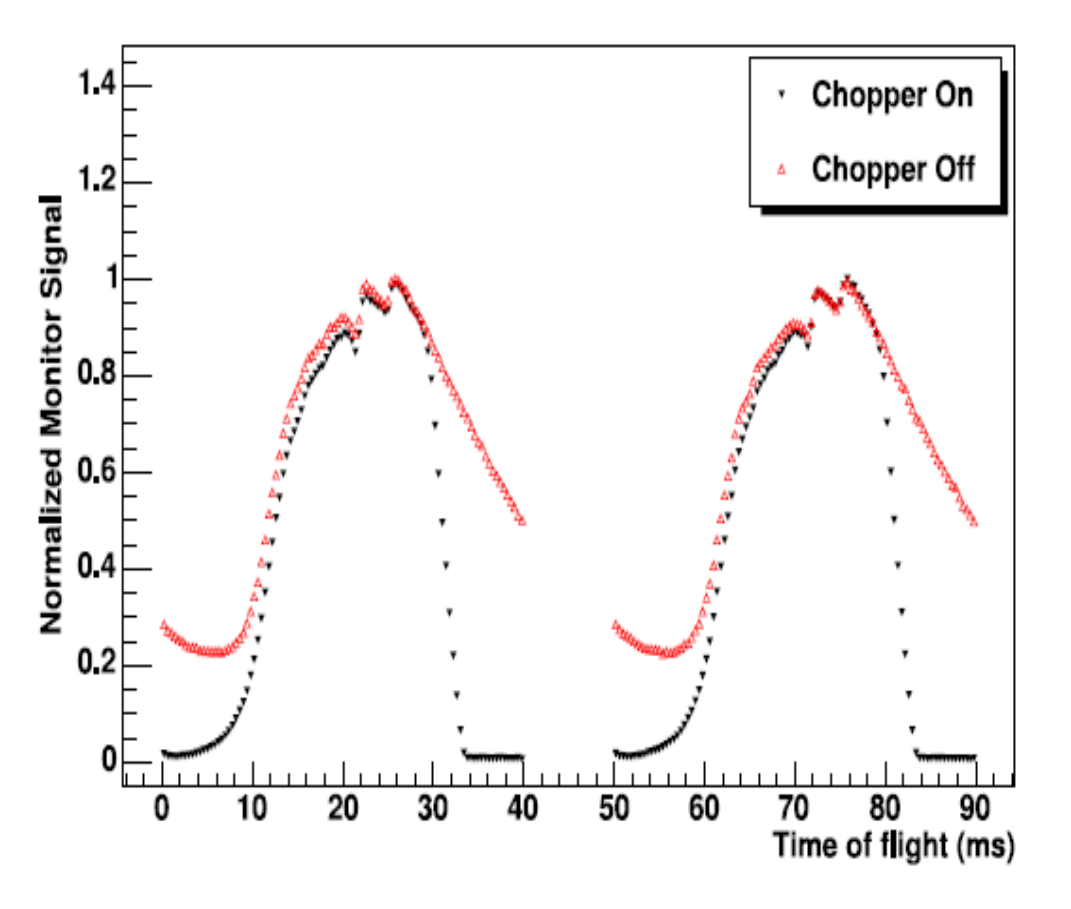
→ Parity is violated.

$$\frac{d\omega}{d\Omega} \propto 1 + A_\gamma \cos\theta_{s,\gamma}$$

the correlation between neutron spin and photon momentum $\langle \vec{s}_n \cdot \vec{k}_\gamma \rangle$ is odd under parity transformation ($\vec{k}_\gamma$ changes sign, $\vec{s}_n$ does not)

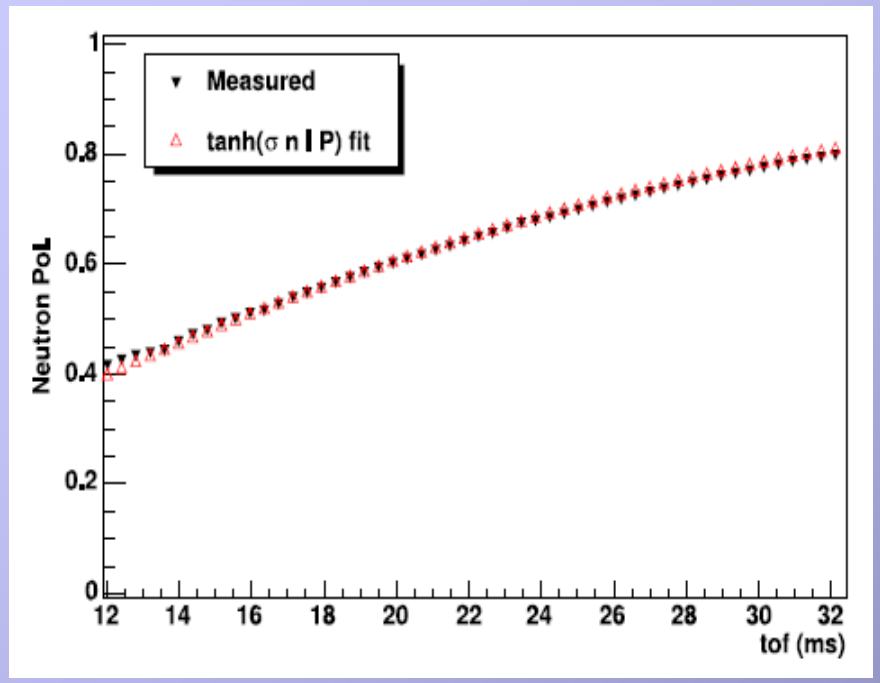
-- a measure of $\Delta s = 0, \Delta I = 1$ neutral current weak hadronic interaction.

Frame Overlap Chopper



- Pulsed beam: neutron time-of-flight determines neutron velocity, energy
- PV asymmetry is independent of energy
- Very slow neutrons can overlap with faster neutrons from later pulse
- Chopper rotor coated with Gd_2O_3 absorbs slow neutrons up to 30 meV, opens window for faster ones
- up to 200 RPM
- settings opens with n-pulse onset

Neutron Transmission Measurement for ^{3}He Polarization Analysis



$$T_0 = \exp(-\sigma_a nl)$$

$$T_n = T_0 \cosh(\sigma_a nlP_{He})$$

$$T_\pm = \exp(-\sigma_a nl(1 \mp P_{He}))$$

$$P_n = \frac{T_+ - T_-}{T_+ + T_-} = \tanh(\sigma_a nlP_{He}) = \sqrt{1 - \left(\frac{T_0}{T_n}\right)^2}$$

$$T = M_2 / M_1$$

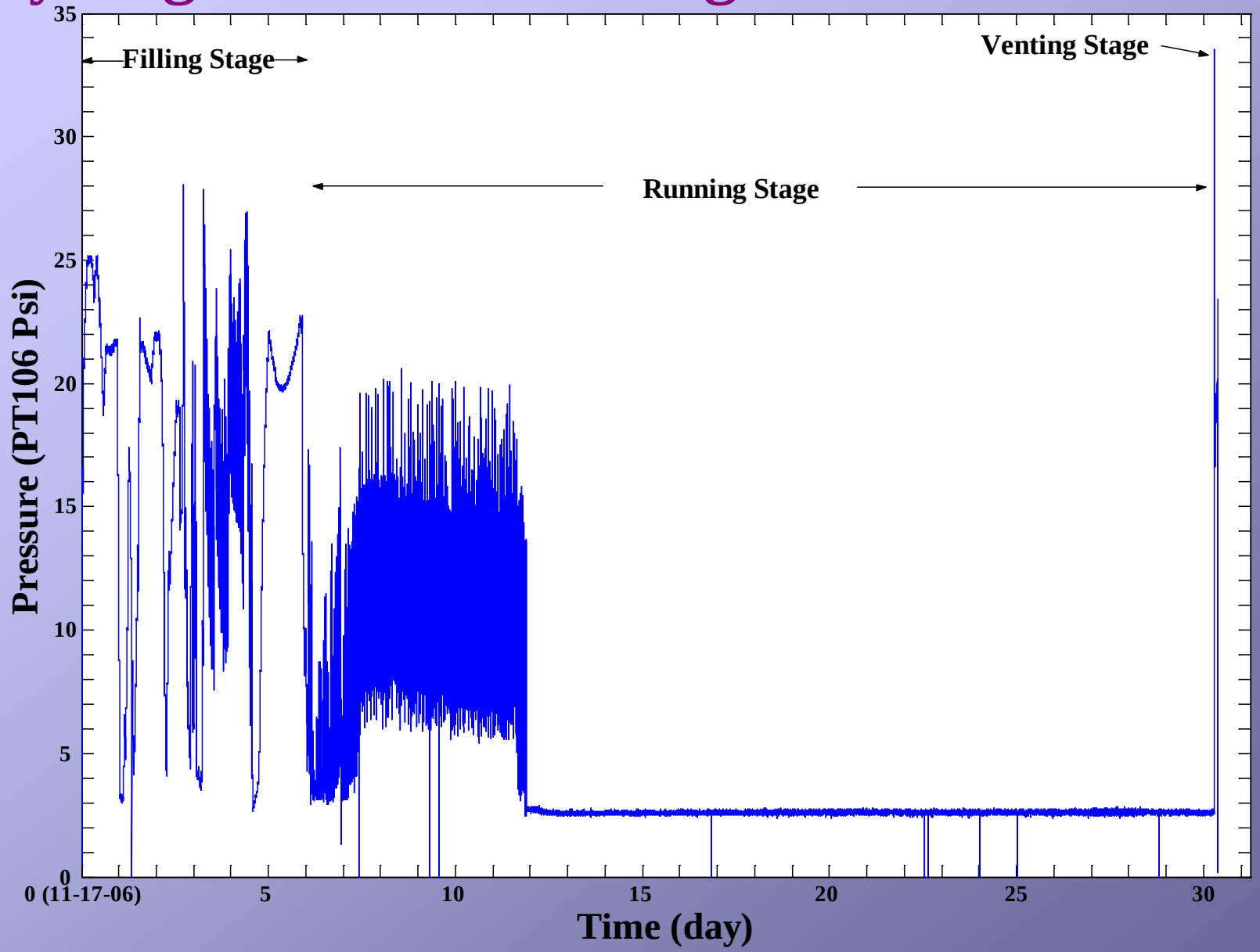
P_{He}= the 3He polarization.

n = the number density of P_{He} atoms in the cell.

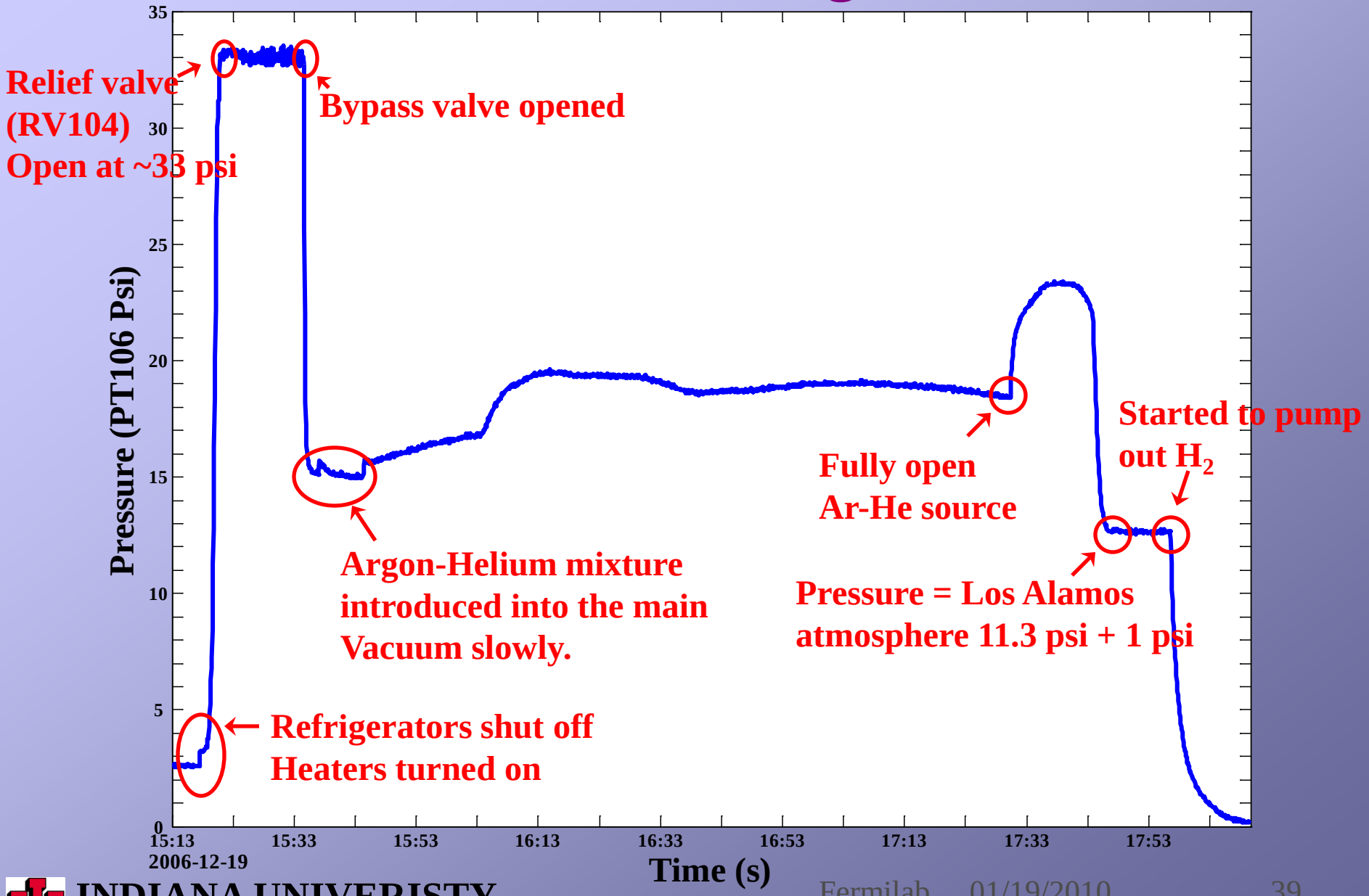
l = the length of the cell.

σ_a= capture cross section.

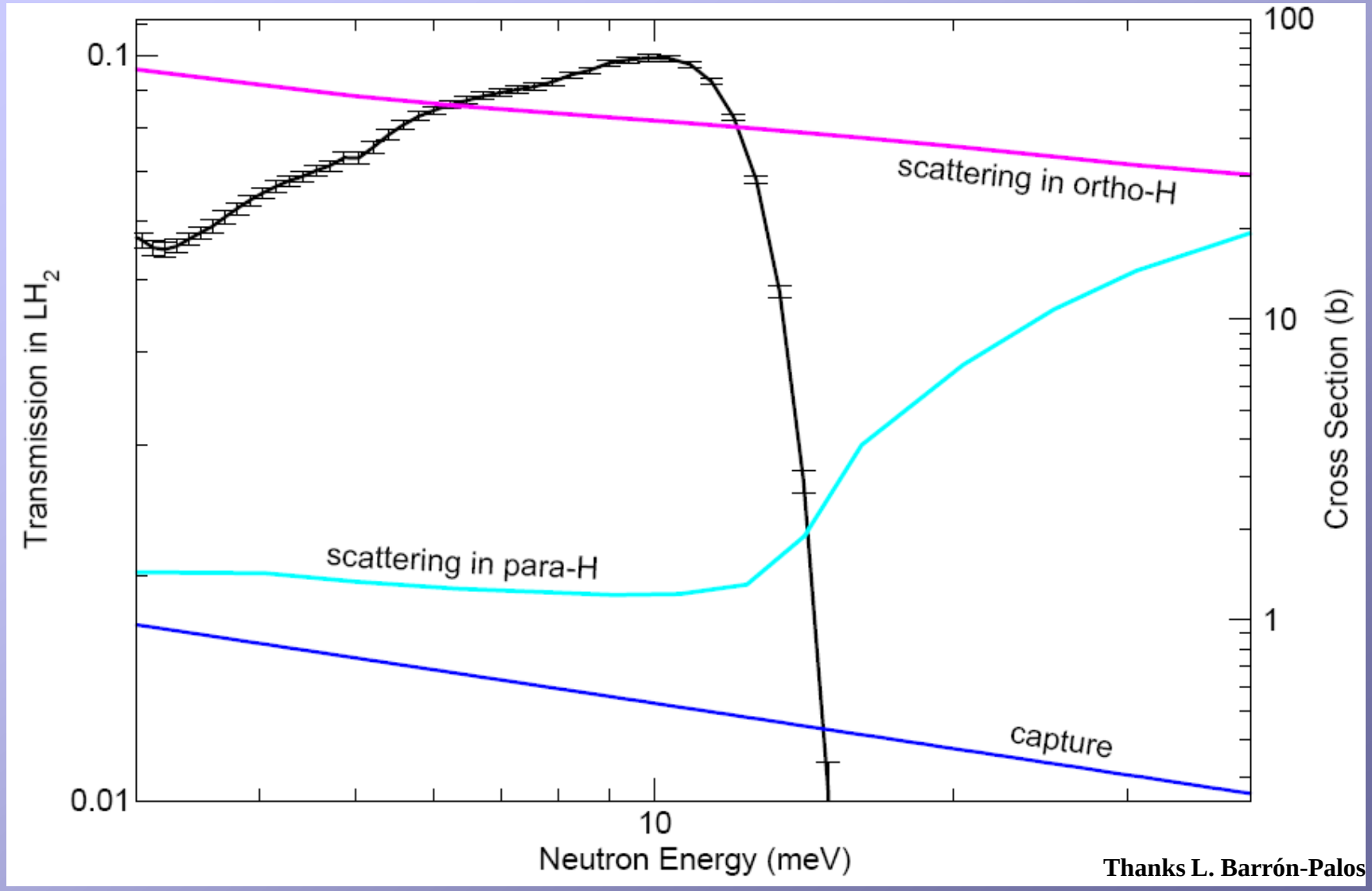
Hydrogen Pressure during 2006 Nov-Dec Run



Pressure in the Vessel During Vent



Neutron Transmission through LH_2 Target



Thanks L. Barrón-Palos

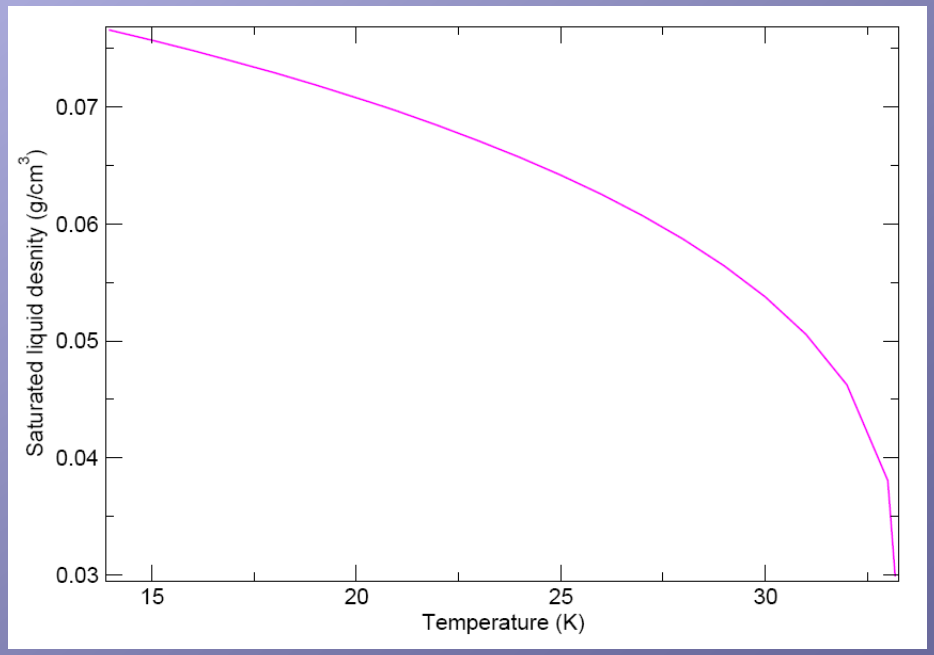
The Fraction of Para-hydrogen

$$T_{H_2} = \exp\left\{-nl\left[\sigma_c + (n_p/n)\sigma_p + (n_o/n)\sigma_o\right]\right\}, \quad n = n_p + n_o$$

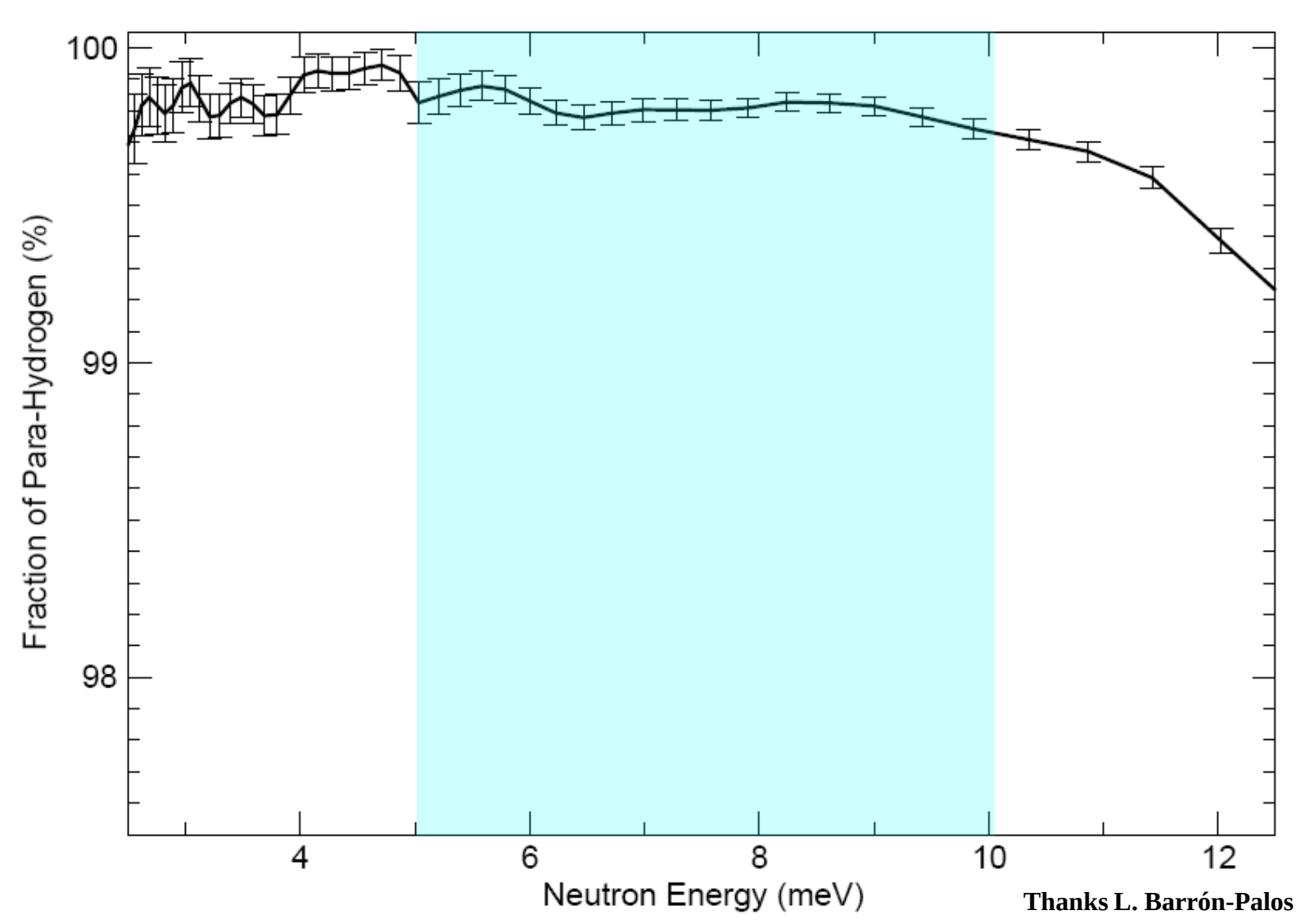
$$\boxed{\frac{n_p}{n}(E_n) = \frac{1}{\sigma_o - \sigma_p}\left[\frac{\log(T_{H_2})}{nl} + \sigma_o + \sigma_c\right]}$$

$$n = \rho N_A \frac{2\ \text{atoms/molecule}}{2.016\ \text{g/mol}}$$

$$l = 28.83\ \text{cm}$$



Fraction of Para-hydrogen



Time Constant

Natural conversion

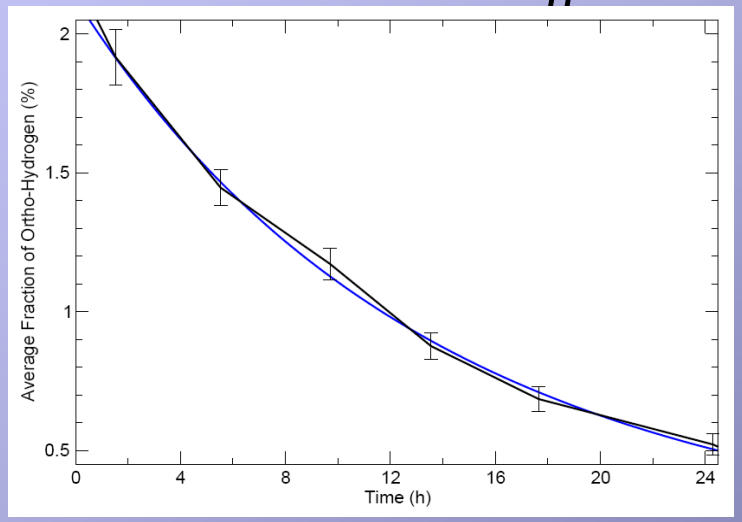
$$\frac{dc}{dt} = -K_n c^2 + \frac{c_e}{1-c_e} K_n c(1-c)$$

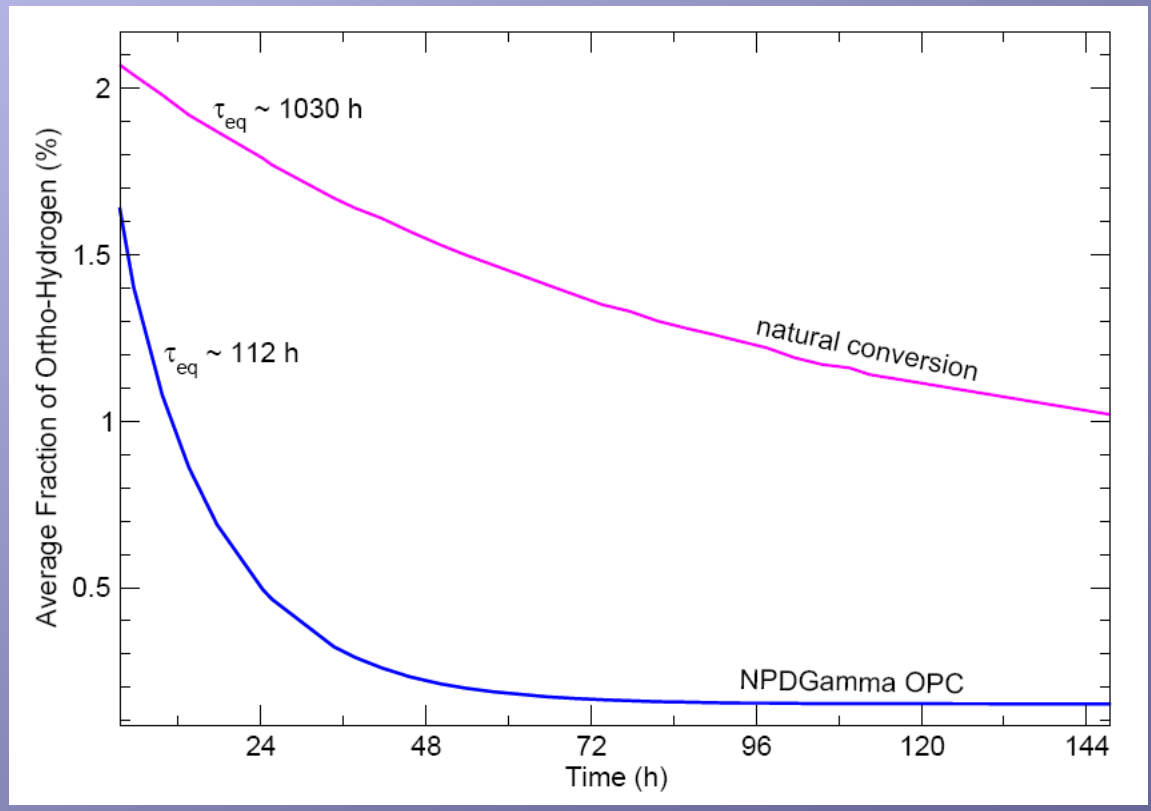
Catalyzed conversion

$$\frac{dc}{dt} = -K_n c^2 + \frac{c_e}{1-c_e} K_n c(1-c) - K_{OPC} c + \frac{c_e}{1-c_e} K_{OPC}(1-c)$$

$$K_N = 1.94\%/\mathrm{h}$$
$$K_{OPC} = 6.09\%/\mathrm{h}$$

n





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