Parity-odd Gamma-ray Asymmetry in Polarized Neutron Capture on Hydrogen: The NPDGamma Experiment

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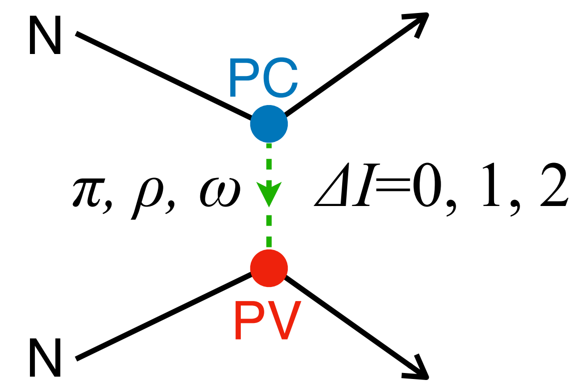
UNAM

Traditional Theoretical Description

Meson-exchange Model

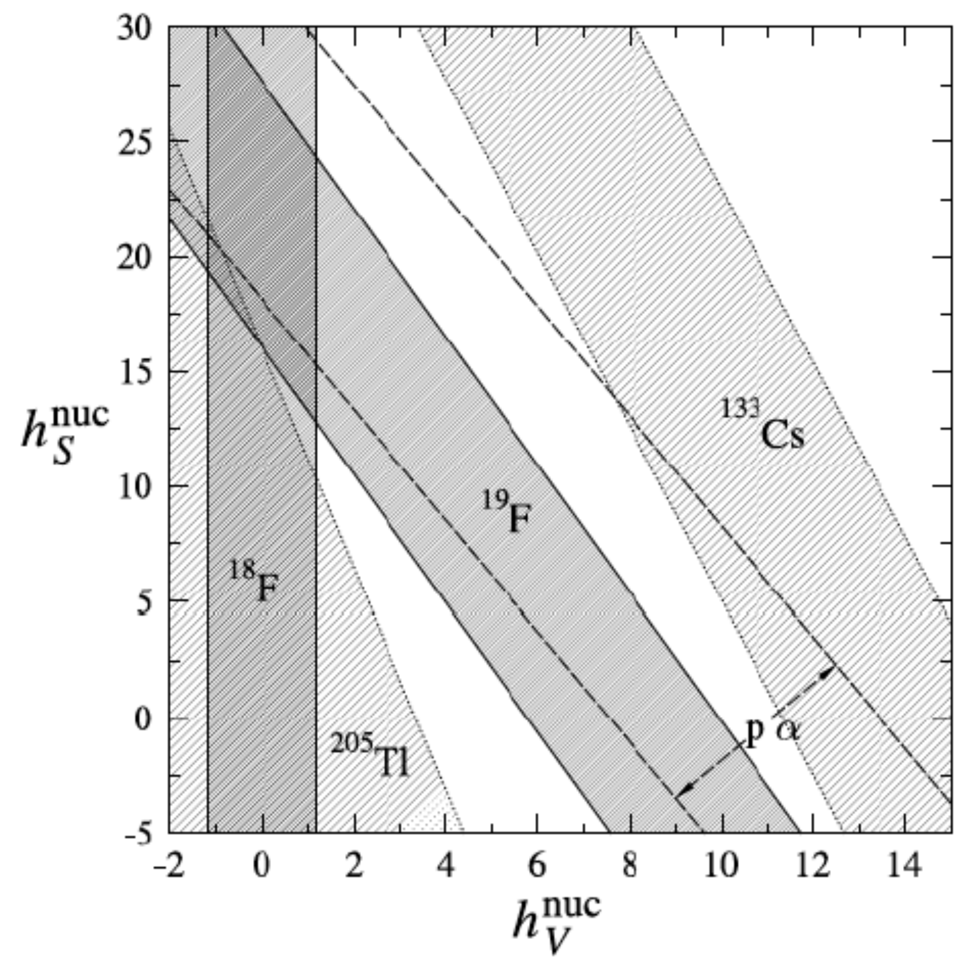
- One-meson-exchange potential
- Model dependent



Coupling	DDH reasonable range	DDH "best value"
h_π^1	0 → 11	+4.6
h_ρ^0	11 → -31	-11
h_ρ^1	-0.4 → 0	-0.2
h_ρ^2	-7.6 → -11	-9.5
h_ω^0	5.7 → -10.3	-1.9
h_ω^1	-1.9 → -0.8	-1.2

in units of $\times 10^{-7}$ $h_\rho^{1'}$ is set to zero

Desplanques, Donoghue, Holstein, *Annals of Physics* 124, 449 (1980)



$$h_V^{nuc} = h_\pi^1 - 0.12\, h_\rho^1 - 0.18\, h_\omega^1$$
$$h_S^{nuc} = -(h_\rho^0 + 0.7\, h_\omega^0)$$

Ramsey-Musolf, Page, *Annu. Rev. Nucl. Part. Sci.* 56, 1-52 (2006)

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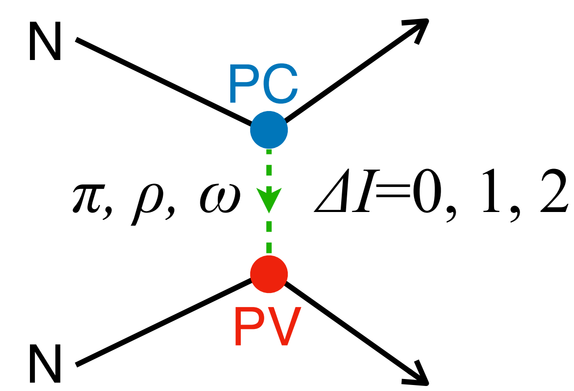

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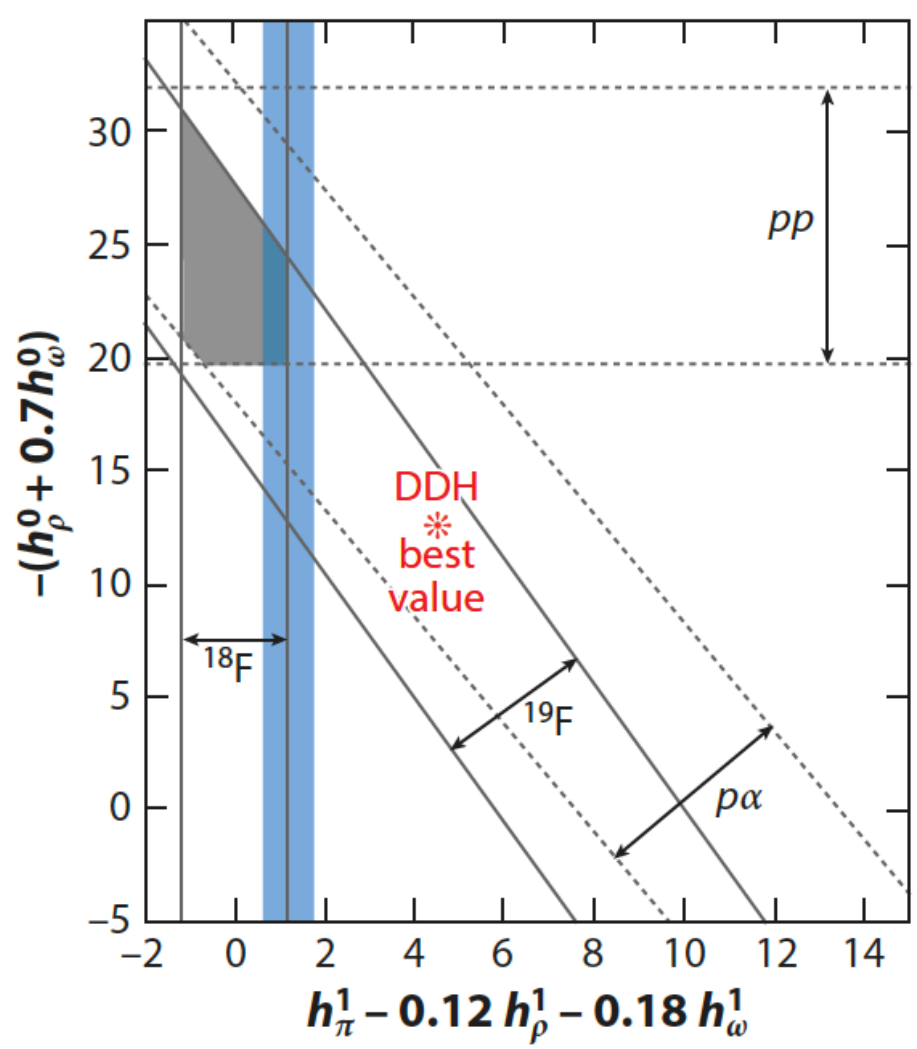
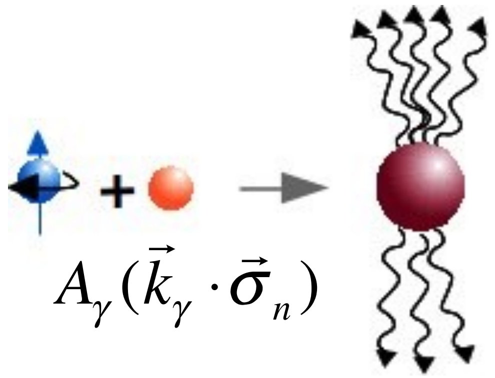
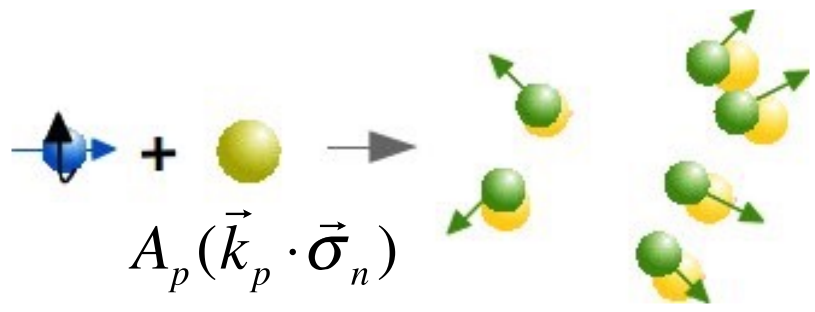
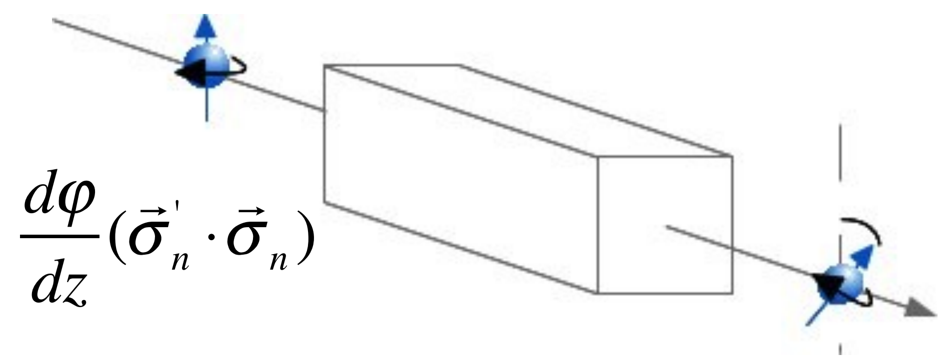


Haxton, Holstein, *Prog. Part. Nucl. Phys.* 71, 187 (2013)

Motivation for NPDGamma and other few-nucleon experiments using neutrons







NPDGamma

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

- Dominated by a $\Delta I=1$ $^3S_1$-$^3P_1$ parity-odd transition in the n-p system (π-exchange)
- h_π^1 coupling can be isolated (heavy meson contributions very small)
- $A_\gamma \approx -0.11\ h_\pi^1$ ($A_\gamma \approx -5\times10^{-8}$ using DDH “best value”)
- Also charged currents are suppressed for $\Delta I=1$, so potential to study neutral currents (not present in strangeness-changing HWI)

More Recent Theoretical Developments

Effective Field Theory (EFT)

$$\Lambda_0^{{}^1S_0-{}^3P_0} = -g_\rho(2+\chi_\rho)h_\rho^0 - g_\omega(2+\chi_\omega)h_\omega^0$$

$$\Lambda_0^{{}^3S_1-{}^1P_1} = -3g_\rho\chi_\rho h_\rho^0 + g_\omega\chi_\omega h_\omega^0$$

$$\Lambda_1^{{}^1S_0-{}^3P_0} = -g_\rho(2+\chi_\rho)h_\rho^1 - g_\omega(2+\chi_\omega)h_\omega^1$$

$$\Lambda_1^{{}^3S_1-{}^3P_1} = \sqrt{\tfrac{1}{2}}\, g_{\pi NN}\left(\frac{m_\rho}{m_\pi}\right)^2 h_\pi^1 + g_\rho(h_\rho^1 - h_\rho^{1\prime}) - g_\omega h_\omega^1$$

$$\Lambda_2^{{}^1S_0-{}^3P_0} = -g_\rho(2+\chi_\rho)h_\rho^2$$

- Not dependent on a model
- Consistent with the symmetries and degrees of freedom of QCD

Haxton, Holstein, *Prog. Part. Nucl. Phys.* 71, 187 (2013)

Hierarchy of Parameters in Large-N_c Expansion

Two leading order (LO)

$$\Lambda_0^+ \equiv \frac{3}{4}\Lambda_0^{{}^3S_1-{}^1P_1} + \frac{1}{4}\Lambda_0^{{}^1S_0-{}^3P_0} \sim N_c$$

$$\Lambda_2^{{}^1S_0-{}^3P_0} \sim N_c$$

Three next-to-next-to leading order (N^2LO)

$$\Lambda_0^- \equiv \frac{1}{4}\Lambda_0^{{}^3S_1-{}^1P_1} - \frac{3}{4}\Lambda_0^{{}^1S_0-{}^3P_0} \sim 1/N_c$$

$$\Lambda_1^{{}^1S_0-{}^3P_0} \sim \sin^2\theta_W$$

$$\Lambda_1^{{}^3S_1-{}^3P_1} \sim \sin^2\theta_W$$

Schindler, Springer, Vanasse, *Phys. Rev. C.* 93, 025502 (2016)
Gardner, Haxton, Holstein, *Annu. Rev. Nucl. Part. Sci.* 67, 69-95 (2017)

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Isolated in γ polarization in ^{18}F decay and NPDGamma

$$\Lambda_1^{{}^1S_0-{}^3P_0} \sim \sin^2\theta_W$$

$$\Lambda_1^{{}^3S_1-{}^3P_1} \sim \sin^2\theta_W$$

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A Long Way Coming

First Stage at the Los Alamos Neutron Science Center (LANL)

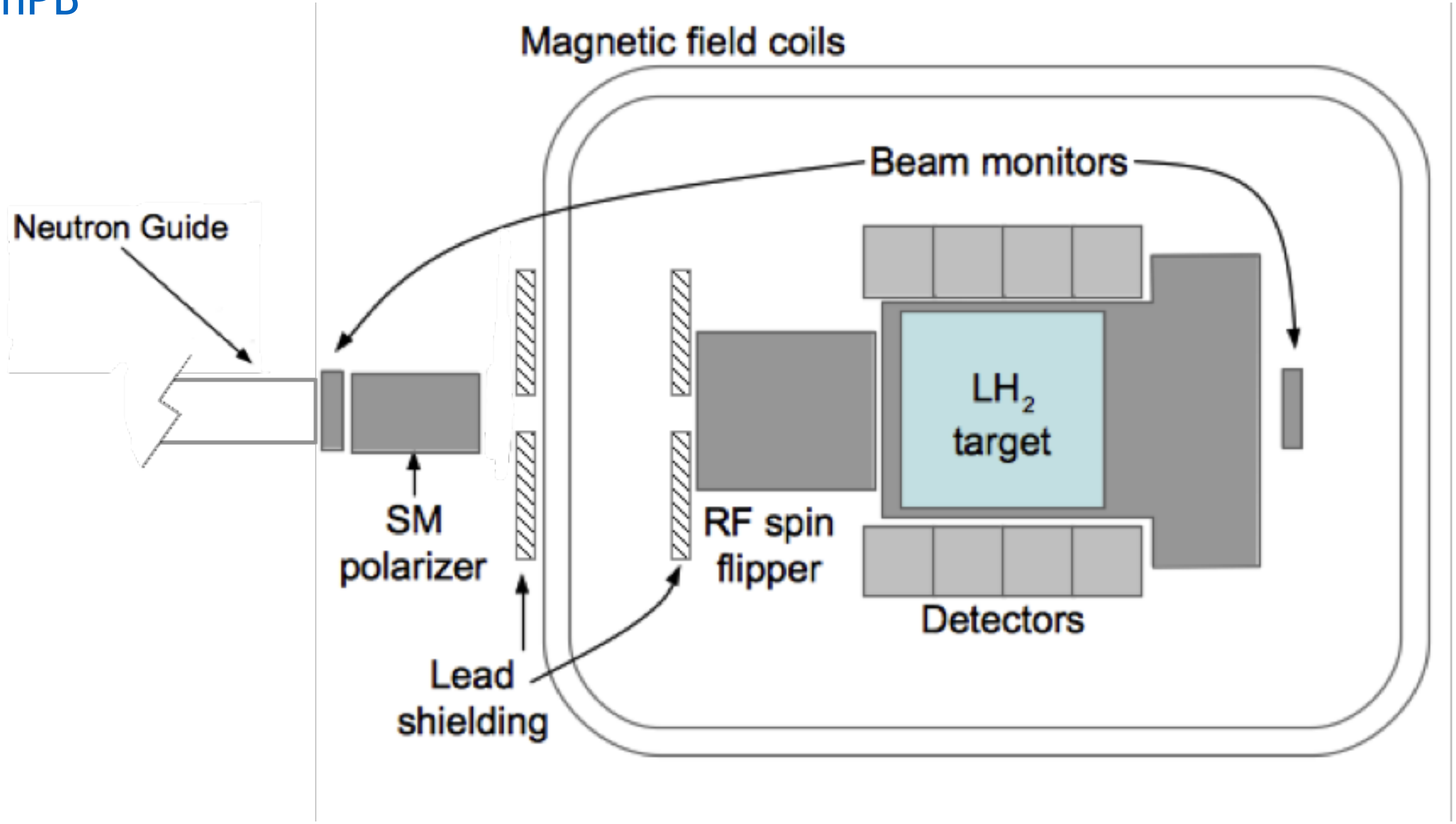
- Letter of intent in 1998
- Construction of FP12
- Data taking at Los Alamos in 2006-2007
- Statistically limited result: $A_\gamma = [-1.2 \pm 2.1(\mathrm{stat.}) \pm 0.2(\mathrm{syst.})] \times 10^{-7}$
  [Gericke et al. *Phys. Rev. C* 83, 015505 (2011)]

Second Stage at the Spallation Neutron Source (ORNL)

- More intense neutron flux available
- Modifications to some components, installation and commissioning (2008-2012)
- H_2 data taking at the SNS (November 2012 - March 2014)
- Apparatus decommissioned in the Summer of 2014 and partially reinstalled again in 2016 for background asymmetry measurement (Aluminium inconsistencies)
- Final result to be announced at the CIPANP 2018 meeting
- Preliminary result: $A_\gamma = [-3.1 \pm 1.5(\mathrm{stat.}) \pm 0.3\,(\mathrm{syst.})] \times 10^{-8}$
  [David Blyth, PhD thesis, Arizona State University (2017)]

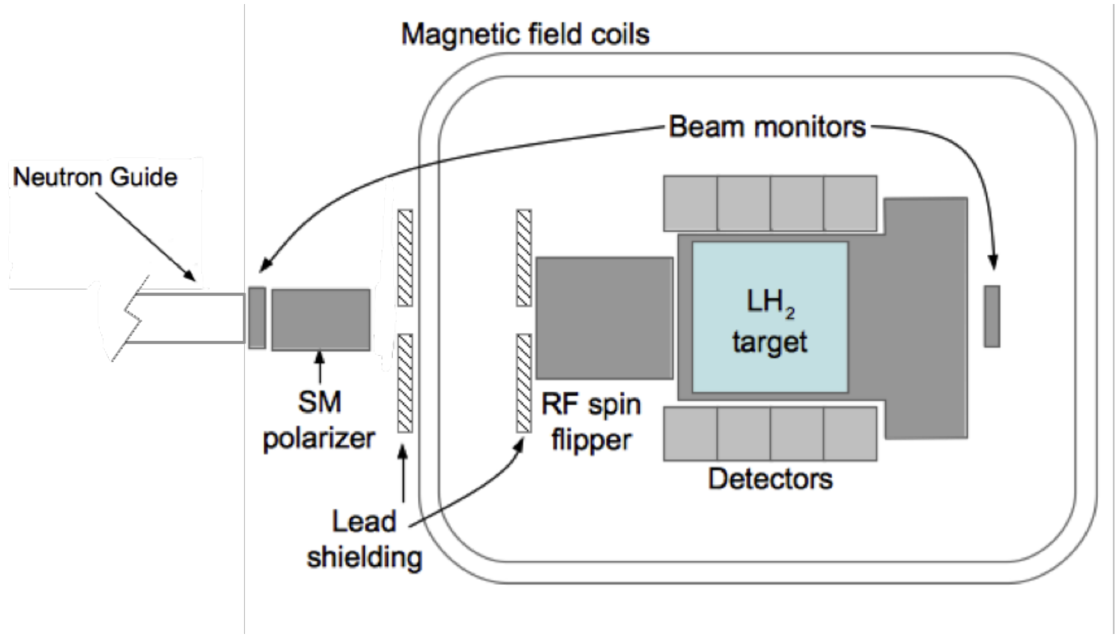
The Experiment

@ FnPB

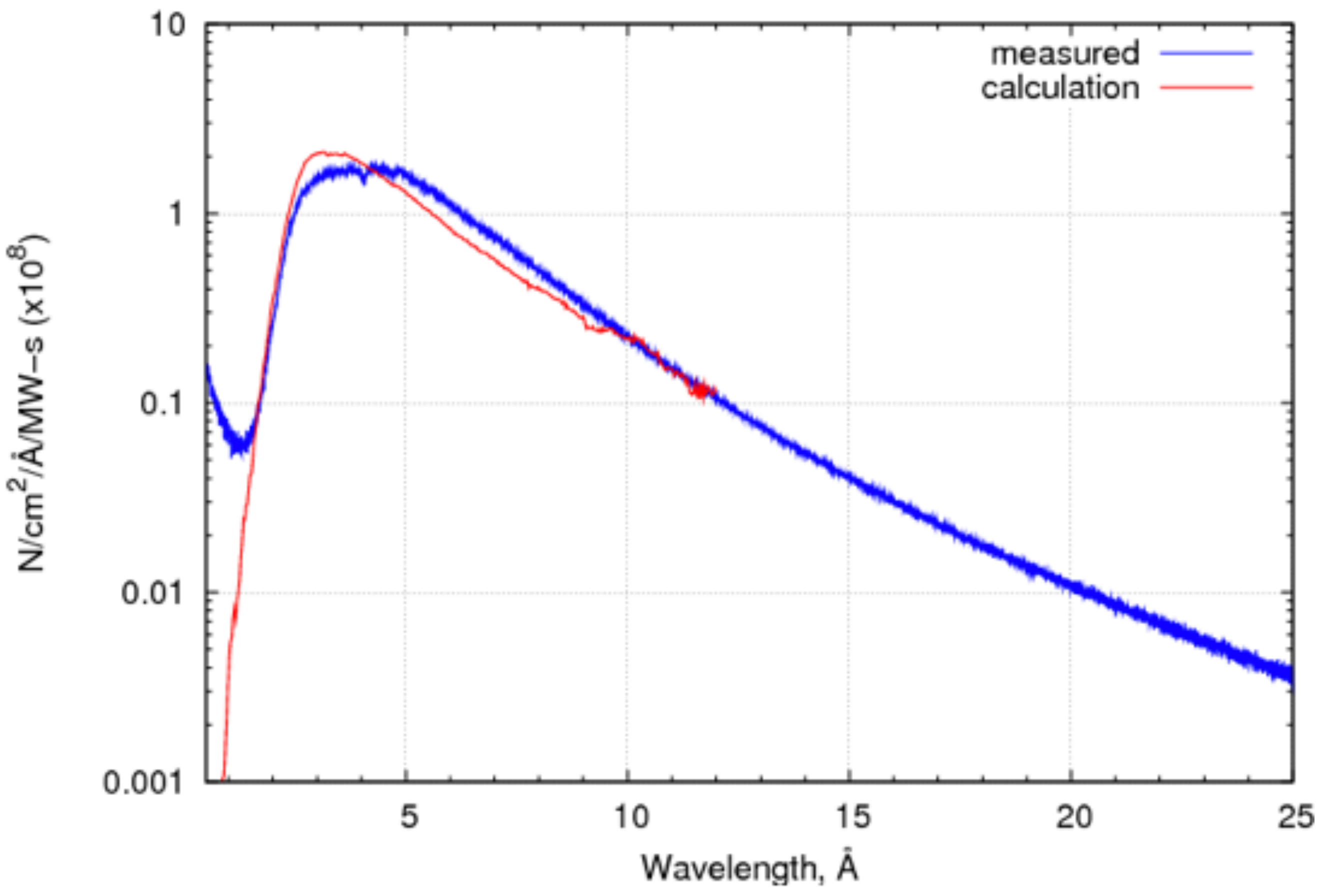


The Experiment

Neutron Flux



60 pulses per second



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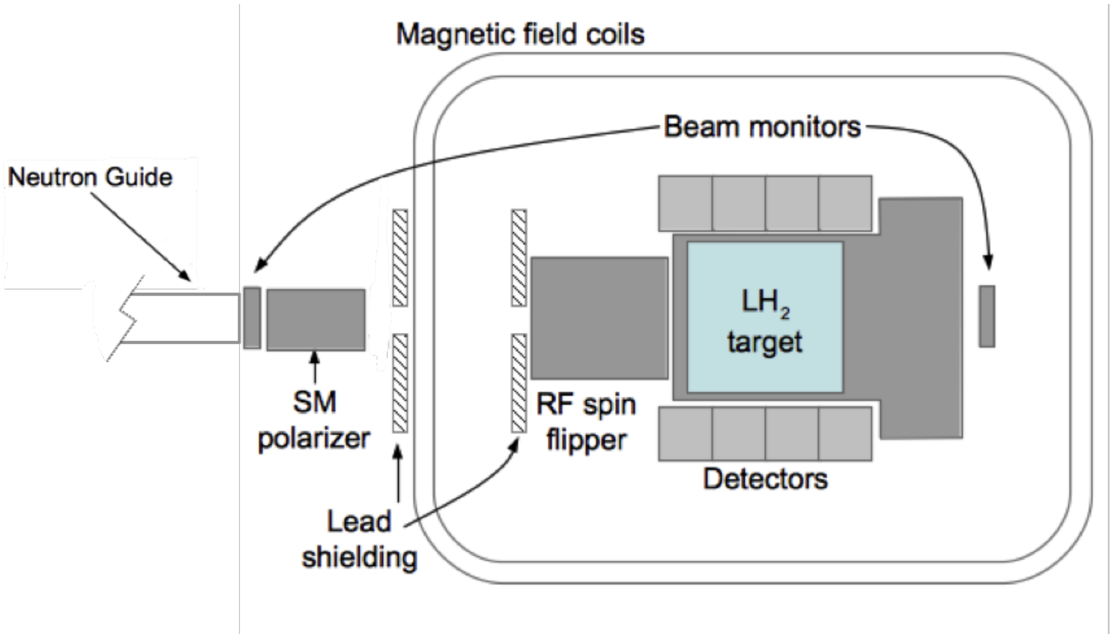
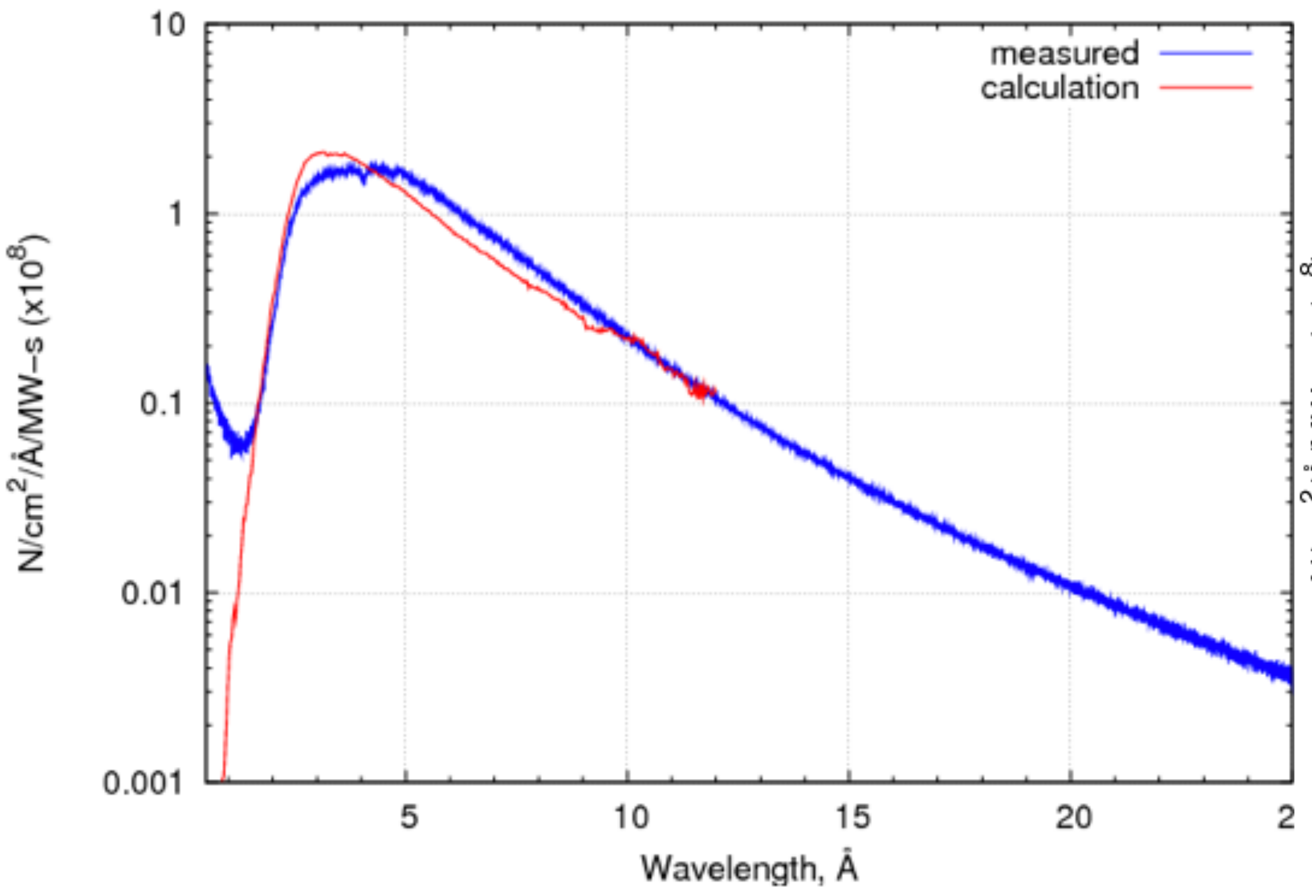
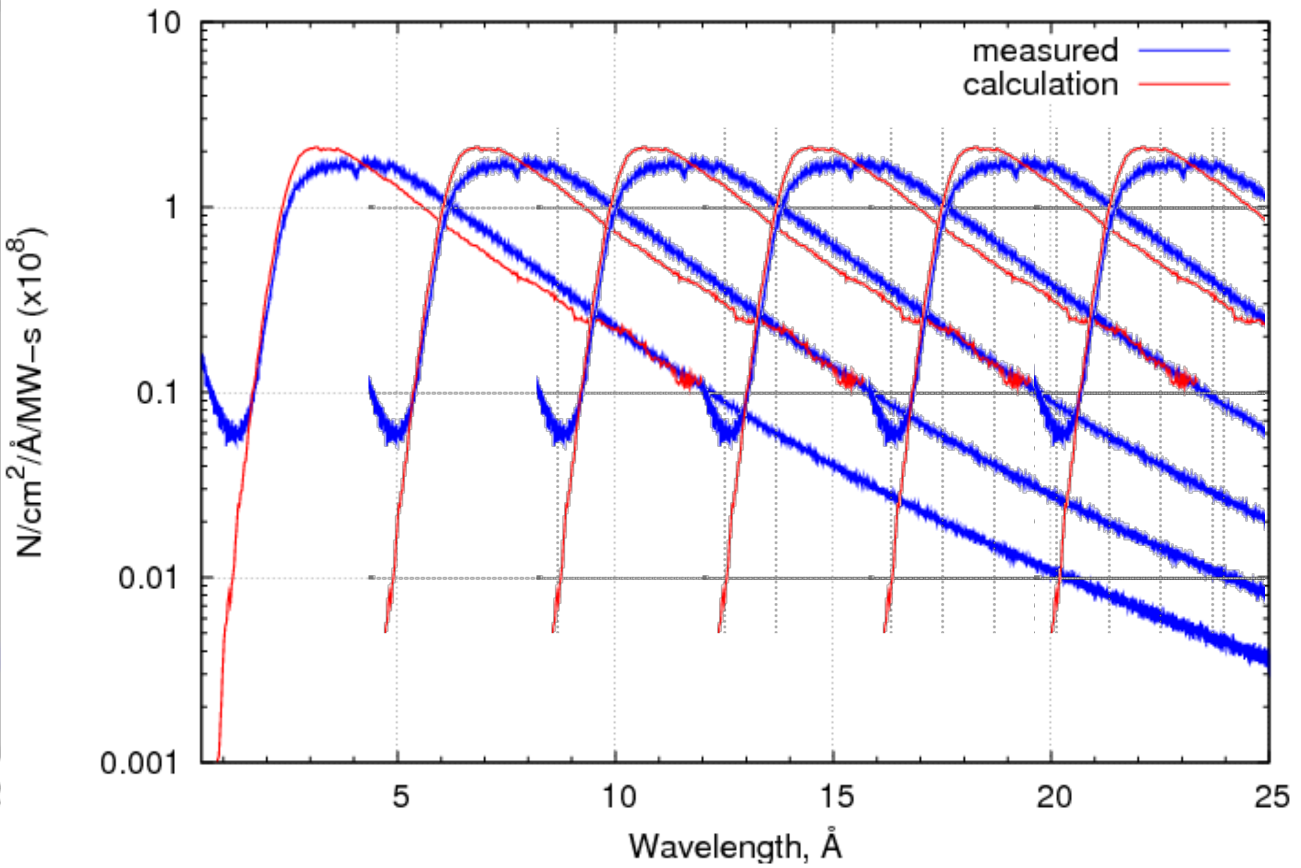
The Experiment

Neutron Flux

60 pulses per second







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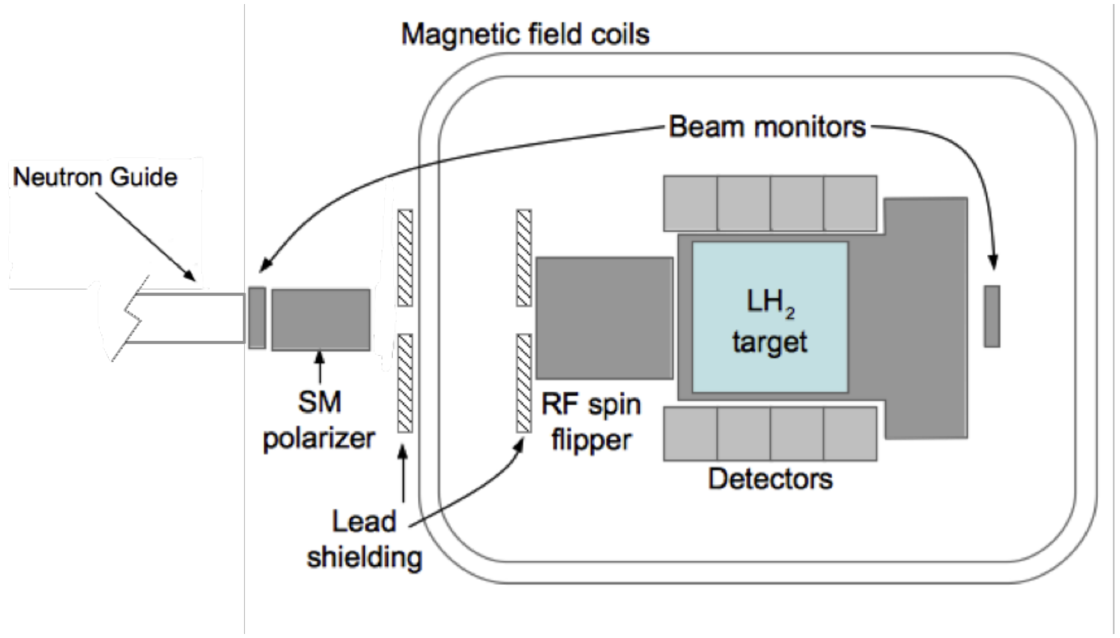

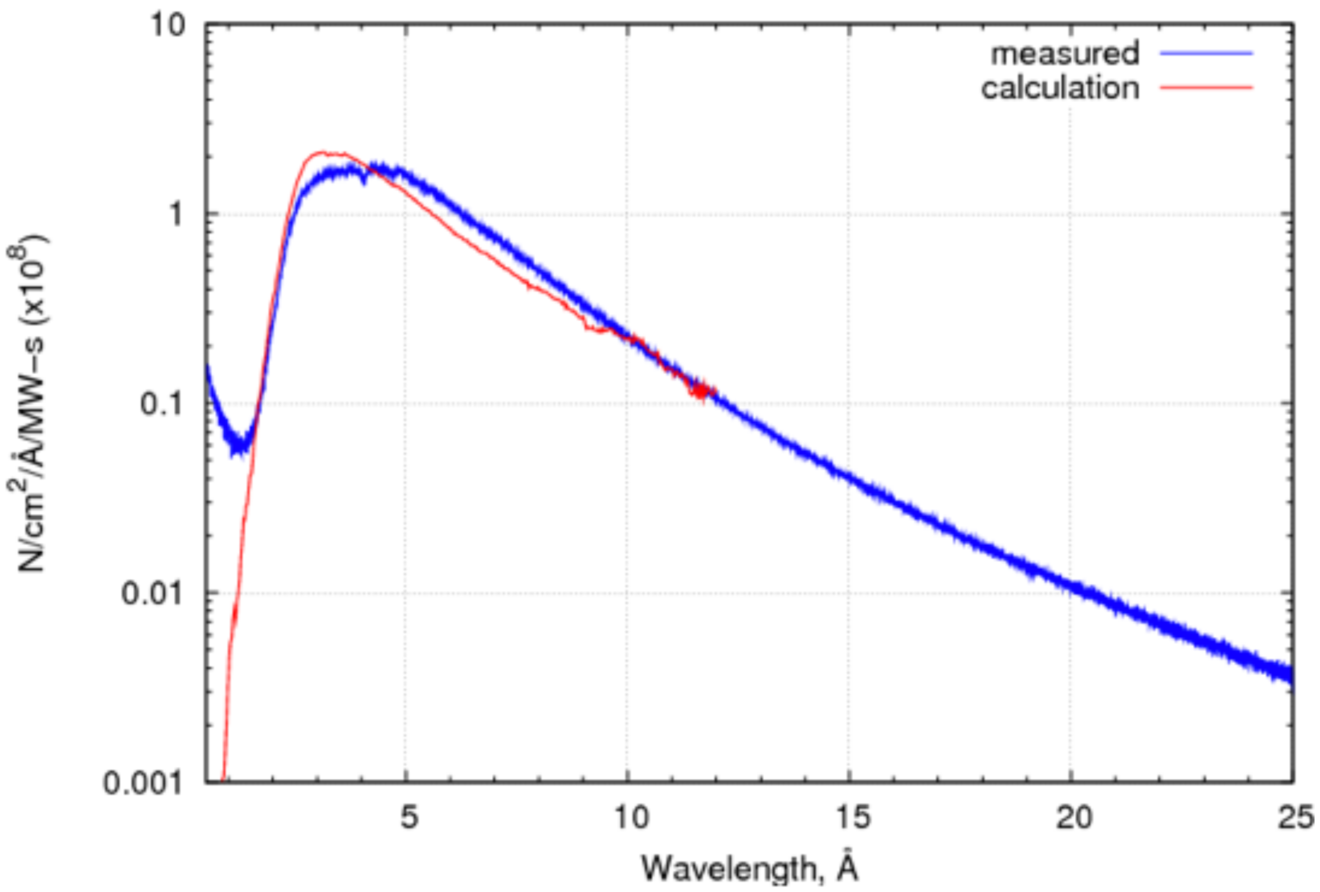

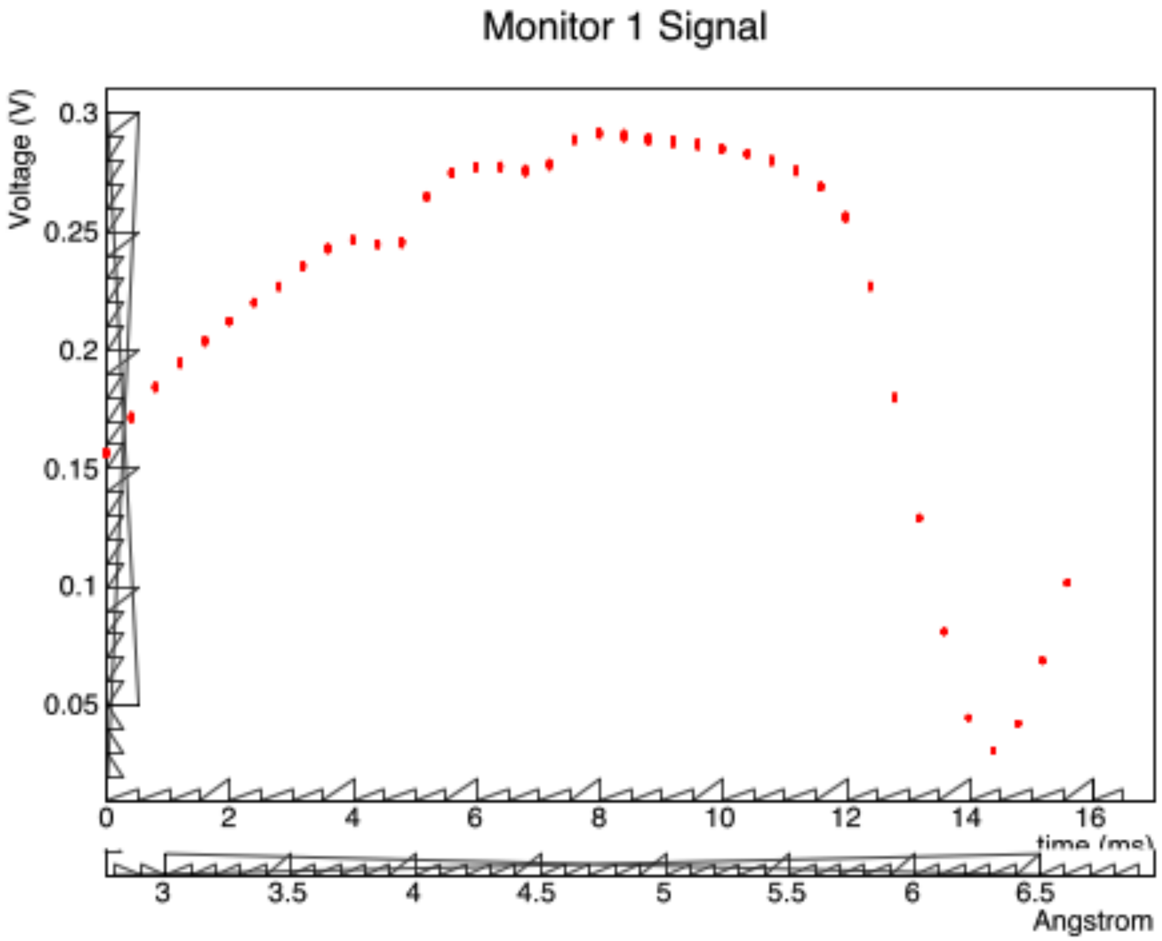

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The Experiment

Neutron Flux

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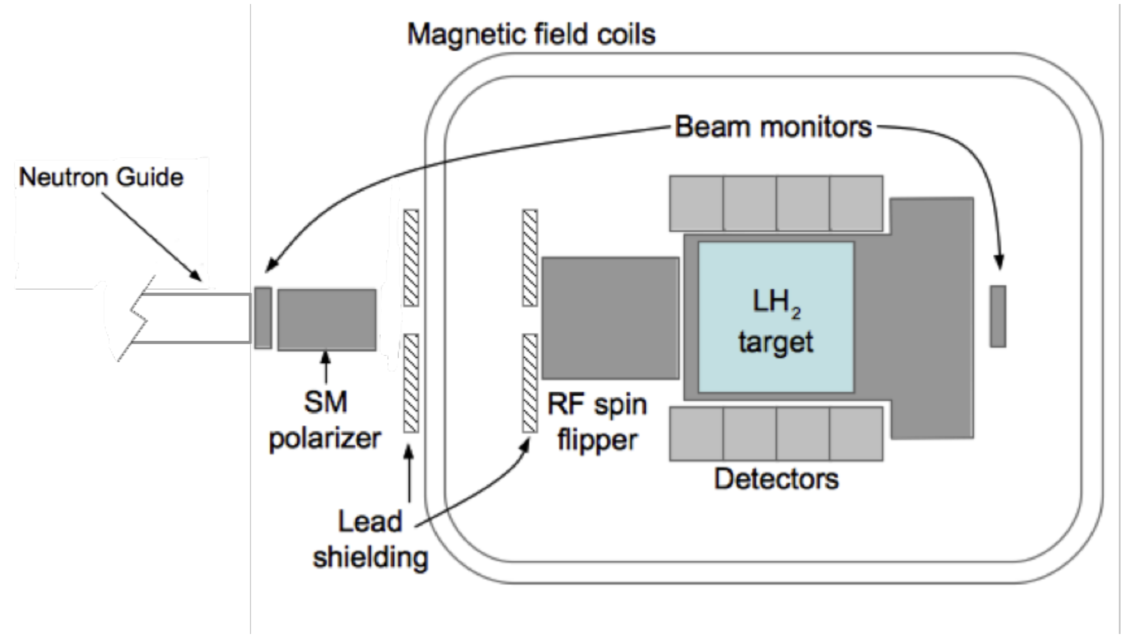

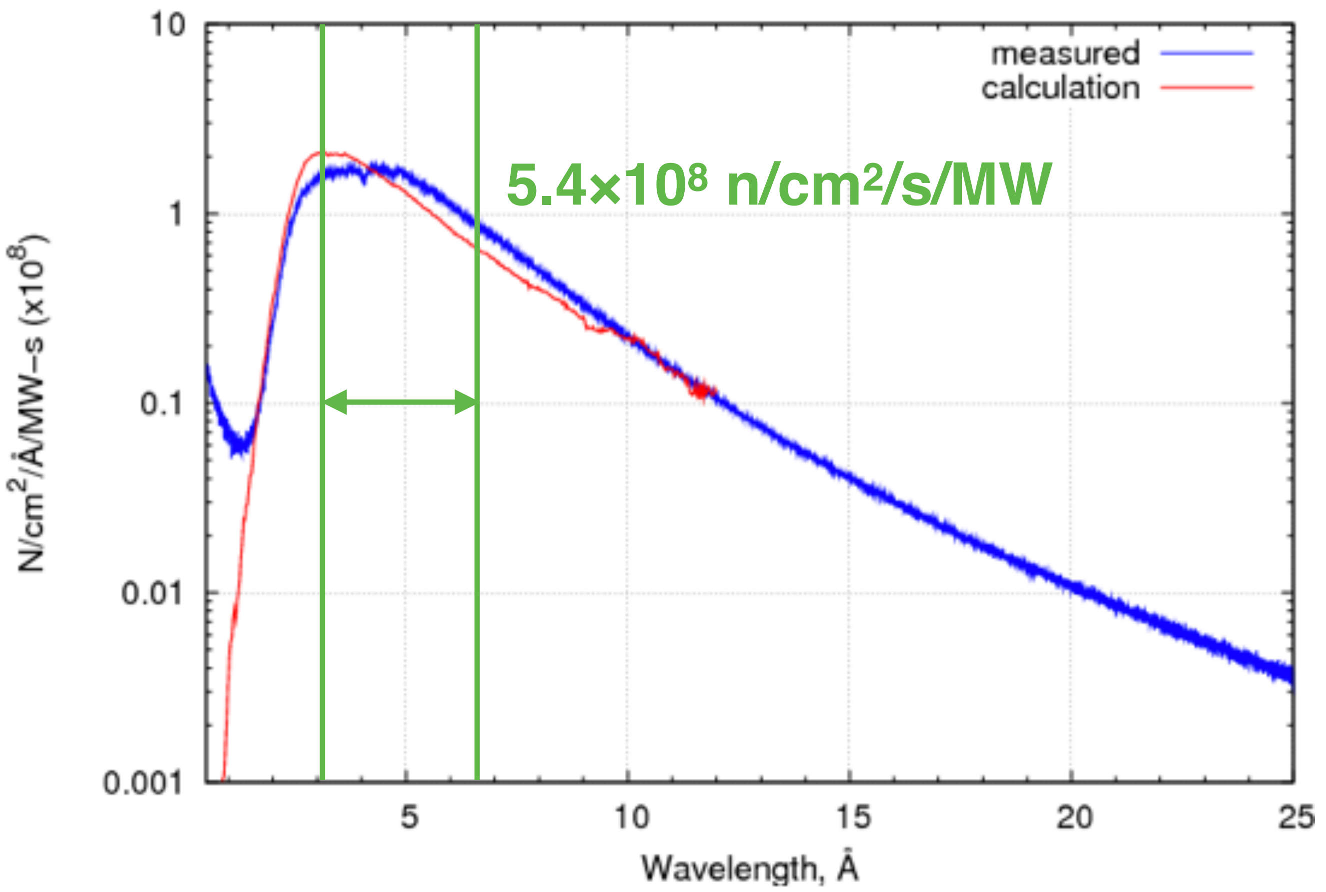

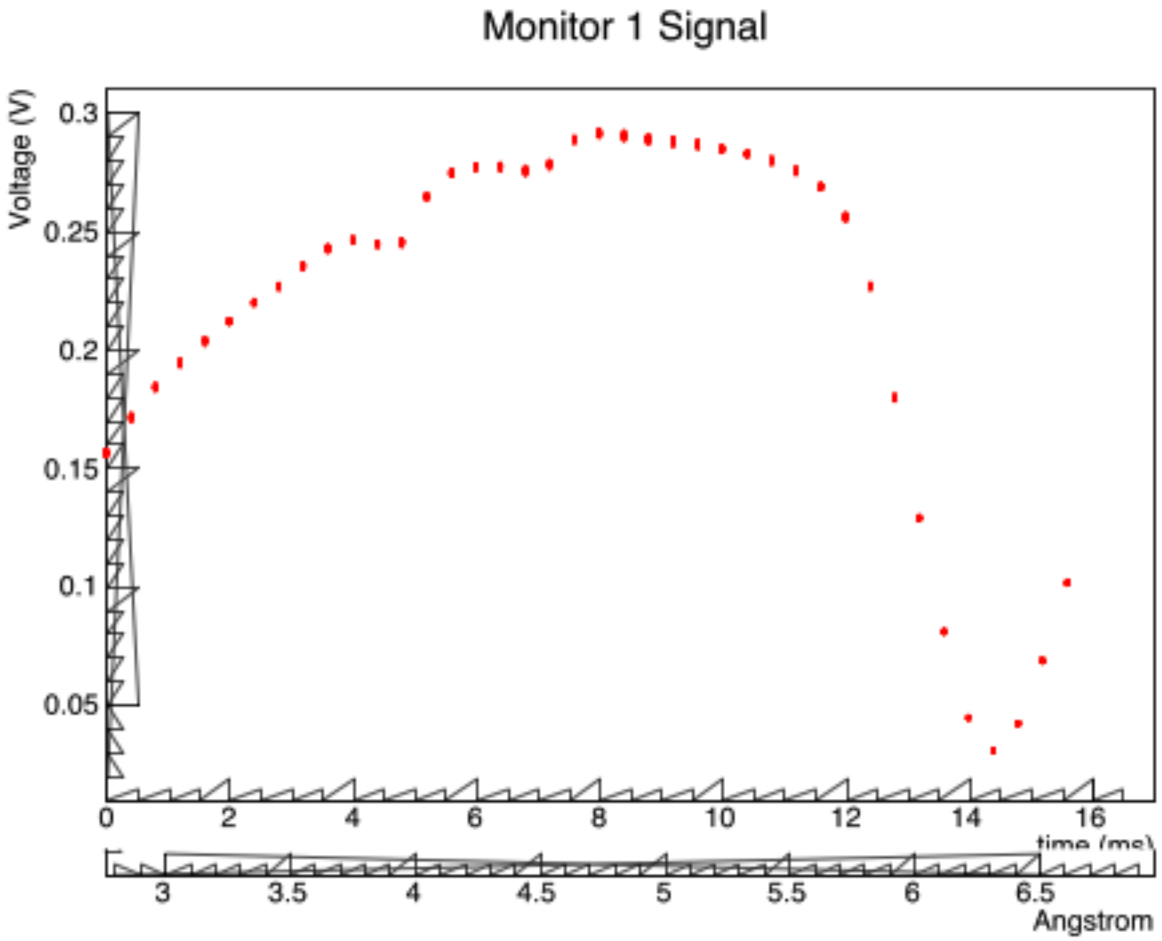

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The Experiment

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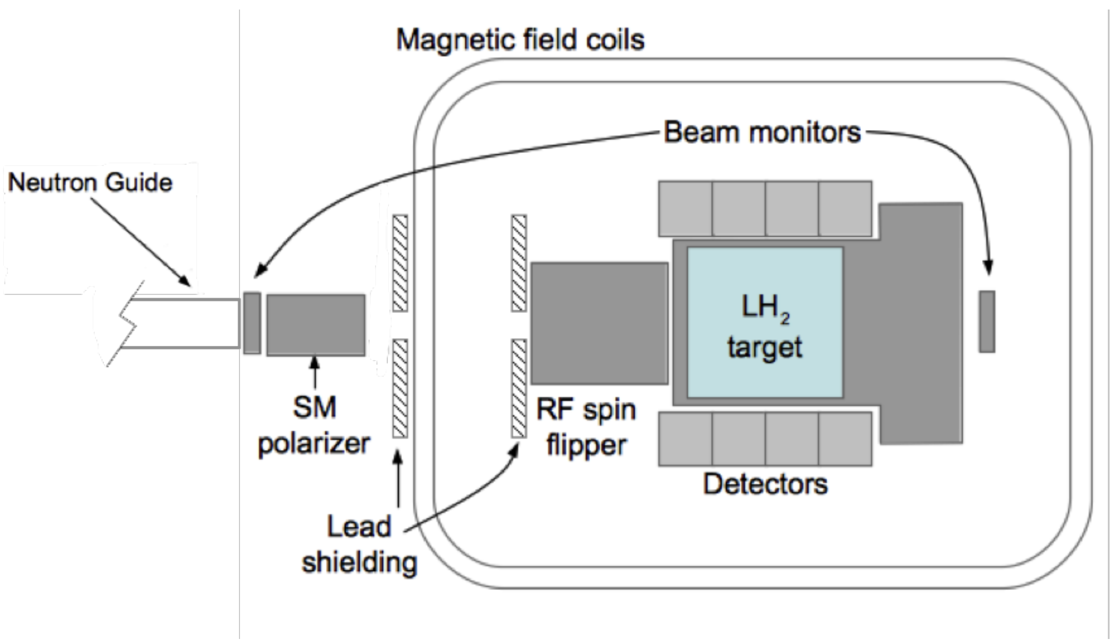

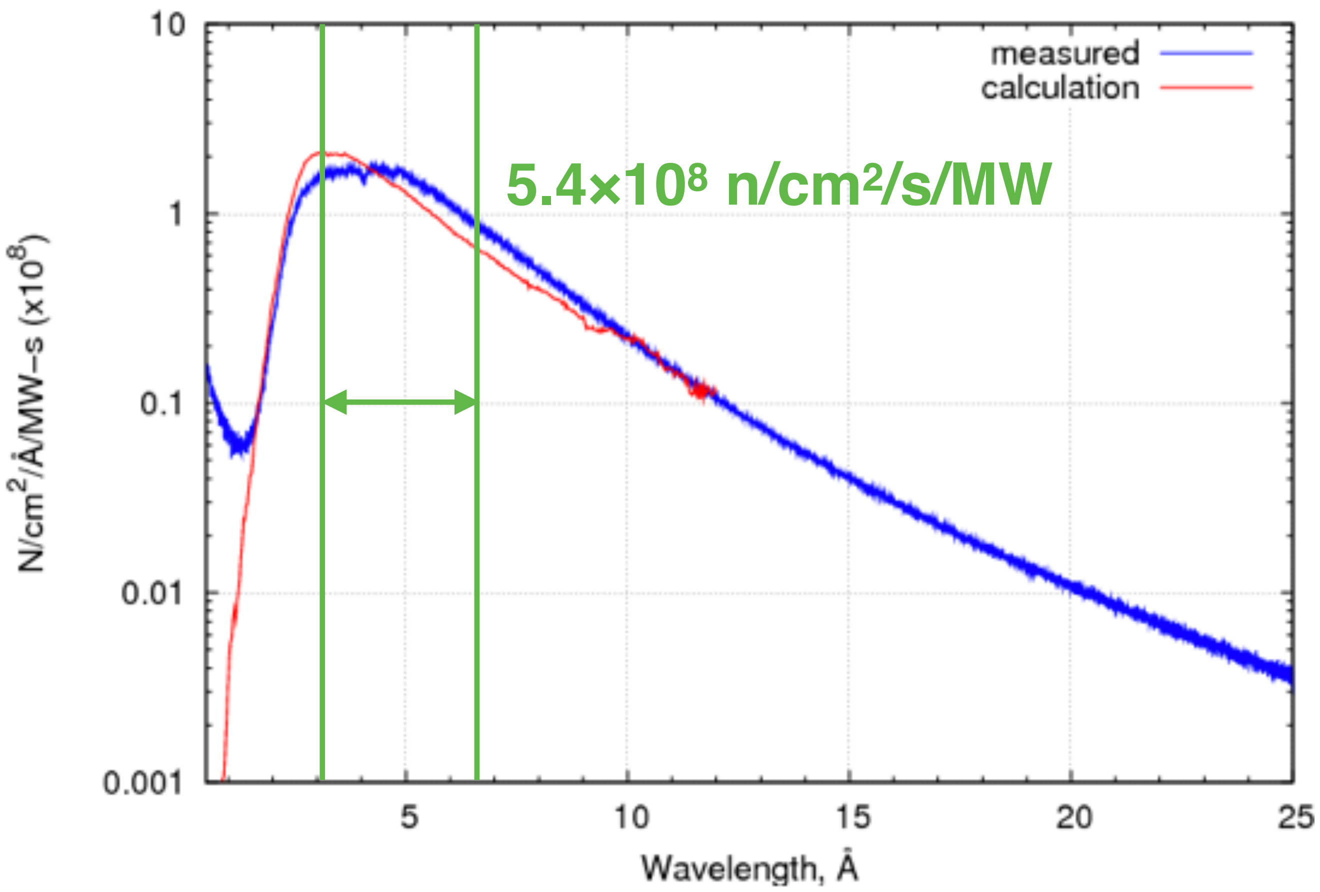

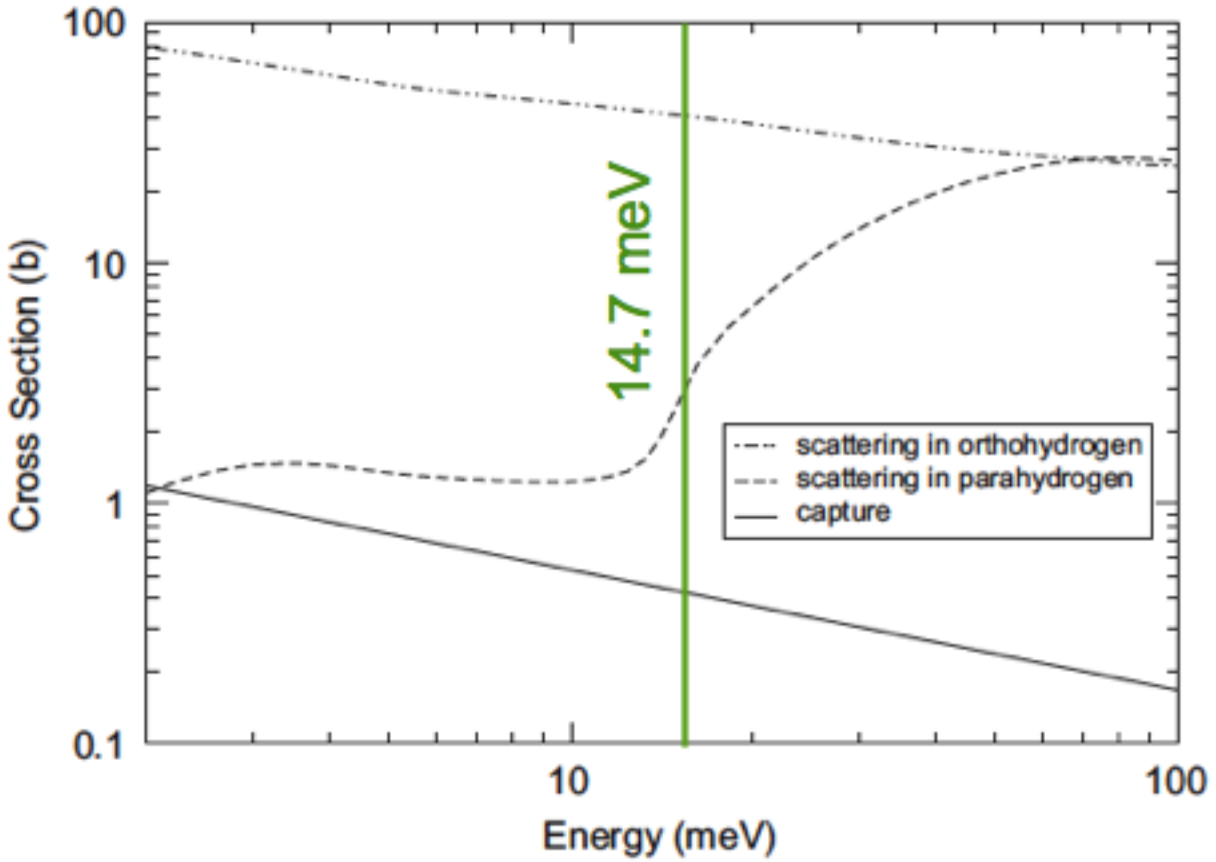

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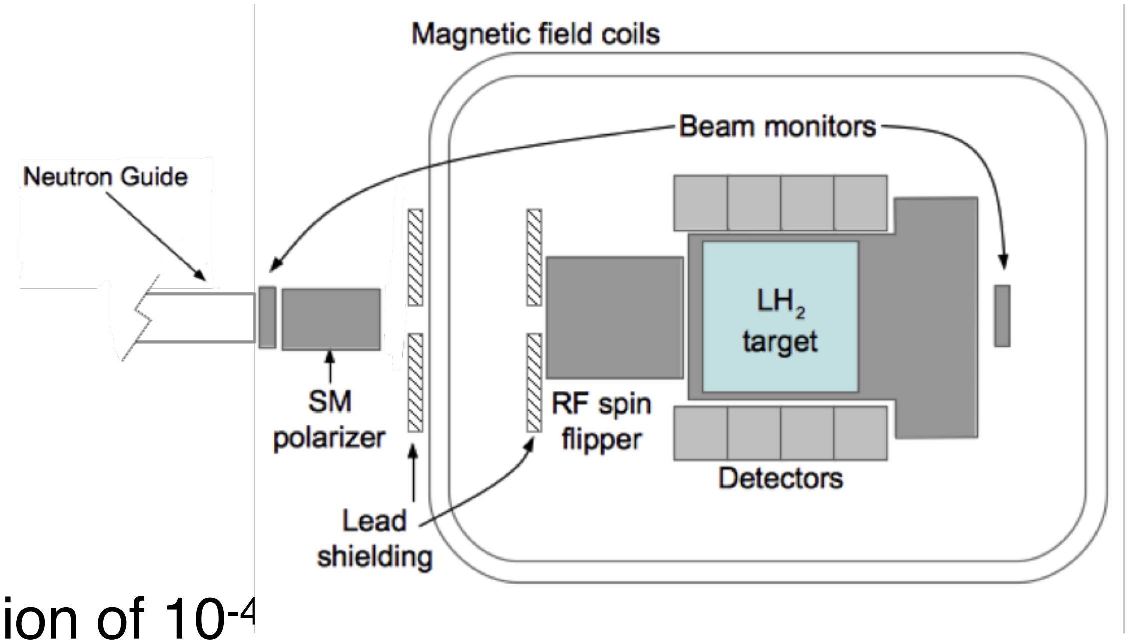
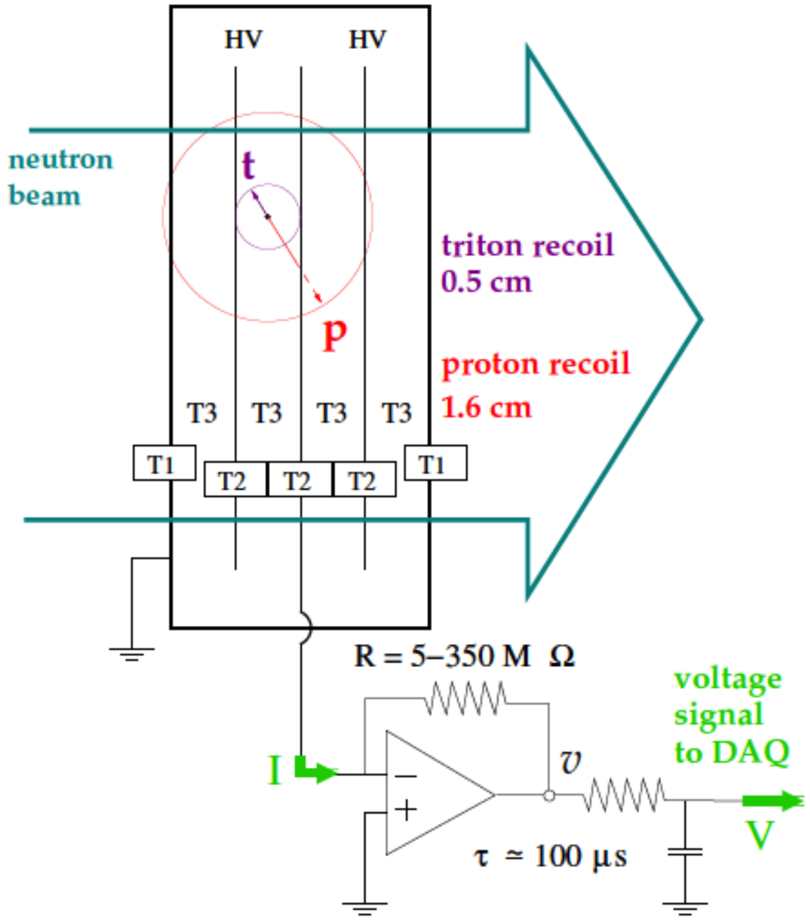
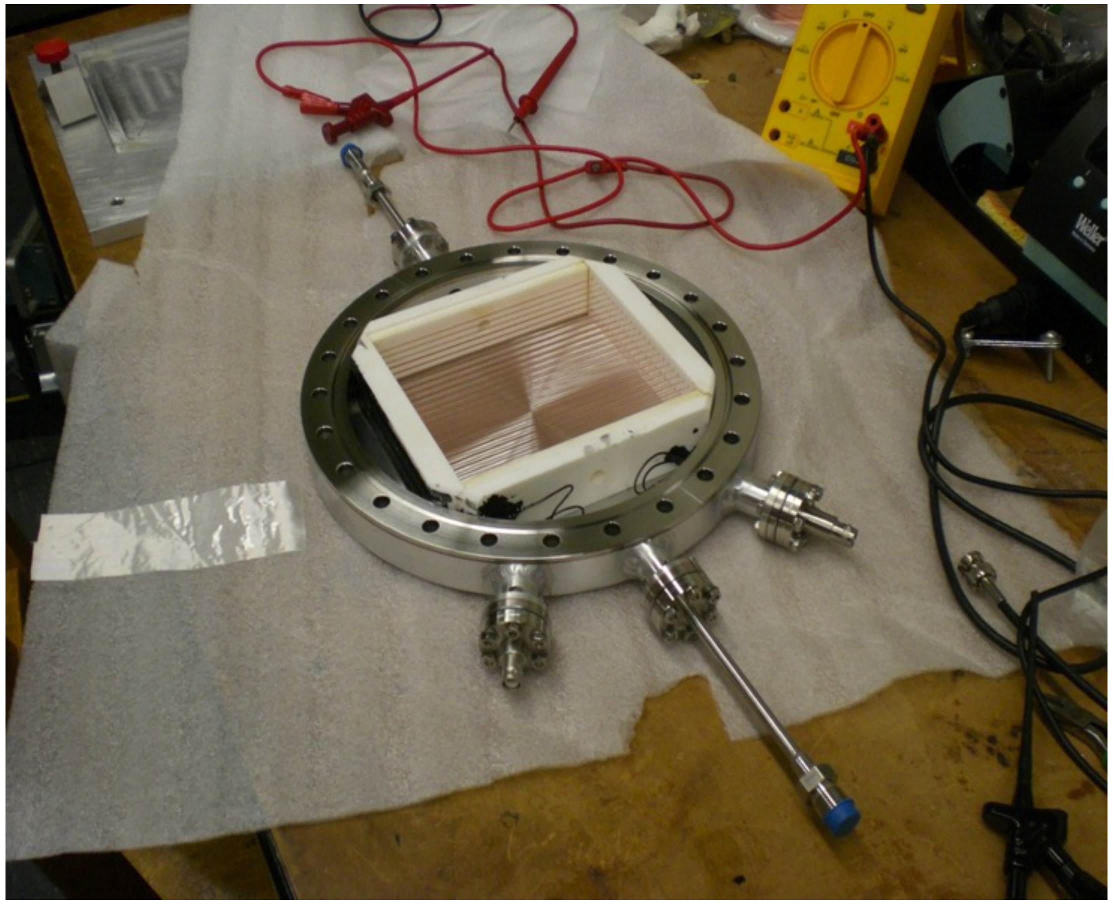


Beam Monitors

- Ionization chamber with N_2 and some ^3He (1-2%)
- About 1% of the neutrons are absorbed
- Number of neutron per pulse determined to a precision of 10^{-4}





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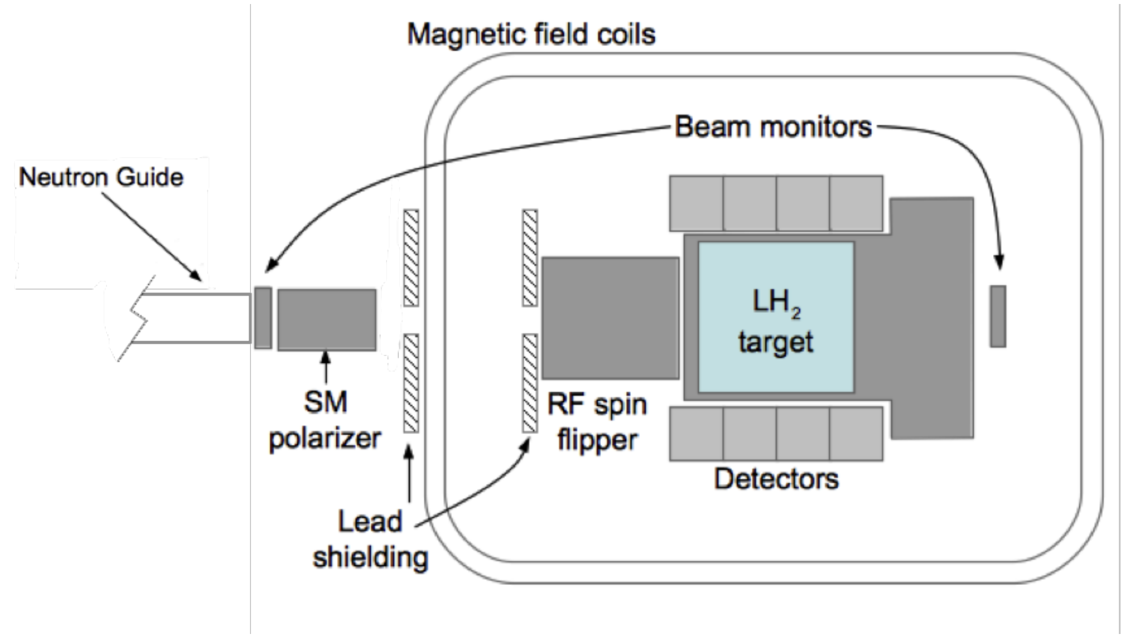
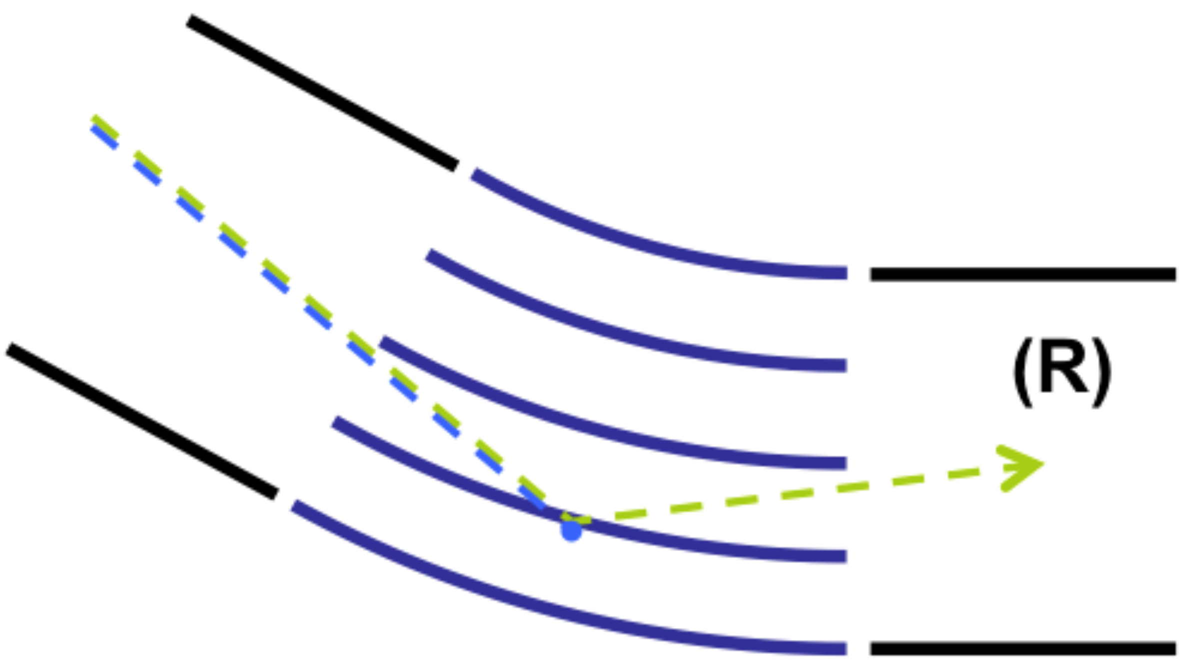


Super Mirror (SM) Polarizer

- Magnetized Fe/Si SM
- Scattering length $b \pm p$, with p the magnetic component

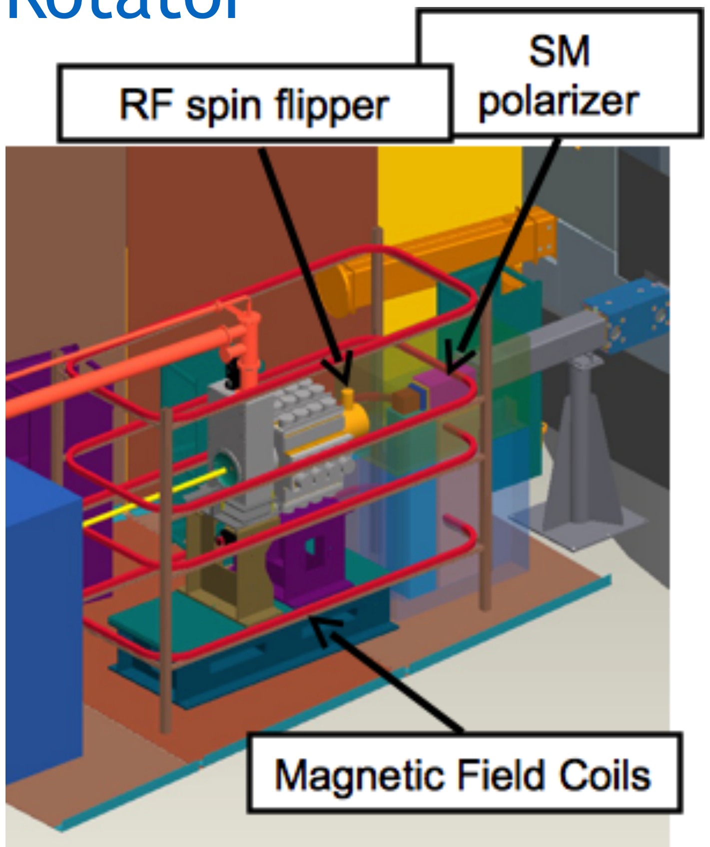


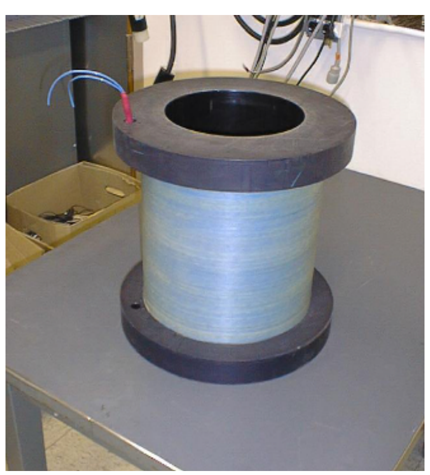
Fe/Si on boron float glass, no Gd

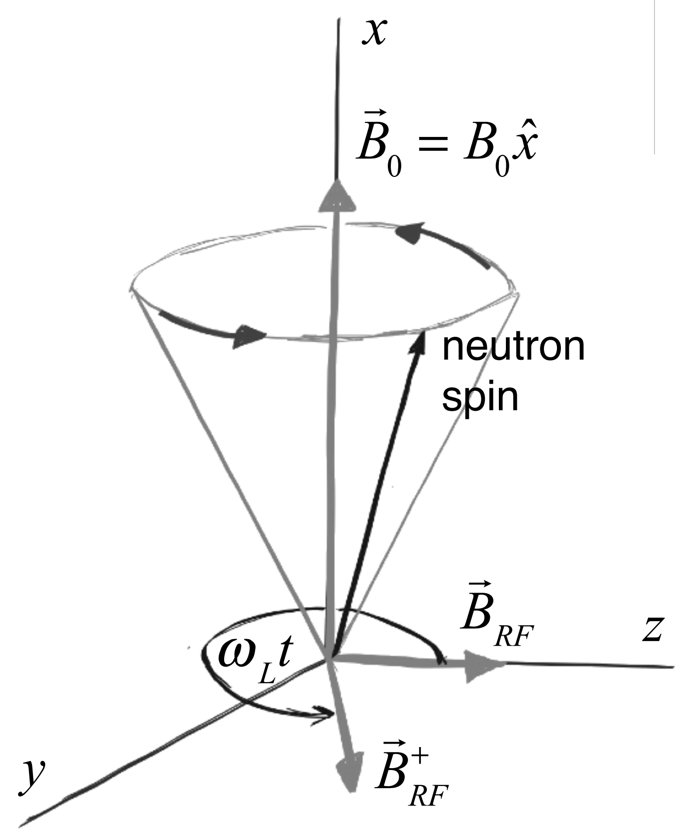
m=3.0	critical angle
n=45	channels
R=9.6 m	radius of curvature
L=40 cm	length
d=0.3mm	vane thickness
T=25.8%	transmission
P=95.3%	polarization
N=2.2×10^{10} n/s	output flux (chopped)

The Experiment

Holding Magnetic Field and RF Spin Rotator

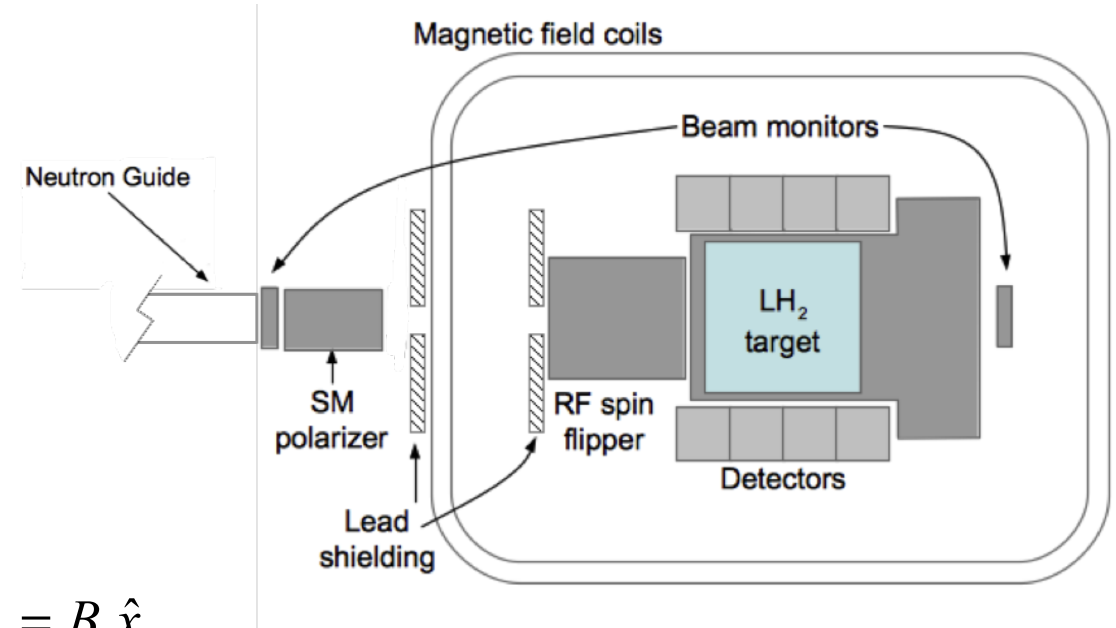




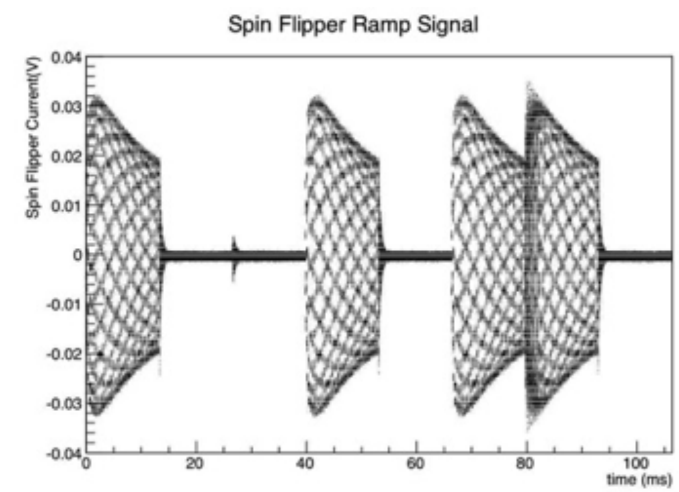


$$\vec{B}_{RF} = B_1\hat{z}\cos(\omega_L t) = \vec{B}^+_{RF} + \vec{B}^-_{RF}$$

$$\vec{B}^{\pm}_{RF} = \frac{B_1}{2}[\hat{z}\cos(\pm\omega_L t) - \hat{y}\sin(\pm\omega_L t)]$$



$$B_1 = \frac{n\pi\hbar}{\mu_n}\frac{1}{L}\frac{1}{t_{tof}}$$



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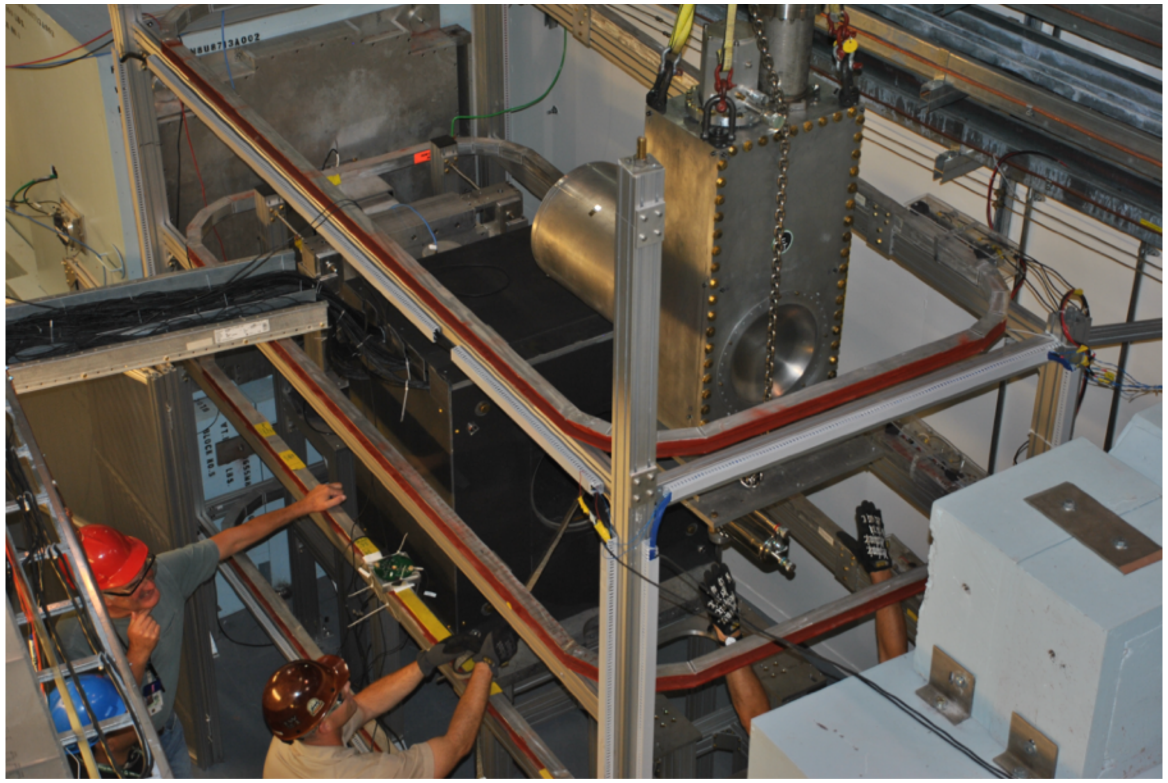
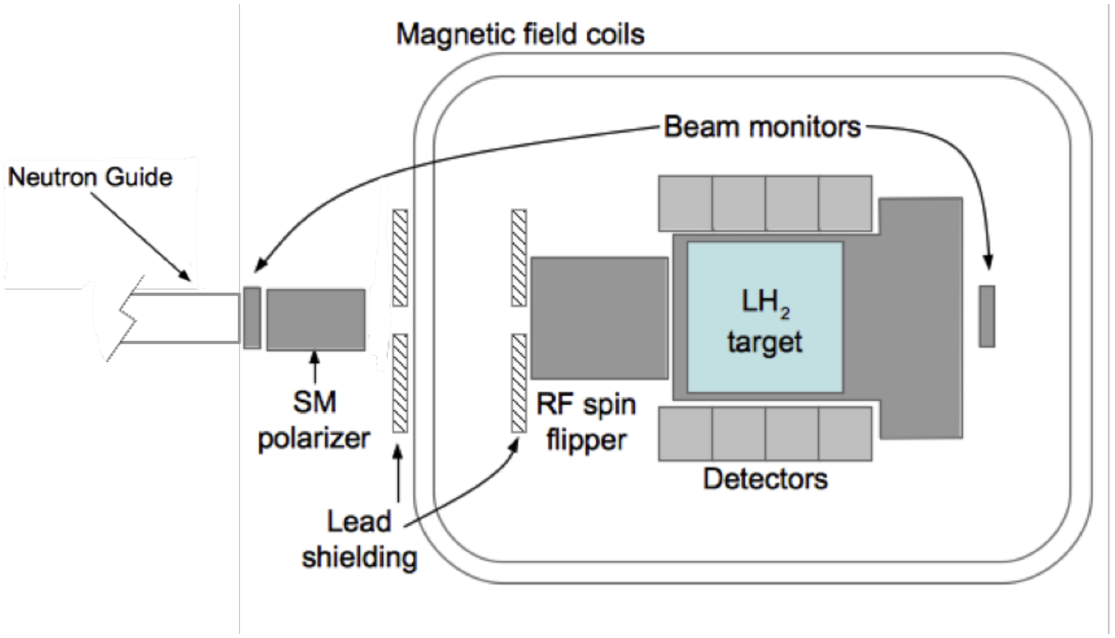
Seo et al., *Phys. Rev. ST AB* 11, 084701 (2008)

The Experiment

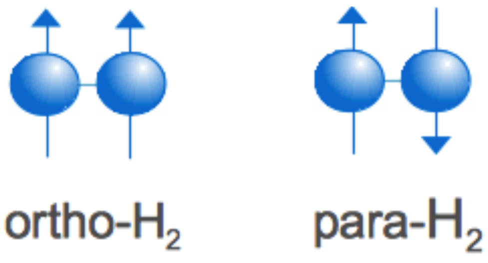
LH_2 Target

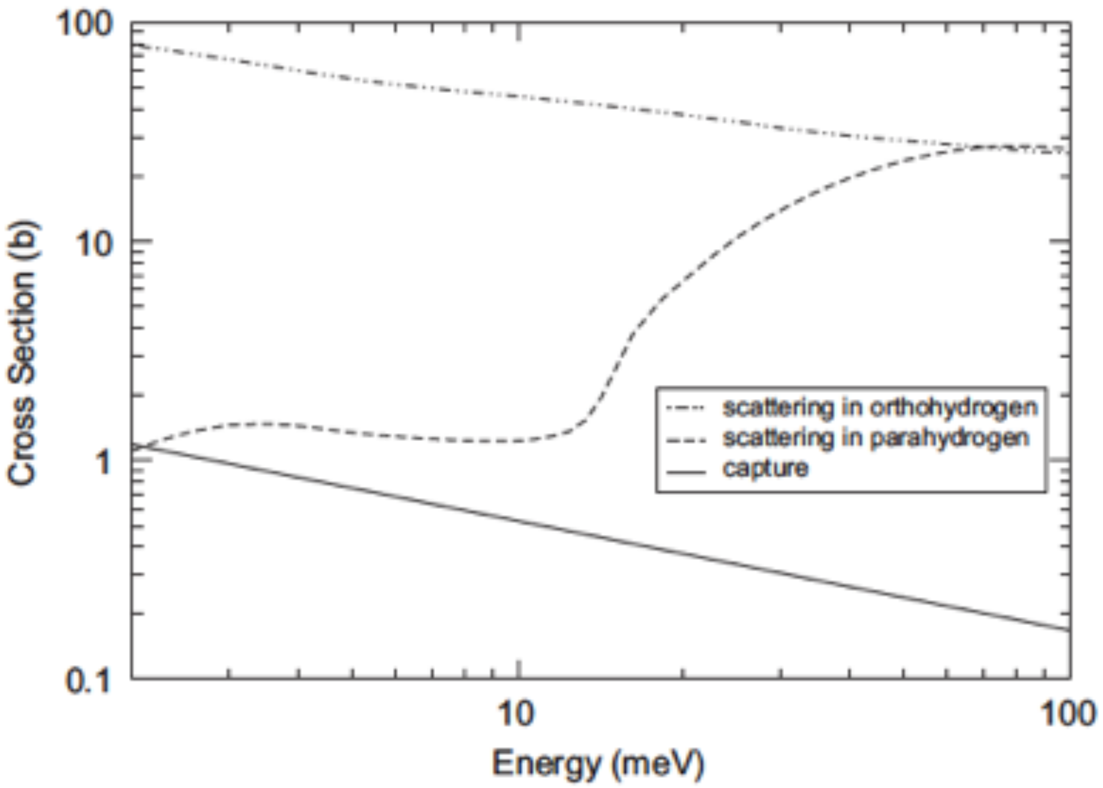


Santra et al., *Nucl. Instrum. and Meth. A* 620, 421 (2010)



$f_{\text{ortho-H}_2} < 0.0015$





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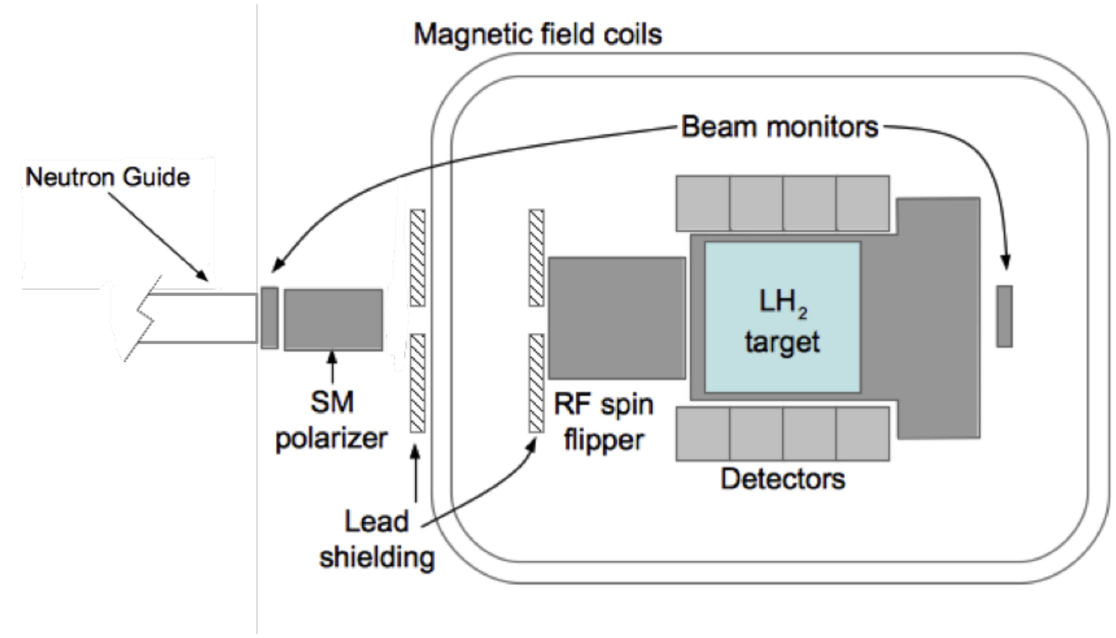
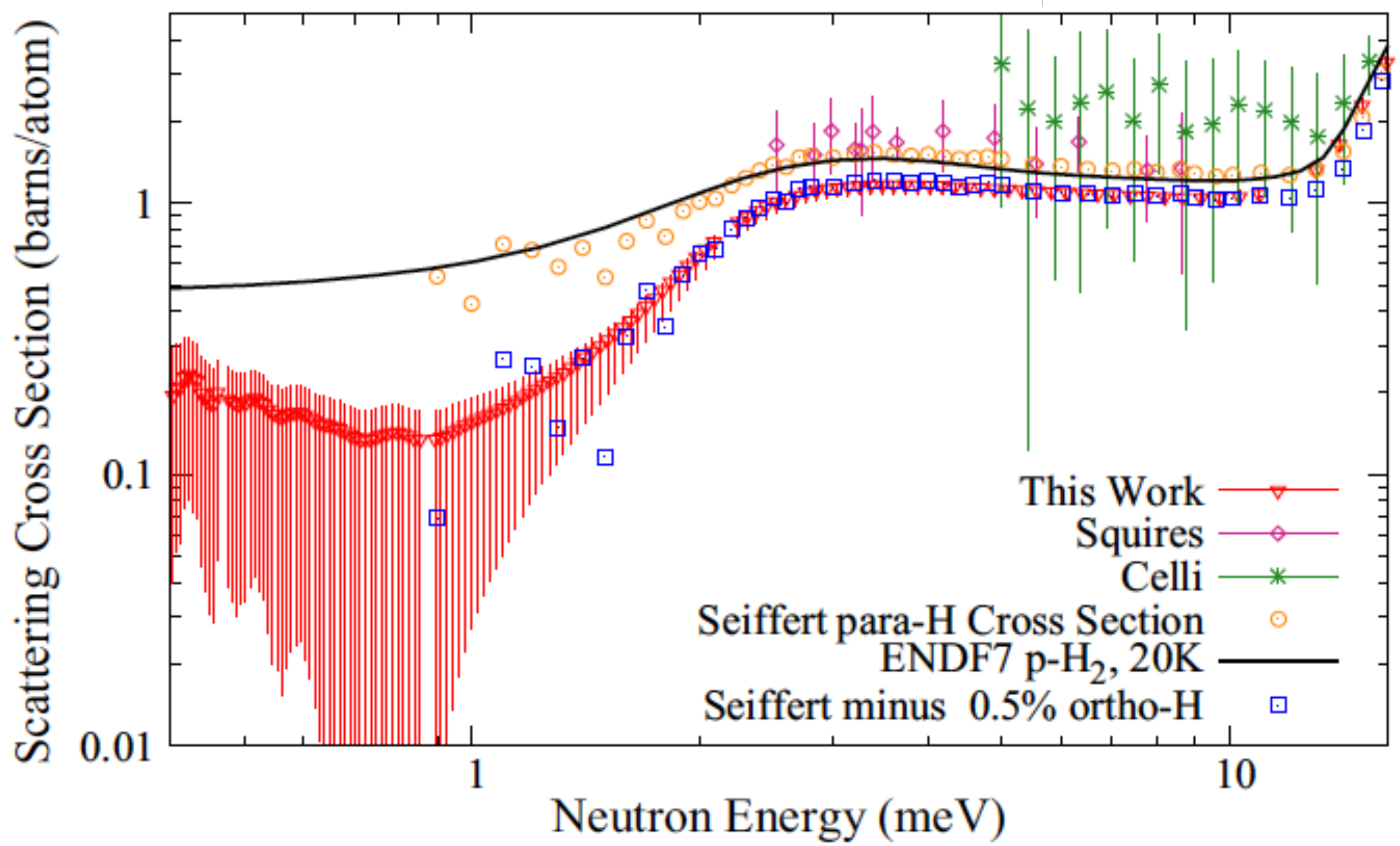


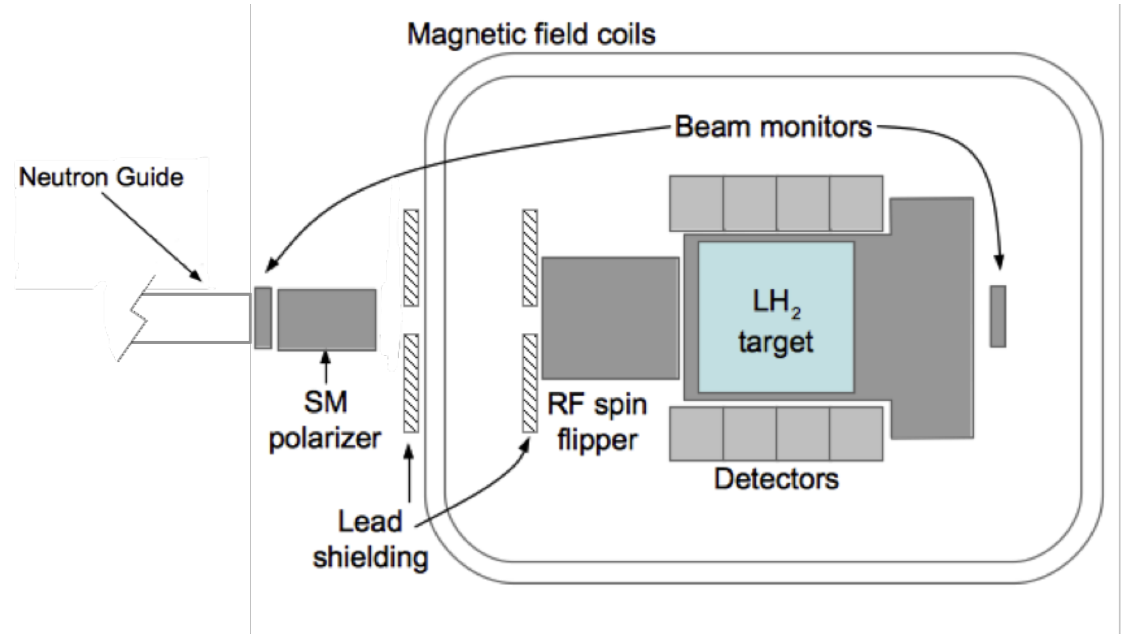
Scattering cross section of neutrons on para-H_2

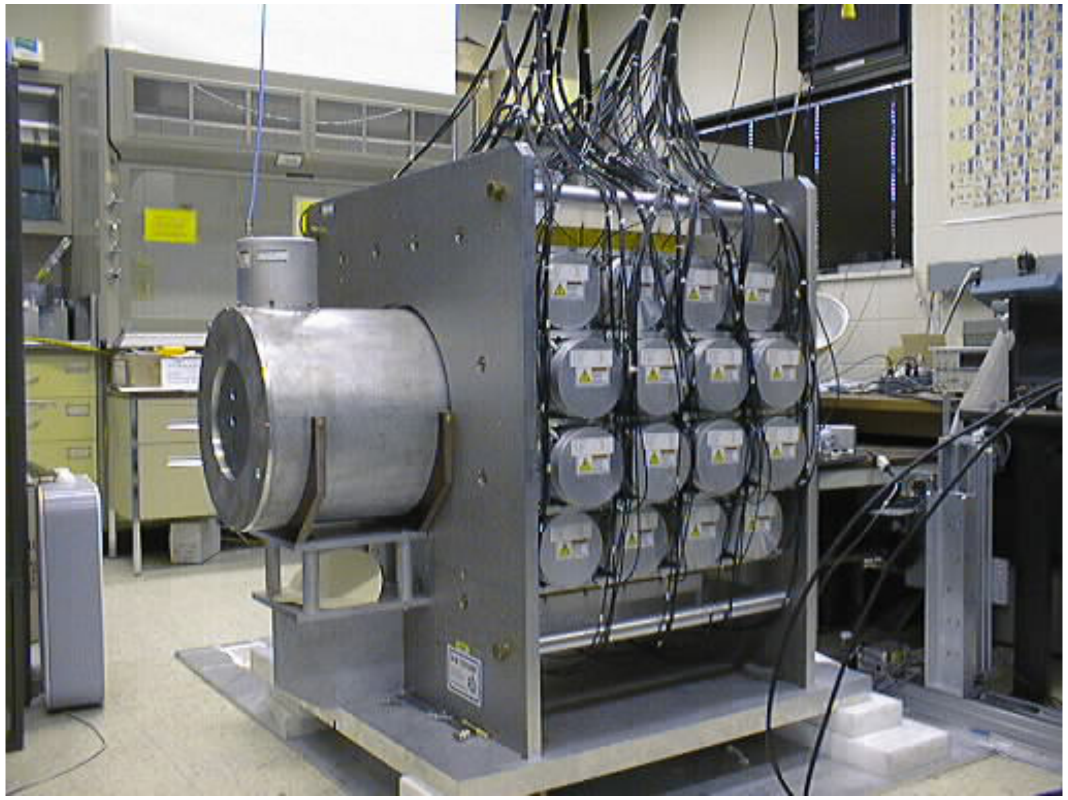


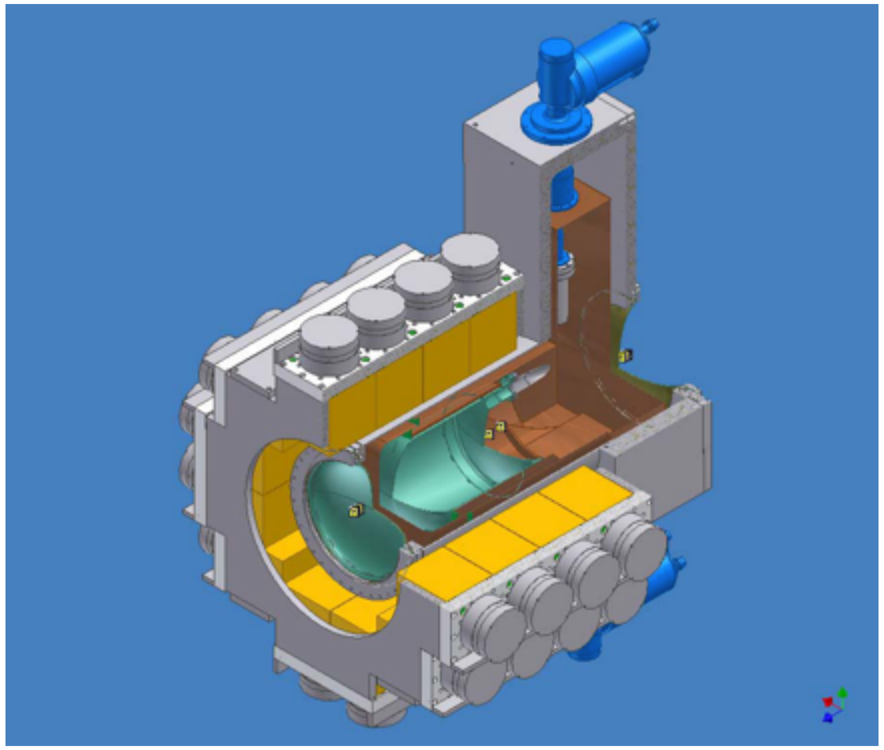
Grammer et al., *Phys. Rev. B* 91, 180301(R) (2015)

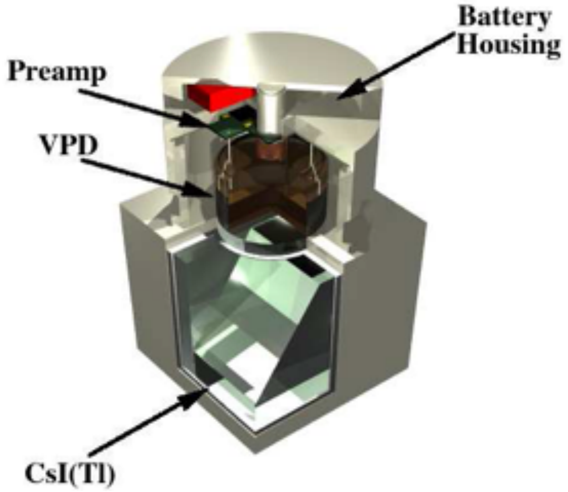
The Experiment

Gamma-ray Detector









- 48 CsI detectors
- 3π acceptance
- Current mode operation (5×10^7 gammas/pulse)

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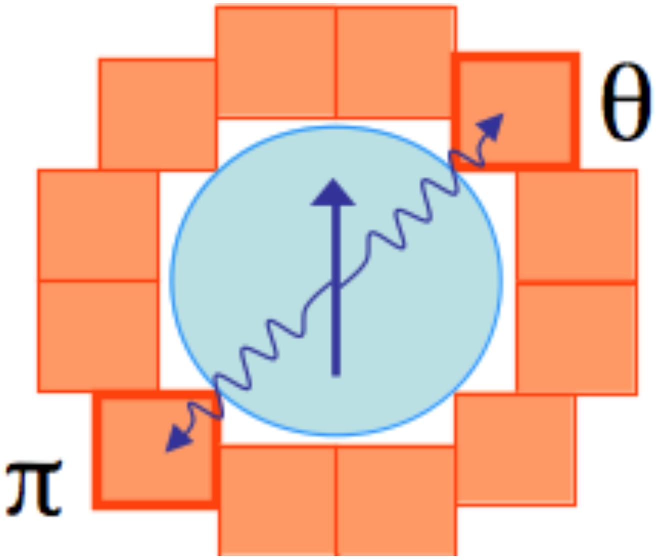
Extraction of A_γ



$$A_{\gamma,raw} = \frac{1}{2}\left(\frac{Y_\theta^\uparrow - Y_{\theta+\pi}^\uparrow}{Y_\theta^\uparrow + Y_{\theta+\pi}^\uparrow} - \frac{Y_\theta^\downarrow - Y_{\theta+\pi}^\downarrow}{Y_\theta^\downarrow + Y_{\theta+\pi}^\downarrow}\right)$$

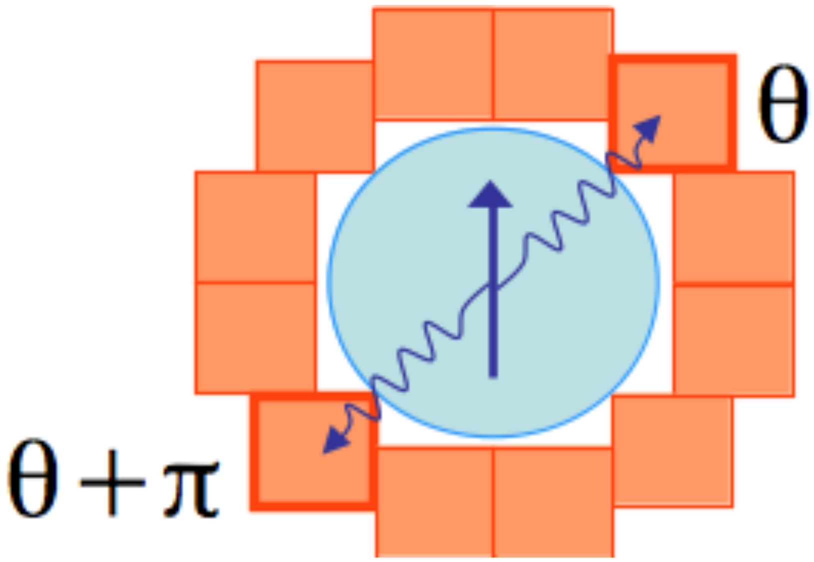
$$A_\gamma = P_n \epsilon_{SR} C_d \left(A_{\gamma,raw} - \sum_i F_{BG,i} \frac{A_{\gamma,i}}{P_{n,i}\epsilon_{SR,i}C_{d,i}} \right)$$

$$A_{\gamma,i} = A_{\gamma,i}^{PV} G_{UD,i} + A_{\gamma,i}^{PC} G_{LR,i}$$

Corrections

- Neutron polarization (P_n)
- Spin Flipper efficientcy (ϵ_{SR})
- Neutron depolarization (C_d)
- Background prompt gammas from materials other than hydrogen, which contribute in different fractions (F_{BG}). The main background contribution comes from Aluminum (～20%)
- Geometrical factors (G_{UD} and G_{LR}), which include the finite structure of the beam, the effective solid angle of the detector, the spatial distribution of the material in question and other effects

Extraction of A_γ



$$A_{\gamma,raw} = \frac{1}{2}\left(\frac{Y_\theta^\uparrow - Y_{\theta+\pi}^\uparrow}{Y_\theta^\uparrow + Y_{\theta+\pi}^\uparrow} - \frac{Y_\theta^\downarrow - Y_{\theta+\pi}^\downarrow}{Y_\theta^\downarrow + Y_{\theta+\pi}^\downarrow} \right)$$

$$A_\gamma = P_n \epsilon_{SR} C_d \left(A_{\gamma,raw} - \sum_i F_{BG,i} \frac{A_{\gamma,i}}{P_{n,i}\epsilon_{SR,i} C_{d,i}} \right)$$

$$A_{\gamma,i} = A_{\gamma,i}^{PV} G_{UD,i} + A_{\gamma,i}^{PC} G_{LR,i}$$

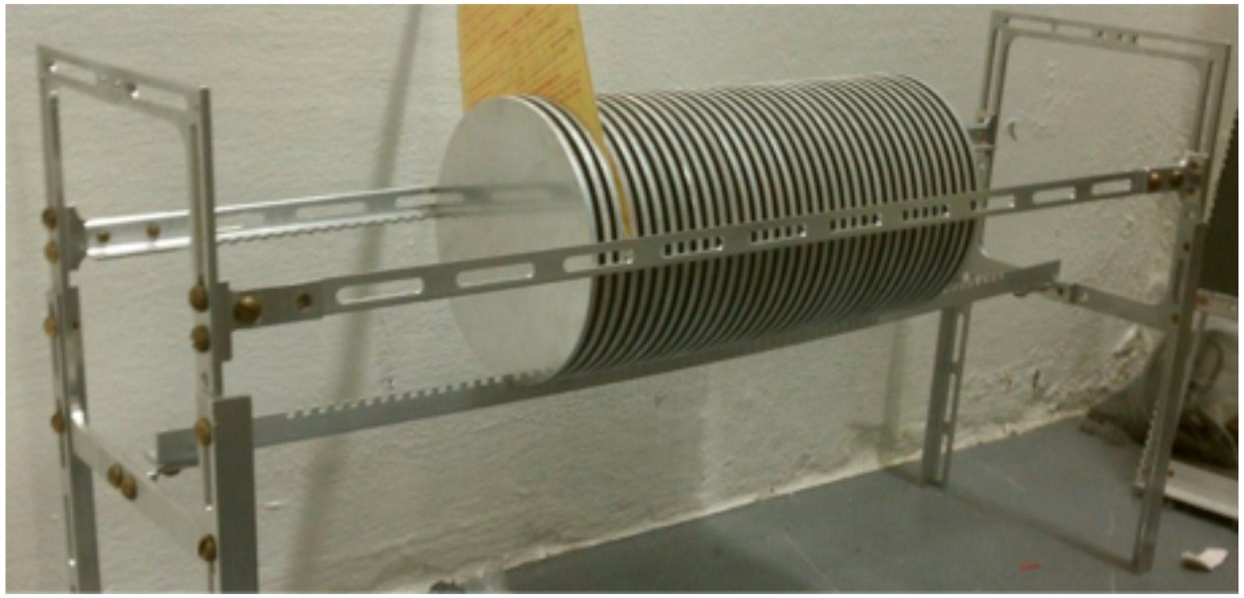
Monte Carlo

Corrections

- Neutron polarization (P_n)
- Spin Flipper efficientcy (ϵ_{SR})
- Neutron depolarization (C_d)
- Background prompt gammas from materials other than hydrogen, which contribute in different fractions (F_{BG}). The main background contribution comes from Aluminum (∼20%)
- Geometrical factors (G_{UD} and G_{LR}), which include the finite structure of the beam, the effective solid angle of the detector, the spatial distribution of the material in question and other effects

The Aluminium Background

- Capture of neutrons on ^{27}Al produces $^{28}Al^*$
- Several (3-4) prompt gammas are emitted in the transition to ^{28}Al g.s. (total energy of 7.8 MeV)
- Asymmetries (PV and PC) correlated to the neutron spin are expected in the emission of prompt gammas



- After the experiment was decommissioned and analysis was nearing completion, inconsistencies revealed the dedicated Aluminium target was not 6061 alloy
- The uncertainty goal of the experiment was not achievable without a new background subtraction strategy
- The experiment was partially mounted again in 2016 to perform measurements with background targets made out of the actual windows of the LH_2 target cryostat and other components

Systematic Uncertainties (preliminary)

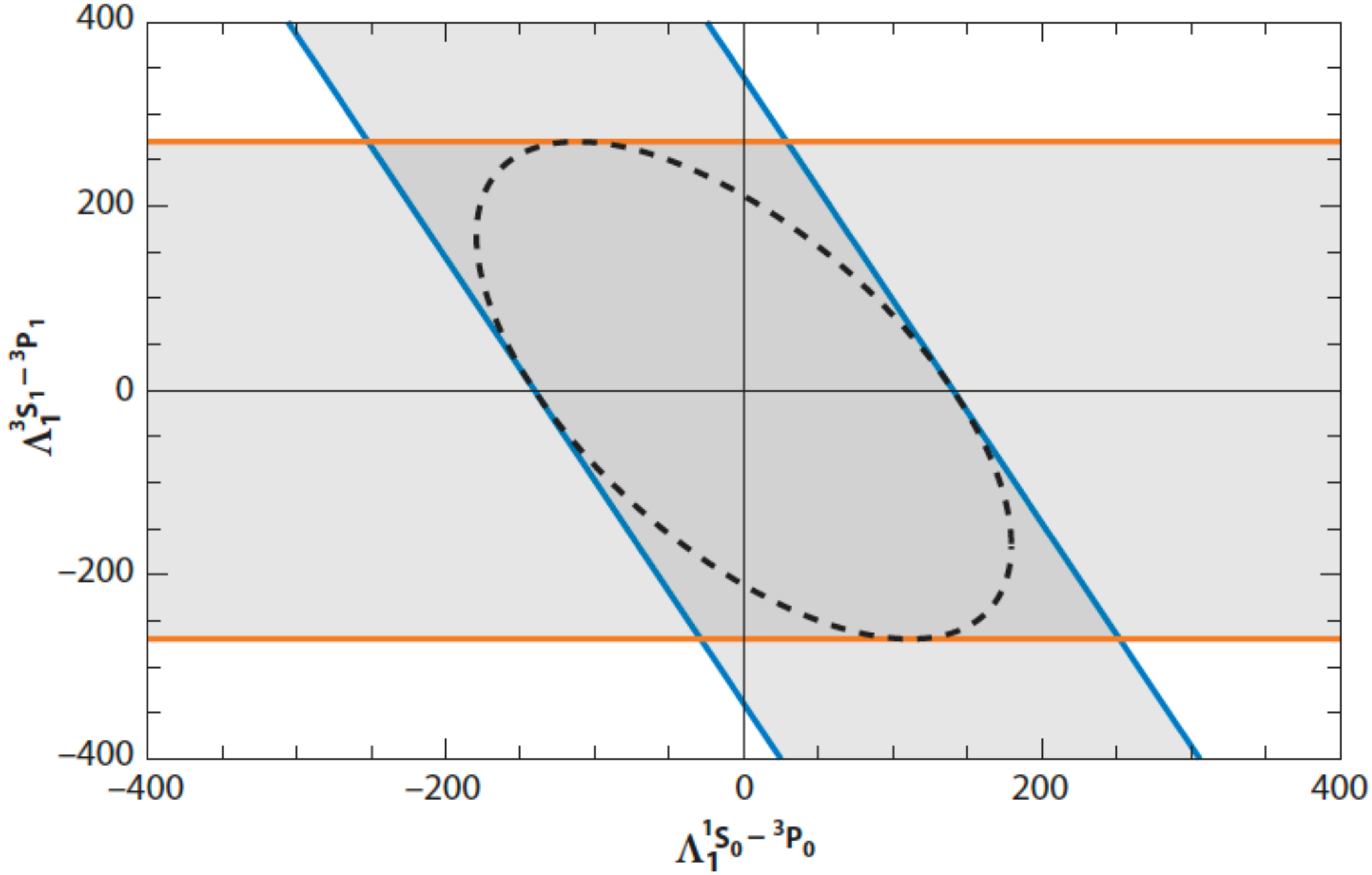
False Asymmetries	Process	Aγ, PV unc.	Aγ, PC unc.
Stern-Gerlach	$\vec{\mu}\cdot\nabla B$	8×10^{-11}	
Mott-Schwinger	$\vec{n}+p\to\vec{n}+p$		9×10^{-9}
γ-ray circular polarization	$\vec{n}+p\to d+\gamma$	7×10^{-13}	
β decay in flight	$\vec{n}\to e^{-}+p+\bar{\nu}$	3×10^{-11}	
Radiative β decay	$\vec{n}\to e^{-}+p+\bar{\nu}+\gamma$	2×10^{-11}	
Capture on ^{6}Li	$\vec{n}+{}^{6}\mathrm{Li}\to{}^{7}\mathrm{Li}^{*}\to\alpha+t$	2×10^{-12}	
^{28}Al β decay	$\vec{n}+{}^{27}\mathrm{Al}\to{}^{28}\mathrm{Al}\to{}^{28}\mathrm{Si}+e^{-}$	$<1\times10^{-9}$	
Capture on Al alloy	$\mathrm{alloy}(\vec{n},\gamma\mathrm{s})$	2×10^{-9}	6×10^{-9}
Beam power modulation		6×10^{-10}	8×10^{-10}
Instrumental		$<1\times10^{-9}$	$<1\times10^{-9}$

Multiplicative Factors	Value	Aγ unc.
Geometric factors	Detector-dependent	3%
Beam polarization	0.936(5)	0.5%
LH_2 SF efficiency	0.969(9)	0.9%
2016 SF efficiency	0.997(3)	0.3%
Beam depolarization	0.946 (avg. for LH_2)	1.4%

David Blyth, PhD thesis, Arizona State University (2017)

The New Landscape for NPDGamma

In the context of new theoretical descriptions and the hierarchization of parameters in large-N_c expansion, NPDGamma, as well as gamma polarization from ^{18}F, can provide a tests for this theory, measuring the two N^2LO parameters



Gardner, Haxton, Holstein, *Annu. Rev. Nucl. Part. Sci.* 67, 69-95 (2017)

NPDGamma preliminary result is

$$A_\gamma = [-3.1 \pm 1.5(\text{stat.}) \pm 0.3\ (\text{syst.})] \times 10^{-8}$$

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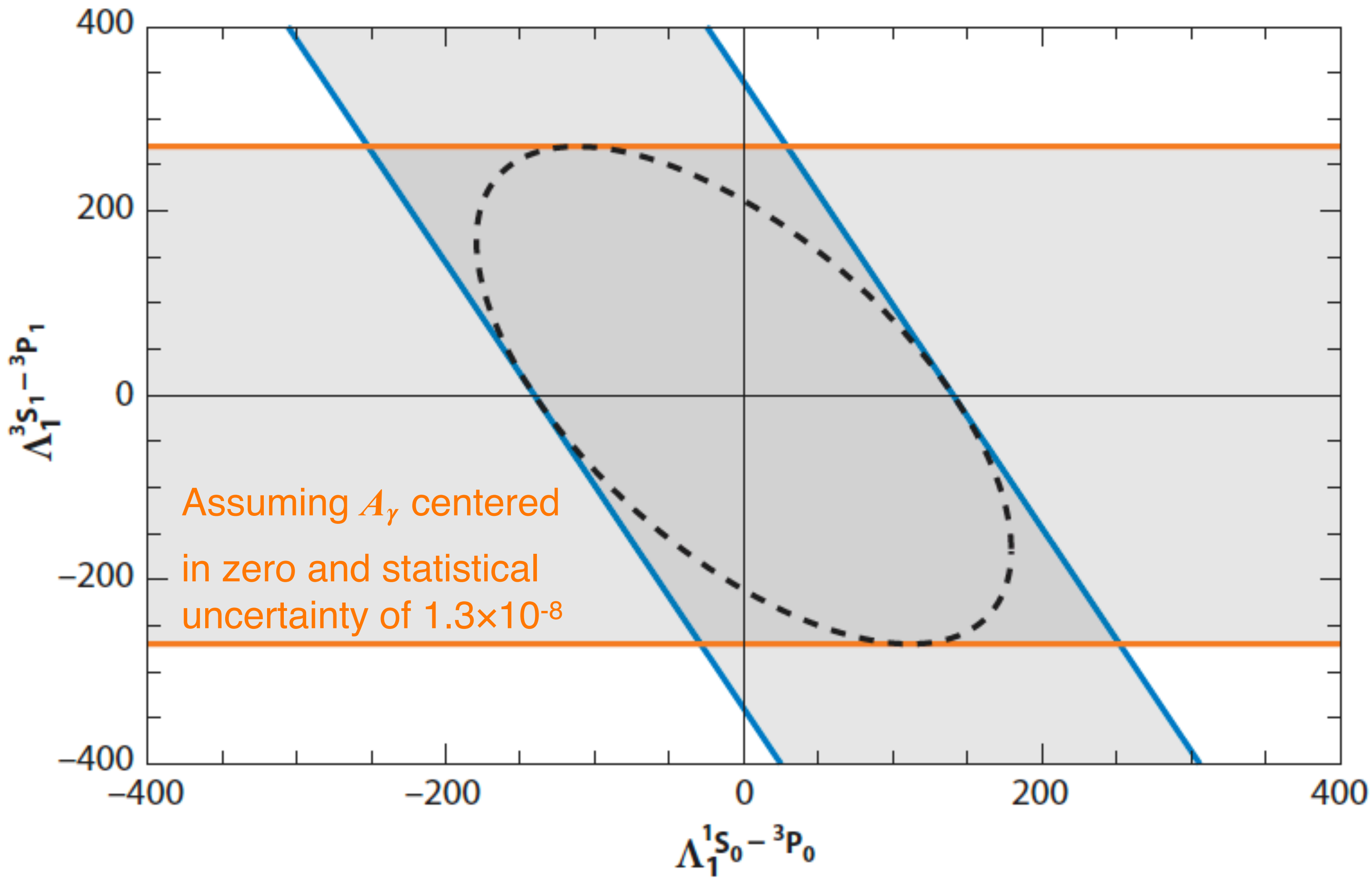

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Improvement Possibilities

- One either has to do this measurement on a pulsed neutron beam or at least pulse the beam in some way so that one can analyze the transient signals in the gamma detectors.

- We were not limited by systematics. In this experiment they were ~3×10^{-9}. This could be decreased to about 1×10^{-9}.

- It would be nice to try to find something better than Aluminum. A different Al alloy or one could try Titanium for the target vessel.

- Put the Lithium plastic inside the hydrogen target vessel?

- 4300 hours life time with average beam power about 1 MW at SNS for the LH_2 running gave a statistical error of ~1.5×10^{-8}. Other potential beams/sources?

Summary

- The NPDGamma is about to conclude a long-time effort to measure the gamma asymmetry in the capture of polarized neutrons on Hydrogen, with in unprecedented precision (～1.5×10^{-8} stat.)

- The process is dominated by a $\Delta I=1$ $^3S_1$ - $^3P_1$ parity-odd transition (π-exchange) and therefore this experiment is appropriate to constrain the h_π^1 weak coupling (longest range interaction in meson-exchange models).

- The value observed by the NPDGamma collaboration is smaller than the value predicted in the DDH model by about a factor of 0.6.

- More recent theoretical approaches (EFT + large-N_c expansion) have produced a hierarchization of LEC in LO (2) and N^2LO (3). The LEC related to the observable measured in NPDGamma, $\Lambda_1^{^3S_1-^3P_1}$, is a N^2LO.

The NPDGamma Collaboration

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SCIENCE BRINGING NATIONS TOGETHER

The NPDGamma Collaboration

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