CD2015

Hadronic Weak Interaction: The NPGamma Experiment

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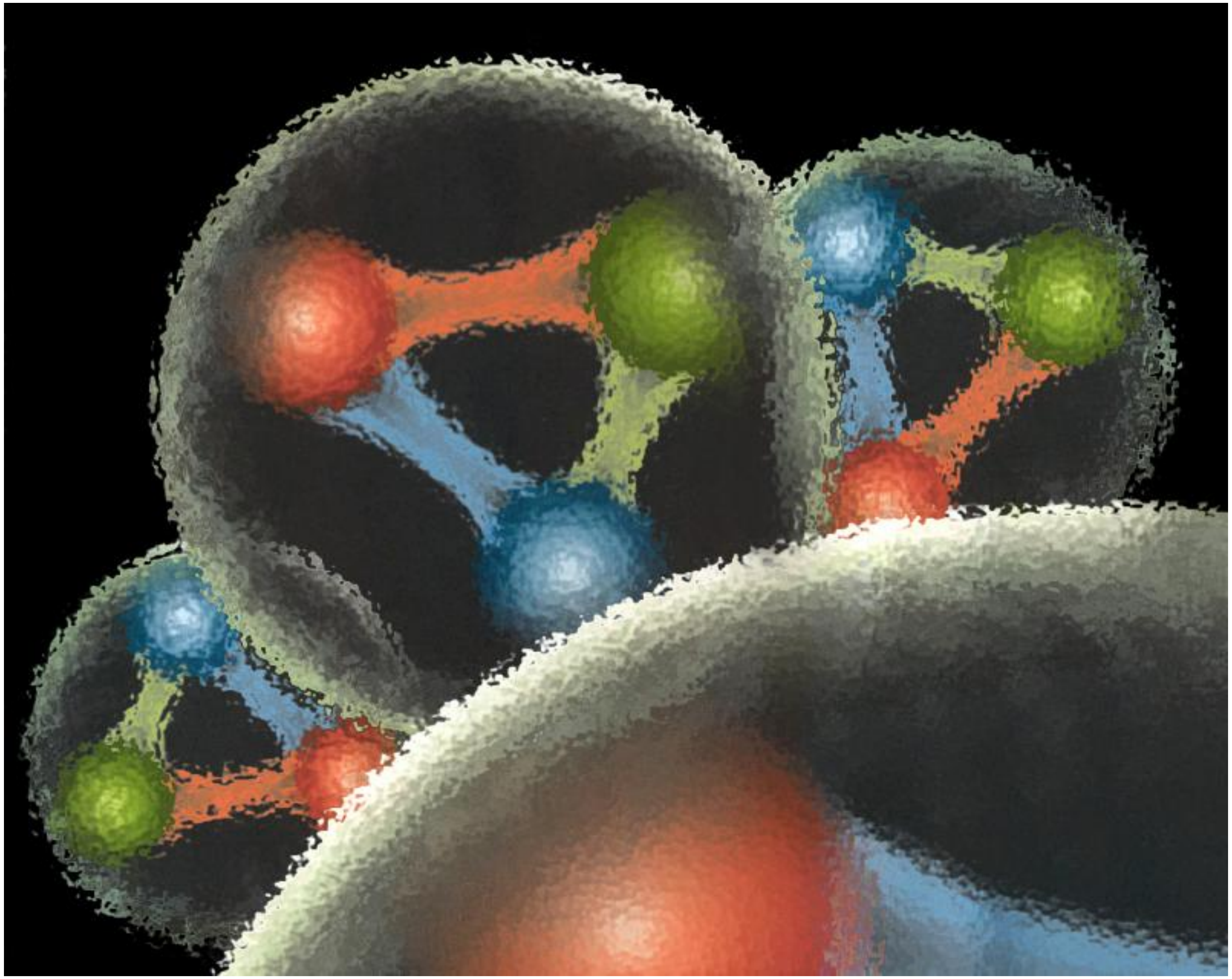
June 30, 2015

Hadronic Weak Interaction (HWI)



QCD is nonperturbative at low energies

Hadronic Weak Interaction

Strangeness-Changing

- Nonleptonic decays of mesons and baryons
- Observed dominance of the $\Delta I=1/2$ channel in nonleptonic decays of kaons
- Relative PV and PC decay amplitudes in nonleptonic decays of hyperons
- Large PV asymmetries in radiative hyperon decays

Parity-Violating ($\Delta S=0$)

- Isolation of weak interaction in hadronic and nuclear physics processes that violate parity
- The natural scale of hadronic PV effects is $\sim 10^{-7}$, however they can be amplified by nuclear structure in many-body systems
- PV observables have been measured in nuclear systems for many years
- Uncertainties associated to nuclear wave functions affect the theoretical interpretation of observables

Reasons to study the $\Delta S=0$ HWI

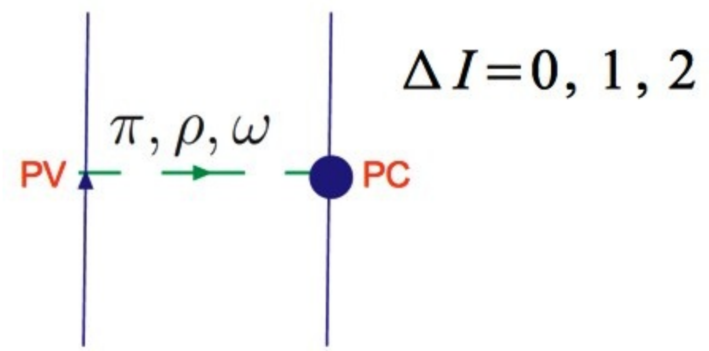
- Unresolved puzzles in the flavour changing HWI
- It offers a possibility to study weak neutral currents at low energies
- Constitutes a probe for quark-quark correlations in nucleons
- Test of nuclear structure models using PV effects in nuclear and atomic systems
- Physics input to PV electron scattering experiments

Theoretical description

DDH

- One meson exchange potential
- Model dependent

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



$$h_\pi^1,\ h_\rho^0,\ h_\rho^1,\ h_\rho^2,\ h'^1_\rho,\ h_\omega^0,\ h_\omega^1$$

EFT

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

  Zhu, Maekawa, Holstein, Ramsey-Musolf, Van Kolck, Nuclear Physics A 748, 435 (2005)

$$\lambda_s^0,\ \lambda_s^1,\ \lambda_s^2,\ \lambda_t,\ \rho_t$$

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

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

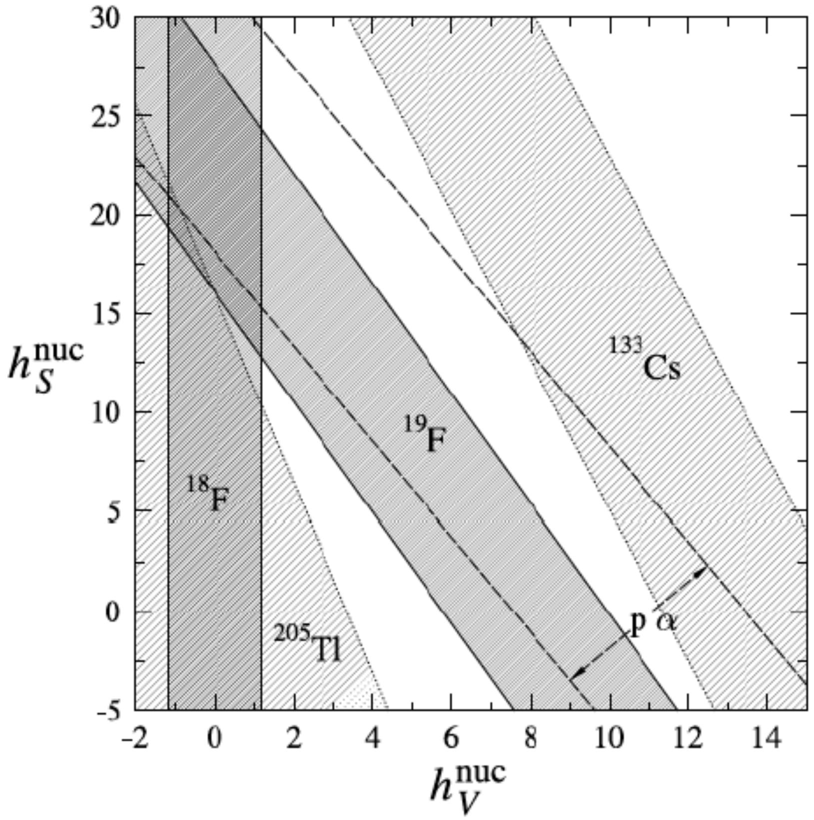
$$^3S_1 \to {}^3P_1 \quad (\Delta I = 1)$$

Lattice QCD

- Theoretical exploration of observables in the nonperturbative regime of QCD with quantifiable uncertainties
- Confrontation of theory and experiment

  J. Wasem, Physical Review C 85, 022501 (2012)

PV observables in nuclear systems



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

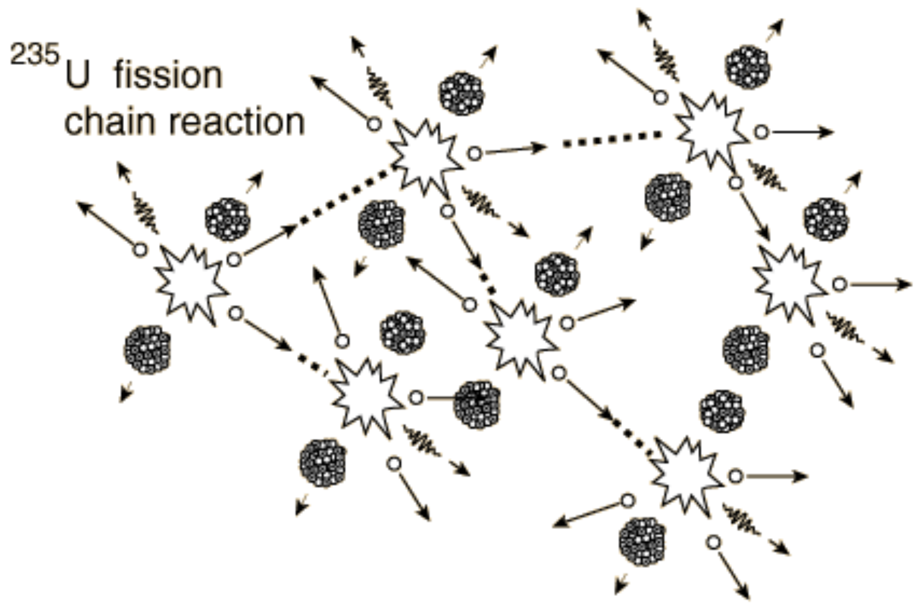
Ramsey-Musolf, Page, Annual Review of Nuclear and Particle Science 56, 1-52 (2006)

Few-nucleon systems

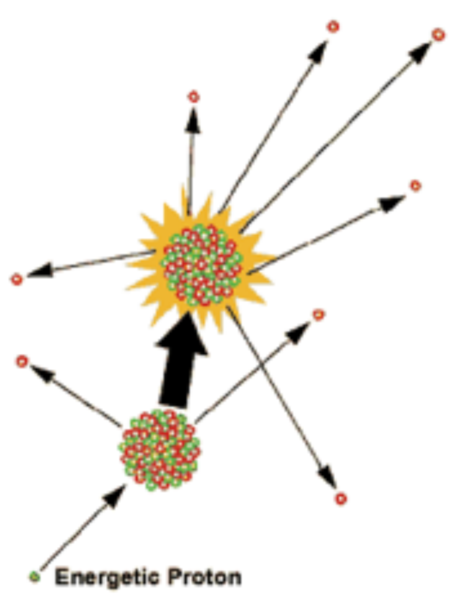
- Less uncertainties related to nuclear structure and more reliable interpretation of observables
- Theoretical calculations with quasi-exact nonperturbative methods are more feasible and in some cases already available for few-body systems
- Intense sources of neutrons allow the measurement of PV effects with sensitivity in the 10^{-8} level

Program with low energy neutrons

Nuclear reactor



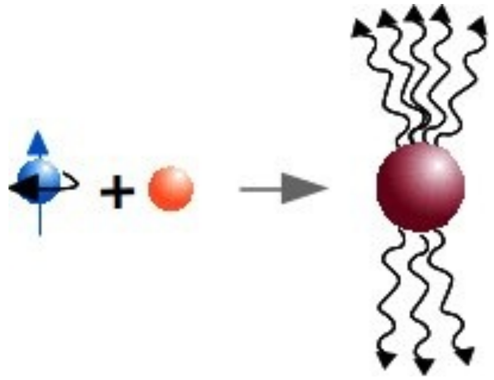
Spallation source



PV observables in experiments with neutrons

NPDGamma

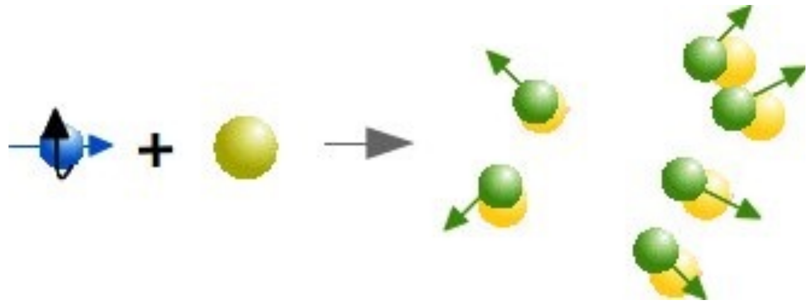
$$\vec{n} + p \to d + \gamma$$



$$A_\gamma (\vec{k}_\gamma \cdot \vec{\sigma}_n)$$

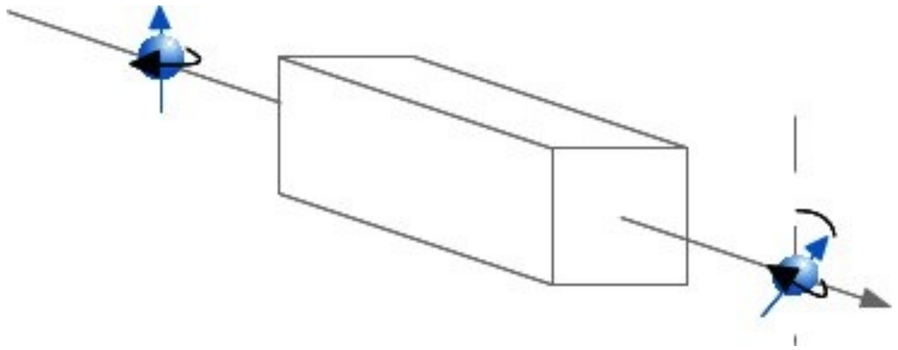
n-^{3}He

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



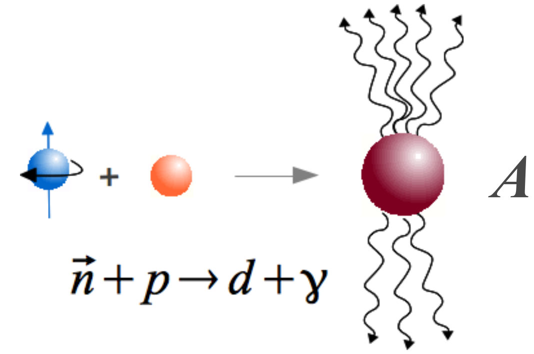
$$A_p (\vec{k}_p \cdot \vec{\sigma}_n)$$

Neutron Spin Rotation (NSR)



$$\frac{d\varphi}{dz} (\vec{\sigma}_n^{'} \cdot \vec{\sigma}_n)$$

NPDGamma



- Dominated by a ΔI=1 $^3S_1$-$^3P_1$ parity-odd transition in the n-p system (accessible through π exchange)

- In the DDH model $A_\gamma \approx -0.11 h_\pi^1$
  With DDH "best" value $A_\gamma = -5\times 10^{-8}$

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

Coupling	Reasonable range (each $\times 3.8\times 10^{-8}$)	"Best" value (each $\times 3.8\times 10^{-8}$)
h_π^1	$0 \rightarrow 30$	12
h_ρ^0	$30 \rightarrow -81$	-30
h_ρ^1	$-1 \rightarrow 0$	-0.5
h_ρ^2	$-20 \rightarrow -29$	-25
h_ω^0	$15 \rightarrow -27$	-5
h_ω^1	$-5 \rightarrow -2$	-3

- First lattice QCD result $h_\pi^1 = 1.099 \pm 0.505^{+0.058}_{-0.064}\left[\times 10^{-7}\right]$

  J. Wasem, Physical Review C 85, 022501 (2012)

NPDGamma

Experimental results

W.C. Haxton and B. R. Holstein, Progress in Particle and Nuclear Physics 71, 185 (2013)

Gamma asymmetry in $\vec{n} + p \rightarrow d + \gamma$

$A_\gamma = 0.6 \pm 2.1 \left[\times 10^{-7}\right]$ Grenoble

J.F. Cavaignac et al., Physics Letters B 67, 148 (1977)

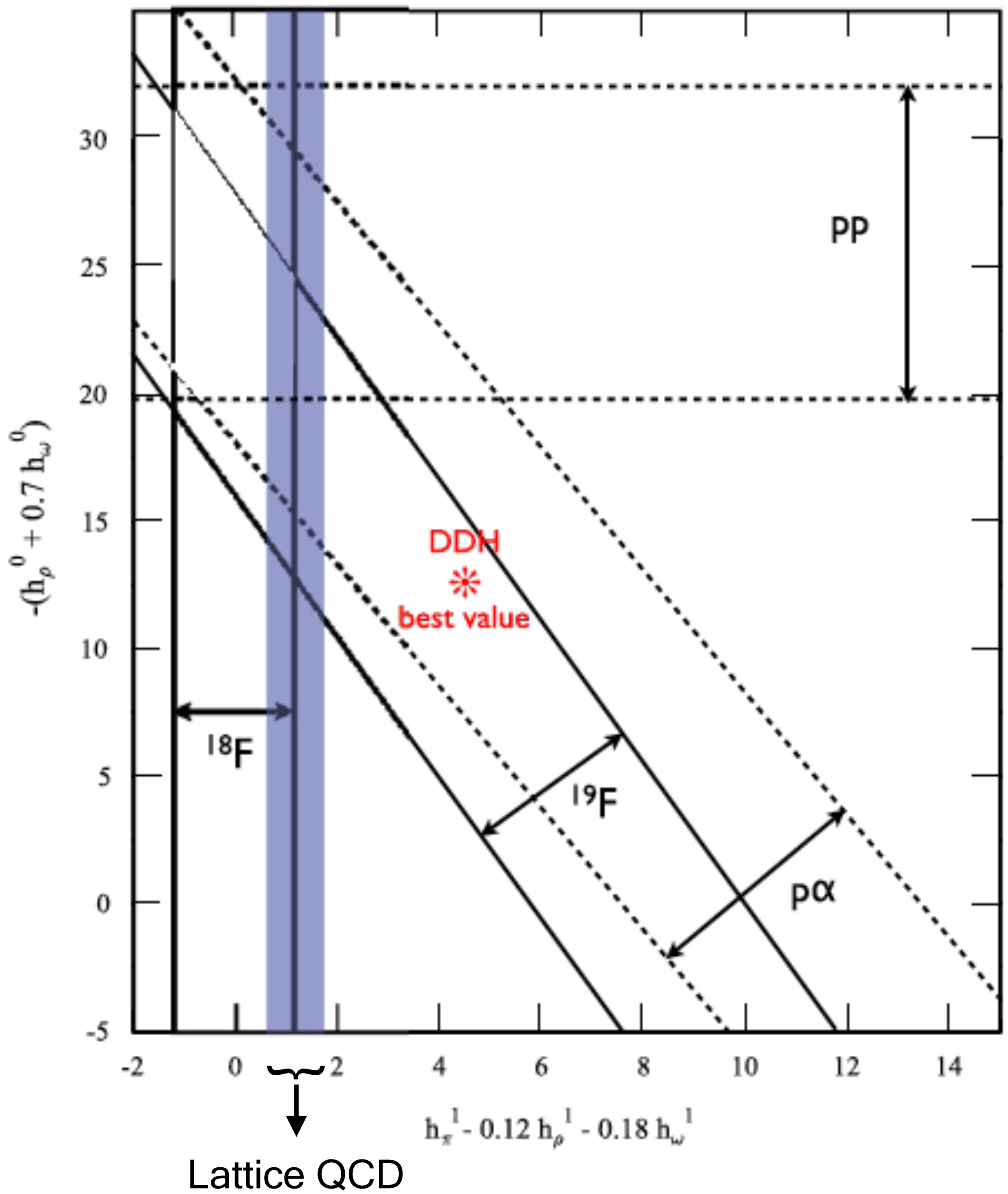
$A_\gamma = -1.21 \pm 2.1 \pm 0.2 \left[\times 10^{-7}\right]$ LANSCE

Gericke et al., Physical Review C 83, 015505 (2011)

Gamma circular polarization in ^{18}F decay

$h_\pi^1 \leq 1.3 \times 10^{-7}$

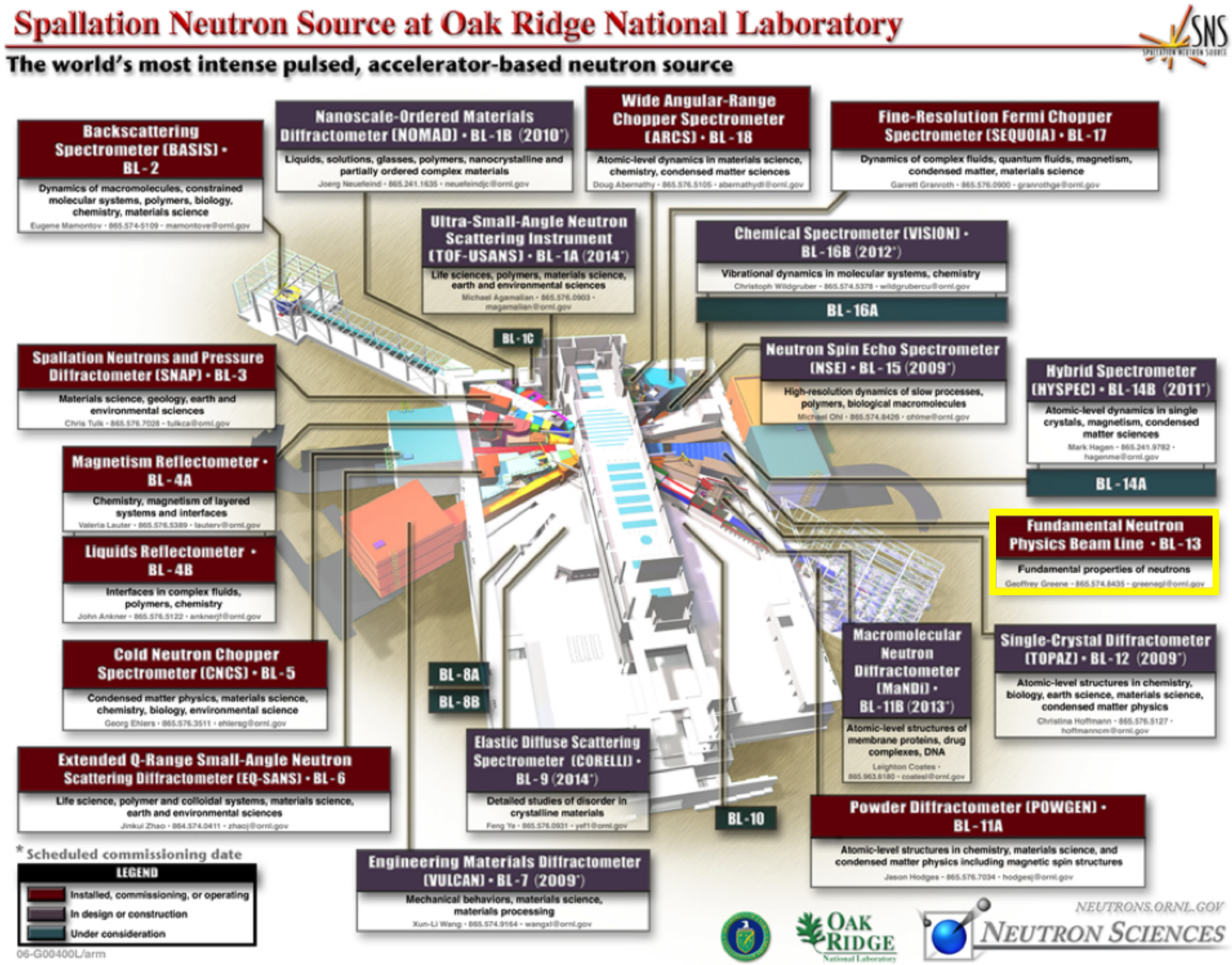
E.G. Adelberger et al., Physical Review C 27, 2833 (1983)



units are 10^{-7}

The Spallation Neutron Source at the ORNL

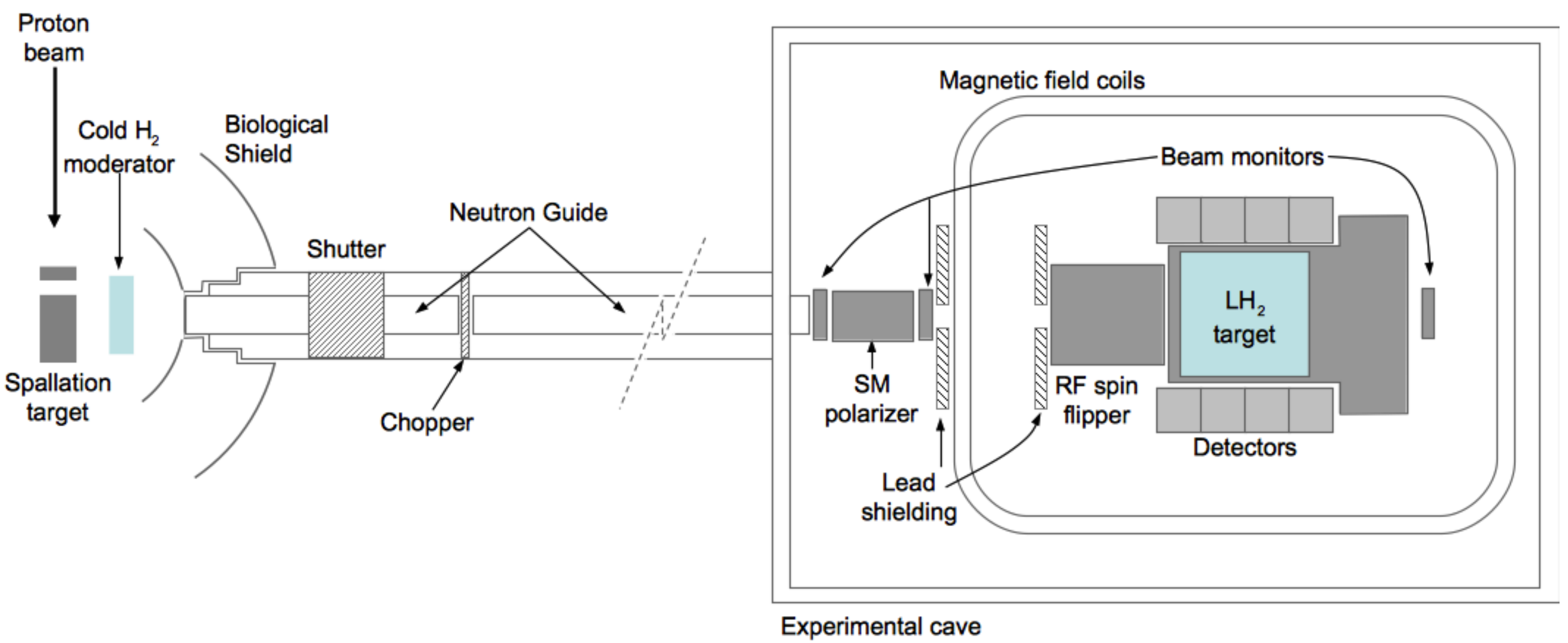
Fundamental Neutron Physics Beamline



N. Fomin et al., Nuclear Instruments and Methods A 773, 45(2015)

NPDGamma

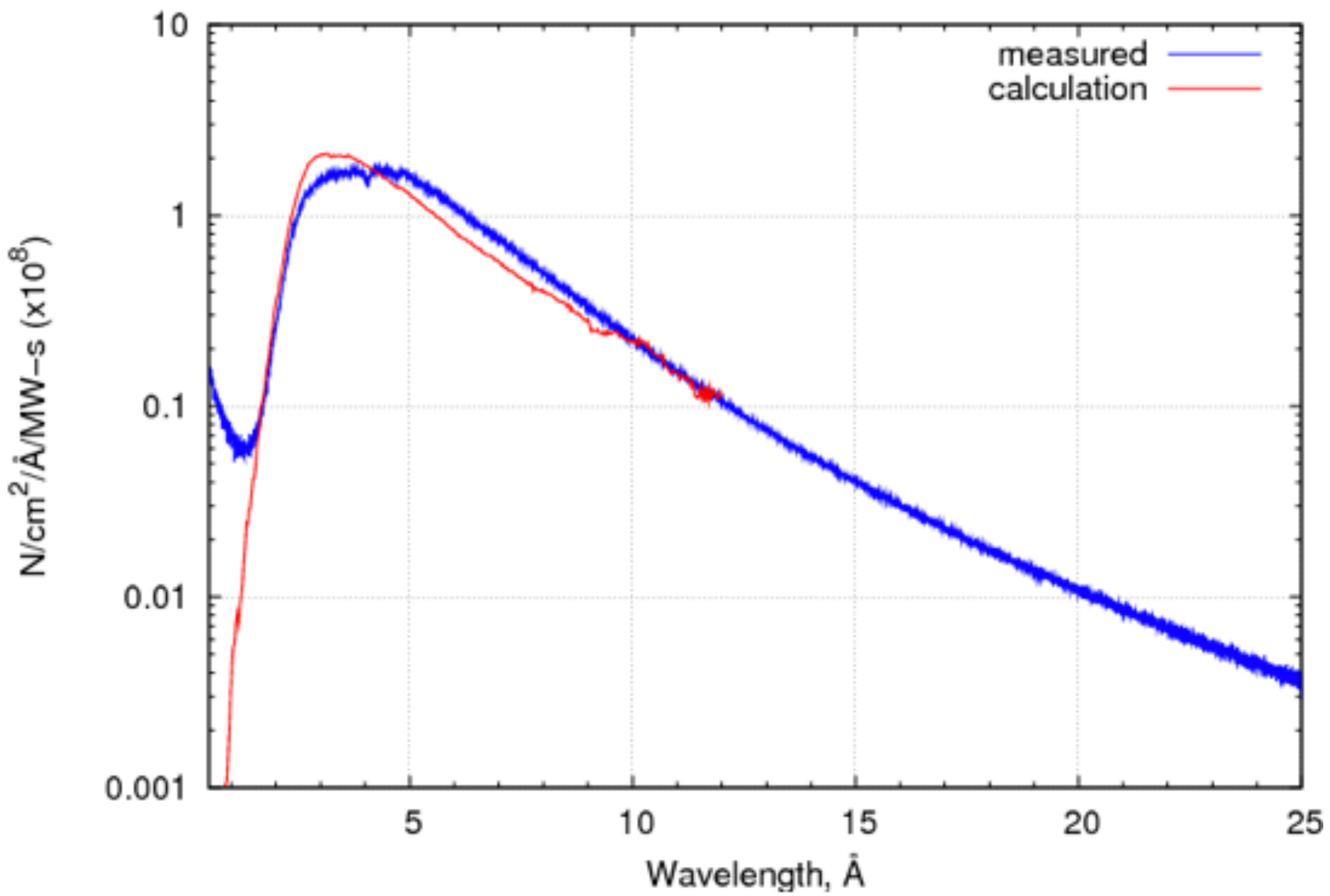
Experimental apparatus



Experiment

Neutron flux

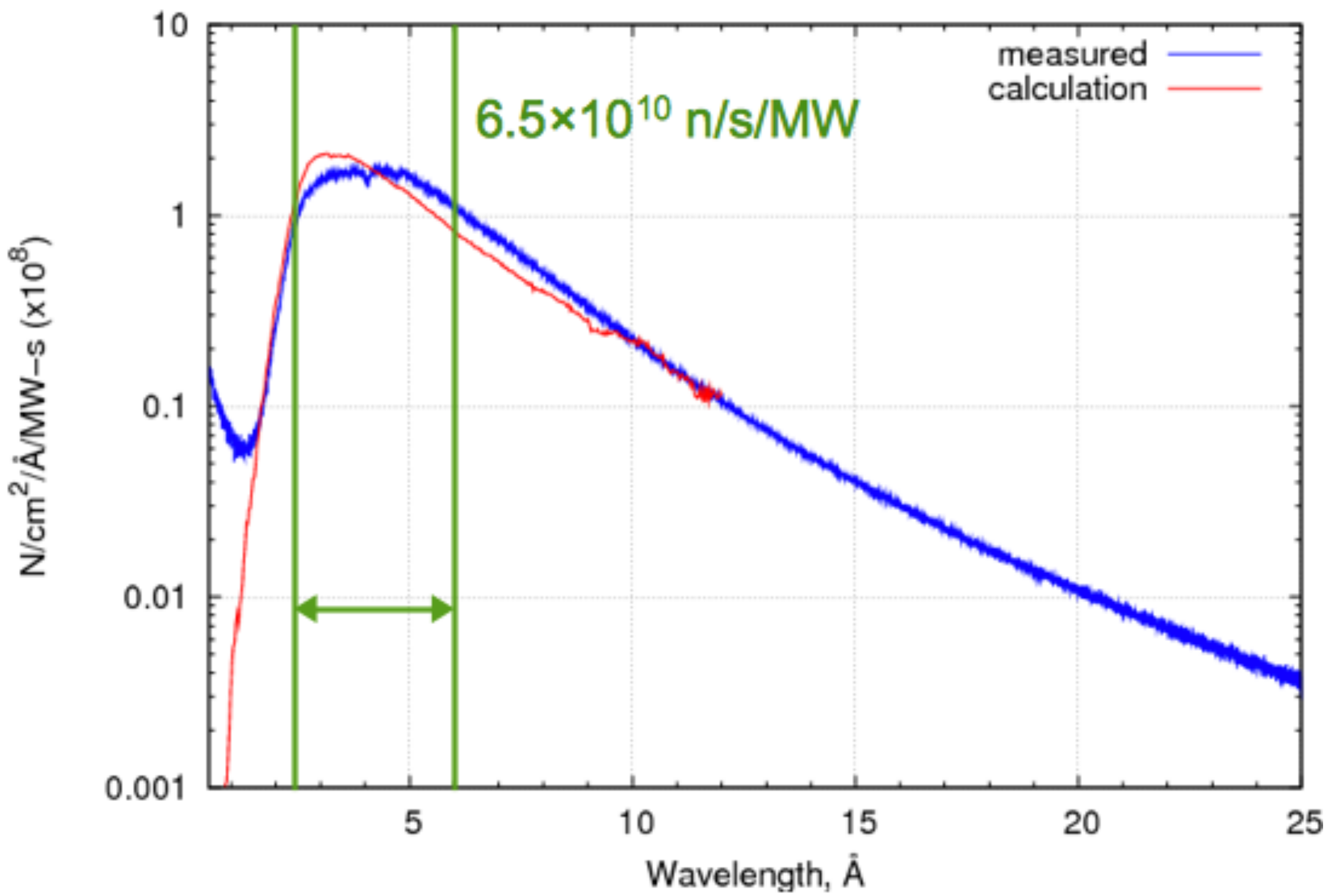
60 pulses per second



Experiment

Neutron flux

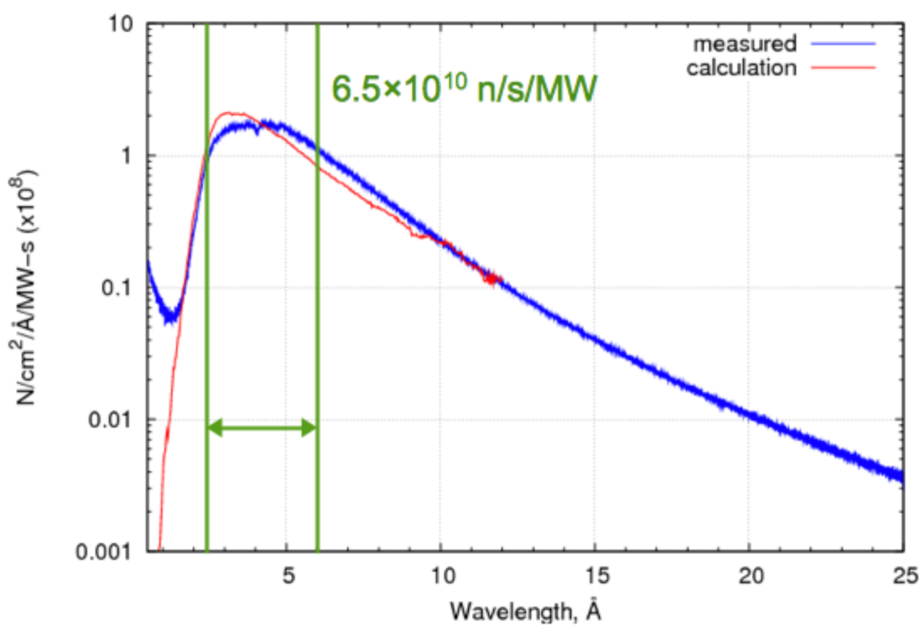
60 pulses per second



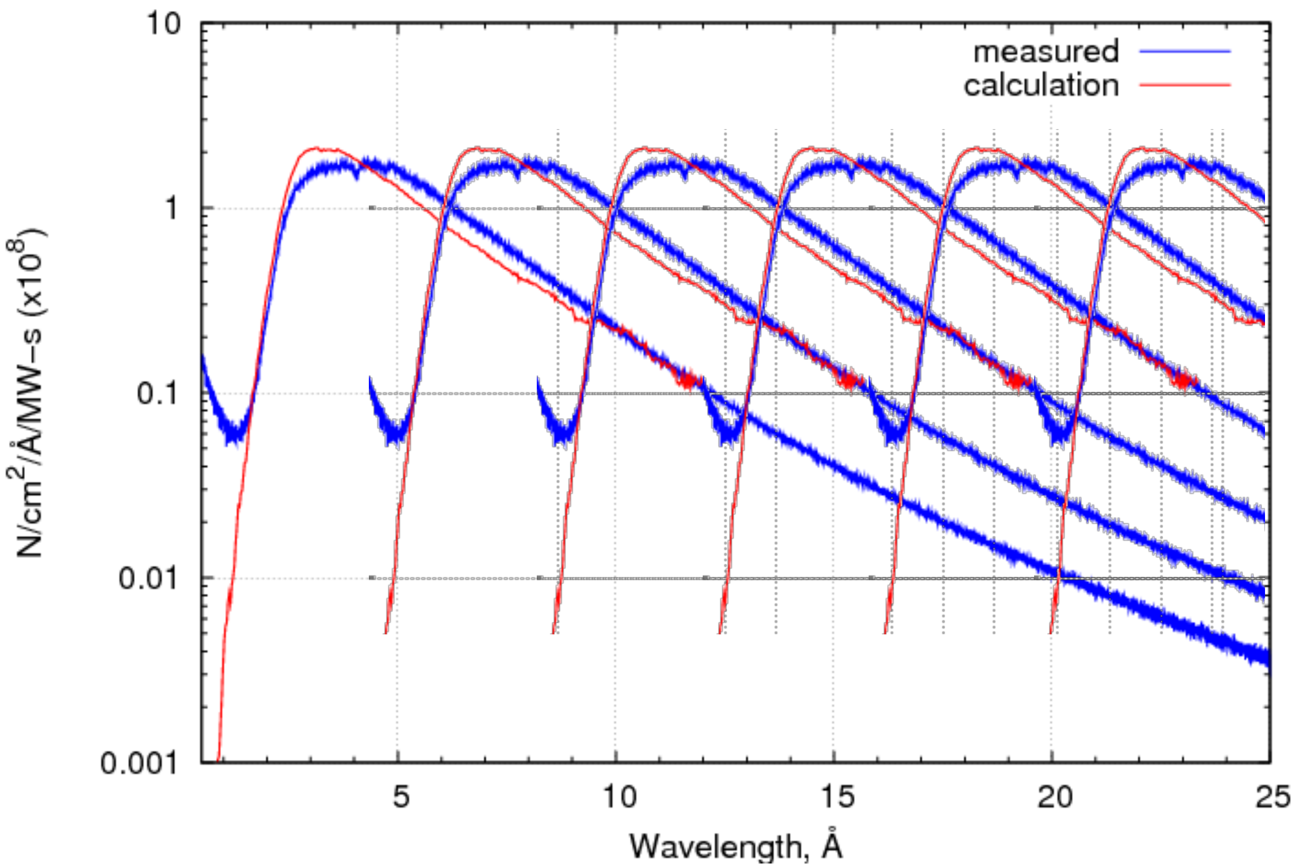
Experiment

Neutron flux

60 pulses per second



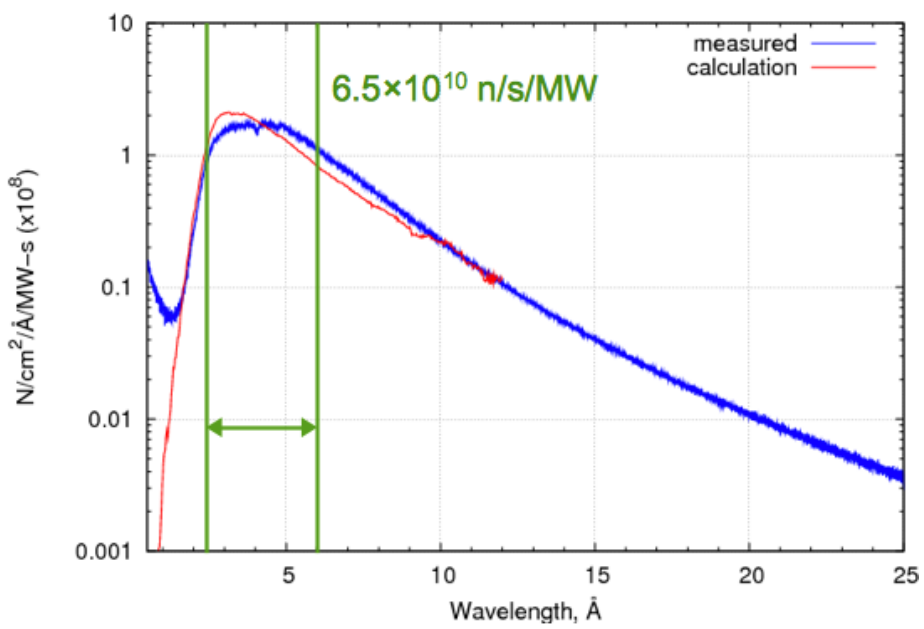
overlap of neutrons from different pulses and energies

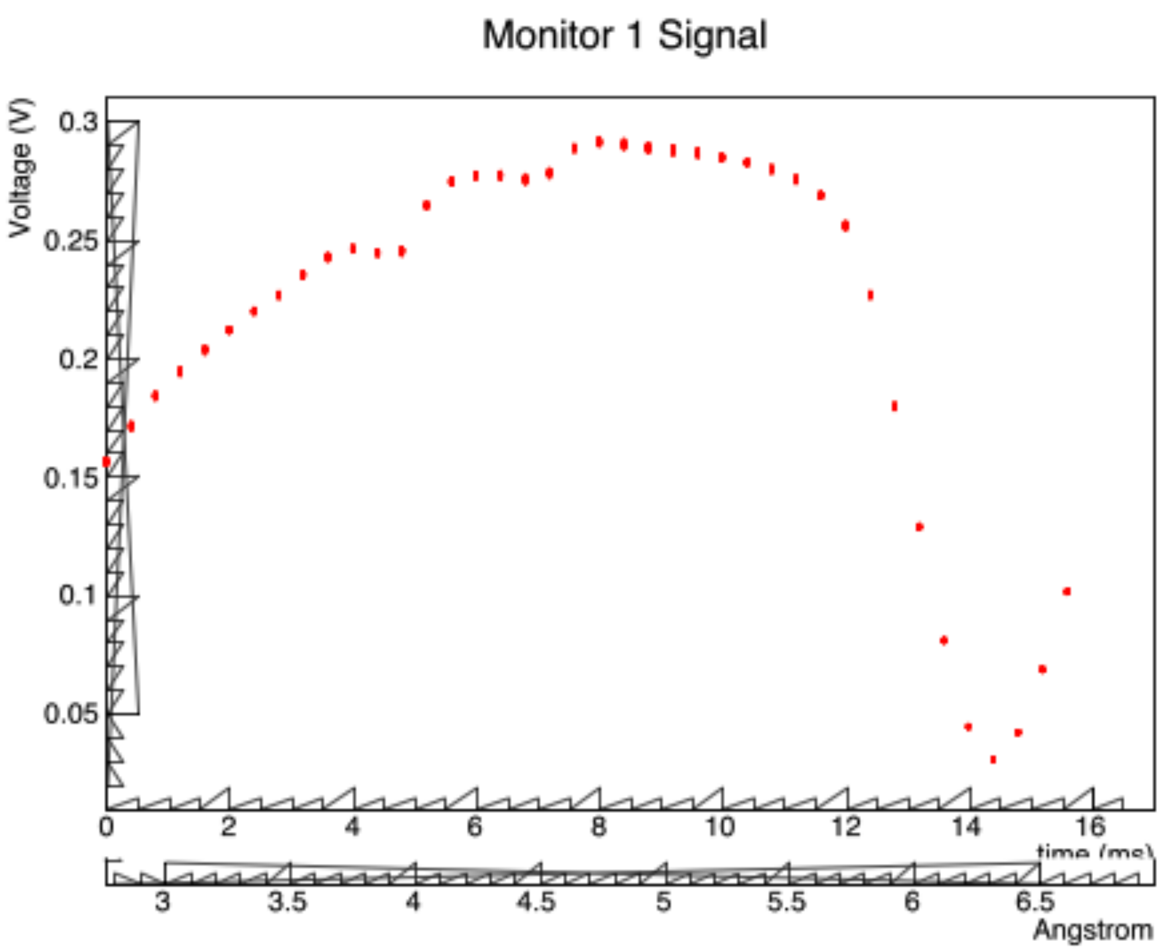


Experiment

Neutron flux

60 pulses per second

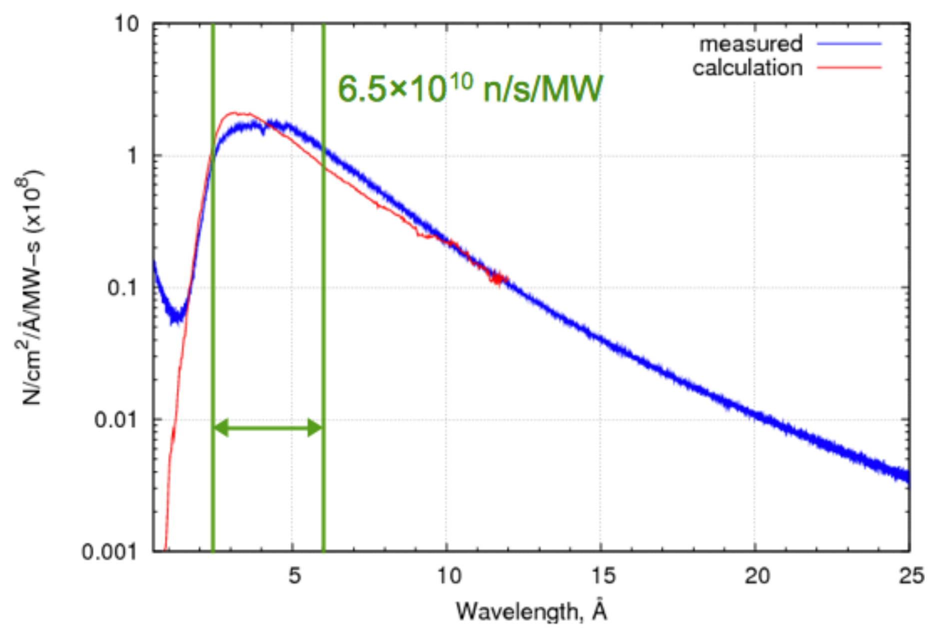




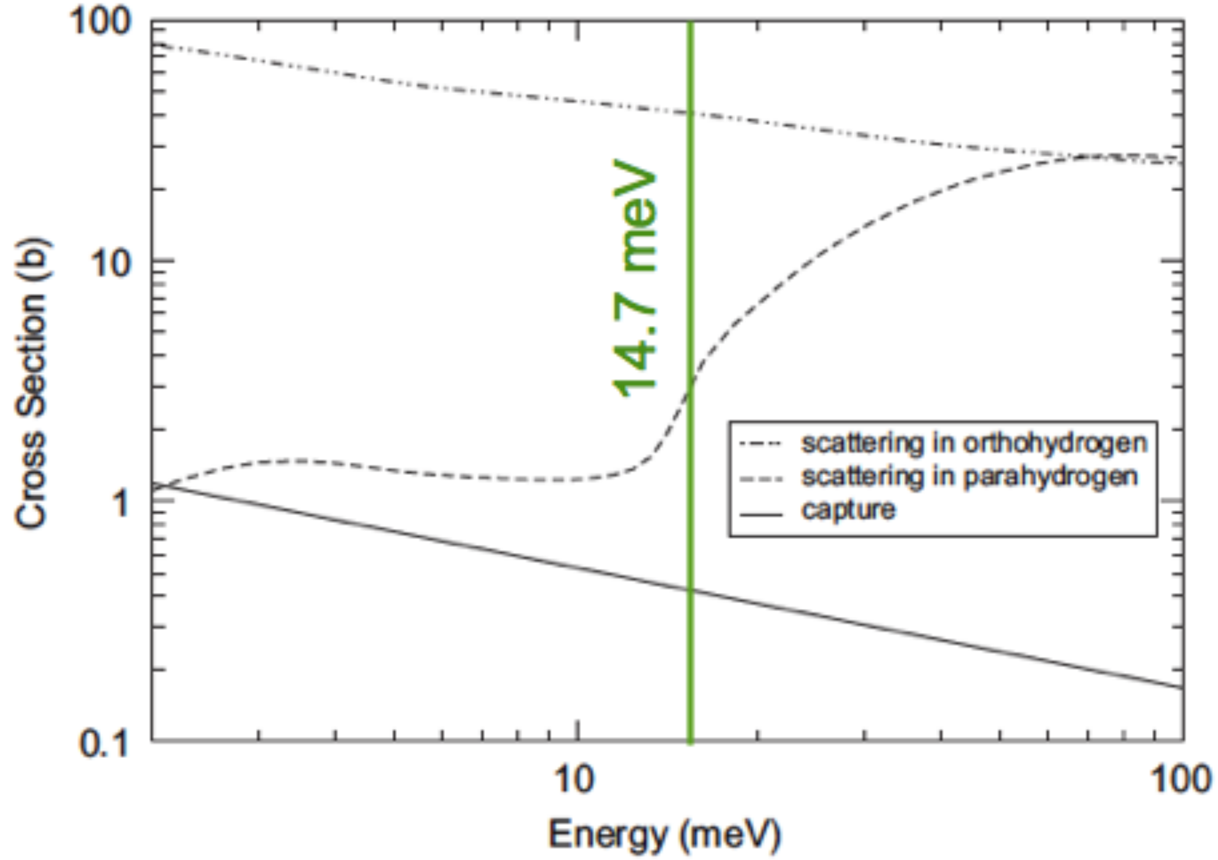
Experiment

Neutron flux

60 pulses per second

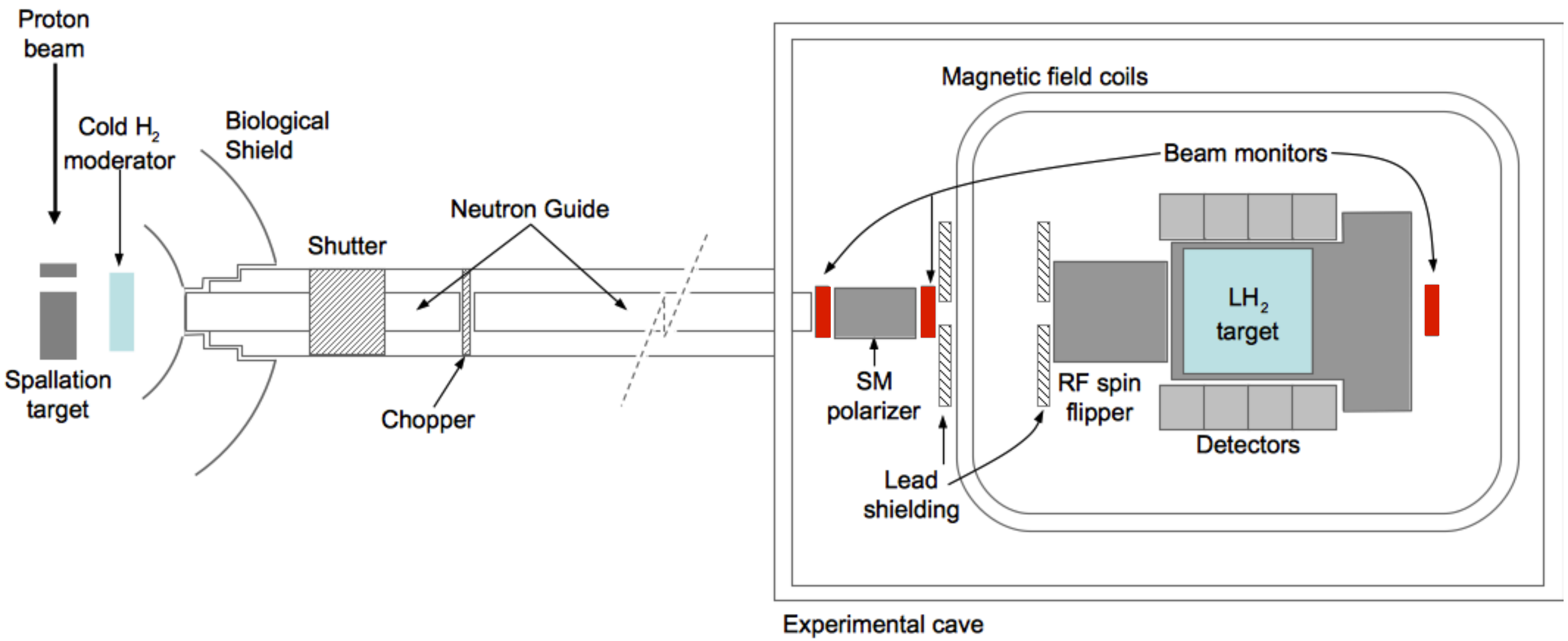


para-to-ortho threshold



Experiment

Beam monitors



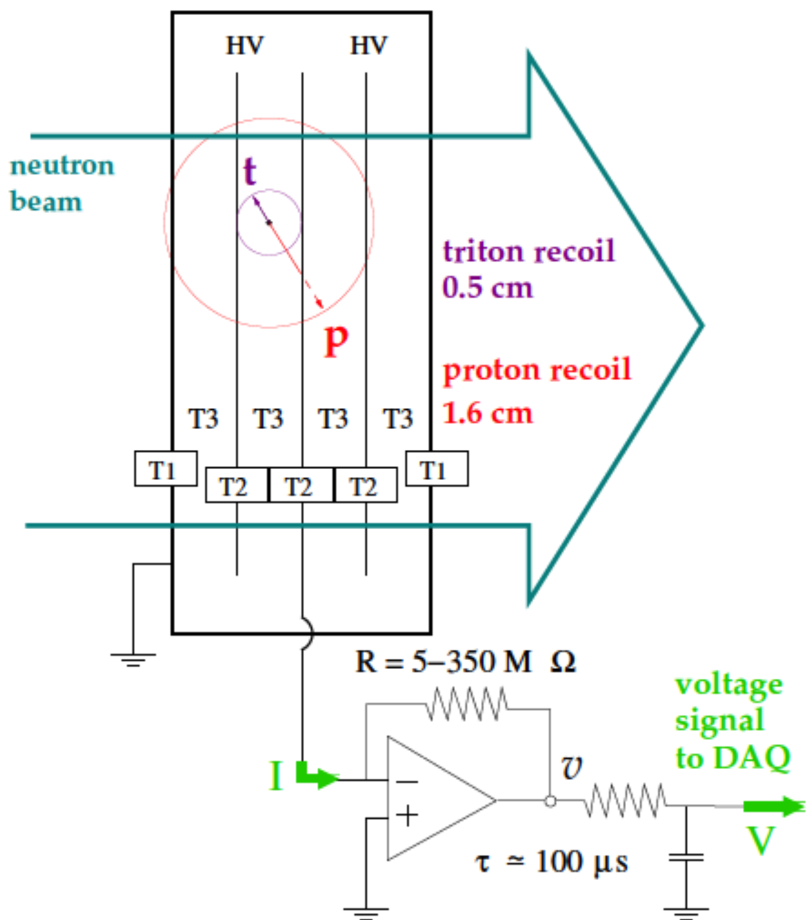
Experiment

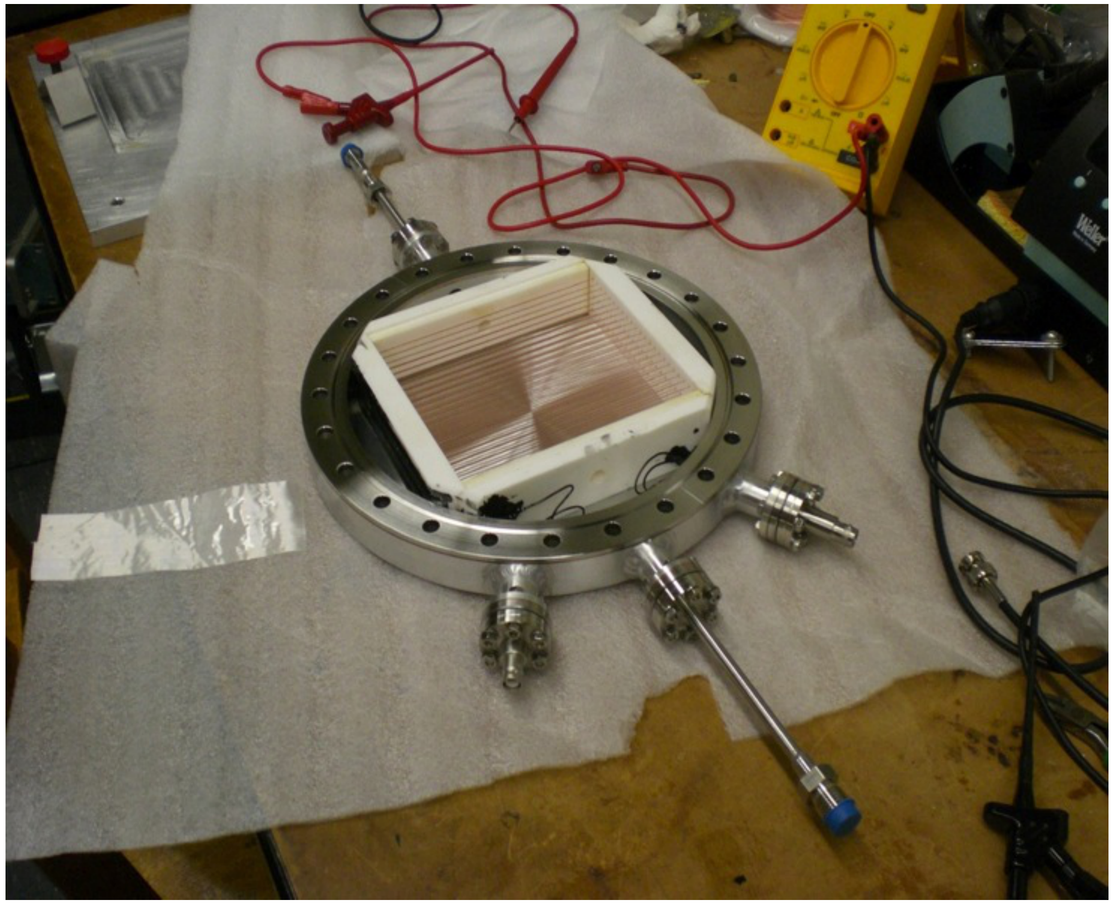
Beam monitors

- Ionization chamber with N_2 and some ^{3}He (1-2%)

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

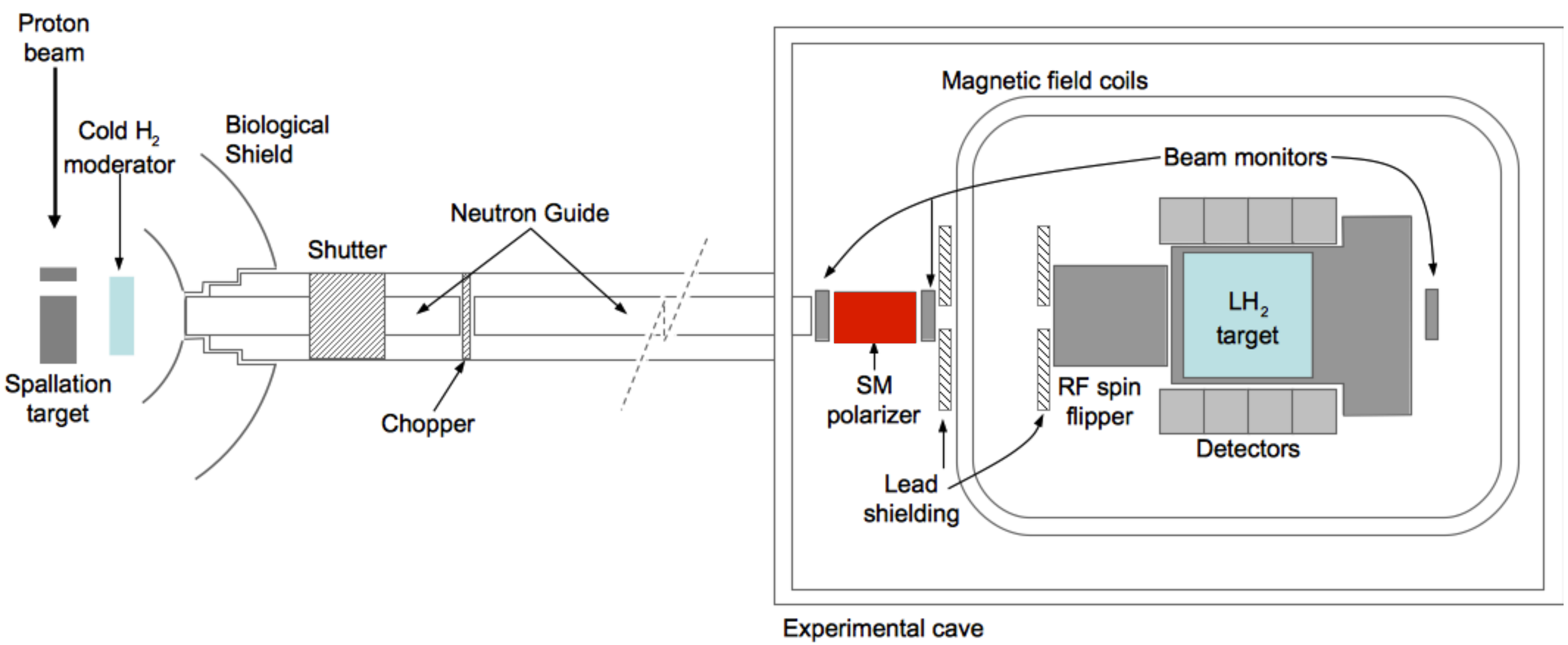
- At most 2% of the neutrons at 4 meV are captured





Experiment

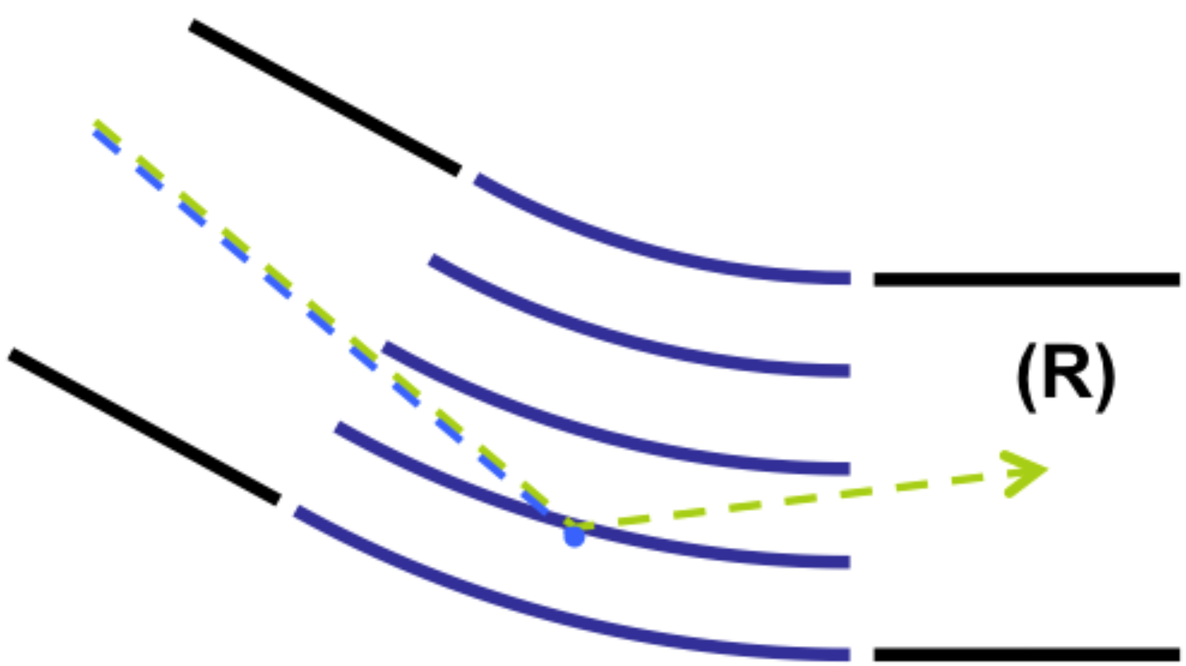
Supermirror (SM) Polarizer



Experiment

Supermirror (SM) Polarizer

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

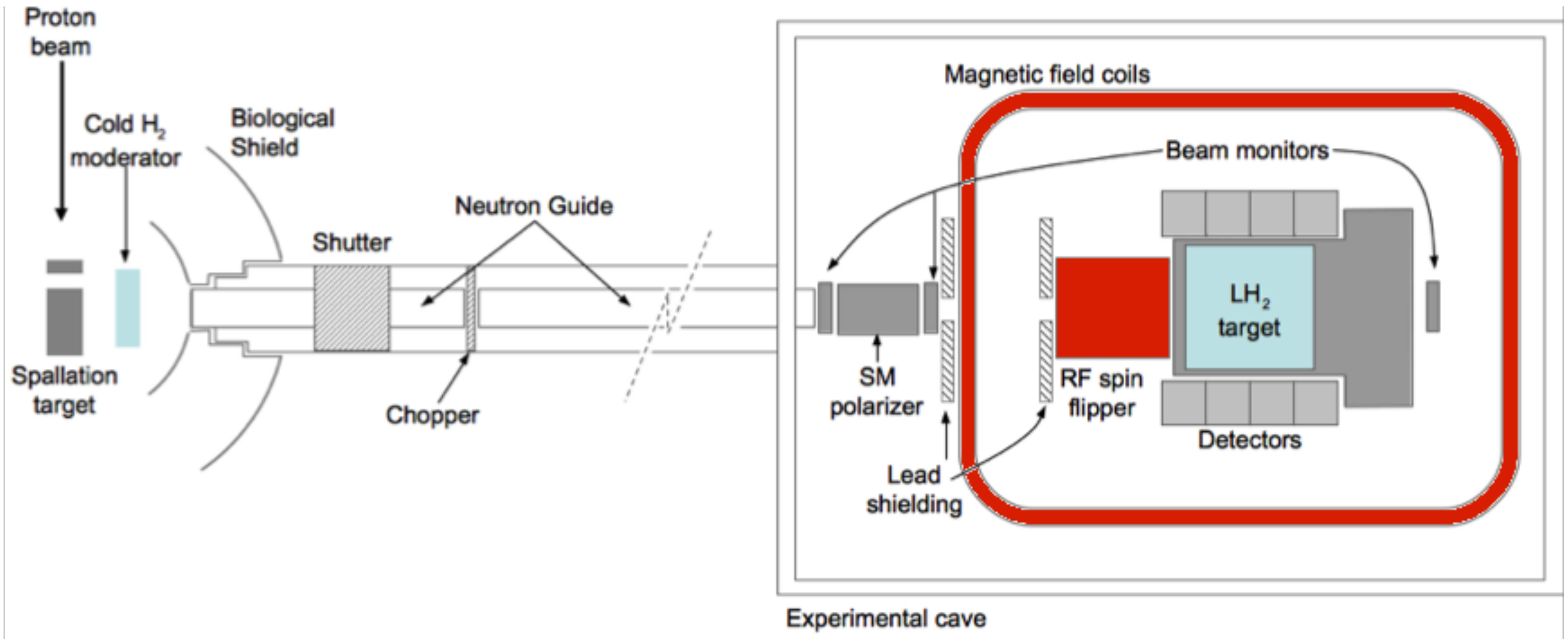


Fe/Si on boron float glass, no Gd

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
$N=2.2\times10^{10}$ n/s	output flux (chopped)

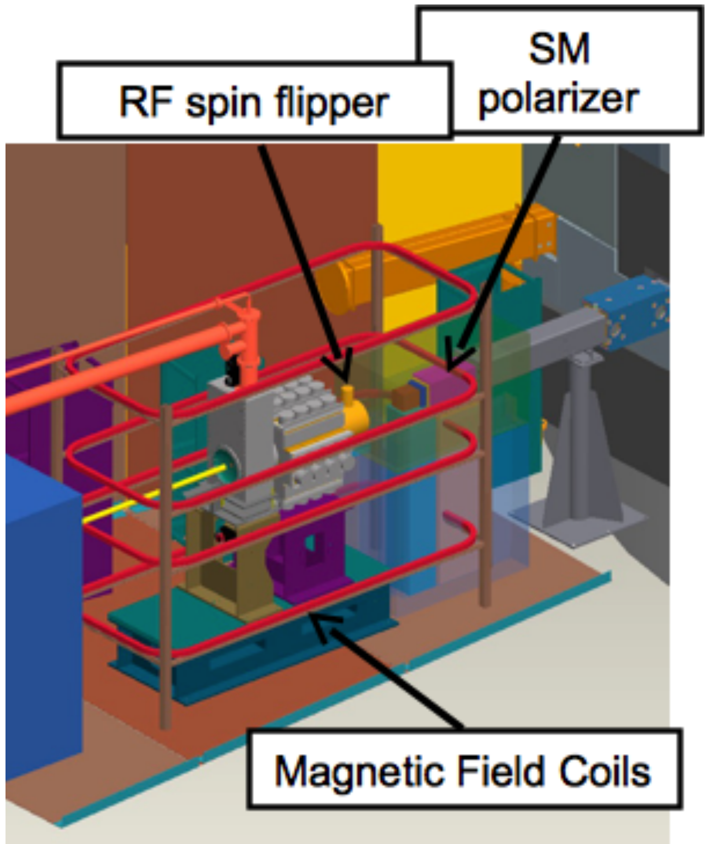
Experiment

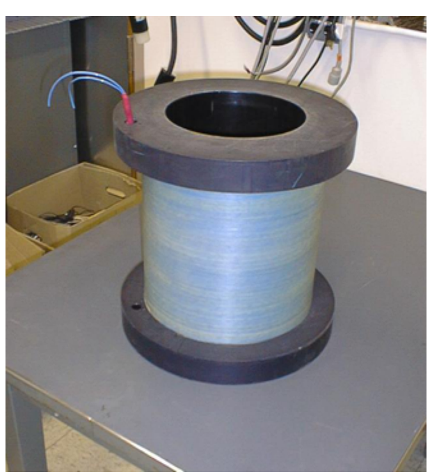
Holding magnetic field and RF spin flipper



Experiment

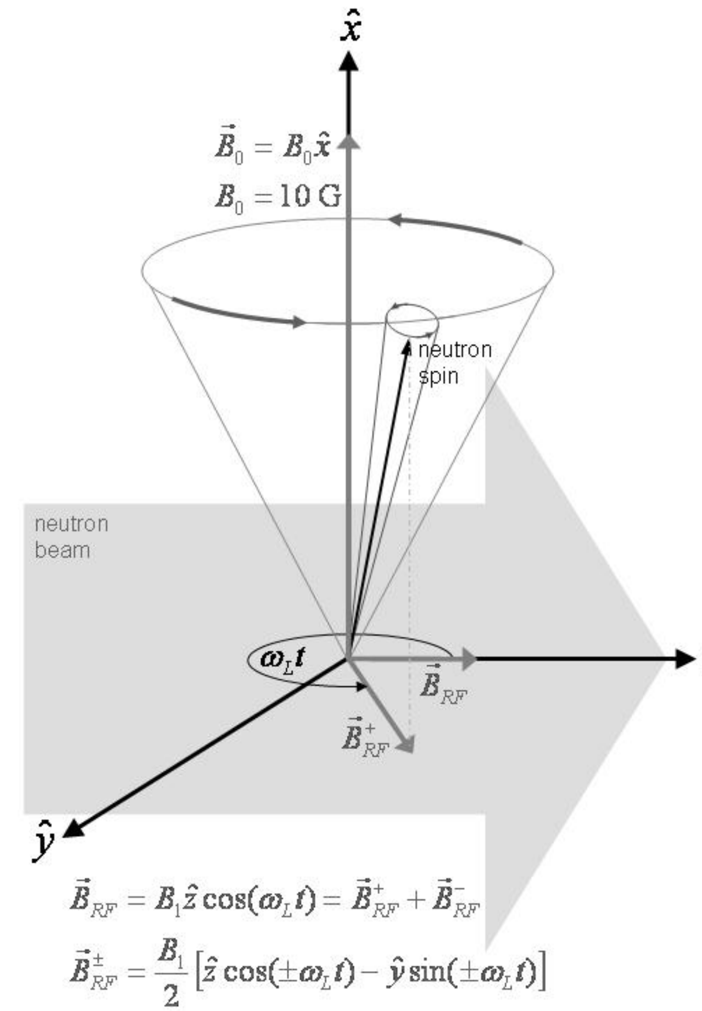
Holding magnetic field and RF spin flipper

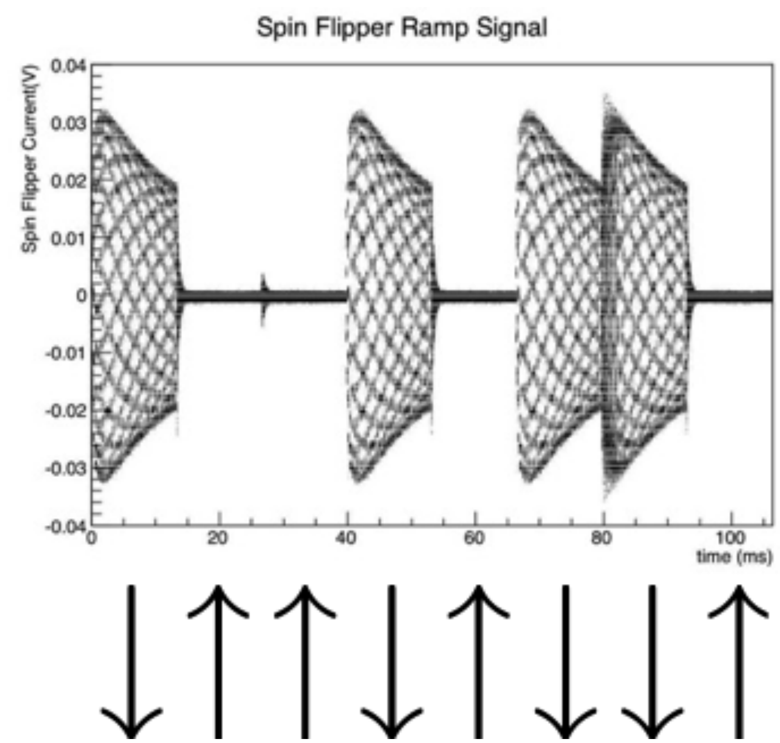




$$B_1 = \frac{n\pi\hbar}{\mu_n}\left(\frac{l}{L}\right)\frac{1}{t_{\mathrm{tof}}}$$

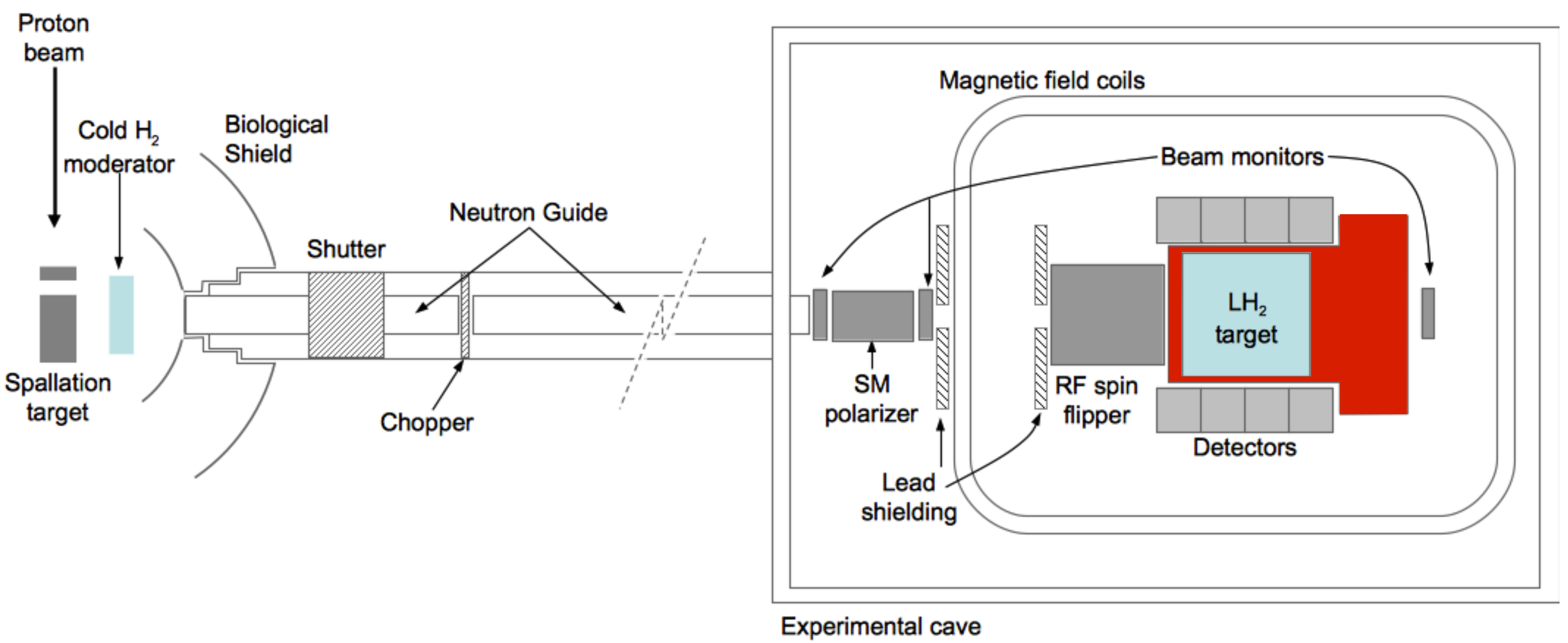
P.-N. Seo et al., Phys. Rev. ST AB 11, 084701 (2008)





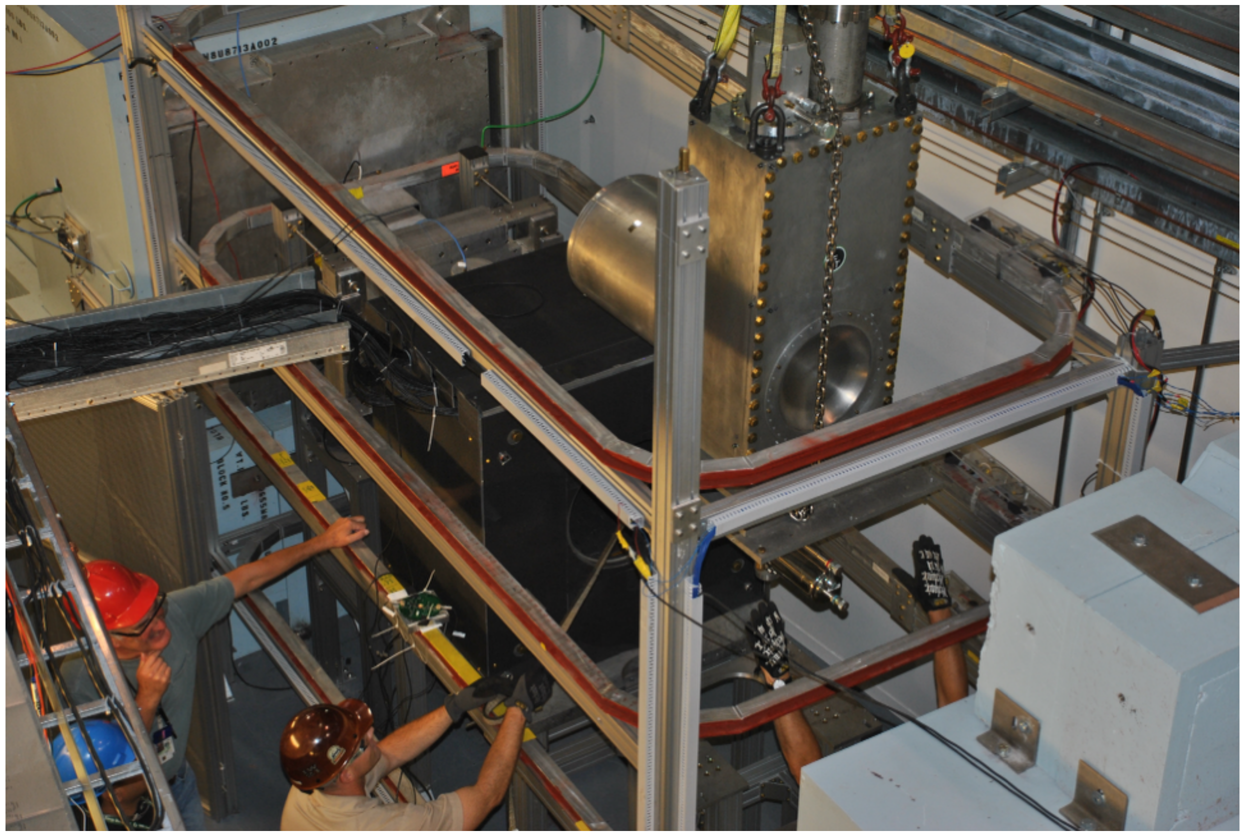
Experiment

LH_2 target

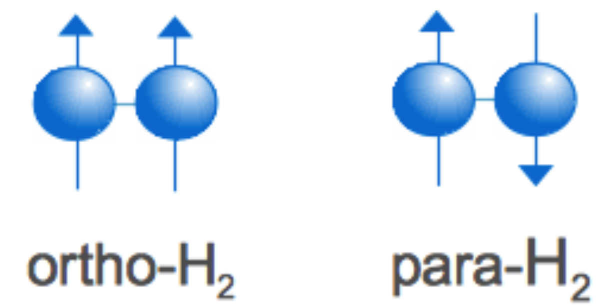


Experiment

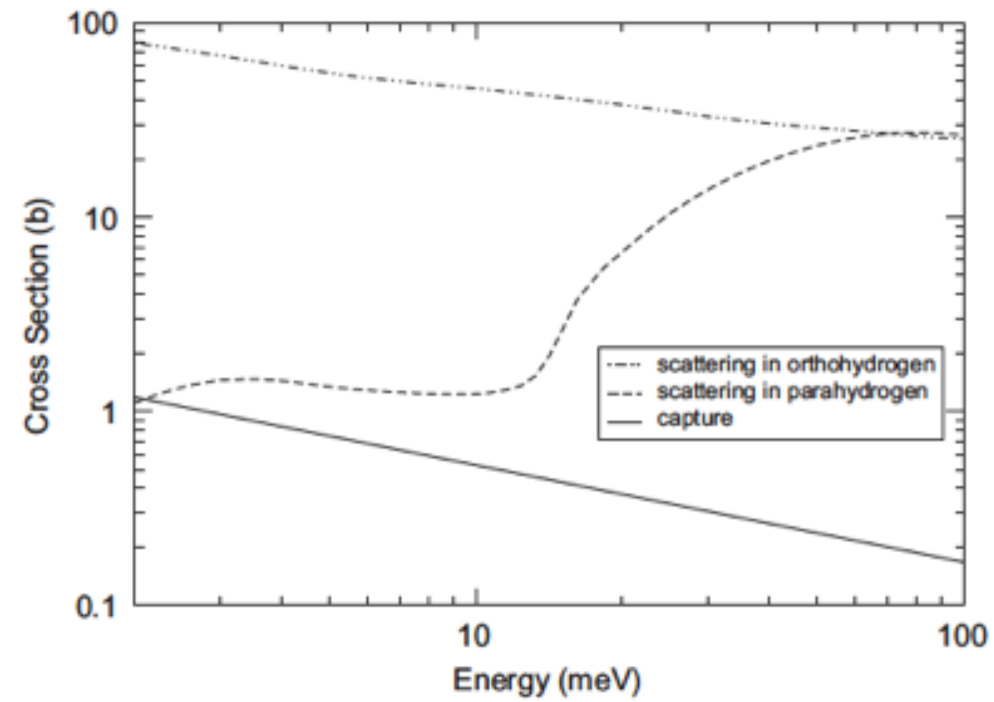
LH_2 target



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



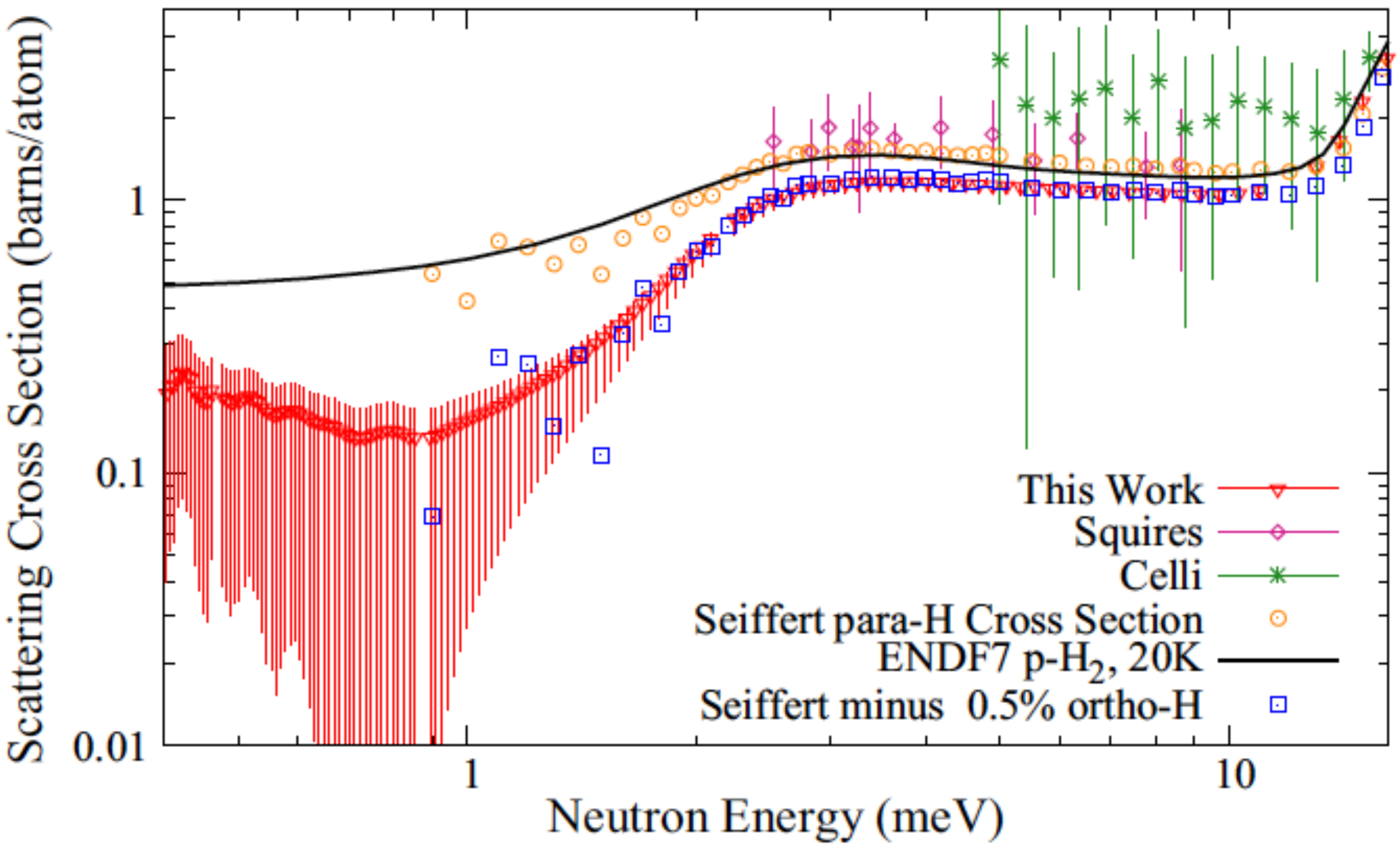
at room temperature ortho/para is 3/1, but at 17 K 99.98% of H_2 is in the para-H_2 state



Experiment

LH_2 target

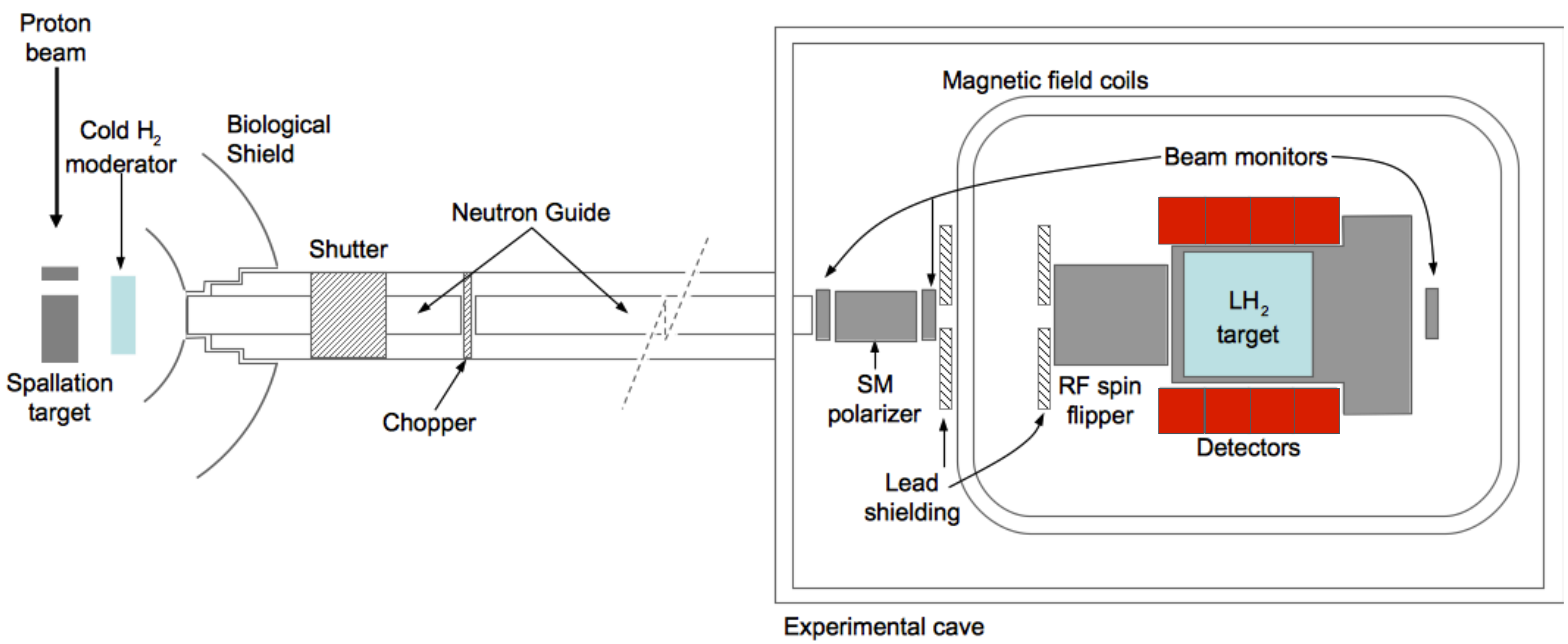
Scattering cross section of neutrons on para-H_2



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

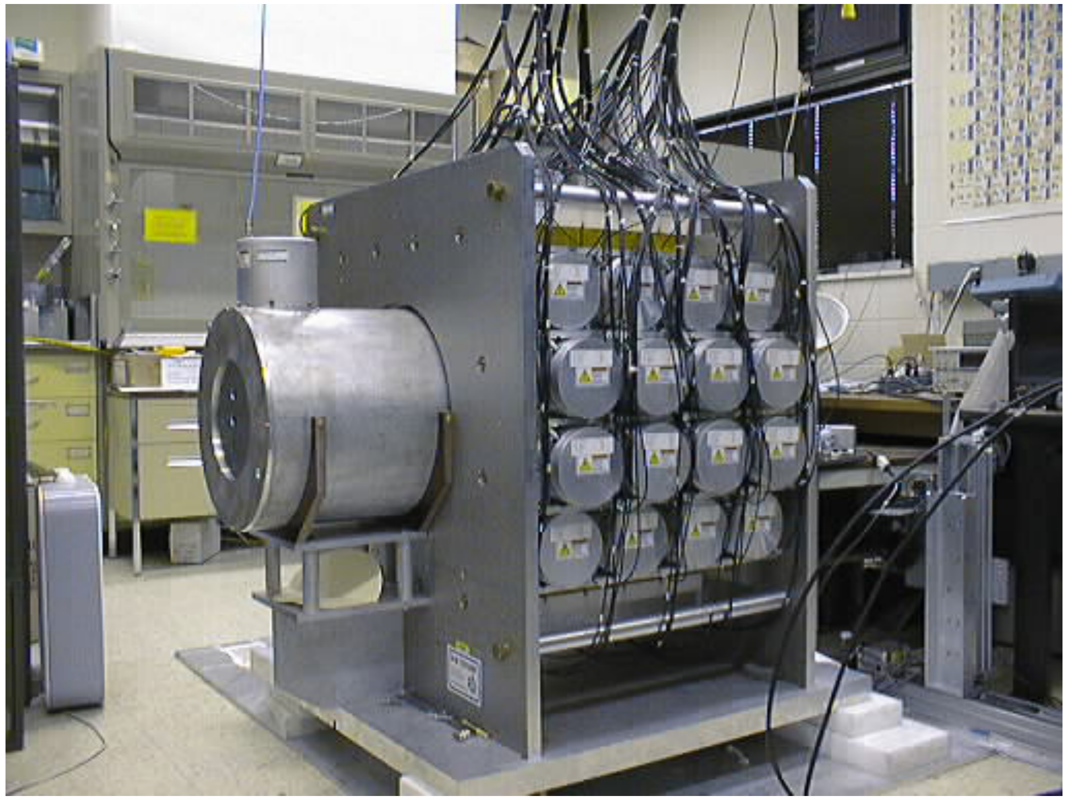
Experiment

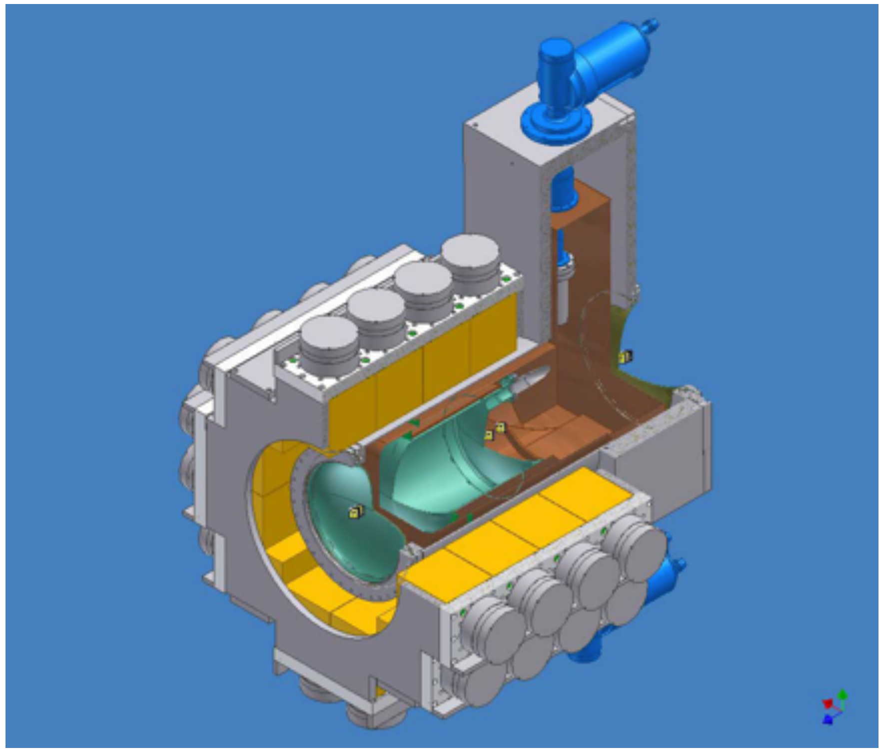
Gamma ray detector

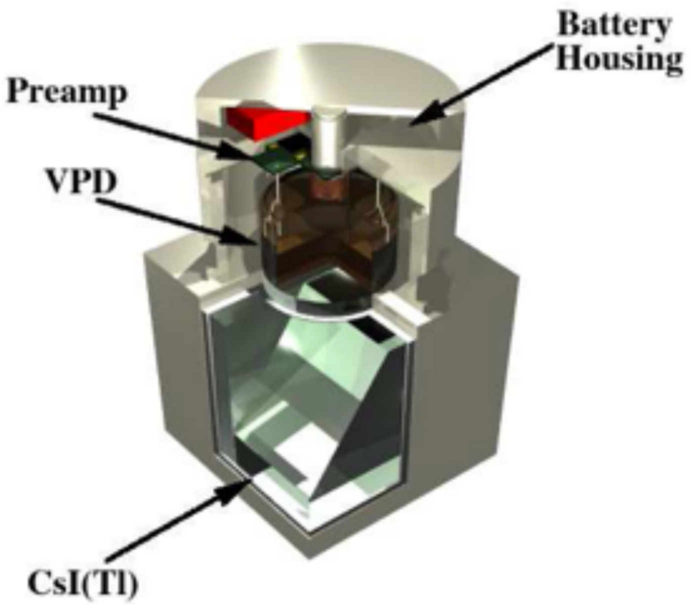


Experiment

Gamma ray detector

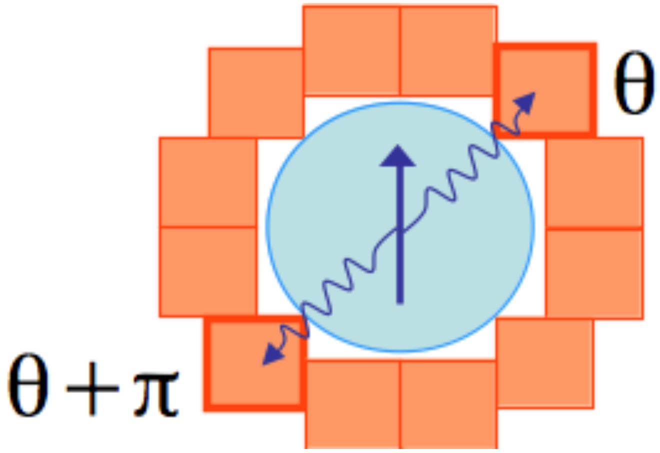






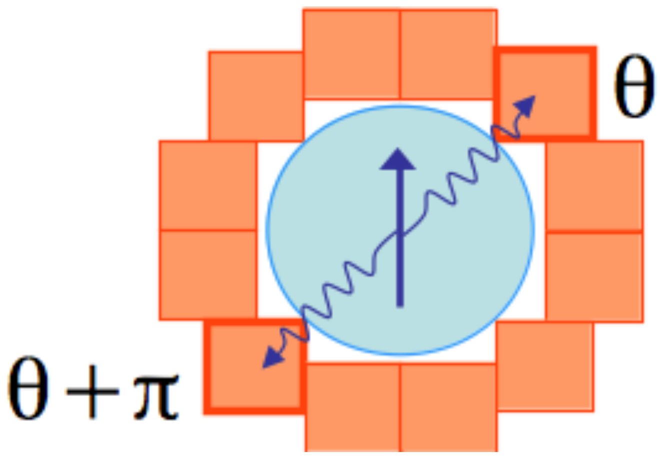
- 48 CsI detectors
- 3π acceptance
- Current mode operation ($5x10^7$ gammas/pulse)

Extraction of A_γ



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

Extraction of A_γ



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

up-down (PV) and left-right (PC) asymmetries

up-down left-right

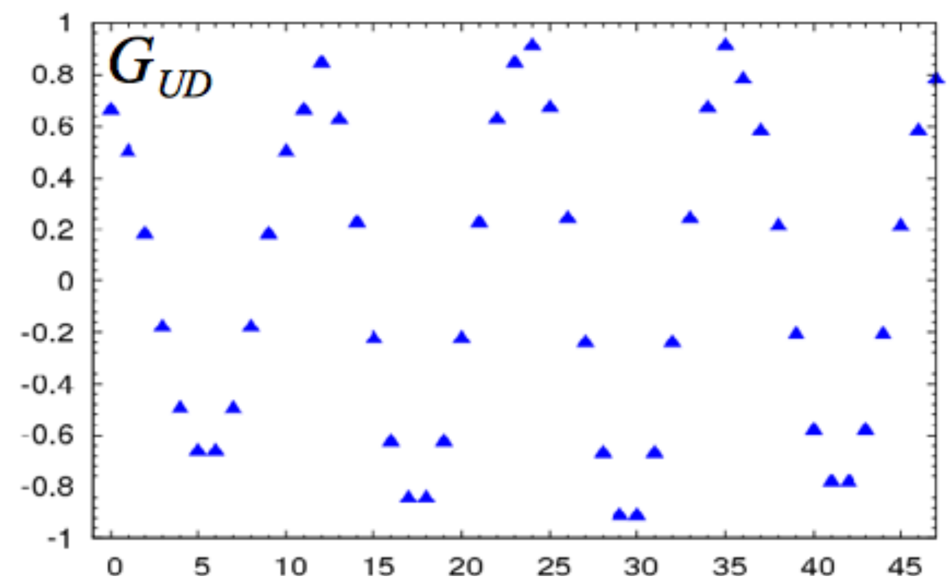
$$A_{\gamma,\,raw} = A_\gamma^{PV} \underline{G_{UD}} + A_\gamma^{PC} \underline{G_{LR}} + A_{offset}$$

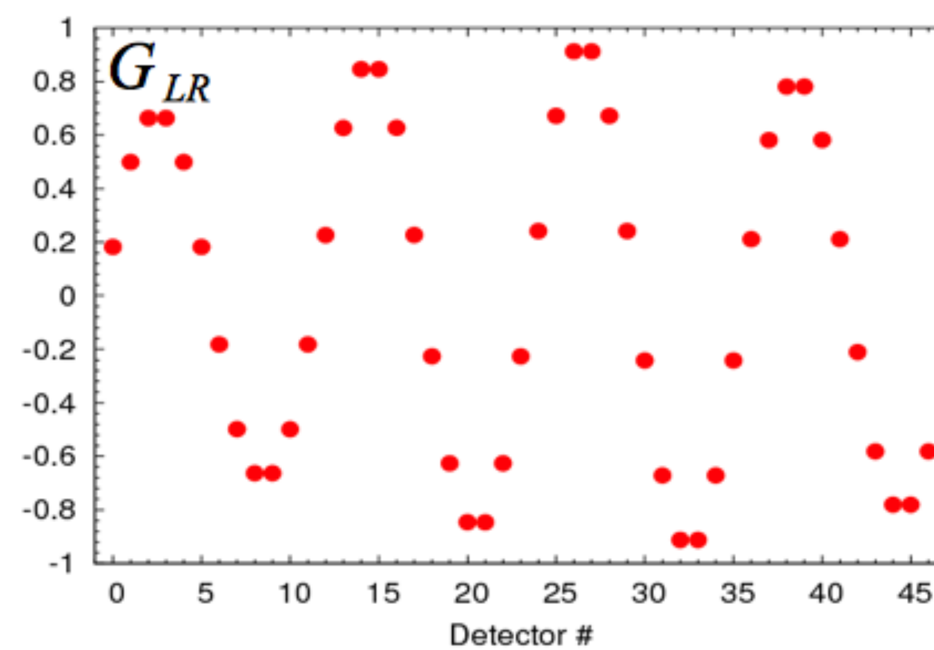
$$\langle \hat{k}_\gamma \cdot \hat{\sigma}_n = \cos\theta \rangle \qquad \langle \hat{k}_\gamma \cdot (\hat{\sigma}_n \times \hat{k}_n) = \sin\theta \rangle$$

G_{UD} and G_{LR} geometrical factors

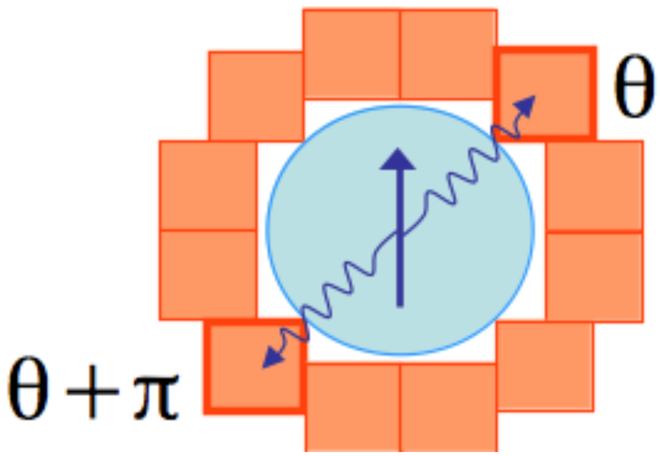
$$G_{UD}(i) = \langle \hat{k}_\gamma \cdot \hat{\sigma}_n \rangle = \langle \hat{k}_\gamma \cdot \hat{y} \rangle$$

$$G_{LR}(i) = \langle \hat{k}_\gamma \cdot (\hat{\sigma}_n \times \hat{k}_n) \rangle = \langle \hat{k}_\gamma \cdot \hat{x} \rangle$$





Extraction of A_γ



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

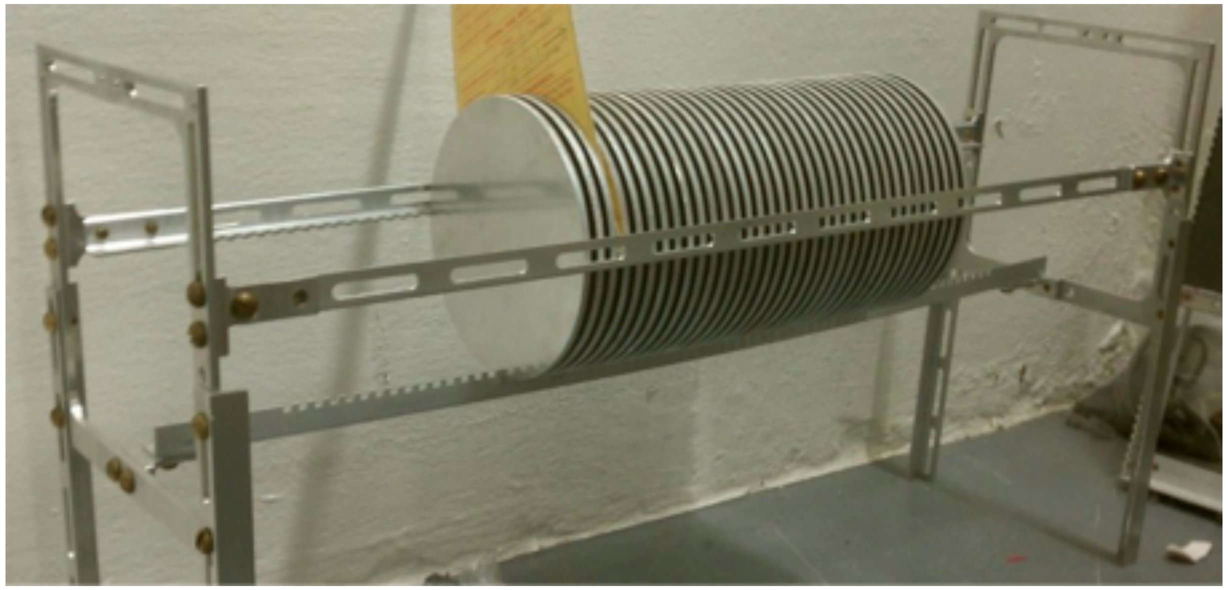
Corrections

- Beam polarization
- Beam depolarization in target
- RF SF efficiency
- Subtraction of background (Aluminium)

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

Aluminium asymmetry

- 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 $\vec{\sigma}_n$ are expected in the emission of prompt gammas
- ^{28}Al beta decays to $^{28}Si^*$ with a lifetime of 194 s. Delayed gammas of 1.8 MeV are emitted in the transition of $^{28}Si^*$ to g.s., however these delayed gammas make negligible contribution to the PV Al asymmetry



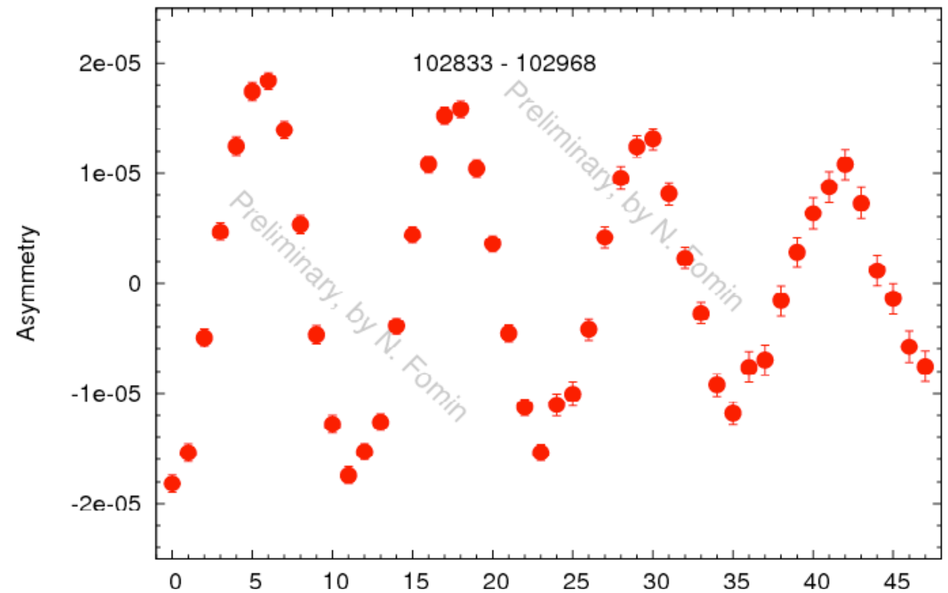
Results with a partial data set

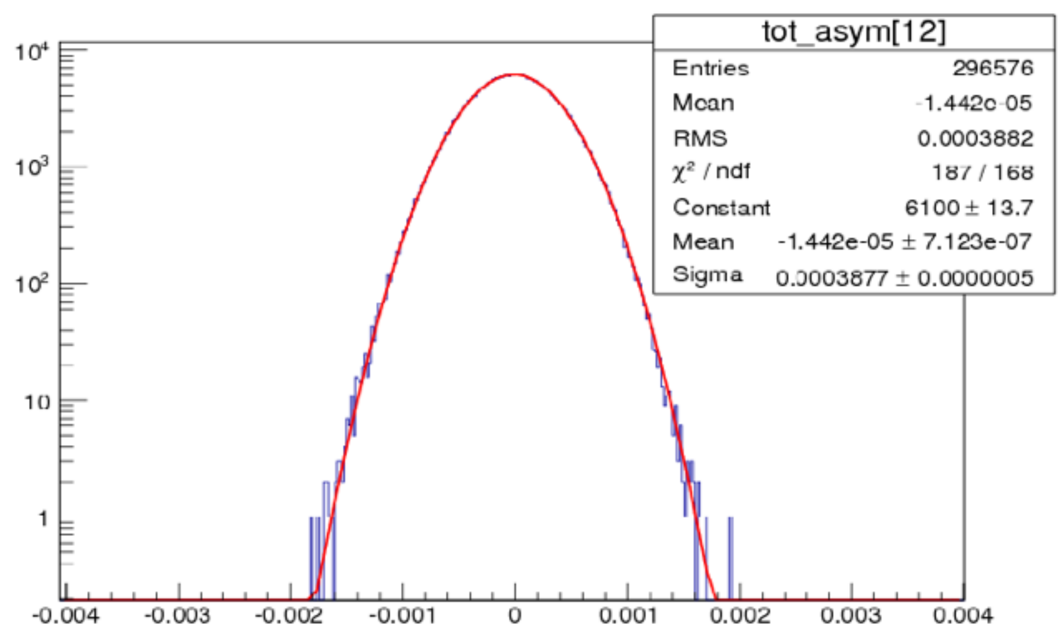
$$A_{\gamma,UD} = -18 \pm 7.1 \left[\times 10^{-8}\right]$$
$$A_{\gamma,\mathrm{LR}} = -6.8 \pm 7.1 \left[\times 10^{-8}\right]$$

Z. Tang et al., in preparation

Chlorine asymmetry

- Test of sensitivity with large and well known PV gamma asymmetry
- In $\vec{n} + {}^{35}\mathrm{Cl} \rightarrow {}^{36}\mathrm{Cl} + \gamma$, the PV effect is amplified by the mixing and interference of nearly degenerate states of opposite parity





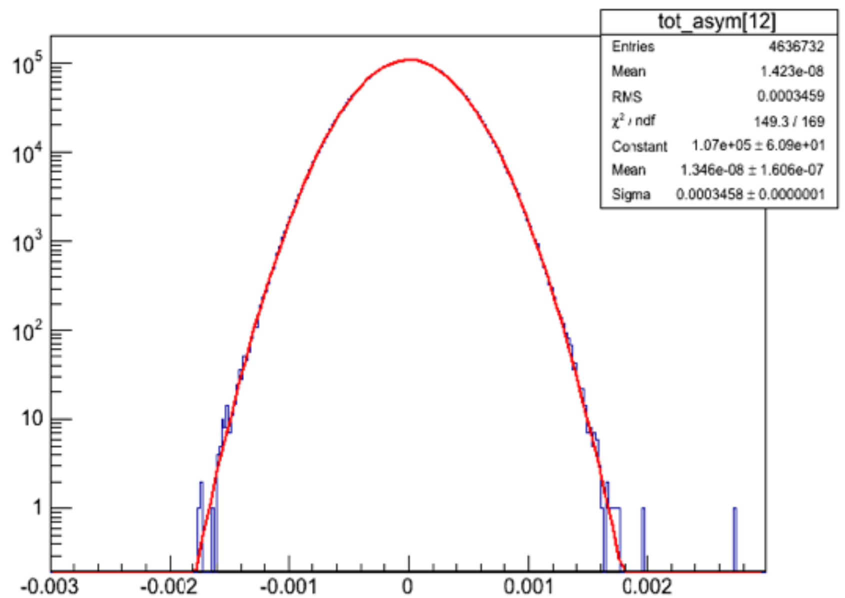
Measurement	Asymmetry ($\times 10^{-6}$)
LANL	-29.1 ± 6.7
Leningrad	-27.8 ± 4.9
ILL	-21.2 ± 1.72
SNS (data analysis not completed yet)	-25.9 ± 0.6

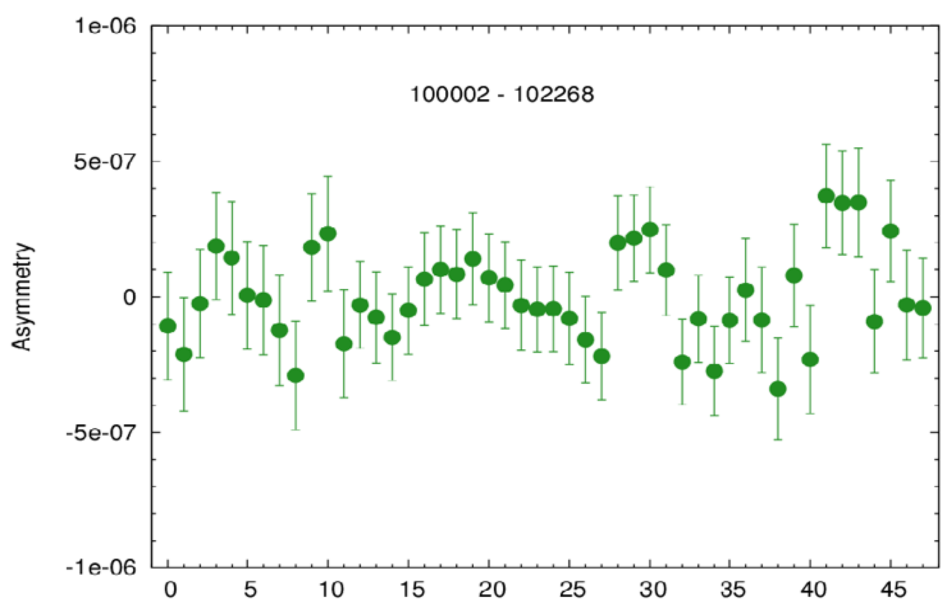
N. Fomin et al., in preparation

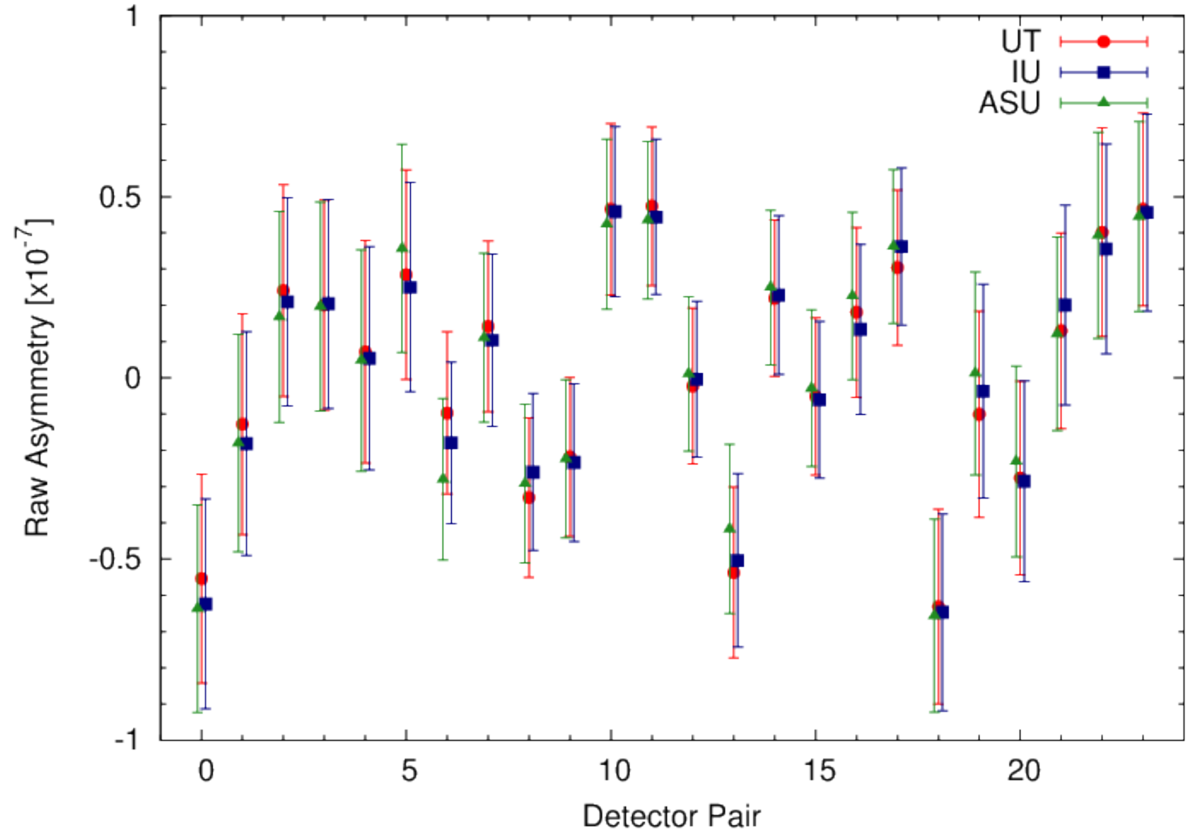
Hydrogen asymmetry

- Completed data acquisition in June 2014 (250 beam days)
- Data analysis in progress (final results to be announced soon)

200 hour data from Fall 2012







The analyzed data indicates that A_γ is small with a statistical uncertainty of ~1.3×10^{-8}

Systematic and statistical uncertainties

Systematic effects which may cause false asymmetry	
Additive asymmetry (instrumental)	$< 1\times10^{-9}$
Multiplicative asymmetry (instrumental)	$< 1\times10^{-9}$
Stern-Gerlach (steering of the beam)	$< 1\times10^{-10}$
γ-ray circular polarization	$< 1\times10^{-12}$
β-decay in flight	$< 1\times10^{-11}$
Capture on ^{6}Li	$< 1\times10^{-11}$
Radiative β-decay	$< 1\times10^{-12}$
β-delayed Al gammas (internal+external)	$< 1\times10^{-9}$
Uncertainties in applied corrections	
Neutron beam polarization	< 2%
RF SF efficiency	~ 0.5%
Depolarization of the neutron beam	< 0.5% (target-dependent)
Geometric factors	1%
Polarization of overlap neutrons	0.1%
Target position	0.03%
Statistical uncertainty in current result	
Combined hydrogen and aluminum data	$\sim 1.3\times10^{-8}$

Summary

- The study of the ΔS=0 HWI is relevant not only to have a better understanding of the interaction itself, but also to shed light on aspects like neutral currents at low energies, dynamics of QCD in nonperturbative regime, test of nuclear structure models, etc.
- To complement the theory, measurement of several independent PV observables is needed to determine the weak couplings or effective parameters
- Studies with few-nucleon systems (for which *ab initio* calculations are feasible) have the advantage of dealing with less nuclear structure uncertainties
- The availability of intense low-energy neutron fluxes makes it possible to measure PV effects that are ~10^{-7}. There is a program to measure PV observables in the interaction of neutrons and light nuclei
- The NN weak interaction is dominated by the exchange of pions, and therefore the weak coupling constant h_π^1 is very important
- The ΔI=1 channel (π exchange) gets isolated in the $\vec{n}+p \rightarrow d+\gamma$ reaction. There are experimental values (statistically limited) and recent lattice QCD calculation. Need for more precise measurements
- NPDGamma finalized data acquisition at the SNS a year ago and several independent analysis are consistent and near conclusion. The achieved statistical uncertainty is ~1.3×10^{-8}

The NPDGamma collaboration

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Work supported by DOE and NSF (USA)
NSERC (Canada)
CONACYT (Mexico)
BARC (India)