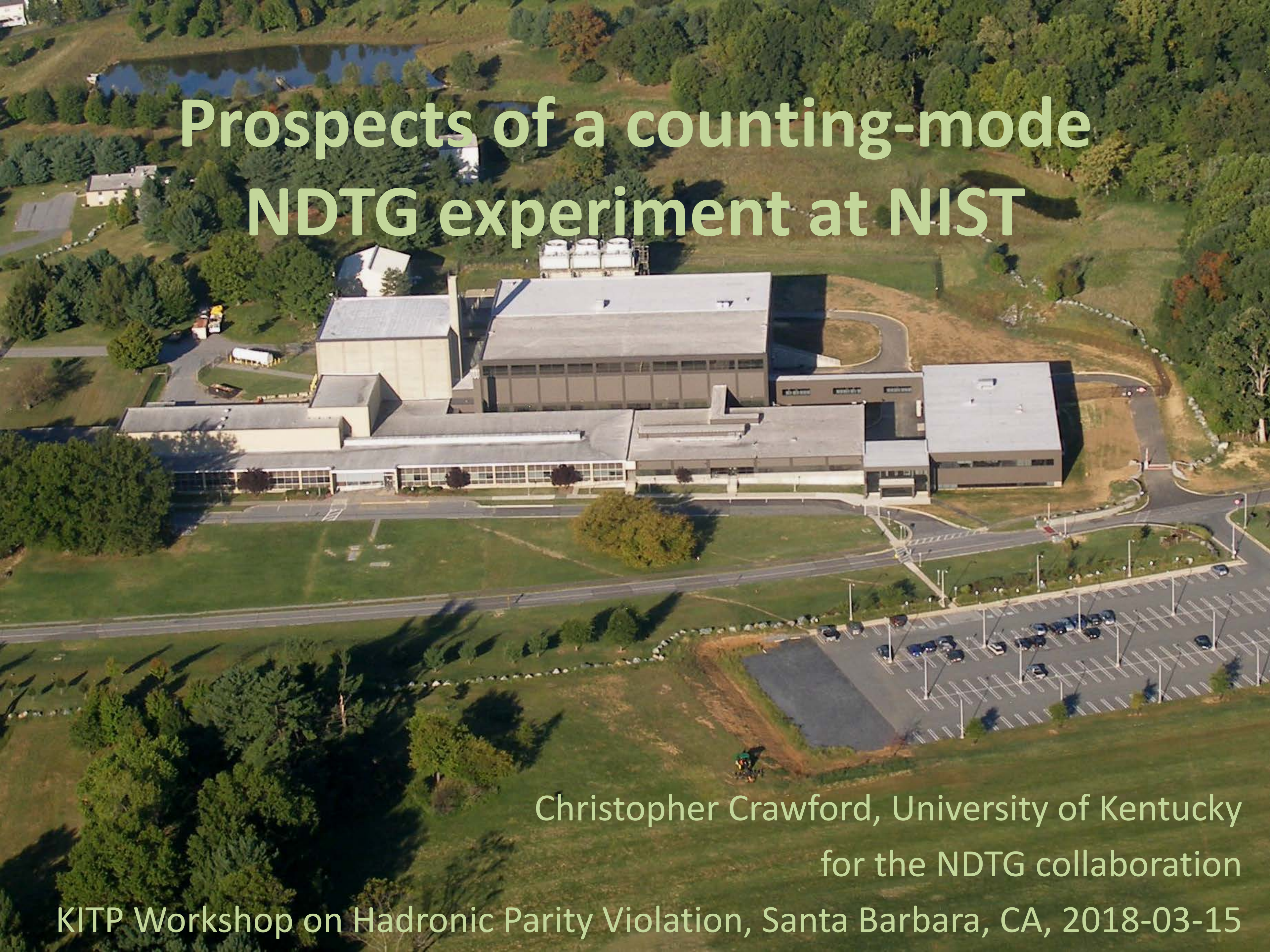


Prospects of a counting-mode NDTG experiment at NIST

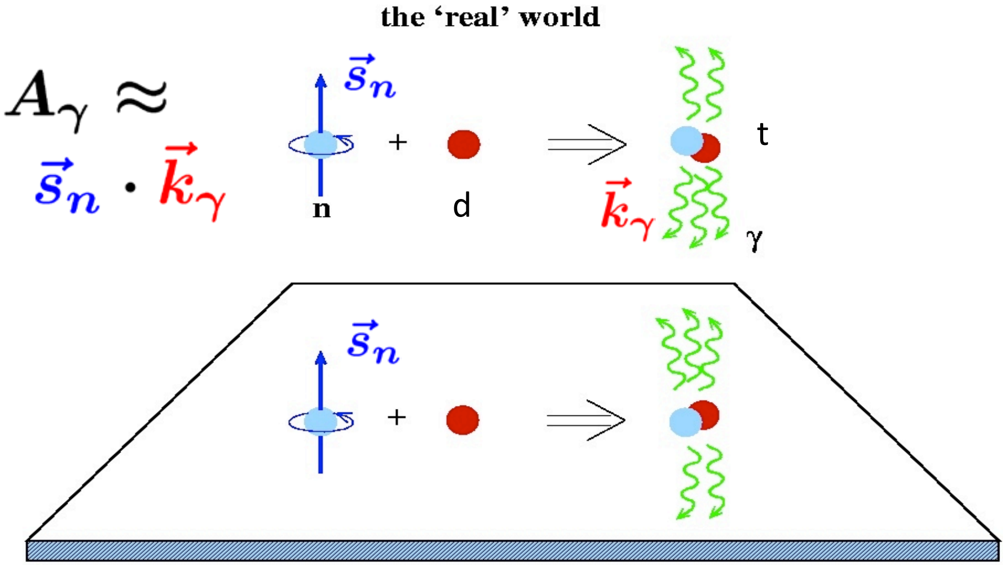
Christopher Crawford, University of Kentucky

for the NDTG collaboration

KITP Workshop on Hadronic Parity Violation, Santa Barbara, CA, 2018-03-15

Outline

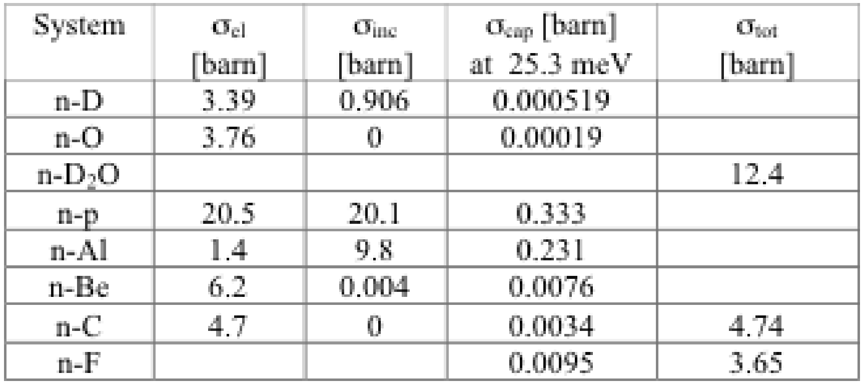
- General considerations
  - Cross section / asymmetry
- Experimental setup
  - NG-C + ^{3}He polarizer
- D_2O target + shielding
  - LANL depolarization measurement
- CsI array + counting mode
  - Efficiency simulations
- Experimental sensitivity
  - Statistical errors
  - Systematic errors



$$A_\gamma \approx \vec{s}_n \cdot \vec{k}_\gamma$$

General considerations

- D capture cross section 642 × smaller than H !
  - 25× reduction in statistical sensitivity vs NPDGamma
  - background can easily dominate such a weak signal
  - J=1 deuteron allows spin-flip scattering → neutron depolarization



System	σ_{el} [barn]	σ_{inc} [barn]	σ_{cap} [barn] at 25.3 meV	σ_{tot} [barn]
n-D	3.39	0.906	0.000519	
n-O	3.76	0	0.00019	
n-D_2O				12.4
n-p	20.5	20.1	0.333	
n-Al	1.4	9.8	0.231	
n-Be	6.2	0.004	0.0076	
n-C	4.7	0	0.0034	4.74
n-F			0.0095	3.65

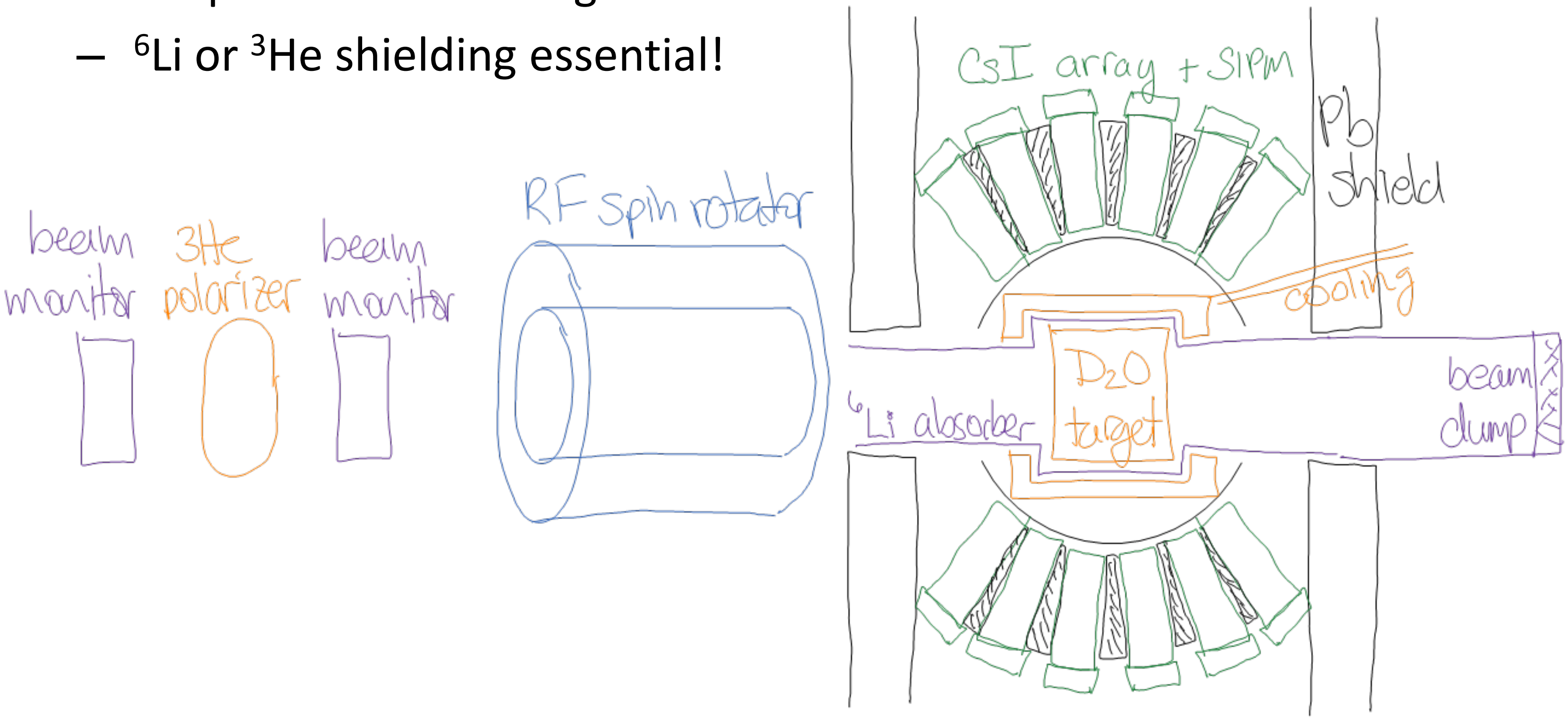
- Asymmetry $A_\gamma \approx 1.7 \times 10^{-6}$ expected to be 30 × larger !
  - measurement at ILL: $A_\gamma = (4.2 \pm 3.8) \times 10^{-6}$ PLB 137, 125 (1984)
  - all other neutron capture asymmetries so far have been small
  - possibility of measuring a large asymmetry in a neutron system
  - need to measure MORE observables that couplings to test formalism

NDTG Collaboration

- J.D. Bowman, S.I. Penttilä (Co-spokesperson), and P. Muller,
  - Oak Ridge National Laboratory
- S. Santra, Bhabha Atomic Research Center
- A. Komives (Co-spokesperson), DePauw University
- R.C. Gillis, J. Mei, H. Nann, W.M. Snow and Z. Tang, Indiana University
- E. Sharapov, Joint Institute of Nuclear Resesearch (Dubna)
- B. Lauss, Paul Scherrer Institut
- P.-N. Seo, Triangle Universities Nuclear Laboratory
- L. Barrón-Palos (Co-spokesperson), E. Chávez, M.E. Ortiz, A. Huerta, Q.M. Curiel-García, D.J. Marín-Lámbarri, P. Rodríguez Zamora, Universidad Nacional Autónoma de México
- C. Crawford (Co-spokesperson), University of Kentucky
- M. Dabaghyan, University of New Hampshire

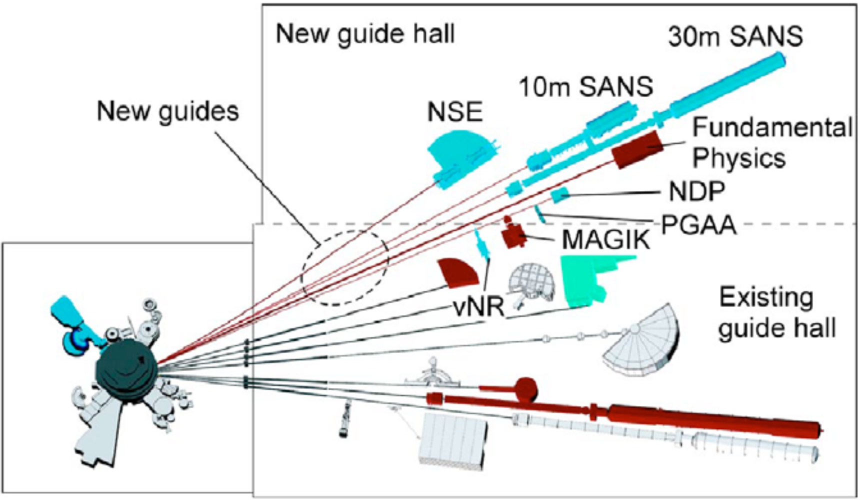
NDTG experimental setup

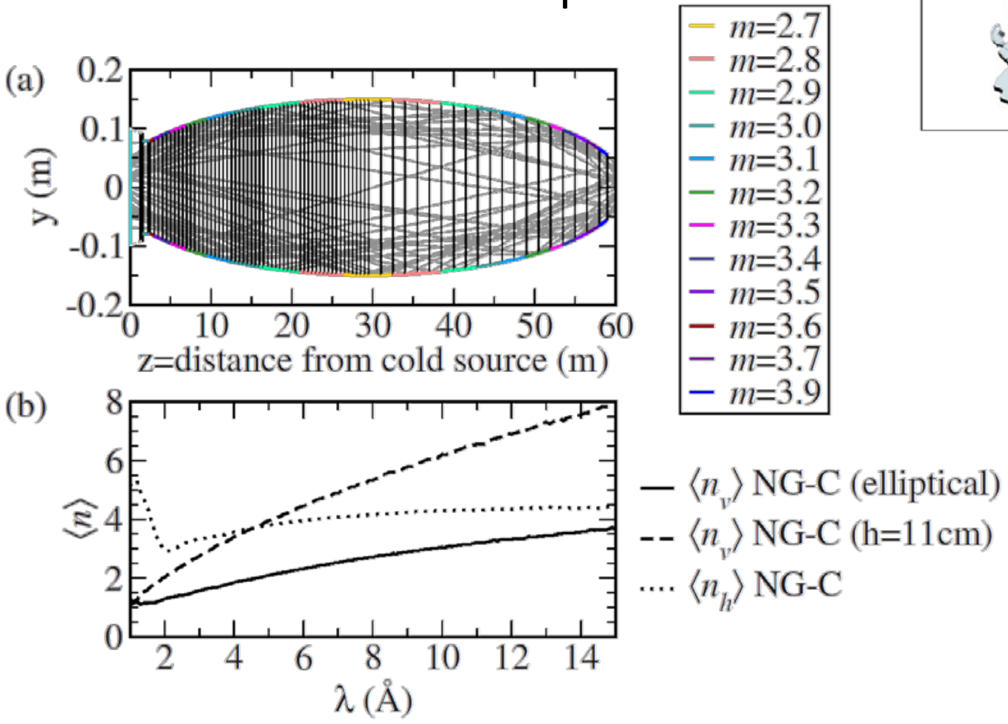
- schematic of component layout
  - background-less ^{3}He polarizer
  - highly segmented CsI array to spread out counting rate
  - ^{6}Li or ^{3}He shielding essential!

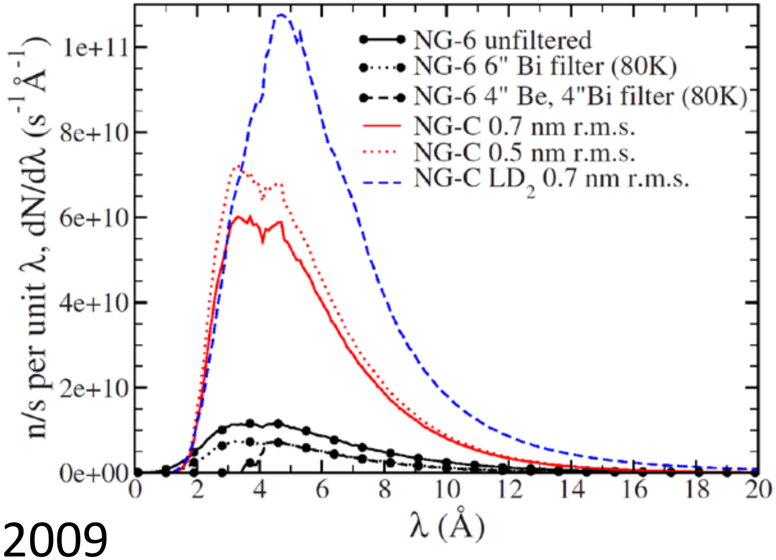


NIST NG-C beamline

- new guide hall, NCNR reactor
  - 60 m long ballistic guide (vertical)
  - curved for gamma reduction
  - capture flux: $\Phi = 9.1 \times 10^{11}$ n/s
  - 11×11 cm^2 output







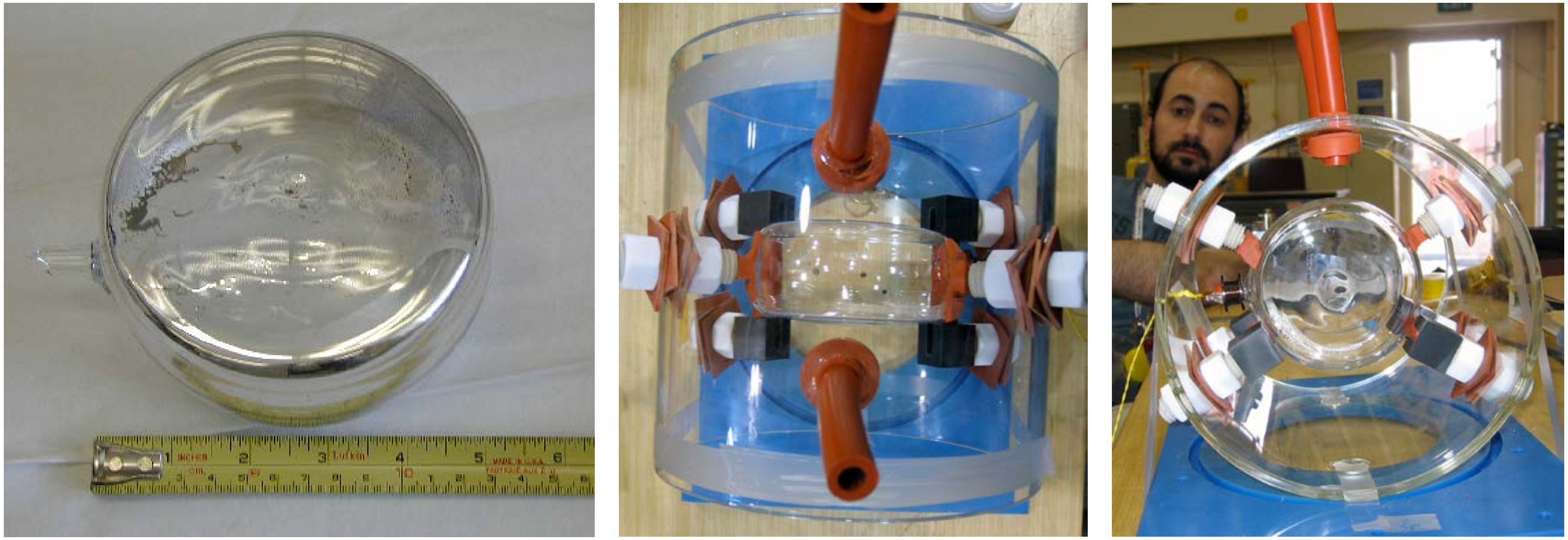
  - J. Cook, Rev. Sci. Instrum. **80**, 023101, 2009

^{3}He neutron polarizer

- $n + {}^3\mathrm{He} \rightarrow {}^3\mathrm{H} + p$ cross section highly spin-dependent

  $\sigma_{J=0} = 5333\ \mathrm{b}\ \lambda/\lambda_0, \qquad \sigma_{J=1} \approx 0$

  - no capture gammas from ^{3}He capture—important for NDTG!
  - highest polarization at long wavelength—largest capture cross section on D
- new large-area, high polarization cells in development at NIST
  - $P_3 \approx 85\% \quad \rightarrow \quad P_n = 90\%, \ \ T_n = 25\%$

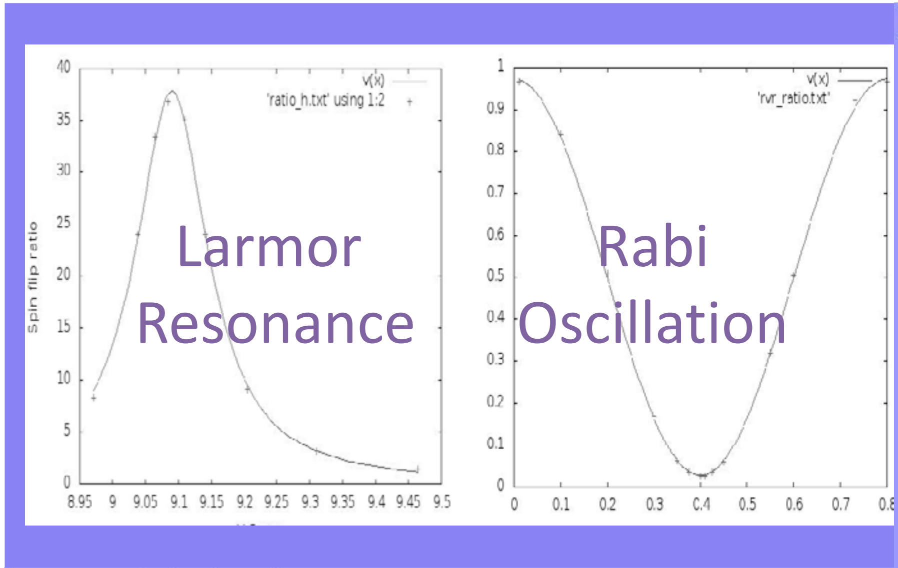


Transverse RF spin rotator

- Double-cosine-theta coil
  - Fringeless transverse RF field
  - Longitudinal OR transverse
  - Designed using scalar potential

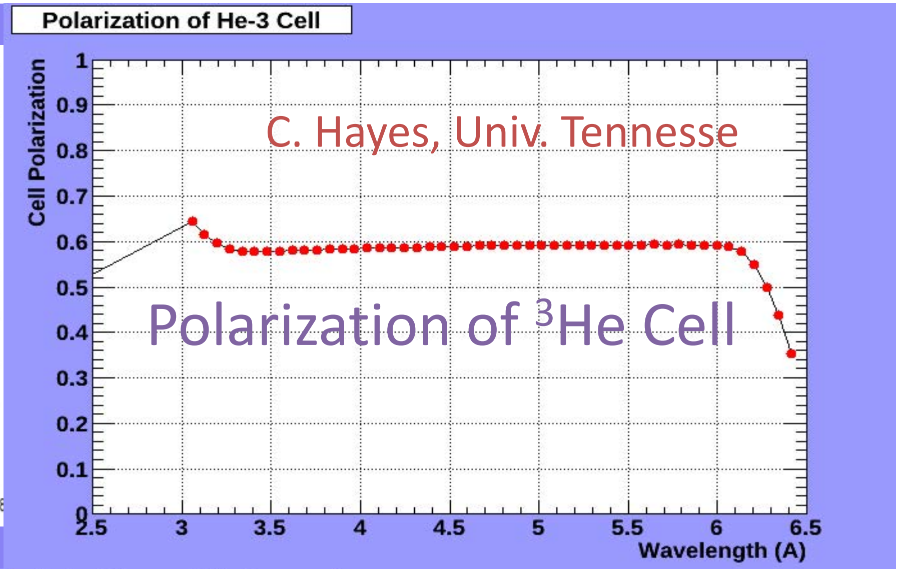
Univ. Kentucky / Univ. Tennessee

^{3}He transmission polarimetry



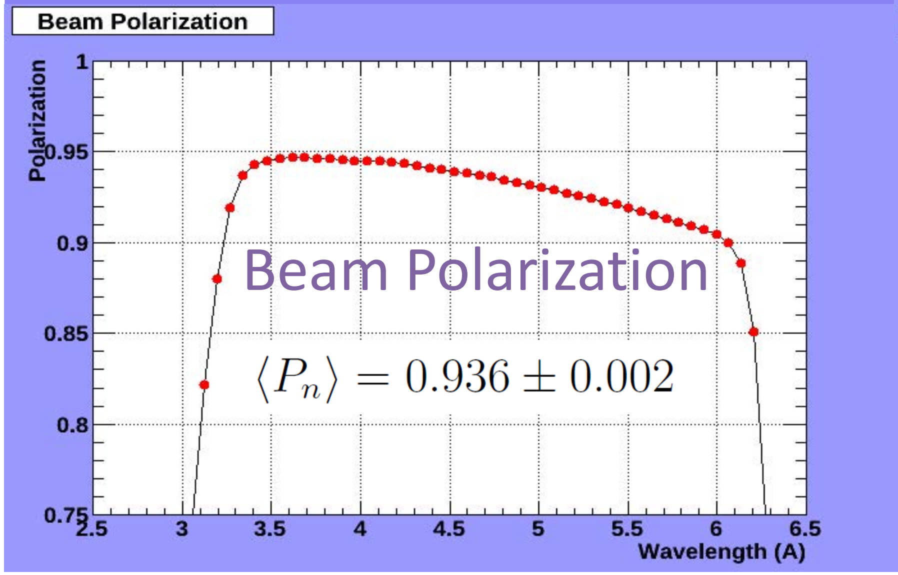
Larmor Resonance

Rabi Oscillation



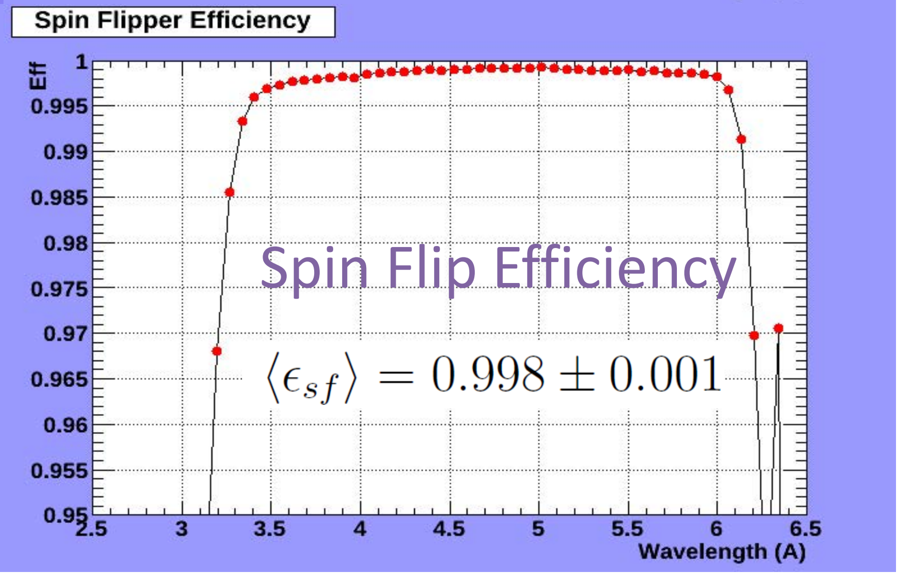
C. Hayes, Univ. Tennesse

Polarization of ^{3}He Cell



Beam Polarization

$$\langle P_n \rangle = 0.936 \pm 0.002$$

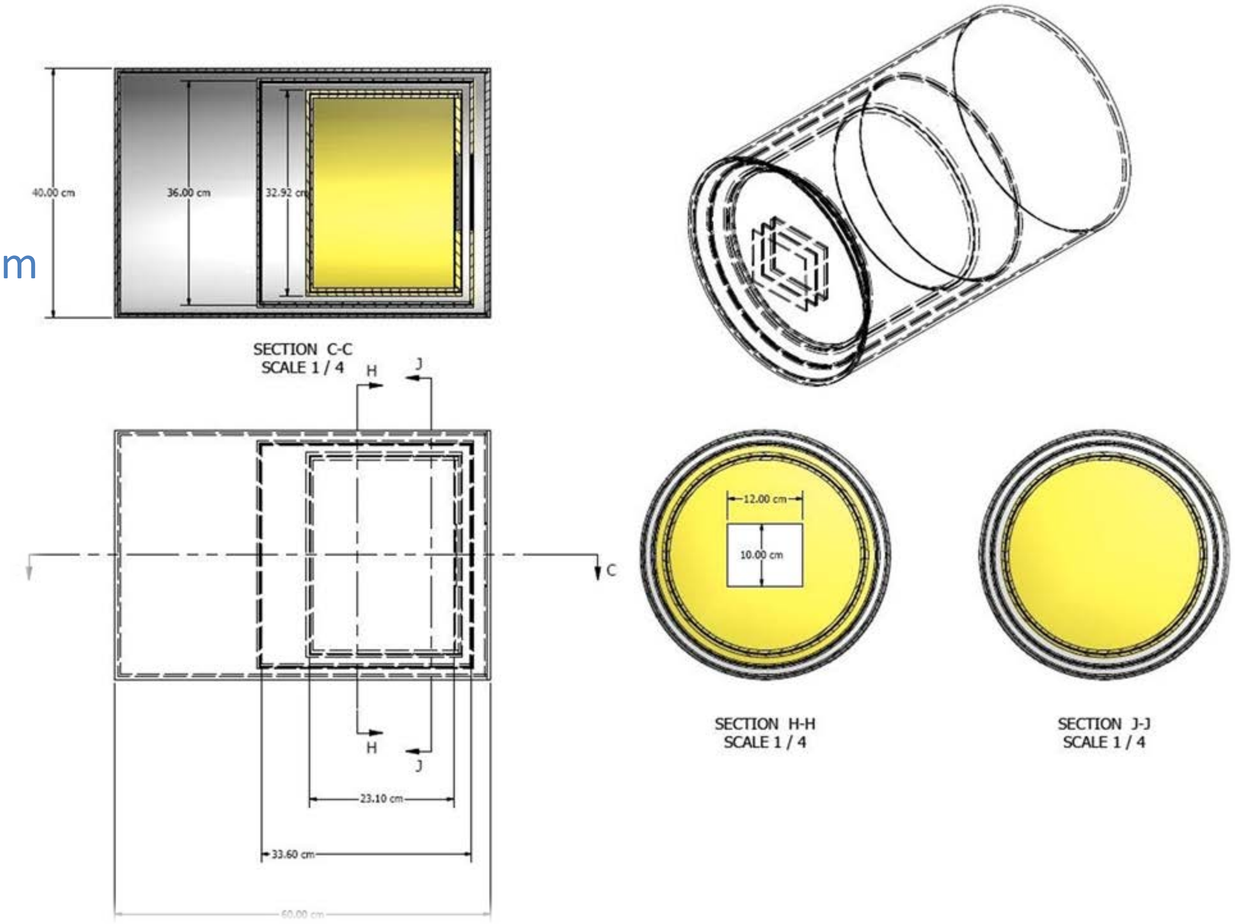


Spin Flip Efficiency

$$\langle \epsilon_{sf} \rangle = 0.998 \pm 0.001$$

D_2O target design

- cross sections
  - length: 13 cm
  - average 12.5 scatters before capture
  - mean free path 2.44 cm
  - capture probability $\kappa = 0.00117$ (MC)
  - 14% background from capture on O
  - 75% of beam scatters from target
- Polarization
  - 10% depolarization per elastic scatter
  - Depolarization upon capture on D: $d = 57\%$ (E. Sharapov, MCNP calculation)



D_2O depolarization measurement

- measurement of P_γ, Summer 2009 at FP12, LANSCE, LANL
  - Compton polarimeter
  - resolved spectrum with capture on both
    6.26 MeV n+D,
    5.42 MeV n+^{32}S

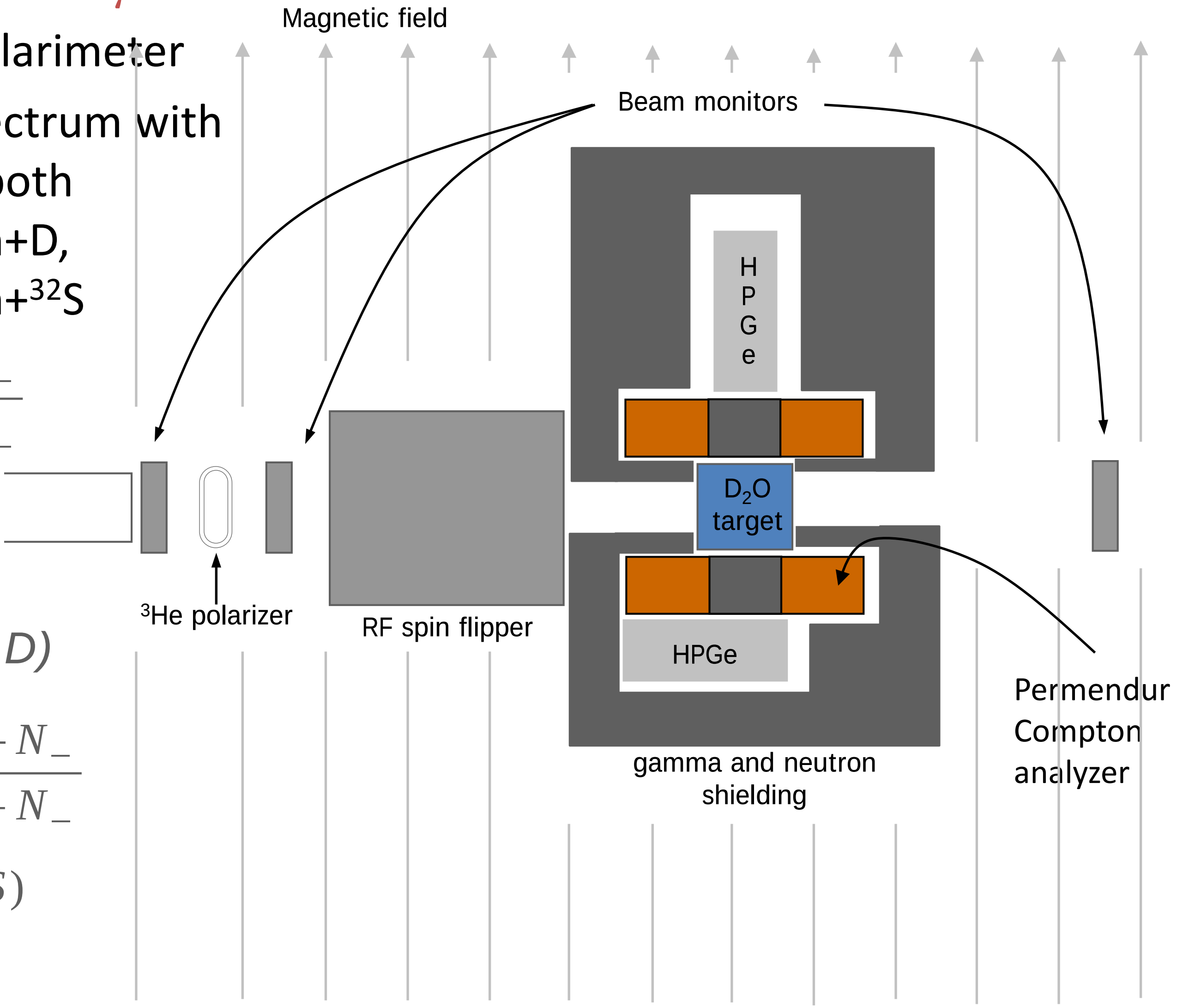
$$P_\gamma = \frac{1}{\eta}\frac{N_+ - N_-}{N_+ + N_-}$$

$$P_n = \frac{P_\gamma}{R^d}$$

$$R^d = -0.42 \ (n\text{-}D)$$

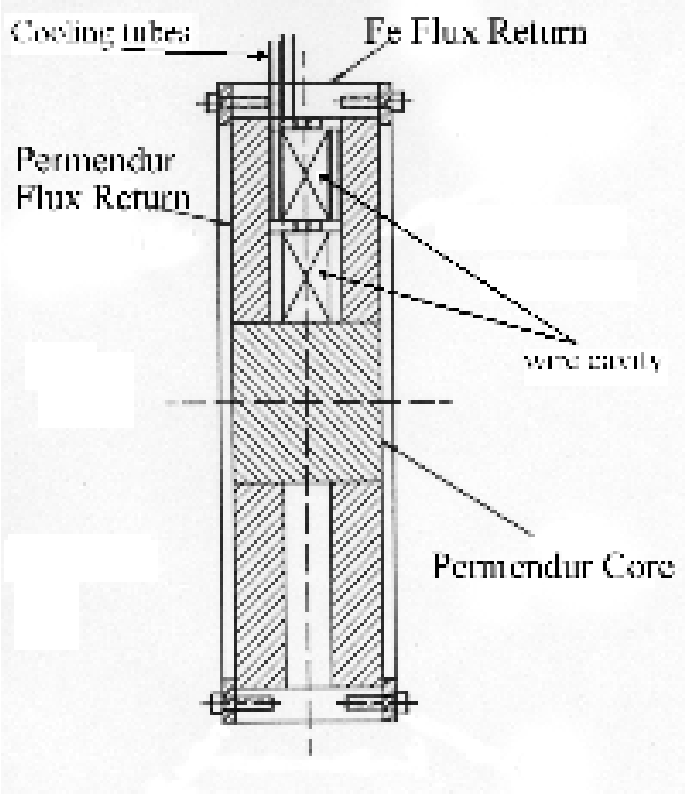
$$\eta = \frac{1}{P_n R^S}\frac{N_+ - N_-}{N_+ + N_-}$$

$$R^S = 0.5\,(n\text{-}{}^{32}S)$$

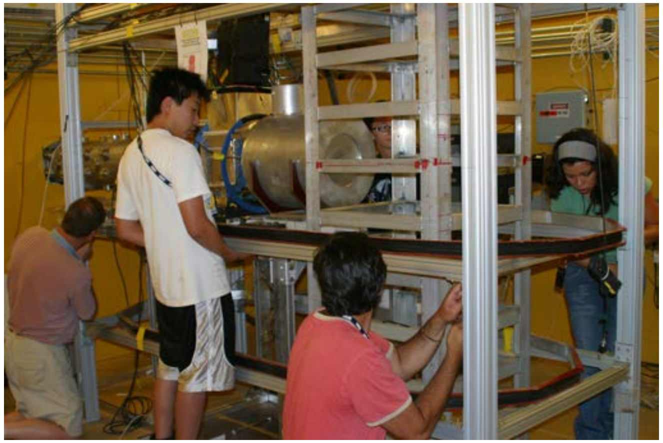


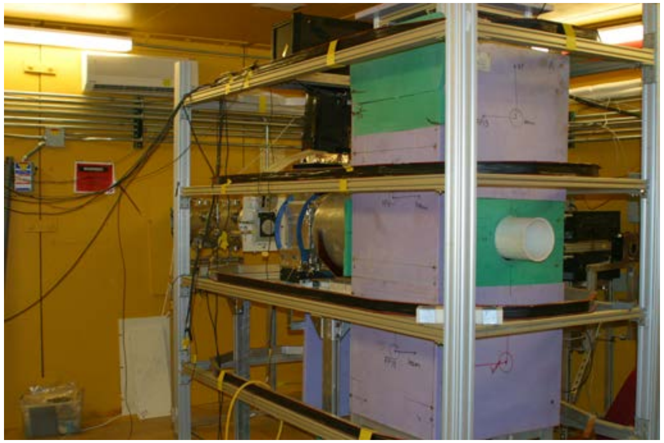
Compton polarimeter

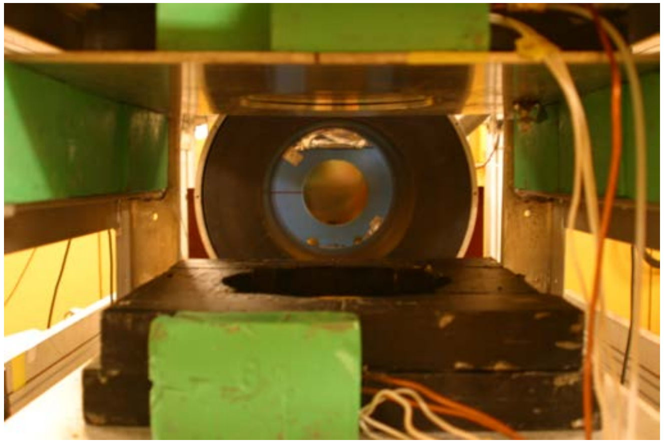
- Magnetized analyzer for γ's (A. Komives, DePauw University)
  - solenoid with a Permendur (copper-nickel-vanadium alloy) core
  - 3000 A turns, 2.5 T core field, $n_0 = 2.2 \times 10^{24}\ \mathrm{cm}^3$, $f = 0.077$ e/atom
  - Compton scattering cross section $\sigma_c = 0.045 \times 10^{-24}\ \mathrm{cm}^2$

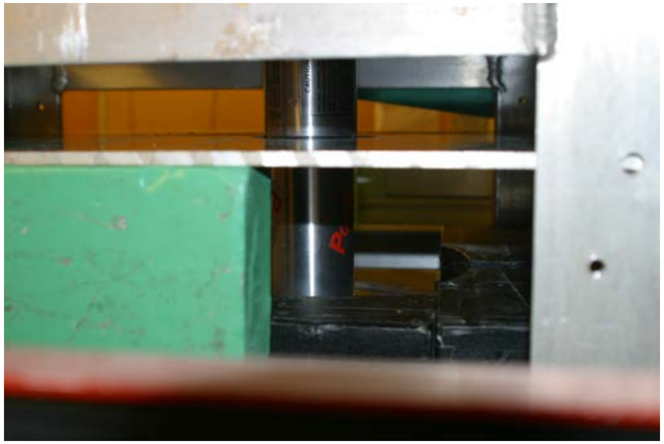


Setup at LANL





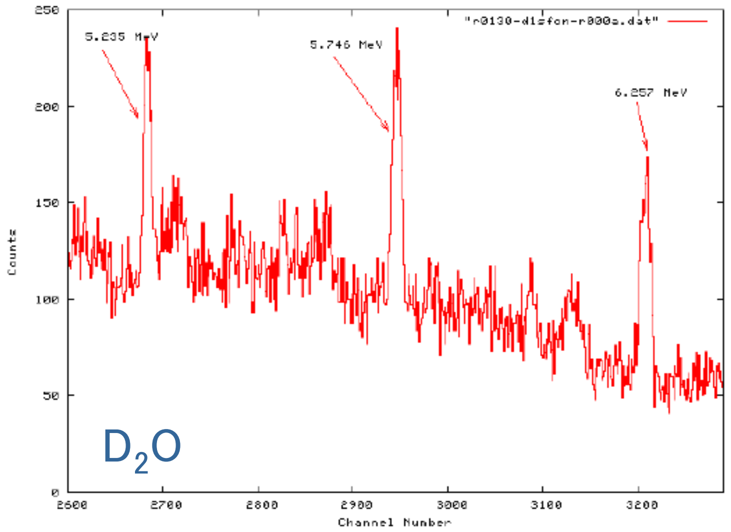


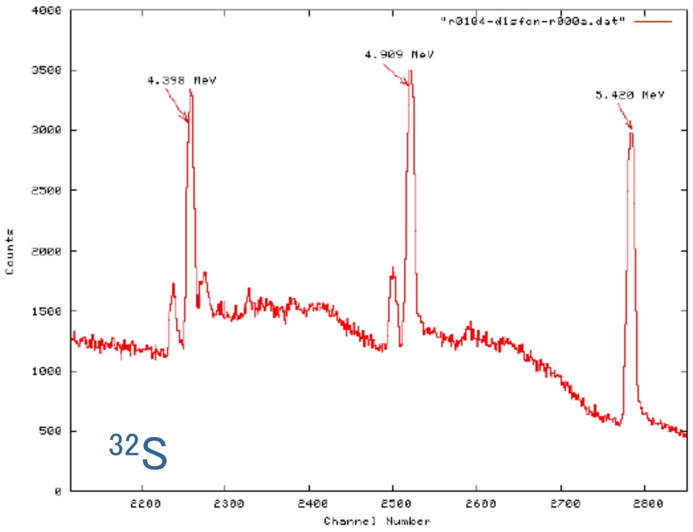


D_2O depolarization measurement

- photo-peak asymmetry (Z. Tang, Indiana Univ.):

$$A_D = (1.80 \pm 0.77) \times 10^{-3} \qquad A_S = (2.66 \pm 0.63) \times 10^{-3}$$





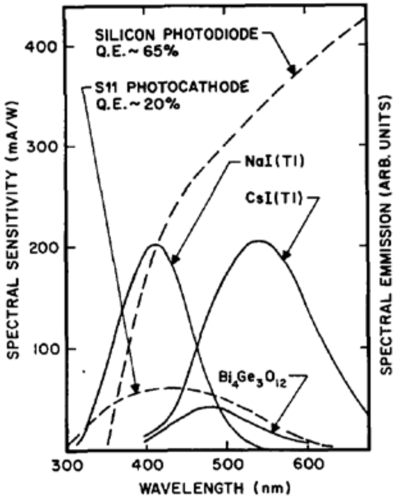
- determination of polarization $P_n = \frac{1}{\eta R} \frac{N_+ - N_-}{N_+ + N_-}$

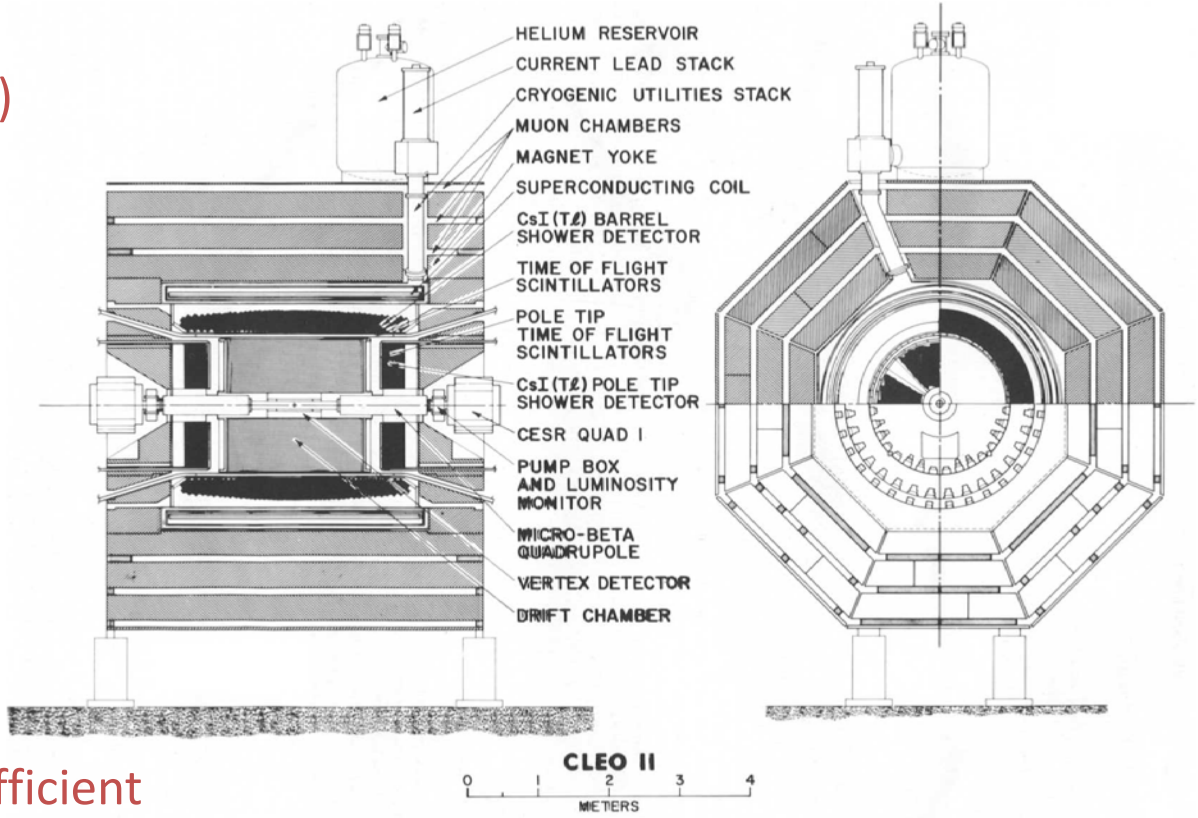
where $R_D = -0.42 \pm 0.03$ (Phys. Lett. B 205, 215, 1988); $R_S = 0.50$

η is the Compton polarimeter efficiency

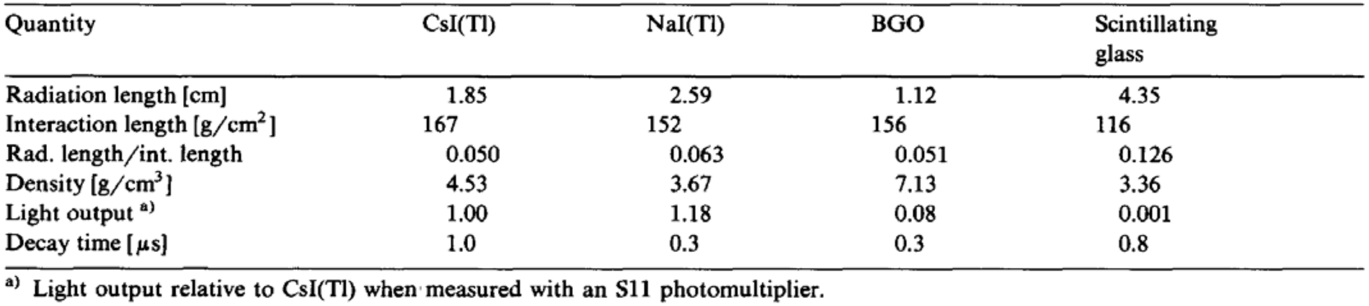
CsI(Tl) crystals — CLEO II detector

- Blucher et al,
  NIM A249, 201(1986)
- 5 x 5 x 30 cm^2 crystal





- relatively slow, but efficient

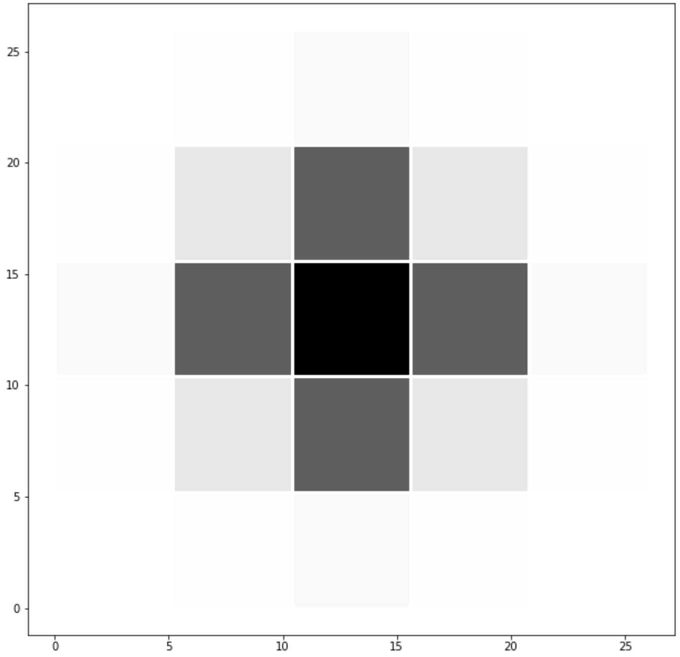


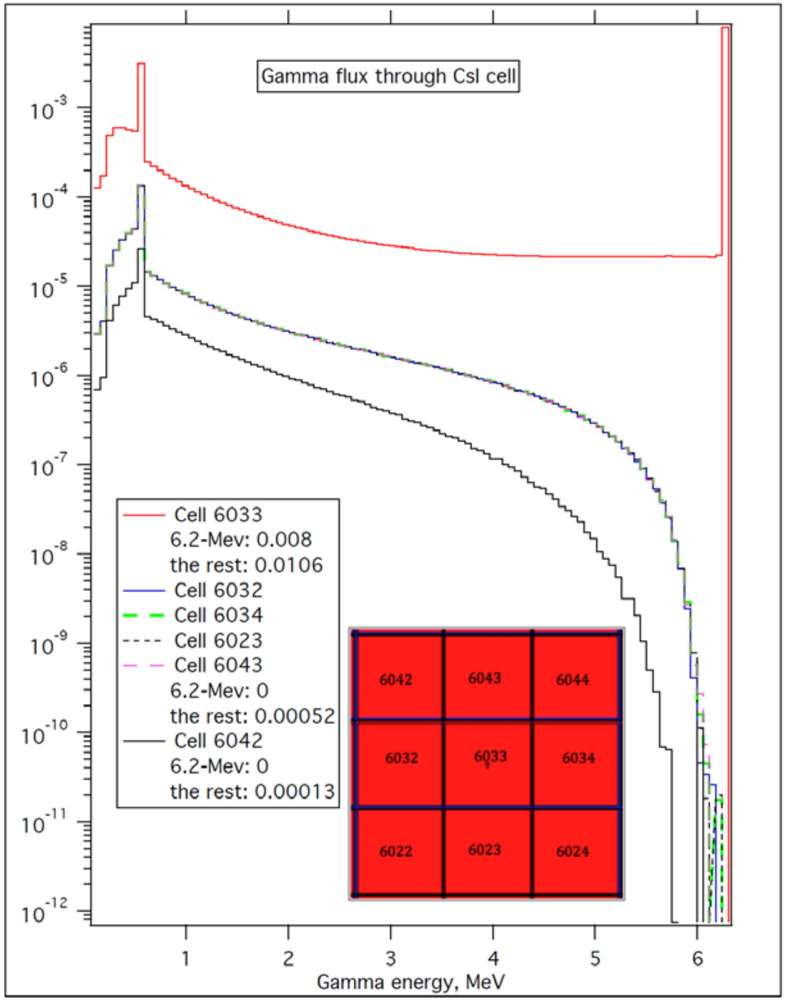
Quantity	CsI(Tl)	NaI(Tl)	BGO	Scintillating glass
Radiation length [cm]	1.85	2.59	1.12	4.35
Interaction length [g/cm^2]	167	152	156	116
Rad. length/int. length	0.050	0.063	0.051	0.126
Density [g/cm^3]	4.53	3.67	7.13	3.36
Light output [a]	1.00	1.18	0.08	0.001
Decay time [μs]	1.0	0.3	0.3	0.8

[a] Light output relative to CsI(Tl) when measured with an S11 photomultiplier.

Gamma Detection in CsI array

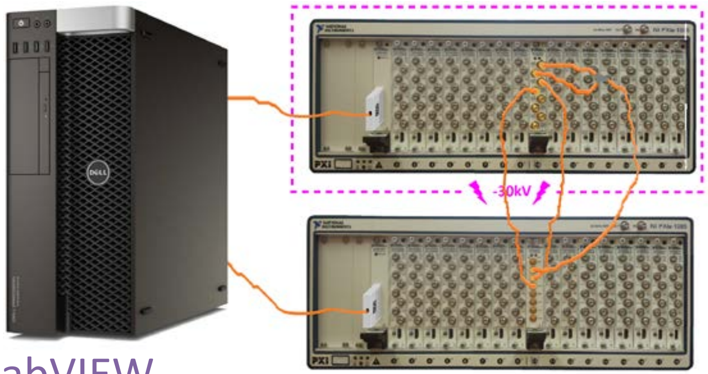
- MCNP simulation (I. Novikov, Western Kentucky University)
  - 5x5 array of $5 \times 5 \times 30\ \text{cm}^3$ crystals
  - unidirectional 6.2 MeV point-source
  - ϵ=80.5% photopeak in center crystal
  - 6.1% leakage through 1 mm of Pb
  - 285 keV max energy in neighbor





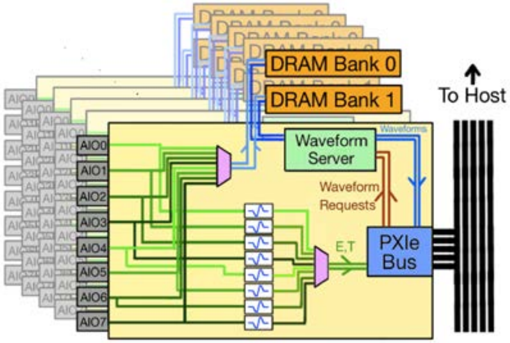
DAQ system

- candidate system: Nab DAQ (Aaron Sprow, Univ. Kentucky)
  - user-programmable energy filter and trigger logic onboard FPGA
  - for example: to implement energy recovery in pile-up events



LabVIEW controller

Optical fiber bus, clock & sync



LabVIEW FPGA low-threshold trapezoid trigger on ADC

- low-cost solution: RedPitaya digitizer SOC platform $150/ch
  - 2 RF input + 2 RF output 75 MHz bandwidth 14 bit, 125 MS/s
  - Xilinx Zynq: 2 ARM cores + FPGA; Linux + open source firmware
  - trapezoid filter developed (Yuke Wang, University of Kentucky)

Extraction of Asymmetry

- Geometry factors:
  - Averaging capture $\sigma_\pm = \sigma_0(1 \pm PA\cos\theta)$ over each crystal,
  - yields $Y_{i,\pm} = Y_{i,0}(1 \pm PAG_i)$ form crystal asym $A_i \equiv \frac{Y_{i,+} - Y_{i,-}}{Y_{i,+} + Y_{i,-}} = PAG_i$
  - where geom factor $G_i \equiv \langle\cos\theta\rangle$ is averaged over γ's in each crystal.
  - Each physics $A'_i \equiv A_i / PG_i$ is weighted by $w_i = \delta^{-2} A'_i = P^2 N_i G_i^2$
  - to extract physics asymmetry $A' = \sum w_i A_i / \sum w_i$,
  - which has statistical error

    $\boldsymbol{\delta A'} = 1/\sqrt{\sum w_i} = \mathbf{1}/\boldsymbol{P}\sqrt{\boldsymbol{N}}\boldsymbol{G}$,
  - The global geometry factor is:

    $G^2 \equiv \sum \Omega_i G_i^2 / 4\pi$
  - for an ideal spherical detector:

    $G_0^2 \equiv \int d\Omega \cos\theta / 4\pi = 1/3$

# rings	# crystals	coverage	G / G$_0$
2	52	23.5%	58.9%
4	100	45.1%	79.5%
6	144	65.0%	91.4%
8	180	81.2%	97.3%
10	204	92.0%	99.2%
12	216	97.4%	99.4%

Statistical Sensitivity

- Neutron polarization at capture $P = P_0 \epsilon d = 0.511 \times 53\%$
  - ^{3}He polarizer: $P_0 \approx 90\%$
  - Spin flipper efficiency: $\epsilon = 99.8\% \times 53\%$ (white beam)
  - Depolarization: $d = 57\%$ (simple MC, data)
- Neutron capture gammas $N = \Phi T \eta \kappa = 2.7 \times 10^{15}\ \gamma\text{'s}$
  - Neutron fluence at NG-C: $\Phi = 9.1 \times 10^{11}\text{n/s}$
  - Run time: $T = 1 \times 10^{7}\text{s}$ (nominal)
  - Polarizer transmission: $\eta \approx 25\%$
  - Neutron capture probability: $\kappa = 0.00117$ (MC simulation)
- Geometry factor $G = f\sqrt{\epsilon}/\sqrt{3} = 0.473$
  - Fraction of $\langle \cos\theta \rangle$ coverage: $f = 91.4\%$ (analytic)
  - Gamma detection efficiency: $\epsilon = 80.4\%$ (MCNP)

$$\delta A' = 1/P\sqrt{N}G = \mathbf{1.5 \times 10^{-7}}$$

Counting rates

- peta-gamma counting — $10^{15}\ \gamma's$ / year!
  - count rate: $R = \Phi\eta\kappa\Omega/4\pi =$ 390 kHz per detector
  - CsI rise time: $\tau = 1\ \mu s \rightarrow$ 1 MHz limit (NaI 3 × faster; availability?)
- background reduction (below 1 γ / 1000 n)
  - need count rate dominated by σ_{cap}=0.52 mb on D to limit pile-up
  - unlike NPDG, almost no dilution of asymmetry due to background
  - capture on O in target: σ_{cap}=0.19 mb → 80 kHz (3.3 MeV)
  - ^{6}Li shielding: 0.0003 γ/n → 100 kHz (2.2 MeV)
  - Pb shielding between crystals requires optimization
- running conditions not optimized for above estimates
  - increased thickness of ^{3}He polarizer to improve polarization
  - reduction of target thickness to increase P_n on capture
  - possible 3x reduction of elastic scattering (cryogenic target)
  - possible ^{3}He neutron shielding? Neutron absorption in beam?

Systematic Errors

- Similar to NPDGamma, except counting mode
  - cut on $E_\gamma = 6.2$ MeV essentially removes background

Description	**Process**	**Invariant**	**Size**	
Stern-Gerlach asy.	$\mu \cdot \nabla B$	$\mu \cdot \nabla B$	$\leq 10^{-10}$	E
Mott-Schwinger asy.	$\vec{n} + p \rightarrow \vec{n} + p$	$s_n \cdot k_i \times k_f$	$\leq 10^{-8}$	C/M
PA left-right asy.	$\vec{n} + p \rightarrow d + \gamma$	$k_\gamma \cdot s_n \times k_i$	$\leq 10^{-8}$	C
circ. pol. asy.	$\vec{n} + p \rightarrow d + \vec{\gamma}$	$k_n \cdot P_\gamma$	$\leq 10^{-10}$	E
β-decay in flight asy.	$\vec{n} \rightarrow e^- + p + \bar{\nu}$	$s_n \cdot k_\beta$	$\leq 10^{-10}$	E
Radiative β-decay asy.	$\vec{n} \rightarrow e^- + p + \bar{\nu} + \gamma$	$s_n \cdot k_\gamma$	$\leq 10^{-11}$	E
Capture on ^6Li asy.	$\vec{n} + {}^6Li \rightarrow {}^7Li^* \rightarrow \alpha + T$	$s_n \cdot k_\alpha$	$\leq 10^{-9}$	E
Capture on $9Be$ asy.	$\vec{n} + {}^9Be \rightarrow {}^1 0Be^* \rightarrow \gamma + T$	$s_n \cdot k_\gamma$	$\leq 10^{-9}$	E
β-decay of $10Be$	${}^{10}\vec{Be} \rightarrow e^- + {}^9Be + \bar{\nu}$	$s_n \cdot k_\beta$	$\leq 10^{-10}$	E
Capture on $9C$ asy.	$\vec{n} + {}^9Be \rightarrow {}^1 0Be^* \rightarrow \gamma + T$	$s_n \cdot k_\gamma$	$\leq 10^{-9}$	E
β-decay of C	${}^{10}\vec{Be} \rightarrow e^- + {}^9Be + \bar{\nu}$	$s_n \cdot k_\beta$	$\leq 10^{-10}$	E
Capture on F asy.	$\vec{n} + {}^9Be \rightarrow {}^1 0Be^* \rightarrow \gamma + T$	$s_n \cdot k_\gamma$	$\leq 10^{-9}$	E
β-decay of F	${}^{10}\vec{Be} \rightarrow e^- + {}^9Be + \bar{\nu}$	$s_n \cdot k_\beta$	$\leq 10^{-10}$	E

Implementation

- subject to availability of highly subscribed NG-C
- R&D needed for ^{3}He polarizer
  - double-cell to prevent ^{3}He depolarization at high neutron intensity
- realistic design, hardware required for D_2O cryogenic target
- additional ^{6}Li shielding required
- 100 CsI scintillators shipped from Cornell
- PMT’s on hand at IU, SIPMs preferable
- required DAQ hardware

Conclusion

Preliminary investigations indicate possibility of

$$n + d \to t + \gamma$$

experiment at NIST NG-C with a sensitivity of

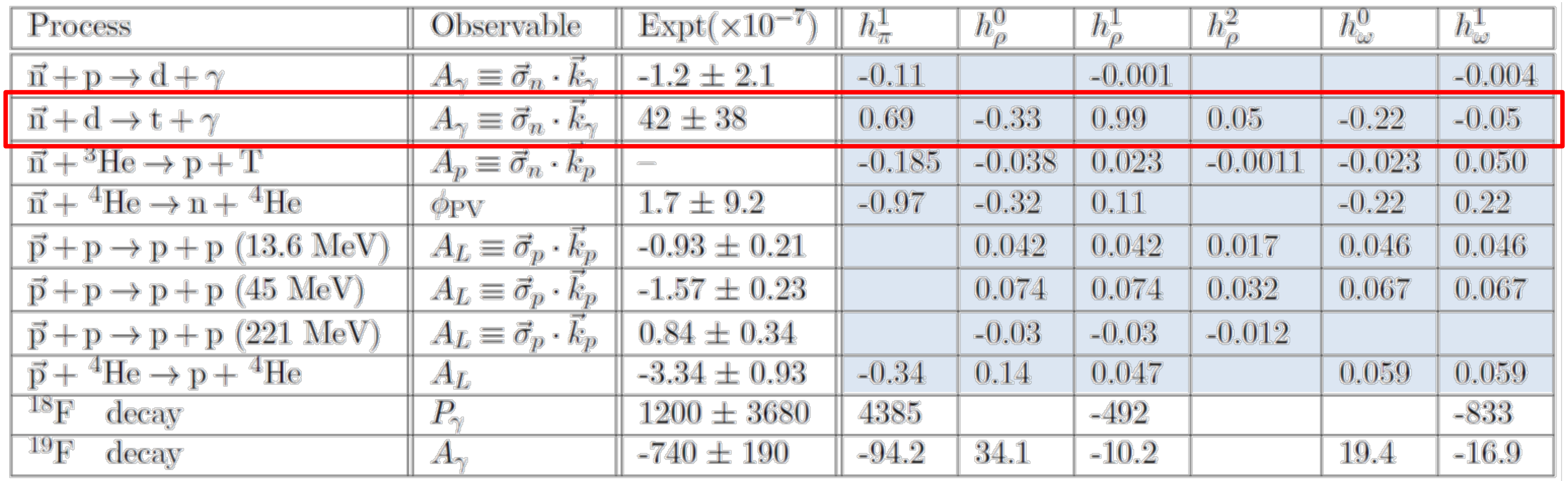
$$\delta A \approx 10^{-7}$$

(~10% measurement)!

Counting mode experiment: to prevent dilution from background asymmetry.

Challenge: reduction of background for maximum counting efficiency.

Sensitivities of few-body reactions



Process	Observable	Expt$(\times 10^{-7})$	h_π^1	h_ρ^0	h_ρ^1	h_ρ^2	h_ω^0	h_ω^1
$\vec{\mathrm{n}} + \mathrm{p} \to \mathrm{d} + \gamma$	$A_\gamma \equiv \vec{\sigma}_n \cdot \vec{k}_\gamma$	-1.2 ± 2.1	-0.11		-0.001			-0.004
$\vec{\mathrm{n}} + \mathrm{d} \to \mathrm{t} + \gamma$	$A_\gamma \equiv \vec{\sigma}_n \cdot \vec{k}_\gamma$	42 ± 38	0.69	-0.33	0.99	0.05	-0.22	-0.05
$\vec{\mathrm{n}} + {}^3\mathrm{He} \to \mathrm{p} + \mathrm{T}$	$A_p \equiv \vec{\sigma}_n \cdot \vec{k}_p$	–	-0.185	-0.038	0.023	-0.0011	-0.023	0.050
$\vec{\mathrm{n}} + {}^4\mathrm{He} \to \mathrm{n} + {}^4\mathrm{He}$	ϕ_{PV}	1.7 ± 9.2	-0.97	-0.32	0.11		-0.22	0.22
$\vec{\mathrm{p}} + \mathrm{p} \to \mathrm{p} + \mathrm{p}$ (13.6 MeV)	$A_L \equiv \vec{\sigma}_p \cdot \vec{k}_p$	-0.93 ± 0.21		0.042	0.042	0.017	0.046	0.046
$\vec{\mathrm{p}} + \mathrm{p} \to \mathrm{p} + \mathrm{p}$ (45 MeV)	$A_L \equiv \vec{\sigma}_p \cdot \vec{k}_p$	-1.57 ± 0.23		0.074	0.074	0.032	0.067	0.067
$\vec{\mathrm{p}} + \mathrm{p} \to \mathrm{p} + \mathrm{p}$ (221 MeV)	$A_L \equiv \vec{\sigma}_p \cdot \vec{k}_p$	0.84 ± 0.34		-0.03	-0.03	-0.012		
$\vec{\mathrm{p}} + {}^4\mathrm{He} \to \mathrm{p} + {}^4\mathrm{He}$	A_L	-3.34 ± 0.93	-0.34	0.14	0.047		0.059	0.059
${}^{18}\mathrm{F}$ decay	P_γ	1200 ± 3680	4385		-492			-833
${}^{19}\mathrm{F}$ decay	A_γ	-740 ± 190	-94.2	34.1	-10.2		19.4	-16.9

Adelberger, Haxton,
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