Neutron-decay correlation measurements with polarized and pulsed beams

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Outline

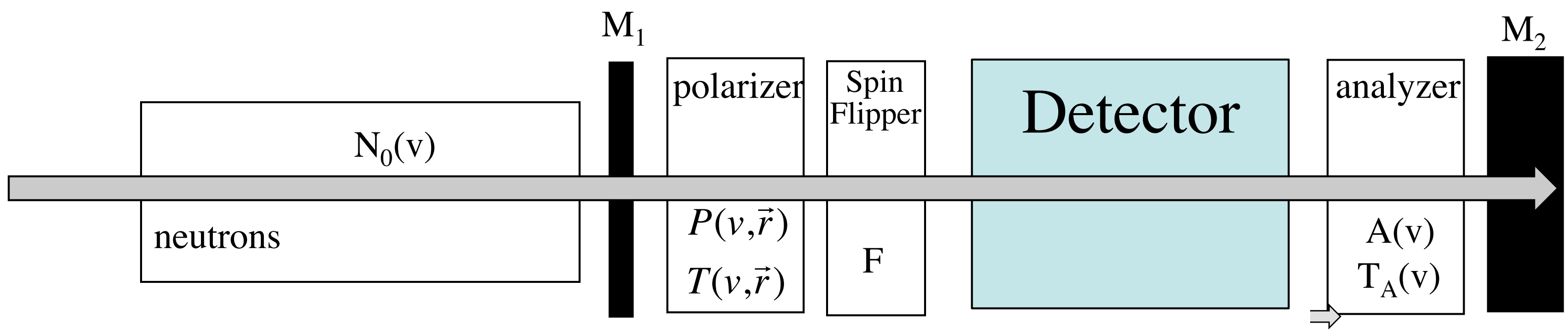
Polarization observables

Polarization

Polarimetry

Polarimetry of unpolarized neutrons

Polarized neutron decay



$$\frac{d^5\Gamma}{dE_e\,d\Omega_e\,d\Omega_\nu} = G(E_e)\left(1 + a\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} + A\frac{\langle\vec{\sigma}_n\rangle\cdot\vec{p}_e}{E_e} + B\frac{\langle\vec{\sigma}_n\rangle\cdot\vec{p}_\nu}{E_\nu} + D\frac{\langle\vec{\sigma}_n\rangle\cdot(\vec{p}_e\times\vec{p}_\nu)}{E_e E_\nu}\right)$$

$$Asymmetry = \frac{N_+ - N_-}{N_+ + N_-} = k\left(\int dE\right)\alpha P_n \mathrm{A} F(1 - f_b) + A_{false}$$

background
spin flip efficacy
analyzing power
neutron polarization–Averaged appropriately
PHYSICS (A,B,C,D)

A New Limit on Time-Reversal-Invariance Violation in Beta Decay: Results of the emiT-II Experiment

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NEW RESULT: D=[-0.94±1.89(STAT)±0.97(SYS)]x10^{-4}

$$\varphi_{AV} = 180.012 \pm 0.028 \qquad \frac{g_A}{g_V} = |\lambda| e^{i\varphi_{AV}}$$

Mumm et al.
PRL 107 102301 (2011)
PRC 86 35505(2012)

Work supported in part by NIST and grants from the DOE and NSF

$$\text{Models: } D_{\not{T}} = \sum_{sources} D_{source}$$

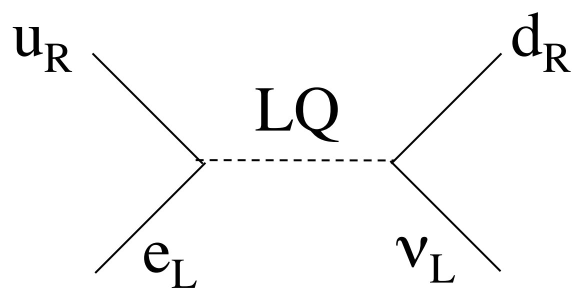
$$\Gamma \propto \left| A_{\not{P}T} + A_{P\not{T}} + \underbrace{A_{\not{P}\not{T}}}_{\text{EDM}} \right|^2 \sim \Gamma_{\not{P}T} + \frac{A_{P\not{T}}}{A_{\not{P}T}} \sin\varphi_{P\not{T}} + \frac{A_{\not{P}\not{T}}}{A_{\not{P}T}} \sin\varphi_{\not{P}\not{T}} + \ldots$$

Model	Contribution to D	Constrained by
CKM	10^{-12}	Mixing
θ_{QCD}	$2\text{x}10^{-15}$	EDMs (n, ^{199}Hg)
Left-right symmetry	10^{-7}-10^{-5}	W_L limits (B)+EDMs
Non-SM Fermions	10^{-7}-10^{-5}	Direct production+EDMs
Charged Higgs SUSY	10^{-7}-10^{-6}	
4-fermion/leptoquark	$<10^{-4}$	Ng/Tulin (nEDM)

$D_{FSI} \sim 2\text{x}10^{-5}$

Relationship to EDM (4 quark operator)

(Ng & Tulin: PRD **85** 033001 ‘12)

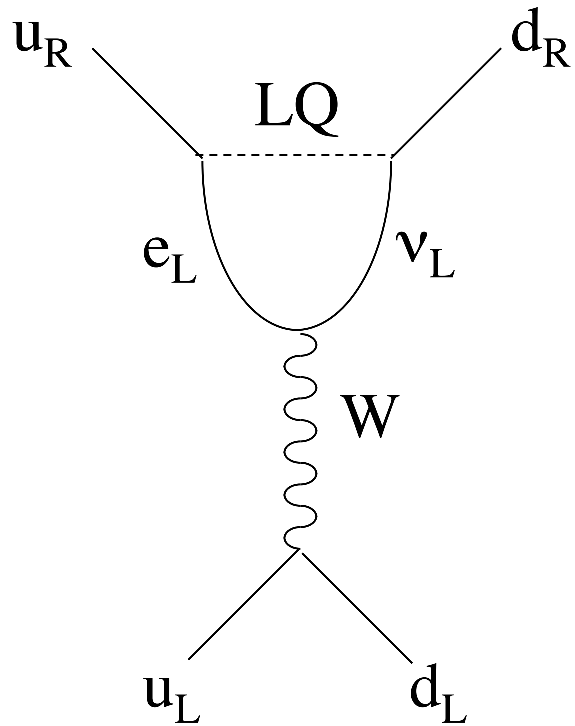


nDecay

Relationship to EDM (4 quark operator)

(Ng & Tulin: PRD **85** 033001 '12)

ONLY ONE nEDM contribution



EDM

Current Status

$$\frac{d^5\Gamma}{dE_e d\Omega_e d\Omega_\nu} = G(E_e)\left(1 + a\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} + A\frac{\langle\vec{\sigma}_n\rangle\cdot\vec{p}_e}{E_e} + B\frac{\langle\vec{\sigma}_n\rangle\cdot\vec{p}_\nu}{E_\nu} + D\frac{\langle\vec{\sigma}_n\rangle\cdot(\vec{p}_e\times\vec{p}_\nu)}{E_e E_\nu}\right)$$

		% error	Ref	SM (tree level)	$\frac{1}{\alpha}\lvert\partial\alpha/\partial\lambda\rvert$
λ	-1.2701±0.0025	0.2	PDG		
a	-0.103±0.004	3.9	PDG	$\frac{1-\lvert\lambda\rvert^2}{1+3\lvert\lambda\rvert^2}$	2.8
A	-0.1176 ± 0.0011	0.7	PDG	$-2\frac{\lvert\lambda\rvert^2+\mathrm{Re}(\lambda)}{1+3\lvert\lambda\rvert^2}$	3.2
B	0.9807 ± 0.0030	0.3	PDG	$+2\frac{\lvert\lambda\rvert^2-\mathrm{Re}(\lambda)}{1+3\lvert\lambda\rvert^2}$	0.08
C	-0.2377 ± 0.0036	1.1	PERKEOII-B	$C = 4\frac{\mathrm{Re}(\lambda)}{1+3\lvert\lambda\rvert^2}$	0.52
D	$(-0.94\pm2.12)\mathrm{x}10^{-4}$	-	emiT-II	$2\frac{\mathrm{Im}(\lambda)}{1+3\lvert\lambda\rvert^2}$	
ϕ_{AV}	180.012±0.0028	-	same		

k=0.27484 for $0 \le E_p \le 750$ eV

C/k=-0.8649±0.0095

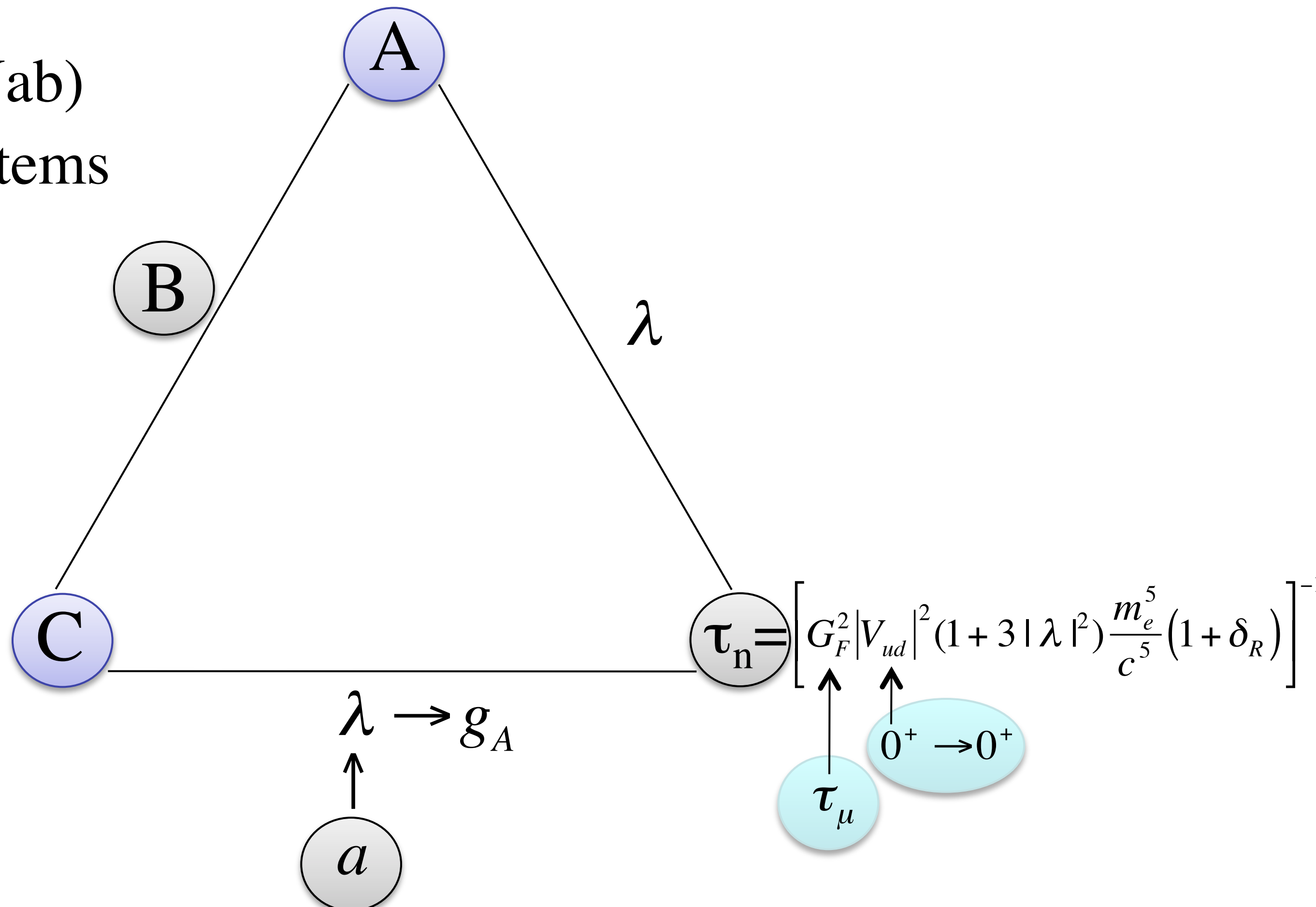
$A+B$=0.8631±0.0032

$k(A+B)$=0.2372±0.0009

$$\frac{1}{(1+3\,|\,\lambda\,|^2)} = \tau_n G_F^2 |V_{ud}|^2 \frac{m_e^5}{c^5}(1+\delta_R)$$

SM has two parameters: V_{ud} and λ
$\geq$ 5 Observables

- Polarized Nab
- Other neutron (Nab)
- Input – other systems



$$\frac{1}{(1+3|\lambda|^2)} = \tau_n G_F^2 |V_{ud}|^2 \frac{m_e^5}{c^5} (1+\delta_R)$$

Beyond SM Physics:

Scalar and Tensor Currents

$$A \approx +2\frac{|\lambda|^2 - \mathrm{Re}(\lambda)}{1+3|\lambda|^2} + \frac{\alpha m}{p_e}\frac{\left(2|\lambda|^2+\lambda\right)\mathrm{Im}(T)+\lambda\,\mathrm{Im}(S)}{1+3|\lambda|^2}$$

$$S = \frac{C_S + C_S{}'}{C_V}$$

$$B \approx -2\frac{|\lambda|^2 + \mathrm{Re}(\lambda)}{1+3|\lambda|^2} + \frac{m}{E_e}\frac{(2|\lambda|^2+\lambda)\mathrm{Re}(T)+\lambda\,\mathrm{Re}(S)}{1+3|\lambda|^2}$$

$$T = \frac{C_T + C_T{}'}{C_A}$$

$$\boxed{C(1+3|\lambda|^2) - 4\lambda \approx \frac{m}{E_e}(2|\lambda|^2+\lambda)\mathrm{Re}(T)+\lambda\,\mathrm{Re}(S)}$$

Right Handed *W*

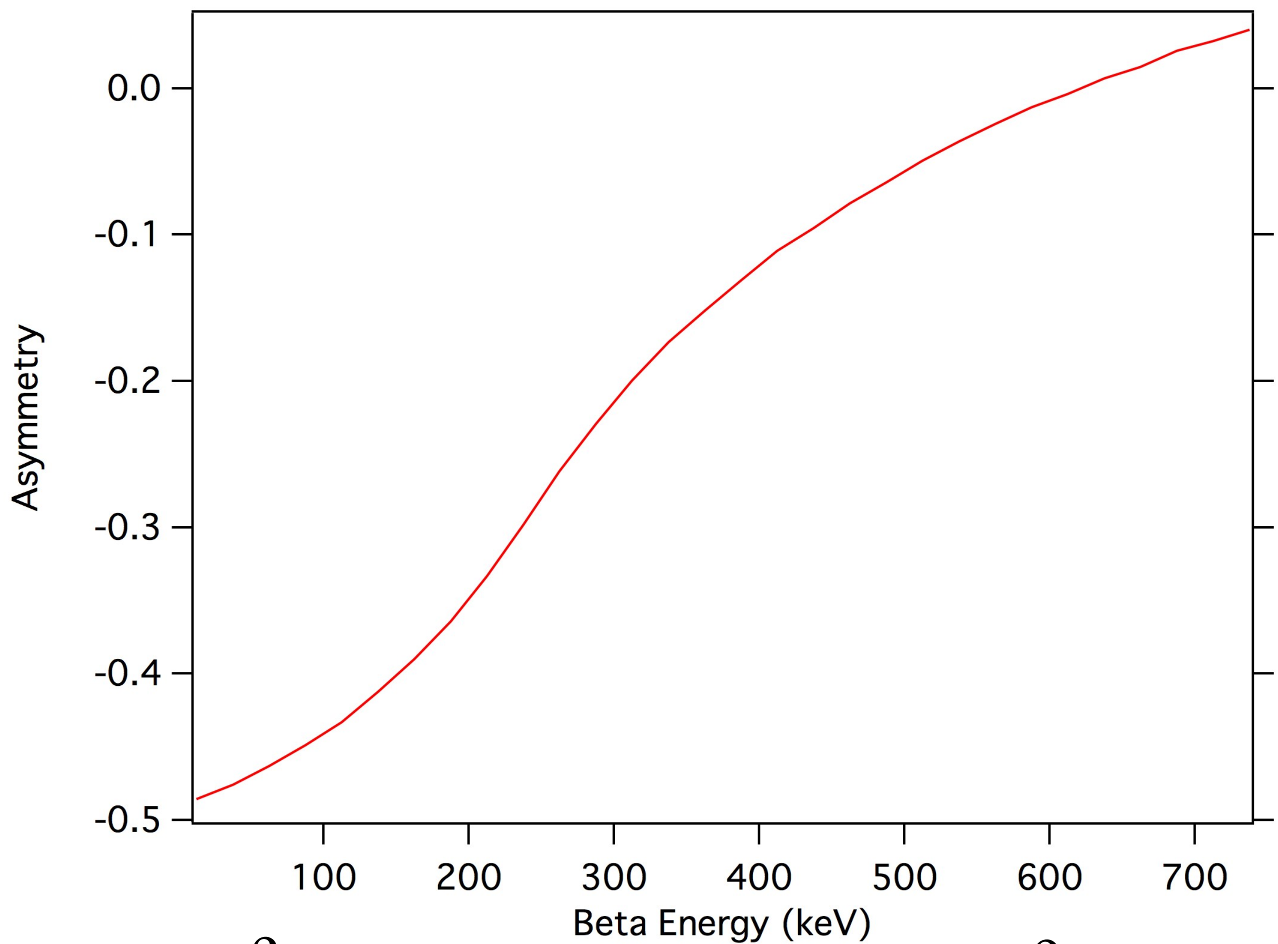
$$W_L = (W_1\cos\zeta + W_2\sin\zeta)$$

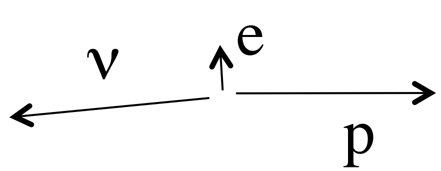
$$W_R = (-W_1\sin\zeta + W_2\cos\zeta)e^{i\varphi_{LR}}$$

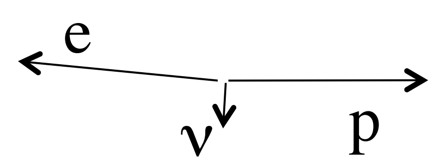
$$A \approx A_{SM}\left(1 - 2\delta^2 + \frac{-12\lambda^3+6|\lambda|^2-2}{\lambda-(1+3|\lambda|^2)}\delta\zeta - \frac{3\lambda}{(\lambda-1)}\zeta^2\right) \approx A_{SM} - (0.24\delta^2 + 0.54\delta\zeta + 0.20\zeta^2)$$

$$B \approx B_{SM} + \frac{2\lambda(\delta^2-\zeta^2) - 3|\lambda|^2(\delta+\zeta)^2}{1+3|\lambda|^2} \approx B_{SM} - (1.08\delta^2 + 1.30\delta\zeta + 0.22\zeta^2)$$

Proton Asymmetry vs E_e





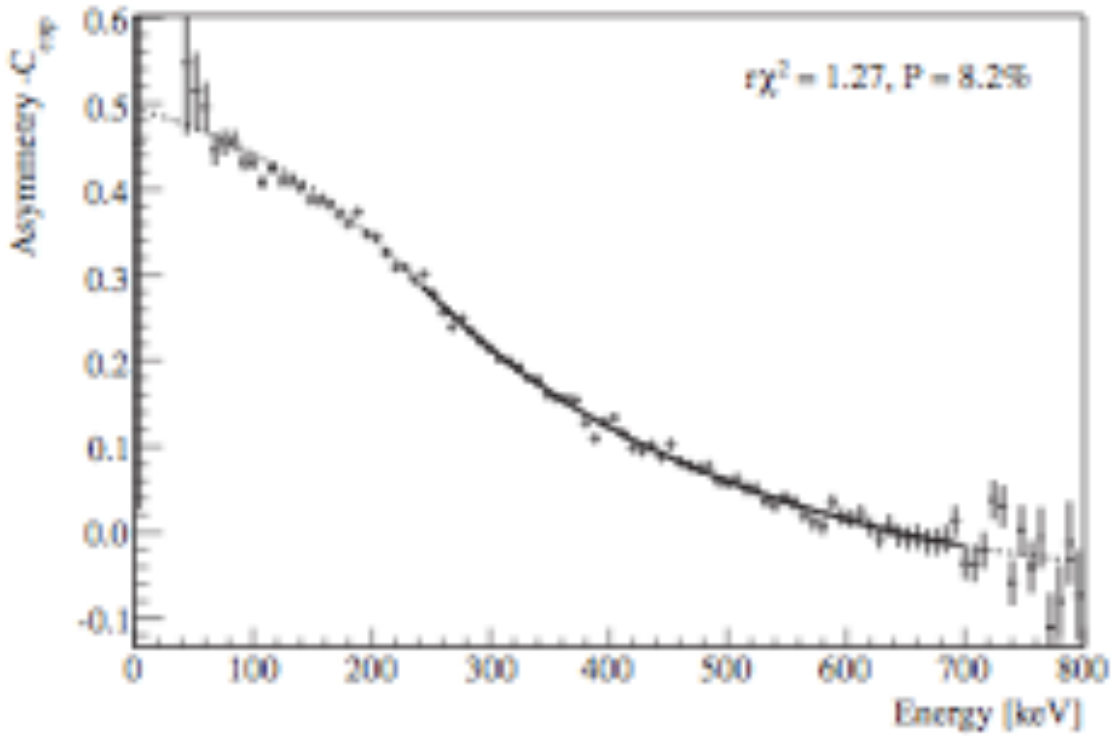


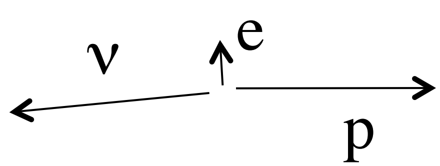
A+**B**

A+B

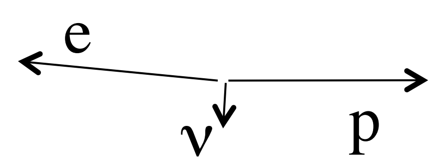
Proton Asymmetry vs E_e

Schumann et al. PRL 100, 151801 (2008)





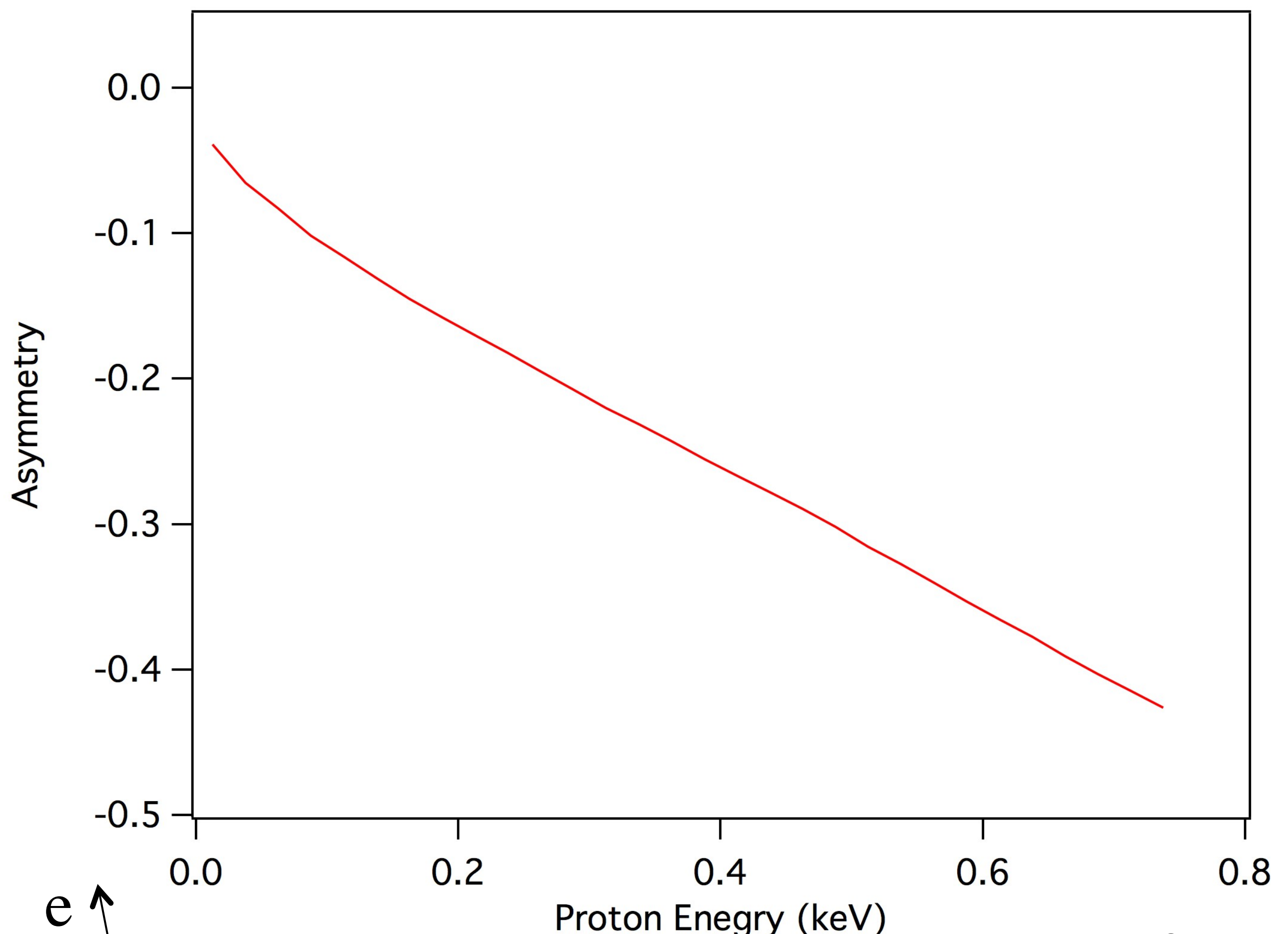
A+**B**

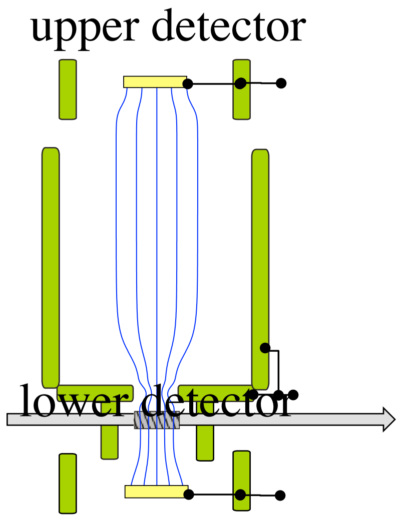


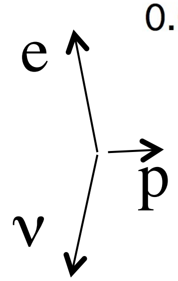
A+B

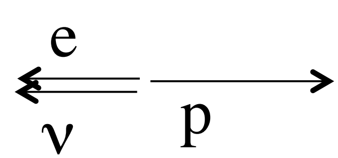
Proton Asymmetry vs E_p

(Nab/abBA/PANDA)







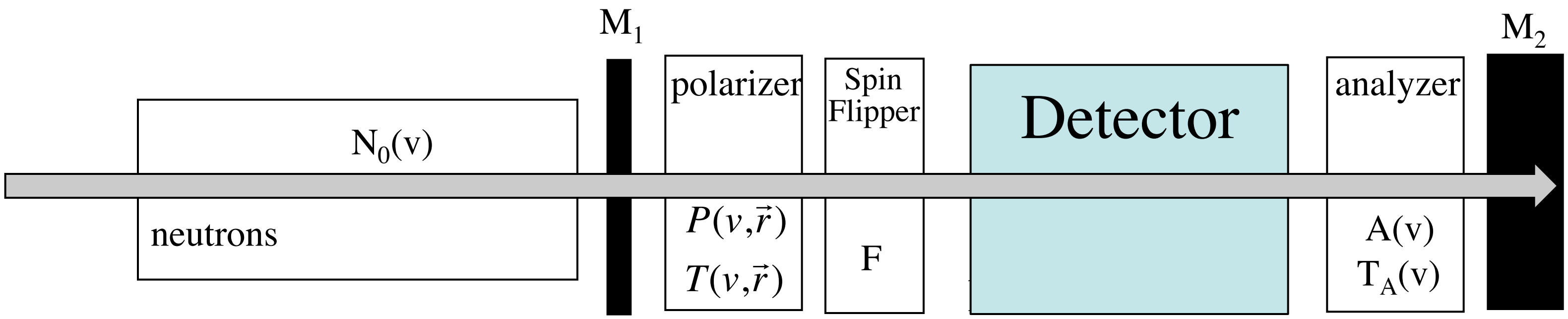


Summary of Motivations

- $A/C(E_p,E_e)$ – LARGE
- $C = k(A+B)$ (+ corrections) ~ $4\mathrm{Re}(\lambda)/(1+3|\lambda|^2)$ (SM)
- Use (A) C, $|V_{ud}|$, τ_n as a SM test
- Sensitive to Scalar, Tensor, RH currents
- Theory: Treiman (1948), Glück (1996), Gudkov (EFT)
- Corrections: calculable to $<<10^{-3}$ (10^{-4})

Ivanov arXiv:1212.0332)

Polarization

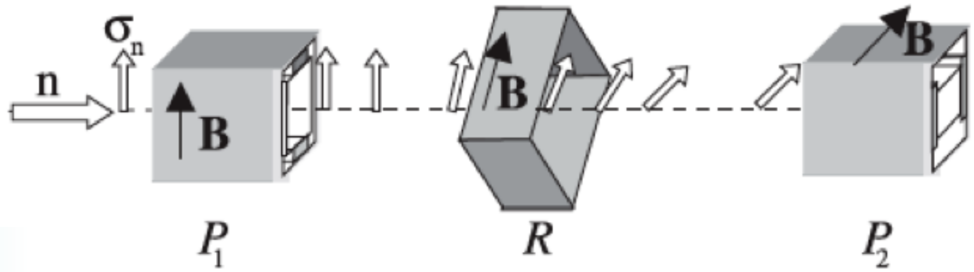


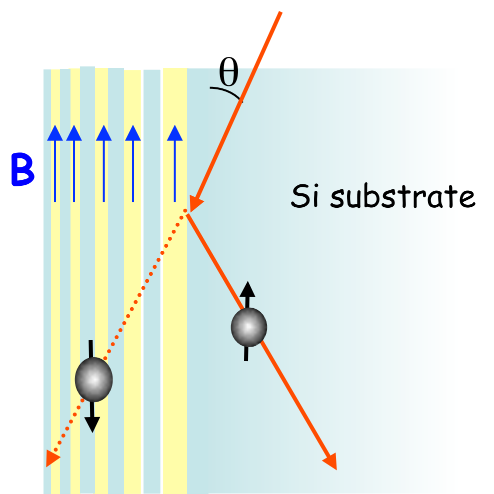
P/A	P_n (5Å)	T_n	$P^2\rho$	features
PSM	98%	25%	0.24	Pn~ 1; static
XSM	99.x%	10%	0.10	``
He (60%)	80%	30%	0.19	**Flip** P_3; P_3 varies

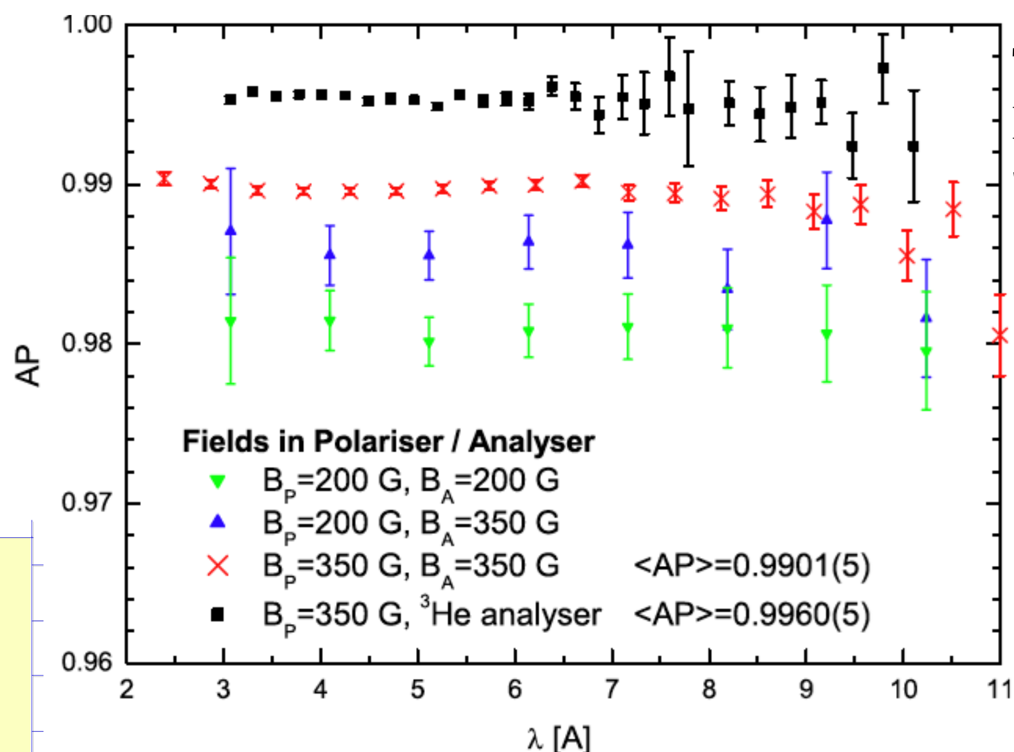
Need < 0.1% measurment of $<P_n>$, F

Crossed Supermirror (XSM)

Kreuz et al.



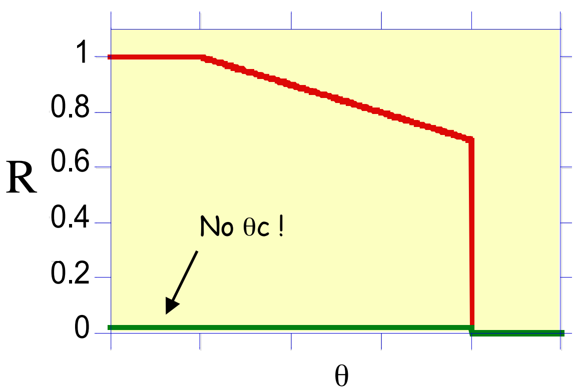




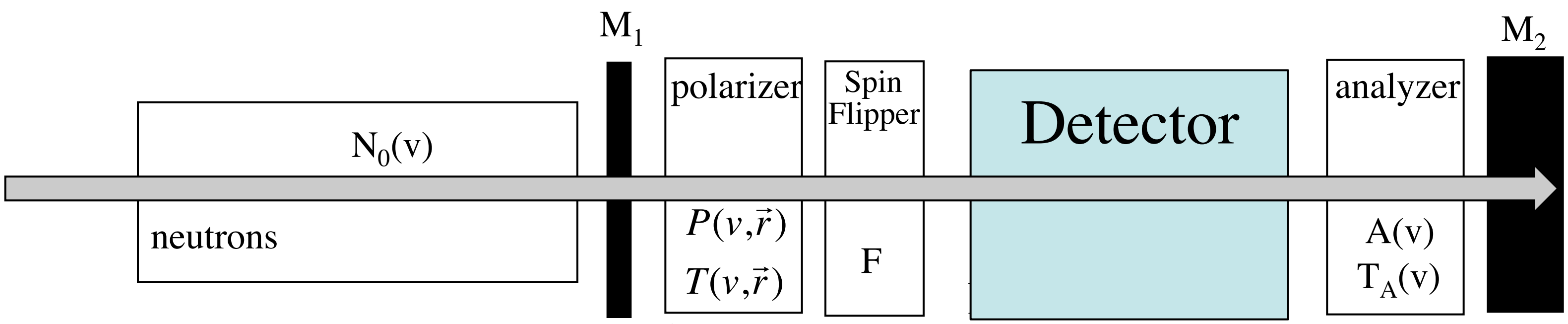
Thick ^{3}He analyser

P_n=0.997±0.001

Schuman PRL **99, 191803** (2007)

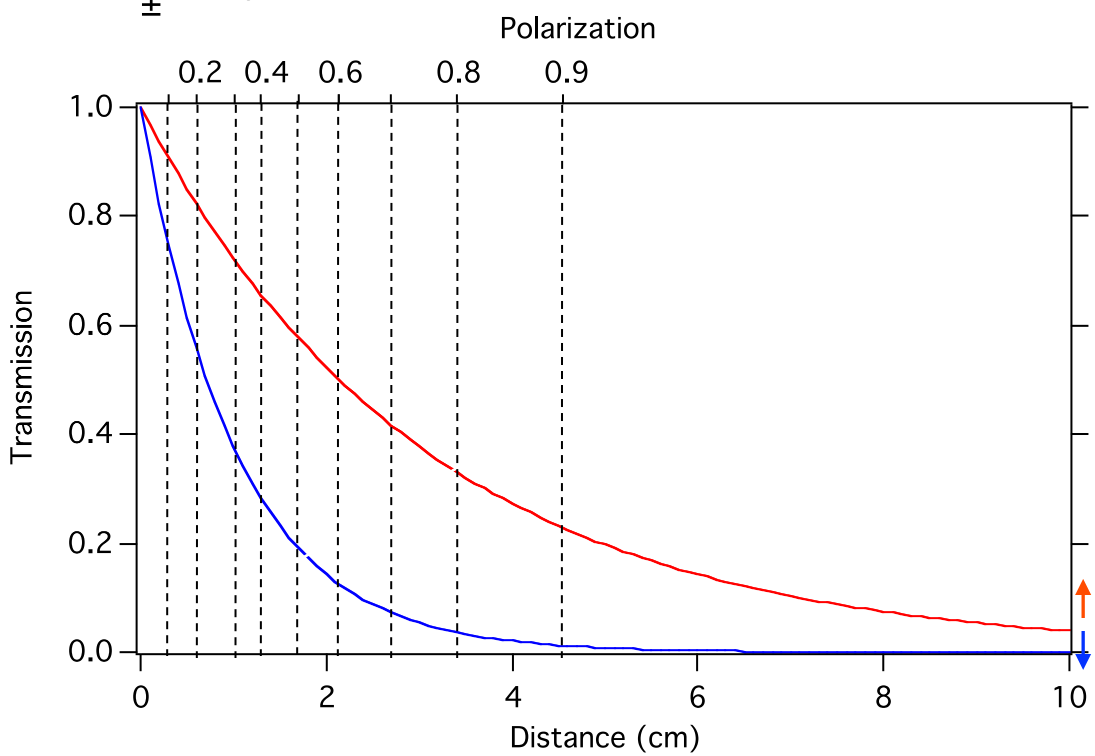


^{3}He spin filter: n + ^{3}He -> ^{1}H + ^{3}H



$$T_{\pm} = e^{-n_3 \sigma_0 t \frac{v_0}{v}(1 \mp P_3)}$$

σ_0=5333 b

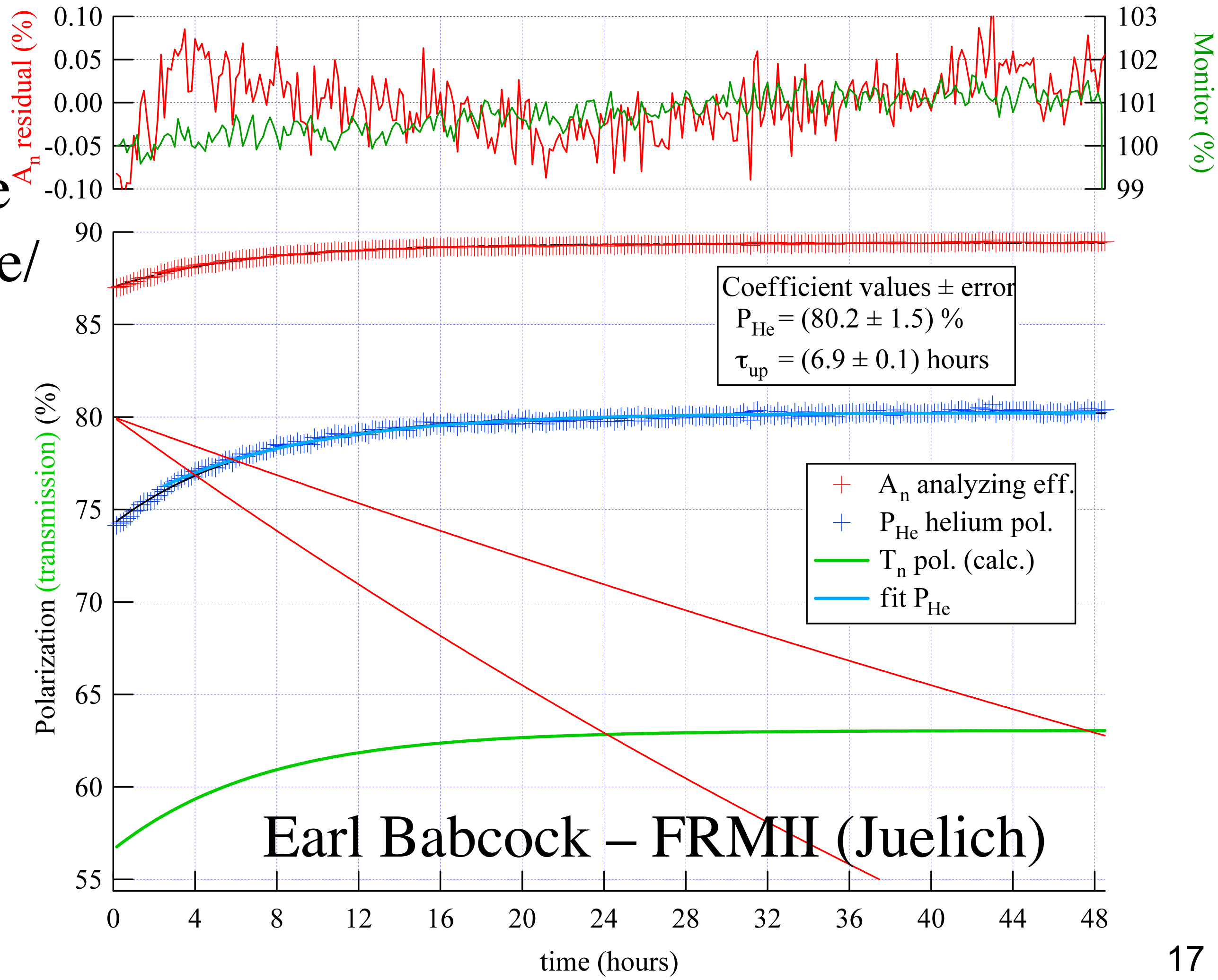


^{3}He: continuous polarization by Spin Exchange

Huge Progress with ^{3}He (NIST-Wisc/ILL/UVa/Jlab…)

- Glass/cell technology (GE180)
- Hybrid Spin Exchange
- Metastability exchange/ compressors
- Lasers
- Magnetic boxes

…

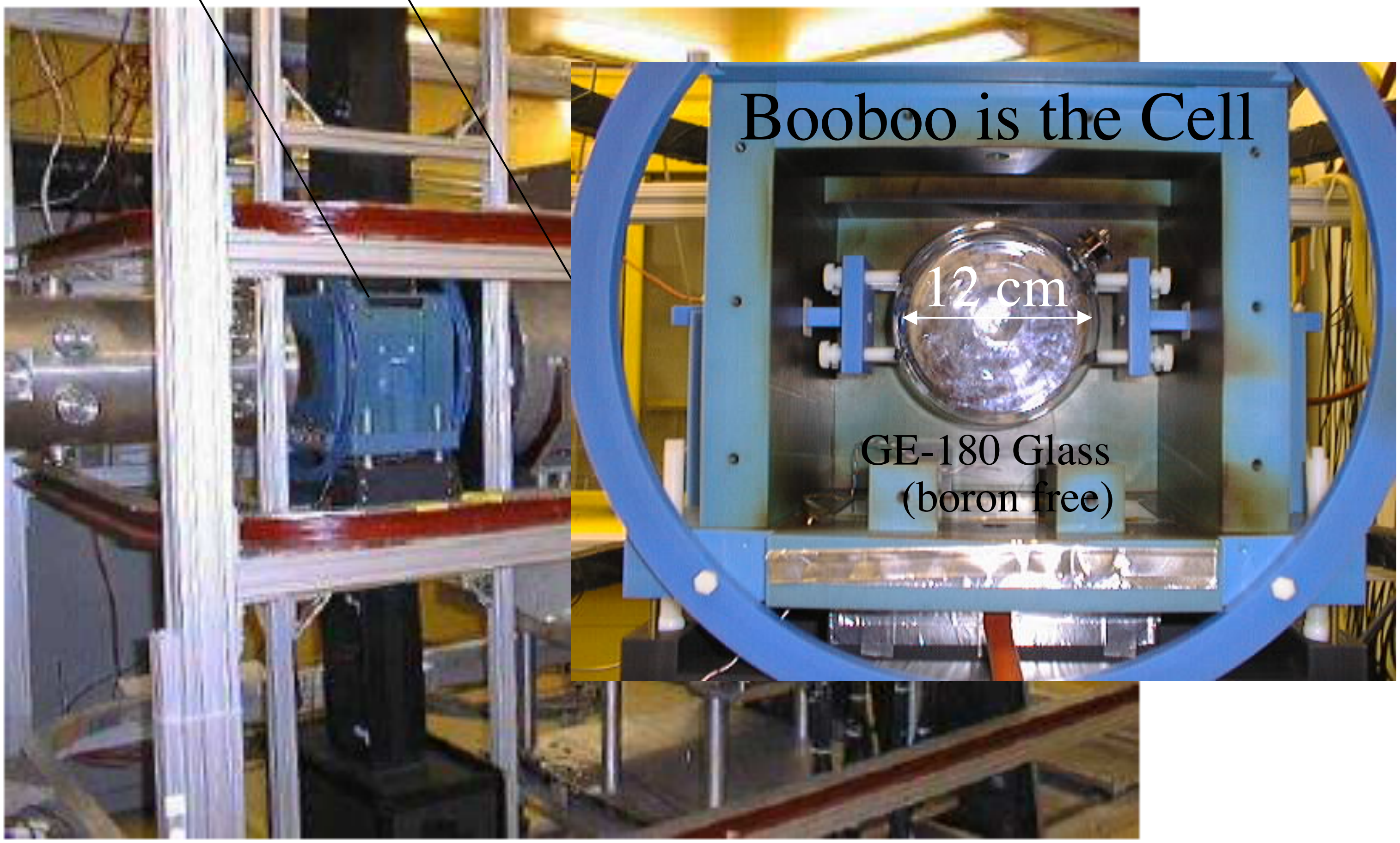


^{3}He spin filter $n+p \longrightarrow d + \gamma$ (@LANSCE)

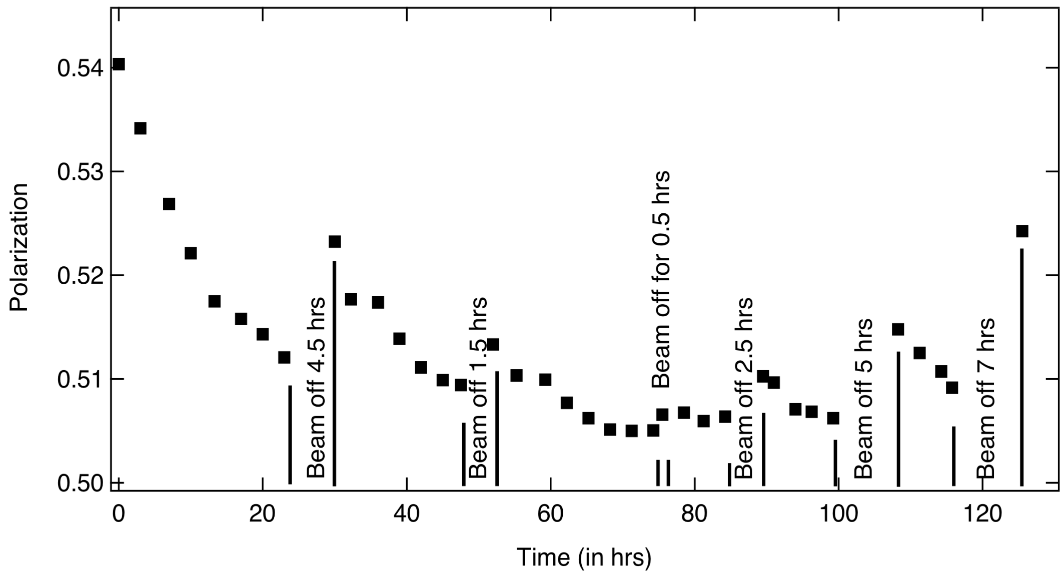
NIM **A 57**, 500 (2007).

Spin Flipper

^{3}He Spin Filter



^{3}He Polarizer Neutron-flux Limitations?

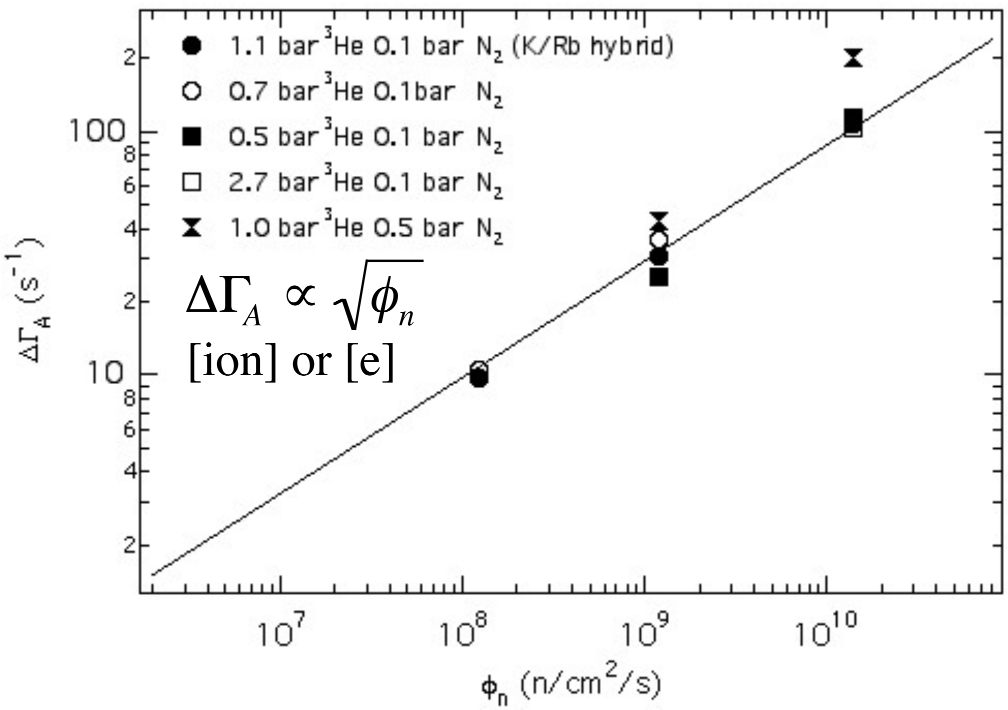


Sharma, Babcock, Soldner et al. show effect on P_{Rb}

$$P_{Rb} = \frac{\gamma_{opt}}{\gamma_{opt} + S\Gamma_A}$$

$S_{Rb} = 10.8$
$S_K = 6$

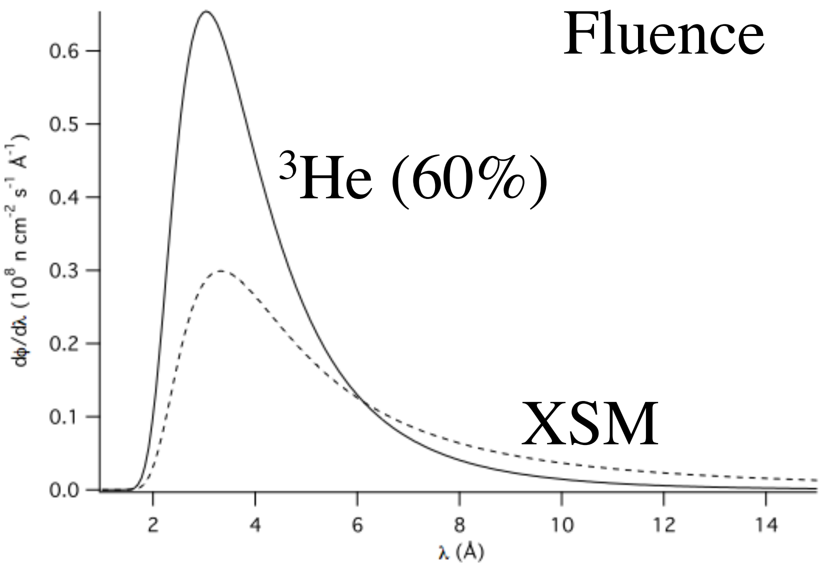
Rb relaxation rate increase

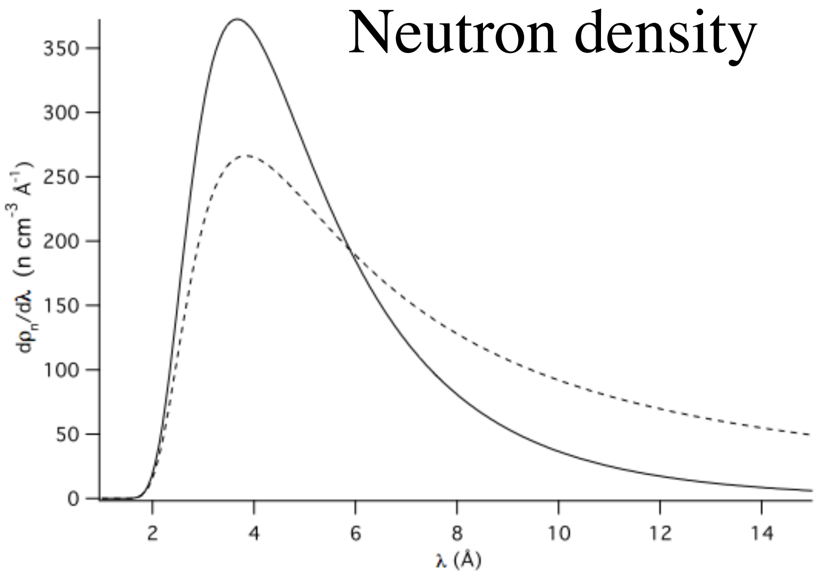


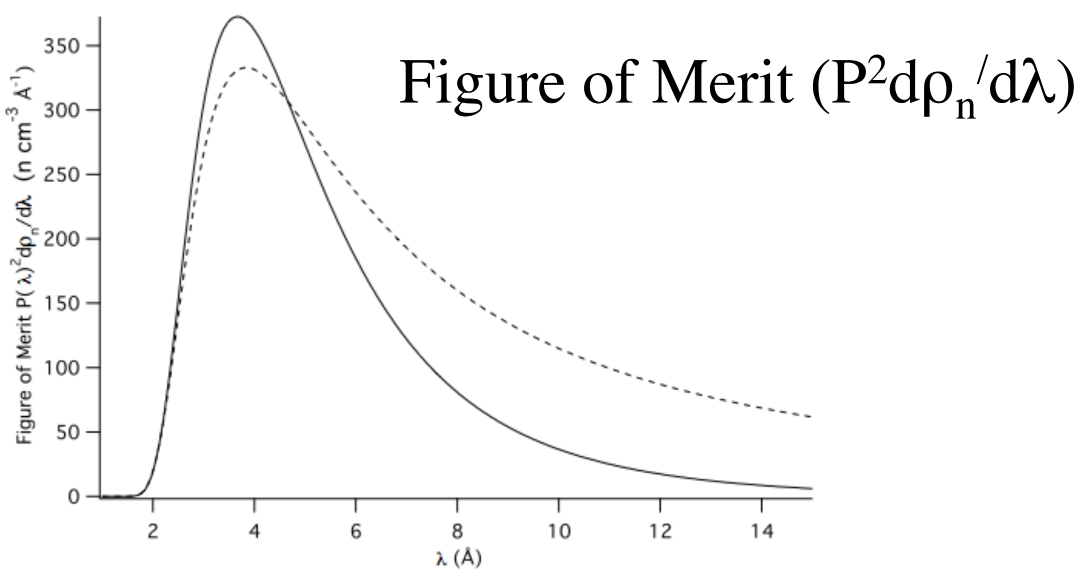
Requires increased laser power (e.g. few times)
Double cell – E. Babcock

T_1>100 h; P3~46% (in progress)

Cold Neutron Beam



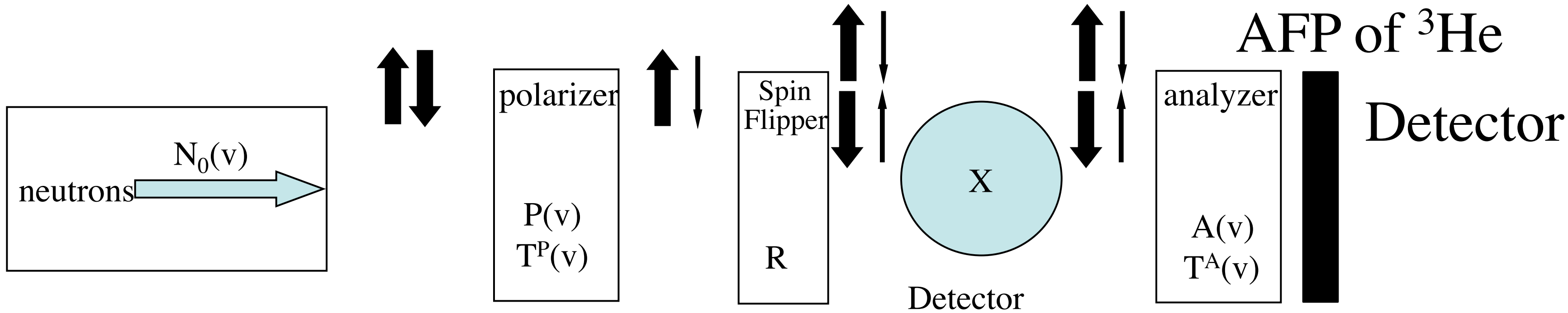




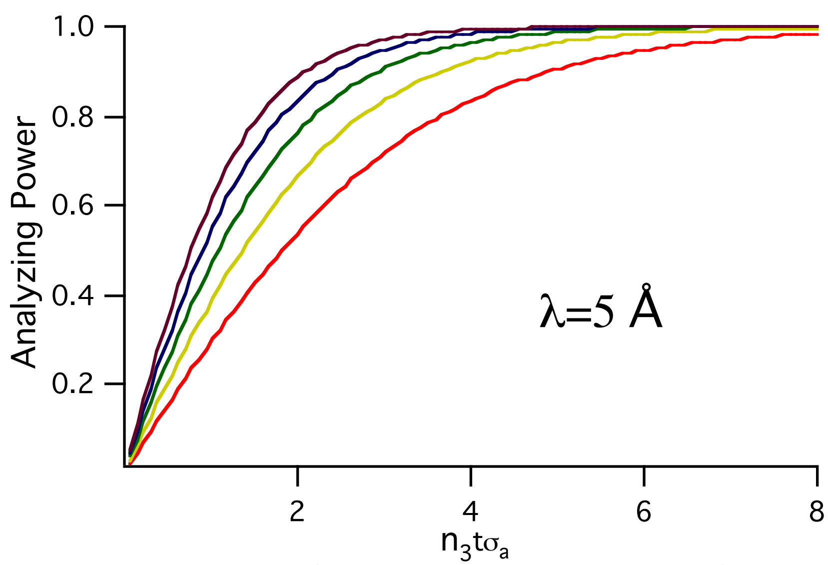
Polarization Summary

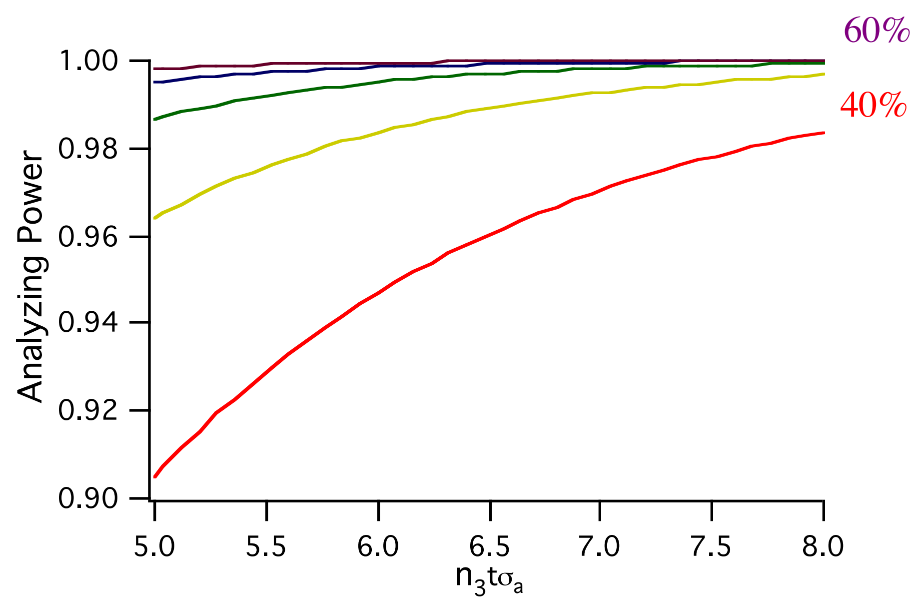
- XSM vs ^{3}He: TBD
- ^{3}He provides $P\underbrace{\alpha}_{}$(tof) (Bowman and Penttila)
- Supermirror design for m=3+ guides needed
- Magnetic field accomodations for spin transport
- Nab estimates for C (0.1%): 5 days

Neutron Polarimetry – thick ^{3}He



$$\frac{[T_A^P/T_A^0]^+ - [T_A^P/T_A^0]^-}{[T_A^P/T_A^0]^+ + [T_A^P/T_A^0]^-} = P_n(\lambda)\tanh(P_A\sigma_0 t_A \frac{\lambda}{\lambda_0}).$$



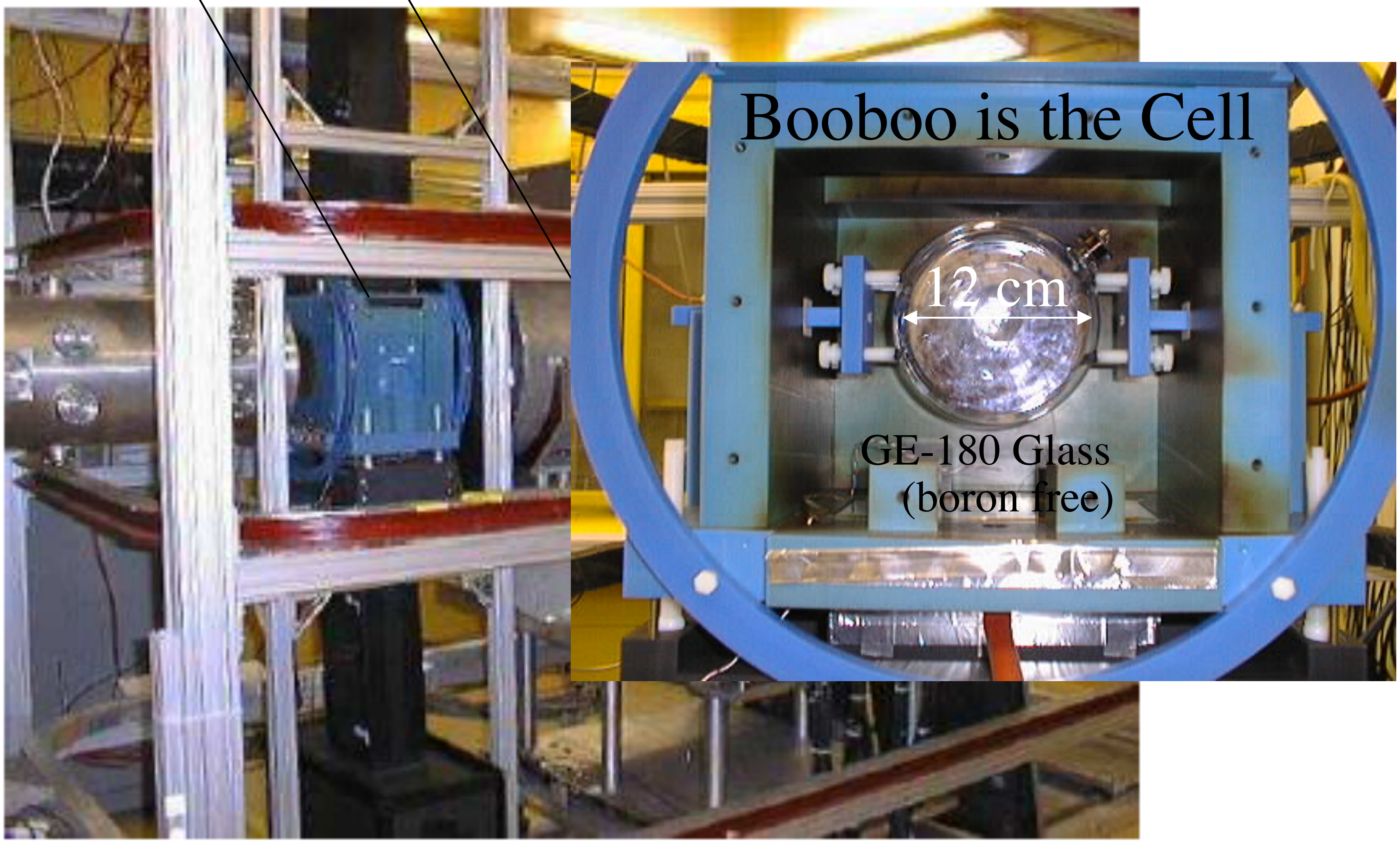


Opaque Analyzer: For $n_3 t\sigma_a$ large enough (1-A) small enough (Zimmer)
Characterize Polarizer AND Flipper

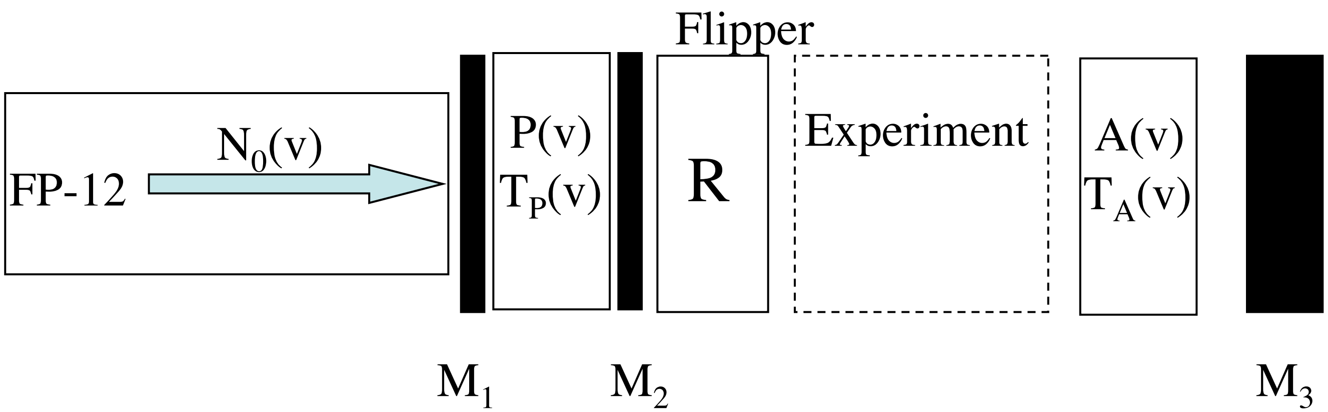
^{3}He and P_n test: n+p —> d + γ (@LANSCE)

Spin Flipper

^{3}He Spin Filter



Pulsed Beam Neutron Polarimetry



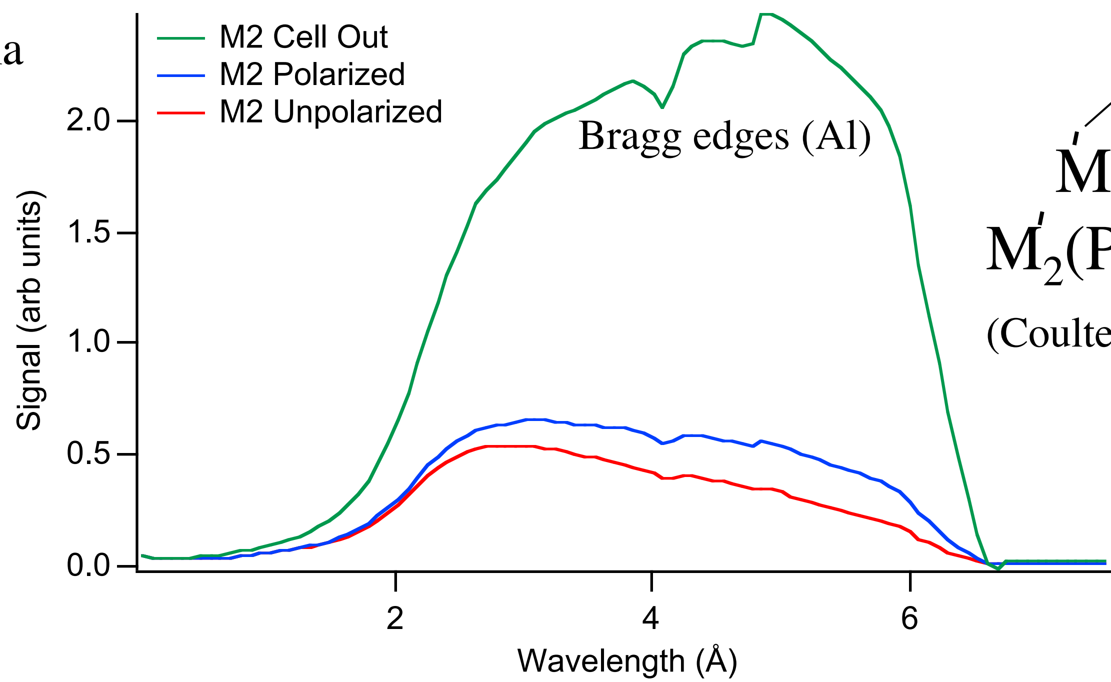
$$T_{A/P} = T_0 \cosh \alpha_{A/P} P_{A/P}$$

$$T_0 = \exp(-\alpha_{A/P} - \alpha_{gl} - \ldots)$$

$$P/A = \tanh \alpha_{A/P} P_{A/P}$$

$$M_1 = N_0 \varepsilon_1 + B_1 \qquad M_2 = N_0 T_1 T_P \varepsilon_2 + B_2$$

npdgamma
FP12



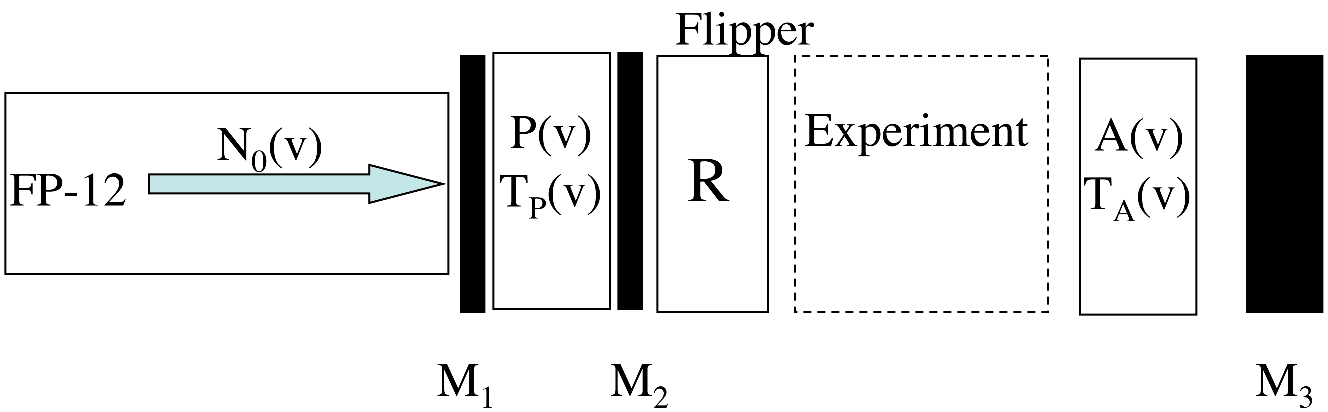
normalized to M1

$$M'_2(0)/M'_2(\mathrm{out}) = T_0$$

$$M'_2(P)/M'_2(0) = \cosh \alpha_P P_P$$

(Coulter et al. NIMA ***288***, 463 (1989))

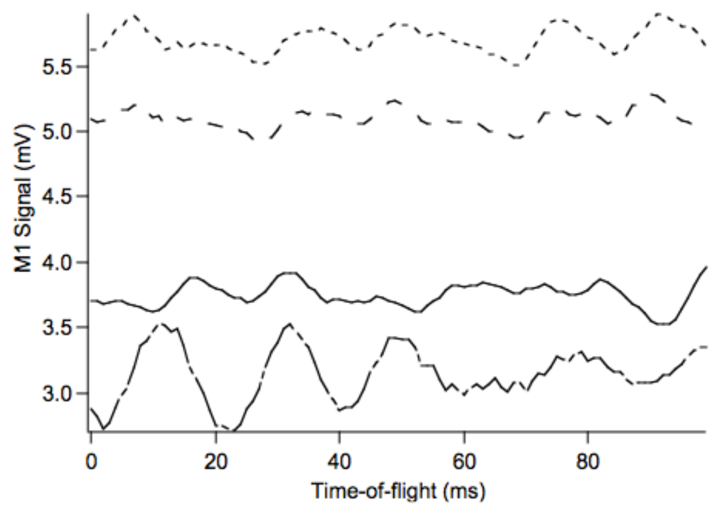
Pulsed Beam Neutron Polarimetry



$$T_{A/P}=T_0 \cosh \alpha_{A/P}P_{A/P}$$
$$T_0=\exp(-\alpha_{A/P}-\alpha_{gl}-\ldots)$$
$$P/A=\tanh \alpha_{A/P}P_{A/P}$$

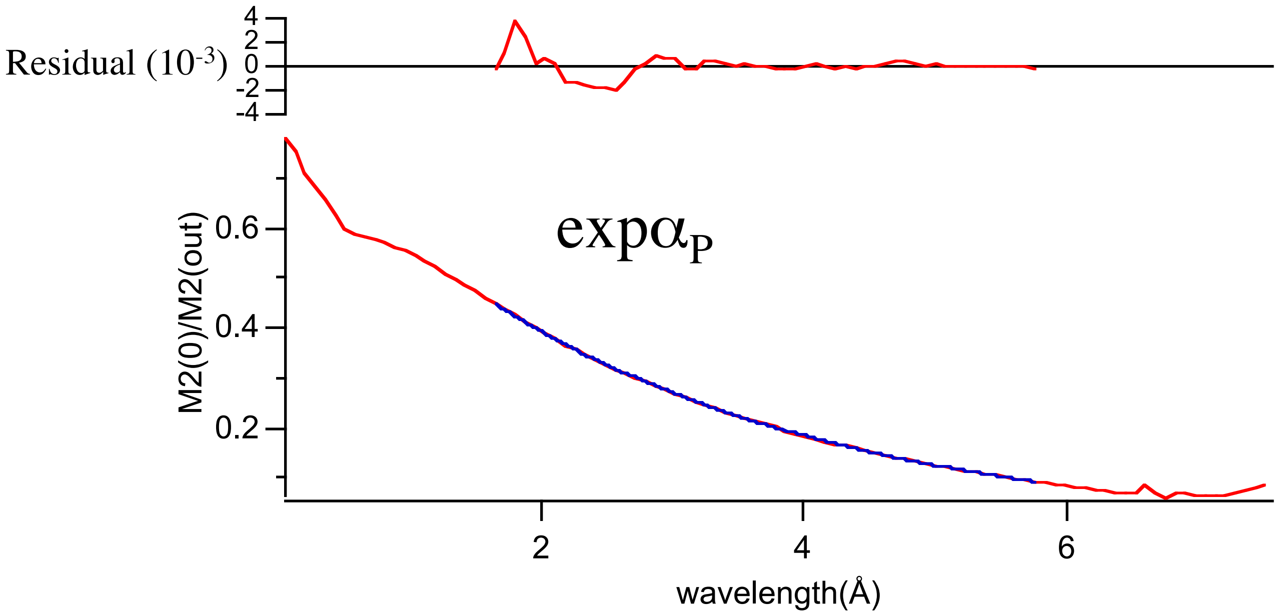
$$M_1= N_0\varepsilon_1+B_1 \qquad M_2= N_0T_1T_P\,\varepsilon_2+B_2$$

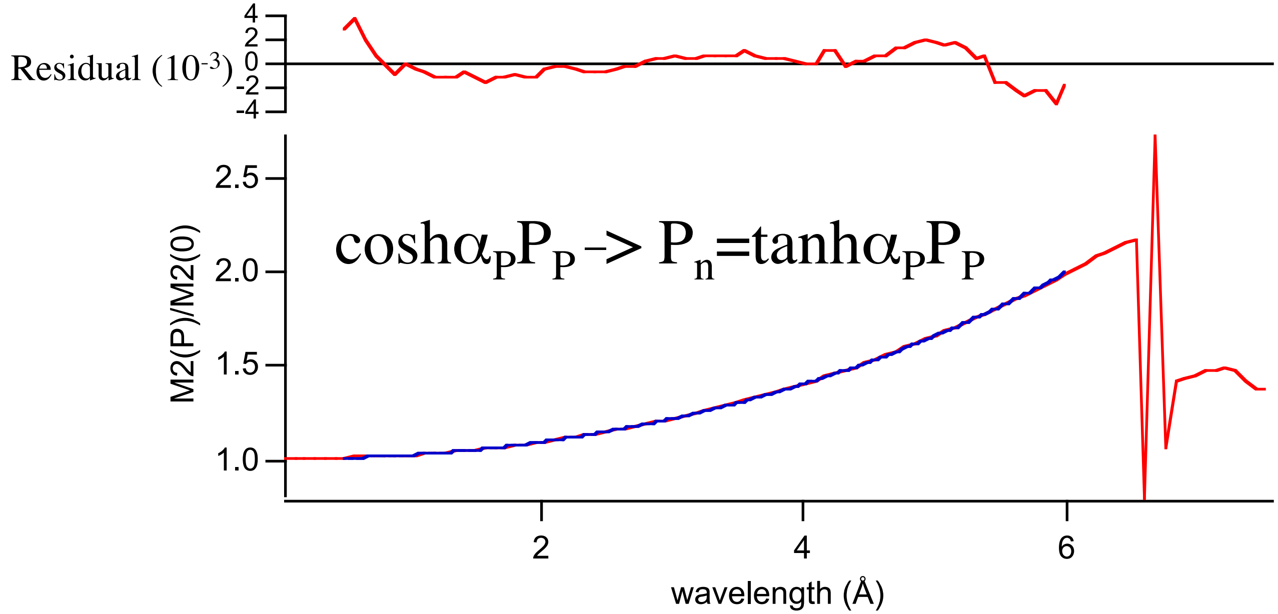
npdgamma
FP12



Offsets/Backgrounds

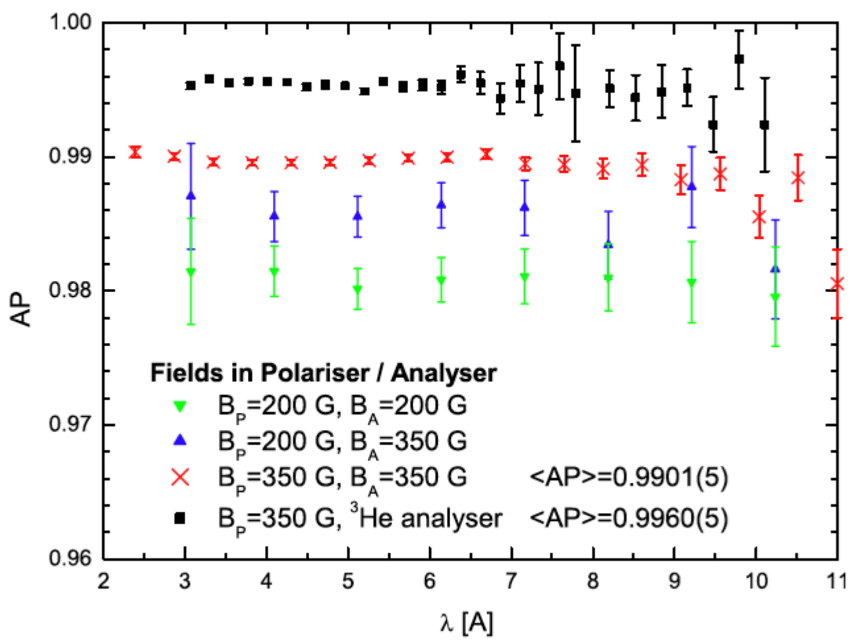
Demonstrates understanding at 10^{-3} level (10^{-4} achieved)





Polarimetry Summary

- Use opaque 3He and pulsed/chopped beam: measure $P(v,\vec{r})$, $R(v,\vec{r})$
- Pulsed beam (SNS): measure continuously
- Chopped beam (NIST): monitor continuously – calibrate monitor
- Neutron flux-^{3}He issues not limiting
- Statistics not limiting
- Systematics: backgrounds (beta delayed neutrons), ^{3}He AFP losses
  ~10^{-4} at LANSCE Should be ~constant vs tof at SNS
- LANSCE FP12 test beam available

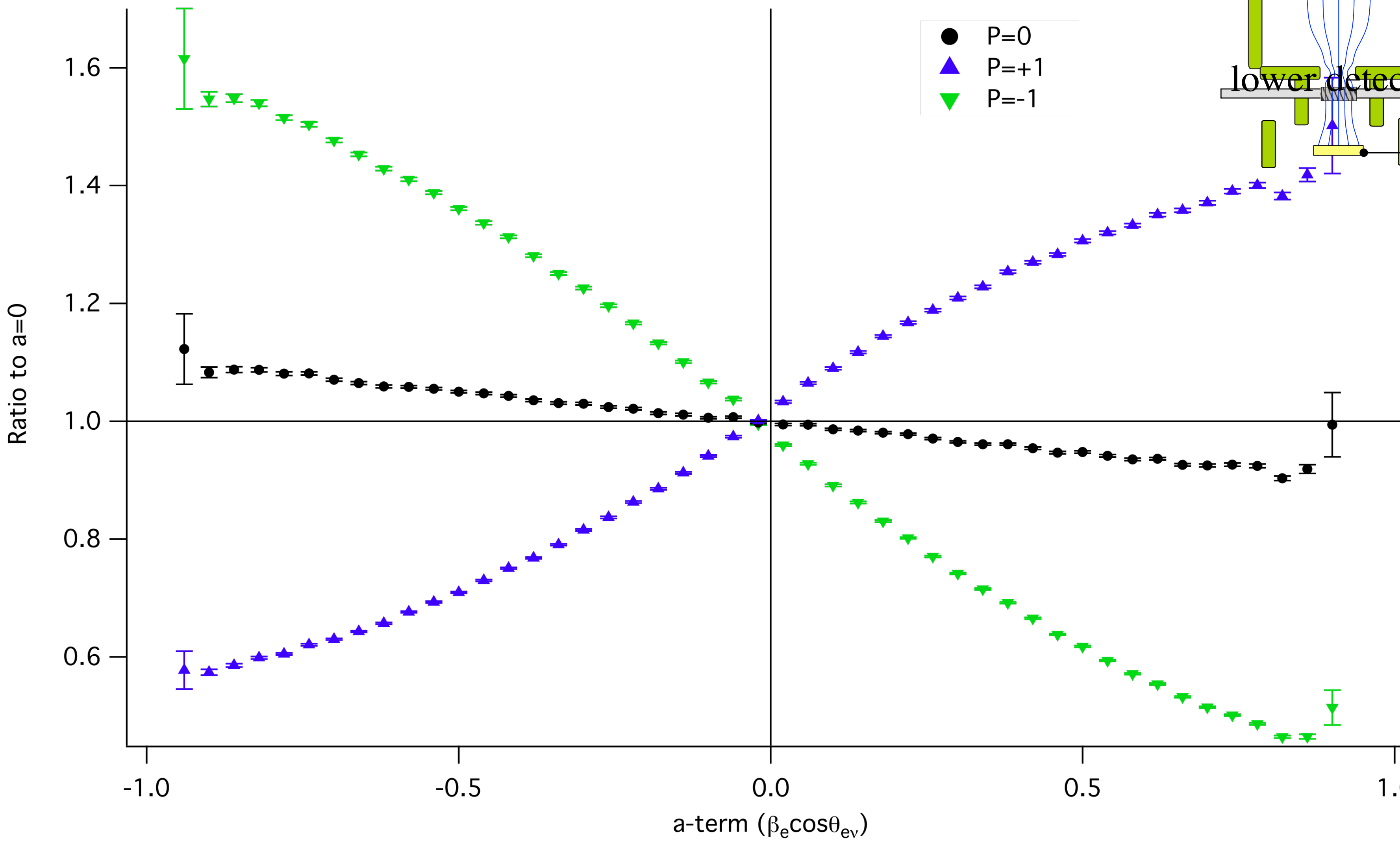


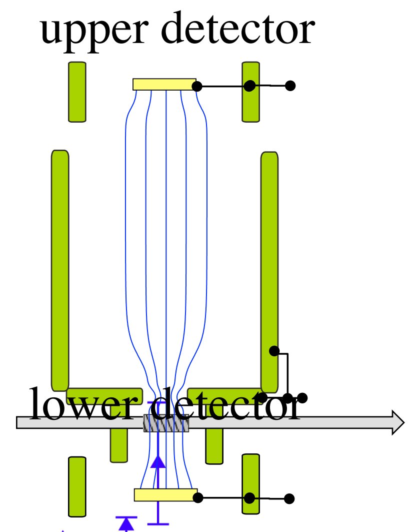
Thick ^{3}He analyser
$P_{n=}0.997 \pm 0.001$
(0.0001 reasonable)

T. Soldner

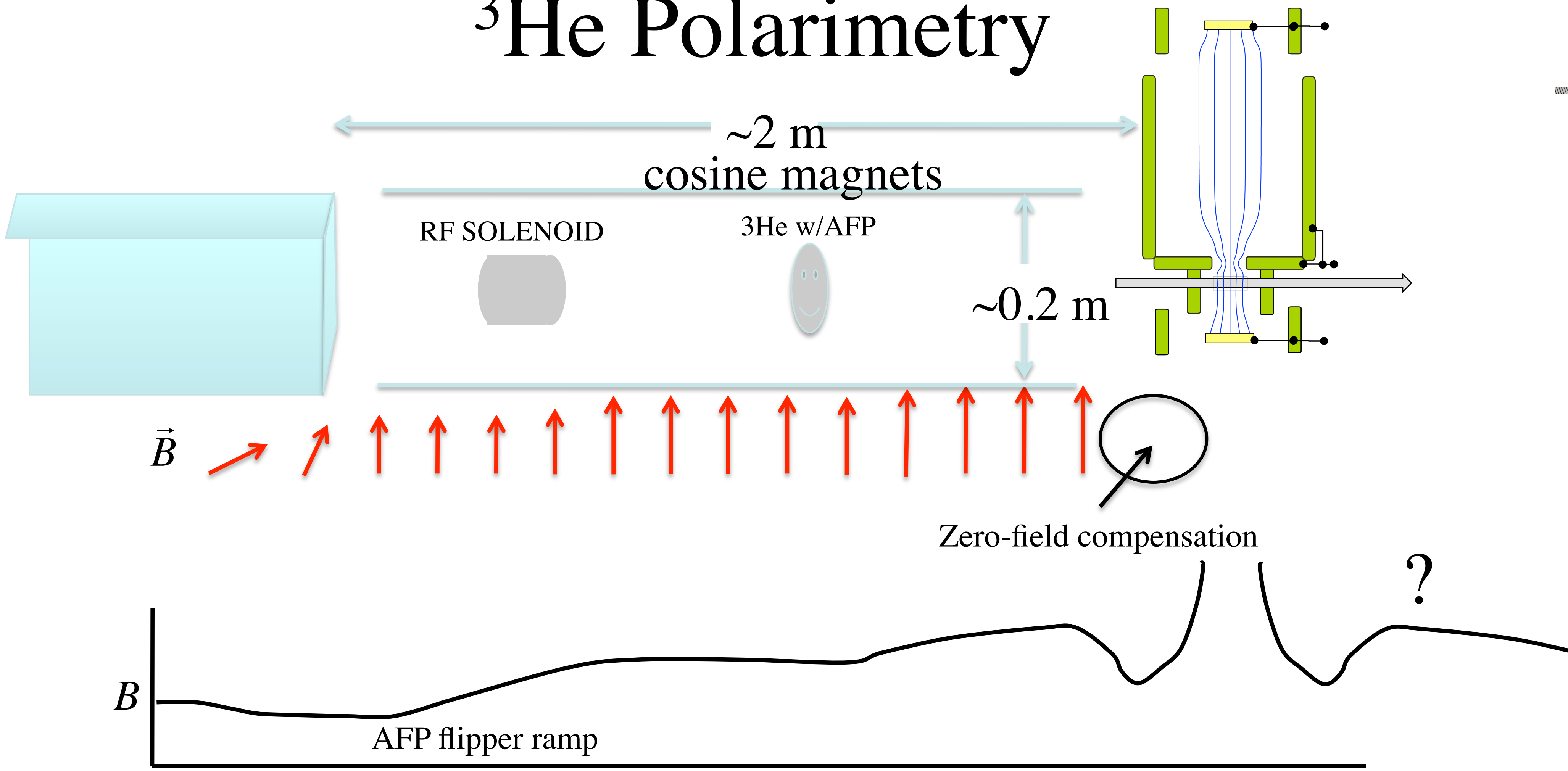
Nab polarization?

$$P_n = 0.01\% \Rightarrow \Delta a \approx 6\times 10^{-4}$$





^{3}He Polarimetry



AFP Flip ^{3}He polarization:

$$R(v_n) = \frac{T_+ - T_-}{T_+ + T_-} = P_n \tanh(P_3 n_3 \sigma_a t_3)$$

Summary

- Interesting and important physics in A, B (C), D @<10^{-3}
- D measured to 2×10^{-4}
- ^{3}He polarizer: 99.xx % P_n; 10% transmission – neutron beam effects
- 0.1% (0.01%) measurement of $\langle P_n \rangle_{,}$ spin flipper with ^{3}He