Precision measurements of neutron beta decay II – Correlations –

Torsten Soldner

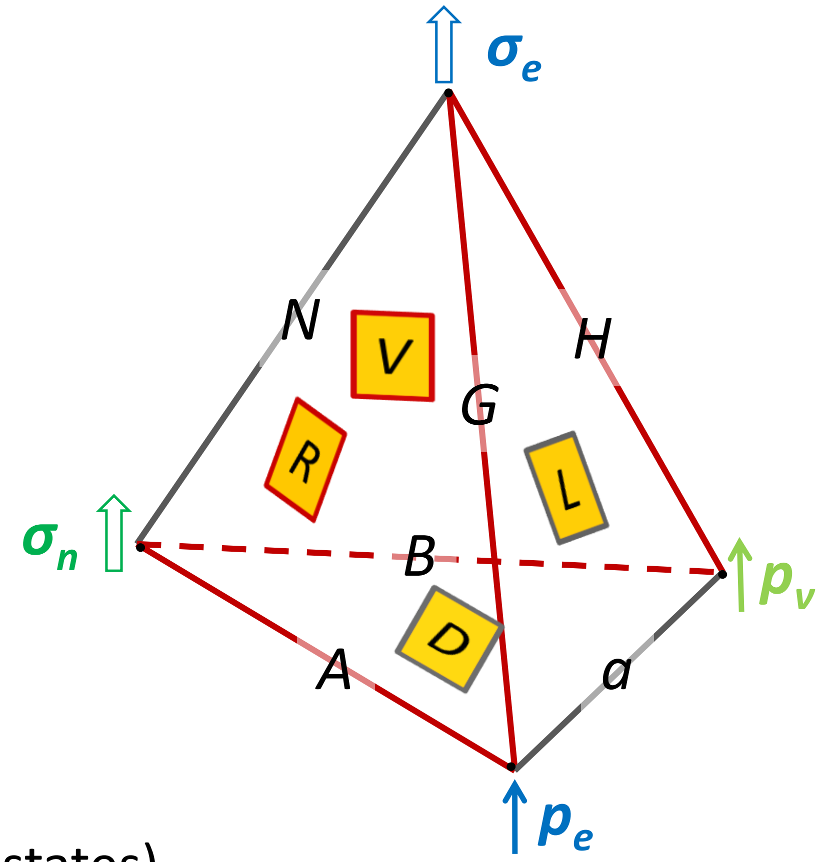
Institut Laue-Langevin

Grenoble, France

Experimentalist’s approach on neutron decay

- **What can we measure?** $\boldsymbol{n \rightarrow p + e + \bar{\nu}_e}$
  - Neutron: spin direction $\boldsymbol{\sigma_n}$
  - Proton: momentum $\boldsymbol{p_p}$
  - Electron: momentum $\boldsymbol{p_e}$, spin direction $\boldsymbol{\sigma_e}$
  - Neutrino: momentum $\boldsymbol{p_\nu = -p_p + p_e}$

➔ 2 vectors $(\boldsymbol{p_e}, \boldsymbol{p_\nu})$ &
2 axial vectors $\boldsymbol{\sigma_n}, \boldsymbol{\sigma_e}$



- **Possible correlations (this lecture):**
  - 6 twofold: $\boldsymbol{\sigma_n p_e}, \boldsymbol{\sigma_n p_\nu}, \boldsymbol{p_e p_\nu}, \ldots$
  - 4 threefold: $\boldsymbol{\sigma_n(\sigma_e \times p_e)}, \ldots$
  - 5 fourfold: $\boldsymbol{(\sigma_e p_e)\,(p_e p_\nu)}, \ldots$
  - 1 fivefold: $\boldsymbol{(\sigma_e p_e)\sigma_n(p_e \times p_\nu)}$

  \+ Deformation of electron spectrum (Fierz term)

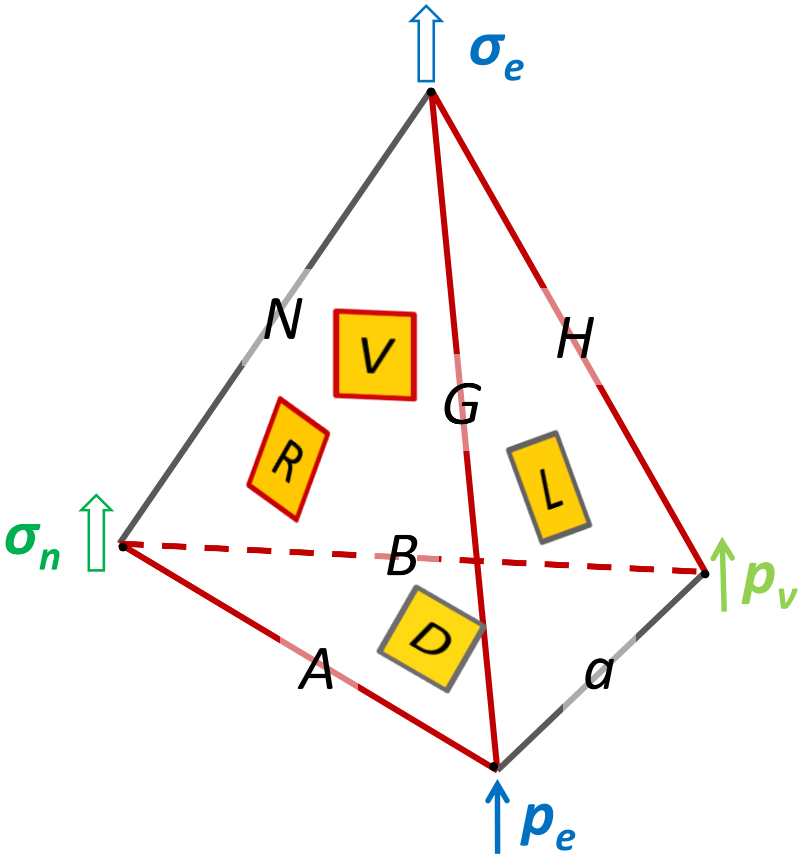
- **Further observables:**
  - Lifetime (lecture I)
  - Rare decay modes: $n \rightarrow \mathrm{H} + \bar{\nu}_e$ (branching ratio, H atomic states)
    $n \rightarrow p + e + \bar{\nu}_e + \gamma$ (branching ratio, even more correlations)

Content

- Principles & Concepts & Tools & Examples
  - ➢PERKEO *n*: The quest for accuracy

- Status and outlook

The neutron alphabet



- $\boldsymbol{\sigma}_n, \boldsymbol{p}_e, \boldsymbol{p}_\nu$: **Oriented neutrons, momenta of electron and neutrino**

$$\mathrm{d}W(\langle\boldsymbol{\sigma}_n\rangle|E_e,\Omega_e,\Omega_\nu) \propto G_E(E_e)\cdot \left\{1 + a\frac{\boldsymbol{p}_e\boldsymbol{p}_\nu}{E_eE_\nu} + b\frac{m_e}{E_e} + \frac{\langle\boldsymbol{\sigma}_n\rangle}{\sigma_n}\left(A\frac{\boldsymbol{p}_e}{E_e} + B\frac{\boldsymbol{p}_\nu}{E_\nu} + D\frac{\boldsymbol{p}_e\times\boldsymbol{p}_\nu}{E_eE_\nu}\right)\right\}$$

- $\boldsymbol{\sigma}_e, \boldsymbol{p}_e, \boldsymbol{p}_\nu$: **Spin and momentum of electron, momentum of neutrino**

$$\mathrm{d}W(\langle\boldsymbol{\sigma}_e\rangle|E_e,\Omega_e,\Omega_\nu) \propto G_E(E_e)\cdot \left\{1 + a\frac{\boldsymbol{p}_e\boldsymbol{p}_\nu}{E_eE_\nu} + b\frac{m_e}{E_e} + \frac{\langle\boldsymbol{\sigma}_e\rangle}{\sigma_e}\left(G\frac{\boldsymbol{p}_e}{E_e} + H\frac{\boldsymbol{p}_\nu}{E_\nu} + K\frac{\boldsymbol{p}_e}{E_e+m_e}\frac{\boldsymbol{p}_e\boldsymbol{p}_\nu}{E_eE_\nu} + L\frac{\boldsymbol{p}_e\times\boldsymbol{p}_\nu}{E_eE_\nu}\right)\right\}$$

- $\boldsymbol{\sigma}_n, \boldsymbol{\sigma}_e, \boldsymbol{p}_e$: **Oriented neutrons, momentum and spin of electron**

$$\mathrm{d}W(\langle\boldsymbol{\sigma}_n\rangle,\langle\boldsymbol{\sigma}_e\rangle|E_e,\Omega_e) \propto G_E(E_e)\cdot \left\{1 + b\frac{m_e}{E_e} + \frac{\langle\boldsymbol{\sigma}_n\rangle}{\sigma_n}A\frac{\boldsymbol{p}_e}{E_e} + \frac{\langle\boldsymbol{\sigma}_e\rangle}{\sigma_e}\left(G\frac{\boldsymbol{p}_e}{E_e} + N\frac{\langle\boldsymbol{\sigma}_n\rangle}{\sigma_n} + Q\frac{\boldsymbol{p}_e}{E_e+m_e}\frac{\langle\boldsymbol{\sigma}_n\rangle\boldsymbol{p}_e}{\sigma_nE_e} + R\frac{\langle\boldsymbol{\sigma}_n\rangle\times\boldsymbol{p}_e}{\sigma_nE_e}\right)\right\}$$

- $\boldsymbol{\sigma}_n, \boldsymbol{\sigma}_e, \boldsymbol{p}_e, \boldsymbol{p}_\nu$: **Oriented neutrons, spin and momentum of electron, momentum of and neutrino**

$$\mathrm{d}W(\langle\boldsymbol{\sigma}_n\rangle,\langle\boldsymbol{\sigma}_e\rangle|E_e,\Omega_e,\Omega_\nu) \propto G_E(E_e)\cdot \left\{1 + \begin{matrix}\text{All terms}\\ \text{from above}\end{matrix} + \frac{\langle\boldsymbol{\sigma}_n\rangle}{\sigma_n}\left(S\frac{\langle\boldsymbol{\sigma}_e\rangle}{\sigma_e}\frac{\boldsymbol{p}_e\boldsymbol{p}_\nu}{E_eE_\nu} + T\frac{\boldsymbol{p}_\nu}{E_\nu}\frac{\langle\boldsymbol{\sigma}_e\rangle\boldsymbol{p}_e}{\sigma_eE_e} + U\frac{\boldsymbol{p}_e}{E_e}\frac{\langle\boldsymbol{\sigma}_e\rangle\boldsymbol{p}_\nu}{\sigma_eE_\nu} + V\frac{\langle\boldsymbol{\sigma}_e\rangle\times\boldsymbol{p}_\nu}{\sigma_eE_\nu} + W\frac{\langle\boldsymbol{\sigma}_e\rangle\boldsymbol{p}_e}{\sigma_e(E_e+m_e)}\frac{\boldsymbol{p}_e\times\boldsymbol{p}_\nu}{E_eE_\nu}\right)\right\}$$

[Jackson, Treiman, Wyld, Phys. Rev. 106 (1957) 517; Ebel&Feldman, Nucl. Phys. 4 (1957) 213]
Further terms in NLO [Ando et al, Phys. Lett B 595 (2004) 250; Gudkov et al, Phys. Rev. C 73 (2006) 035501]

Challenges in $n \to pe\nu$, $m_n - m_p - m_e = 782\ \mathrm{keV}$

Proton energy $E_p < 751\ \mathrm{eV}$

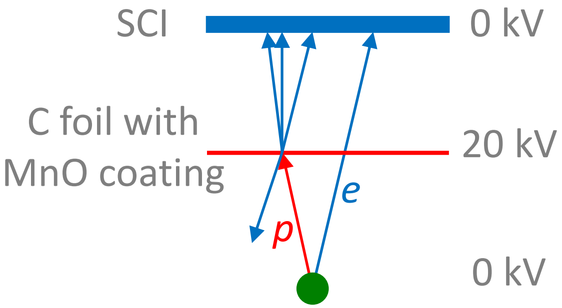
→*Sensitive to small electric fields*

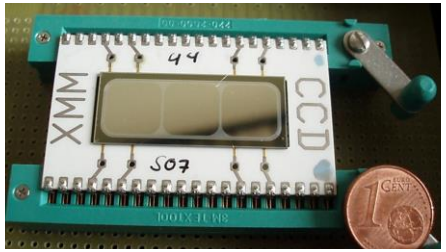
- ✓Control space charges
- ✓Control work functions of surfaces
- ✓Control field leakages

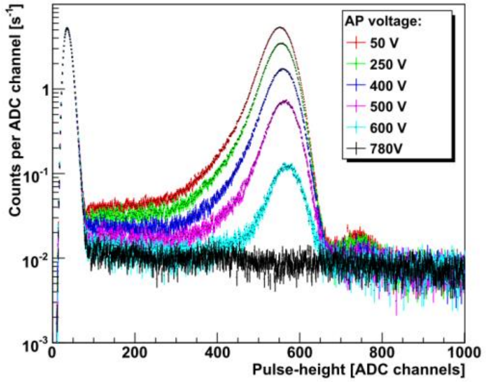
→*Acceleration needed prior to detection*

→*Optimized detectors*

- ✓Low noise, low thresholds, tiny dead layers
- ✓Specific technologies







Electron energy $E_e < 782\ \mathrm{keV}$

→*Range of background from* (n, γ)*, beta decays*

- ✓Shielding
- ✓Magnetic fields for Signal/Background
- ✓Coincidences (Δ*E*-*E* detectors, proton)

→*Exposed to backscattering by detector and scattering by windows/materials*

- ✓Backscatter-suppression or detection
- ✓Proper design of spectrometer

Long lifetime $\tau_n \approx 880\ \mathrm{s}$

→*Low decay rate, low statistics*

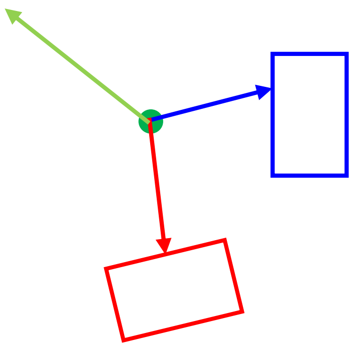
→*Low relative decay rate for cold neutrons*

$\sim 1000\ m/s$: $\sim 10^{-7}/m$

→*All other neutrons can create background*

- ➢Captures (n, γ), …
- ➢Scattering from apertures $\sim 10^{-3}$

Detector geometry – principles



$\boldsymbol{K_{i,\parallel}}$: ∥ to detectors’ surfaces, ⊥ to plane of drawing

$\boldsymbol{K_{i,\perp}}$: ⊥ to $\boldsymbol{K_{i,\parallel}}$, i.e. in plane of drawing (not necessarily ⊥ on detector surface)

K	e	p	ep
b	K	K	K
a	0	0	K
$A,\perp$	K	K	K
$A,\parallel$	0	0	0
$B,\perp$	0	K	K
$B,\parallel$	0	0	0
$D,\perp$	0	0	0
$D,\parallel$	0	0	K

$$\mathrm{d}W(\langle\boldsymbol{\sigma_n}\rangle|E_e,\Omega_e,\Omega_\nu) \propto G_E(E_e)\cdot\left\{1 + a\frac{\boldsymbol{p_e p_\nu}}{E_eE_\nu} + b\frac{m_e}{E_e} + \boldsymbol{P}\left(A\frac{\boldsymbol{p_e}}{E_e} + B\frac{\boldsymbol{p_\nu}}{E_\nu} + D\frac{\boldsymbol{p_e}\times\boldsymbol{p_\nu}}{E_eE_\nu}\right)\right\}$$

$$K_a = \int_{\mathrm{eDet,pDet}} G_E(E_e)\frac{\boldsymbol{p_e p_\nu}}{E_eE_\nu}\mathrm{d}E_e\mathrm{d}\Omega_e\mathrm{d}\Omega_\nu$$

$$\boldsymbol{K_A} = \int_{\mathrm{eDet,pDet}} G_E(E_e)\frac{\boldsymbol{p_e}}{E_e}\mathrm{d}E_e\mathrm{d}\Omega_e\mathrm{d}\Omega_\nu$$

$$K_b = \int_{\mathrm{eDet,pDet}} G_E(E_e)\frac{m_e}{E_e}\mathrm{d}E_e\mathrm{d}\Omega_e\mathrm{d}\Omega_\nu$$

$$\boldsymbol{K_B} = \int_{\mathrm{eDet,pDet}} G_E(E_e)\frac{\boldsymbol{p_\nu}}{E_\nu}\mathrm{d}E_e\mathrm{d}\Omega_e\mathrm{d}\Omega_\nu$$

Often analysis in function of E_e (i.e. $K_i = K_i(E_e)$, no integration over E_e)

$$\boldsymbol{K_D} = \int_{\mathrm{eDet,pDet}} G_E(E_e)\frac{\boldsymbol{p_e}\times\boldsymbol{p_\nu}}{E_eE_\nu}\mathrm{d}E_e\mathrm{d}\Omega_e\mathrm{d}\Omega_\nu$$

$$N_{\mathrm{e,p}} \propto 1 + aK_a + bK_b + \boldsymbol{P}(A\boldsymbol{K_A} + B\boldsymbol{K_B} + D\boldsymbol{K_D})$$

Asymmetries with neutron spin:

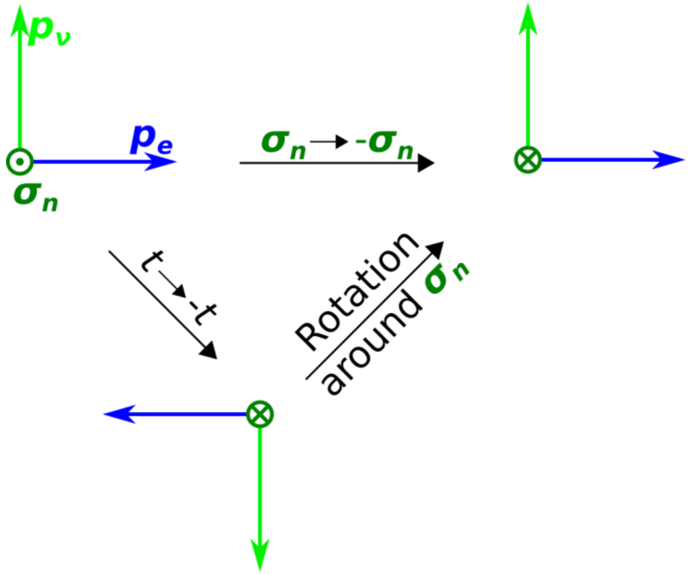
$$\alpha = \frac{N_{\mathrm{e,p}}(\boldsymbol{P}) - N_{\mathrm{e,p}}(-\boldsymbol{P})}{N_{\mathrm{e,p}}(\boldsymbol{P}) + N_{\mathrm{e,p}}(-\boldsymbol{P})} = \frac{\boldsymbol{P}(A\boldsymbol{K_A} + B\boldsymbol{K_B} + D\boldsymbol{K_D})}{1 + aK_a + bK_b}$$

Goals of detector design:

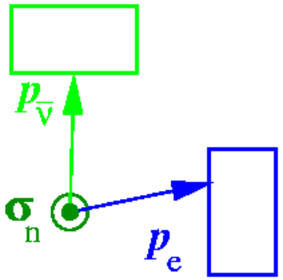
- Maximize sensitivity to wanted coefficient i
  - ➢ Maximize K_i
  - ➢ Maximize statistics
- Suppress other coefficients
  - ➢ Suppress by symmetry or minimize $K_{j\neq i}$

Example *D*: Discrete symmetries and detector design

$$\mathrm{d}W \propto 1 + D\,\frac{\langle \boldsymbol{\sigma}_n \rangle}{\sigma_n}\,\frac{\boldsymbol{p}_e \times \boldsymbol{p}_\nu}{E_e E_\nu}$$

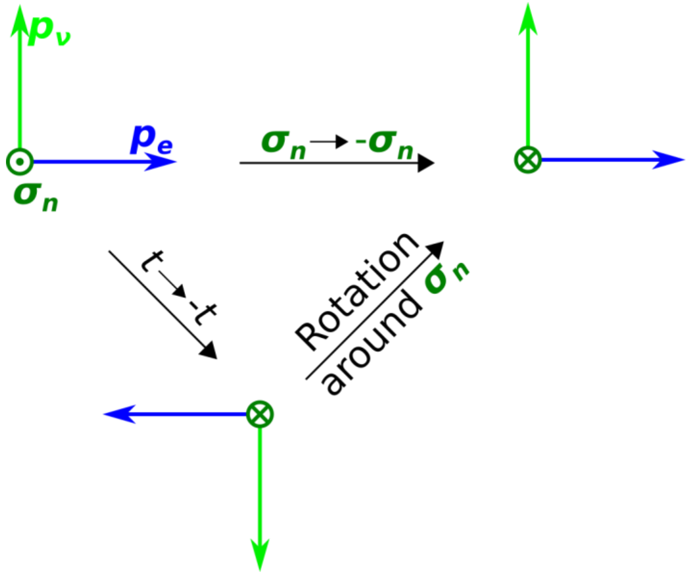


Principle Set-Up

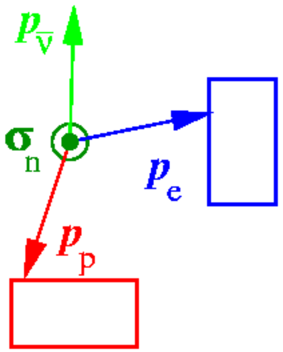


Example *D*: Discrete symmetries and detector design

$$\mathrm{d}W \propto 1 + D\,\frac{\langle \boldsymbol{\sigma}_{\boldsymbol{n}} \rangle}{\sigma_n}\,\frac{\boldsymbol{p}_{\boldsymbol{e}} \times \boldsymbol{p}_{\boldsymbol{\nu}}}{E_e E_\nu}$$



Principle Set-Up



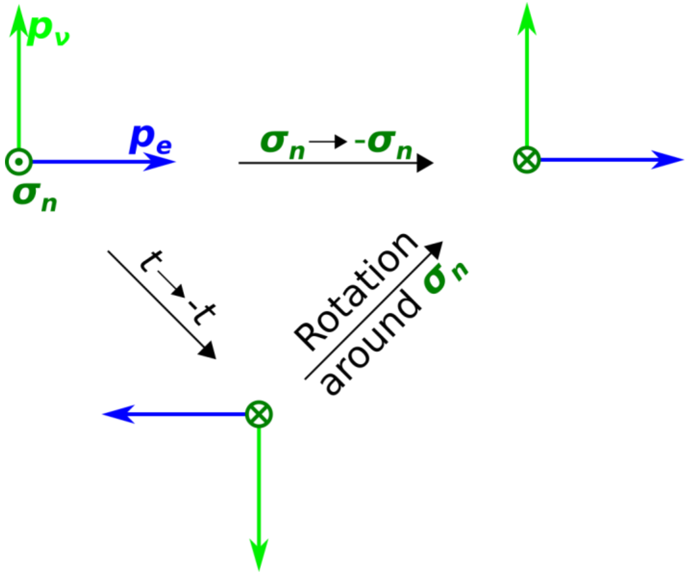
$$\boldsymbol{\kappa}_{\xi} = \frac{\boldsymbol{K}_{\xi}}{1 + aK_a + bK_b}$$

$$\alpha = \frac{n_{ep}^{\odot} - n_{ep}^{\otimes}}{n_{ep}^{\odot} + n_{ep}^{\otimes}} = D\boldsymbol{P}\boldsymbol{\kappa}_{\boldsymbol{D}}$$

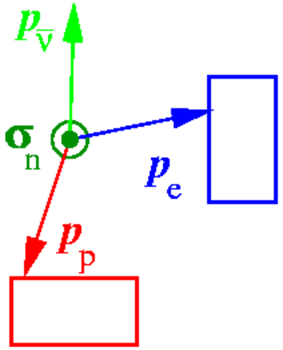
Example *D*: Discrete symmetries and detector design

$$\mathrm{d}W(\langle\boldsymbol{\sigma_n}\rangle|E_e,\Omega_e,\Omega_\nu) \propto G_E(E_e)\cdot\left\{1 + a\frac{\boldsymbol{p_e}\boldsymbol{p_\nu}}{E_eE_\nu} + b\frac{m_e}{E_e} + \frac{\langle\boldsymbol{\sigma_n}\rangle}{\sigma_n}\left(A\frac{\boldsymbol{p_e}}{E_e} + B\frac{\boldsymbol{p_\nu}}{E_\nu}\right) + D\frac{\langle\boldsymbol{\sigma_n}\rangle}{\sigma_n}\frac{\boldsymbol{p_e}\times\boldsymbol{p_\nu}}{E_eE_\nu}\right\}$$

P violating, asymmetry
with spin flip



Principle Set-Up



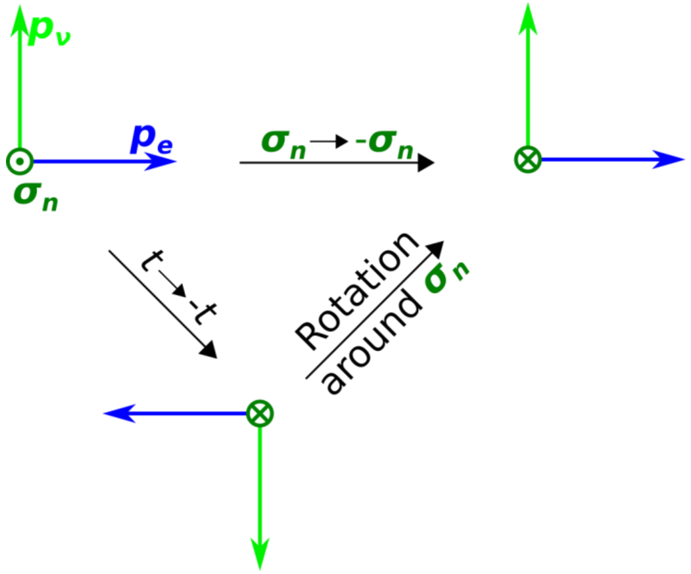
$$\boldsymbol{\kappa_\xi} = \frac{\boldsymbol{K_\xi}}{1 + aK_a + bK_b}$$

$$\alpha = \frac{n_{ep}^{\odot} - n_{ep}^{\otimes}}{n_{ep}^{\odot} + n_{ep}^{\otimes}} = D\boldsymbol{P\kappa_D} + A\boldsymbol{P\kappa_A} + B\boldsymbol{P\kappa_B}$$

Example *D*: Discrete symmetries and detector design

$$\mathrm{d}W(\langle\boldsymbol{\sigma_n}\rangle|E_e,\Omega_e,\Omega_\nu) \propto G_E(E_e)\cdot\left\{1 + a\frac{\boldsymbol{p_e}\boldsymbol{p_\nu}}{E_eE_\nu} + b\frac{m_e}{E_e} + \frac{\langle\boldsymbol{\sigma_n}\rangle}{\sigma_n}\left(A\frac{\boldsymbol{p_e}}{E_e} + B\frac{\boldsymbol{p_\nu}}{E_\nu}\right) + D\frac{\langle\boldsymbol{\sigma_n}\rangle}{\sigma_n}\frac{\boldsymbol{p_e}\times\boldsymbol{p_\nu}}{E_eE_\nu}\right\}$$

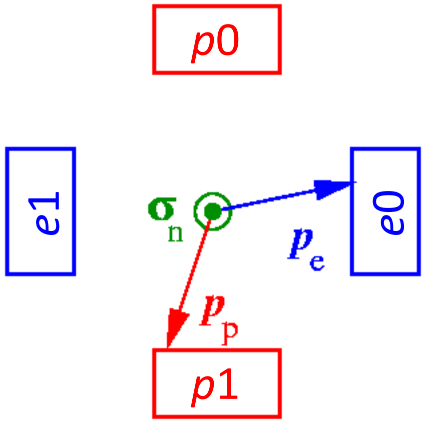
P violating, asymmetry
with spin flip



Suppression of parity-violating correlations if detector setup and neutron volume share two orthogonal mirror planes

Breaking of symmetry → Systematic effects

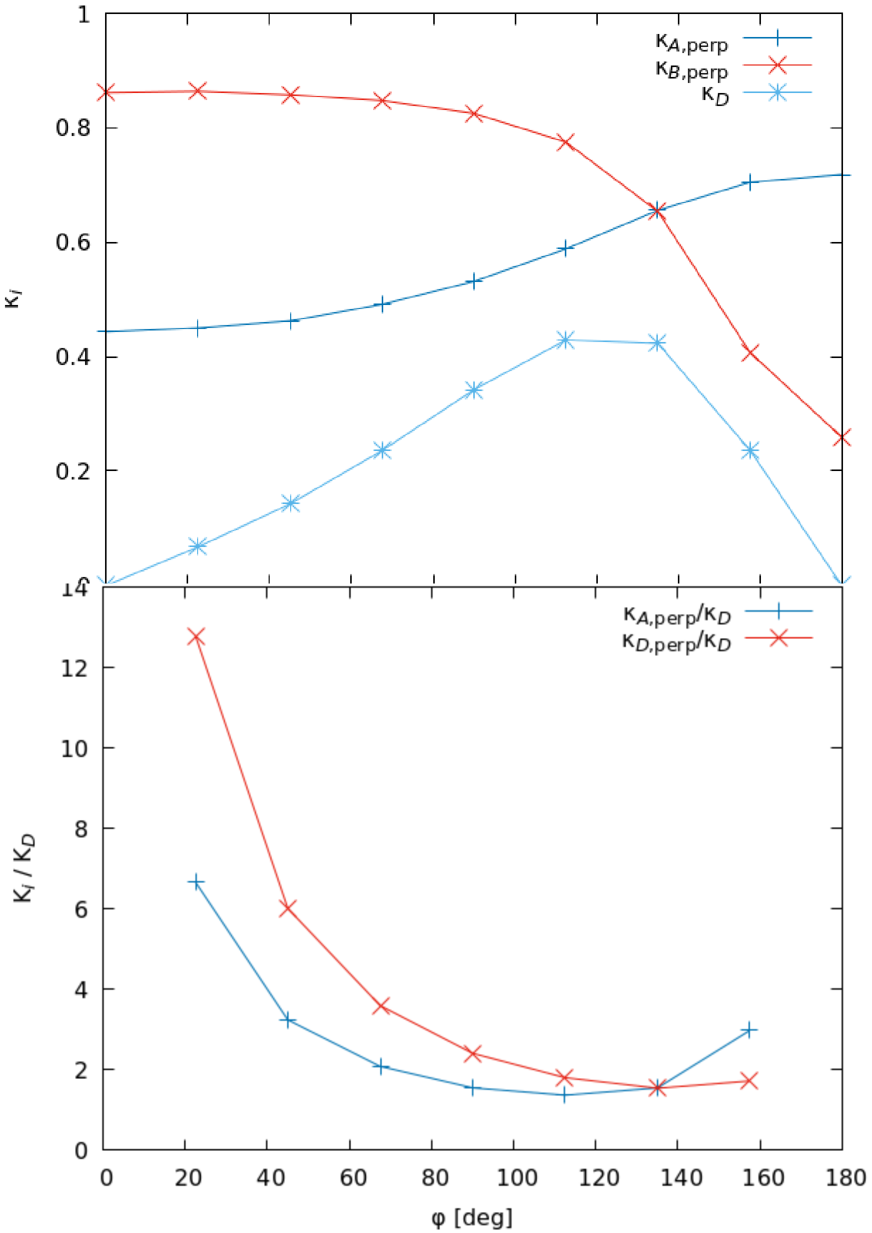
Principle Set-Up



$$D = \frac{\alpha^{00} - \alpha^{01} - \alpha^{10} + \alpha^{11}}{4\boldsymbol{P}\boldsymbol{\kappa}_D^{00}}$$

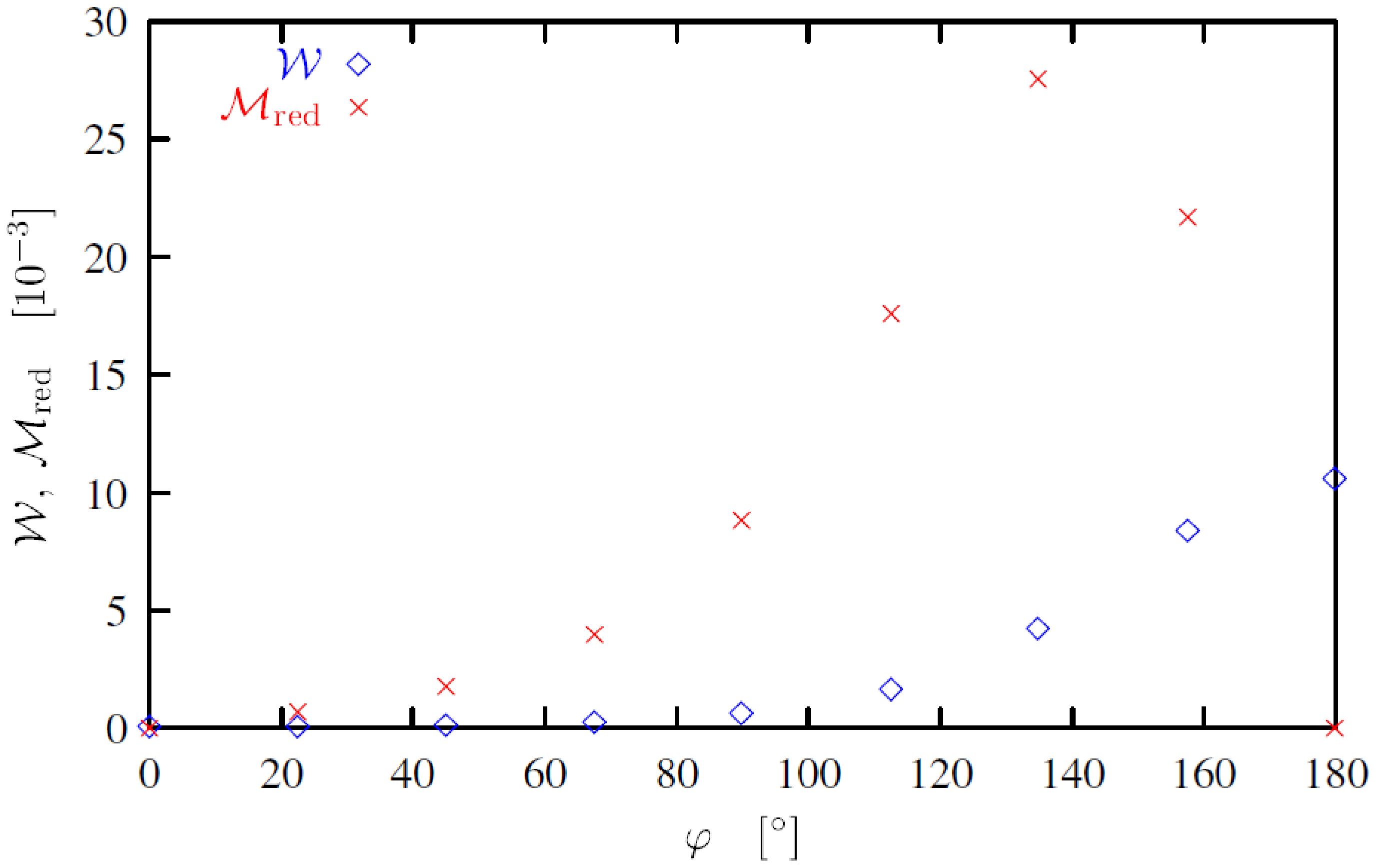
$$\boldsymbol{\kappa}_\xi = \frac{\boldsymbol{K}_\xi}{1 + aK_a + bK_b}$$

D: Detector design – Minimizing and maximizing



← Minimize $\kappa_{A,B}/\kappa_D$

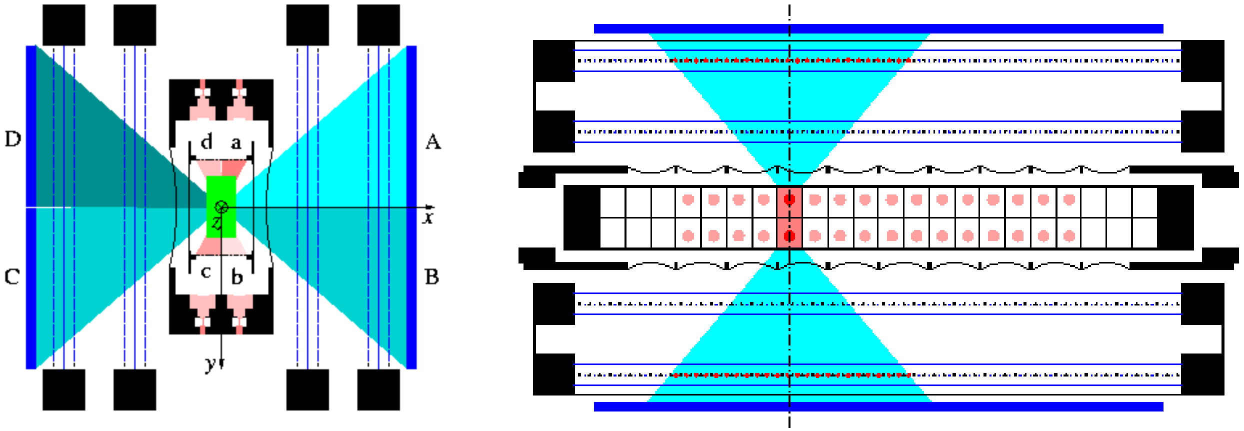
↓ Maximize Figure of merit $w(P\kappa_D)^2$



D: Status

Trine

- Electron tracking



Leading systematics:

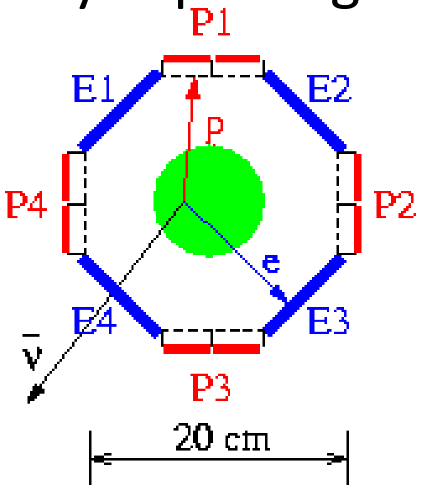
- Inhomogeneity of MWPC
- Asymmetry of beam profile
- Asymmetry of scintillator

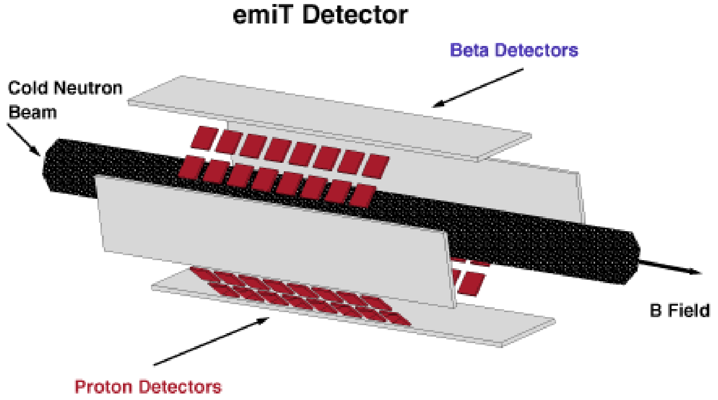
TS et al, Phys. Lett. B 581 (2004) 49

$D = (-2.8\pm6.4^{\text{stat}}\pm3.0^{\text{syst}})\cdot10^{-4}$

emiT

- Fully exploits geometrical optimization





Chupp et al, Phys.Rev. C 86 (2012) 035505

$D = (-0.94\pm1.89^{\text{stat}}\pm0.97^{\text{syst}})\cdot10^{-4}$

Measurements of “0” systematically easier than absolute measurements:

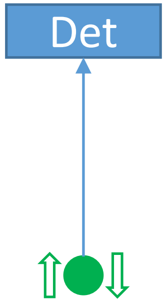
- One “just” needs a symmetric detector
- Most systematic effects scale with the measured asymmetry

Theory says: EDMs are more sensitive than ~~TRI~~ searches in *n* decay … ☹

How to measure spin asymmetries

$$\mathrm{d}W(\boldsymbol{P}_n|E_e,\Omega_e) \propto G_E(E_e)\cdot\left(1 + A\frac{\boldsymbol{P}_n\boldsymbol{p}_e}{E_e}\right)$$

(observe only electron → Ω_ν integrated out. $\frac{\langle\sigma_n\rangle}{\sigma_n} \equiv \boldsymbol{P}_n$)



$$N_{\overset{\Uparrow}{\Downarrow}\uparrow}(E_e) = \mathrm{const}\cdot G_E(E_e)\cdot\int_{\mathrm{Det}}\{1 \pm AP_n\beta(E_e)\cos(\measuredangle(\boldsymbol{P}_n,\boldsymbol{p}_e))\}\mathrm{d}\Omega_e$$

$$\frac{p_e}{E_e} = \beta(E_e) \equiv \frac{v_e}{c}$$

$$k = k(\mathrm{Det},\mathrm{Beam}) = \left\langle \int_{\mathrm{Det}} \cos(\measuredangle(\boldsymbol{P}_n,\boldsymbol{p}_e))\mathrm{d}\Omega_e \right\rangle_{\mathrm{Beam}}$$

$$\frac{N_{\Uparrow\uparrow} - N_{\Downarrow\uparrow}}{N_{\Uparrow\uparrow} + N_{\Downarrow\uparrow}}(E_e) = A\beta(E_e)kP_n$$

We need:

- Polarization P_n
- Identical polarization (and amount of neutrons) in both states
- Precise detector solid angle with respect to polarized neutrons k
- Electron energy $\beta = \beta(E_e)$

Sensitive to neutron flux variations in first order!

If flipping efficiency (probability that a spin gets flipped) $f<1$:

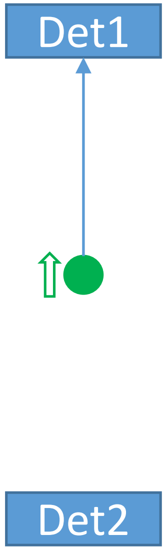
- Polarization after flipper: $P_\Downarrow = -(2f-1)P_\Uparrow$
- Resulting asymmetry:

$$\frac{N_{\Uparrow\uparrow} - N_{\Downarrow\uparrow}}{N_{\Uparrow\uparrow} + N_{\Downarrow\uparrow}} = A\beta kP_n f\cdot\left[1 - A\beta kP_n(1-f) + \mathfrak{O}\left((A\beta kP_n(1-f))^2\right)\right]$$

How to measure spin asymmetries

$$\mathrm{d}W(\boldsymbol{P}_n|E_e,\Omega_e) \propto G_E(E_e)\cdot\left(1 + A\frac{\boldsymbol{P}_n\boldsymbol{p}_e}{E_e}\right)$$

(observe only electron → Ω_ν integrated out. $\frac{\langle\sigma_n\rangle}{\sigma_n} \equiv \boldsymbol{P}_n$)



$$N_{\Uparrow{}^{1}_{2}}(E_e) = \mathrm{const}\cdot G_E(E_e)\cdot\int_{\mathrm{Det}^{1}_{2}}\{1 + AP_n\beta(E_e)\cos(\measuredangle(\boldsymbol{P}_n,\boldsymbol{p}_e))\}\mathrm{d}\Omega_e$$

$$\frac{p_e}{E_e} = \beta(E_e) \equiv \frac{v_e}{c}$$

$$k_i = k(\mathrm{Det}\ i,\mathrm{Beam}) = \left\langle \int_{\mathrm{Det}\ i}\cos(\measuredangle(\boldsymbol{P}_n,\boldsymbol{p}_e))\mathrm{d}\Omega_e\right\rangle_{\mathrm{Beam}}$$

$$\frac{N_{\Uparrow\uparrow}-N_{\Uparrow\downarrow}}{N_{\Uparrow\uparrow}+N_{\Uparrow\downarrow}}(E_e) = A\beta(E_e)kP_n$$

Insensitive to neutron flux variations!

But to Det1≠Det2

We need:

- Polarization P_n
- 2 identical detectors (same efficiency, same response)
- Precise detector solid angle with respect to polarized neutrons k
- Electron energy $\beta = \beta(E_e)$

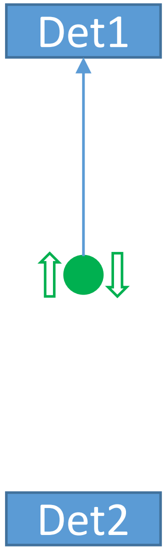
With different detectors k_i: $\bar{k} \equiv \frac{k_1+k_2}{2}$, $\Delta_{k,\mathrm{rel}} \equiv \frac{k_1-k_2}{k_1+k_2}$

- Resulting asymmetry:

$$\frac{N_{\Uparrow\uparrow}-N_{\Uparrow\downarrow}}{N_{\Uparrow\uparrow}+N_{\Uparrow\downarrow}} = A\beta\bar{k}P_n\cdot\left[1 - A\beta\bar{k}P_n\Delta_{k,\mathrm{rel}} + \mathfrak{O}\left((A\beta\bar{k}P_n\Delta_{k,\mathrm{rel}})^2\right)\right]$$

How to measure spin asymmetries

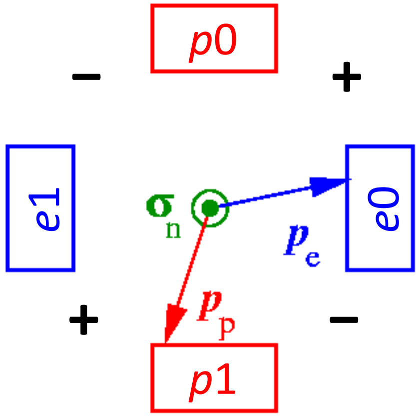
Two detectors + neutron spin flipping



$$A_{\text{exp},1} \equiv \frac{N_{\Uparrow\uparrow} - N_{\Downarrow\uparrow}}{N_{\Uparrow\uparrow} + N_{\Downarrow\uparrow}} = A\beta k_1 P_n f$$

$$A_{\text{exp},2} \equiv \frac{N_{\Uparrow\downarrow} - N_{\Downarrow\downarrow}}{N_{\Uparrow\downarrow} + N_{\Downarrow\downarrow}} = -A\beta k_2 P_n f$$

Note: for D this applies, too:



→Measures both signs of the asymmetry at the same time

- **Analysis by detector, arithmetic average of both results** $A = \frac{A_1 + A_2}{2}$ or **joint fit**
  - → Suppresses neutron flux fluctuations in first order
  - → Compensates some systematics (e.g. shift of beam towards one detector), depending on experiment
- **Super-ratio of detector rates**:

$$A_{\text{SR}} = \frac{1 - \sqrt{R}}{1 + \sqrt{R}} = A\beta k P_n, \quad \text{with} \quad R = \frac{N_{\Uparrow\uparrow} N_{\Downarrow\downarrow}}{N_{\Downarrow\uparrow} N_{\Downarrow\downarrow}}$$

→Neutron flux fluctuations fully cancel

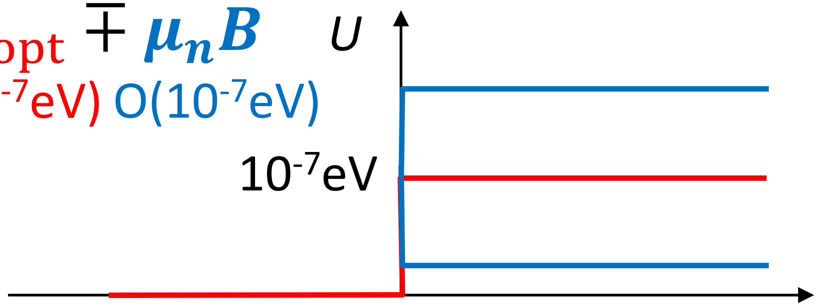
- Both have similar sensitivity to Δ_k and to $f < 1$

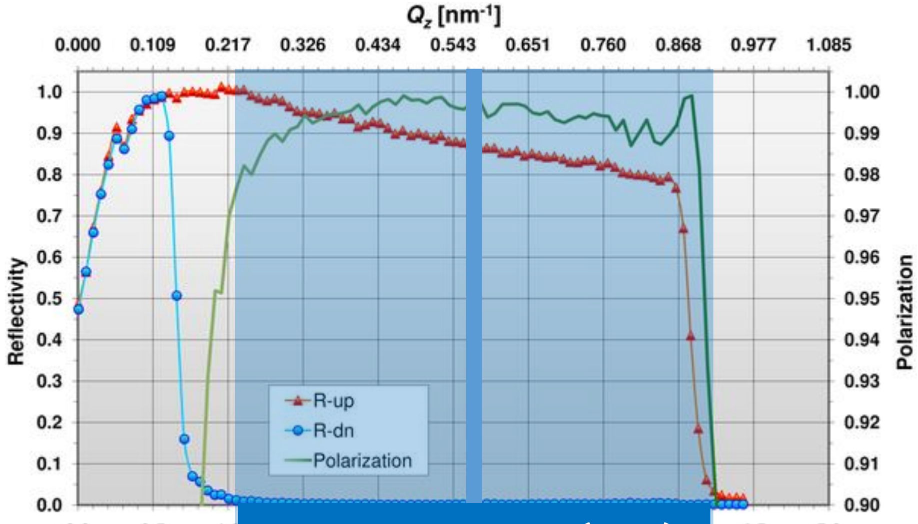
Cold neutron polarization in a nutshell

Magnetic mirrors and supermirrors

$$U = U_{\mathrm{opt}} \mp \boldsymbol{\mu_n B}$$

$O(10^{-7}\mathrm{eV})$ $O(10^{-7}\mathrm{eV})$

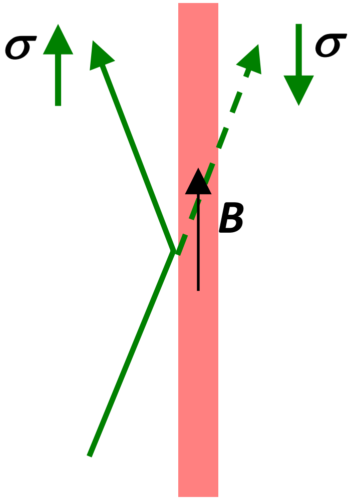


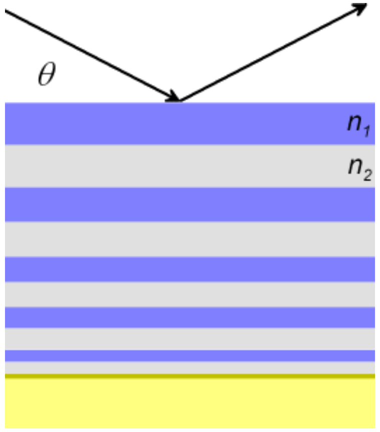


$$q_0, \Delta q = q_0, \Delta q(\lambda, \theta)$$

Match index of refraction

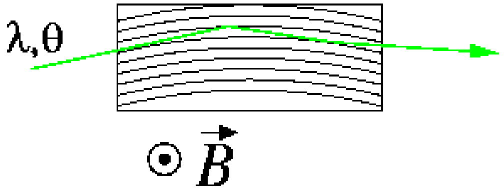
Increase critical angle



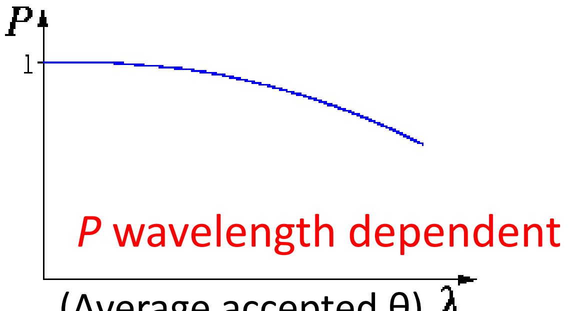


Polarizing benders

- ➢ No passage without reflection

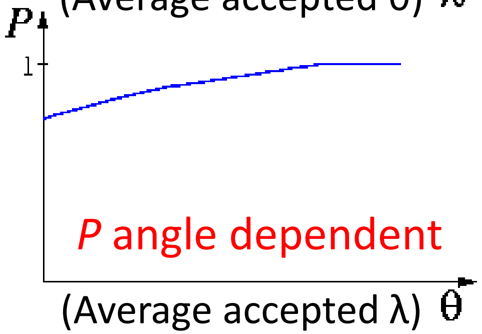


- ➢ Typical performance: $\langle P \rangle_{\mathrm{Beam}} \sim 98\%$



P wavelength dependent

(Average accepted θ)

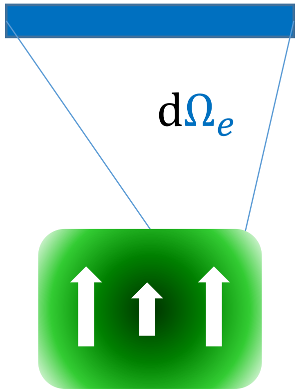


P angle dependent

(Average accepted λ)

Neutron polarization and systematics

Beam average may not be relevant!



$$dW \propto 1 + A\frac{\boldsymbol{P}_n \boldsymbol{p}_e}{E_e}$$

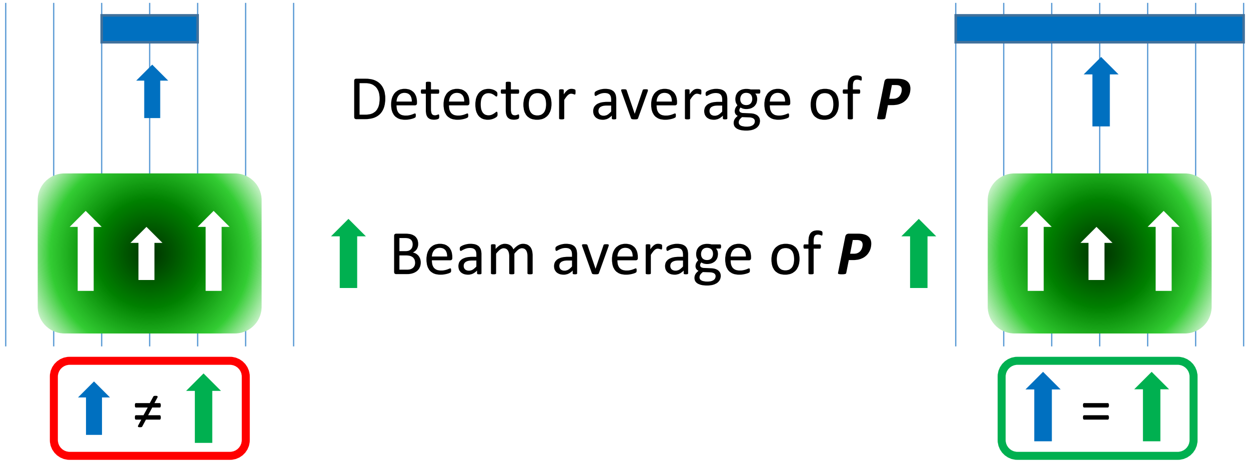
$$\frac{N_\Uparrow - N_\Downarrow}{N_\Uparrow + N_\Downarrow} \propto A\left\langle \int_{\text{Det}} \boldsymbol{P}_n \boldsymbol{p}_e \, d\Omega_e \right\rangle_{\text{Beam}}$$

$$\left\langle \int_{\text{Det}} \boldsymbol{P}_n \boldsymbol{p}_e \, d\Omega_e \right\rangle_{\text{Beam}} \neq \langle \boldsymbol{P}_n \rangle_{\text{Beam}} \left\langle \int_{\text{Det}} \boldsymbol{p}_e \, d\Omega_e \right\rangle_{\text{Beam}}$$

Neutron beams are large, divergent, inhomogeneous

Solutions

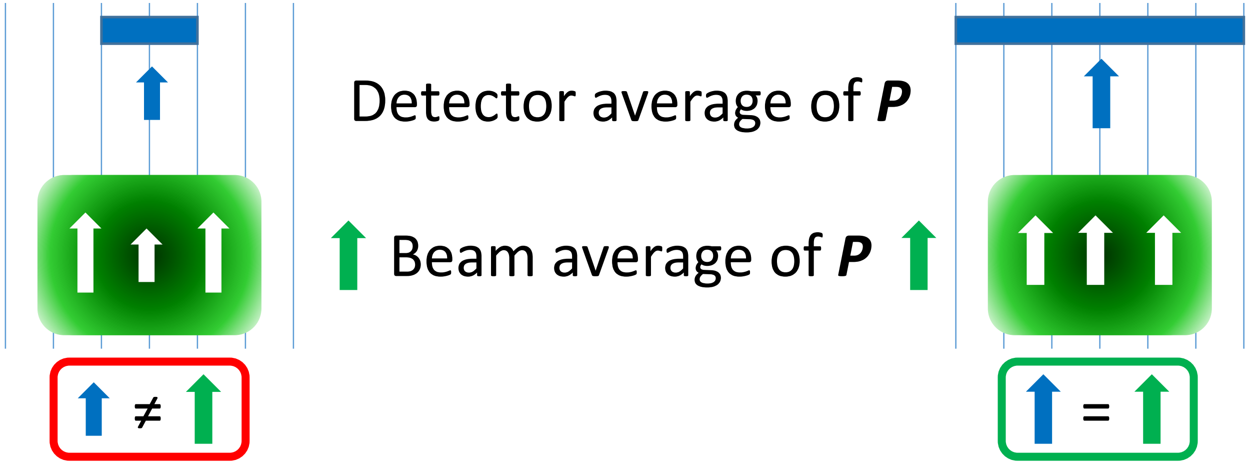
1) Detector averages beam (requires mag field)



Detector average of ***P***

↑ Beam average of ***P*** ↑

2) "Perfect" polarization (here: homogeneous)

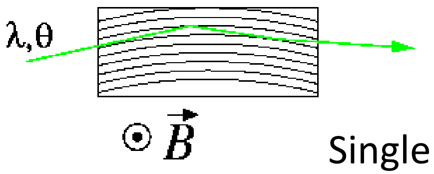


Detector average of ***P***

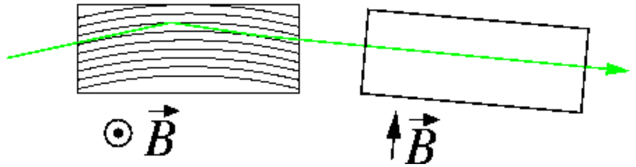
↑ Beam average of ***P*** ↑

(Almost) perfect polarization

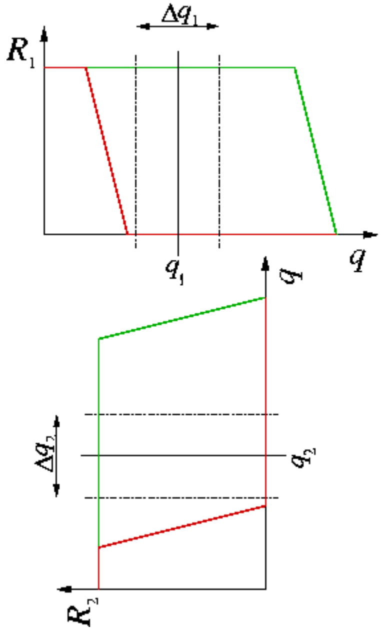
X-SM geometry



Single bender



X-SM geometry

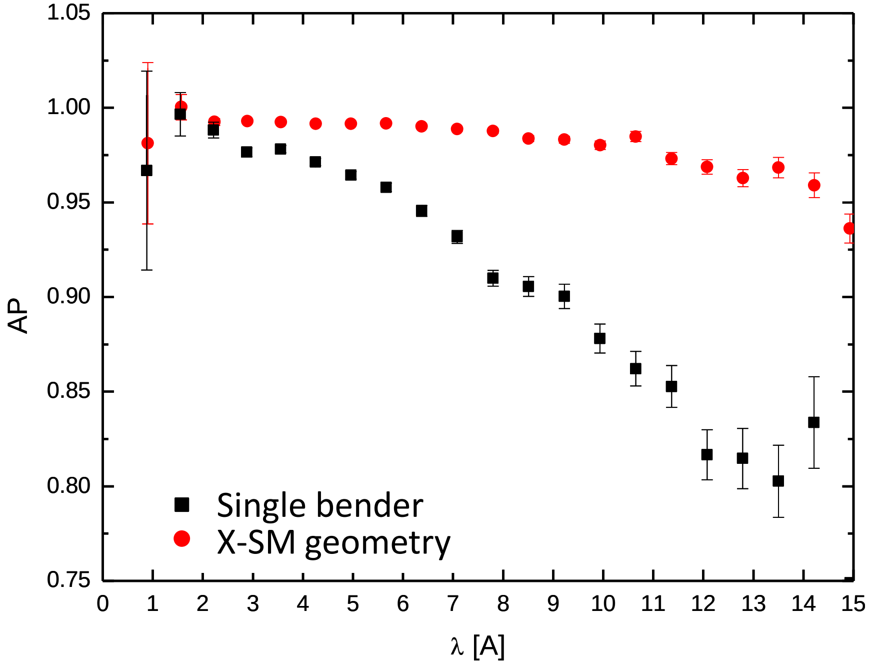


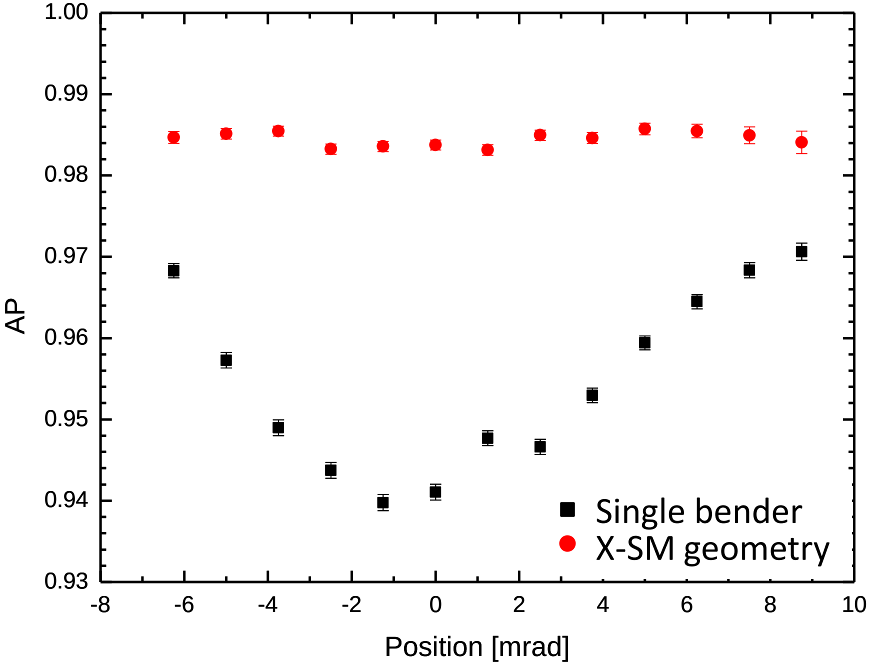
$$P_\times = \frac{P_1 + P_2}{1 + P_1 P_2} \approx 1 - \frac{1}{2}(1-P)^2$$

→ Imperfections suppressed quadratically

→ Dependences on λ, θ strongly reduced

$$T_{1\times 2} = T_1 T_2$$

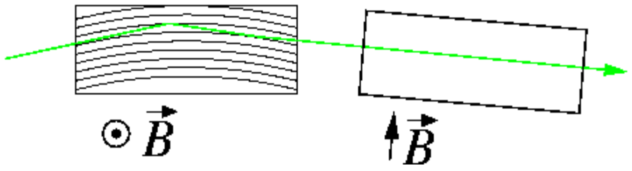




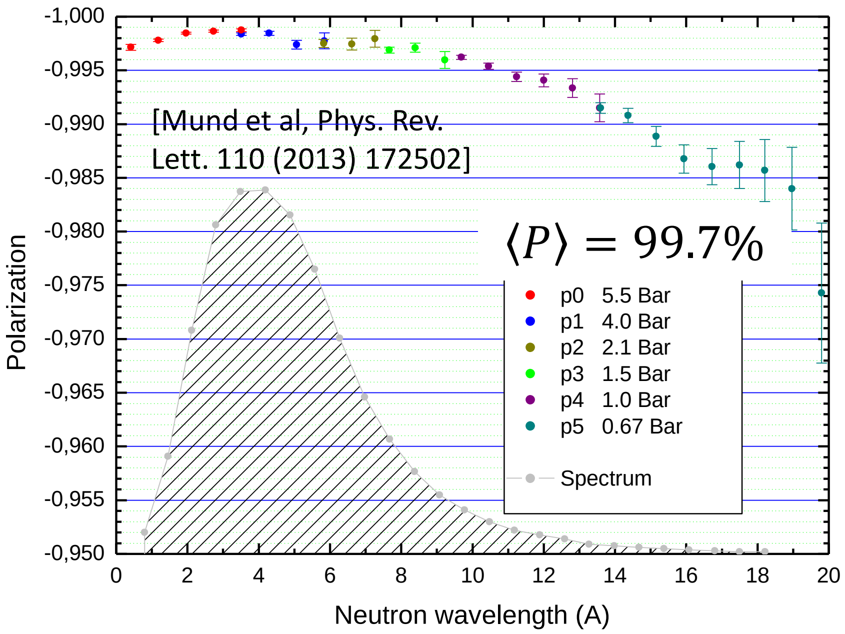
[Kreuz et al, Nucl. Instrum. Meth. A 547 (2005) 583]

(Almost) perfect polarization

X-SM geometry



$$P_\times \approx 1 - \frac{1}{2}(1-P)^2,\ T_{1\times2} = T_1 T_2$$

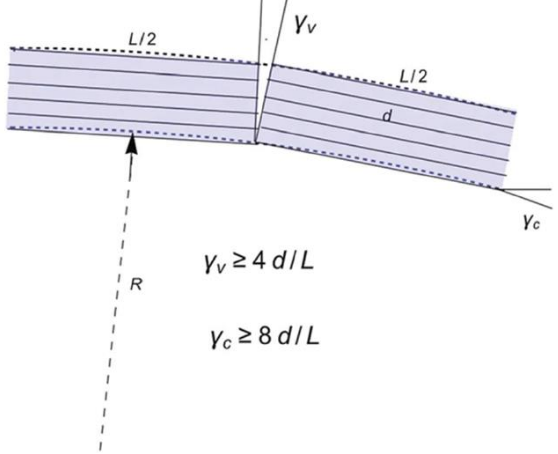


[Mund et al, Phys. Rev. Lett. 110 (2013) 172502]

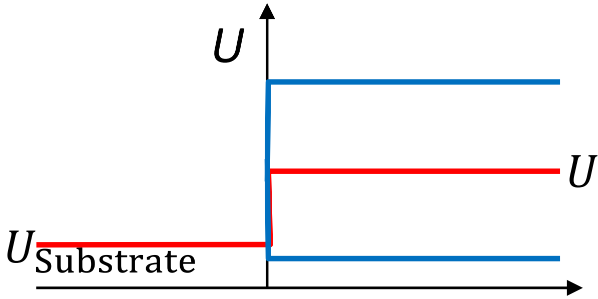
$\langle P \rangle = 99.7\%$

[Kreuz et al, Nucl. Instrum. Meth. A 547 (2005) 583]

Solid-state polarizer with quartz or sapphire substrate

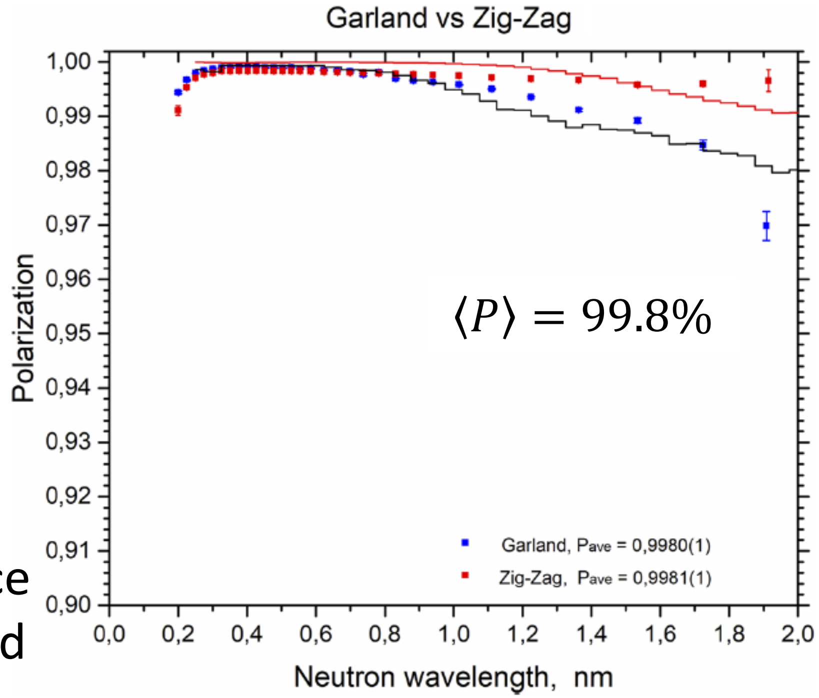


- Finite minimum angle θ, thus q
- $U_{\text{Substrate}} \geq U_{\text{Fe}} - |\mu_n B|$



→Strongly reduced λ, θ dependence

- Compact → high magnetizing field



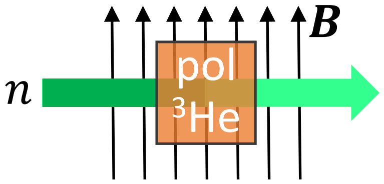
$\langle P \rangle = 99.8\%$

[Petoukhov et al, Rev. Sci. Instrum. 94 (2023) 023304]

Polarization analysis

^{3}He spin filters ^{3}He(n,p) ^{3}H: $\sigma_{\Uparrow\Downarrow} \gg \sigma_{\Uparrow\Uparrow}$

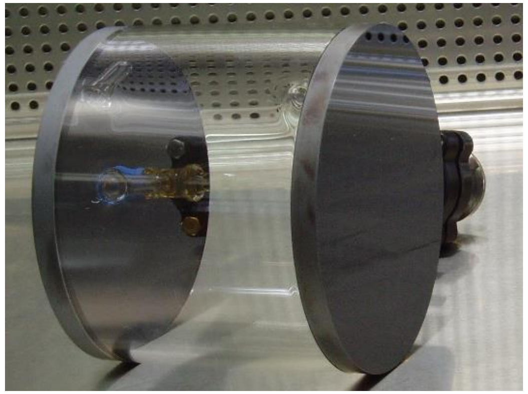
- $\sigma_{\mathrm{c},0} = 5333(7)$ barn, $\sigma_{\Uparrow\Downarrow}/\sigma_{\mathrm{c},0} = 1.010(32)$



$$T_{\substack{\Uparrow\\\Downarrow}\Uparrow} = \frac{1}{2}\exp\left(-[\mathrm{He}]\,l\,\sigma_{\mathrm{c}}(\lambda)\,(1 \mp P_{\mathrm{He}})\right)$$

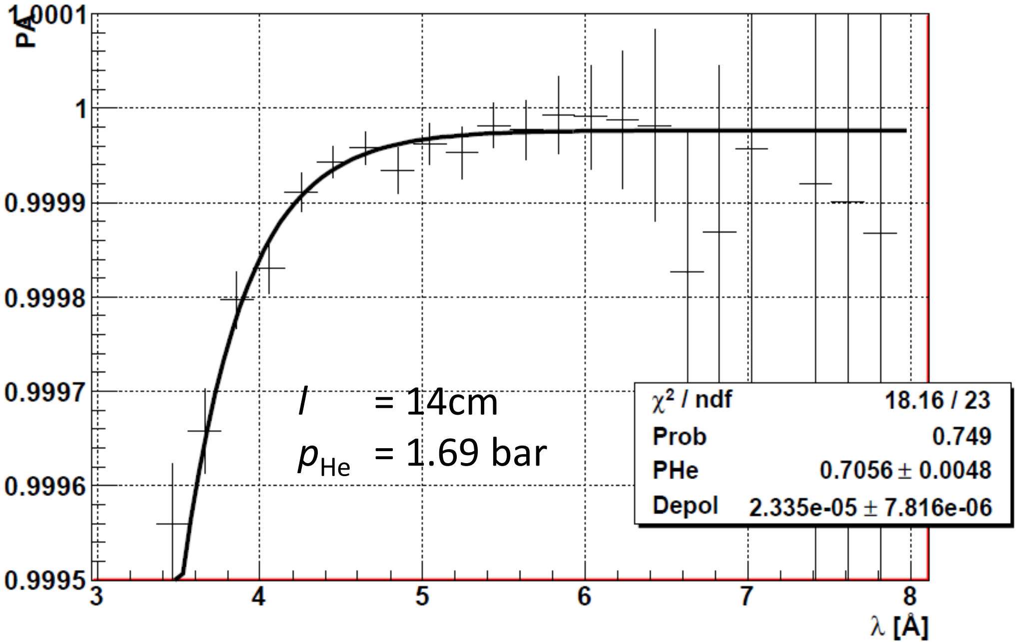
- For unpolarized beam: $O(\lambda) = \dfrac{0.0733\,p\,l\,\lambda}{\text{bar cm Å}}$
  - $\boldsymbol{P_n(\lambda) = \tanh(O(\lambda)P_{He})}$
  - $\boldsymbol{T_n(\lambda) = \exp\left(-O(\lambda)\right)\cosh(-O(\lambda)P_{He})}$
- Relaxation of hyperpolarized ^{3}He polarization:
  - $P_{\mathrm{He}}(t) = P_{\mathrm{He}}(t)\exp\left(-\dfrac{t}{t_0}\right)$
- **In-situ flipping of ^{3}He spin →** separation of neutron spin flip efficiency and polarization:

$$PA = \frac{n_{\Uparrow\Uparrow} - n_{\Uparrow\Downarrow}}{n_{\Uparrow\Uparrow} + n_{\Uparrow\Downarrow}},\quad 2f - 1 = \frac{n_{\Uparrow\Uparrow} - 2n_{\Downarrow\Uparrow} + n_{\Uparrow\Downarrow}}{n_{\Uparrow\Uparrow} - n_{\Uparrow\Downarrow}}$$



Performance

- ~Angle-independent
- $P_n \xrightarrow{O\to\infty} 1.$ P_n >99.99% demonstrated:



C. Klauser, PhD thesis (2013)

- Typical numbers: $P_{\mathrm{He}}(0) > 75\%$, $t_0 > 400$ h, P_{He} loss per in-situ ^{3}He spin flip: $\lesssim 10^{-5}$

Precise detector solid angle?

Infinitely small and far away

- No integration needed:

$$\cos(\measuredangle(\boldsymbol{P}_n,\boldsymbol{p}_e)) = 1 \quad \text{(if aligned)}$$

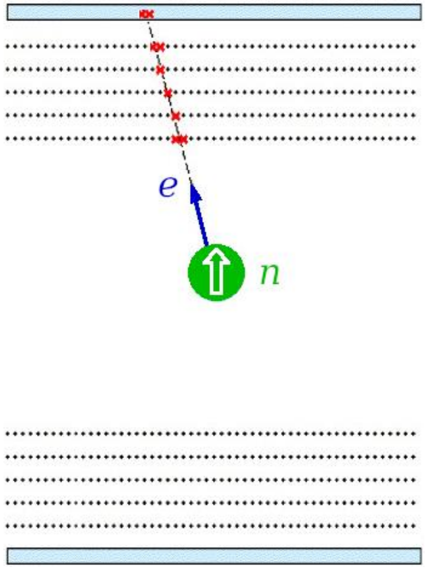
- No statistics
- ***Approximation:*** tracking detector → $\cos(\measuredangle(\boldsymbol{P}_n,\boldsymbol{p}_e))$ known for each track

Infinitely large

- Integration = mean over hemisphere:

$$\langle\cos(\measuredangle(\boldsymbol{P}_n,\boldsymbol{p}_e))\rangle_{2\pi} = \frac{1}{2}$$

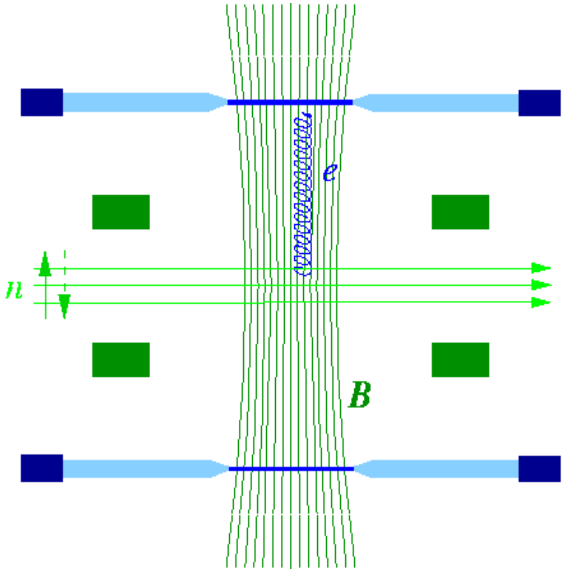
- Full statistics (but dilution factor 1/2)
- ***Realization:*** Strong magnetic field



In between → Monte Carlo

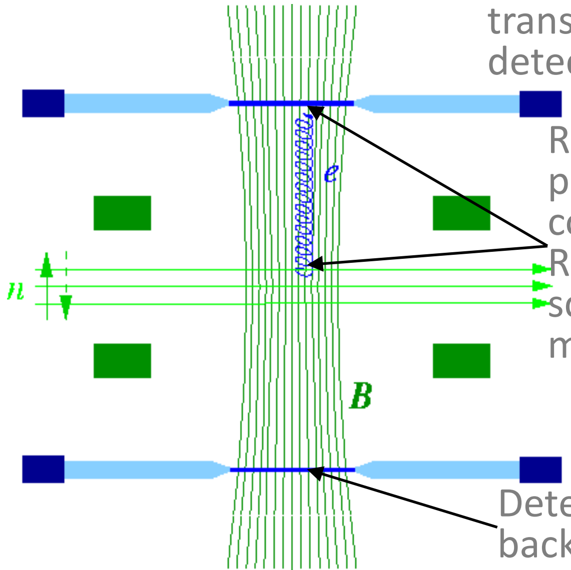
Requires accurate knowledge of neutron distribution and detector response in space

Neutron beams are large, divergent, inhomogeneous



The beauty of (strong) magnetic fields

- Defined solid-angle integration
- Full beam averaging (if large detector)
- Collection of full statistics
- Transport to detectors far away from beam
- Confinement of backscattered particles, too
- Momentum manipulation by **magnetic mirror effect**



All decay electrons transported to 2 “small” detectors far from beam

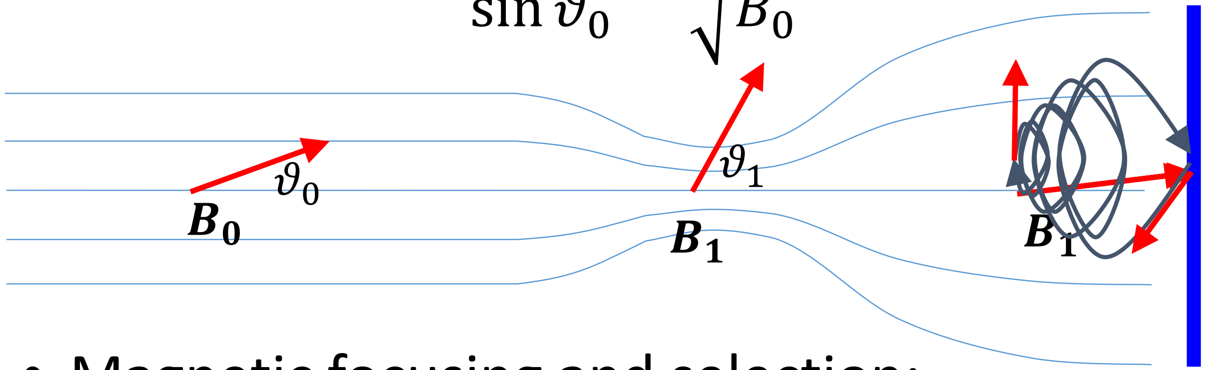
Reduction of backscattering probability by magnetic collimation

Reflection of some back-scattered electrons by magnetic mirror

Detection of remaining backscattered electrons

Magnetic mirror effect

$$\frac{\sin\vartheta}{\sin\vartheta_0} = \sqrt{\frac{B}{B_0}}$$



- Magnetic focusing and selection:
  $\sin\vartheta_C = \sqrt{B_0/B_1}$
- Magnetic alignment/collimation
  →Reduced backscattering probability
  →Improved resolution of electrostatic filters
- Magnetic mirror → part of backscattered particles reflected

Parameters of the SM, Sensitivities to $\lambda = g_\mathrm{A}/g_\mathrm{V}$

$$a = \frac{1-\lambda^2}{1+3\lambda^2}$$

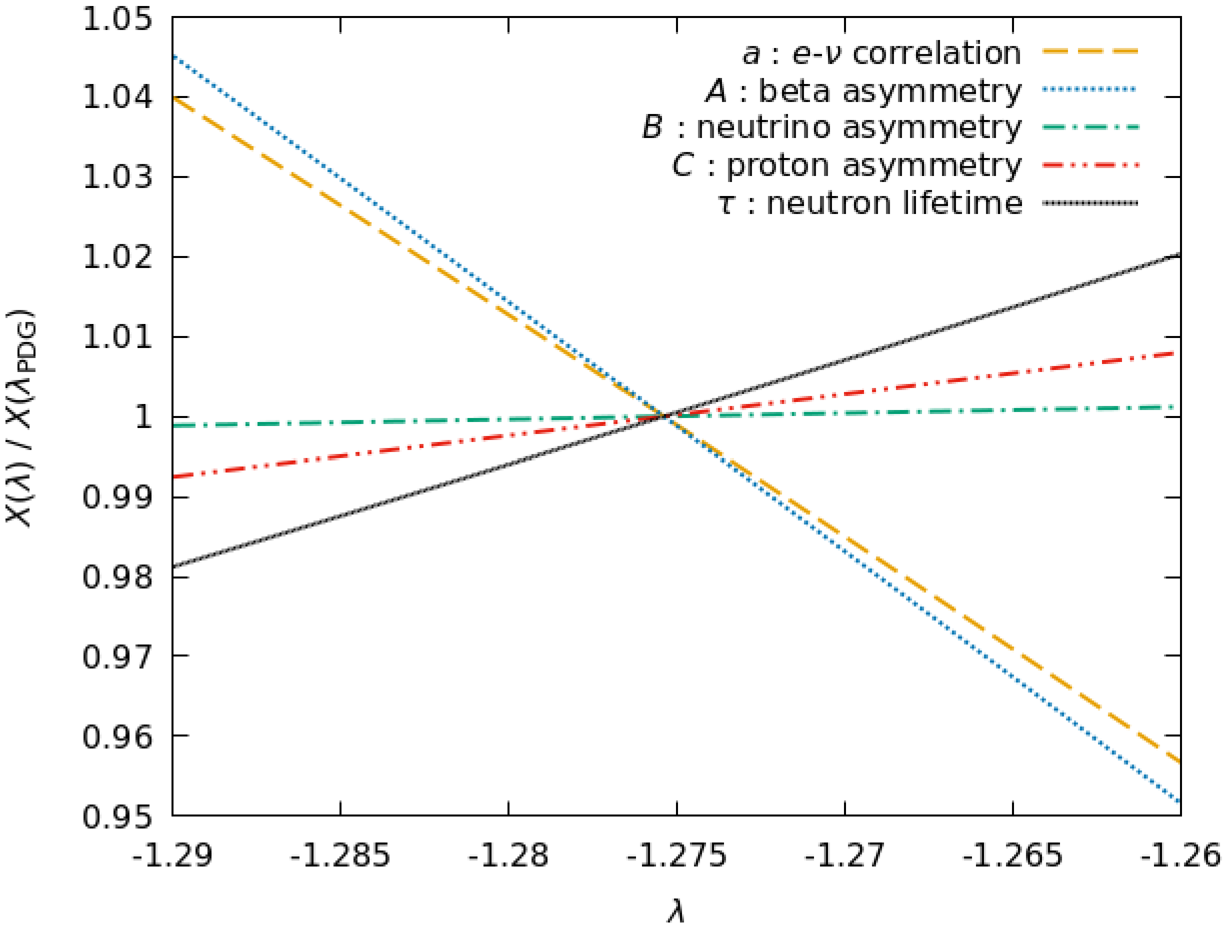
$$A = -2\frac{\lambda(1+\lambda)}{1+3\lambda^2}$$

$$B = 2\frac{\lambda(\lambda-1)}{1+3\lambda^2}$$

$$C = x_C(A+B)$$

$$\tau = \frac{4908.6(1.9)\ \mathrm{s}}{|V_{ud}|^2(1+3\lambda^2)}$$

(Lecture I)



τ and λ necessary to determine SM parameter V_{ud}

- *a*, *A* most sensitive for determination of λ
- *B*, *C* most suitable to search for new physics

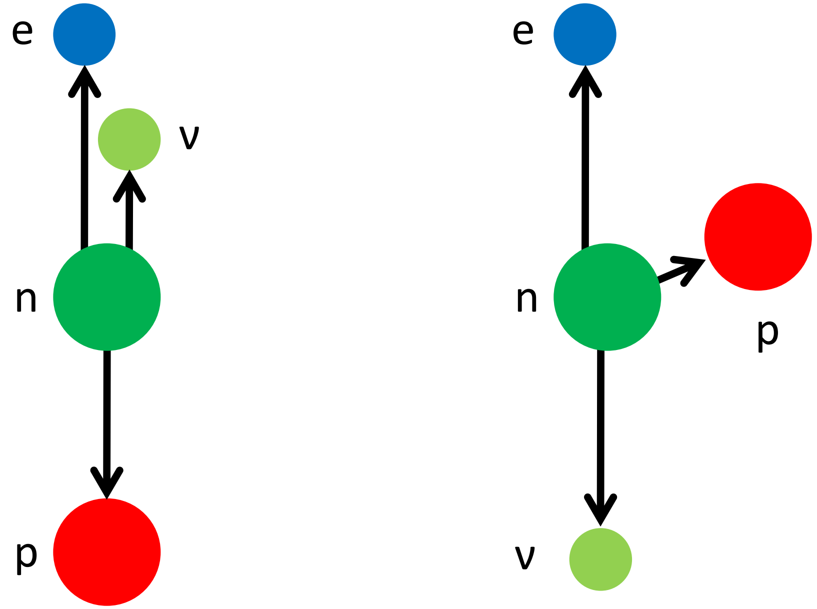
(assuming similar experimental accuracy)

a: $$dW \propto 1 + a\frac{\boldsymbol{p}_e\boldsymbol{p}_\nu}{E_eE_\nu}$$

$e-\nu$ asymmetry and proton spectrum

- Correlation as spatial asymmetry:

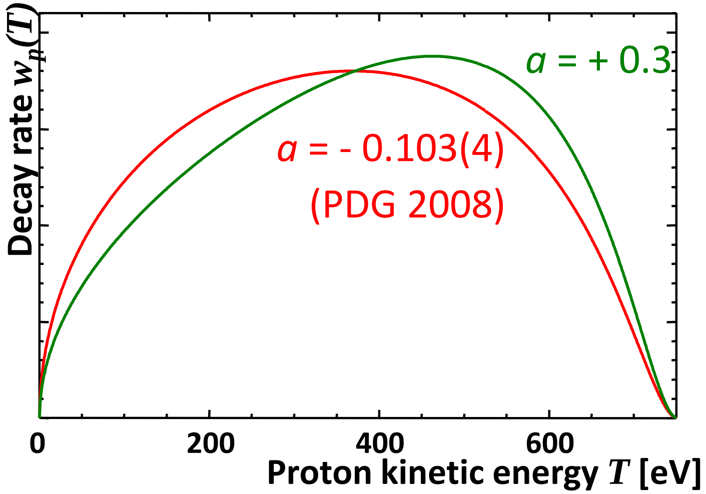
$$a \propto \frac{n_{\uparrow\uparrow} - n_{\uparrow\downarrow}}{n_{\uparrow\uparrow} + n_{\uparrow\downarrow}}$$



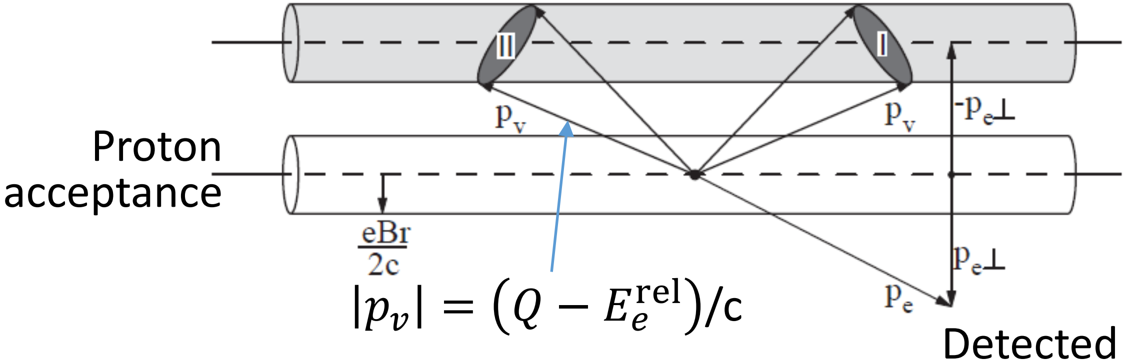
$a > 0$ Proton spectrum shifted to higher energy
$a < 0$ Proton spectrum shifted to lower energy

Two principles of measurement

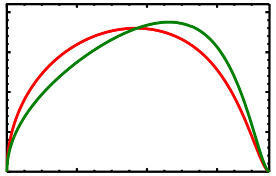
- Proton spectrum (Example aSPECT)



- $e-p$ Asymmetry (example aCORN)



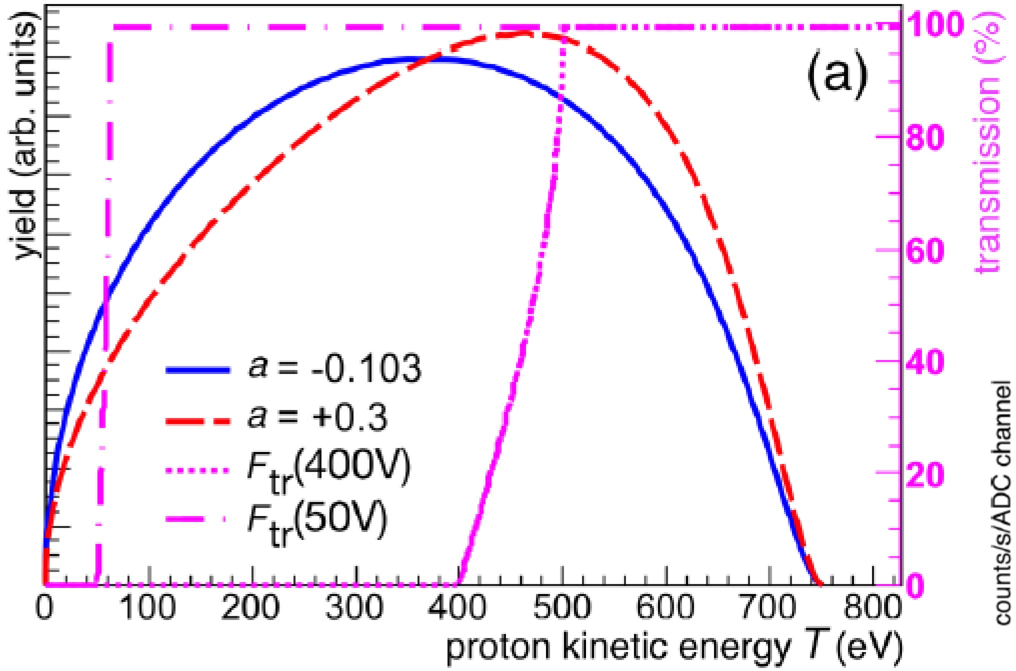
→Asymmetry I versus II from *p*-TOF



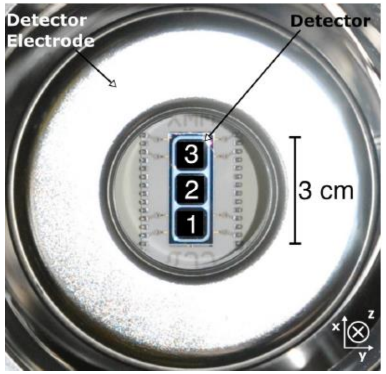
a: aSPECT

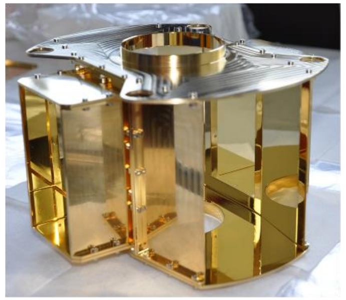
Integral proton spectrum from MAC-E filter

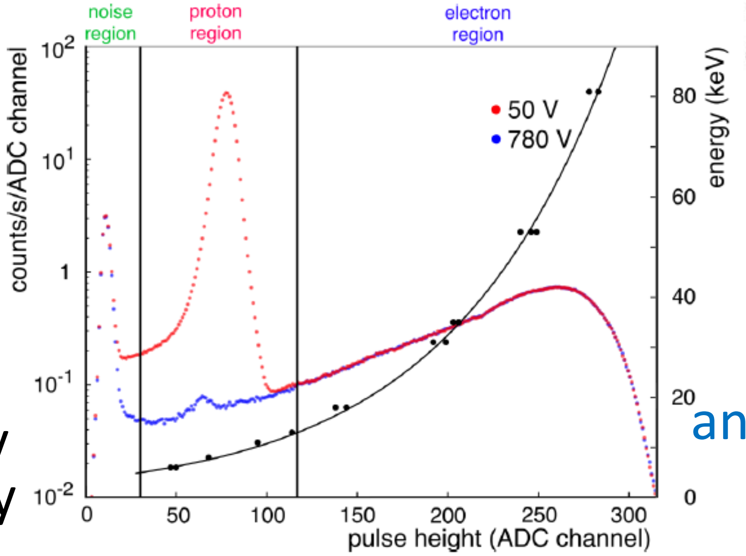
- Magnetic Adiabatic Collimation 2.2 T → 0.44 T sharpens transmission function of electrostatic filter

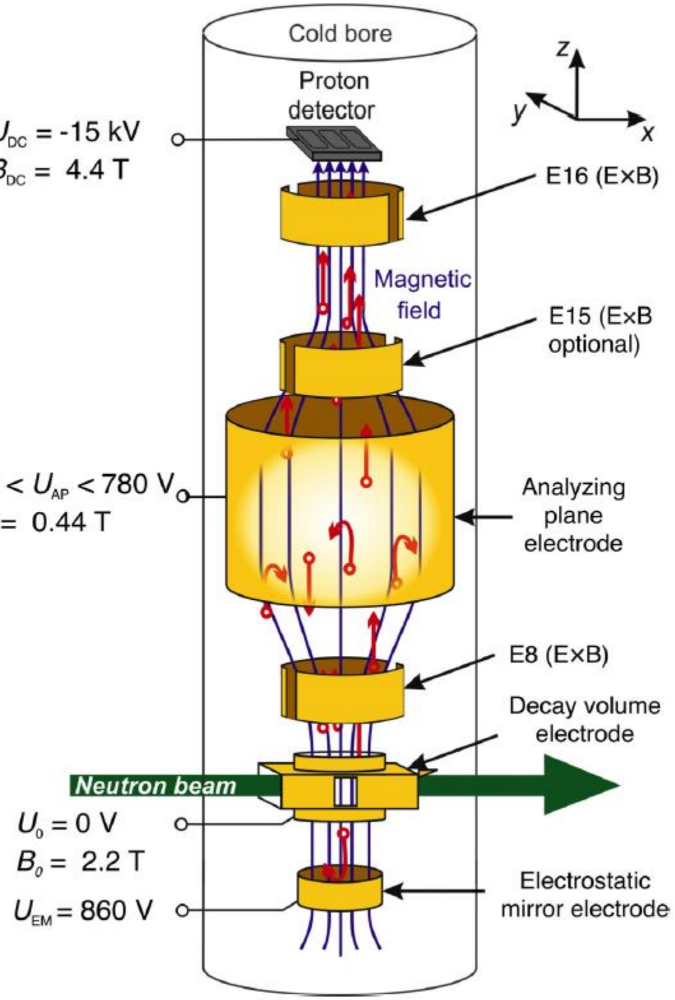


- Stringent requirements on magnetic field, electrodes work functions, detector energy dependence, vacuum, high-voltage stability





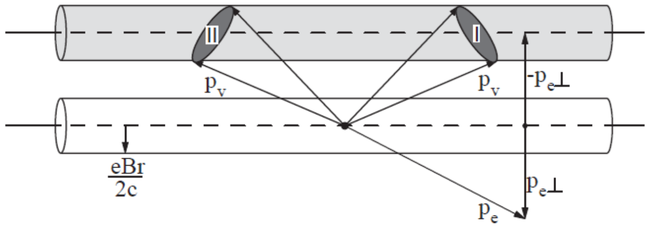


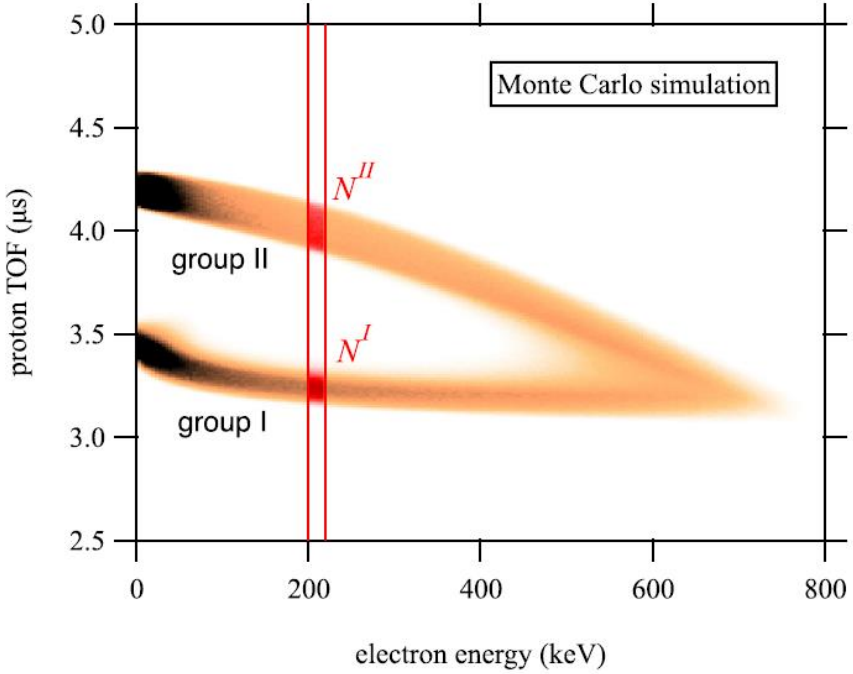


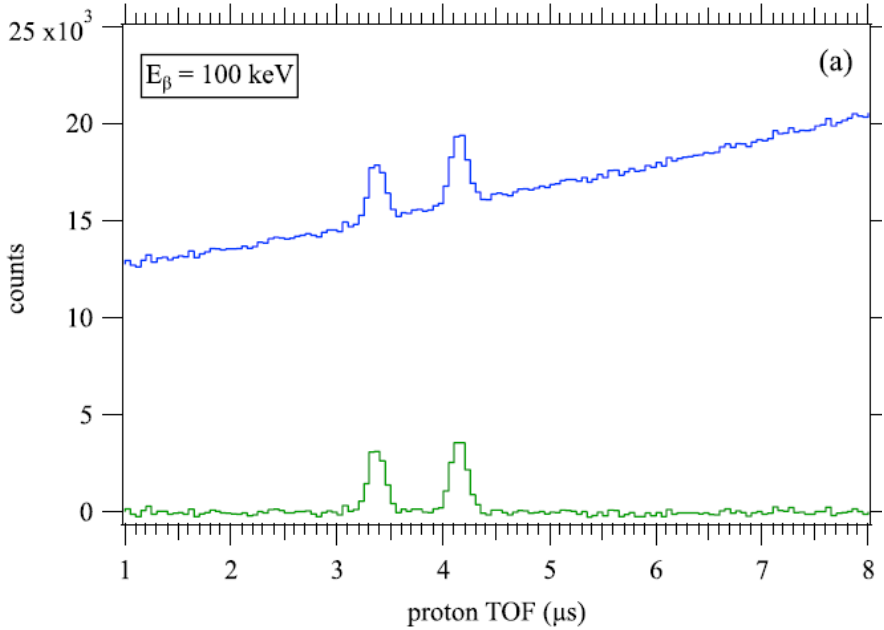
$a = -0.10402(82)$ $(b = 0)$
and correlated (a, b) analysis

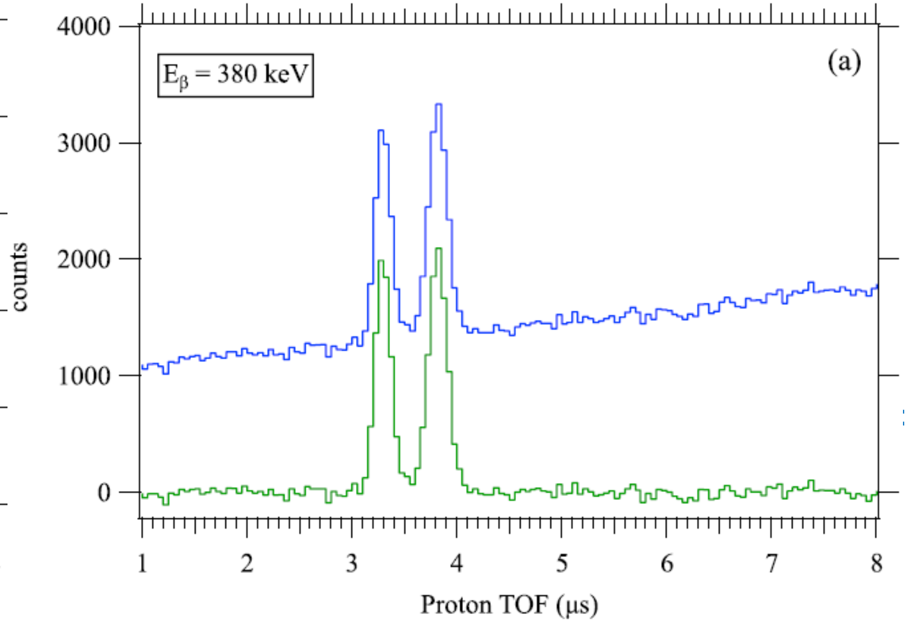
Beck et al., Phys. Rev. C 101 (2020) 055506
Beck et al., arXiv:2308.16170

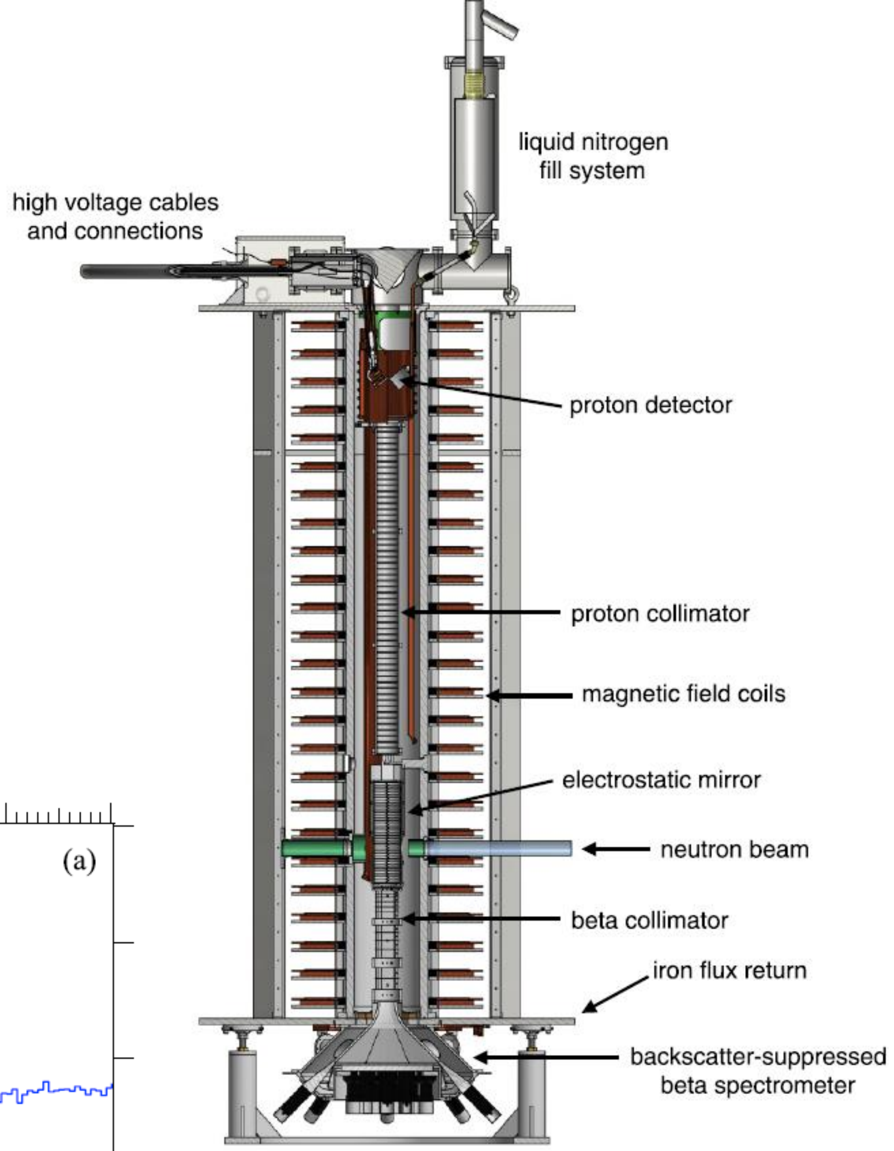
a: aCORN





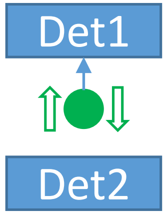






$-0.10859(125^{\mathrm{stat}})(133^{\mathrm{sys}})$

Darius et al., Phys. Rev. Lett. 119 (2017) 042502
Hassan et al., Phys. Rev. C 103 (2021) 045502
Wietfeldt et al, arXiv:2306.15042



Beta asymmetry A

[Burgy et al, Phys. Rev. 120 (1960) 1829]

Early experiments

- Coincidence of electron and proton (needed close to reactor) to reduce background
  - Proton detection by electron multiplication
  - Electron detection by scintillator

→Small decay volume, low rate

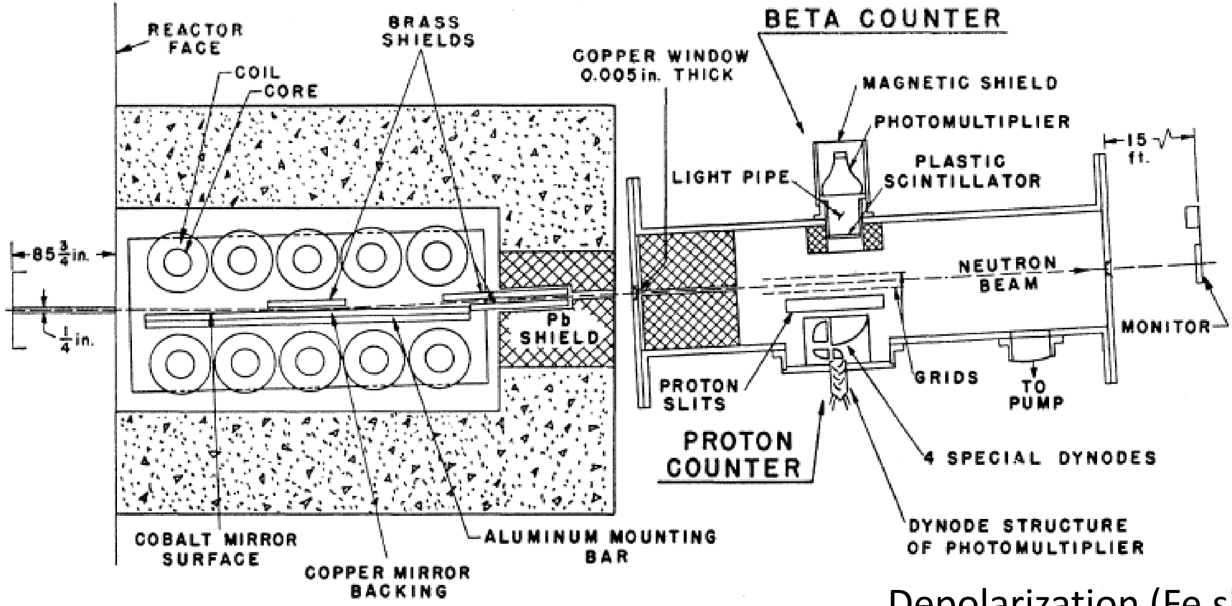
→Not compatible with 2 symmetric detectors

→One needs to collect all protons in order to integrate out neutrino:

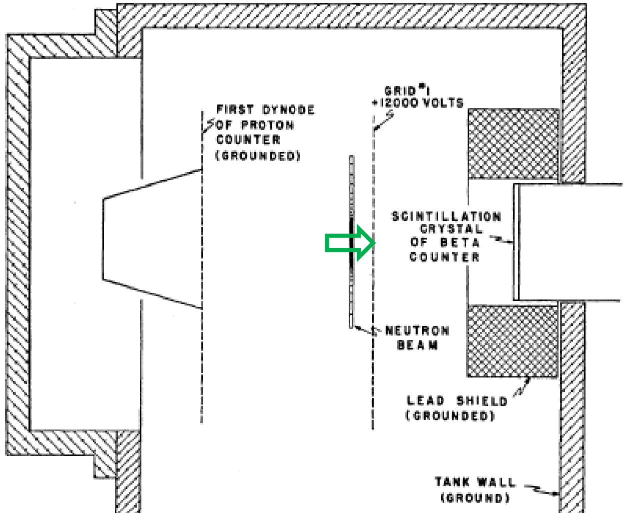
$$\mathrm{d}W(\langle\boldsymbol{\sigma}_{\boldsymbol{n}}\rangle|E_e,\Omega_e,\Omega_\nu) \propto \left\{1 + a\frac{\boldsymbol{p}_{\boldsymbol{e}}\boldsymbol{p}_{\boldsymbol{\nu}}}{E_eE_\nu} + \frac{\langle\boldsymbol{\sigma}_{\boldsymbol{n}}\rangle}{\sigma_n}\left(A\frac{\boldsymbol{p}_{\boldsymbol{e}}}{E_e} + B\frac{\boldsymbol{p}_{\boldsymbol{\nu}}}{E_\nu}\right)\right\}$$

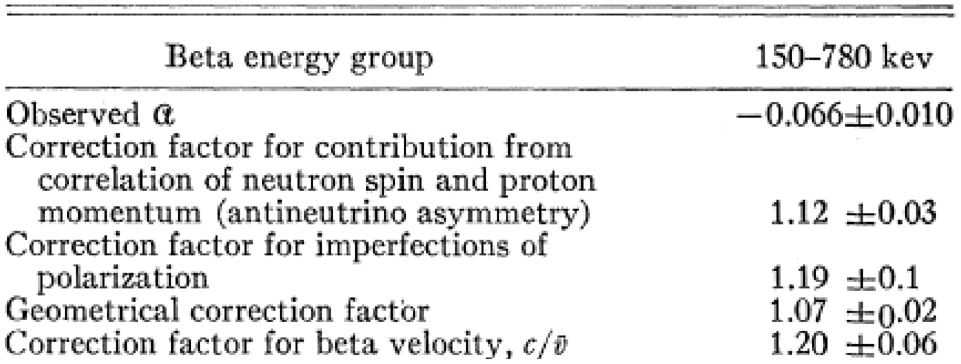
Incomplete collection → systematics from B and a

Example: First measurement of A (& B, D)



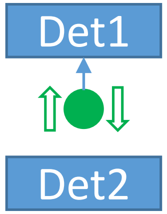
Depolarization (Fe sheet) instead of flipper





Beta energy group	150–780 kev
Observed $\mathfrak{A}$	−0.066±0.010
Correction factor for contribution from correlation of neutron spin and proton momentum (antineutrino asymmetry)	1.12 ±0.03
Correction factor for imperfections of polarization	1.19 ±0.1
Geometrical correction factor	1.07 ±0.02
Correction factor for beta velocity, $c/\bar{v}$	1.20 ±0.06
$\mathfrak{A}$	

$$A = -0.114(19),\ \frac{\Delta A}{A} = 17\%$$



A: PERKEO [1986]

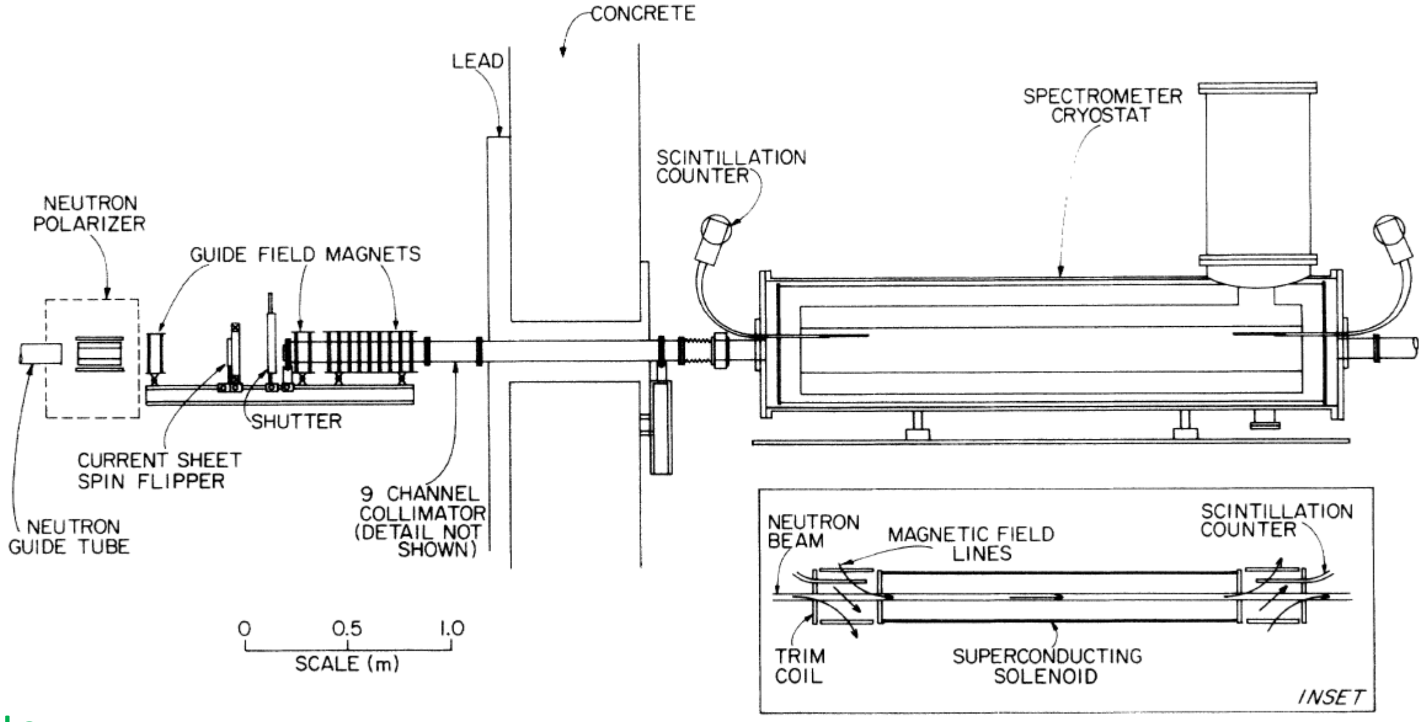
[Bopp et al, Phys. Rev. Lett. 56 (1986) 919]

New possibilities and new concept

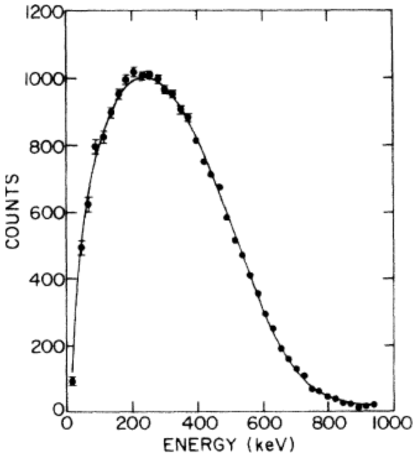
- Cold neutron guide of 120 m length
- Supermirror polarizer

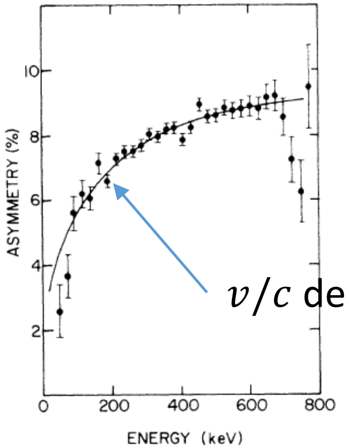
PERKEO spectrometer:

- Longitudinal magnetic field (1.5 T, 1.7 m)
  - ➢ Strongly enhanced counting rate
  - ➢ Strongly improved signal/background
  - ➢ Accurate knowledge of solid angle
  - ➢ Reconstruction of electron backscatter events after transport to other detector



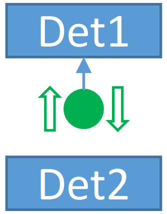
- Downstream detector difficult to shield
- Field maximum in center, decreases to both sides to avoid traps
  - ➢ Magnetic mirror effect: 10% correction on asymmetry
  - ➢ (Inverse) magnetic mirror effect reduces backscattering
- Background subtraction with shutter after pol
  - ➢ Downstream beam-related BG not included





v/c dependence

$$A = -0.1146(19), \frac{\Delta A}{A} = 1.7\%$$



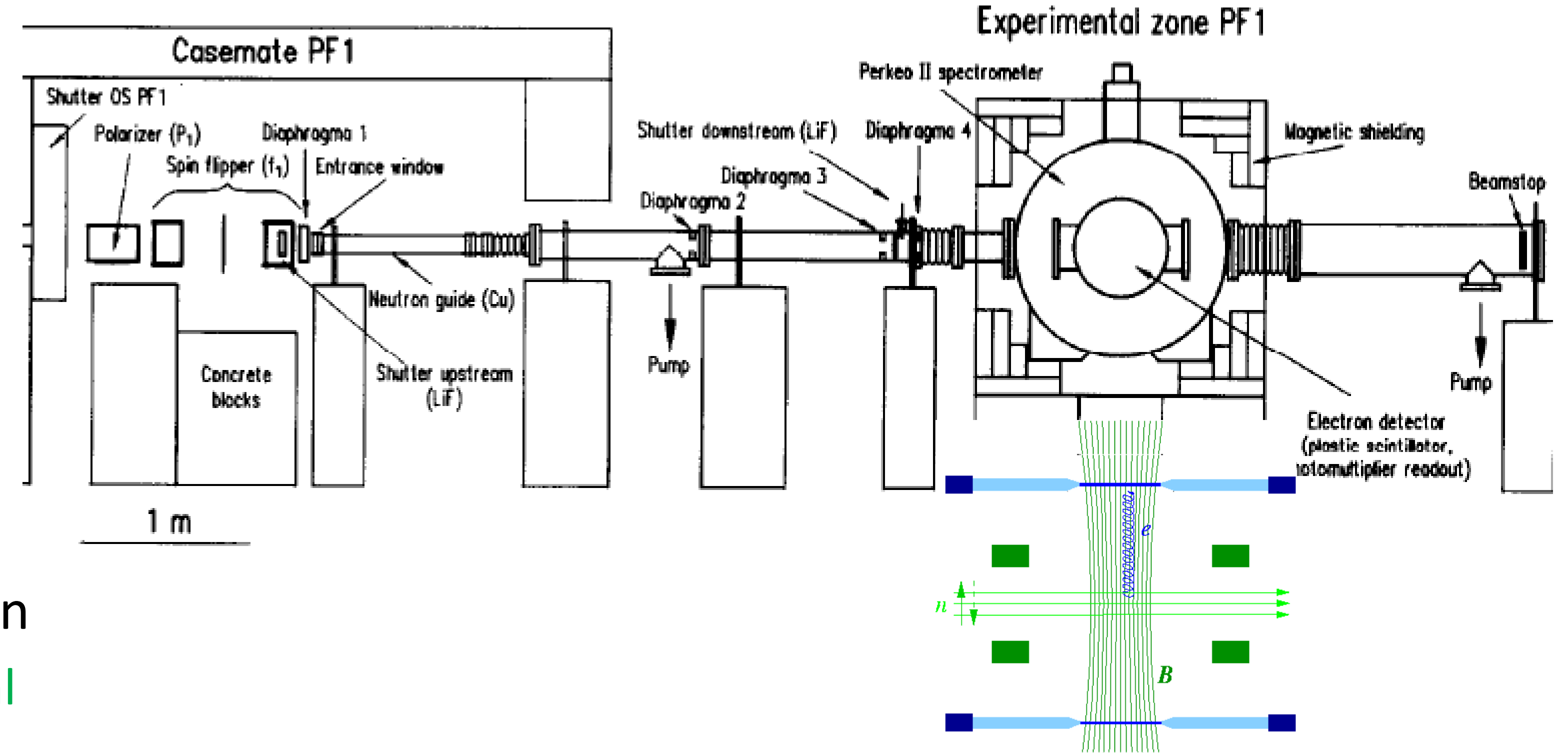
A: PERKEO II [1997]

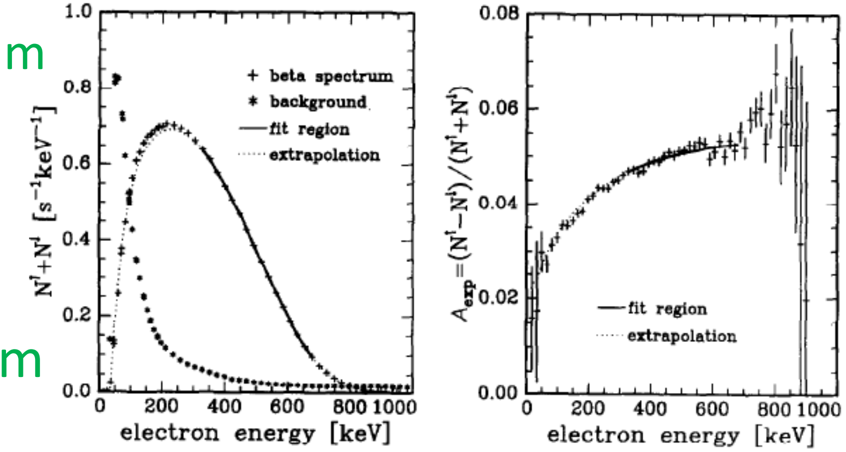
[Abele et al, Phys. Lett. B 407 (1997) 212]

Improvements to PERKEO

- **Magnetic field perpendicular** to neutron beam (1.1 T, Ø of coils 1 m)
  - ➢ Detectors at larger distance to beam → Signal/Background in ROI 20:1
  - ➢ Decays only close to maximum → Reduced magn. mirror effect
- **Two shutters** for background estimation
  - ➢ **Upstream shutter** → only environmental background
  - ➢ **Downstream shutter** → (enhanced) beam related background
  - ➢ **Strong n and γ sources along beam line** → same shape as from downstr. shutter (multiple scattering to reach detectors)

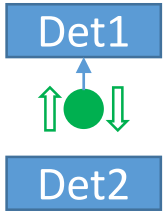
→ Extrapolation of background spectrum above beta endpoint into fit region





Effect	correction	error
Polarization	+2.34%	0.75%
Background	+1.55%	0.45%
Detector response	-0.20%	0.25%
Other sys + rad corr	+0.19%	0.10%
Statistics		0.42%

$$A = -0.1189(12),\ \frac{\Delta A}{A} = 1.0\%$$

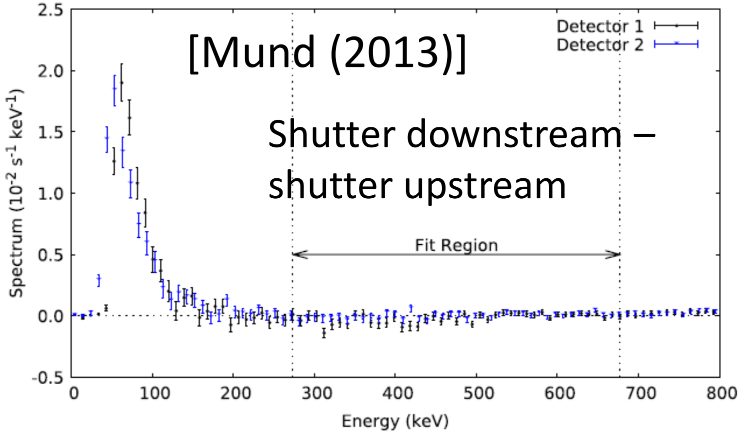


A: PERKEO II [1997 → 2002 → 2013]

[Abele et al, Phys. Lett. B 407 (1997) 212]
[Reich et al, Nucl. Instr. Meth. A 440 (2000) 535,
Abele et al, Phys. Rev. Lett. 88 (2002) 211801]
[Mund et al, Phys. Rev. Lett. 110 (2013) 172502]

Improvements [1997] → [2002]

- **Cutter for long wavelengths** (>13Å)
  - ➢ Suppression of lowly polarized neutrons
- **"Horse" for polarization measurement, non-depolarizing chopper**
  - ➢ Separately benchmarked against ^{3}He spin filter and polarized proton spin filter
- **Improved beam line and shielding**
  - ➢ Beam stop further away
  - ➢ Removal of scattered neutrons
  - → Sg/beam-related Bg improved by factor 3

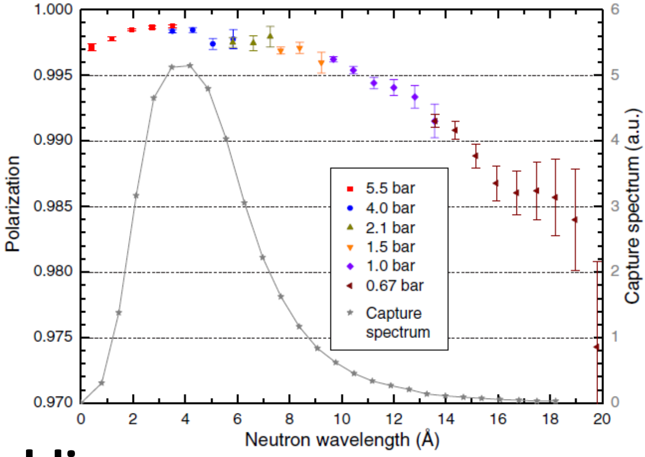


[Mund (2013)]

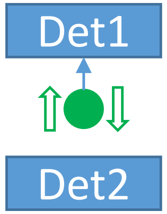
Shutter downstream – shutter upstream

Improvements [2002] → [2013]

- **X-SM polarizer, ^{3}He spin filters**
  - ➢ Strongly reduced spatial and λ_n dependence, correction and error
- **New beam line PF1B, 4 × higher flux**
  - ➢ Part traded for systematics (X-SM)
- **Further improved beam line and shielding**
  - → Sg/beam-related Bg improved by factor 8



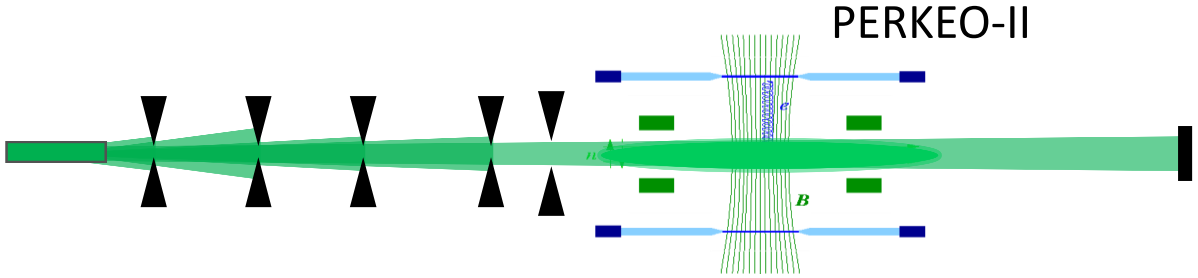
	[1997]		[2002]		[2013]	
	Cor [%]	**Err [%]**	**Cor [%]**	**Err [%]**	**Cor [%]**	**Err [%]**
Polarization	+2.34	0.75	+1.4	0.31	+0.30	0.14
Background	+1.55	0.45	+0.5	0.25	+0.10	0.10
Detector response	–0.20	0.25	–0.24	0.25	–0.13	0.26
Other systematics	+0.10	0.10	+0.29	0.17	–0.06	0.02
Total systematics		**0.91**		**0.51**		**0.31**
Radiative cor.	*+0.09*	0.01	*+0.09*	0.05	–0.11	0.05
Statistics		**0.42**		**0.45**		**0.38**
Total error		1.0		0.68		0.49
$\boldsymbol{A}$	$\mathbf{-0.1189(12)}$		$\mathbf{-0.1189(7)}$		$\mathbf{-0.11972(^{+53}_{-65})}$	



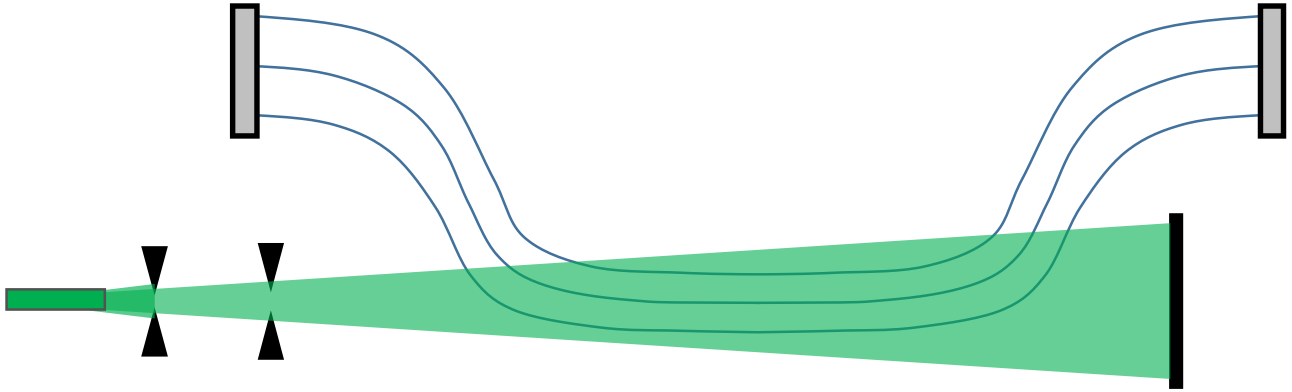
A: PERKEO III

[Märkisch et al, Phys. Rev. Lett. 122 (2019) 242501,
Märkisch et al, Nucl Instr. Meth. A 611 (2009) 216]

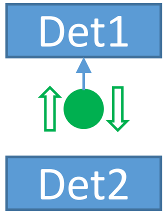
- PERKEO II finally limited by statistics. Strong cut in beam divergence to minimize background



- **PERKEO III**: Accept full beam divergence, long decay volume → Factor 100 in event rate



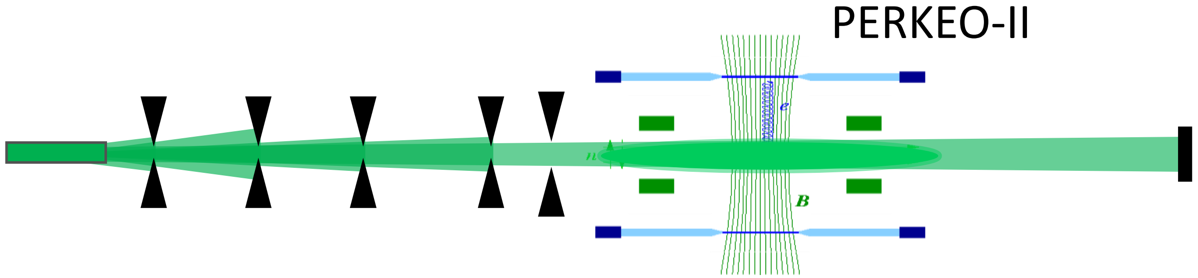
- Large beam → can accept large gyration radii, lower magnetic field (160 mT), normal conducting
- Detectors can be placed far from beam compared to PERKEO I. However, larger area detectors, downstream detector difficult to shield



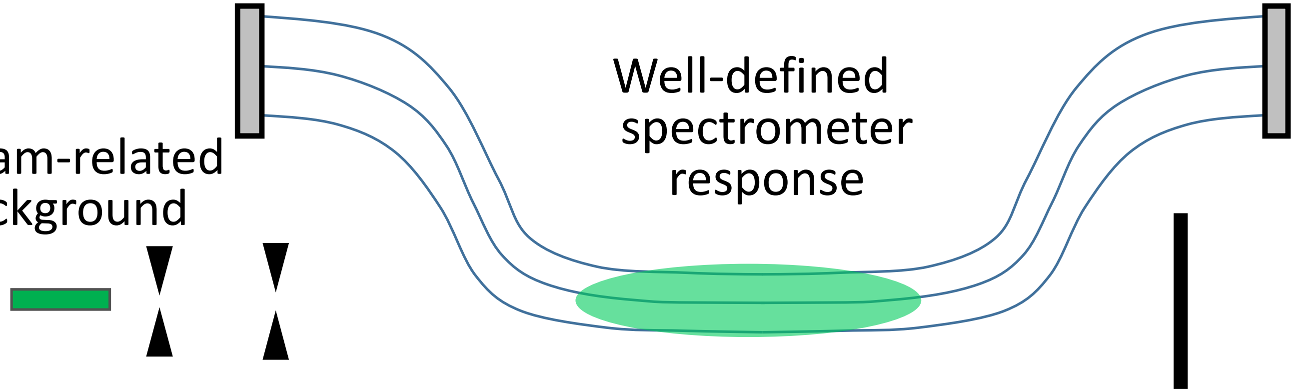
A: PERKEO III

[Märkisch et al, Phys. Rev. Lett. 122 (2019) 242501,
Märkisch et al, Nucl Instr. Meth. A 611 (2009) 216]

- PERKEO II finally limited by statistics. Strong cut in beam divergence to minimize background



- **PERKEO III**: Accept full beam divergence, long decay volume → Factor 100 in event rate



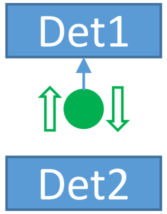
No
beam-related
background

Well-defined
spectrometer
response

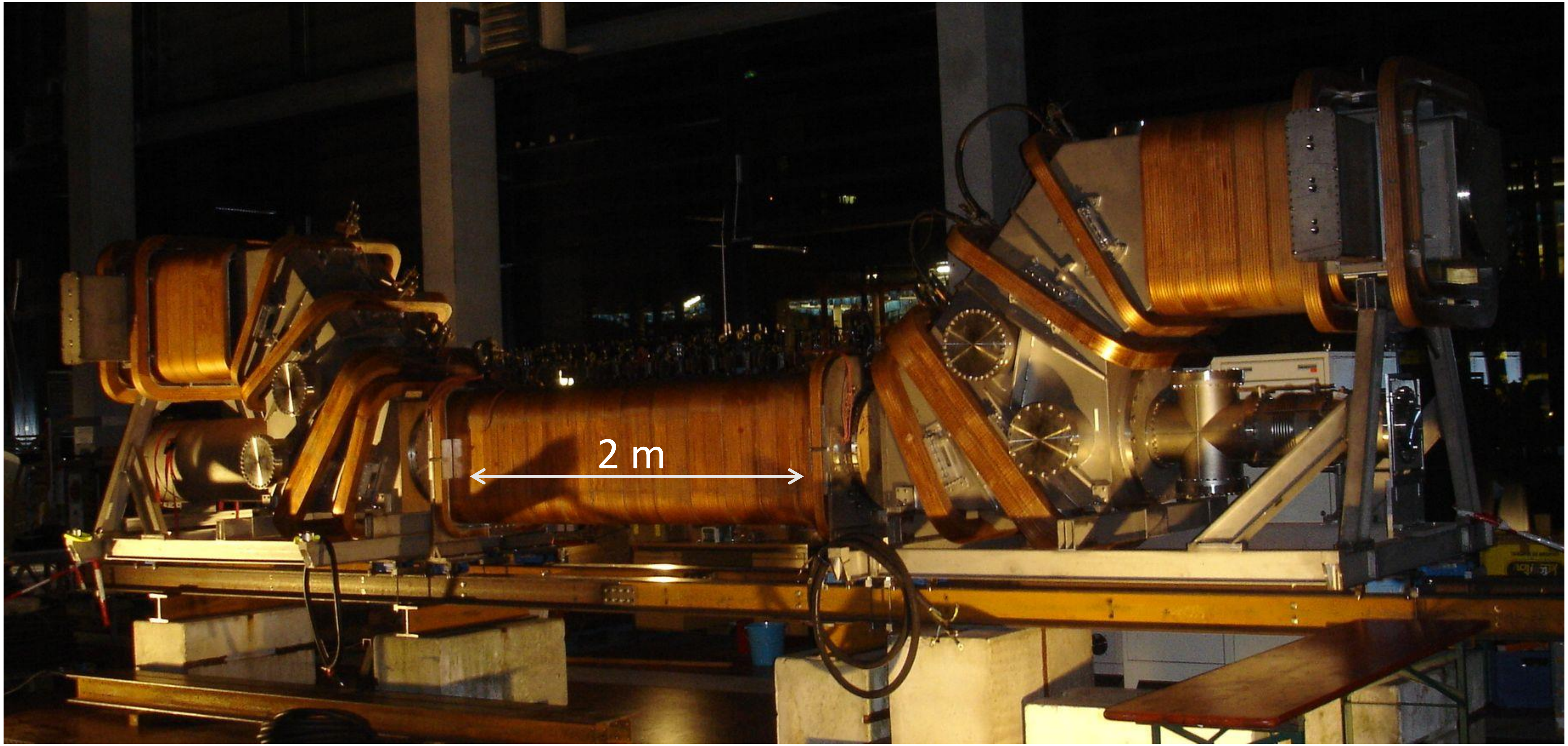
Pulsed beam
- ➢ Velocity selector
- ➢ Chopper

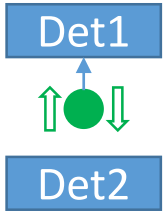
→ Improved systematics,
but at cost of factor 100
in event rate

- Large beam → can accept large gyration radii, lower magnetic field (160 mT), normal conducting
- Detectors can be placed far from beam compared to PERKEO I. However, larger area detectors, downstream detector difficult to shield



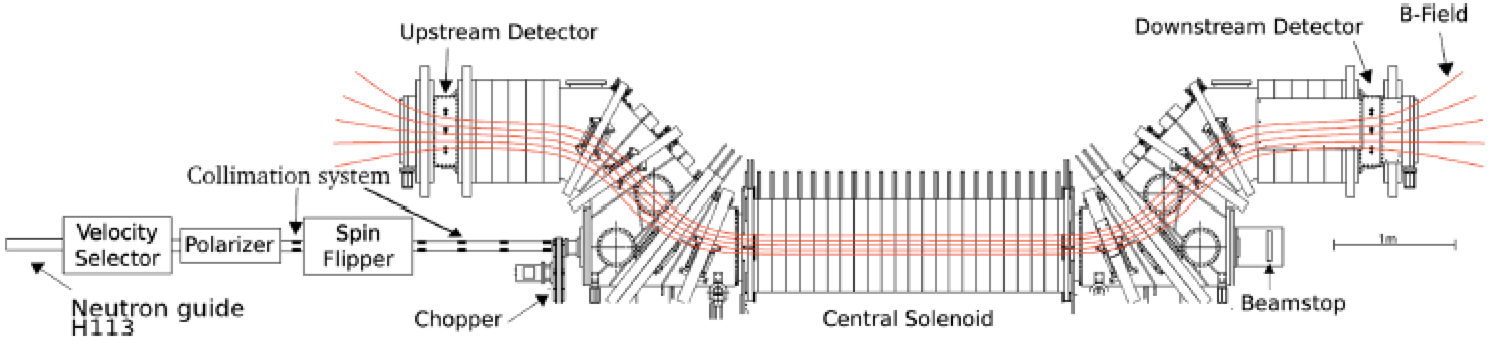
A: PERKEO III



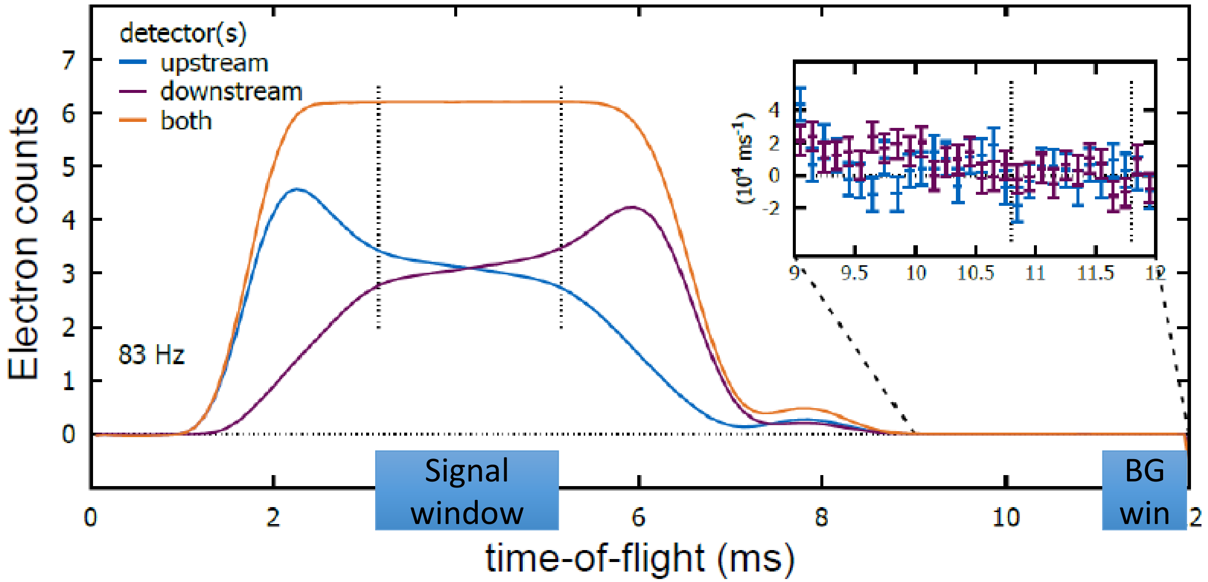


A: PERKEO III

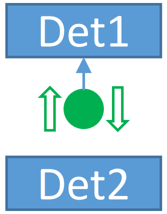
[Märkisch et al, Phys. Rev. Lett. 122 (2019) 242501]



- **Almost monochromatic beam → X-SM** polarizer not needed, only single bender
  - ➢ Polarization analysis with opaque ^{3}He spin filters, exact mapping of full beam
- **Pulsed beam suppresses beam-related background**
- **Improved detector homogeneity**
- **Blind analysis:** Polarization, Asymmetry and Mirror effect analyzed by independent people, combined only at the end
- **Longitudinal field →** increased magnetic mirror effect and uncertainty $(0.45 \cdot 10^{-3})$

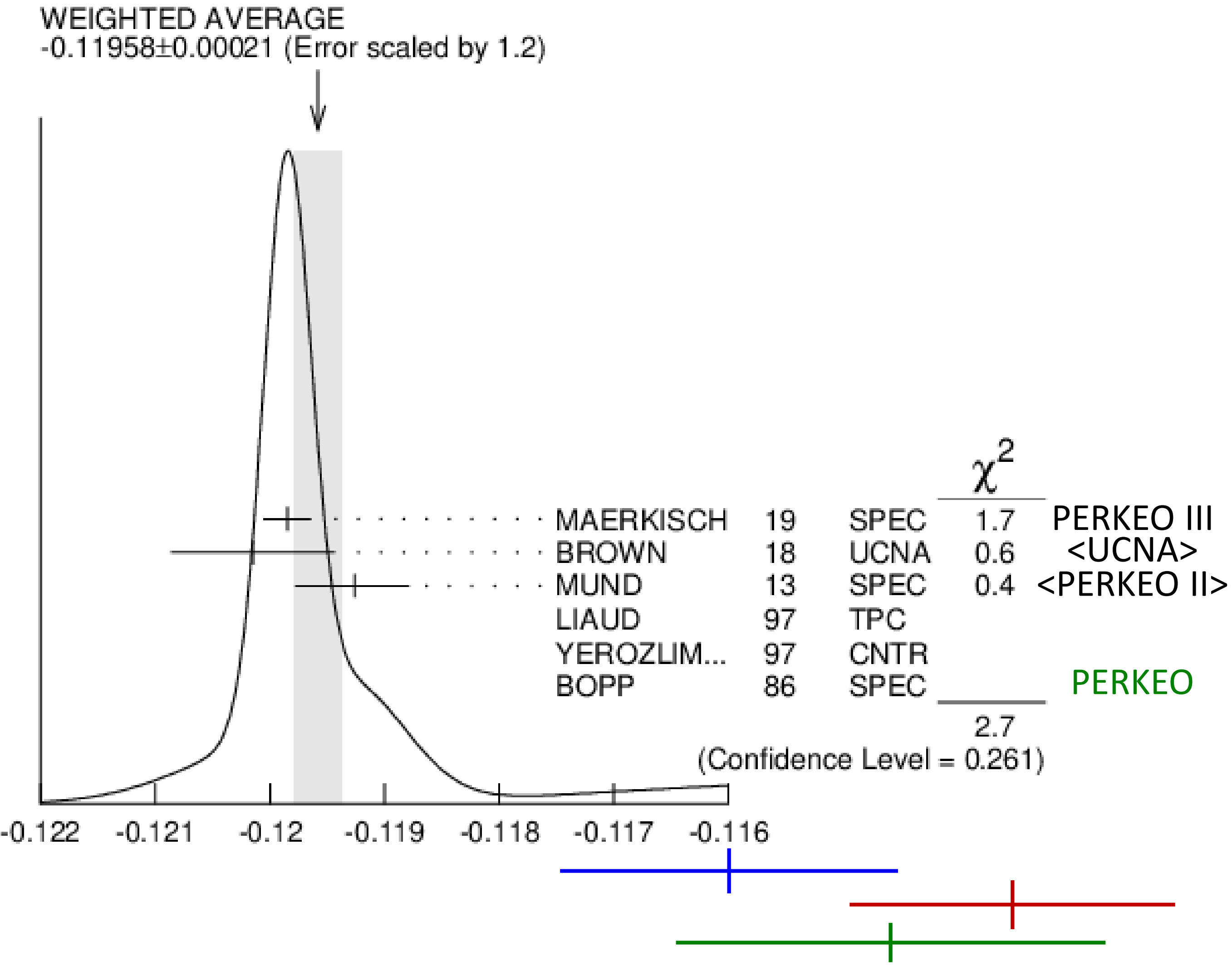


	[2013]		[2019]	
	Cor [10^{-3}]	Err [10^{-3}]	Cor [10^{-3}]	Err [10^{-3}]
Polarization	+3.0	1.4	+9.07	0.64
Background	+1.0	1.0	−0.27	0.11
Detector response	−1.3	2.6	−1.32	0.63
Other systematics	−0.6	0.2	+4.61	0.45
Total systematics		**3.1**		**1.03**
Radiative cor.	−1.1	0.5	−1.0	0.1
Statistics		**3.8**		**1.40**
Total error		4.9		1.74
A	$\mathbf{-0.11972(^{+53}_{-65})}$		$\mathbf{-0.11985(21)}$	



A: Status

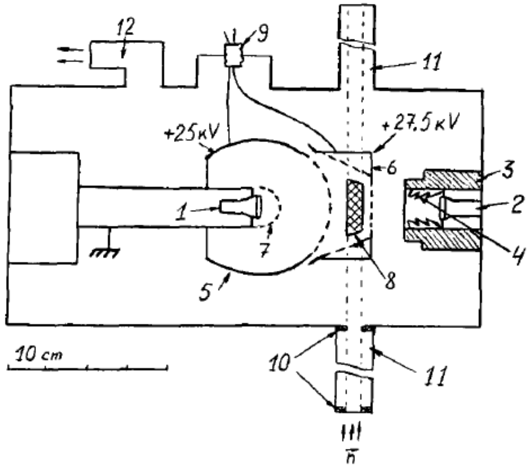
PDG world average of *A*


WEIGHTED AVERAGE
-0.11958±0.00021 (Error scaled by 1.2)

			χ^2	
MAERKISCH	19	SPEC	1.7	PERKEO III
BROWN	18	UCNA	0.6	<UCNA>
MUND	13	SPEC	0.4	<PERKEO II>
LIAUD	97	TPC		
YEROZLIM...	97	CNTR		
BOPP	86	SPEC		PERKEO
			2.7	

(Confidence Level = 0.261)

- **Yerozolimsky et al** (PNPI): Traditional

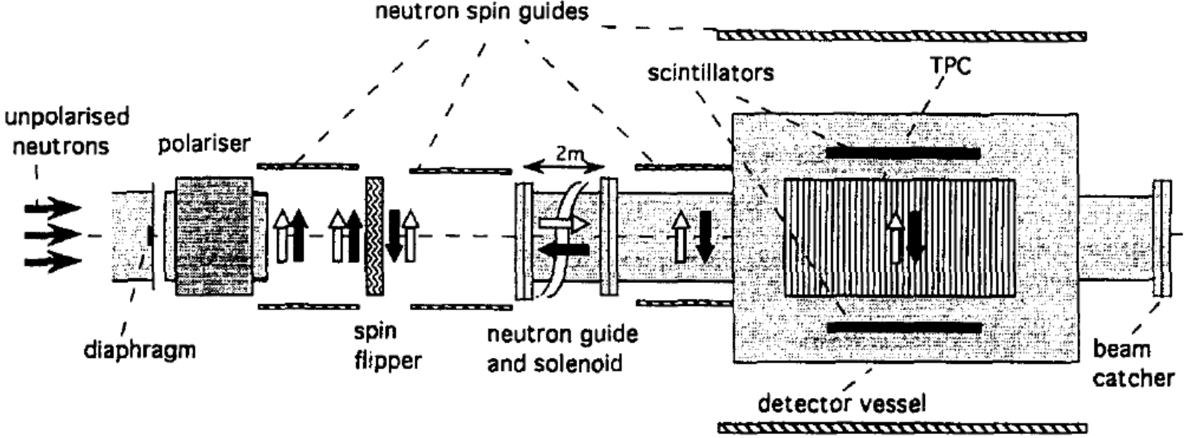


$$A = -0.1135(14), \frac{\Delta A}{A} = 1.2\%$$

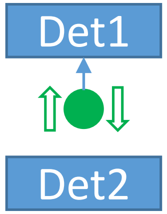
[Erozolimskii et al,
Phys. Lett. B 263 (1991) 33,
Yerozolimsky et al,
Phys. Lett. B 412 (1997) 240]

- **Liaud et al** (ILL): TPC $A = -0.1160(15), \frac{\Delta A}{A} = 1.3\%$

[Liaud et al, Nucl Phys. A 612 (1997) 53]



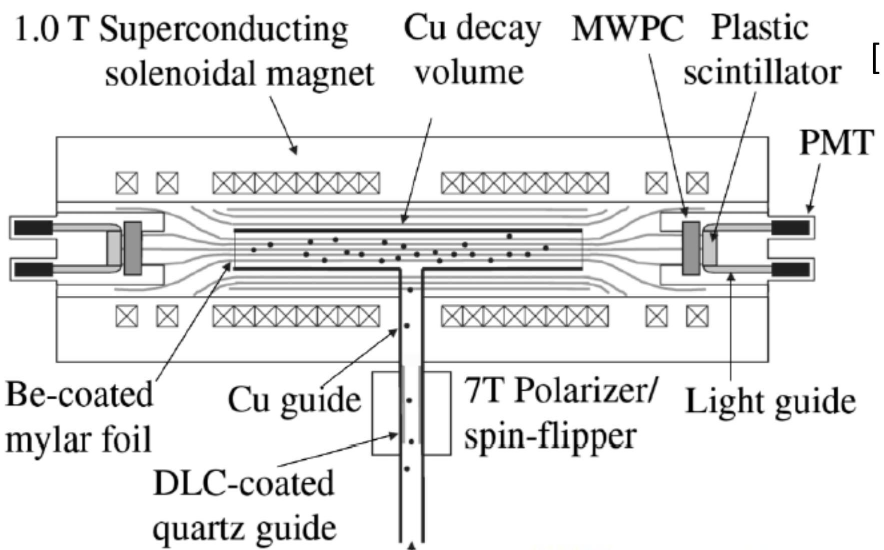
- **Brown et al: UCNA** → next slide

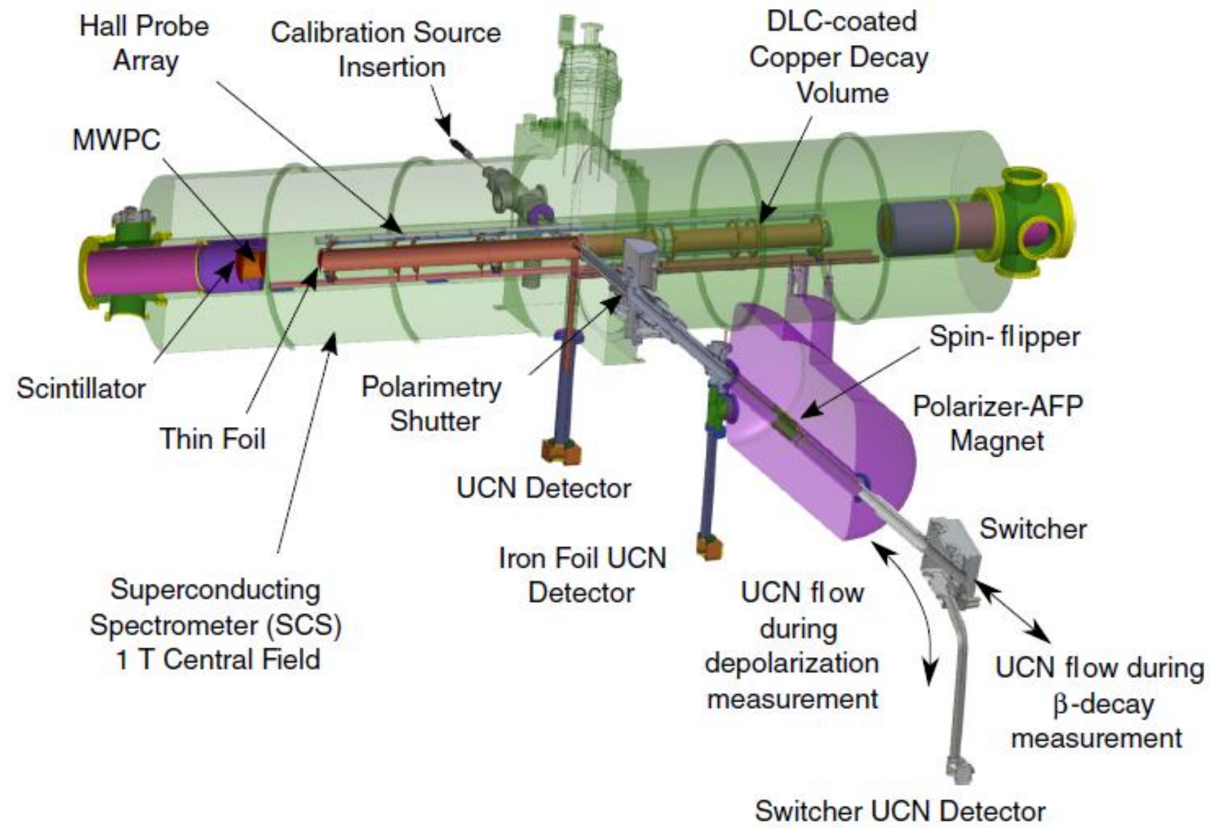


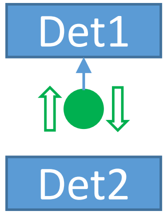
A: UCNA

[Brown et al, Phys. Rev. C 97 (2018) 035505]
[Mendenhall et al, Phys. Rev. C 87 (2013) 032501(R)]
[Plaster et al, Phys. Rev. C 86 (2012) 055501]
[Liu et al, Phys. Rev. Lett. 105 (2010) 181803]
[Pattie et al, Phys. Rev. Lett. 102 (2009) 012301]

- First measurements of any angular correlation with UCN
- **1 T solenoidal spectrometer with 3 m long UCN decay volume**
- **Polarization:**
  - passage through 7 T magnet
  - AFP spin flipper with single-pass spin-flip efficiency > 99.9%
- **Detectors:**
  - **MWPC** (position reconstruction and backscattering identification)
  - **Plastic scintillator** (timing and energy reconstruction)







A: UCNA

[Brown et al, Phys. Rev. C 97 (2018) 035505]
[Mendenhall et al, Phys. Rev. C 87 (2013) 032501(R)]
[Plaster et al, Phys. Rev. C 86 (2012) 055501]
[Liu et al, Phys. Rev. Lett. 105 (2010) 181803]
[Pattie et al, Phys. Rev. Lett. 102 (2009) 012301]

Systematics

Foils at end of UCN decay trap

- affect backscattering and angular acceptance
- Measurements (and MC) with different foils

Calibration

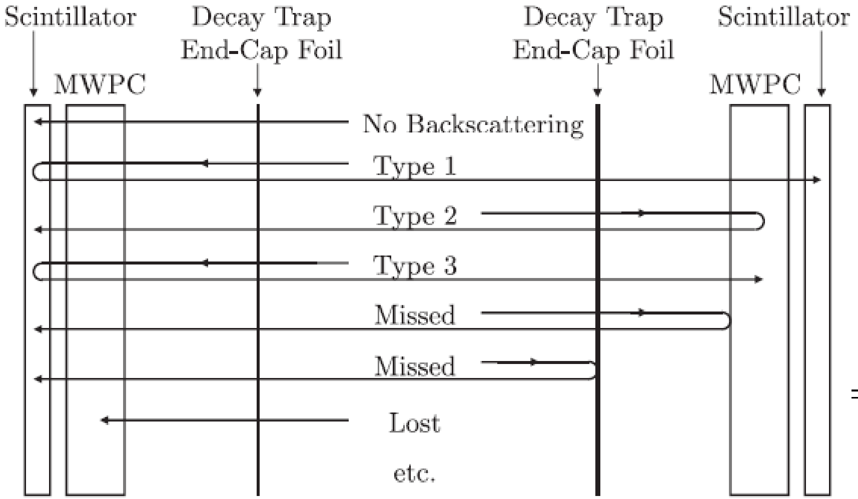
- neutron activated Xe gas with MWPC for homogeneity, conversion electron lines for linearity

Backscattering classification

- Energy cut on MWPC to statistically assign Type 2/3 events to the correct side, reduces Monte Carlo corrections for backscattering events

cos θ correction

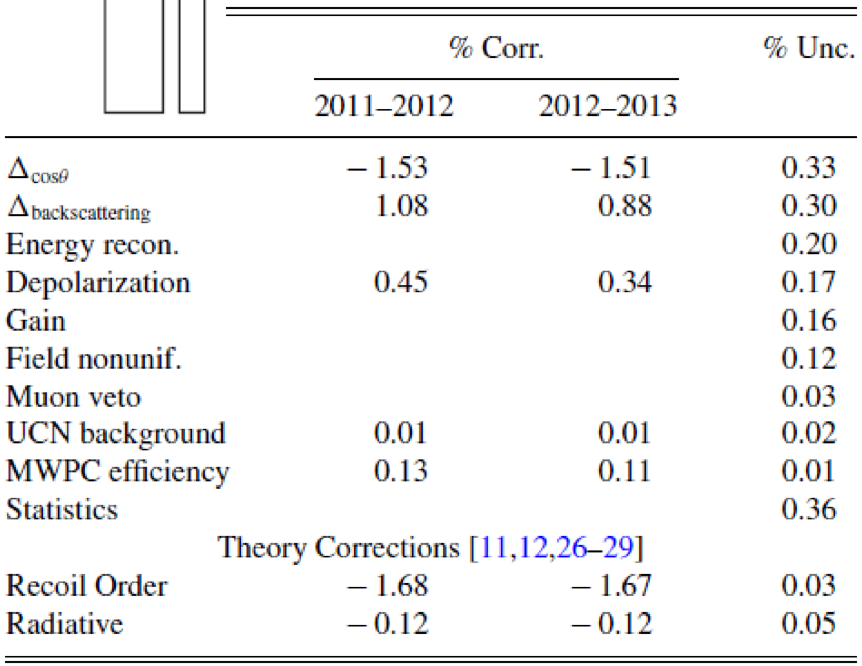
- High energy, low pitch angle events more apt to trigger the detectors and carry higher asymmetry information
- Increase measured asymmetry



Super-ratio method

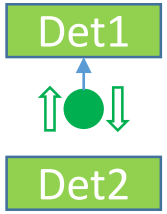
- Suppression of spin-dependent trap filling

$$A_{\text{SR}} = \frac{1-\sqrt{R}}{1+\sqrt{R}}$$



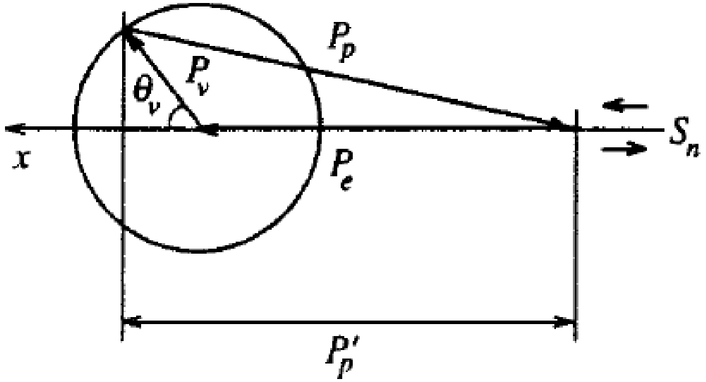
	% Corr.		% Unc.
	2011–2012	2012–2013	
$\Delta_{\cos\theta}$	– 1.53	– 1.51	0.33
$\Delta_{\text{backscattering}}$	1.08	0.88	0.30
Energy recon.			0.20
Depolarization	0.45	0.34	0.17
Gain			0.16
Field nonunif.			0.12
Muon veto			0.03
UCN background	0.01	0.01	0.02
MWPC efficiency	0.13	0.11	0.01
Statistics			0.36
Theory Corrections [11,12,26–29]			
Recoil Order	– 1.68	– 1.67	0.03
Radiative	– 0.12	– 0.12	0.05

$$A = -0.12054(44)^{\text{stat}}(68)^{\text{syst}}, \frac{\Delta A}{A} = 0.7\%$$

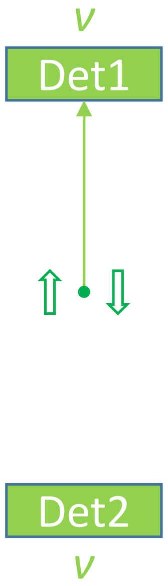


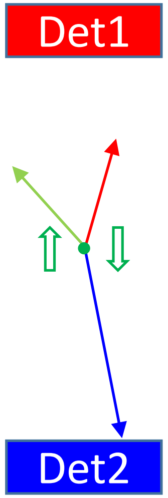
B:

$$dW \propto 1 + B\,\frac{\langle\boldsymbol{\sigma_n}\rangle}{\sigma_n}\,\frac{\boldsymbol{p_\nu}}{E_\nu}$$

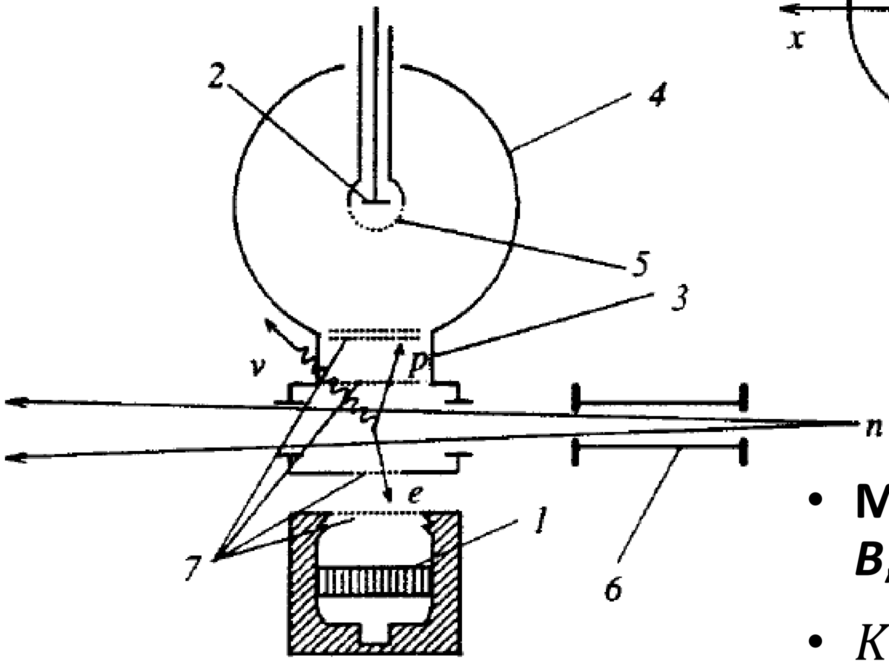


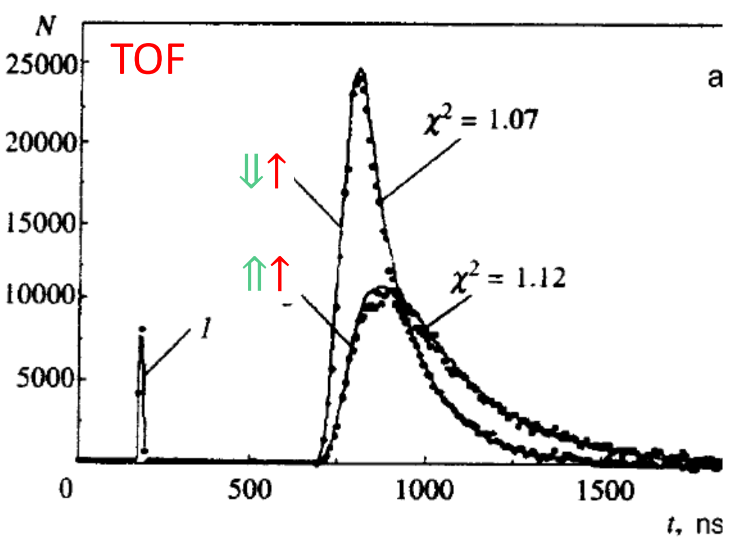
Just the same with *ν* detector…

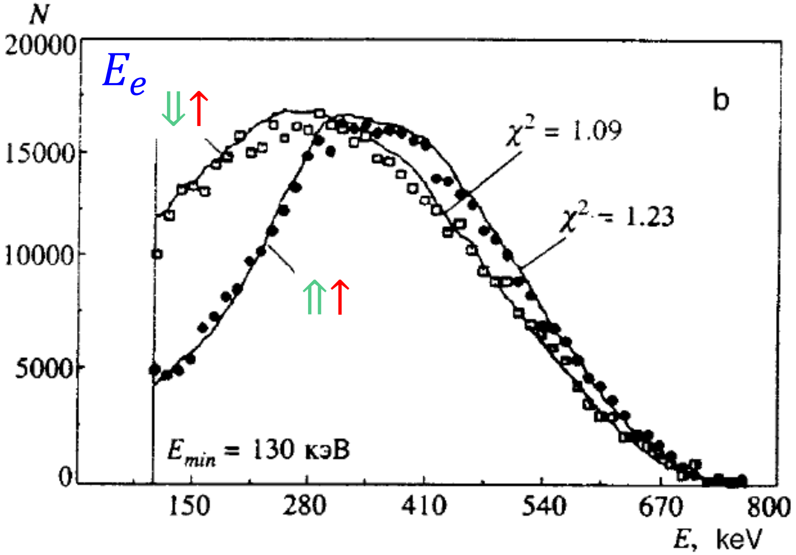




- **Opposite e, p detectors: $\boldsymbol{p_\nu}$** reconstruction very sensitive to E_e



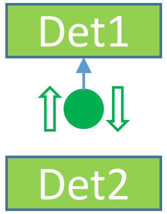




- **Measures combination of *B*, *a* and *A***
- K_B, K_a, K_A to be calculated, *a* and *A* from other experiments
- Dominating systematics:
  - Polarization
  - E_e energy resolution

$B = 0.9801 \pm 0.0025^{stat} \pm 0.0038^{sys}$

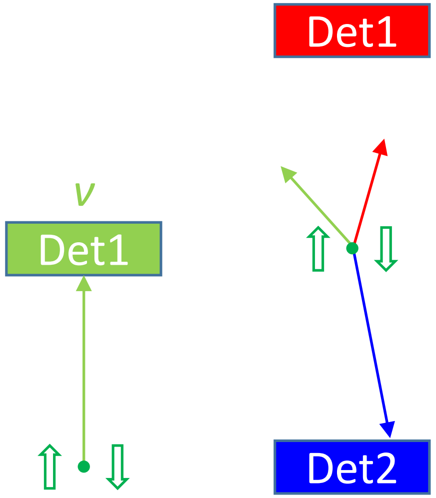
Serebrov et al., JETP 86 (1998) 1074



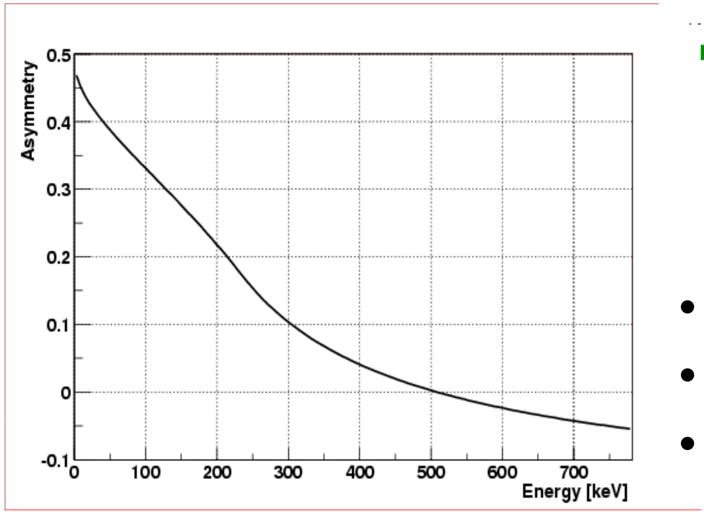
B:

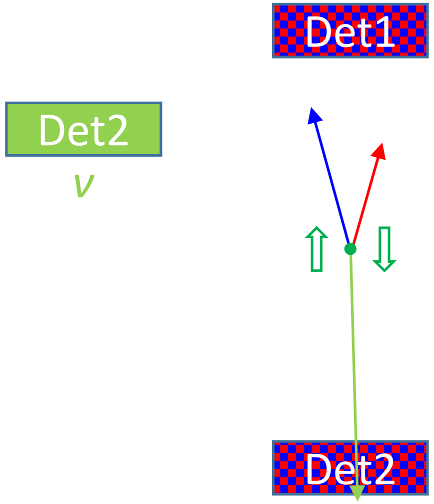
$$\mathrm{d}W \propto 1 + B\,\frac{\langle\boldsymbol{\sigma}_n\rangle}{\sigma_n}\frac{\boldsymbol{p}_\nu}{E_\nu}$$

Just the same with ν detector…

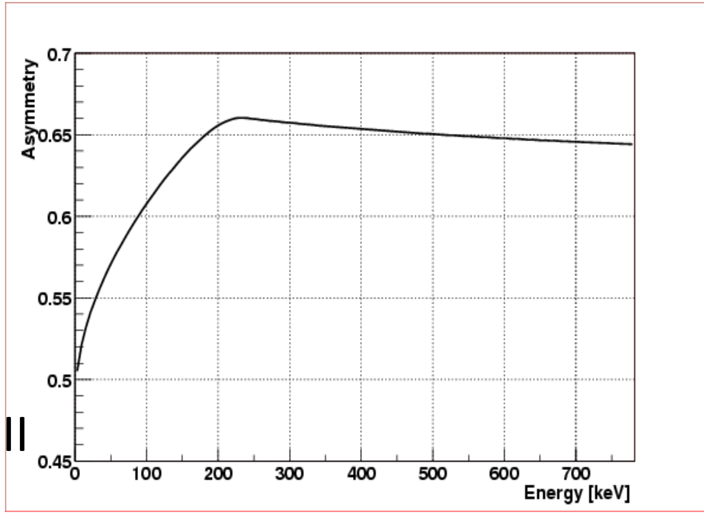


- **Opposite e, p detectors: $\boldsymbol{p}_\nu$** reconstruction very sensitive to E_e
  - ➢Only used for cross-checks in PERKEO II analysis

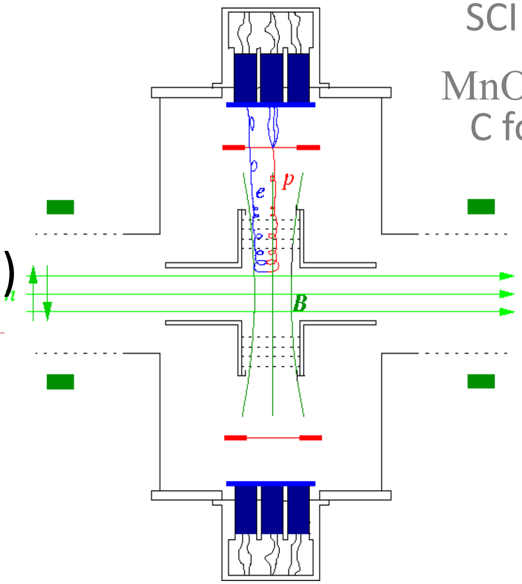


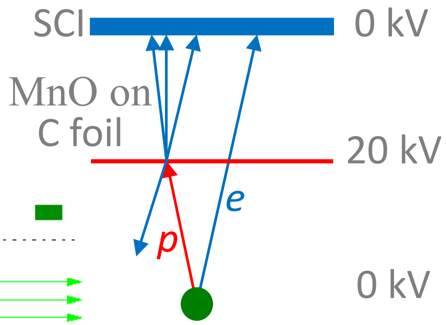


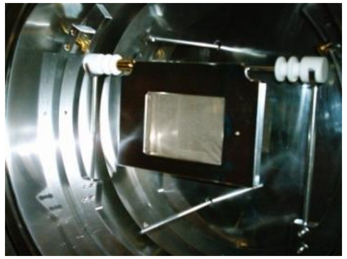
- **e, p in same detector:** → $\boldsymbol{p}_\nu$ emitted in opposite direction, reconstruction insensitive to E_e
  - ➢Result of PERKEO II



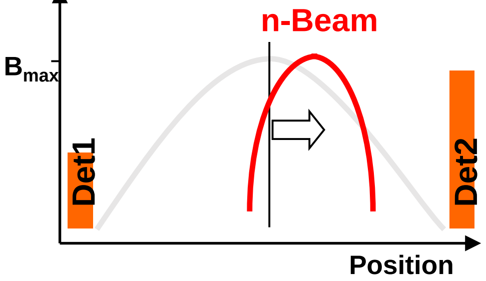
PERKEO II B (with X-SM)





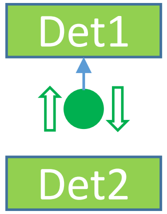


- ***A* and *a* enter** (here in fit function)
- Very clean systematics in principle
- ***But***: Very different statistical weight of the two detectors (because of high voltage instabilities) → inefficient compensation of beam displacement in arithmetic mean



$B = 0.9802 \pm 0.0034^{stat} \pm 0.0036^{sys}$

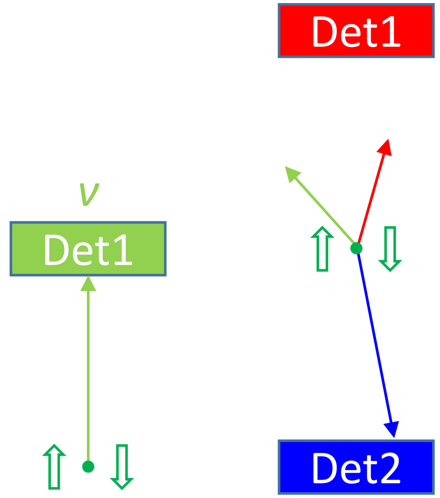
Schumann et al., Phys. Rev. Lett 99 (2007) 191803



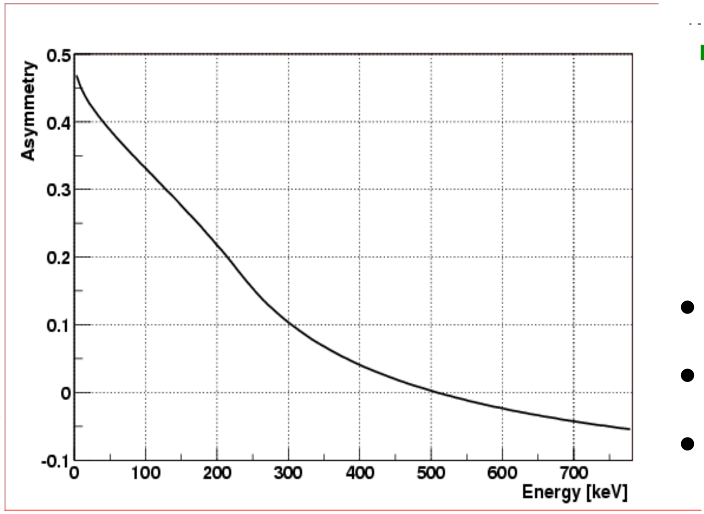
$$B: \qquad \mathrm{d}W \propto 1 + B\,\frac{\langle \boldsymbol{\sigma}_n \rangle}{\sigma_n}\,\frac{\boldsymbol{p}_\nu}{E_\nu}$$

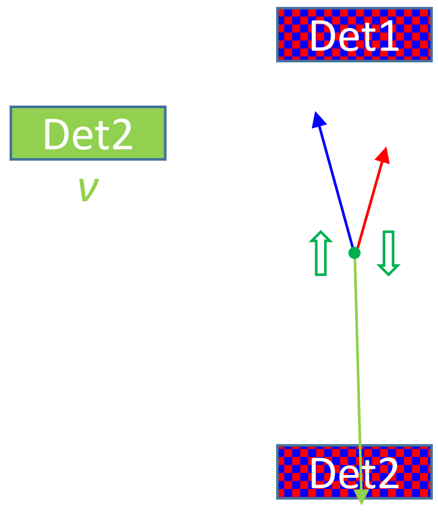
Just the same with *ν* detector…

PERKEO II B (with X-SM)

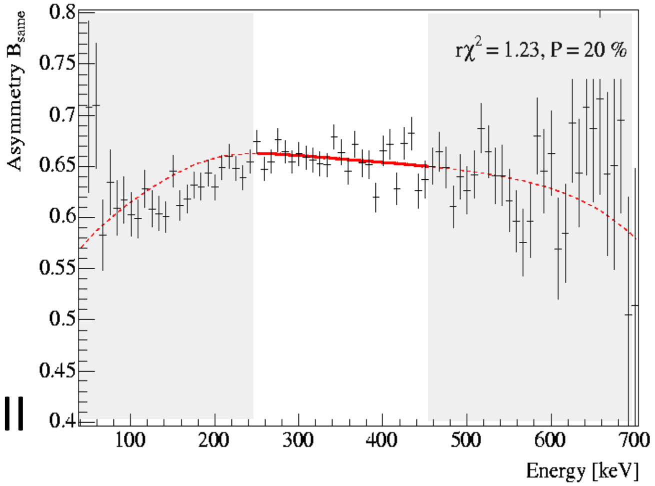


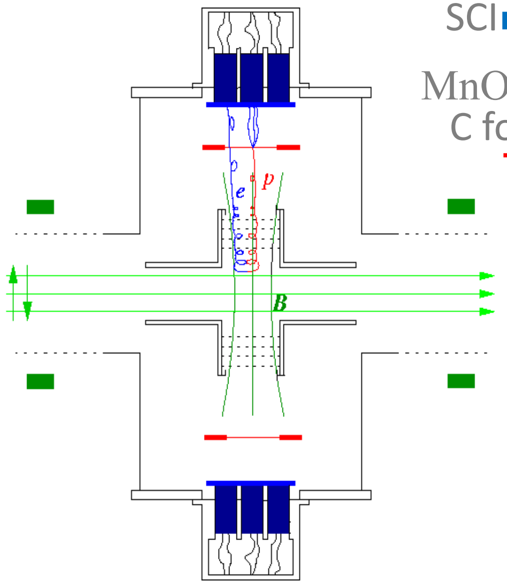
- **Opposite e, p detectors: $\boldsymbol{p}_\nu$** reconstruction very sensitive to E_e
  - ➢Only used for cross-checks in PERKEO II analysis

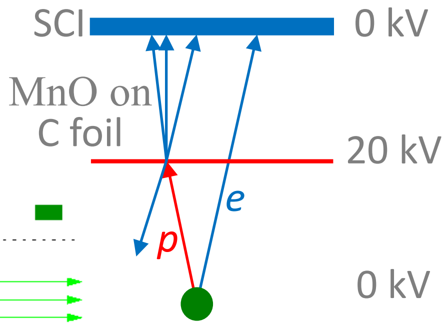


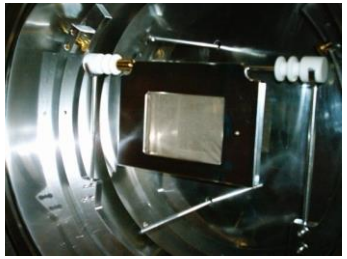


- **e, p in same detector:**
  → $\boldsymbol{p}_\nu$ emitted in opposite direction, reconstruction insensitive to E_e
  - ➢Result of PERKEO II

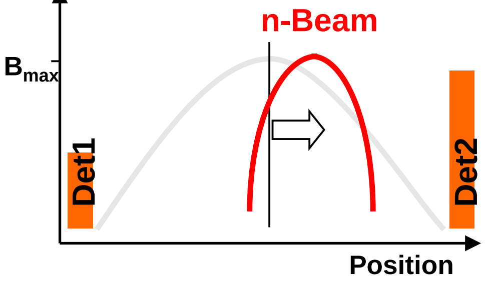






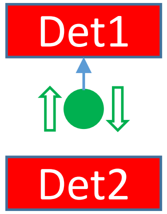


- ***A* and *a* enter** (here in fit function)
- Very clean systematics in principle
- ***But***: Very different statistical weight of the two detectors (because of high voltage instabilities) → inefficient compensation of beam displacement in arithmetic mean



$B = 0.9802 \pm 0.0034^{stat} \pm 0.0036^{sys}$

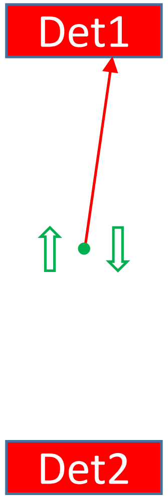
Schumann et al., Phys. Rev. Lett 99 (2007) 191803



C:

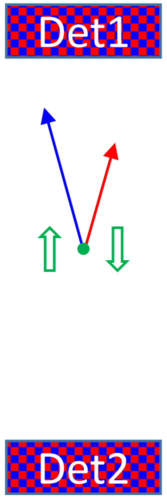
$$\mathrm{d}W \propto 1 + C\,\frac{\langle\boldsymbol{\sigma_n}\rangle}{\sigma_n}\,\frac{\boldsymbol{p_p}}{p_p}$$

Proton asymmetry parameter *C*

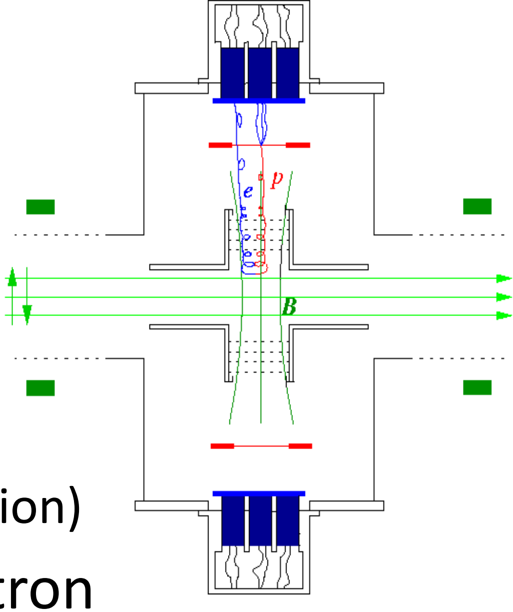


- Not included in alphabet
- Proton detection sufficient, in principle
- Related to A and B by kinematics:
  $C = x_C(A+B)$, $x_C = 0.274\,84$

→ Access to B without coincidence measurement



So far only: Perkeo II B



- **Coincident e-p detection:**
  - ➢ Distinguish p from e by TOF
  - ➢ Suppresses background, too
  - ➢ ***a, A, B* enter** (here in fit function)
- Need to integrate out electron

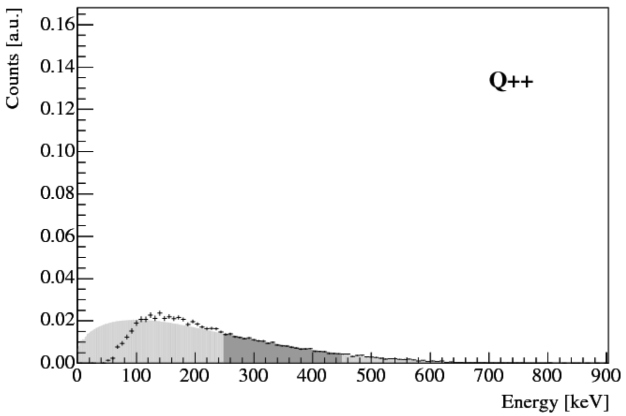
$$p^1_{\Uparrow,\Downarrow} = \int_{E_e} \left(Q^{\mathrm{p1,e1}}_{\Uparrow,\Downarrow}(E_e) + Q^{\mathrm{p1,e2}}_{\Uparrow,\Downarrow}(E_e) \right) \mathrm{d}E_e$$

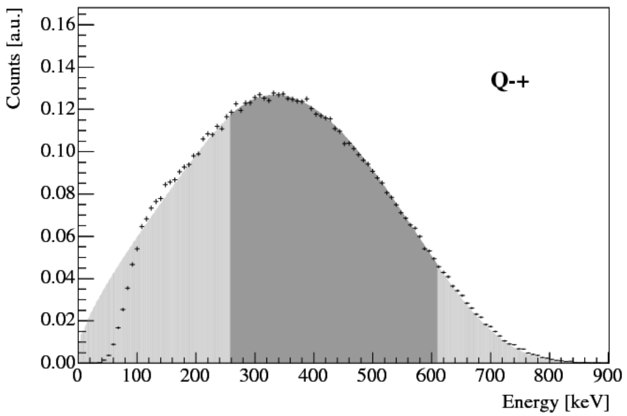
$$\alpha^1 = \frac{p^1_{\Uparrow} - p^1_{\Uparrow}}{p^1_{\Uparrow} + p^1_{\Uparrow}}$$

- ➢ Proton efficiency drops out but electron energy integral in two different detectors
- ➢ Electron threshold + lower cutoff by HV
- → Fit theoretical spectra and extrapolate
- → Dominating systematics: E_e calibration & resolution
- ➢ Only one proton detector used for result

$C = -0.2377 \pm 0.0010^{\mathrm{stat}} \pm 0.0024^{\mathrm{sys}}$

Schumann et al., Phys. Rev. Lett. 100 (2008) 151801



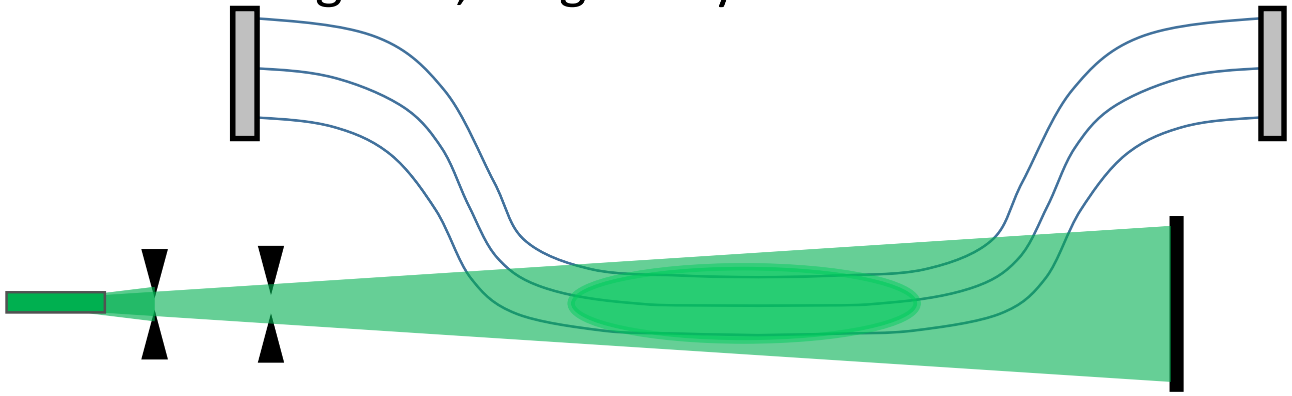


Det

: How to go further – PERC

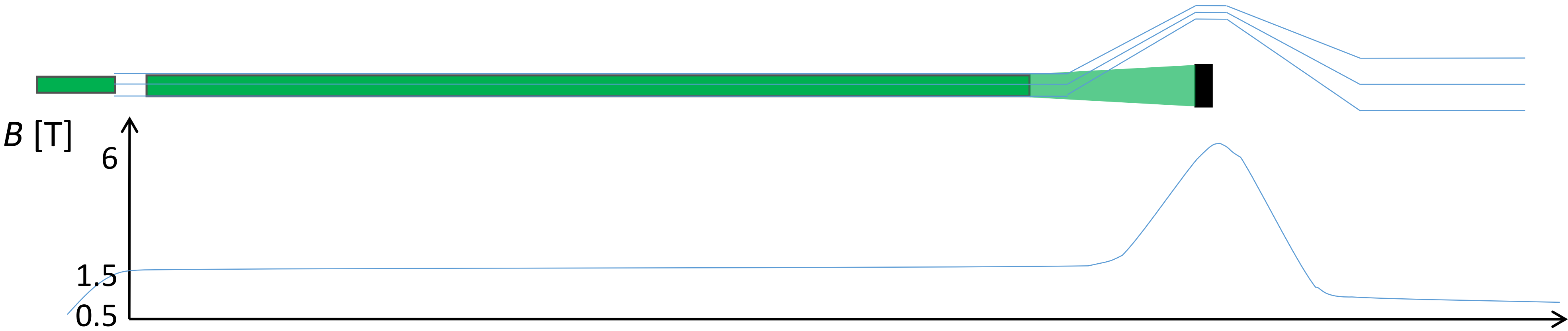
[Märkisch et al, Phys. Rev. Lett. 122 (2019) 242501,
Märkisch et al, Nucl Instr. Meth. A 611 (2009) 216]

- **PERKEO III**: Accept full beam divergence, long decay volume → Factor 100 in event rate



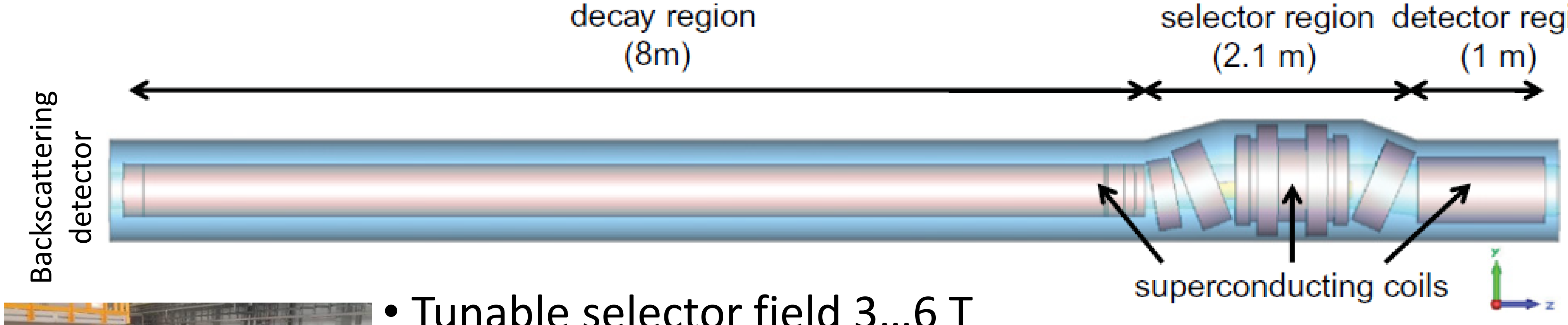
- Yet, beam divergence limits length of decay volume. Large beam, low field → Large detectors

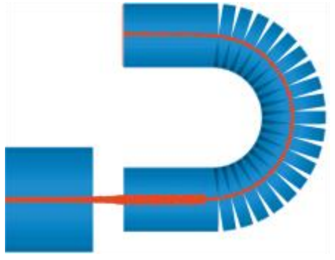
→**PERC**:



- **Conserve neutron density** by keeping them in guide. Strong field to collect charged decay products
- **Magnetic filter for improved systematics** – compensates absence of upstream detector
- **Pulsed neutron beam** to avoid regions of ill-defined spectrometer response (not needed for all observables)

PERC

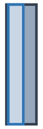




Example: Secondary
R×B spectrometer

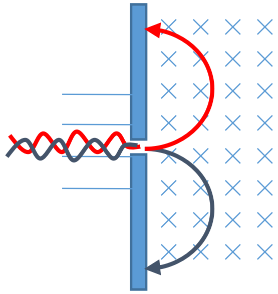
- Tunable selector field 3…6 T
- **Secondary spectrometers** optimized for observable
- Observables:
  - Electrons: *A*, *b*
  - Protons: *a*, *C*
  - Coincidences: no

Electron
detector

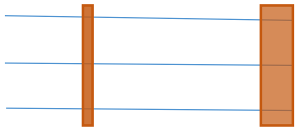


Wien filter
for protons

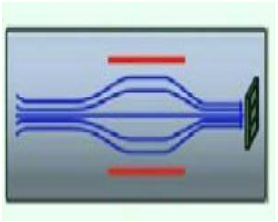
Magnetic
spectrometer



Electrostatic
chopper & p
detector



MAC-E filter



- Target sensitivity: $\mathfrak{O}(10^{-4})$
  - Individual systematic effects for PERC estimated < 10^{-4}
  - Depends on secondary spectrometer
- Installation in progress at FRM-II

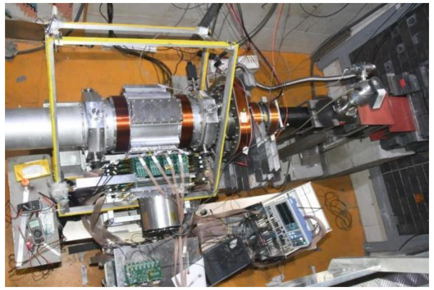
Dubbers et al., Nucl. Instr. Meth. A 596 (2008) 238 and arXiv:0709.4440
Wang et al, EPJ Web of Conferences 219 (2019) 04007

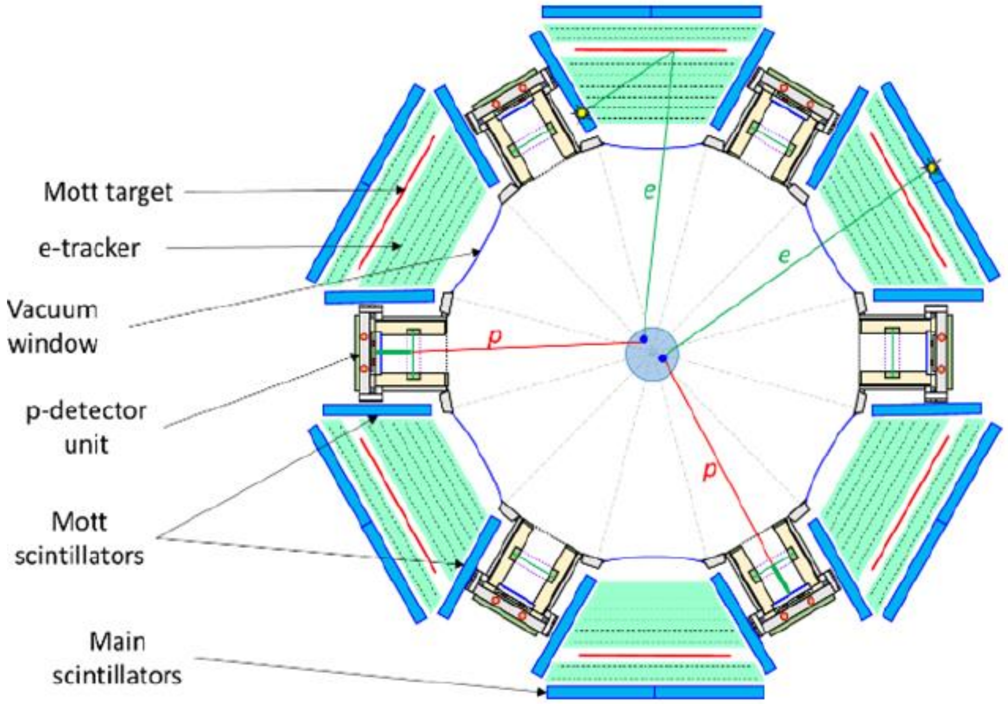
BRAND

Bodek et al, EPJ Web of Conf. 219 (2019) 04001
Abele et al, Phys. Rep. 1023 (2023) 1

Measure all correlations simultaneously

- Only existing project with **electron tracking** and **measurement of transversal electron polarisation**
- Access to yet unmeasured correlations
- Independent systematics for measured correlations (*a*, *b*, *A*, *B*, *D*)
- Based on measurement of *N*, *R* at PSI
- **Target statistical sensitivity**:
  - $5 \cdot 10^{-4}$ for coefficients involving electron polarisation
  - A few times 10^{-5} for *a*, *A*, *B*, *D*
- First tests of prototype components at PF1B, R&D ongoing





Reminder from start of lecture:

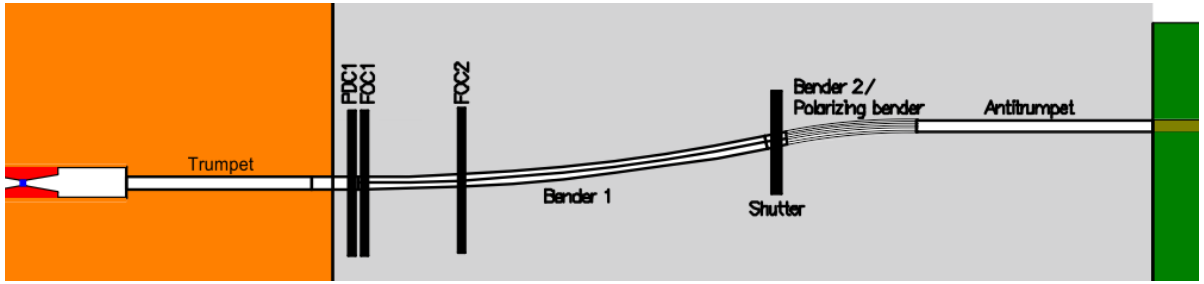
$$\mathrm{d}W(\langle\boldsymbol{\sigma}_n\rangle,\langle\boldsymbol{\sigma}_e\rangle|E_e,\Omega_e,\Omega_\nu) \propto G_E(E_e)\cdot \left\{1 + a\frac{\boldsymbol{p}_e\boldsymbol{p}_\nu}{E_eE_\nu} + \cdots\right.$$

How to go further – ANNI @ ESS (proposal)

Pulsed beams are good for us!

- ξ Spatial localization of neutron pulse
  - ➢ Separation of beam-related background
  - ➢ Separation of ill-defined spectrometer response
- λ Separation by neutron wavelength
  - ➢ Velocity dependence of signal and systematics
  - ➢ Time-dependent neutron optics
  - ➢ Loss-free monochromatization
- τ Time localization of neutron pulse
  - ➢ Improved signal/background
  - ➢ Suppression of background and drifts with different time constant than signal

ANNI simulated gain factors (@ 5 MW)



Experiment	Facility	Gain Event rate
NPDGamma	FnPB (SNS)	**27**
PERC	MEPHISTO (FRM II)	**15**
PERKEO III	PF1B (ILL)	**17**
aSPECT	PF1B (ILL)	1.3 2.8

TS et al., EPJ Web of Conferences 219 (2019) 10003
Abele et al, Physics Reports 1023 (2023) 1–84

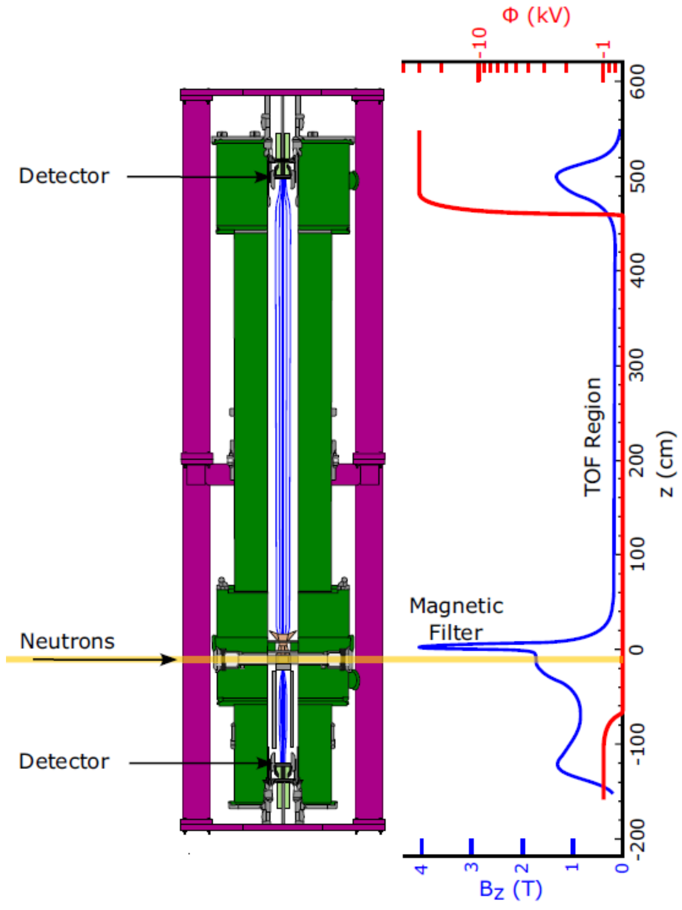
Status and outlook

Presently most precise experiment

- $\Delta a/a = 8\cdot10^{-3}$ [aSPECT 2020]
- $\Delta b = 0.02$ [PERKEO III 2020]
- **$\Delta A/A = 1.7\cdot10^{-3}$ [PERKEO III 2019]**
- $\Delta B/B = 5\cdot10^{-3}$ [Serebrov 98, PERKEO II 2008]
- $\Delta C/C = 1\%$ [PERKEO II 2007]
- **$\Delta D = 2\cdot10^{-4}$ [emiT 2012]**
- $\Delta R = 0.013$ [Kozela 2012]

Ongoing projects

- **Nab @ SNS**: a, b
  - First data taken
  - Goals: $\Delta a/a \approx 0.1\%$, $\Delta b \approx 0.003$
  - Proposal for pNab



Hayen et al, Phys. Rev. C 107 (2023) 065503
Baeßler et al, J. Phys. G 41 (2014) 114003

- **PERC @ FRM-II**: A, b, a, C
  - Installation in progress
  - Goals: a few times 10^{-4}
- **BRAND @ ILL / ESS**: a, A, B, D, H, L, N, R, S, U, V
  - R&D ongoing
  - Goals: a, A, B, D : not limited by stat (few times 10^{-5})
    H, L, ... (with transversal electron polarization): $5\cdot10^{-4}$