Fierz Interference in Neutron Decay

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Beta Decay as a Probe of New Physics
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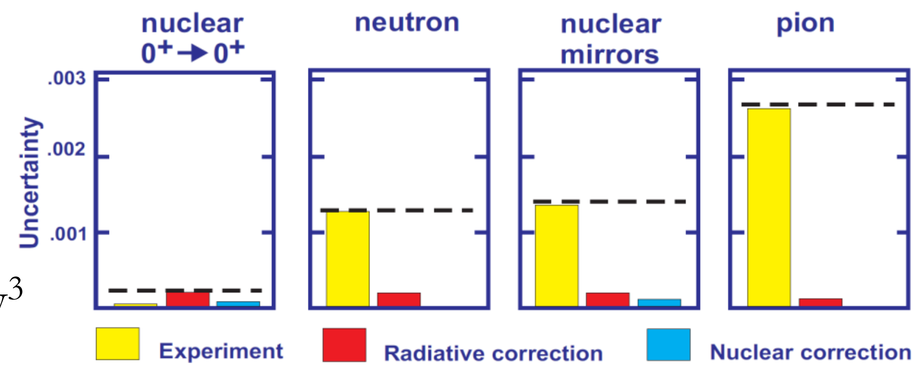
University of Massachusetts Amherst

A probe for new physics

- CKM unitarity
  - Competitive with LHC limits[1]
  - LQCD calc g_A now 1%[2]
  - New Δ_R^V calc shifts from unitarity[3]



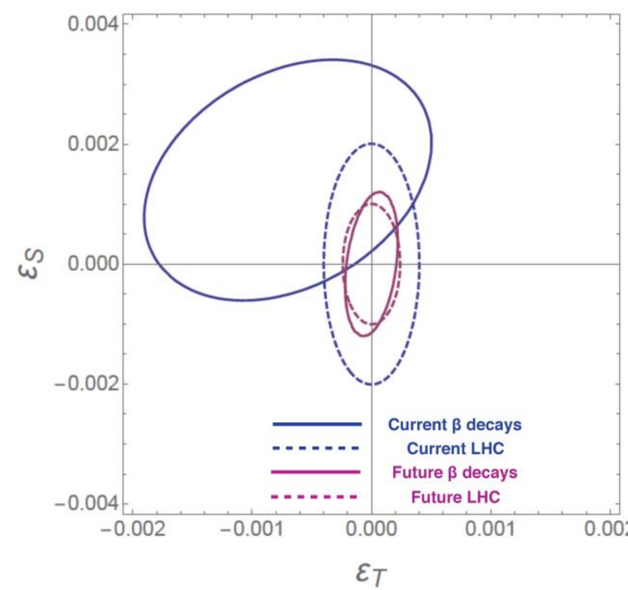
Hardy and Towner, CIPANP2018

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} \boldsymbol{V_{ud}} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$|\boldsymbol{V_{ud}}|^2 + |V_{us}|^2 + \cancel{|V_{ub}|^2}^{\,10^{-5}} = 0.9994(5) \quad \text{(PDG 18)}$$

$$\longrightarrow 0.9984(4)$$

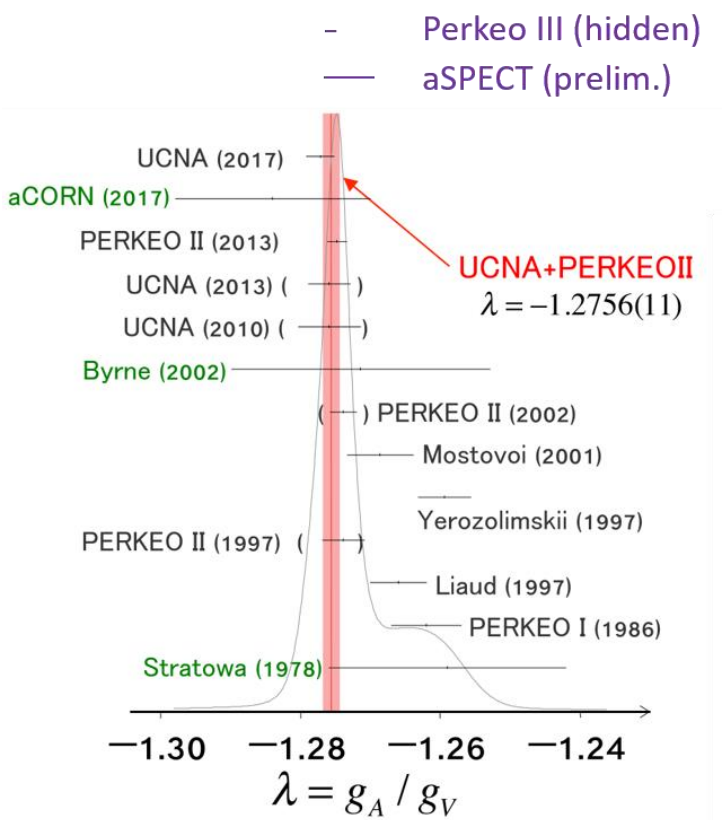
- Beyond Standard Model
  - Scalar, Tensor, Right-handed currents
  - Improved LQCD calcs of g_A, g_S, g_T[4]



[1]Gonzalez-Alonso, Naviliat-Cuncic, and Severijns, arXiv:1803.08732
[2]Chang *et al*, *Nature* **558** (2018) 91-94
[3]Seng, Gorchtein, Patel, Ramsey-Musolf, arXiv:1807.10197
[4]Gupta *et al*, PRD **98** (2018) 034503

Neutron β-decay observables

$$dW \propto 1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} + \langle\vec{\sigma}_n\rangle \cdot \left(A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu}\right)$$



$$A = -2\frac{\lambda^2+\lambda}{1+3\lambda^2} \qquad a = \frac{1-\lambda^2}{1+3\lambda^2} \qquad \lambda = \frac{g_A}{g_V}$$

Asymmetries: $\alpha_{\text{meas}}(E_e) = \frac{\alpha(E_e)}{1+bm_e/E_e}$

CKM unitarity:

$$\tau^{-1} = W \propto (V_{ud})^2(1+3(\lambda)^2)$$

Goal: **dA/A or da/a → 0.1% and dτ → 0.1 s**

B (b_ν), **b** linear sensitivity to BSM **S**,**T**:

$$b^{BSM} = \frac{2}{1+3\lambda^2}[g_S\epsilon_S - 12\lambda g_T\epsilon_T]$$

$$b_\nu^{BSM} = \frac{2}{1+3\lambda^2}[\lambda g_S\epsilon_S - 4g_T\epsilon_T(1+2\lambda)]$$

Not yet measured in neutron decay, until…

UCNA collaboration

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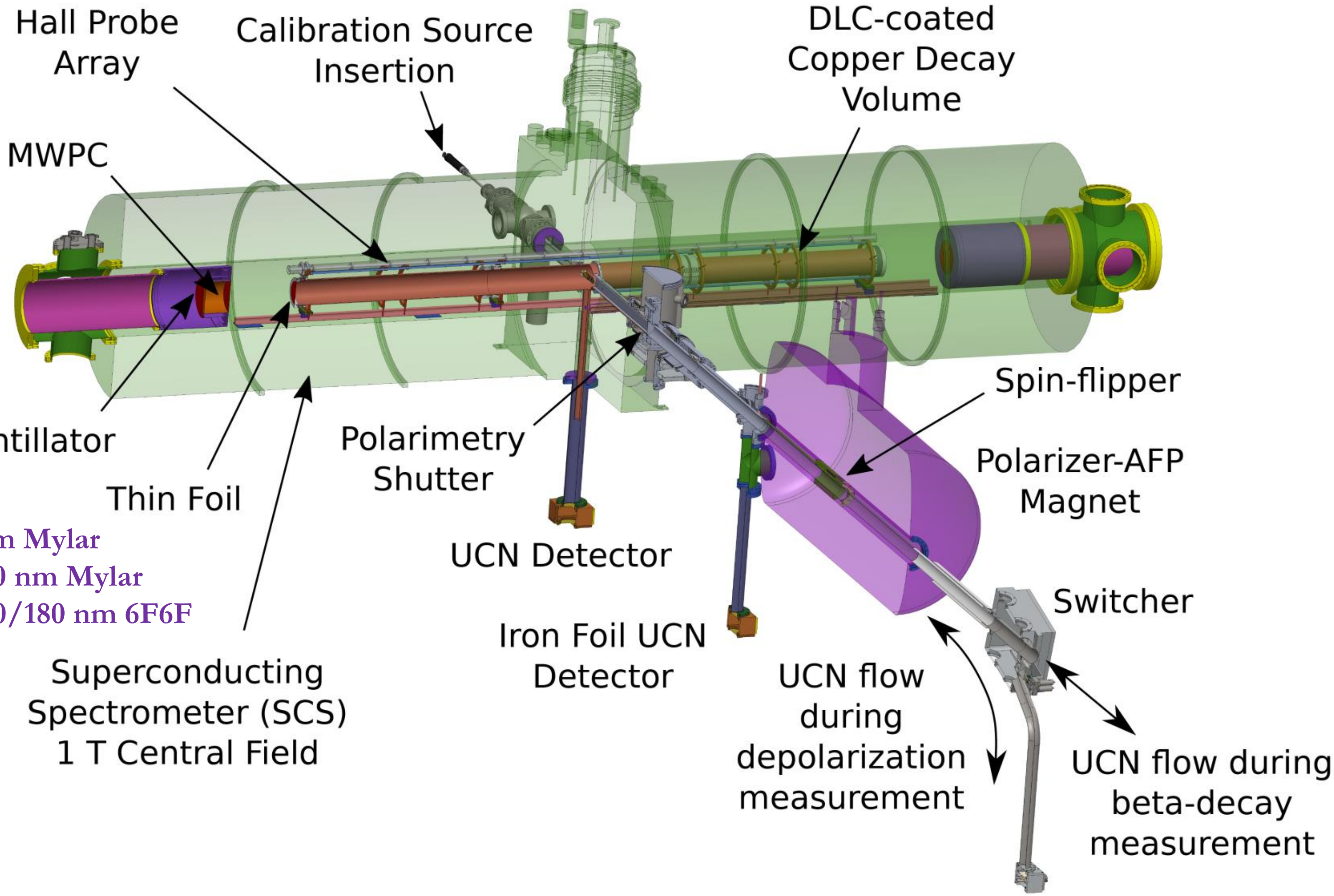
UCNA experiment

More from Andy Saunders, next



2010: 700 nm Mylar
2011-12: 500 nm Mylar
2012-13: 130/180 nm 6F6F

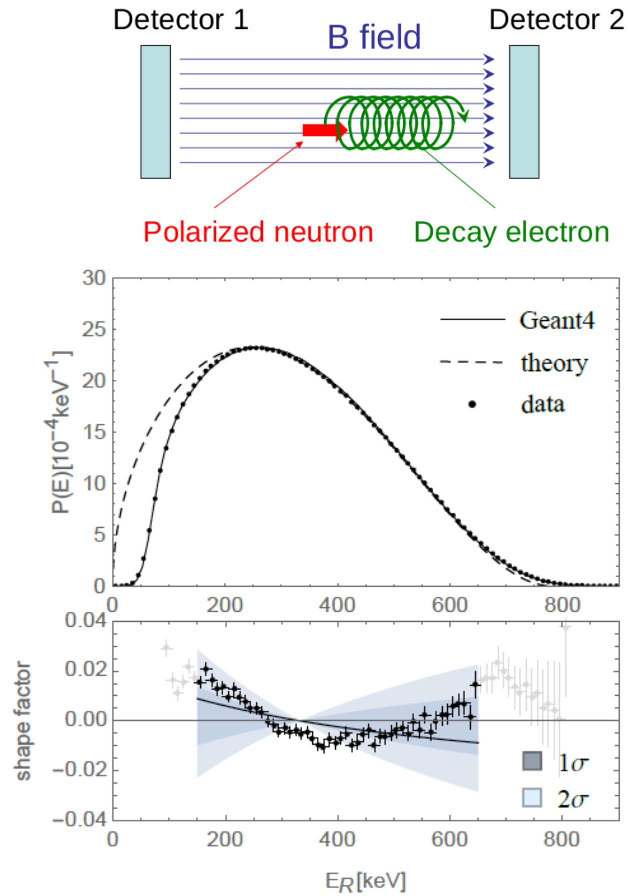
[1]Brown et al, PRC **97** 035505 (2018)

Fierz term from UCNA

- UCNA: 4π β acceptance, low neutron/ambient backgrounds, energy reconstruction → direct spectral extraction of **b_n**
- "Super-sum" removes distortion from **A**

$$\Sigma = \frac{1}{2}\sqrt{N(E)_1^{+}N(E)_2^{-}} + \frac{1}{2}\sqrt{N(E)_1^{-}N(E)_2^{+}}$$

- 2010 data set dominant error: energy calibration



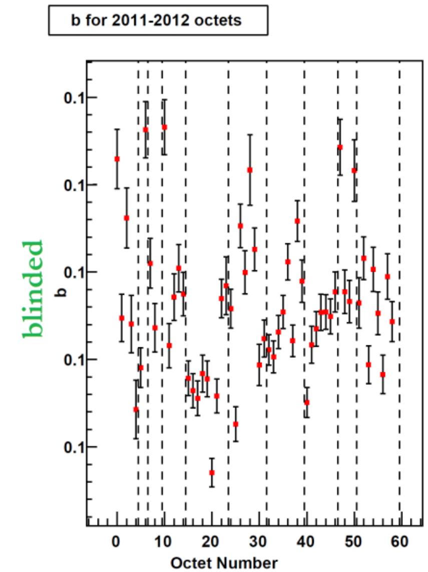
$$b_n = 0.067 \pm 0.005_{stat} \,{}^{+0.090}_{-0.061}\, sys$$

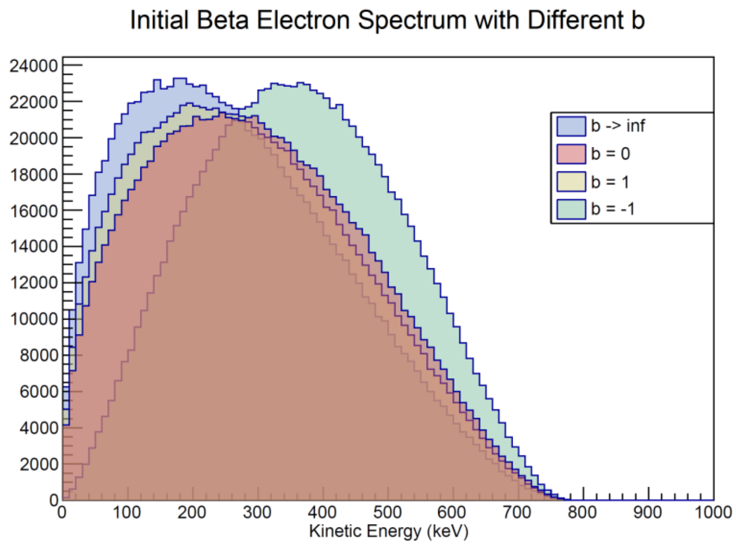
$$-0.041 < b_n < 0.225 \text{ (90\% CL)}$$

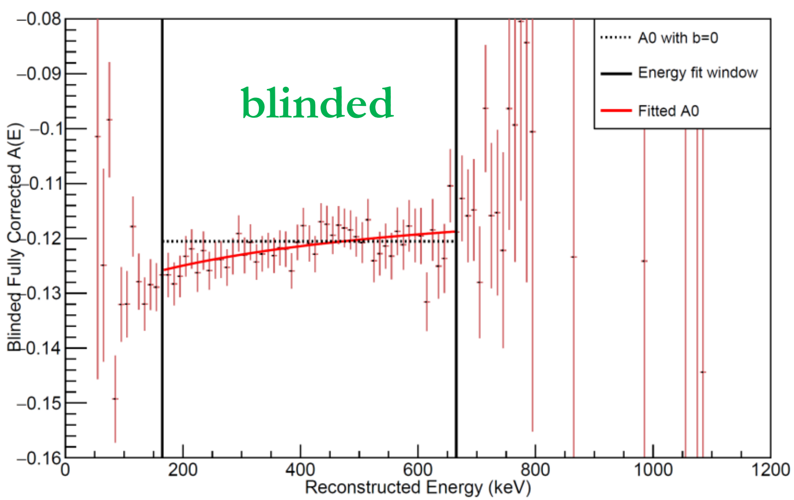
[1]Hickerson *et al*, PRC **96** (2017) 042501

Complementary approaches for **b**

- 2 new datasets: 2011-12, 2012-13
  - 2012 improved E reconstruction: b vs octet →
- 2 techniques: spectrum $\boldsymbol{\Sigma}$ vs asymmetry $\dfrac{\boldsymbol{A}}{1+\boldsymbol{b}\frac{\mathrm{m}}{\mathrm{E}}}$
  - $\boldsymbol{\Sigma}$ limited by E calibration, $\boldsymbol{A_m}$ by statistics
- <u>Preliminary</u>: $\boldsymbol{b_n} = x.xx \pm 0.03$ (blinded)







Thanks X. Sun (Caltech) for slide content

Fundamental Neutron Physics at the Spallation Neutron Source

Nab Collaboration

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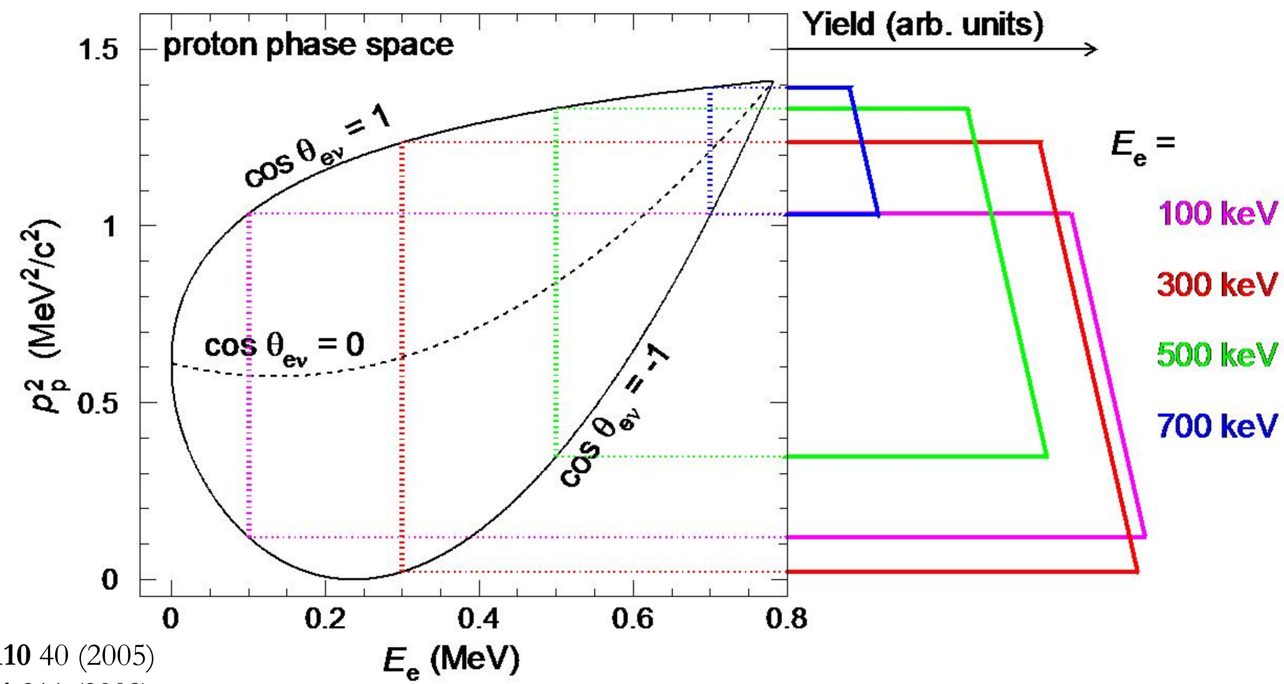
UNIVERSITY of VIRGINIA

Nab measurement principles

- Goal: **Δa/a**~10^{-3} and **Δb**~3×10^{-3}
- 4π β acceptance : "tear-drop"
- $p_p^2 = p_e^2 + 2p_e p_\nu \cos\theta_{e\nu} + p_\nu^2$

Yield: $\propto 1 + a\frac{p_e}{E_e}\cos\theta_{e\nu}$



Bowman, J Res NIST **110** 40 (2005)
Pocanic *et al*, NIMA **611** 211 (2009)
Baessler *et al*, J Phys G **41** 114003 (2014)

Nab measurement principles

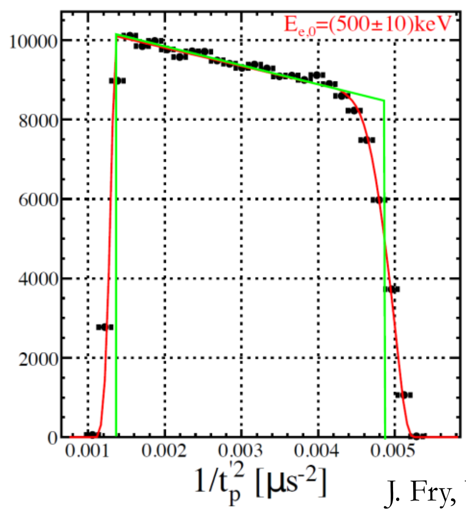
- Asymmetric spectrometer with long TOF arm: proton TOF ⇒ momentum

$$t_p = L\frac{m_p}{p_p} = \frac{f(\cos\theta)}{p_p}$$

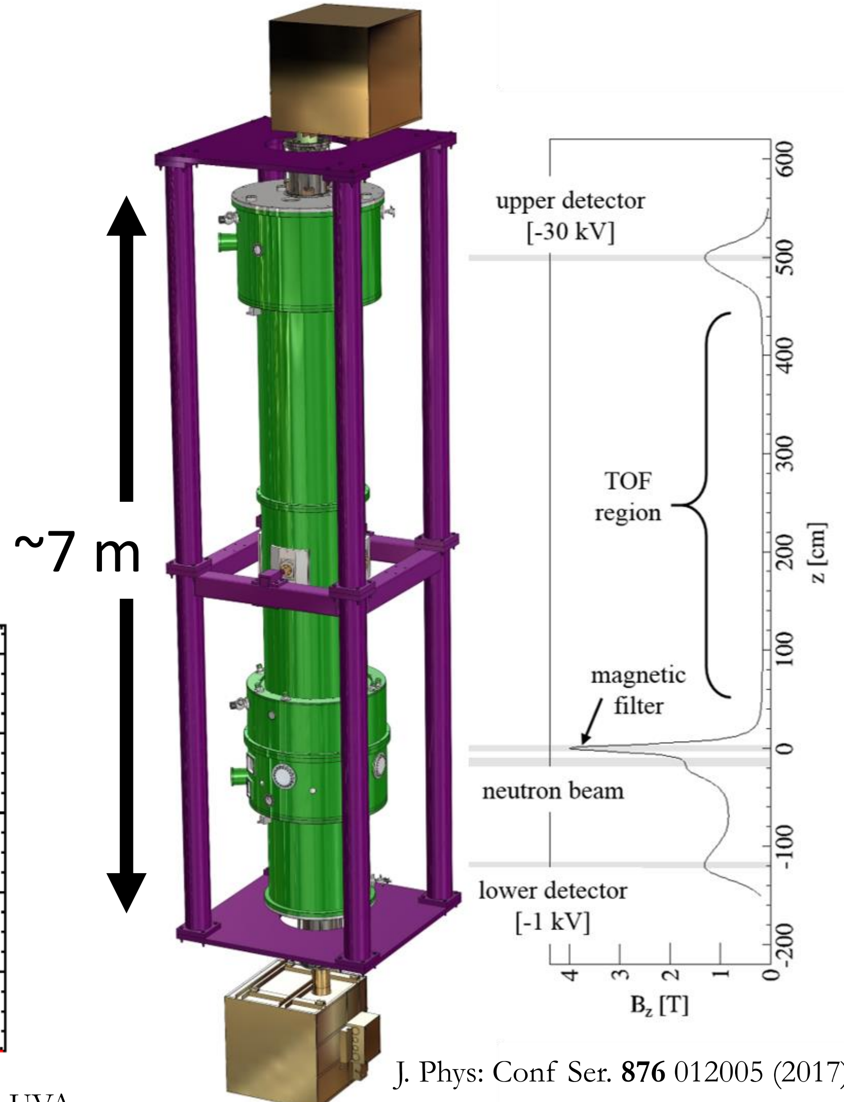
- Adiabatic field expansion

$$t_p = \frac{m_p}{p_p}\int_{z_0}^{L}\frac{dz}{\sqrt{1-\frac{B(z)}{B_0}\sin^2\theta+\frac{q(V(z)-V_0)}{E_0}}}$$

- For each E_e fit central 75% to obtain **a**
- Edges verify spectrometer response



J. Fry, UVA



J. Phys: Conf Ser. **876** 012005 (2017)

Nab spectrometer installation

gif credit: J. Fry, UVA

Installation crew nominated for ORNL "Significant Event Award"

Expected statistical uncertainty

- 1.4 MW routine at SNS
  - Expect 1600 decays/s = 200 p/s in top detector
- Up to **Δa/a**~2×10^{-3} each run-cycle
- Require 2 years SNS running for statistics goal
  - Including 50% duty factor, 10% background, several systematic runs

Δa/a~7×10^{-4}

Statistical uncertainties σ_a for a SM fit [$b \equiv 0$]

varied ⇓	$E_{e,\min}$: / $t_{p,\max}$:	0 / –	100 keV / –	100 keV / 40 μs	100 keV / 30 μs	300 keV / 40 μs
N_u, a		$2.4/\sqrt{N_u}$	$2.4/\sqrt{N_u}$	$2.6/\sqrt{N_u}$	$2.8/\sqrt{N_u}$	$3.1/\sqrt{N_u}$
+ E_{calib}, L_{TOF}		$2.6/\sqrt{N_u}$	$2.6/\sqrt{N_u}$	$2.8/\sqrt{N_u}$	$3.1/\sqrt{N_u}$	$3.5/\sqrt{N_u}$
+ use 75%§		$3.3/\sqrt{N_u}$	$3.4/\sqrt{N_u}$	$3.6/\sqrt{N_u}$	$4.0/\sqrt{N_u}$	$4.6/\sqrt{N_u}$
+ 10% bgd.		$4.3/\sqrt{N_u}$	$4.4/\sqrt{N_u}$	$4.5/\sqrt{N_u}$	$4.9/\sqrt{N_u}$	$5.5/\sqrt{N_u}$

§ fits for a use only the inner 75% of p_p^2 data.
[N_u . . . number of protons detected in upper detector.]

Statistical uncertainties σ_a for a BSM fit [variable b]

varied ⇓	$E_{e,\min}$: / $t_{p,\max}$:	0 / –	100 keV / –	100 keV / 40 μs	100 keV / 30 μs	300 keV / 40 μs
N_u, a, b		$2.4/\sqrt{N_u}$	$2.5/\sqrt{N_u}$	$2.7/\sqrt{N_u}$	$3.0/\sqrt{N_u}$	$3.6/\sqrt{N_u}$
+ E_{calib}, L_{TOF}		$2.6/\sqrt{N_u}$	$2.7/\sqrt{N_u}$	$2.9/\sqrt{N_u}$	$3.2/\sqrt{N_u}$	$3.9/\sqrt{N_u}$
+ use 75%§		$3.4/\sqrt{N_u}$	$3.5/\sqrt{N_u}$	$3.8/\sqrt{N_u}$	$4.4/\sqrt{N_u}$	$5.1/\sqrt{N_u}$
+ 10% bgd.		$4.4/\sqrt{N_u}$	$4.6/\sqrt{N_u}$	$4.7/\sqrt{N_u}$	$5.2/\sqrt{N_u}$	$6.3/\sqrt{N_u}$

Projected statistical uncertainties σ_b (for completeness)

$E_{e,\min}$	0	100 keV	200 keV	300 keV
σ_b	$7.5/\sqrt{N}$	$10.1/\sqrt{N}$	$15.6/\sqrt{N}$	$26.3/\sqrt{N}$
σ_b†	$7.7/\sqrt{N}$	$10.3/\sqrt{N}$	$16.3/\sqrt{N}$	$27.7/\sqrt{N}$

† with E_{calib} variable.
[N . . . number of n-decay electrons detected in either detector.]

D. Pocanic

Nab expected systematics for a

Experimental parameter	Principal specification (comment)	$(\Delta a/a)_{\text{SYST}}$
Magnetic field:		
curvature at pinch	$\Delta\gamma/\gamma = 2\%$ with $\gamma = (\mathrm{d}^2 B_z(z)/\mathrm{d}z^2)/B_z(0)$	5.3×10^{-4}
ratio $r_B = B_{\text{TOF}}/B_0$	$(\Delta r_B)/r_B = 1\%$	2.2×10^{-4}
ratio $r_{B,\text{DV}} = B_{\text{DV}}/B_0$	$(\Delta r_{B,\text{DV}})/r_{B,\text{DV}} = 1\%$	1.8×10^{-4}
L_{TOF}, length of TOF region		(*)
U inhomogeneity:		
in decay / filter region	$\lvert U_F - U_{\text{DV}}\rvert < 10\,\text{mV}$	5×10^{-4}
in TOF region	$\lvert U_F - U_{\text{TOF}}\rvert < 200\,\text{mV}$	2.2×10^{-4}
Neutron beam:		
position	$\Delta\langle z_{\text{DV}}\rangle < 2\,\text{mm}$	1.7×10^{-4}
profile (incl. edge effect)	slope at edges $< 10\%/\text{cm}$	2.5×10^{-4}
Doppler effect	(analytical correction)	small
unwanted beam polarization	$\Delta\langle P_n\rangle < 2 \cdot 10^{-5}$ (with spin flipper)	1×10^{-4}
Adiabaticity of proton motion		1×10^{-4}
Detector effects:		
E_e calibration	$\Delta E_e < 200\,\text{eV}$	$2 \cdot 10^{-4}$
shape of E_e response	$\Delta N_{\text{tail}}/N_{\text{tail}} \leq 1\%$	4.4×10^{-4}
proton trigger efficiency	$\epsilon_p < 100\,\text{ppm/keV}$	3.4×10^{-4}
TOF shift (det./electronics)	$\Delta t_p < 0.3\,\text{ns}$	3×10^{-4}
TOF in accel. region	$\Delta r_{\text{GROUND EL.}} < 0.5\,\text{mm}$ (preliminary)	3.4×10^{-4}
BGD/accid. coinc's	(will subtract out of time coinc)	small
Residual gas	$P < 2 \cdot 10^{-9}$ torr	3.8×10^{-4}
Overall sum		1.2×10^{-3}

(*) Free fit parameter

Systematics for Fierz term **b**

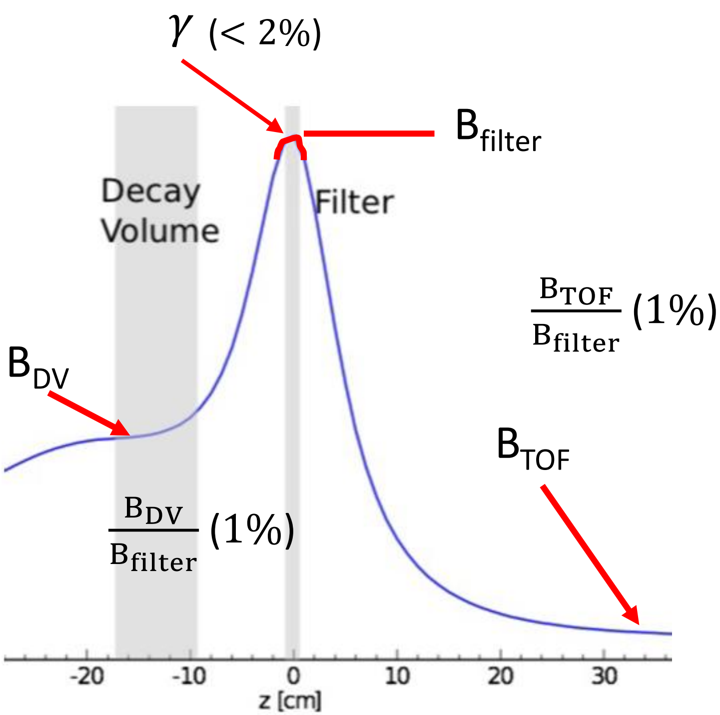
- Full β energy collected, except:
  - Bounce history (deadlayer), bremsstrahlung, detector response…
  - Also backgrounds, edge effects, timing cutoff, proton efficiency…
- Statistical uncertainty $\sim 3 \times 10^{-4}$
  - if gain free parameter → 5×10^{-4}
- Initial (partial) parametric study of systematics:

Systematic	Requirement
Gain	Free parameter
Offset	± 0.06 keV
Max. nonlinearity	± 0.05 keV
Resolution	± 2 keV
Energy tail	$\pm 10\%$

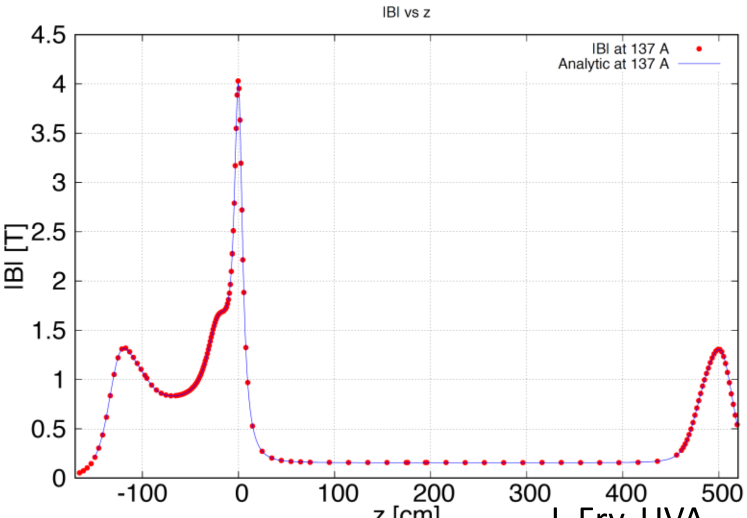
H. Li, UVA

Magnetic field

- Precise (relative) field mapping
- Locate electron/proton flux tubes



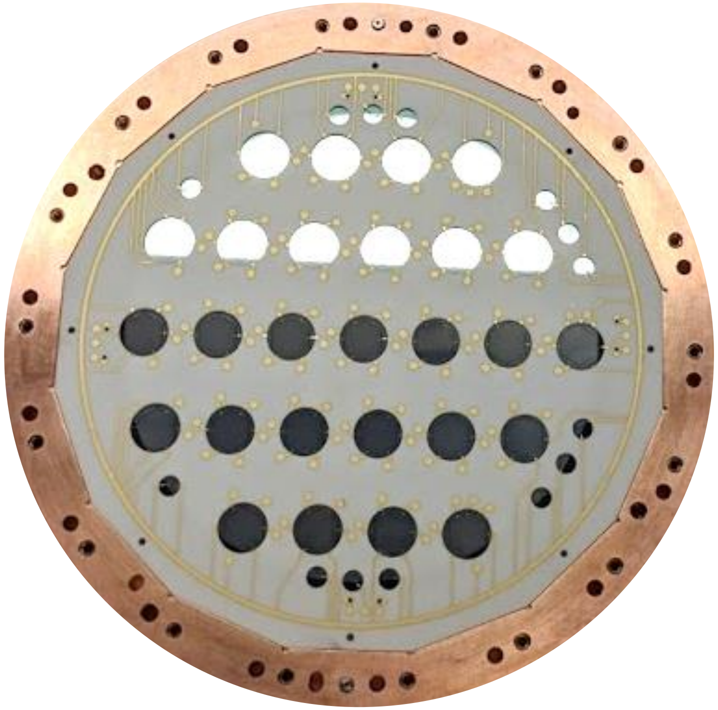
S. Penttila, ORNL



J. Fry, UVA

Detector effects

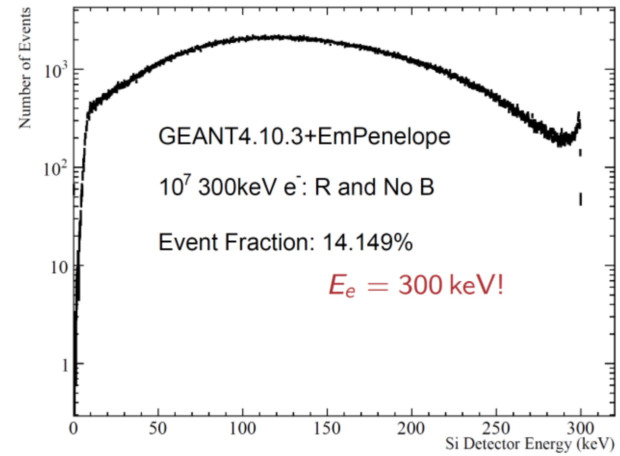
- Calibration (dE ~ 0.2 keV for **a**)
  - Linearity to $\sim 10^{-4}$ → radioactive sources; need high precision calibrated pulser
  - Temperature stability to 0.5 K → sensors, leakage current, pulser gain?
  - Detector response vs. event energy/hit location; uniformity → collimated radioactive sources; electron-gun studies
  - Cross-talk → radioactive sources, proton beam (physical); pulsers (electronic)

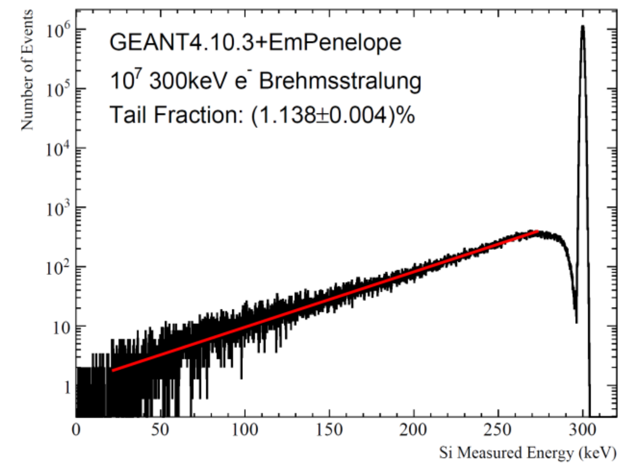


- Si detector: 2 mm thick, 11 cm diameter active area, 100 nm deadlayer, 127 hex pixels
- 40-50 ns rise times
- 3 keV @ 30 keV FWHM

Detector effects

- Energy loss ($dN_{tail}/N_{tail} < 1\%$ for **a**)
  - Backscattering = sum both detectors but…
  - Bounce history of electrons → radioactive source studies to benchmark simulations
  - Detector deadlayer uniformity → measure with proton and electron gun
  - Bremsstrahlung needs ×10 improvement → characterize in situ with radioactive sources; electron-gun and gamma detector
- Rate-dependent effects: backgrounds, accidentals, deadtime

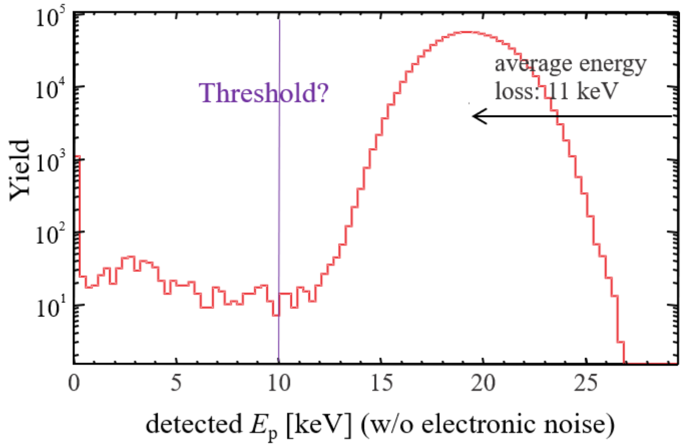




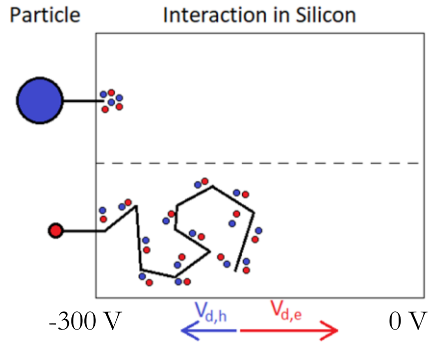
E. Frlez, UVA

Detector effects

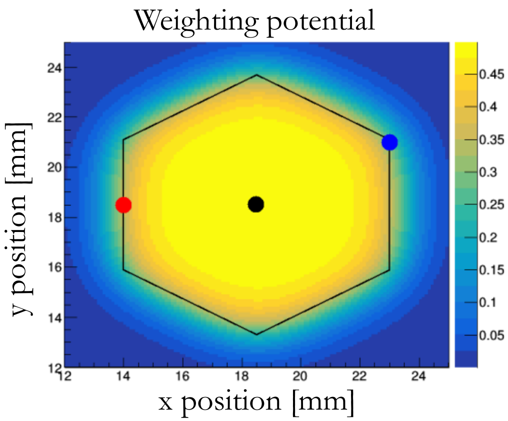
- Proton trigger efficiency < 100 ppm/keV (efficiency slope 50%) → proton gun
- TOF bias <0.3 ns **on average** between electrons and protons (from detector response) → collimated fast timing source, electron-gun

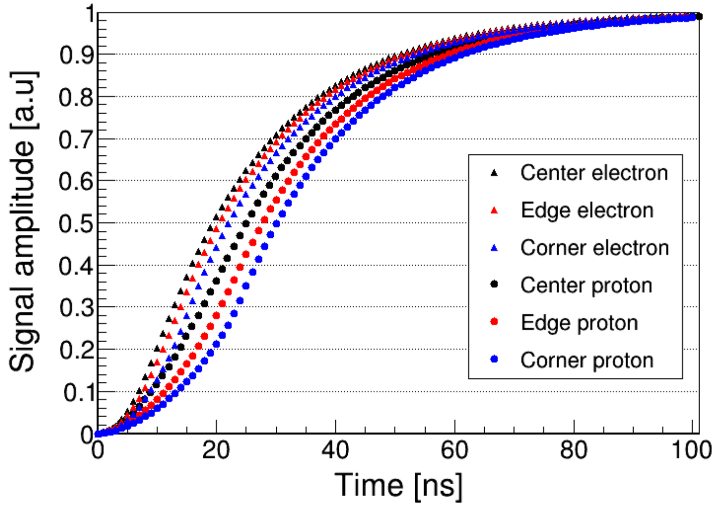


S. Baessler



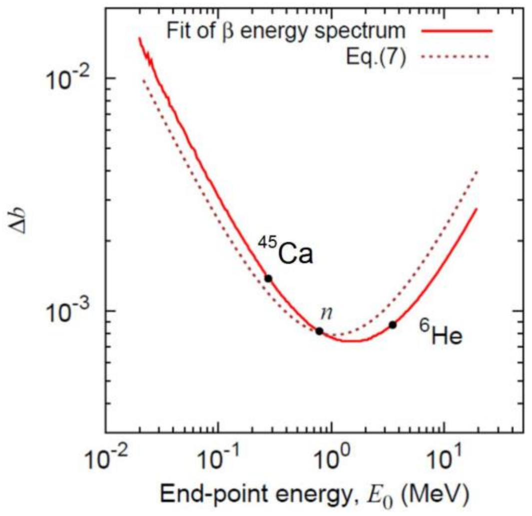
Graphic by A. Jezghani, UKY

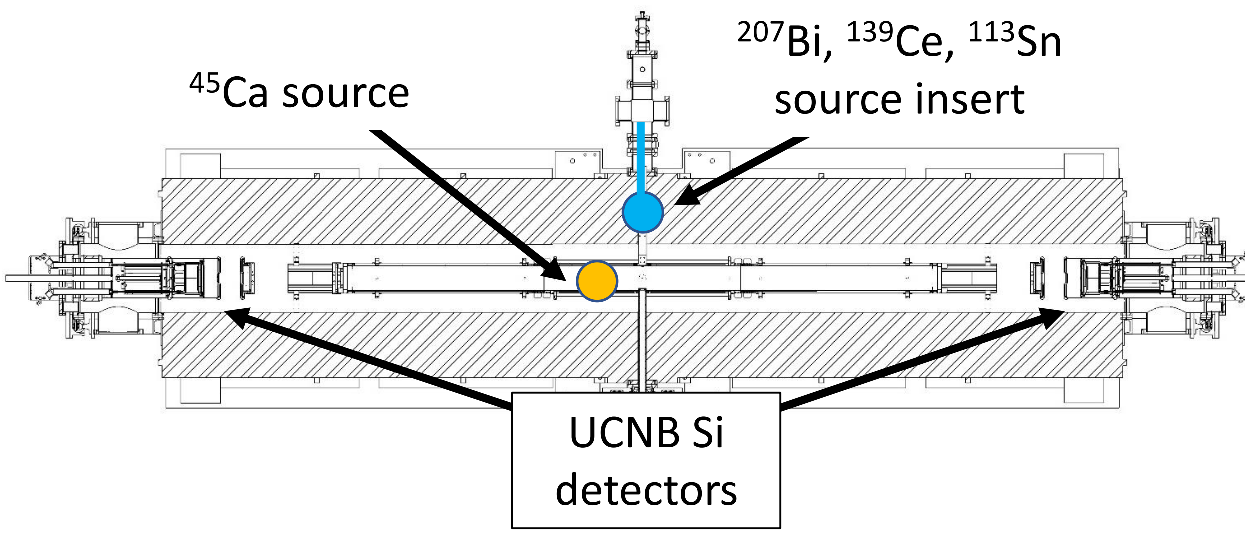


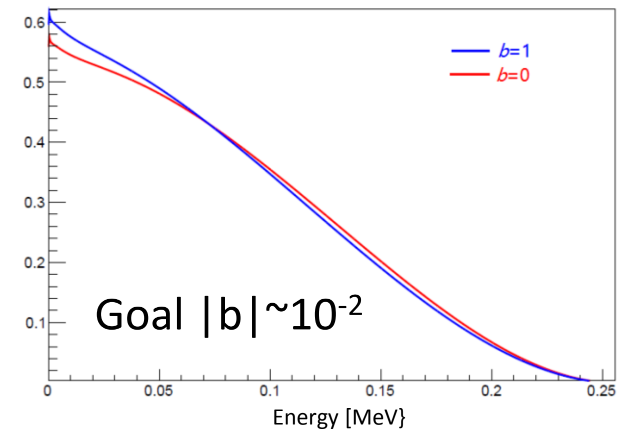


^{45}Ca Fierz term

- Learn high precision calibration
- Also nice BSM target
  - Source on thin 6F6F foil
  - UCNA spectrometer with UCNB/Nab detectors
  - 10^8 events collected







L. Hayen, KU Leuven

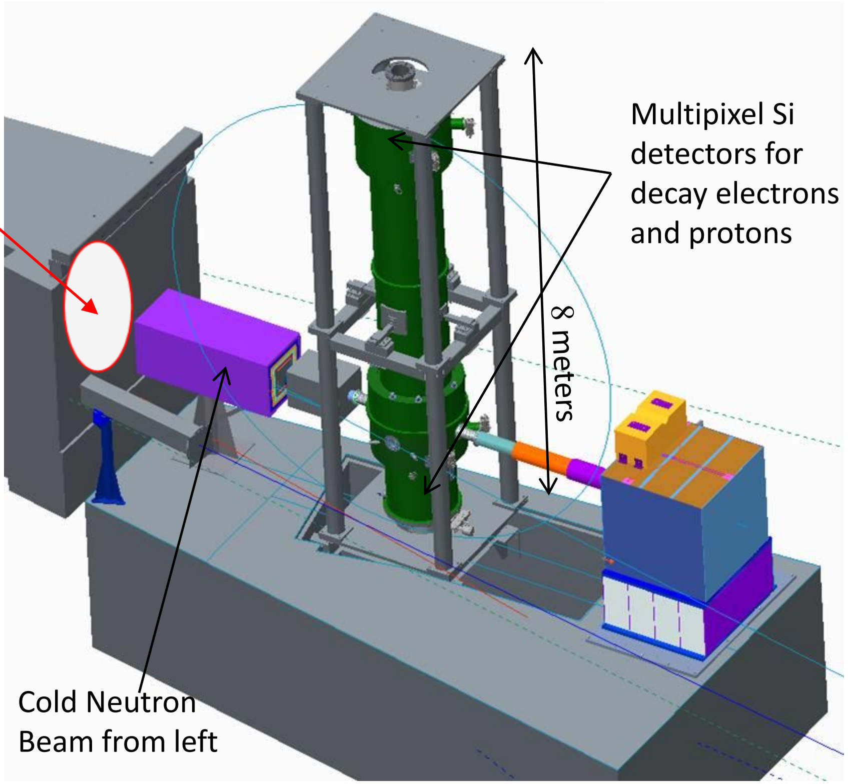
[1]Gonzalez-Alonso and Naviliat-Cuncic, PRC **94** (2016) 035503
[2]Hayen *et al*, RMP **90** (2018) 015008

Polarized $\vec{N}$ab (abBA/PANDA)

Only major modification: Addition of a neutron beam polarizer

Main uncertainties in previous best experiments: statistics, detector, background, polarization

- Statistics @ SNS or NIST is sufficient for a competitive measurement of A, but could be better
- Superior detector energy resolution, good enough time resolution
- Keep coincidence detection (electrons and protons) to improve background
- Polarization measurement seems manageable (Crossed supermirrors or He-3)



Goal: $\Delta A/A \leq 10^{-3}$, $\Delta B/B \leq 10^{-3}$

Thanks S. Baessler for slide

Summary

- UCNA has produced first spectral determination of $-0.041 < \boldsymbol{b_n} < 0.225$ (90% CL), **Δb**~0.03 in analysis
- Nab is now commissioning, aiming for **Δa/a**$\sim 10^{-3}$ and **Δb**$\sim 3\times 10^{-3}$
- Key systematics for **a** include relative magnetic field determination and electron energy reconstruction
- Detection systematics both challenging and an opportunity for other physics targets

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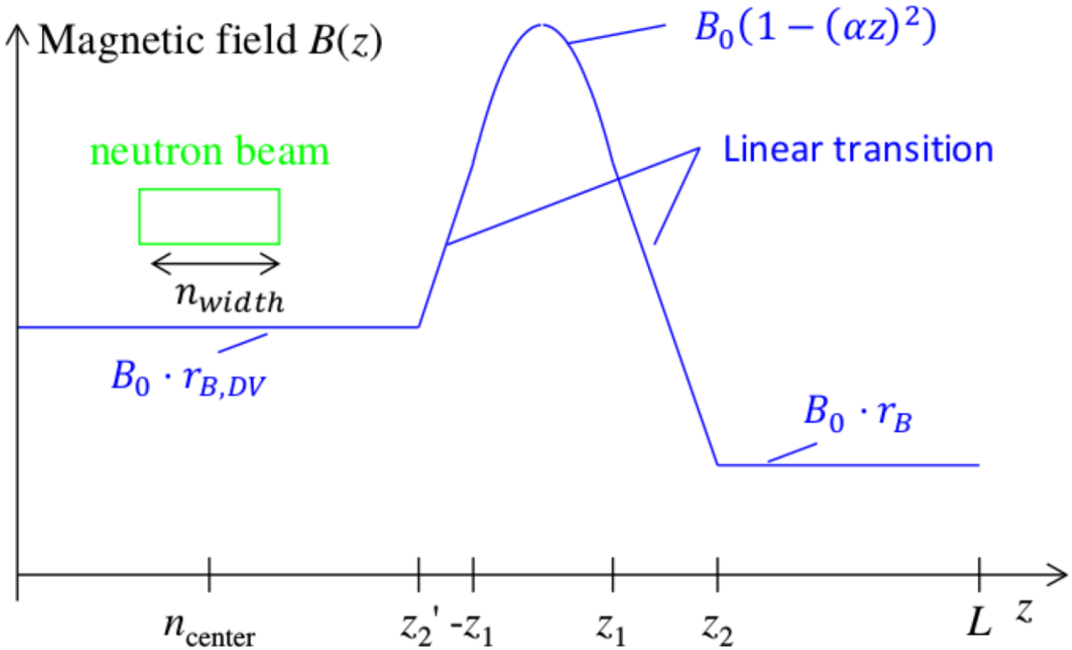
Nab uncertainty analysis

- Simple model for parametric studies

$$t_p = \frac{m_p}{p_p}\int_{z_0}^{L} \frac{dz}{\sqrt{1-\frac{B(z)}{B_0}\sin^2\theta + \frac{q(V(z)-V_0)}{E_0}}}$$

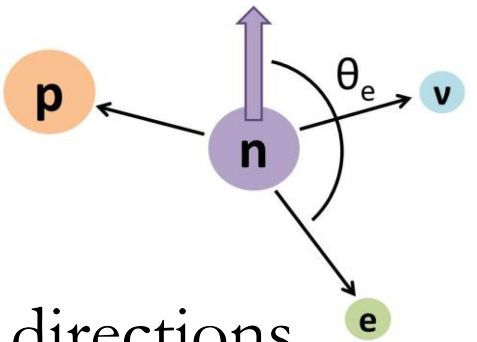
- Piecewise quadratic approximation
- Compute analytically
- Neglect $V(z)$ term for speed, then apply correction factor



S. Baessler

UCNA measurement principles

- $W \propto 1 + \frac{v}{c}\langle P\rangle A(E)\cos\theta$
- Magnetic spectrometer: $\langle\cos\theta\rangle = \pm\frac{1}{2}$
- Measure asymmetry: 2 detectors, 2 spin directions
  - Spin-dependent and detector-dependent efficiencies?
- Cancel systematics with Super-Ratio



$$S(E) = \frac{N(E)_1^+ N(E)_2^-}{N(E)_1^- N(E)_2^+}$$

$$A_{SR} = \frac{1-\sqrt{R}}{1+\sqrt{R}} = \frac{v}{c}\langle P\rangle A(E)\cos\theta$$