Commissioning The Nab Experiment

FRANK GONZALEZ

APS DNP NEW ORLEANS

OCTOBER 28, 2022

Beta-Decay: Why Use Neutrons?

Neutron decay:

- $n \rightarrow p^+ + e^- + \bar{\nu}_e$
- $|V_{ud}|^2 = \frac{5099.3\ \text{s}}{\tau_n\ (1+3\ \lambda^2)(1+\Delta_R)}$

Experimentally Determine:

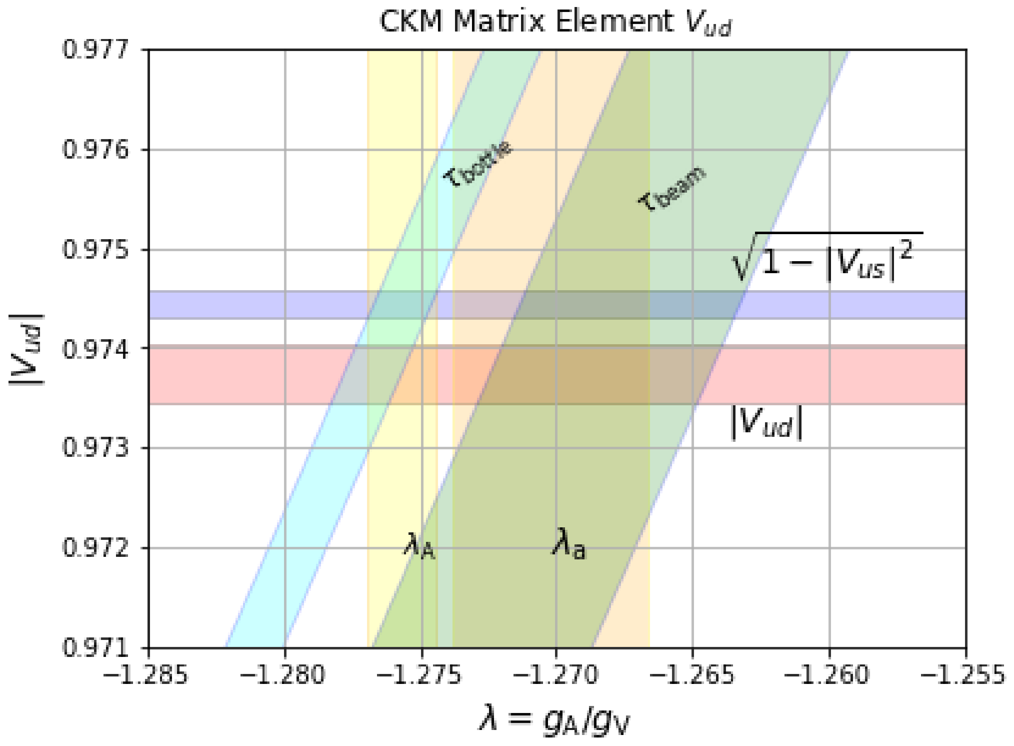
- τ_n: Neutron Lifetime
- $\lambda = g_A / g_V$: Ratio of coupling constants

Theoretically Straightforward:

- No nuclear structure corrections!
- Inner radiative correction Δ_R

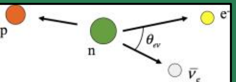
To compete with nuclear measurements:

- $\Delta\tau_n / \tau_n < 3 \times 10^{-4}$ (or $\Delta\tau_n < 0.3$ s)
- $\Delta\lambda/\lambda < 1 \times 10^{-3}$ (or $\Delta\lambda < 1 \times 10^{-3}$)



Data from:

- Workman, R. L. *et al*, Particle Data Group (2022)



Beta- … e N

Neutron …
- $n \rightarrow p$ …
- $|V_{ud}|^2$ …

Experimentally Determine:
- τ_n …
- λ …

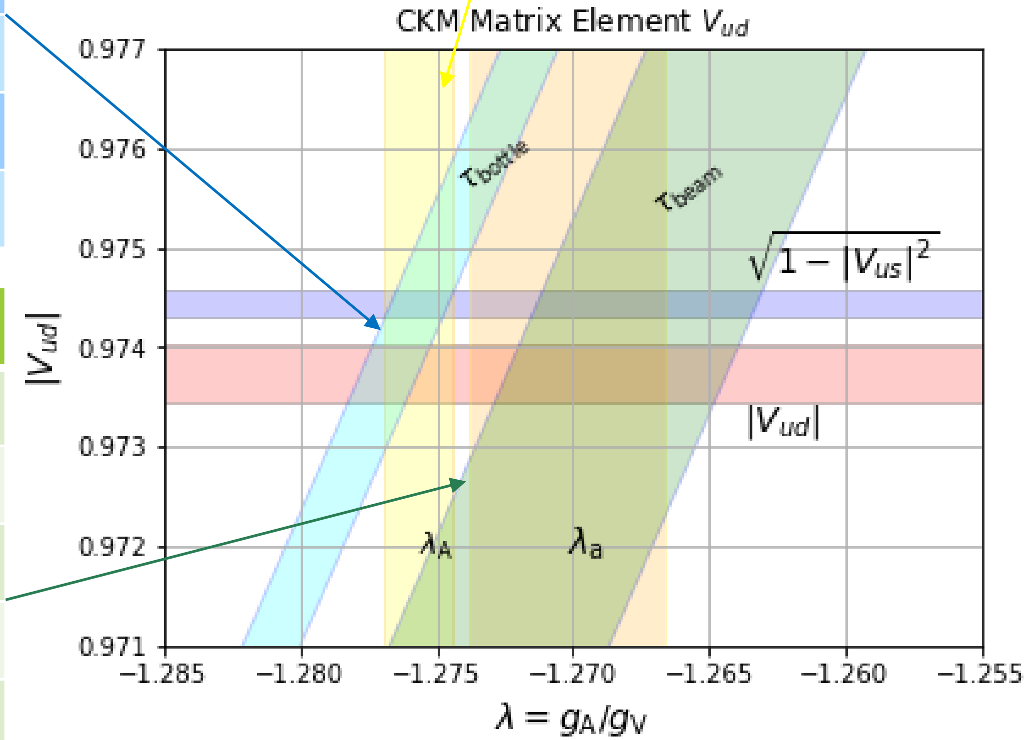
Theo…
- N…
- In…

To co…
- Δ …
- $\Delta\lambda$ …

τ_{bottle}	Session
Adam Holley	GL.00003
Andy Saunders	GL.00004
Cornelius Salonis	HA.00101
Chris Morris	KL.00005
Alex Komives	KL.00006

τ_{beam}	Session
Shannon Hoogerheide	ML.00001
Jimmy Caylor	ML.00002
Maynard Dewey	ML.00003
Fred Wietfeldt	ML.00007
William Greene	HA.00013
Chris Crawford	GL.00002
Nicholas Floyd	PL.00003

λ_A	Session
Robby Pattie	GL.00006
Rashika Gupta	PL.00001



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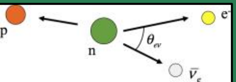


Kinematics of Unpolarized Neutron β-Decay

For unpolarized neutrons:

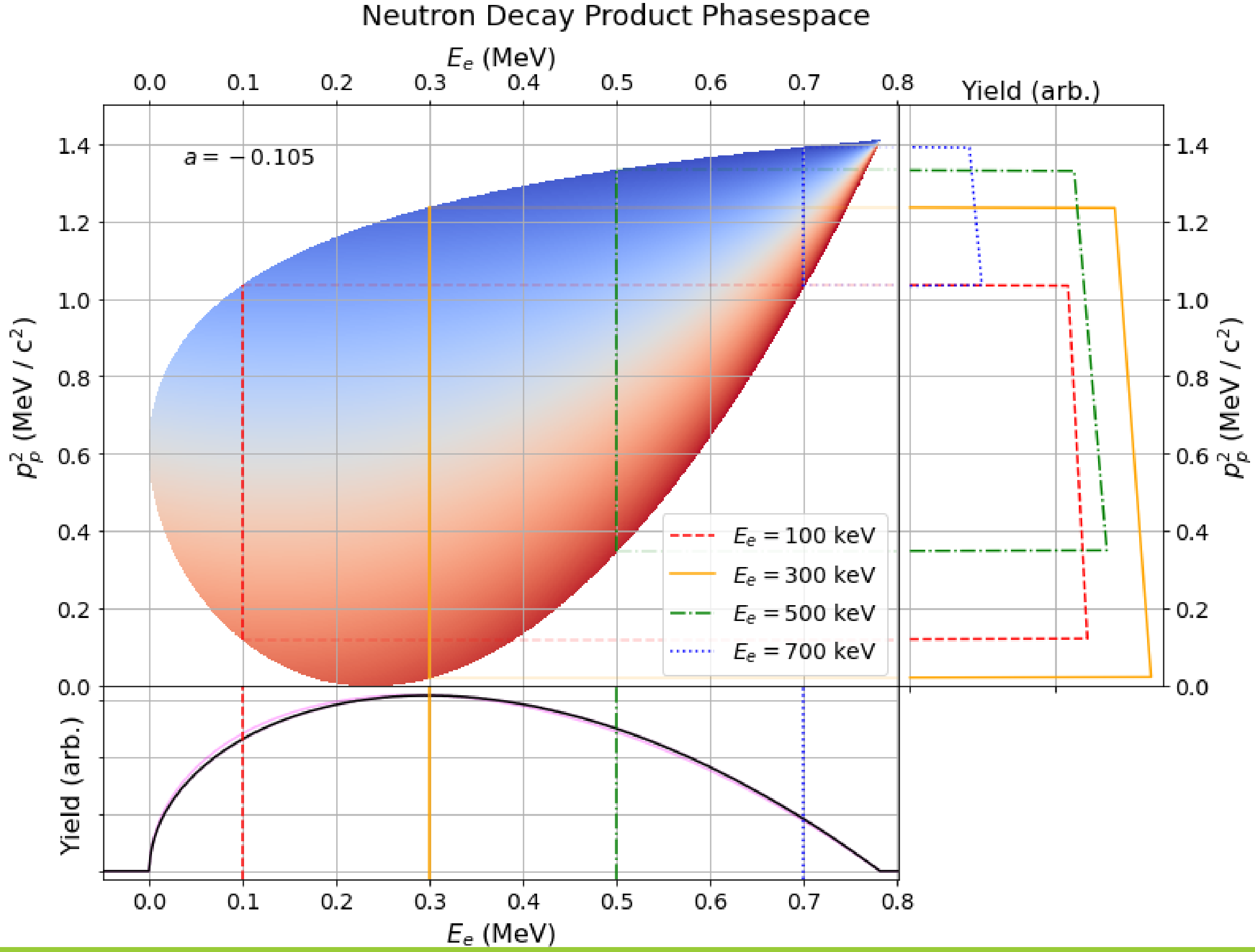
- $d\Gamma^3 \propto 1 + a\frac{|\overrightarrow{p_e}|\,|\overrightarrow{p_\nu}|}{E_e E_\nu}\cos(\theta_{e\nu}) + b\frac{m_e}{E_e}$

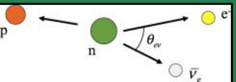
Relativistic kinematics:

- For $i \in \{n, p^+, e^-, \nu\}$, can relate $E_i^2 = \overrightarrow{p_i}^2 + m_i^2$
- Conservation of E: $E_\nu = E_n - (E_e + E_p)$
- Conservation of $\vec{p}$: $\cos(\theta_{e\nu}) = \frac{\overrightarrow{p_p}^2 - \overrightarrow{p_e}^2 - \overrightarrow{p_\nu}^2}{2|\overrightarrow{p_e}||\overrightarrow{p_\nu}|}$

After some algebra, find $d\Gamma^3(E_e, p_p^2)$

- If we can reconstruct E_e, p_p^2 for each decay, we can extract a, b…





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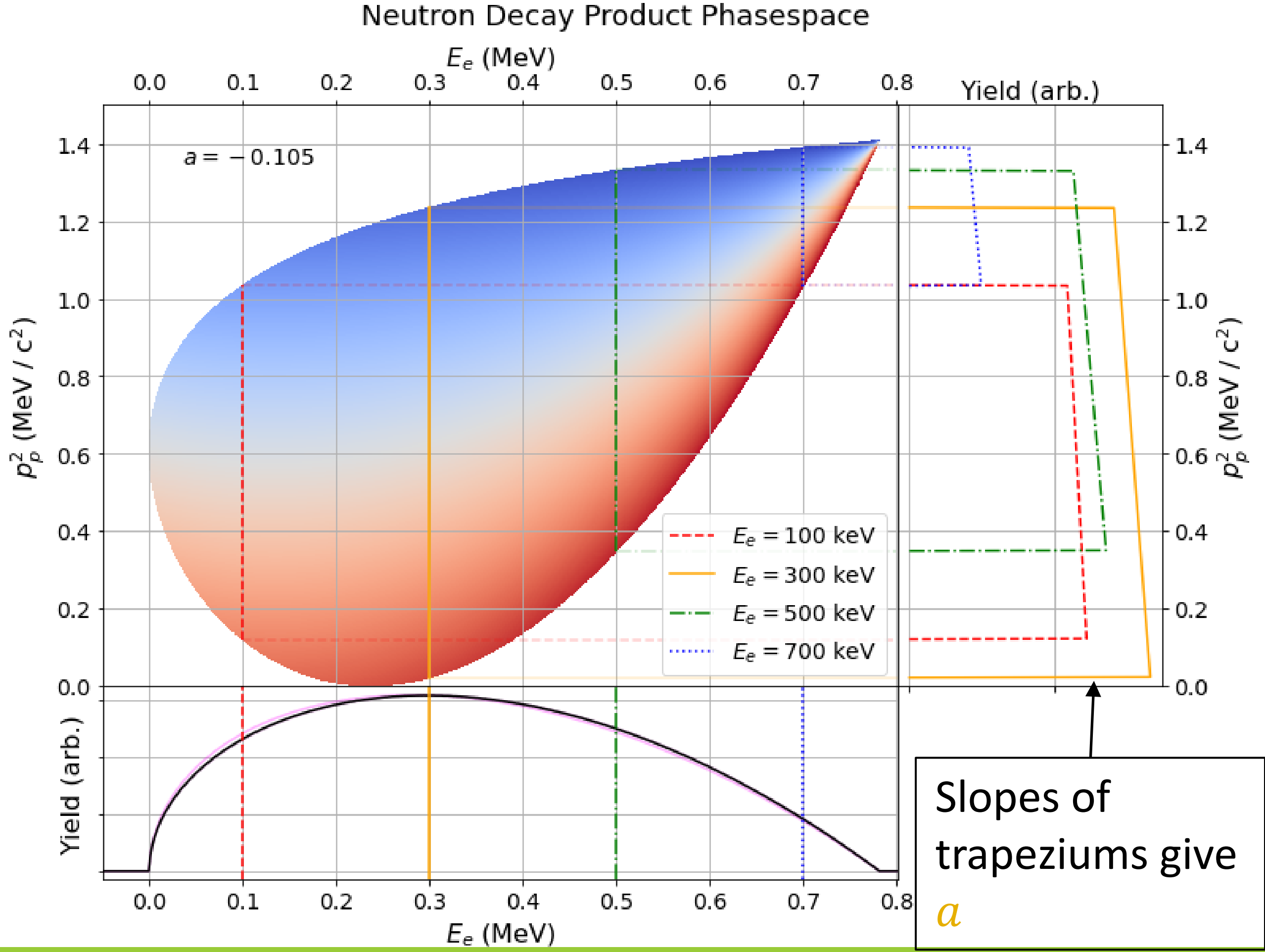

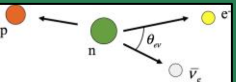

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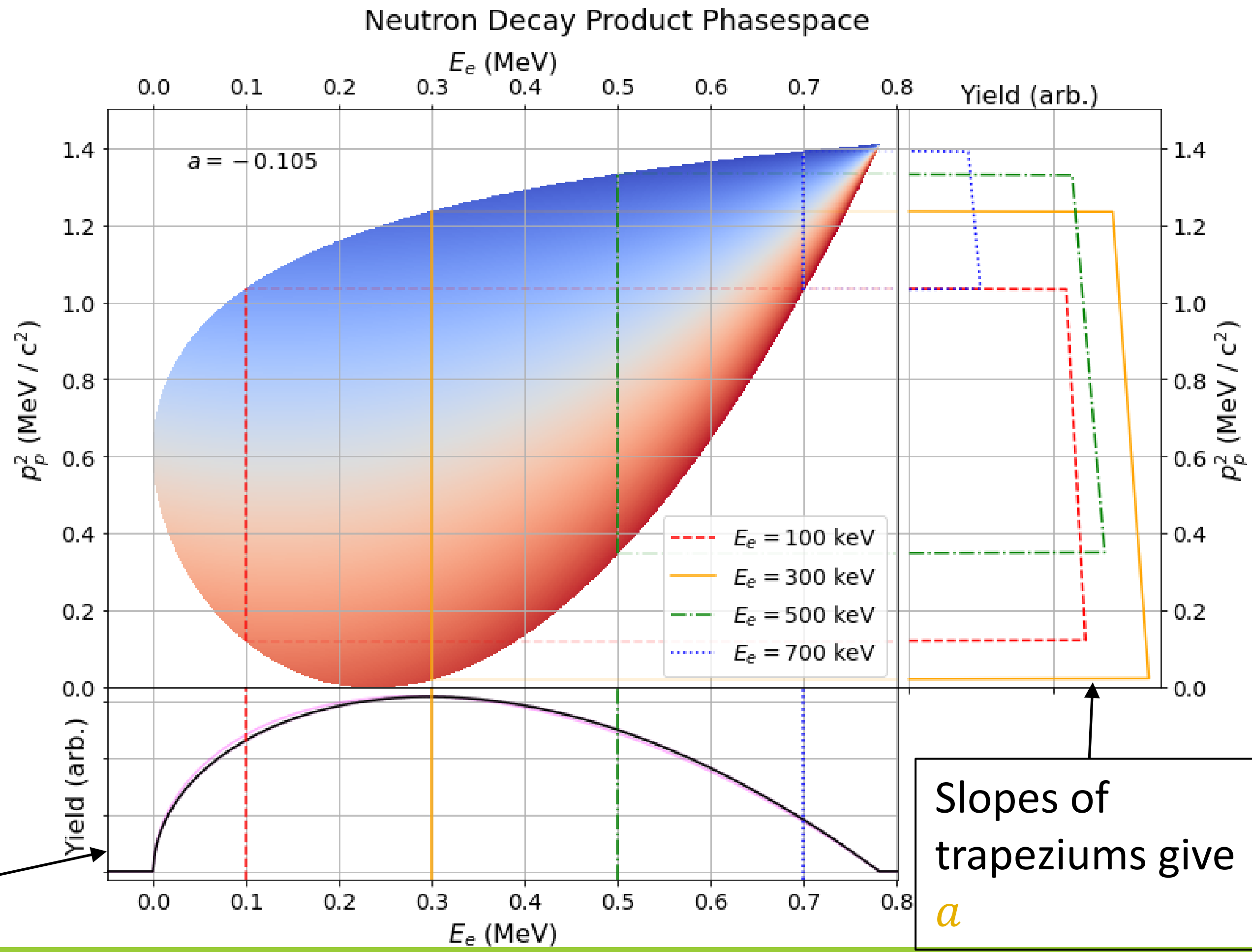
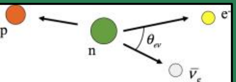


Shape of e^- spectrum gives b

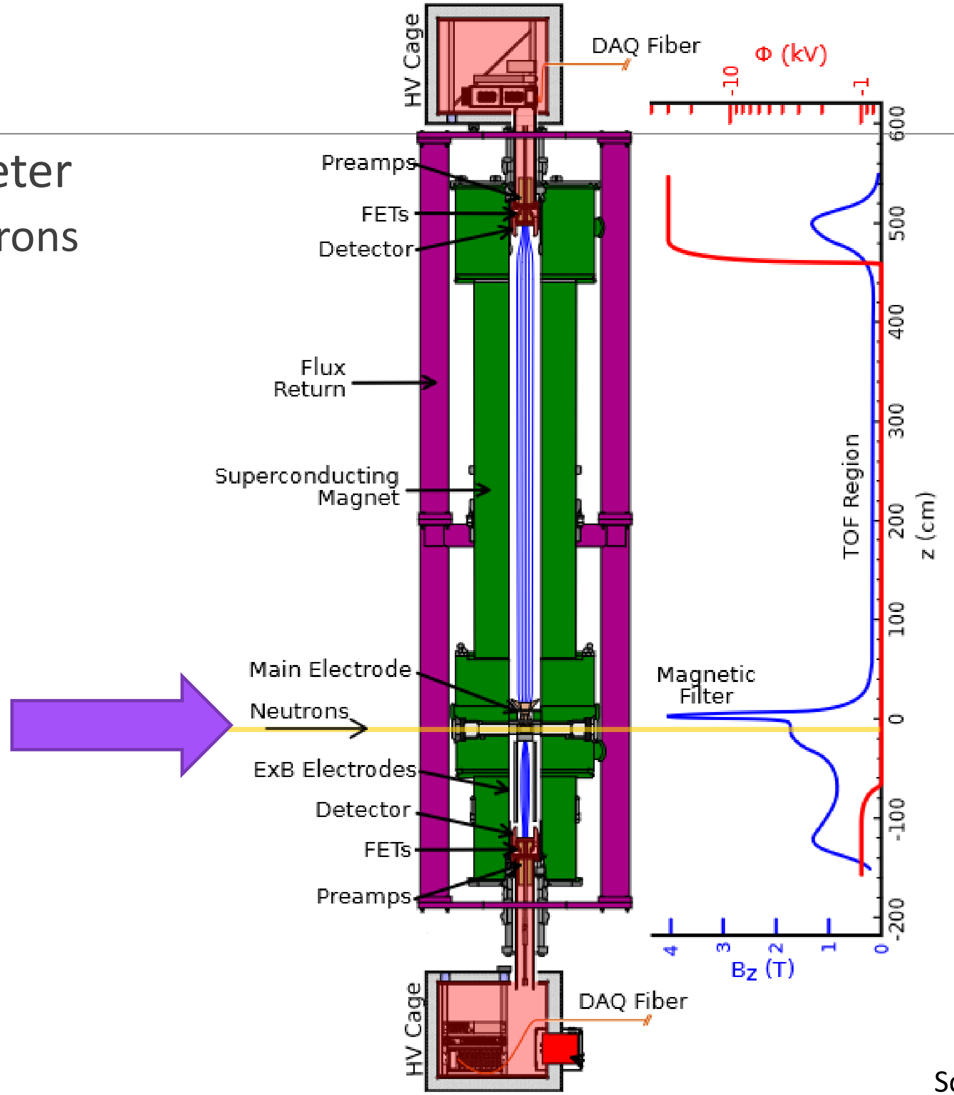
Slopes of trapeziums give a



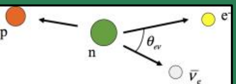
Reconstructing β-Decay Product Kinematics

Use an asymmetric (7m high) spectrometer

- Beam of unpolarized cold spallation neutrons
- Expect 1600 decays/s



Schematic by A. Jezghani, UKY



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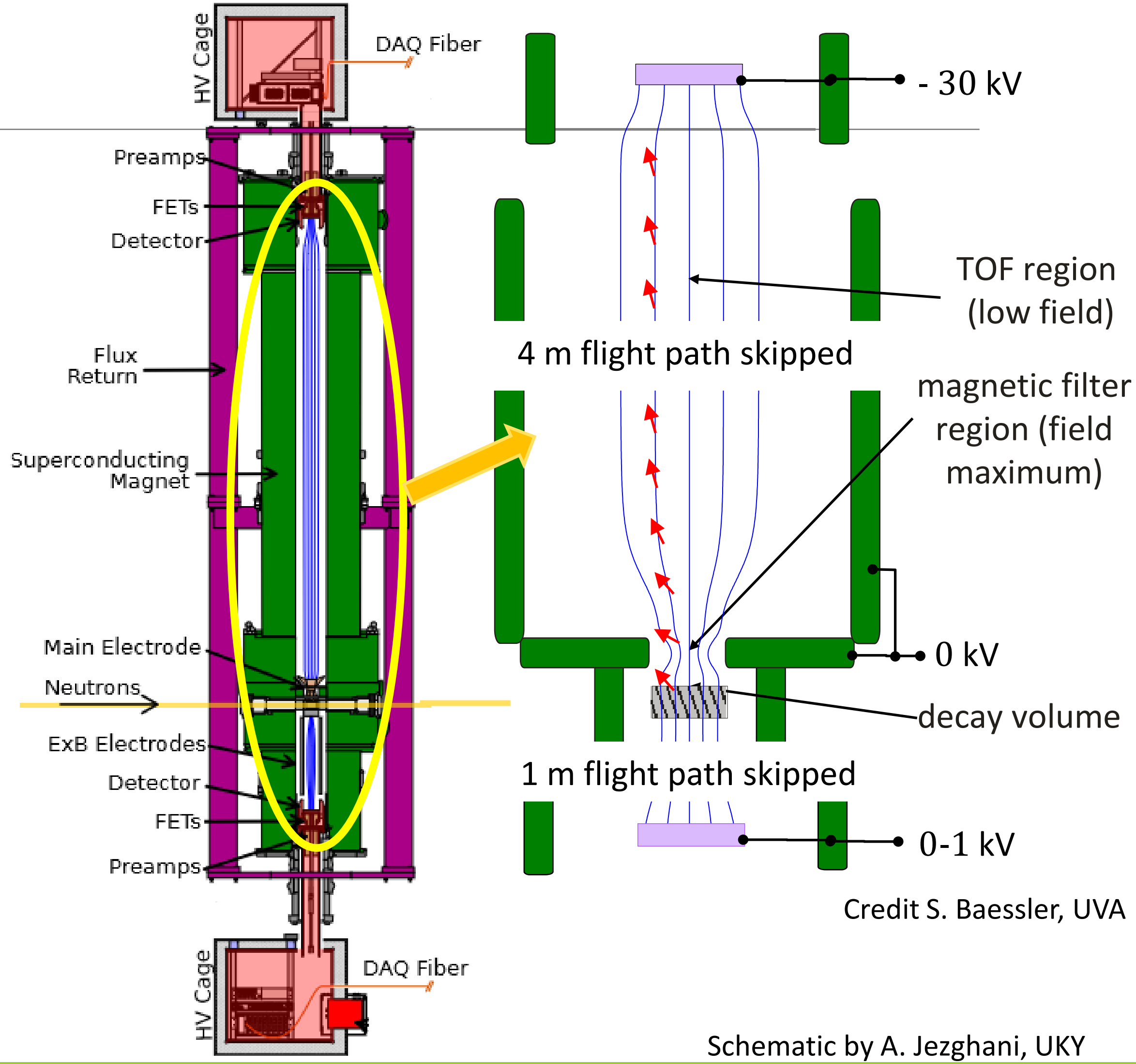
Magnetic fields guide decay products

- High-field decay filter region
- Low-field time of flight region longitudinalizes momentum



Credit S. Baessler, UVA

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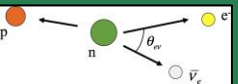

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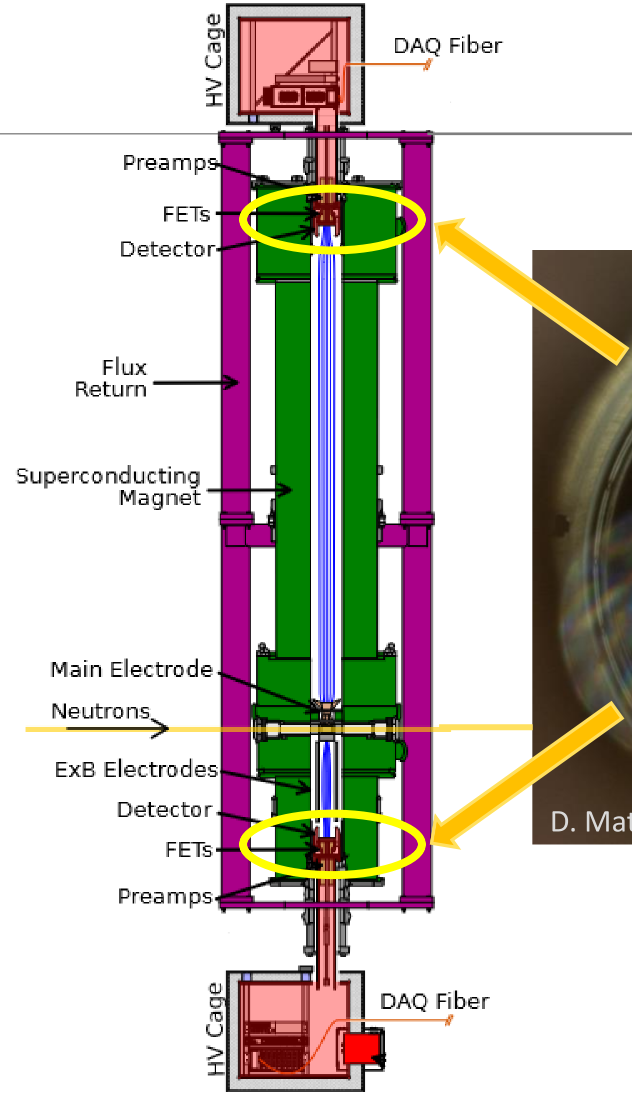
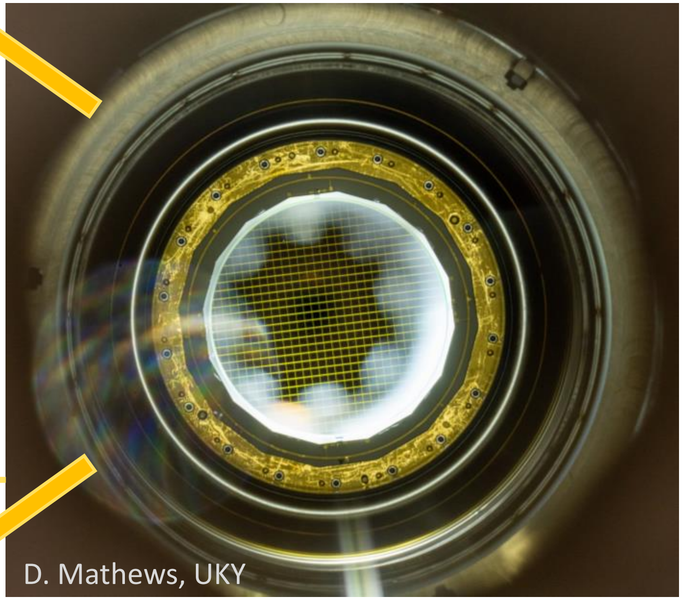
Detect coincident p^+ and e^- at silicon detectors

- Maximum $E_e = 782$ keV
- Maximum $E_p = 752$ eV

Detector at HV to accelerate protons past dead layer





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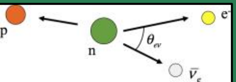


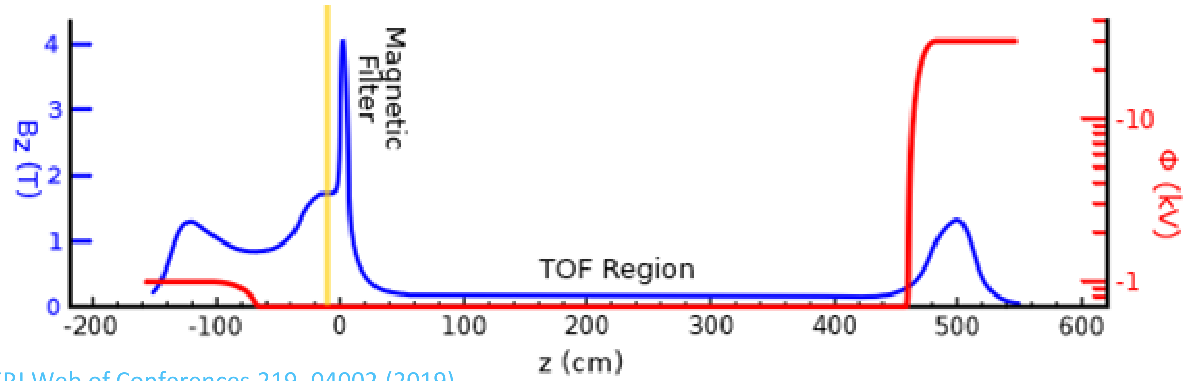
Determining p_p from Time of Flight

Charged particle (p^+) moving through EM field:

- $t_p = \frac{m_p}{p_p}\int_{z_0}^{L}\frac{dz}{\sqrt{1-\frac{B(z)}{B_0}\sin^2(\theta_0)+\frac{q(V(z)-V_0)}{E_0}}}$
- High magnetic field rejects p^+ with:
  - $\cos(\theta_0) < \sqrt{1 - B_0/B_f} \sim 0.7$

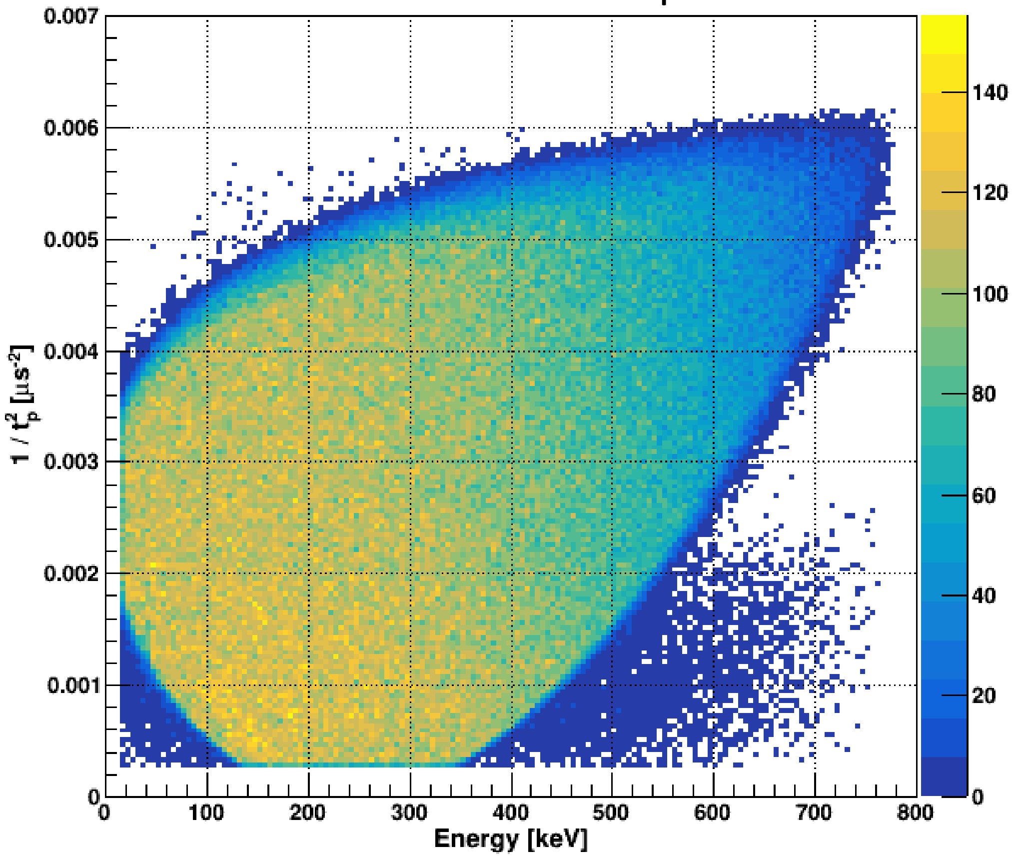
Simulate response function

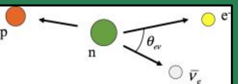
- Use edges to confirm response



Fry et al. EPJ Web of Conferences 219, 04002 (2019)

Simulated Teardrop





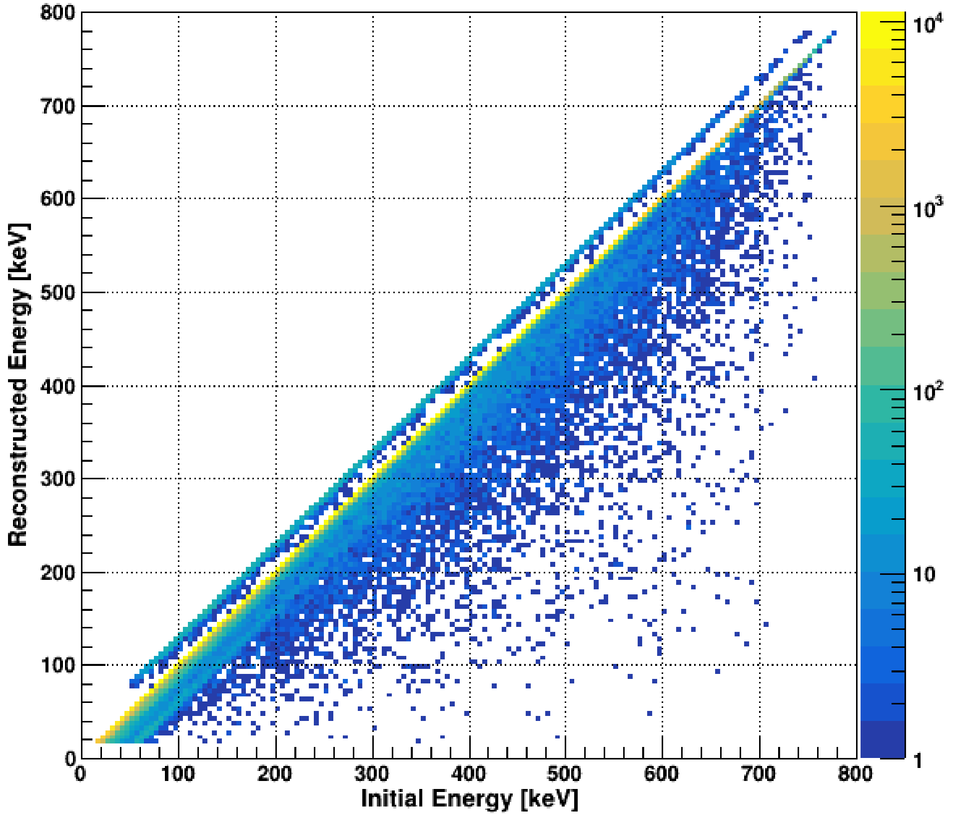
Electron Response Function

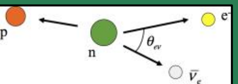
Need to understand $E_{e,meas}$ for each E_{e} to 1%

- Fast + Linear electronics response
- Electron bounce history
- Energy loss in detector due to Bremsstrahlung

Simulate detector response and measure with radioactive sources

Simulated Electron Energy





Target Uncertainties for a and b

Leading uncertainties:

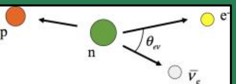
- Magnetic Field (only a)
- Detector Effects (both a and b)
- Neutron Beam (only a)

Goal precision:

- $\Delta a/a \sim (1 \times 10^{-3})_{tot.}$
- $\Delta\lambda/\lambda \sim (4 \times 10^{-4})_{tot.}$
- $\Delta b \sim (3 \times 10^{-3})_{tot.}$

Not statistically limited!

Experimental Parameter	$(\Delta a\ /\ a)_{sys.}$
Magnetic Field	6.0×10^{-4}
Electric Potential Inhomogeneity	5.5×10^{-4}
Neutron Beam	3.3×10^{-4}
Adiabaticity of Proton Motion	1×10^{-4}
Detector Effects	7.1×10^{-4}
Electron TOF	$< 1 \times 10^{-4}$
Residual Gas	3.8×10^{-4}
TOF in Acceleration Region	3×10^{-4}
Background/Accidental Coincidences	$< 1 \times 10^{-4}$
Length of the TOF Region	N/A
SUM	$1.2 \times\ 10^{-3}$



Tar… es for a and b

Beam Studies	Session
Sepehr Samiei	GL.00007
Hitesh Rahangdale	PL.00008
Paul Harmston	HA.00021

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- Dete…
- Neutron Beam (only a)

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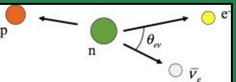

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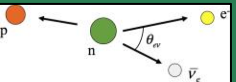
Proton Studies	Session
August Mendelsohn	GL.00008
Leendert Hayen	PL.00002



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Sepehr Samiei	GL.00007
Hitesh Rahangdale	PL.00008
Paul Harmston	HA.00021

Leading…
- Magn…
- Dete… Effects (both a and b)

Detector Studies	Session
Jin Ha Choi	PL.00004
Love Christie	PL.00005
Michelle Gervais	PL.00006
Austin Nelsen	PL.00007
Jackson Ricketts	HA.00091

Proton Studies	Session
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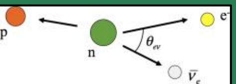


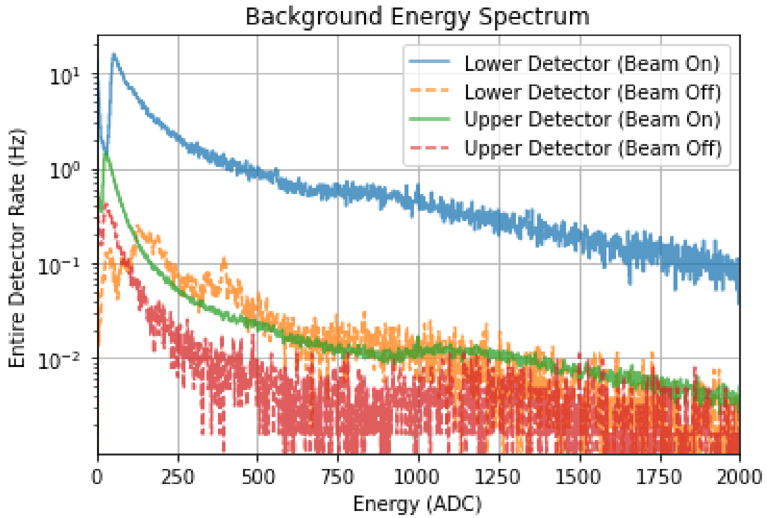
Commissioning Update: Two detectors at ORNL, Warm Magnet

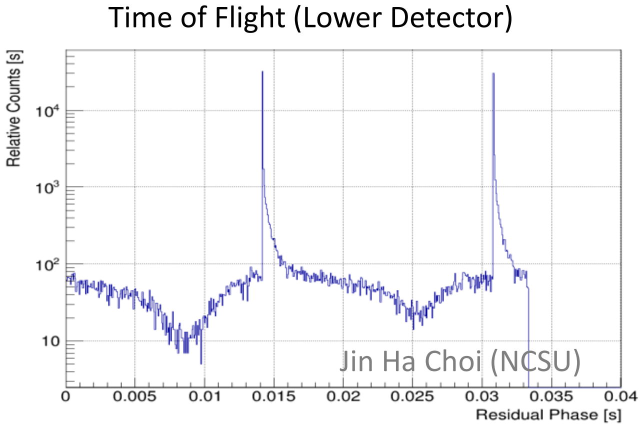
Detector Installation:
- Upper detector at 30 kV with full field
- Installed two detectors at ORNL
- Magnet now too warm to ramp (likely not detectors)…

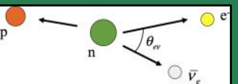
DAQ Studies
- Ability to simultaneously read data from two DAQ chassis
- Optimization of trigger logic and waveform readout
  - Trigger logic 0.4×10^3 s^{-1} → 31×10^3 s^{-1}
  - Waveform readout 3×10^3 s^{-1} → 50×10^3 s^{-1}

Detector Studies:
- Stability improvements:
  - Reading out 40% → 90% of pixels simultaneously
- Detector gain linearity studies

Background + Noise Measurements
- Lower Detector: $\sim 3 \times 10^3$ s^{-1}
  - Lower detector backgrounds partially due to SNS pulses
- Upper Detector: $\sim 0.1 \times 10^3$ s^{-1}







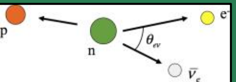
The Nab Collaboration

Nab Collaborating Institutions:

Oak Ridge National Laboratory
Los Alamos National Laboratory
University of Virginia
The University of Tennessee Knoxville
Massachusetts Institute of Technology
Arizona State University
NC State University
University of Kentucky
University of Michigan
EKU Eastern Kentucky University
The University of Tennessee Chattanooga
Universidad Nacional Autónoma de México
University of Manitoba
The University of Winnipeg
WKU
Universität Karlsruhe (TH) Forschungsuniversität • gegründet 1825
University of South Carolina

Main Project Funding:

NSF
U.S. Department of Energy Office of Science
Oak Ridge National Laboratory
University of Virginia



Extra Slides

How to Measure λ?

Decay rate of the neutron is proportional to:

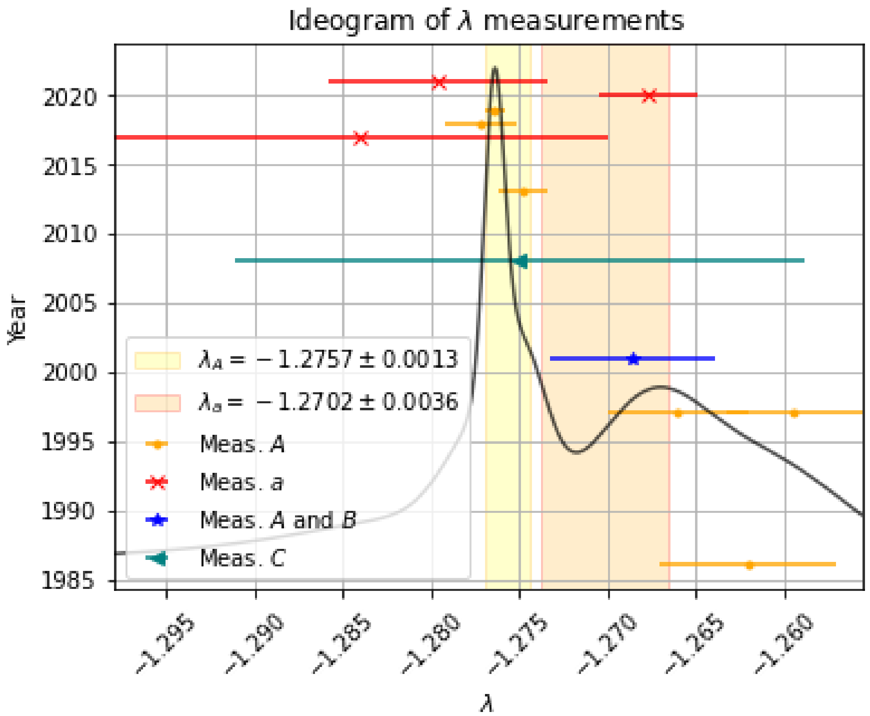
$$\frac{d\Gamma^3}{dE_e d\Omega_e d\Omega_\nu} \sim p_e E_e E_\nu^2 (1+3\lambda^2)\left[1 + b\frac{m_e}{E_e} + a\frac{\vec{p_e}\cdot\vec{p_\nu}}{E_e E_\nu} + \langle\vec{\sigma_n}\rangle\cdot\left(A\frac{\vec{p_e}}{E_e} + B\frac{\vec{p_\nu}}{E_\nu}\right) + \cdots\right]$$

These correlation terms relate to λ:

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

Fierz Interference term b couples to scalar, tensor terms in weak interaction

- Non-zero b is new physics

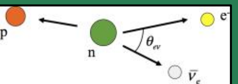


Data from:

- Workman, R. L. *et al*, Particle Data Group (2022)

Most recent a measurements:

- Beck, et al., Phys. Rev. C 101, 055506 (2020)
- Hassan et al., Phys. Rev. C 103, 045502 (2021)



Characterization of Magnetic Field

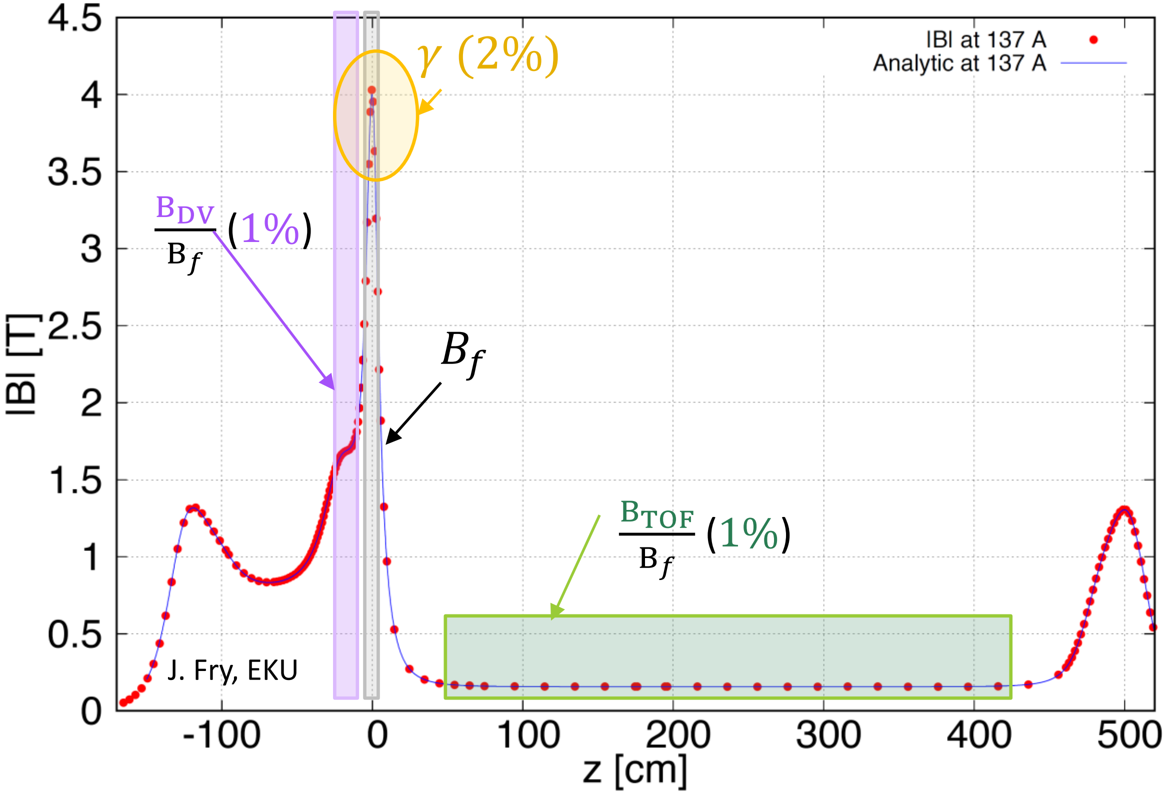
Need to understand $B(z)$ to determine t_p

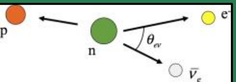
- Have done measurements with Hall probe
- Good agreement with simulation

Analysis of magnetometry data ongoing

Magnetic Field	Target Uncertainty	$(\Delta a\ /\ a)_{sys.}$
Curvature at Pinch γ	$\Delta\gamma/\gamma = 2\%$	5.3×10^{-4}
Ratio $r_{B,\mathrm{TOF}} = B_{TOF}/B_f$	$(\Delta r_{B,\mathrm{TOF}})/r_{B,\mathrm{TOF}} = 1\%$	2.2×10^{-4}
Ratio $r_{B,DV} = B_{DV}/B_f$	$(\Delta r_{B,DV})/r_{B,DV} = 1\%$	1.8×10^{-4}
SUM		6.0×10^{-4}

$|B|$ vs. z



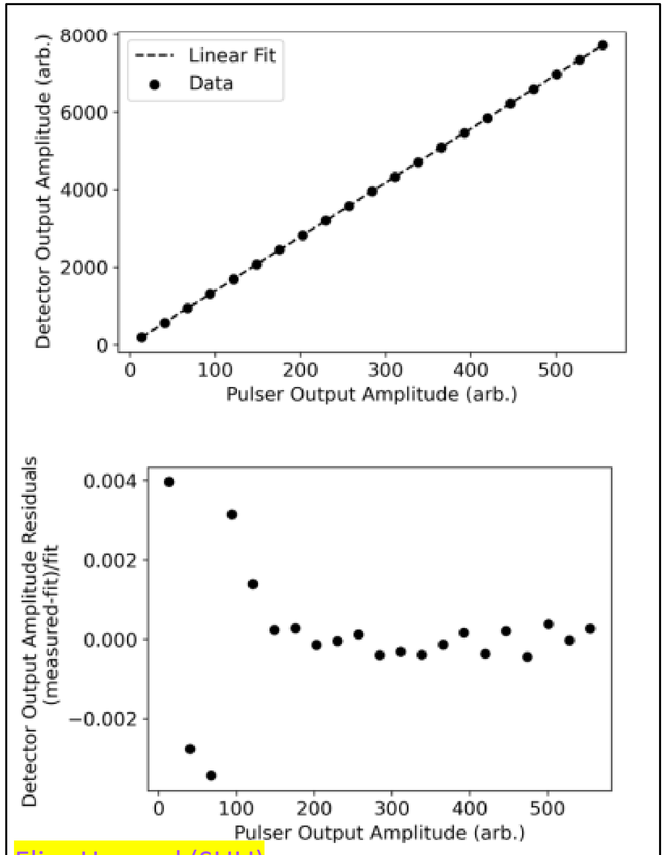


Detector Linearity

Based on SULI student report using the pulser

- Detector linearity
- Nonlinearities at 0.068%

Detector Linearity



Eliza Howard (SULI)

Statistical Reach of Nab

Expect 1600 decays/second in decay volume

- 12.7% of protons go to upper detector
- 200 protons/second

Can see 3.8×10^8 events in 6 weeks

- $(\Delta a/a)_{stat} \sim 2 \times 10^{-3}$
- $\Delta b_{stat} \sim 2 \times 10^{-4}$

Over 2 years of dedicated running, reach 4.4×10^9 protons in upper detector

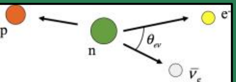
- $(\Delta a/a)_{stat} \sim 7 \times 10^{-4}$
- $\Delta b_{stat} \sim 7 \times 10^{-5}$

$E_{e,min}$ (keV)	0	100	100	100
$t_{p,max}$ (μs)	∞	∞	40	30
Δa (N_u, a, b)	$2.4/\sqrt{N_u}$	$2.5/\sqrt{N_u}$	$2.7/\sqrt{N_u}$	$3.0/\sqrt{N_u}$
$+ E_{cal}, L_{TOF}$	$2.6/\sqrt{N_u}$	$2.7/\sqrt{N_u}$	$2.9/\sqrt{N_u}$	$3.2/\sqrt{N_u}$
+ 75% of data	$3.4/\sqrt{N_u}$	$3.5/\sqrt{N_u}$	$3.8/\sqrt{N_u}$	$4.4/\sqrt{N_u}$
+10% bkg.	$4.4/\sqrt{N_u}$	$4.6/\sqrt{N_u}$	$4.7/\sqrt{N_u}$	$5.2/\sqrt{N_u}$

D. Počanić, UVA

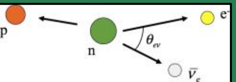
$E_{e,min}$ (keV)	0	100	200	300
Δb (N, a, b)	$7.5/\sqrt{N}$	$10.1/\sqrt{N}$	$15.6/\sqrt{N}$	$26.3/\sqrt{N}$
$+ E_{cal}$	$9.1/\sqrt{N}$	$12.7/\sqrt{N}$	$20.4/\sqrt{N}$	$36.0/\sqrt{N}$

H. Li, UVA



Full Systematics Budget a

Experimental Parameter	Parameter Breakdown	Design Specifications or Other Comments	$(\Delta a \,/\, a)_{sys.}$
Magnetic Field	Curvature at Pinch	$\Delta\gamma/\gamma = 2\%$ with $\gamma = d^2\, B_z(z)/dz^2/B_z(0)$	5.3×10^{-4}
	Ratio $r_B = B_{TOF}/B_0$	$(\Delta r_B)/r_B = 1\%$	2.2×10^{-4}
	Ratio $r_{B,DV} = B_{DV}/B_0$	$(\Delta r_{B,DV})/r_{B,DV} = 1\%$	1.8×10^{-4}
Electric Potential Inhomogeneity	In Decay Volume / Filter Region	$\lvert U_F - U_{DV}\rvert < 10$ mV	5×10^{-4}
	In TOF Region	$\lvert U_F - U_{TOF}\rvert < 200$ mV	2.2×10^{-4}
Neutron Beam	Position	$\Delta\overline{z_{DV}} < 2$ mm	1.7×10^{-4}
	Profile	Slope at edges $< 10\%$ / cm	2.5×10^{-4}
	Doppler Effect	Analytical Correction	$< 1 \times 10^{-4}$
	Unwanted Beam Polarization	$\lvert\overline{P_n}\rvert \ll 10^{-4}$	1×10^{-4}
Detector Effects	Electron Energy Calibration	$\Delta E < 0.2$ keV	2×10^{-4}
	Shape of Electron Energy Response	fraction of events in tail to 1%	4.4×10^{-4}
	Proton Trigger Efficiency	$\epsilon_p < 100$ ppm / keV	3.4×10^{-4}
	TOF Shift due to Detector/Electronics	$\Delta t_p < 0.3$ ns	3.9×10^{-4}
Adiabaticity of Proton Motion			1×10^{-4}
Electron TOF		Analytical Correction	$< 1 \times 10^{-4}$
Residual Gas		$P < 2 \times 10^{-9}$ torr	3.8×10^{-4}
TOF in Acceleration Region		$\Delta r_{ground\ el.} < 0.5$ mm	3×10^{-4}
Background/Accidental Coincidences		Will subtract out of time coinc.	$< 1 \times 10^{-4}$
Length of the TOF Region		Fitted Parameter in Analysis	N/A
Sum			1.2×10^{-3}



Systematic Reach for *b*

Experimental Parameter	**Parameter Breakdown**	**Design Specifications or Other Comments**	$(\Delta a\ /\ a)_{sys.}$
Detector Calibration and Response	Gain Factor	Fitted Parameter in Analysis	N/A
	Offset	$\Delta_{off} < 0.08$ keV	1×10^{-3}
	Nonlinearity Determination	$\vert$Maximum Discrepancy$\vert < 0.07$ keV	1×10^{-3}
	Full Width-Half Mean Determination	Negligible	N/A
	Tail	$\Delta_{tail} < 1\%$	1×10^{-3}
Time of Flight Cut		$\mathrm{TOF\ Cut} > 22\ \mu\mathrm{s}$	5×10^{-4}
Neutron beam polarization		Negligible	N/A
Proton Detection Efficiency		Negligible	N/A
Edge effect		Detection Radius < 2.9 cm	1×10^{-3}
Sum			$2.2 \times\ 10^{-3}$

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