Measurements of Neutron and Nuclear β Decay Using Highly-Segmented Silicon Detectors in a Magnetic Spectrometer

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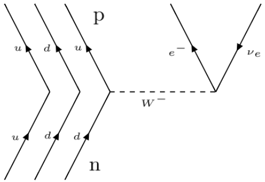
Overview

- Neutron and nuclear β decay defined by correlation parameters, relating the momenta of decay products & neutron spin.
- These parameters serve as inputs to test of SM & BSM physics
- The UCNB experiment and ^{45}Ca decay data taken at Los Alamos National Laboratory (LANL) motivated by searches for non-zero scalar/tensor couplings.
- UCNB & ^{45}Ca measurements serve as a testbed for the detectors for the Nab experiment at Oak Ridge National Laboratory (ORNL).
- These experiments require simulation support to understand sensitivity of our measurements to these parameters.

β Decay

β decay of the neutron,

$$n \rightarrow p + e^- + \bar{\nu}_e$$



is dependent on a number of SM parameters (g_V, g_A, V_{ud})

$$H = \frac{G_F V_{ud}}{\sqrt{2}} \left[\bar{e}\gamma^\mu \left(1 - \gamma_5\right) \nu_e \bar{u}\gamma^\nu \left(g_V - g_A\gamma_5\right) d\right]$$

In the neutron β decay rate [1]

$$\frac{d\omega}{dE_e d\Omega_e d\Omega_\nu} \propto p_e E_e \left(E_0 - E_e\right)^2 \Bigg[1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} + \langle\vec{\sigma}_n\rangle \cdot \left(A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu}\right)\Bigg]$$

a&A are sensitive to $\lambda = \frac{g_A}{g_V}$ while b sensitive to scalar and tensor couplings. B also sensitive to λ (but less so than a&A), but is also sensitive to S/T couplings via $b_\nu \frac{m_e}{E_e}$ perturbation.

[1] Jackson, Treiman, and Wyld (1957)

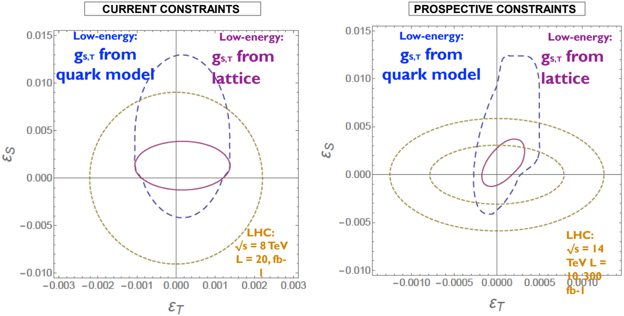
Theoretical Implications of β Decay Measurements - SM & BSM Physics

Standard Model (SM) Tests

- β decay involves V_{ud}, g_A, τ_n
- Measurements of a, A neutron lifetime constrain these.
- Results feed into Big Bang Nucleosynthesis & Unitarity

Beyond Standard Model (BSM) Tests

- $b \neq 0 \rightarrow$ non-zero scalar/tensor couplings
- b_ν perturbation of B also sensitive to non-zero scalar/tensor couplings



Sensitivity to b

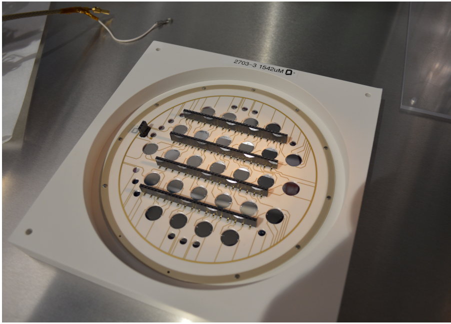
Measurements of parameter b probes TeV-scale BSM physics, but requires high precision measurements.

- Sensitivity of β decay spectrum measurements to $b \sim \mathcal{O}\left(\frac{10}{\sqrt{N}}\right)$
- Need linearity $\sim 10^{-4}$ for $\delta b \sim 3 \times 10^{-3}$
- Need MC corrections for energy loss vectors

Our approach: β spectroscopy using silicon detectors in a 4π magnetic spectrometer.

Loss vectors of concern for silicon detector β measurements are

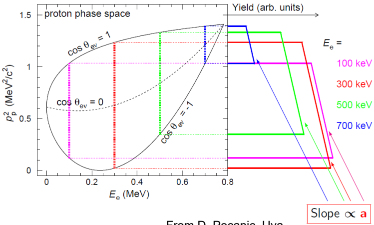
- Bremsstrahlung
- Inactive dead layer of detectors
- 'Sub-threshold' energy deposits



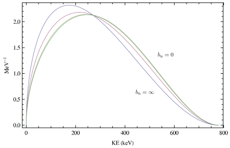
Experimental Goals

The Nab experiment at ORNL aims to measure the electron and proton in unpolarized cold neutron decays in a geometry that probes both a and b.

- Measure p_p yield at given E_{e^-}, slope is $\propto a$.
- Distortion of β spectrum probes b at sensitivity $\mathcal{O}\left(\frac{14.8}{\sqrt{N}}\right)$.



From D. Pocanic, Uva



K. Hickerson, 2013 Ph.D Thesis.

Plotted for β spectrum from ultracold neutrons.

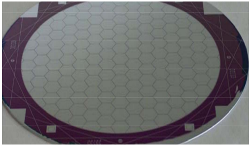
In addition to testing detectors for Nab at LANL,

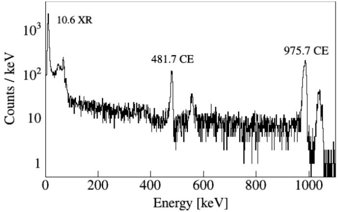
- UCNB: Measure proton and electron coincidences from UCN decays $\rightarrow$ sensitive to b_ν (Data runs 2014-2016)
- ^{45}Ca: Measure β spectrum from ^{45}Ca source $\rightarrow$ can extract b from spectral shape (Data run May, 2016)

Silicon Detectors

Properties of these highly-segmented Si wafer detectors are

- 127 hexagonal pixels, 0.89 cm separation of parallel sides.
- Thin (80 nm) dead layers minimize losses, needed for proton measurements.
- 1.5-2 mm thickness completely stop electrons from free neutron decays.
- Meets Nab requirements ($\leq$10 keV threshold, 3 keV FWHM resolutioni, 50 ns rise time).





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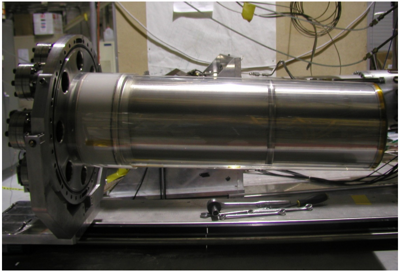
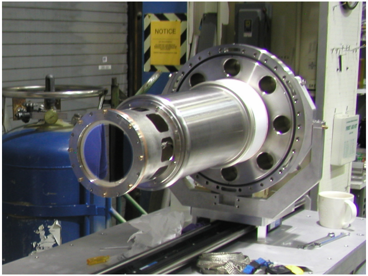
^{207}Bi spectra, as measured by Nab/UCNB detectors.

Silicon Detector Mount



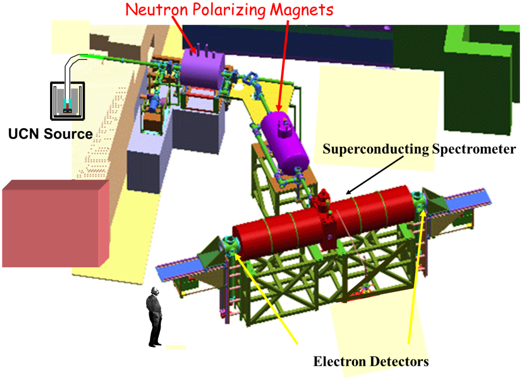


Detector mount for the highly-segmented Si Nab/UCNB detectors. The large plate attaches directly to entrance of the 4π magnet at LANSCE.

UCN Experimental Area at LANSCE

Los Alamos's Neutron Science CEnter's UCN area houses the Superconducting Solenoid (SCS) magnet.

- Uniform 1T field across the decay trap
- Field expands to 0.6T near the detectors.
- Can fill with highly polarized sample of UCN and select sample's spin state.

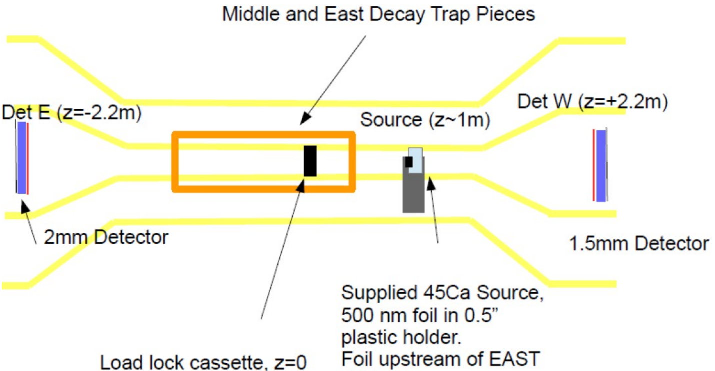


^{45}Ca Run

In May 2016, a ^{45}Ca source, evaporated onto a 500 nm 6F6F foil, was installed in the SCS.

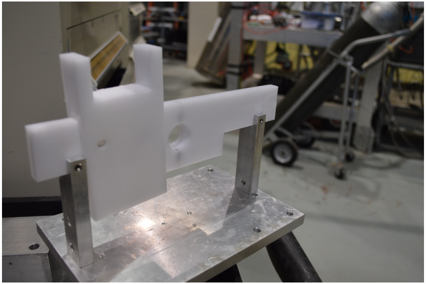
99.998% of ^{45}Ca decays produce a β with endpoint 255.8 keV. These β decays are predominantly Gamow-Teller decays$\rightarrow$ highly sensitive to tensor coupling.

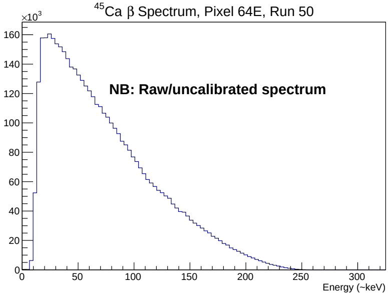
Sensitivity to b expected $\sim \mathcal{O}\left(\frac{9}{\sqrt{N}}\right)$



^{45}Ca Run Summary

Collected ∼175M β decays in the full field (1T across decay trap) configuration and ∼70M in a 1/4T field configuration to probe backscattering.



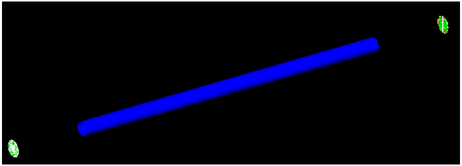


Left: Holder for source - mounts on rail system, aligns source with each detector's central pixel.
Right: Measured ^{45}Ca β spectrum from a single run & single pixel as reported in the online analyzer (uncalibrated/uncorrected).

Simulation

Simulations use a minimal representation of the geometry, with the

- Silicon detectors with dead layers and ceramic backing
- Decay trap guide
- Electric and magnetic fields



Loss vectors to study:

- Bremsstrahlung: Uncaptured photons produced in the silicon
- Dead layer: Inactive 80 nm layer, deposited energy does not contribute to measured energy of an event.
- Sub-threshold: Energy deposits $\leq$10 keV cannot be separated from pedestal

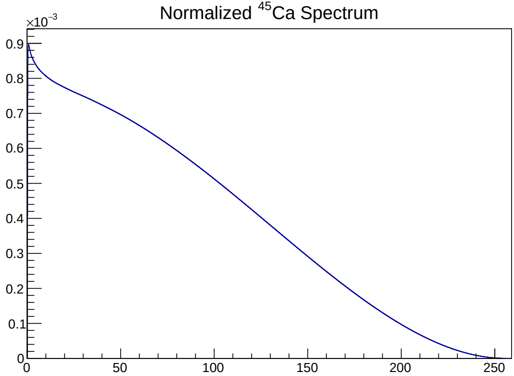
where the necessary correction is calculated as

$$\%_{corr.} = 100 - 100 * \frac{E_0 - E_{Loss}}{E_0}$$

^{45}Ca Simulation

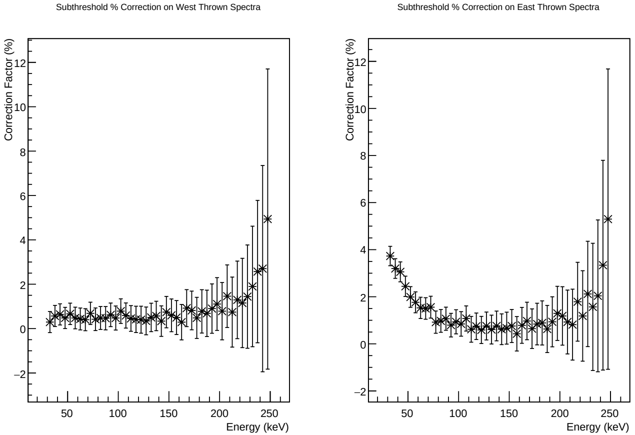
For specifically ^{45}Ca decays, the simulation has

- B-field only, no accelerating potential
- β spectrum, peak 78 keV & endpoint 255.8 keV.
- Add a thin 6F6F foil & inactive carrier calcium.



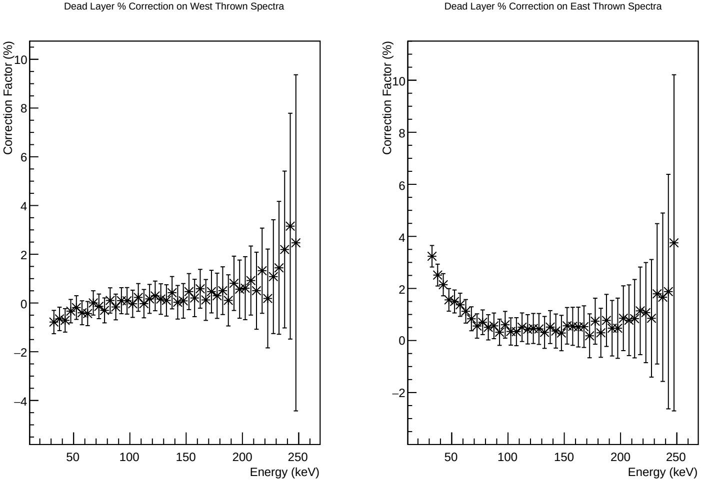
Simulation uses a ^{45}Ca spectrum generator written by L. Hayen & N. Severijns in the Weak Interactions group at KU Leuven University.

^{45}Ca Simulated Correction - Sub-Threshold hits

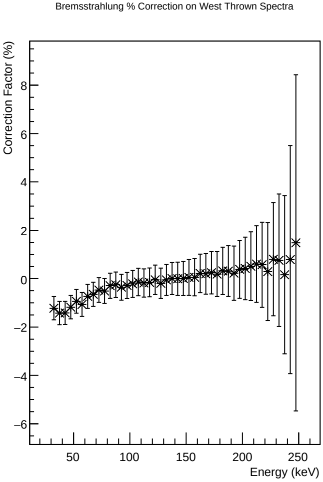


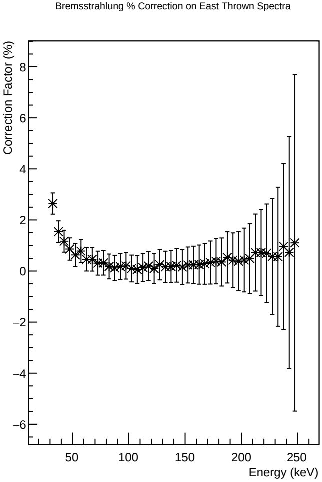
From $\%_{Loss}$ we can look at the correction to the thrown spectra from a given loss vector as a function of thrown energy.

^{45}Ca Simulated Correction - Dead Layer Losses



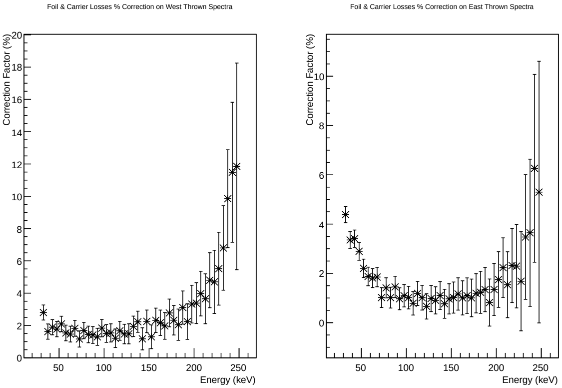
^{45}Ca Simulated Correction - Bremsstrahlung Losses





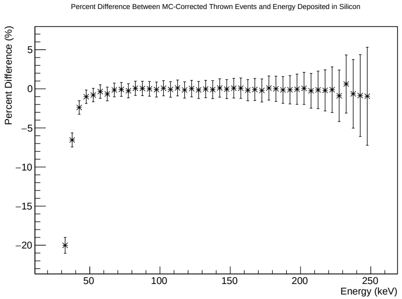
^{45}Ca Simulated Correction - Foil/Carrier

For running sources, the foil & carrier add a new energy loss vector to calculate, shown to have an energy dependence. Asymmetry between detectors parallels asymmetry of having a single foil.



^{45}Ca Energy-Corrected Spectra

Difference between MC-corrected thrown spectra and the above-threshold simulated energy deposit in silicon spectra for 50-240 keV is $-0.132 \pm 0.194\%$.

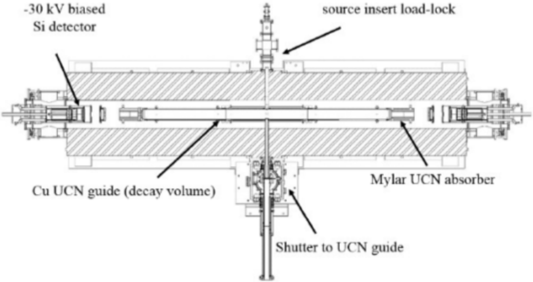


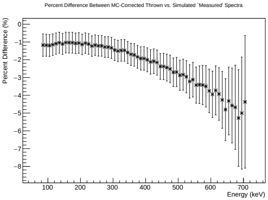
Loss Vector (50-240 keV)	Det. 1 $\%_{diff}$	Det. 2 $\%_{diff}$
6F6F Foil	$1.794 \pm 0.111\%$	$1.294 \pm 0.092\%$
Dead Layer	$0.042 \pm 0.109\%$	$0.653 \pm 0.105\%$
Subthreshold	$0.560 \pm 0.112\%$	$1.060 \pm 0.105\%$
Bremsstrahlung	$-0.263 \pm 0.112\%$	$0.304 \pm 0.105\%$

UCNB

UCNB measures electron-proton coincidences to extract information on B, the correlation between the neutron spin and neutrino emission direction.

- A -30 kV accelerating potential after the magnetic field expansion accelerates protons$\rightarrow$ energy deposits above threshold after dead layer.
- Asymmetries of electron/proton coincidences sensitive to $b_\nu \& b \rightarrow$ see cancellation effect.
- Ratio of asymmetries cancels $b \rightarrow$ can be used to extract information about b_ν.



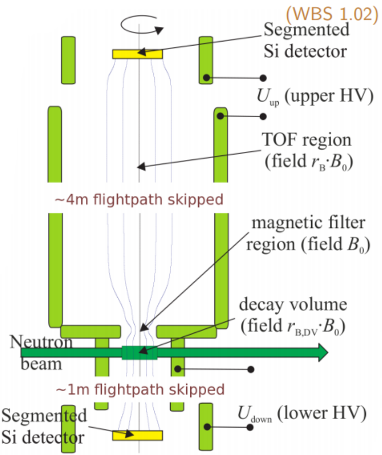


Simulation work in progress...

Future Simulation Work - Nab

At Oak Ridge, Nab aims to measure the proton and electron from cold neutron decays to extract *a* and *b*.
Simulation work underway to test the viability of open source studies in the Nab geometry.

- Study energy loss associate with same loss effects as ^{45}Ca study
- Varying foil thicknesses & orientation→find a configuration with ≤1% energy loss.



Outlook

Experiment:

- Finish analysis of 2014-2016 UCNB data sets and the 2016 ^{45}Ca data set.
- More UCNB running, improving our results/decreasing our statistical error.
- Possibly(?) measuring ^{45}Ca decays with an 10 keV accelerating gradient $\rightarrow$ measure the ^{45}Ca spectrum to 0 keV.
- The Nab spectrometer is expected to arrive late 2016/early 2017, begin commissioning equipment.

Simulation:

- Increase statistics to improve precision in the calculation of effects of loss vectors for both UCNB/^{45}Ca.
- Adapt/complete simulation for Nab's source calibrations using similar framework but different geometry

Conclusion

- Measurements of neutron decays can probe for BSM scalar/tensor couplings via b & b_ν.
- Detector tests at LANL have measured UCN and ^{45}Ca decays to look for non-zero S/T couplings, with analysis underway.
- A simulation of the behavior of decay products in the LANSCE spectrometer exist and has been run to find MC corrections for various experimental configurations.

The Nab and UCNB Collaborations

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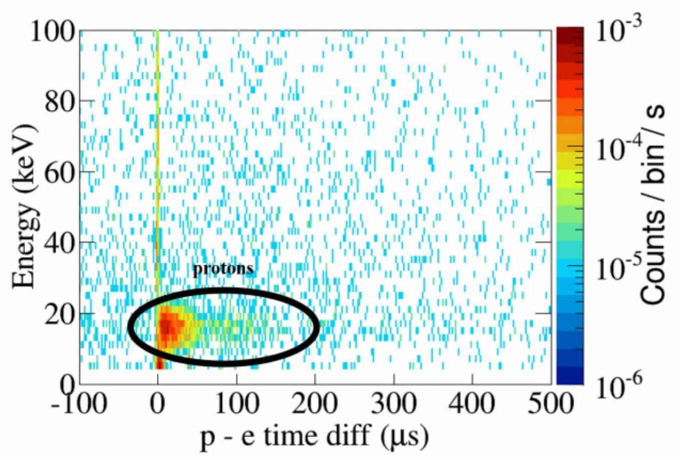
Also thank you to ^{45}Ca run collaborator L. Hayen & N. Severijns, KU Leuven University.

EXTRA SLIDES

UCNB Data - Proton Coincidences



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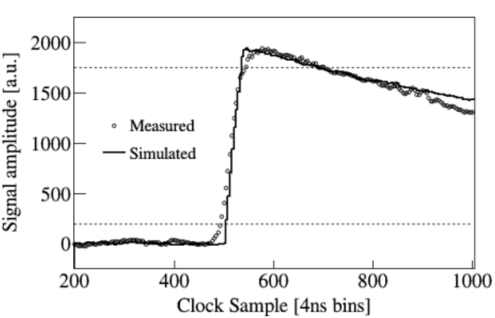
Si Detector - Rise Time



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b_ν extraction

From decay rate ρ (first subscript p_e·σ_n, second subscript for p_p·σ_n).

$$\rho_{\pm\pm} = \int_{m_e}^{\Delta} dE_e \; w_{\pm\pm}(E_e), \quad w_{\pm\pm}(E_e) \equiv \frac{1}{4}\, w_s(E_e)\, Q_{\pm\pm}$$

and Q the allowed angular spectra.

$$w_s(E_e) = \frac{G_F^2 V_{ud}^2 (1+3\lambda^2)}{2\pi^3} |\vec{p}_e| E_e (\Delta - E_e)^2.$$

$$\alpha_p(E_e) = \frac{Q_-^p - Q_+^p}{Q_-^p + Q_+^p},$$

$$\alpha_p(E_e) = \begin{cases} P\dfrac{\frac{2r}{3}A\beta_e + B\left(1-\frac{r^2}{3}\right)}{2f_b}, & r<1, \\[2ex] P\dfrac{A\beta_e\left(1-\frac{1}{3r^2}\right)+\frac{2}{3r}B}{2f_b}, & r> \end{cases}$$

$$\alpha_e(E_e) = \frac{Q_-^e - Q_+^e}{Q_-^e + Q_+^e} = -\frac{1}{2f_b} P A \beta_e$$

$$\frac{\alpha_p(E_e)}{\alpha_e(E_e)} = \begin{cases} \frac{2}{3}r + \frac{1}{\beta_e}\left(1-\frac{r^2}{3}\right)\frac{B}{A}, & r<1 \\[2ex] \left(1-\frac{1}{3r^2}\right) + \frac{2}{3r}\frac{1}{\beta_e}\frac{B}{A}, & r>1 \end{cases}$$

Ratio of proton and electron asymmetries sensitive to B (and b_ν) but insensitive to b (via f_b)!

Eqs. c/o B. Plaster

^{45}Ca MC-Corrected vs. Simulation 'Measured' Spectra