Tensor current limits from the beta-neutrino correlation in mass 8 systems

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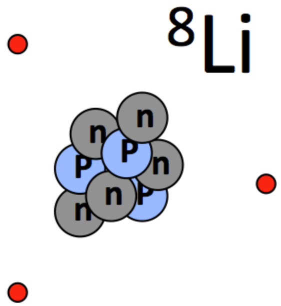
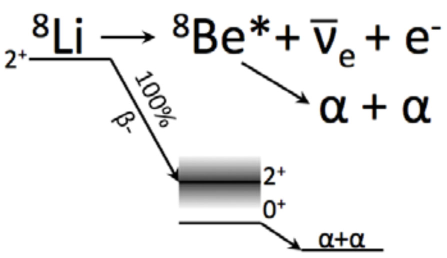
UMass, November 03 2018

Using ^{8}Li β decay to measure $a_{\beta\upsilon}$

- ✓ Has an essentially pure G-T decay (only A & T interactions).
- ✓ High Q-value/light mass allow for easy-to-measure recoils.
- ✓ Immediately decays into 2 alphas (<E_{α}> ~ 1.5MeV) making a clean "triple" event with almost no background
- ✓ Has a mirror nucleus: ^{8}B that can be used to compare systematics

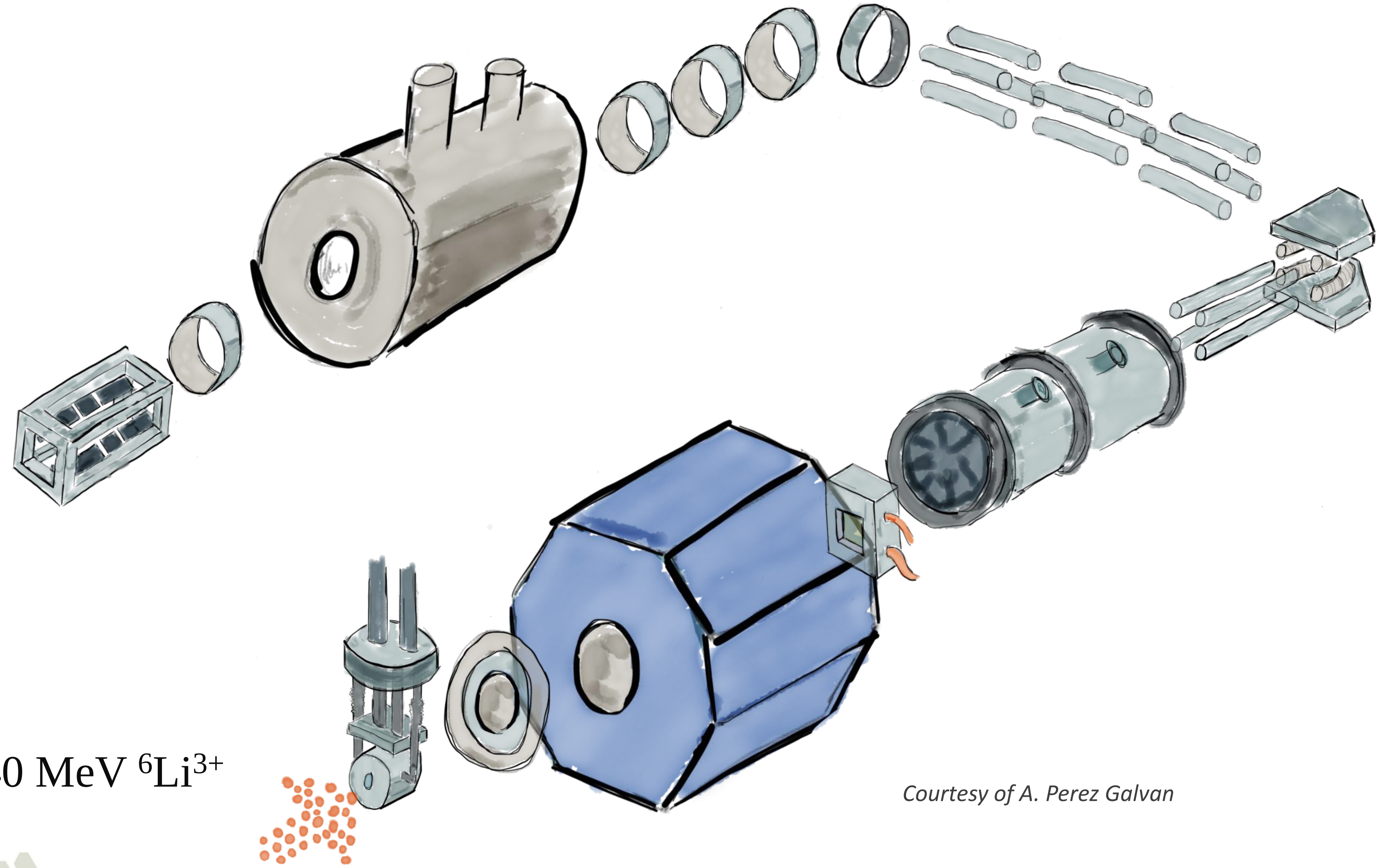
$$a_{\beta\nu} = -\frac{1}{3}\frac{|C_A|^2 - |C_T|^2}{|C_A|^2 + |C_T|^2}$$





Q=16.004 MeV, $t_{1/2}$=0.84 s

Production of ^{8}B and ^{8}Li at ATLAS

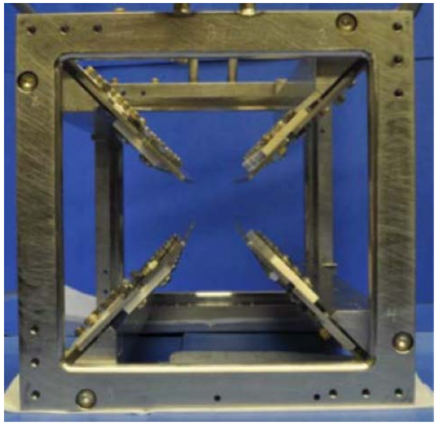


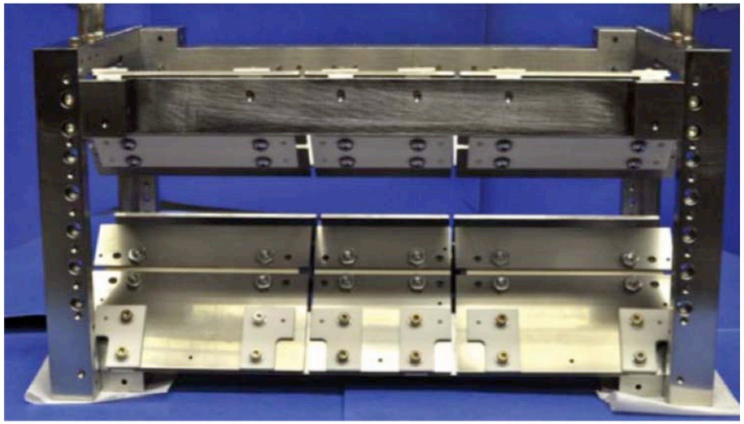
40 MeV $^{6}Li^{3+}$

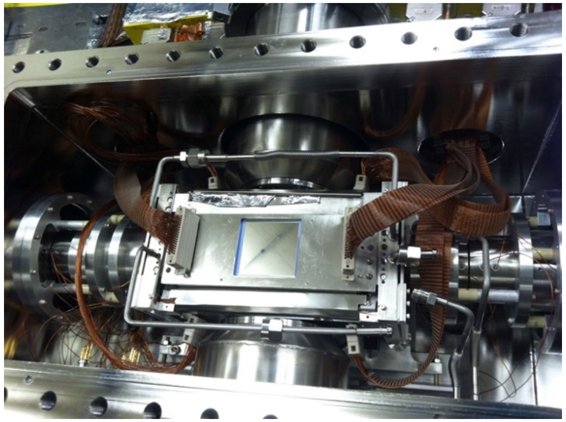
Courtesy of A. Perez Galvan

The Beta Decay Paul Trap

- RF fields (1.33 MHz, ~400 Vpp), a DC gradient (60V depth), and 25 μTorr of helium gas are used to trap ions.
- Cooled with liquid nitrogen.
- Capture Efficiency close to 100%.
- Electrodes designed to minimize scattering.
- Ions are held within a $1mm^3$ volume.

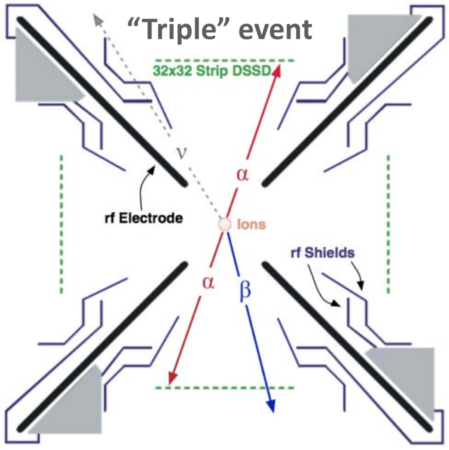


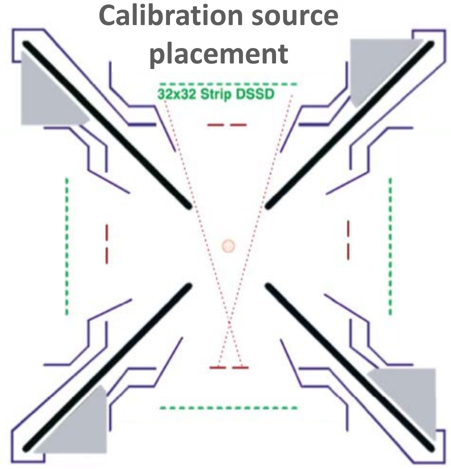


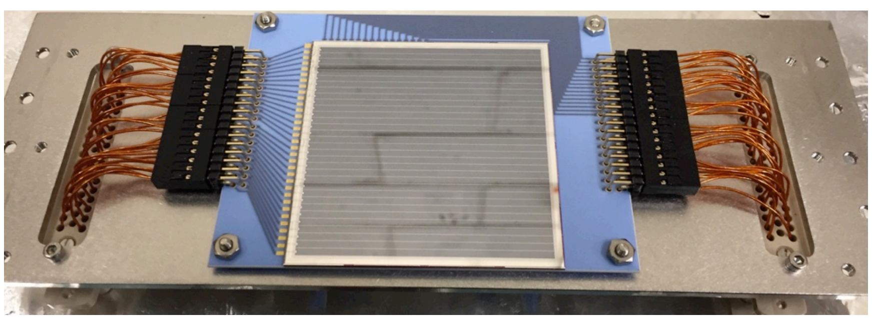


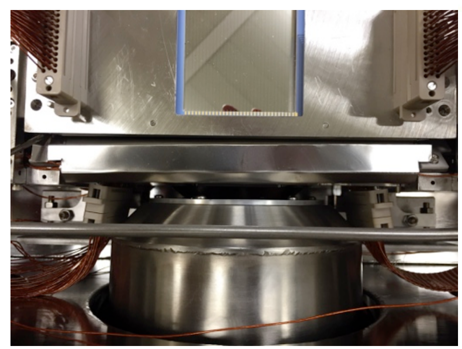
The Detector System

- The trap is surrounded by a set of 4 32x32 Double Sided Silicon Strip Detectors (DSSSD's) backed by plastic scintillator detectors.
- 2º spatial resolution and 25% solid angle coverage.
- For a "triple" event, kinematic reconstruction is over-determined.
- Outfitted with 8 sets of ^{148}Gd and ^{244}Cm *in situ* calibration sources.









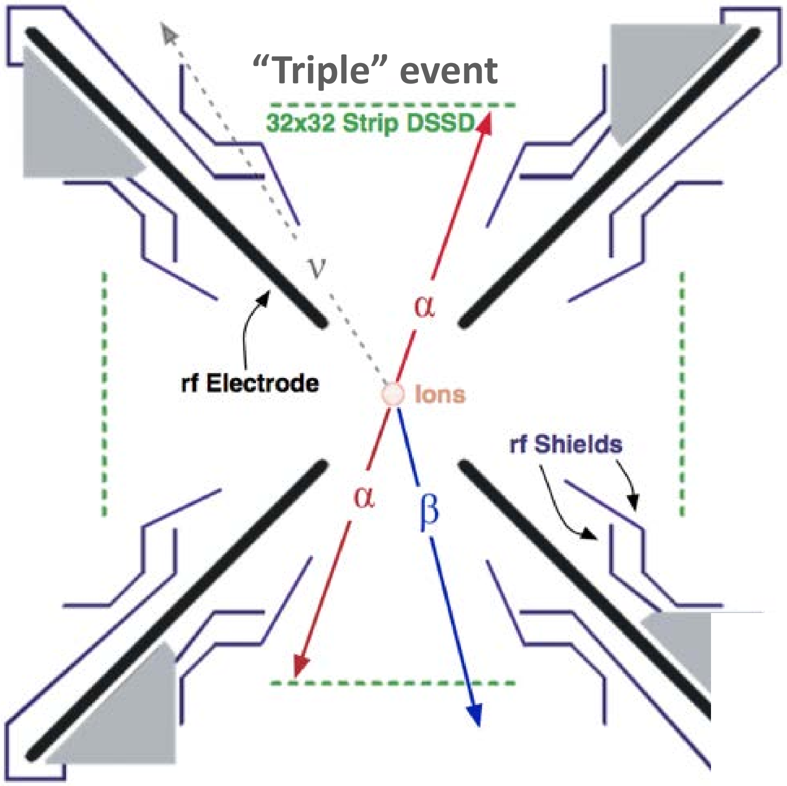
Picture courtesy of Dr. Perez Galvan, M.G Sternberg's thesis

The Data

$$W(\theta_{\beta\nu}) = 1 + a_{\beta\nu}\frac{v_\beta}{c}\cos(\theta_{\beta\nu})$$

$$\text{Axial Vector: } a_{\beta\nu} = -\frac{1}{3}, \quad \text{Tensor: } a_{\beta\nu} = \frac{1}{3}$$

- Axial Vector events favor lepton emissions in the opposite direction.
- Tensor events favor lepton emissions in the same direction.
- ΔE(α's) is larger and more sensitive to $a_{\beta\nu}$ when the β is emitted roughly parallel to an α
- We only use "triple" events where the β and an α hit the same detector.

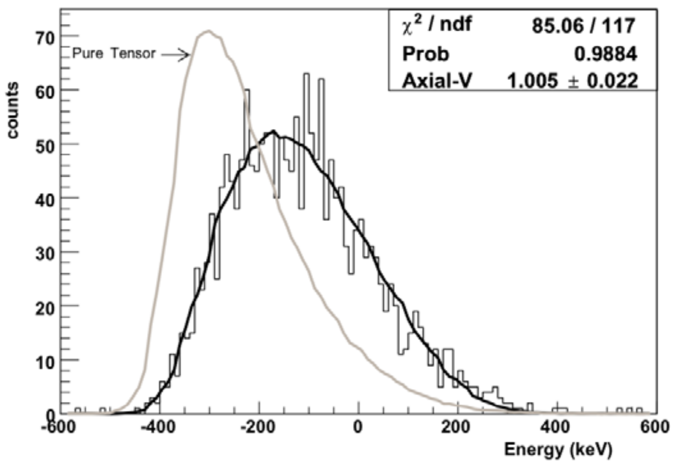


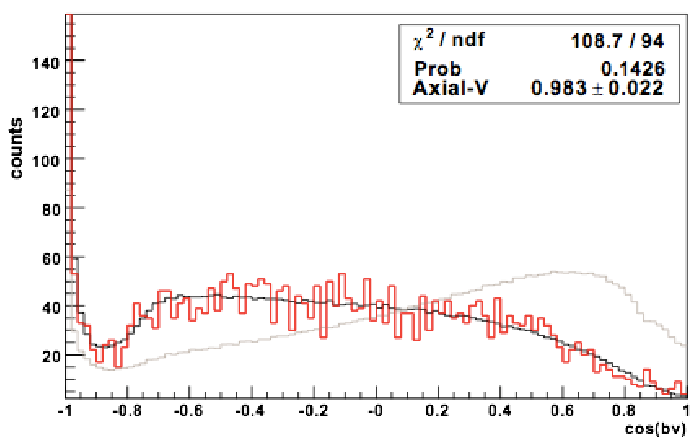
$$\Gamma(E_e)dE_e \propto p_e E_e (E_0 - E_e)^2 dE_e \left(g_1 + g_2 \frac{(\boldsymbol{p_e} \cdot \boldsymbol{p_\nu})}{|E_e||E_\nu|} + g_{12}\left(\frac{(\boldsymbol{p_e} \cdot \boldsymbol{p_\alpha})(\boldsymbol{p_\nu} \cdot \boldsymbol{p_\alpha})}{|E_e||E_\nu|} - \frac{1}{3}\frac{(\boldsymbol{p_e} \cdot \boldsymbol{p_\nu})}{|E_e||E_\nu|} \right) + \ldots \right)$$

Picture courtesy of M.G Sternberg's thesis

Our previous experiments

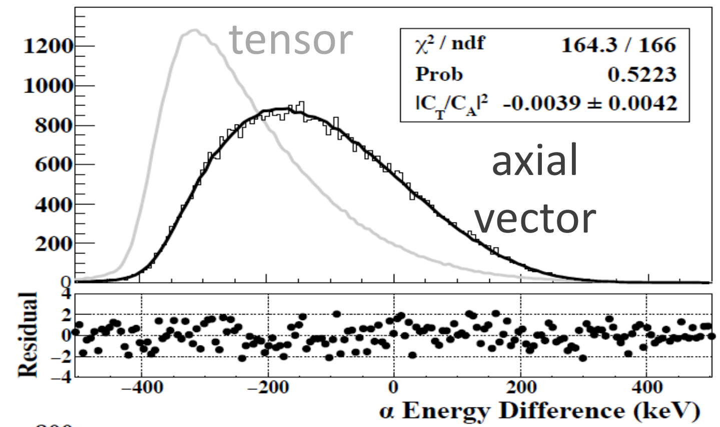
Gang Li: Graduated 2012
Phys. Rev. Lett. **110**, 092502 (2013)

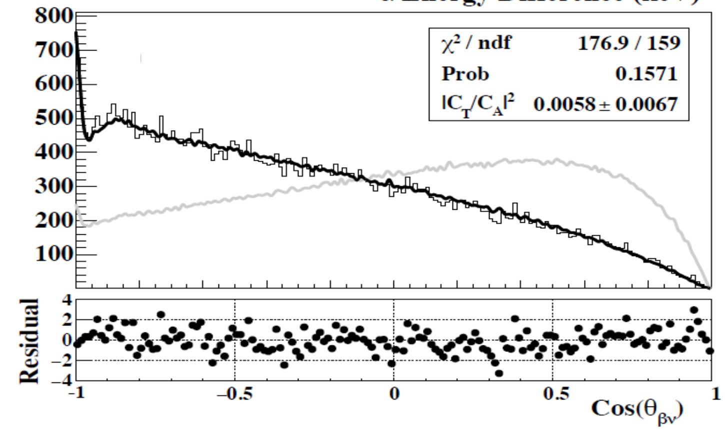




$$|C_T/C_A|^2 = 0.004 \pm 0.009_{stat} \pm 0.010_{syst}.$$

Matt Sternberg: Graduated 2013
Phys. Rev. Lett. **115**, 182501 (2015)





$$a_{\beta\nu} = -0.3342 \pm 0.0026_{stat} \pm 0.0029_{syst}$$

$$|C_T/C_A|^2 = -0.0013 \pm 0.0038_{stat} \pm 0.0043_{syst}$$

2015 PRL Experiment:

- Utilized 72,000 "triple" events alongside simulated tensor and axial-vector data to limit $|C_T/C_A|^2$ to < 0.011 (95.5 C.L) with a statistical error of 0.0038 (1σ).
- Plenty of room for improvement, both statistically and systematically.

TABLE I. Dominant sources of systematic uncertainty at 1σ.

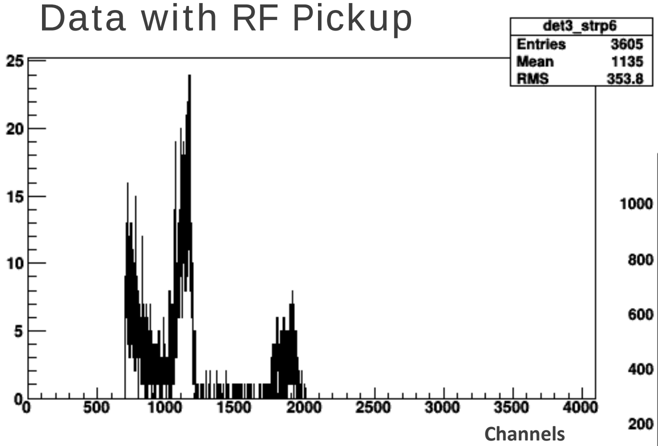
Source	$\Delta\|C_T/C_A\|^2$
Energy calibration	0.0013
α line shape	0.0018
Dead layer thickness	0.0008
β scattering	0.0020
Backgrounds	0.0011
Recoil and radiative	0.0026
Nondominant systematics	0.0007
Total	0.0043

Pictures from PRL 115, 182501 (2015)

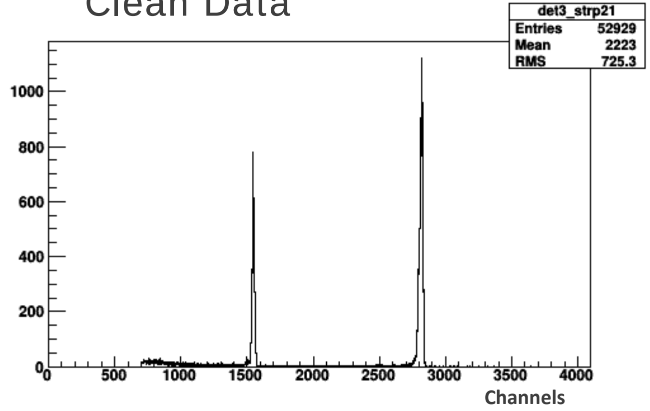
Our Most Recent Experiment

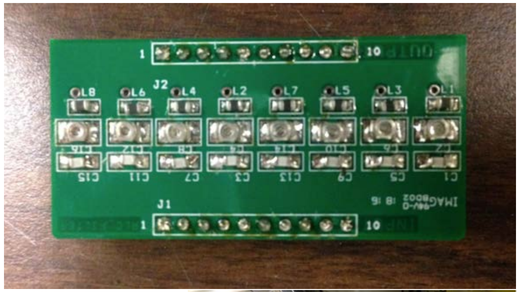
- Updated the beamline to produce higher yields of Lithium-8
- RF pickup was completely removed from data using tunable notch filters applied to the front strips.
- August, 2016: over 2 weeks, obtained **10x** the statistics used in the 2015 PRL.
- Result: $|C_T/C_A|^2$ statistical error reduced to **0.0013**.

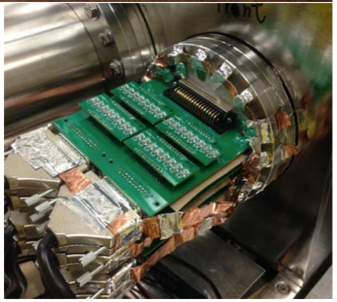
Data with RF Pickup



Clean Data



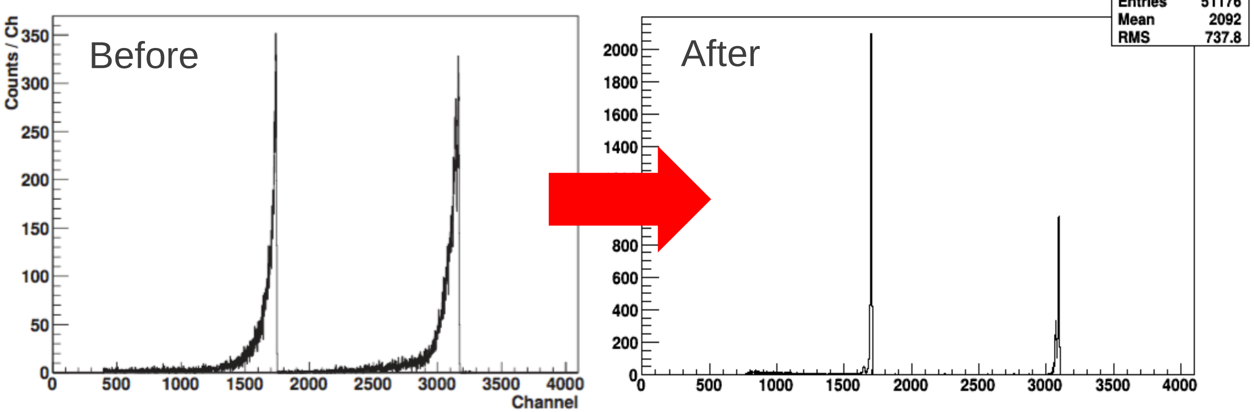




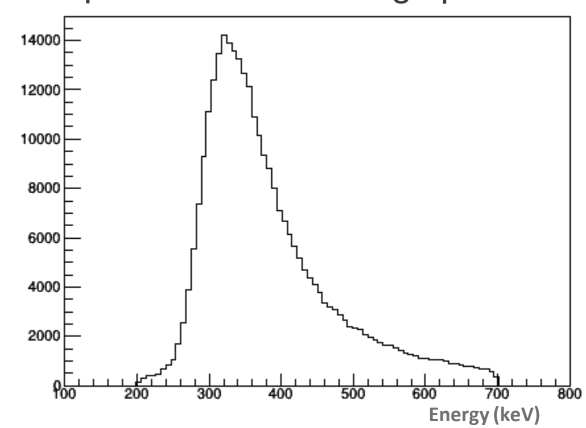
Updated Calibration:

- ✓ Replaced in-house made sources with commercial, spectroscopy-grade sources (^{148}Gd, 3182.69 keV and ^{244}Cm 5804.77 keV, 76.9%)
- ✓ Added the Lithium-8 beta spectrum as a third low-energy point.
- ✓ Energies corrected for pulse height defect, nonionizing energy loss, and the detector dead layer.
- ✓ Reduced $|C_T/C_A|^2$ calibration systematic error from 0.0013 to **0.0005**.

New Spectroscopy-grade α sources (FWHM < 20 keV)

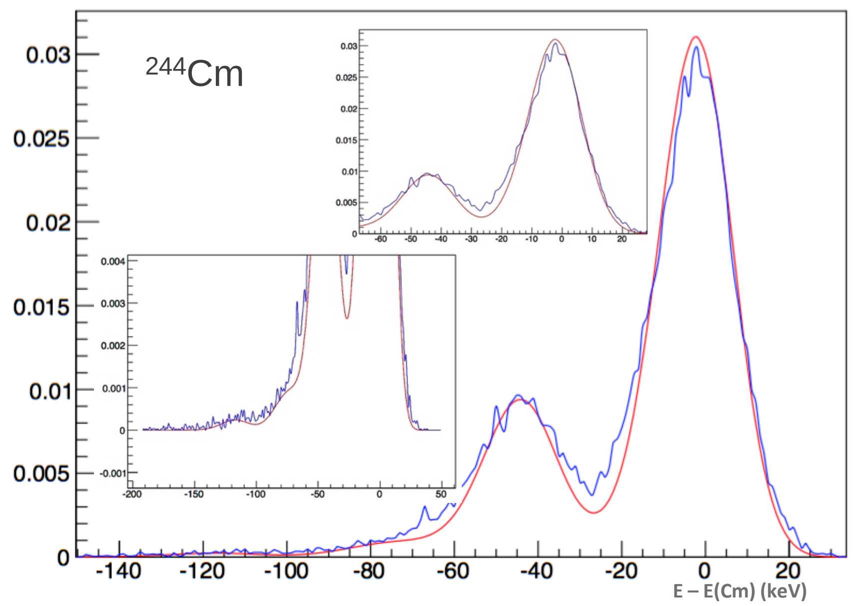


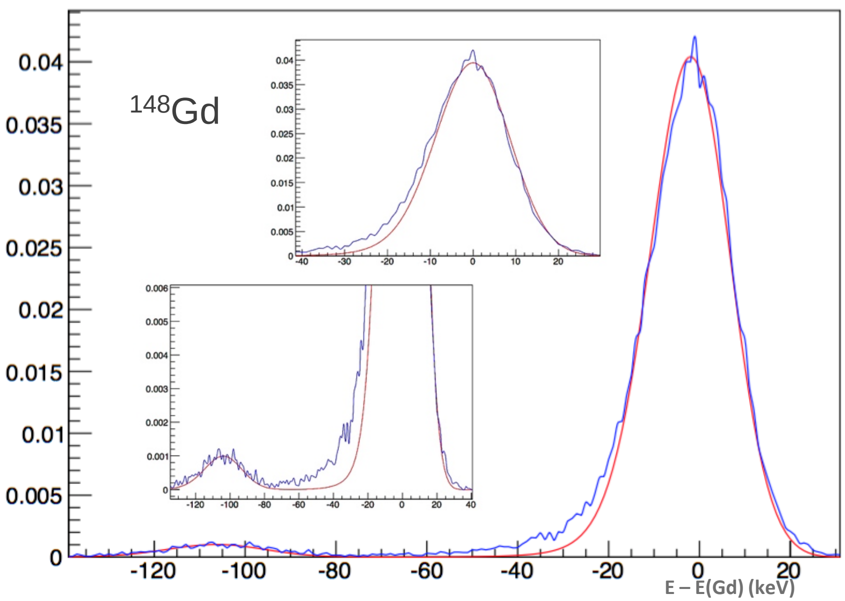
^{8}Li β^- minimum ionizing spectra



Simulated α Lineshape:

- Fully calculated lineshape includes:
  - Individual detector/strip electronic noise
  - Nonionizing energy loss
  - Fano factor resolution
  - Dispersion through dead layers



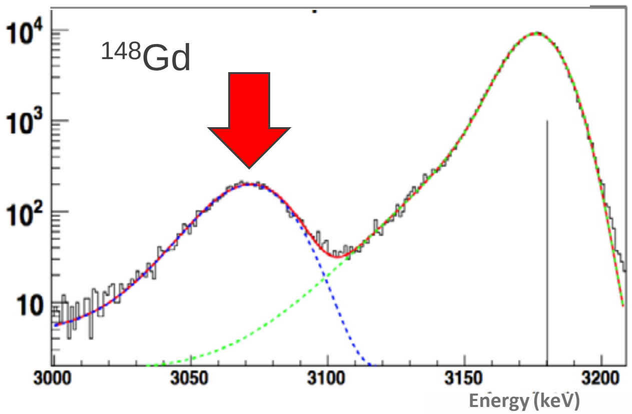


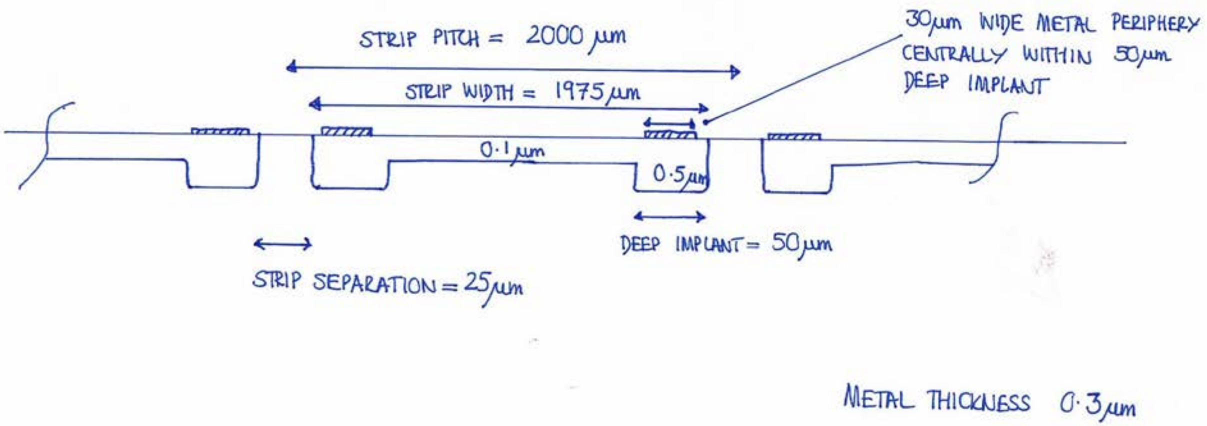
Calculated Lineshape — Spectra from Data

Decreased $|C_T/C_A|^2$ lineshape systematic from 0.0018 to **0.0006**.

Discrepancies between the spectra and calculations are due to a source dead layer.

Dead layer thickness:





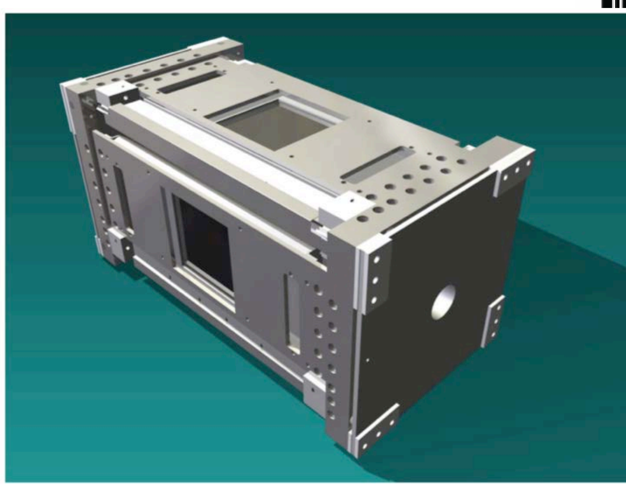
New calibration sources revealed previously overlooked dead layer systematic: the thicker dead layers on the edge of each strip.

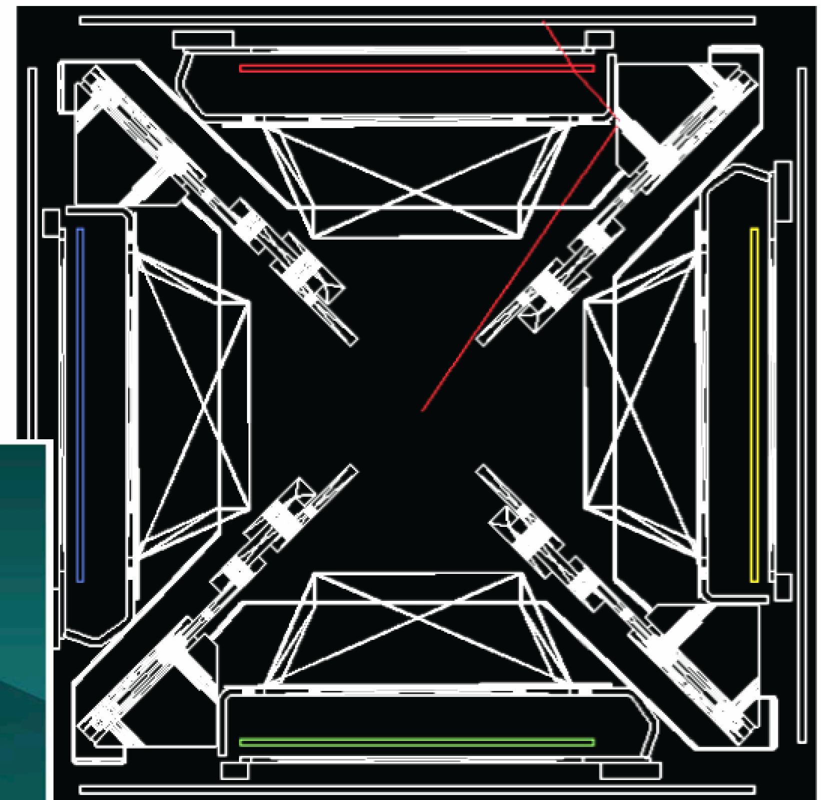
In progress: new dead layer calculation using calibration sources with confirmation with from ^{8}Li alpha spectra.

We anticipate that the error bar will remain unchanged, but the dead layer thickness will be more accurate.

Beta Scattering with Geant4

- ~20% of detected β's are scattered into the silicon detectors.
- All generated events are run through a Geant4 simulation.
- Includes a full AutoCad geometry of the trap and chamber.



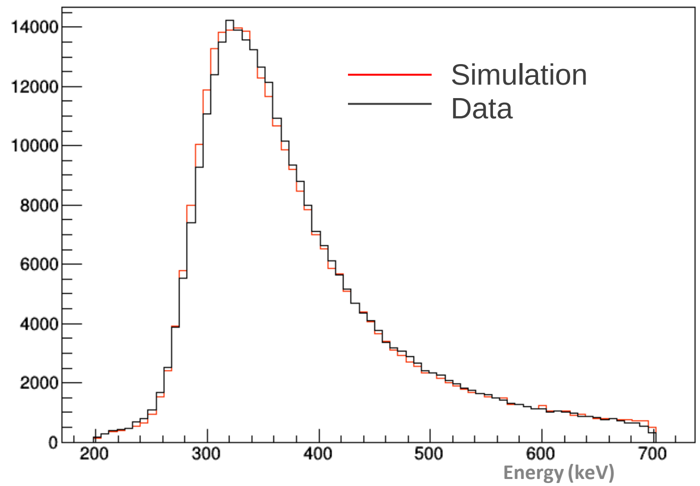


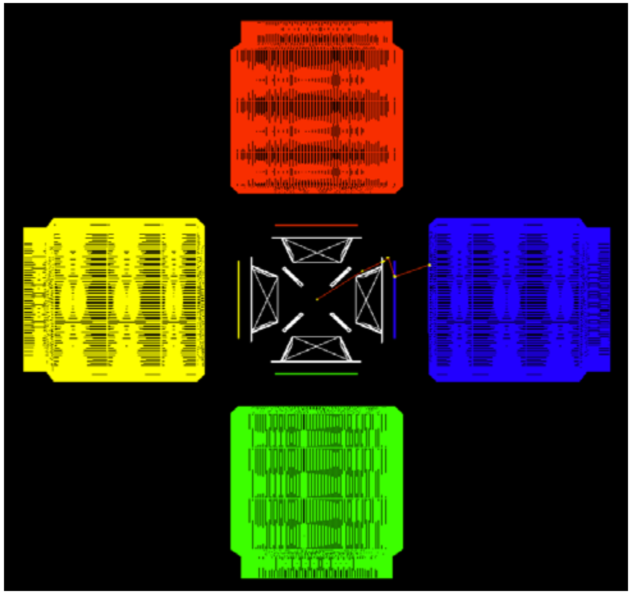
Pictures courtesy of M.G Sternberg's thesis

Beta Scattering:

- Geant4 itself is updated now and the physics packages are more complete.
- Plastic Scintillators allow for extra cross-checking
- Current benchmarks (triples/doubles and backscattered/triples fractions) are met even with higher statistics

Simulated ^{8}Li β spectrum matches data

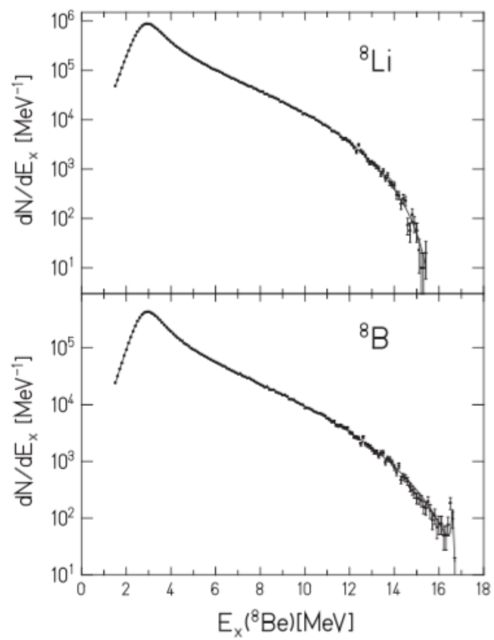




Decreasing scattering systematic error from 0.0020 to < 0.0010.

The Event Generator Simulation

- Based on code written by Scielzo *et al.* for ^{21}Na decay.
- Includes/features:
  I. Final State distributions from Bhattacharya *et al.*
  II. Recoil order terms (Gluck (1997) & Holstein (1974))
  III. Ion cloud distribution
  IV. Easy to switch between ^{8}B and ^{8}Li
  V. Event acceptance/rejection based on strip functionality



$$
\begin{aligned}
d^7\Gamma = {} & F_{\mp}(Z,E)\,\frac{G_v^{\,2}\cos^2\theta_c}{2(2\pi)^6}\,(E_0-E)^2 pE\,dE\,d\Omega_e\,d\Omega_\nu\,d\Omega_n \\
& \times\Bigg(g_1(E) + g_2(E)\,\frac{\mathbf{p}}{E}\cdot\hat{k} + g_3(E)\left[\left(\frac{\mathbf{p}}{E}\cdot\hat{k}\right)^2 - \frac{1}{3}\frac{\mathbf{p}^2}{E^2}\right] \\
& + \delta_1(E, v^*, \tau_{J',J''}(L))\,\frac{\hat{n}\cdot\mathbf{p}}{E} \\
& + \delta_2(E, v^*, \tau_{J',J''}(L))\,\hat{n}\cdot\frac{\mathbf{p}}{E}\,\frac{\mathbf{p}}{E}\cdot\hat{k} \\
& + \delta_3(E, v^*, \tau_{J',J''}(L))\,\hat{n}\cdot\hat{k} \\
& + \delta_4(E, v^*, \tau_{J',J''}(L))\,\hat{n}\cdot\hat{k}\,\frac{\mathbf{p}}{E}\cdot\hat{k} \\
& + \tfrac{1}{10}\tau_{J',J''}(L)\,T^{(2)}(\hat{n}):\Big\{ g_{10}(E)[\mathbf{p}/E, \mathbf{p}/E] \\
& + g_{11}(E)[\mathbf{p}/E, \mathbf{p}/E]\,\frac{\mathbf{p}}{E}\cdot\hat{k} + g_{11}(E)[\mathbf{p}/E, \hat{k}] \\
& + g_{12}(E)[\mathbf{p}/E, \hat{k}]\,\frac{\mathbf{p}}{E}\cdot\hat{k} + g_{13}(E)[\hat{k}, \hat{k}] \\
& + g_{15}(E)[\hat{k}, \hat{k}]\,\frac{\mathbf{p}}{\mathrm{E}}\cdot\hat{k} + g_{16}(E)\left[\frac{\mathbf{p}}{E}, \frac{\mathbf{p}}{E}\times\hat{k}\right] \\
& + g_{17}(E)\left[\hat{k}, \frac{\mathbf{p}}{E}\times\hat{k}\right]\Big\} \\
& + \delta_8(E, v^*, \tau_{J'J''}(L))\,T^{(3)}(\hat{n}):[\mathbf{p}/E, \mathbf{p}/E, \hat{k}] \\
& + \delta_9(E, v^*, \tau_{J'J''}(L))\,T^{(3)}(\hat{n}):[\mathbf{p}/E, \hat{k}, \hat{k}] \\
& + \tfrac{1}{10}\omega_{J'J''}(L)\,T^{(4)}(\hat{n}):\{ g_{25}(E)[\mathbf{p}/E, \mathbf{p}/E, \mathbf{p}/E, \hat{k}] \\
& + g_{26}(E)[\mathbf{p}/E, \mathbf{p}/E, \hat{k}, \hat{k}] \\
& + g_{27}(E)[\mathbf{p}/E, \hat{k}, \hat{k}, \hat{k}]\}\Bigg). \qquad (53)
\end{aligned}
$$

B. Holstein Rev. Mod. Phys., Vol 46, No. 4 (1974) and
M. Bhattacharya *et al.* Phys Rev C 73:055802 (2006)

Recoil and Radiative terms:

$$
\begin{aligned}
d^7\Gamma = {} & F_{\mp}(Z,E)\,\frac{G_v^2\cos^2\theta_c}{2(2\pi)^6}\,(E_0-E)^2 pE\,dE\,d\Omega_e\,d\Omega_\nu\,d\Omega_n \\
& \times\Bigg(g_1(E) + g_2(E)\,\frac{\mathbf{p}}{E}\cdot\hat{k} + g_3(E)\left[\left(\frac{\mathbf{p}}{E}\cdot\hat{k}\right)^2 - \frac{1}{3}\frac{\mathbf{p}^2}{E^2}\right] \\
& + \delta_1(E, v^*, \tau_{J',J''}(L))\,\frac{\hat{n}\cdot\mathbf{p}}{E} \\
& + \delta_2(E, v^*, \tau_{J',J''}(L))\,\hat{n}\cdot\frac{\mathbf{p}}{E}\,\frac{\mathbf{p}}{E}\cdot\hat{k} \\
& + \delta_3(E, v^*, \tau_{J',J''}(L))\,\hat{n}\cdot\hat{k} \\
& + \delta_4(E, v^*, \tau_{J',J''}(L))\,\hat{n}\cdot\hat{k}\,\frac{\mathbf{p}}{E}\cdot\hat{k} \\
& + \tfrac{1}{10}\tau_{J',J''}(L)\,T^{(2)}(\hat{n}):\Big\{ g_{10}(E)[\mathbf{p}/E, \mathbf{p}/E] \\
& + g_{11}(E)[\mathbf{p}/E, \mathbf{p}/E]\,\frac{\mathbf{p}}{E}\cdot\hat{k} + g_{11}(E)[\mathbf{p}/E, \hat{k}] \\
& + g_{12}(E)[\mathbf{p}/E, \hat{k}]\,\frac{\mathbf{p}}{E}\cdot\hat{k} + g_{13}(E)[\hat{k}, \hat{k}] \\
& + g_{15}(E)[\hat{k}, \hat{k}]\,\frac{\mathbf{p}}{\mathrm{E}}\cdot\hat{k} + g_{16}(E)\left[\frac{\mathbf{p}}{E}, \frac{\mathbf{p}}{E}\times\hat{k}\right] \\
& + g_{17}(E)\left[\hat{k}, \frac{\mathbf{p}}{E}\times\hat{k}\right]\Big\} \\
& + \delta_8(E, v^*, \tau_{J'J''}(L))\,T^{(3)}(\hat{n}):[\mathbf{p}/E, \mathbf{p}/E, \hat{k}] \\
& + \delta_9(E, v^*, \tau_{J'J''}(L))\,T^{(3)}(\hat{n}):[\mathbf{p}/E, \hat{k}, \hat{k}] \\
& + \tfrac{1}{10}\omega_{J'J''}(L)\,T^{(4)}(\hat{n}):\{ g_{25}(E)[\mathbf{p}/E, \mathbf{p}/E, \mathbf{p}/E, \hat{k}] \\
& + g_{26}(E)[\mathbf{p}/E, \mathbf{p}/E, \hat{k}, \hat{k}] \\
& + g_{27}(E)[\mathbf{p}/E, \hat{k}, \hat{k}, \hat{k}]\}\Bigg). \qquad (53)
\end{aligned}
$$

T. Sumikama. Phys. Rev. C **83** 065501 (2011) and
B. Holstein Rev. Mod. Phys., Vol 46, No. 4 (1974)

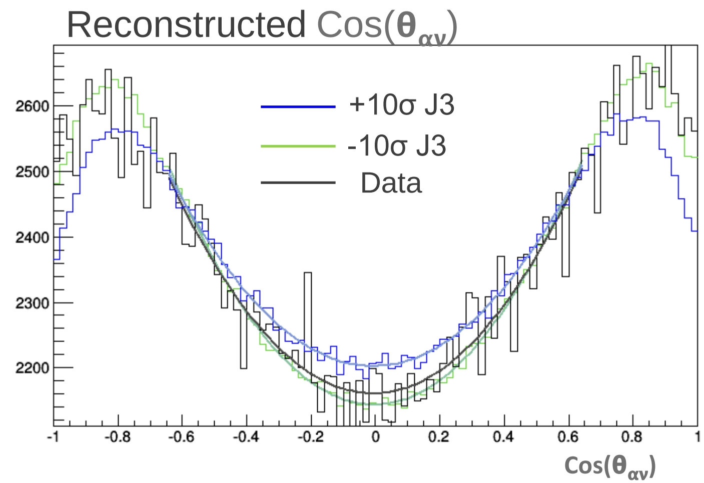
Measured second class currents come with error bars.

Some terms contribute differently based on decay type ($\beta^{\pm}$), can use ^{8}B data to compare.

Proportional to:
j_2 = -31000 ± 4000 j_3 = -63000 ± 18000

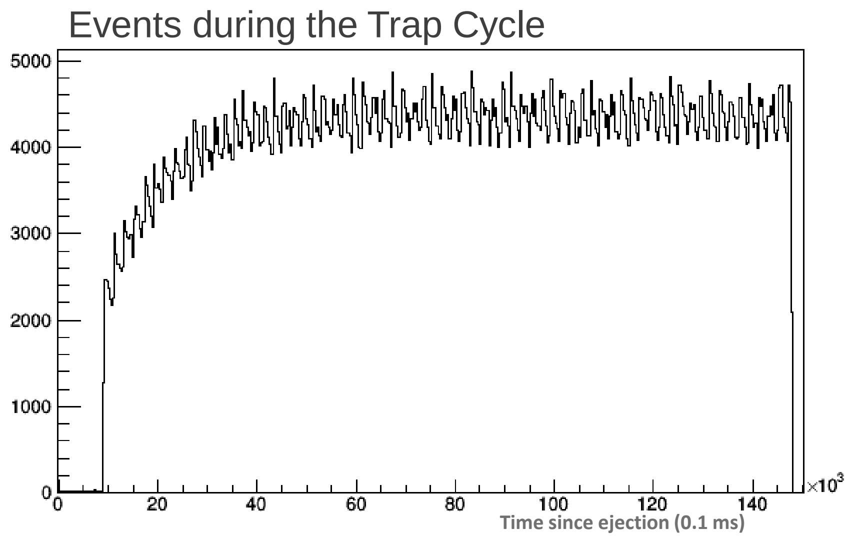
Currently working to set a smaller error on j_3 with unused data

Total systematic error is still uncertain.



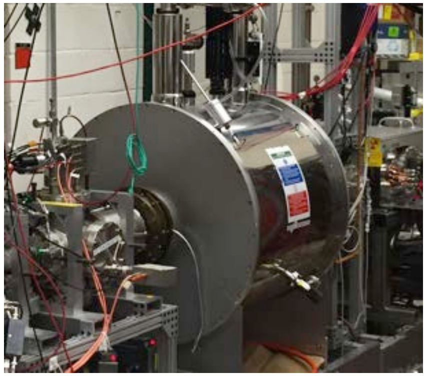
Background:

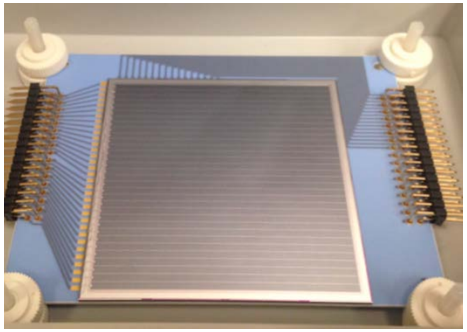
- Un-trapped ^8Li poses a concern for contaminating the data.
- Solution: measure more background in trap empty-cycle (x4).
- 25 un-trapped triples detected, scales to ~300 for the whole run (0.03% of total)
- Background systematic error has been eliminated.

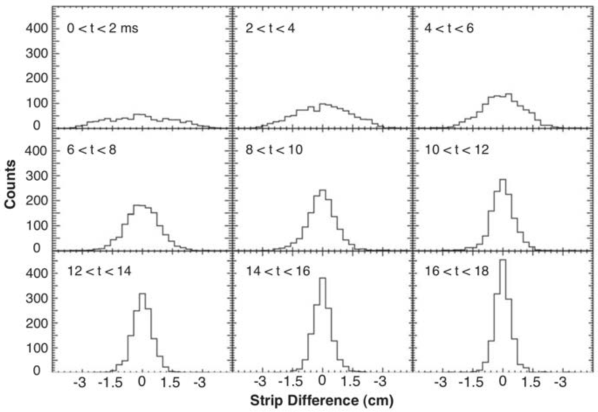


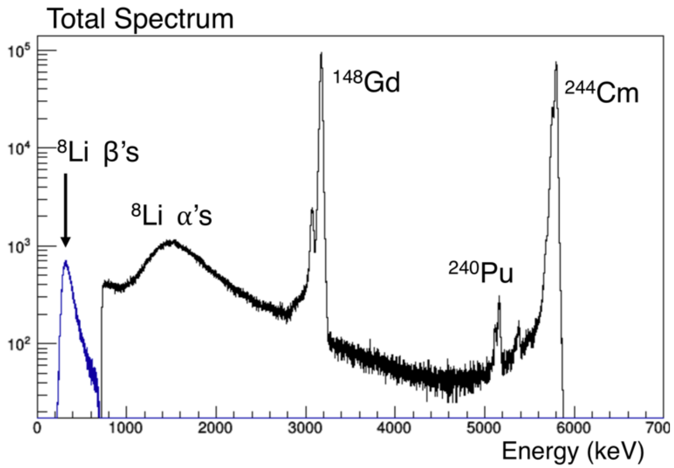
Non-dominant systematics:

- Smaller systematics that are harder to get rid of:
  - Magnetic field and trap voltages perturbing the particle trajectories
  - Cuts to the data (threshold between β and α spectra)
  - Ion cloud behavior
  - Normal dead layer uniformity









List almost complete!

TABLE I. Dominant sources of systematic uncertainty at 1σ.

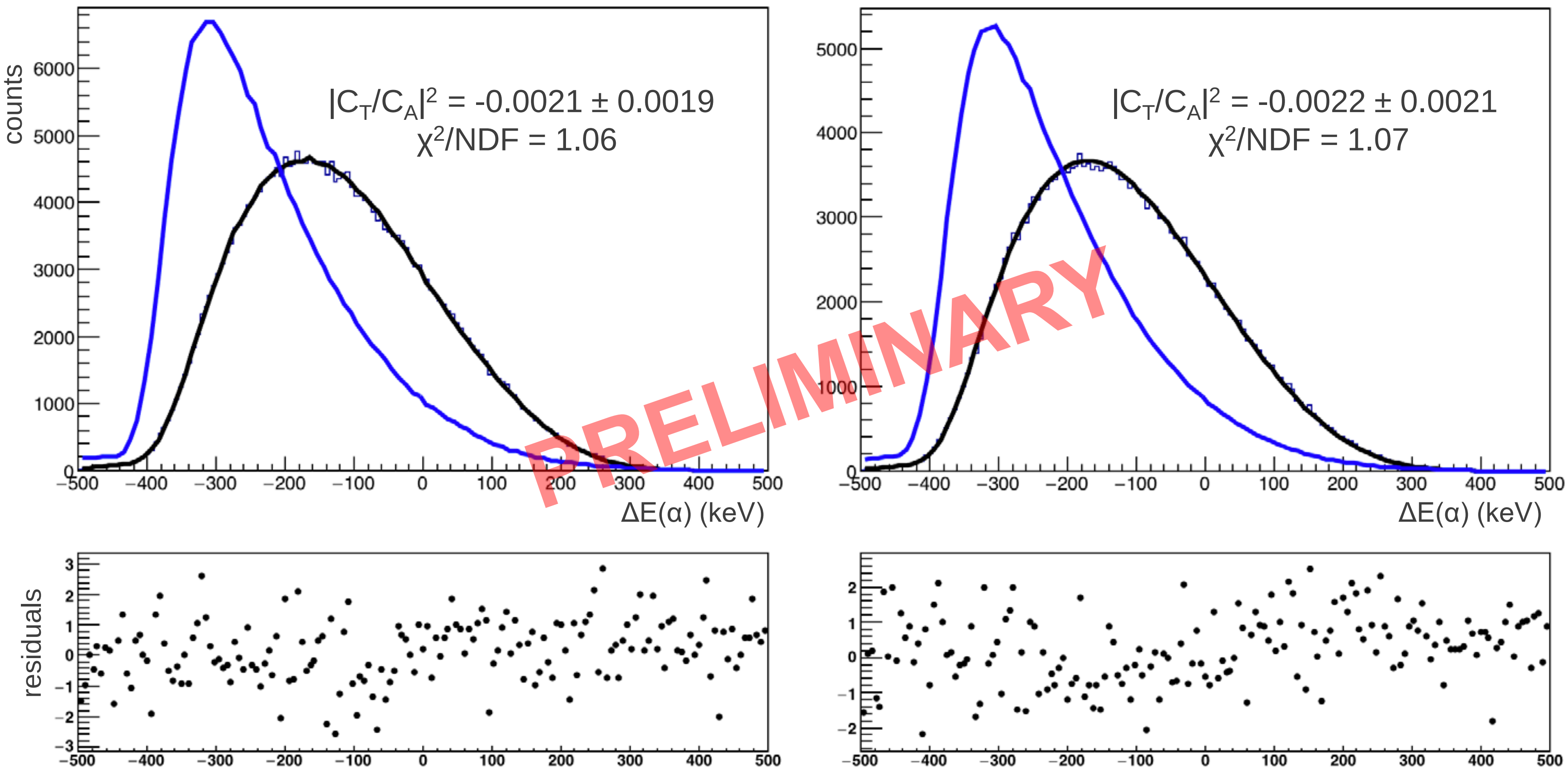
Source		$\Delta\|C_T/C_A\|^2$	
Energy calibration		~~0.0013~~	0.0005
α line shape		~~0.0018~~	0.0006
Dead layer thickness	More accurate value	0.0008	
β scattering		~~0.0020~~	0.0010
Backgrounds		~~0.0011~~	
Recoil and radiative		0.0026	?
Nondominant systematics	Not expected to change	0.0007	
Total	Still in progress.	~~0.0043~~	~0.0029*

Our dominating systematics

Pictures from PRL 115, 182501 (2015)

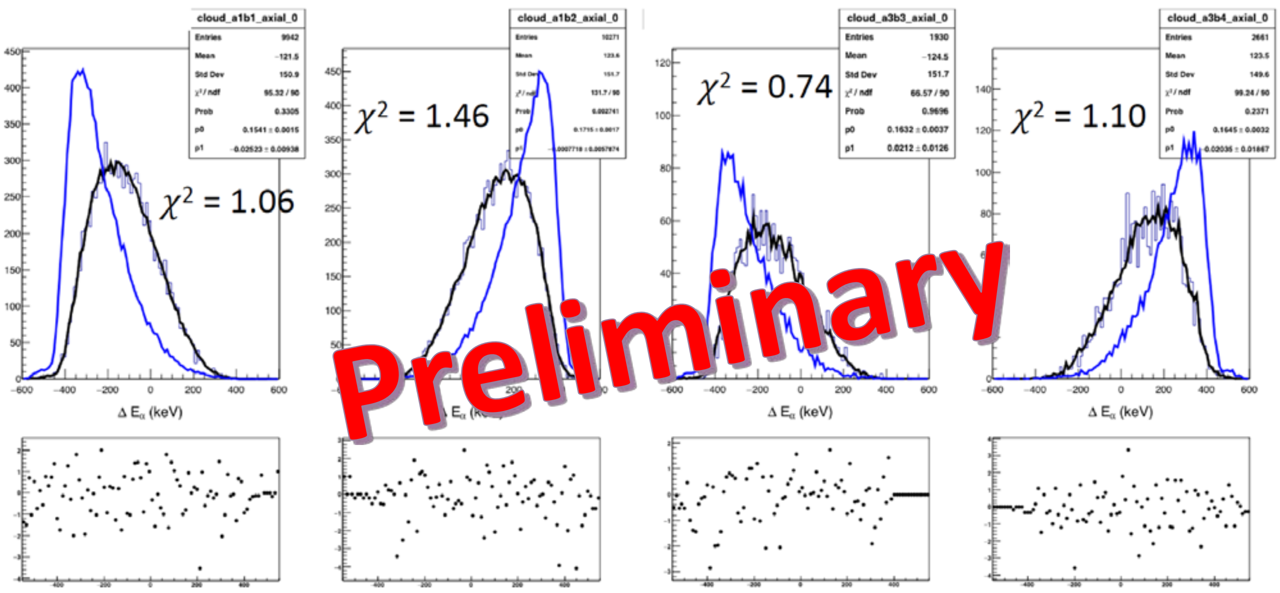
Almost there:

E(α) Difference Spectra: Top/Bottom and Left/Right Detector systems



Ongoing: ^{8}B in the works

- Analysis of a dataset similar to the 2015 PRL is almost complete.
- Plans for another data-taking campaign this winter.
- Graphs courtesy of Aaron Gallant.

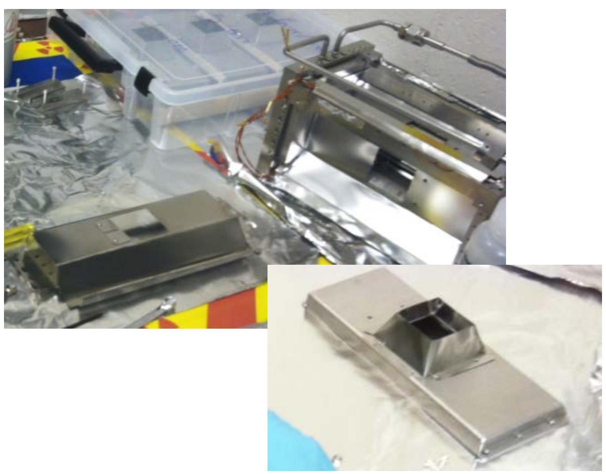


$$\left|{}^{C_T}/_{C_A}\right|^2 = -0.0046 +/- 0.0047$$

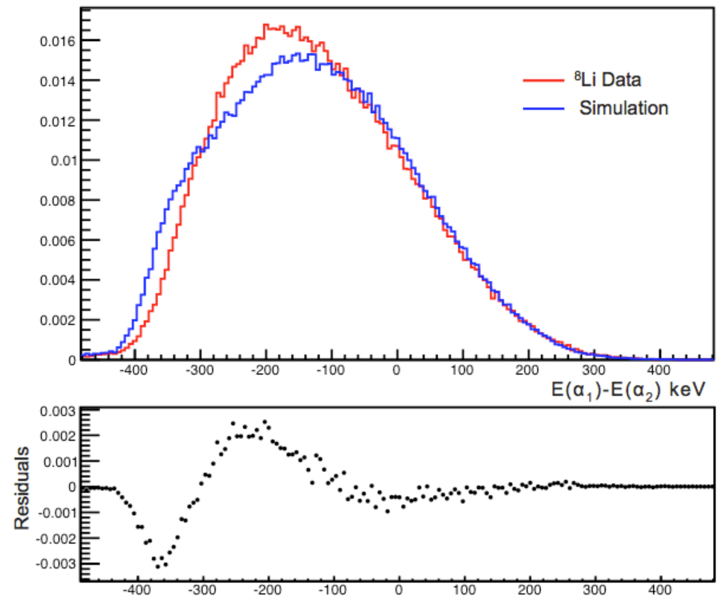
Possible improvements:

- More statistics?
- Stable linearity calibration
- Remove RF shielding to reduce scattering
- Solve the mystery surrounding the $g_{>20}(E)$ terms

$$
\begin{aligned}
d^7\Gamma = {} & F_{\mp}(Z,E)\,\frac{G_v^2\cos^2\theta_c}{2(2\pi)^6}\,(E_0-E)^2 pE\,dE\,d\Omega_e\,d\Omega_\nu\,d\Omega_n \\
& \times\Bigg(g_1(E) + g_2(E)\,\frac{\mathbf{p}}{E}\cdot\hat{k} + g_3(E)\left[\left(\frac{\mathbf{p}}{E}\cdot\hat{k}\right)^2 - \frac{1}{3}\frac{\mathbf{p}^2}{E^2}\right] \\
& + \delta_1(E, v^*, \tau_{J',J''}(L))\,\frac{\hat{n}\cdot\mathbf{p}}{E} \\
& + \delta_2(E, v^*, \tau_{J',J''}(L))\,\hat{n}\cdot\frac{\mathbf{p}}{E}\,\frac{\mathbf{p}}{E}\cdot\hat{k} \\
& + \delta_3(E, v^*, \tau_{J',J''}(L))\,\hat{n}\cdot\hat{k} \\
& + \delta_4(E, v^*, \tau_{J',J''}(L))\,\hat{n}\cdot\hat{k}\,\frac{\mathbf{p}}{E}\cdot\hat{k} \\
& + \tfrac{1}{10}\tau_{J',J''}(L)\,T^{(2)}(\hat{n}):\Big\{g_{10}(E)[\mathbf{p}/E, \mathbf{p}/E] \\
& + g_{11}(E)[\mathbf{p}/E, \mathbf{p}/E]\,\frac{\mathbf{p}}{E}\cdot\hat{k} + g_{11}(E)[\mathbf{p}/E, \hat{k}] \\
& + g_{12}(E)[\mathbf{p}/E, \hat{k}]\,\frac{\mathbf{p}}{E}\cdot\hat{k} + g_{13}(E)[\hat{k}, \hat{k}] \\
& + g_{15}(E)[\hat{k}, \hat{k}]\,\frac{\mathbf{p}}{\mathbf{E}}\cdot\hat{k} + g_{16}(E)\left[\frac{\mathbf{p}}{E}, \frac{\mathbf{p}}{E}\times\hat{k}\right] \\
& + g_{17}(E)\left[\hat{k}, \frac{\mathbf{p}}{E}\times\hat{k}\right]\Big\} \\
& + \delta_8(E, v^*, \tau_{J'J''}(L))\,T^{(3)}(\hat{n}):[\mathbf{p}/E, \mathbf{p}/E, \hat{k}] \\
& + \delta_9(E, v^*, \tau_{J'J''}(L))\,T^{(3)}(\hat{n}):[\mathbf{p}/E, \hat{k}, \hat{k}] \\
& + \tfrac{1}{10}\omega_{J'J''}(L)\,T^{(4)}(\hat{n}):\{g_{25}(E)[\mathbf{p}/E, \mathbf{p}/E, \mathbf{p}/E, \hat{k}] \\
& + g_{26}(E)[\mathbf{p}/E, \mathbf{p}/E, \hat{k}, \hat{k}] \\
& + g_{27}(E)[\mathbf{p}/E, \hat{k}, \hat{k}, \hat{k}]\}\Bigg). \qquad (53)
\end{aligned}
$$



Non-zero $g_{>20}$ terms do not match the data



Summary and Outlook

- $a_{\beta\nu}$ is sensitive to tensor contributions/new physics in the weak interaction.
- The BPT is well-equipped to precisely measure the kinematics of β-decay reactions.
- We obtained 10x the data from our 2015 PRL ^{8}Li experiment with a new statistical error of: $\Delta|C_T / C_A|^2 < 0.0013$, a 2.5x improvement to the existing statistical tensor limit.
- All major systematic errors have or are being addressed.
- Our goal is to eventually limit $|C_T / C_A|^2$ with relative precision below 0.1% … if we can control the theoretical corrections, the experiment can probably go below 0.05%, i.e. to $\Delta a \sim 0.0004$

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