Beta-decay correlations in $^{8}Li/^{8}B$

Solvay Workshop on “Beta-Decay Weak Interaction Studies in the Era of the LHC”

September 4, 2014

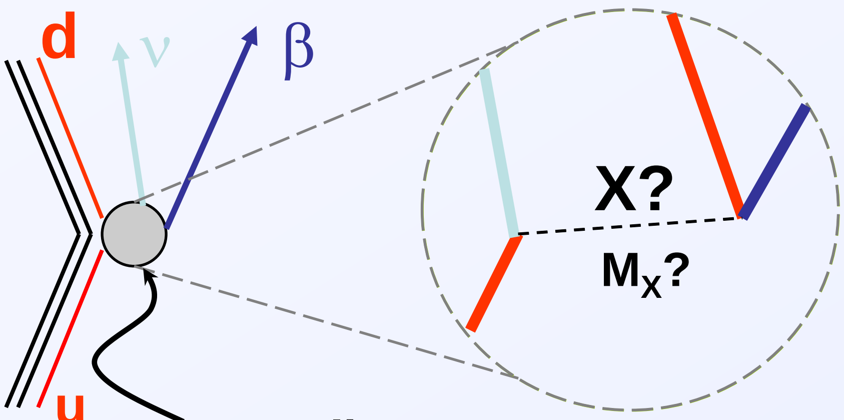
Nicholas Scielzo
Experimental Nuclear Physics Group

Lawrence Livermore National Laboratory

LLNL-PRES-??????

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

Nuclear β decay correlations



Coupling constants:
C_V, C_A, C_S?, C_T?

The form of the interaction results in correlations between the β and ν…

$$dW \sim \left[1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e}\right]$$

Compare experimental values to SM predictions (a)

Put limits on terms "forbidden" by SM (b)

Today, precise measurements of the beta-neutrino correlation search for scalar or tensor contributions from exotic weak bosons

For a pure Gamow-Teller transition

$$a = -\frac{1}{3}\frac{|C_A|^2 + |C_A'|^2 - |C_T|^2 - |C_T'|^2}{|C_A|^2 + |C_A'|^2 + |C_T|^2 + |C_T'|^2}$$

Experimental searches for $|C_T/C_A|^2$ have been made at the ~1% level…

…aiming for 0.1% (beyond perhaps) in the upcoming years…

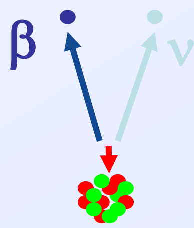
Beta-decay spectroscopy using trapped ions

Ion traps provide a "massless" sample of radioactive nuclei suspended in vacuum

- **Nuclear recoil available for study**
  → reconstruct particles from energy/momentum
- **Collect sample in ~1-mm^3 volume**
  → excellent geometry for radiation detection
- **Make efficient use of rare nuclei**
  → high statistics needed for precision measurements
- **Element independent**
  →many isotopes available for study and calibrations

New opportunities for precise studies of:

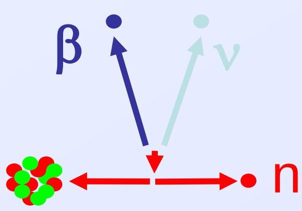
(1) Neutrinos



β + recoil
→ neutrino

G. Li *et al*., Phys. Rev. Lett. 110, 092502 (2013)

(2) Neutrons



Neutron emission

recoil
→ neutron

R.M. Yee *et al*., Phys. Rev. Lett. 110, 092501 (2013)

Beta-decay spectroscopy using trapped ions

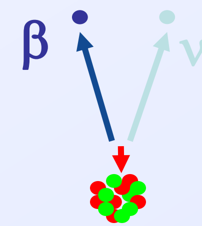
However, have to contend with certain challenges:

- No guarantee of sample purity
- Challenging detector environment
- Have to contend with EM fields

Best to choose experiments minimally impacted by the disadvantages…

New opportunities for precise studies of:

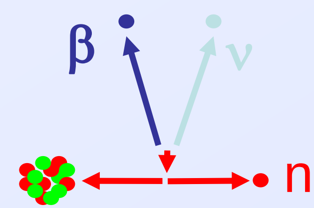
(1) Neutrinos



β + recoil
→ neutrino

G. Li *et al*., Phys. Rev. Lett. 110, 092502 (2013)

(2) Neutrons



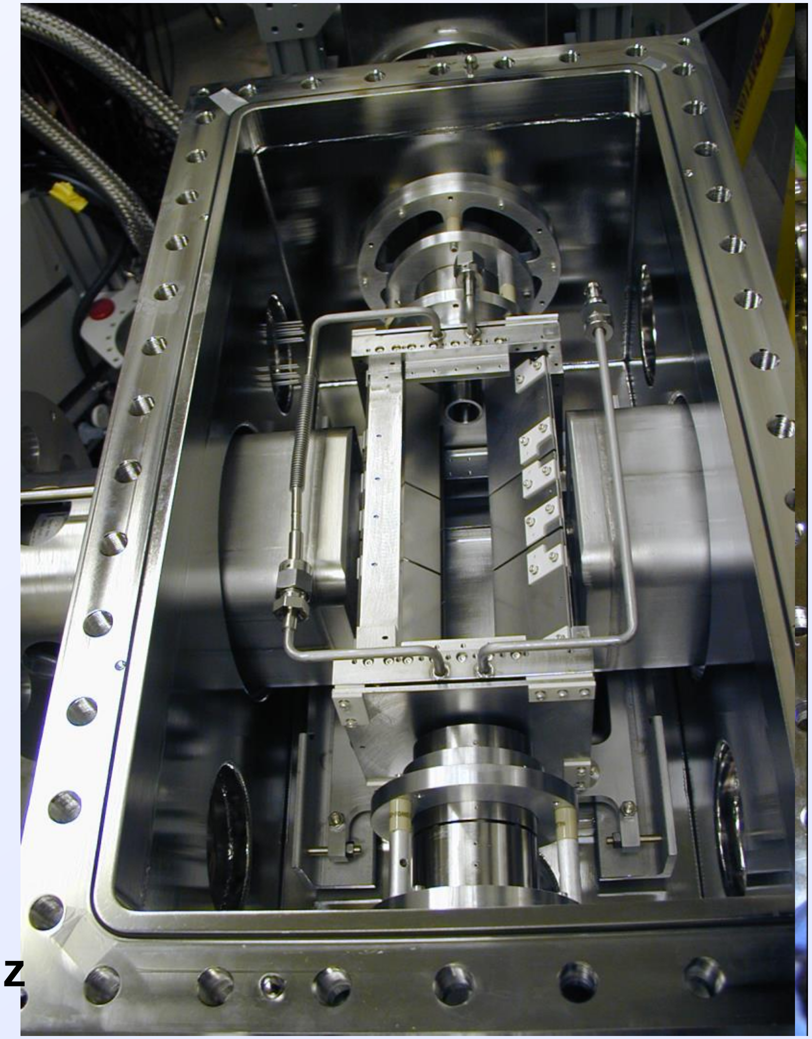
Neutron emission

recoil
→ neutron

R.M. Yee *et al*., Phys. Rev. Lett. 110, 092501 (2013)

The Beta-decay Paul Trap

N.D. Scielzo *et al.*, NIM A **681**, 94 (2012)



- **Confine up to ~10^6 ions at once**
- **Hold for >200 sec**
- **Accessible half-life > 50 ms**
- **Confine in ~1-mm^3 volume**
- **DC fields of ~100V**
- **RF fields of 200-1000 V_{pp} at 0.2-1.3 MHz**
- **He buffer gas cools ions to ~0.1 eV**

Why is ^{8}Li a promising candidate for improvement?

$^{8}Li \rightarrow {}^{8}Be^* + \beta^- + \nu$

$\hookrightarrow \alpha + \alpha$

Q **≈ 13 MeV** (broad ^{8}Be* state at 3 MeV)

$t_{1/2}$ **= 0.840 sec**

$2^+ \rightarrow 2^+$ decay is essentially pure allowed Gamow-Teller

- only axial vector and tensor contribute
- Fermi admixture is only $(5.0 \pm 1.5) \times 10^{-4}$

R.B. Wiringa *et al*., PRC **88**, 044333 (2013).

Large *Q* value and small nuclear mass

- 12-keV nuclear recoils
- Large kinematic shifts imparted to break-up α particles
  - E_α difference $\pm$400 keV
  - angle deviation from 180^0 by up to 7^0

$t_{1/2}$~840 ms convenient for traps

Additional β–ν–α correlation

Delayed-α emission in a Gamow-Teller decay: The β-ν-α triple correlation

$^{8}\mathrm{Li} \rightarrow {}^{8}\mathrm{Be}^{*} + \beta^{-} + \nu$

$\quad\quad\quad\quad \hookrightarrow \alpha + \alpha$

Q **≈ 13 MeV** (broad ^{8}Be* state at 3 MeV)

$t_{1/2}$ **= 0.840 sec**

The lepton emission leaves the daughter ^{8}Be nucleus oriented, and for a spin sequence of $2^{+} \rightarrow 2^{+} \rightarrow 0^{+}$ in delayed α emission:

$$dW \sim \left[1 \mp \frac{1}{3}\frac{v}{c}\cos\theta_{e\nu} + b\frac{m_e}{E_e} \mp \frac{v}{c}\left(\cos\theta_{e\alpha}\cos\theta_{\alpha\nu} - \frac{1}{3}\cos\theta_{e\nu}\right)\right]$$

where the "-" is for A and the "+" for T.

For parallel p_e and p_α simplifies to:

$$dW \sim \left[1 \mp \frac{v}{c}\cos\theta_{e\nu} + b\frac{m_e}{E_e}\right]$$

Sensitivity to difference between A and T increased by 3 × !

Correlations determined from β-α-α coincidences

Ion cloud surrounded by array of double-sided silicon strip detectors (DSSDs)

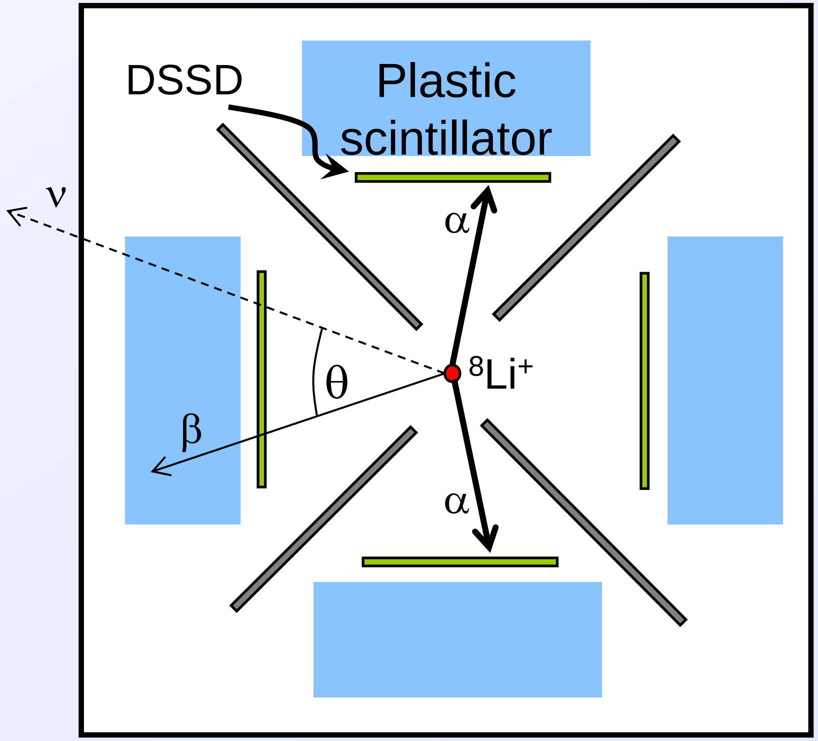
- Determine β momentum direction
- Determine momentum and energy for both α particles

This is sufficient to fully reconstruct the decay kinematics

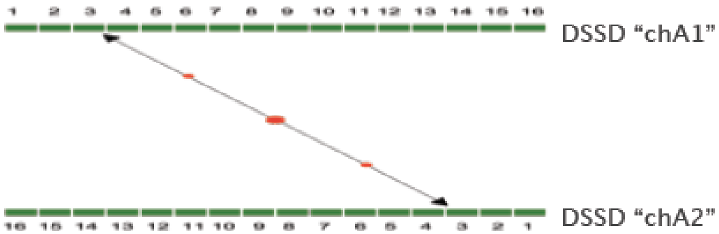
- $E_{\alpha 1} + E_{\alpha 2}$: ^{8}Be excitation energy
- $p_{\alpha 1} + p_{\alpha 2}$: nuclear recoil

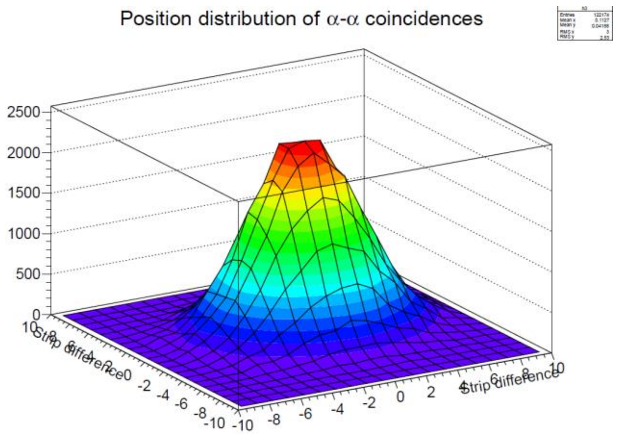
Additional measurement of β energy not required… but overconstrains the kinematics

trapped ions surrounded by DSSDs and plastic scintillators



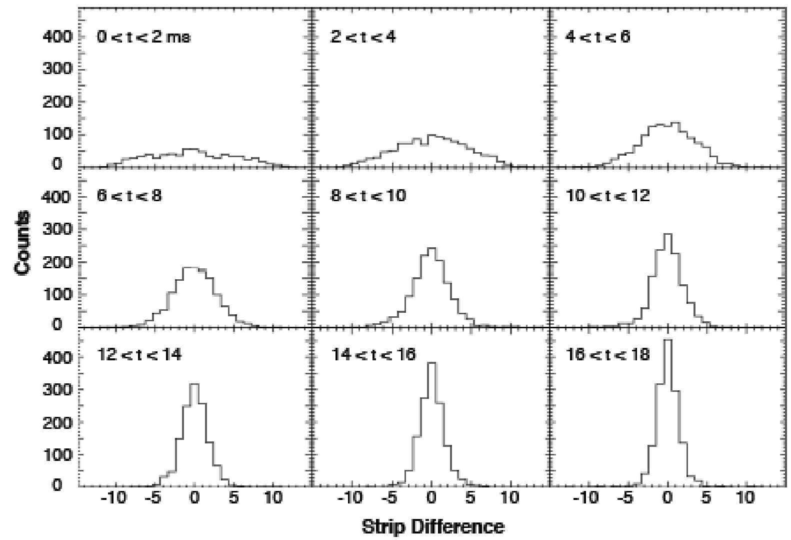
Imaging the ion cloud with back-to-back coincidences

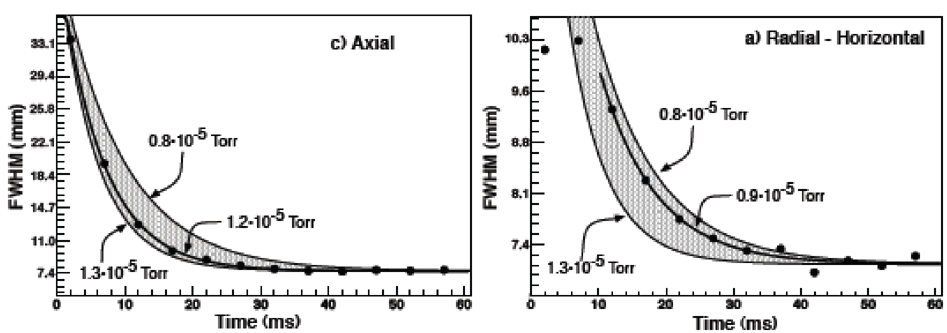




- Slight broadening due to resolution of strips & angular broadening of α's from recoil
- Image is consistent with ion cloud ~1 mm^3
- Finer strips will provide more precise imaging

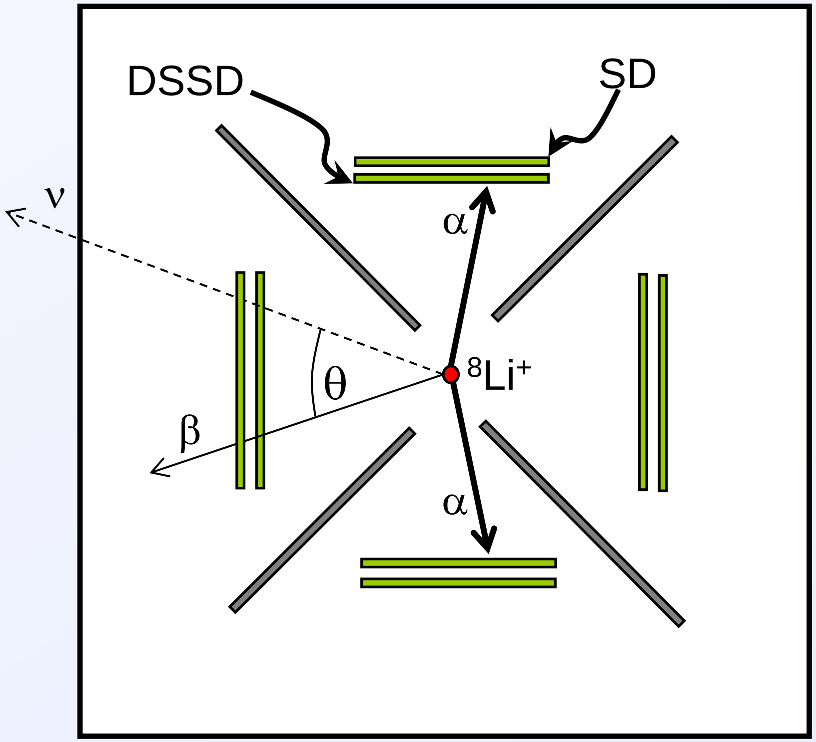
- Looking at the strip differences over time we can watch the ion cloud cool



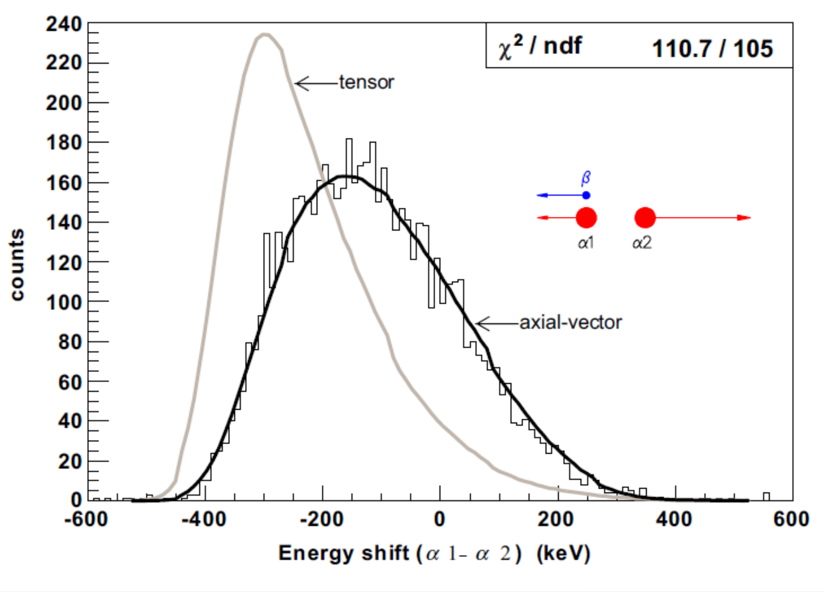


1^{st} results: β–α–α coincidences from ^{8}Li held in the ion trap

trapped ions surrounded by
50 × 50 × 0.3 mm^3 DSSDs (with
3.2-mm strips) backed by
50 × 50 × 1 mm^3 SD



G. Li *et al*., Phys. Rev. Lett. 110, 092502 (2013)



"Pure" Gamow-Teller decay

a_{SM} = -1/3

a = -0.3307±0.0090

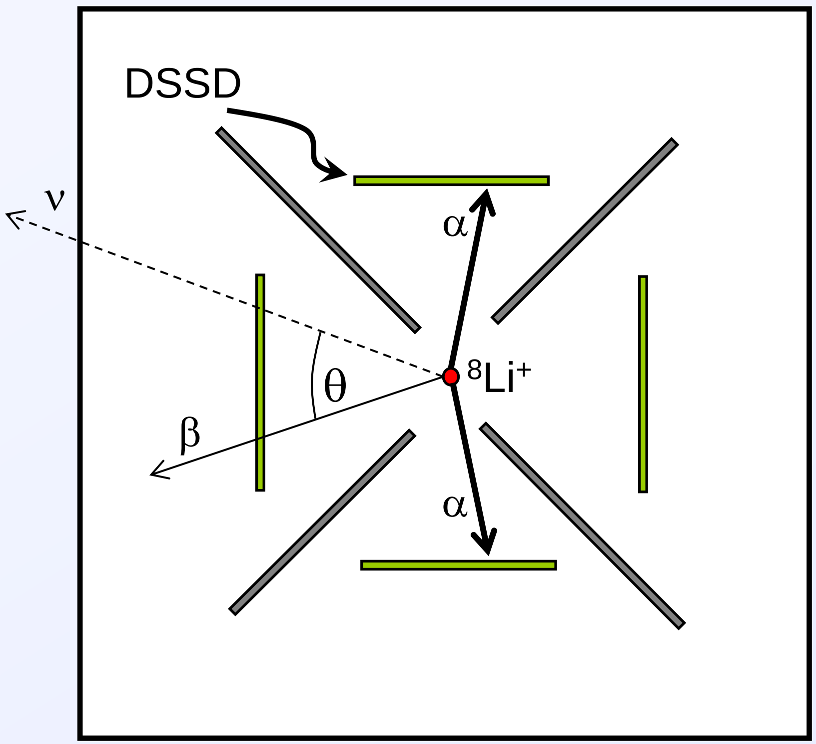
$$|C_T/C_A|^2 = 0.004 \pm 0.009_{\text{stat}} \pm 0.010_{\text{syst}}$$

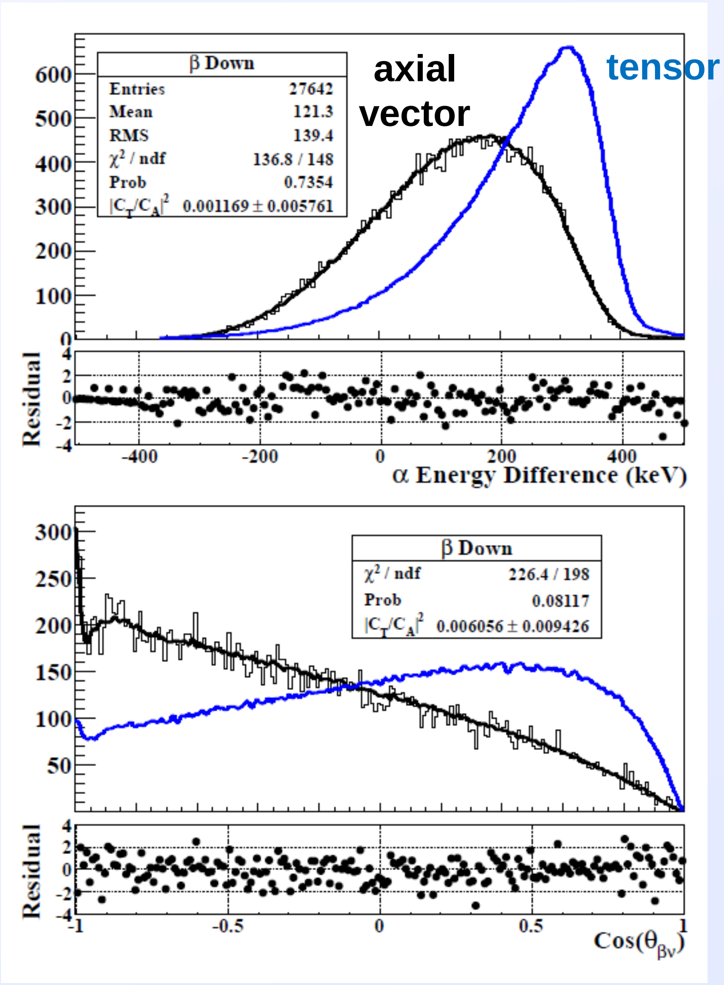
(note: fractional uncert. on a is 2 × worse that of $|C_T/C_A|^2$)

2^{nd} Campaign

Improvements: 10 × statistics
Finer segmentation on DSSD
Thinner dead layer on DSSD

trapped ions surrounded by
64 × 64 × 1 mm^3 DSSDs
(with 2.0-mm strips and
100-nm dead layer)

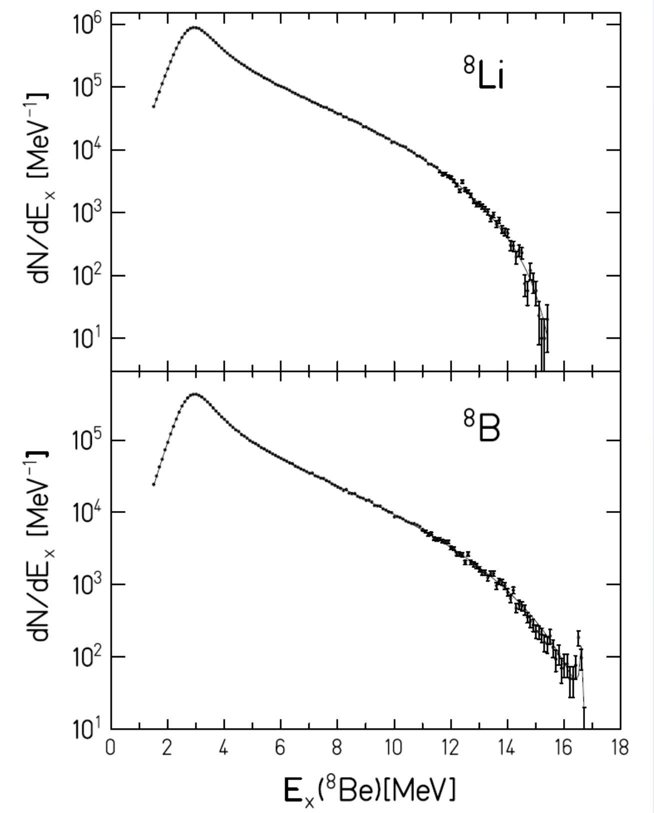




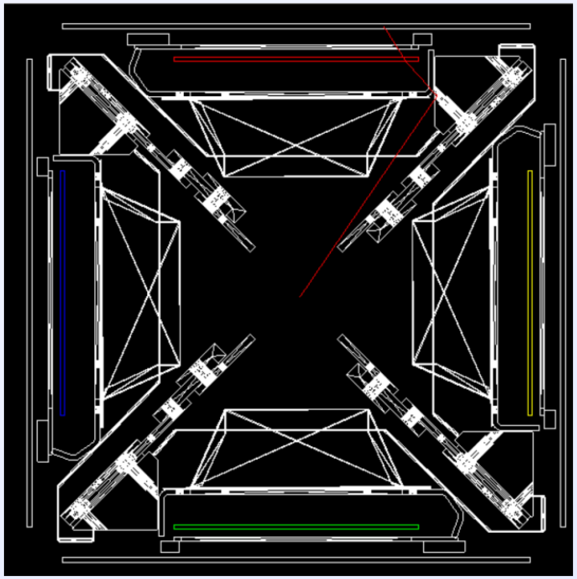
Analysis depends on detailed simulations…

Beta-decay event generator

- **Beta-decay phase space and angular correlations**
  - N.D. Scielzo *et al*., Phys. Rev. Lett. 93, 102501 (2004)
  - B.R. Holstein, Rev. Mod. Phys. 46, 789 (1974)
  - H. Behrens and J. Janecke (1969)
- **Final-state distribution of $^{8}Be^{*}$**
  - M. Bhattacharya *et al*., Phys. Rev. C 73, 055802 (2006)
- **Recoil-order terms and radiative corrections**
  - B.R. Holstein, Rev. Mod. Phys. 46, 789 (1974)
  - F. Gluck, Comp. Phys. Comm. 101, 223 (1997)
  - **Estimated size of radiative corrections for β-ν-α correlation term (need theory help to do this right!)**
- **Ion cloud distribution**
  - **Imaged cloud dimensions are ~1.8 mm**



Analysis depends on detailed simulations…

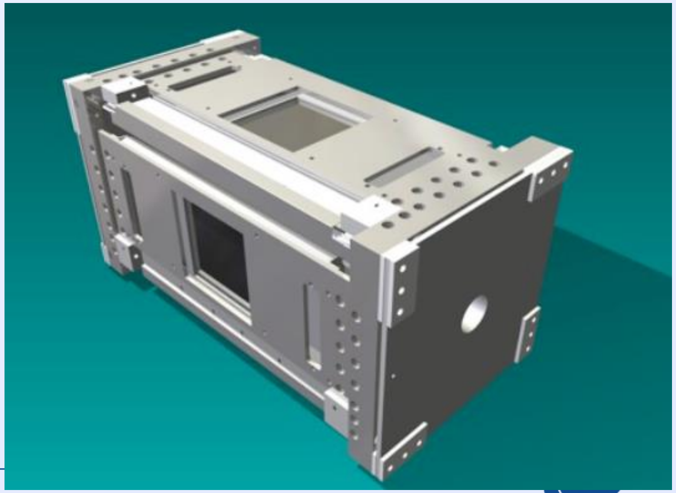


Beta-decay event generator

- Beta-decay phase space and angular correlations
- Final-state distribution of $^{8}Be^{*}$
- Recoil-order terms and radiative corrections
- Ion cloud distribution

GEANT4 Simulation

- **Selects coincident events**
  - Reconstruct βs using algorithms used for data
- **Beta scattering in experimental geometry**
  - PENELOPE physics package
  - full 3D model of trap, detector array, and chamber
- **Detector response**
  - energy loss in dead layers
  - energy resolution



Systematic effects – still to be finalized

Source	$\Delta\lvert C_T/C_A\rvert^2{}_{TB}$	$\Delta\lvert C_T/C_A\rvert^2{}_{LR}$
Energy Calibration	0.0009	0.0025
Dead Layer Thickness	0.0020	0.0020
Dead Layer Uniformity	0.0014	0.0014
β Scattering	0.0015	0.0015
Energy Cuts	0.0012	0.0012
α Line Shape	0.0018	0.0018
Rare Backgrounds	0.0011	0.0011
Induced Tensor Currents	0.0006	0.0006
Bremsstrahlung Emission	0.0006	0.0006
Total	0.0040	0.0046

$$\lvert C_T/C_A\rvert^2 = 0.0018 \pm 0.0036_{stat} \pm 0.0041_{syst}$$

$$a_{\beta\nu} = -0.3321 \pm 0.0036$$

M.G. Sternberg, PhD Thesis, UChicago (2013)

M.G. Sternberg *et al*., to be submitted to Phys. Rev. Lett. (2014)

Further reduction of systematic effects

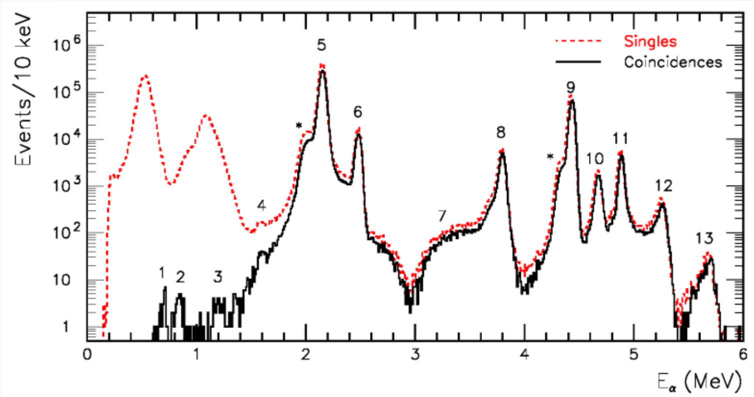
Source	$\Delta\|C_T/C_A\|^2{}_{TB}$	$\Delta\|C_T/C_A\|^2{}_{LR}$
Energy Calibration	0.0009	0.0025
Dead Layer Thickness	0.0020	0.0020
Dead Layer Uniformity	0.0014	0.0014
β Scattering	0.0015	0.0015
Energy Cuts	0.0012	0.0012
α Line Shape	0.0018	0.0018
Rare Backgrounds	0.0011	0.0011
Induced Tensor Currents	0.0006	0.0006
Bremsstrahlung Emission	0.0006	0.0006
Total	0.0040	0.0046

Reduce β scattering

- lower-Z materials
- modified electrode structure
- guidance from GEANT4 simulations

Better understanding of detector response

- better dead-layer measurement
- calibration with ^{20}Na β-delayed α emission

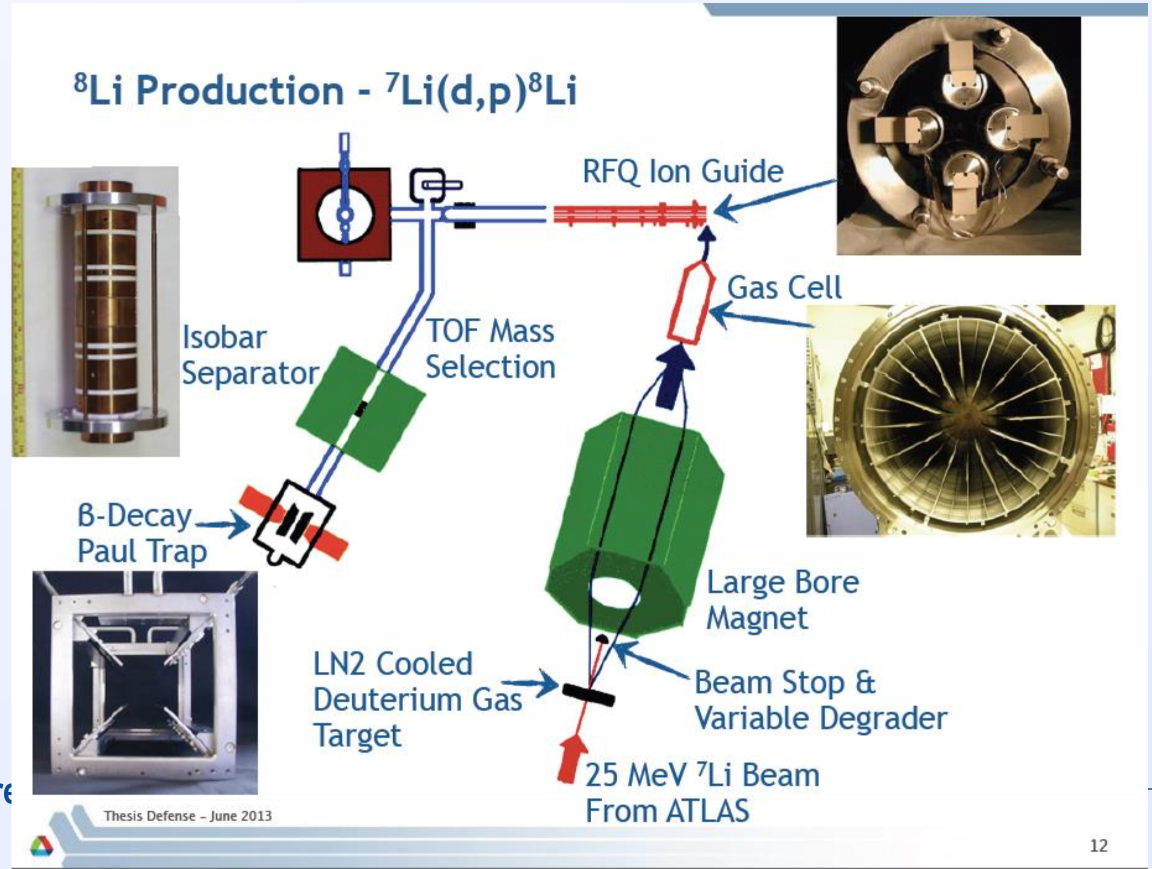


K.L. Laursen *et al.*, Eur. Phys. J A 49, 79 (2013)

Towards $|C_T/C_A|^2 \sim 0.001$

Higher statistics

- Improved beam tuning diagnostics
- Optimized gas target geometry
- High-frequency gas catcher



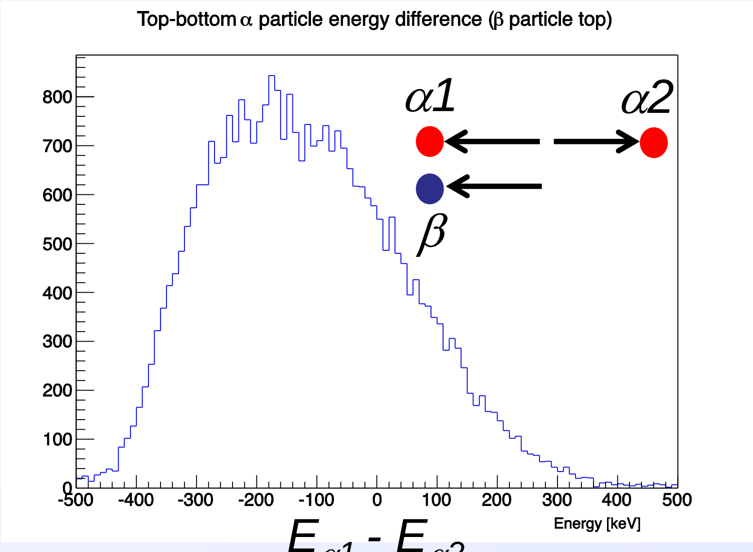
Towards $|C_T/C_A|^2 \sim 0.001$

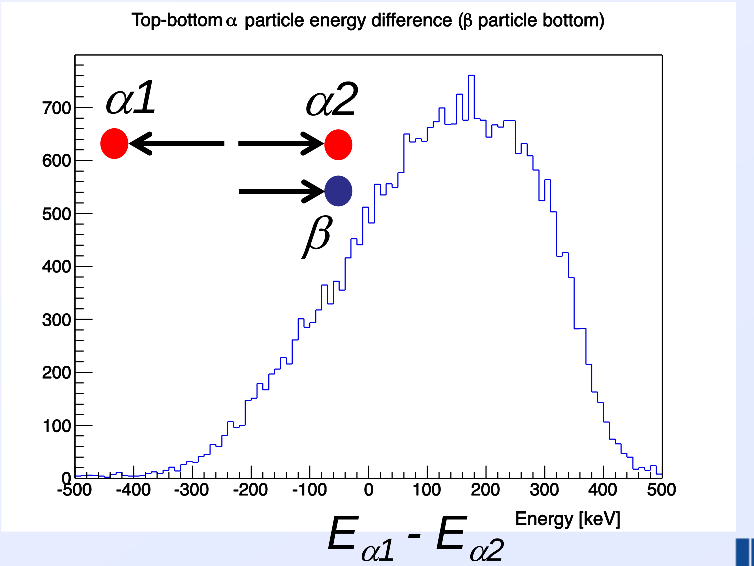
Higher statistics

- Improved beam tuning diagnostics
- Optimized gas target geometry
- High-frequency gas catcher

Achieved ~10× increase in efficiency for ^8B

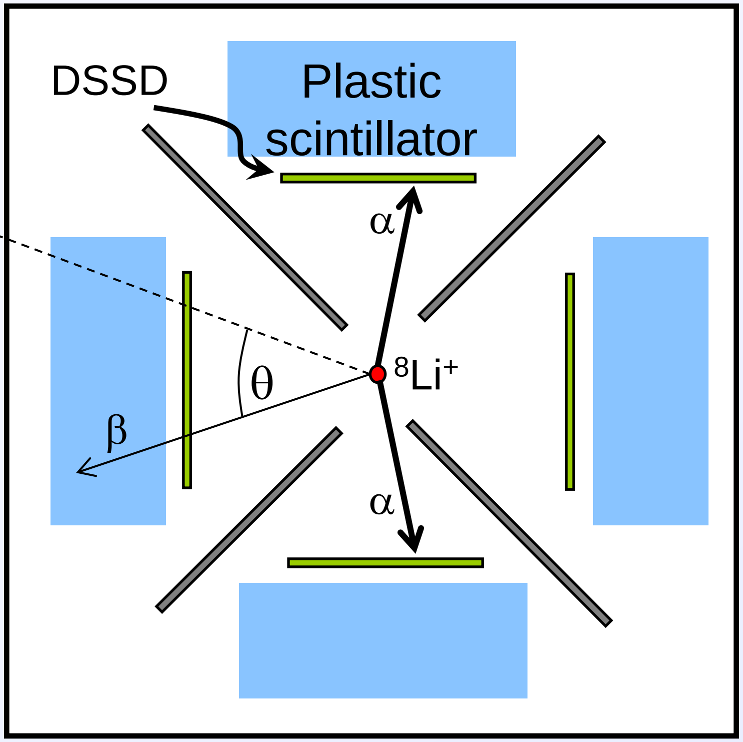
β-α-α coincidences from ^8B decay from July 2014

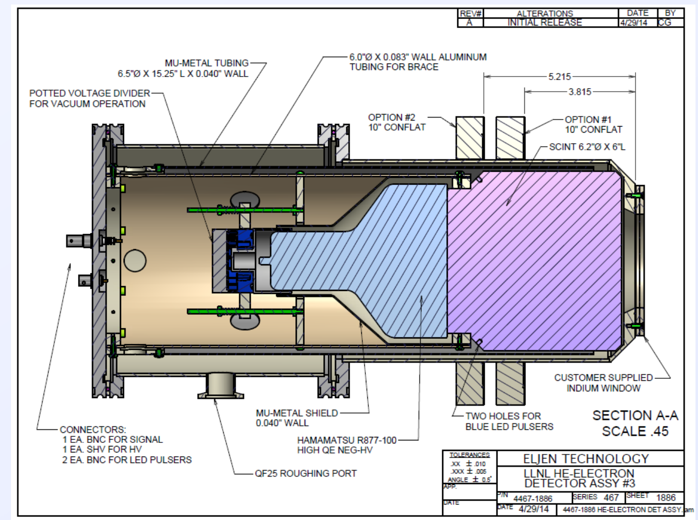




Addition of plastic scintillator detectors for direct β energy measurement

trapped ions surrounded by DSSDs and plastic scintillators





Overconstrain decay kinematics for systematic checks

Select events that are most sensitive to difference between A and T

On the horizon… pursuing even higher precision ^{8}Li/^{8}B measurements

β-decay angular correlations

- Further improve limits on β–ν correlation
- Search for Fierz interference term

$$dW \sim \left[1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e}\right]$$

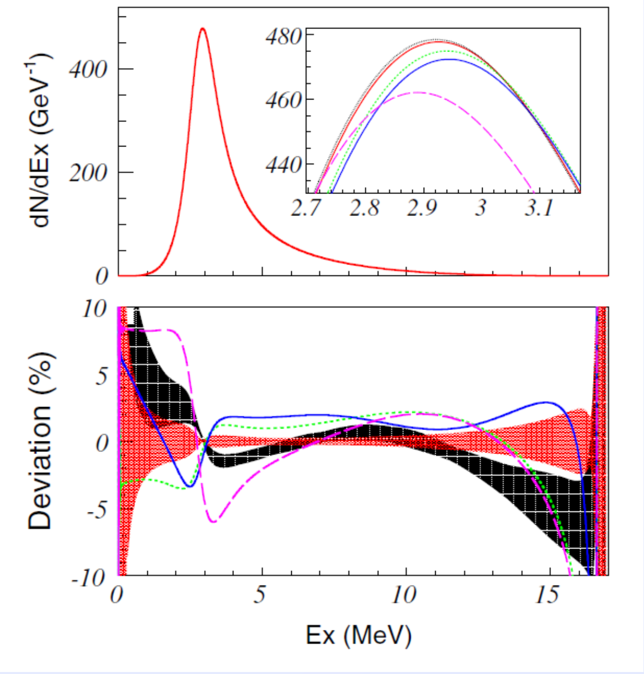
~0.1% ~1%

Recoil-order terms (small E_e dependence)

- CVC hypothesis – weak vector current is related to the isovector EM current for analog γ decay
- Second-class currents – do induced terms obey same symmetries as strong interaction

^{8}B neutrino spectrum

- Neutrino spectrum calculated once E_x known
- Resolve disagreement between recent measurements (~20 keV calibration shifts)



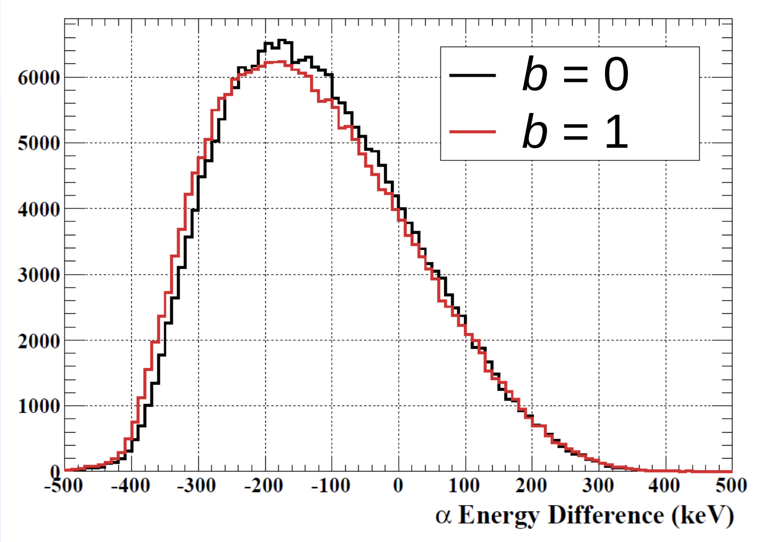
On the horizon… pursuing even higher precision $^{8}Li/^{8}B$ measurements

β-decay angular correlations

- Further improve limits on β–ν correlation
- Search for Fierz interference term

$$dW \sim \left[1 + a \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b \frac{m_e}{E_e} \right]$$

~0.1% ~1%



Sensitivity to Fierz interference term is ~10 × less than for tensor contribution

Systematics need to be carefully investigated

On the horizon… pursuing even higher precision in mirror $^8Li/^8B$ decays

Recoil-order terms (small E_e dependence)

- Weak magnetism term b_{wm} (change sign with $\beta^{\pm}$)
- Second-class current term d (independent of $\beta^{\pm}$)

These small terms are amplified in $^8Li/^8B$ because $E_e/M \sim 0.001$ and $b_{wm} \sim 60$

B.R. Holstein, Rev. Mod. Phys. 46, 789 (1974)
(ignoring $(E_e/M)^2$ terms)

$$dW \sim \left[g_1(E_e) - g_2(E_e)\frac{v}{c}\cos\theta_{e\nu} + b\frac{m_e}{E_e} - g_{12}(E_e)\frac{v}{c}\left(\cos\theta_{e\alpha}\cos\theta_{\alpha\nu} - \frac{1}{3}\cos\theta_{e\nu} \right) \right]$$

$$g_1(E_e) = \left(1 - \frac{2E_0}{3M}(1 + d \pm b_{wm}) + \frac{2E_e}{3M}(5 \pm 2b_{wm}) \right)$$

Plus additional correlations:

$$g_{10}(E_e) = -\frac{E_e}{M}(1 + d \mp b_{wm}) \cdot \cos^2\theta_{e\alpha}$$

Fully-reconstructed decay allows determination of b_{wm} and d from several correlations

Summary

- **$^{8}Li/^{8}B$ has many favorable features for precision tests of fundamental symmetries**
  - Large *Q* value and small *M* yield recoil energies and easy to measure kinematic shifts in delayed α particles
  - β-ν-α correlation gives additional contrast between A and T currents
  - Measurement technique has different systematic uncertainties than TOF measurements
- **Program well underway with $|C_T/C_A|^2$ already determined to ~0.005 and a sensitivity of 0.001 on the horizon…**
- **Additional terms accessible**

Ion Trap Collaborators

Graduate Students

Postdoctoral Researchers

N.D. Scielzo, A. Czeszumska, E.B. Norman, S. Padgett, B.S. Wang, R.M. Yee

G. Savard, M. Burkey, S. Caldwell, J.A. Clark, A.F. Levand, A. Perez Galvan, P. Mueller, M.G. Sternberg

F. Buchinger, J. Crawford, R. Orford

R. Segel

K.S. Sharma, G. Morgan, T. Hirsch

A. Aprahamian, S. Marley, N. Paul, S. Strauss, K. Siegl