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

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UMass, November 03 2018
Using $^8\text{Li} \beta$ decay to measure $a_{\beta\nu}$

- 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 ($<E_{\alpha}> \sim 1.5\text{MeV}$) making a clean “triple” event with almost no background.
- Has a mirror nucleus: $^8\text{B}$ 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 $^8B$ and $^8Li$ at ATLAS

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

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 $1\text{mm}^3$ 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.
- 2° 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
Axial Vector events favor lepton emissions in the opposite direction.

Tensor events favor lepton emissions in the same direction.

$\Delta E(\alpha's)$ is larger and more sensitive to $a_{\beta\nu}$ when the $\beta$ is emitted roughly parallel to an $\alpha$.

We only use "triple" events where the $\beta$ and an $\alpha$ hit the same detector.

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

Axial Vector: $a_{\beta\nu} = -\frac{1}{3}$, Tensor: $a_{\beta\nu} = \frac{1}{3}$
Our previous experiments

Gang Li: Graduated 2012

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

Matt Sternberg: Graduated 2013

\[
|C_T/C_A|^2 = -0.0013 \pm 0.0038_{\text{stat}} \pm 0.0043_{\text{syst}}.
\]
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.

| Source                        | $\Delta|C_T/C_A|^2$ |
|-------------------------------|------------------|
| Energy calibration            | 0.0013           |
| $\alpha$ line shape           | 0.0018           |
| Dead layer thickness          | 0.0008           |
| $\beta$ scattering            | 0.0020           |
| Backgrounds                   | 0.0011           |
| Recoil and radiative          | 0.0026           |
| Nondominant systematics       | 0.0007           |
| **Total**                     | **0.0043**       |
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 $\alpha$ sources (FWHM < 20 keV)

![Graphs showing before and after results](image-url)
Simulated $\alpha$ Lineshape:

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

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 $\beta$ 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

Recoil and Radiative terms:

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:

$$j_2 = -31000 \pm 4000 \quad j_3 = -63000 \pm 18000$$

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

Total systematic error is still uncertain.

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Background:

- Un-trapped $^8$Li 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 $\beta$ and $\alpha$ spectra)
  - Ion cloud behavior
  - Normal dead layer uniformity
List almost complete!

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| Nondominant systematics             | 0.0007               |
| Total                               | 0.0043               |

Our dominating systematics

Pictures from PRL 115, 182501 (2015)
Almost there:

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

\[ |C_T/C_A|^2 = -0.0021 \pm 0.0019 \]
\[ \chi^2/\text{NDF} = 1.06 \]

\[ |C_T/C_A|^2 = -0.0022 \pm 0.0021 \]
\[ \chi^2/\text{NDF} = 1.07 \]
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.
Possible improvements:

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

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

• $a_{\beta v}$ is sensitive to tensor contributions/new physics in the weak interaction.
• The BPT is well-equipped to precisely measure the kinematics of $\beta$-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 $\Delta a \sim 0.0004$
Collaborators and Acknowledgements

M.T. Burkey, G. Savard, L. Varriano, J. Pierce
N.D. Scielzo, A. Gallant B. Wang, S. Padgett, Kay Kolos,
E. Heckmaier
R. Segel
R. Orford, F. Buchinger
K.S. Sharma,
D. Burdette, M. Brodeur
T. Hirsh, D. Gazit
S. Marley, G. Morgan

We would like to acknowledge NSERC, Canada, App. No. 216974, the U.S.
DOE Contract No. DEAC0206CH11357 [ANL] and DEAC5207NA27344 [LLNL],
NSF grant no. 1144082 and the ANL ATLAS facility.