

Precision Measurements with the Beta-decay Paul Trap

FRIB TA Topical Program

Future directions in nuclear beta decay at FRIB

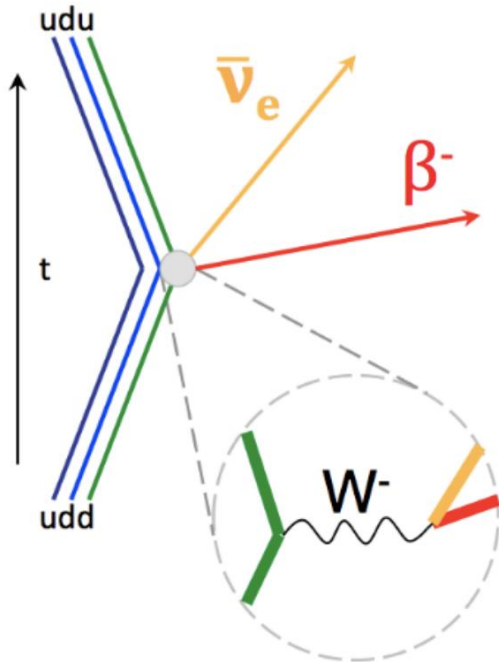
Brenden Longfellow

10 September 2025



Most General Hamiltonian for Beta Decay

$$\begin{aligned}
 &\text{Fermi} \quad \left\{ \begin{aligned} H_\beta = & (\bar{p}n) [\bar{e} (C_S + C'_S \gamma_5) \nu] \quad \text{Scalar} \\ & + (\bar{p} \gamma_\mu n) [\bar{e} \gamma_\mu (C_V + C'_V \gamma_5) \nu] \quad \text{Vector} \end{aligned} \right. \\
 &\text{Gamow-Teller} \quad \left\{ \begin{aligned} & + \frac{1}{2} (\bar{p} \sigma_{\lambda\mu} n) [\bar{e} \sigma_{\lambda\mu} (C_T + C'_T \gamma_5) \nu] \quad \text{Tensor} \\ & - (\bar{p} \gamma_\mu \gamma_5 n) [\bar{e} \gamma_\mu \gamma_5 (C_A + C'_A \gamma_5) \nu] \quad \text{Axial Vector} \\ & + (\bar{p} \gamma_5 n) [\bar{e} \gamma_5 (C_P + C'_P \gamma_5) \nu] + \text{H.c.} \quad \text{Pseudo-Scalar} \end{aligned} \right.
 \end{aligned}$$



Coupling constants

$$C_S, C'_S, C_V, C'_V, C_T, C'_T, C_A, C'_A, C_P, C'_P$$

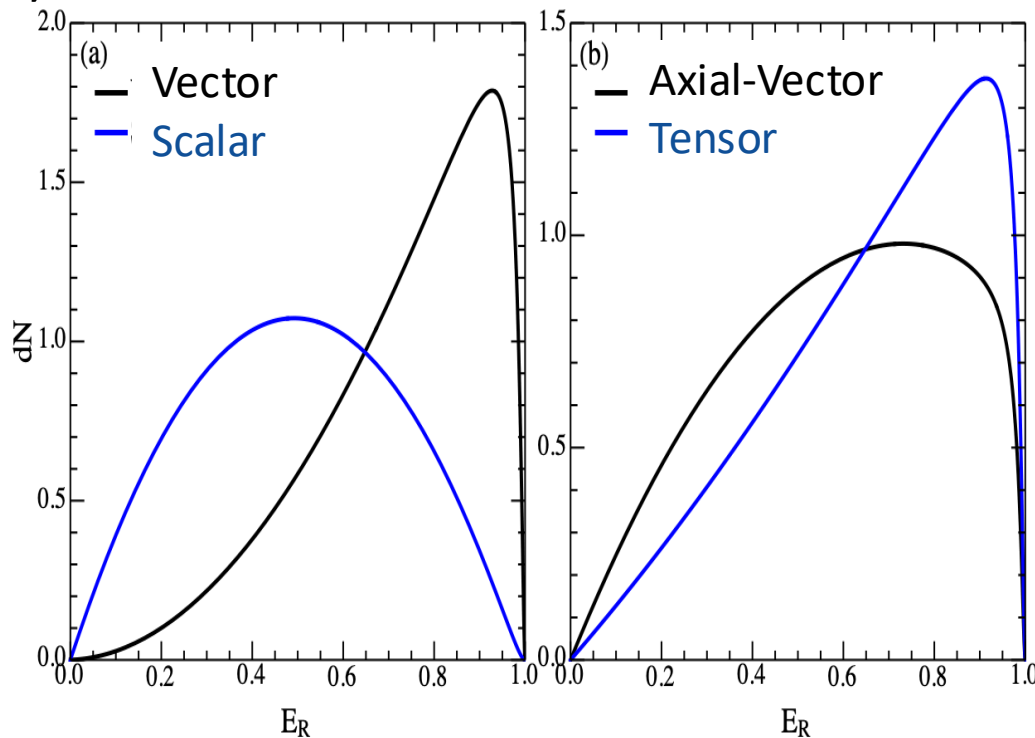
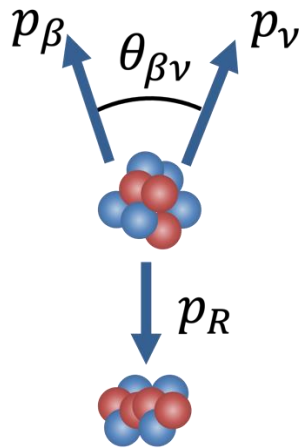
where C' give parity-nonconserving interactions, must be determined by experiment

Beta-Neutrino Angular Correlations

$$d\Gamma \propto F(Z, E_e) p E_e (E_0 - E_e)^2 \left(1 + a_{\beta\nu} \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} \right)$$

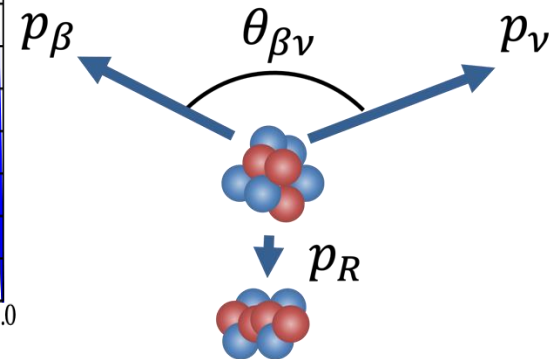
Fermi (Vector)

$a_{\beta\nu} = +1$
Preferred
 $\theta = 0^\circ$



Gamow-Teller
(Axial Vector)

$a_{\beta\nu} = -1/3$
Preferred
 $\theta = 180^\circ$



- Recoil energy spectrum imprinted with lepton correlation information

Physics Beyond the Standard Model

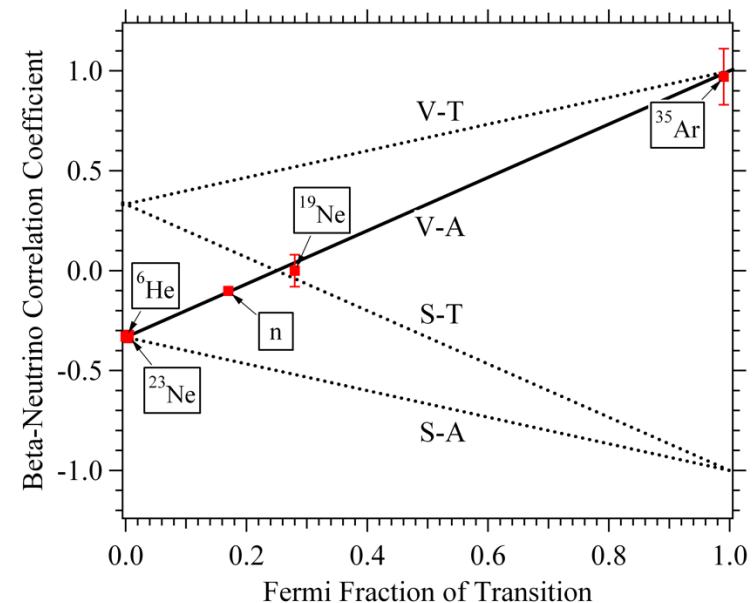
- In the 1960's, the V-A structure of the weak interaction was determined by measurements of the beta-neutrino angular correlation coefficient ($a_{\beta\nu}$) in noble gas nuclei
- Beyond Standard Model: Scalar (S) and Tensor (T) may be present with small coefficients

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

$$a_{\beta\nu} = \frac{(|C_V|^2 - |C_S|^2) |M_F|^2 - \frac{1}{3} (|C_A|^2 - |C_T|^2) |M_{GT}|^2}{(|C_V|^2 + |C_S|^2) |M_F|^2 + (|C_A|^2 + |C_T|^2) |M_{GT}|^2}$$

Fermi decay only sensitive to V, S

Gamow-Teller decay only sensitive to A, T



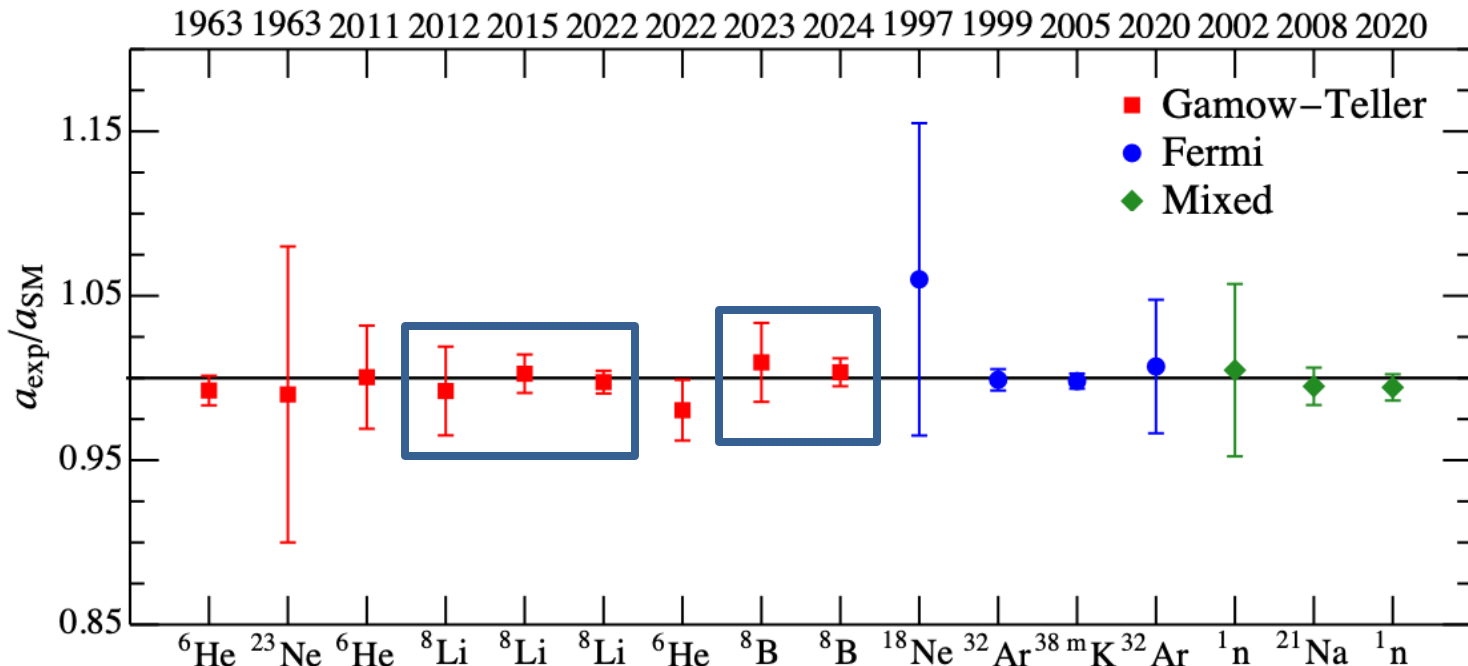
Limits on Tensor Currents from Mass 8

- ^8Li and ^8B beta decays are nearly pure Gamow-Teller: sensitive to exotic Tensor currents

$$a_{\beta\nu} = \frac{(|C_V|^2 - |C_S|^2) |M_F|^2 - \frac{1}{3} (|C_A|^2 - |C_T|^2) |M_{GT}|^2}{(|C_V|^2 + |C_S|^2) |M_F|^2 + (|C_A|^2 + |C_T|^2) |M_{GT}|^2}$$

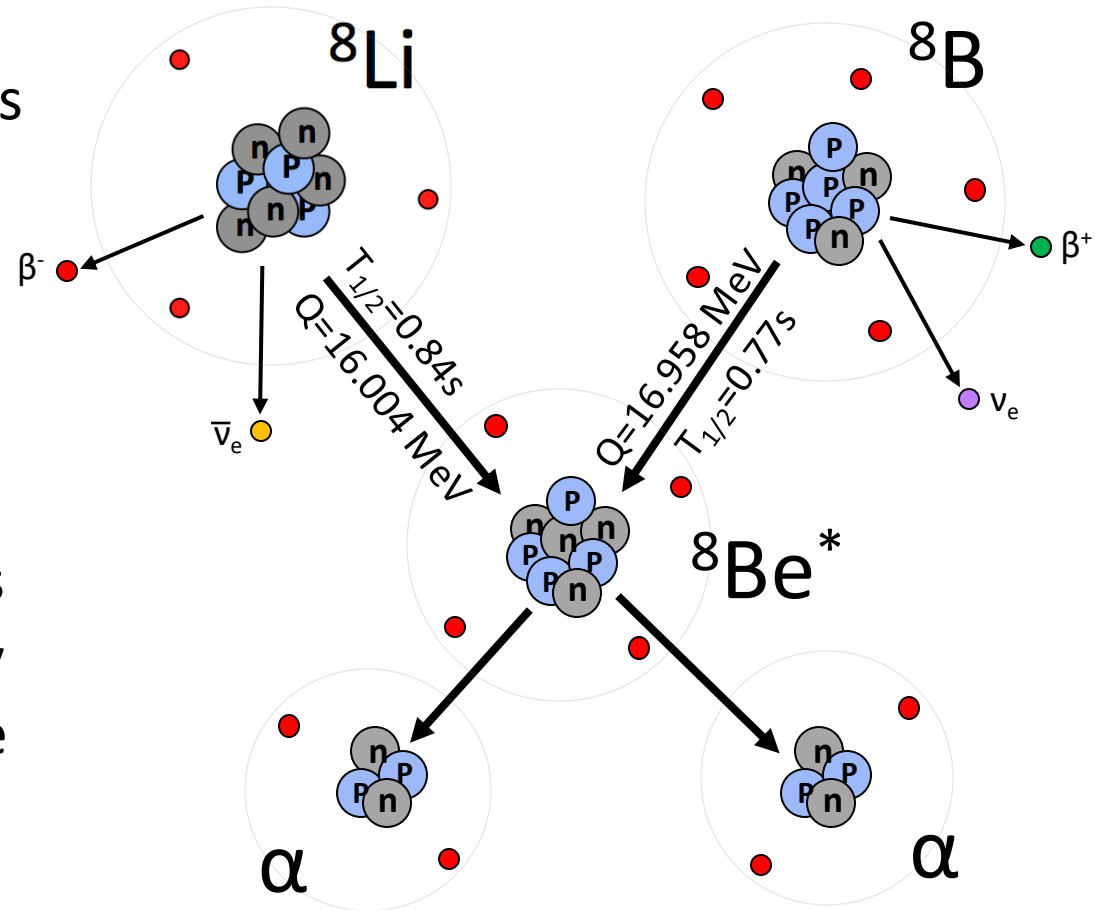
$$W(\theta_{\beta\nu}) = 1 + a_{\beta\nu} \frac{v_\beta}{c} \cos(\theta_{\beta\nu})$$

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



^8Li and ^8B Beta Decay Properties

- Both beta decay into ^8Be , which is unbound and breaks up into two alpha particles
- Q values are large, masses are small leading to MeV scale decay products
- Charged particle coincidences (α - α , α - α - β) can be precisely measured to reconstruct the beta-neutrino angular correlation



^8Li and ^8B Beta Decay Kinematics

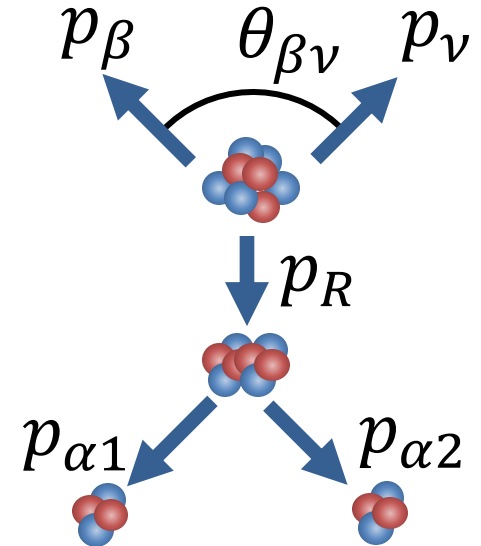
$$\Gamma \propto F(Z, E_e) p_e E_e (E_0 - E_e)^2$$

$$\left\{ g_1(E_e) \right.$$

Fierz Interference Term $+ b_F \frac{m_e}{E_e}$

$\beta\nu$ angular correlation $+ g_2(E_e) \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu}$

“Triple” correlation $+ g_{12}(E_e) \left(\frac{(\vec{p}_e \cdot \hat{p}_\alpha)(\vec{p}_\nu \cdot \hat{p}_\alpha)}{E_e E_\nu} - \frac{1}{3} \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} \right) \Bigg\}$



$$b_F = \pm 2 \frac{\Re(C_T C_A^* + C_T' C_A'^*)}{|C_A|^2 + |C_A'|^2 + |C_T|^2 + |C_T'|^2} \quad a_{\beta\nu} = -\frac{1}{3} \frac{|C_A|^2 + |C_A'|^2 - |C_T|^2 - |C_T'|^2}{|C_A|^2 + |C_A'|^2 + |C_T|^2 + |C_T'|^2}$$

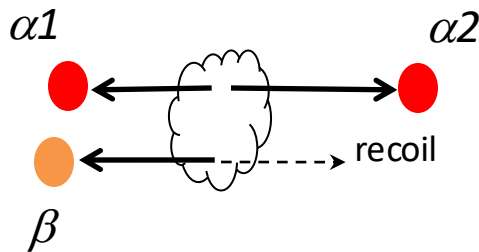
Enhancement from “Triple” Correlation

$\beta\nu$ angular correlation

$$\frac{-1}{3} \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu}$$

“Triple” correlation

$$-1 \left(\underbrace{\frac{(\vec{p}_e \cdot \hat{p}_\alpha)(\vec{p}_\nu \cdot \hat{p}_\alpha)}{E_e E_\nu} - \frac{1}{3} \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu}} \right)$$



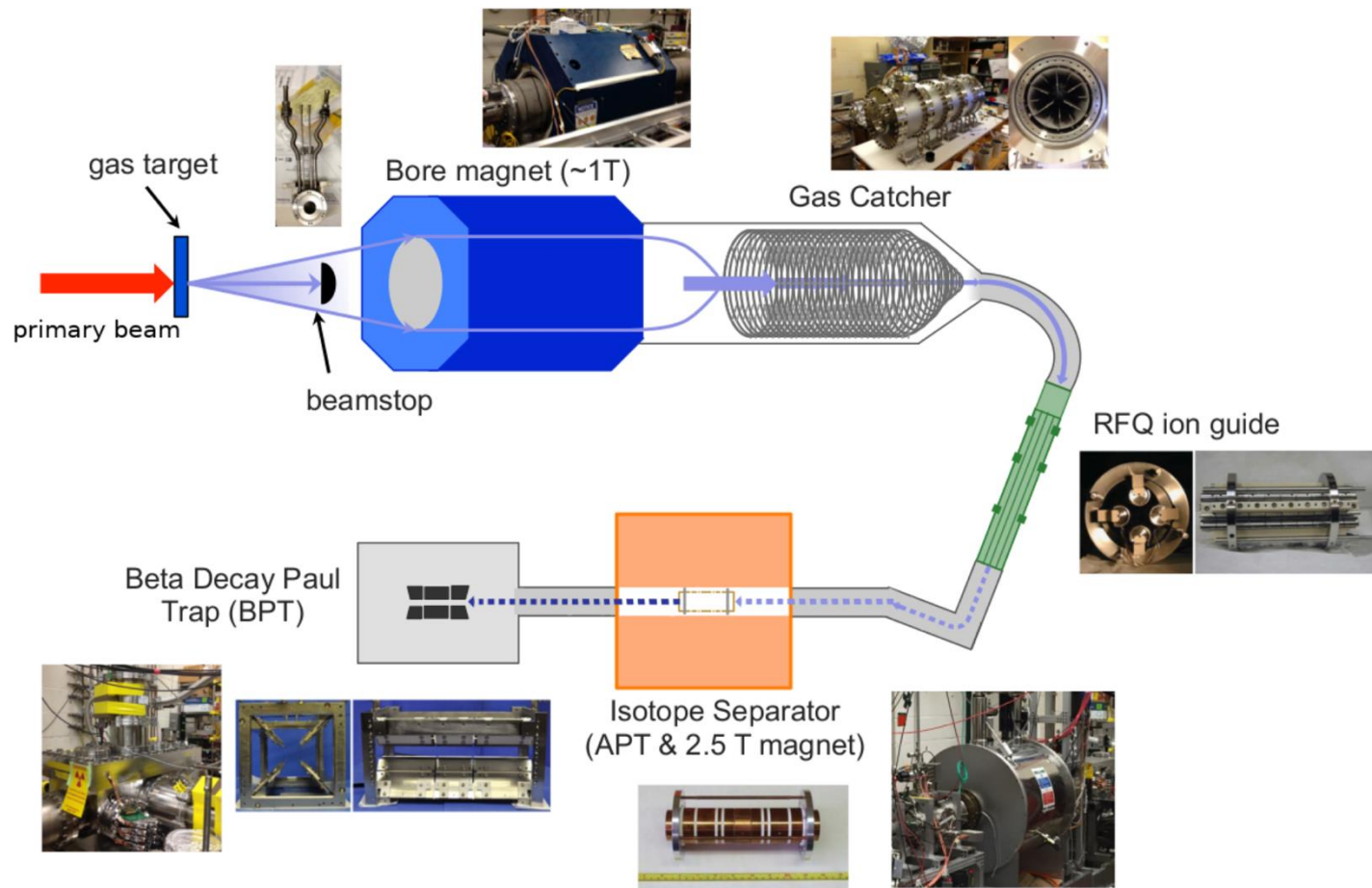
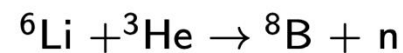
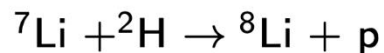
$$\hat{p}_e \cdot \hat{p}_\alpha \approx 1$$



$$\frac{2}{3} \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu}$$

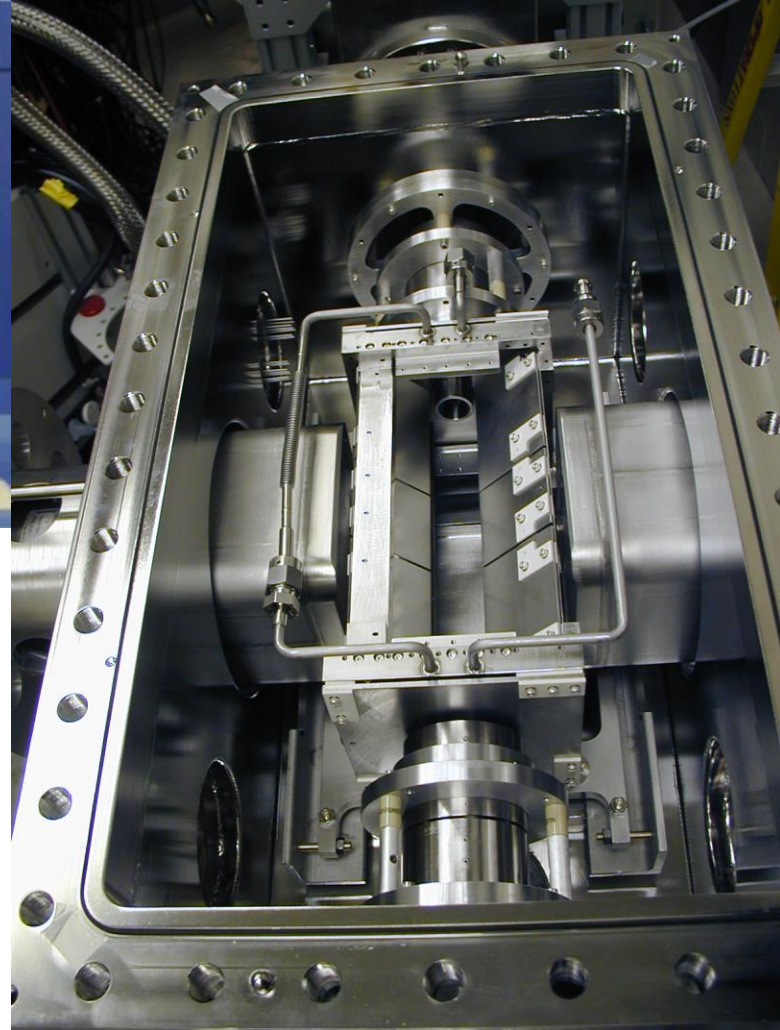
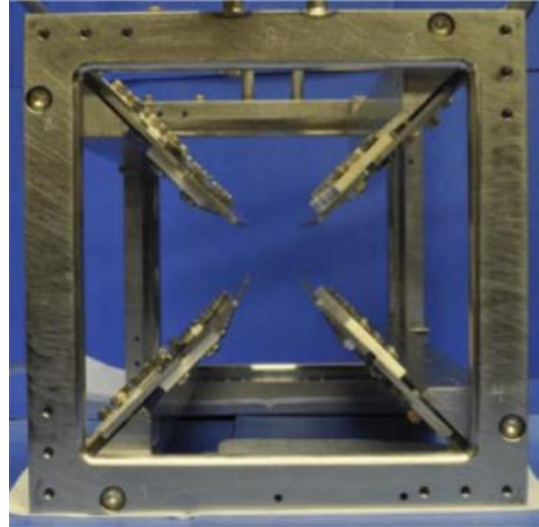
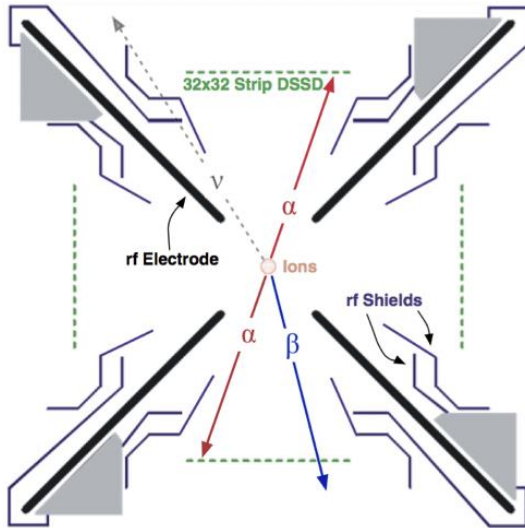
At leading order: $a_{\text{eff}} = 3a_{\beta\nu} = -1$

^8Li and ^8B Production and Delivery at Argonne National Laboratory ATLAS Facility



Pictures from Thesis of M.G. Sternberg (UChicago)

Beta-decay Paul Trap (BPT)



- Confine up to $\sim 10^6$ ions at once in $\sim 1 \text{ mm}^3$ volume for $> 200 \text{ sec}$
- Works for any element, accessible half-lives $> 50 \text{ ms}$
- Surrounded by four 32x32 Double-sided Silicon Strip Detectors (DSSDs) to measure energies of charged decay products (α 's and β 's for ^8B)

Decay Simulations

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

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

- Beta-decay Event Generator: energies and momenta of beta-decay products generated assuming Axial Vector, Tensor
- Includes recoil-order and radiative corrections, ion cloud size
- GEANT4: beta particles propagated through experimental geometry to account for scattering, DSSD detector response
- Sortcode: simulated data passed through same sortcode as experimental data, including same data cuts

$$d^7\Gamma = F_{\mp}(Z, E) \frac{G_o^2 \cos^2 \theta_c}{2(2\pi)^6} (E_0 - E)^2 p E dE d\Omega_e d\Omega_{\nu}$$

$$\times \left(g_1(E) + g_2(E) \frac{\mathbf{p}}{E} \cdot \hat{\mathbf{k}} + g_3(E) \left[\left(\frac{\mathbf{p}}{E} \cdot \hat{\mathbf{k}} \right)^2 - \frac{1}{3} \frac{\mathbf{p}^2}{E^2} \right] \right.$$

$$+ \delta_1(E, v^*, \tau_{J', J''}(L)) \frac{\hat{\mathbf{n}} \cdot \mathbf{p}}{E}$$

$$+ \delta_2(E, v^*, \tau_{J', J''}(L)) \hat{\mathbf{n}} \cdot \frac{\mathbf{p}}{E} \frac{\mathbf{p}}{E} \cdot \hat{\mathbf{k}}$$

$$+ \delta_3(E, v^*, \tau_{J', J''}(L)) \hat{\mathbf{n}} \cdot \hat{\mathbf{k}}$$

$$+ \delta_4(E, v^*, \tau_{J', J''}(L)) \hat{\mathbf{n}} \cdot \hat{\mathbf{k}} \frac{\mathbf{p}}{E} \cdot \hat{\mathbf{k}}$$

$$+ \frac{1}{10} \tau_{J', J''}(L) T^{(2)}(\hat{\mathbf{n}}) : \left\{ g_{10}(E) [\mathbf{p}/E, \mathbf{p}/E] \right.$$

$$+ g_{11}(E) [\mathbf{p}/E, \mathbf{p}/E] \frac{\mathbf{p}}{E} \cdot \hat{\mathbf{k}} + g_{11}(E) [\mathbf{p}/E, \hat{\mathbf{k}}]$$

$$+ g_{12}(E) [\mathbf{p}/E, \hat{\mathbf{k}}] \frac{\mathbf{p}}{E} \cdot \hat{\mathbf{k}} + g_{13}(E) [\hat{\mathbf{k}}, \hat{\mathbf{k}}]$$

$$+ g_{15}(E) [\hat{\mathbf{k}}, \hat{\mathbf{k}}] \frac{\mathbf{p}}{E} \cdot \hat{\mathbf{k}} + g_{16}(E) \left[\frac{\mathbf{p}}{E}, \frac{\mathbf{p}}{E} \times \hat{\mathbf{k}} \right]$$

$$+ g_{17}(E) \left[\hat{\mathbf{k}}, \frac{\mathbf{p}}{E} \times \hat{\mathbf{k}} \right] \left. \right\}$$

$$+ \delta_8(E, v^*, \tau_{J', J''}(L)) T^{(3)}(\hat{\mathbf{n}}) : [\mathbf{p}/E, \mathbf{p}/E, \hat{\mathbf{k}}]$$

$$+ \delta_9(E, v^*, \tau_{J', J''}(L)) T^{(3)}(\hat{\mathbf{n}}) : [\mathbf{p}/E, \hat{\mathbf{k}}, \hat{\mathbf{k}}]$$

$$+ \frac{1}{10} \omega_{J', J''}(L) T^{(4)}(\hat{\mathbf{n}}) : \{ g_{25}(E) [\mathbf{p}/E, \mathbf{p}/E, \mathbf{p}/E, \hat{\mathbf{k}}]$$

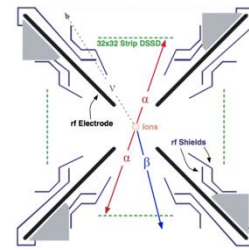
$$+ g_{26}(E) [\mathbf{p}/E, \mathbf{p}/E, \hat{\mathbf{k}}, \hat{\mathbf{k}}]$$

$$+ g_{27}(E) [\mathbf{p}/E, \hat{\mathbf{k}}, \hat{\mathbf{k}}, \hat{\mathbf{k}}] \}. \quad (53)$$

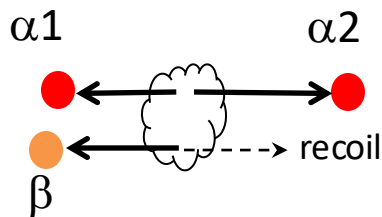
B. R. Holstein, Rev. Mod. Phys. 46, 789 (1974)

Alpha Energy Difference

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

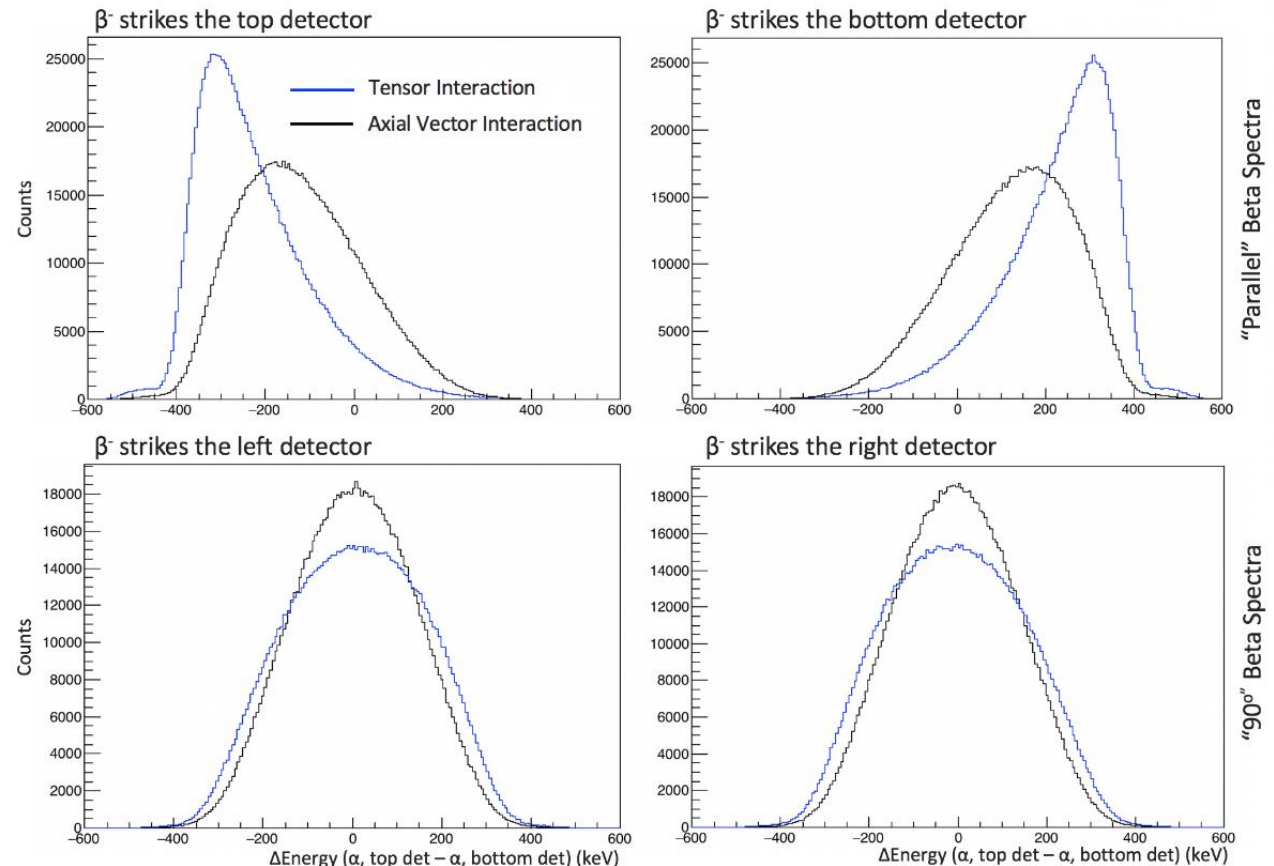


- Alpha energy difference when beta strikes same detector as an alpha (“parallel”) is most sensitive to difference between Tensor and Axial Vector simulations



Axial Vector: beta and neutrino preferentially emitted in opposite directions
 → Smaller nuclear recoil, smaller ΔE_α

Tensor: beta and neutrino preferentially emitted in same direction
 → Larger nuclear recoil, larger ΔE_α



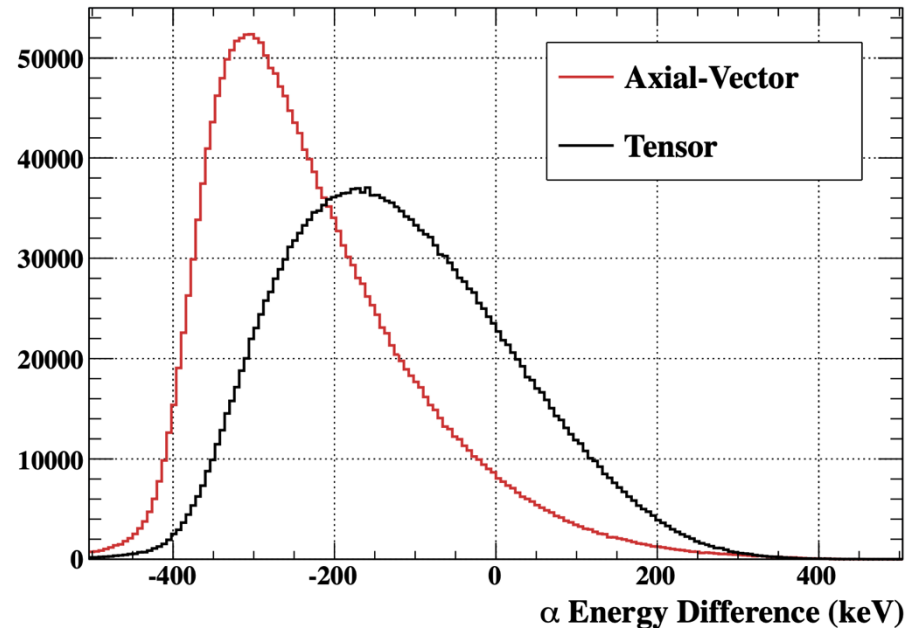
Fitting Alpha Energy Difference

- Generate template spectra for pure T and A
- Fit linear combination of spectra for $|C_T/C_A|^2$

$$N \propto \left(1 - \left|\frac{C_T}{C_A}\right|^2\right) N_{\text{GT}} + \left|\frac{C_T}{C_A}\right|^2 N_{\text{T}}$$

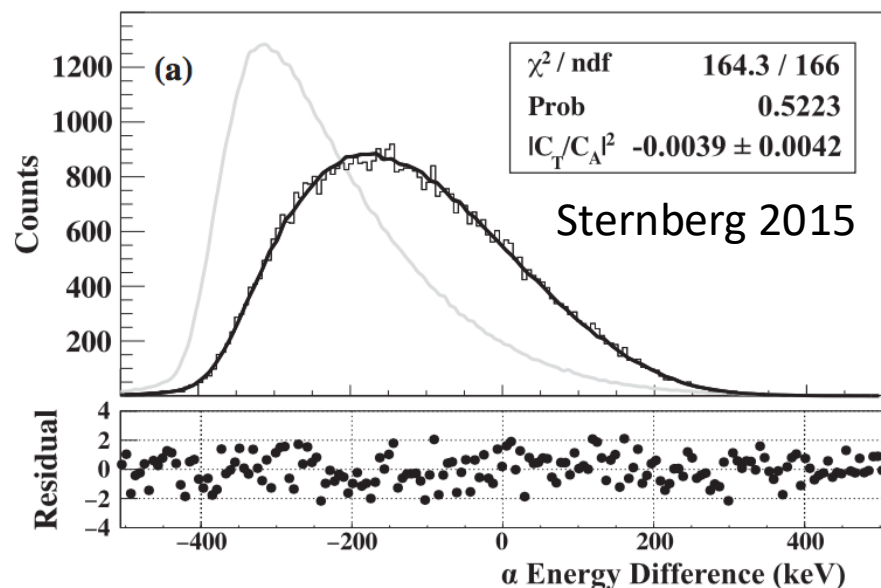
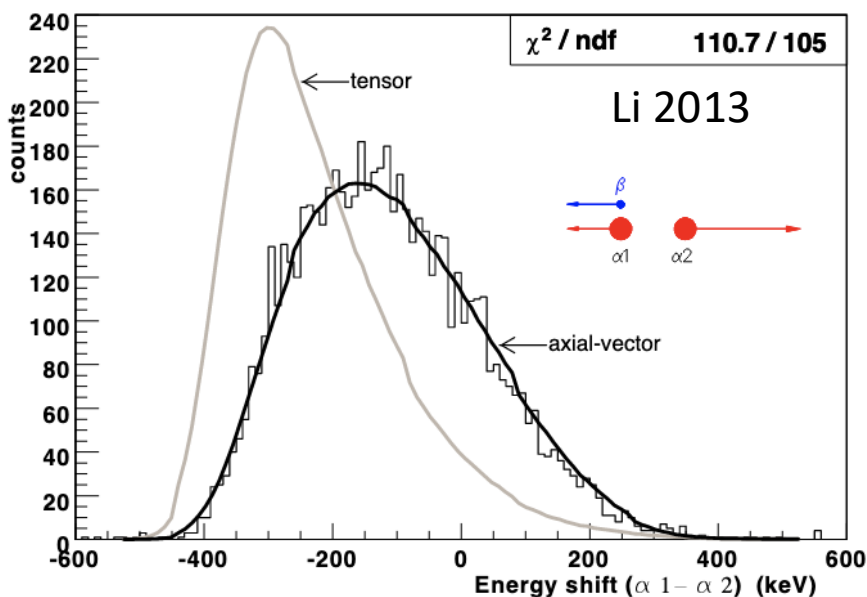
- Transform $|C_T/C_A|^2$ into $a_{\beta\nu}$

$$a_{\beta\nu} = -\frac{1}{3} \left(1 - 2 \left|\frac{C_T}{C_A}\right|^2\right) \quad \sigma_{a_{\beta\nu}} = \frac{2}{3} \left|\frac{C_T}{C_A}\right|^2$$



Our Collaboration's Previous Work on ^8Li

- α energy difference spectrum for parallel α - α - β “triples” fit varying ratio of exotic Tensor and Standard Model Axial Vector coupling constants and scaling factor
- 2013 PRL (G. Li et al.): $a_{\beta v} = -0.3307(90)$
- 2015 PRL (M. G. Sternberg et al.): $a_{\beta v} = -0.3342(39)$



Improvements for ^8Li Run in 2016

- 10x statistics compared to 2015 PRL

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

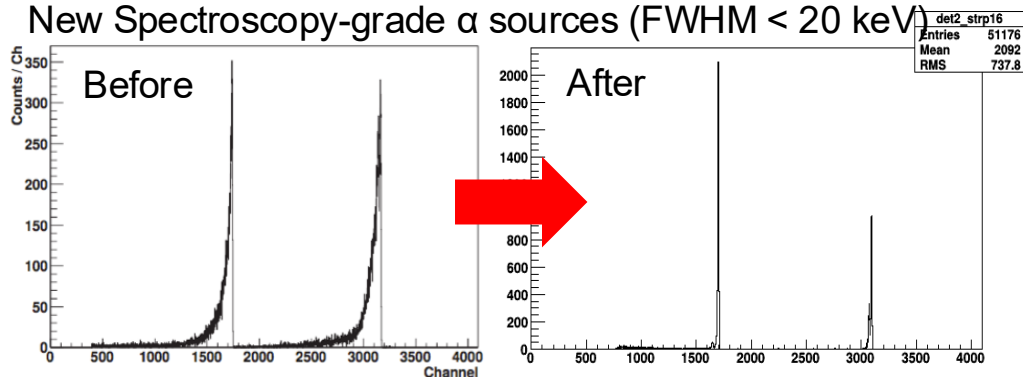
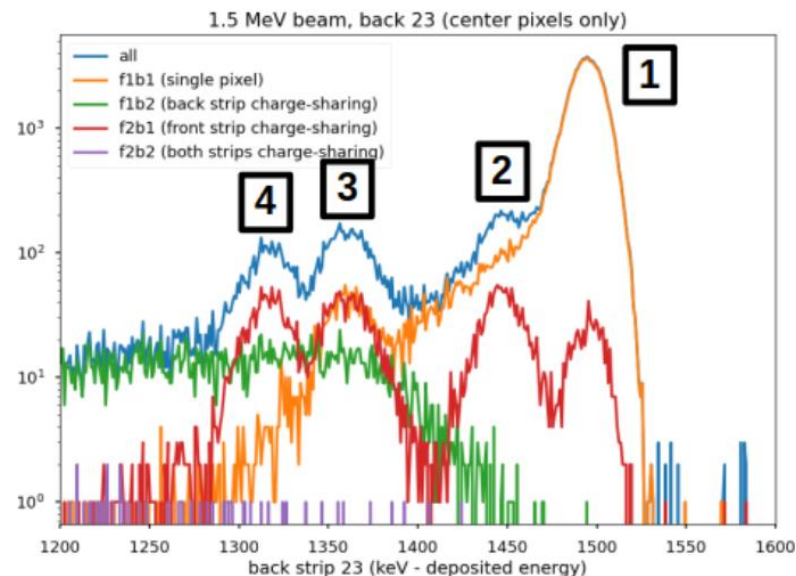
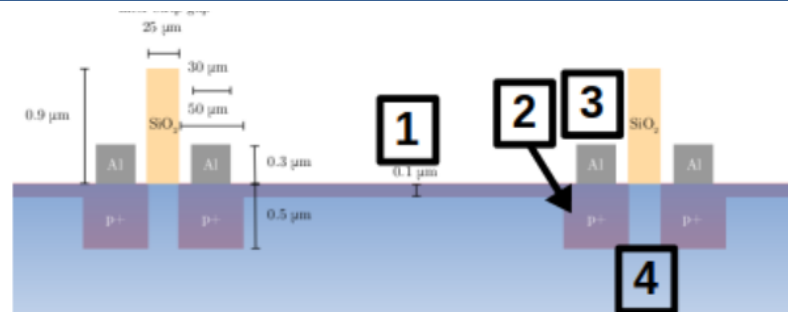


TABLE I. Dominant sources of systematic uncertainty at 1σ .

Source	$\Delta C_T/C_A ^2$
Energy calibration Better α sources, more points	0.0007
~~Dead layer thickness~~	~~0.0008~~
α line shape Accounting for all DSSD effects	0.0009
β scattering Geant is better & we have plastics	0.0010
~~Backgrounds Longer trap empty measurements~~	~~0.0011~~
Recoil and radiative	0.0026
Nondominant systematics	0.0007
Total	0.0043



2021 detector characterization experiment with alpha beam (L. Varriano)

Improvements from New Recoil-Order Term Calculations

- Symmetry-Adapted No Core Shell Model (SA-NCSM) calculations reduced uncertainties on recoil-order terms (b , d , j_2 , j_3) by exploiting correlation with ^8Li ground state quadrupole moment
- Recoil and radiative systematic uncertainty $0.0026 \rightarrow 0.0015^*$

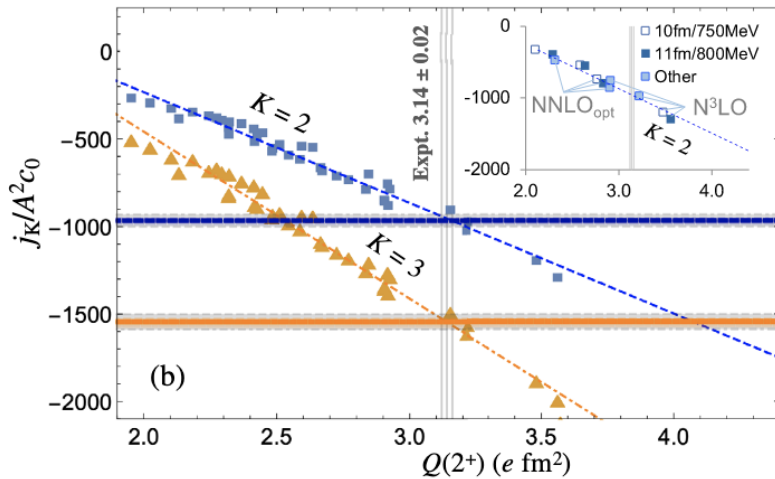
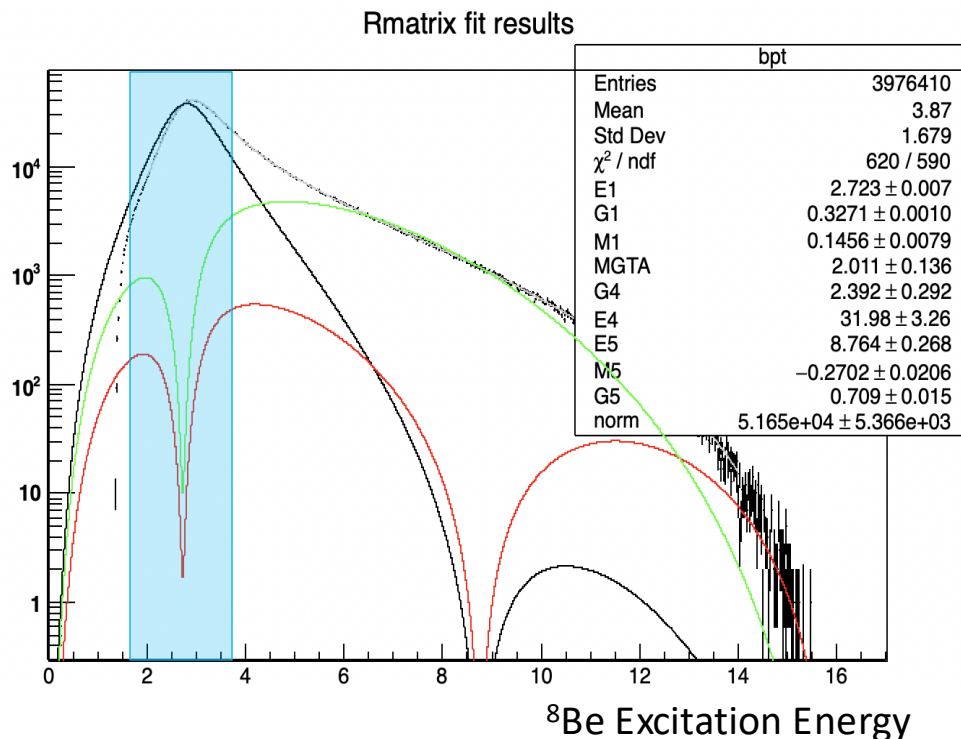


TABLE I. The recoil-order terms from SA-NCSM. Results for the 2_1^+ $j_{2,3}/A^2 c_0$ and d/Ac_0 are based on the correlation to $Q(2_{\text{g.s.}}^+)$; all other calculations use NNLO_{opt} and have error bars from variations in $\hbar\Omega$ by 5 MeV and in model-space sizes up to $N_{\text{max}} = 16$ (12) for $j_{2,3}/A^2 c_0$ (d/Ac_0 and b/Ac_0).

	$j_2/A^2 c_0$	$j_3/A^2 c_0$	d/Ac_0	b/Ac_0
2_1^+	-966 ± 36	-1546 ± 44	10.0 ± 1.0	6.0 ± 0.4
2_2^+ (new)	-10 ± 10	-80 ± 30	-0.5 ± 0.5	3.7 ± 0.4
2_3^+ (doublet 1)	12 ± 5	-60 ± 15	0.3 ± 0.2	3.8 ± 0.2
2_4^+ (doublet 2)	11 ± 3	-65 ± 11	0.2 ± 0.2	3.8 ± 0.2

Complication from New Recoil-Order Term Calculations

^8Be
Excitation Levels
<u>$2+ 16.92 \text{ MeV}$</u>
<u>$2+ 16.63 \text{ MeV}$</u>
$4+ 11.35 \text{ MeV}$
<u>$2+ \sim 10 \text{ MeV}$</u>
??????
<u>$2+ 3.03 \text{ MeV}$</u>
$0+ 0.0 \text{ MeV}$



- $2+$ State at $\sim 3 \text{ MeV}$ (main peak)
- Doublet $2+$ State at $\sim 16 \text{ MeV}$
- $\sim 10 \text{ MeV}$ "Intruder State"

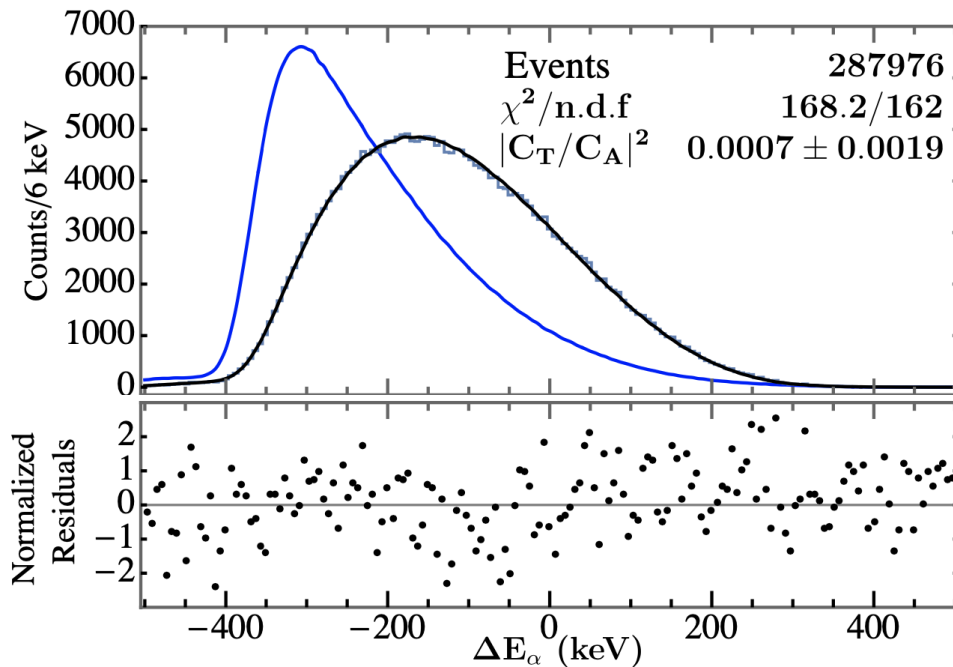
- *Ab Initio* calculations give new, more precise values for recoil-order terms to each state populated in beta decay but suggest existence of "intruder" $2+$ state; experimental data can be fit well with or without "intruder"

Experiment and Theory PRLs on ^8Li Results Published Back-to-Back

- First improvement on uncertainty since 1963 ^6He measurement

$$a_{\beta\nu} = -0.3325 \pm 0.0013_{\text{stat}} \pm 0.0019_{\text{sys}}$$

M. T. Burkey *et al.*, PRL 128, 202502 (2022)



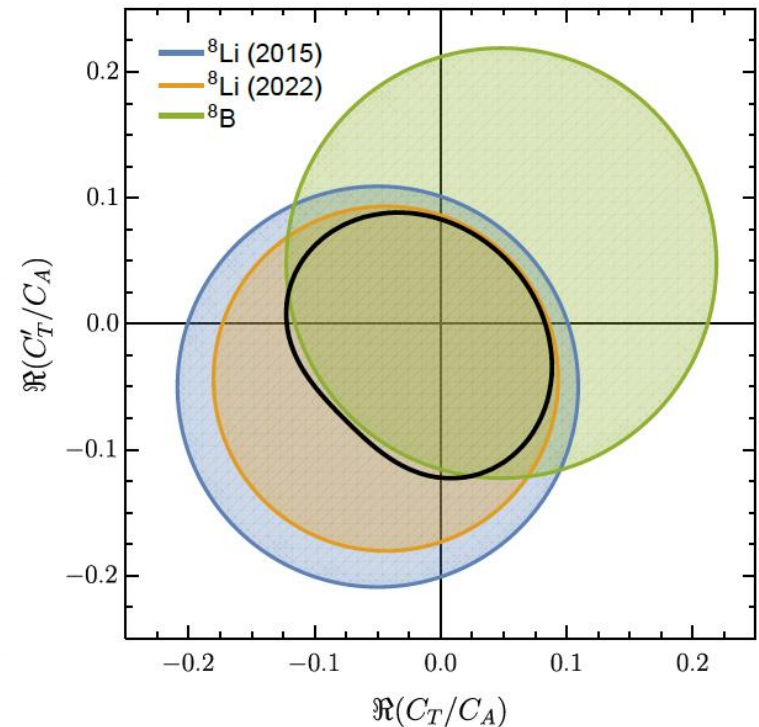
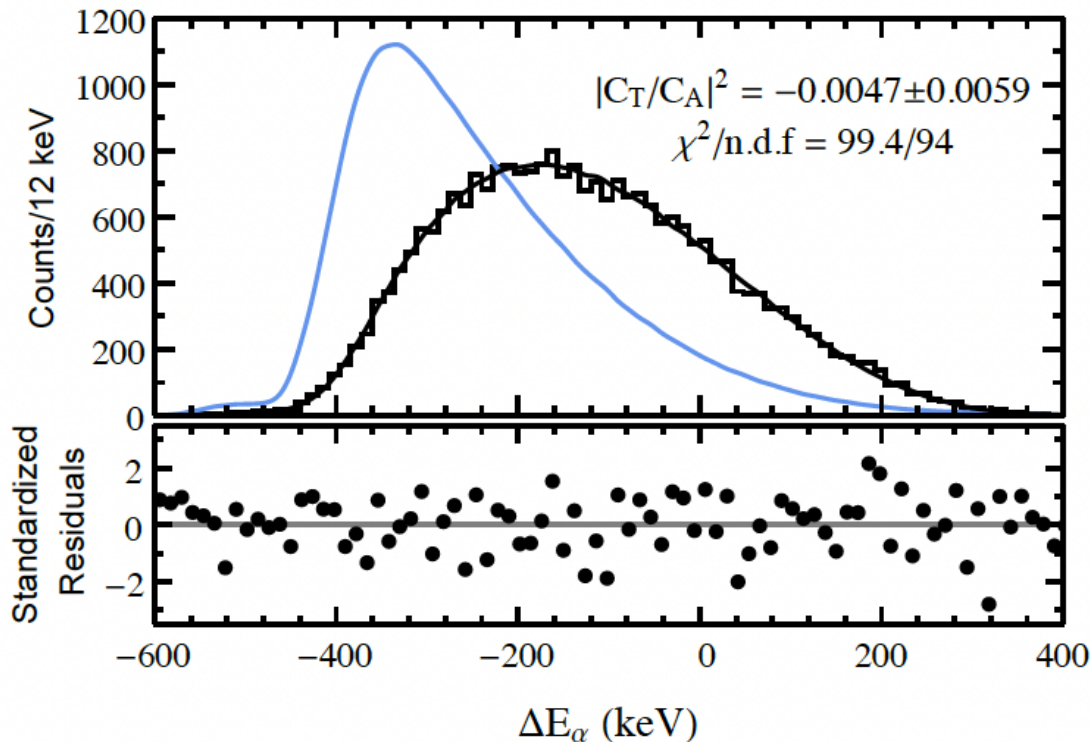
G. H. Sargsyan *et al.*, PRL 128, 202503 (2022)

TABLE I. β recoil-order terms from SA-NCSM. Results for the 2_1^+ $j_{2,3}/A^2c_0$ are from Eq. (2); all other calculations use NNLO_{opt} and have error bars from variations in $\hbar\Omega$ by 5 MeV and in model-space sizes up to $N_{\text{max}} = 16$ (12) for $j_{2,3}/A^2c_0$ (d/Ac_0 and b/Ac_0).

	j_2/A^2c_0	j_3/A^2c_0	d/Ac_0	b/Ac_0
2_1^+	-962 ± 56	-1547 ± 80	10.0 ± 1.0	6.0 ± 0.4
2_2^+ (new)	-10 ± 10	-80 ± 30	-0.5 ± 0.5	3.7 ± 0.4
2_3^+ (doublet 1)	12 ± 5	-60 ± 15	0.3 ± 0.2	3.8 ± 0.2
2_4^+ (doublet 2)	11 ± 3	-65 ± 11	0.2 ± 0.2	3.8 ± 0.2

^8B Results from 2014 Experiment also Published in PRL

- First precision measurements of a mirror-nucleus pair, demonstrates a new pathway for increasing the precision of exotic current searches
- Follows the “ $\tilde{a}$ ” prescription to assign limits on C_T and C'_T :
$$\tilde{a}_{\beta\nu} = \frac{a_{\beta\nu}}{1 \pm b_F \langle m_e/E_e \rangle}$$



Improvements for ^8B in 2019 Experiment

- Statistical uncertainty improved by over factor of 2 from previous ^8B data set, same systematic improvements as most recent ^8Li run
- Same systematic improvements as ^8Li and new SA-NCSM performed for ^8B to reduce recoil and radiative uncertainty from 0.0048 $\rightarrow$ 0.0023

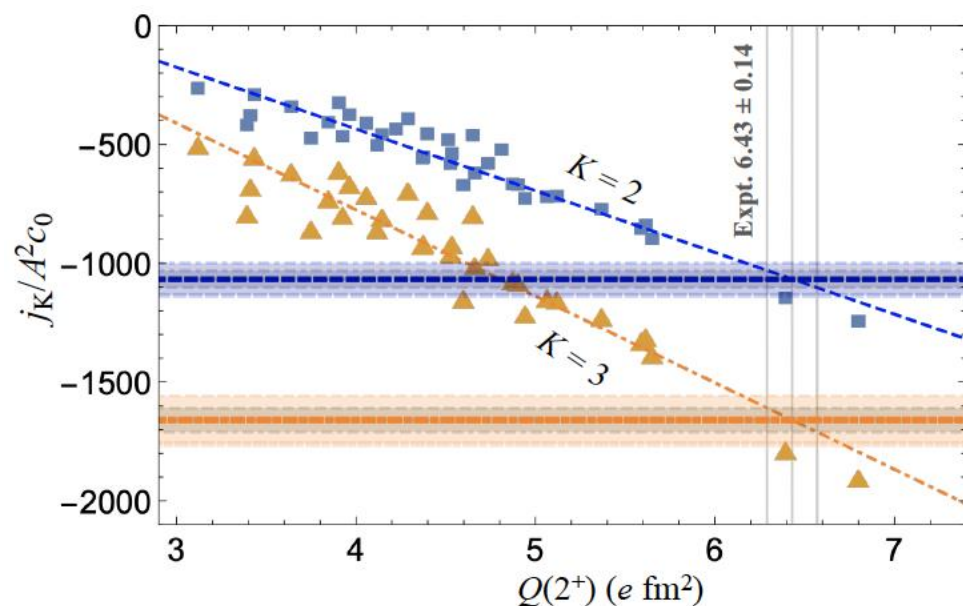


TABLE II. Summary of dominant systematic uncertainties on $|C_T/C_A|^2$ at 1σ .

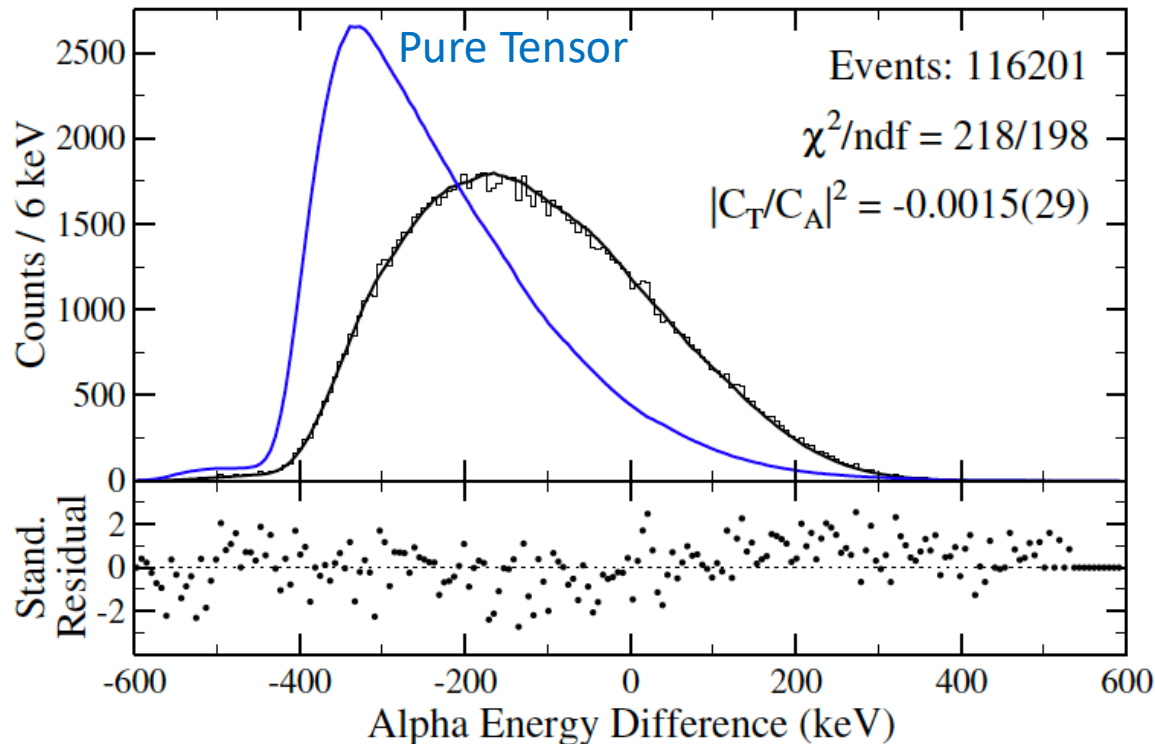
Source		Uncertainty
Theory	Intruder state ^a	0.0002
	Recoil and radiative terms	0.0021
Experiment	Energy calibration	0.0008
	Detector line shape	0.0010
	Data cuts	0.0011
	β scattering	0.0010
	Ion cloud size	0.0003
Total		0.0031

^a Added linearly

Tensor Limit from ^8B 2019

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

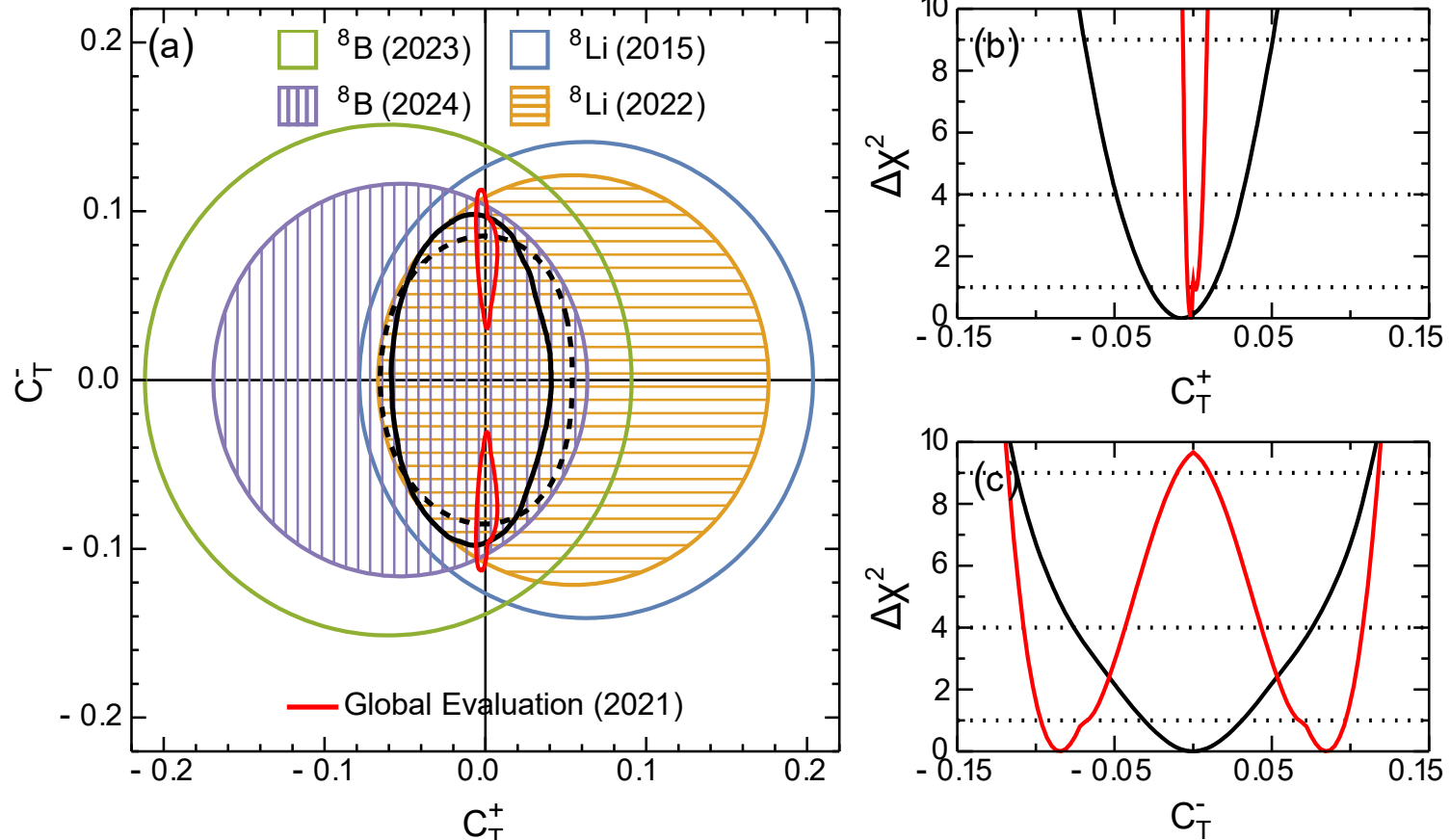
- α energy difference spectrum for parallel α - α - β “triples” fit varying ratio of exotic Tensor and Standard Model Axial Vector coupling constants and scaling factor
- $a_{\beta v} = -0.3345 \pm 0.0019_{\text{stat}} \pm 0.0021_{\text{sys}}$ of similar precision to ^8Li Tensor current limit



Comparison with Global Evaluation

$$\tilde{a}_{\beta\nu} = \frac{a_{\beta\nu}}{1 \pm b_F \langle m_e/E_e \rangle}$$

- Mass 8 joint limit consistent with Standard Model for right-handed C_T^- while current global evaluation favors non-zero value

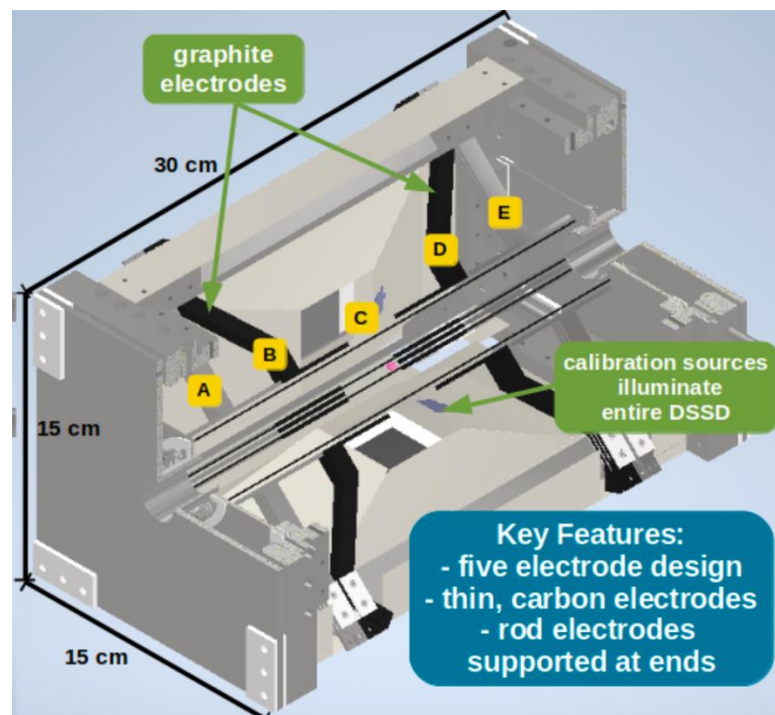
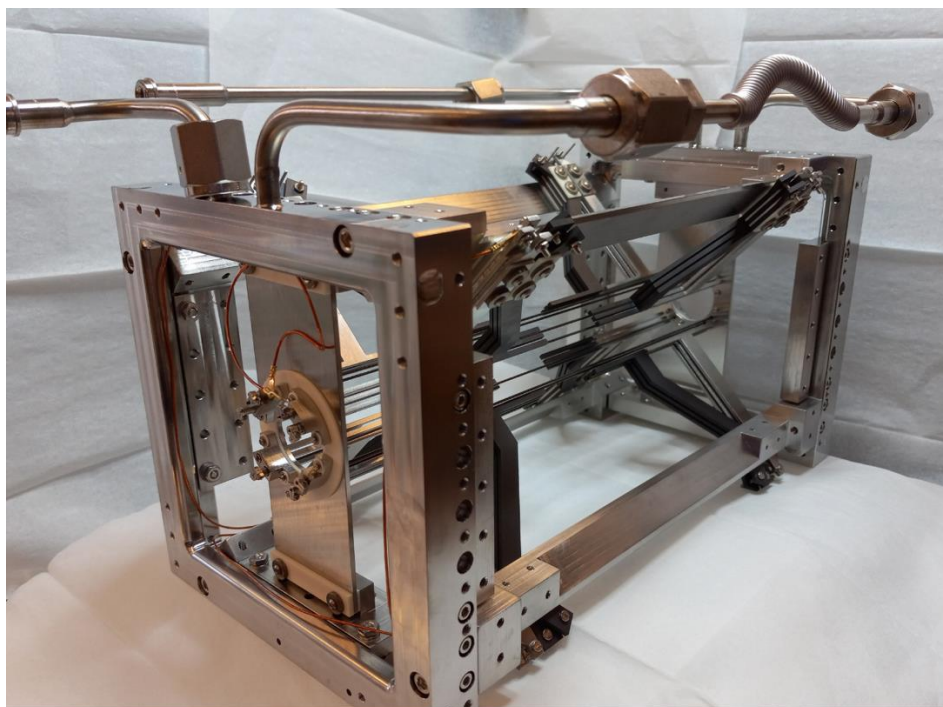


B. Longfellow *et al.*, Phys. Rev. Lett. 132, 142502 (2024)

Global Evaluation: A. Falkowski, M. Gonzalez-Alonso, and O. Naviliat-Cuncic, J. High Energy Phys. 2021, 126 (2021)

Next Steps for Mass-8 Tensor Limits: BPT Mk IV

- ^8Li run with new BPT trap design to lower β scattering by factor of 4 completed summer 2022, 35% higher statistics than 2016 ^8Li experiment
- Some ideas to improve ^8B statistics: better molecule breakup, add water or SF_6 to gas catcher so ^8B is incorporated across smaller range of molecules, implant all molecules into external foil



Issues with Holstein's Formulation

Many typos....

$$\epsilon_{u,v} = (-)^{u-v} [4u(u+1)(2u+1)/(2u-1)(2u+3)]^{1/2} \times W(u1u3; v2)$$

$$= -2 \frac{(10)^{1/2}}{35} \left\{ \begin{array}{l} (2u-1)^{-1} \left[\frac{u(u-1)(2u-3)}{2u+3} \right]^{1/2} \\ \quad u = v+1 \\ \left[\frac{3(u+2)(u-1)}{2(2u-1)(2u+3)} \right]^{1/2} \\ \quad u = v \\ (2u+3)^{-1} \left[\frac{u(u+2)(2u+5)}{2u-1} \right]^{1/2} \\ \quad u = v-1 \end{array} \right.$$

$$\epsilon_{u,v} = -\frac{2}{5} \sqrt{\frac{10}{7}} \left\{ \begin{array}{l} (2u-1)^{-1} \left[\frac{(u-1)(u+1)(2u-3)}{2u+3} \right]^{1/2} \\ \left[\frac{3(u+2)(u-1)}{2(2u-1)(2u+3)} \right]^{1/2} \\ (2u+3)^{-1} \left[\frac{u(u+2)(2u+5)}{2u-1} \right]^{1/2} \end{array} \right.$$

- $\tau_{u,v}$ not defined, but $\tau_{J',J''}(L)$ is defined
- Data suggests this term is zero...

$$F_{25}(E, u, v, s)$$

$$= \tau_{u,v} \text{Rec}_1^* j_3(35E^2/4M^2)$$

$$F_{26}(E, u, v, s)$$

$$= \tau_{u,v} \text{Rec}_1^* j_3[(35EE_0 - 35E^2)/2M^2]$$

$$F_{27}(E, u, v, s)$$

$$= \tau_{u,v} \text{Rec}_1^* j_3[(35E_0^2 - 70EE_0 + 35E^2)/4M^2].$$

- $\epsilon_{u,v}$ affects j_3 – large effect on simulated ^8B and ^8Li spectra!
- Similar spin coupling issues found by TRINAT
 - <https://trinat.triumf.ca/documents/old-report-on-recoil-order-corrections>
- Data suggests that Holstein's simplified rather than general expression is correct...

Electromagnetic Corrections

Having obtained the “best values” for the shape factors, we proceed to interpret them *vis à vis* the weak magnetism form factor. We begin by recalling that the spectral function $h_1(E)$ which should be used with the Behrens-Jänecke Fermi function is obtained by combining eqs. (4), (13) and (18). This gives

$$h_1(E) = c_1^2 \left\{ 1 + \frac{2}{9} \frac{c_2}{c_1} (11m_e^2 + 20EE_0 - 20E^2 - 2m_e^2 E_0/E) \right. \\ \left. - \frac{c_2}{c_1} \left(\frac{9}{2} \left(\frac{\alpha Z}{R} \right)^2 \mp \frac{4}{3} \frac{\alpha Z E_0}{R} \pm \frac{22}{3} \frac{\alpha Z E}{R} \right) + \frac{\sqrt{10}}{6} \frac{\alpha Z}{MR} \left(2 \frac{b}{c_1} \pm \frac{d^I}{c_1} + \frac{d^{II}}{c_1} \pm 1 \right) \right. \\ \left. - \frac{2}{3} \frac{E_0}{M} \left(1 + \frac{d^I}{c_1} \pm \frac{d^{II}}{c_1} \pm \frac{b}{c_1} \right) + \frac{2}{3} \frac{E}{M} \left(5 \pm 2 \frac{b}{c_1} \right) \right. \\ \left. - \frac{m_e^2}{3ME} \left[2 + \frac{d^I}{c_1} \pm \frac{d^{II}}{c_1} \pm \frac{2b}{c_1} - \frac{h}{c_1} (E_0 - E)/M \right] \right\}.$$

Blue: Spectral Function, Red: EM correction, Green: “Induced” EM

- Electromagnetic corrections depend on which Fermi function is used
- Corrections truncated at order $\alpha Z R$
- Report by Towner showed that this truncation can lead to shifts in a of up to 1%!
- Induced EM corrections are not included in Holstein’s RMP

- Calaprice and Holstein [https://doi.org/10.1016/0375-9474\(76\)90593-5](https://doi.org/10.1016/0375-9474(76)90593-5)

Theory Need

- Consistent formulation in a modern framework
 - Control order of truncation as precision of experiment improves
- Include EM corrections, including effect on form factors
 - Higher order corrections are dropped by Holstein, but Towner showed these may have a large impact on correlation terms
- Radiative Correction for triple correlation
 - Large systematic remains from incomplete theory for radiative correction to triple correlation term in beta-delayed particle emission

Collaboration and Acknowledgements (2019 ⁸B)

Special thanks to collaborators: B. Longfellow, A. T. Gallant, G. H. Sargsyan, T. Y. Hirsh, M. T. Burkey, G. Savard, N. D. Scielzo, L. Varriano, M. Brodeur, D. P. Burdette, J. A. Clark, D. Lascar, K. D. Launey, P. Mueller, D. Ray, K. S. Sharma, A. A. Valverde, G. L. Wilson, and X. L. Yan

Prepared by LLNL under Contract DE-AC52-07NA27344





Disclaimer

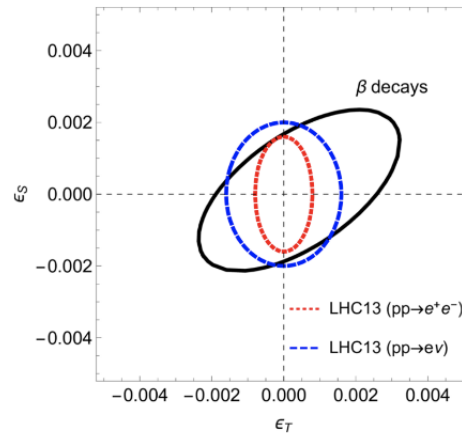
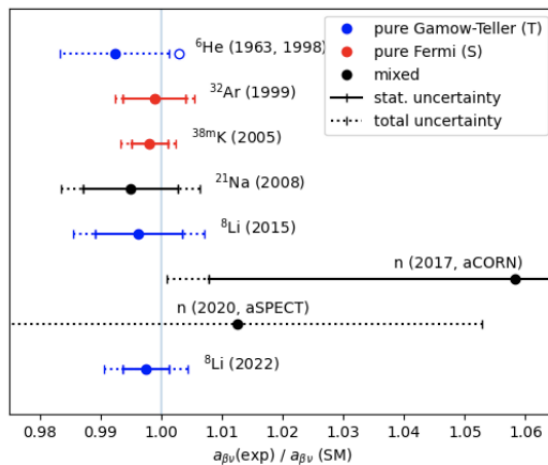
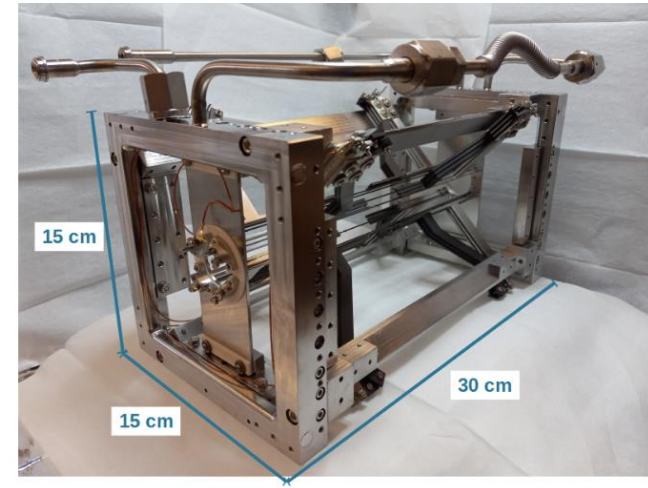
This document was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor Lawrence Livermore National Security, LLC, nor any of their employees makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or Lawrence Livermore National Security, LLC. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or Lawrence Livermore National Security, LLC, and shall not be used for advertising or product endorsement purposes.

Summary and Outlook

- Beta decay of ^8Li and ^8B can probe physics beyond the Standard Model and contribute to solar neutrino astrophysics
- Two newest ^8Li PRLs (experiment and theory): first improvement to Tensor limit uncertainty since 1963
- First two ^8B Tensor limits published in PRL: demonstrate a novel method for high-precision measurements of mirror decays to provide stringent tests of exotic currents
- BPT provides a backing-free method to determine the ^8B neutrino spectrum: resolves discrepancy between Winter/Bhattacharya and Kirsebom/Roger results for FSD maximum; will be the recommended ^8B neutrino spectrum for next generation of solar neutrino experiments

Limits on BSM Physics from Nuclear Decays

Nuclear physics
experimental
setups $\sim 10^5$ times
smaller than LHC



β -decays currently competitive with LHC results.

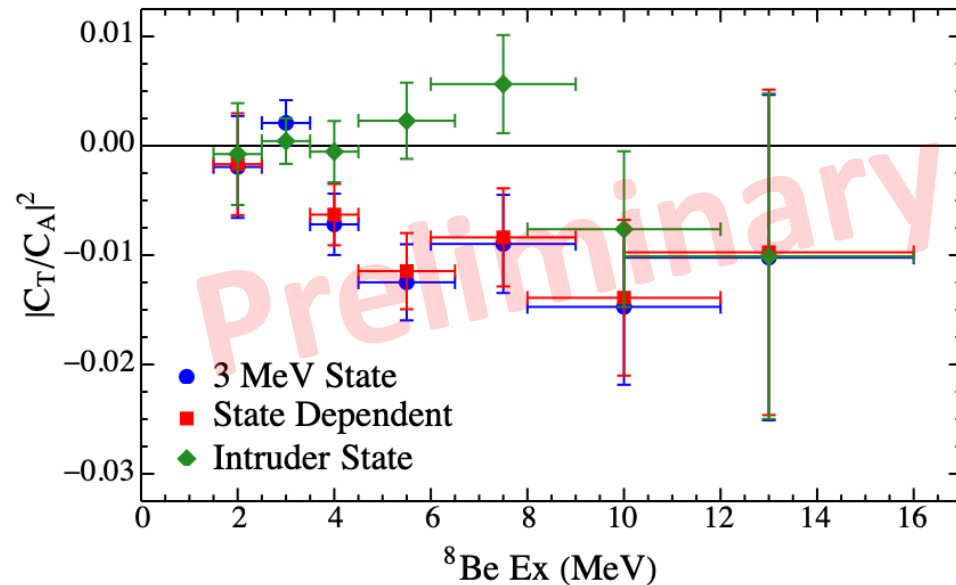
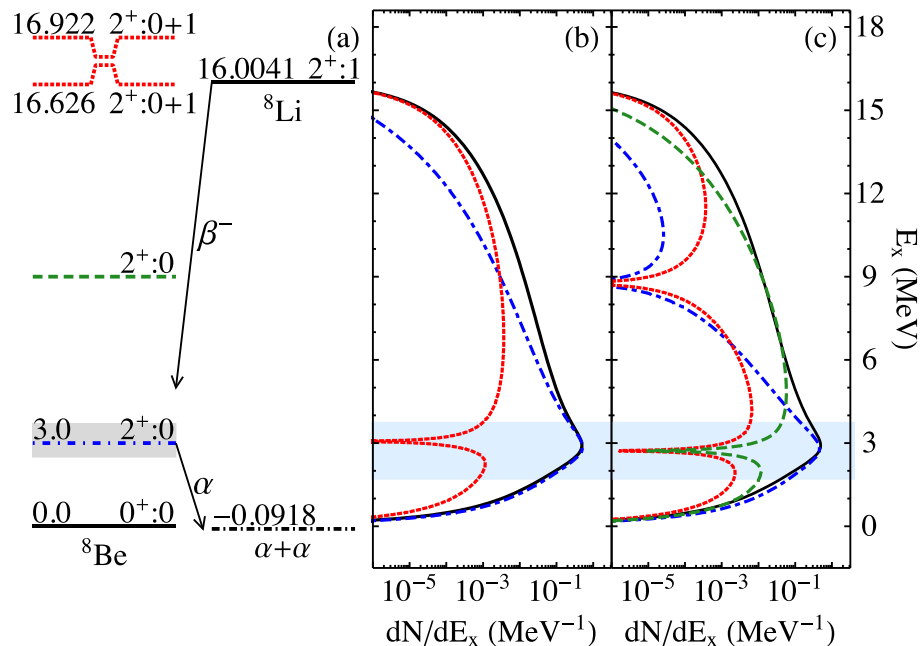
- A. Falkowski, M. González-Alonso, and O. Naviliat-Cuncic, J. High Energ. Phys. 2021, 126 (2021).

But can yield
competitive physics
results

Next Steps for Mass-8 Tensor Limits: Intruder?

R-Matrix fits provide equally good fits with and without intruder state

Currently only taking narrow energy region around 3 MeV peak; intruder existence is systematic and reduces statistics

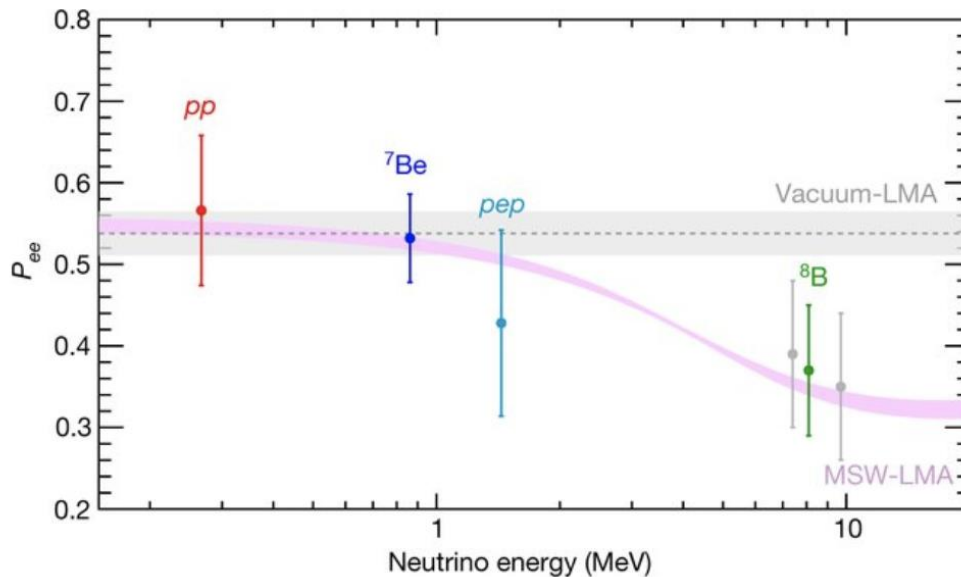


Excitation energy and state dependent analysis of $|C_T/C_A|^2$ may provide some hint at existence of this state

Solar Neutrino Astrophysics

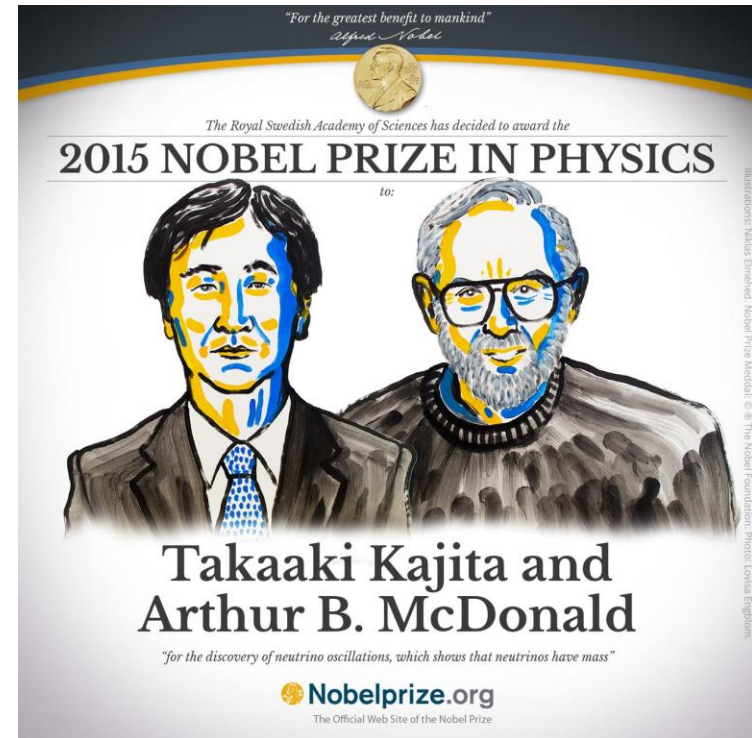
- Neutrinos produced in reactions in the Sun are initially electron neutrinos, oscillate between neutrino flavors (electron, muon, and tau) [governed by mixing angle; enhanced in matter – MSW effect]

Electron Neutrino Survival Probability



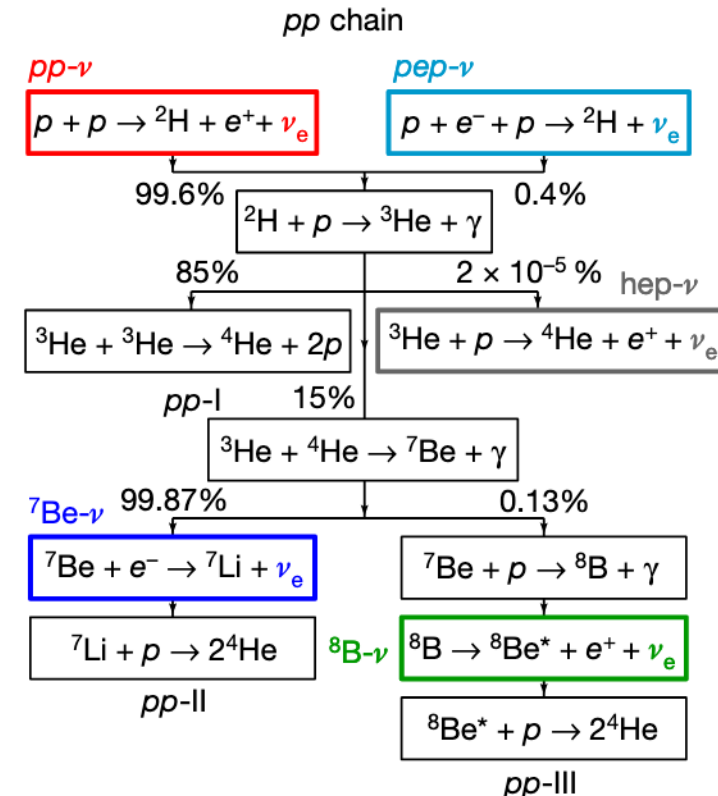
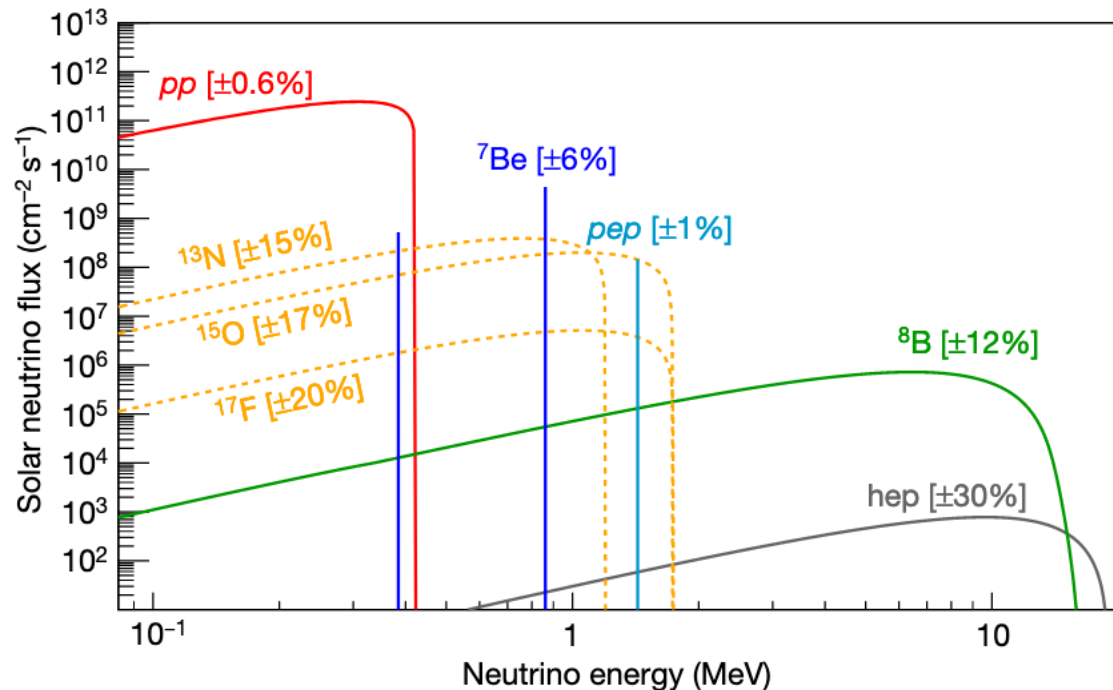
LMA: large mixing angle

MSW: Mikheyev–Smirnov–Wolfenstein



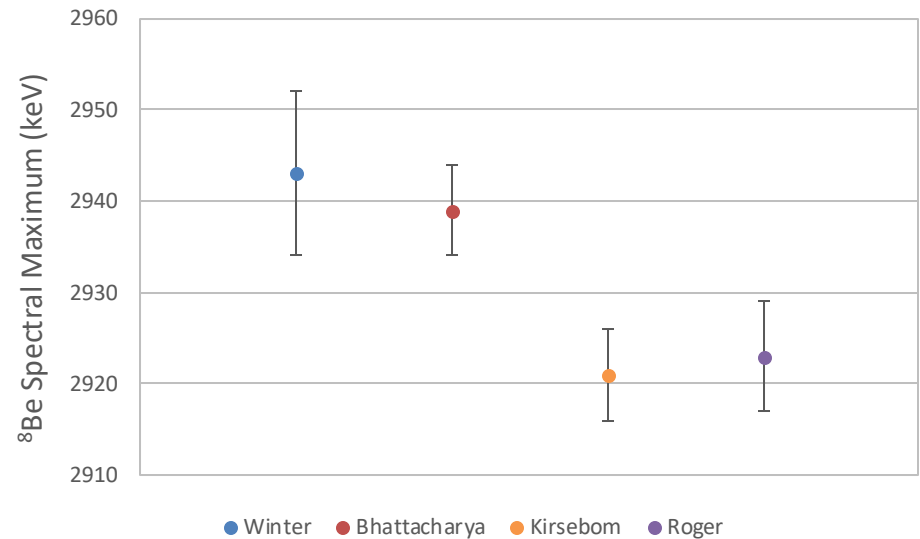
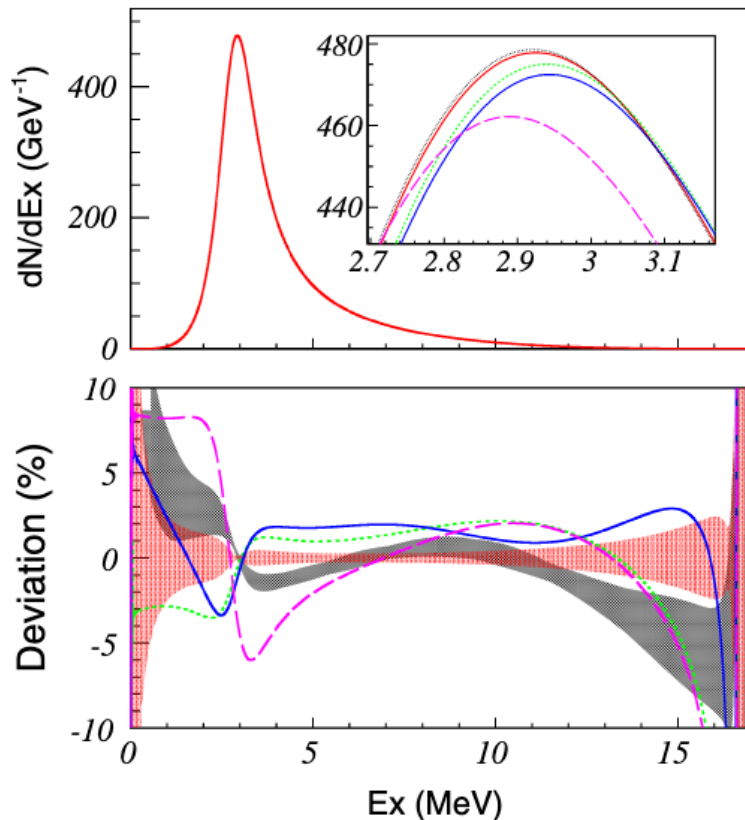
^8B Solar Neutrinos

- ^8B beta decay provides high energy solar neutrinos detected by SNO, Super-K, Borexino; shape of unoscillated neutrino energy spectrum important model input



^8Be Final State Distribution (FSD) $E_x = E_{\alpha 1} + E_{\alpha 2} - 91.8 \text{ keV} - E_{\text{recoil}}$

- Unoscillated neutrino energy spectrum calculated from FSD; there are inconsistent results for spectral maximum from previous experiments

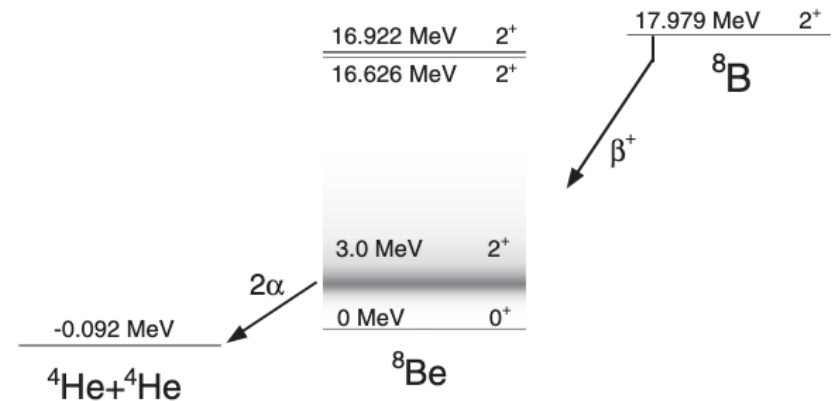
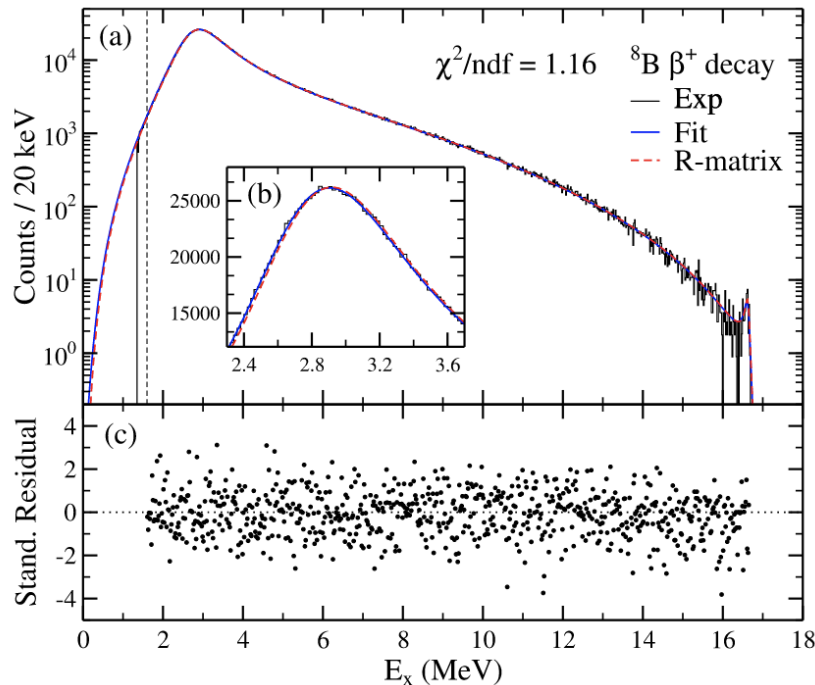


W. T. Winter *et al.*, Phys. Rev. C 73, 025503 (2006)
M. Bhattacharya *et al.*, Phys. Rev. C 73, 055802 (2006)
O. S. Kirsebom *et al.*, Phys. Rev. C 83, 065802 (2011)
T. Roger *et al.*, Phys. Rev. Lett. 108, 162502 (2012)

BPT Measurement of FSD

$$E_x = E_{\alpha 1} + E_{\alpha 2} - 91.8 \text{ keV} - E_{\text{recoil}}$$

- First measurement of FSD using trapped ions; no energy loss in implant foil, beta summing
- Standard R-matrix fit with broad 2^+ at 3 MeV and 2^+ isospin doublet at 16.6, 16.9 MeV, background 2^+ with energy fixed at 37 MeV also included



$$N(E) = \frac{Nt_{1/2}}{\pi B} f_{\beta}(Q - E) P_c(E) \frac{\left| \sum_{\lambda} \frac{g_{\lambda, F} \gamma_{\lambda c}}{E_{\lambda} - E} \right|^2 + \left| \sum_{\lambda} \frac{g_{\lambda, GT} \gamma_{\lambda c}}{E_{\lambda} - E} \right|^2}{\left| 1 - [S_c(E) - B_c + iP_c(E)] \sum_{\lambda} \frac{\gamma_{\lambda c}^2}{E_{\lambda} - E} \right|^2}$$

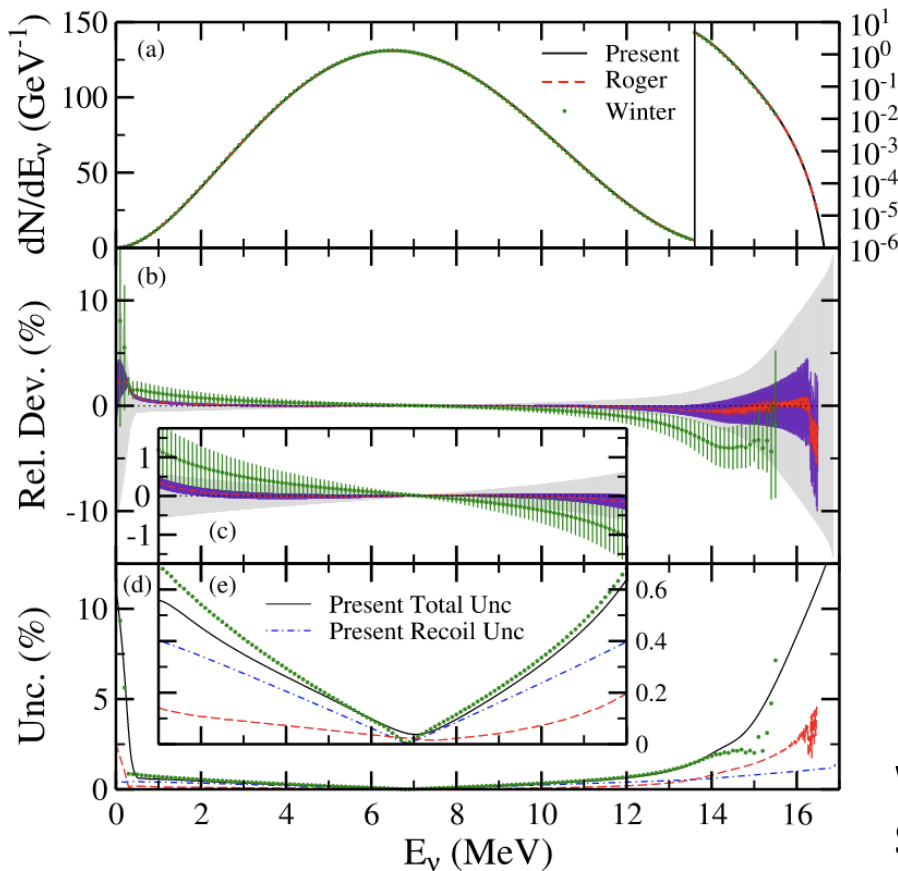
- Maximum of 2918(8) keV in agreement with Kirsebom/Roger rather than Winter/Bhattacharya

Neutrino Spectrum Calculation

$$Q = 16.958 \text{ MeV}$$

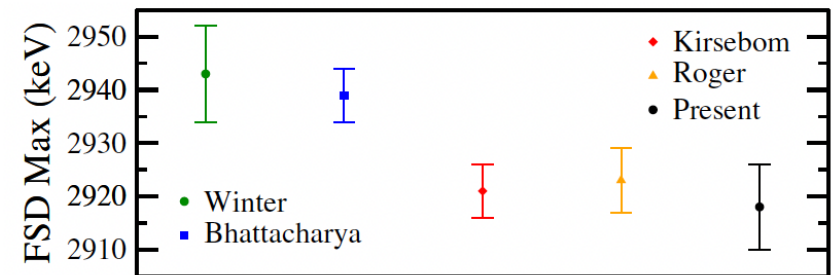
$$E_0 = Q + m_e$$

- Integrate over allowed energies weighted by FSD; F is Fermi function, R is radiative correction, C is recoil-order correction



$$\frac{dN}{dE_\nu} \sim p_\beta E_\nu^2 (E_0 - E_\nu) F(-Z, E_\beta) R(E_\nu, E_0) C(E_\nu, E_0)$$

$$E_\nu = E_0 - E_\beta$$



B. Longfellow *et al.*, Phys. Rev. C
107, L032801 (2023)

Will be the new recommended ^8B spectrum for Solar neutrinos