Precision Measurements of ^{8}Li and ^{8}B Beta Decay: Tensor Current Limits and Solar Neutrinos

UW INT Workshop “New physics searches at the precision frontier”

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Hamiltonian for Beta Decay

Fermi

$$H_\beta = (\bar{p}n)\left[\bar{e}\left(C_S + C_s'\gamma_5\right)\nu\right]$$ Scalar

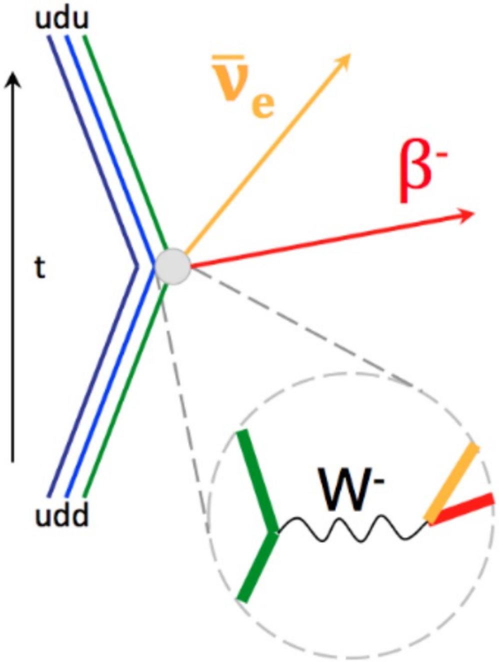
$$+ (\bar{p}\gamma_\mu n)\left[\bar{e}\gamma_\mu\left(C_V + C_V'\gamma_5\right)\nu\right]$$ Vector

Gamow-Teller

$$+ \frac{1}{2}(\bar{p}\sigma_{\lambda\mu} n)\left[\bar{e}\sigma_{\lambda\mu}\left(C_T + C_T'\gamma_5\right)\nu\right]$$ Tensor

$$- (\bar{p}\gamma_\mu\gamma_5 n)\left[\bar{e}\gamma_\mu\gamma_5\left(C_A + C_A'\gamma_5\right)\nu\right]$$ Axial-Vector

$$+ (\bar{p}\gamma_5 n)\left[\bar{e}\gamma_5\left(C_P + C_P'\gamma_5\right)\nu\right] + \text{H.c.}$$ Pseudo-Scalar



Coupling constants:

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

$\Longrightarrow$ 20 Real Parameters

Determines Hamiltonian properties w.r.t. CPT symmetries

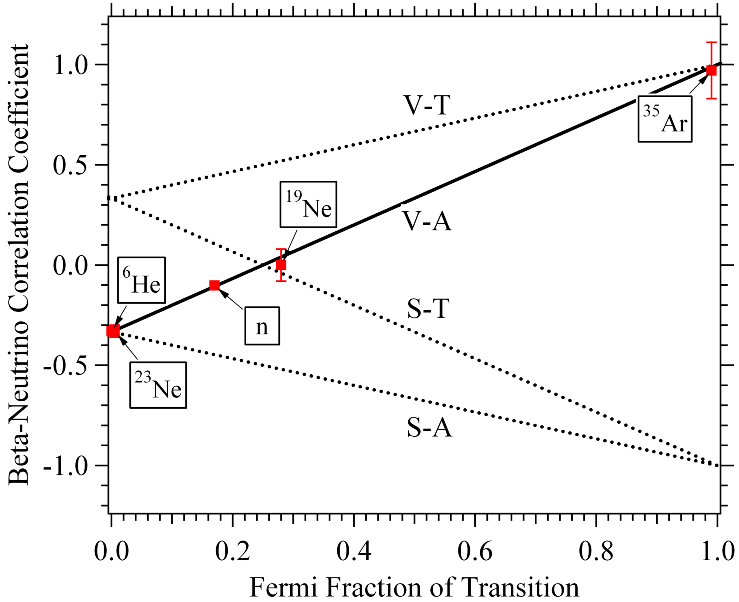
Physics Beyond the Standard Model

- In the 1960's, the V-A structure of the weak interaction was determined by measurements of the beta-neutrino correlation ($a_{\beta\nu}$) in noble gas nuclei

- Beyond Standard Model: Scalar (S) and Tensor (T) may be present with small coefficients

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

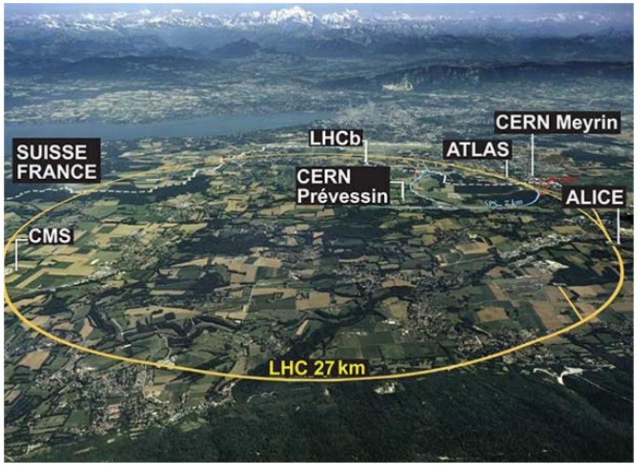
$$a_{\beta\nu} = \frac{\left(|C_V|^2 - |C_S|^2\right)|M_F|^2 - \frac{1}{3}\left(|C_A|^2 - |C_T|^2\right)|M_{GT}|^2}{\left(|C_V|^2 + |C_S|^2\right)|M_F|^2 + \left(|C_A|^2 + |C_T|^2\right)|M_{GT}|^2}$$

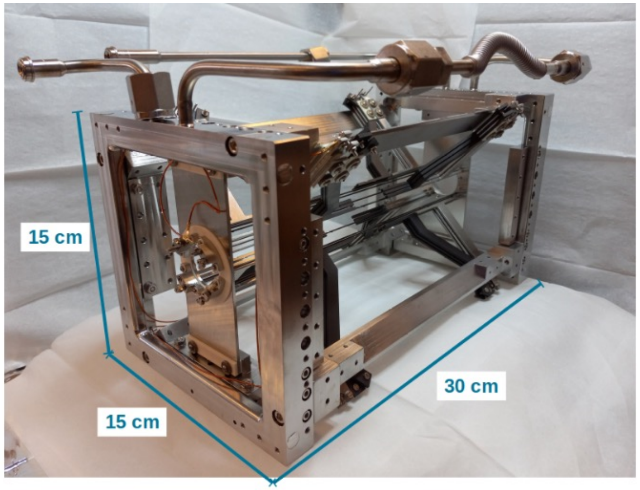


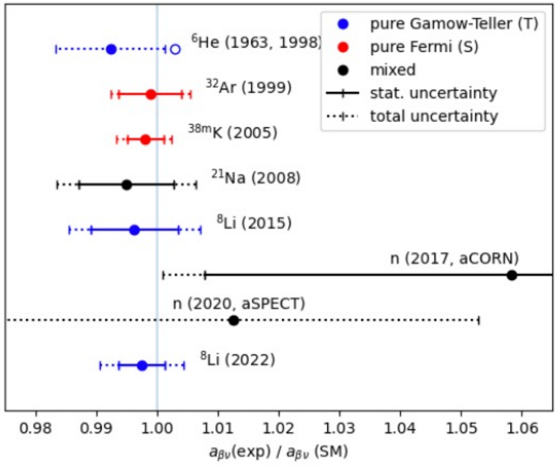
Fermi decay only sensitive to V, S
Gamow-Teller decay only sensitive to A, T

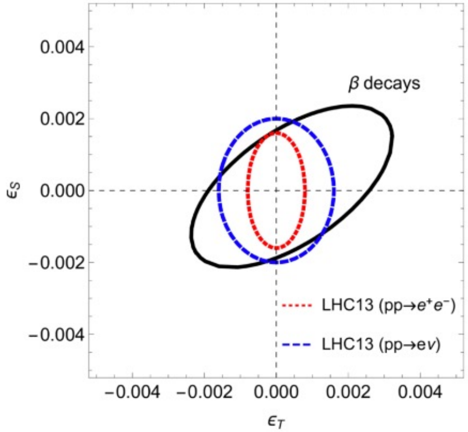
Limits on BSM Physics from Nuclear Decays

Nuclear physics experimental setups ~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

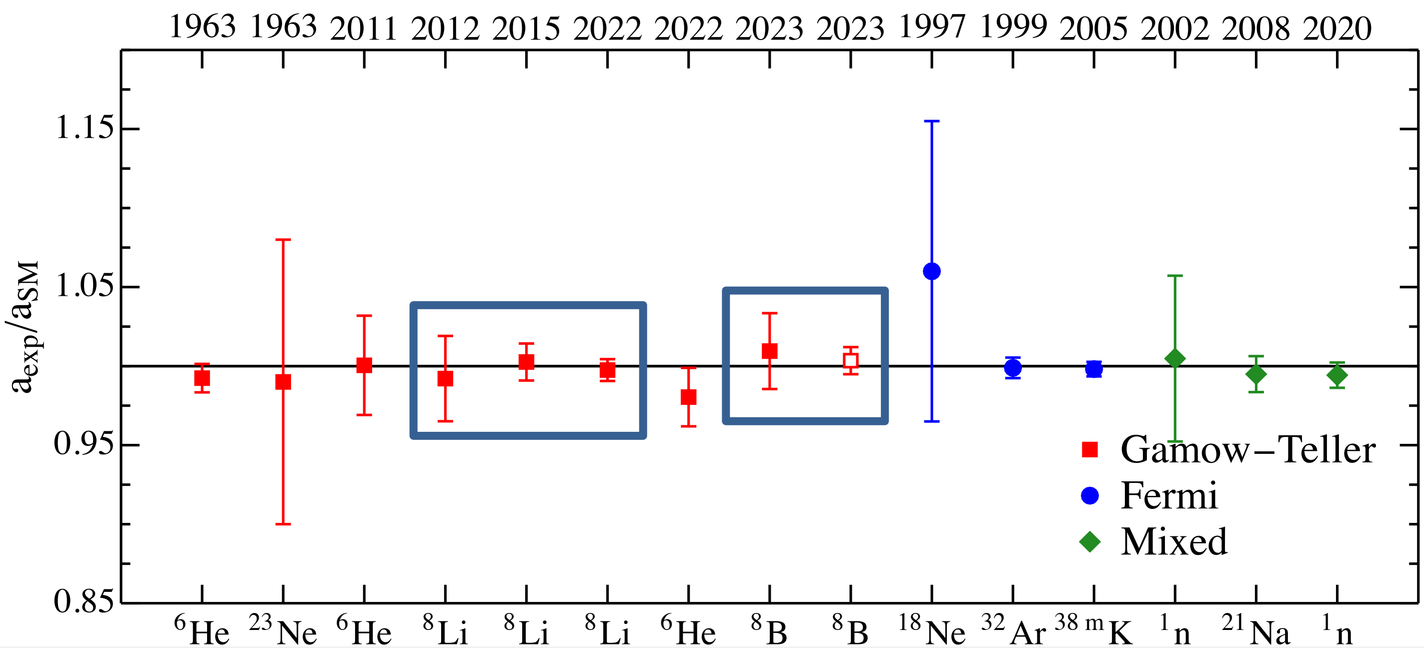
Limits on Tensor Currents from Mass-8

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

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

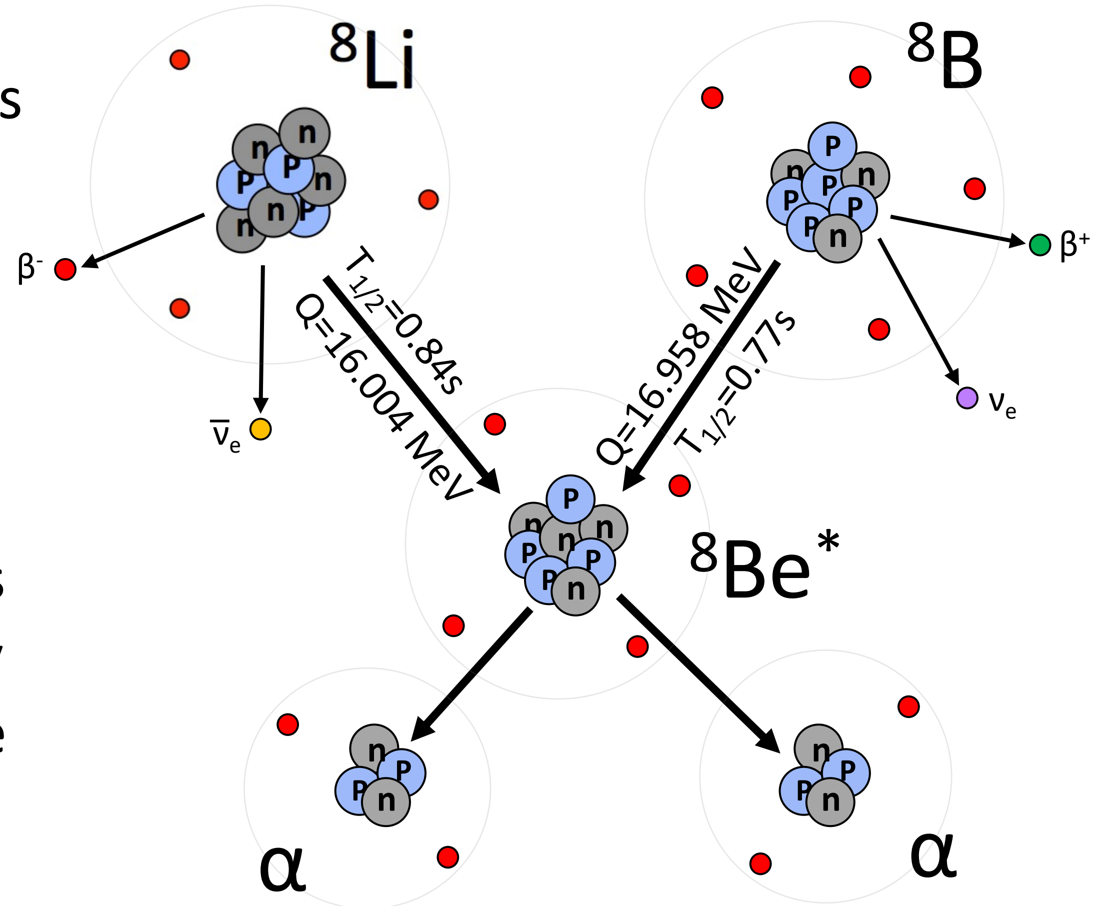
$$W(\theta_{\beta\nu}) = 1 + a_{\beta\nu}\frac{v_\beta}{c}\cos(\theta_{\beta\nu})$$

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



^{8}Li and ^{8}B Beta Decay Properties

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



^{8}Li and ^{8}B Beta Decay Properties

Triple correlation between delayed alphas and beta enhances effective sensitivity to beta-neutrino angular correlation by 3X for "parallel" betas

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

$$\Big\{\ (1+\delta_1(E_e))$$

Fierz Interference Term $\quad + b_{\mathrm{F}}\dfrac{m_e}{E_e}$

***βν* angular correlation** $\quad + (a_{\beta\nu}+\delta_{\beta\nu}(E_e))\dfrac{\vec{p}_e\cdot\vec{p}_\nu}{E_e E_v}$

"Triple" correlation $\quad + (a_{\alpha\beta\nu}+\delta_{\alpha\beta\nu}(E_e))\left(\dfrac{(\vec{p}_e\cdot\hat{p}_\alpha)(\vec{p}_\nu\cdot\hat{p}_\alpha)}{E_e E_\nu}-\dfrac{1}{3}\dfrac{\vec{p}_e\cdot\vec{p}_\nu}{E_e E_v}\right)\Big\}$

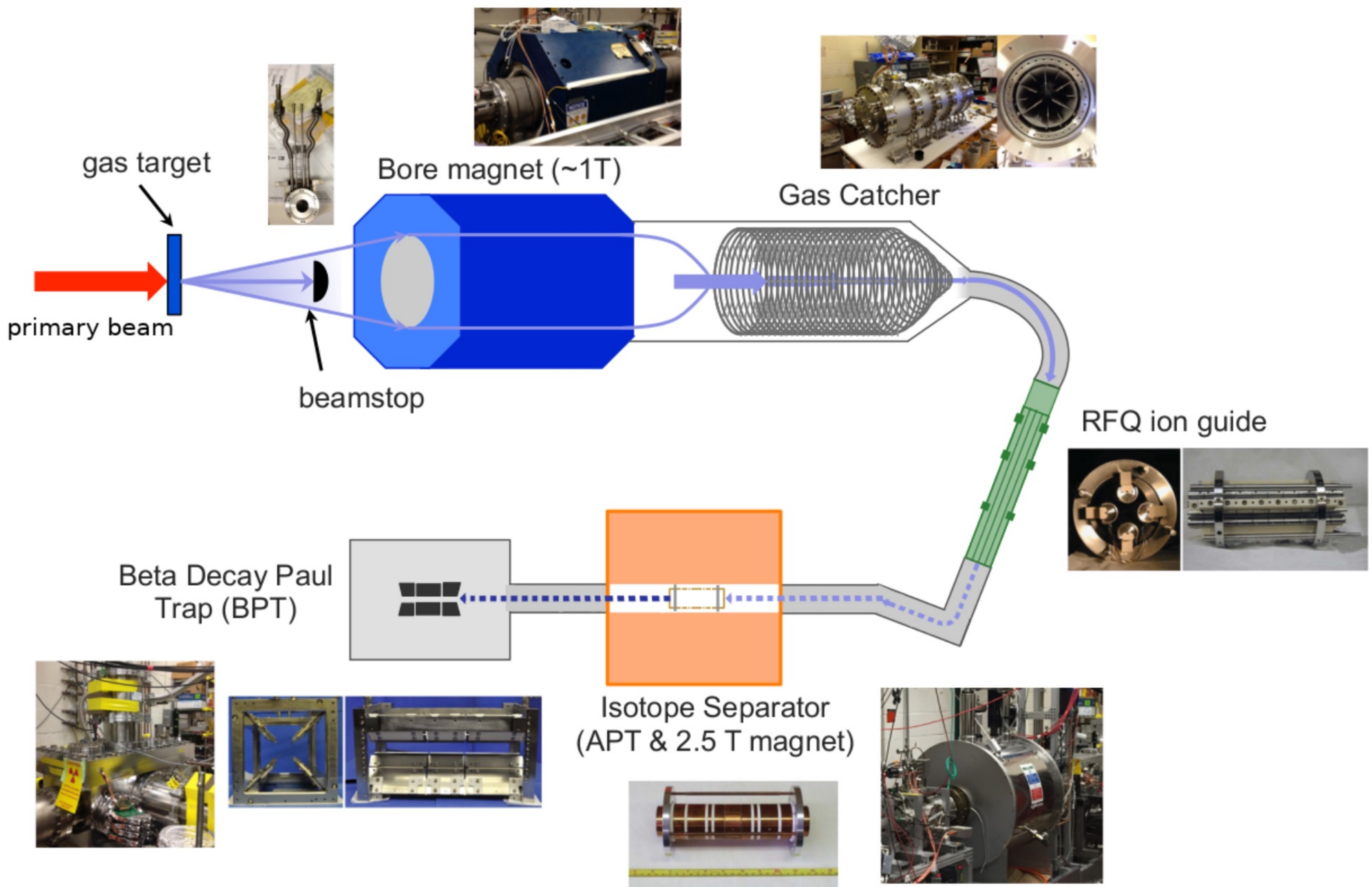
$$b_{\mathrm{F}} = \pm 2\frac{\Re\left(C_T C_A^* + C_T' C_A'^*\right)}{|C_A|^2+|C_A'|^2+|C_T|^2+|C_T'|^2} \qquad a_{\beta\nu} = -\frac{1}{3}\frac{|C_A|^2+|C_A'|^2-|C_T|^2-|C_T'|^2}{|C_A|^2+|C_A'|^2+|C_T|^2+|C_T'|^2}$$

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

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

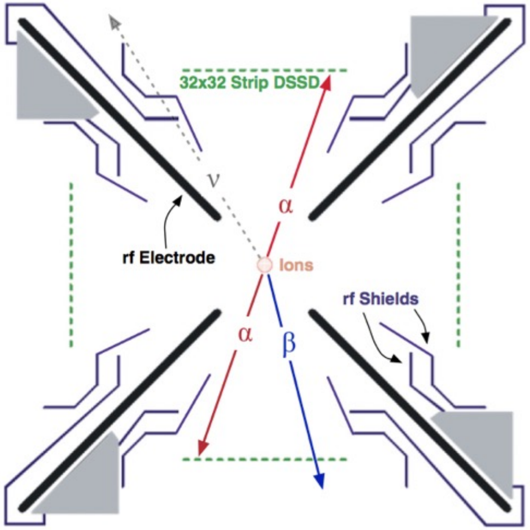
$^{7}\mathrm{Li} + ^{2}\mathrm{H} \rightarrow ^{8}\mathrm{Li} + \mathrm{p}$

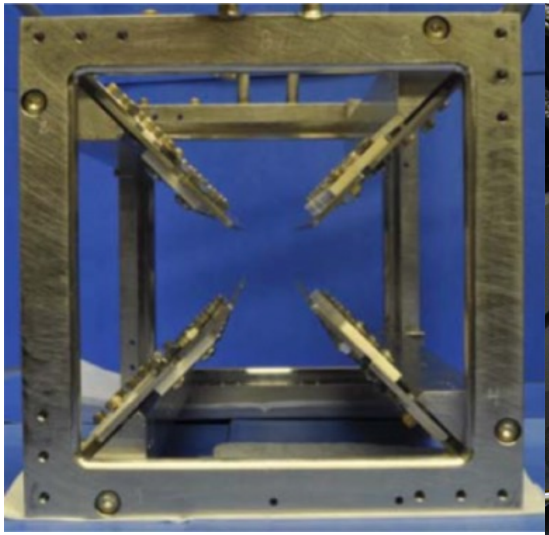
$^{6}\mathrm{Li} + ^{3}\mathrm{He} \rightarrow ^{8}\mathrm{B} + \mathrm{n}$

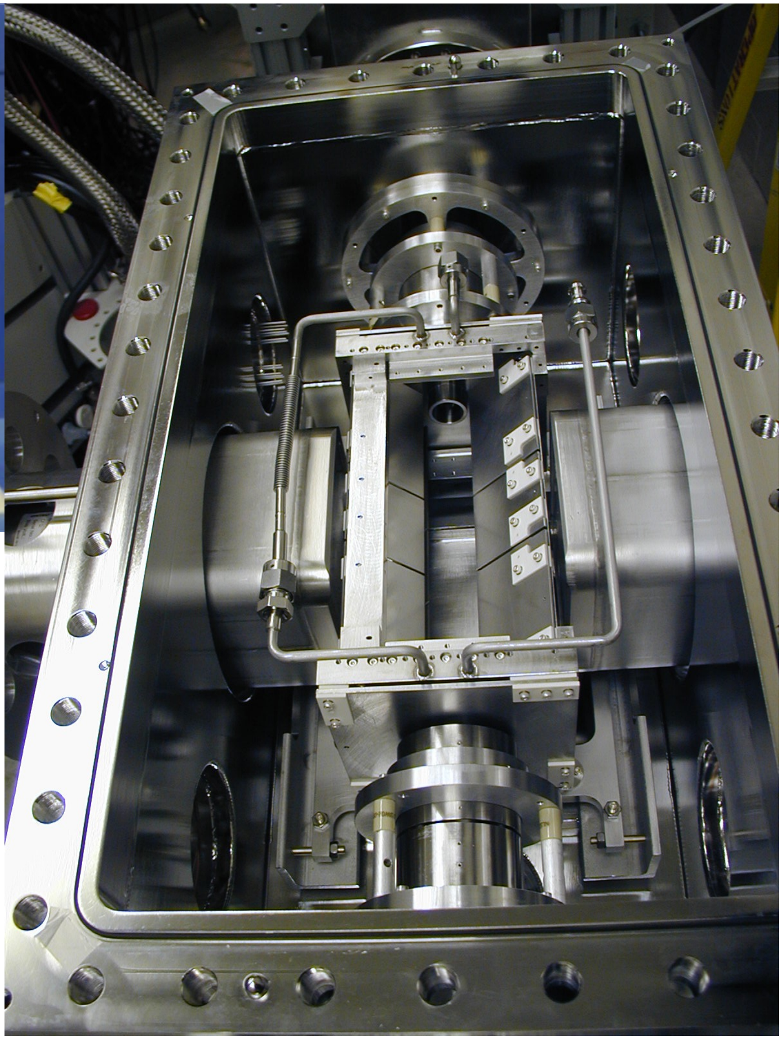


Pictures from Thesis of M.G. Sternberg (UChicago)

Beta-decay Paul Trap (BPT)







- Confine up to ~10^6 ions at once in ~1 mm^3 volume for > 200 sec
- Works for any element, accessible half-lives > 50 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)

N. D. Scielzo *et al.*, Nucl. Instrum. Methods Phys. Res. A 681, 94 (2012)

Decay Simulations

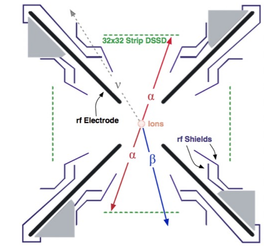
$$W(\theta_{\beta\nu}) = 1 + a_{\beta\nu}\frac{v_\beta}{c}\cos(\theta_{\beta\nu})$$

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

- 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

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

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

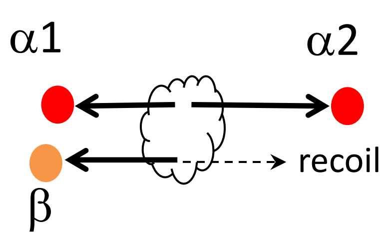


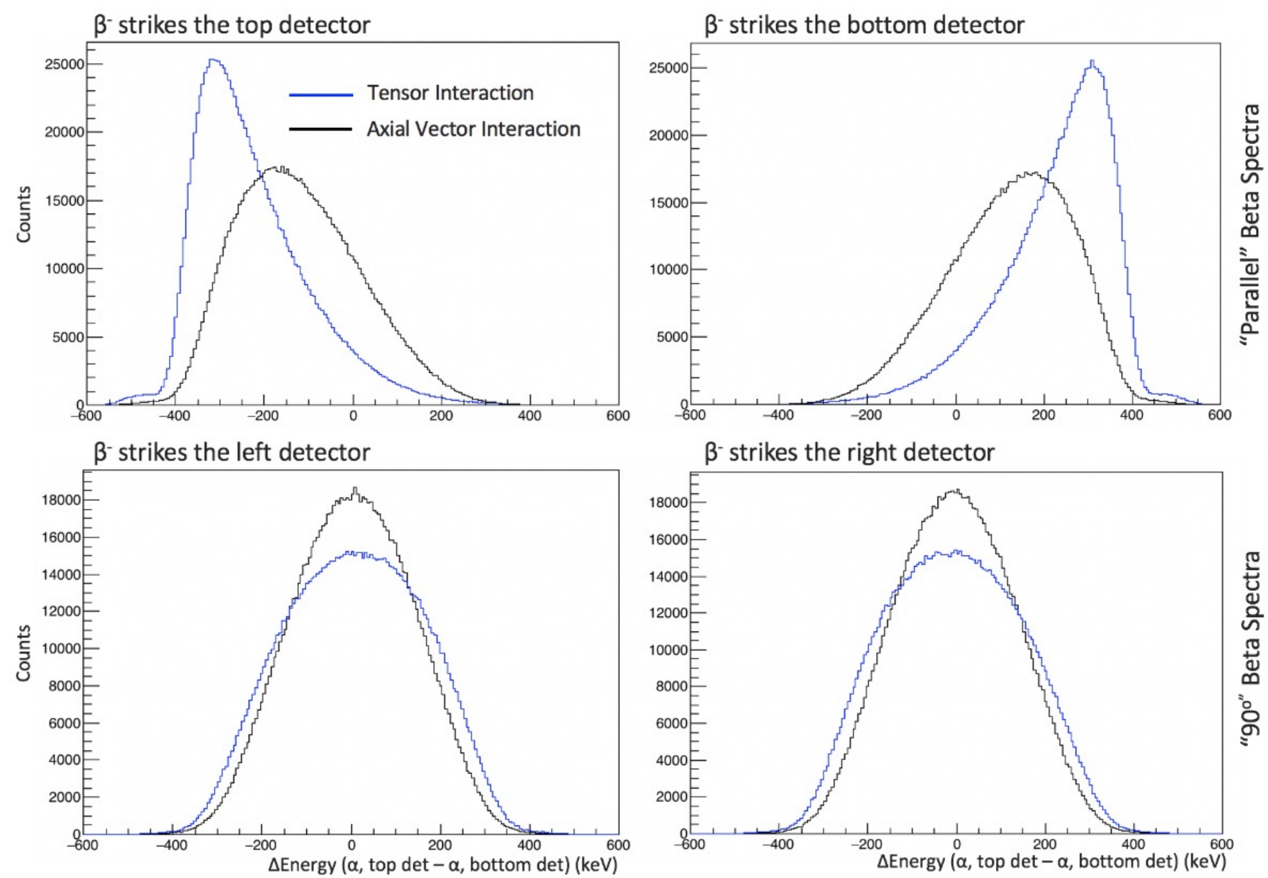
Alpha Energy Difference

- 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

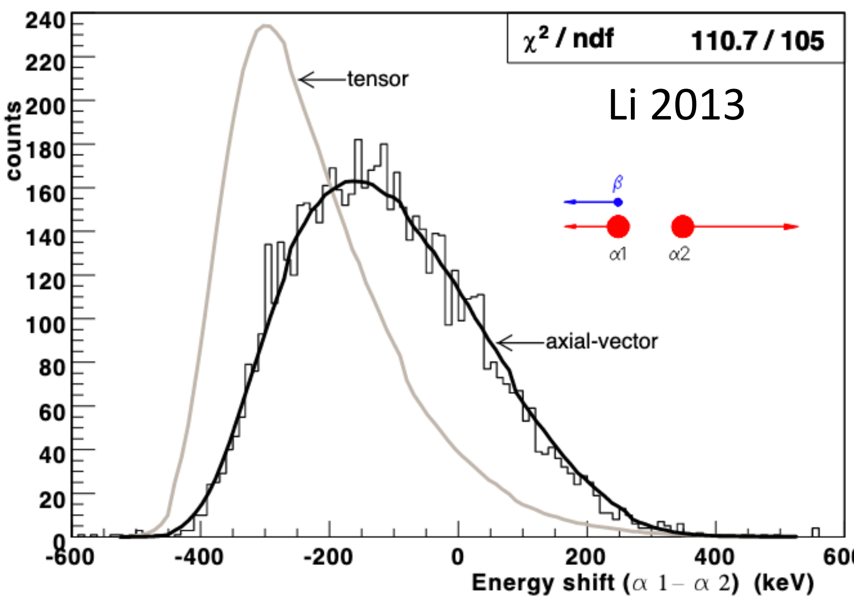
Tensor: beta and neutrino preferentially emitted in same direction
→ Larger nuclear recoil, larger ΔE_α

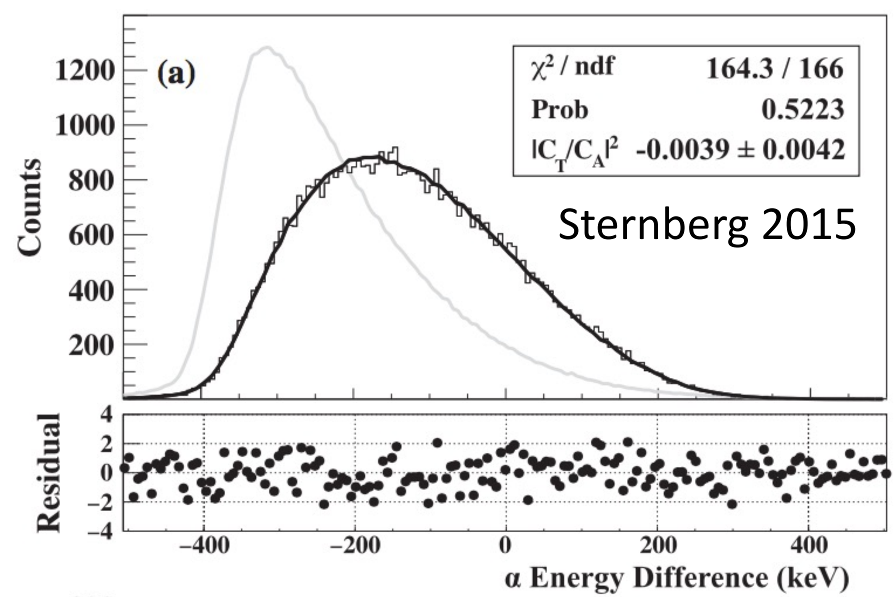




Our Collaboration's Previous Work on ^{8}Li

- 1963 ^{6}He (C. H. Johnson et al., corrected by Glück): $a_{\beta\nu}$= -0.3308(30)
- 2013 PRL (G. Li et al.): $a_{\beta\nu}$= −0.3307(90)
- 2015 PRL (M. G. Sternberg et al.): $a_{\beta\nu}$= -0.3342(39)





Improvements for ^{8}Li Run in 2016

- 10x statistics compared to 2015 PRL

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

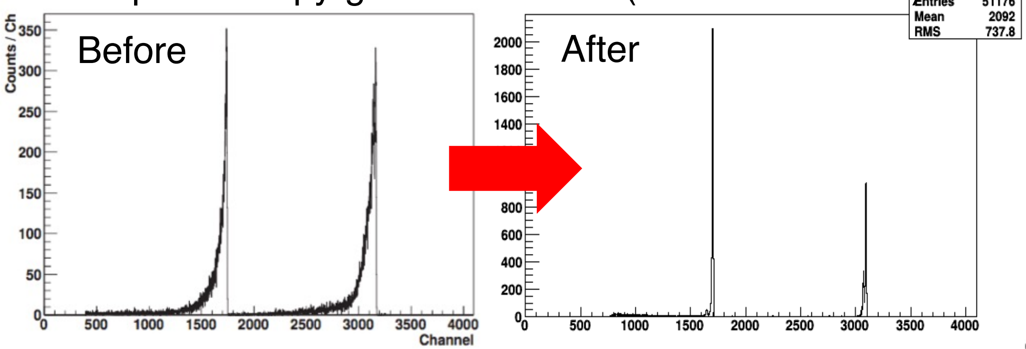
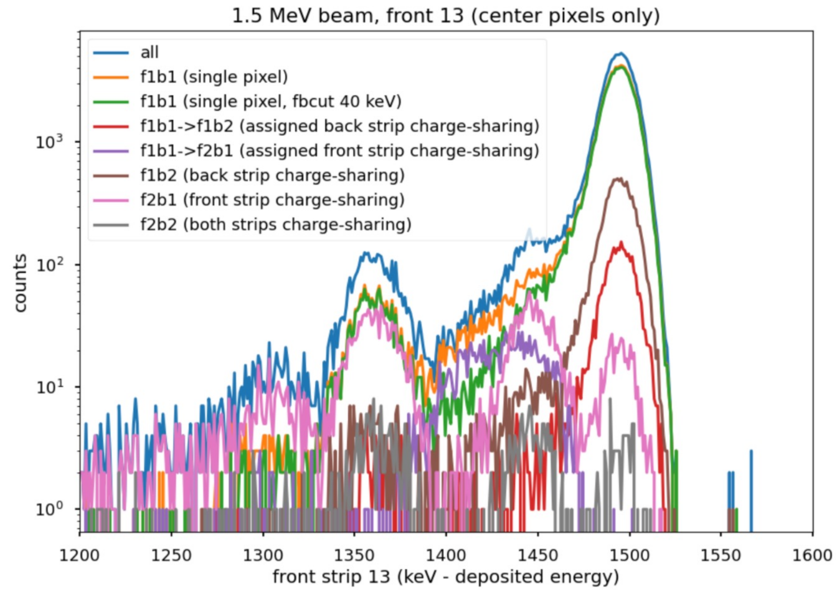


TABLE I. Dominant sources of systematic uncertainty at 1σ.

Source		$\Delta\lvert C_T/C_A\rvert^2$
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 ^{8}Li ground state quadrupole moment
- Recoil and radiative systematic uncertainty 0.0026 → 0.0015*

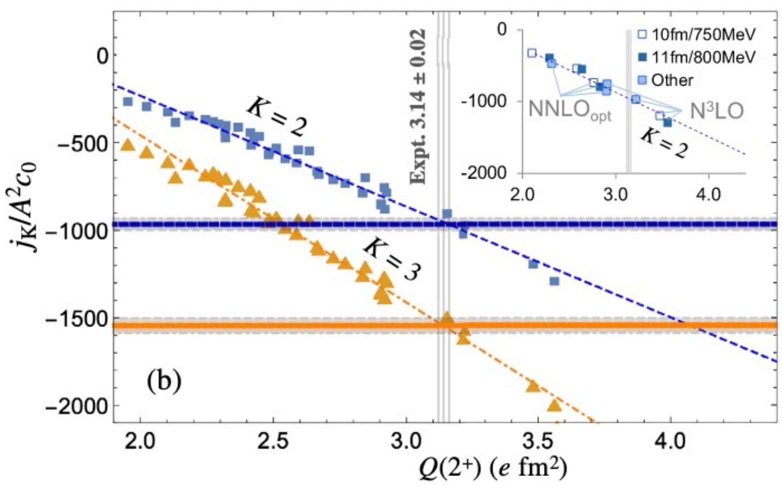
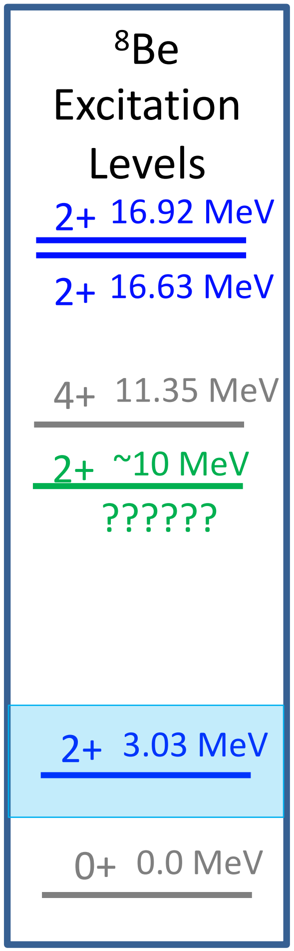


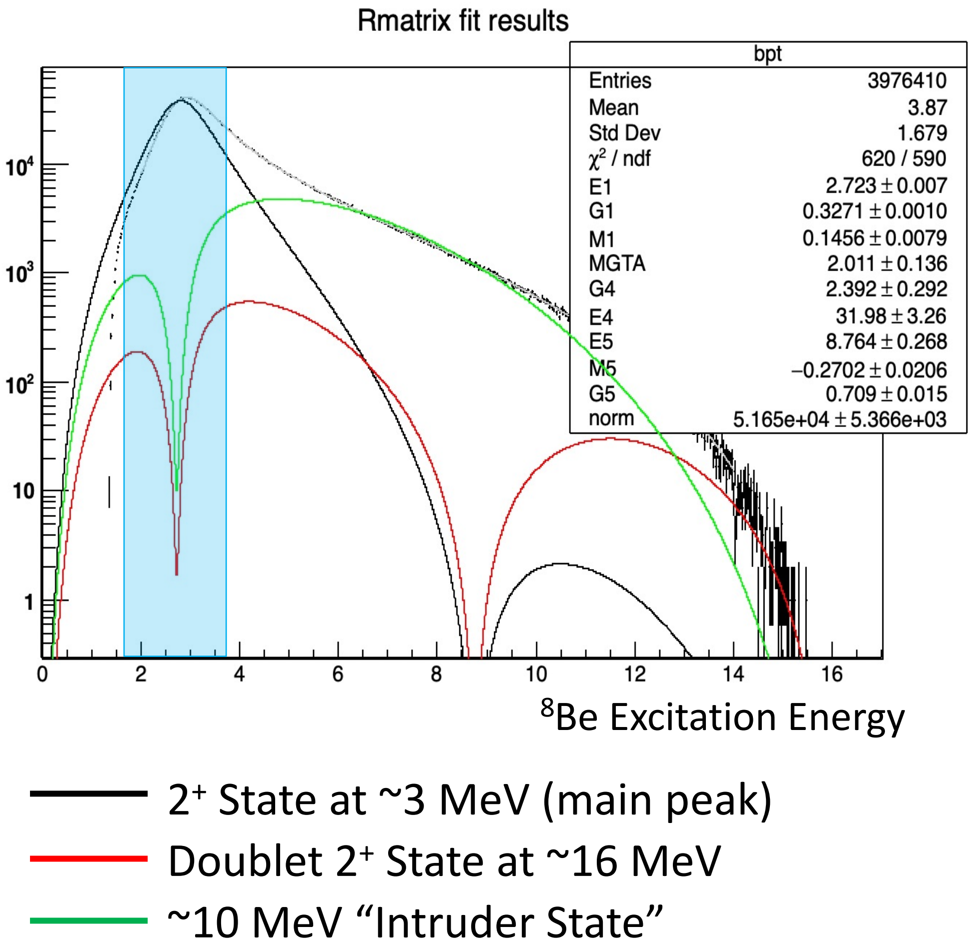
TABLE I. The recoil-order terms from SA-NCSM. Results for the 2_1^+ $j_{2,3}/A^2c_0$ and d/Ac_0 are based on the correlation to $Q(2^+_{\text{g.s.}})$; all other calculations use NNLO$_{\text{opt}}$ and have error bars from variations in $\hbar\Omega$ by 5 MeV and in model-space sizes up to $N_{\max}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

G. H. Sargsyan et al., Phys. Rev. Lett. 128, 202503 (2022)

Complication from New Recoil-Order Term Calculations





- *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"

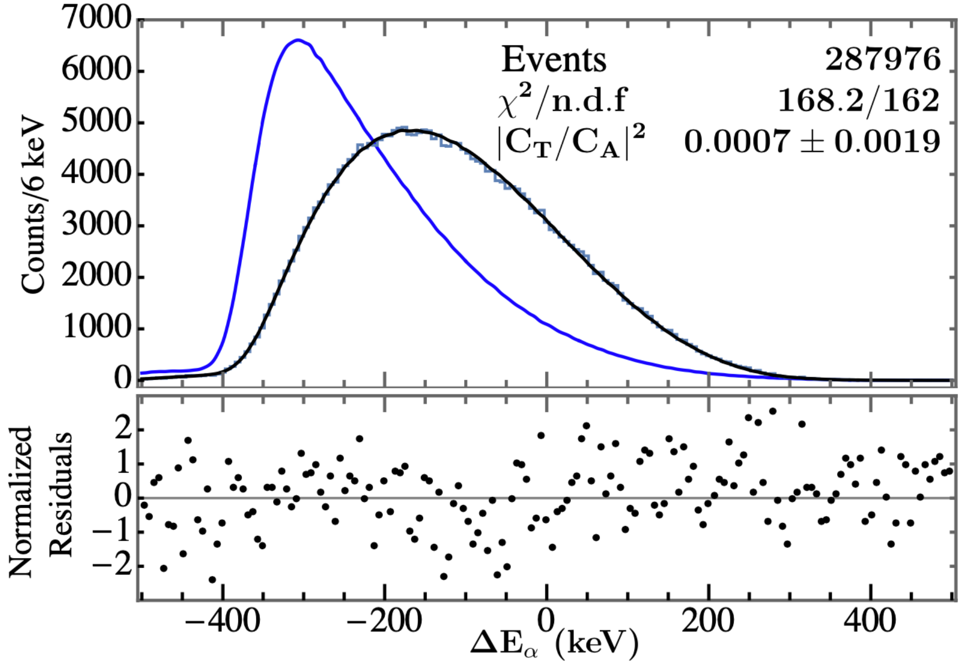
Plot from M. T. Burkey

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

- First improvement on uncertainty since 1963 ^{6}He measurement

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

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



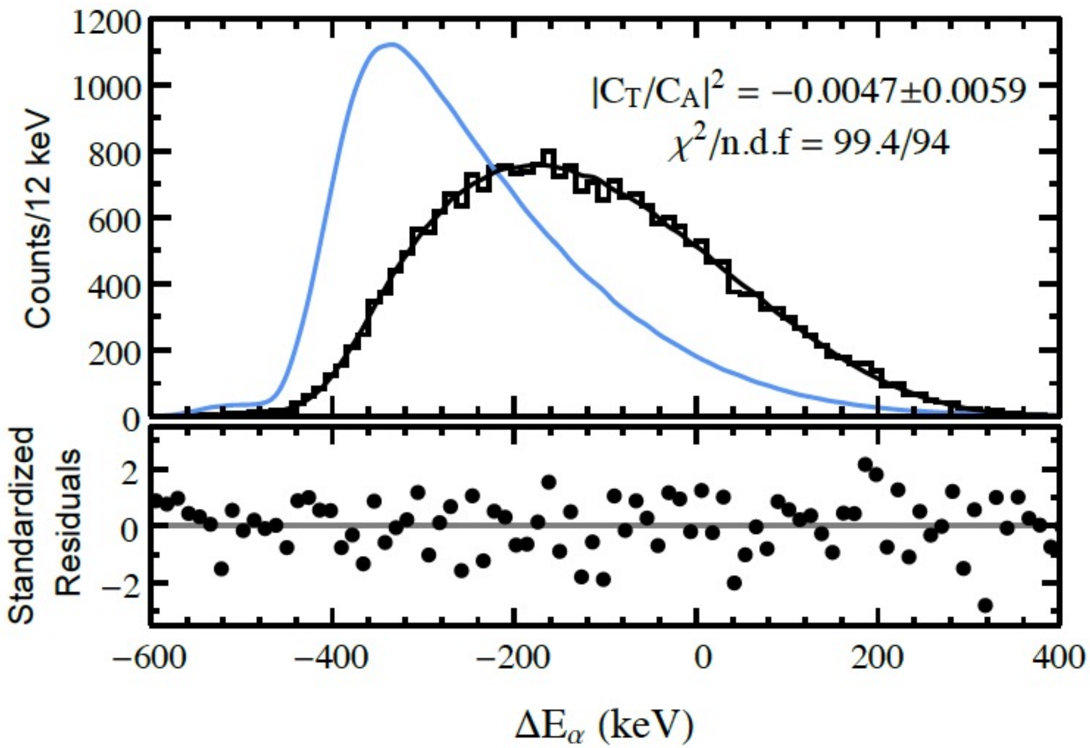
G. H. Sargsyan *et al.*, PRL 128, 202503 (2022)

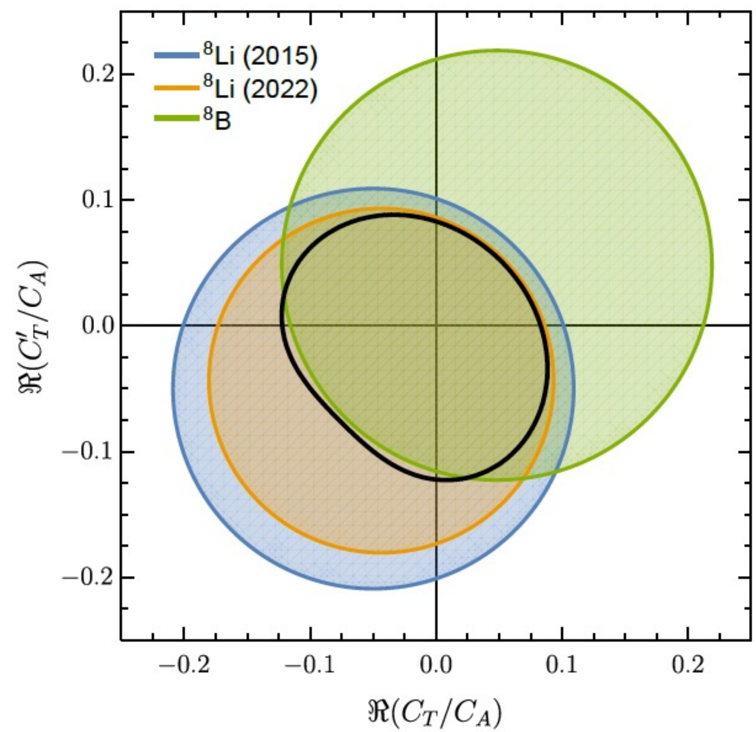
TABLE I. β recoil-order terms from SA-NCSM. Results for the 2_1^+ $j_{2,3}/A^2c_0$ are from Eq. (2); all other calculations use NNLO$_{opt}$ and have error bars from variations in $\hbar\Omega$ by 5 MeV and in model-space sizes up to N_{max} =16 (12) for $j_{2,3}/A^2c_0$ (d/Ac_0 and b/Ac_0).

	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

^{8}B Results from 2014 Experiment Accepted for Publication in PRL

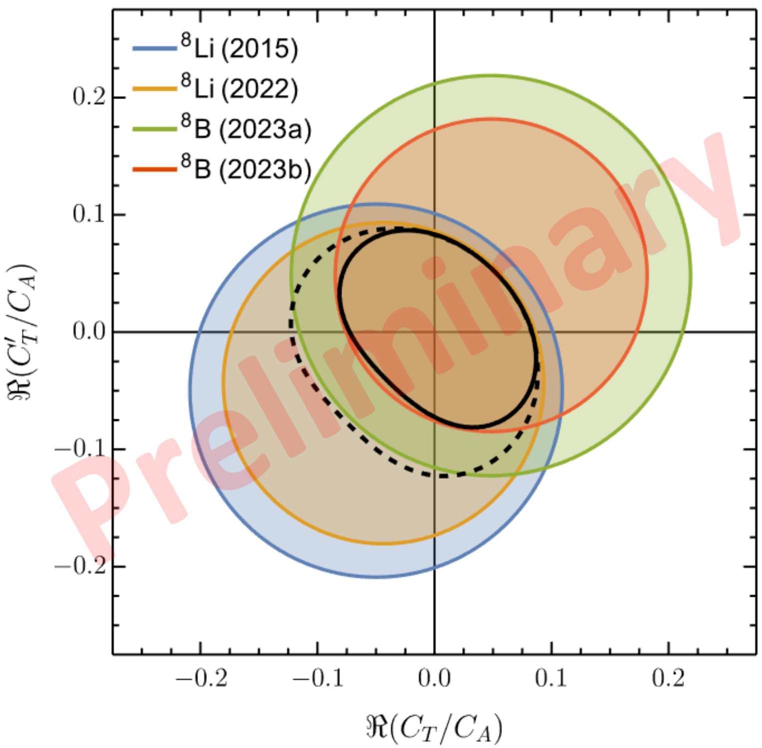
- First precision measurements of a mirror-nucleus pair, demonstrates a new pathway for increasing the precision of exotic current searches
- Follows the "$\tilde{a}$" prescription to assign limits on C_T and C'_T: $$\tilde{a}_{\beta\nu} = \frac{a_{\beta\nu}}{1 \pm b_F \langle m_e/E_e \rangle}$$

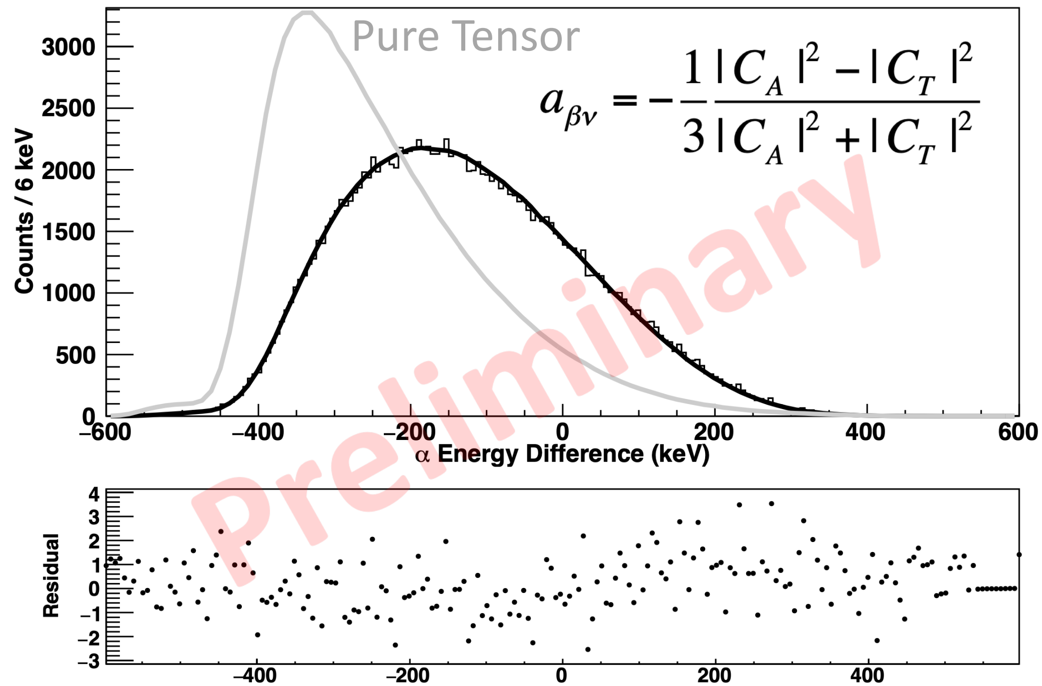




^{8}B from 2019 Experiment Under Analysis

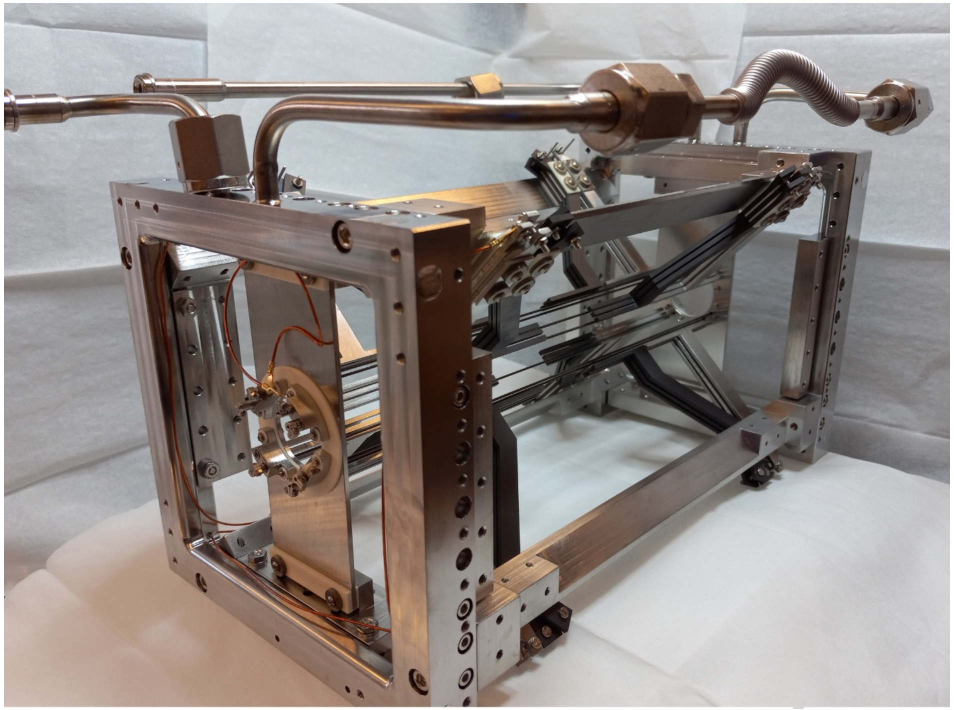
- Statistical uncertainty improved by over factor of 2 from previous ^{8}B data set, same systematic improvements as most recent ^{8}Li run





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

- New calculation of recoil-order terms for ^{8}B beta decay compete, finalizing analysis of systematic uncertainties for 2019 data set
- ^{8}Li run with new BPT trap design to lower β scattering by factor of 4 scheduled completed summer 2022, 35% higher statistics than 2016 ^{8}Li experiment



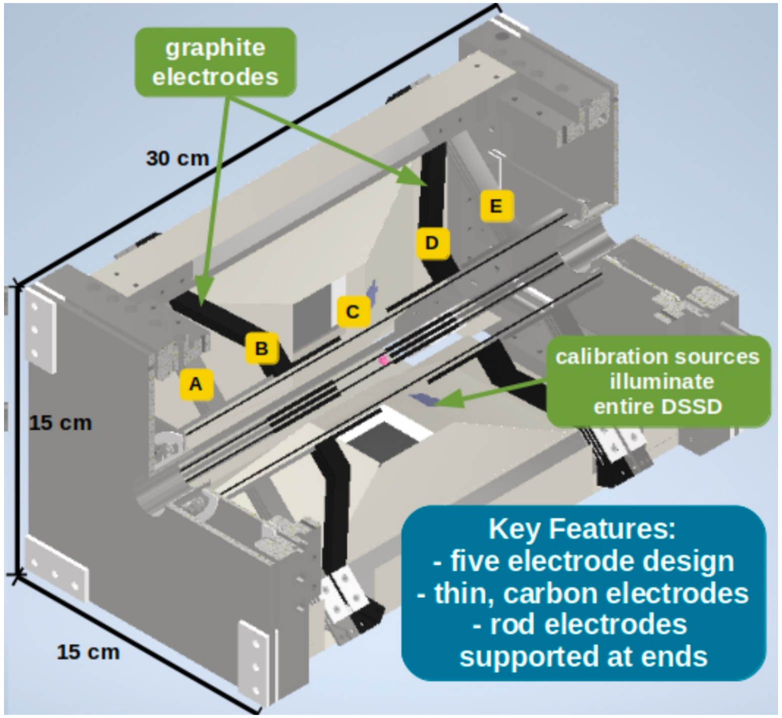
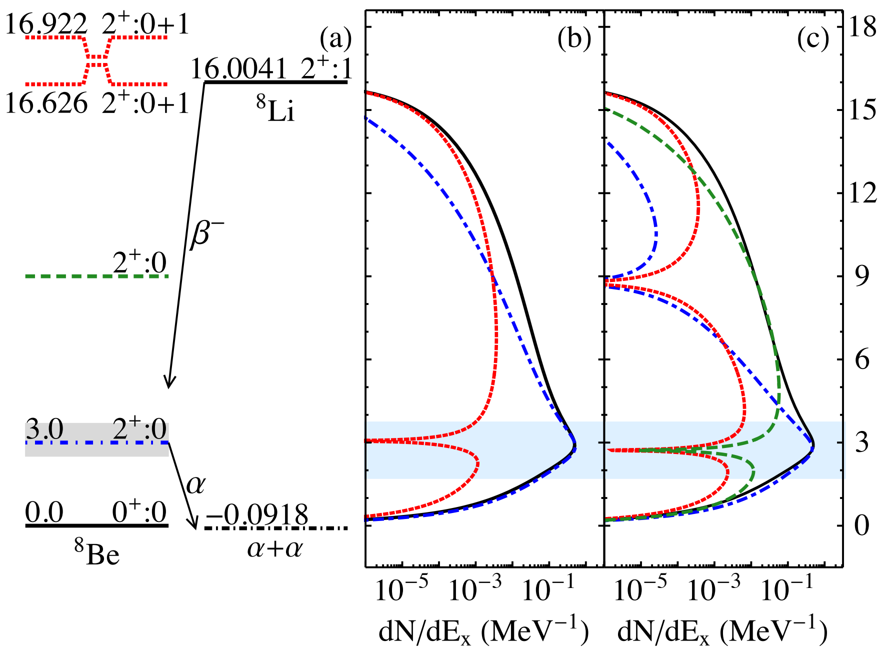


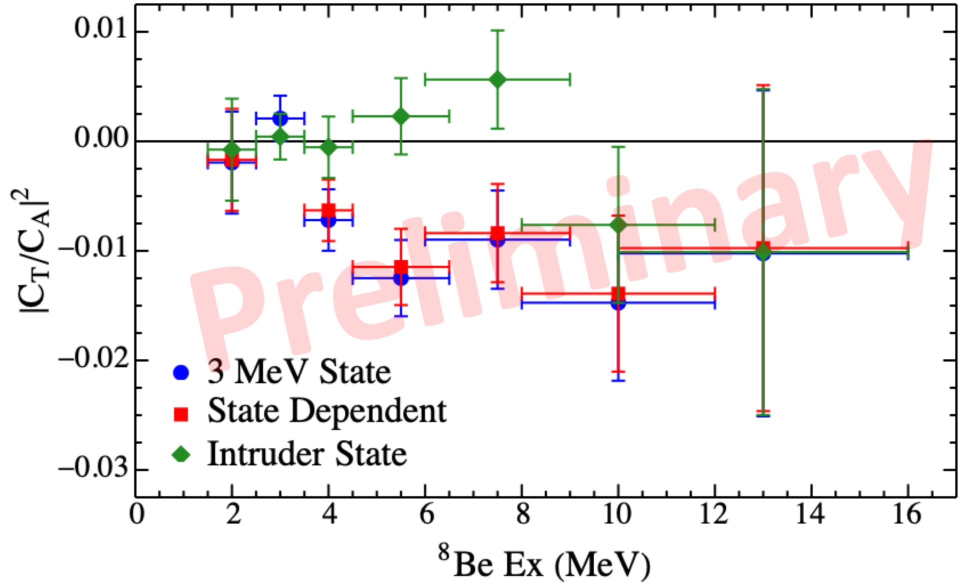
Photo and schematic from L. Varriano

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



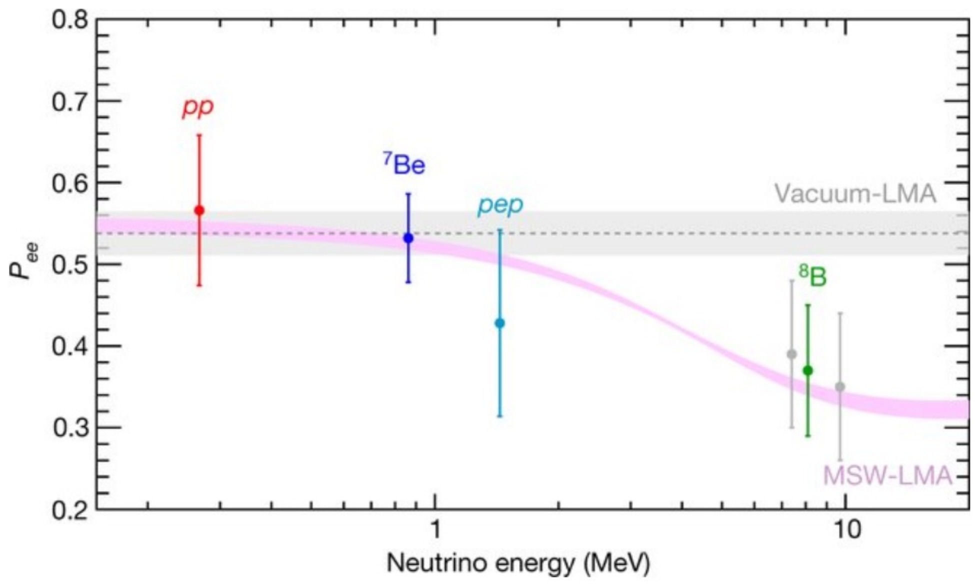


Excitation energy and state dependent analysis of $|C_T / C_A|^2$ may provide some hint at existence of this state

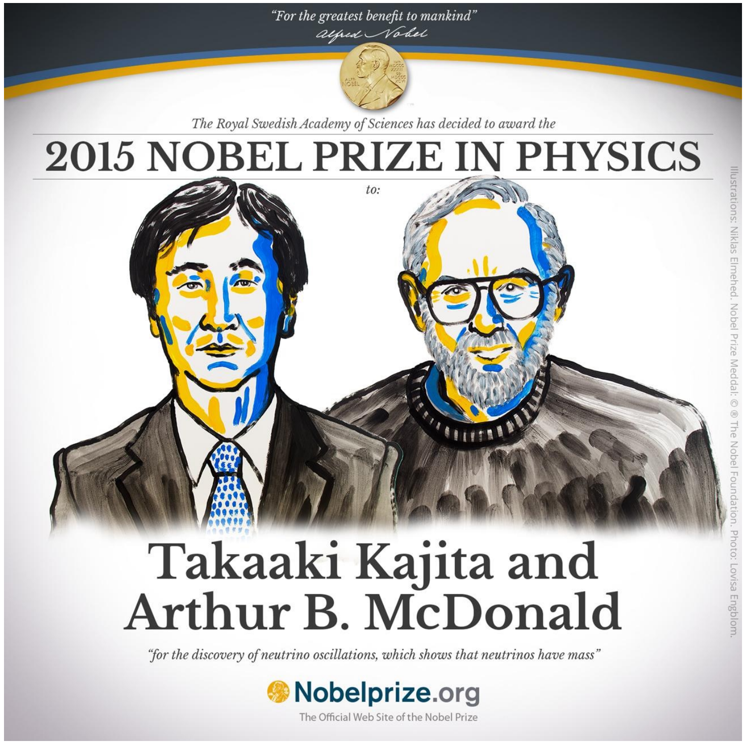
Solar Neutrino Astrophysics

- 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



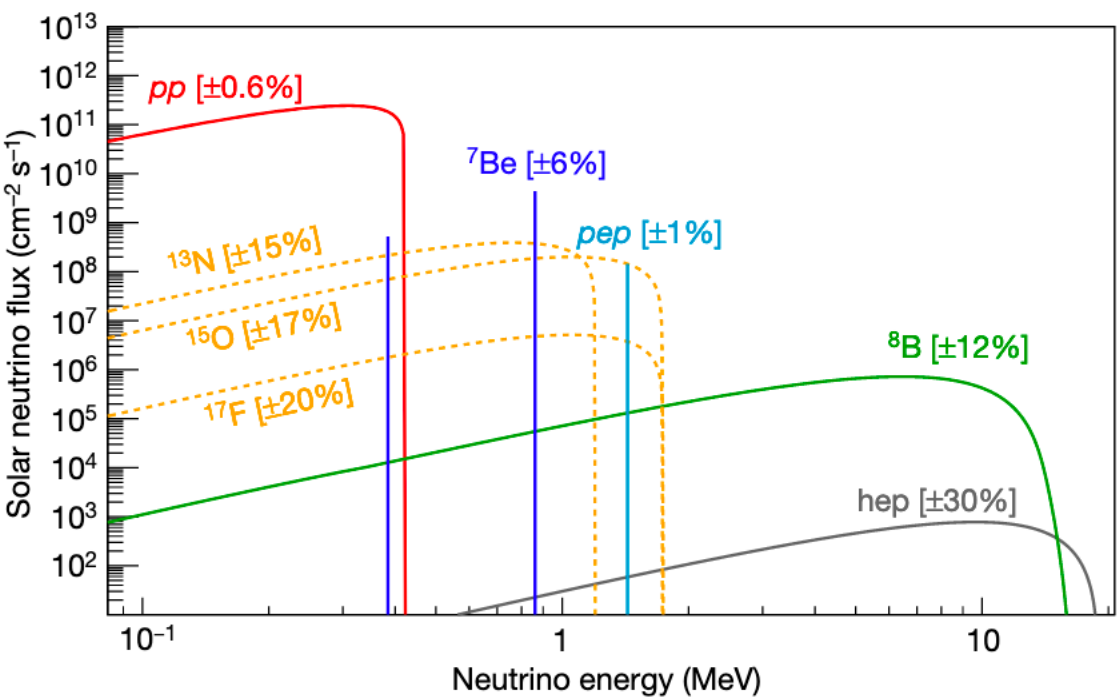
LMA: large mixing angle
MSW: Mikheyev–Smirnov–Wolfenstein

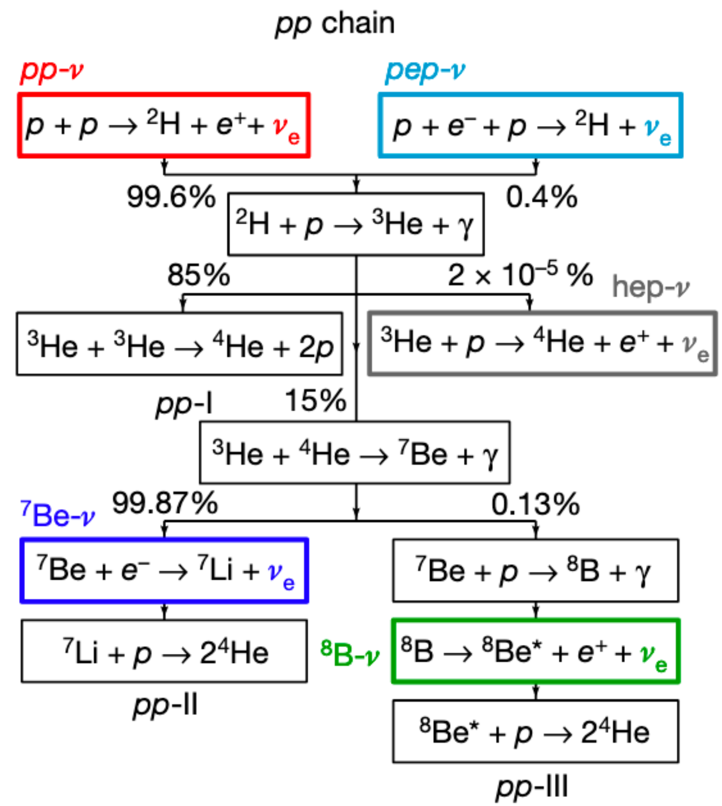


M. Agostini *et al*. (Borexino Collaboration), Nature 562, 505 (2018)

^{8}B Solar Neutrinos

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



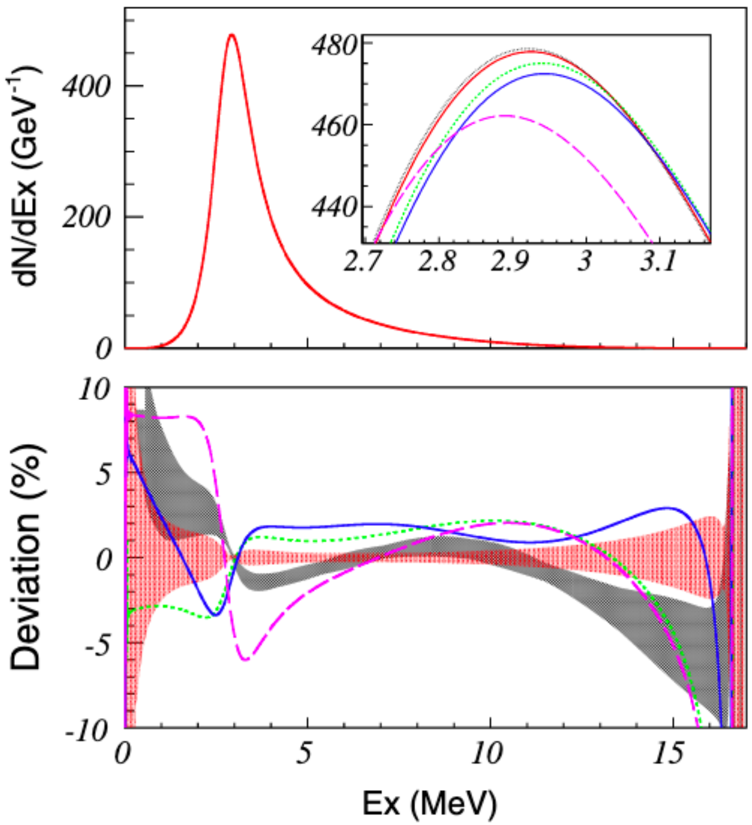


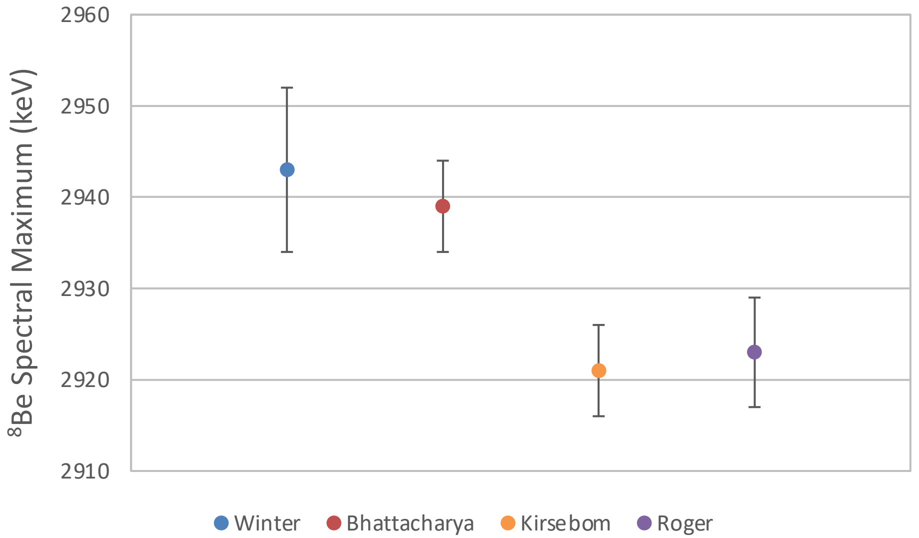
M. Agostini *et al*. (Borexino Collaboration), Nature 562, 505 (2018)

^{8}Be Final State Distribution (FSD)

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

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



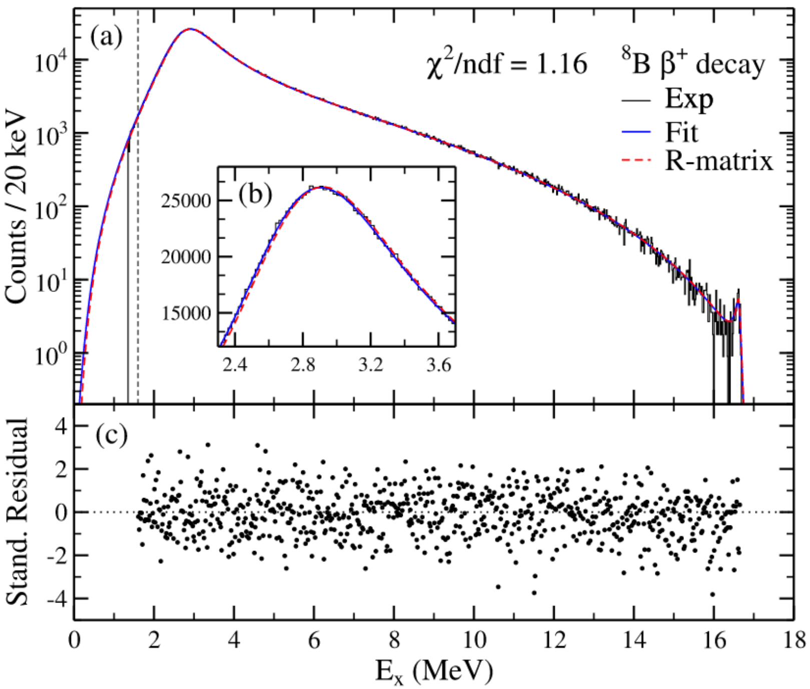


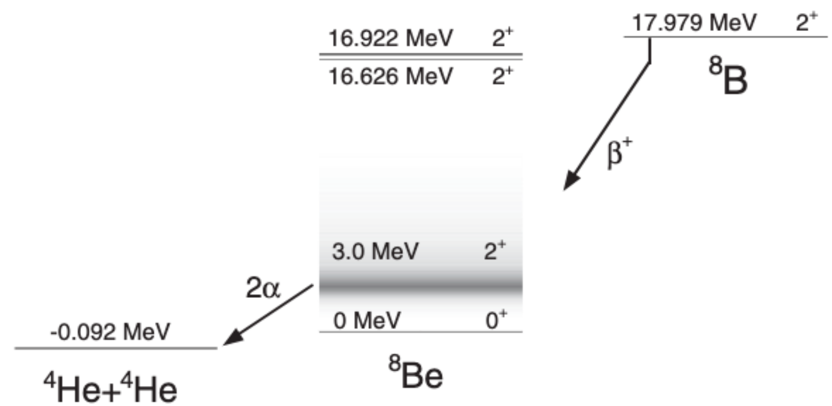
W. T. Winter *et al.*, Phys. Rev. C 73, 025503 (2006)
M. Bhattacharya *et al.*, Phys. Rev. C 73, 055802 (2006)
O. S. Kirsebom *et al.*, Phys. Rev. C 83, 065802 (2011)
T. Roger *et al.*, Phys. Rev. Lett. 108, 162502 (2012)

BPT Measurement of FSD

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



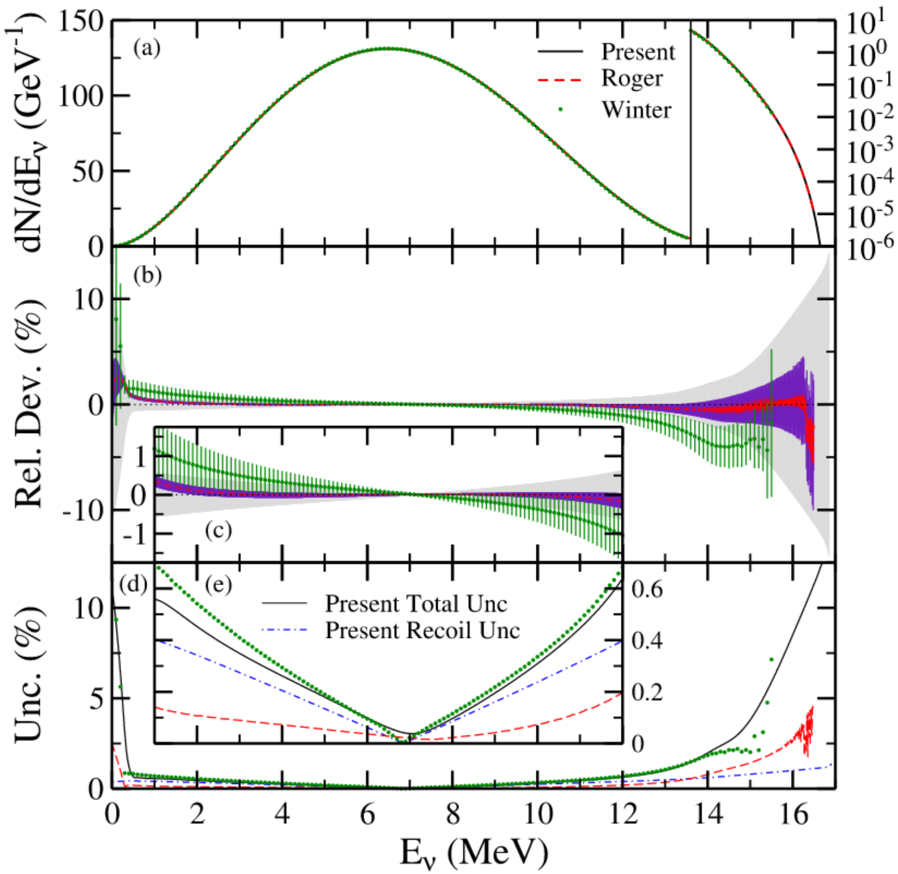


$$N(E) = \frac{N t_{1/2}}{\pi B} f_\beta(Q-E) P_c(E) \frac{\left|\sum_\lambda \frac{g_{\lambda,F}\gamma_{\lambda c}}{E_\lambda - E}\right|^2 + \left|\sum_\lambda \frac{g_{\lambda,GT}\gamma_{\lambda c}}{E_\lambda - E}\right|^2}{\left|1 - [S_c(E) - B_c + iP_c(E)]\sum_\lambda \frac{\gamma^2_{\lambda c}}{E_\lambda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

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

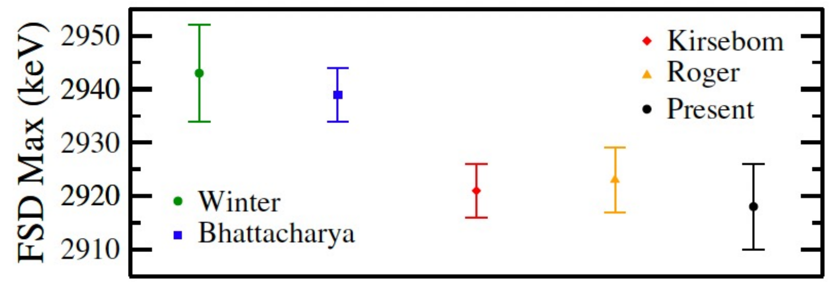
Neutrino Spectrum Calculation

- 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)

Q = 16.958 MeV

$E_0 = Q + m_e$

Summary and Outlook

- Beta decay of ^{8}Li and ^{8}B can probe physics beyond the Standard Model and contribute to solar neutrino astrophysics
- Two new ^{8}Li PRLs (experiment and theory): first improvement to Tensor limit uncertainty since 1963
- First ^{8}B Tensor limit accepted by PRL; new theory calculations for recoil-order terms for ^{8}B complete; Analysis of uncertainties for higher-statistics ^{8}B data set to be finalized
- New ^{8}B data set resolves discrepancy between Winter/Bhattacharya and Kirsebom/Roger results for FSD maximum, full neutrino spectrum calculation with uncertainties complete, results just published as PRC Letter

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