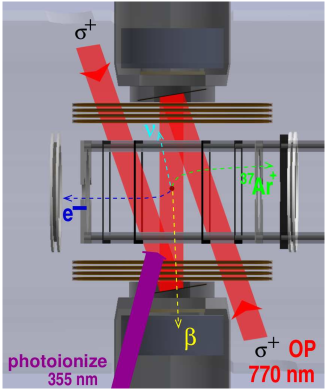
S1188 Spin-polarized ^{37}K β^+ Decay with TRINAT



$p_{37\mathrm{Ar}}$ from TOF and
MCP position, uniform $\vec{E}$
(β^+ or e$^-$ TOF trigger)
β^+ detection for A_β

- **Update Motivation:**
  High-energy physics progress
  Competition in β decay
- **Experimental improvements, projected uncertainty:**
  A_{recoil}
  A_β
  a_{pol}
- **Discovery Potential**
- **Request**

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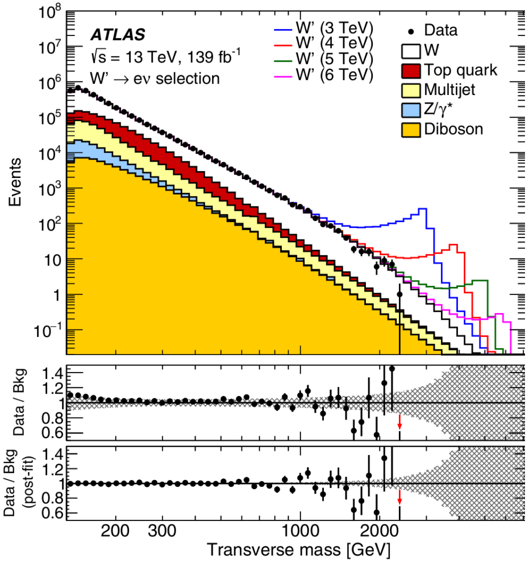
J. McNeil will do requested A_{recoil} for his Ph.D. * M. Anholm finished b_{Fierz} Ph.D. Dec 2023

Supported by NSERC, NRC through TRIUMF, DOE

Quasi-direct limits from high-energy colliders: update



LHC13 $\sigma[p + p \to e + \text{missing } p_\perp]$ is related to $n \to p + e + \nu$ by EFT (to scale the momentum transfer dependence, etc.) see Gonzalez-Alonso, Naviliat-Cuncic, Severijns, Prog Par Nuc Phys 104 165 (2019):

← 13 TeV data:

ATLAS expected 3, saw 2 Phys Rev D 100 052013 2019

CMS expected 2.5 events, saw 2 JHEP06 128 2018

LHC won't say more until ∼ 2025

A tight constraint on exchange of new TeV-scale bosons

Nuclear and neutron β decay progress since 2019

- V_{ud} radiative corrections, including as a function of E_β, heighten interest
- PERKEO III has improved neutron A_β, including a Fierz term measurement

Saul PRL 115 112502 (2020)

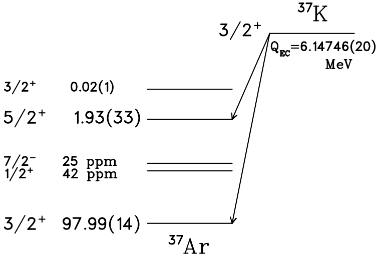
- aSPECT $a_{\beta-\nu}$ Beck PRC 101 055506 (2020) differs by 0.008 at 2.8 σ from PERKEO III in GT/F. One explanation is a Lorentz tensor coupling to right-handed ν (global fit Falkowski JHEP04 (2021) 126)

ANL ^8Li, ^8B β decay in a Paul trap Burkey PRL 128 202502 (2022); Sargsyan PRL 128 202503 (2022) has tension with aSPECT as a Lorentz tensor

- First cyclotron resonance microwave emission in ^{6}He/^{19}Ne Byron arXiv:2209.02870 to contrain Fierz interference distortion of β spectra

WISArD: WITCH magnet, β-delayed proton decay of ^{32}Ar, proton energy shift with β^+. Araujo-Escalona PRC 101 055501 (2020) Uses catcher foil, so backscattering...

^{37}K: TAMU *Ft* progress: recoil-order corrections status



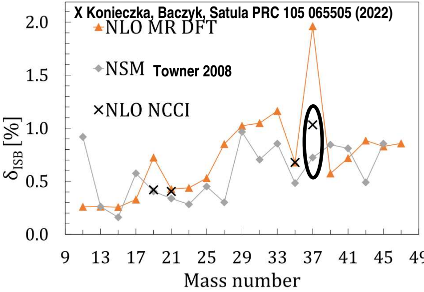
$\mathcal{F}t$ (Shidling PRC 2014) = 4576 ± 8 s
Ozmetin et al. TAMU
Branch to 5/2$^+$ improved
$\rightarrow$ PRELIM 4585 ± 4 s
$\sim$0.0005 for V_{ud} from A_{recoil} becomes possible

CVC $\Rightarrow$ most important corrections:

- $\mu \Rightarrow b_{WM}$ (small for $\pi d_{3/2}$)
- Induced tensor $d_1 \approx 0$ for isobaric mirror
- $Q \Rightarrow$ largest 2nd-order recoil + Coulomb + finite-size $\Rightarrow$

$\Delta A_\beta \approx -0.0028\ (E_\beta / E_0)$ Holstein RMP 1975

Our deduced V_{ud} from ^{37}K A_β agrees with Hayen Young arXiv:2009.11364



DFT with extra isospin-breaking QCD isovector interactions tuned to fix Nolen-Schiffer anomaly in mirror masses differs from Towner 2008 for ^{37}K β decay

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Polarization=0.991(1) → projected 0.9960(5)

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Source	ΔP [$\times 10^{-4}$] σ^-	ΔP [$\times 10^{-4}$] σ^+	ΔT [$\times 10^{-4}$] σ^-	ΔT [$\times 10^{-4}$] σ^+	ΔP σ^-
SYSTEMATICS					PROJ
Initial T	3	3	10	8	2
Global fit v. ave	2	2	7	6	1
$S_3^{\rm out}$ Uncertainty	1	2	11	5	0
Cloud temp	2	0.5	3	2	1
Binning	1	1	4	3	0
B_z Uncertainty	0.5	3	2	7	0.5
Initial P	0.1	0.1	0.4	0.4	0.1
Require $\mathcal{I}_+ = \mathcal{I}_-$	0.1	0.1	0.1	0.2	0
Total Systematic	5	5	17	14	2.5
STATISTICS	7	6	21	17	4

Patient undergrads lead most of these improvements

0.25 mm SiC-backed mirrors → pellicles for less β^+ scattering

Stern Family of National Photocolor

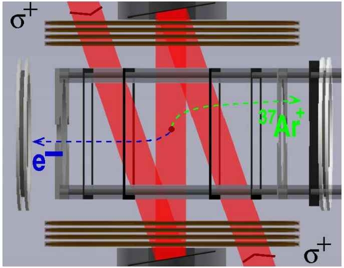
70nm Au + 4μ Kapton 5λ flatness

- PCTFE viewport seals
- Lower-frequency AC-MOT
- Double OP power: fight Larmor precession
- Better spin flips TnLC
- 2x more photoionizing light

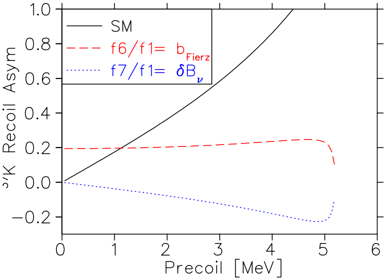
- Uncertainty $\propto (1 - P)$

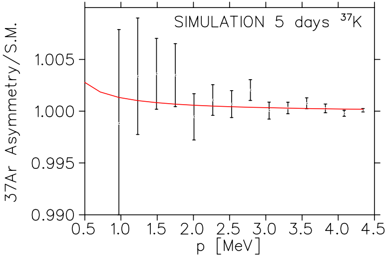
TRIUMF

$A_{\mathrm{recoil}} \propto A_\beta + B_\nu$ in ^{37}K decay



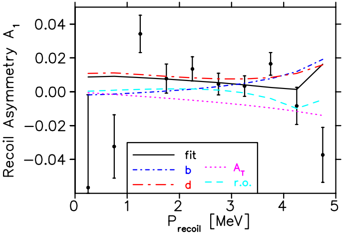
$A_{\mathrm{recoil}}[p_{\mathrm{recoil}}]$ independent of M_{GT}/M_F





see ^{80}Rb Pitcairn PRC09

$A_T = 0.015(29)(19)$



A_{recoil} Uncertainties / 100 scaling from Melconian PLB 649 270 (2007)

	B_ν	Improvements	Projected
Polarization	0.8	$B_\perp$, $\sigma^\pm$	0.05
Cloud position	1.3	500 μm $\rightarrow$ 20μm	0.05
Cloud size/Temp	0.3	" "	0.03
MCP Position cal	1.0	DLA+ mask	$\leq$ 0.1
E field	0.2	Data at 3 fields	$\leq$ 0.1

^{37}K A_β

Improvements

- **Minimize Background by sweeping away e^- with larger $\vec{E}$**
- **Reduce scattering by 2 with lower-Z materials Improve understanding**
- **Reduced energy threshold using pellicle mirrors**
- **Improve statistics**

Uncertainty budget for A_β:

Items with † are related to β scattering.

A_β Systematics	$\Delta A_\beta \times 10^{-4}$	Proj
Background (Correction 1.0014 1.0000)	8	0
β scattering† (Correction 1.0234 1.01)	7	3
Trap Position (typ. $\leq \pm 20\mu$m)	4	2
Sail velocity (typ. $\leq \pm 30\mu$m/ms)	5	3
Temperature (typ. $\leq$ 0.2mK) & width	1	0.7
BB1 Radius† $15^{+3.5}_{-5.5}$ mm	4	4
Energy agreement ($3\sigma \leftrightarrow 5\sigma$)	2	2
threshold (60↔40 keV)	1	1
Scintillator threshold (0.4 ↔ 1.0 MeV)	0.3	0.3
Shakeoff electron t.o.f. region	3	1
SiC mirror thickness† ($\pm 6\mu$m)	1	0
Be window thickness† ($\pm 23\mu$m)	0.9	0.9
BB1 thickness† ($\pm 5\mu$m)	0.1	0.1
Scintillator or summed†	1	1
Scintillator calibration ($\pm$0.4ch/keV)	0.1	0.1
Total systematics	12	7
Statistics	13	6
Polarization	5	2
Total uncertainty	18	8

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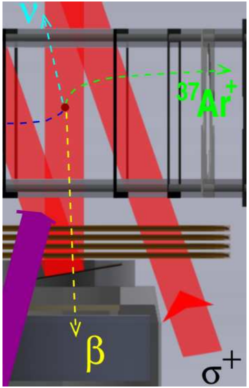
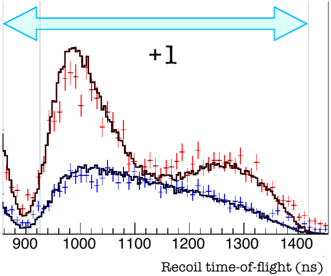
A different isospin mirror-decay spin-polarized observable

Isobaric mirror decay has helicity-driven null



2014 polarized β-recoil



$v_{\mathrm{TOFaxis}} = 0$ suppressed. Dip would be deeper with ion MCP position cut or $\cos(\theta_{\beta-\nu})$ determination

a_{pol} is likely to be statistics-limited. Our proposal's statement of direct sensitivity to the ν helicity assumes for ^{37}K the β^+ SM helicity (The $I^\pi = 3^+ \rightarrow 2^+$ decay of ^{38g}K would require both leptons to have non-SM helicity and complete such an interpretation)

$$W(\theta, P) \approx 1 + a_{\mathrm{pol}} \cos(\theta_{\beta\nu})$$

with $a_{\mathrm{pol}} = (A_\beta - B_\nu)P - a_{\beta\nu} + 2c/3$ = 1 or 0, independent of $\frac{M_{GT}}{M_F}$

The neutron community checks this combination of observables for consistency Mostovoi+Frank Pis'ma Zh. Eksp. Teor. Fiz. 24 45 (1976)

Discovery potential ^{37}K A_β, $A_{\rm recoil}$, $a_{\rm pol}$

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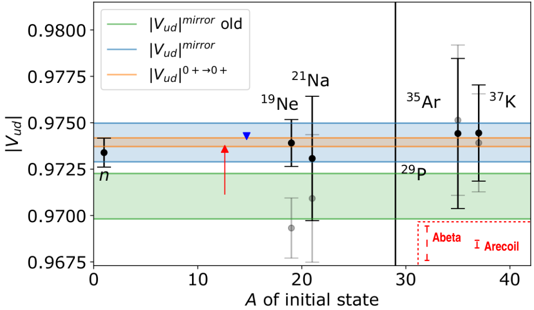
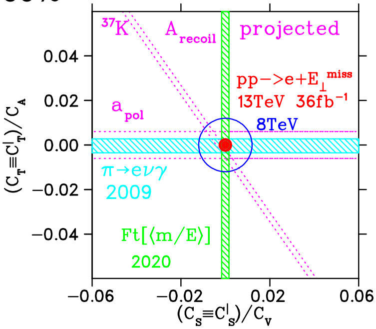
Deduced V_{ud} from mirror decays
Hayen and Young,
arXiv:2009.11364
including G-T radiative correction



We **project** **to reach 0.0005 accuracy, as good as any $0^+ \to 0^+$ except ^{26m}Al. Assumes 5% isospin breaking**

Assuming known $M_{\rm GT}/M_{\rm F}$
90%



Completed upgrade to 1 kV/cm, fine-tuning polarization.

TRIUMF S1188 Request and TRINAT plans TEXAS A&M UNIVERSITY

After tests with 9 of 20 approved shifts with small ^{45}K beam from Ta, UCx, we are ready for full experiment with ^{37}K from TiC.

- **We request an inventory of 23 shifts total:**

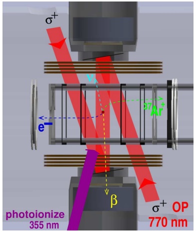
*15 shifts for complete statistics+

*5 shifts, using unpolarized part of duty cycle, to change Efield 1000V/cm $\rightarrow$ 950 V/cm to calibrate ion MCP in situ and test E field+

*3 shifts for in-situe β energy calibration from trapped atoms ^{38g}K, $Q_{\beta+}$=2.96 MeV (^{37}K $Q_{\beta+}$=5.12 MeV)

This produces discovery potential on previous slide, assuming 8e7/s ^{37}K

this is the Ph.D. thesis of J. McNeil, UBC



Relation to TRINAT experiments:

S1810 ^{92}Rb 0^- to 0^+ β decay with TRINAT, ν spectrum of fission product

Data-taking complete. (Will not use 8 H + 4 M priority shifts remaining).

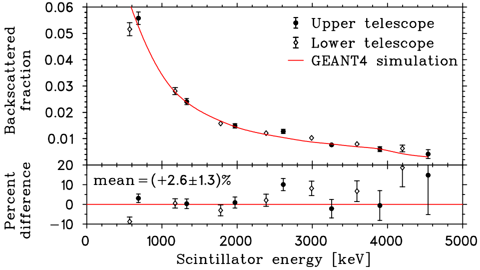
- S1603 Time-reversal violation in radiative β decay. 8 H priority shifts remaining on TiC. Recruiting a student. Ready. Best done with ^{38m}K, trigger incompatible with S1188

new S2266 ^{45,47}K Isospin breaking and time-reversal symmetry in ^{45,47}K decay

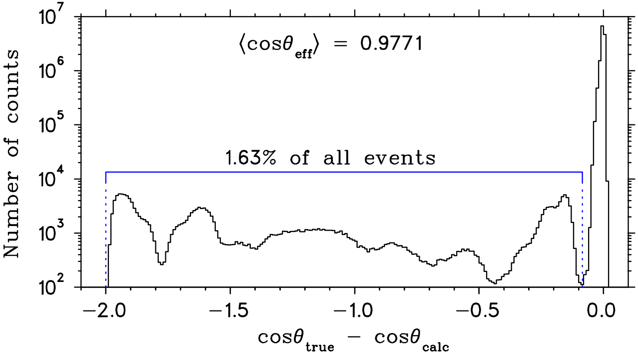
See 2266 talk. Request is 15 shifts TiC and 15 shifts UCx

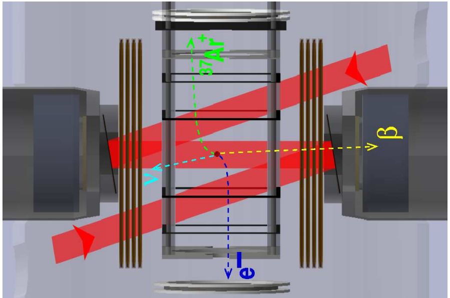
Scattered β's

E_β backscatter is well-characterized by our measurements benchmarking simulations (Fenker 2018 PRL).

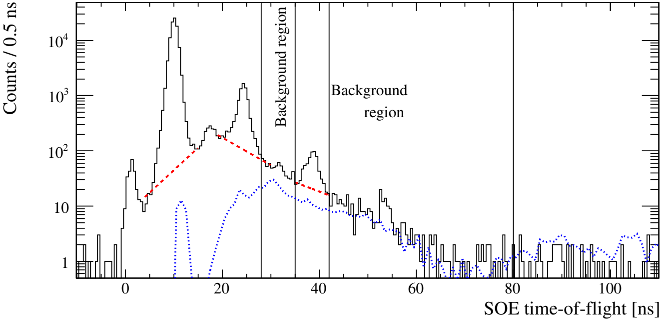


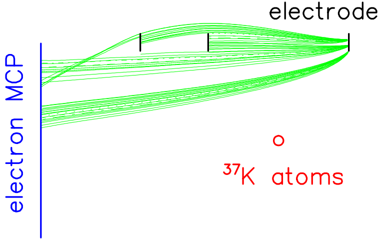
We are reducing the backscattering 2-3x by covering SS collimator with glassy carbon.
Extend to lower E_β, benchmark GEANT4 with higher statistics





Background in β - shakeoff e^- coincidence





$|\vec{E}|$ = 0.15 kV/cm

- 2.8×10^{-3} of events in main peak are background from non-trapped atoms
- Conservatively assume polarized between 0 and 100%.
  $\rightarrow A_\beta \times (1.0014 \pm 0.0014)$
- These will be removed by MCP position info when we run at design *E* field 1 kV/cm

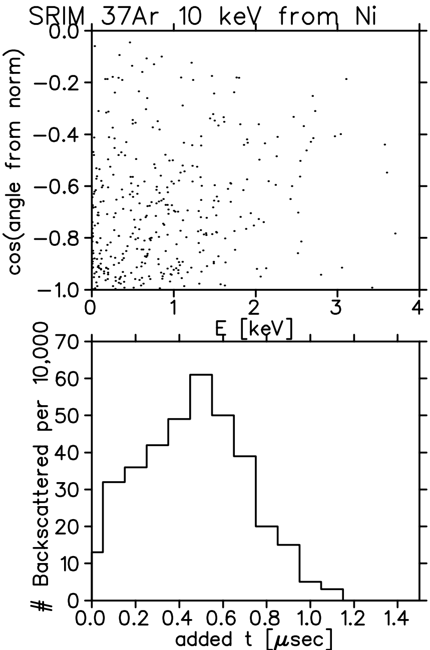
TRIUMF Ions backscatter

- **SRIM: ∼ 5% 10 keV Ar backscatter from nichrome**
  the $\vec{E}$ field will re-collect ions

- **F. Meyer et al. Phys. Scr. T92 182 (2001) experiment suggests ∼ 10% remain ionized.**

So ∼ 0.1% of the ions could trigger events significantly later. Study by multiple hits?

This effect was measured to be larger in ^{6}He decay where recoils have higher kinetic energy and velocity (P. Mueller et al. PRL 129 182502 (2022))



ISAC Yields ^{37}K from TiC

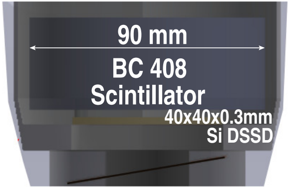
2002	6.4e7/s	40 μA
2012	3.2e7/s	40 μA
2012	3.8e7/s	40 μA
2014	8e7/s	70 μA

2014 target yield was very robust through 3+ weeks of running

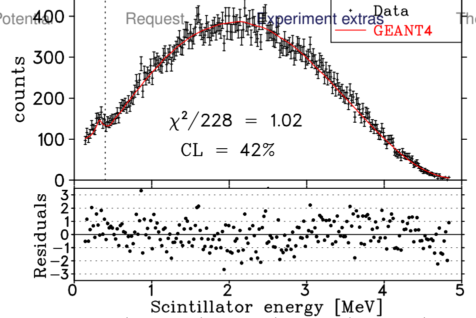
The increase from 2012 to 2014 was thought to be at least partly from finer mesh of ground TiC.

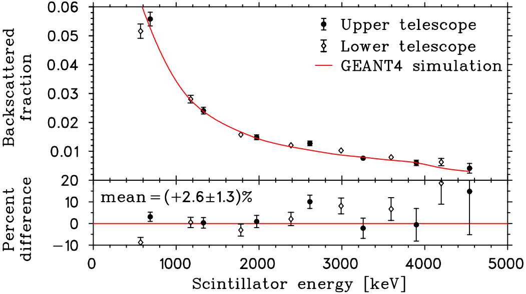
Note rotating proton beam has not been tried on the 2014 HP TiC design

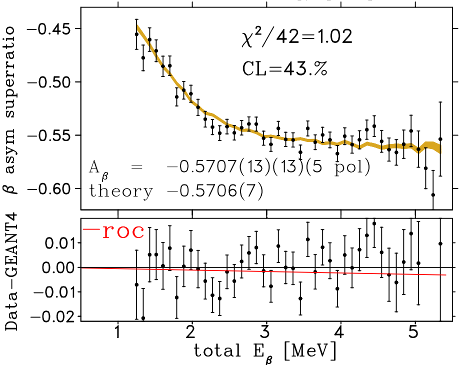
β^+ asymmetry ^{37}K data



DSSD rejects BC408 backscatter

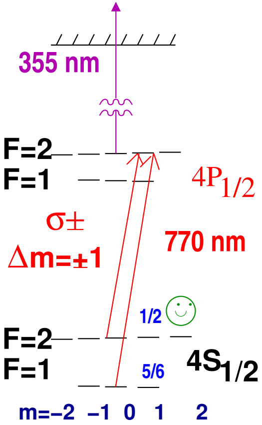






- **Backscatter from scint agrees to ≈5% over $E_{\beta+}$ range of interest**

Optical pumping and probing ^{37}K

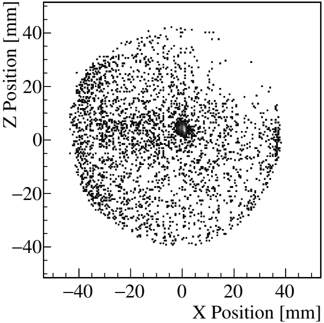


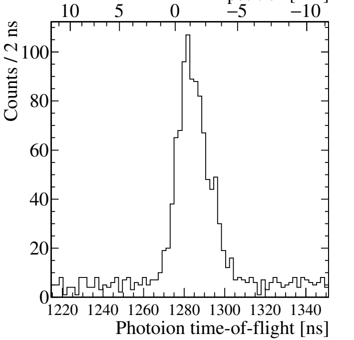
1 of 10 data sets

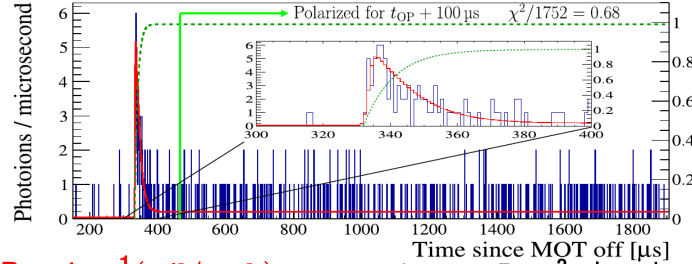
Photoionize 1% ***in situ* probe**

P_+=+0.9913(8) P_-=–0.9912(9)

Fenker NJP 2016





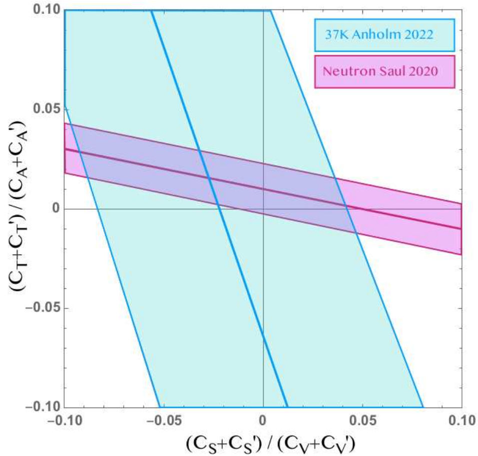


$P \approx 1 - \frac{1}{3}(\text{tail}/\text{peak})$ unpumped atoms $P \sim \frac{2}{3}$ already

b_{Fierz} from $A_\beta[E_\beta]$ M. Anholm Ph.D. thesis, U. Manitoba, Dec 2022

Uncertainty budget		Projected
Scintillator Calibration	0.003	
Scintillator Threshold	0.004	
DSSD Individual Strip SNR	0.006	
DSSD Energy Agreement	0.005	
DSSD Detection Radius	0.006	
DSSD Energy Threshold	0.005	
Atomic Cloud	0.002	
Background	0.004	
Beta Scattering	0.031	$\rightarrow$ 0.010
Low Energy Tail	0.008	
Mirror Thickness	0.013	$\rightarrow$ 0.001
DSSD Thickness	0.013	
Beryllium Foil Thickness	0.004	
Total Systematics	0.039	$\rightarrow$ 0.022

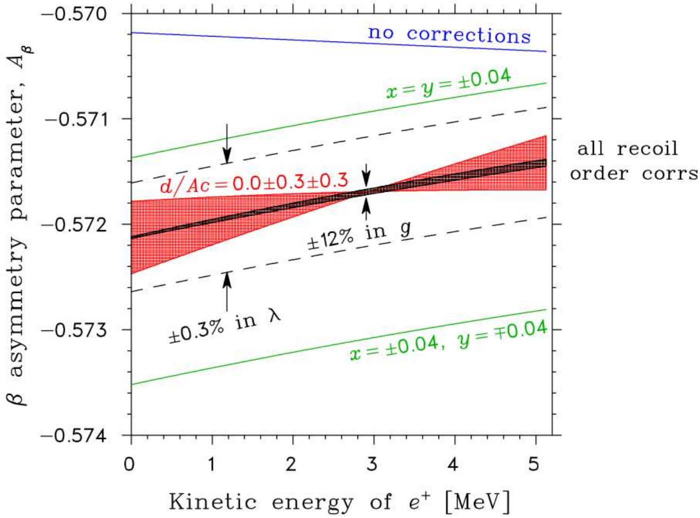
$b_{\mathrm{Fierz}} = 0.033 \pm 0.084(\mathrm{stat}) \pm 0.039(\mathrm{syst})$



S,T sensitivity is complementary to neutron β decay
$|M_{GT}|^2 \approx 3/5$ for ^{37}K, 5x smaller than in neutron decay

^{37}K: recoil-order effects to 2nd order

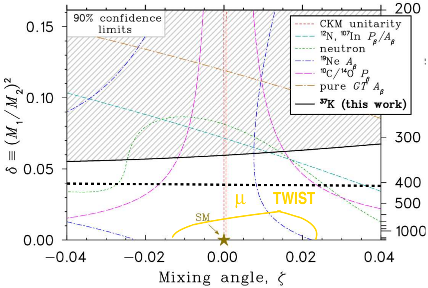
from D. Melconian TRIUMF EEC 2008 proposal

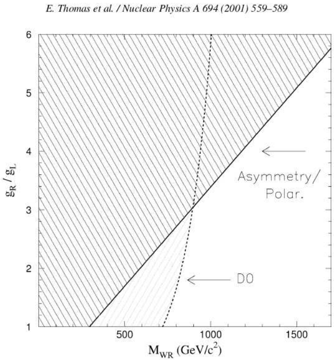


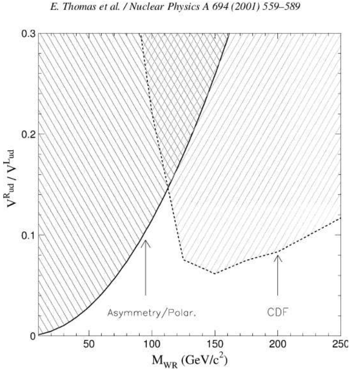
g is the 2nd-order electric quadrupole moment weak analog CVC prediction, measured better now

Other physics of A_β Independent of E_β

as of Fenker et al. PRL 2018:





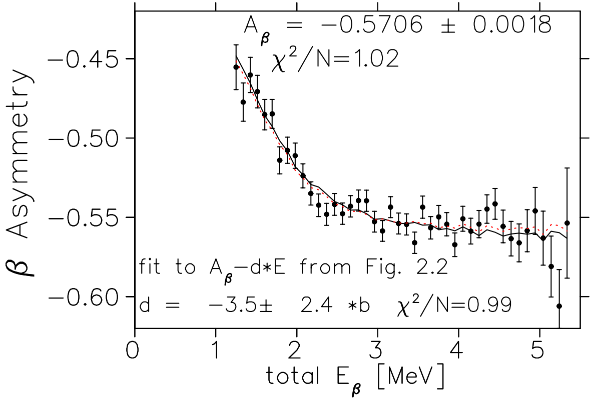


Right-handed V+A currents from nuclear and neutron β decay, in manifest left-right model
Projection for 3x better A_β

$g_R > g_L$:
^{37}K $\Rightarrow g_R \lesssim 7.7$ at 4 TeV (or $g_R < 4$, at 2 TeV but LHC7 2 TeV 'bump' had $g \sim 0.5$)

$V^R_{ud} < V^L_{ud}$
For $M'_W < 70$ GeV, nuclear β decay constrains $V^{\rm R}_{\rm ud}$

2nd-class currents: unconstrained by $pp \to e + p_\perp$



"2nd-class" weak interactions violate g-parity (charge symmetry) when quarks are combined by QCD into nucleons.

"Induced tensor" $d \approx 0$ in isobaric mirror decay.

- **"To provide for 2nd-class currents it would be necessary... to introduce 2 pairs of quarks and to suppose that each is a doublet under strong interactions..." Holstein and Treiman, PRD 13 3059 (1976). There are more experimental constraints now on this interesting possibility**

↑ A strongly interacting dark sector?

Complementary to other nuclear β decay (Sumikama PRC 2011) in models with two strong-interaction couplings, where 2nd-class currents change with nucleus (Wilkinson EPJA 2000)

BABAR set best 3rd-generation constraints PRL 2009 $\tau^- \to \omega\pi^-\nu_\tau$