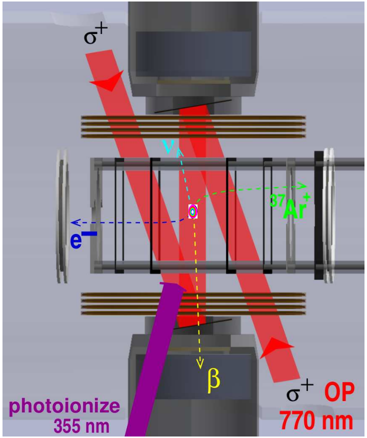
ν helicity & time-reversal breaking with TRIUMF's neutral atom trap for β decay



- **get ν momentum from the decay products**
- **Spin-polarize ^{37}K 99.1±0.1% by direct optical pumping**

- **Angular correlations of β^+ and ν are determined by their helicities (and angular momentum conservation)**

  We test whether parity is completely broken $\leftrightarrow$ leptons left-handed, antileptons right-handed

  In ^{37}K decay we plan the most direct ν helicity measurement since BNL 1957

- **Sensitivity to time-reversal breaking $\vec{I} \cdot \vec{v_\beta} \times \vec{v_\nu}$ enhanced in isospin-forbidden β decay ^{47,45}K**

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This is traditional Wolastoqey land; TRIUMF acknowledges centuries of ongoing stewardship by the Musqueam people.

"Good people are key. **Be Nice.**" Jan Hall, APS DAMOP 2006 Nobel lecture

Nuclear and neutron β decay progress

- V_{ud} new radiative corrections break CKM unitarity at 0.1% at 3σ ☺

Seng Gorchtein Ramsey-Musolf PRD 100 013001 (2019)

Seng PRL 130 152501 (2023) (1- $q^2 R^2_{\rm weak}$) fixes CKM but breaks CVC? ☺ ☺

- PERKEO III has improved neutron $A_\beta[E_\beta]$, 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. ☺

Consistent with a Lorentz tensor (i.e. not like E&M vector!)

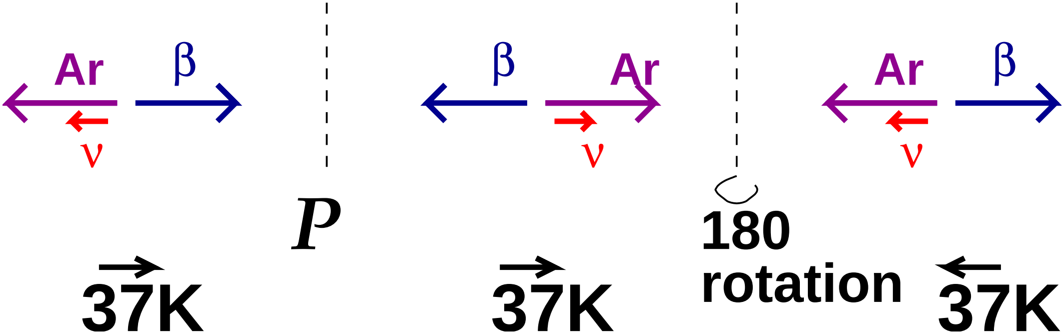
coupling to right-handed ν (global fit Falkowski JHEP04 (2021) 126)

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

Decays: Parity Operation can be simulated by Spin Flip

Under Parity operation $\mathcal{P}$:

$\vec{r} \rightarrow -\vec{r}$ $\quad$ $\vec{p} \sim \frac{d\vec{r}}{dt} \rightarrow -\vec{p}$ $\quad$ $\vec{J}=\vec{r} \times \vec{p} \rightarrow +\vec{J}$



$\Rightarrow$ A spin flip corresponds exactly to $\mathcal{P}$ reversal.

Decays don't exactly test T-reversal symmetry because $|i\rangle \not\leftrightarrow |f\rangle$ ☹

One experimental discovery of parity violation

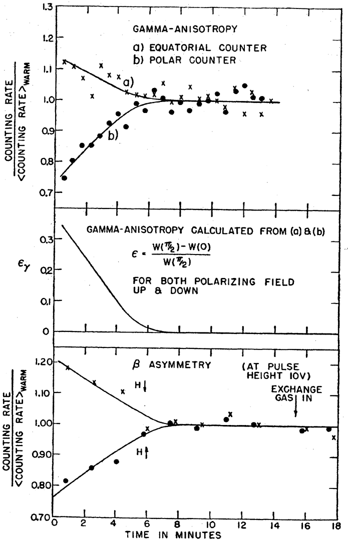
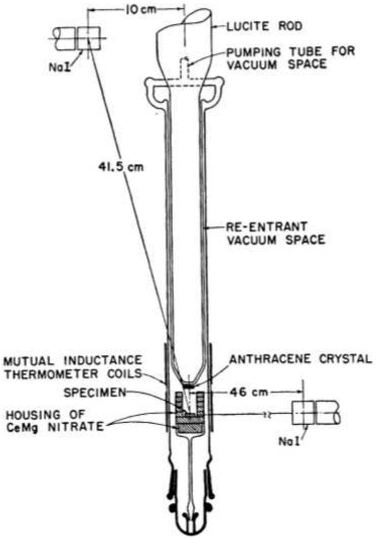


FIG. 2. Gamma anisotropy and beta asymmetry for polarizing field pointing up and pointing down.



Wu, Ambler, Hayward, Hopper, Hobson, PR 105 1413 Feb '57

Dilution Refrigerator to spin-polarize

$$^{60}\text{Co} \to {}^{60}\text{Ni} + \beta^- + \bar{\nu}$$

$$I^\pi = 5^+ \quad 4^+$$

$$W[\theta] = 1 + PA\hat{I} \cdot \frac{\vec{p}_\beta}{E_\beta}$$

$$= 1 + A\frac{v}{c}\cos[\theta]$$

$$A_{\beta-} \approx -1.0$$

This measures the β^- helicity, but not ν

Measure ν helicity $\epsilon=\hat{s}_\nu \cdot \hat{k}_\nu$ directly: transfer $\hat{s}_\nu$ to γ circular polarization; boost $\vec{k}_\gamma$ by $\pm\vec{k}_\nu$

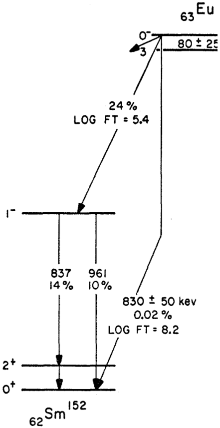
Goldhaber, Grodzins, Sunyar Phys Rev 109 1015 (Dec 1957)

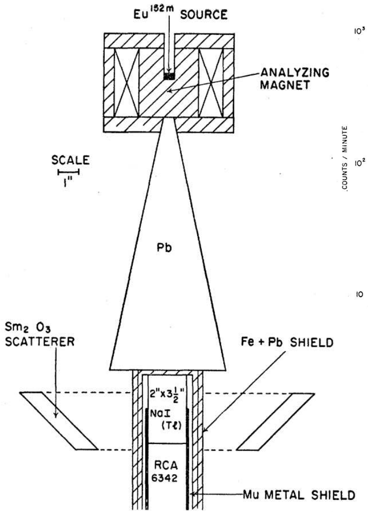
$$e^- + {}^{152m}\mathrm{Eu} \to \nu + {}^{152}\mathrm{Sm}$$

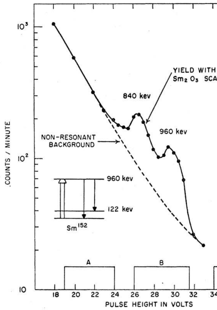
- **Upward-going ν populates $\langle I_z \rangle = 0, +1$ not -1**
- **So γ is circularly polarized–transmission through magnet depends on iron polarization: $\frac{N_+ - N_-}{N_+ + N_-}$=0.017$\pm$0.003**
- **Upward ν boosts γ momentum so it can be absorbed on-resonance**

$\Rightarrow$ ν helicity -1 $\pm$ 10%

(• $\bar{\nu}$ helicity $\sim$ +1 Palathingal PRL 524 24 '69)







Surprisingly enough, this is the best direct measurement of ν helicity = $\hat{s}_\nu \cdot \hat{k}_\nu$

β^+ asymmetry ^{37}K data

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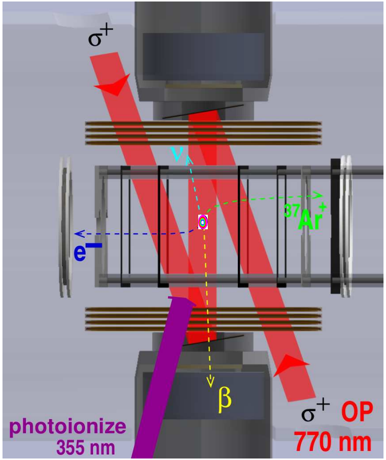
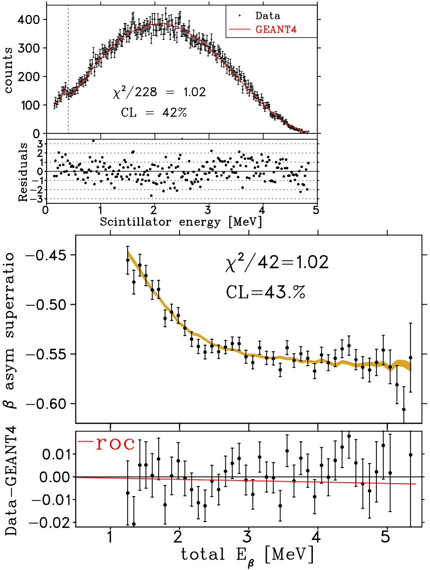




Fenker et al. Phys Rev Lett 120, 062502 (2018)

A_β[experiment]= -0.5707 $\pm$ 0.0019

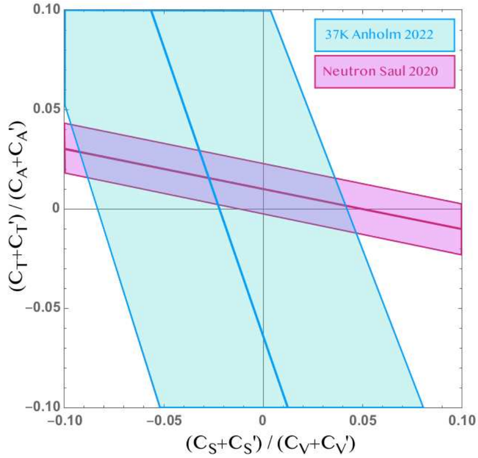
A_β[theory] = -0.5706 $\pm$ 0.0007

Neutron and ^{19}Ne have since achieved similar fractional accuracy

$A_\beta[E_\beta]$ contrains $(1+b_{\rm Fierz}m/E)$ 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

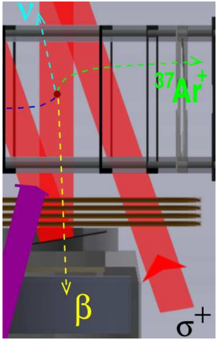
$b_{\rm Fierz}$ = 0.033$\pm$0.084(stat)$\pm$0.039(syst)

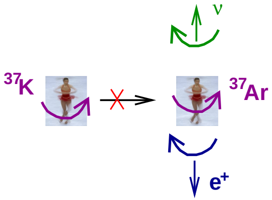


S,T sensitivity is complementary to neutron β decay
$|M_{GT}|^2 \approx 3/5$ for ^{37}K, 5x smaller than in neutron decay

A different isospin mirror-decay spin-polarized observable

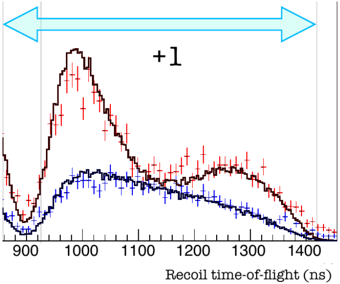
Isobaric mirror decay has helicity-driven null





Nearly direct ν helicity measurement (assuming the β^+ helicity)

2014 polarized β-recoil



$I^\pi = 3^+ \rightarrow 2^+$ decay of ^{38g}K or $I^\pi = 1^+ \rightarrow 0^+$ ^{80}Rb would complete a direct ν helicity determination

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

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

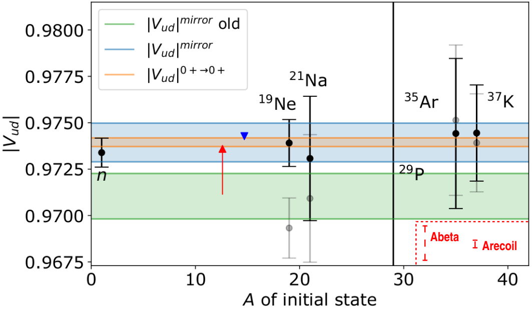
The neutron community checks this combination of observables for consistency

Mostovoi+Frank Pis'ma Zh. Eksp. Teor. Fiz. 24 45 (1976)

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

TEXAS A&M UNIVERSITY

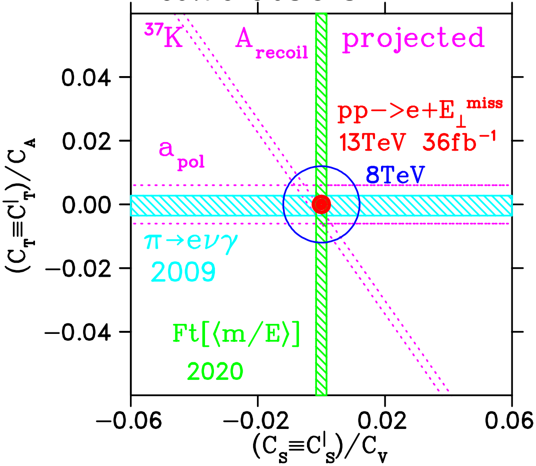
Deduced V_{ud} from mirror decays
Hayen and Young,
arXiv:2009.11364
including G-T radiative correction



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

A_{recoil} depends on $M_{\mathrm{GT}}/M_{\mathrm{F}}$,
a_{pol} does not

90% exclusions:

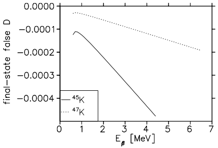


Assuming T2K confirms $\not{CP}$ Nature 580 339 (2020) and convincingly generates Sakharov's baryon asymmetry, looking for $\not{T}$ remains kewl for its own sake

When designing $\not{T}$ decay experiments like D $\vec{I} \cdot \vec{v_\beta} \times \vec{v_\nu}$:

- **What underlying physics generates the $\not{T}$?**

parity-even isospin-breaking nucleon-nucleon interactions



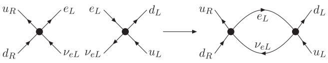
- **(For Decays) How big are the 'final state effects'?**

Estimate in ^{47,45}K is much smaller than our projected experimental uncertainty

- **Is anyone else doing it better?**

Our projected sensitivity to $\not{T}$ parity-even interactions is similar to NOPTREX neutron resonance experiments. Isospin-breaking $\not{T}$ makes us complementary

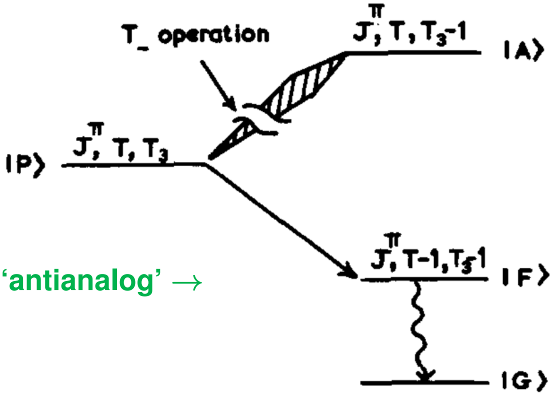
- **How strong are the contraints from null EDM's?**



By specializing to isospin-breaking $\not{T}$, we relax the Ng-Tulin PRD85 033011 bound– i.e. D $< 10^{-4}$ from neutron EDM– by about two orders of magnitude

$\not{T}$ in isospin-hindered β^- decay

Barroso and Blin-Stoyle, PL 45B 178 (1973) observables:



'antianalog' $\rightarrow$

$D\,\hat{\mathbf{J}}\cdot\frac{\vec{p}_\beta}{E_\beta}\times\frac{\vec{p}_\nu}{E_\beta}$

$E_1\,(\hat{\mathbf{J}}\cdot\hat{k}_\gamma)(\hat{\mathbf{J}}\cdot\hat{p}_\beta\times\hat{k}_\gamma)$

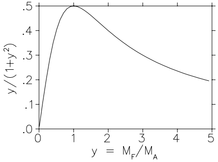
D, E_1 are both proportional to

$$K = \frac{Im(G_V G_A^* M_V M_A^*)}{|G_V|^2|M_V|^2+|G_A|^2|M_A|^2}$$

$$= y/(1+y^2)\,\sin(\alpha_V - \alpha_A)$$

with $y = \frac{g_V|M_V|}{g_A|M_A|}$

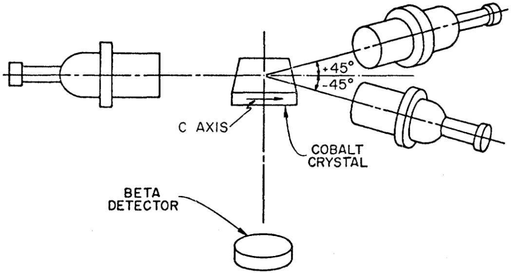
In this system, $\tan\alpha_{\rm V} = -{\rm i}\,\frac{\langle F|V_{\not{T}}|A\rangle}{\langle F|V_{\rm Coul}|A\rangle}$



So for $\not{T}$ physics mixing $|F\rangle$ with $|A\rangle$, then $V_{\not{T}}$ is only competing with $V_{\rm Coul}$, not $V_{\rm strong}$, enhancing α_V by $\sim 10^3$ ☺

^{56}Co $\not{T}$ experiment

Asymmetry of the 45º γ detectors with nuclear alignment



"Test of time-reversal invariance in the beta decay of ^{56}Co"
Calaprice, Freedman, (Princeton); Osgood, Thomlinson (BNL)
PRC 15 381 (1977)

E_1 = -0.01 $\pm$ 0.02

log(ft) = 8.7, yet known allowed: E_β spectrum, no β-γ correlation)

y = -0.13$\pm$0.02 PRC 26 287R (1982)
Markey, Boehm (RIP Felix 2021)

$V_{\rm Coul}$= 2.9 keV, $V_{\not{T}} = 54 \pm 110$eV
(J.L. Mortara Ph.D. thesis 1999 UCB
$E_1 = -0.001 \pm 0.006$
$\Rightarrow$ $V_{\not{T}}$ = 5$\pm$ 33 eV)

We believe we can measure D in ^{47,45}K much more accurately than E in ^{56}Co, but we must find a case with $|M_{GT}|$, $V_{\rm Coul}$, and $\not{T}$ N-N matrix elements to allow complementary or better sensitivity to $V_{\not{T}}$

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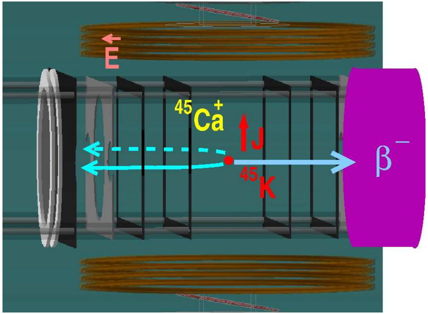
D $\vec{I} \cdot \vec{v_\beta} \times \vec{v_\nu}$ in atom trap: Features, Systematics



- **Collect recoils going into 4 pi with electric field of 1 kV/cm**
- **Full reconstruction of recoil and beta momenta**
- **Point source: we know where it is (by sampling photoionization) and it doesn't move when we flip the polarization**

D Uncertainties / 100 scaling from Melconian PLB 649 270 (2007)

	B_ν	Improvements	Projected
Cloud position $\sigma^\pm$	1.3	$\pm 500\mu$m $\rightarrow \pm 20\mu$m	0.05
Cloud size/Temp	0.3	" "	0.03
MCP Position cal	1.0	DLA+ mask	$\lesssim 0.1$
$\hat{x}$-OP alignment	0.25	Geometry is $\perp$	$\lesssim 0.02$
E field	0.2		$\lesssim 0.1$

- **Any stray polarization along wrong axis is deadly, a lowest-order fake D: Measure with singles asymmetry for recoils and β's**

Motivation for Analog-antianalog mixing

N. Auerbach, B.M. Loc arXiv:2101.06199v3

Coulomb corrections Fermi β decay

- **A-$\bar{A}$ mixing (T $>$ 1: only T=2 0^+ for V_{ud} are affected)**

$\delta_C[A\bar{A}]$ can be a few %.

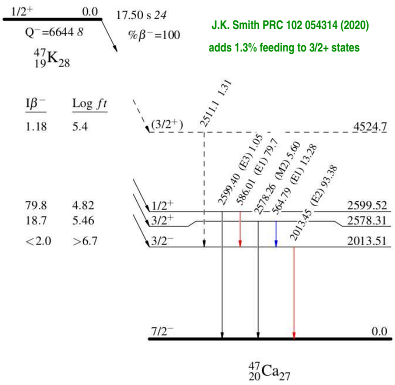
They consider nuclei with the excess neutrons occupying orbits in different major shells, with relatively small isospin.

$A\bar{A}$ mixing explains isospin-forbidden particle decays, Γ_A: A a well-defined single resonance.

Fragmentation of $\bar{A}$ is usually greater, but...

HO estimate: $\langle\bar{A}|V_C|A\rangle = 0.35\frac{\sqrt{n_1 n_2}}{2T}\frac{Z}{A^{2/3}}$ **MeV**

^{88}Sr	250 keV	Skyrme interactions $\Rightarrow$ 250 to 310
^{71}As	300	28$\pm$ 4 Severijns PRC 71 064310 2005 Fragmented $\bar{A}$
^{56}Co	160	2.9$\pm$0.5 Markey PRC 26 287R 1982 Fragmented $\bar{A}$
^{45}K	200	? $\bar{A}$ fragmented like 71As?
^{47}K	190	$\bar{A}$ might be one state! ☺
A=32	δ_C=0.25%	T=2 A δ_C= 1-2% Melconian PRL 107 182301 2011



J.K. Smith PRC 102 054314 (2020)
adds 1.3% feeding to 3/2+ states

The analog is:

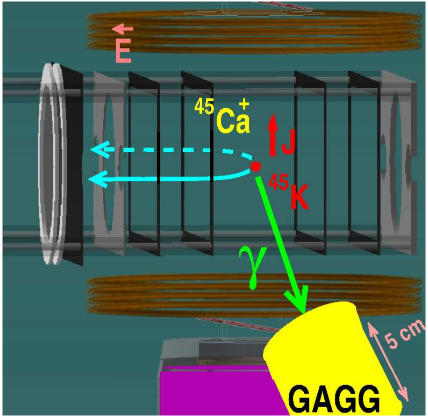
$$|A\rangle = \frac{1}{\sqrt{2T}}\left[\sqrt{n_1}\,|j_1^{n_1-1}(n)j_1(p)j_2^{n_2}(n)\rangle + \sqrt{n_2}\,|j_1^{n_1}(n)j_2^{n_2-1}(n)j_2(p)\rangle\right]$$

The anti-analog $|\bar{A}\rangle$ is then:

$$|\bar{A}\rangle = \frac{1}{\sqrt{2T}}\left[\sqrt{n_2}\,|j_1^{n_1-1}(n)j_1(p)j_2^{n_2}(n)\rangle - \sqrt{n_1}\,|j_1^{n_1}(n)j_2^{n_2-1}(n)j_2(p)\rangle\right].$$

TRIUMF

$A_{\rm recoil}$ to measure $\langle F|V_{\rm Coul}|A\rangle$ in ^{45,47}K



- $A_{\rm recoil} \propto A_\beta + B_\nu$ $A_{\rm recoil} \xrightarrow{p_{\rm recoil} \gg m_\beta} 5/8(A_\beta + B_\nu)$
  - So $A_{\rm recoil}$ = 0 for pure Gamow-Teller

$$A_{\rm recoil} = 2\sqrt{\frac{J}{J+1}}G_V M_V/G_A M_A$$

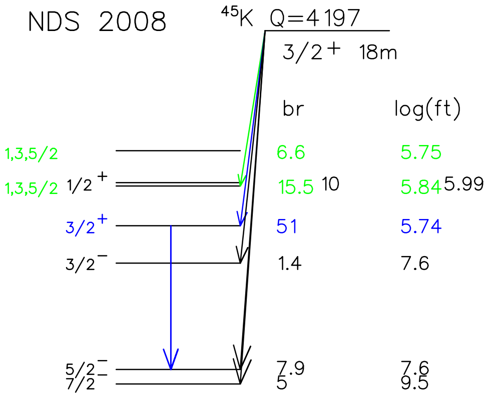
linear in M_V/M_A

- Recoil-γ coincidences to select the antianalog

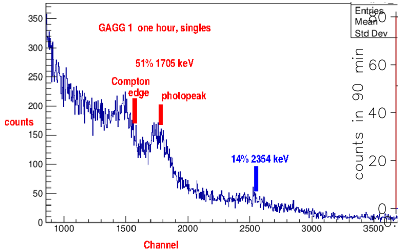
$A_{\rm recoil}$ Uncertainties*100

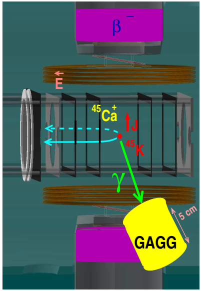
Melconian PLB 649 270 (2007)	B_ν	Improvements	Projected
Polarization	0.8	$B_\perp$, $\sigma^\pm$	0.05
Cloud position	1.3	500 μm $\rightarrow$ 20μm	0.05
Cloud size/Temp	0.3	" "	0.03
MCP Position cal	1.0	DLA+ mask	$\lesssim$ 0.1
E field	0.2	Data at 2 fields	$\lesssim$ 0.1

We measured $A_T = 0.015(29)(19)$ for G-T decay of ^{80}Rb see Pitcairn PRC 79 015501 (2009)



^{45}K decay to antianalog



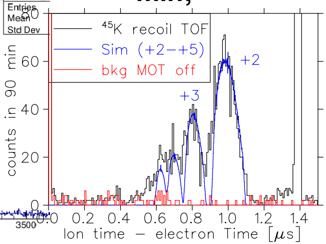


51% branch to 3/2+ state in ^{45}Ca. Should include the antianalog configuration,

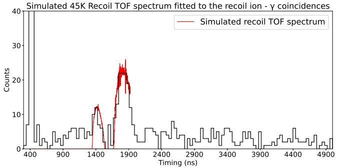
$\langle F|V_{\rm coul}|A\rangle \sim$ 5 to 50 keV ?

A_β, $A_{\rm recoil}$ would answer 15.5% branch to 1/2.3/2.5/2?

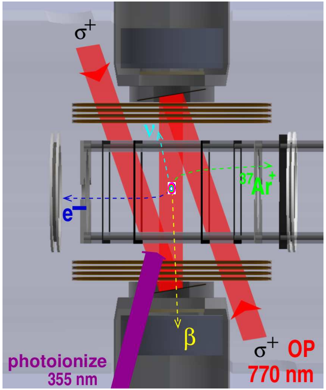
shakeoff e$^-$ & recoil clean even for $t_{1/2}$=18 min;



γ & recoil is a challenge that will be cleaner in ^{47}K:



ν helicity & time-reversal breaking with TRIUMF's neutral atom trap for β decay



$p_{^{37}\mathrm{Ar}}$: uniform $\vec{E}$,
MCP for TOF and position
p_β: from δE + E
$\rightarrow p_\nu$ event-by-event
Spin-polarized ^{37}K 99.1$\pm$0.1%
Our ν's must have $m_\nu < 5$ MeV

- Angular correlations of β^+ and ν are determined by their helicities (and angular momentum conservation)

  We want to improve our A_β measurement in ^{37}K decay (and A_{recoil}, a_{pol}) to ask: is parity completely broken ? $\leftrightarrow$ leptons left-handed? , antileptons right-handed?

  We plan the most direct ν helicity measurements since BNL 1957

- ν spectrum from fission product ^{92}Rb
- $\not{T}$ in $p_\gamma \cdot p_\beta \times p_\nu$ would be unique in first generation

- Measuring ~~isospin~~ in ^{47,45}K will measure antianalog configuration purity and determine sensitivity to parity-even ~~isospin~~ $\not{T}$ interactions via $D\vec{I} \cdot \vec{v_\beta} \times \vec{v_\nu}$

Entanglement? $\rightarrow$

entanglement ? consider EC decay in an atom trap next to SNO+

SNO$^+ \leftarrow \nu$ ^{131}Cs ^{131}Xe$^+ \rightarrow$ MCP

Given:

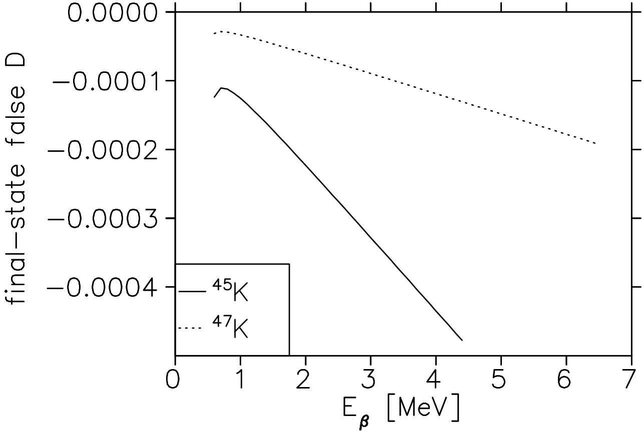
- Cohen Glashow Ligeti PLB 678 191 (2009): ψ_f has ν_e mass eigenstates entangled with $\psi_{^{131}Xe}$ to keep E and p conserved
- Formaggio Kaiser Murskyj WeissPRL 117 050402 (2016) ν oscillations show Leggett-Garg inequality
- Kayser Kopp Robertson Vogel PRD 82 093003 (2010): recovered the standard oscillation relation between path length, E_ν, and m_ν

It is simple to sweep the electric field collecting the ^{131}Xe to change detection t over the range of t's of SM ν_e oscillations to cover the normal (or inverted) hierarchy i.e.

10^{-4} or 10^{-2} eV$^2 \rightarrow 10^4$ or 10^2 m $\rightarrow$ 300 μs or 3 μs

? Does this cause some kind of Leggett-Garg inequality or delayed-choice experiment?

Final-state (false) D

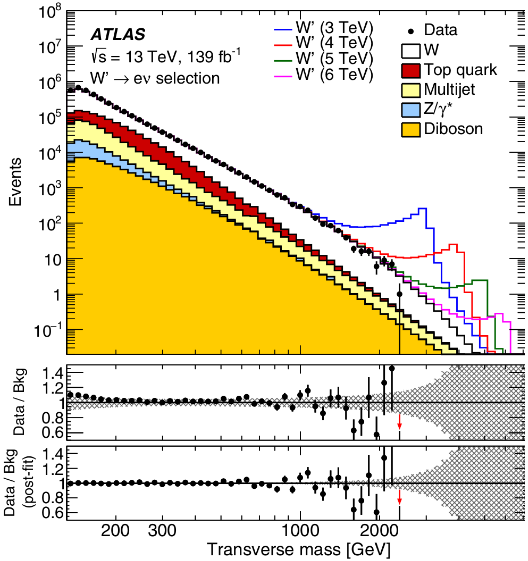


For ^{56}Co final-state E_1=0.0002 (Calaprice 1977)

Holstein PRC 5 1529 (1972)

- **Assumes weak magnetism *b* and induced tensor *d* are single-particle values, not suppressed like M_A $\Rightarrow$ Should be an upper limit**
- **Needs a full calculation, but should be OK**

Quasi-direct limits from high-energy colliders: update

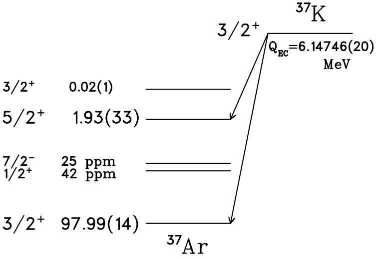


LHC13 $\sigma[p + p \to e + \text{missing } p_\perp]$ is related to $n \to p + e + \nu$ by EFT (to scale the momentum transfer dependence, etc.) see Gonzalez-Alonso, Naviliat-Cuncic, Severijns, Prog Par Nuc Phys 104 165 (2019):

$\leftarrow$ 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 $\sim$ 2025
A tight constraint on exchange of new TeV-scale bosons

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



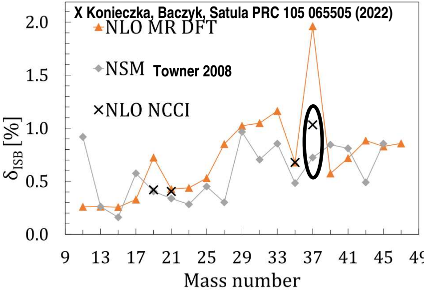
$\mathcal{F}t$ (Shidling PRC 2014) = 4576 $\pm$ 8 s
Ozmetin et al. TAMU Branch to 5/2$^+$ improved → PRELIM 4585$\pm$4 s
$\sim$0.0005 for V_{ud} from A_{recoil} becomes possible

CVC ⇒ 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 ⇒**

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

TRIUMF

Polarization=0.991(1) $\rightarrow$ projected 0.9960(5)

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Source	ΔP $[\times 10^{-4}]$ σ^-	σ^+	ΔT $[\times 10^{-4}]$ σ^-	σ^+	ΔP σ^-
SYSTEMATICS					PROJ
Initial T	3	3	10	8	2
Global fit v. ave	2	2	7	6	1
S_3^{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 $\rightarrow$ pellicles for less β^+ scattering

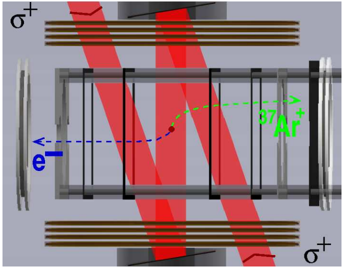
Stern Family of National Photocolor

70nm Au + 4μ Kapton 5λ flatness

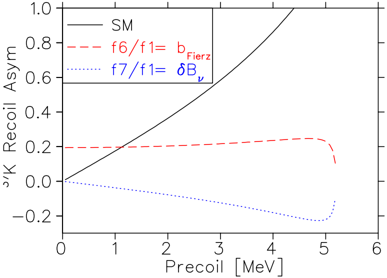
- PCTFE viewport seals
- Lower-frequency AC-MOT
- Double OP power: fight Larmor precession
- Better spin flips TnLC
- 2x more photoionizing light

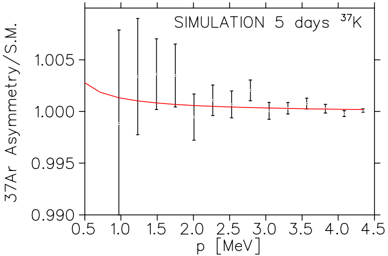
- Uncertainty $\propto (1 - P)$

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



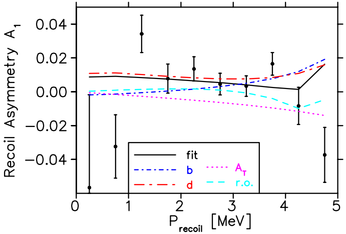
$A_{recoil}[p_{recoil}]$ independent of M_{GT}/M_F





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 $\to$ 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

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Improvements TRIUMF

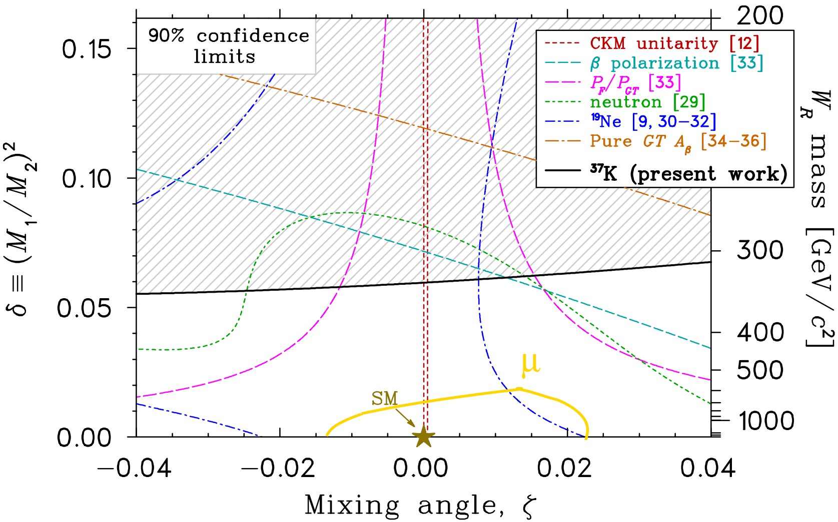
- **Minimize Background by sweeping away e^- with larger $\vec{E}$**
- **Reduce scattering by 2 with lower-Z materials Improve understanding**
- **Reduced energy threshold using pellicle mirrors**
- **Improve statistics**

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 ($\pm 0.4 ch/keV$)	0.1	0.1
Total systematics	12	7
Statistics	13	6
Polarization	5	2
Total uncertainty	18	8

Still no wrong-handed ν's



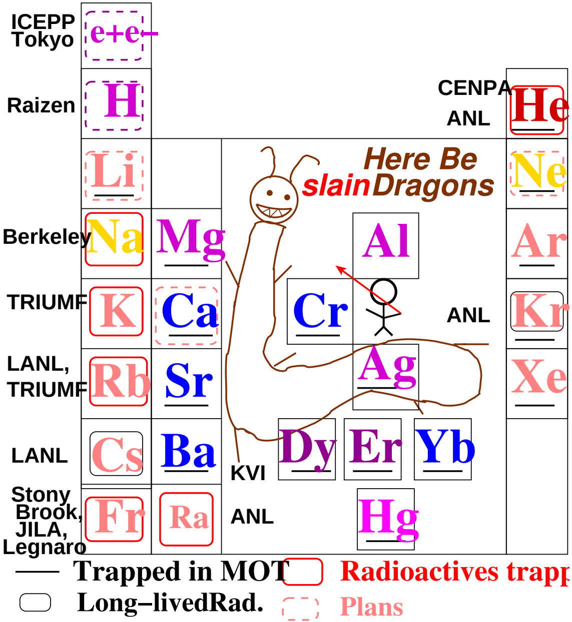
Extra W' with heavier mass, couples to wrong-handed ν_R

We can evade TWIST limits by assuming the muon ν_R is heavy

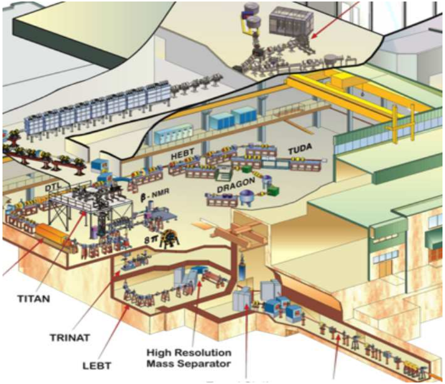
LHC $M'_W > 3.7$ TeV 90%

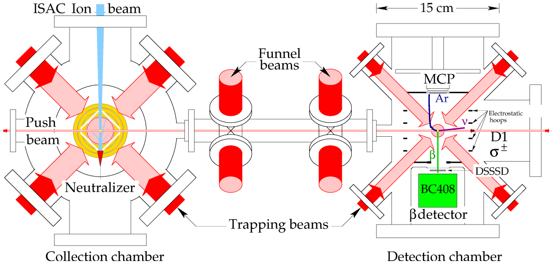
our result does imply $g_R > 8g_L$ for a 4 TeV W'

What elements can be laser cooled?



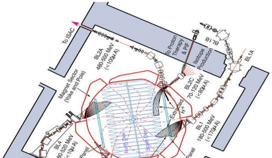
TRIUMF TRIumf Neutral Atom trap at ISAC





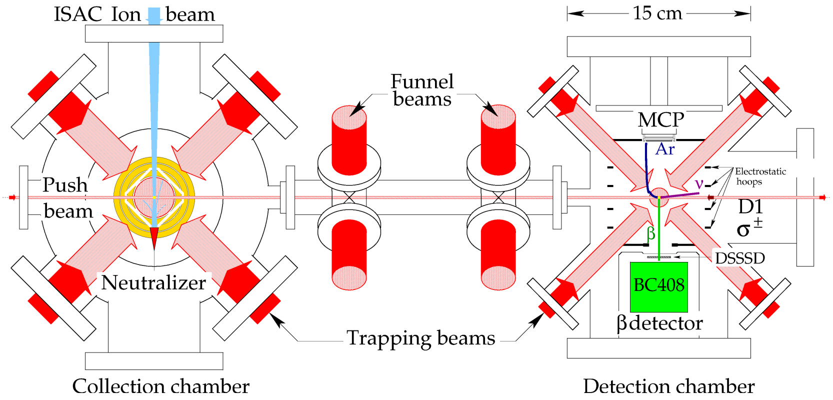
^{37}K 8x10^7/s TiC target 1750^{o}C 70 μA protons

main TRIUMF cyclotron
'world's largest'
500 MeV H$^-$ (0.5 Tesla)



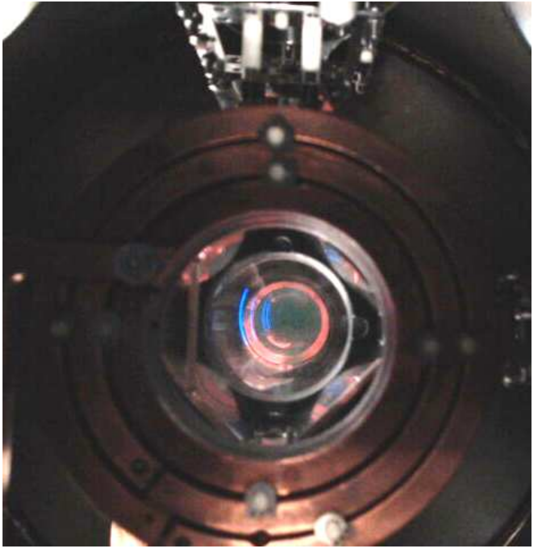
TRINAT plan view

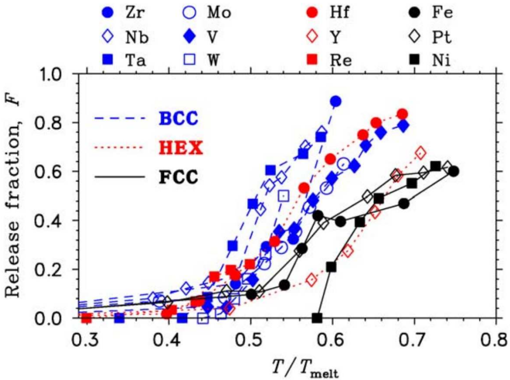
- **Isotope/Isomer selective**
- **75% transfer**
- **Avoid untrapped atom background with 2nd trap**
- **0.7 mm cloud for β-$Ar^+ \to \nu$ momentum**

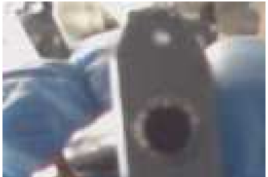


- **Spin-polarized 99.1±0.1%**

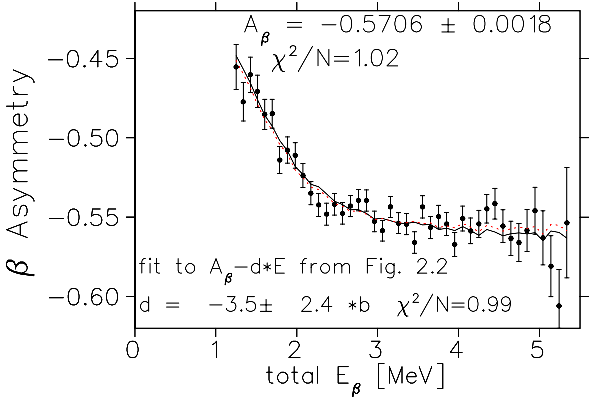
Neutralizer and Collection trap







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 $\to$ d would be 2nd-class

- **"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). (Feynman called the quantum # needed 'smell'.) This scenario constrained by non-beta decay.**

$\uparrow$ 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 $\tau^- \to \omega\pi^-\nu_\tau$

Optical pumping and probing ^{37}K

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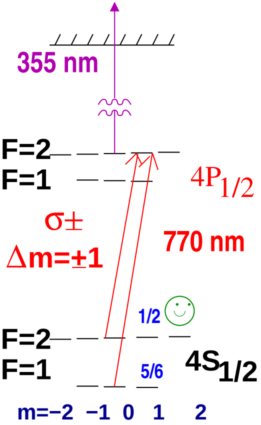
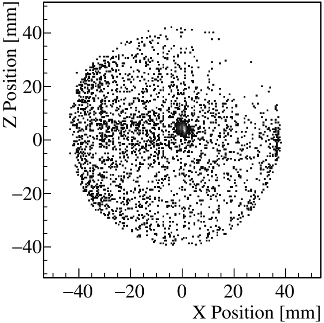
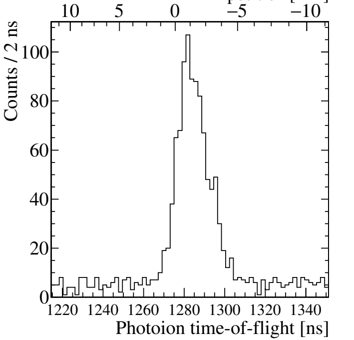
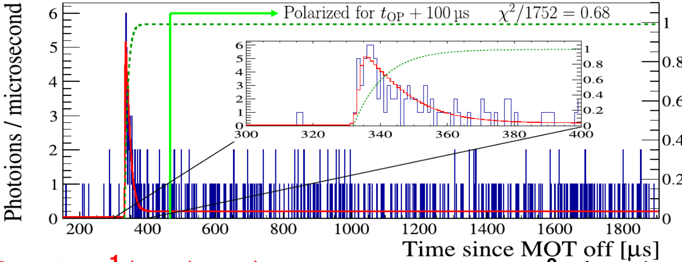


1 of 10 data sets







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

P_+=+0.9913(8) P_-=−0.9912(9)

Fenker NJP 2016

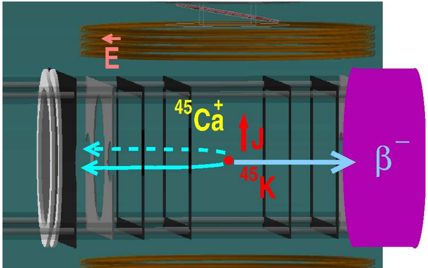
$P \approx 1 - \frac{1}{3}(\text{tail}/\text{peak})$ unpumped atoms $P \sim \frac{2}{3}$ already

TRIUMF

D sensitivity

Extrapolating from Melconian PLB 649 270 (2007) and realizing β^- decay always makes a charged recoil, we estimate 3 weeks for D to $\approx$ 0.001 for ^{45}K from TiC or ^{47}K from UCx.

Given E_1 = -0.01 $\pm$ 0.02 in ^{56}Co and a limit on D about 20x better:



	^{56}Co	^{47}K	^{45}K
exp. $\lvert M_{\rm GT}\rvert$	0.0034	0.30	0.11
$\sqrt{2T}$	2	3	$\sqrt{7}$
y for ^{56}Co	-0.13$\pm$0.02		
for 50keV/10 MeV, $\lvert M_F\rvert$=0.005$\sqrt{2T}$			
$\Rightarrow y$=		0.045	0.12

Then for $\langle \bar{A}| V_C |A\rangle$ = 50 keV
we would get 20x better sensitivity to $\not{T}$ phase α
and similar sensitivity to $V_{\not{T}}$ for ^{45}K vs. ^{56}Co
(and a factor of 3 poorer for ^{47}K because of $|M_{GT}|$)
True sensitivity will be determined by our measurements of $\langle \bar{A}| V_C |A\rangle$ = 50 keV
Since we are sensitive to isovector and isotensor $\not{T}$ parameters (and possible spin dependence) a measurement at similar sensitivity becomes complementary