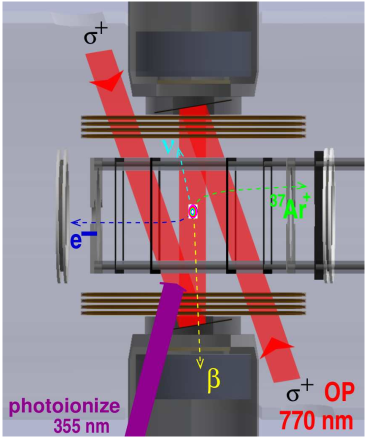
# $\nu$ helicity & time-reversal breaking with TRIUMF's neutral atom trap for $\beta$ decay




- **Angular correlations of $\beta^+$ and $\nu$ 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 $\nu$ helicity measurement since BNL 1957**

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

- **get $\nu$ momentum from the decay products**
- **Spin-polarize $^{37}$K 99.1$\pm$0.1% by direct optical pumping**

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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 $\beta$ decay progress

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

Seng Gorchtein Ramsey-Musolf PRD 100 013001 (2019)

Seng PRL 130 152501 (2023) (1- $q^2 R^2_{\mathrm{weak}}$) 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 $\sigma$ from PERKEO III in GT/F. ☺

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

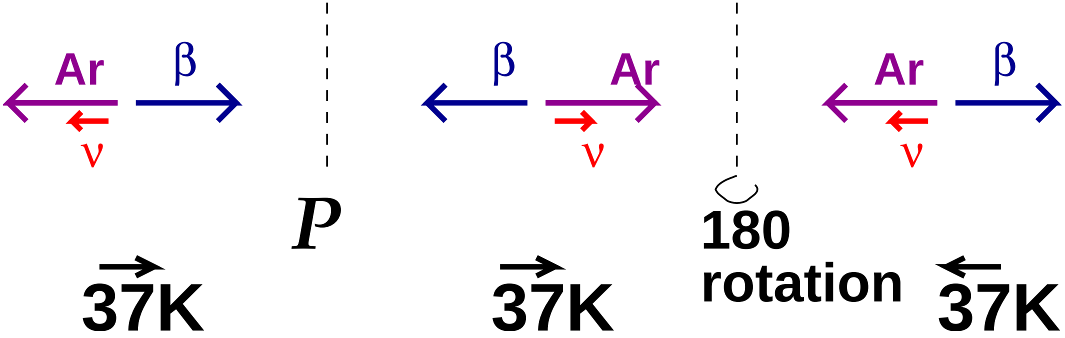
  coupling to right-handed $\nu$ (global fit Falkowski JHEP04 (2021) 126)

  yet ANL $^8Li$, $^8B$ $\beta$ 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 $\mathcal{P}$ :**

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




**$\Rightarrow$ 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

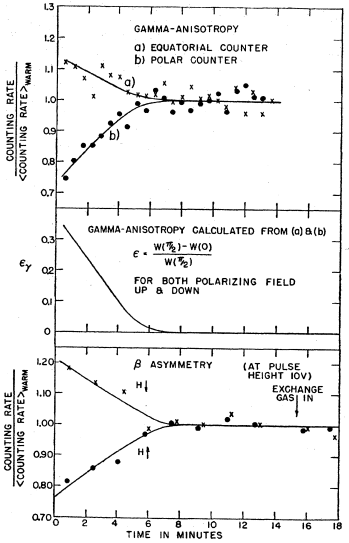
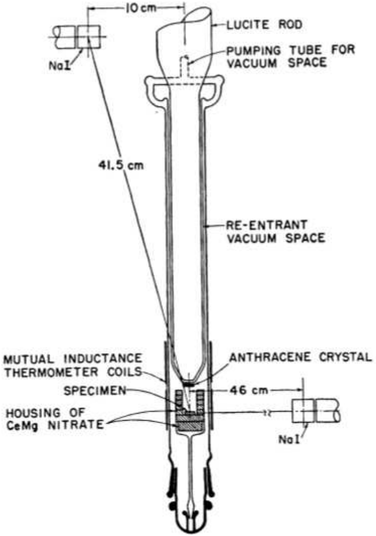



FIG. 2. Gamma anisotropy and beta asymmetry for polarizing field pointing up and pointing down.




**Wu, Ambler, Hayward, Hopper, Hobson, PR 105 1413 Feb ’57**

**Dilution Refrigerator to spin-polarize**

$^{60}\mathrm{Co} \rightarrow {}^{60}\mathrm{Ni} + \beta^- + \bar{\nu}$

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

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

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

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

**This measures the $\beta^-$ helicity, but not $\nu$**

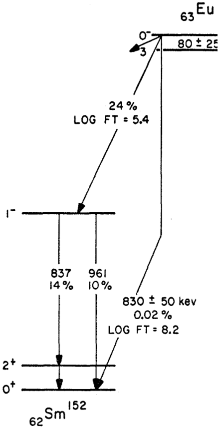
# Measure $\nu$ helicity $\epsilon=\hat{s}_\nu \cdot \hat{k}_\nu$ directly: transfer $\hat{s}_\nu$ to $\gamma$ circular polarization; boost $\vec{k}_\gamma$ by $\pm\vec{k}_\nu$

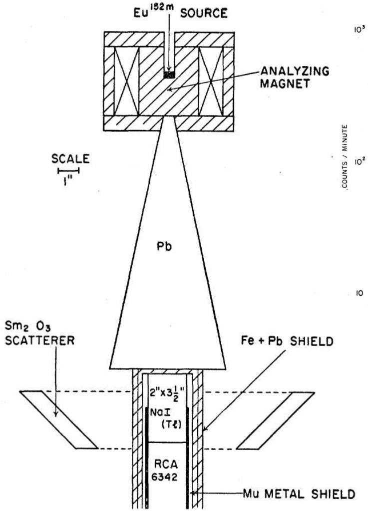
**Goldhaber, Grodzins, Sunyar Phys Rev 109 1015 (Dec 1957)**

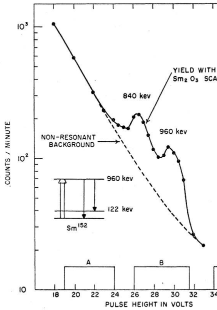
$$e^- + {}^{152m}\mathrm{Eu} \rightarrow \nu + {}^{152}\mathrm{Sm}$$

- **Upward-going $\nu$ populates $\langle I_z \rangle = 0, +1$ not -1**
- **So $\gamma$ is circularly polarized– transmission through magnet depends on iron polarization:** $\frac{N_+ - N_-}{N_+ + N_-}$**=0.017$\pm$0.003**
- **Upward $\nu$ boosts $\gamma$ momentum so it can be absorbed on-resonance $\Rightarrow$ $\nu$ helicity -1 $\pm$ 10%**

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

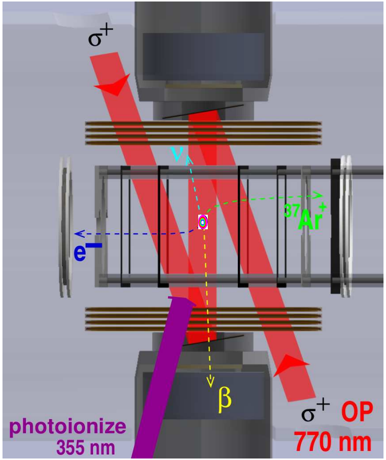


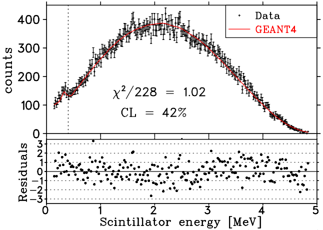



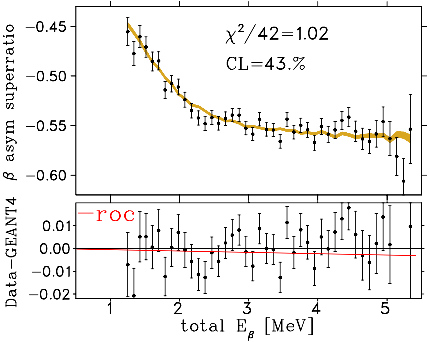




**Surprisingly enough, this is the best direct measurement of $\nu$ helicity = $\hat{s}_\nu \cdot \hat{k}_\nu$**

# $\beta^+$ asymmetry $^{37}$K data




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

**$A_\beta$[experiment]= -0.5707 $\pm$ 0.0019**

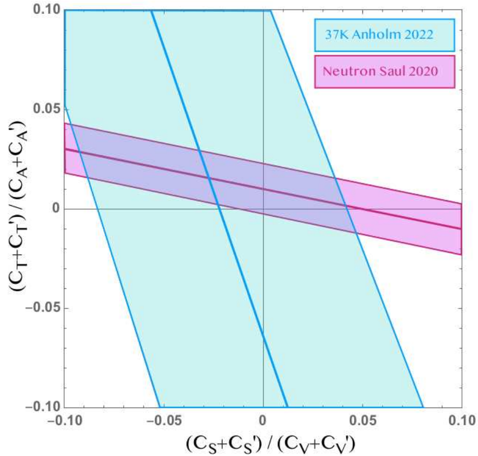
**$A_\beta$[theory] = -0.5706 $\pm$ 0.0007**

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

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

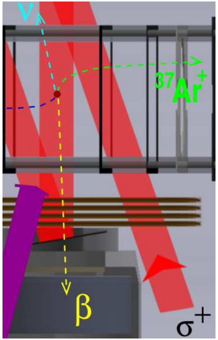
$b_{\mathrm{Fierz}} = 0.033 \pm 0.084(\mathrm{stat}) \pm 0.039(\mathrm{syst})$

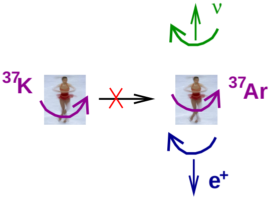



S,T sensitivity is complementary to neutron $\beta$ decay
$|M_{GT}|^2 \approx 3/5$ for $^{37}$K, 5x smaller than in neutron decay

# A different isospin mirror-decay spin-polarized observable

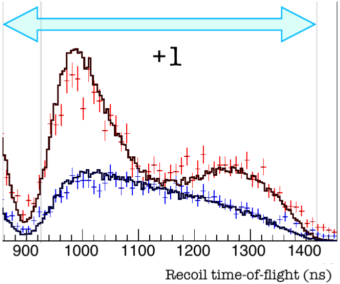
**Isobaric mirror decay has helicity-driven null**




**Nearly direct $\nu$ helicity measurement (assuming the $\beta^+$ helicity)**

**2014 polarized $\beta$-recoil**




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

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

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

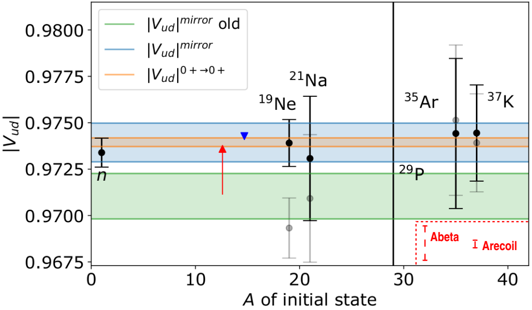
**The neutron community checks this combination of observables for consistency**

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

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

TEXAS A&M UNIVERSITY

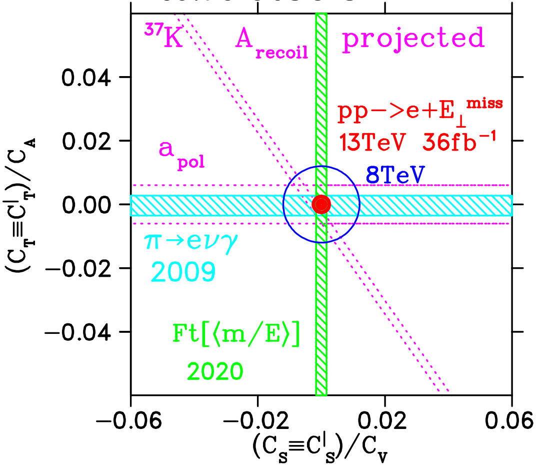
**Deduced $V_{ud}$ from mirror decays**
**Hayen and Young,**
**arXiv:2009.11364**
**including G-T radiative correction**




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

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

**90% exclusions:**

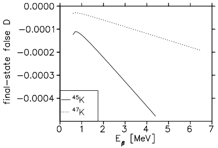


**Assuming T2K confirms $\not{CP}$ Nature 580 339 (2020) and convincingly generates Sakharov's baryon asymmetry, looking for $\not{T}$ remains kewl for its own sake**

**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**



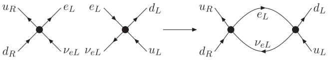

- **(For Decays) How big are the 'final state effects'?**

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

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

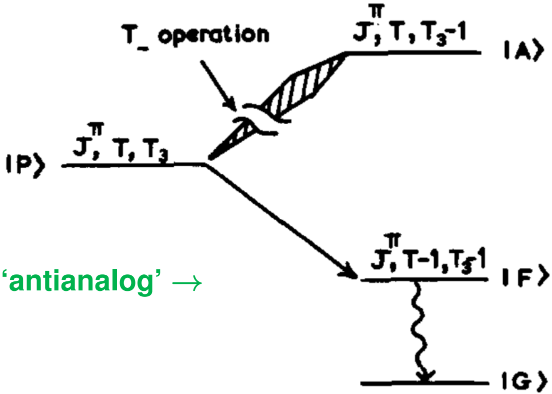
**Our projected sensitivity to $\not{T}$ parity-even interactions is similar to NOPTREX neutron resonance experiments. Isospin-breaking $\not{T}$ makes us complementary**

- **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 $\beta^-$ decay
# Barroso and Blin-Stoyle, PL 45B 178 (1973) observables:




'antianalog' $\rightarrow$

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

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

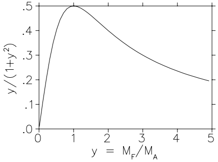
$D$, $E_1$ are both proportional to

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

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

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

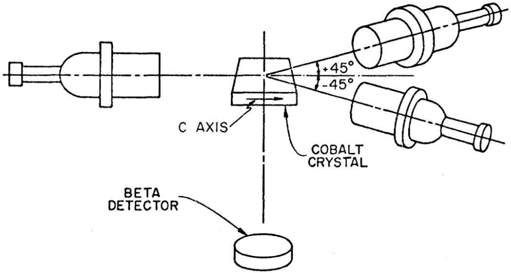
In this system, $\tan\alpha_V = -i\,\frac{\langle F|V_{\not{T}}|A\rangle}{\langle F|V_{\rm Coul}|A\rangle}$




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 $\alpha_V$ by $\sim 10^3$ ☺

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

**Asymmetry of the 45º $\gamma$ 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**

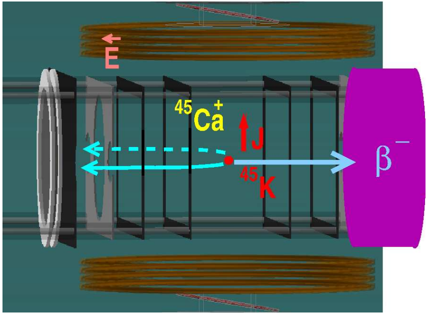
**log(ft) = 8.7, yet known allowed: $E_\beta$ spectrum, no $\beta$-$\gamma$ correlation)**

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

**$V_{\mathrm{Coul}}$= 2.9 keV, $V_{\not{T}} = 54 \pm 110\mathrm{eV}$**
**(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 $|M_{GT}|$, $V_{\mathrm{Coul}}$, and $\not{T}$ N-N matrix elements to allow complementary or better sensitivity to $V_{\not{T}}$**

TRIUMF

# 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)

| | $B_\nu$ | 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 $\beta$'s**

# Motivation for Analog-antianalog mixing

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

**Coulomb corrections Fermi $\beta$ 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.**

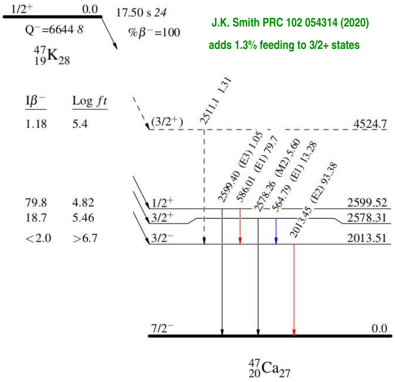
**$A\bar{A}$ mixing explains isospin-forbidden particle decays, $\Gamma_A$: $A$ a well-defined single resonance.**

**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 | $\delta_C$=0.25% | T=2 $A$ $\delta_C$= 1-2% Melconian PRL 107 182301 2011 |

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



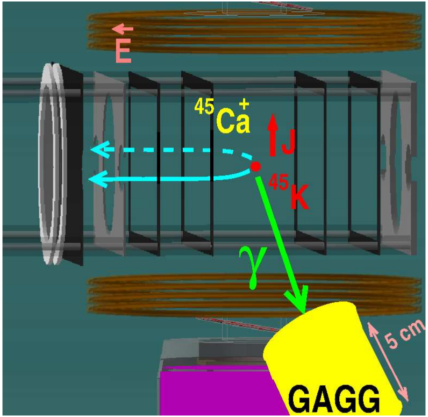

The analog is:

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

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

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

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




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

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

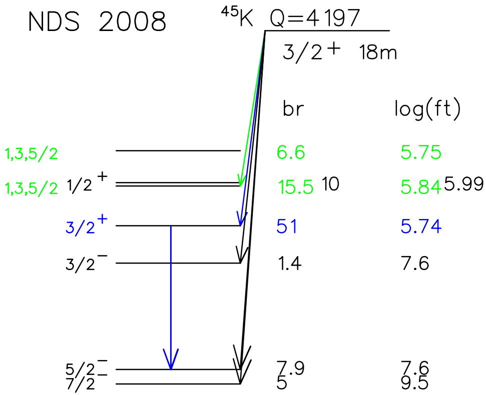
linear in $M_V/M_A$

- Recoil-$\gamma$ coincidences to select the antianalog

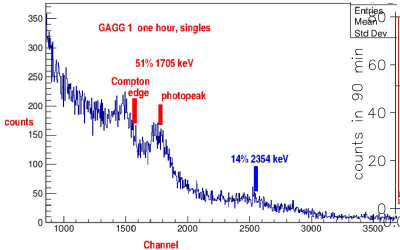
$A_{\rm recoil}$ Uncertainties*100

| Melconian PLB 649 270 (2007) | $B_\nu$ | Improvements | Projected |
|---|---|---|---|
| Polarization | 0.8 | $B_\perp, \sigma^\pm$ | 0.05 |
| Cloud position | 1.3 | 500 $\mu$m $\rightarrow$ 20$\mu$m | 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 |

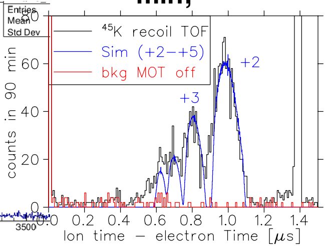
We measured $A_T = 0.015(29)(19)$ for G-T decay of $^{80}$Rb see Pitcairn PRC 79 015501 (2009)

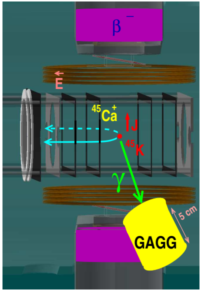



## $^{45}$K decay to antianalog

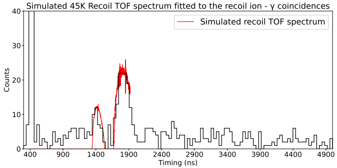



## shakeoff e$^-$ & recoil clean even for $t_{1/2}$=18 min;




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

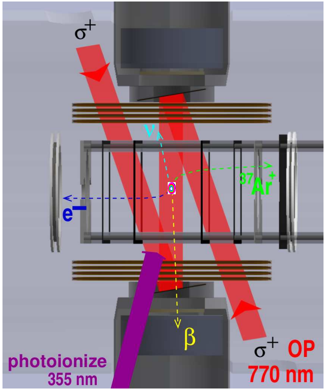



**51% branch to 3/2+ state in $^{45}$Ca. Should include the antianalog configuration,**

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

**$A_\beta$, $A_{\rm recoil}$ would answer 15.5% branch to 1/2,3/2,5/2?**

# $\nu$ helicity & time-reversal breaking with TRIUMF's neutral atom trap for $\beta$ decay




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

- Angular correlations of $\beta^+$ and $\nu$ are determined by their helicities (and angular momentum conservation)

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

  We plan the most direct $\nu$ helicity measurements since BNL 1957

- $\nu$ 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+

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

**Given:**

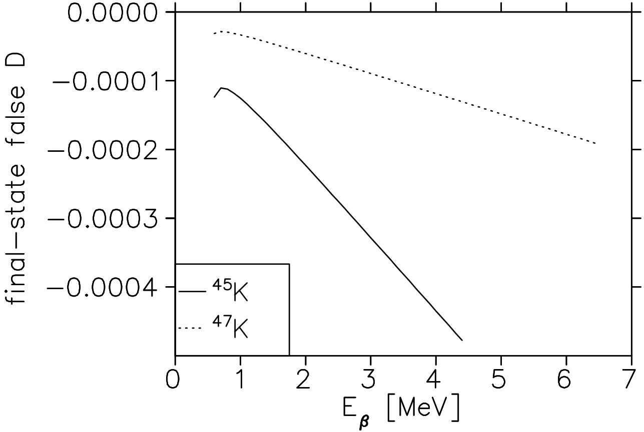
- **Cohen Glashow Ligeti PLB 678 191 (2009): $\psi_f$ has $\nu_e$ mass eigenstates entangled with $\psi_{^{131}Xe}$ to keep E and p conserved**
- **Formaggio Kaiser Murskyj WeissPRL 117 050402 (2016) $\nu$ oscillations show Leggett-Garg inequality**
- **Kayser Kopp Robertson Vogel PRD 82 093003 (2010):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

**It is simple to sweep the electric field collecting the $^{131}$Xe to change detection t over the range of t's of SM $\nu_e$ 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 $\mu$s or 3 $\mu$s**

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

# Final-state (false) *D*

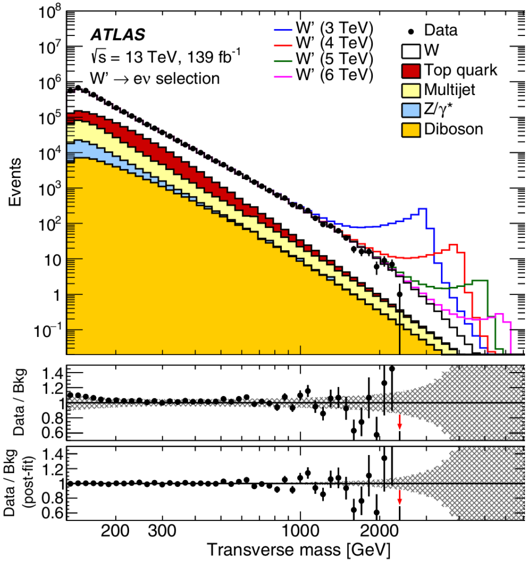



For $^{56}$Co final-state $E_1$=0.0002 (Calaprice 1977)

**Holstein PRC 5 1529 (1972)**

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

# Quasi-direct limits from high-energy colliders: update

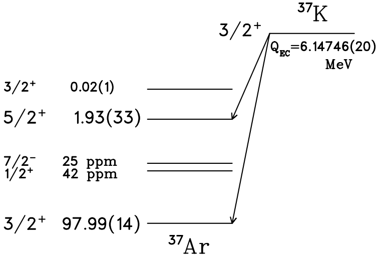



**LHC13 $\sigma[p + p \rightarrow e + \text{missing } p_\perp]$ is related to $n \rightarrow p + e + \nu$ by EFT (to scale the momentum transfer dependence, etc.) see Gonzalez-Alonso, Naviliat-Cuncic, Severijns, Prog Par Nuc Phys 104 165 (2019):**

**$\leftarrow$ 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



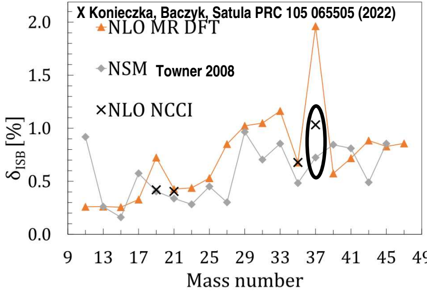

$\mathcal{F}t$ (Shidling PRC 2014) = 4576 $\pm$ 8 s
Ozmetin et al. TAMU
Branch to 5/2$^+$ improved
$\rightarrow$ PRELIM 4585$\pm$4 s
$\sim$0.0005 for $V_{ud}$ from $A_{\rm recoil}$ becomes possible

**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 $A_\beta$ 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 $\beta$ decay

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

| Source | $\Delta P$ [$\times 10^{-4}$] $\sigma^-$ | $\sigma^+$ | $\Delta T$ [$\times 10^{-4}$] $\sigma^-$ | $\sigma^+$ | $\Delta P$ $\sigma^-$ |
|---|---|---|---|---|---|
| SYSTEMATICS | | | | | PROJ |
| Initial $T$ | 3 | 3 | 10 | 8 | 2 |
| Global fit v. ave | 2 | 2 | 7 | 6 | 1 |
| $S_3^{\mathrm{out}}$ 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 $\beta^+$ scattering**

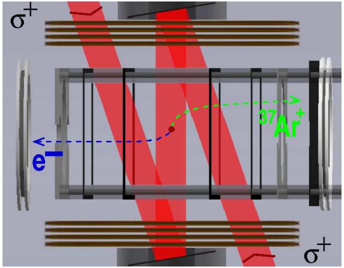
Stern Family of National Photocolor

**70nm Au + $4\mu$ Kapton $5\lambda$ flatness**

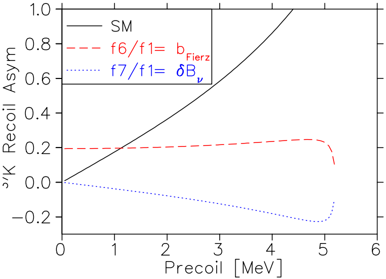
- PCTFE viewport seals
- Lower-frequency AC-MOT
- Double OP power: fight Larmor precession
- Better spin flips TnLC
- 2x more photoionizing light

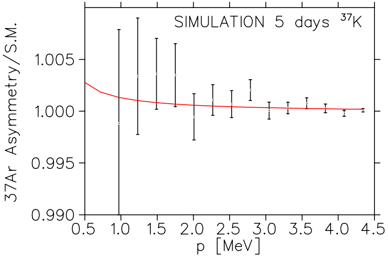
- Uncertainty $\propto (1 - P)$

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



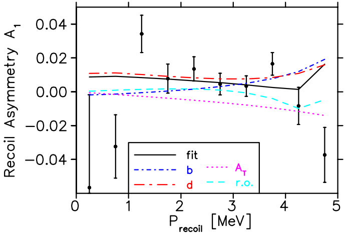

## $A_{recoil}[p_{recoil}]$ independent of $M_{GT}/M_F$




**see $^{80}$Rb Pitcairn PRC09**

$A_T = 0.015(29)(19)$




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

| | $B_\nu$ | Improvements | Projected |
|---|---|---|---|
| Polarization | 0.8 | $B_\perp$, $\sigma^\pm$ | 0.05 |
| Cloud position | 1.3 | 500 $\mu$m $\rightarrow$ 20$\mu$m | 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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# $^{37}$K $A_\beta$

## Improvements TRIUMF

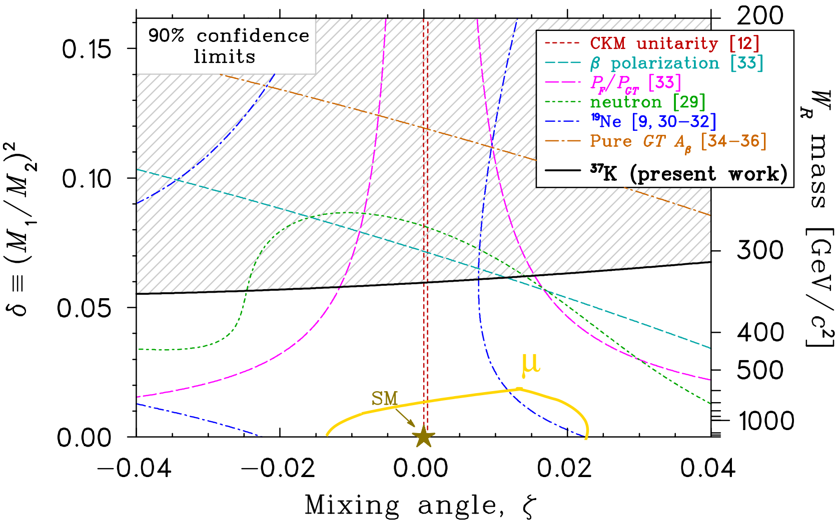
- **Minimize Background by sweeping away $e^-$ with larger $\vec{E}$**
- **Reduce scattering by 2 with lower-Z materials Improve understanding**
- **Reduced energy threshold using pellicle mirrors**
- **Improve statistics**

**Uncertainty budget for $A_\beta$:**

**Items with † are related to $\beta$ scattering.**

| $A_\beta$ Systematics | $\Delta A_\beta \times 10^{-4}$ | Proj |
|---|---|---|
| Background (Correction 1.0014 1.0000) | 8 | 0 |
| $\beta$ 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 |

# Still no wrong-handed $\nu$'s

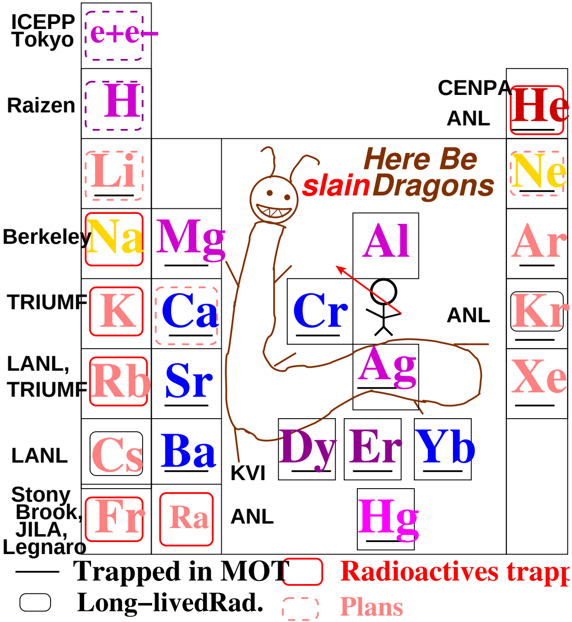



Extra $W'$ with heavier mass, couples to wrong-handed $\nu_R$

We can evade TWIST limits by assuming the muon $\nu_R$ is heavy

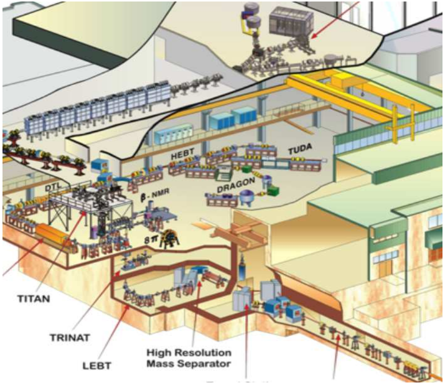
LHC $M'_W > 3.7$ TeV 90%

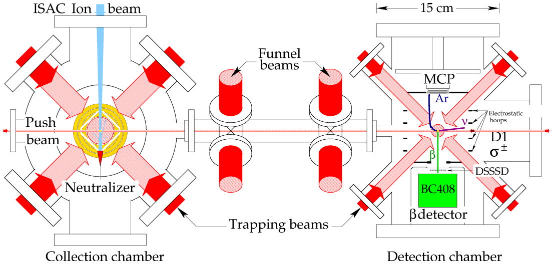
our result does imply $g_R > 8 g_L$ for a 4 TeV $W'$




## What elements can be laser cooled?

# TRIUMF TRIumf Neutral Atom trap at ISAC



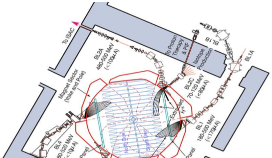




$^{37}$K 8x10$^{7}$/s

TiC target 1750$^{o}$C

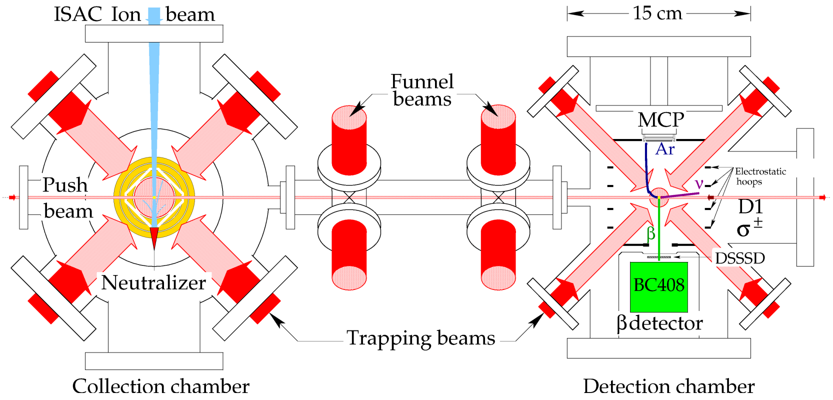
70 $\mu$A protons

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



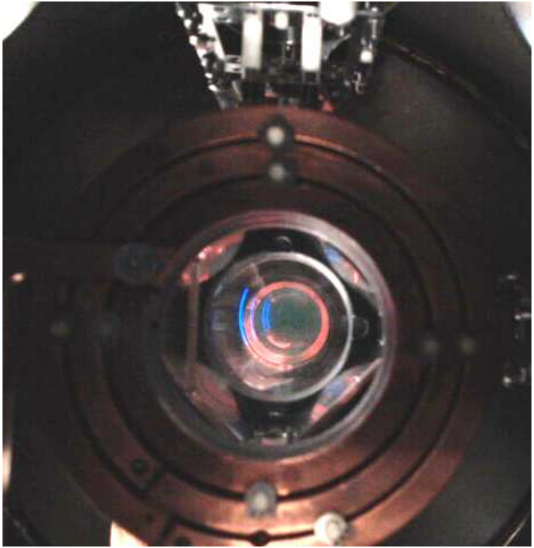
# TRINAT plan view

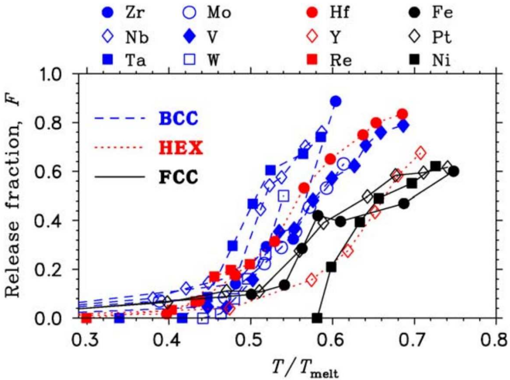
- **Isotope/Isomer selective**
- **75% transfer**
- **Avoid untrapped atom background with 2nd trap**
- **0.7 mm cloud for $\beta$-Ar$^+$ $\rightarrow$ $\nu$ momentum**

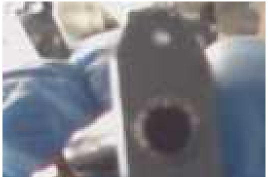



- **Spin-polarized 99.1±0.1%**

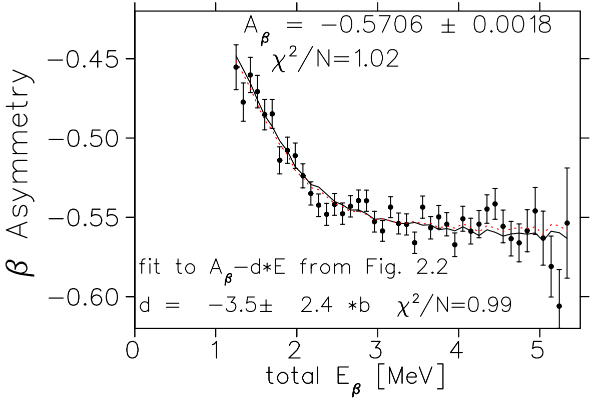
# Neutralizer and Collection trap





# 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 $\beta$ 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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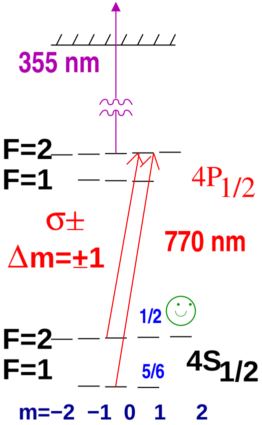
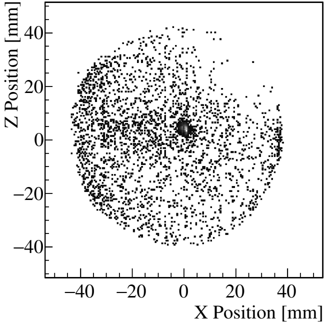
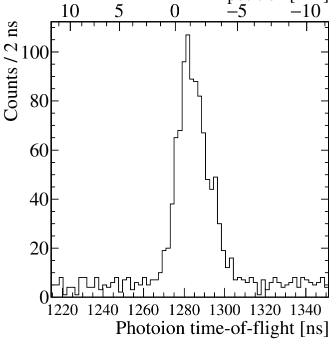
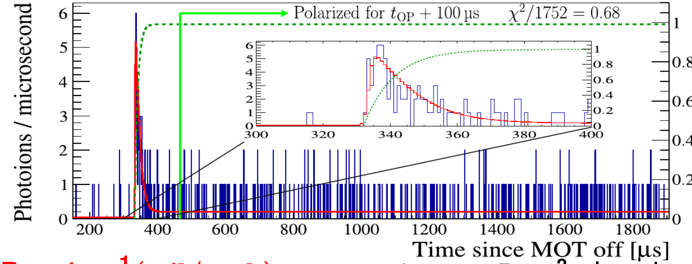



**1 of 10 data sets**




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

$P_+$**=+0.9913(8)** $P_-$**=−0.9912(9)**

**Fenker NJP 2016**

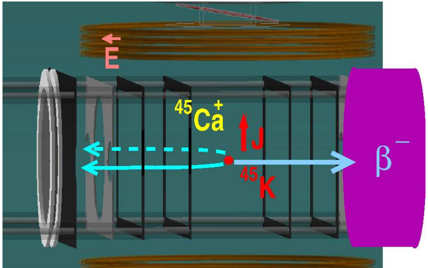
$P \approx 1 - \frac{1}{3}(\text{tail}/\text{peak})$ unpumped atoms $P \sim \frac{2}{3}$ already

TRIUMF

# D sensitivity

Extrapolating from Melconian PLB 649 270 (2007) and realizing $\beta^-$ 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 $\alpha$
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