Time-reversal violation (*TRV*) in radiative β decay

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When designing *TRV* decay experiments:

- What underlying physics generates the *TRV*?
- How big are the 'final state effects'?
- Is anyone else doing it better?
- How strong are the contraints from null EDM's?

Our TRV observable needs 3 uncorrelated momenta:

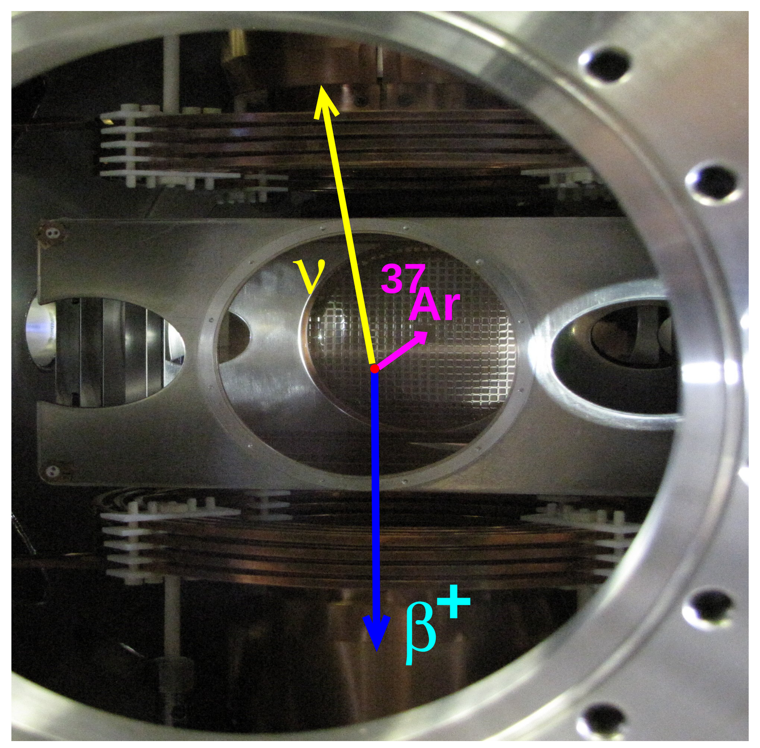
t → -t ⇒ $\vec{p} \propto \frac{d\vec{r}}{dt} \rightarrow -\vec{p}$

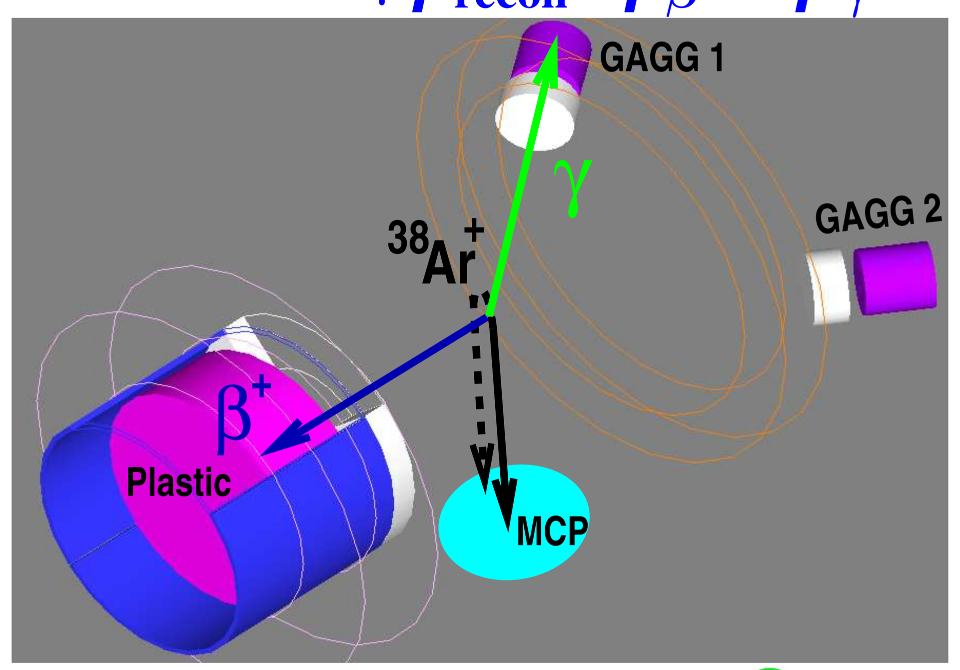
We routinely measure

$\vec{p}_\nu = -\vec{p}_\beta - \vec{p}_{\rm recoil}$

but $\vec{p}_{\rm recoil} \cdot \vec{p}_\beta \times \vec{p}_\nu \equiv 0$ ☹

$$\vec{p}_\nu \cdot \vec{p}_\beta \times \vec{p}_\gamma = -\vec{p}_{\rm recoil} \cdot \vec{p}_\beta \times \vec{p}_\gamma \xrightarrow{t\to -t} +\vec{p}_{\rm recoil} \cdot \vec{p}_\beta \times \vec{p}_\gamma$$

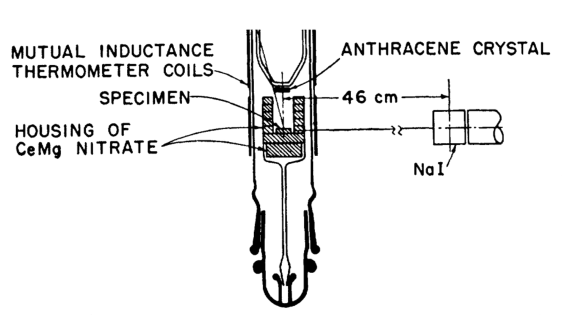




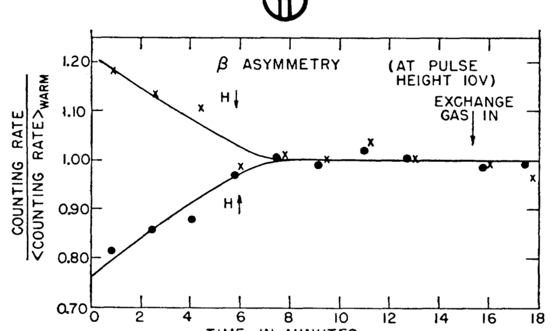
***TRV* makes ≠ γ rates** ☺
Coincident pairs test detector symmetry ☺

- Not exact: don't flip $\psi_i \leftrightarrow \psi_f$. Outgoing particles interact by *E&M* → 'final-state' *TRV* asym $\leq 10^{-3}$ for ^{37}K ☺ (Gardner,He 2013)
- Would be unique to 1st generation, complementary to $K^- \rightarrow \pi^0 e^- \bar{\nu}_e \gamma$ INR Moscow 2007, $A_{TRV} = -0.015 \pm 0.021$

Parity broken, why not *Time*?



Immediately after *Parity* was seen to be totally broken in β decay ('ν left-handed')
Wu, Ambler, Hayward, Hopper, Hobson, PR 105 (1957) 1413



many T-odd observables were proposed:

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Possible Tests of Time Reversal Invariance in Beta Decay

J. D. Jackson,* S. B. Treiman, and H. W. Wyld, Jr.
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey
(Received January 28, 1957)

Observables with spin $D\hat{J} \cdot \frac{\vec{p}_\beta}{E_\beta} \times \frac{\vec{p}_\nu}{E_\beta}$ $R\vec{\sigma}_\beta \cdot \hat{J} \times \frac{\vec{p}_\beta}{E_\beta}$ show *TRV* asymmetries < 0.001 (We consider *D* in 'isospin-forbidden mirror' decay of ^{45}K, sensitivity enhanced 4 to 100x)
$\beta\nu\gamma$ TRV asymmetry could still be bigger ☺

QCD-like interactions generate antisymmetry

Harvey, Hill, Hill, PRL 2007; **Gardner, He PRD 2013:**

$$\mathcal{L} = \frac{-4c_5}{m_{\rm nucleon}^2}\frac{eG_F V_{ud}}{\sqrt{2}}\underbrace{\epsilon^{\sigma\mu\nu\rho}}_{\rm QCD}\bar{p}\gamma_\sigma n\underbrace{\bar{\psi}_{eL}\gamma_\mu\psi_{\nu L}}_{\rm Weak\ decay}\underbrace{F_{\nu\rho}}_{\rm E\&M}$$

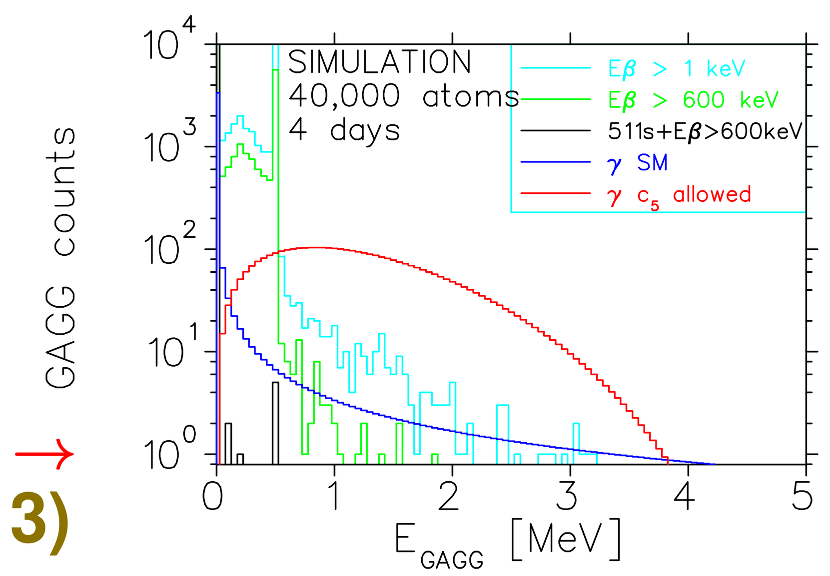
Interference with S.M. β decay 'vector current' makes the scalar triple product we seek ☺:

$$|\mathcal{M}_{c5}|^2 \propto \frac{Im(c_5 g_V)}{M^2}\frac{E_e}{p_e k}(\vec{p}_e \times \vec{k}_\gamma)\cdot\vec{p}_\nu$$

Needs QCD-like physics, scale $M \sim$ 10's of MeV

- This *TRV* scales with $p^2_{\rm lepton}$ → ~10^2 larger in ^{37}K decay than neutron
- Direct constraint from n → p $\beta\nu\gamma$ branch $\propto |c_5|^2$
Bales PRL 2016: $3.4 \pm 0.2 \times 10^{-3}$ (theory 3.1×10^{-3})
$\Rightarrow \frac{{\rm Im}(c_5)}{M^2} \leq 8 MeV^{-2} \Rightarrow$ ^{37}K *TRV* asym can be ~ 1 ☺

E_γ spectrum is distinctive ☺



- Classical bremsstrahlung ∝ $1/E_\gamma$, but
- Any time-reversal violating interaction involves β, ν, γ ⇒ 4-body phase space $\propto E_\gamma(Q - E_\gamma)^3$ Bernard PLB 2004

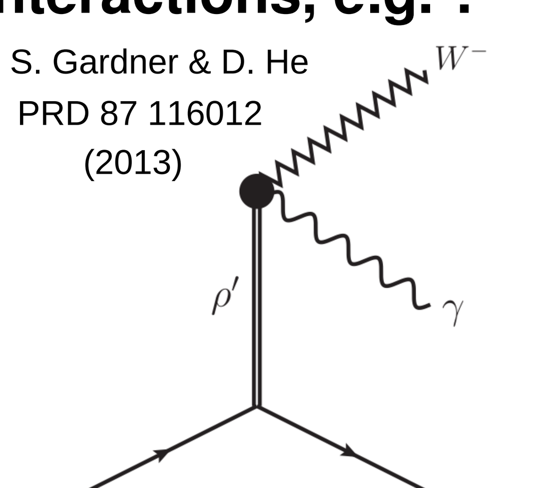
We are concentrating on $E_\gamma > 511$ keV, with the β^+ in the opposite detector, though a thin-thick high-Z scintillator sandwich distinguishes low $E_\gamma \sim$ 5:1

Constraint from neutron EDM on *TRV* $\beta\nu\gamma$

Though $\vec{p}_\nu \cdot \vec{p}_\beta \times \vec{p}_\gamma$ doesn't involve spin, EDM's indirectly constrain:

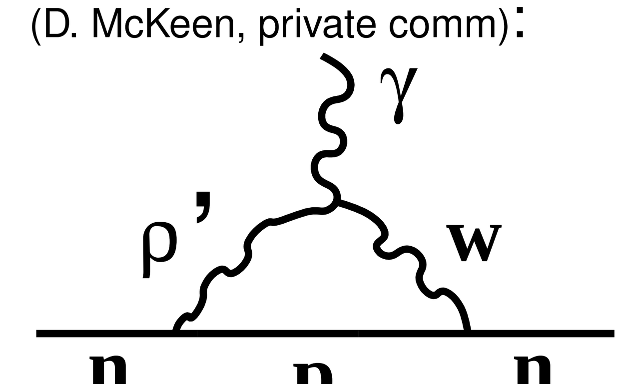
Some *TRV* $\gamma\beta\nu$ interactions, e.g. :

S. Gardner & D. He PRD 87 116012 (2013)



make neutron EDM at "1-loop" order

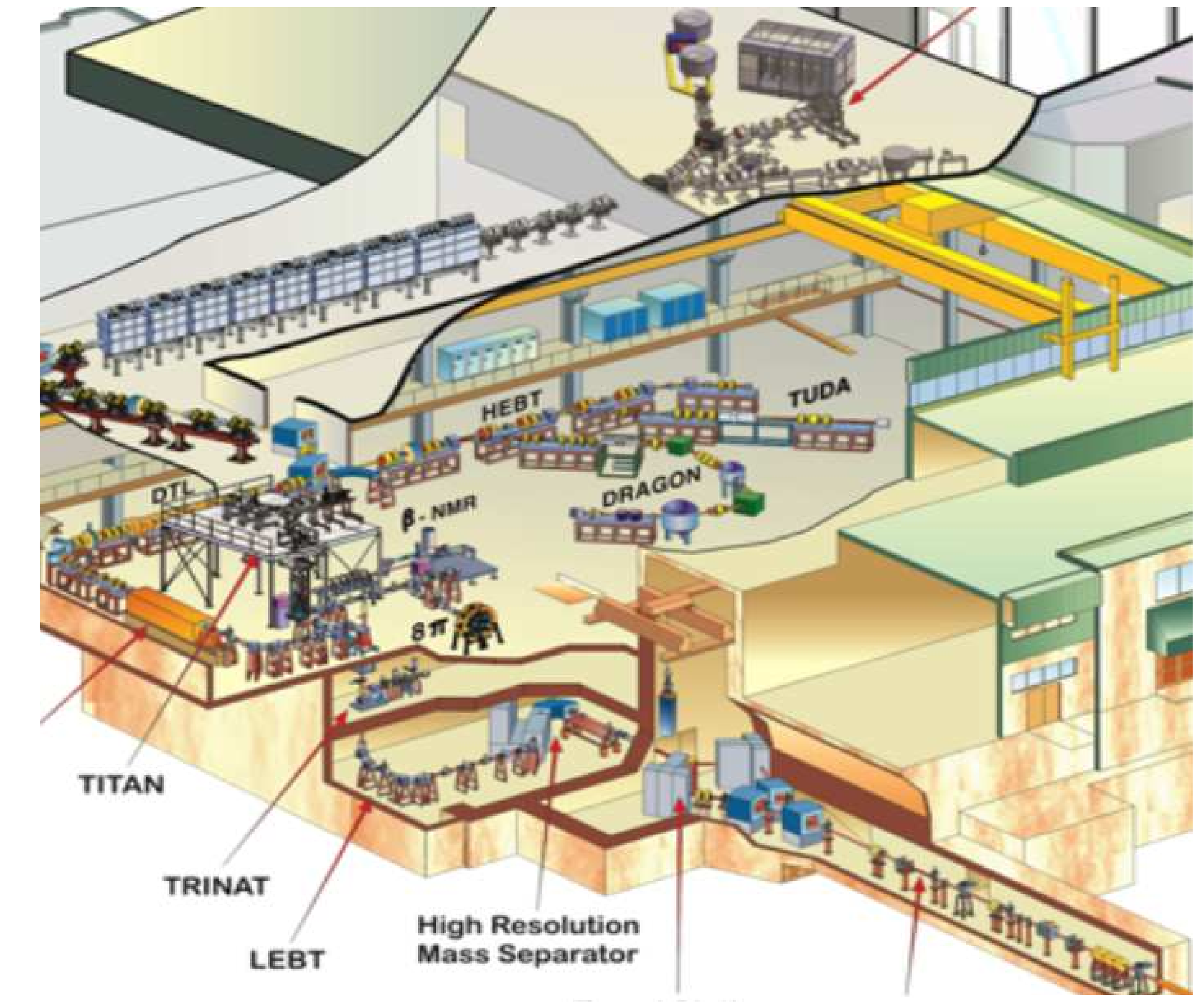
(D. McKeen, private comm):



"Naive Dimensional Analysis" $c_5\frac{e^2 G_F M_W^3}{16\pi^2 m^2_{\rho'}}$ suggests nEDM larger than experiment by ~ 10^8.

→ *TRV* $\beta\nu\gamma$ from such interactions likely too tiny to measure ☹

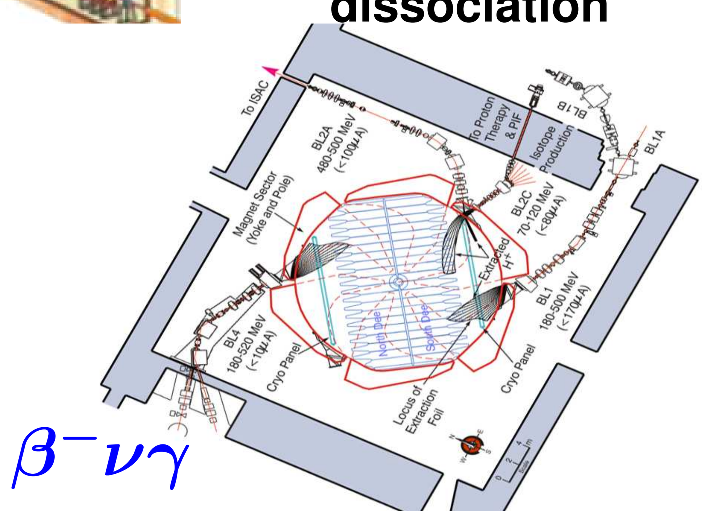
- Other interactions (e.g. leptoquarks) need "2 loops" so generate comparatively tiny nEDM so are less constrained, could generate *TRV*$\beta\nu\gamma$ large enough to measure ☺



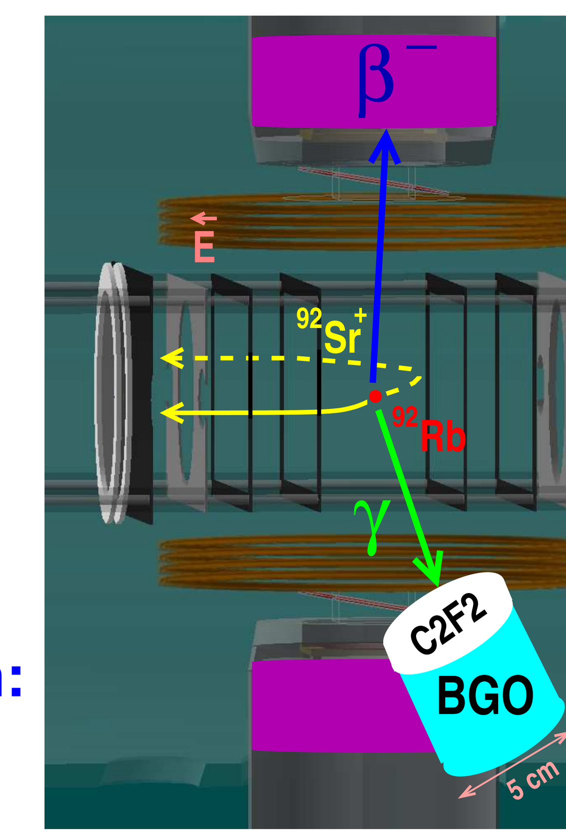
^{37}K $8x10^7$/s TiC target 70 μA 1750°C protons
^{92}Rb $6x10^8$/s UC$_x$ target

TRIumf Neutral Atom Trap at ISAC

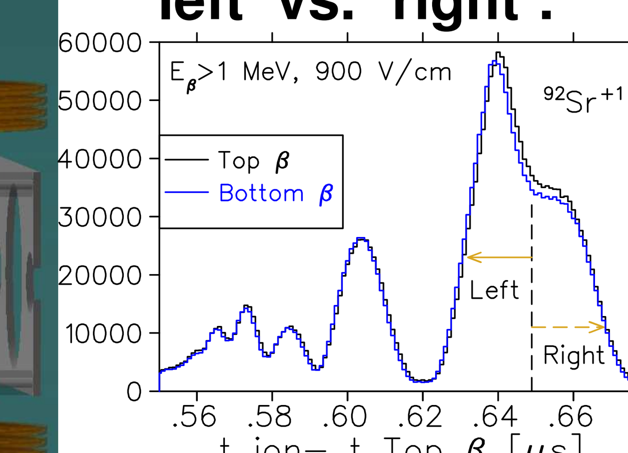
500 MeV TRIUMF cyclotron
H$^-$, 0.5 Tesla 'world's largest' orbits needed to avoid $\vec{E} = \vec{v} \times \vec{B}$ dissociation



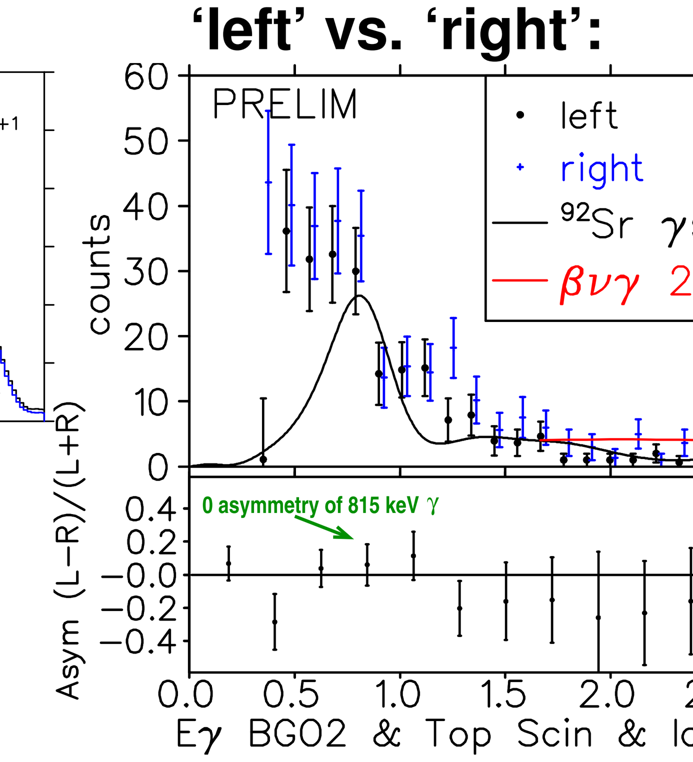
TRV test ^{92}Rb $0^- \rightarrow$ ^{92}Sr 0^+ + $\beta^-\nu\gamma$

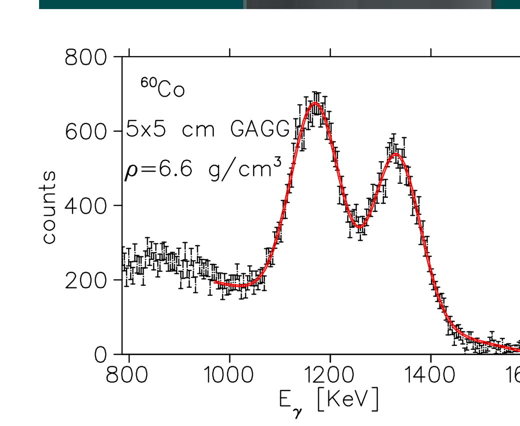


$\beta^- \cap$ ^{92}Sr$^+$ 'left' vs. 'right':



$\beta^- \cap$ ^{92}Sr$^+ \cap \gamma$ 'left' vs. 'right':





BGO → GAGG (Ce:Gd$_3$Al$_2$Ga$_3$O$_{12}$)
- better E_γ resolution and timing, ρ= 6.6 g/cm^3
- Good photopeak efficiency (55% at 1 MeV)
- not radioactive like LYSO

Sensitivity to ~ 0.05 to 0.10 asymmetries of few percent branches

^{92}Rb decay: no vector current, constrains pseudoscalar TRV?

- Plan: simple geometry has sensitivity to ~ 5-10% TRV asymmetry in ^{37}K or ^{38m}K

That result could motivate a dedicated geometry