Experimental Measurement of Isospin Symmetry Breaking in ^{47}K Beta Decay

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Outline

- Testing time reversal symmetry (why and how)
- Isospin-Suppressed decay in ^{47}K
- Beta decay with trapped atoms in TRINAT
- Preliminary results for the decay asymmetry and isospin mixing

Testing Time Reversal Symmetry

- Symmetry of flipping the sign of time
- Violated in weak interaction, but so far doesn't account for matter/antimatter asymmetry in the universe
- Enhanced in Isospin-Suppressed Decay...

When $t \to -t$:

$\vec{r} \to \vec{r} \qquad \vec{p} \sim \frac{d\vec{r}}{dt} \to -\vec{p}$

i.e. any scalar triple product of momenta

(i) An "oriented nucleus-electron-neutrino" correlation, $W_{e\nu}$, of the form

$$W_{e\nu} \propto 1 + A J \cdot p_e \times p_\nu \qquad (1)$$

Aka "D"

and

(ii) An "oriented nucleus-electron-γ" correlation, $W_{e\gamma}$, of the form

(e.g. Calaprice et al. PRC 1977)

$$W_{e\gamma} \propto 1 + B J \cdot p_e \times k \left[\sum_{n=1,3} c_n (J \cdot k)^n + \ldots \right] \qquad (2)$$

A. Barroso and R.J.Blin-Stoyle (1973)

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Approach we utilize:

(i) An "oriented nucleus-electron-neutrino" correlation, $W_{e\nu}$, of the form

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Isospin-Suppressed Decay (anti-analog)

- Total isospin conserving decay ($\Delta T = 0$) not energetically possible
- Pure Gamow-Teller without mixing
- Coulomb potential mixing of |A› and |F› contributes Fermi component, which impacts angular correlations
- Barroso and Blin-Stoyle suggest this simple system can enhance **Isospin Symmetry Breaking Time Reversal Violation** effects by a factor of ~100 (because TRV is referenced to the small isospin symmetry breaking)

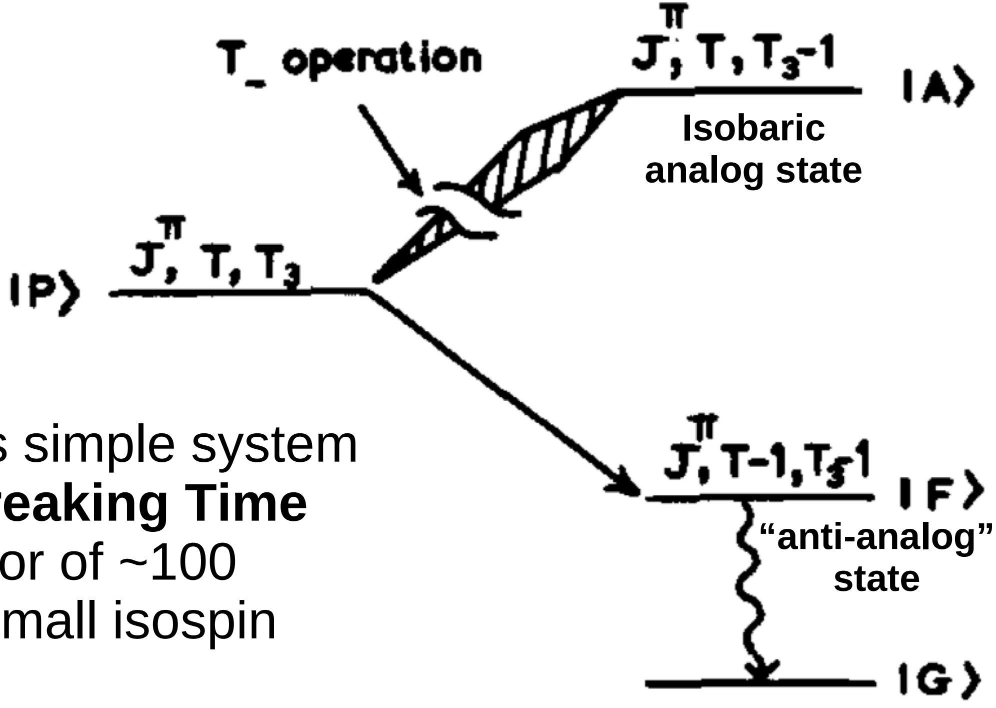
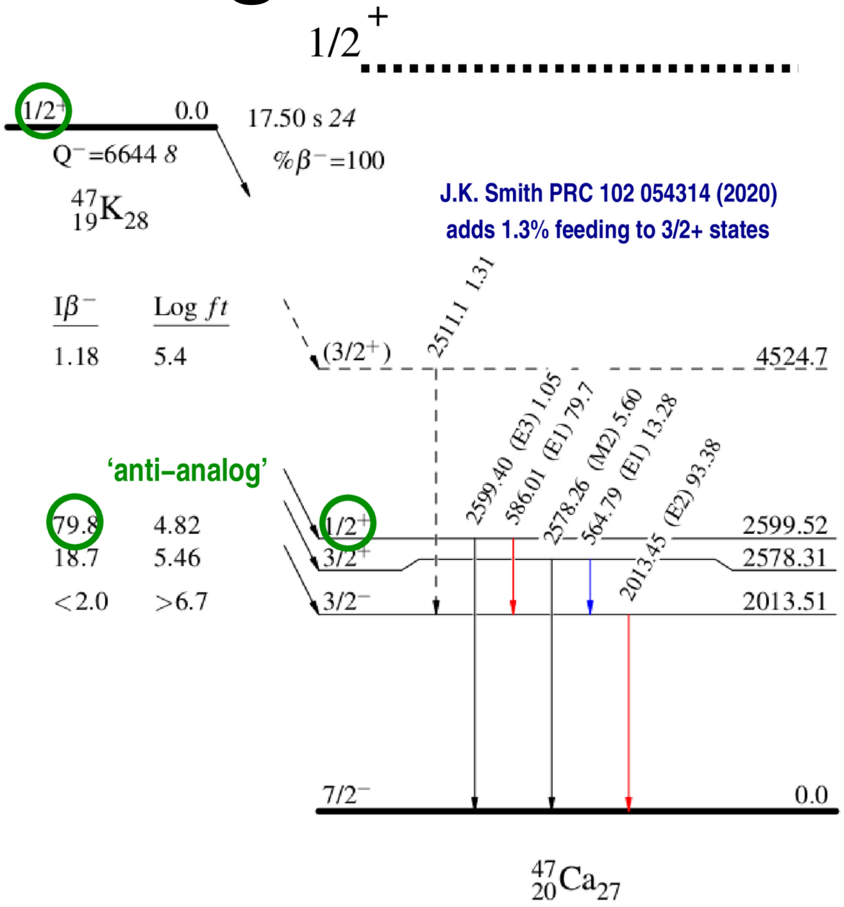


Fig. 1. Level diagram for isospin-hindered β-decay

A. Barroso and R.J.Blin-Stoyle (1973)

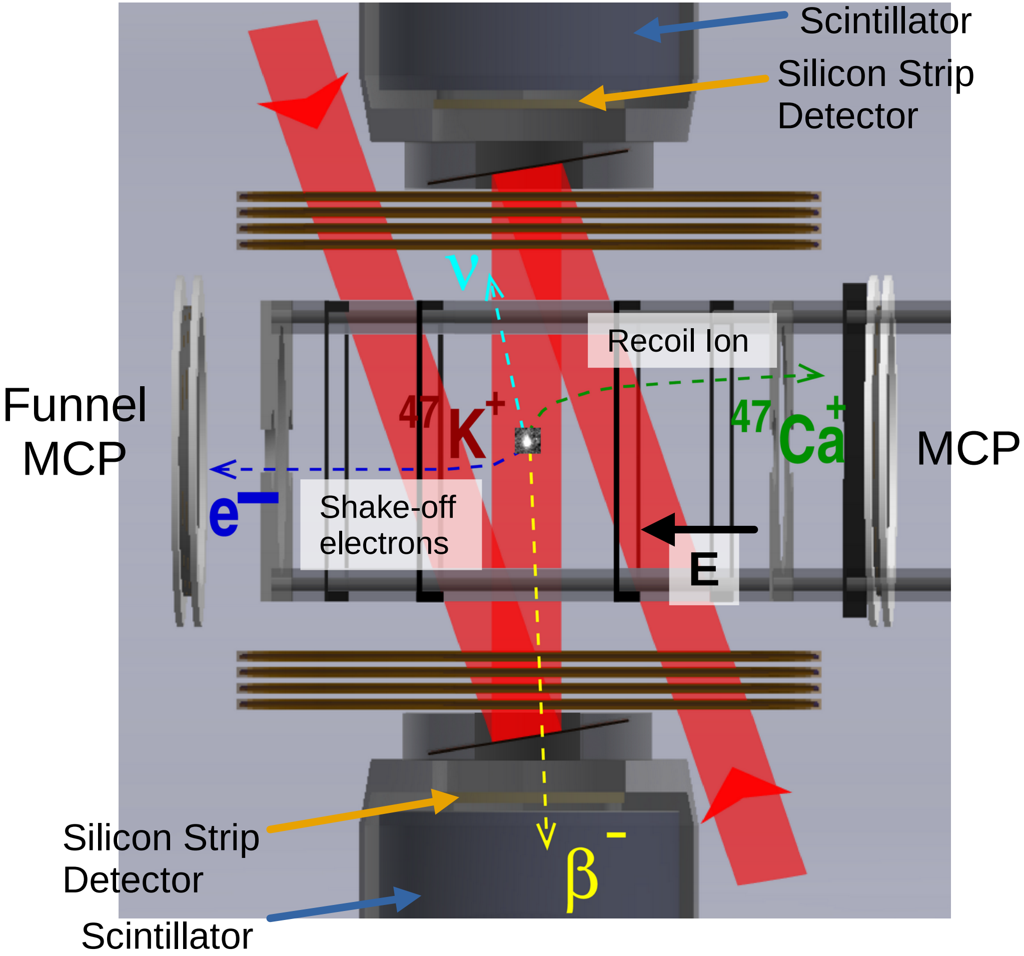
Isospin and Time Reversal Symmetry Breaking in ^{47}K

- Mixing of analog and "anti-analog" states is an intrinsically interesting test of isospin symmetry breaking
- Large branching ratio into anti-analog state
- N=28 to Z=20 decay simplifies structure
- ^{47}K Can be laser trapped and polarized
- We hope to achieve sensitivity that will complement NOPTREX (A Neutron OPtics Time Reversal Experiment) and Calaprice et al. (1977 ^{56}Co β-γ) for **isospin symmetry breaking, Parity-symmetric, Time-asymmetric** effects
- Complementary to neutron EDM; not constrained by bound set by Ng, Tulin Phys. Rev. D 85, 033001 (2012) providing $D < 10^{-2}$



β Decays in TRINAT

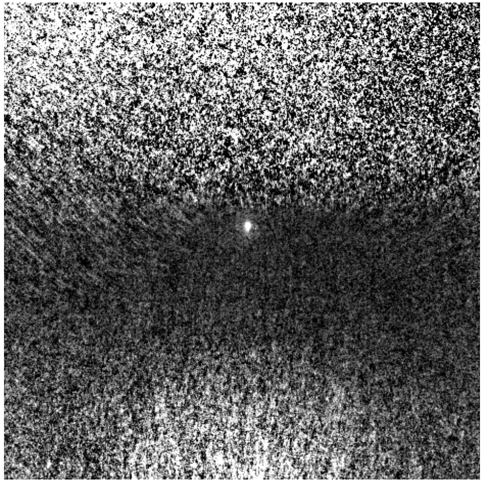
- Beta, decay product, and “shake-off” electron(s) are detected
- Energy and timing used to make cuts
- Atoms are polarized up or down



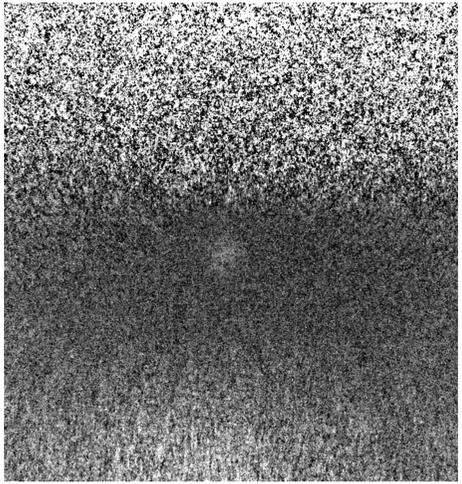
Trapping and Pumping

- Magneto-optical trap: de-tuned lasers and quadrupole B-field make a damped harmonic oscillator
- Optical pumping defines the initial polarization (“stretched” state)
- Trapping laser momentarily interrupted for decay measurement
- We alternate polarizations during measurement
- 1000 atoms trapped for 1 day

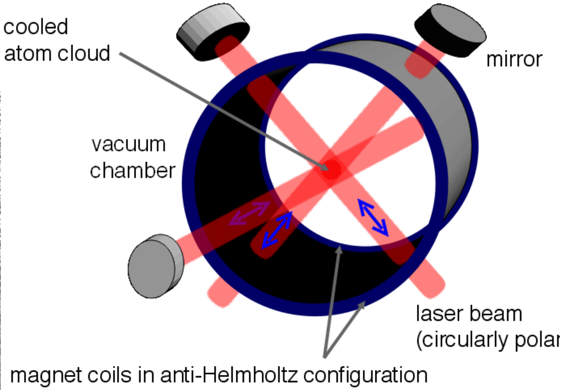
Summed ^{47}K images (Summer 2023):



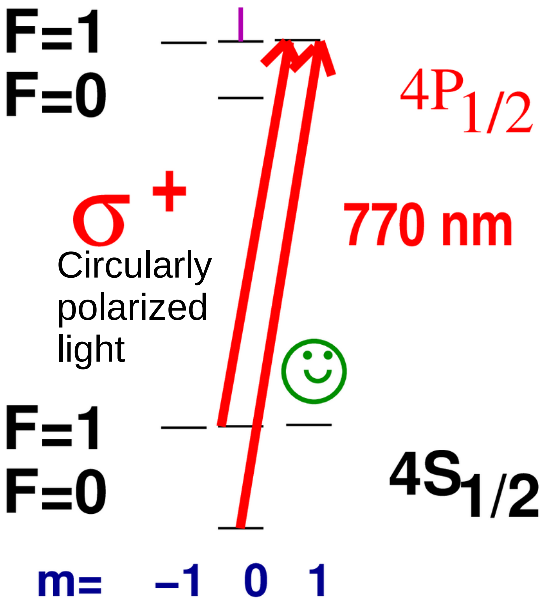
Trapping



Chopping laser and B field



Courtesy of Wikipedia



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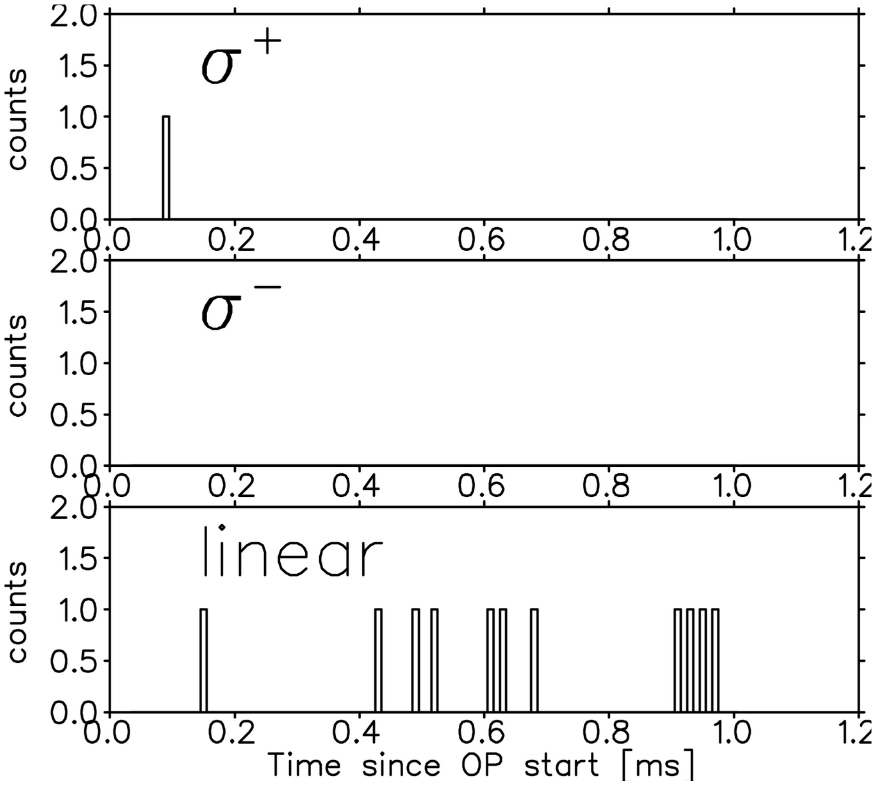
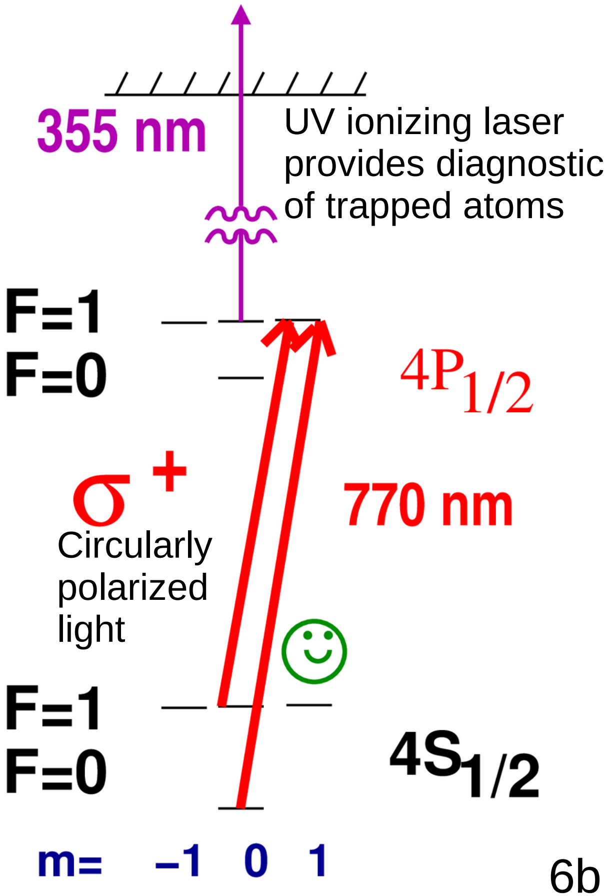
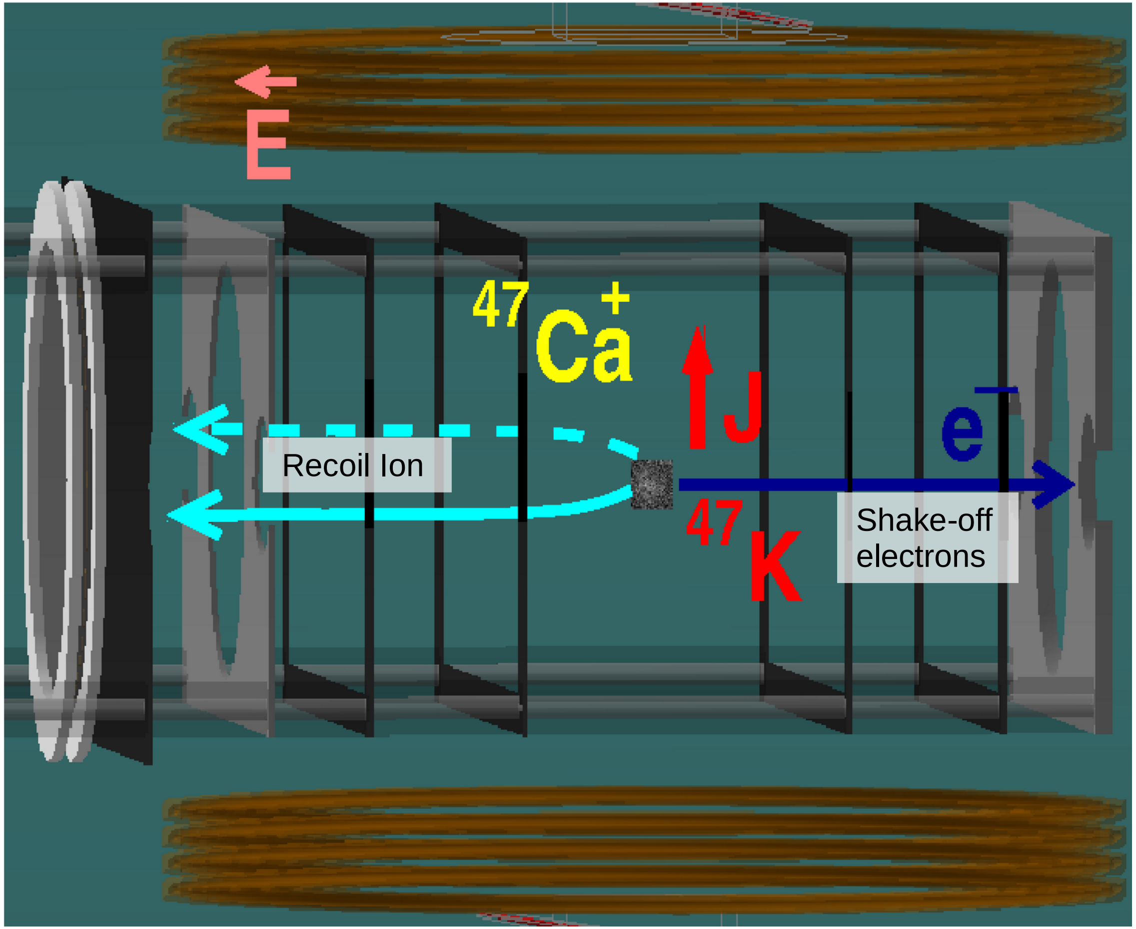


96 ± 6% polarized

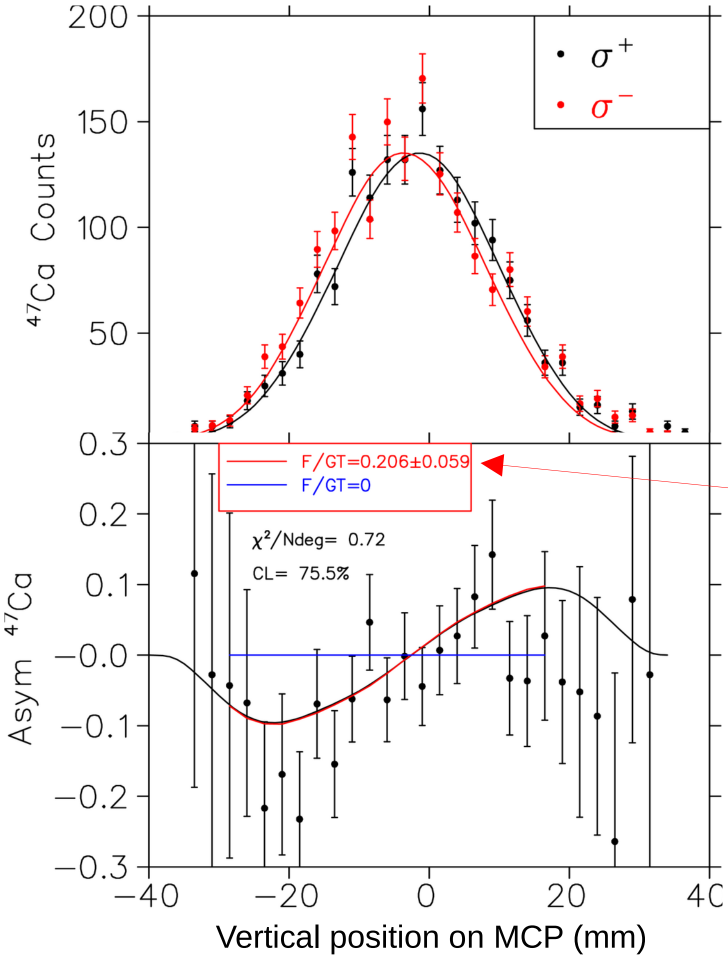


$^{47}Ca^{+}$ Recoil Asymmetry Result

Charge State >1+ in coincidence with shakeoff electrons



$^{47}Ca^{+}$ Recoil Asymmetry Result



Polarization dependence of recoils visible on MCP

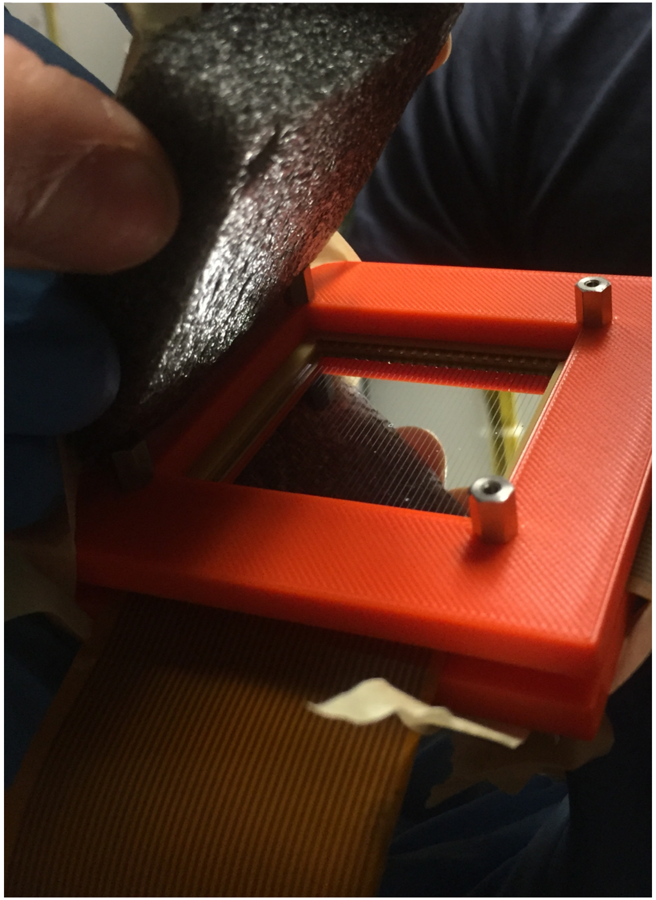
$$A_{\text{recoil}} = 2\sqrt{\frac{J}{J+1}} G_V M_F / G_A M_{\text{GT}} \cdot f(p_r)$$

(preliminary)

$$\frac{M_F}{M_{GT}} = 0.21 \pm 0.06(stat) \pm 0.02(syst)$$

Beta Energy/Electron Tagging for Beta Asymmetry

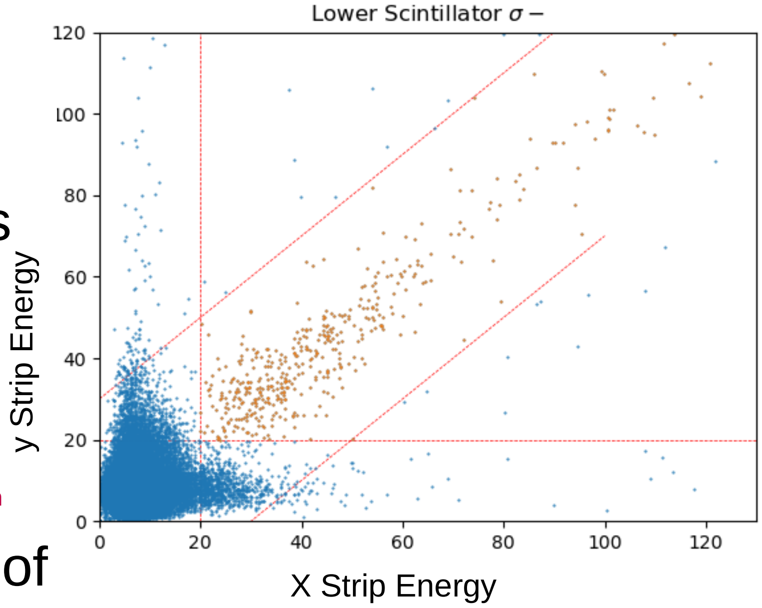
Double-Sided Silicon Strip Detector



- DSSSD tests revealed several failed strips
- Wires sensitive to vibration and air currents
- Refurbishment of silicon strip detector (ATLAS wire-bonding)

Thanks to Nicolas Massacret and Sebastian Manson

- Enabled energy tagging of betas
- Suppressed background events from scintillator-shakeoff electron coincidences



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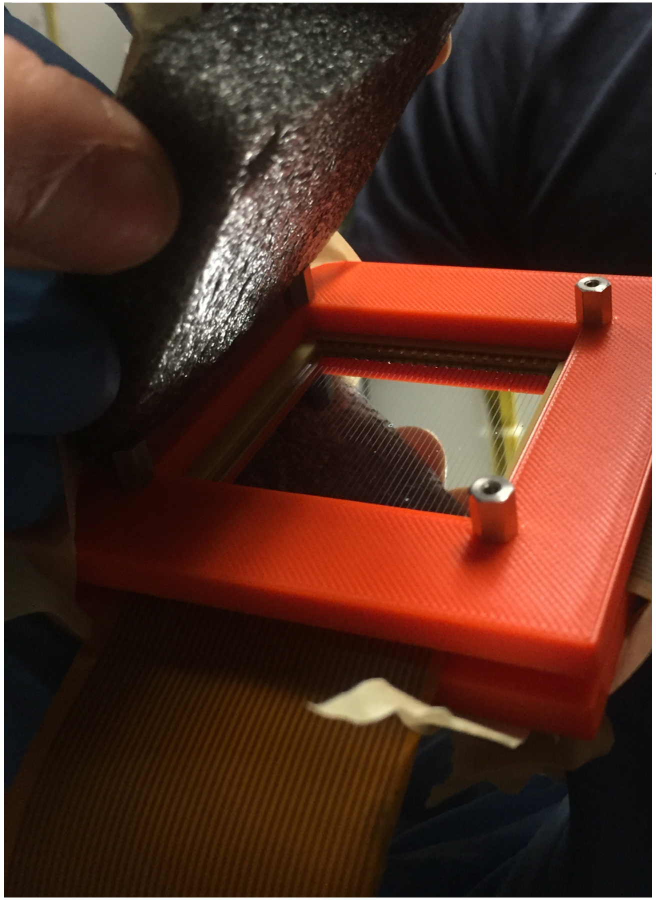
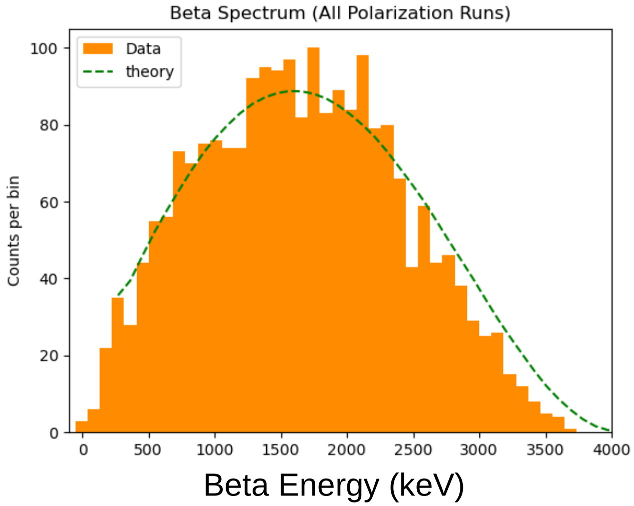


Preliminary Result:

$$A_\beta = -0.489 \pm 0.121 \pm systematics$$

(C.S. Wu's observable to show parity violation)



Comparing to the pure GT asymmetry:

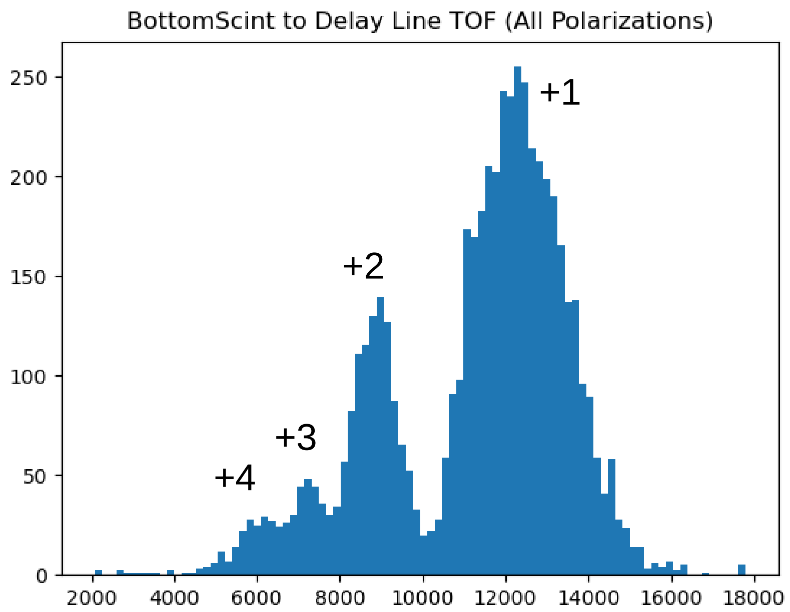
$$A_\beta = -0.467$$

Gives

$$\frac{M_F}{M_{GT}} = 0.02 \pm 0.10 \pm systematics$$

Additional Statistics from Beta-Recoil Coincidences

- +1 recoils partly miss MCP
- Opportunity for greater statistics if not dependent on shakeoff electrons
- Need to model missed ions



Recoil time-of-flight (β/recoil MCP delay)

Preliminary Isospin Symmetry Breaking Result

Weighted Average of our Recoil and Beta Asymmetries (also preliminary):

$$\frac{M_F}{M_{GT}} = 0.17 \pm 0.05(stat) \pm 0.02(syst)$$

Gives E_{analog} = 10MeV, M_{GT} = 0.3, and

$$\langle \bar{A} | V_{Coulomb} | A \rangle = 160 \pm 50 \pm systematic \text{ (keV)}$$

Harmonic oscillator estimate from N. Auerbach & B.M. Loc. Nuc. Phys. A, 1027 (2022):

$$\langle \bar{A} | V_{Coulomb} | A \rangle = 0.35 \frac{\sqrt{n_1 n_2}}{2T} \frac{Z}{A^{2/3}} \text{MeV}$$ = 190 keV for ^{47}Ca

- In contrast to ^{56}Co (3 keV) *Markey Bohm PRC 1982* and ^{71}At (28 keV) *Severijns PRC 2005*), Our result exhausts most of the A/Ā mixing
- Statistics lacking, but we expect 10x the ^{47}K data over 2 shifts, pending improvements to the laser
- We would love to see theory calculations for the time reversal violating nuclear matrix elements!

Thank You!

On behalf of the TRINAT collaboration

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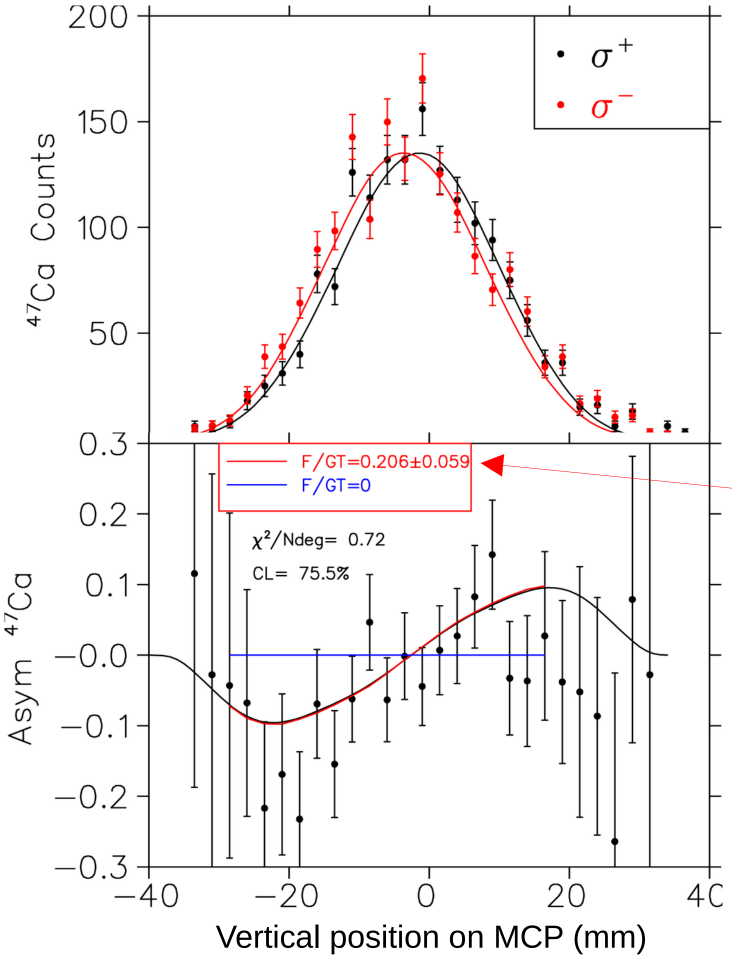
$^{47}Ca^{+}$ Recoil Asymmetry Result



$$A_{\rm recoil} = 2\sqrt{\frac{J}{J+1}} G_V M_F / G_A M_{\rm GT} \cdot f(p_r)$$

- 20% eMCP efficiency (<0.01 correction)
- <0.01 asymmetry from betas on eMCP

(preliminary)

- Asymmetry damped at extreme Z by ~6% background due to untrapped ^{47}K

$$\frac{M_F}{M_{GT}} = 0.21 \pm 0.06(stat) \pm 0.02(syst)$$

If $\langle \bar{A}|V_C|A\rangle$ = 160 $\pm$ 50 keV holds in ^{47}Ca, that's a large fraction of $\langle \bar{A}|V_C|A\rangle = 0.35\frac{\sqrt{n_1 n_2}}{2T}\frac{Z}{A^{2/3}}\text{MeV}$ =190 keV Auerbach Loc NPA2022 (unlike ^{56}Co 3 keV Markey, Boehm 1977 and ^{71}At 28 keV Severijns 2005) $\Rightarrow$ that single 1/2$^+$ final state is the antianalog ☺, so the schematic ψ might be accurate Auerbach Loc NPA2022:

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

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

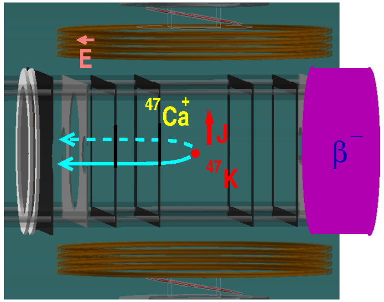
By inspection, the isovector piece of Herzceg 1965 P-even T-odd N-N interaction will flip the 'orthogonalizing' minus sign, enabling large matrix elements Barroso Blin-Stoyle 1973

$$V_{\text{t.v.}} = G_{\text{t.v.}}\tfrac{1}{2}[f(r)\hat{r}\cdot p + \text{h.c.}] \times [1 + a\,\sigma^{(1)}\cdot\sigma^{(2)})(\tau_3^{(1)}+\tau_3^{(2)}) + (b + c\,\sigma^{(1)}\cdot\sigma^{(2)})\tau_3^{(1)}\tau_3^{(2)}]$$

One still needs accurate $\psi(r)$ because $\hat{r}\cdot p$ needs good tails! (Is this why Calaprice, Freedman never extracted microscopic TRV physics a,b, c from ^{56}Co?)

So our ^{47}K goal: measuring isospin-enhanced TRV in a system that can be understood theoretically well enough to extract useful microscopic physics

For future TRV D:



In ^{56}Co, E_1 = -0.01 $\pm$ 0.02, $\langle \bar{A}|V_C|A\rangle$= 2.9$\pm$ 0.5, $\langle \bar{A}|V_{TRV}|A\rangle$ = 54 $\pm$ 110 eV, M_{GT}=0.0034.
$\langle \bar{A}|V_C|A\rangle$ cancels in D or E: sensitivity scales with $1/M_{GT}$ (=1/0.3 in ^{47}K).
Measuring D to 0.001 in ^{47}K ($\sim$ 3 weeks) leaves us 3x short in sensitivity to $\langle \bar{A}|V_{TRV}|A\rangle$ compared to ^{56}Co, but the simpler TRV N-N matrix elements are likely larger and calculable

^{47}K recoil order estimates still in progress

$^{47}_{19}$K^{28} μ = 1.9 μ_{nucleon} $\Rightarrow$ thought to be 71% 2s$_{1/2}$ Choudhary, Kumar, Srivasta, Suzuki PRC 103 064325 (2021)

Assuming 1/2$^+$$\rightarrow$ 1/2$^+$ transition is 2s$_{1/2}$$\rightarrow$2s$_{1/2}$ (no orbital *l* contributions):

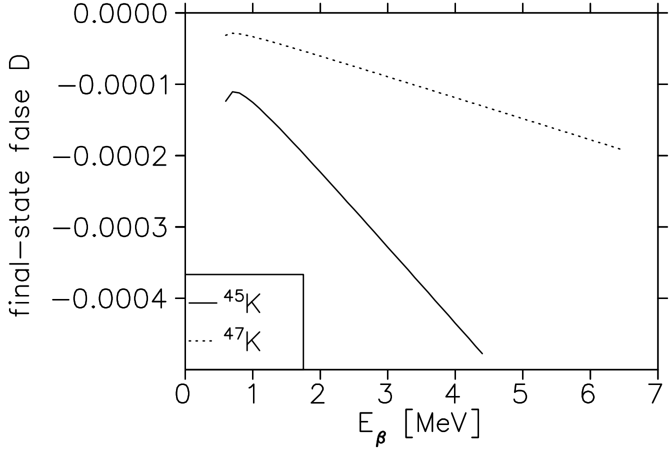
- Weak magnetism $b_W \sim$ the nucleon value
- 1st-class induced tensor $d_I \sim 0$

For our M_F/M_{GT} measurement,

A_β changed by $\leq$ 0.01

Recoil-order effects small at present level of accuracy $\rightarrow$ statistics-limited measurement

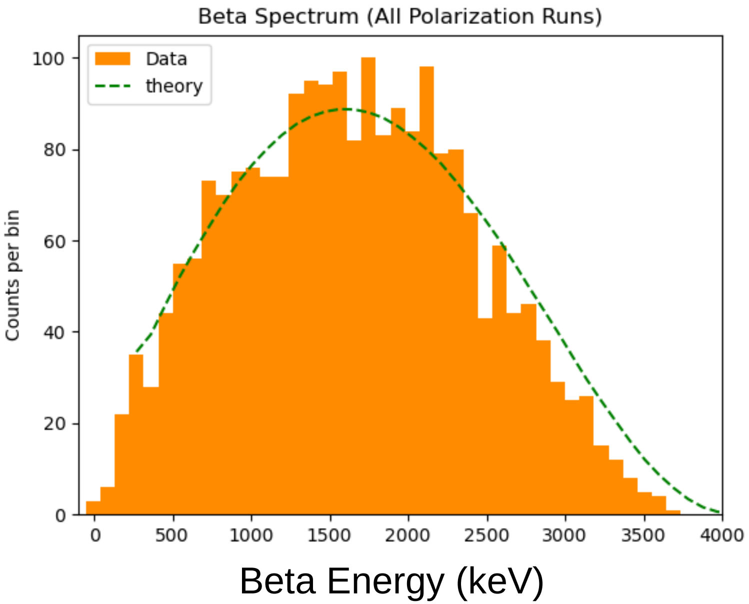
Future *D* final-state effects Holstein PRC 5 1529 (1972) small at this accuracy:

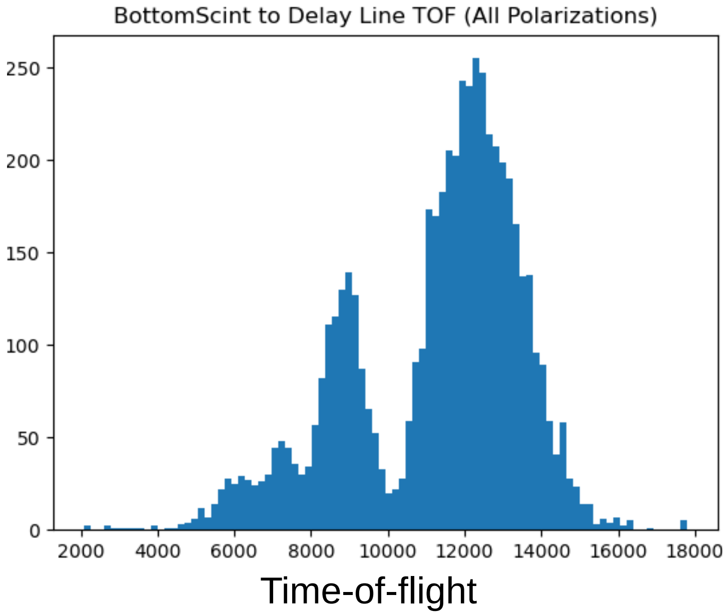


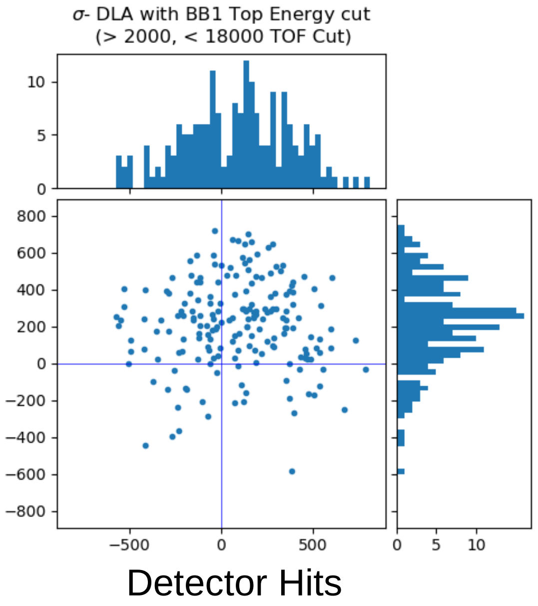
Note: ^{56}Co final-state E_1=0.0002 Calaprice 1977

6)Check Beta Spectrum/Look for Asymmetry

Many +1 recoils left on the table







What is a Funnel MCP?