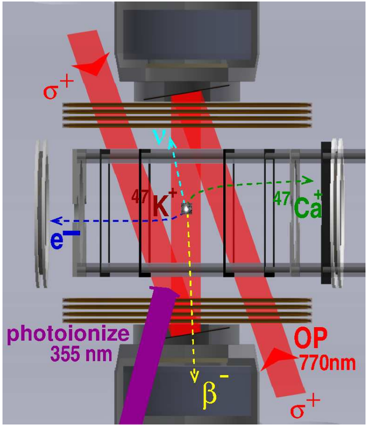
Isospin breaking and time reversal symmetry in ^{47}K beta decay



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

- **Isospin symmetry and "isobaric analog states"**
- **Sensitivity to time-reversal breaking enhanced in isospin-forbidden β decay ^{47}K**
- **^{47}K isospin breaking experiment: preliminary results**

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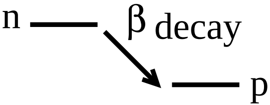
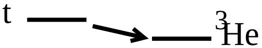
Isospin: The neutron and proton are isospin projections of the isospin-1/2 "nucleon". One consequence of isospin symmetry:

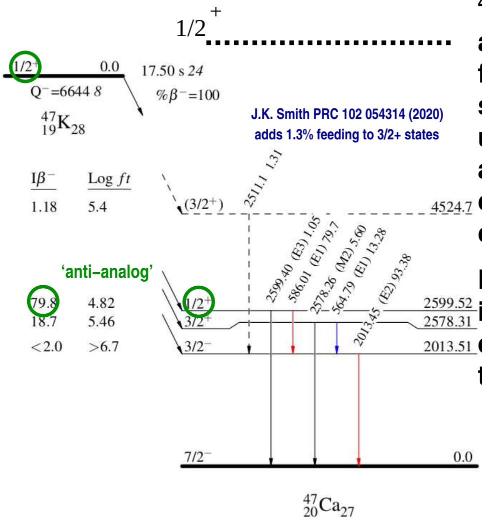
neutron β^- decay is to the proton, its isobaric analog



tritium β^- decay is also to its isobaric analog



Contributions from Fermi operator $\tau^{\pm}$ (Only changes n to p) and Gamow-Teller $\sigma \cdot \tau$ (Can flip spin and isospin)

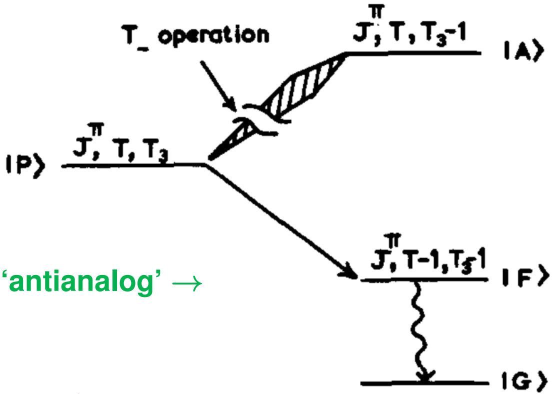


^{47}K decay to its isobaric analog is energetically forbidden, so is purely Gamow-Teller, unless isospin mixing of analog and "antianalog" configurations lets Fermi contribute.

Fermi/Gamow-Teller interference changes β decay angular correlations that we meausure.

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

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



'antianalog' $\rightarrow$

$$D\,\hat{\mathbf{J}}\cdot\frac{\vec{p_\beta}}{E_\beta}\times\frac{\vec{p_\nu}}{E_\beta}\ \overset{t\rightarrow -t}{\longrightarrow}\ -D\,\hat{\mathbf{J}}\cdot\frac{\vec{p_\beta}}{E_\beta}\times\frac{\vec{p_\nu}}{E_\beta}$$

$$D=\sqrt{\frac{J}{J+1}}\,y/(1+y^2)\sin(\alpha_V-\alpha_A)$$

with $y=\frac{|M_F|}{|M_{GT}|}$

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

So for $\not{T}$ physics mixing antianalog $|F\rangle$ with analog $|A\rangle$, then $V_{\not{T}}$ is only competing with V_{Coul}, not V_{strong}, enhancing α_V by $\sim 10^2$ or 10^3 ☺

Any $\not{T}$ decay experiment should answer:

- Does interaction between outgoing particles mimic $\not{T}$? (We hope we can reach the $D < 10^-3$ level of such false $\not{T}$)
- Have null EDM's ruled you out? (Not if we reach $D < 10^-2$)
- Has your experiment been done better? (Our goal is 3x better than Calaprice et al. ^{56}Co, and complementary to NOPTREX neutron scattering resonances for parity-even isospin-breaking interactions)

Measuring Analog-antianalog mixing for its own sake

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

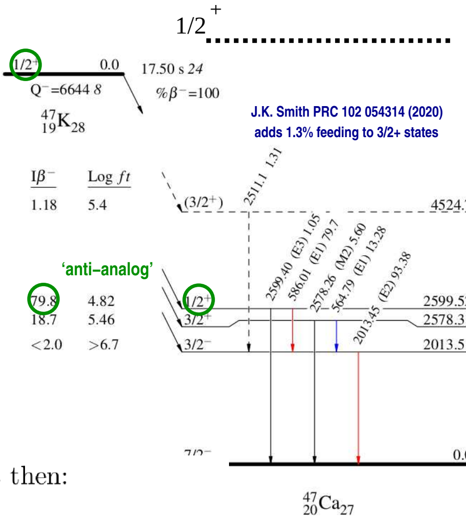
$A\bar{A}$ mixing explains isospin-forbidden particle decays, Γ_A, where A is a well-defined single resonance.

$\bar{A}$ configuration is typically part of several eigenstates:

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

	HO	Experiment
^{88}Sr	250 keV	Skyrme interactions agree: 250 to 310
^{71}As	300	28± 4 Severijns PRC 71 064310 2005 Fragmented $\bar{A}$
^{56}Co	160	2.9±0.5 Markey PRC 26 287R 1982 Fragmented $\bar{A}$
^{47}K	190	$\bar{A}$ might be one state ☺

^{47}K, ^{47}Ca are near shell closures 20 and 28 so structure is simpler



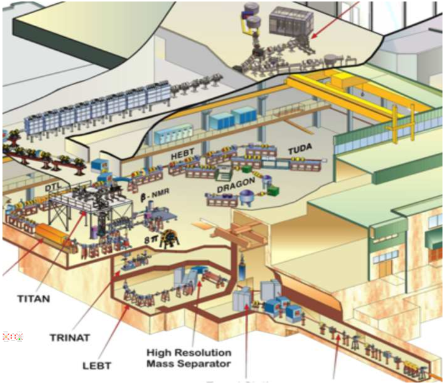
The analog is:

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

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

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

TRIumf Neutral Atom trap at Isotope Separator + ACcelerator

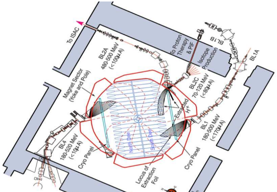


^{47}K 8x10^{6}/s

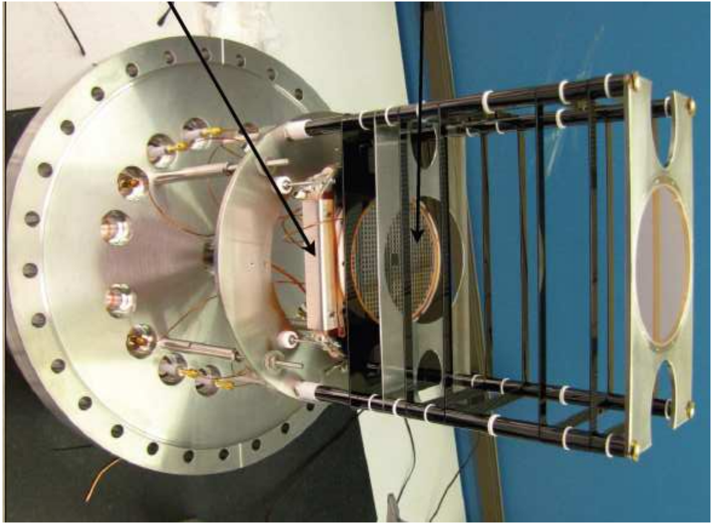
UC target $\sim$ 2000^{o}C

20 μA protons

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



ion MCP assembly



14 inch CF flange

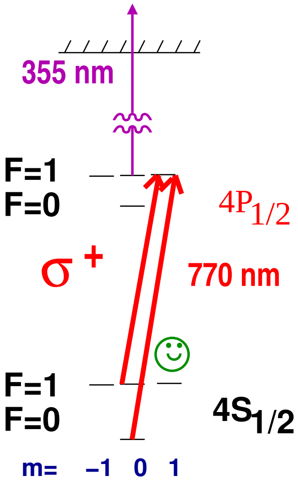
Electrostatic field

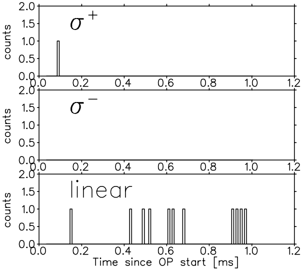
delay-line anode for position info

no stray wires

Low-Z (glassy carbon, titanium) to minimize β^+ scattering

Optical pumping of I=1/2 ^{47}K





(tight cuts on timing wrt pulse laser and center position exclude background: H. Gallop. U. Waterloo)

We alternate trap/optical pumping

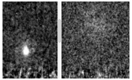
Apply circularly polarized light along z quantization axis.

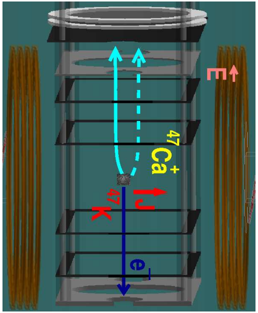
Once we start OP cycle, atoms increase spin to maximum, then stop absorbing If light is linearly polarized, atoms keep absorbing.

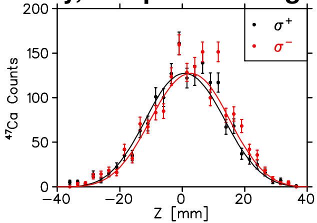
When excited, a pulsed laser has enough energy/photon to photoionize (a small fraction) of them.

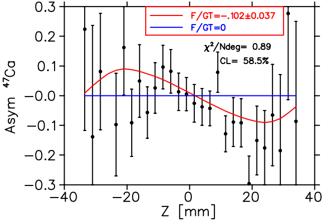
11 photoions while linearly polarized, 1 photon circularly polarized $\rightarrow$ nuclear polarization 96$\pm$4%

1000 atoms trapped for 1 day, isospin breaking ^{47}K 29 Jan without weak mag

DC  MOT then OP







- **Nonzero ^{47}Ca asymmetry wrt spin $\Rightarrow$ a nonzero M_{Fermi}**
  M_F / M_{GT} =
  -0.102 $\pm$ 0.037 stat $\pm$ 0.018 syst $\Rightarrow$
  $\langle \bar{A} | V_{\mathrm{Coulomb}} | A \rangle$ =
  -78 $\pm$ 28 stat $\pm$ 14 syst keV
- **A_{recoil} is damped at extreme Z by a $\sim$6% bkg from untrapped ^{47}K, measured by dedicated 'poof' tests**
- **Apparatus is symmetric: X projection flat at 1σ to 0.05; Unpolarized data has X, Z projections flat $\sim$ 0.01**
- **$\beta' s$ fire the eMCP with $\sim$ 20% quantum efficiency– these we measure to be $\sim$ 0.002 correction**

To do: check TOF spectrum to refine 2+ 3+ 4+ ratio
Weak magnetism correction

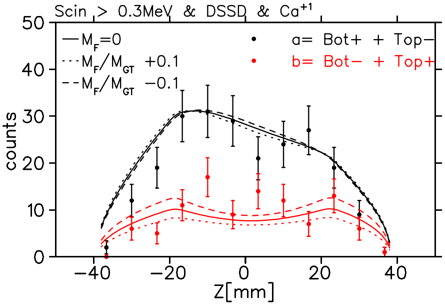
β-recoil (Confirms sign of polarization)

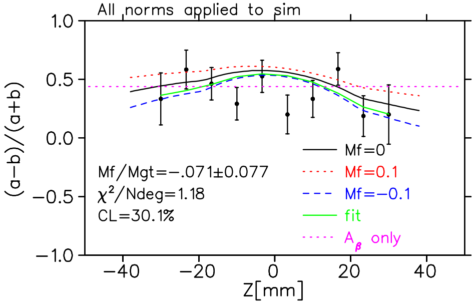
Fit to similar numerical integration, including pointlike β detector and a 2 MeV photon. Scaling with number of +,-; DSSSD XY strips; solid angle from Z shift of trap; 0.99 for $\langle \cos\theta_\beta \rangle$; divide asymmetry by 1.023 as in 37K to account for backscatter; all put into calculation, not data

There is an evident change in the β & ^{47}Ca asymmetry with radius; acceptance in the other dimension with trap offset + the γ-ray momentum forces some Ca^{+1} to miss.

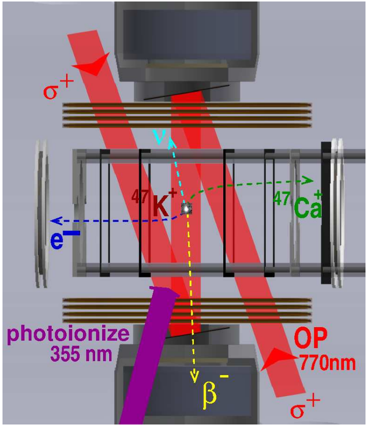
Mf/Mgt = -0.071 $\pm$ 0.077 stat $\pm$ 0.033 syst
Uncertainties: polarization 0.96$\pm$0.04 $\rightarrow$ uncertainty 0.022
Scale Z by 0.9 to make the distribution fit better by eye, uncertainty $\rightarrow$ 0.025 ("E field uncertainty")
assume 20% uncertainty backscatter $\rightarrow$ 0.0024
Added in quadrature $\rightarrow$ Mf/Mgt= -0.071 $\pm$ 0.084

To do: Quantify weak magnetism correction $\sim$ 0.01





Isospin breaking and time reversal symmetry in ^{47}K beta 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 ^{47}K 96$\pm$4%

- Preliminary results suggest a nonzero measureable Fermi component to the main branch of ^{47}K β decay

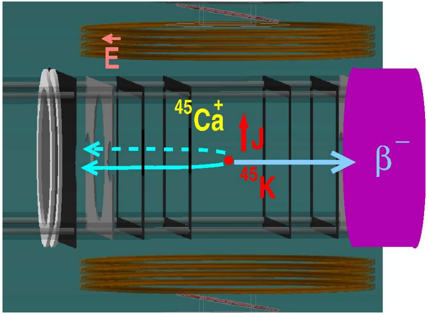
  We're measuring something that isn't 'zero' ☺ !
  Our standard model tests have all agreed with predictions ☹

- The possibly large value of the Coulomb-induced isospin breaking is predicted because near-closed shell ^{47}Ca has only one bound state with same J^π as ^{47}K

- Measuring ~~*isospin*~~ in ^{47}K will determine sensitivity to parity-even ~~*isospin*~~ $\not T$ interactions via future $D\vec{I} \cdot \vec{v_\beta} \times \vec{v_\nu}$

Isospin: The neutron and proton are isospin projections of the isospin-1/2 "nucleon"
It provides another degree of freedom for antisymmeterization of fermion wf's under exchange of identical fermions
Isospin is an abstract symmetry,
yet Wigner's SU(4) = SU(2) spin X SU(2) isospin explains most quantized states in light nuclei: one can classify complexity of states in light nuclei by the number of SU(4) configurations (Ormand and Vogel)
The Coulomb interaction breaks isospin. We will interpret our measurement of 47K isospin breaking in terms of a Coulomb matrix element.
QCD only breaks isospin a little, because with $m_u \neq m_d$. More is commonly invoked phenomenologically to explain the Nolen-Schiffer anomaly of mirror nuclear masses: this has consequences for the isospin breaking needed for 1% corrections to the absolute strength of β decay and for our other β decay project

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**

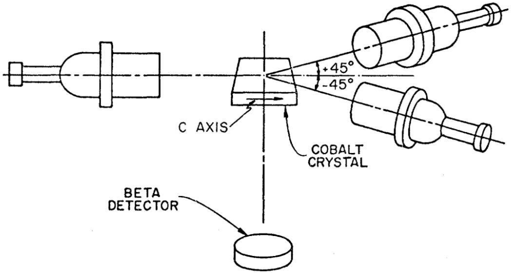
D Uncertainties / 100 scaling from Melconian PLB 649 270 (2007)

	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**

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

Asymmetry of the 45° γ detectors with nuclear alignment



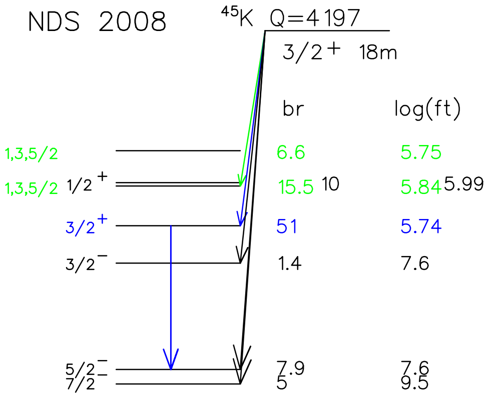
"Test of time-reversal invariance in the beta decay of ^{56}Co"
Calaprice, Freedman, (Princeton); Osgood, Thomlinson (BNL)
PRC 15 381 (1977)

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)

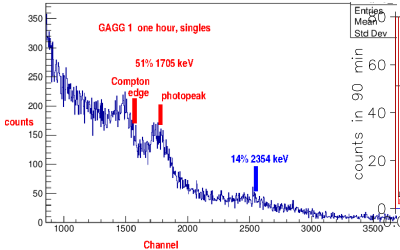
$V_{\rm Coul}$= 2.9 keV, $V_{\not{T}} = 54 \pm 110 {\rm eV}$
(J.L. Mortara Ph.D. thesis 1999 UCB
$E_1 = -0.001 \pm 0.006$
$\Rightarrow$ $V_{\not{T}}$ = 5$\pm$ 33 eV)
We believe we can measure D in ^{47,45}K much more accurately than E in ^{56}Co, but we must find a case with $|M_{GT}|$, $V_{\rm Coul}$, and $\not{T}$ N-N matrix elements to allow complementary or better sensitivity to $V_{\not{T}}$

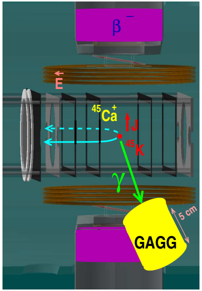


51% branch to 3/2+ state in ^{45}Ca. Should include the antianalog configuration,
$\langle F|V_{\rm coul}|A\rangle \sim$ 5 to 50 keV ?

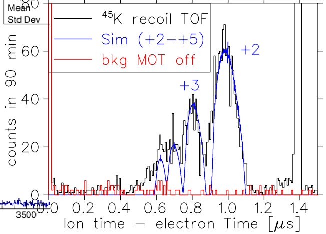
A_β, $A_{\rm recoil}$ would answer 15.5% branch to 1/2.3/2.5/2?

^{45}K decay to antianalog

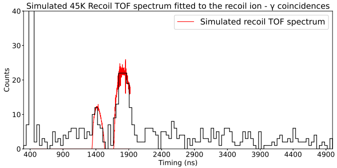




shakeoff e$^-$ & recoil clean even for $t_{1/2}$=18 min;

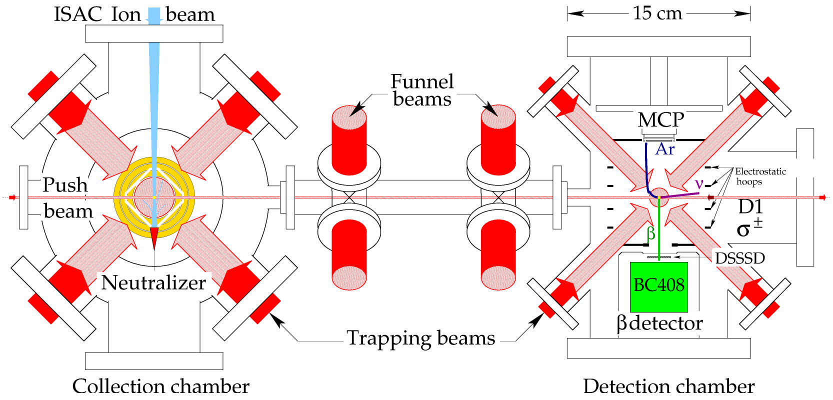


γ & recoil is a challenge that will be cleaner in ^{47}K:



TRINAT plan view

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



- **Spin-polarized 99.1±0.1%**

Neutralizer and Collection trap