Overview and Theory needs

- **^{47}K isospin breaking and time reversal**

Theory needs: recoil-order corrections like weak magnetism for TRV
matrix elements on nucleon-nucleon TRV interactions like $\hat{r} \cdot p$, compare sensitivity to ^{56}Co

- **^{92}Rb $0^- \to 0^+$ decay for reactor ν physics**

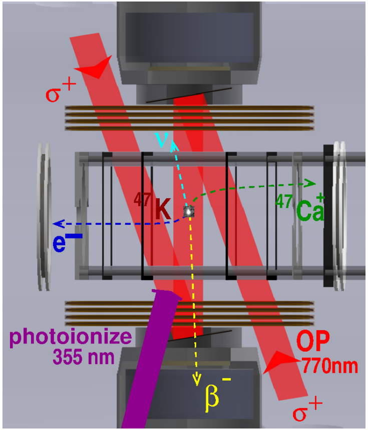
Q-value cut lets us isolate $0^- \to 0^+$ g.s. to g.s. branch
$a_{\beta\nu}$ close to 1: we don't fully understand at low β energy
theory needs: Do we have the Coulomb correction right from Behrens and Bühring?
Calculation of the smaller matrix element $\sigma \cdot r$?

- **^{37}K Mirror decay: bFierz; ν helicity**

Theory needs: ^{38g}K GT 3^+ to 2^+ recoil order corrections
Isospin breaking calculations ^{37}K

- *Community: Revisit 2nd-class currents*

Analog-Antianalog isospin mixing in ^{47}K β^- decay + time-reversal symmetry



- Spin-polarize by direct optical pumping
- Measure asymmetry of decay products wrt initial nuclear spin

- Isobaric analog states and isospin-suppressed β decay
- In ^{47}K isospin-suppressed decay, we measure:

a large Fermi contribution and Coulomb matrix element

a large fraction of predicted analog-antianalog mixing

- Sensitivity to time-reversal breaking $\not T$ enhanced in isospin-forbidden β decay ^{47}K

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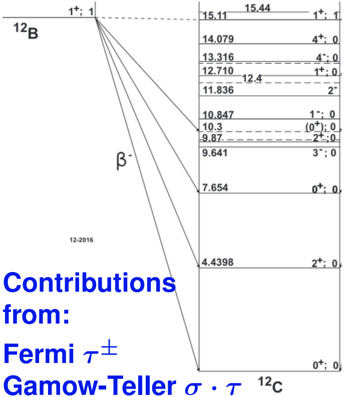
Supported by NSERC, NRC through TRIUMF, DOE, RBC Foundation

***co-spokesperson**

^{47}K β^- decay and Analog- “Anti-analog” isospin mixing

n, tritium β^- decay to their isobaric mirrors

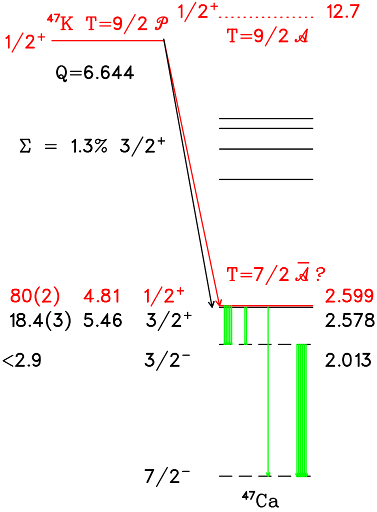
^{12}B β^- decays to ^{12}C E_x=15.11 isobaric analog



Contributions from:

Fermi $\tau^{\pm}$

Gamow-Teller $\sigma \cdot \tau$



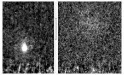
data from J.K. Smith PRC 102 054314 (2020)

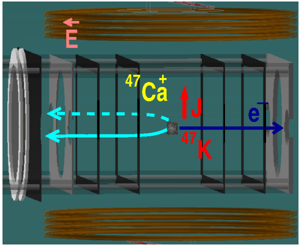
^{47}K decay to its isobaric analog is energetically forbidden, so is purely G-T, unless isospin mixing of analog and “antianalog” configurations lets Fermi contribute → nonzero ^{47}Ca asymmetry wrt ^{47}K nuclear spin

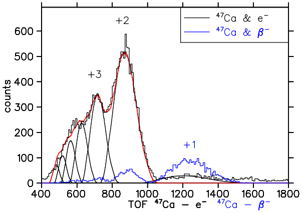
Barroso and Blin-Stoyle PL45B 178 (1973):

sensitivity of $\not{T}$ correlations to $\not{T}$ P even N-N isovector interactions is enhanced by $\sim 10^2$, because $\not{T}$ is referenced to Coulomb (not strong) interactions

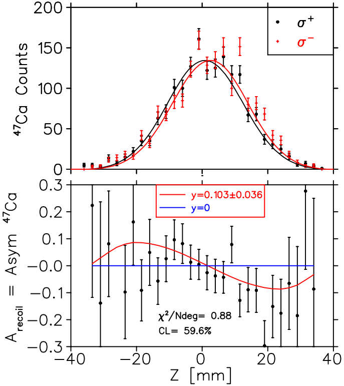
1000 atoms trapped

DC  MOT then OP

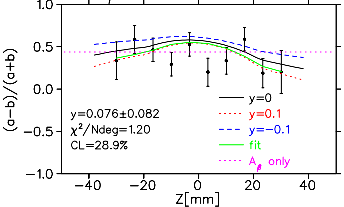




^{47}Ca & atomic e^-



β^- & ^{47}Ca



Source	A_{recoil}	pseudoA_β
A_{recoil} bkg 6$\pm$4%	0.014	$<$ 0.002
Polarization 0.96$\pm$0.04	0.004	0.023
β^- Branching ratio	0.002	0.022
Weak magnetism	0.0006	0.0003
Fit range in Z $\pm$20 to 34 mm	0.012	NA
^{47}Ca^{+1} percent bkg	0.001	NA
^{47}Ca^{+N} distribution from TOF	$<$ 0.0005	NA
E field	negligible	0.025
Backscatter correction -0.012$\pm$20%	NA	0.0024
Fit statistics	0.037	0.082
Total	0.041	0.091

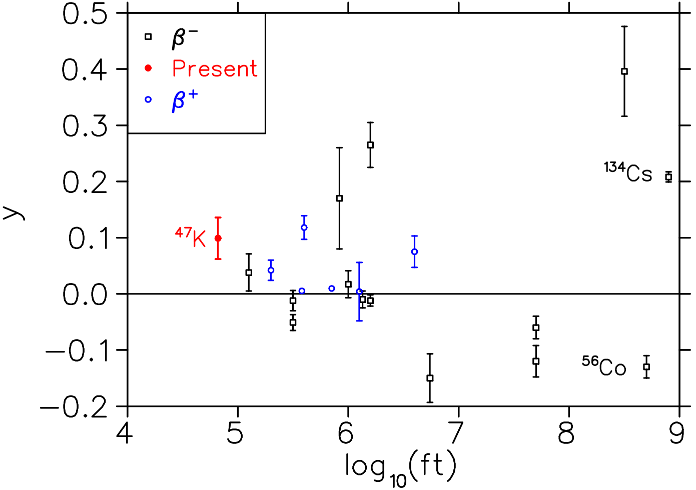
- **Nonzero ^{47}Ca asymmetry wrt spin $\Rightarrow$**

a nonzero $M_{\rm Fermi}$

$$y = g_V M_F / g_A M_{GT} = 0.098 \pm 0.037$$

$$\langle \bar{\mathcal{A}} | V_{\rm Coulomb} | \mathcal{A} \rangle = 101 \pm 37 \text{ keV}$$

Isospin mixing in isospin-suppressed β decay:



- M_F can remain $\sim$ to M_{GT} as M_{GT} falls two orders

but is always smaller

Implications for planned $\not{T}$

$y = g_V M_F / g_A M_{GT}$ large enough to be favorable for D $\not{T}$ measurement

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

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

In $\mathcal{A} - \bar{\mathcal{A}}$ systems Barroso and Blin-Stoyle PL45B 178 (1973)

$$\sin \alpha_V = -i \frac{\langle \bar{\mathcal{A}} | V_{\not{T}} | \mathcal{A} \rangle}{\langle \bar{\mathcal{A}} | V_{Coul} | \mathcal{A} \rangle} \Rightarrow$$

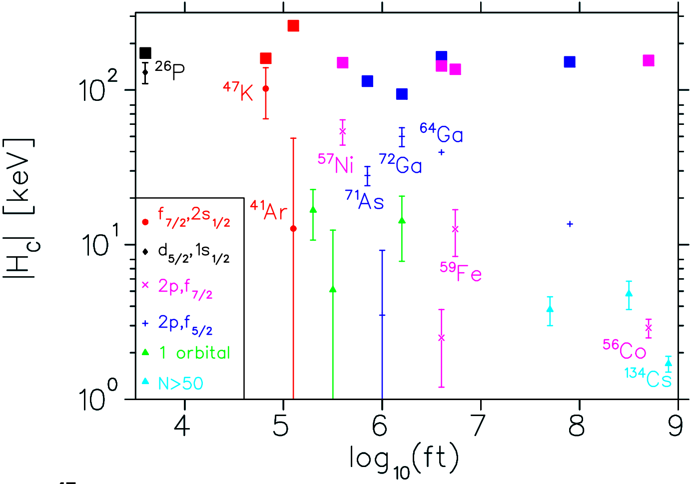
$$D \propto \delta E \frac{\langle \bar{\mathcal{A}} | V_{\not{T}} | \mathcal{A} \rangle}{M_{GT}}$$

- To get same sensitivity to $\langle \bar{\mathcal{A}} | V_{\not{T}} | \mathcal{A} \rangle$ we need D 30x better in ^{47}K compared to ^{56}Co

$E = -0.01 \pm 0.02$ Calaprice Freedman ... PRC 15 381 (1977) no worries

- However, nuclear matrix elements $\langle \bar{\mathcal{A}} | V_{\not{T}} | \mathcal{A} \rangle$ might also fall with M_{GT} i.e. 'complexity' so may favor ^{47}K

Analog-antianalog mixing in β decay:



Schematic model for $\mathcal{A}$ and $\bar{\mathcal{A}} \Rightarrow$

$$H_C = \langle \bar{\mathcal{A}} | V_C | \mathcal{A} \rangle$$

$$= \frac{\sqrt{n_1 n_2}}{2T} \left(\langle j_1 | V_C | j_1 \rangle - \langle j_2 | V_C | j_2 \rangle \right)$$

$$\to 0.35 \frac{\sqrt{n_1 n_2}}{2T} \frac{Z}{A^{2/3}} \mathrm{MeV}, \text{ for HO wf's}$$

and excess n's occupy 2 major shells

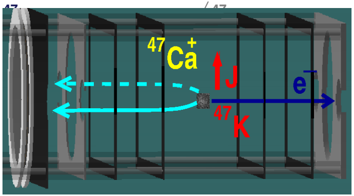
H_C for many β decays is a small fraction of the prediction: attributed to fragmentation of $\bar{\mathcal{A}}$ configuration among several eigenstates

Auerbach, Loc NPA 1027 122521 (2022)

^{47}K β^- decay has:

- **Large $H_C = \langle \bar{\mathcal{A}} | V_{\mathrm{Coul}} | \mathcal{A} \rangle$ = 101 $\pm$ 37 keV**
- **Large fraction of $\mathcal{A} - \bar{\mathcal{A}}$ mixing prediction** Auerbach Loc NPA 1027 122521 (2022)

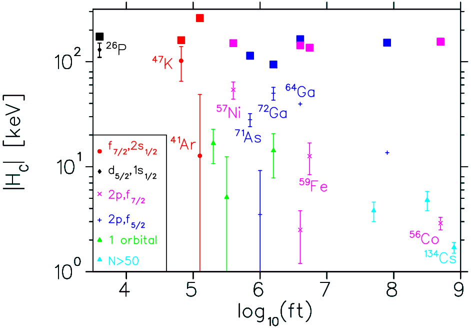
$\Leftarrow$ $^{47}_{20}$Ca^{27} has only one 1/2$^+$ state, $\bar{\mathcal{A}}$ configuration not fragmented



Analog-Antianalog isospin mixing in ^{47}K β^- decay and $\not{T}$

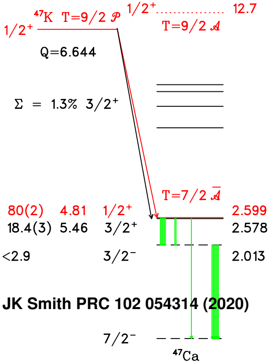
Measuring ~~isospin~~ in $^{47}_{19}K^{28}$ decay determines sensitivity to parity-even ~~isospin~~ $\not{T}$ N-N interactions via future $D\vec{I} \cdot \vec{v_\beta} \times \vec{v_\nu}$

B. Kootte et al. Phys Rev C 109 L052501 2024



I=1/2$^+$ ^{47}K β^- decay has large:

- $H_C = \langle\bar{\mathcal{A}}|V_{\rm Coul}|\mathcal{A}\rangle$ = 101 $\pm$ 37 keV
- fraction of $\mathcal{A} - \bar{\mathcal{A}}$ mixing prediction Auerbach, Loc NPA 1027 122521 (2022)



JK Smith PRC 102 054314 (2020)

$^{47}_{20}Ca^{27}$'s single 1/2$^+$ state contains most of the $\bar{\mathcal{A}}$ config

$y = g_V M_F / g_A M_{GT}$ = 0.098$\pm$0.037 large enough to be favorable for D, enhanced by $\sim 10^2$ in isospin-suppressed β decay

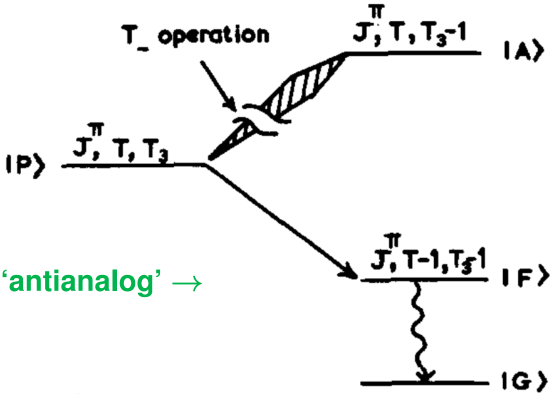
Barroso and Blin-Stoyle PL45B 178 (1973)

calculate reasonably large ^{134}Cs $\not{T}$ matrix elements:

^{47}Ca's 1/2$^+$ simple structure should make calculating $\not{T}$ nuclear matrix elements of $\hat{r} \cdot \vec{p}$ practical

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

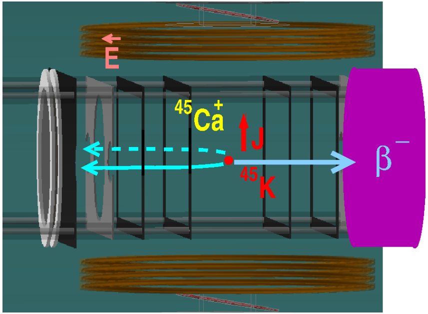
So for $\not{T}$ physics mixing antianalog $|F\rangle$ with analog $|A\rangle$, then $V_{\not{T}}$ is only competing with $V_{\rm Coul}$, not $V_{\rm strong}$,

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)

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**

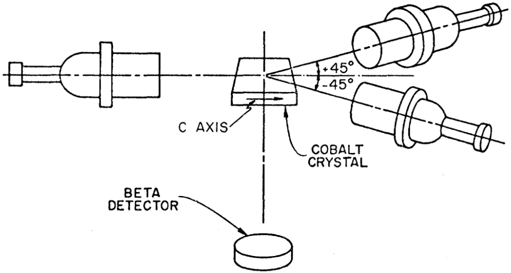
D Uncertainties / 100 scaling from Melconian PLB 649 270 (2007)

	B_ν	Improvements	Projected
Cloud position $\sigma^\pm$	1.3	$\pm 500\mu$m $\to \pm 20\mu$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, $V_{\not{T}} = 54 \pm 110$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 $V_{\not{T}}$

^{47}K recoil order estimates still in progress

$^{47}_{19}K^{28}$ μ = 1.9 $\mu_{\rm nucleon}$ $\Rightarrow$ 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**

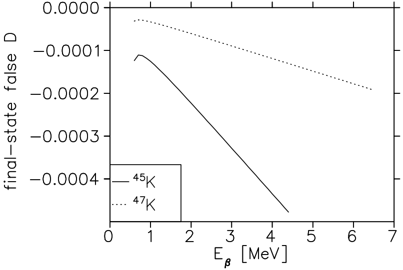
For our M_F / M_{GT} measurement,

$A_{\rm recoil}$, A_β changed by $\leq$ 0.01

Finite-size correction cancels most of this in $A_{\rm recoil}$

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

- ***P* even N-N isovector/tensor $\not{T}$: complementary to $\not{T}$ neutron resonance experiments**

Barroso and Blin-Stoyle

using Herczeg NP **75** 655 (1966):

$$V_{\text{t.v.}} = G_{\text{t.v.}} \tfrac{1}{2}[f(r)\hat{r}\cdot p + \text{h.c.}]$$

$$\times \; [1 + a\,\sigma^{(1)}\cdot\sigma^{(2)})(\tau_3^{(1)} + \tau_3^{(2)})$$

$$+ (b + c\,\sigma^{(1)}\cdot\sigma^{(2)})\tau_3^{(1)}\tau_3^{(2)}]$$

Samart Schat Schindler Phillips PRC 2016: Isoscalar and isotensor *P* even $\not{T}$ π-N suppressed by $1/N_C$; isovector a_1 contributes, not ρ and h_1

***D* produced by most $\not{T}$ interactions would make a large neutron EDM $\Rightarrow$ *D* less than 10^{-4} (Ng and Tulin PRD 85 033001 (2012).**

Isotensor $\not{T}$ interaction would make *D* but not T=1/2 neutron EDM, but tricky microscopically without making isovector $\not{T}$.

Barroso and Blin-Stoyle 10^2 $\mathcal{A} - \bar{\mathcal{A}}$ enhancement $\Rightarrow$ our goal of $D < 10^{-3}$ in ^{47}K evades Ng-Tulin bound.

NOPTREX: P-even $\not{T}$ neutron resonance experiments are ongoing (in addition to $\not{P}$ ones), with planned sensitivity to matrix elements $\sim$ eV.

We hope to be complementary on isovector P-even $\not{T}$ by reaching similar sensitivity.

$0^- \rightarrow 0^+$ decays make ∼1/3 of reactor E_ν = 5-7 MeV

Warburton PRC 1982:

$$P(E,\theta_{\beta\nu}) = 1 + a\, v/c \cos(\theta_{\beta\nu})$$

$$a = \frac{1 - \frac{\omega^2}{9\xi_0^2}}{1 + \frac{\omega^2}{9\xi_0^2} - \frac{2\omega m_\beta \gamma}{3\xi_0 E_\beta}} \overset{\omega \ll \xi_0?}{\longrightarrow} 1$$

Nuclear matrix elements:

$$\langle i || \sigma \cdot r || f \rangle / R_{\mathrm{nucleus}} = \omega$$

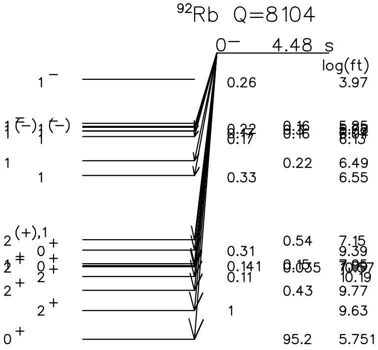
$$\langle i || \gamma_5 || f \rangle \rightarrow \xi_0$$

Which ⇒ β spectrum distorted by:

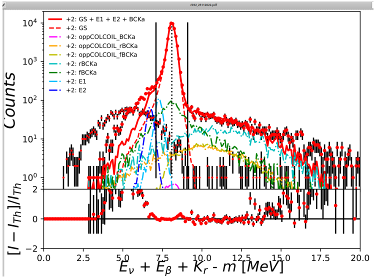
$$1 + \frac{\omega^2}{9\xi_0^2} - \frac{2\omega m_\beta \gamma}{3\xi_0 E_\beta}$$

We see that a changes with E_β

E_ν spectrum changed by $\lesssim$ 10%



Three experiments (two T.A.S., one careful β-γ) now concur on ≈10% excited state feeding

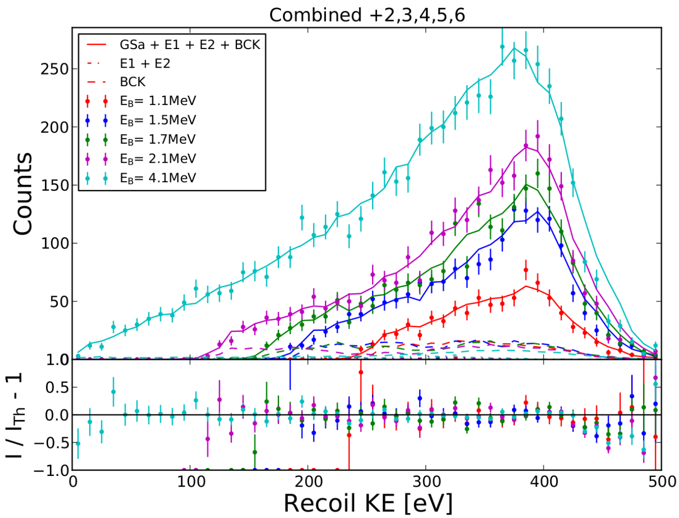


We separate the decay to the ground state quite cleanly from the reconstructed total energy:

<1% correction from the lowest 1st forbidden unique $0^- \rightarrow 2^+$ branch

TRIUMF

Preliminary: $0^- \to 0^+$ ^{92}Rb decay



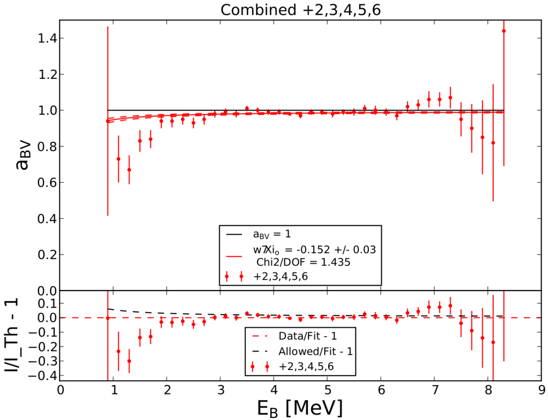
- **Recoil energy spectra as a function of $E_\beta \to a_{\beta\nu}[E_\beta]$**

Remaining issues from progeny accidental background at low E_β
James McNeil, APS DNP 2020 RF.00004
June 24, 2022 update

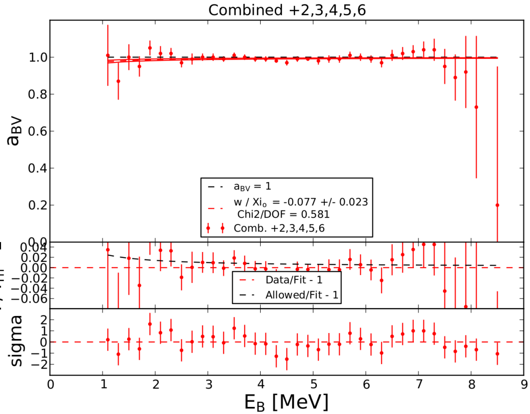
- **Coulomb from Behrens and Bühring $\sim$0.01**
- **Low-E_β (high E_ν) systs from progeny random bkg and from β backscatter**
- **Contribution from $\sigma \cdot r$ small, it is a question of quantifying:**

Preliminary: $0^- \to 0^+$ ^{92}Rb decay

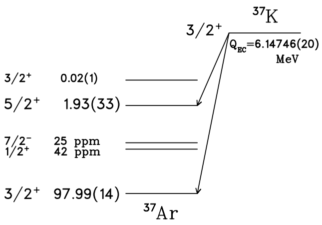
- **Measured progeny background not included below**
- **Fitting low-E_β with $\frac{\omega m_\beta}{\xi_0 E_\beta}$ changes $a_{\beta\nu}$ too much at higher E_β**



- **Floating measured background by eye can force $\frac{\omega m_\beta}{\xi_0 E_\beta}$=0 artificially**
- **Still need to normalize progeny background, evaluate E_β backscatter uncertainty, and extract $\frac{\omega m_\beta}{\xi_0 E_\beta}$**



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



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

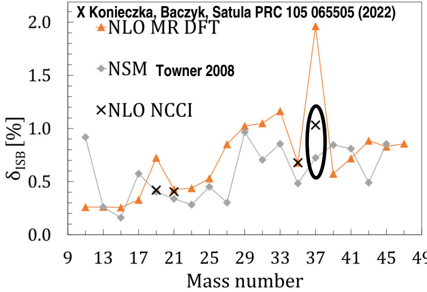
CVC ⇒ most important corrections:

μ ⇒ b_{WM} (small for $\pi d_{3/2}$)

Induced tensor $d_I \approx 0$ for isobaric mirror

Q ⇒ 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

Improved measurement of ^{38m}K $\langle r^2_{ch}\rangle$ for V_{ud} corrections

J.A. Behr, L. Haddad, F. Klose, B. Ohayon, B.K. Sahoo

Isospin breaking of β decay

ψ_i and ψ_f can be related to triplets of isobaric charge radii Seng, Gorchtein Phys Lett B 2023

Only triplet with $\langle r^2_{charge}\rangle^{\frac{1}{2}}$ known is A=38:

^{38}Ca 3.467(1) fm,

^{38m}K 3.437(4) fm,

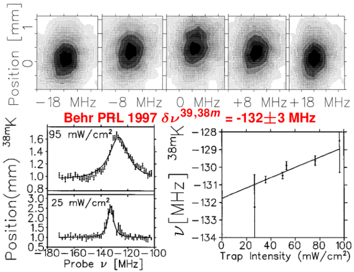
^{38}Ar 3.4028(19) fm

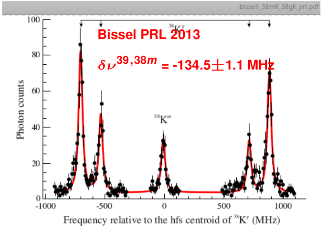
$\Rightarrow \Delta M_B^{(1)}$ = -0.03(54) fm^2;

models span 0.42 to 0.04 fm^2

Needs order of magnitude better $\langle r^2_{charge}\rangle^{\frac{1}{2}}$!

$4S \to 4P_{1/2}$ Γ=6 MHz



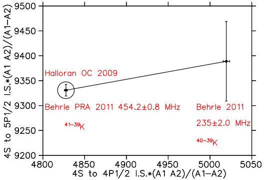


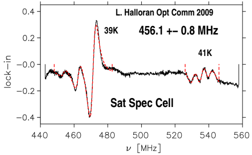
ISOLDE did much better

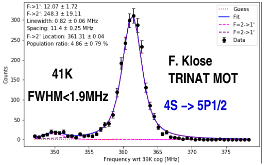
$4S_{1/2} \to 5P_{1/2}$: Γ = 1.1 MHz

for 0.1 MHz accuracy?

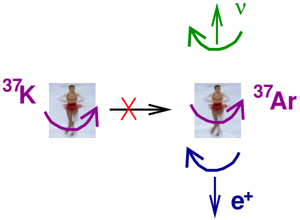
Katyal 2412.05921 RCC K_{SMS}=-30.6±5.2







A spin-polarized angular distribution sensitive to ν helicity



If $I_z = I_{\rm initial}$ and $I_{\rm initial} = I_{\rm final}$, the leptons can't increase $I_{z\ \rm final}$

If β^+ down, the ν can't go up, unless either β or ν have wrong helicity

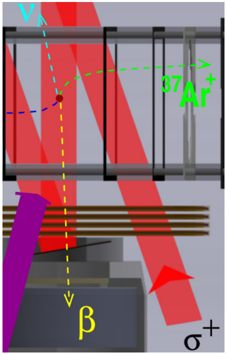
Any imperfect I_z/I mimics a wrong-handed ν

^{38}K G.T. $3^+ \to 2^+$ needs both ν and β^+ helicities wrong:

would be most direct ν helicity measurement

since Goldhaber 1957

Helicity-driven null



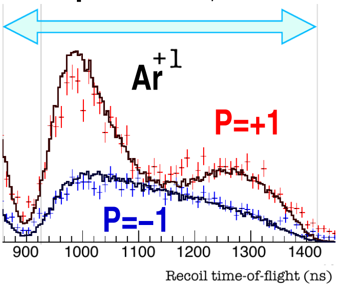
Fenker et al. PRL 2018

A_β= -0.5707$\pm$ 0.001913 in agreement with SM

achieved I_z/I = 0.991 $\pm$ 0.001

0.993 to 0.994 in 2024

2014 polarized β-recoil



$v_{\rm TOFaxis} = 0$ suppressed. Dip would be deeper with ion MCP position cut or $\cos(\theta_{\beta-\nu})$ determination

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

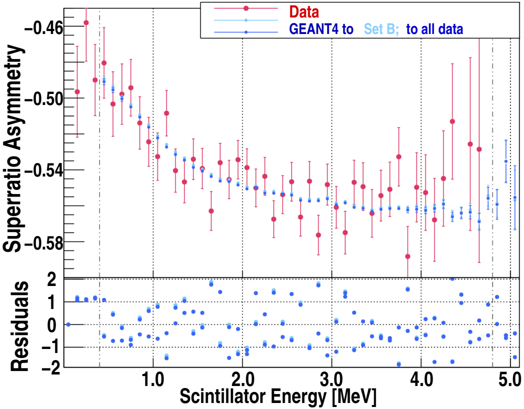
$$a_{\rm pol} = \frac{a_{\beta\nu} - 2c/3T + PB_\nu}{1 + PA_\beta + bm/E}$$

= 1 or 0, independent of $\frac{M_{GT}}{M_F}$

$A_\beta[E_\beta]$ ^{37}K (data of Fenker et al. PRL 2018)

M. Anholm Ph.D. thesis U. Manitoba 2022 (and to be submitted)

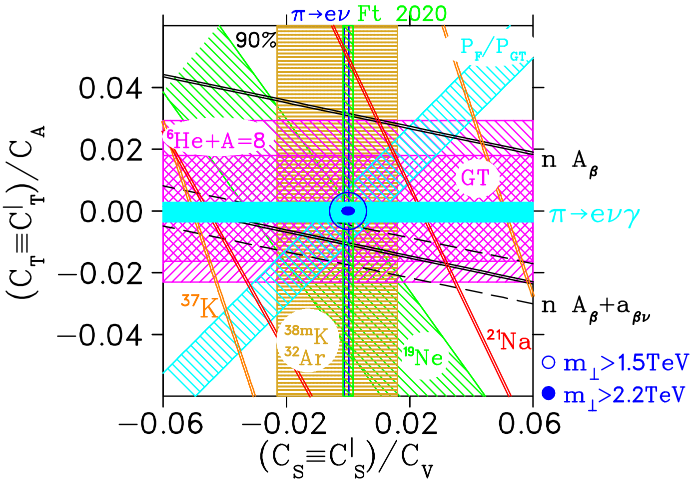
b_F=-0.0002±0.024 (stat) ±0.039 (syst)



new MWPC's for ΔE, pellicle mirrors, low-Z mirror mounting → 5x improvement

Source	Present b_F	Future b_F
β Scattering	0.031	0.003
Mirror Thickness	0.013	0.001
DSSD Thickness	0.013	0.001
DSSD Detection Radius	0.006	0.001
DSSD signal/noise	0.006	0.001
Low-E_β lineshape	0.008	0.008
DSSD XY Energy Agreement	0.005	0.001
DSSD E threshold	0.005	0.001
Scintillator Threshold	0.004	0.001
Scintillator Calibration	0.003	0.003
Atomic Cloud	0.002	0.002
Background	0.004	0.004
Be Foil Thickness	0.004	0.004
Total Systematics	0.039	0.0041

5x better ^{37}K b_F would reach helpful complementarity



Beck et al. PRL 2024 neutron combining aSPECT $a_{\beta\nu}$ and Perkeo III Saul et al. PRL 2022 A_β can be accommodated by:

- **2nd-class "induced scalar" in $e - N$ vector current $e \approx$ -30 (in one parameterization)**
- **2nd-class induced tensor in $e - N$ axial vector current [Kubodera PRL '77 has *n* and nucleus-dependent SCC's]**
- **There is $<$ 90% tension between n decay here and LHC 8 TeV data $\to$ fine-tune scales to avoid tension with LHC 13 TeV.**

Comments on scales and physics following 4 slides:

So now our full lepton-nucleon interaction density is (Morita Hyp. Int. 21 143 (1985)):

$$\sqrt{2}L = [V_\lambda + A_\lambda]\left[\bar{\psi}_e\gamma_\lambda(1+\gamma_5)\psi_\nu\right] + \left[V'_\lambda + A'_\lambda\right]\left[\bar{\psi}_\nu\gamma_\lambda(1+\gamma_5)\psi_e\right]$$

with explicitly different forms for $\beta^\pm$ decay:

$$V_\lambda = \bar{\psi}_p\left(g_V\gamma_\lambda + \frac{g_M}{2m}\sigma_{\lambda\rho}k_\rho + ig_S k_\lambda\right)\psi_n \quad A_\lambda = \bar{\psi}_p\gamma_5\left(g_A\gamma_\lambda + \frac{g_T}{2m}\sigma_{\lambda\rho}k_\rho + ig_P k_\lambda\right)\psi_n$$

$$V'_\lambda = \bar{\psi}_n\left(g^*_V\gamma_\lambda + \frac{g^*_M}{2m}\sigma_{\lambda\rho}k'_\rho - ig^*_S k'_\lambda\right)\psi_p \quad A'_\lambda = \bar{\psi}_n\gamma_5\left(g^*_A\gamma_\lambda - \frac{g^*_T}{2m}\sigma_{\lambda\rho}k'_\rho + ig_P k'_\lambda\right)\psi_n$$

$$k = k_p - k_n = -k'$$

Yes, the hadron part, because of the QCD-driven “dressing” within the nucleon, is more complicated than the lepton part.
g_S and g_T terms change sign from electron to positron decay. These are therefore odd under charge symmetry. So they vanish in isobaric analog decays to the extent that charge symmetry is good. These are called “2nd-class currents”

Divergence of $g_S k_\lambda$ is nonzero, i.e. breaks CVC

"An induced scalar would be sensational" D. Wilkinson, ca. 2005

- "Induced (by QCD combining quarks into nucleons) scalar" is part of the $e - N$ vector current.
- Produces same $\langle m/E_\beta \rangle$ as Fierz term
- Fit to $0^+ \to 0^+$ Ft

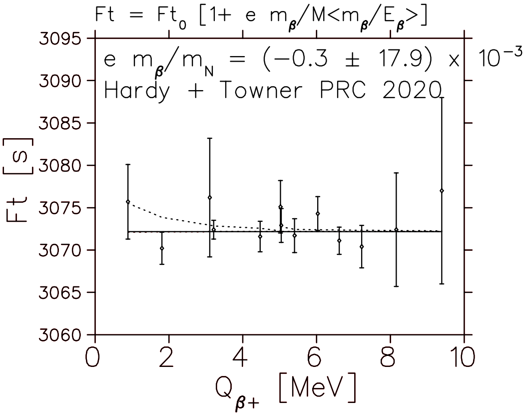
Holstein 1984 parameterization: $g_S = e m_\beta/(A m_{\rm N}) m_\beta/E_\beta$

$\Rightarrow e = 4 \pm 32$

$e \approx$ -30 explains neutron decay

Beck et al. PRL 2024 $a_{\beta\nu}$ using Saul PRL 2022 A_β

and is consistent with other β decay experiments



Caveats: Holstein 1984 contrains e/A, not e;

Weak magnetism for mirror nuclei b/A is $\propto \mu_f - \mu_i$;

Kobodera Delorme Rho NPB'73 do not find the coherent scaling of 2nd-class "induced tensor" term with A predicted by Lipkin.

Induced 2nd-class "tensor" current in axial vector e-N

There are constraints from BABAR PRL 2009
but in 1st-generation 2nd-class currents are (almost by tautology) best constrained by β decay
Wilkinson EPJ 2005 using
General model of Kubodera DeLorme and Rho PRL 1977
A constant characterizing neutron β decay
Terms with interactions between nucleons, short range and by meson exchange
Most recent update is Minamisono 2011 $\to$
Do these limits allow a n β-decay SCC?

K. MINAMISONO *et al.*

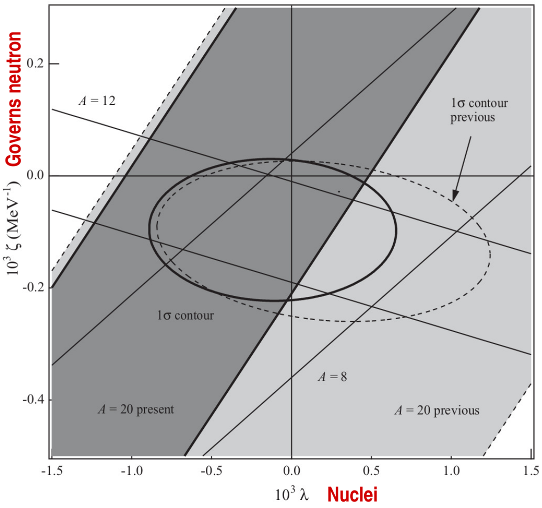
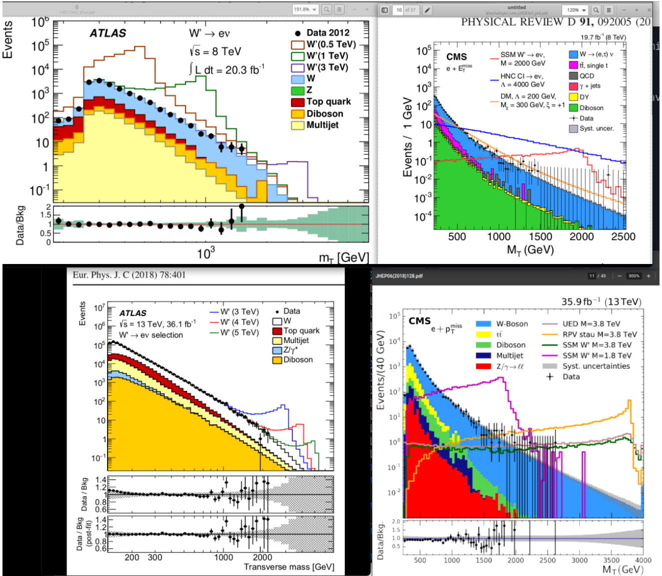


FIG. 14. KDR parameter space with L calculated without a short-range correlation. The shaded area is the present result and the light-shaded area is the previous result for the $A = 20$ system. The solid

An amazing yet SM background-limited channel

10% agreement with SM $W \rightarrow e\nu$ over 3-4 orders of magnitude!



Sensitivity improvements at higher $\sqrt{s}$ require higher scale:

- **The 8 TeV pp$\rightarrow$ e + missing transverse energy**
  20 fb^{-1} data was used to exclude C_T and C_S values with transverse mass $m_{\perp} > 1.5$ TeV
- **The 13 TeV 36 fb^{-1} data had more sensitivity to production of such events, yet had to consider somewhat higher scales producing $m_{\perp} > 2.2$ Tev,**
- **Adding more 13 TeV data to 138 fb^{-1} changed**
  4 events seen with 6 expected to 22 events seen with 20 expected
  Similar limits on C_S,C_T

Summary and Theory needs

- **^{47}K isospin breaking and time reversal**

Theory needs: recoil-order corrections like weak magnetism for TRV
matrix elements on nucleon-nucleon TRV interactions like $\hat{r} \cdot p$, compare sensitivity to ^{56}Co

- **^{92}Rb $0^- \to 0^+$ decay for reactor ν physics**

Q-value cut lets us isolate $0^- \to 0^+$ g.s. to g.s. branch
$a_{\beta\nu}$ close to 1: we don't fully understand at low β energy
theory needs: Do we have the Coulomb correction right from Behrens and Bühring?
Calculation of the smaller matrix element $\sigma \cdot r$?

- **^{37}K Mirror decay: bFierz; ν helicity**

Theory needs: ^{38g}K GT 3^+ to 2^+ recoil order corrections
Isospin breaking calculations ^{37}K

- *Community: Revisit 2nd-class currents*

There are at least 2 ways to make 2nd-class currents in a quark model:

• Remembering Standard Model has $\bar{u}\gamma_\mu d$ and $\bar{u}\gamma_5 d$ terms only, add derivative terms like $\partial_\mu \bar{u} d$ and $\partial^\nu \bar{u}\sigma_{\mu\nu}\gamma_5 d$ Chiral EFT has these

These are not renormalizable, one large reason they were excluded from the Standard Model (Weinberg Phys. Rev. 112 1375 (1958)).

[One perspective is that the Standard Model itself may be an Effective Field Theory good up to some very high energy. Naively, maybe that means renormalizability is not an exact logical requirement. However, deliberately introducing a manifestly unrenormalizable term would still be a very complicated move for the main part of one's basic theory.]

• Introduce a new quantum number in addition to color and flavor! (Feynman famously called this q.n. 'smell'?). You can also interpret this as a second set of quarks (Holstein Treiman PRD 13 3059 (1976)) carrying this quantum number.

A related scenario: recently people consider extra sectors of particles not interacting much with us, but interacting strongly among themselves. QCD-like symmetries turn out to be a feasible way to generate dark matter. There are tight constraints from experiment on such scenarios.

• The best experimental limits on 2nd-class currents, from dedicated β decay measurements, allow 2nd-class current effects about an order of magnitude larger than the known ones from charge-symmetry breaking in QCD.

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:

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

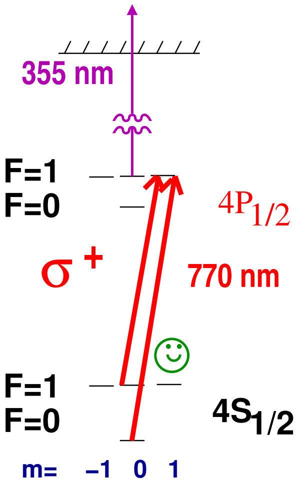
Schematic model for $\mathcal{A}$ and $\bar{\mathcal{A}} \Rightarrow$
$H_C = \langle\bar{\mathcal{A}}|V_{\mathrm{C}}|\mathcal{A}\rangle$
$= \frac{\sqrt{n_1 n_2}}{2T}(\langle j_1|V_C|j_1\rangle - \langle j_2|V_C|j_2\rangle)$
$\to 0.35\frac{\sqrt{n_1 n_2}}{2T}\frac{Z}{A^{2/3}}\mathrm{MeV}$,
for HO wf's and excess n's occupy 2 major shells

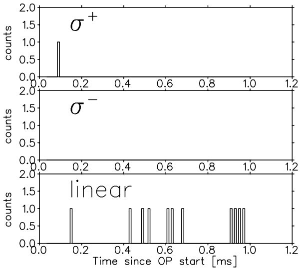
H_C for many β decays is a small fraction of the prediction: attributed to fragmentation of $\bar{\mathcal{A}}$ configuration among several eigenstates

Auerbach, Loc NPA 1027 122521 (2022)

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

We measure by atomic techniques the polarization of the β-decaying nuclei





(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%

^{37}K polarization 2024 (PRELIM)

σ^+/lin = 0.027 ± 0.006

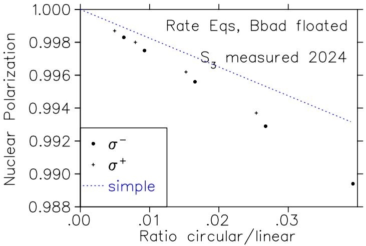
σ^-/lin = 0.021 ± 0.007

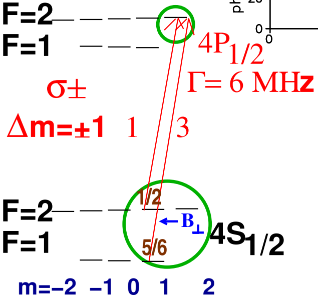
Rate equations with measured S_3 and fit $B_\perp$ ⇒

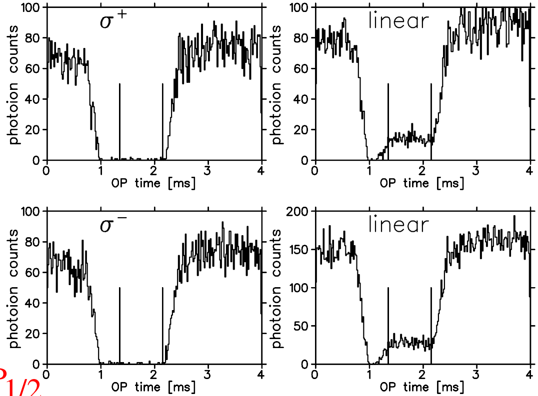
σ^+: I_z/I = 0.993 ± 0.001 (stat)

σ^-: I_z/I = 0.994 ± 0.001 (stat)

σ/lin measures change from 1.







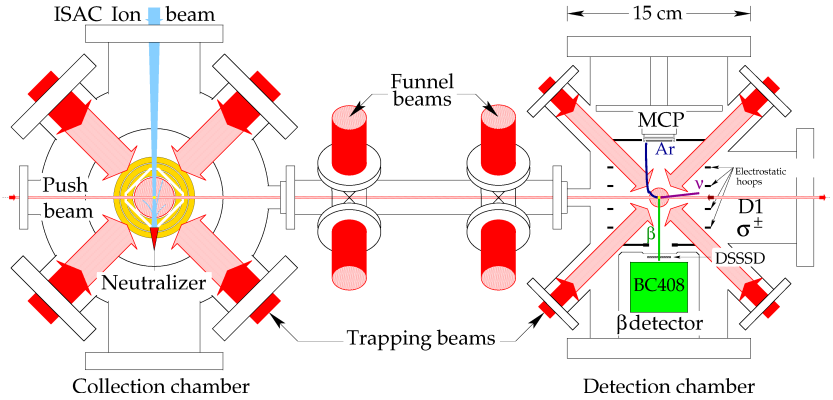
Simpler model (perfect S_3, Larmor precessiononly):

$I_z/I \approx$ 1-0.175 N_σ/N_{lin}

0.175 is small because the main depolarized states still have very good nuclear polarization

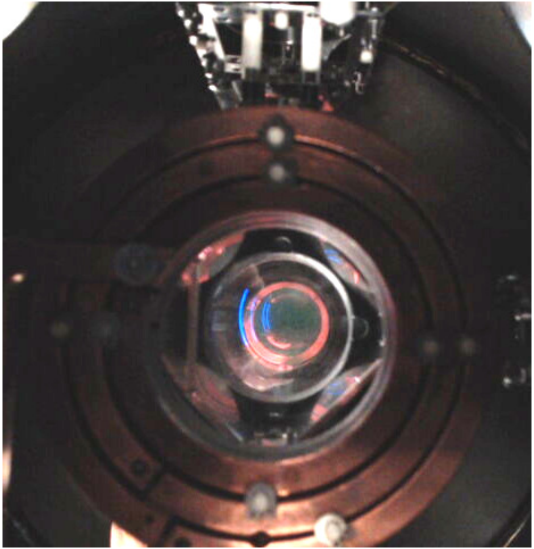
TRIUMF TRINAT plan view

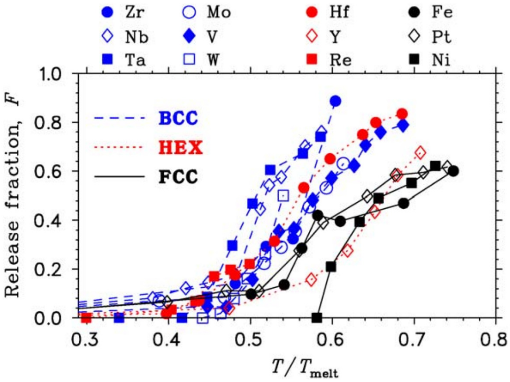
- **Isotope/Isomer selective**
- **75% transfer**
- **Avoid untrapped atom background with 2nd trap**
- **0.7 mm cloud for β-Ar$^+$ $\to$ ν momentum**



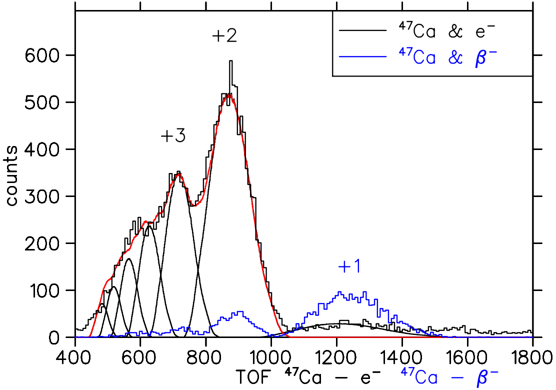
- **Spin-polarized 99.1±0.1%**

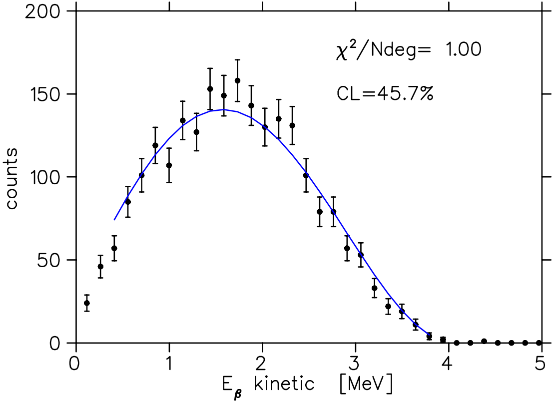
Neutralizer and Collection trap





^{47}K TOF and β spectra





H_{Coul} from isospin-forbidden β-decay

[17] L. G. Mann, D. C. Camp, J. A. Miskel, and R. J. Nagle, New measurements of β-circularly-polarized γ angular-correlation asymmetry parameters in allowed β decay, Phys. Rev. **139**, AB2 (1965).

[18] J. Atkinson, L. Mann, K. Tirsell, and S. Bloom, Coulomb matrix elements from $\beta-\gamma$(cp) correlation measurements in 57ni and 65ni, Nuclear Physics A **114**, 143 (1968).

[19] H. Behrens, Messung des asymmetrie-koeffizienten der $\beta - \gamma$-zirkularpolarisationskorrelation an erlaubten β-übergängen, Z. Physik **201**, 153 (1967).

[20] J. Markey and F. Boehm, Fermi—gamow-teller interference in ^{56}Co decay, Phys. Rev. C **26**, 287 (1982).

[21] S. Bhattacherjee, S. Mitra, and H. Padhi, Fermi matrix elements in allowed beta transitions in 56co, 58co and 134cs, Nuclear Physics A **96**, 81 (1967).

[22] N. Severijns, D. Vénos, P. Schuurmans, T. Phalet, M. Honusek, D. Srnka, B. Vereecke, S. Versyck, D. Zákoucký, U. Köster, M. Beck, B. Delauré, V. Golovko, and I. Kraev, Isospin mixing in the $t = 5/2$ ground state of ^{71}As, Phys. Rev. C **71**, 064310 (2005).

[23] P. Schuurmans, J. Camps, T. Phalet, N. Severijns, B. Vereecke, and S. Versyck, Isospin mixing in the ground state of 52mn, Nuclear Physics A **672**, 89 (2000).

[24] J. J. Liu, X. X. Xu, L. J. Sun, C. X. Yuan, K. Kaneko, Y. Sun, P. F. Liang, H. Y. Wu, G. Z. Shi, C. J. Lin, J. Lee, S. M. Wang, C. Qi, J. G. Li, H. H. Li, L. Xayavong, Z. H. Li, P. J. Li, Y. Y. Yang, H. Jian, Y. F. Gao, R. Fan, S. X. Zha, F. C. Dai, H. F. Zhu, J. H. Li, Z. F. Chang, S. L. Qin, Z. Z. Zhang, B. S. Cai, R. F. Chen, J. S. Wang, D. X. Wang, K. Wang, F. F. Duan, Y. H. Lam, P. Ma, Z. H. Gao, Q. Hu, Z. Bai, J. B. Ma, J. G. Wang, C. G. Wu, D. W. Luo, Y. Jiang, Y. Liu, D. S. Hou, R. Li, N. R. Ma, W. H. Ma, G. M. Yu, D. Patel, S. Y. Jin, Y. F. Wang, Y. C. Yu, L. Y. Hu, X. Wang, H. L. Zang, K. L. Wang, B. Ding, Q. Q. Zhao, L. Yang, P. W. Wen, F. Yang, H. M. Jia, G. L. Zhang, M. Pan, X. Y. Wang, H. H. Sun, H. S. Xu, X. H. Zhou, Y. H. Zhang, Z. G. Hu, M. Wang, M. L. Liu, H. J. Ong, and W. Q. Yang (RIBLL Collaboration), Observation of a strongly isospin-mixed doublet in ^{26}Si via β-delayed two-proton decay of ^{26}P, Phys. Rev. Lett. **129**, 242502 (2022).

[25] S. D. Bloom, Isotopic-spin conservation in allowed β-transitions and coulomb matrix elements, Il Nuovo Cimento **32**, 1023 (1964).

C_T vs C_S exclusion plot references

Accelerators, Spectrometers, Detectors and Associated Equipment **1055**, 168490 (2023).

[6] B. R. Holstein, Recoil effects in allowed beta decay: The elementary particle approach, Rev. Mod. Phys. **46**, 789 (1974).

[7] B. R. Holstein, Erratum: Recoil effects in allowed beta decay: The elementary particle approach, Rev. Mod. Phys. **48**, 673 (1976)
.

[8] "Induced scalar effects in semileptonic weak interactions," B. Holstein Phys. Rev. D **26** 698 (1982).

[9] "Weak Interaction Form Factors Magnetic Moments of Octet Baryons: Chiral bag model with gluonic effects," Kazuo Tsushima, Tetsuya Yamaguchi, Y. Kohyama, and K. Kubodera, Nucl. Phys. **A489** 557 (1988).

[10] "Consistent description of angular correlations in decay for Beyond Standard Model physics searches," Leendert Hayen and Albert R. Young, arXiv:2009.11364

[11] "Effects of Radioactive Disintegrations on Inner Electrons of the Atom," J.S. Levinger, Phys. Rev. **90** 11 (1953).

[12] "Low-energy test of second-class current in β decays of spin-aligned ^{20}F and ^{20}Na," K. Minamisono, T. Nagatomo, K. Matsuta, C. D. P. Levy, Y. Tagishi, M. Ogura, M. Yamaguchi, H. Ota, J. A. Behr, K.P. Jackson, A. Ozawa, M. Fukuda, T. Sumikama, H. Fujiwara, T. Iwakoshi, R. Matsumiya, M. Mihara, A. Chiba, Y. Hashizume, T. Yasuno, and T. Minamisono, Phys. Rev. C 84, 055501.

[13] "Review of Particle Physics," S. Navas et al. (Particle Data Group), Phys. Rev. D **110** 030001 (2024)

[14] "Comprehensive analysis of beta decays within and beyond the Standard Model," A. Falkowski, M. González-Alonso, and Oscar Naviliat-Cuncic, JHEP04 126 (2021)

[15] "Isovector charges of the nucleon from 2+1+1-flavor lattice QCD," R. Gupta, Y.-C. Jang, B. Yoon, H.-W. Lin, V. Cirigliano and T. Bhattacharya, Phys. Rev. D 98 (2018) 034503

[16] M. Aaboud et al. (ATLAS), Eur. Phys. J. C78, 401 (2018)

[17] "Search for new physics in the lepton plus missing transverse momentum final state in proton-proton collisions at $\sqrt{s} = 13$ TeV," The CMS Collaboration, JHEP07 (2022) 067.

[18] "Constraints on scalar couplings from $\pi^\pm \to l^\pm \nu_l$," Bruce A. Campbell and David W. Maybury, Nucl. Phys. B **709** 419 (2005).

[19] "Precision half-life measurement of the β^+ decay of ^{37}K," P.D. Shidling, D. Melconian, S. Behling, B. Fenker, J.C. Hardy, V.E. Iacob, E. McCleskey, M. McCleskey, M. Mehlman, H.I. Park, and B.T. Roeder, Phys. Rev. C **90** 032501 (2014).

[20] "Limits on the presence of scalar and induced-scalar currents in superallowed β decay," W.E. Ormand, B.A. Brown, and B.R. Holstein, Phys. Rev.C **40** 2914 (1989)

[21] "Limits to second-class nucleonic and mesonic currents," D.H. Wilkinson, Eur. Phys. Jour. A **7** 307 (2000)

[22] "The Second-Class Current Problem in Nuclear Beta Decay," K. Kubodera, J. Delorme, and M. Rho, Nucl. Phys. **B66** 253 (1973).

[23] "Second-Class Currents," Kuniharu Kubodera, Jean Delorme, and Mannque Rho, Phys. Rev. Lett. **38** 321 (1977).

[24] "Positron-neutrino correlation in the $0^+ \to 0^+$ decay of ^{32}Ar" E.G. Adelberger, C. Ortiz, A. Garcia, H.E. Swanson, M. Beck, O. Tengblad, M.J. G. Borge, I. Martel, H. Bichsel, and the ISOLDE Collaboration, Phys. Rev. Lett. **83** 1299 (1999).

[25] "Electron–neutrino correlation and isospin breaking in $0^+ \to 0^+$ decay of ^{32}Ar" A. Garcia, Proc. from the Institute for Nuclear Theory: Rare Isotopes and Fundamental Symmetries (Proc. of the Fourth Argonne/MSU/INT/JINA RIA Theory Workshop vol 16) 2009, ed B A Brown (Seattle: World Scientific), www.int.washington.edu/talks/WorkShops/int_07_36W

[26] "β-decay angular correlations with neutral atom traps," J.A. Behr and A. Gorelov, J. Phys. G: Nucl. Part. Phys. **41** 114005 (2014)

[27] "New physics searches in nuclear and neutron β decay," M. González-Alonso, O. Naviliat-Cuncic, and N. Severijns, Progress in Particle and Nuclear Physics **104** 165 (2019)

[28] CMS Collaboration, V. Khachatryan et al., Phys. Rev. D **91** 092005 2015

[29] "Search for new physics in the lepton plus missing transverse momentum final state in proton-proton collisions at $\sqrt{s} = 13$ TeV," The CMS Collaboration, JHEP07 067 (2022)

[30] "Search for a heavy charged boson in events with a charged lepton and missing transverse momentum from pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector," G. Aad et al. (ATLAS Collaboration), Phys Rev D **100** 052013 (2019).

[31] "Superallowed $0^+ \to 0^+$ nuclear β decays: 2020 critical survey, with implications for Vud and CKM unitarity," J. C. Hardy and I. S. Towner, Phys. Rev. C **102** 045501 (2020).

[32] "Limit on the Fierz Interference Term b from a Measurement of the Beta Asymmetry in Neutron Decay" H. Saul, C. Roick, H. Abele, H. Mest, M. Klopf, A.K. Petukhov, T. Soldner, X. Wang, D. Werder, and B. Märkisch, Phys. Rev. Lett. 125, 112501 (2020)

[33] "Reanalysis of the $\beta - \bar{\nu}_e$ Angular Correlation Measurement from the aSPECT Experiment with New Constraints on Fierz Interference," M. Beck, W. Heil, Ch. Schmidt, S. Baeßler, F. Glück, G. Konrad, and U. Schmidt, Phys. Rev. Lett. **132** 102501 (2024)

[34] "Experimental Study of Weak Magnetism and Second-Class Interaction Effects in the β Decay of Polarized ^{19}Ne," F.P. Calaprice, S.J. Freedman, W.C. Mead, and H.C. Vantine, Phys. Rev. Lett. **35** 1566 (1975).

[35] "Measurement of the Half-Life of the T=1/2 Mirror Decay of ^{19}Ne and its Implication on Physics Beyond the Standard Model," L. J. Broussard, H. O. Back, M. S. Boswell, A. S. Crowell, P. Dendooven, G. S. Giri, C. R. Howell, M. F. Kidd, K. Jungmann, W. L. Kruithof, A. Mol, C. J. G. Onderwater, R. W. Pattie, Jr., P. D. Shidling, M. Sohani, D. J. van der Hoek, A. Rogachevskiy, E. Traykov, O. O. Versolato, L. Willmann, H. W. Wilschut, and A. R. Young, Phys. Rev. Lett. **112** 212301 (2014)

[36] "A look into mirrors: A measurement of the β asymmetry in ^{19}Ne decay and searches for new physics," Dustin Combs, Gordon Jones, William Anderson, Frank Calaprice, Leendert Hayen, and Albert Young arXiv:2009.13700

[37] "Measurement of the β-ν correlation of ^{21}Na using shake-off electrons," P.A. Vetter, J.R. Abo-Shaeer, S.J. Freedman, and R. Maruyama, Phys. Rev. C **77** 035502 (2008).

[38] "Limits on nonstandard weak currents from the polarization of ^{14}O and ^{10}C decay positrons," A.S. Carnoy, J. Deutsch, T.A. Girard, R. Prieels, Phys. Rev. C **43** 2825 (1991)

[39] "Limits on tensor-type weak currents from nuclear and neutron β decays," F. Wauters, A. García, and R. Hong, Phys. Rev. C **89** 025501 (2014)

[40] Johnson CH, Pleasonton F and Carlson TA 1963 Precision Measurements of the Recoil Energy Spectrum from the Decay of He^6 *Phys. Rev.* **132** 1149

[41] Gluck F 1998 Order-α radiative correction to ^{6}He and ^{32}Ar β decay recoil spectra *Nuclear Physics A* **628** 493.

[42] "Measurement of the β-ν correlation coefficient $a_{\beta\nu}$ in the β decay of trapped ^{6}He$^+$ ions," X. Fléchard, Ph. Velten, E. Liénard, A. Méry, D. Rodríguez, G. Ban, D. Durand, F. Mauger, O. Naviliat-Cuncic and J.C. Thomas, J. Phys. G: Nucl. Part. Phys. 38 055101 (2011).

[43] "β-Nuclear-Recoil Correlation from ^{6}He Decay in a Laser Trap," P. Müller, Y. Bagdasarova, R. Hong, A. Leredde, K.G. Bailey, X. Fléchard, A. Garcia, B. Graner, A. Knecht, O. Naviliat-Cuncic, T.P. O'Connor, M.G. Sternberg, D.W. Storm, H.E. Swanson, F. Wauters, and D.W. Zumwalt, Phys. Rev. Lett. **129** 182502 (2022).

[44] "Improved Tensor Current Limit from ^{8}B β Decay Including New Recoil-Order Calculations," B. Longfellow, A.T. Gallant, G.H. Sargsyan, M.T. Burkey, T.Y. Hirsh, G. Savard, N.D. Scielzo, L. Varriano, M. Brodeur, D.P. Burdette, J.A. Clark, D. Lascar, K.D. Launey, P. Mueller, D. Ray, K.S. Sharma, A.A. Valverde, G.L. Wilson, and X.L Yan, Phys. Rev. Lett. **132**, 142502 (2024).

[45] "Improved Limit on Tensor Currents in the Weak Interaction from ^{8}Li Decay," M.T. Burkey, G. Savard, A.T. Gallant, N.D. Scielzo, J.A. Clark, T.Y. Hirsh, L. Varriano, G.H. Sargsyan, K.D. Launey, M. Brodeur, D.P. Burdette, E. Heckmaier, K. Joerres, J.W. Klimes, K. Kolos, A. Laminack, K.G. Leach, A.F. Levand, B. Longfellow, B. Maaß, S.T. Marley, G.E. Morgan, P. Mueller, R. Orford, S.W. Padgett, A. Pérez Galván, J.R. Pierce, D. Ray, R. Segel, K. Siegl, K.S. Sharma, and B.S. Wang, Phys. Rev. Lett. **128**, 202502 (2022).

[46] F. Wauters et al., Precision measurements of the ^{60}Co β-asymmetry parameter in search for tensor currents in weak interactions, Phys. Rev. C 82 055502 (2010)

[47] G. Soti et al., Measurement of the β-asymmetry parameter of ^{67}Cu in search for tensor-type currents in the weak interaction, Phys. Rev. C **90** 035502 (2014)

[48] F. Wauters, I. Kraev, M. Tandecki, E. Traykov, S. Van Gorp and N. Severijns, β-asymmetry parameter in the decay of ^{114}In, Phys. Rev. C **80** 062501 (2009)

[49] "New Precise Measurement of the Pion Weak Form Factors in $\pi^+ \to e^+\nu\gamma$ Decay" M. Bychkov, D. Pocanić, B. A. VanDevender, V. A. Baranov, W. Bertl, Yu. M. Bystritsky, E. Frlez, V. A. Kalinniko, N. V. Khomutov, A. S. Korenchenko, S. M. Korenchenko, M. Korolija, T. Kozlowski, N. P. Kravchuk, N. A. Kuchinsky, W. Li, D. Mekterović, D. Mzhavia, S. Ritt, P. Robmann, O. A. Rondon-Aramayo, A. M. Rozhdestvensky, T. Sakhelashvili, S. Scheu, U. Straumann, I. Supek, Z. Tsamalaidze, A. van der Schaaf, E. P. Velicheva, V. P. Volnykh, Y. Wang, and H.-P. Wirtz, Phys. Rev. Lett. **103**, 051802 (2009)

[50] "Data-driven reevaluation of ft values in superallowed β decays," Chien-Yeah Seng and Mikhail Gorchtein, Phys. Rev. C **109** 045501 (2024).

[51] "Ab Initio Ab Strategy for Taming the Nuclear-Structure Dependence of Vud Extractions: The ^{10}C $\to$ ^{10}B Superallowed Transition," Michael Gennari, Mehdi Drissi, Mikhail Gorchtein, Petr Navrátil, and Chien-Yeah Seng, Phys. Rev. Lett. **134** 012501 (2025)

[52] "Precision calculation of isospin-symmetry-breaking corrections to T=1/2 mirror decays using configuration-interaction framework built upon multireference charge-dependent density functional theory," M. Konieczka, P. Baczyk, and W. Satula, Phys. Rev. C **105** 065505 (2022).

[53] "Crucial influence of the relativistic form factor coefficients on the determination of f_S," L. Szybisz and V.M. Silbergleit J. Phys. G: Nucl. Phys. **7** L201 (1981)

[54] "Limit on second class polar vector couplings in semileptonic weak interactions," Barry R. Holstein, Phys. Rev. C **29** 623 (1984).