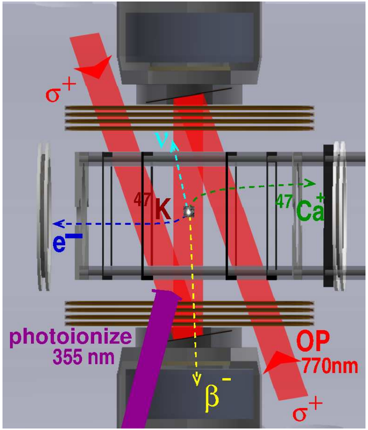
Analog-Antianalog isospin mixing in ^{47}K β^- decay + time-reversal symmetry



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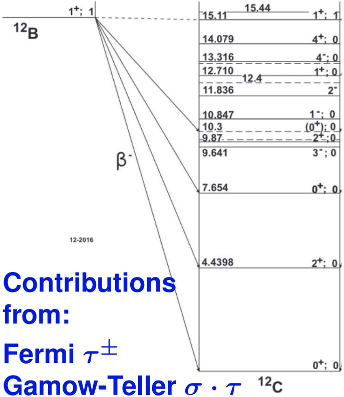
^{47}K β^- decay and Analog- "Anti-analog" isospin mixing

n, tritium β^- decay to their isobaric mirrors

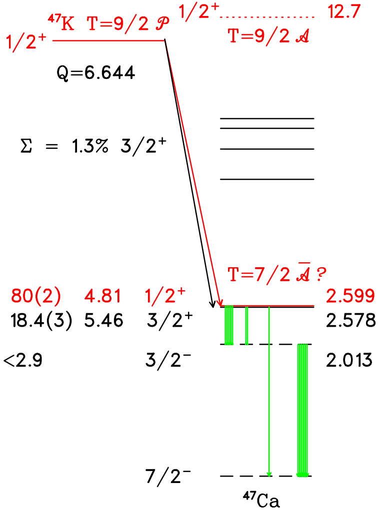
^{12}B β^- decays to ^{12}C E_x=15.11 isobaric analog



Contributions from:

Fermi $\tau^{\pm}$

Gamow-Teller $\sigma \cdot \tau$



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

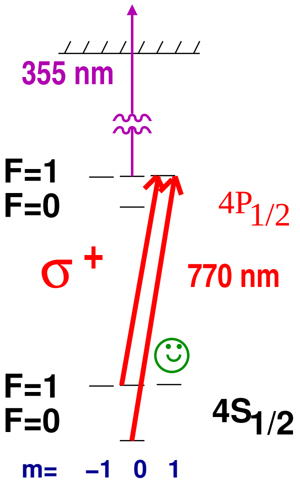
^{47}K decay to its isobaric analog is energetically forbidden, so is purely G-T, unless isospin mixing of analog and "antianalog" configurations lets Fermi contribute $\to$ nonzero ^{47}Ca asymmetry wrt ^{47}K nuclear spin

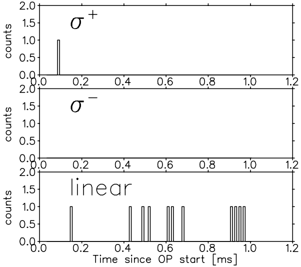
Barroso and Blin-Stoyle PL45B 178 (1973):

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

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

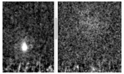
Apply circularly polarized light along z quantization axis.

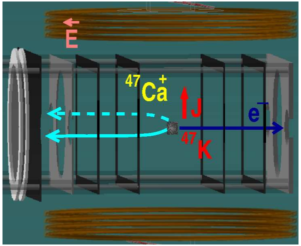
Once we start OP cycle, atoms increase spin to maximum, then stop absorbing
If light is linearly polarized, atoms keep absorbing.

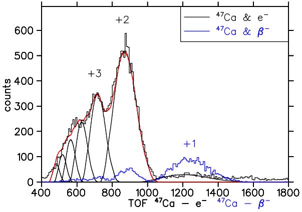
When excited, a pulsed laser has enough energy/photon to photoionize (a small fraction) of them.

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

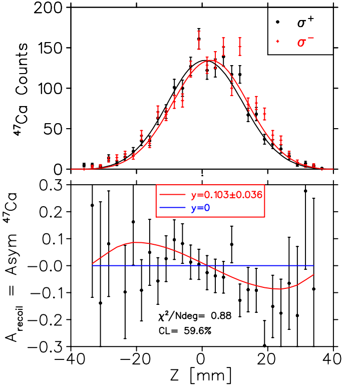
1000 atoms trapped

DC  MOT then OP

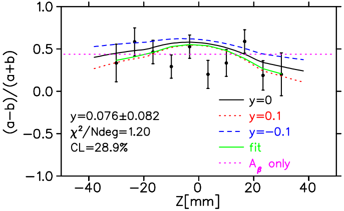




^{47}Ca & atomic e^-



β^- & ^{47}Ca



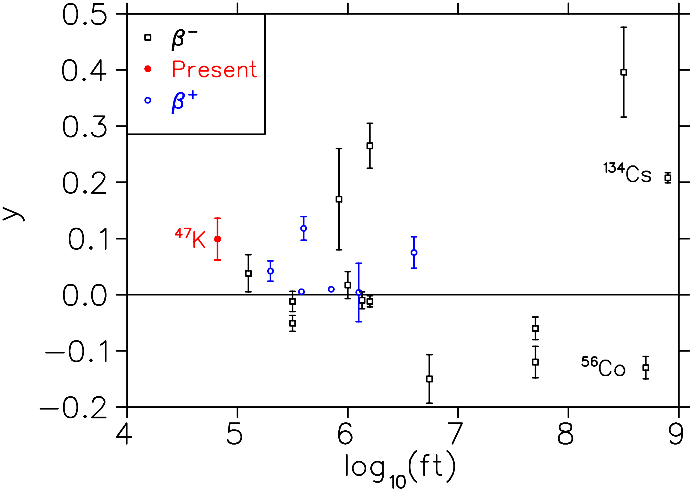
Source	$A_{\rm recoil}$	pseudoA_β
$A_{\rm recoil}$ bkg 6±4%	0.014	< 0.002
Polarization 0.96±0.04	0.004	0.023
β^- Branching ratio	0.002	0.022
Weak magnetism	0.0006	0.0003
Fit range in Z ±20 to 34 mm	0.012	NA
$^{47}Ca^{+1}$ percent bkg	0.001	NA
$^{47}Ca^{+N}$ distribution from TOF	< 0.0005	NA
E field	negligible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

- **Nonzero ^{47}Ca asymmetry wrt spin ⇒ 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

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

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

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

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

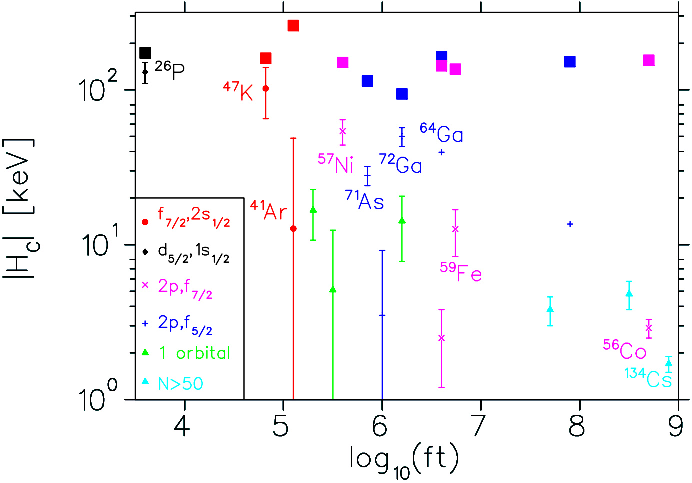
$$D \propto \delta E \frac{\langle \bar{\mathcal{A}} | V_{\not{T}} | \mathcal{A} \rangle}{M_{GT}}$$

- 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 $\bar{\mathcal{A}} \Rightarrow$

$$H_C = \langle \bar{\mathcal{A}} | V_C | \mathcal{A} \rangle$$
$$= \frac{\sqrt{n_1 n_2}}{2T} \left(\langle j_1 | V_C | j_1 \rangle - \langle j_2 | V_C | j_2 \rangle \right)$$
$$\rightarrow 0.35 \frac{\sqrt{n_1 n_2}}{2T} \frac{Z}{A^{2/3}} \mathrm{MeV}$$

, for HO wf's and excess n's occupy 2 major shells

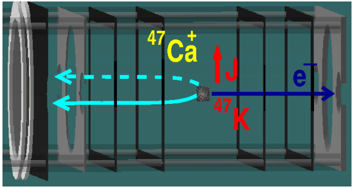
H_C for many β decays is a small fraction of the prediction: attributed to fragmentation of $\bar{\mathcal{A}}$ configuration among several eigenstates

Auerbach, Loc NPA 1027 122521 (2022)

^{47}K β^- decay has:

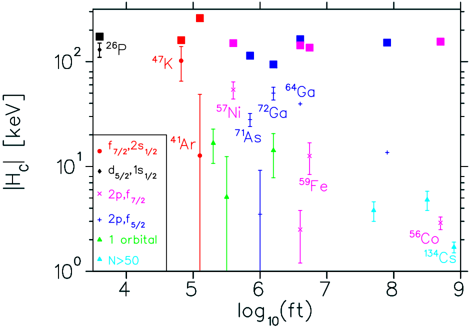
- Large $H_C = \langle \bar{\mathcal{A}} | V_{\mathrm{Coul}} | \mathcal{A} \rangle$ = 101 $\pm$ 37 keV
- Large fraction of $\mathcal{A} - \bar{\mathcal{A}}$ mixing prediction Auerbach Loc NPA 1027 122521 (2022)

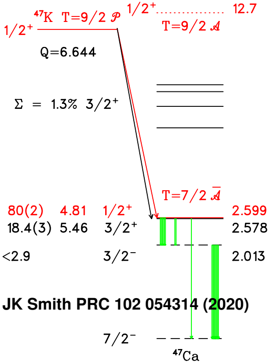
$\Leftarrow$ $^{47}_{20}$Ca^{27} has only one $1/2^+$ state, $\bar{\mathcal{A}}$ configuration not fragmented



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 $D\vec{I} \cdot \vec{v_\beta} \times \vec{v_\nu}$





JK Smith PRC 102 054314 (2020)

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)

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

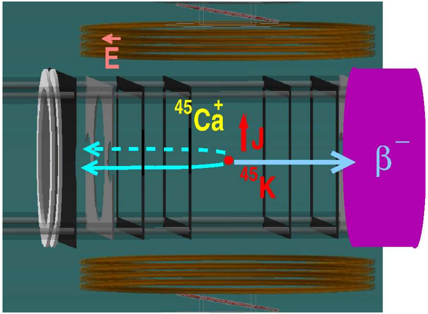
$y = g_V M_F / g_A M_{GT}$ = 0.098$\pm$0.037 large enough to be favorable for D, enhanced by $\sim 10^2$ in isospin-suppressed β decay

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

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**

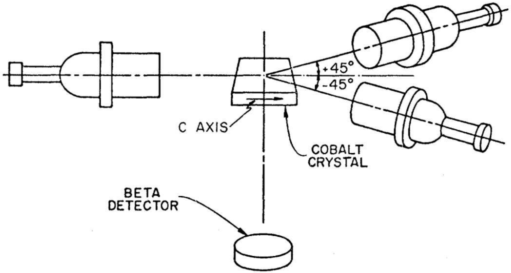
D Uncertainties / 100 scaling from Melconian PLB 649 270 (2007)

	B_ν	Improvements	Projected
Cloud position $\sigma^\pm$	1.3	$\pm 500\mu$m $\rightarrow \pm 20\mu$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)

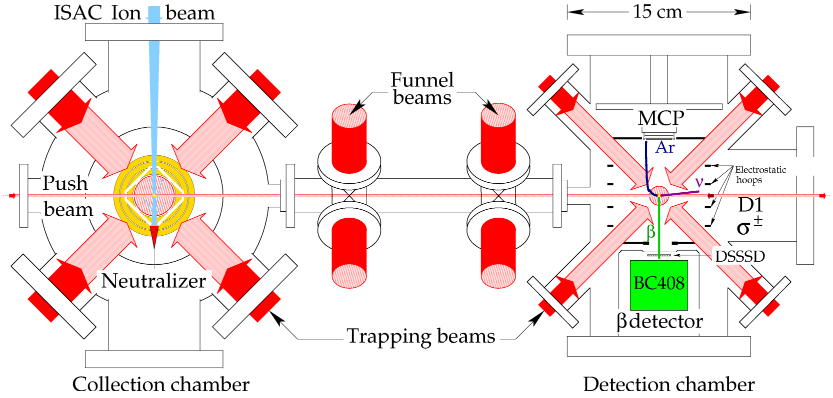
V_{Coul}= 2.9 keV, $V_{\not{T}} = 54 \pm 110\mathrm{eV}$
(J.L. Mortara Ph.D. thesis 1999 UCB
$E_1 = -0.001 \pm 0.006$
$\Rightarrow$ $V_{\not{T}}$ = 5$\pm$ 33 eV)

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_{Coul}, and $\not{T}$ N-N matrix elements to allow complementary or better sensitivity to $V_{\not{T}}$

TRINAT plan view

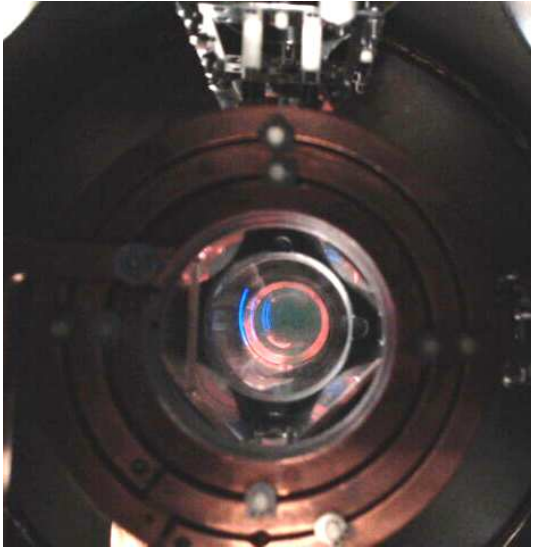
TRIUMF

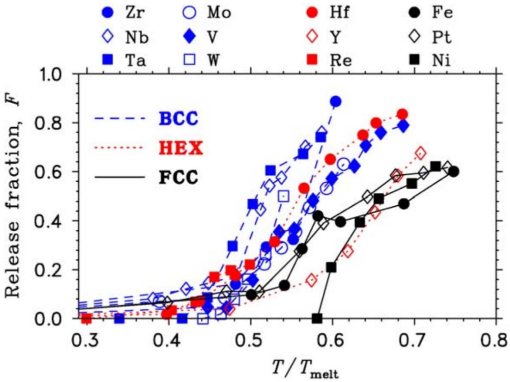
- Isotope/Isomer selective
- 75% transfer
- Avoid untrapped atom background with 2nd trap
- 0.7 mm cloud for β-Ar$^+$ $\rightarrow$ ν momentum

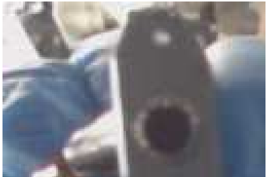


- Spin-polarized 99.1±0.1%

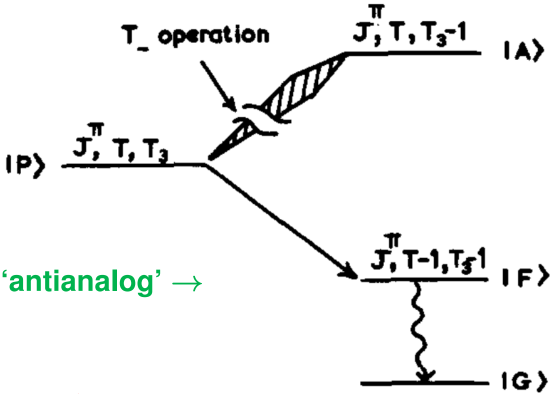
Neutralizer and Collection trap







$\not{T}$ in isospin-hindered β^- decay
Barroso and Blin-Stoyle, PL 45B 178 (1973



'antianalog' →

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

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

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

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

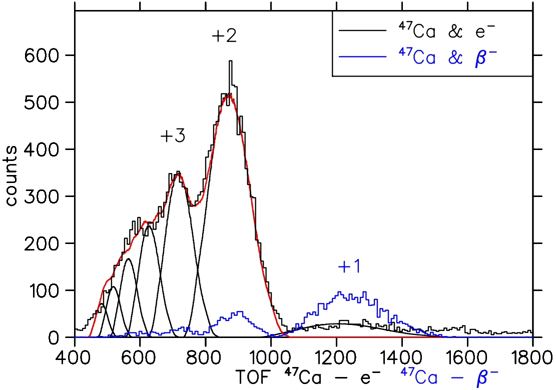
So for $\not{T}$ physics mixing antianalog $|F\rangle$ with analog $|A\rangle$, then $V_{\not{T}}$ is only competing with V_{Coul}, not V_{strong},

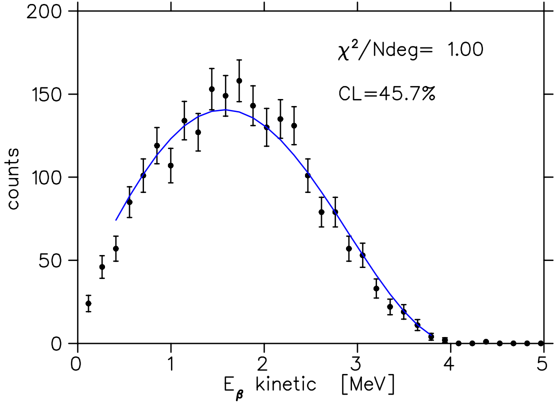
enhancing α_V by $\sim 10^2$ or 10^3 ☺

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)

TOF and β spectra





^{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 $d_I \sim 0$

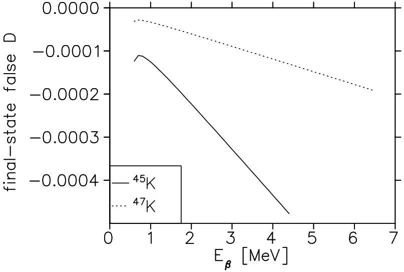
For our M_F/M_{GT} measurement,

$A_{\rm recoil}$, 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.

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).

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[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).

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 $\bar{\mathcal{A}} \Rightarrow$

$H_C = \langle\bar{\mathcal{A}}|V_{\mathrm{C}}|\mathcal{A}\rangle$

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

$\rightarrow 0.35\frac{\sqrt{n_1 n_2}}{2T}\frac{Z}{A^{2/3}}\mathrm{MeV}$,

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)