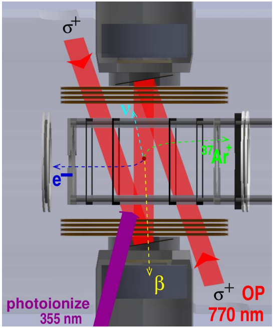
β^+ asymmetry in spin-polarized ^{37}K decay

- **The most accurate A_β measurement**
  Agrees with theory prediction
- **Constraints on:**

Weak interaction changes within nuclei
Non-SM lepton helicities:
Left-right symmetric models.
4-fermi contact Lorentz 'scalar','tensor'



TRIumf Neutral Atom Trap collaboration:

TEXAS A&M UNIVERSITY
S. Behling
B. Fenker
M. Mehlman
P. Shidling
D. Melconian

TRIUMF
A. Gorelov
J.A. Behr
M.R. Pearson
Undergrad
E. Broatch

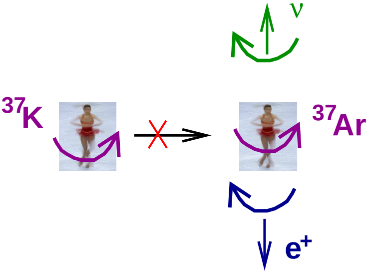
UBC
J. McNeil

UNIVERSITY OF MANITOBA
M. Anholm
G. Gwinner

אוניברסיטת תל-אביב
TEL AVIV UNIVERSITY
D. Ashery
I. Cohen

Supported by NSERC, NRC through TRIUMF, Israel Science Foundation, DOE, State of Texas

Lepton helicity → angular distribution



← **This decay pattern needs non-S.M. chirality**

I=3/2 → I=3/2:

Leptons can't increase nuclear spin any further

One experimental discovery of parity violation

Wu, Ambler, Hayward, Hopper, Hobson, PR 105 (1957) 1413

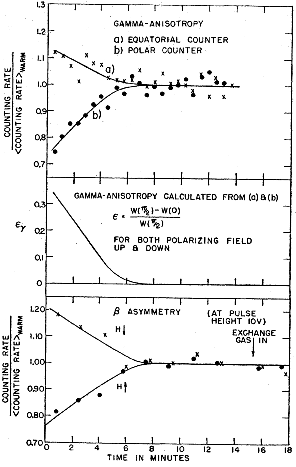
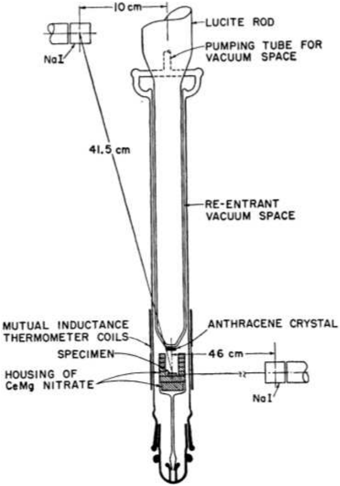


FIG. 2. Gamma anisotropy and beta asymmetry for polarizing field pointing up and pointing down.



Dilution Refrigerator to spin-polarize

^{60}Co $\rightarrow$ ^{60}Ni + β^- + $\bar{\nu}$

$$W[\theta] = 1 + P A \hat{I} \cdot \frac{\vec{p_\beta}}{E_\beta} = 1 + A \frac{v}{c} \cos[\theta]$$

$A_{\beta-} \approx -1.0$

Followup ^{58}Co $\rightarrow$ ^{58}Fe + β^+ + ν

$A_{\beta+} > 0$

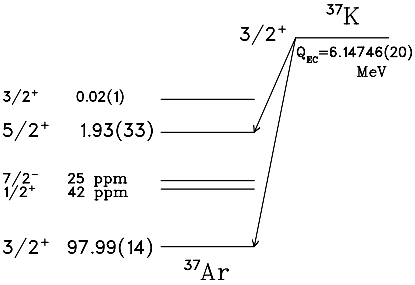
Wauters 2010 PRC $A_{^{60}\mathrm{Co}} = -1.014 \pm 0.020$ [SM -0.987 ± 0.009]

^{37}K isobaric mirror decay: a ‘heavy neutron’ ?

Here A_β isn’t 1 or -1 or a clean fraction
there are 2 operators:

‘Fermi’ changes n to p
‘Gamow-Teller’ changes n to p and nucleon spin

τ, Q, and branch $\Rightarrow$ decay strength $\mathcal{F}t$
We know the Fermi $\mathcal{F}t_0$ from the $0^+ \rightarrow 0^+$ decays, so from $\mathcal{F}t$ we can get the Gamow-Teller strength:



$\mathcal{F}t$ (Shidling PRC 2014) $\Rightarrow$

$\rho = C_A M_{GT} / C_V M_F =$
0.5768 ± 0.0021

$\Rightarrow A_\beta[SM] = -0.5706 \pm 0.0007$
main uncertainty is experimental branching ratio

^{37}K isobaric mirror decay: a ‘heavy neutron’

$\Rightarrow A_\beta[SM] = -0.5706 \pm 0.0007$

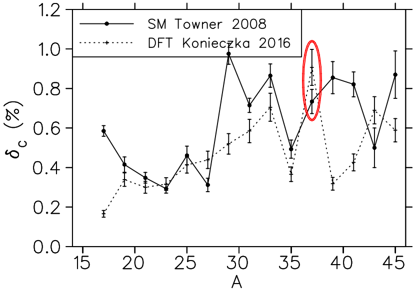
Dominant uncertainty is exp. branching ratio

1st-order recoil-order from E&M moments:

- **Induced tensor $d_1 \approx 0$,**
- **Small $\mu \Rightarrow$ small weak magnetism**

Recoil-order + Coulomb + finite-size corrections $\Rightarrow$

$\Delta A_\beta \approx -0.0028\ (E_\beta / E_0)$ Holstein RMP 1975



Isospin mixing contributes 0.0004 uncertainty from shell model

DFT for isospin mixing has improved its functional

Using weighted average for δ_C would $\Rightarrow 0.0004 \rightarrow 0.0005$

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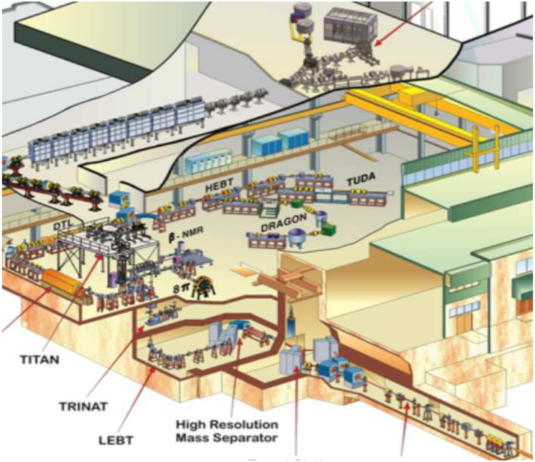
TRIumf Neutral Atom trap at ISAC

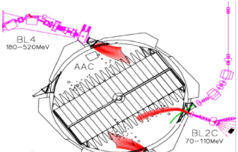


^{37}K 8x10^{7}/s

TiC target
1750^{o}C

70 μA
protons

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



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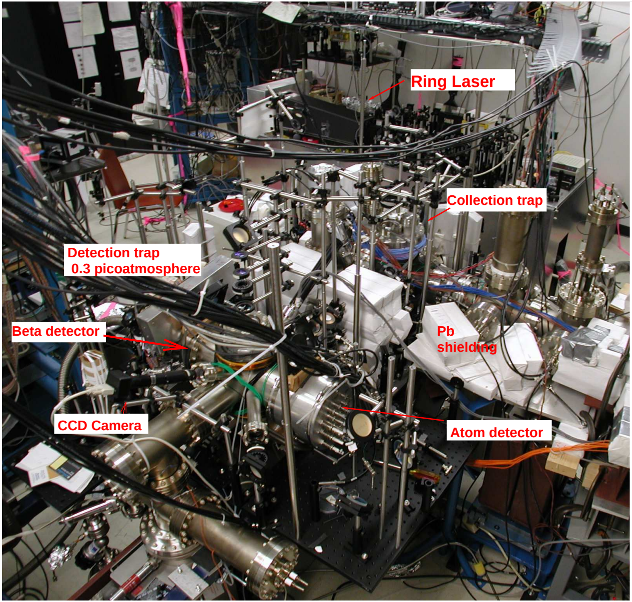
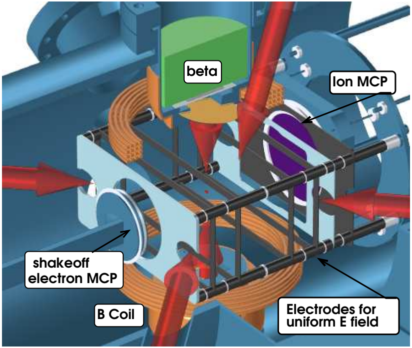
TRINAT lab: “tabletop experiment”

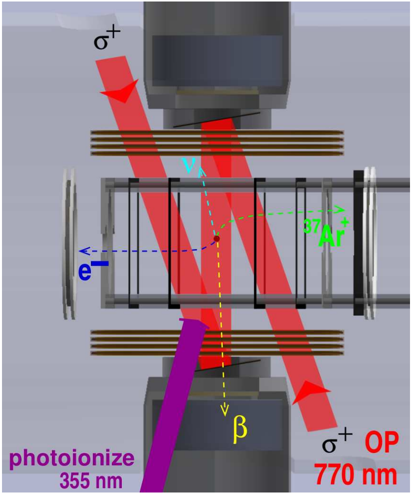


ISAC ion beam

^{37}K decay geometry



- β, recoil nucleus
- shakeoff e^- for TOF trigger



This decay pattern is helicity-forbidden if the ν goes straight up,
independent of Gamow-Teller/Fermi ratio.

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Optical pumping and probing ^{37}K

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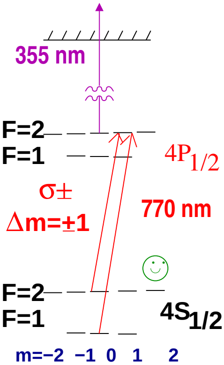
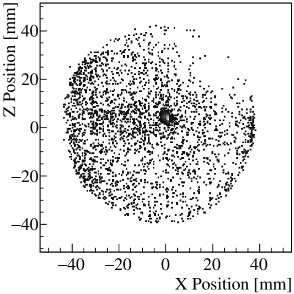
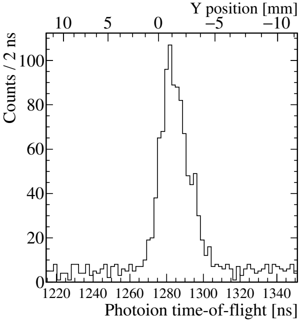






Photoionize 1%

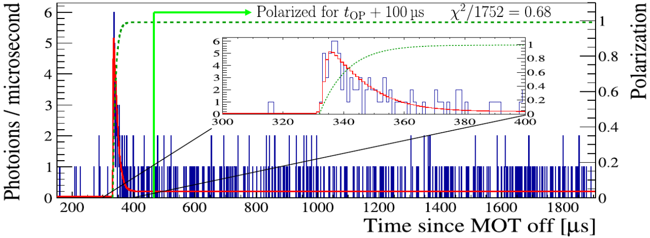
***in situ* probe**

P_+=+0.9913(8)

P_-=−0.9912(9)

$\sigma \propto$ (1-P)

Fenker NJP 2016



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β^+ asymmetry ^{37}K data

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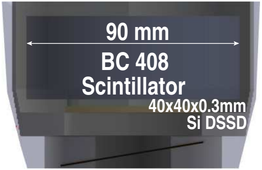
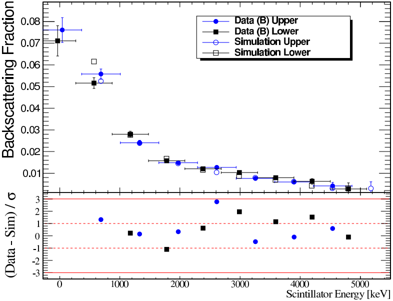
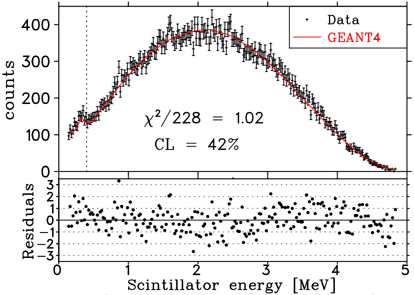
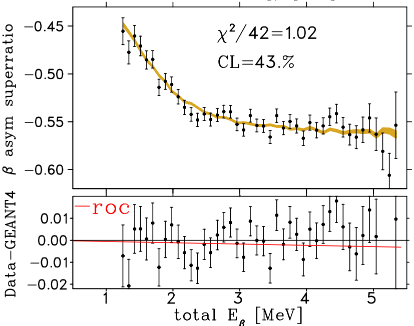


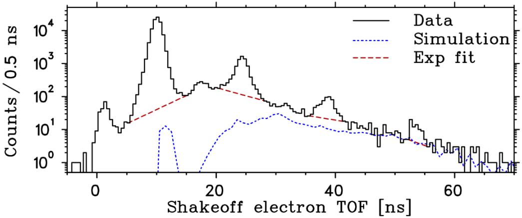


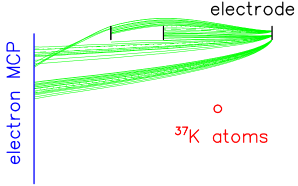




- **Backscatter from scint agrees to ∼10%**

Background





- 2.8×10^{-3} of events in main peak are background from non-trapped atoms
- Conservatively assume polarized between 0 and 100%. $\rightarrow A_\beta \times (1.0014 \pm 0.0014)$
- These will be removed by MCP position info when we increase to design E field

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^{37}K $A_{\beta+}$ Uncertainties

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Source $\times 10^{-4}$ [†: β scattering]	ΔA_β
Background (Correction 1.0014)	7
Trap Position	4
Trap Sail velocity	5
Trap Temperature & width	1
BB1 Radius†	4
BB1 Energy agreement	2
BB1 threshold	1
Scintillator threshold	0.3
GEANT4 physics list†	4
Shakeoff electon t.o.f. region	3
SiC mirror thickness†	1
Be window thickness†	0.9
Scintillator or summed†	1
Scintillator calibration	0.1
Total systematics	12
Statistics	13
Polarization	5
Total uncertainty	18

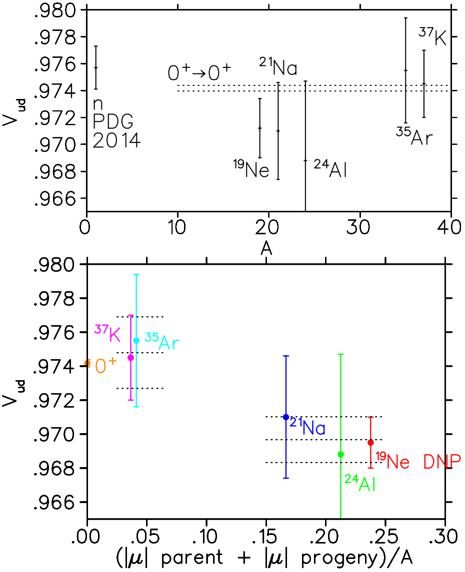
A_β = –0.5707 $\pm$ 0.0013 (stat) $\pm$ 0.0012 (syst) $\pm$ 0.0005 (pol) = -0.5707 $\pm$ 0.0018

A_β[SM] = –0.5706 $\pm$ 0.0007

Better relative uncertainty than ^{19}Ne –0.0360$\pm$0.0008 [Calaprice 1975] and neutron 0.1197$\pm$0.0006 [PERKEO II PRL 2013, UCNA PRCr 2013]

Physics →

Weak interaction: same strength, all nuclei?



$A_\beta \Rightarrow$ GT/F

Then $\mathcal{F}t$ of ^{37}K $\Rightarrow V_{ud}$

- **An isospin mixing test useful for $0^+ \to 0^+$ determination of V_{ud} i.e. $\psi[n] \neq \psi[p]$**

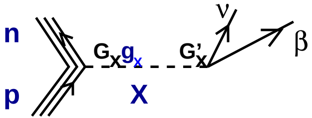
- **Salam and Strathdee Nature 1974: phase transitions at very high B fields could drive $V_{ud} \to 1$**

Hardy Towner PLB 1975 applied to the ^{35}Ar A_β controversy.

^{19}Ne Broussard DNP 2016

Why the weak interaction is 'weak' at low energy

'more massive virtual particles are created for shorter times'



Propagator+vertices:

$$T \propto \frac{G_X(-g^{\mu\nu}+p^\mu p^\nu/M_X^2)G_X}{p^2-M_X^2} \xrightarrow{p<<M_X}$$

$$T \propto \frac{G_X^2}{M_X^2} \Rightarrow$$

- **Decay rates** $\propto \frac{G_X^2 G_x'^2}{M_X^4}$

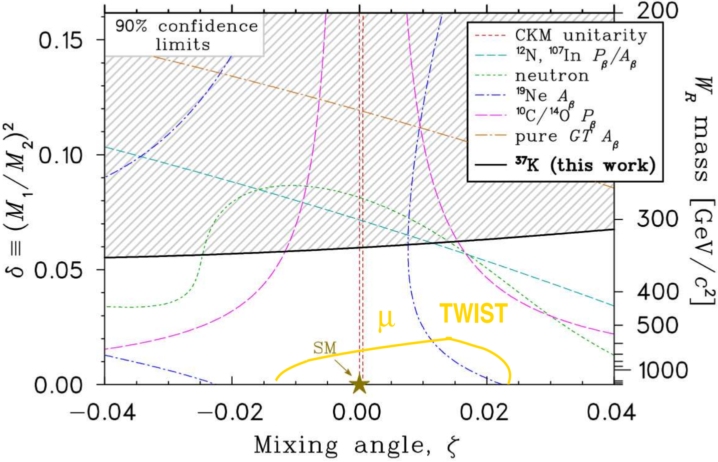
  or $\propto \frac{G^2}{M_W^2}\frac{G_X G_x'}{M_X^2}$ if process interferes with W (couples to SM-handed ν)

  e.g. Fierz term $\propto \frac{m}{E_\beta}$

- **IF** $G_X \sim$ **electroweak coupling, then 0.1% sensitivity in angular correlations** $\rightarrow M_X \sim 6$ **or 30** M_W

Left-Right Symmetric model

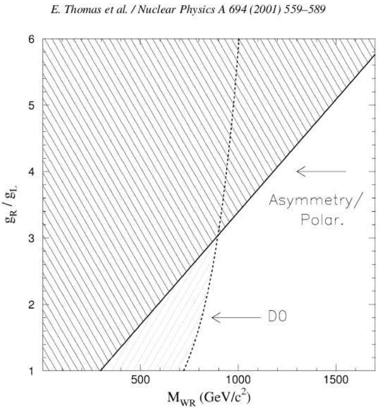
Extra W' with heavier mass, couples to ν_R
Otherwise same coupling strength, so parity is a good symmetry at very high energy

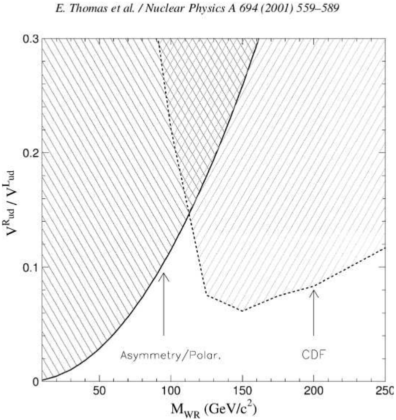


^{37}K:
$M_W^R >$ 352 GeV 90%

$(m[\nu_\mu^R] > m_\mu)$ but **LHC $M'_W > 3.7$ TeV 90%** $\rightarrow$

‘Non-manifest’ Left-Right models





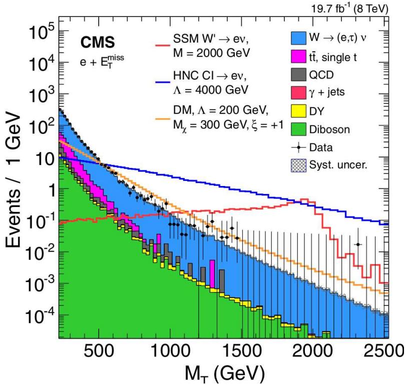
$g_R > g_L$:
^{37}K $\Rightarrow g_R \lesssim 7.7$ at 4 TeV (or $g_R < 4$, at 2 TeV but LHC7 2 TeV ‘bump’ had $g \sim 0.5$)

$V^R_{ud} < V^L_{ud}$
For $M'_W < 70$ GeV, nuclear β decay constrains $V^{\mathrm{R}}_{\mathrm{ud}}$

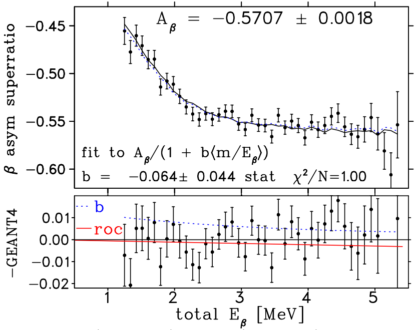
A_β [E_β] agrees with S.M.

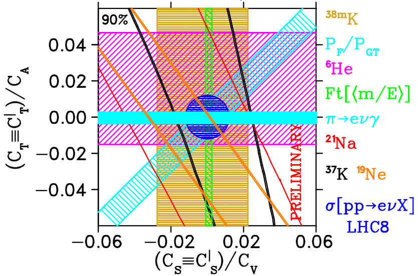
New interactions that make normal-helicity ν's 'interfere' with S.M. Fierz term $\propto \frac{m_\beta}{E_\beta}$

CMS PRD 91 92005



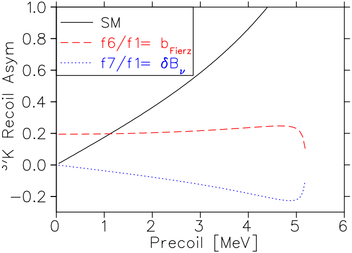
Bhattacharya PRD 94 054508 (2016) combined ATLAS, CMS:

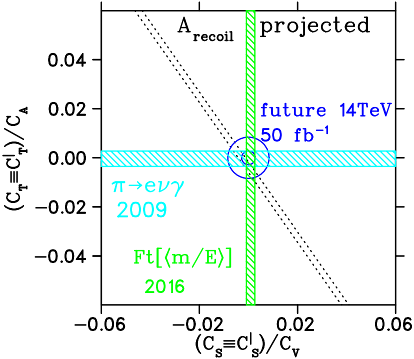




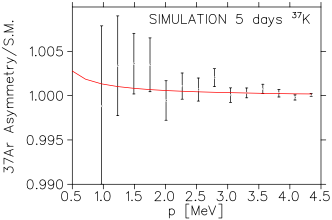
future $A_{recoil} \propto A_\beta + B_\nu$

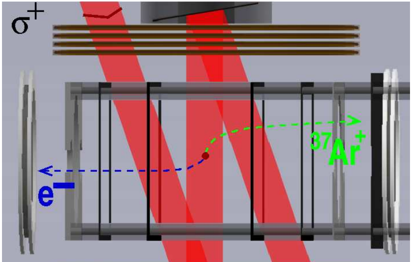
Technique demonstrated in ^{80}Rb Pitcairn PRC 2009





Ave A_{recoil} depends on ρ; p dependence doesn't





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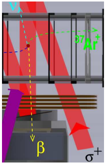
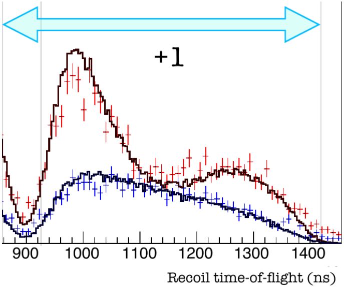
Helicity-driven null in mirror decay

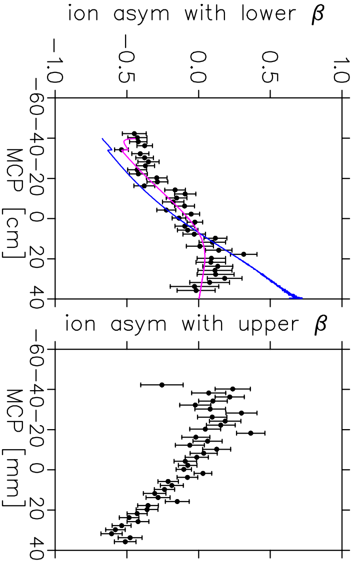


$$W(\theta_{\beta\nu i}) \approx 1 + \mathcal{A}_{\beta\nu i} \cos(\theta_{\beta\nu i})$$

$$\mathcal{A}_{\beta\nu i} = \frac{a+PB-2cT/3}{1+PA}$$

For P=-1, $\mathcal{A}_{\beta\nu i}$=1, independent of M_{GT}/M_F





2014 data under analysis

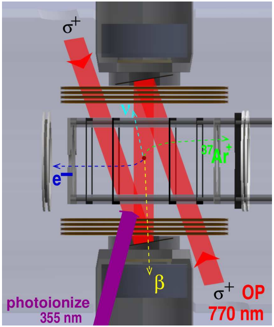
TRIUMF Neutral Atom Trap: Near Future

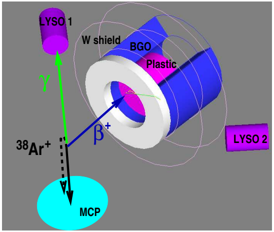
We have measured the β asymmetry of ^{37}K decay to be A_β=–0.5707 $\pm$ 0.0018

Agrees with theory –0.5706 $\pm$ 0.0007, complements the best β decay measurements

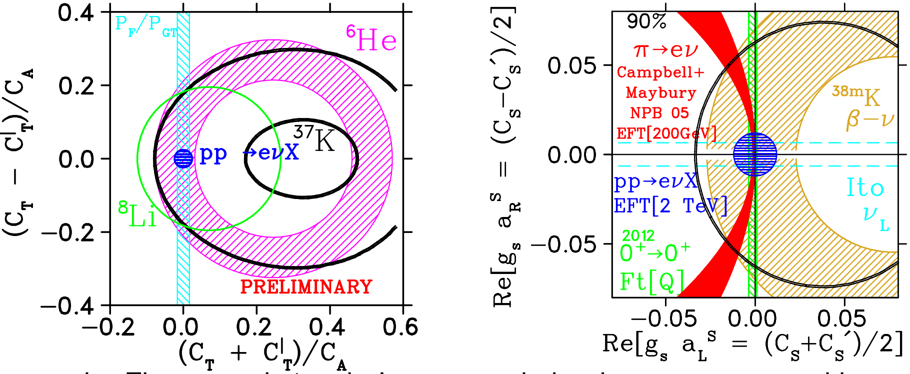
We plan to measure $A_\beta[E_\beta]$ 3-5 x better, and $A_{\rm recoil}$ with sensitivity to '4-fermion contact' interactions complementary to $\pi \rightarrow e\nu\gamma$, $\pi \rightarrow e\nu$, and LHC $p + p \rightarrow e + E_\perp$

We also plan a TRV $\beta\nu\gamma$ 3-momentum correlation, first of its type in 1st-generation particles





Couplings to wrong-handed ν



the Fierz term is 'easier' to constrain but has more competition

For scalars coupling to wrong-chirality ν, we compete with our own ^{38m}K β-ν Gorelov 2005

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Polarization Improvements

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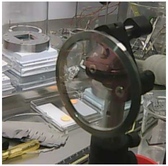
SYST $\times 10^{-4}$	ΔP σ^-	ΔP σ^+	ΔT σ^-	ΔT σ^+
Initial T	3	3	10	8
Global fit v. ave	2	2	7	6
$S_3^{\rm out}$ Uncertainty	1	2	11	5
Cloud temp	2	0.5	3	2
Binning	1	1	4	3
B_z Uncertainty	0.5	3	2	7
Initial P	0.1	0.1	0.4	0.4
Require $\mathcal{I}_+ = \mathcal{I}_-$	0.1	0.1	0.1	0.2
Total SYSTEMATIC	5	5	17	14
STATISTICS	7	6	21	17

B. Fenker New J. Phys **18** 073028 2016



- **pellicle mirrors: less β^+ scattering**

- **define T by OP**
- **trim B gradients**
- **improve S_3 flipping and gradients**
- **add flipping of B_z**
- **higher-power photoionizing laser**
- **gentler RAC-MOT**

$$P(\sigma^+) = +0.9913(8) \quad T(\sigma^+) = -0.9770(22)$$
$$P(\sigma^-) = -0.9912(9) \quad T(\sigma^-) = -0.9761(27)$$

- Uncertainty $\propto$ (1-P)

MSSM and β decay correlations

Profumo, Ramsey-Musolf, Tulin
PRD 75 075017 2017
C_S+C'_S can be 0.001 in MSSM in 1-loop order including mixing

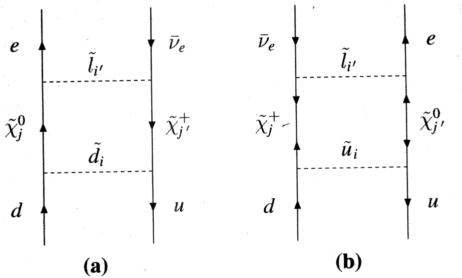


FIG. 2. Feynman diagrams relative to supersymmetric contributions giving rise to anomalous amplitudes in β decay processes.

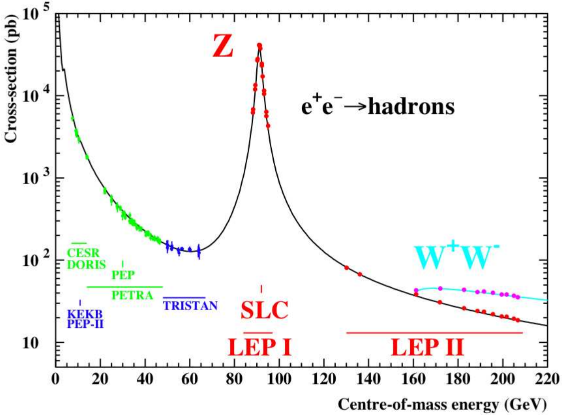
Include mixing of:

• left and right sfermions (this is where β decay can help; constraints are said to be few)

• sfamily mixing (already tightly constrained, e.g. by $\mu \rightarrow e\ \gamma$...)

Effective 4-fermi scalar and tensor couplings are generated that contribute to $b_{\rm Fierz}$ and spin correlation observables like B_ν as large as 0.001.

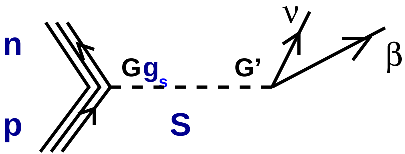
Weakly-coupled W’ still has electric charge



Does σ $e^+ + e^- \rightarrow W^+ + W^-$ double for W’?
Depends on the cut for W: typically this cut (explicitly listed in PDG) excludes low-mass W because of serious background

nucleon form factors

Herczeg Prog Part Nucl Phys 46 (2001) 413 pointed out need for form factors



$$\langle p|\bar{u}d|n\rangle = g_s(q^2)\bar{u}_p u_n$$
$$\langle p|\bar{u}\sigma_{\lambda\mu}d|n\rangle = g_T(q^2)\bar{u}_p\sigma_{\lambda\mu}u_n$$

2001: "$\mathbf{0.25} < g_s < \mathbf{1}$" depressing to the experimentalist

g_T related to transverse spin structure function

Bhattacharya, Cirigliano, et al. PRD 85 05412 (2012) first lattice gauge calculations,

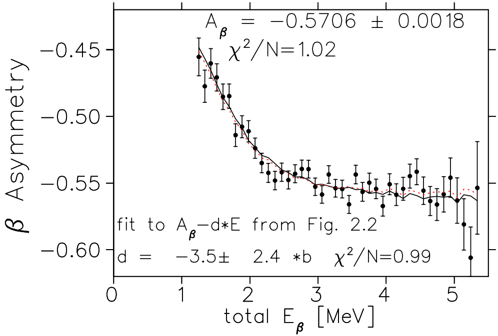
g_s = 0.8±0.4, g_T = 1.05±0.35

→ (2016) PRD 94 054508

g_s = 0.97±0.12±0.06, g_T = 0.987±0.051±0.020

g_s=1.02±0.10 Gonzalez-Alonso, Camalich PRL 112 042501 (2014) isospin symmetry

2nd-class currents



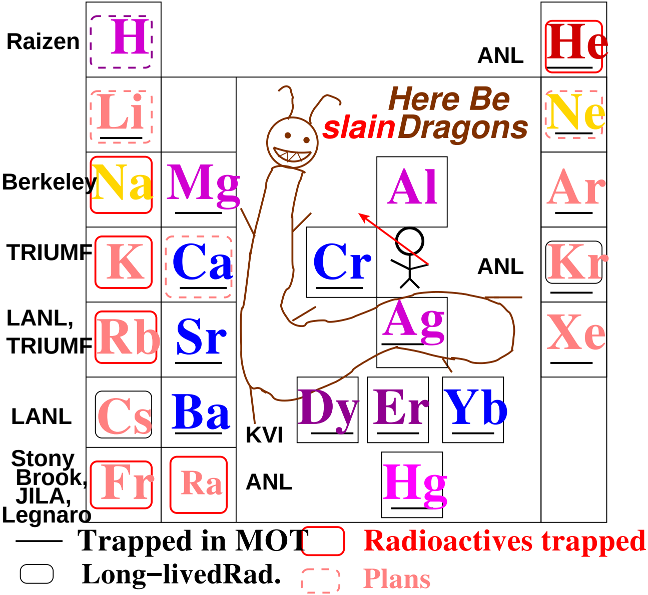
"2nd-class" weak interactions would violate isospin symmetry when quarks are combined by QCD into nucleons. "Induced tensor" ***d*** is near zero in isobaric mirror decay.

This result is complementary to other nuclear β decay (Sumikama PRC 2011) in models where 2nd-class currents change with system (Wilkinson EPJA 2000)

Babar set best 3-generation constraints PRL 2009

$\tau^- \rightarrow \omega\pi^-\nu_\tau$

What elements can be laser cooled?



Super-ratio

$$A_{\rm obs}^{\rm SR}(E_e) = \frac{1-s(E_e)}{1+s(E_e)} = A_{\rm obs}$$

$$s(E_e) = \sqrt{\frac{r_1^-(E_e)r_2^+(E_e)}{r_1^+(E_e)r_2^-(E_e)}}$$

Gay, T.J. and Dunning, F.B. Rev. Sci. Instrum. 63 (1992) 1635

B. Plaster et al. PRC 86 (2012) 055501