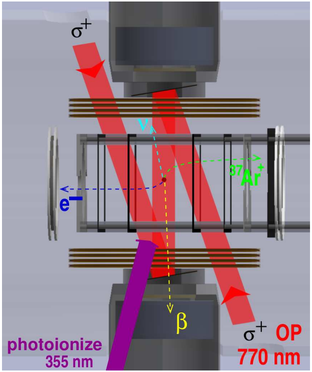
Beta Decay with Atom Traps

- **In the decay of ^{37}K, we've made the most accurate measurement of the asymmetry of the β^+ direction with respect to the nuclear spin**
  Agrees with theory prediction
  Fenker et al. PRL 120 062502 (last week)



- **Motivated by:**
  Weak interaction changes within nuclei
  Left-right symmetric models.
  4-fermi contact Lorentz 'scalar','tensor' from $A_\beta[E_\beta]$
- Plans with recoil progeny:
  A_{recoil} asymmetry of recoils
  Time-reversal violation in $\beta\ \nu\ \gamma$ decay
  ^{92}Rb E_ν spectrum

TRIumf Neutral Atom Trap collaboration:

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[TiC target chemists and 2 exhausted mortar/pestles]

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

A_β is the Ph.D. thesis work of B. Fenker

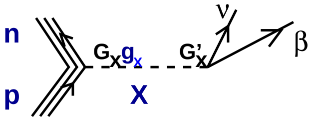
Why the weak interaction is 'weak' at low energy

'more massive virtual particles are created for shorter times'

Propagator+vertices:

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

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



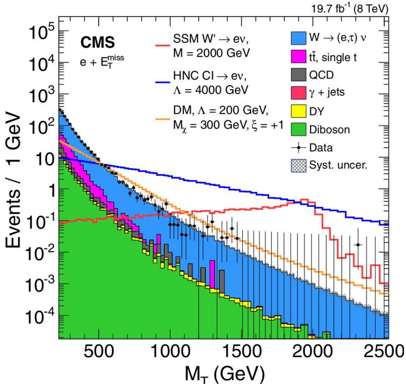
- Decay rates $\propto \frac{G_X^2 G_x'^2}{M_X^4}$

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

Quasi-direct limits from high-energy colliders

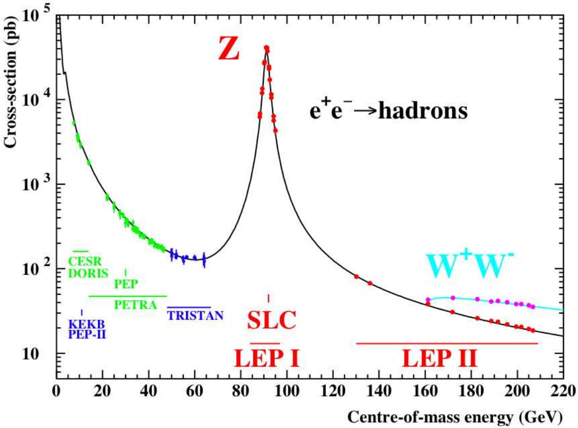


Along with peak searches:
LHC8 $\sigma[p + p \rightarrow e + \text{invisible}]$
Just like $n \rightarrow p + e + \nu$
CMS PRD 91 92005
Naviliat-Cuncic →
Gonzalez-Alonso AnDP 2013
(Cirigliano JHEP 2013)
2 events expected, 1 seen
(later Bhattacharya PRD 94 054508 (2016) combined ATLAS, CMS.)

E.g. Left-Right symmetric models
Extra W' with heavier mass, couples to ν_R
Otherwise same coupling strength, so parity is a good symmetry at very high energy
Renormalizable

Exchange bosons with lower m and smaller couplings?

Neutral exchange bosons can hide, but ‘weakly-coupled’ W’ still has electric charge



Does $e^+ + e^- \rightarrow W^+ + W^-$ cross-section double for W’?

Depends on the cut for W: typically this cut (explicitly listed in PDG) excludes low-mass W because of serious background

Weak interaction: same strength, all nuclei?

- Salam+Strathdee Nature 1974: phase transitions at very high B fields (10^{16} G) could drive $\theta_{\text{Cabibbo}} \to 0$ i.e. $V_{ud} \to 1$
- Suranyi+Hedinger PLB 56 151 1975: 10^{16}G possible in nuclei

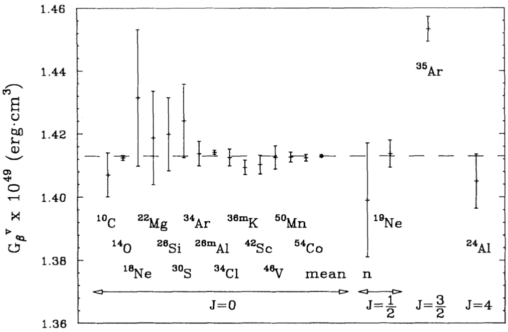


FIG. 2. Measured values of G_β^V. The $0^+ \to 0^+$ values are inferred from Ref. 1. The $J=\frac{1}{2}$ and $J=\frac{3}{2}$ values are inferred from Refs. 3 and 4.

Hardy+Towner PLB 1975: ^{35}Ar $A_\beta \leftrightarrow \theta_{\text{Cabibbo}} = 0$

Adelberger, Fernandez, Gossett, Osborne, Zeps PRL 55 2129 (1985): J=4 ^{24}Al $\leftrightarrow 0^+ \to 0^-$

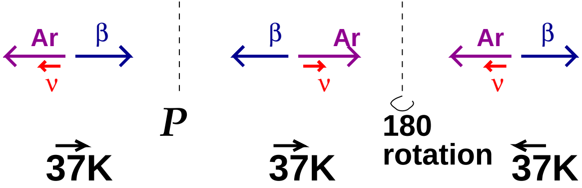
Two more recent measurements bring ^{35}Ar A_β into agreement

Suganuma+Tatsumi Ann.Phys. 208 407 (1991): 10^{19}G breaks symmetry more

Parity Operation can be simulated by Spin Flip

Under Parity operation *P*:

$\vec{r} \rightarrow -\vec{r}$ $\vec{p} \sim \frac{d\vec{r}}{dt} \rightarrow -\vec{p}$ $\vec{J} = \vec{r} \times \vec{p} \rightarrow +\vec{J}$



This is exact

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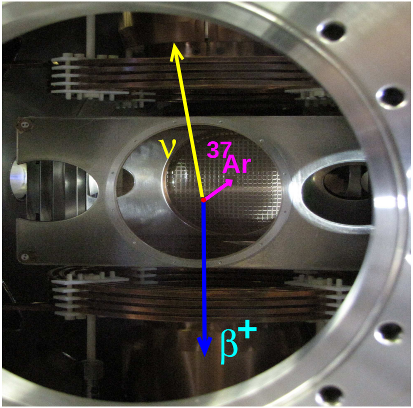
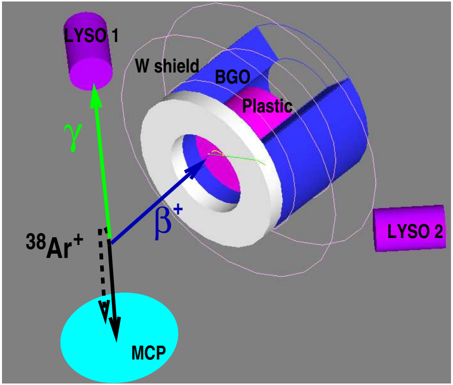
3-momentum $\not{T}$ correlation

When t → -t :

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

$$\vec{p_\nu} \cdot \vec{p_\beta} \times \vec{p_\gamma} = -\vec{p}_{\mathrm{recoil}} \cdot \vec{p_\beta} \times \vec{p_\gamma} \xrightarrow{t \rightarrow -t} \vec{p}_{\mathrm{recoil}} \cdot \vec{p_\beta} \times \vec{p_\gamma}$$





BUT flipping t is not the same thing as running the decay backwards.

Particles interact on the way out, and you don't reverse that part.

One experimental discovery of parity violation

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

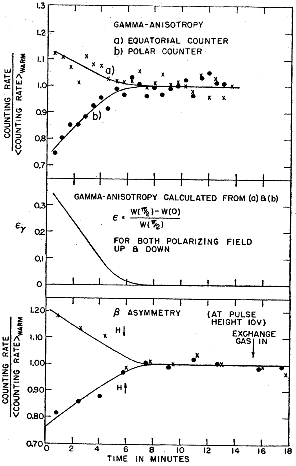
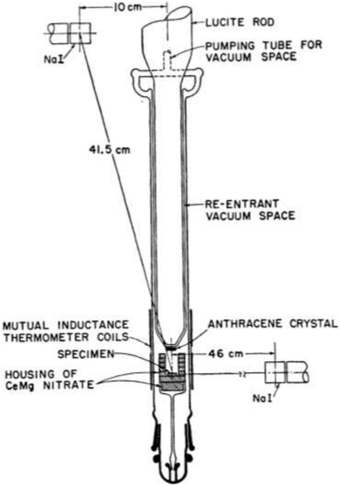


FIG. 2. Gamma anisotropy and beta asymmetry for polarizing field pointing up and pointing down.



Dilution Refrigerator to spin-polarize

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

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

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

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

$A_{\beta+} > 0$

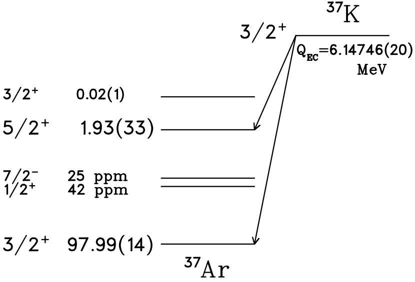
Wauters 2010 PRC $A_{^{60}\mathrm{Co}} = -1.014 \pm 0.020$ [SM -0.987 ± 0.009]

^{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

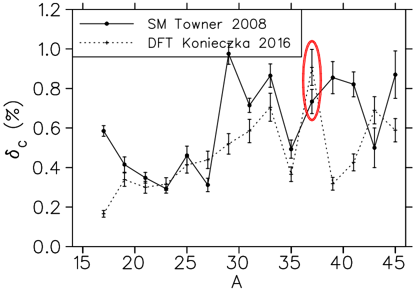
$\Rightarrow A_\beta[SM] = -0.5706 \pm 0.0007$
main uncertainty is experimental branching ratio

^{37}K isobaric mirror decay: a 'heavy neutron'.

$\Rightarrow A_\beta[SM]$ = -0.5706$\pm$0.0007
Dominant uncertainty is exp. branching ratio

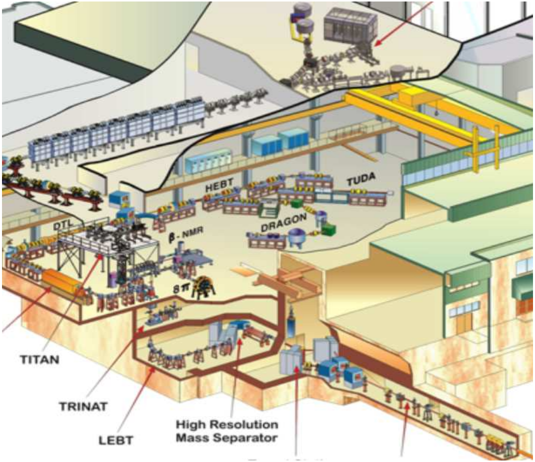
1st-order recoil-order from E&M moments:
Induced tensor $d_1 \approx 0$ for isobaric mirror
Small $\mu \Rightarrow$ small weak magnetism

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 (10%)
DFT for isospin mixing has improved functional for A$\sim$37
Using weighted average for δ_C would $\Rightarrow$ 0.0004 $\rightarrow$ 0.0005

TRIUMF TRIumf Neutral Atom trap at ISAC

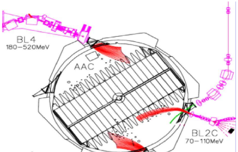


^{37}K 8x10^7/s

TiC target
1750^{o}C

70 μA
protons

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



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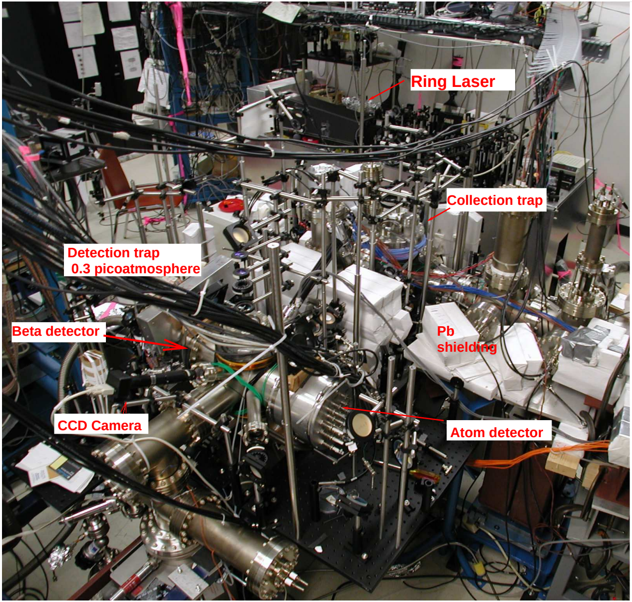
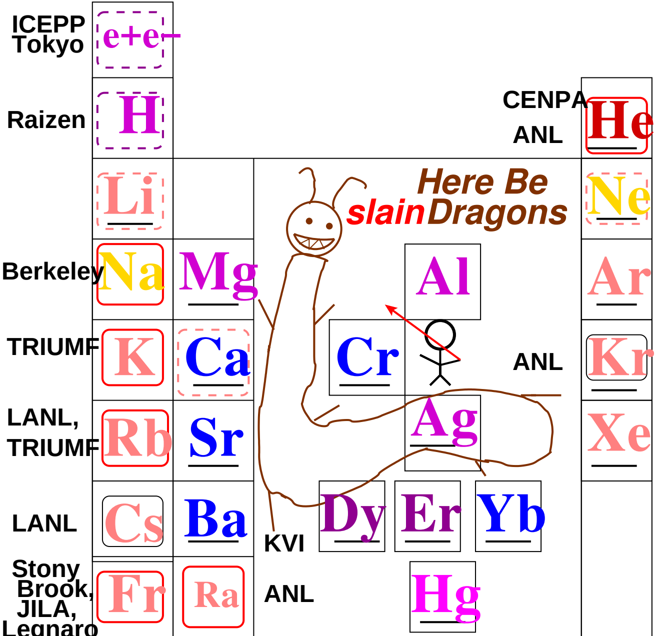
TRINAT lab: “tabletop experiment”

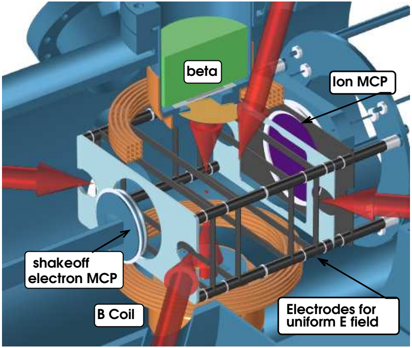


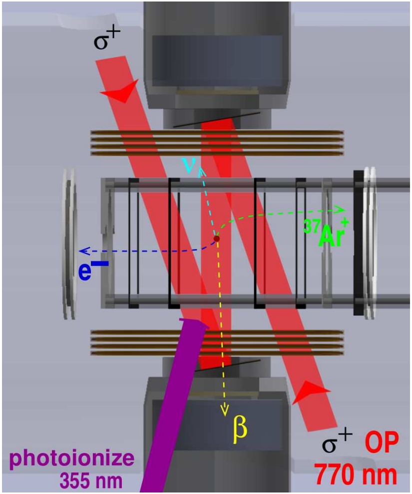
ISAC ion beam

What elements can be laser cooled?



^{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.

TRIUMF Optical pumping and probing ^{37}K

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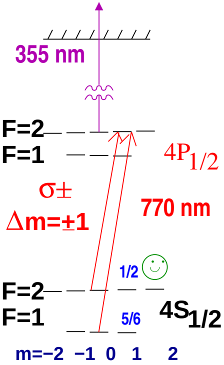
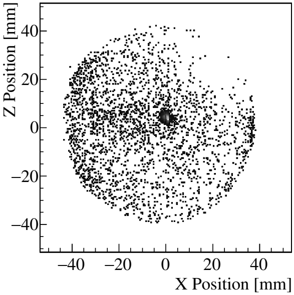
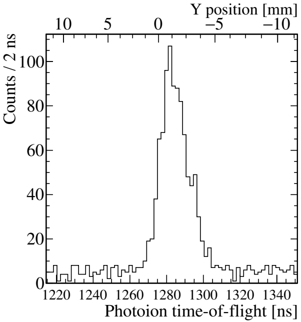






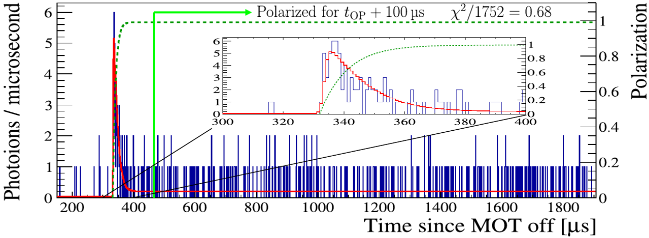
Photoionize 1%

***in situ* probe**

P_{+}**=+0.9913(8)**

P_{-}**=–0.9912(9)**

Fenker NJP 2016



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β^+ asymmetry ^{37}K data

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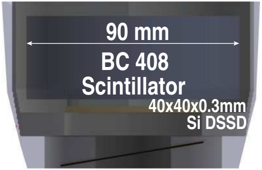
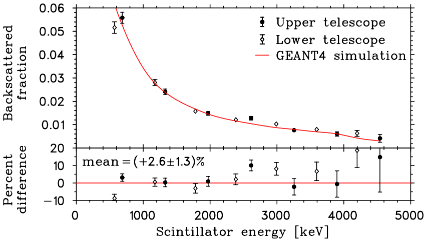
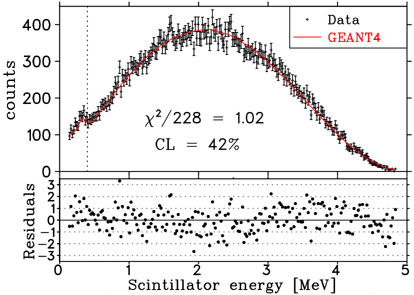
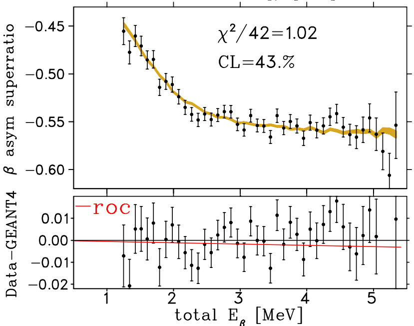




- **Backscatter from scint agrees to ≈5% over $E_{\beta+}$ range of interest (in preparation)**





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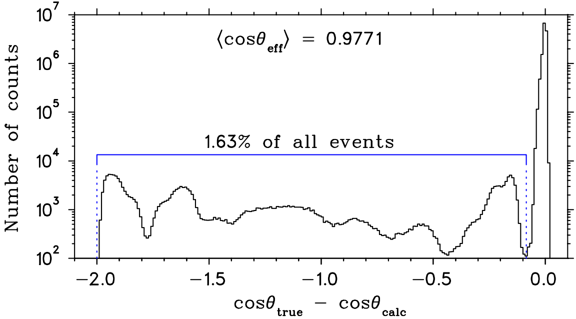
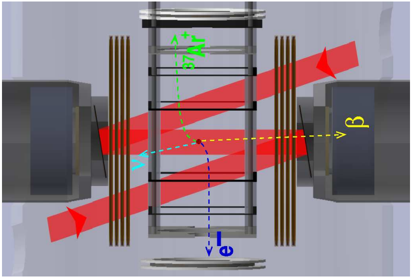
Scattered β's





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Background

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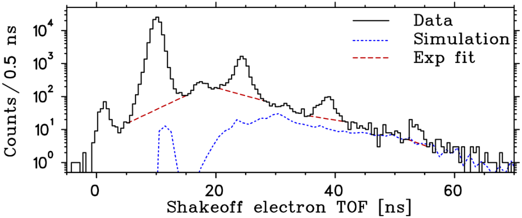

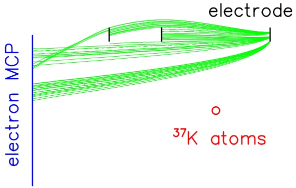

- 2.8×10^{-3} of events in main peak are background from non-trapped atoms
- Conservatively assume polarized between 0 and 100%. $\rightarrow A_\beta \times (1.0014 \pm 0.0014)$
- These will be removed by MCP position info when we increase to design *E* field

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

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Source		Correction	Uncertainty
Systematics			
Background		1.0014	0.0008
β scattering[a]		1.0230	0.0007
Trap (σ^+ vs σ^-)	position (typ $\lesssim \pm 20$ μm)		0.0004
	sail velocity (typ $\lesssim \pm 30$ μm/ms)		0.0005
	temperature (typ $\lesssim \pm 0.2$ mK)		0.0001
Si-strip	radius[a] ($15.5^{+3.5}_{-5.5}$ mm)		0.0004
	energy agreement ($\pm 3\sigma \rightarrow \pm 5\sigma$)		0.0002
	threshold (60 $\rightarrow$ 40 keV)		0.0001
Shakeoff electron TOF region ($\pm 3.8 \rightarrow \pm 4.6$ ns)			0.0003
Thicknesses	SiC mirror[a] (± 6 μm)		0.0001
	Be window[a] (± 23 μm)		0.000 09
	Si-strip[a] (± 5 μm)		0.000 01
Scintillator only vs. $E + \Delta E$[a]			0.0001
Scintillator threshold (400 $\rightarrow$ 1000 keV)			0.000 03
Scintillator calibration (± 0.4 ch/keV)			0.000 01
Total systematics			0.0013
Statistics			0.0013
Polarization		1.0088	0.0005
Total		1.0338	0.0019

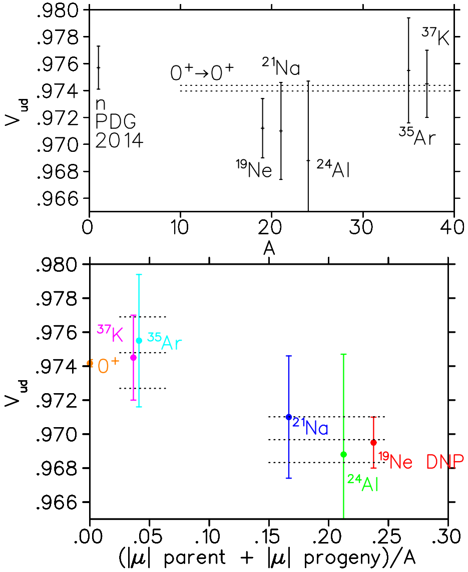
[a]Denotes sources that are related to β^+ scattering.

A_β = –0.5707 $\pm$ 0.0013 (stat) $\pm$ 0.0013 (syst) $\pm$ 0.0005 (pol) = -0.5707 $\pm$ 0.0019

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]

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. $\psi[n] \neq \psi[p]$**

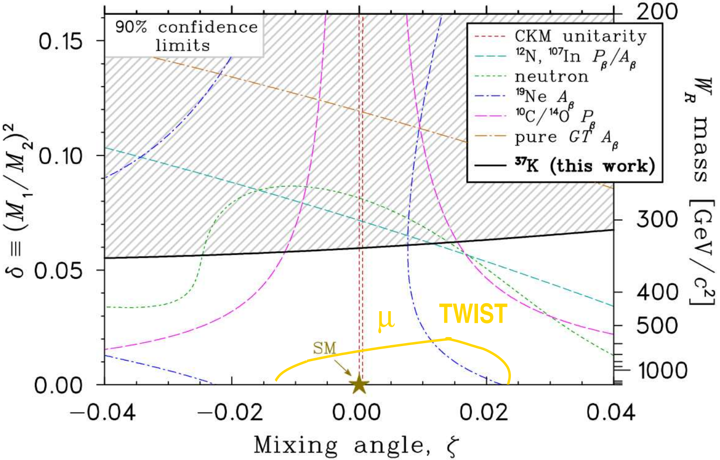
- **Salam and Strathdee Nature 1974: phase transitions at very high B fields could drive $V_{ud} \to 1$**

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

^{19}**Ne Broussard DNP 2016**

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%** →

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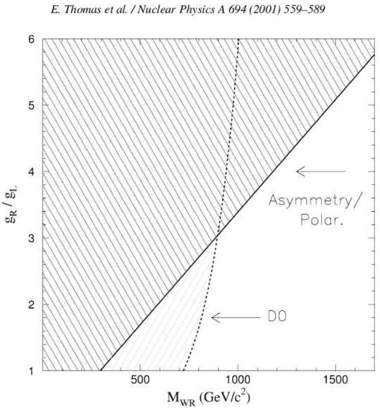
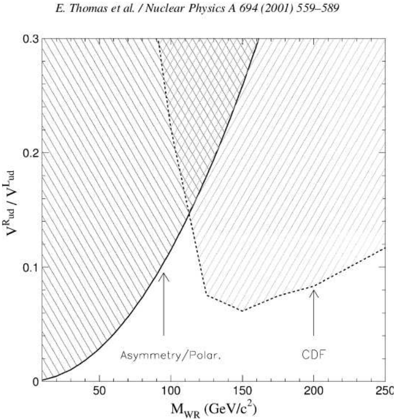
'Non-manifest' Left-Right models





$g_R > g_L$:
^{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 $V^{\rm R}_{\rm ud}$

PRELIM: A_β [E_β] agrees with S.M.

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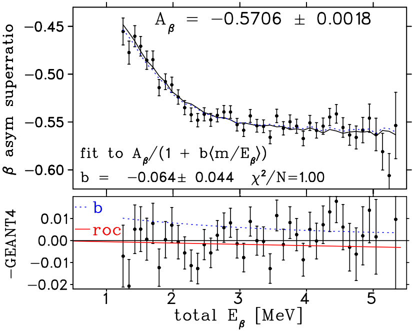
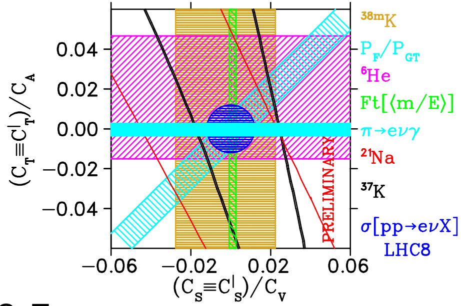


Nucleon, Lepton Currents making up Lagrangian (a scalar) can separately transform like *S*, *T*, *V*, *A*

1957 version of EFT.

Fierz term $\propto \langle \frac{m_\beta}{E_\beta} \rangle$



LHC8 $\sigma[p + p \to e\nu X]$
Naviliat-Cuncic
Gonzalez-Alonso AnDP 2013
(Cirigliano JHEP 2013)
1 event expected, 2 seen

Specific models: leptoquarks → S, T;
Profumo 2007 PRD: MSUSY sum over sparticles → S,T

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Couplings to wrong-handed ν

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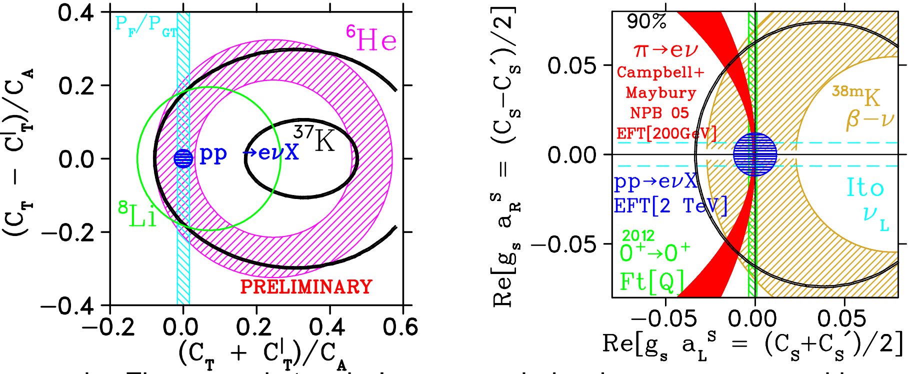

the Fierz term is ‘easier’ to constrain but has more competition

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

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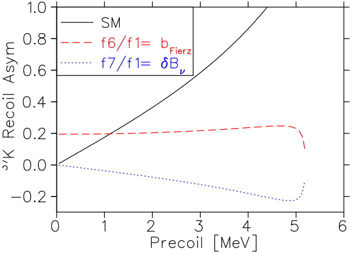
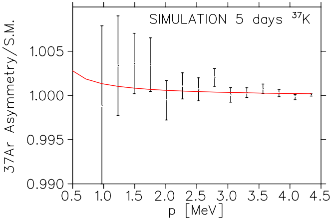
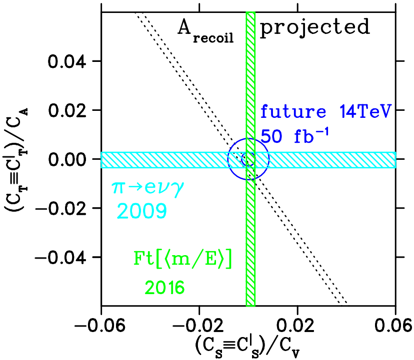
future $A_{recoil} \propto A_\beta + B_\nu$

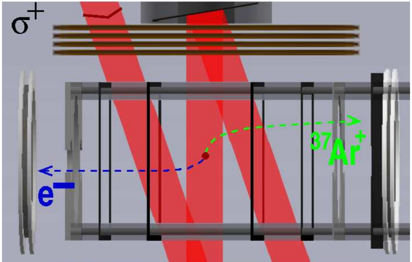
Technique demonstrated in ^{80}Rb Pitcairn PRC 2009



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







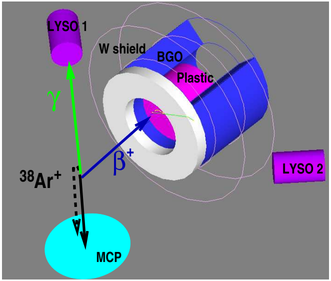
TRIUMF $\gamma\beta\nu\not{T}$ Experiment

Harvey Hill Hill PRL 99 261601
combine QCD+electroweak
interaction in the nucleon's $\mathcal{L}$, and
Gardner, He PRD 87 116012 (2013)
reduce this to $\mathcal{L}$ =

$$-\frac{4c_5}{m_{\rm nucleon}^2}\frac{eG_F V_{ud}}{\sqrt{2}}\epsilon^{\sigma\mu\nu\rho}\bar{p}\gamma_\sigma n\bar{\psi}_{eL}\gamma_\mu\psi_{\nu L}F_{\nu\rho}$$

which upon interference with S.M.
gives $\not{T}$ decay contribution $\rightarrow$

$$|\mathcal{M}_{c5}|^2 \propto \frac{Im(c_5 g_V)}{\rm M^2}\frac{E_e}{p_e k}(\vec{p_e}\times\vec{k_\gamma})\cdot\vec{p_\nu}$$

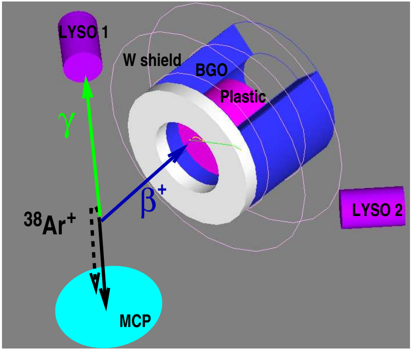


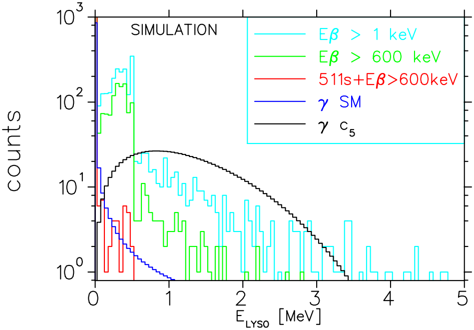
new physics $M \sim$ MeV

- $\not{T}$ 250x larger in $^{38\rm m}$K decay than n
- final state fake effect 8x10^{-4}
- $^{38\rm m}$K 40,000 atoms, 30000 events/week $\Rightarrow \sigma \sim 0.02$
- Test asymmetry of apparatus with coincidence pairs
- n $\rightarrow$ p $\beta\nu\gamma$ branch (Nico Nature 06, Bales PRL 16) $\Rightarrow$ $\frac{\rm Im(c_5)}{M^2} \leq 8 MeV^{-2} \Rightarrow$ Asym can be 100%

GEANT4 simulation of $\gamma\beta\nu\not{T}$

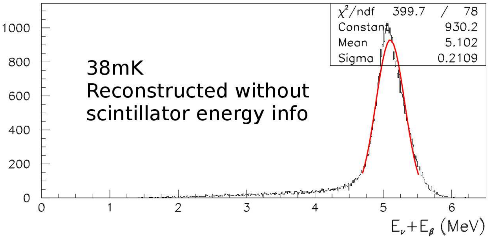
- the new 'c5' term needs Fermi or Fermi+GT transition $\Rightarrow$ β^+ emitters
- background from β 'external bremsstrahlung' suppressed by requiring β^+ to hit plastic
- Require two 511's in BGO, so we know they didn't go to γ detector, enables measurements at $E_\gamma < 0.2$ MeV.

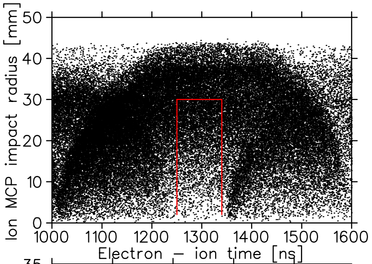


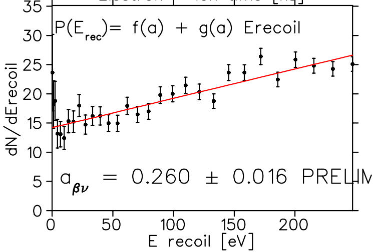


Reactor $\bar{\nu}$'s from $0^- \rightarrow 0^+$ ^{92}Rb decay

^{92}Rb produces $\sim$ 10% of reactor $\bar{\nu}$'s from 5-7 MeV, important for possible sterile ν and for non-proliferation.





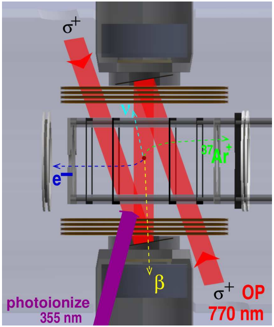


- **Isolate and measure g.s. branch (3 exps have settled on $\sim$ 90%)**
- **Reconstruct the E_ν spectrum. (4 $0^- \rightarrow 0^+$ exps disagree.) Such decays make 1/3 of the 5-7 MeV reactor $\bar{\nu}$'s)**
- **$a_{\beta\nu}$ too far from 1 to look for pseudoscalar interaction $\rightarrow$**

TRIUMF Neutral Atom Trap: Near Future

We have measured the β asymmetry of ^{37}K decay to be A_β=–0.5707 $\pm$ 0.0019

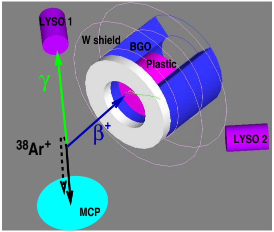
Agrees with theory –0.5706 $\pm$ 0.0007, complements the best β decay measurements



Plans: measure $A_\beta[E_\beta]$ 3-5 x better

- **$A_{\rm recoil}$ with sensitivity to '4-fermion contact' interactions complementary to $\pi \rightarrow e\nu\gamma$, $\pi \rightarrow e\nu$, and LHC $p + p \rightarrow e + E_\perp$**

- **A TRV $\beta\nu\gamma$ 3-momentum correlation, first of its type in 1st-generation particles**
- **^{92}Rb $0^- \rightarrow 0^+$ E_ν spectrum**



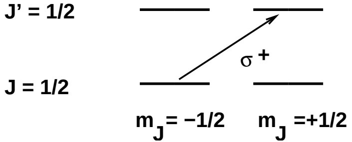
TRIUMF

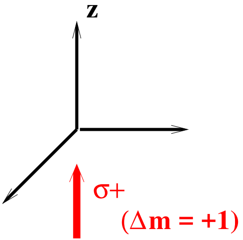
How to spin-polarize a nucleus with a laser: Part I

Polarize atom by Direct Optical Pumping

Biased random walk

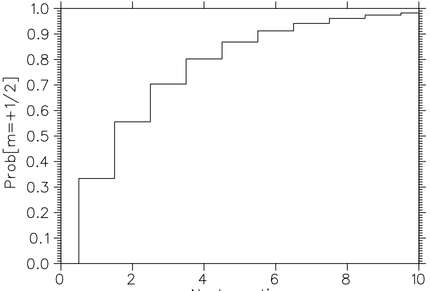
Simple example:





P(m=1/2) = 1 - $(2/3)^N$ after N steps

Need 12 photons absorbed to get to 99% of maximum.



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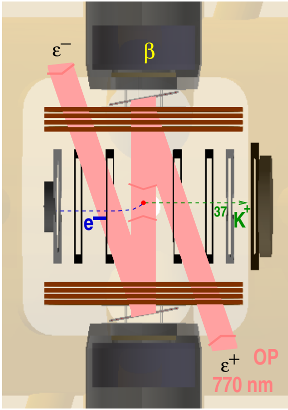
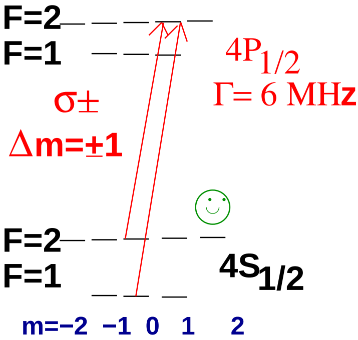
Direct Optical Pumping, I=3/2



- Biased random walk
- $\sigma^{\pm}$ light $4S_{1/2} \rightarrow 4P_{1/2}$ transition



- optimize with ^{41}K, almost same hyperfine splitting as ^{37}K

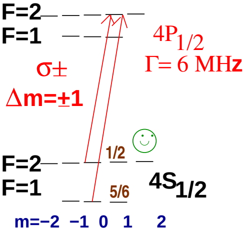
$\vec{F} = \vec{J}_{\mathrm{atom}} + \vec{I}_{\mathrm{nucleus}}$ $\quad H_{\mathrm{hyperfine}} = - \vec{\mu_N} \cdot \vec{B_e} = A\, \vec{I} \cdot \vec{J}$

Spin flips: $\sigma^{+} \rightarrow \sigma^{-}$;

small frequency shift (-2 MHz) to compensate Zeeman shift

TRIUMF

Quantifying Polarization from excited state population



Tail $\sim$ few % of peak $\Rightarrow$ We need tail/peak to $\sim$ 10% accuracy to extract P to $\sim$ 0.1%

We can't quite extract P by inspection:

$\Delta F = 0$ for Larmor precession

Same centroid P from 2 approaches:

Rate eqs for classical populations

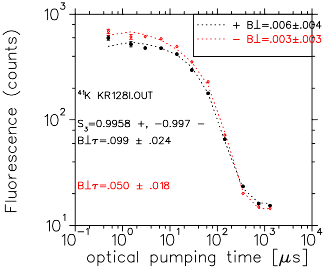
$$\frac{dN_i}{dt} = -R_{ji}N_i + R_{ij}N_j + \lambda N_j$$

Optical Bloch Eqs include $B_\perp$ rigorously

$$\frac{d\rho}{dt} = \frac{1}{i\hbar}[H, \rho] + \lambda$$

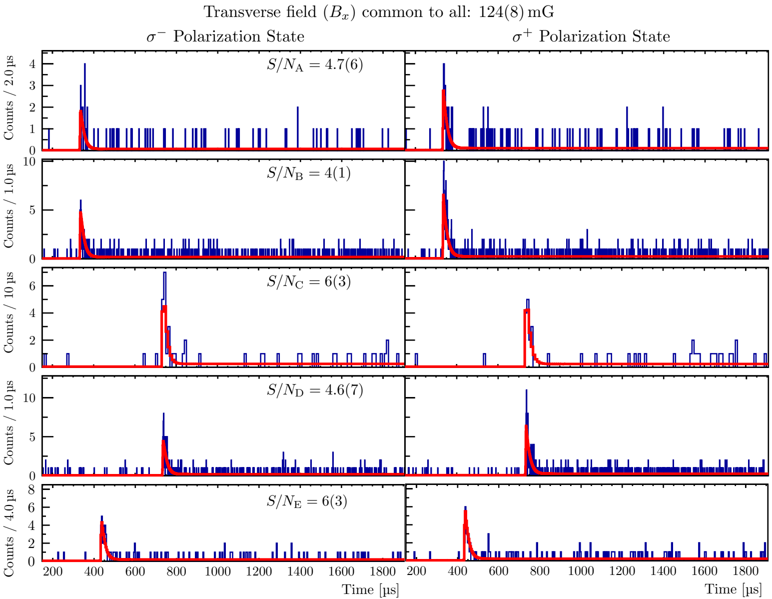
We measure S_3 and float $B_\perp$

(S_3=-0.9958(8), -0.9984(13), +0.9893(14), +0.9994(5))

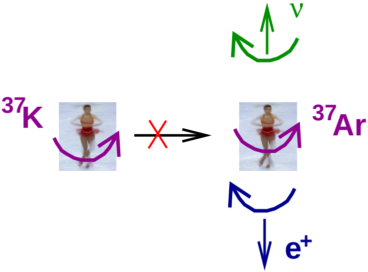


TRIUMF

Polarization fit to all ^{37}K data



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

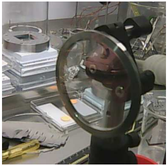
TRIUMF

Polarization Improvements

TEXAS A&M UNIVERSITY

SYST $\times 10^{-4}$	ΔP		ΔT	
	σ^-	σ^+	σ^-	σ^+
Initial T	3	3	10	8
Global fit v. ave	2	2	7	6
S_3^{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

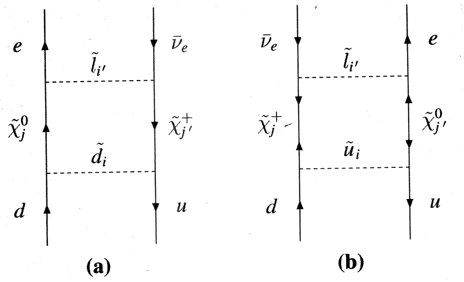


FIG. 2. Feynman diagrams relative to supersymmetric contributions giving rise to anomalous amplitudes in β decay processes.

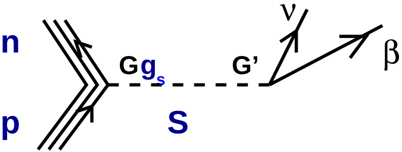
Include mixing of:

- 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 γ...)

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.

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,

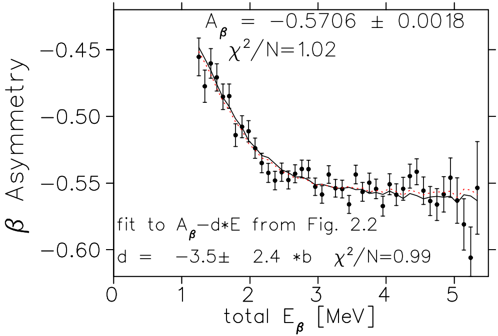
g_s = 0.8$\pm$0.4, g_T = 1.05$\pm$0.35

$\rightarrow$ (2016) PRD 94 054508

g_s = 0.97$\pm$0.12$\pm$0.06, g_T = 0.987$\pm$0.051$\pm$0.020

g_s=1.02$\pm$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

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

TRIUMF

Super-ratio

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

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

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

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