Beta Decay with Atom Traps

- In the decay of $^{37}$K, we’ve made the most accurate measurement of the asymmetry of the $\beta^+$ 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:
  $A_{\text{recoil}}$ asymmetry of recoils
  Time-reversal violation in $\beta \nu \gamma$ decay
  $^{92}$Rb $E\nu$ spectrum
TRIumf Neutral Atom Trap collaboration:

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L. Lambert]  
Undergrad  
A. Forestell

[TiC target chemists and 2 exhausted mortar/pestles]  
Supported by NSERC, NRC through TRIUMF, Israel Science Foundation, DOE, State of Texas

$A_\beta$ 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:

\[ T \propto \frac{G_X(-g^{\mu\nu} + p^\mu p^\nu / M_X^2)G_X}{p^2 - M_X^2} p \ll M_X \]

\[ T \propto \frac{G_X^2}{M_X^2} \Rightarrow \]

- 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 \( \nu \))

- 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:
$\text{LHC8 } \sigma[p + p \rightarrow e + \text{invisible}]$

Just like $n \rightarrow p + e + \nu$

CMS PRD 91 92005

Naviliat-Cuncic $\rightarrow$

Gonzalez-Alonso AnDP 2013

(Cirigliano JHEP 2013)

2 events expected, 1 seen

( later Bhattacharyya PRD 94 054508 (2016) combined

ATLAS, CMS.)

E.g. Left-Right symmetric models

Extra $W'$ with heavier mass, couples to $\nu_R$

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 $\theta_{\text{Cabibbo}} \rightarrow 0$ i.e. $V_{ud} \rightarrow 1$
- Suranyi+Hedinger PLB 56 151 1975: $10^{16}$G possible in nuclei

$^{35}\text{Ar} A_{\beta} \leftrightarrow \theta_{\text{Cabibbo}} = 0$

$J=4\ 24\text{Al} \leftrightarrow 0^+ \rightarrow 0^-$

Two more recent measurements bring $^{35}\text{Ar} A_{\beta}$ into agreement

$10^{19}$G breaks symmetry more

**FIG. 2.** Measured values of $G_{\beta}^V$. The $0^+ \rightarrow 0^+$ values are inferred from Ref. 1. The $J=\frac{1}{2}$ and $J=\frac{3}{2}$ values are inferred from Refs. 3 and 4.
Parity Operation can be simulated by Spin Flip

Under Parity operation $P$:

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

This is exact
When $t \rightarrow -t$:

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

$$\vec{p}_\nu \cdot \vec{p}_\beta \times \vec{p}_\gamma = -\vec{p}_{\text{recoil}} \cdot \vec{p}_\beta \times \vec{p}_\gamma$$

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

Dilution
Refrigerator
to spin-polarize

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

$W[\theta] = 1 + PA\hat{T} \cdot \frac{\vec{p}_\beta}{E_\beta}$

$= 1 + A_\beta^\nu \cos[\theta]$  

$A_\beta^- \approx -1.0$

Followup $^{58}\text{Co} \rightarrow ^{58}\text{Fe} + \beta^+ + \nu$

$A_\beta^+ > 0$

Wauters 2010 PRC $A_{^{60}\text{Co}} = -1.014 \pm 0.020$ [SM $-0.987 \pm 0.009$]
37K isobaric mirror decay: a ‘heavy neutron’?

Here $A_\beta$ 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 $\tau$, $Q$, 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) $\Rightarrow$

$\rho = \frac{C_A M_{GT}}{C_V M_F} = 0.5768 \pm 0.0021$

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

main uncertainty is experimental branching ratio
37 K isobaric mirror decay: a ‘heavy neutron’.

⇒ $A_\beta [SM] = -0.5706 \pm 0.0007$

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 ⇒ $\Delta A_\beta \approx -0.0028 \left( \frac{E_\beta}{E_0} \right)$ 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 $\delta_C$ would ⇒ 0.0004 → 0.0005
TRIumf Neutral Atom trap at ISAC

- $^{37}\text{K} A_\beta$ results
- future
- extras
- j.a.behr triumf 2018

$^{37}\text{K} 8 \times 10^7$/s

TiC target
1750°C
70 $\mu$A protons

main TRIUMF cyclotron
‘world’s largest’
500 MeV H$^-$ (0.5 Tesla)
TRINAT lab: “tabletop experiment”

- TRINA T lab: “tabletop experiment”
- ISAC ion beam
- Detection trap
- Pb shielding
- Collection trap
- Atom detector
- Beta detector
- CCD Camera
- Ring Laser
- 0.3 picoatmosphere
- 37K $A_\beta$
- $A_\beta$ results
- future
- extras
- j.a.behr triumf 2018

motivation methods
What elements can be laser cooled?

- K
- Aβ
- 37K
- Aβ results
- future
- extras
- j.a.behr triumf 2018

LANL, TRIUMF

Berkeley

TRIUMF

LANL, TRIUMF

LANL

Stony Brook, JILA, Legnaro

ICEPP
Tokyo

Here Be slain Dragons

He

Mg

Ne

Sr

Mg

Ba

Cr

Al

Ag

Yb

Cs

Dy

Fr

RA

Hg

KVI

ANL

CENPA

ANL

e+e−
$^{37}$K decay geometry

- $\beta$, recoil nucleus
- shakeoff $e^-$ for TOF trigger

This decay pattern is helicity-forbidden if the $\nu$ goes straight up, independent of Gamow-Teller/Fermi ratio.
Optical pumping and probing $^{37}$K

Photoionize 1% *in situ* probe

$P_+ = +0.9913(8)$

$P_- = -0.9912(9)$

Fenker NJP 2016
$\beta^+$ asymmetry $^{37}$K data

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

Motivation methods $^{37}$K $A_\beta$ $A_\beta$ results future extras j.a.behr triumf 2018

90 mm BC 408 Scintillator 40x40x0.3mm Si DSSD

Backscatter from scint agrees to $\approx 5\%$ over $E_{\beta^+}$ range of interest (in preparation)
Scattered $\beta$'s

\[ \langle \cos\theta_{\text{eff}} \rangle = 0.9771 \]

1.63% of all events
Background

- $2.8 \times 10^{-3}$ 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
### $^{37}$K $A_\beta^+$ Uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>Correction</th>
<th>Uncertainty</th>
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<tbody>
<tr>
<td>Systematics</td>
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<tr>
<td>Background</td>
<td>1.0014</td>
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<tr>
<td>$\beta$ scattering$^a$</td>
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<td>Trap ($\sigma^+ \text{vs} \sigma^-$)</td>
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<td>position (typ $\lesssim \pm 20 , \mu$m)</td>
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<td>sail velocity (typ $\lesssim \pm 30 , \mu$m/ms)</td>
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<tr>
<td>radius$^a$ (15.5$^{+3.5}_{-5.5}$ mm)</td>
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<td>Si-strip</td>
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<tr>
<td>energy agreement ($\pm 3\sigma \rightarrow \pm 5\sigma$)</td>
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<td>threshold (60 $\rightarrow$ 40 keV)</td>
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<td>Shakeoff electron TOF region ($\pm 3.8 \rightarrow \pm 4.6$ ns)</td>
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<td>SiC mirror$^a$ ($\pm 6 , \mu$m)</td>
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<td>Thicknesses</td>
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<td>Be window$^a$ ($\pm 23 , \mu$m)</td>
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<td>Si-strip$^a$ ($\pm 5 , \mu$m)</td>
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<td>Scintillator only vs. $E + \Delta E^a$</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>1.0338</strong></td>
<td><strong>0.0019</strong></td>
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</table>

$^a$Denotes sources that are related to $\beta^+$ scattering.

\[ A_\beta = -0.5707 \pm 0.0013 \text{ (stat)} \pm 0.0013 \text{ (syst)} \pm 0.0005 \text{ (pol)} \]

\[ A_\beta[\text{SM}] = -0.5706 \pm 0.0007 \]

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?**

\[ A_\beta \Rightarrow \text{GT/F} \]

Then \( \mathcal{F}t \) of \( ^{37}\text{K} \Rightarrow V_{ud} \)

- An isospin mixing test useful for
  \( 0^+ \rightarrow 0^+ \) 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 \( V_{ud} \rightarrow 1 \)

Hardy Towner PLB 1975 applied to the \( ^{35}\text{Ar} \) \( A_\beta \) controversy.

\( ^{19}\text{Ne} \) Broussard DNP 2016
**Left-Right Symmetric model**

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

\[
\delta \equiv \left( \frac{M_1}{M_2} \right)^2
\]

90% confidence limits

\[
M_{W'} > 3.7 \text{ TeV}
\]

90%

\[
M_{W'}^R > 352 \text{ GeV}
\]

90%

\(m_{[\nu_{\mu}^R]} > m_{\mu}\) but LHC $M_{W'} > 3.7 \text{ TeV}$ 90%
\( g_R > g_L : \)
\[ ^{37}\text{K} \Rightarrow g_R \lesssim 7.7 \text{ at 4 TeV} \]
(or \( g_R < 4 \), at 2 TeV but LHC7 2 TeV ‘bump’ had \( g \sim 0.5 \))

\[ V_{ud}^R < V_{ud}^L \]
For \( M_W' < 70 \text{ GeV} \), nuclear \( \beta \)
decay constrains \( V_{ud}^R \)
PRELIM: $A_\beta [E_\beta]$ agrees with S.M.

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 $\sigma[p + p \rightarrow e\nu X]$

Naviliat-Cuncic
Gonzalez-Alonso AnDP 2013
(Cirigliano JHEP 2013)
1 event expected, 2 seen

Specific models: leptoquarks $\rightarrow S, T$;
Profumo 2007 PRD: MSUSY sum over sparticles $\rightarrow S, T$
the Fierz term is ‘easier’ to constrain but has more competition

For scalars coupling to wrong-chirality $\nu$, we compete with our own $^{38mK} \beta-\nu$ Gorelov 2005
Technique demonstrated in $^{80}\text{Rb}$ Pitcairn PRC 2009

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

Ave $A_{\text{recoil}}$ depends on $\rho$; p dependence doesn’t.

SIMULATION 5 days $^{37}\text{K}$
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 $\mathcal{L} = \frac{-4c_5}{m_{\text{nucleon}}^2} \frac{eG_F V_{ud}}{\sqrt{2}} \bar{p}_\gamma \gamma_\sigma n\bar{\psi}_e L \gamma_\mu \psi_\nu L F_{\nu\rho}$
which upon interference with S.M. gives $T$ decay contribution $\rightarrow$
$|\mathcal{M}_{c5}|^2 \propto \frac{\text{Im}(c_5 g_V)}{M^2} \frac{E_e}{p_e k} (\vec{p}_e \times \vec{k}_\gamma) \cdot \vec{p}_\nu$

- $T$ 250x larger in $^{38}\text{mK}$ decay than n
- final state fake effect $8 \times 10^{-4}$
- $^{38}\text{mK}$ 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) $\Rightarrow \frac{\text{Im}(c_5)}{M^2} \leq 8 \text{MeV}^{-2} \Rightarrow$ Asym can be 100%
GEANT4 simulation of $\gamma \beta \nu T$

- the new ‘c5’ term needs Fermi or Fermi+GT transition $\Rightarrow \beta^+$ emitters
- background from $\beta$ ‘external bremsstrahlung’ suppressed by requiring $\beta^+$ to hit plastic
- Require two 511’s in BGO, so we know they didn’t go to $\gamma$ detector, enables measurements at $E_\gamma < 0.2$ MeV.
Reactor $\bar{\nu}$’s from $0^- \rightarrow 0^+ \, ^{92}\text{Rb}$ decay

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

- Isolate and measure g.s. branch (3 exps have settled on $\sim 90\%$)
- Reconstruct the $E_\nu$ 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 →
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 $A_β[E_β]$ 3-5 x better

- $A_{recoil}$ 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 $0^- \rightarrow 0^+ E_\nu$ spectrum
How to spin-polarize a nucleus with a laser: Part I

Polarize atom by Direct Optical Pumping

Biased random walk

Simple example:

\[ J' = 1/2 \]
\[ J = 1/2 \]
\[ m_J = -1/2 \]
\[ m_J = +1/2 \]

\[ P(m=1/2) = 1 - \left( \frac{2}{3} \right)^N \] after N steps

Need 12 photons absorbed to get to 99% of maximum.
Direct Optical Pumping, $I=3/2$

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

- Optimize with $^{41}\text{K}$, almost same hyperfine splitting as $^{37}\text{K}$

$$\vec{F} = \vec{J}_{\text{atom}} + \vec{I}_{\text{nucleus}}$$

$$H_{\text{hyperfine}} = -\mu_N \cdot \vec{B}_e = A \vec{I} \cdot \vec{J}$$

Spin flips: $\sigma^+ \rightarrow \sigma^-$;
small frequency shift (-2 MHz) to compensate Zeeman shift
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 Eqns include $B_\perp$ rigorously
\[
\frac{d\rho}{dt} = \frac{1}{i\hbar}[H, \rho] + \lambda
\]
We measure $S_3$ and float $B_\perp$
($S_3=-0.9958(8), -0.9984(13), +0.9893(14), +0.9994(5)$)
Polarization fit to all $^{37}$K data

Transverse field ($B_x$) common to all: 124(8) mG

$\sigma^-$ Polarization State

$S/N_A = 4.7(6)$

$S/N_B = 4(1)$

$S/N_C = 6(3)$

$S/N_D = 4.6(7)$

$S/N_E = 6(3)$

$\sigma^+$ Polarization State
Lepton helicity → angular distribution

$^{37}\text{K} \rightarrow ^{37}\text{Ar}$

$\nu$ 

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

$I=3/2 \rightarrow I=3/2$

Leptons can’t increase nuclear spin any further
### Polarization Improvements

**SYST $\times 10^{-4}$**

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<tr>
<th></th>
<th>$\Delta P$</th>
<th>$\Delta T$</th>
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</thead>
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<tr>
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<td>$\sigma^-$</td>
<td>$\sigma^+$</td>
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<td>Initial $T$</td>
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<td>Cloud temp</td>
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<td>Binning</td>
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</tr>
<tr>
<td>$B_z$ Uncertainty</td>
<td>0.5</td>
<td>3</td>
</tr>
</tbody>
</table>

- 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

- Pellicle mirrors: less $\beta^+$ scattering

- Uncertainty $\propto (1-P)$

- Binning

- Cloud temp

- Binning

- $B_z$ Uncertainty

- Initial $P$

- Require $I_+ = I_-$

- Total SYSTEMATIC

- STATISTICS

B. Fenker New J. Phys 18 073028

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

2016
MSSM and $\beta$ 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

Include mixing of:
- left and right sfermions (this is where $\beta$ 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 $b_{\text{Fierz}}$ and spin correlation observables like $B_\nu$ as large as 0.001.
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: "0.25 < g_s < 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,

\( g_s = 0.8\pm0.4, \quad g_T = 1.05\pm0.35 \)

→ (2016) PRD 94 054508

\( g_s = 0.97\pm0.12\pm0.06, \quad g_T = 0.987\pm0.051\pm0.020 \)

\( g_s = 1.02\pm0.10 \) 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 $\beta$ decay (Sumikama PRC 2011) in models where 2nd-class currents change with system (Wilkinson EPJA 2000).

Babar set best 3-generation constraints PRL 2009

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

\[ A^{SR}_{\text{obs}}(E_e) = \frac{1 - s(E_e)}{1 + s(E_e)} = A_{\text{obs}} \]

\[ s(E_e) = \sqrt{\frac{r^-_1(E_e)r^+_2(E_e)}{r^+_1(E_e)r^-_2(E_e)}} \]


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