Symmetry violations in β decay

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Theor. Physik 1

FOR 1873

Motivation

- Recently non-SM interactions studied using SM EFT Cirigliano *et al.* [2010, 2013]
  - Model independent (*)
  - All fields obey SM symmetry groups
  - New physics generated by higher-dimensional operators

$$\mathcal{L}_{\text{eff}} = \mathcal{L}^{(4)} + \frac{1}{\Lambda}\mathcal{L}^{(5)} + \frac{1}{\Lambda^2}\mathcal{L}^{(6)}$$

- Interplay between different searches for new physics
  - What is the role of β decay?
  - Can we study Lorentz-symmetry breaking?

EFT Formalism

Lee and Yang [1956]
Jackson *et al.* [1957]

SM + "V+A"

$$\mathcal{L}^{(\mathrm{eff})} = \frac{G_F V_{ud}}{\sqrt{2}} \Bigg[\sum_{\epsilon,\delta=L,R} a_{\epsilon\delta}\; \bar{e}\gamma^{\mu}\nu_e^{\epsilon} \cdot \bar{u}\gamma_{\mu} d_{\delta}$$

Scalar

$$+ A_L\; \bar{e}(1-\gamma_5)\nu_e^{\epsilon} \cdot \bar{u} d_{\delta} + A_R\; \bar{e}(1+\gamma_5)\nu_e^{\epsilon} \cdot \bar{u} d_{\delta}$$

$$+ \alpha_R\; \bar{e}\frac{\sigma^{\mu\nu}}{\sqrt{2}}(1+\gamma_5)\nu_e^{\epsilon} \cdot \bar{u} + \alpha_L\; \bar{e}\frac{\sigma^{\mu\nu}}{\sqrt{2}}(1-\gamma_5)\nu_e^{\epsilon} \cdot \bar{u} \Bigg],$$

Tensor

- Related to "Lee-Yang" formalism using form factors g_A, g_S, g_T
- T (CP)-violation probed by imaginary couplings

Correlation coefficients

Jackson *et al.* [1957]

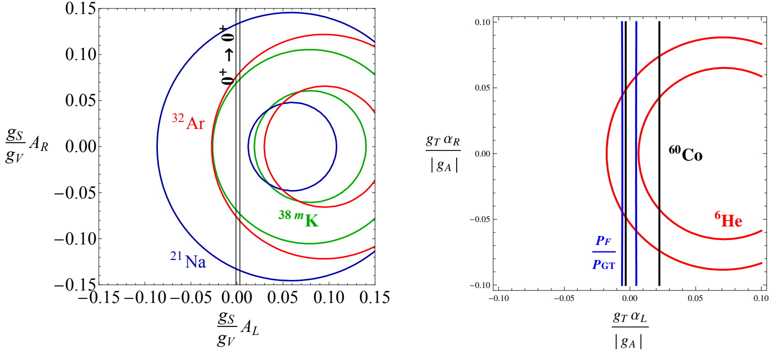
$$\frac{dW}{dW_0} \propto 1 + a\frac{\vec{p}_e\vec{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} + \frac{\left\langle \vec{J} \right\rangle}{J} \cdot \left[A\frac{\vec{p}_e}{E_e} + D\frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} \right] + \cdots$$

- Correlations coefficients measure deviations from "*V*-*A*"
  - Scalar/Vector: Fermi transitions
  - Axial-Vector/Tensor: Gamow-Teller transitions
- Only Fierz-interference term *b* depends linearly on left-handed scalar and tensor couplings
- Usually measured

$$\tilde{A} = \frac{A}{1 + b\left\langle m_e/E_e \right\rangle}$$

Searches for exotic couplings - Current limits

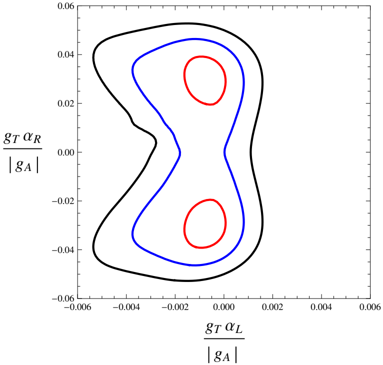
KKV, Wilschut, Timmermans [2015]



$$\frac{1}{ft_F} \propto V_{ud}^2 \left(1 + \frac{g_S^2}{g_V^2}\left[A_L^2 + A_R^2\right] - 2\sqrt{1 - Z^2\alpha^2}\left\langle \frac{m_e}{E_e} \right\rangle \frac{g_S}{g_V} A_L\right)$$

Searches for exotic couplings - Global fit

KKV, Wilschut, Timmermans [2015]



- Neutron decay can also be used to study new physics
  - Tensor limits improve
  - But issues with neutron life time
  - g_A as input from lattice ?

Interplay with LHC constraints

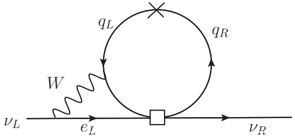
Cirigliano *et al.* [2013]
Bhattacharya *et al.* [2012, 2014]
Gonzalez-Alonso and Camalich [2014]

- New particles with high mass would also gives deviations from SM predictions at LHC
- $pp \to e + \text{MET} + X$ same quark process as β decay
  - sensitive to same scalar and tensor interactions
- Upper limit on new physics events can be translated into constraint on exotic couplings
- Values for g_S and g_T important/limiting factor

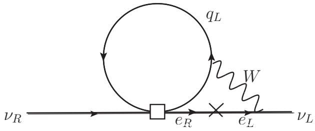
$$gs = \frac{\delta M^{QCD}}{\delta m_q} = \underset{\text{CVC-relation}}{1.02 \pm 0.11} \quad \text{and} \quad g_T = \underset{\text{Lattice}}{1.047 \pm 0.061}$$

Interplay with neutrino mass

Ito and Prezeau [2005]



Constraint on A_{RR}, A_{RL} and α_R



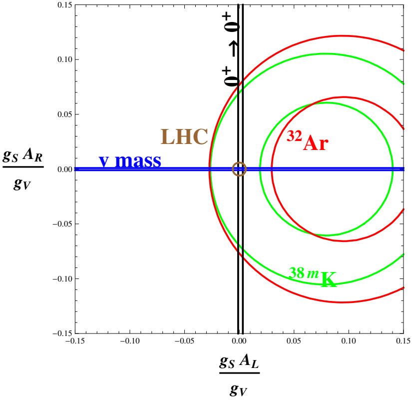
Constraint on a_{RL}

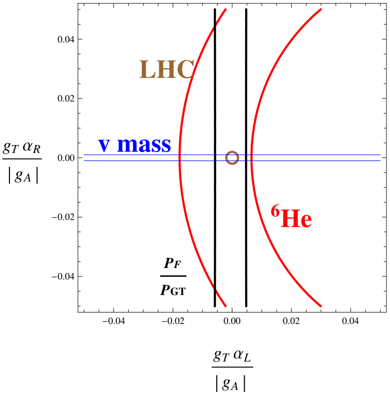
- Electroweak radiative corrections constrain right-handed couplings neutrino couplings
  - Two-loop W contribution dominant
  - Simple estimate considering only logarithmic part

$$\delta m_\nu \sim 3 g^2 G_F \bar{a} \frac{m_f M_W^2}{(4\pi)^4} \left(\ln \frac{\mu^2}{M_W^2} \right)^2$$

Combined limits on exotic couplings

KKV, Wilschut, Timmermans[2015]





Time-reversal violation in β decay

Chupp *et al.* [2012]
Kozela [2012]

- Imaginary couplings probed by triple-correlation coefficients in β decay

$$D\vec{J}\cdot(\vec{p}_e\times\vec{p}_\nu) \text{ and } R\vec{\sigma}_e\cdot(\vec{J}\times\vec{p}_e)$$

  where $D \propto \text{Im } a_{LR}$ and $R \propto c' g_T \text{ Im } \alpha_L - c'' g_S \text{ Im } A_L$

- Final-state-interactions mimic time-reversal violation: $D = D_t + D_f$
- For neutron decay $D_f \sim 10^{-5}$ and $|\text{Im } a_{LR}| < 4 \times 10^{-4}$
- From neutron and pure GT ^{8}Li
  $g_T|\text{Im } \alpha_L| < 3^{-3}$ and $g_S|\text{Im } A_L| < 6 \times 10^{-2}$

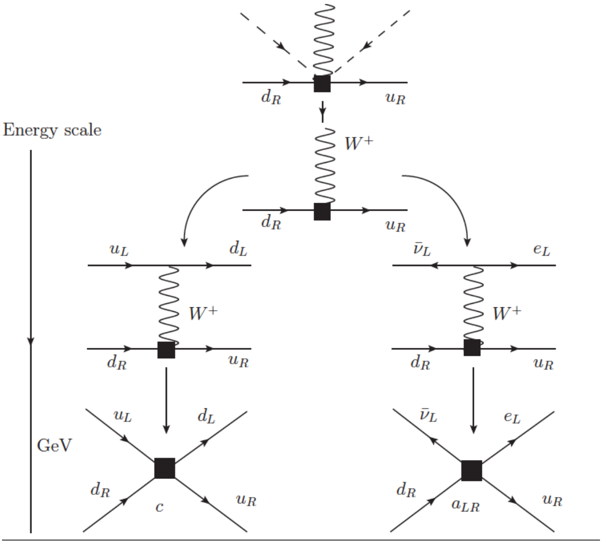
Time-reversal violation in EDMs

Ng and Tulin [2005]
Khriplovich [1991, 1997]

- Atomic and molecular EDM measurements limit same couplings
  - Any coupling imaginary part a_{LR} always contributes to neutron EDM
  - C_S and C_T couplings linked to electron-quark interactions in β decay

EDM	e cm (90% C.L.)	Coeff. β decay
n	2.9×10^{-26}	D
^{199}Hg	2.6×10^{-29}	D, R
^{205}Tl	0.9×10^{-24}	R
YbF	$\lvert d_e \rvert < 10.5 \times 10^{-28}$	R
ThO	$\lvert d_e \rvert < 8.7 \times 10^{-29}$	R

Time reversal violation in EDMs



$$\mathcal{L} = \frac{c}{\Lambda^2} \bar{u}_R \gamma^\mu d_R \tilde{\varphi}^\dagger i D_\mu \varphi$$

Using χPT and NDA

$$d_n = -10^{-20} \frac{\mathrm{Im} c}{2\sqrt{2} G_F \Lambda^2} e \text{ cm}$$

De Vries *et al.*, Seng *et al.*

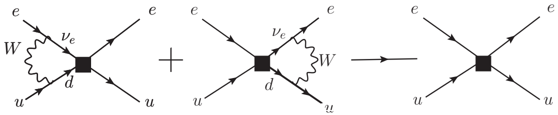
Time-reversal violation in EDMs

KKV, Wilschut, Timmermans [2015]
Khriplovich [1991, 1997]

- Molecular EDMs constrain C_S and $C_T < 10^{-8}$

$$\mathcal{L} = \sum_N \frac{G_f}{\sqrt{2}} \left[C_S \bar{N} N \bar{e} i\gamma_5 e + C_T \bar{N} \sigma_{\mu\nu} N \bar{e} i \gamma_5 \sigma^{\mu\nu} e \right]$$

- Can be linked to e-u coupling



$$\frac{-G_F}{\sqrt{2}} \frac{\alpha}{4\pi} \ln\left(\frac{\mu^2}{M_W^2}\right) V_{ud}\, \mathrm{Im}\left(2A_L + 24\alpha_L\right) \left[\bar{e} i\gamma_5 e \bar{u} u + \tfrac{1}{2} \bar{e} i \gamma_5 \sigma_{\mu\nu} e \bar{u} \sigma^{\mu\nu} u\right]$$

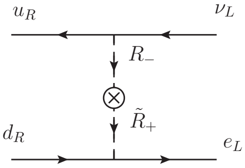
- Very rough estimate

T-violation: Current constraints

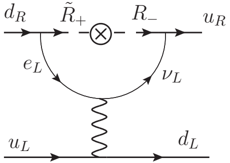
KKV, Wilschut, Timmermans[2015]

	Im a_{LR}	Im A_L	Im α_L
β decay	4×10^{-4}	6×10^{-2}	3×10^{-3}
EDM	3×10^{-6}	10^{-5}	10^{-6}

- EDM constraints beyond the FSIs
- Limits for a_{LR} apply to R-parity violating MSSM, LRSM ...



dim-8 contribution to β decay



Loop contribution to EDM

- Example: Leptoquarks also not "EDM-safe"

Discussion

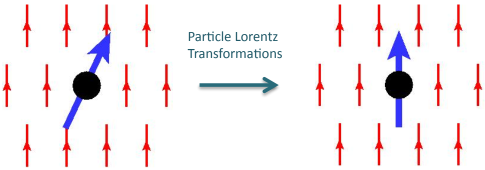
KKV, Wilschut, Timmermans[2015]

- LHC experiments will give stronger constraints
- EDMs will be improved with factor $10 - 100$
- β decay experiments should focus on left-handed new couplings
  - β shape measurements
  - Super allowed Fermi decays (also V_{ud}) and mirror nuclei
  - Neutron lifetime and g_A
  - Theory updates needed

- Cancellation between coefficients $\rightarrow$ strong finetuning
- Specific models $\rightarrow$ no dim-6 operators
- Light new degrees of freedom?

Lorentz-Symmetry Breaking: Motivation

- Standard Model + General Relativity → Quantum Gravity?
- Viable scenarios for Lorentz symmetry breaking
  - Mechanism for CPT violation
- Use effective field theory approach
  - Can be probed in low-energy precision experiments



- Observer invariance maintained
- Breaking of particle Lorentz invariance

EFT approach: SME

Colladay and Kostelecky[1988]

- SME = SM + all Lorentz symmetry breaking terms
- Most general EFT and gauge invariant (also dim-3 and dim-4)

$$\mathcal{L}^{(3)} = -m\bar{\varphi}\varphi - a_\mu \bar{\phi}\gamma^\mu \phi - b_\mu \bar{\varphi}\gamma^\mu \gamma_5 \varphi$$
$$\mathcal{L}^{(4)} = i\bar{\varphi}\gamma_\nu \partial^\nu \varphi + c_{\mu\nu}\bar{\phi}\gamma^\mu \partial^\nu \varphi + d_{\mu\nu}\bar{\varphi}\gamma_5 \gamma^\mu \partial^\nu \varphi$$

CPT-odd Lorentz violating

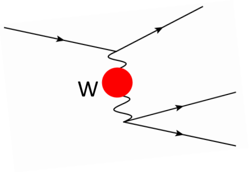
CPT-even Lorentz violating

- Fundamental theory is still Lorentz invariant
- Unique experimental signatures
- Weak interaction mainly unexplored

Lorentz Violation in the weak interaction

J.P. Noordmans *et al.* [2013]
KKV *et al.* [2015]

Theoretical framework $\rightarrow$ modified W-boson propagator



General Lorentz violating tensor

$$\langle W^{\mu+}(p)W^{\nu-}(-p)\rangle = \frac{-i(g^{\mu\nu} + \chi^{\mu\nu})}{M_W^2}$$

- In the minimal SME $\chi^{\mu\nu} = -k_{\phi\phi}^{\mu\nu} - \frac{i}{2g}k_{\phi W}^{\mu\nu} + \frac{2p_\rho p_\sigma}{M_W^2}k_W^{\rho\mu\sigma\nu}$
- Best constraints $\mathcal{O}(10^{-7})$ from forbidden β decay searches in 70s
  - Enhancement of Lorentz-violating effects
  - High intensity sources

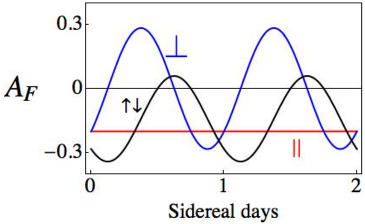
Lorentz violation in β decay

Example Fermi decay

KKV *et al.* [2015]

$$\frac{dW_F}{dW_0} = \left(1 + b\frac{m_e}{E_e} + 2\chi_r^{00} + 2\chi_r^{0l}\frac{p_e^l}{E_e} + (a + \chi_r^{00})\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_e E_\nu} + 2\chi_i^{0l}\frac{(\vec{p}_e\times\vec{p}_\nu)^l}{E_e E_\nu} + \cdots\right)$$

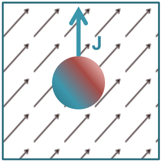
- Many new correlations
- Possible to probe different components directly
- Anisotropic emission
  - Preferred fermion direction or reaction plane
- Study in parallel with $\beta\nu$-correlation a



Lorentz violation in β decay - Experiment

First experiment in allowed β decay

Muller *et al.* [2013]
Sytema *et al.* [2016]



$$\frac{dW}{dW_0} = \left(1 + A\left[\vec{\beta}\cdot\hat{\vec{J}} + \tilde{\chi}_i^l \hat{J}^l\right]\right)$$

- Spin J flip of polarized Gamow-Teller decay
  - search for sidereal variation to reduce systematic errors
  - sensitive to imaginary part of χ
- Final result $\tilde{\chi}_i < 10^{-4}$

Discussion

- Established a program to test Lorentz Violation in weak decays
- Lorentz violation could be studied parallel to BSM physics in β decay

Outlook

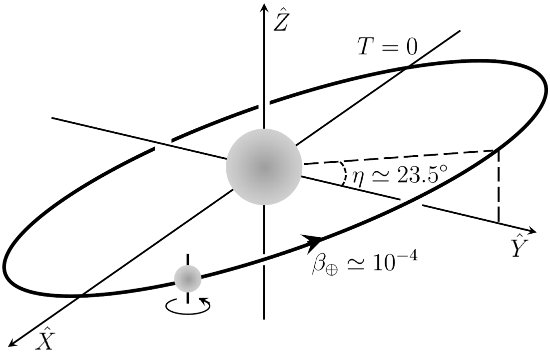
High statistics necessary to improve existing constraints topologies

- Use γ^2 enhancement at LHC or future beta beam facilities

$$\frac{dW}{dW_0} = 1 + 2\gamma^2(\chi_r^{00} + 2\chi_r^{0l}\hat{v}_l + \chi_r^{lk}\hat{v}_l\hat{v}_k)$$

- Electron capture

Backup Slides



Backup: Forbidden β decay

J.P. Noordmans *et al.* [2013]

Best current bounds from forbidden β-decay experiments

- enhancement of Lorentz-violating effects
- high intensity sources still allowed in the 70s

$$\chi_r^{\mu\nu} = \begin{bmatrix} 10^{-6} & 10^{-7} & 10^{-7} & 10^{-8} \\ 10^{-7} & 10^{-6} & 10^{-6} & 10^{-6} \\ 10^{-7} & 10^{-6} & 10^{-6} & 10^{-6} \\ 10^{-8} & 10^{-6} & 10^{-6} & 10^{-6} \end{bmatrix} \quad \chi_i^{\mu\nu} \begin{bmatrix} \times & - & - & - \\ - & \times & 10^{-8} & 10^{-7} \\ - & 10^{-8} & \times & 10^{-7} \\ - & 10^{-7} & 10^{-7} & \times \end{bmatrix}$$

- High statistics necessary to improve existing constraints
- Unconstrained coefficients

Backup: Search for Lorentz Violation

Kostelecky and Russell [2011]

More than 70 pages of limits in "Data Tables"

- Window on Quantum Gravity
- Weak interaction relatively unexplored

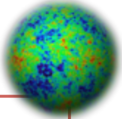
Particle-antiparticle comparisons
Spectroscopy of hydrogen and antihydrogen

Baryon asymmetry
Laboratory tests of gravity
Clock-comparison measurements

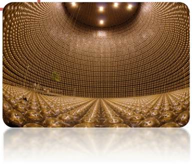
High-energy astrophysical observations
Tests with microwave cavities and lasers

Muon g-2
Neutrino oscillations
Matter interferometry
Oscillations of K, B, D mesons
QED tests in Penning traps

CMB Polarization



CMB polarization
Collider experiments
Cosmological birefringence
Dispersion from cosmological sources
High-energy astrophysical observations



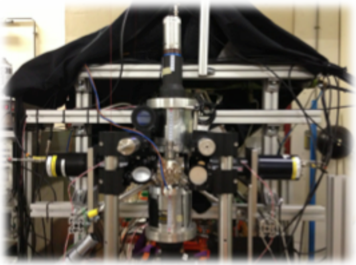
Neutrino experiments

Backup: Efforts in weak decays

S.E. Muller *et al.* [2013]
J.P. Noordmans *et al.* [2013, 2014]
KKV *et al.* [2015]
A. Sytema *et al.* [2016]

- Allowed β decay
- Forbidden β decay
- Pion decay at MINOS
- Kaon decay at KLOE
- Muon decay at $g-2$
- Electron capture

Setup for allowed β decay experiment



χ momentum-independent and CPT-even

- 15 independent components

Backup: Naturalness

Pospelov *et al.* [2005,2008]

$$\underline{a_\mu, b_\mu} \sim \Lambda \qquad \underline{c_{\mu\nu}, d_{\mu\nu}} \sim 1$$

- Dim-3 and 4 operators forbidden by SUSY
  - Generated by radiative corrections
- Dim-3 and 4 operators naturally suppressed

$$a_\mu, b_\mu \sim \frac{M_{\text{NP}}^2}{\Lambda} \qquad c_{\mu\nu}, d_{\mu\nu} \sim \frac{M_{\text{NP}}}{\Lambda}$$

- No assumptions on new theories between the electroweak and Planck scale