Probing TeV Physics through Lattice Neutron-Decay Matrix Elements

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Fermi Theory of Beta Decay

§ Four-fermion interaction explained beta decay before electroweak theory was proposed

✿ New operators in effective low-energy theories

§ Electroweak theory adds 3 vector bosons

✿ $W$ and $Z$ bosons directly detected later at CERN

\[
\Lambda \approx m_W \approx 80 \text{ GeV}, \quad m_Z \approx 90 \text{ GeV}
\]
What You See/How You Look

$\Lambda_{\text{BSM}} \approx \text{TeV}$

$E$

$M_{W,Z}$

$\Lambda_{\text{QCD}} \approx \text{GeV}$

$L_{\text{SM}} + L_{\text{BSM}}$

$L_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} \hat{O}_i$

$g_S = \langle n|\bar{u}d|p\rangle$

$g_T = \langle n|\bar{u}\sigma_{\mu\nu}d|p\rangle$
Neutron Beta Decay

§ Experiments measure the total neutron decay rate

\[ \frac{d\Gamma}{dE} \propto F(E_e) \left[ 1 + a \frac{p_e \cdot p_{\nu}}{E_e E_{\nu}} + A \frac{\vec{\sigma}_n \cdot \vec{p}_e}{E_e} + b \frac{m_e}{E_e} + \left( B_0 + B_1 \frac{m_e}{E_e} \right) \frac{E_{\nu}}{E_e} + \ldots \right] \]

_within the Standard Model, \( a \) and \( A \) are \( O(10^{-1}) \), \( B_0 \) is \( O(1) \), \( b \) and \( B_1 \) are \( O(10^{-3}) \)
BSM Interactions

Theoretically, $b$ and $B_1$ are related to new interactions: the scalar and tensor

$$H_{\text{eff}} = G_F \left( J_{V-A}^{\text{lept}} \times J_{V-A}^{\text{quark}} + \sum_i \epsilon_i^{\text{BSM}} \hat{O}_i^{\text{lept}} \times \hat{O}_i^{\text{quark}} \right)$$

$$\hat{O}_S = \bar{u}d \times \bar{e}(1 - \gamma_5)\nu_e \quad \rightarrow \quad g_S = \langle n|\bar{u}d|p\rangle$$

$$\hat{O}_T = \bar{u}\sigma_{\mu\nu}d \times \bar{e}\sigma^{\mu\nu}(1 - \gamma_5)\nu_e \quad \rightarrow \quad g_T = \langle n|\bar{u}\sigma_{\mu\nu}d|p\rangle$$

$\epsilon_S$ and $\epsilon_T$ are related to the masses of the new TeV-scale particles

... but the unknown coupling constants $g_{S,T}$ are needed

These are nonperturbative functions of the neutron structure, described by quantum chromodynamics (QCD)
§ Given precision $g_{S,T}$ and $b, B_1$, we can predict possible new particles.

$\varepsilon_S$ and $\varepsilon_T$

Give the scale of particles mediating new forces.

$g_{S,T} = 1$

UCNs by 2013

Precision LQCD input ($m_\pi \approx 140$ MeV, $a \to 0$)

$\varepsilon_S$ and $\varepsilon_T$
Current Constraints

§ Given precision $g_{S,T}$ and $O_{BSM}$, predict new-physics scales

$O_{BSM} = f_0(\varepsilon_{S,T} g_{S,T})$

Nuclear Exp.

Model input

$\varepsilon_{S,T} \propto \Lambda_{S,T}^{-2}$

Nuclear beta decays
- $0^+ \rightarrow 0^+$ transitions
- $\beta$ asym in Gamow-Teller $^{60}\text{Co}$
- polarization ratio between Fermi and GT in $^{114}\text{In}$
- positron polarization in polarized $^{107}\text{In}$
- $\beta-\nu$ correlation parameter $a$
§ Given precision $g_{S,T}$ and $O_{BSM}$, predict new-physics scales

\[ O_{BSM} = f_0(\varepsilon_{S,T} g_{S,T}) \]

Model input

\[ \varepsilon_{S,T} \propto \Lambda_{S,T}^{-2} \]

LANL UCN neutron decay exp’t

\[
d\Gamma \propto F(E_e) \left[ 1 + \left( B_0 + B_1 \frac{m_e}{E_e} \right) \frac{\bar{n}_e \bar{p}_\nu}{E_\nu} + \cdots \right]
\]

Expect by 2013:

\[
|B_1 - b|_{BSM} < 10^{-3} \\
|b|_{BSM} < 10^{-3}
\]

Similar proposal at ORNL by 2015
Crucial Role of Theory

§ Given precision $g_{S,T}$ and $O_{BSM}$, predict new-physics scales

New UCN Exp.

$O_{BSM} = f_0(\varepsilon_{S,T} g_{S,T})$

Precision LQCD input

$(m_\pi \to 140$ MeV, $a \to 0)$

$\varepsilon_{S,T} \propto \Lambda_{S,T}^{-2}$

LANL UCN neutron decay exp’t

$$d\Gamma \propto F(E_e) \left[ 1 + \left( B_0 + B_1 \frac{m_e}{E_e} \right) \frac{\vec{\sigma}_n \vec{p}_\nu}{E_\nu} + \cdots \right]$$

Expect by 2013:

$|B_1 - b|_{BSM} < 10^{-3}$

$|b|_{BSM} < 10^{-3}$

Similar proposal at ORNL by 2015
§ Constraints from high-energy experiments?
LHC current bounds and near-term expectation

Estimated though effective $L$

$$L = -\frac{\eta_S}{\Lambda_S^2} V_{ud} \bar{u}d (\bar{e}P_L \nu_e)$$
$$- \frac{\eta_T}{\Lambda_T^2} V_{ud} \bar{u} \sigma^{\mu\nu} P_L d (\bar{e}\sigma_{\mu\nu} P_L \nu_e)$$

Looking at high transverse mass in $e\nu + X$ channel

Compare with $W$ background

Estimated 90% C.L. constraints on $\varepsilon_{S,T} \propto \Lambda_{S,T}^{-2}$

HWL, 1112.2435; 1109.2542
T. Bhattacharyya et al, 1110.6448
§ Lattice uncertainties:

- Statistical noise
- Unphysical scales $a, L$
- Extrapolation to $M_\pi$

§ Computational costs

- Scaling: $a^{-(5-6)}, L^5, M_\pi^{-(2-4)}$

§ Most major 2+1-flavor gauge ensembles: $M_\pi < 200$ MeV

- Now including physical pion-mass ensembles

§ Charm dynamics: 2+1+1-flavor gauge ensembles

- MILC (HISQ), ETMC (TMW)

§ Pion-mass extrapolation $M_\pi \rightarrow (M_\pi)_{\text{phys}}$

(Bonus products: low-energy constants)
§ Difficulties in Euclidean space

§ Exponentially worse signal-to-noise ratios

Consider a baryon correlator \( C = \langle O \rangle = \langle qqq(t) \bar{q}\bar{q}\bar{q}(0) \rangle \)

Variance (noise squared) of \( C \propto \langle O^\dagger O \rangle - \langle O \rangle^2 \)

What you want: \( N \quad \pi \quad \pi \quad \pi \)

What you get: \( N^\dagger \quad \pi \quad \pi \quad \pi \)
The Trouble with Nucleons

§ Difficulties in Euclidean space

§ Exponentially worse signal-to-noise ratios

☞ Consider a baryon correlator \( C = \langle O \rangle = \langle qqq(t) \bar{q}\bar{q}\bar{q}(0) \rangle \)

☞ Variance (noise squared) of \( C \propto \langle O^\dagger O \rangle - \langle O \rangle^2 \)

What you want: \( \pi \) \( \pi \) \( \pi \) \( \pi \)

What you get: \( N \) \( N^\dagger \) \( N \) \( N^\dagger \)

☞ Signal falls exponentially as \( e^{-m_N t} \)

☞ Noise falls as \( e^{-(3/2)m_\pi t} \)

☞ Problem worsens with:
  - increasing baryon number
  - decreasing quark (pion) mass
Targeted statistical on charges: 2% estimation

Other sources of error: 8% (NPR + continuum extrap. + mixed sys.)

g_s would be most challenging
§ Chiral extrapolation suffers biggest systematic uncertainty
   ✂ Huge obstacle to precision measurement
   ✂ Issues: validity of XPT over the range of pion masses used, convergence, SU(3) vs. SU(2) flavor, etc.

§ Remaining systematics: finite-volume effects
   ✂ Seems pretty well controlled
     \[ m_\pi L \geq 4 \]
   RBC/UKQCD arXiv:1003.3387[hep-lat]

§ Solutions
   ✂ Include the physical pion mass in the calculation
   ✂ Extrapolate to the continuum limit (use multiple \( a \))
§ Plan

☞ MILC HISQ (140-MeV \( \pi \) available)
☞ Jan. 1 – Jun. 30, 2011 (USQCD)
☞ Apr. 1, 2011 (Teragrid 8M SUs)
☞ Jul. 1– (USQCD), Dec. (NERSC)
☞ 10% within 2 years
☞ O(1%) in 3–4 years

| \( a / \text{fm} \) | \( m_1 / m_s \) | Lattice | \( m_{\pi L} \)  | \( m_{\pi} \text{(MeV)} \) |
|-----------------|--------------|----------|---------------|------------------|
| 0.15 | 1/5 | \( 16^3 \times 48 \)  | 3.78 | 306  |
| 0.15 | 1/10 | \( 24^3 \times 48 \)  | 3.99 | 217  |
| 0.12 | 1/5 | \( 24^3 \times 64 \)  | 4.54 | 309  |
| 0.12 | 1/10 | \( 32^3 \times 64 \)  | 4.29 | 221  |
| 0.12 | 1/27 | \( 48^3 \times 64 \)  | 4.08 | 140  |
| 0.09 | 1/5 | \( 32^3 \times 96 \)  | 4.50 | 314  |
| 0.09 | 1/10 | \( 48^3 \times 96 \)  | 4.77 | 222  |
| 0.09 | 1/27 | \( 64^3 \times 96 \)  | 3.66 | 129  |
| 0.06 | 1/5 | \( 48^3 \times 144 \) | 4.51 | 315  |
| 0.06 | 1/10 | \( 64^3 \times 144 \) | 4.25 | 227  |
Excited-State Contamination

§ Explore optimal smearing parameters and multiple source-sink separations

§ Analyze the three-point function including excited state
Excited-State Contamination

§ Explore optimal smearing parameters and multiple source-sink separations (0.96—1.44fm)

§ Analyze the three-point function including excited state

![Graphs showing data analysis for excited-state contamination](chart)
§ Our preliminary numbers and world $N_f = 2 + 1$ values

\( a = 0.06, 0.09, 0.12 \) fm, 220- and 310-MeV pion
§ Our numbers (unrenormalized) and other $N_f=2+1$ values
$x = 0.06, 0.09, 0.12$ fm, 220- and 310-MeV pion
§ Our numbers (unrenormalized) and other $N_f=2+1$ values
§ $g_S$ becomes much noisier at light pion mass

![Graph showing the relationship between $g_S^{2+1f}$ and $m_{\pi}^2 (\text{GeV}^2)$.

- HSC anisoCl(2011)
- Mixed(2011)
- PNDME

Saul D. Cohen — Project-X Physics Study 2012

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§ Tensor charge: the zeroth moment of transversity

≲ Probed through SIDIS: $g_T(Q^2=0.8 \text{ GeV}^2) = 0.77^{+0.18}_{-0.24}$

≲ Model estimate 0.8(4)

§ Scalar charge $\langle n|\bar{u}d|p\rangle$  Prior model estimate: $1 \gtrsim g_S \gtrsim 0.25$

\[ g_{T}^{\text{LQCD}} = 1.05(4) \quad m_{\pi}^2 \left( \text{GeV}^2 \right) \quad g_{S}^{\text{LQCD}} = 0.79(9) \]

HWL, 1112.2435; 1109.2542
Summary

The name of the game is precision

§ The precision frontier enables us to probe BSM physics
   ☝ Opportunities combining both high- (TeV) and low- (GeV) energy
§ Exciting era using LQCD for precision inputs from SM
   ☝ Increasing computational resources and improved algorithms
   ☝ Enables exploration of formerly impossible calculations
§ Necessary when experiment is limited
§ Bringing all systematics under control