Neutron-antineutron oscillations

Enrico Rinaldi

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Neutron-Antineutron Oscillation Matrix Elements with Domain Wall Fermions at the Physical Point

Sergey Syritsyn, Michael Buchoff, Chris Schroeder, Joe Wasem
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[PoS, Lattice 2012, 128]

[PoS, Lattice 2015, 132]
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Neutron-antineutron matrix elements from lattice QCD with physical pions

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5 Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

[in preparation]
Motivations

- Oscillations of neutral particles can teach us about new physics
  
  | K^0 | B^0 | ν | N |
  | CP  | CP  | m_ν | ? |

- Neutron oscillations violate baryon number (B) and baryon-lepton (B-L) number:
  \[ \Delta B = 2 \]
  \[ \Delta L = 0 \]

- Contrary to proton decay, scale of new physics is within reach and can explain baryogenesis

- Future experiments have the potential for a great increase in sensitivity to oscillations (ESS and DUNE)
Synopsis of oscillations

\[ \mathcal{M}_B = \begin{pmatrix} m_n - \vec{\mu}_n \cdot \vec{B} - i\lambda/2 & \delta m \\ \delta m & m_n + \vec{\mu}_n \cdot \vec{B} - i\lambda/2 \end{pmatrix} \]

\[ \langle n | \mathcal{M}_B | \bar{n} \rangle = \delta m \]

Coupling between neutrons and anti-neutrons
Synopsis of oscillations

\[ \mathcal{M}_B = \begin{pmatrix} m_n - \bar{\mu}_n \cdot \vec{B} - i\lambda/2 & \delta m \\ \delta m & m_n + \bar{\mu}_n \cdot \vec{B} - i\lambda/2 \end{pmatrix} \]

\[ \langle n | \mathcal{M}_B | \bar{n} \rangle = \delta m \]

Energy difference \( \Delta E \)

Coupling between neutrons and anti-neutrons
Synopsis of oscillations

\[ \mathcal{M}_B = \left( \begin{array}{cc} m_n - \vec{\mu}_n \cdot \vec{B} & i\lambda/2 \\ \delta m & m_n + \vec{\mu}_n \cdot \vec{B} - i\lambda/2 \end{array} \right) \]

Energy difference \( \Delta E \)

Coupling between neutrons and anti-neutrons

\[ \langle n | \mathcal{M}_B | \bar{n} \rangle = \delta m \]

\[ P(n(t) = \bar{n}) = \left( \frac{2\delta m}{\Delta E} \right)^2 \sin^2 \left( \frac{\Delta E \cdot t}{2} \right) e^{-\lambda t} \]
Synopsis of oscillations

\[ M_B = \begin{pmatrix} m_n - \vec{\mu}_n \cdot \vec{B} & -i\lambda/2 \\ \delta m & m_n + \vec{\mu}_n \cdot \vec{B} - i\lambda/2 \end{pmatrix} \]

Coupling between neutrons and anti-neutrons

\[ \langle n | M_B | \bar{n} \rangle = \delta m \]

Energy difference \( \Delta E \)

\[ P(n(t) = \bar{n}) = \left( \frac{2\delta m}{\Delta E} \right)^2 \sin^2 \left( \frac{\Delta E \cdot t}{2} \right) e^{-\lambda t} \]

quasi-free limit \( |\Delta E| t \ll 1 \)
Synopsis of oscillations

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\[ P(n(t) = \bar{n}) = [(\delta m) t]^2 e^{-\lambda t} = (t/\tau_{n-\bar{n}})^2 e^{-\lambda t} \]
Synopsis of oscillations

\[ \mathcal{M}_B = \begin{pmatrix} m_n - \mu_n \cdot \vec{B} & i\lambda/2 \\ \delta m & m_n + \mu_n \cdot \vec{B} - i\lambda/2 \end{pmatrix} \]

Energy difference \( \Delta E \)

\[ \langle n | \mathcal{M}_B | \bar{n} \rangle = \delta m \]

Coupling between neutrons and anti-neutrons

\[ P(n(t) = \bar{n}) = \left( \frac{2\delta m}{\Delta E} \right)^2 \sin^2 \left( \frac{\Delta E \cdot t}{2} \right) e^{-\lambda t} \]

quasi-free limit \( |\Delta E| t \ll 1 \)

\[ P(n(t) = \bar{n}) = [(\delta m) t]^2 e^{-\lambda t} = \left( t / \tau_{n-\bar{n}} \right)^2 e^{-\lambda t} \]

\[ \tau_{n-\bar{n}} = \frac{1}{\delta m} \]
New physics

- Relate the off-diagonal matrix element of the effective Hamiltonian to the microscopic operator
  \[
  \langle n | \mathcal{H}_{\text{eff}} | \bar{n} \rangle = \frac{1}{\Lambda_{\text{BSM}}^5} \sum_i c_i \langle n | \mathcal{O}_i | \bar{n} \rangle
  \]

- The process is mediated by an effective 6-quark operator of dimension 9
  \[
  \delta m = \langle n | \int d^3x \mathcal{H}_{\text{eff}} | \bar{n} \rangle \sim c \frac{\Lambda_{\text{QCD}}^6}{\Lambda_{\text{BSM}}^5}
  \]

- The mass scale for new physics is obtained roughly as $\Lambda_{\text{BSM}} \sim 100 - 1000$ TeV

[Phillips et al., 1410.1100]
## Operators

<table>
<thead>
<tr>
<th>Chiral Basis</th>
<th>Fixed-Flavor Basis</th>
<th>Chiral Tensor Structure</th>
<th>Chiral Irrep</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_1$</td>
<td>$\mathcal{O}_{RRR}^3$</td>
<td>$\mathcal{D}_R \mathcal{D}_R^{+} T^{AAS}$</td>
<td>$(1_L, 3_R)$</td>
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<tr>
<td>$Q_2$</td>
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<td>$Q_4$</td>
<td>$4/5 \mathcal{O}<em>{RRR}^2 + 1/5 \mathcal{O}</em>{RRR}^1$</td>
<td>$\mathcal{D}_R^{33} + T^{SSS}$</td>
<td>$(1_L, 7_R)$</td>
</tr>
<tr>
<td>$Q_5$</td>
<td>$\mathcal{O}_{RLL}^1$</td>
<td>$\mathcal{D}_R^{-} \mathcal{D}_L^{++} T^{SSS}$</td>
<td>$(5_L, 3_R)$</td>
</tr>
<tr>
<td>$Q_6$</td>
<td>$\mathcal{O}_{RLL}^2$</td>
<td>$\mathcal{D}_R^{3} \mathcal{D}_L^{3+} T^{SSS}$</td>
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<tr>
<td>$Q_7$</td>
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Experimental searches

- free neutrons: $\tau_{n-\bar{n}} = (\delta m)^{-1}$
  - prepare cold neutrons
  - free propagation in vacuum
  - detector to look for multiple pions after annihilation

- bound neutrons: $\tau_A \propto (\delta m)^{-2} \rightarrow R_A \tau_{n-\bar{n}}^2$
  - large amount of nuclei in underground detector
  - irreducible atmospheric neutrino background

[Phillips et al., 1410.1100]
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\[ \tau \nu = \frac{1}{\Delta m^2} \]

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---

Almost background free sensitivity \( \propto N_n(t^2_{obs}) \)

Nuclear suppression factor due to different nuclear potential can be improved with particle tracking

[Phillips et al., 1410.1100]
Super-K
\[ \tau_{n-\bar{n}} > 2.8 \times 10^8 \, s \]

ILL
\[ \tau_{n-\bar{n}} > 0.86 \times 10^8 \, s \]

SNO
\[ \tau_{n-\bar{n}} > 1.2 \times 10^8 \, s \]
Lattice details

- Configurations and propagators from RBC/UKQCD
  [RBC/UKQCD, 1411.7017]

- Møbius Domain Wall fermions

- Physical pion mass

- $48^3 \times 96$ with $a=0.123$ fm

- 30 independent configs.
Lattice details

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\[\text{chiral} \quad \text{no extrapolation}\]
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  \( 48^3 \times 96 \) with \( a = 0.123 \) fm

- 30 independent configs.

  +AMA to increase stat.
Methodology

- Calculate 3-point function of operator inserted at time $\tau$
- Only 1 propagator (point-to-all) needed: fix source at $\tau = 0$
- All time separations accessible
  \[ t_f - \tau \quad \tau - t_i \]
- Only point insertions, but point and gaussian smeared nucleons

\[
\langle 0 \mid N(t_f) \mathcal{O}_i(\tau) \bar{N}(t_i) \mid 0 \rangle
\]

\[
C_{PP,PS}^{2pt}(t_f, t_i) \quad C_{PP,PS,SP,SS}^{3pt}(t_f, \tau, t_i)
\]
Signals: $C_{PP,PS}^{2pt}(t_f, t_i)$
Signals: $C_{PP,PS}^{2pt}(t_f, t_i)$
Signals: $C_{PP,PS}^{2pt}(t_f, t_i)$ described well by a 2-state fit
Signals: $C^{3pt}_{PP,PS,SP,SS}(t_f, \tau, t_i)$
Signals: \( C_{PP,PS,SP,SS}^{3pt}(t_f, \tau, t_i) \)
Signals: $C_{PP,PS,SP,SS}^{3pt}(t_f, \tau, t_i)$

initial analysis: fitting only SS 3pt with a 2-state fit
Outlook

- Non-perturbative renormalization to scales above the hadronic world already exists
  [Syritsyn et al., PoS, Lattice 2015, 132]

- Perturbative renormalization to the scale of new physics already exists
  [Buchoff & Wagman, 1506.00647]

- More statistics (configurations and propagators) already exists: can reduce errors below 20%

- Excited state analysis almost finalized
  [Syritsyn et al, in preparation]
Summary

- Improvement of the experimental limits on oscillations is expected in the next decade $\tau_{n-\bar{n}} > 10^{10} \text{ s}$

- New EFT approaches connecting new physics to nuclear matrix elements are in progress: need precision to compare to experiments [Grojean et al., 1806.00011]

- Fully non-perturbative estimates of nuclear ME are needed for translating experimental bounds to constraints on new physics models

- LQCD calculations are now replacing old and uncertain MIT bag model estimates for nuclear ME
Part of this research was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344 and supported by the LLNL LDRD “Illuminating the Dark Universe with PetaFlops Supercomputing” 13-ERD-023.

Computing support comes from the LLNL Institutional Computing Grand Challenge program and from the USQCD Collaboration, which is funded by the Office of Science of the US Department of Energy.

We are indebted to Norman Christ, Bob Mawhinney, Taku Izubuchi, Oliver Witzel, and the rest of the RBC/UKQCD collaboration for access to the physical point, domain-wall lattices and propagators used in this work.
Fit functions

\[ C_{\text{2pt}}^{2pt}(t_f, t_i) = |A_0|^2 e^{-M_0(t_f-t_i)} + |A_1|^2 e^{-M_1(t_f-t_i)} \]

\[ C_{\Gamma}^{3pt}(t_f, \tau, t_i) = |A_0|^2 \langle 0 | \mathcal{O}_\Gamma | 0 \rangle e^{-M_0(t_f-t_i)} + |A_1|^2 \langle 1 | \mathcal{O}_\Gamma | 1 \rangle e^{-M_1(t_f-t_i)} + A_0 A_1^* \langle 0 | \mathcal{O}_\Gamma | 1 \rangle e^{-M_0(\tau-t_i)} e^{-M_1(t_f-\tau)} + A_0^* A_1 \langle 1 | \mathcal{O}_\Gamma | 0 \rangle e^{-M_1(\tau-t_i)} e^{-M_0(t_f-\tau)}, \]
Renormalization

\[ u(p) \rightarrow u(-p) \]
\[ d(p) \rightarrow d(-p) \]

\[ \mathcal{O}_I \]

\[ p^2 \ [\text{GeV}^2] \]

[Syritsyn et al., PoS, Lattice 2015, 132]
[Syritsyn et al, in preparation]
Renormalization

\[ u(p) \quad d(p) \quad \overline{d}(p) \]

\[ p^2 \text{ [GeV}^2 \text{]} \]

\[ (RRR)_1 \]

\[ R_1(LL)_0 \]

\[ (RR)_1L_0 \]

\[ (RR)_2L_1 \]
Preliminary results (do not quote)

<table>
<thead>
<tr>
<th>Operator</th>
<th>Bare Matrix Element</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_1$</td>
<td>$1.19(42)(15) \times 10^{-5}$</td>
</tr>
<tr>
<td>$Q_2$</td>
<td>$-2.80(56)(31) \times 10^{-5}$</td>
</tr>
<tr>
<td>$Q_3$</td>
<td>$2.04(35)(26) \times 10^{-5}$</td>
</tr>
<tr>
<td>$Q_6$</td>
<td>$0.0366(105)(152) \times 10^{-5}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chiral Basis</th>
<th>RI-MOM, 2 GeV</th>
<th>$\overline{\text{MS}}$, 10 TeV</th>
<th>RI-MOM, 2 GeV MIT Bag 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_1$</td>
<td>-60.5(7.5)</td>
<td>-33.1(4.1)</td>
<td>6.8</td>
</tr>
<tr>
<td>$Q_2$</td>
<td>88.8(10.2)</td>
<td>133(15.2)</td>
<td>8.1</td>
</tr>
<tr>
<td>$Q_3$</td>
<td>-58.7(5.4)</td>
<td>-53.7(4.9)</td>
<td>7.2</td>
</tr>
<tr>
<td>$Q_4$</td>
<td>0</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>$Q_5$</td>
<td>8.84 (1.04)</td>
<td>2.11(0.25)</td>
<td>3.2</td>
</tr>
<tr>
<td>$Q_6$</td>
<td>-2.12 (0.26)</td>
<td>-0.506(0.062)</td>
<td>3.2</td>
</tr>
<tr>
<td>$Q_7$</td>
<td>1.41 (0.17)</td>
<td>0.337(0.041)</td>
<td>3.2</td>
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[Syritsyn et al, in preparation]