Joseph Wasem
Lawrence Livermore National Laboratory

Nuclear Parity Violation from Lattice QCD

LLNL-PRES-490285

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.
Faster computers & better algorithms
- Precise calculations
- Use of GPUs
- Calculation of poorly known observables

Nuclear Parity Violation
Discovered in 1957 in beta and mu decays
Weak force effect mediated by $W$ or $Z$
Tested extensively in leptonic and semileptonic processes
What about the quarks?
- Neutral current interactions
- NN interactions are the only answer
- Hadronic PV much harder
**NN Parity Violating Interaction**

- Predicted 1958, confirmed experimentally 1967
- PV interaction $\sim 0.002$ fm
- PV NN force dominated by long-range interactions
  - meson exchange models
  - weak physics encapsulated in weak vertex
- PV signal is dwarfed by QCD: $\Theta(10^{-7})$
  - Experimental ways around this
  - Large uncertainties and many-body effects
Extracting $h_{\pi NN}$

- NPDGamma (LANL & ORNL) want to extract at the 20% level
- Lattice QCD needs to match this precision...
Anisotropic Clover Lattices

- Aniso parameters generated by Jlab
- $20^3 \times 256$ generated at LLNL on BGL
- $a_x \sim 0.125$ fm, $a_t \sim 0.036$ fm
- $m_\pi \sim 390$ MeV
- 1150 thermalized configs.

Good lattices for 1^{st} attempt
Avoid quark loop contributions, use N* interpolator

\[ m_\pi = 0.06901 \pm 0.00004 \]

\[ m_p = 0.20489 \pm 0.00040 \]

\[ m_{N\pi} = 0.27882 \pm 0.00107 \]
Quark & Hadron Level PV Operators

- Quark operators known at W, Z scale

\[ L_{PV} = - \frac{G_F \sin^2(\theta_w)}{3\sqrt{2}} \sum_i C_i(\lambda, m_c, m_b) \theta_i \]

- Operator coefficients are scale-dependent
Quark & Hadron Level PV Operators

- Quark operators known at W, Z scale

\[ L_{PV} = - \frac{G_F \sin^2(\theta_W)}{3\sqrt{2}} \sum_i C_i(\lambda, m_c, m_b) \theta_i \]

- Operator coefficients are scale-dependent
Quark & Hadron Level PV Operators

- Quark operators known at $W, Z$ scale

$$L_{PV} = -\frac{G_F \sin^2(\theta_W)}{3\sqrt{2}} \sum_i C_i(\lambda, m_c, m_b) \theta_i$$

- Operator coefficients are scale-dependent

- Match to dominant LO hadron interaction: $h_{\pi NN}$

$$L_{weak}^{\Delta I=1} \sim h_{\pi NN} \left( \bar{p}n\pi^+ - \bar{n}p\pi^- \right)$$
The Weak Operator

- 8 operators, Fierz transformation eliminates 1
- Three ways to put together:
  - Connected:
  - Quark Loop:
  - Disconnected:
Disconnected diagrams are zero in isospin limit.

\[ \left[ q \Gamma_{A,V} q \right] \left[ u \Gamma_{A,V} u - d \Gamma_{A,V} d \right] \]
Quark loop diagrams require point-to-all propagator on operator timeslice

- Different from normal 3 point calcs.
The Weak Operator

- Quark loop diagrams require point-to-all propagator on operator timeslice
  - Different from normal 3 point calcs.
  - Restricted to single point on ops timeslice.
  - Sample all spatial points over full calc.
The Weak Operator

- Connected diagrams cannot use sequential props
- Can use previous propagators
- 3 propagators/meas:
  - Light quark from srce
  - Light/strange quark for quark loop and to sink
Calculation Requirements

- $O(100k)$ measurements for anisotropic clover
  - $O(700k)$ 3 pt. contractions, one set for each operator
    - ~10 CPU-minutes per contraction
  - $O(300k)$ propagators
    - $O(10M)$ CPU-hours with normal inverters
    - Use of GPUs needed to make significant progress
The Edge Cluster

- 200 nodes
  - 12 CPUs/node (Intel Westmere)
  - 2 GPUs/node (NVIDIA Tesla M2050)
  - 96 GB/node
  - 3 GB/GPU

- Turns 10M CPU-hours into 100k GPU-hours
- Running only standby, still able to achieve 100k measurements in ~4 months.
- Thanks to BU and Balint Joo for GPU code help...
Matrix Element Extraction

- Standard 3 pt ratio function (source at t=0):

\[
R_{A\rightarrow B} = \frac{C_3(t_{snk}, t_{ops})}{C_B(t_{ops})} \left[ \frac{C_A(t_{snk} - t_{ops})C_B(t_{snk})C_B(t_{ops})}{C_B(t_{snk} - t_{ops})C_A(t_{snk})C_A(t_{ops})} \right]^{1/2}
\]

- \(C_A\) the 2 pt. function for state A
- \(C_B\) the 2 pt. function for state B
- \(t_{ops} = 24\)
  - Chosen to be well into the proton/π-π plateau
Matrix Element Extraction

\[ R_{p \rightarrow n\pi} = \frac{C_3(t_{snk}, t_{ops})}{C_{n\pi}(t_{ops})} \left[ \frac{C_p(t_{snk} - t_{ops}) C_{n\pi}(t_{snk}) C_{n\pi}(t_{ops})}{C_{n\pi}(t_{snk} - t_{ops}) C_p(t_{snk}) C_p(t_{ops})} \right]^{1/2} \]

\[ = \left( h_{\pi NN} + \Delta E \cdot h_a \right) + Z \left( h'_{\pi NN} + \Delta E' \cdot h'_a \right) e^{-\delta(t_{snk} - t_{ops})} \]

- Remove inserted energy contribution.

\[ L_{PV} \big|_{p \rightarrow n\pi} = -L_{PV} \big|_{n\pi \rightarrow p}, \quad \Delta E \big|_{p \rightarrow n\pi} = -\Delta E \big|_{n\pi \rightarrow p} \]

\[ \Rightarrow M = \frac{1}{2} \left( R_{p \rightarrow n\pi} - R_{n\pi \rightarrow p} \right) = h_{\pi NN} + Zh'_{\pi NN} e^{-\delta(t_{snk} - t_{ops})} \]
Matrix Element Extraction

\[ M_i = \frac{1}{2} \left( R_{p \rightarrow n\pi} - R_{n\pi \rightarrow p} \right) = h_{\pi NN} + Z_i h'_{\pi NN} e^{-\delta(t_{snk} - t_{ops})} \]

- Use matrix-prony methods with SS & SP meas. to remove (or lessen) excited states

\[ \frac{aM_{SS} + bM_{SP}}{a + b} = h_{\pi NN} \]

- Can do same thing for PP & PS
- Must rotate on sink, as source is “frozen”
Results

$h^{1}_{\pi NN}(\theta_{con}) = (1.394 \pm 0.563^{+0.138}_{-0.017}) \times 10^{-7}$

$h^{1}_{\pi NN}(\theta_{con}) = (1.069 \pm 0.669^{+0.153}_{-0.014}) \times 10^{-7}$
Results

- Connected diagrams only!

\[ h_{\pi NN}(\theta_{\text{con}}) = (1.232 \pm 0.437^{+0.146}_{-0.016}) \times 10^{-7} \]
Contraction Improvements

- Need better way to do contractions for quark loop contributions
  - Similar to disconnected diagrams in scope
- Can we emulate sequential propagator method to get full spatial data?
Use set of interpolating operators

- Analytically does spin components (i.e. faster contractions)
- Increased statistics (more operator combos)
- 6 operators, $2 \times 3 \times 3 = 18$ combinations
Conclusions

- First calculation
  - Obtains non-zero answer consistent with experiment
  - Missing several important contributions...
- Need to Extract More
  - Longer run time
  - ORNL GPU Machine?
- Need to Extract More with Less
  - Better contractions