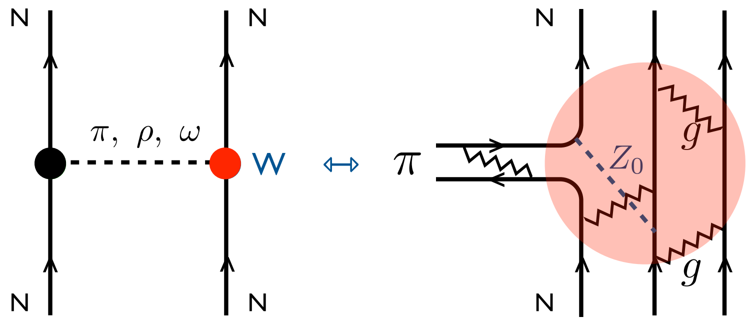
Hadronic Parity Violation and Lattice QCD

CalLat Collaboration

Abstract: The strangeness-conserving neutral weak current has not been isolated experimentally, but is the subject of a major experiment now underway on the cold neutron beamline of the SNS. This interaction dominates the parity non-conserving (PNC) long-range weak interaction between nucleons. A CalLat goal is to evaluate the isovector πNN coupling corresponding to this interaction as well as the isotensor ρNN coupling: without the latter result, the most significant experiment in the field, the asymmetry in p+p scattering, loses impact. We describe our global analysis motivating this work, a recent Lattice QCD calculation of the PNC πNN coupling, and plans to improve this result and undertake similar LQCD calculations for the isotensor ρNN coupling.

Hadronic PNC

The elementary couplings of weak currents to quarks are determined by the Standard Model (SM). The strangeness-conserving hadronic weak interaction is only accessible through nucleon-nucleon and nuclear experiments, with PNC the filter that allows one to identify the weak interaction despite the dominance of the strong interaction (SI). However the SI acting in the nucleon will alter couplings. A key goal of the field has been to isolate the neutral current contribution and to evaluate associated SI renormalization effects.

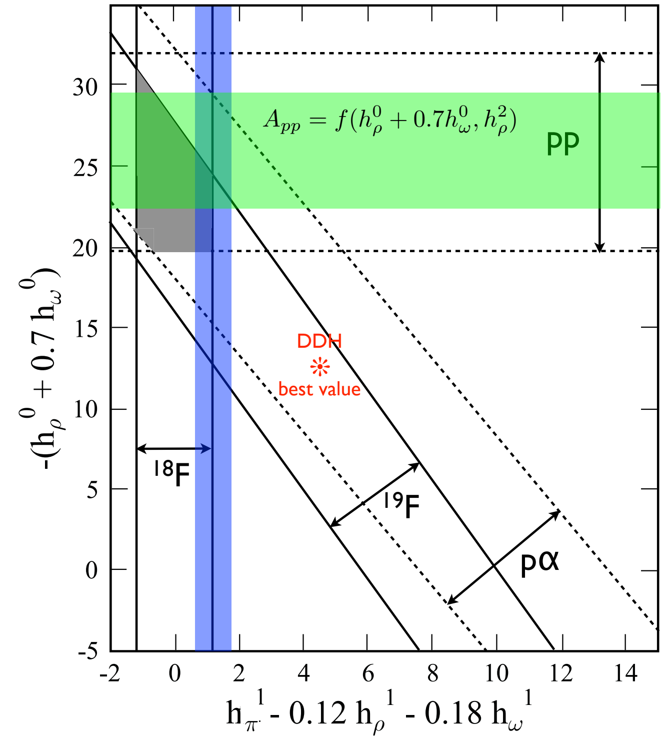


The low-energy PNC NN interaction can be viewed as arising from meson exchange, with one strong and one weak vertex, with the latter modified by SI effects. A controlled calculation of the PNC meson-nucleon coupling in lattice QCD would provide the basic information needed to calculate PNC observables for more complex nuclear systems in perturbation theory.

This program is timely because of the ongoing experimental effort at the cold neutron beamline at the SNS to measure the PNC asymmetry in n+p → D+γ, which is expected to be at the level of one part in 10^8. This observable isolates the isovector pion-exchange contribution to NN PNC, a channel that should be dominated by the so-far unobserved hadronic neutral current. There are strong indications from PNC measurements in ^{18}F that the PNC neutral current effects are much smaller than expected. Initial lattice QCD results confirm this result. Thus the SNS experiment with need to reach its design sensitivity to see a signal.

Global PNC Analysis

There are four sets of interpretable measurements constraining PNC: the longitudinal asymmetries for p+p and p+α, the photon circular polarization in ^{18}F, and the photon asymmetry in ^{19}F. For some time it has been believed that these measurements lead to an inconsistent description of PNC. The situation greatly improved in a recent global analysis in which identified and corrected inconsistencies in previous analyses of the p+p measurements.



The analysis shows that the isovector pion coupling h_π is suppressed by at least a factor of three and the isoscalar ρ/ω coupling is enhanced by a factor of two relative to SM estimates (DDH best values). The factor-of-six difference in the ratio of isospin I=0 to I=1 couplings is superficially reminiscent of the ΔI=1/2 rule describing the analogous I=1/2 to I=3/2 ratio in strangeness-changing weak hadronic decays.

First LQCD Efforts on PNC

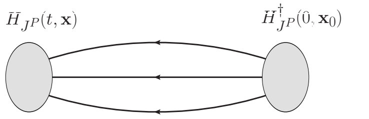
The blue band on the global analysis graph shows the first LQCD calculation of h_π^1. The contractions performed by Wasem required approximately 6 months of running on LLNL's Edge GPU cluster. This initial calculation was performed on a single ensemble of n_f=2+1 dynamical anisotropic clover gauge configurations for a lattice of dimension 2.5 fm, spacing 0.123 fm, and pion mass 389 MeV, and includes only connected diagrams. The error band is an estimate of the systematic uncertainties associated with these lattice parameters. The result is consistent with the ^{18}F bound.

PNC Lattice QCD: Future Work

The improvement of the h_π^1 calculation and the extension of the work to the isotensor PNC ρNN coupling h_ρ^2 is one of the initial goals of the CalLat Collaboration. An LQCD calculation of h_π^1 at nearly physical pion masses with the inclusion of quark-loop contributions appears within reach, given new machines such as LLNL's 5-pflop Vulcan, Titan and Oak Ridge and Edison at NERSC. h_ρ^2 contributes to the precisely measured p+p asymmetry but is otherwise unconstrained by experiment. Consequently the p+p band between the dashed horizontal lines in the figure has been enlarged due to "marginalizing" against h_ρ^2. A lattice calculation of h_ρ^2, which requires no costly quark-loop contributions, could narrow the band to the area indicated in green.

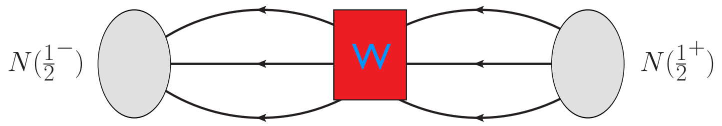
Improving the Lattice Calculation

In order to improve the calculation of h_π^1 and perform the calculation of h_ρ^2, new techniques must be implemented. The interpolating fields can be projected onto definite quantum numbers, such as total angular momentum, J, and parity, P, but they couple to all the eigenstates of QCD with those definite quantum numbers.

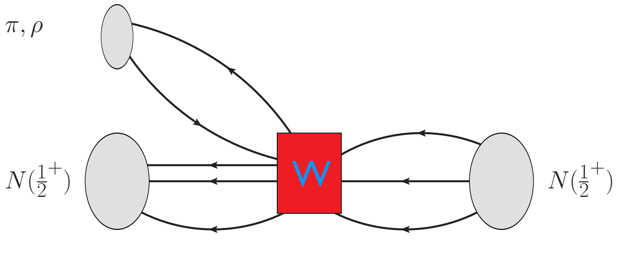


$$
\begin{aligned}
C_{J^P}(t) &= \sum_{\mathbf{x}} \langle 0 | H_{J^P}(t,\mathbf{x}) H^\dagger_{J^P}(0,\mathbf{x}_0) | 0 \rangle \\
&= \sum_{\mathbf{x}} \langle 0 | H_{J^P}(t,\mathbf{x}) \sum_n |n\rangle \langle n | H^\dagger_{J^P}(0,\mathbf{x}_0) | 0 \rangle \\
&= \sum_n A_{n,J^P}\ e^{-E_n^{J,P} t}
\end{aligned}
$$

The first calculation (Wasem) used a simple interpolating field for the Nπ final state:



In order to improve the coupling to the matrix element of interest, we need to construct interpolating fields which more closely resemble the state of interest. A large basis of such operators will allow us to "filter" the excited states out of the calculation. To accomplish this goal, we will implement several new features into the calculation:



1) a large basis of interpolating fields ("wave-functions"), used to perform a variational analysis
2) disconnected quark-diagrams connected to the source or sink operators
3) fast calculation of all the necessary quark level Wick-contractions (tensor-contractions)

Conclusions: Implementation of these new methods will be more computationally demanding, but will allow for significantly improved calculations of Parity-Non-Conserving processes in low-energy nucleon interactions. The first step will allow us to compute the Isospin=2 coupling, which we plan to accomplish within a year. Steps 2 and 3 are necessary for the Isospin=1 coupling and more complex matrix elements.