Lattice QCD calculation of $n - \bar{n}$ transition amplitudes

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In searches for physics beyond the Standard Model, violation of baryon number conservation is an essential direction. The absence of experimental data on baryon number violation has no known particle physics principle beneath it and, on the other hand, would be difficult to understand given the observed baryon asymmetry of the Universe. Two important hypothetic processes may signal the baryon number violation, one is the proton decay changing the baryon number by $\Delta B = 1$ and the other is neutron-antineutron oscillation, $\Delta B = 2$. A number of new experiments with stored neutrons and cold neutron beams have been proposed to look for $n - \bar{n}$ transitions. These experiments have potential to improve current bounds on such by a few orders of magnitude and, as a result, significantly improve bounds on beyond the Standard Model physics.

Bounds on new physics, however, will strongly depend on uncertainties arising from hadron physics. Symmetries of the Standard Model constrain the form of six-quark effective interaction that may turn the neutron into the antineutron[1,2]),

$$\mathcal{O}_{1\,\chi_1\{\chi_2\chi_3\}} = T^{s}_{ijklmn}\left[u^{iT}_{\chi_1}\mathcal{C}u^{j}_{\chi_1}\right]\left[d^{kT}_{\chi_2}\mathcal{C}d^{l}_{\chi_2}\right]\left[d^{mT}_{\chi_3}\mathcal{C}d^{n}_{\chi_3}\right],$$
$$\mathcal{O}_{2\,\{\chi_1\chi_2\}\chi_3} = T^{s}_{ijklmn}\left[u^{iT}_{\chi_1}\mathcal{C}d^{j}_{\chi_1}\right]\left[u^{kT}_{\chi_2}\mathcal{C}d^{l}_{\chi_2}\right]\left[d^{mT}_{\chi_3}\mathcal{C}d^{n}_{\chi_3}\right],$$
$$\mathcal{O}_{3\,\{\chi_1\chi_2\}\chi_3} = T^{a}_{ijklmn}\left[u^{iT}_{\chi_1}\mathcal{C}d^{j}_{\chi_1}\right]\left[u^{kT}_{\chi_2}\mathcal{C}d^{l}_{\chi_2}\right]\left[d^{mT}_{\chi_3}\mathcal{C}d^{n}_{\chi_3}\right],$$

where $\chi_{1,2,3} = L, R$ denote chiral components of the quark fields and $T^{s,a}_{ijklmn}$ are symmetric and antisymmetric color tensors. Symmetry relations reduce the number of independent operators to 14, of which only four are $SU(2)_L$ symmetric. So far, the corresponding $n - \bar{n}$ amplitudes $\langle\bar{n}|\mathcal{O}|n\rangle$ have been computed only using MIT Bag Model[1]).

Advances in lattice QCD, a numerical approach to quantum field theory, only recently made it possible to calculate such amplitudes directly. Preliminary results by our collaboration are shown on Fig. 1, where they are compared to the Bag Model calculation[1]). We perform calculations on an anisotropic QCD lattices with size $\approx (2.5\,\mathrm{fm})^3 \times 9\,\mathrm{fm}$ and lattice spacing $a = 0.123\,\mathrm{fm}$. $N_f = 2 + 1$ "light" and strange quark fields are simulated fully dynamically with $\mathcal{O}(a^2)$-improved Wilson action on anisotropic lattice[3]) such that the mass of the pion is $m_\pi \approx 390\,\mathrm{fm}$. The overall normalization of our lattice QCD results is not known yet; however, the stochastic accuracy of individual amplitudes is surprisingly good. In addition, despite the fact that we use unphysical heavy quarks so that $m_\pi \approx 390$ MeV, the relative magnitude and signs agree very well with the Bag Model.

Currently, our group is working on renormalizing these effective operators on a lattice in order to find their overall factor. The next step is to repeat the calculation using chirally symmetric quarks at the physical point, which are currently possible due to advances in lattice QCD. It is possible that renormalization, operator mixing and light quarks will change the "hierarchy" of operators in Fig. 1 considerably. In addition, the chiral symmetry-violating action we are currently using may lead to additional operator mixing, and chirally-symmetric quark action may be necessary to obtain correct results.

We are excited to report that, as our preliminary results demonstrate, lattice QCD will likely remove hadron physics uncertainties from interpreting future $n - \bar{n}$ oscillation searches.

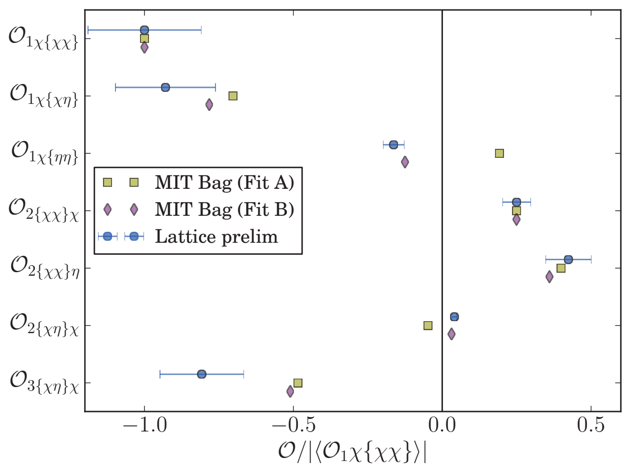

Fig. 1. Comparison of "hierarchy" of matrix elements of 7 different $n - \bar{n}$ operators, $(\{\chi, \eta\} = \{R, L\}$ or $\{L, R\})$, in our calculation to the Bag Model[1]). Since the lattice renormalization factors are not yet known, we normalize results by $|\mathcal{O}_{1\chi\{\chi\chi\}}|$ in each case in order to compare relative size of the matrix elements.

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