Standard-model prediction for direct CP violation in $K \to \pi\pi$ decays

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A first-principles calculation of the amount of direct CP-violation in the Standard Model has long been a goal of the particle physics community. Utilizing recent computational and theoretical advances, the RBC & UKQCD collaborations have performed the first realistic determination of this quantity.

Direct CP-violation occurs in the decays of neutral kaons into two pions and is parameterized by a quantity ϵ', which is very small ($\mathcal{O}(10^{-6})$) in the Standard Model and therefore offers a sensitive probe for the new physics expected to account for the preponderance of matter over antimatter in the observable universe.

In $K \to \pi\pi$ decays, the final $\pi\pi$ state can have isospin quantum numbers of either $I = 2$ or 0, and ϵ' manifests as a difference in the complex phases of the corresponding amplitudes, A_2 and A_0. These amplitudes receive significant contributions from hadronic-scale QCD effects, necessitating the use of lattice QCD. Such calculations require powerful computers, in our case the IBM Blue Gene/Q supercomputers at RBRC, ANL and Edinburgh University, and would otherwise take several thousand years on a typical laptop.

Our most recent determination of A_2[1)] was performed with large physical volumes, physical pion masses and energy-conserving kinematics. We measured A_2 with two different lattice spacings, thereby enabling a continuum limit to be performed. We obtained a very precise result: $\mathrm{Re}(A_2) = 1.50(4)(14) \times 10^{-8}$ and $\mathrm{Im}(A_2) = -6.99(20)(84) \times 10^{-13}$, where the errors are statistical and systematic, respectively. The latter arise mainly from the use of perturbation theory in the renormalization of the underlying lattice matrix elements, and can be reduced by improved perturbative calculations or by renormalizing at higher energies.

Calculating A_0 is significantly more challenging, requiring novel techniques for statistical error reduction and for measuring with energy-conserving kinematics. Our ground-breaking calculation, reported in Physical Review Letters[2)], is the first *ab initio* determination of A_0 with controllable errors. The calculation was performed on a single lattice with a somewhat coarse lattice spacing but a large physical volume, resulting in controlled finite-volume errors (∼7%) but relatively large discretization errors (∼12%). Nevertheless the largest systematic errors are again associated with the perturbative truncation in the renormalization factors (∼15%) and Wilson coefficients (12%). We are presently working to raise the renormalization scale in order to reduce these errors.

As part of the calculation we also measure the $I = 0$ $\pi\pi$-scattering phase-shift at the physical kaon mass,

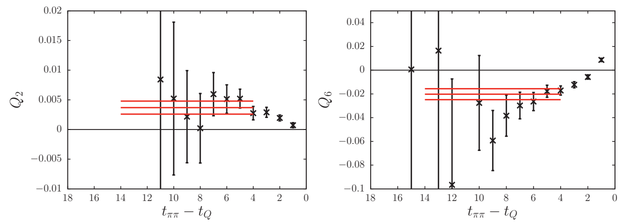

Fig. 1.: The Q_2 and Q_6 three-point functions, plotted in lattice units as functions of $t_{\pi\pi} - t_Q$, with the time dependence removed. The horizontal lines show the central value and errors.

for which we obtain $\delta_0 = 23.8(4.9)(1.2)^\circ$, which is roughly 2.7σ smaller than phenomenological expectations[3,4)]. This is possibly due to the existence of excited-state contamination hidden by the rapidly diminishing signal-to-noise ratio; more statistics are needed to confirm this hypothesis.

For the $I = 0$ $K \to \pi\pi$ amplitude, we obtained

$$\mathrm{Re}(A_0) = 4.66(1.00)(1.26) \times 10^{-7}\ \mathrm{GeV} \tag{1}$$
$$\mathrm{Im}(A_0) = -1.90(1.23)(1.08) \times 10^{-11}\ \mathrm{GeV} \tag{2}$$

where the errors are statistical and systematic, respectively. Our value for $\mathrm{Re}(A_0)$ agrees with the experimental value of $3.3201(18) \times 10^{-7}$ GeV and serves as a test of our method. $\mathrm{Im}(A_0)$ was heretofore unknown.

In Fig. 1 we plot the matrix elements Q_2 and Q_6 which comprise the dominant contributions to the real and imaginary parts of A_0, respectively.

Combining our lattice values for $\mathrm{Im}(A_2)$ and $\mathrm{Im}(A_2)$ with the more precise experimental determinations of the real parts, we obtain the following result.

$$\mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right) = \mathrm{Re}\left\{\frac{i\omega e^{i(\delta_2-\delta_0)}}{\sqrt{2}\varepsilon}\left[\frac{\mathrm{Im}A_2}{\mathrm{Re}A_2} - \frac{\mathrm{Im}A_0}{\mathrm{Re}A_0}\right]\right\} \tag{3}$$
$$= 1.38(5.15)(4.59) \times 10^{-4}\,, \tag{4}$$

which is 2.1σ below the experimental value $16.6(2.3) \times 10^{-4}$. While currently in broad agreement, the possibility of resolving a discrepancy is clear motivation for continued study. With continued effort we expect that a 10% error relative to the measured value of $\mathrm{Re}(\varepsilon'/\varepsilon)$ can be achieved within 5 years.

References

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