Excited Light Meson Spectroscopy from Lattice QCD

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Abstract. I report on recent progress in calculating excited meson spectra using lattice QCD. With novel techniques we can now extract extensive spectra of excited mesons with high statistical precision, including spin-four states and those with exotic quantum numbers. I review a new calculation of a spectrum of excited light isoscalar mesons, something that has up to now been a challenge for lattice QCD. The flavour content of these mesons has been determined, including the η-η' mixing angle, providing a window on annihilation dynamics in QCD. I will also comment on recent work which uses lattice QCD to map out the energy-dependent phase shift in $\pi\pi$ isospin-2 scattering and future applications of the methodology to the study of resonances and decays.

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Over the last few years there has been a resurgence of interest in meson spectroscopy lead by a wealth of data emerging from various experiments which has in turn fuelled much theoretical work. Experimental interest in the light meson sector continues with BESIII, COMPASS, KLOE, upcoming GlueX and CLAS12 (part of Jefferson Lab's 12 GeV upgrade), and the planned PANDA experiment. In particular, GlueX aims to perform a systematic investigation of the light meson spectrum in photoproduction and, notably, to produce mesons with exotic quantum numbers, such as $J^{PC} = 0^{+-}$, 1^{-+} and 2^{+-}. Such an exotic state signals physics beyond that of just a quark-antiquark pair, one possibility being a hybrid meson where the gluonic degrees of freedom play a nontrivial role.

An essential ingredient in testing QCD is the calculation of the spectrum of QCD and comparison against high quality experimental data. Lattice QCD provides a first-principles method for computing the spectrum and the calculation of the masses of the lowest-lying states has long been an important benchmark of such calculations. The Hadron Spectrum Collaboration has recently made significant progress in studying excited states using lattice QCD calculations, first testing techniques for extracting excited spectra [1] and radiative transition amplitudes [2, 3] with a quenched calculation in the charmonium sector, where there is a profusion of experimental data. These methods are now being applied to the light meson sector with an eventual aim of calculating excited and exotic meson photocouplings, relevant for, amongst other things, the GlueX experiment.

The first excited light meson spectra extracted in this programme of dynamical lattice QCD calculations, Refs. [4, 5], were of isovector ($I = 1$) mesons across all parity (P) and charge-conjugation parity (C) combinations. An important advance was the development of techniques which enable the continuum spin of mesons to be extracted in a reliable way at a single lattice spacing. The results include the most extensive excited spectrum ever obtained from a lattice QCD calculation, many states with exotic quantum numbers (0^{+-}, 1^{-+} and 2^{+-}) and, for the first time in such a calculation, spin-four (4^{++}, 4^{-+}, 4^{--}) states. Another highlight is a non-exotic vector hybrid state, identified by its large overlap with an operator proportional to the gluonic field-strength tensor, suggesting that the gluonic field plays a non-trivial role in this state. A more model-dependent analysis of the results, identifying the lightest hybrid supermultiplet, has been performed lately [6]. These techniques are also beginning to be applied to the charmonium sector [7].

More recently we have studied light isoscalar ($I = 0$) mesons [8]. Isoscalars, with no net flavour, can be constructed from quark-antiquark pairs of any flavour and even from states of pure glue. Studying the spectrum of isoscalars and the admixtures of the different flavour basis states in the physical states allows us to probe QCD annihilation dynamics. As described in Ref. [8], isoscalars are a challenging undertaking in lattice QCD and significant progress has been made through novel computational techniques and the use of Graphical Processing Units (GPUs) to perform some parts of the calculations.

An extensive spectrum was extracted [8] and suggests a phenomenology that is in quite good agreement with experiment. The pattern of η-η' observed in experiment is reproduced with a light-strange mixing angle, $42(1)^\circ$, in line with phenomenological determinations. In the vector channel the statistical precision is such that we determine the ω-ρ mass splitting to be $21(5)$ MeV. Another highlight is the first computation of a spectrum of isoscalar mesons with exotic J^{PC}; these appear at a comparable mass scale to the exotic isovectors. We observe that the majority of states we extract are close to ideally mixed with notable exceptions of η and η', the axial vector states (1^{++}), and the 1^{-+} exotics.

Apparently lacking in our extracted spectra are any clear signs of multi-particle states [5]. Scattering and resonance physics can not be calculated directly in an Euclidean theory, but there are approaches which enable indirect study, such as the method due to Lüscher [9] which enables elastic scattering phase shifts to be extracted from computations of multi-particle energy levels in a finite volume. The investigation of multi-particle states is thus essential in order to study scattering and resonance physics using lattice QCD.

As a first test of our techniques for extracting multi-particle energy levels, and hence the scattering phase shift, we studied the relatively simple non-resonant case of $\pi\pi$ scattering in isospin-2 (I=2) [10]. We demonstrated the feasibility of the framework by mapping out the energy-dependent S-wave phase shift and, for the first time in such a calculation, the D-wave phase shift. No significant pion mass dependence was observed below a scattering momentum of ~ 1 GeV and results were in reasonable agreement with experimental data at low scattering momentum.

These calculations lay the groundwork for using lattice QCD to investigate other physically more interesting meson-meson scattering channels which exhibit resonant behaviour. Inclusion of quark annihilation contributions (used in the extraction of the isoscalar meson spectrum) will enable us to study the $I = 1$ $\pi\pi$ sector where the ρ resonance is expected to appear as a rapidly rising phase shift. Some attempts in this direction have already been made [11, 12, 13, 14, 15] but these calculations only extract a limited number of phase shift points. A combination of techniques [16, 17], and the consideration of multi-meson states at overall non-zero momentum [18], will enable us to map out many points on the phase shift curve. Future work will explore a range of scattering channels in various partial waves, with particular emphasis on the determination of hadronic resonances.

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