Baryon Spectroscopy and Resonances

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A short review of current efforts to determine the highly excited state spectrum of QCD, and in particular baryons, using lattice QCD techniques is presented.

The determination of the highly excited spectrum of QCD is a major theoretical and experimental challenge. The experimental investigation of the excited baryon spectrum has been a long-standing element of the hadronic-physics program, an important component of which is the search for so-called "missing resonances", baryonic states predicted by the quark model based on three constituent quarks but which have not yet been observed experimentally. Should such states not be found, it may indicate that the baryon spectrum can be modeled with fewer effective degrees of freedom, such as in quark-diquark models. In the past decade, there has been an extensive program to collect data on electromagnetic production of one and two mesons at Jefferson Lab, MIT-Bates, LEGS, MAMI, ELSA, and GRAAL. To analyze these data, and thereby refine our knowledge of the baryon spectrum, a variety of physics analysis models have been developed at Bonn, George Washington University, Jefferson Laboratory and Mainz.

To provide a theoretical determination and interpretation of the spectrum, *ab initio* computations within lattice QCD have been used. Historically, the calculation of the masses of the lowest-lying states, for both baryons and mesons, has been a benchmark calculation of this discretized, finite-volume computational approach, where the aim is well-understood control over the various systematic errors that enter into a calculation; for a recent review, see [1]. However, there is now increasing effort aimed at calculating the excited states of the theory, with several groups presenting investigations of the low-lying excited baryon spectrum, using a variety of discretizations, numbers of quark flavors, interpolating operators, and fitting methodologies (Refs. [2–5]). Some aspects of these calculations remain unresolved and are the subject of intense effort, notably the ordering of the Roper resonance in the low-lying Nucleon spectrum.

Considerable progress towards the computation of the highly excited spectrum of QCD has been made within recent years through the development and employment of new (and old) theoretical techniques. The energies of excited states are determined from the exponential

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fall-off of two-point (Euclidean) correlation functions. The variational method (Refs. [6–8]), familiar as the Rayleigh-Ritz method in quantum mechanics, uses the time dependence of the eigenvalues of a matrix of such correlation functions to project optimally onto the excited levels. For the success of such a technique, a basis of interpolating operators is required that sufficiently spans the space. This basis of operators must respect the symmetries of the restricted cubic box used in lattice calculations. Here is where some knowledge of the underlying physics is valuable. Namely, QCD appears to prefer excited states with the quarks distributed non-locally within space. This in turn suggests an operator construction where the interpolating fields are also non-local in space and transform according to continuum symmetries like total angular momentum, parity, etc. These operators are then projected into forms that transform suitably on the cubic lattice.

The program outlined above has been underway for a few years now utilizing "anisotropic" lattices, with a finer temporal than spatial resolution, enabling the hadron correlation functions to be observed at short temporal distances and hence many energy levels to be extracted [9, 10]. Calculations have been carried out in quenched [11–13], with two dynamical quark flavors [14], and now two light and one dynamical strange quark flavors [15] where a recent calculation showed a glimpse of the excited Nucleon, Δ and Ω excited-state spectrum. Crucial to the success of this program has been the development of the "distillation" method which enables the efficient computation of correlators involving the non-local operators [16].

The development of new operator constructions that follow from continuum symmetry constructions has allowed, for the first time, the reliable identification of the spin and masses of the single particle spectrum at a statistical precision at or below about 1%. In particular, the excited spectrum of isovector as well as isoscalar mesons (Refs. [17–19]) shows a pattern of states, some of which are very familiar from the $q\bar{q}$ constituent quark model, with up to total spin $J = 4$ and arranged into corresponding multiplets. In addition, there are indications of a rich spectrum of exotic J^{PC} states, as well as a pattern of states interpretable as non-exotic hybrids [20]. The pattern of these multiplets of states, as well as their relative separation in energy, suggest a phenomenology of constituent quarks coupled with effective gluonic degrees of freedom. In particular, the pattern of these exotic and non-exotic hybrid states appears to be consistent with a bag-model description and inconsistent with a flux-tube model [20].

Recently, this lattice program has been extended into the baryon spectrum, revealing for the first time, the excited-state single-particle spectrum of Nucleons and Deltas along with their total spin up to $J = \frac{7}{2}$ in both positive and negative parity [21]. There was found a high multiplicity of levels spanning across J^P which is consistent with $SU(6) \otimes O(3)$ multiplet counting, and hence with that of the non-relativistic qqq constituent quark model. In particular, the counting of levels in the low lying negative parity sectors are consistent with the non-relativistic quark model and with the observed experimental states [22]. The spectrum observed in the first excited positive parity sector is also consistent in counting with the quark model, but the comparison with experiment is less clear with the quark model predicting more states than are observed experimentally, spurring phenomenological investigations to explain the discrepancies (e.g., see Refs. [22–28]).

In addition, it was found that each of the operators in the basis features prominently in some energy level, and there is significant mixing among each of the allowed multiplets, including the **20**-plet that is present in the non-relativistic qqq quark model, but does not appear in quark-diquark models [25], and in particular Ref. [29]. These results lend credence to the assertion that there is no "freezing" of degrees of freedom with respect to those of the non-relativistic quark model. These qualitative features of the calculated spectrum extend across all three of the quark-mass ensembles studied. Furthermore, no evidence was found for the emergence of parity-doubling in the spectrum [30].

It was argued that the extracted N and Δ spectrum can be interpreted in terms of single-hadron states, and based on investigations in the meson sector [18] and initial investigations of the baryon sector at a larger volume [21], little evidence was found for multi-hadron states. To study multi-particle states, and hence the resonant nature of excited states, operator constructions with a larger number of fermion fields are needed. Such constructions are in progress, and it is believed that the addition of these operators will lead to a denser spectrum of states. With suitable understanding of the discrete energy spectrum of the system, the Lüscher formalism [31] and its inelastic extensions [32] can be used to extract the energy dependent phase shift for a resonant system, such as has been performed for the $I = 1$ ρ system [33]. The energy of the resonant state is determined from the energy dependence of the phase shift. It is this resonant energy that is suitable for chiral extrapolations.

The extraction and identification of a highly excited, spin identified single-hadron spectrum, represents an important step towards a determination of the excited baryon spectrum. The calculation of the single-baryon spectrum including strange quarks is ongoing. Combining the methods developed paper with finite volume techniques for the extraction of phase shifts, future work will focus on the determination of hadronic resonances within QCD.

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References

[1] C. Hoelbling, PoS **LATTICE2010**, 011 (2010) [arXiv:1102.0410 [hep-lat]].

[2] M. S. Mahbub, W. Kamleh, D. B. Leinweber, A. O Cais and A. G. Williams, Phys. Lett. B **693**, 351 (2010) [arXiv:1007.4871 [hep-lat]].

[3] M. S. Mahbub, A. O. Cais, W. Kamleh, D. B. Leinweber and A. G. Williams, Phys. Rev. D **82**, 094504 (2010) [arXiv:1004.5455 [hep-lat]].

[4] G. P. Engel, C. B. Lang, M. Limmer, D. Mohler and A. Schafer [BGR [Bern- Graz-Regensburg] Collaboration], Phys. Rev. D **82**, 034505 (2010) [arXiv:1005.1748 [hep-lat]].

[5] N. Mathur *et al.*, Phys. Lett. B **605**, 137 (2005) [arXiv:hep-ph/0306199].

[6] C. Michael, Nucl. Phys. B **259**, 58 (1985).

[7] M. Luscher and U. Wolff, Nucl. Phys. B **339**, 222 (1990).

[8] B. Blossier, M. Della Morte, G. von Hippel, T. Mendes and R. Sommer, JHEP **0904**, 094 (2009) [arXiv:0902.1265 [hep-lat]].

[9] R. G. Edwards, B. Joo and H. W. Lin, Phys. Rev. D **78**, 054501 (2008) [arXiv:0803.3960 [hep-lat]].

[10] H. W. Lin *et al.* [Hadron Spectrum Collaboration], Phys. Rev. D **79**, 034502 (2009) [arXiv:0810.3588 [hep-lat]].

[11] S. Basak *et al.* [Lattice Hadron Physics Collaboration (LHPC)], Phys. Rev. D **72**, 074501 (2005) [arXiv:hep-lat/0508018].

[12] S. Basak *et al.*, Phys. Rev. D **72**, 094506 (2005) [arXiv:hep-lat/0506029].

[13] S. Basak *et al.*, Phys. Rev. D **76**, 074504 (2007) [arXiv:0709.0008 [hep-lat]].

[14] J. M. Bulava *et al.*, Phys. Rev. D **79**, 034505 (2009) [arXiv:0901.0027 [hep-lat]].

[15] J. Bulava *et al.*, Phys. Rev. D **82**, 014507 (2010) [arXiv:1004.5072 [hep-lat]].

[16] M. Peardon *et al.* [Hadron Spectrum Collaboration], Phys. Rev. D **80**, 054506 (2009) [arXiv:0905.2160 [hep-lat]].

[17] J. J. Dudek, R. G. Edwards, M. J. Peardon, D. G. Richards and C. E. Thomas, Phys. Rev. Lett. **103**, 262001 (2009) [arXiv:0909.0200 [hep-ph]].

[18] J. J. Dudek, R. G. Edwards, M. J. Peardon, D. G. Richards and C. E. Thomas, Phys. Rev. D **82**, 034508 (2010) [arXiv:1004.4930 [hep-ph]].

[19] J. J. Dudek, R. G. Edwards, B. Joo, M. J. Peardon, D. G. Richards and C. E. Thomas, Phys. Rev. D **83**, 111502 (2011) [arXiv:1102.4299 [hep-lat]].

[20] J. J. Dudek, arXiv:1106.5515 [hep-ph].

[21] R. G. Edwards, J. J. Dudek, D. G. Richards and S. J. Wallace, arXiv:1104.5152 [hep-ph].

[22] K. Nakamura *et al.* [Particle Data Group], J. Phys. G **37**, 075021 (2010).

[23] N. Isgur and G. Karl, Phys. Rev. D **19**, 2653 (1979) [Erratum-ibid. D **23**, 817 (1981)].

[24] S. Capstick and N. Isgur, Phys. Rev. D **34**, 2809 (1986).

[25] M. Anselmino, E. Predazzi, S. Ekelin, S. Fredriksson and D. B. Lichtenberg, Rev. Mod. Phys. **65**, 1199 (1993).

[26] L. Y. Glozman and D. O. Riska, Phys. Rept. **268**, 263 (1996) [arXiv:hep-ph/9505422].

[27] S. Capstick and W. Roberts, Prog. Part. Nucl. Phys. **45**, S241 (2000) [arXiv:nucl-th/0008028].

[28] J. L. Goity, C. Schat and N. N. Scoccola, Phys. Lett. B **564**, 83 (2003) [arXiv:hep-ph/0304167].

[29] D. B. Lichtenberg and L. J. Tassie, Phys. Rev. **155**, 1601 (1967).

[30] L. Y. Glozman, Phys. Lett. B **475**, 329 (2000) [arXiv:hep-ph/9908207].

[31] M. Luscher, Nucl. Phys. B **364**, 237 (1991).

[32] M. Lage, U. G. Meissner and A. Rusetsky, Phys. Lett. B **681**, 439 (2009) [arXiv:0905.0069 [hep-lat]].

[33] X. Feng, K. Jansen and D. B. Renner, Phys. Rev. D **83**, 094505 (2011) [arXiv:1011.5288 [hep-lat]].