HOW MANY N^* DO WE NEED?

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The development of new computational and theoretical tools have put the goal of reproducing the spectrum of baryon resonances from QCD within reach. However, the extraction of the properties of known states, in addition to the unambiguous identification of hereto unidentified resonances, is known to be a formidable task. A panel at the Baryon Resonance Analysis Group (BRAG) meeting during the N^*2002 conference addressed the following questions: How many N^* do we need to identify to convince ourselves that we understand the baryon spectrum from QCD? How far are we along the way to that goal? What properties must be extracted? Which partial waves play a special role? Discussing these questions in the context of lattice gauge calculations, the constituent quark model and unitarized chiral perturbation theory revealed that much greater efforts and more resources must be devoted to improve and expand present-day coupled-channels analyses that identify resonances and extract their properties.

1. Introduction

The nature of QCD confinement continues to provide an ongoing challenge to our understanding of soft QCD. Studying the baryon spectrum provides one avenue to learn more about this unique feature since the location and properties of excited states reflect the dynamics and relevant degrees of freedom within hadrons. Since the discovery of the first baryon resonance, the $\Delta(1232)$, over fifty years ago over 100 additional baryon resonances have been discovered, mostly in the up, down and strange quark flavor sector, along with a few charmed baryon excited states. Most of these states are broad, with widths of several hundred MeV, and therefore often overlap, even within a particular partial wave. This makes a unique identification of such resonances and the extraction of their properties nontrivial. Difficulties arise from the issue of appropriate background parametrizations, particularly in cases of small resonance signals sitting on top of a large background, and proper modelling of multi-particle final states. A comparison of recent coupled-channels analyses[1] comes to the conclusion that, for most cases, it is only the first excited state in each partial wave whose detailed properties (partial branching fractions, helicity amplitudes) are well known. Different analyses may agree on existence of the second state (in each partial wave) but not their decay widths, while there is no agreement even on the existence of a third state in a particular partial wave. Given the arduous nature of the task involved in these multi-channel analyses it is reasonable to address the question as to the final scope of this effort. In other words: How many resonances do we need to identify in order to convince ourselves that we have achieved a solid understanding of the baryon spectrum from QCD?

2. N^* on the Lattice

Recent lattice calculations have dispelled the myth that Euclidean-space Monte Carlo calculations cannot reliably extract the properties of excited states. For example, using the constrained-fitting method based on Bayesian priors, ref.[2] extracts the masses of the two lowest-lying states of octet and decuplet baryons for both parities. The calculation, using an improved gauge action and overlap fermions with the pion mass as low as 180 MeV, clearly observed the $1/2^+(1440)$ Roper state for the first time as the 1st-excited state of the nucleon from the standard interpolating field. Using correlator matrix techniques with a suitable number of reasonably well chosen operators, lattice simulations can indeed reveal information about higher-lying states in a given symmetry channel. Good progress is being made with respect to the inclusion of quark loops, eliminating the quenched approximation (improved staggered fermions, for example). Good progress is also being made in going to lighter and lighter quark mass. The treatment of unstable states with finite-box techniques is known in principle, but to date, no practical QCD applications have been achieved. Given currently available computer resources and algorithms, the extraction of a half-dozen or so low-lying narrow states in a given partial wave in the near-term future is not impossible. Certainly, this will be achieved in the quenched approximation. Whether or not this can be achieved with adequate precision in the presence of light-quark loops in the near future is much more speculative.

To convince ourselves that we satisfactorily understand the N^* spectrum, we need to study enough states to encompass all of the possible ways in which a baryon can be excited. There are quark vibrational and orbital excitations, spin excitations, and gluonic excitations. The possibility of multi-quark/molecular states must also be considered. Gluonic excitations are expected to be the highest, typically 1 GeV or more, and given that the lowest-lying state is 1 GeV, it seems reasonable to argue that mapping out the spectrum below 2 to 2.5 GeV in a few J^{PC} channels should suffice.

The Lattice Hadron Physics Collaboration (LHPC) centered at JLab and MIT is currently embarking on a large project to compute the N^* spectrum. It is likely that a reasonably accurate determination of a half-dozen states in several J^{PC} channels will be obtained in the quenched approximation for quark masses as light as 300 MeV by the end of this year. This must be contrasted with the results of state-of-the-art coupled-channel analyses[1] that, for a given partial wave, have been able to identify at most three excited states.

3. N^* in the Constituent Quark Model

In this approach the effective degrees of freedom are constituent quarks. Various QCD-based models disagree about the nature of the short-range, tensor and spin-orbit interactions between the quarks. There are now three competing models for the short-range interaction between light quarks in baryons: one-gluon exchange, instanton-induced forces, and Goldstone-boson Exchange (recently supplemented by scalar- and vector-meson exchange). Given the present state of knowledge of the baryon spectrum, all of these models can explain the data to some degree of accuracy. If our knowledge of the baryon spectrum could be improved to perhaps half a dozen excited states in selected partial waves, along with detailed decay properties, a much clearer picture of the quark-quark interactions in baryons would emerge.

In standard potential models such quarks are treated symmetrically, unlike those in quark-diquark and collective models. All symmetric quark models predict an overabundance of excited states relative to what has been observed until now: the well-known "missing" resonances. Diquark models predict fewer states by investing binding energy into a tightly bound isoscalar-scalar diquark which may make push some positive-parity excitations higher in mass, leading to a deficit of positive-parity states at intermediate (1700-2000 MeV) energies.

In addition to the as yet unidentified qqq states, confinement models using flux tubes predict the lightest $qqqg$ hybrid baryons with $P_{11}, P_{13}, P_{31}, P_{33}, F_{35}$ quantum numbers[3]. In addition, there are states such as the Roper resonance which are hard to explain as pure qqq excitations, and so may be mixed with hybrid baryons. All baryon hybrids have conventional quantum numbers, so if they are to be found, we need to find (as has now been convincingly done with the glueball and scalar-isoscalar mesons) a surplus of states above those required by qqq potential models, and extract their predicted anomalous decay properties. Thus, in order to establish the existence of hybrid baryons, coupled-channel analysis methods must be able to extract *all* qqq states in the energy range of about 1700-2200 MeV.

4. N^* in Unitarized Chiral Perturbation Theory

In contrast to lattice gauge and quark model calculations, chiral perturbation theory uses Lagrangians constructed from meson and baryon fields as the effective degrees of freedom. Incorporating chiral symmetry and its dynamical breaking, it organizes contributions in powers of hadron momenta and supplies higher-order Lagrangians that provide counter terms to regularize the theory. While χPT has proven to be successful in low-energy hadronic physics, its obvious shortcomings are its limited range of convergence and its inability to explicitly incorporate bound states and resonances. For example, in s-wave meson-baryon scattering in the $S = -1$ sector, the low-energy $K^- p$ scattering amplitude is dominated by the well-known $\Lambda(1405)$ resonance below threshold. It is thus reasonable to search for suitable re-summation techniques that can extent the range of applicability while still using the chiral Lagrangian. In NN-scattering, following the ideas of Weinberg, power counting is taken to be valid at the level of the potential term which is then inserted into a Lippman-Schwinger equation. Using similar techniques for meson-baryon scattering in a unitary coupled-channels framework leads to a good description of a wide range of scattering data.

In this context, it is important to distinguish between resonances that can be generated using only the lowest-order chiral Lagrangian and states that appear once higher-order terms are included[4]. Clearly, incorporating chiral Lagrangians to higher and higher orders would necessarily contain the entire meson and baryon spectrum since the chiral Lagrangians reflect the dynamics of QCD with effective degrees of freedom. Thus the question is not, if the entire N^* spectrum can be reproduced with chiral Lagrangians of higher order, but rather what order of the chiral Lagrangian amounts to an inclusion of the resonance dynamics. For meson-meson scattering it was shown[5] that the second-order Lagrangian represents the low-energy limit of vector-meson exchange. Therefore, the p-wave resonances ρ and K^* appear only when the second-order Lagrangian is used, while unitarization provides the proper width and extra dressing of the mass[6]. In contrast, the scalar resonances $\sigma(500)$, the $f_0(980)$, the $a_0(980)$, and the $\kappa(900)$ appear when only the lowest-order chiral Lagrangian is employed[6]. The latter states are commonly referred to as dynamically generated resonances since the poles appear solely as a consequence of final-state interaction.

In meson-baryon scattering, using the lowest-order chiral Lagrangian allows the dynamical generation of the entire $J^P = 1/2^-$ ground-state SU(3) octet of s-wave resonances[7,8], the $N^*(1535)$, the $\Lambda(1670)$, the $\Sigma(1620)$, and the $\Xi(1620)$, along with the SU(3) singlet $\Lambda(1405)$. Two of these states, the $\Sigma(1620)$ and the $\Xi(1620)$, are currently listed as 1-star states in PDG and are thus in dire need of confirmation. Interestingly, the lowest-lying $I = 3/2$ state, the $S_{31}(1620)$ resonance, which belongs to a different multiplet, is not reproduced in this approach, unless the $\pi N \to \pi\pi N$ channel is introduced, requiring additional assumptions that go beyond the lowest-order chiral approach. On the other hand, p- and d-wave resonances, such as the $P_{11}(1440)$ and $D_{13}(1520)$ states, appear only at the level of the second-order Lagrangian, in analogy to the ρ and K^* in meson-meson scattering. Recent further work[4] indicates that not one but two octets of $J^P = 1/2^-$ resonances are dynamically generated, raising the intruiging possibility that the observed $\Lambda(1405)$ actually consists of two nearby poles which have different couplings to the asymtotic states. Future work will also explore the feasibility of dynamically generating higher-lying N^* states from the interaction of low-lying resonances with mesons.

5. Outlook

A comprehensive understanding of the baryon spectrum also requires an explanation of the relationships between the various theoretical approaches. For example, should we expect resonances that are dynamically generated within UχPT, such as the $\Lambda(1405)$, to appear in quark model calculations? Or if such states are indeed due entirely to meson-baryon dynamics, should we expect to see them in quenched lattice results where quark loops are suppressed? Such questions have the potential to contribute significantly to our understanding of soft QCD.

In view of the above discussion it is clear that present partial-wave and coupled-channel analysis efforts[1] are only beginning to approach the level of sophistication required. In order to identify of the order of half a dozen excited states *for a given partial wave* and extract its properties, it is imperative to devote more effort and resources to this issue.

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