HADRON PHYSICS ON THE LATTICE

Group 3

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Abstract We review the aspects of Lattice QCD calculations pertaining to the understanding of the structure of hadrons and to the description of many-nucleon systems. The issues of direct interest to experimental programs involving French groups are underlined.

Keywords: Mesons; baryons; nuclei; lattice QCD

1. Overview

The study of hadron spectra and properties on the lattice aims at deriving them directly from QCD in a regime where quark and gluon interactions are nonperturbative. Lattice calculations are of great usefulness to establish the validity of phenomenological models or effective field theories and to compute the parameters of these models from QCD. In some situations, lattice results can be confronted directly to experiment and may suggest the need for new measurements.

The main limitations of lattice calculations of hadron properties stem from the unrealistically heavy u- and d-quark masses and from the quenched approximation, i.e. the neglect of polarization effects of sea quarks on the QCD vacuum.

The necessary extrapolation of lattice results to the light quark mass regime is nontrivial, broad (typically from $m_\pi \gtrsim 500$ MeV to the physical pion mass of 140 MeV) and of much dynamical interest. The light quark mass limit is indeed closely linked to the realization of the chiral symmetry of QCD whose spontaneously breaking in the vacuum generates light Goldstone bosons. The variation of hadron properties with quark masses is a reflection of the role of chiral symmetry in hadron spectra. A particular formulation of chiral perturbation theory enables the extrapolation of lattice QCD results to the light quark limit. This extrapolation procedure provides therefore a way of gaining a deeper understanding of the chiral structure of hadrons and highlights the importance of studying consistently hadron spectra involving light and heavy quarks. There are ongoing experimental programs aiming at finding new heavy quark baryons. Of particular interest is the recent discovery of doubly charmed baryons by the SELEX Collaboration. The quark mass dependence of the structure of mesons is also a topic of current investigation. New and narrow D_s mesons discovered last year by the BABAR, BELLE and CLEO Collaborations, fitting into a chiral multiplet structure, are especially challenging.

QCD lattice calculations are expected to shed light on the very nature of hadronic states, particularly on sea quark and gluon contributions to hadron wave functions (i.e. effects beyond the simple constituent quark model).

Sea quark contributions to hadronic states can be studied by comparing quenched lattice predictions to experimental spectra or dynamical calculations. Contrasted results are obtained in particular for baryonic states, suggesting that sea quark configurations are more important for some states than for others. Relating these findings to the success of the dynamical generation of specific baryon resonances by meson-nucleon scattering (through Bethe-Salpeter or Lippmann-Schwinger equations) is an open and very far reaching problem. The recent discovery of a pentaquark state in various experiments (LEPS, DIANA, CLAS, SAPHIR, HERMES) reinforces the motivation for investigating $q^4\bar{q}$ configurations on the lattice. Similar considerations apply to mesons, in particular those described as "molecular states" ($q^2\bar{q}^2$ bound systems) and generated dynamically through meson-meson dynamics.

Glueballs (hadronic states made from gluons) or hybrid mesons (mesons in which the gluonic degree of freedom is excited) have not yet been identified unambiguously in experiments. Quenched lattice calculations predict 0^{++}, 2^{++}, 0^{-+} and 1^{+-} glueballs. The lowest mass glueball (0^{++} state) appears around 1.5 GeV. Spin-exotic glueballs, which do not mix with $q\overline{q}$ states have been found high lying, around 4 GeV. The lowest spin-exotic hybrid meson is predicted around 2 GeV (in both quenched and full lattice QCD). The experimental identification of these states is made difficult by their mixing with other hadronic states and the lack of reliable studies of their decay channels. Preliminary searches should be extended in the future, in particular at the anti-proton facility planned at GSI-Darmstadt and at JLab-12 GeV.

The internal structure of hadrons in terms of quarks and gluons is investigated on the lattice through various operators besides the energy spectrum. Much of the work focuses on the nucleon structure but other states (belonging to the octet and decuplet baryons and to the meson octets) are beginning to be studied. Electromagnetic radii and form factors of nucleons provide the spatial distribution of charge and magnetization. The Feynman Parton Distribution Functions (PDFs) measure the probability of finding a parton with a given fractional longitudinal momentum in a fast nucleon. They were extensively studied at HERA by the H1, ZEUS and HERMES Collaborations. The Generalized Parton Distributions (GPDs) extend the Feynman Parton Distribution Functions to new kinematic dimensions. They provide additional insight into the behavior of the nucleon electromagnetic form factors, the origin of the nucleon spin and the transverse structure of the nucleon. Moments of GPDs are indeed related to the fractions of the nucleon spin carried separately by quarks and gluons and some kinematic limits of the GPDs determine the orbital angular momentum distributions. The GPDs can be probed in hard exclusive processes, such as Deeply-Virtual Compton scattering or similar processes in which the final photon is replaced by a meson. Programs to study Generalized Parton Distributions are developing at JLab, at HERA (HERMES) and are planned at CERN (COMPASS).

Lattice techniques can be introduced in the framework of the conventional nuclear and hadronic (constituent quark) physics, thus making a bridge between the lattice-QCD and the nuclear communities. The nucleon-nucleon interaction is based on one-boson exchange models which involve large coupling constants values. These models can be studied non-perturbatively on the lattice to check their ability to build bound states out of several nucleons.

2. Specific issues of interest to the French hadronic community

In the following subsections we select a few topics which might be more specifically pertinent to the French hadronic community, both experimental and theoretical, and briefly describe the status of lattice calculations of relevant quantities.

Presently, state-of-the-art lattice QCD calculations with dynamical quarks can only simulate a world with heavy pions, $m_\pi \approx 600 - 900$ MeV, on rather small lattice sizes of about 2.0 fm. Dedicated computers in the Teraflops range will be able to simulate QCD with two, and perhaps three, flavors of dynamical quarks on the same lattice sizes with a pion mass down to 400 MeV and sufficiently high statistics. The hope is that the a better control of chiral extrapolations will help reduce the systematic errors of current simulations. Chiral perturbation theory is largely studied in France, creating a particularly favourable situation for fruitful interactions with lattice QCD theorists.

Parton Distribution Functions

Parton Distribution Functions have been measured extensively at HERA (H1, ZEUS, HERMES). The H1 Collaboration involves a large French component from five laboratories: DAPNIA/SPP (CEA/Saclay), Centre de Physique des Particules de Marseille, Laboratoire de l'Accélérateur Linéaire d'Orsay, Laboratoire Leprince-Ringuet (Palaiseau), Laboratoire de Physique Nucléaire et de Hautes Energies (Universities Paris VI and VII).

The strangeness content of the proton is studied through measurements of the parity-violating electroweak asymmetry in the elastic scattering of polarized electrons from protons. French groups are involved in the HAPPEX experiment (Laboratoire de Physique Corpusculaire at Clermont-Ferrand, DAPNIA/SPhN at CEA/Saclay) and in the G0 experiment (Laboratoire de Physique Subatomique et de Cosmologie of Grenoble, Institut de Physique Nucléaire d'Orsay) at JLab. The Institut de Physique Nucléaire d'Orsay is also participating in the A4 experiment at Mainz.

The helicity contribution of gluons to the nucleon spin is presently investigated at CERN with the COMPASS detector, using the photon-gluon fusion process. The DAPNIA/SPhN

(CEA/Saclay) is strongly involved in this project. The COMPASS detector is also used to measure the transversity distribution of quarks inside the nucleon.

Theoretical work on these issues is done at the Centre de Physique Théorique de Marseille, Centre de Physique Théorique at Ecole Polytechnique, Laboratoire d'Annecy-Le-Vieux de Physique Théorique, Laboratoire de Physique Théorique d'Orsay.

- *Lattice calculations*

The moments $\langle x^n \rangle$ of the Parton Distribution Functions (PDFs) can be formally expressed, using the Operator Product Expansion (OPE), in terms of matrix elements of local operators between hadron states. These matrix elements can be calculated on the lattice.

A number of lattice calculations of PDF moments have been performed over the last decade in the quenched approximation, and more recently with dynamical quarks. A complete determination of lattice moments requires the calculation of the flavor singlet distribution. In the isoscalar case, one has to resolve the numerical problem of obtaining a reliable signal for the contribution from disconnected diagrams, for which some quark propagators must be known between every pair of lattice points. These so-called all-to-all propagators are much more computationally expensive than those that propagate from a fixed source and there have been only exploratory lattice calculations of the flavor singlet matrix elements. Fortunately, charge symmetry implies that the disconnected diagrams cancel rather precisely in the isovector PDFs. Connected isovector lattice moments can therefore be compared unambiguously with experiment.

Lattice simulations yield results for the moments of unpolarized isovector quark distributions in the nucleon which are typically 50% larger than experiment when extrapolated linearly in the quark mass. It has been argued that inclusion of a non-analytic dependence from chiral perturbation theory improves notably the level of agreement between the first three non-trivial moments of the isovector distribution of the nucleon and experiment. Data at smaller quark masses will be crucial to constrain the non-linear dependence.

Because of operator mixing, all calculations have so far been restricted to $n \leq 3$. Reconstructing the x dependence of PDFs from a finite number of moments is difficult. Only the reconstruction of isovector valence distributions has been attempted at present. To better constrain the functional form of the x-dependence of the PDFs, calculations of several higher moments (e.g. $n = 4, 5$) are necessary, especially for the polarized case. Such calculations would require the non-perturbative calculation of operator mixing coefficients.

Separations of the sea quark distributions from the total isoscalar PDFs, based on lattice data alone, have not yet been attempted. They will require an accurate knowledge of moments with $n > 3$ and evaluation of disconnected contributions.

Moments of polarized quark distributions in the nucleon can also be studied on the lattice. The $n = 0$ moment of the spin-dependent isovector PDF is equivalent to the axial charge g_A of the nucleon. There are some indications of significant finite volume effects in the calculation of $n = 0, 1$ and 2 moments of the helicity distributions of the nucleon. The $n = 0$ and 1 moments of the transversity distributions have also been calculated on the lattice.

Lattice calculations have also been extended to moments of the quark distributions in the pion. The same picture is found for the pion as for the nucleon. The PDFs of the pion have been measured down to very low x at HERA.

Generalized Parton Distributions

Generalized Parton Distributions are presently studied at JLab. The participating French groups come from the DAPNIA/SPhN (CEA/Saclay), the Laboratoire de Physique Corpusculaire at Clermont-Ferrand and the Institut de Physique Nucléaire d'Orsay. A first observation of Deeply-Virtual Compton Scattering has been obtained through a beam-spin asymmetry measurement in the $\vec{e}p \to ep\gamma$ using longitudinally polarized electrons at 4.25 GeV. An experiment devoted to Deeply Virtual ω-meson electroproduction is being analyzed and further Deeply-Virtual Compton Scattering experiments are planned in the coming years with 6 GeV electrons.

This is a long-term program. Measurements at higher energies are in prospect with the CEBAF 12 GeV upgrade after 2009 and the possibility of using the COMPASS spectrometer at CERN for Deeply-Virtual Compton Scattering is under investigation.

Deeply-Virtual Compton Scattering has also been studied at HERA by the H1, ZEUS and HERMES collaborations. The $ep \to ep\gamma$ reaction at HERA energies is used to produce initial photons of high virtualities (Q^2).

Theoretical work on Generalized Parton Distributions is pursued at DAPNIA/SPhN (CEA/Saclay), Centre de Physique Théorique at Ecole Polytechnique, Centre de Physique Théorique de Marseille and Laboratoire de Physique Théorique d'Orsay.

- *Lattice calculations*

The moments of the Generalized Parton Distributions are defined by the same local operators as the moments of the PDFs. Diagonal matrix elements of these operators measure the moments of the ordinary parton distributions in a hadron H. Off-diagonal matrix elements of these operators measure the moments of the GPDs and depend also upon the momentum transfer Δ between the hadrons H and H'. The zeroth moments of the GPDs are related to the electromagnetic Dirac and Pauli form factors. The first moments of the GPDs can be related to the nucleon matrix elements of the energy-momentum tensor.

Extracting moments of the nucleon GPDs is also possible from lattice simulations. There are however additional technical challenges in lattice calculations of the GPDs relative to the PDFs. The statistical noise increases with the order of the moments as with PDFs. But, in the case of GPDs, the noise of these moments must be compounded with the additional noise from the finite transfer Δ.

Estimates of the first three moments have recently been obtained in the "heavy pion world" presently accessible to full lattice QCD, both for the spin averaged and spin-polarized isovector GPDs in the proton.

Excited baryon spectrum and pentaquarks

Experiments dedicated to baryon resonance and pentaquark searches are pursued at various facilities. The French groups are participating in the programs involving photon and electron beams at JLab (CLAS detector) and at GRAAL (Grenoble). An original study aiming at determining the coupling of vector mesons to low-lying baryon resonances through their dilepton decay is planned at GSI, using the pion beam and the HADES detector. A group from the Institut de Physique Nucléaire d'Orsay is involved in this project.

The electron-proton collider HERA is a copious producer of both charm and anti-charm quarks, the dominant production mechanism being boson-gluon fusion. The spectroscopy of charmed baryons can be studied using the final states to which the quarks and anti-quarks hadronise. The H1 Collaboration has recently reported the first evidence for a baryon, $\theta_c^0(3099)$, with spin 1/2 or 3/2 and exotic quantum numbers in the charm sector.

Theorists are involved in studies of baryon properties at the Laboratoire de Physique Subatomique et de Cosmologie (Grenoble) and at the DAPNIA (CEA/Saclay).

- *Lattice calculations*

The quark model predicts many more excited states than are currently known. Experiments at Jefferson laboratory are trying to detect these “missing resonances”. If they keep escaping observation, it will become more and more plausible that some degrees of freedom are frozen in baryonic excitations. These issues can best be studied from Lattice QCD calculations.

Lattice QCD can also help solving the long-standing puzzle of the level order of the positive-parity excited nucleon, the Roper resonance $N'(1440)$, and the negative-parity nucleon $N^\star(1535)$. Recent systematic quenched calculations of the nucleon excited states in both parity channels reproduce the $N^\star$ state and have found that the N' is heavier than the $N^\star$ in the relatively heavy-quark mass region, in accordance to quark model predictions. They have also observed that, when using interpolating operators for a $J^P = (1/2)^+$ state built from three quarks, the signal for N' is much more difficult to extract. Moreover lattice results exhibit large finite size effects on the Roper state.

However hadronic physics at realistically light quark masses can differ significantly from that in the heavy pion regime. A suggestive hint at how level orderings may change is shown in Figure 1. The level switching between the $N^\star(1535)$ state and the Roper state has been observed in a very recent simulation using overlap fermions, a lattice discretization scheme which possess almost exact chiral symmetry at non zero lattice spacing and which allows quenched calculations with realistically light valence quark masses.

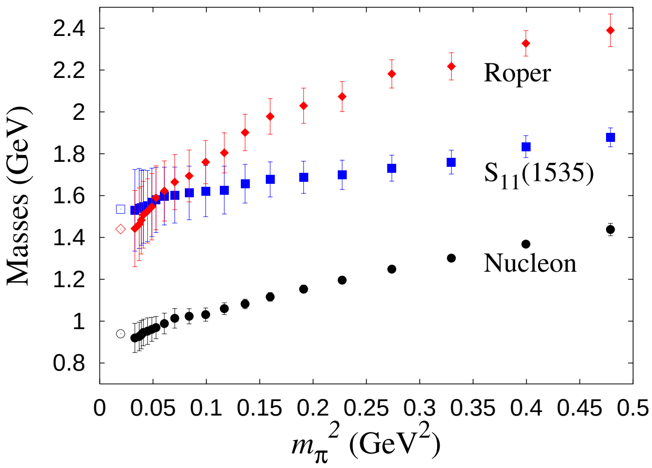

Figure 1. Quenched lattice calculation [7] of the masses of the nucleon, N'(1440) Roper, and $N^\star(1535)$ S_{11} resonances as a function of m_π^2. Experimental values are denoted by the open symbols.

Clearly the appropriate treatment of unstable resonance states on the lattice remains an important conceptual challenge. Extracting information on the lowest excited states of hadrons not only requires the use of more sophisticated interpolating operators and more advanced statistical techniques than for the fundamental states but is apparently very sensitive to chiral extrapolations.

Lattice QCD is also able to study the recently discovered $S = +1$ pentaquark $\theta^+(1540)$. There are several calculations with different interpolating operators of the pentaquark on the lattice. The difficulty is to separate out the S-wave KN scattering state. Quenched results seem to indicate that the J^P assignment of the $\theta^+(1540)$ is most likely $(1/2)^-$. However present-day calculations are done on rather small lattices ($L \approx 2.2$ fm), with rather heavy valence quark masses, and the systematic study of coupled channels has not yet been done.

Excited meson spectrum

Of particular interest in the meson sector is the recent discovery of narrow D_s mesons by the BABAR, BELLE and CLEO Collaborations, the $D_s^*(2317)$ and $D_s^*(2458)$. BABAR has a large French component: DAPNIA/SPP (CEA/Saclay), Laboratoire de Physique des Particules d'Annecy, Laboratoire Leprince-Ringuet (Palaiseau), Laboratoire de l'Accélérateur Linéaire d'Orsay, Laboratoire de Physique Nucléaire et de Hautes Energies (Universities Paris VI and VII).

Quark potential models had predicted that p-wave resonances should exist but they were expected to be heavy and rapidly decaying to a D-meson and a K-meson. The observed states are much lighter and narrower than these resonances.

- *Lattice calculations*

There have been a number of lattice QCD calculations of the spectrum of orbitally excited D_s mesons. Most of the calculations have been done in the quenched approximation in the static limit for the charm quark. Effects of the finite charm quark mass have only been investigated in the quenched approximation using lattice NRQCD or relativistic heavy quarks. Following the discoveries, there has been recent studies with two flavors of dynamical quarks and improved heavy quark action.

The lattice analyses do show a considerable spread in their predictions. More work is needed to exclude the interpretation of the experimental observations by exotic states.

Nuclear Physics ab initio

Lattice techniques are also applied to nuclear physics problems. They cover several aspects of the field and are expected to bring interesting results in the coming years.

On the one hand, they aim at obtaining the basic parameters of the pion-nucleon and nucleon-nucleon interaction in terms of the underlying field theory QCD alone. These parameters should be, in principle, all derived from the only input of quarks masses and α_s. Once mastered, these calculations could be extended to obtain less well-known meson-baryon and baryon-baryon coupling constants.

There have been two approaches to this problem. The first one, due to Lüscher, exploits finite size effects to extract scattering phase shifts. This method has been used successfully to study $\pi\pi$ scattering and attempts have been made to compute NN scattering parameters in lattice QCD. A second approach to the NN system on the lattice is to consider the simplified problem of two interacting heavy-light particles. Indeed the interactions between hadrons containing a static heavy quark exhibit most of the salient features of the nucleon-nucleon system. Exploratory lattice studies have already been made. The complexity of the LQCD calculations will limit these approaches to study the simplest hadronic and nuclear systems.

On the other hand lattice techniques can also be used to perform a non-perturbative study of the so-called one-boson exchange (OBE) models. These models constitute the basis of conventional nuclear physics but also of a large part of hadronic physics formulated in terms of constituent quarks (Q). Their starting point is an interaction lagrangian, involving coupling terms for the basic degrees of freedom, the nucleons or the quarks and the mesons. The Yukawa model of nuclear forces is the first historical example and has been progressively completed by other interaction lagrangians (pseudoscalar, pseudovector, vector,...) as required by NN phenomenology.

Since Weinberg's seminal work in 91, a new family of NN interactions based on chiral perturbation theory have been developed. They have in common to start with chiral invariant effective lagrangians for nucleons and pions and to provide, aside from NN interactions, a rational scheme for developing 3- and many-nucleon forces. The last decade has seen significant progress towards the formulation of such effective field theories (EFT), in particular at the theory group of the Institut de Physique Nucléaire d'Orsay.

In all these cases, the general philosophy in building nuclear potentials is to identify them to the Born amplitude of the corresponding lagrangian and, after some additional non-relativistic reductions, to insert them in an integral Lippmann-Schwinger like equation which sums the ladder terms.

Despite the fact that the interactions describing the NN and QQ physics use large coupling constant values, they have never been explored beyond the ladder approximation. Some work has been devoted to evaluating the cross- and box-diagrams which were found to be, as expected, of significant importance.

Renormalizable models with scalar and pseudo-scalar couplings have been considered on the lattice in the past twenty years, but always in the context of the Higgs mechanism to generate fermion masses. It is also possible to just consider the fermion interactions generated by the full OBE or χPT lagrangians, as the origin of the fermion (N or Q) interactions and to study the corresponding two- and many-body systems.

The relative simplicity of using OBE models compared to full QCD suggests that one might hope to calculate bound states of systems involving large numbers of fermions. There is an on-going project along these lines involving the theoretical group in the LPSC Grenoble with the active collaboration of the Paris lattice group.

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