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QCD and Hadron Structure

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I give a brief and selective overview of QCD as it pertains to determining hadron structure, and the relevant directions in this field for nuclear theory. This document is intended to start discussion about priorities, not end it.

1/29/95

1. QCD — what it is and what it isn't

Although QCD refers to a theory described in one line by the Lagrangian

$$\mathcal{L} = \sum_{f=\text{flavor}} \bar{q}_f[i(\not{D} - m_f]q_f - \frac{1}{4}G^a_{\mu\nu}G^{a\,\mu\nu} \tag{1.1}$$

in practice it is a very broad field of endeavor encompassing a myriad of subfields each with their own special techniques and jargon. Nevertheless, the study of QCD has its boundaries, and as the first speaker in this session on QCD I will preface my discussion with some remarks about what QCD is, and what it isn't.

What makes QCD so interesting and complicated is the running of the coupling constant from a perturbative regime at short distances, to a strongly coupled, nonperturbative regime at hadronic scales. In fact, the coupling constant g hidden in $\not{D}$ is not really a parameter at all, being transformed by dimensional transmutation into the fundamental scale of the theory, $\Lambda \simeq 200\,MeV$. Therefore studies of QCD divide into perturbative and nonperturbative approaches.

1.1. Nonperturbative approaches

The primary nonperturbative approach is numerical simulation of QCD on the lattice, both at zero and nonzero temperature. Such simulations have been improving steadily over the years and can be expected to play a big role in nuclear physics in the future. Of particular use will be the computations of QCD phase transition parameters relevant for RHIC, as well as strong interaction matrix elements, such as the $\pi - N$ sigma term, form factors, etc.

Recent work on instanton liquids by Shuryak collaborators, and by Negele and collaborators, is aimed at vastly simplifying the task of understanding nonperturbative QCD by identifying particular gauge field configurations that saturate the QCD vacuum, allowing one to avoid summing over degrees of freedom that in the end do not play a large role in vacuum and hadron structure.

1.2. Perturbative approaches

In QCD there are essentially four parameters in which one can profitably construct a sensible perturbative expansion. These are:

1. $1/\ln(\Lambda^2/Q^2)$, the α_s expansion in high energy collisions, or in heavy mesons such as the Υ;
2. $1/N_c$, where N_c is the number of colors ($N_c = 3$ in the real world);
3. m_f/Λ for low energy interactions; here $m_f = m_u, m_d, m_s$. This is called "chiral perturbation theory" since the quark masses measure explicit breaking of the approximate chiral symmetries of the QCD Lagrangian (1.1).
4. Λ/m_f for heavy flavors (b and c), useful for discussing transitions between hadrons both containing a heavy quark, such as $B \to D$ decays. The last three expansions are semi-phenomenological, since at each order in the expansion there are a finite number of coefficients that must be determined from experiment or lattice calculation. (Exceptions are matrix elements of symmetry currents, whose normalizations are known).

Finally, while the number of dimensions is not a very useful expansion parameter in QCD, lower dimension analogues of QCD can be instructive. 1+1 dimensional QCD can be exactly solved in the large N_c limit and clarifies the meaning of quark degrees of freedom in a confining theory; 2+1 dimensional QCD is directly relevant to 3+1 dimensional QCD at high temperature.

1.3. Problems mixing perturbative and nonperturbative physics: OPE and effective Lagrangians

Many problems in hadronic physics are amenable to a perturbative treatment up to a point, but still involve nonperturbative aspects. Three examples are deep inelastic scattering, weak decays, and $\pi\pi$ scattering at low energy. The useful tool that allows one to separate the physics into perturbative parts plus a finite number of nonperturbative matrix elements that must be determined phenomenologically — or on the lattice — is the operator product expansion (OPE), and the closely related technique of effective Lagrangians. In deep inelastic scattering the OPE allows one to compute the scaling of of the structure functions in an α_s expansion, even if the structure functions themselves are not computable in perturbative QCD. For weak decays the effective Lagrangian technique accounts for perturbative QCD corrections in scaling 4-quark operators down from the weak scale; in $\pi\pi$ scattering the effective Lagrangian approach allows one to do a chiral perturbation expansion in powers of the π momenta, introducing a few nonperturbative coefficients at each order in p_π that can be related to a number of processes. It is important to stress that while the approaches are partly phenomenological, they are still QCD with the number and nature of the undetermined matrix elements well understood.

1.4. What QCD is not

There are a number of models for QCD in the hadronic regime that are instructive but are not themselves QCD. Typically, these models incorporate the same symmetries as QCD, plus hopefully similar — but different and simpler — dynamics. As such, only "universal" properties that follow solely from symmetry are reliably related to QCD. Dynamical predictions should be treated as phenomenological, and if treated honestly, typically have a free parameter for every prediction (unless there is an implicit $1/N_c$ expansion). These models include:

1. the constituent quark model;
2. the bag model;
3. the Skyrme model;
4. the Nambu–Jona-Lasinio model;
5. "QCD-inspired" models of flux-tubes, monopole condensation, modified chromodielectric constant, modified quark propagator, truncated Schwinger-Dyson equations...

If used honestly these models have their place – particularly as bookkeeping techniques for symmetry properties — but all too often a small and incomplete set of parameters are kept, resulting in unreliable dynamical "predictions".

Initial harangue completed, I now turn to the topic of the talk: hadron structure. I am omitting discussion of topics of overlapping relevance involving QCD sum rules, lattice calculations, and light-cone QCD [1], which are all subjects of other talks at this Town Meeting.

2. QCD and hadron structure

2.1. Hadrons with charm and beauty

Recently there has been an explosion of theoretical work on hadrons with one heavy quark [2]. Weak decays of b hadrons into c hadrons can be studied in a $1/m_b$ and $1/m_c$ expansions of QCD, with a simultaneous expansion in α_s evaluated at the quark mass scale. In weak decays $b \to c$ the nonperturbative aspects of the hadronic transition is surprisingly parametrized by a single, normalized function of the hadron velocities, the Isgur-Wise function. Another significant result is that one can rigorously show that the inclusive decay rate in QCD for hadrons with a heavy quark is given by the leading parton model result, plus perturbative corrections of $\mathcal{O}(\alpha_s(M_Q))$, plus nonperturbative corrections of order Λ/M_Q, where M_Q is the heavy quark mass [3]. An important application of the heavy quark expansion is the extraction of the weak mixing angle V_{cb} and V_{ub} from B decays.

In a separate research direction, lattice studies of the J/Ψ and Υ spectra are competitive with LEP for determination of α_s, or equivalently, of the QCD scale Λ [4].

2.2. Hadrons with u, d, s quarks

The major tools here are the chiral Lagrangian and the large N_c expansion, often used simultaneously. I consider the most important recent advances to be:

1. Systematic inclusion of the decuplet in the chiral Lagrangian and its effects at one loop to renormalization of the baryon octet mass differences, magnetic moments, and axial currents, as well as the πN sigma term. Decuplet contributions are found to be important, improving agreement between experiment and theoretical results obtained by just including the baryon octet [5].
2. Inclusion of four-nucleon terms to the chiral Lagrangian and preliminary attempts to understand nuclear forces in a systematic chiral expansion. It may not work in the end, but it is ambitious and interesting [6].
3. Discussion of π and K condensation in the context of the $SU(3) \times SU(3)$ chiral Lagrangian, which suggest strangeness condensation at 3-4 times nuclear density, and

strangeness enhancement in heavy ion collisions [7]. None of the results in this field can yet be claimed to follow from QCD since they do not employ a consistent chiral expansion in the strange quark mass, but hopefully future progress can make the discussion more rigorous.

4. Large N_c analysis of meson - baryon interactions, which reveal the old $SU(6)$ spin-flavor symmetry to be a symmetry of QCD in the large-N_c limit. Similar analyses reveal that certain baryon mass and coupling relations only get corrections at order $1/N_c^2$. This recent result helps explain a number of the phenomenological successes of the constituent quark and Skyrme models [8].

2.3. Nucleon structure and strange matrix elements

When one looks at structure within a single nucleon, the most surprising feature is the result of SMC and SLAC experiments, which tell us that $\langle p|\bar{s}\gamma_\mu\gamma_5 s|p\rangle = -0.12\pm0.04\pm0.04$ [9]. (Old elastic νp scattering data gave the first indication for this matrix element being nonzero, and analysis of octet enhancement in hadronic weak decays of hyperons also suggests a large value for this matrix element). The dust has not yet settled on this issue, in particular concerning the role of the axial anomaly in QCD. Nevertheless, it adds to the puzzle presented long ago by the measurement and interpretation of $\Sigma_{\pi N}$ which, when $SU(3)$ symmetry is assumed, predicts a large value for $\langle p|m_s\bar{s}s|p\rangle$, on the order of several hundred MeV. Several lattice QCD studies confirm a large value for this strange matrix element (e.g, (291 ± 35 MeV in [10]).

The value for strange matrix elements are important to know, as they affect the inerpretation of many unrelated experiments. Dark matter searches by means of bolometry are sensitive to strange matrix elements, as are nuclear and atomic parity violation experiments [11] Clearly the mystery of strange quarks in the nucleon resides in the structure at low x, and is particularly interesting only at low Q^2. Because it is at low Q^2 it is impossible to do a rigorous QCD calculation, so the ball is in the experimentalists' court. Luckily the Z boson has both axial and vector couplings to the s quark so that elastic neutral current scattering experiments are sensitive to the strange content of the nucleon [12], and a number of experiments underway or approved are exploiting this fact:

1. LSND at Los Alamos is remeasuring the axial matrix element $\langle N|\bar{s}\gamma_\mu\gamma_5 s|N\rangle$ in $\nu\ {}^{12}C$ scattering (taking data now);
2. SAMPLE at Bates is measuring the strange magnetic moment of the nucleon μ_s (the vector matrix element $\langle N|\bar{s}\gamma_\mu s|N\rangle$) in parity violating ep scattering (taking data now);
3. CEBAF experiments 91-004, 91-010 and 91-017 have been approved to measure μ_s and the strange charge radius R_s in PV $e\ {}^4He$, as well as e^p and ed scattering (to start running 1996 - 98).

I mention these experiments in a talk on theory because their results (positive or negative) will undoubtedly stir up the theoretical community.

3. QCD and nuclear structure

3.1. The "old" EMC effect

The famous 1982 result of the EMC collaboration is that there is a dip in the quark distribution functions at $x \sim 0.6 - 0.7$ in large nuclei relative to the deuteron [13]. This has been attributed by some to quarks being less confined in the nuclear medium, and as such could presage deconfinement at higher densities. As such it is a very interesting effect to understand; however, I am not very sanguine of it being understood directly from QCD calculations (but would like to be proven wrong). I suspect that progress in the near future will be the refinement of understanding how much of the dip can be accounted for by conventional nuclear (*i.e,* long distance) effects: shadowing, Fermi motion, and nucleon-nucleon correlations.

3.2. Parton distributions at low x

There is an enormous amount of activity in the field of using perturbative QCD to compute the parton distributions of nucleons and nuclei at low x; the latter should be relevant for all observables in relativistic heavy ion collisions. I only wish to highlight an interesting recent development due to McLerran, Venugopalan and collaborators [14] who exploit the fact that nuclei in the infinite momentum frame look like sheets with high densities of uncorrelated valence quarks. They treat this sheet as a classical color source and from this compute gluon correlation function, which is related to the low x parton distributions in the nucleus prior to the collision. It will be interesting to understand if this is the leading term in some rigorous expansion in QCD, and to further pursue its implications for phenomenology.

3.3. Color transparency

Color transparency is based on the idea that hadrons have a component to their wave function for which they are color-neutral point-like objects which can penetrate easily through nuclear matter, and that in quasielastic scattering at sufficiently high Q^2 this component is projected out. One possible signal would be a cross section for knocking out a proton in electron-nucleus scattering that is not diminished by the usual absorptive effects in the nucleus [15].

A very nice treatment of a related system has been done by Luke, Manohar and Savage where they treat nucleus-charmonium boundstates [16]. Using effective field theory techniques, they show rigorously that in the heavy quark mass limit of QCD, the binding energy of the quarkonia in a nucleus scales like r_B^3, where r_B is the Bohr radius of the meson. This calculation exhibits how the nucleus-hadron interaction vanishes as the hadron size decreases. It would be interesting to see if similar techniques can be applied to other situations where color transparency is expected.

4. Outlook

QCD is hard but that's how the world works, and any discussion of hadron structure must deal with it. I have tried to suggest that there has actually been a lot of progress in the last few years, and I expect progress to continue. We are also seeing increasing cross fertilization between nuclear and particle physics...this may be problematic from a funding point of view, but is excellent for intellectual stimulation.

The field will only stay interesting, however, if there is a steady influx of young theorists. The subject continues to attract young post-docs, but the tight job situation either scares them away, or convinces them to work on hallowed but not very useful models.

Nothing could benefit the field more than the allocation of money earmarked for post-doctoral and junior faculty positions in nuclear theory, coupled with high standards among those doing the hiring.

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