Physics Questions of Interest

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1. The States of QCD

Two (interrelated) intellectual questions of fundamental interest to nuclear science:

1. What are the states of QCD?
2. How does QCD give rise to these states?

We know some of the answers:

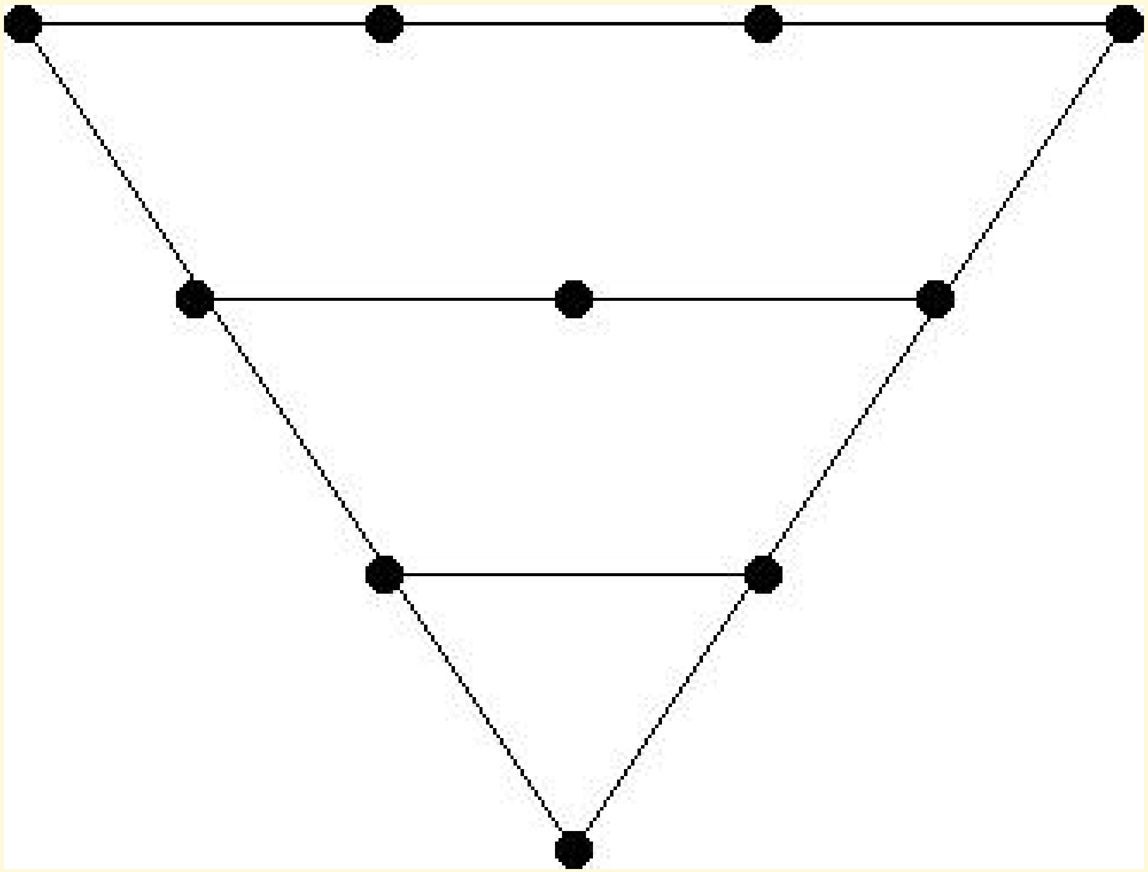
1. Hadrons (of at least 2 kinds)
   - Mesons
   - Baryons
   - Hybrids (in both sectors)(?)
   - Glueballs (?)
   - Multi-quark states(?)
2. Work in progress!

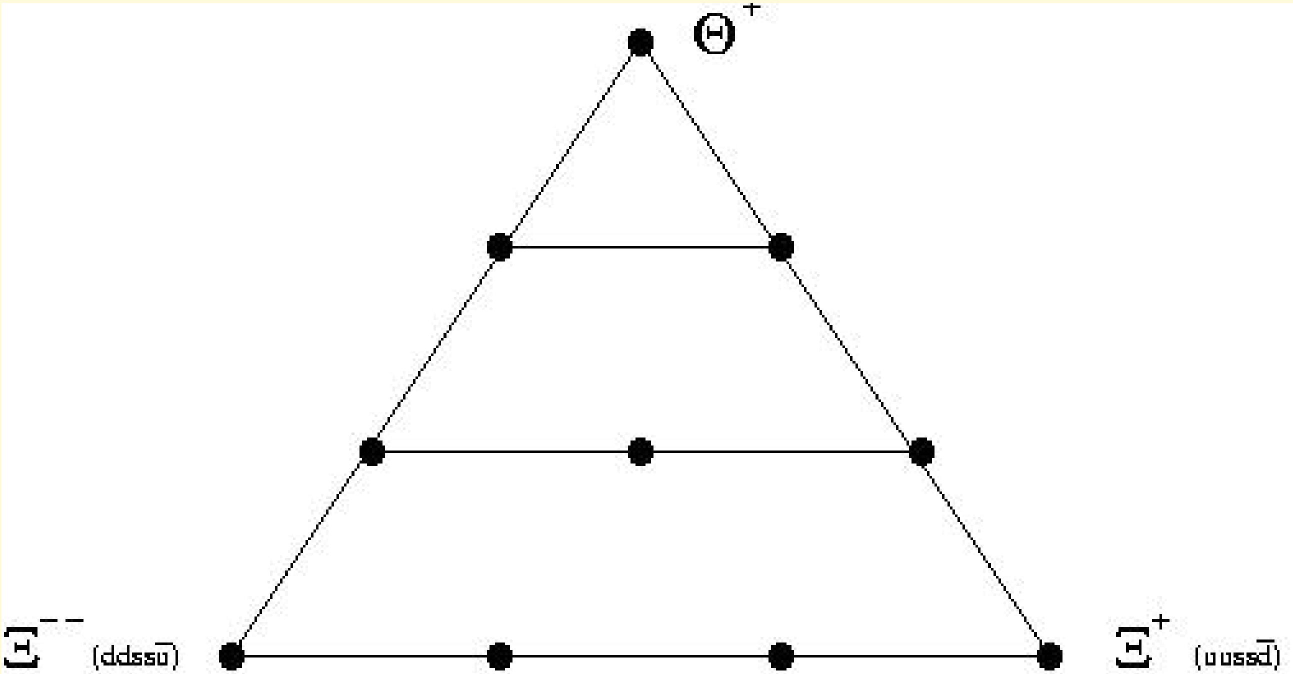
There are many facets to these two questions, all of which can only be addressed through experiments of high precision (and the analysis effort which MUST accompany such experiments).

These facets include (in random order):

- Existence (or not) of multiquark hadrons such as pentaquarks, and implications for spectroscopy and dynamics;

  May turn much of what we know on its head





What mechanism gives rise to such a light, apparently narrow state?

What are the implications for the rest of the spectrum?

Are there pentaquarks in other partial waves? Which ones?

How does the rest of the baryon spectrum, beyond the ground state octet and (anti)decuplet, fit into the chiral soliton picture?

- The antidecuplet is predicted to have $J^P = 1/2^+$, thus increasing the population in that sector.

  How do we understand the states in the P_{11} partial wave? E. g. : $N(1440)$ has been described as

  (i) pentaquark partner;

  (ii) qqq radial excitation of ground-state nucleon;

  (iii) hybrid baryon;

  (iv) dynamically generated state.

  Which picture, if any, is correct?

  If the N(1710) is a pentaquark, where is the non-exotic N^* expected near the same energy?

  Similar questions arise for the 'non-exotic' members of the antidecuplet

- Restoration (or not) of chiral symmetry, and the accompanying existence of chiral doublets, or other multiplets, high in the baryon spectrum;

  Where in the spectrum would this start to occur? 2.0 GeV? 2.5 GeV? ...?

  Are there expected to be relations among the couplings of states within such a multiplet to (a) other multiplets; (b) lower lying states?

- Understanding the relevant effective degrees of freedom inside a baryon: 3 independent valence quarks, or (tightly-bound) diquark and quark? This has profound implications for the spectrum (and related phenomenology) of baryons:

n_ρ	n_λ	ℓ_ρ	ℓ_λ	L	S	J^P
0	0	0	0	0	1/2	$1/2^+$
0	0	0	0	0	3/2	$3/2^+$
1	0	0	0	0	1/2	$1/2^+$
1	0	0	0	0	3/2	$3/2^+$
0	1	0	0	0	1/2	$1/2^+$
0	1	0	0	0	3/2	$3/2^+$
0	0	2	0	2	1/2	$3/2^+$, $5/2^+$
0	0	2	0	2	3/2	$1/2^+$, $3/2^+$, $5/2^+$, $7/2^+$
0	0	0	2	2	1/2	$3/2^+$, $5/2^+$
0	0	0	2	2	3/2	$1/2^+$, $3/2^+$, $5/2^+$, $7/2^+$
0	0	1	1	2	1/2	$3/2^+$, $5/2^+$
0	0	1	1	2	3/2	$1/2^+$, $3/2^+$, $5/2^+$, $7/2^+$
0	0	1	1	1	1/2	$1/2^+$, $3/2^+$
0	0	1	1	1	3/2	$1/2^+$, $3/2^+$, $5/2^+$
0	0	1	1	0	1/2	$1/2^+$
0	0	1	1	0	3/2	$3/2^+$

Up to $N = 4$, there are 30 states with $J^P = 1/2^+$, 45 states with $J^P = 3/2^+$

n_ρ	n_λ	ℓ_ρ	ℓ_λ	L	S	J^P
0	0	0	0	0	1/2	$1/2^+$
0	0	0	0	0	3/2	$3/2^+$
0	1	0	0	0	1/2	$1/2^+$
0	1	0	0	0	3/2	$3/2^+$
0	0	0	2	2	1/2	$3/2^+$, $5/2^+$
0	0	0	2	2	3/2	$1/2^+$,$3/2^+$, $5/2^+$, $7/2^+$
0	2	0	0	0	1/2	$1/2^+$
0	2	0	0	0	3/2	$3/2^+$
0	1	0	2	2	1/2	$3/2^+$, $5/2^+$
0	1	0	2	2	3/2	$1/2^+$, $3/2^+$, $5/2^+$, $7/2^+$
0	0	0	4	4	1/2	$7/2^+$, $9/2^+$
0	0	0	4	4	3/2	$5/2^+$, $7/2^+$, $9/2^+$, $11/2^+$

$\Longrightarrow$ in diquark model, 5 states with $J^P = 1/2^+$, 7 states with $J^P = 3/2^+$.

These are clearly very different spectra, and the implications for decays are similarly different between the two scenarios.

If diquark scenario is correct, what is the mechanism that leads to the diquark?

- Building a consistent (and single?) framework for describing the spectra of hadrons, and for understanding the mechanism of confinement

  OGE, OBE, some combination, or something else?

  Instantons?

  Solitons, chiral or otherwise

  Large N_c

  Skyrme, NJL, bags of different shapes, sizes and clarity...

- Obtaining a framework for describing the couplings of hadrons

  $^3P_0$, chiral quark, or other models for strong decays;

  Can we build a framework for describing both the spectra and strong decays (can we go beyond the 'narrow resonance' approximation in obtaining the spectra?

  Electromagnetic and weak transitions;

- Understanding the successes and failures of the 'simple' quark models, such as

  Spin-orbit puzzle;

  The ratio $\frac{A_{1/2}}{A_{3/2}}$ is well predicted for the $\Delta(1232)$, but model predictions of each amplitude are typically ≈ 70 % of extracted values;

  The role of vertex dressing?

  Do pions cloud the issue?

  Description of $S_{11}(1535)$ and its decays;

  Models fail to provide a consistent picture of the $P_{11}(1440)$, but the results from pwas (based mainly on πN scattering data) have 'significant spread': 1380$\leq M \leq$ 1518, $113 \leq \Gamma \leq 668$, $-0.029 \leq A^n_{1/2} \leq 0.121$, $-0.129 \leq A^p_{1/2} \leq -0.0584$

- Existence (or not) of Höhler clusters (Lorentz multiplets of different representations, depending on the flavor and masses of the states), or the validity of simple 'mass formulae', à la Klempt, and implications for dynamics;

- Significance and relevance of 'dynamically-generated states', and their relationship with non-dynamically-generated ones.

To attempt to formulate reliable, consistent answers to any of these questions, it is essential to have better, more precise data on baryon masses, at least up to 2.5 GeV.

This means that there is a need for higher precision data, not only with electromagnetic beams, but especially with hadronic ones (see talk by Simon Capstick)

Precise data on couplings (not just amplitudes, but signs of amplitudes, where these are obtainable) are also crucial, as the locations of the states are in some sense the crudest manifestation of the dynamics.

$\Longrightarrow$ same conclusion with regard to needed experiments.

2. Link to Lattice Effort

It has become generally accepted that lattice simulations offer the only means of *calculating* non-perturbative QCD.

A very large investment (by theory standards) has been made in the lattice effort. It is expected that this investment will continue.

In the past, much of the lattice effort was geared toward 'high energy physics', with emphasis on controling the theoretical uncertainties in our understanding of strong interaction dynamics and their effect on the extraction of fundamental quantities in the standard model (like CKM matrix elements).

Now, significant lattice effort is aimed at understanding non-perturbative qcd, and the spectrum of states that results from it.

The nuclear physics community strongly endorses this line of research (via the Long Range Plan), and the funding agencies support it.

For this investment to pay off, lattice calculations must be compared to high-precision experimental numbers, such as masses, current matrix elements, etc.

$\Longrightarrow$ Spectroscopy experiments are essential, and experiments with hadronic beams are crucial.

3. Connection to JLab (and other EM probe) Experiments

JLab is one of the two flagship facilities of the DOE.

N* program of Hall B has been highly touted for its attack on the problem of missing baryons.

Many final states are being (or can be) studied (in both photoproduction and electroproduction experiments) including

$$N\pi,\ N\eta,\ \ N\pi\pi,\ N\omega,\ N\pi\eta,$$
$$\Lambda K,\ \Sigma K,\ \ NKK,\ \Lambda K\pi,\ \Sigma K\pi,\ \text{etc.}$$

Useful information is obtained by applying various reaction-theory techniques to interpret the cross sections and polarization observables in terms of baryon resonances, and their properties.

Statistical precision expected to be $\mathcal{O}$ few percent, and will dominate database (in many cases, JLab measurements are/will be the first measurements).

This could lead to high-precision extractions of baryon properties (crucial for lattice studies, for instance).

But...

None of these channels can be analysed in isolation (see talks by Simon Capstick and Cornelius Bennhold).

Unitarity condition is

$$\mathcal{S}^\dagger \mathcal{S} = 1, \quad \mathcal{S} = 1 + i\mathcal{T},$$
$$\mathcal{S}^\dagger \mathcal{S} = 1 \Longrightarrow i\left(\mathcal{T}^\dagger - \mathcal{T}\right) = \mathcal{T}^\dagger \mathcal{T}.$$

Below the threshold for two-pion production,

$$\left\langle \pi N \left| i\left(\mathcal{T}^\dagger - \mathcal{T}\right)\right| \gamma N \right\rangle = \left\langle \pi N \left|\mathcal{T}^\dagger\right| \pi N \right\rangle \left\langle \pi N \left|\mathcal{T}\right| \gamma N \right\rangle.$$

The unitarity condition leads to a strict constraint on multipole amplitudes:

$$M_{\gamma N \to \pi N}(s) = \pm e^{i\delta_{\pi N \to \pi N}(s)} \left| M_{\gamma N \to \pi N}(s) \right|,$$
$$M_{\pi N \to \pi N}(s) = \sin\left(\delta_{\pi N \to \pi N}(s)\right) e^{\delta_{\pi N \to \pi N}(s)}.$$

More generally,

$$\left\langle X \left| i\left(\mathcal{T}^\dagger - \mathcal{T}\right)\right| \gamma N \right\rangle = \left\langle X \left|\mathcal{T}^\dagger\right| \pi N \right\rangle \left\langle \pi N \left|\mathcal{T}\right| \gamma N \right\rangle,$$

or, even more generally,

$$\left\langle X \left| i\left(\mathcal{T}^\dagger - \mathcal{T}\right)\right| \gamma N \right\rangle = \sum_Y \left\langle X \left|\mathcal{T}^\dagger\right| Y \right\rangle \left\langle Y \left|\mathcal{T}\right| \gamma N \right\rangle,$$

4. Summary

Hadron spectroscopy experiments with hadronic beams are an essential part of our arsenal in the assault on the nonperturbative QCD frontlines.

πN experiments up to $\sqrt{s} \approx 2.5$ GeV, and KN experiments up to $\sqrt{s} \approx 3.0$ GeV are needed to help bring the investment in Jlab to fruition.

Higher energies required for examining cascade spectrum.

Very exciting prospects for confirmation (or otherwise) of pentaquark states, and for exploring their phenomenology.

This is a unique opportunity for an experimental program that draws on the strengths of both of the flagship facilities of the DOE Office of Nuclear Physics to answer difficult intellectual questions.