Baryon Spectroscopy with Meson Beams

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1. Questions in Baryon Spectroscopy

1.1. 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. $\Longrightarrow$ Hadrons (of at least 2 kinds)

   Mesons

   Baryons

   Hybrids (in both sectors)(?)

   Glueballs (?)

   Multi-quark states(?)

2. $\Longrightarrow$ Work in progress!

1.2. Why Study Baryons?

- The world of common experience is composed of baryons: any study of the nature of matter must include its most prevalent form;
- Baryons are the simplest system that manifest the non-Abelian nature of QCD.
- The constraints on constructing baryon multiplets are quite different from those for mesons:

  $$\text{mesons} \longrightarrow 8 \bigoplus 1;$$

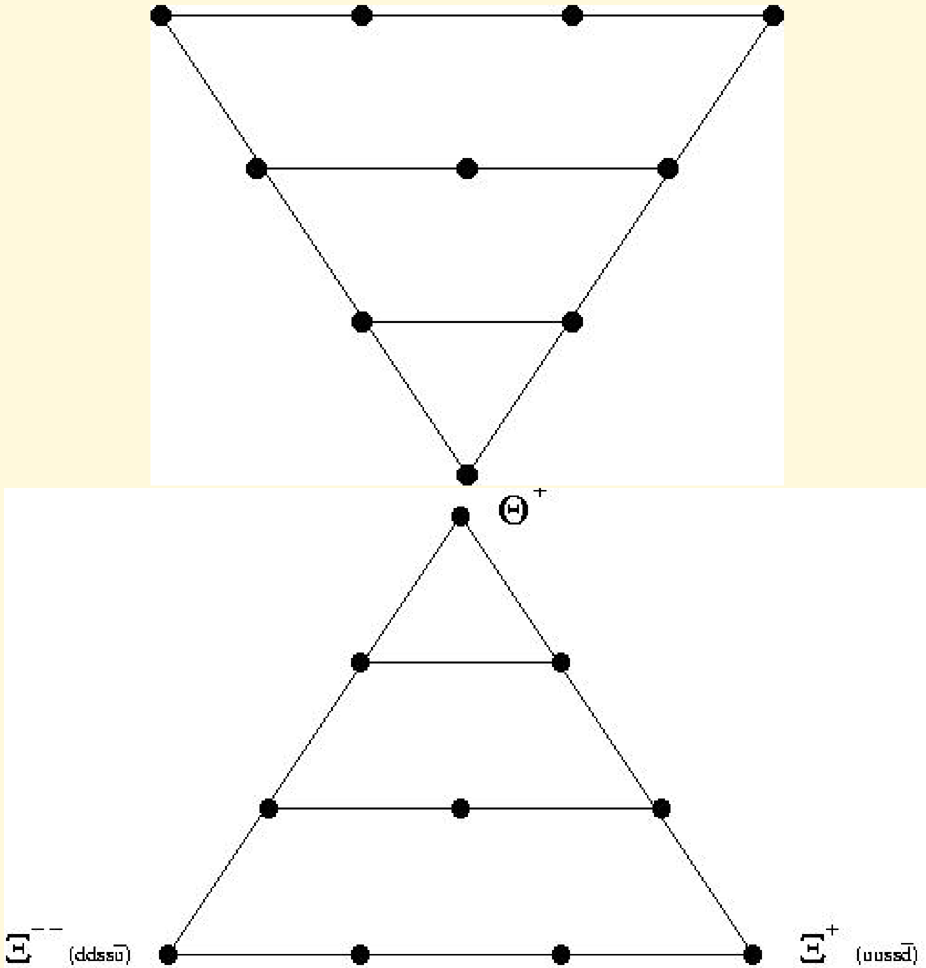
  $$\text{baryons} \longrightarrow 56,\ 70,\ 20.$$

There are many facets to the 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 upside down



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?

- Missing or Undiscovered Baryons

  The underlying assumption in most quark models is that a baryon is composed of three valence quarks; resulting spectrum understood as various excitations of these three quarks;

  Regardless of the details of the model, the number of excitations predicted are the same. The ordering and positions of states may vary, but the number of states predicted depends only on the number of degrees of freedom in the baryon;

  Only a fraction of the states predicted by such models have been seen with any certainty: "missing baryon" problem;

  Missing states must be sought in $N\pi\pi$, ΛK, ΣK, etc., final states produced in scattering experiments;

1.3. Lattice Effort

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

An unprecedented 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 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 NSAC 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.

- 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...

- 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': $1380 \leq M \leq 1518$, $113 \leq \Gamma \leq 668$, $-0.029 \leq A^n_{1/2} \leq 0.121$, $-0.129 \leq A^p_{1/2} \leq -0.0584$

- 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 more precise data on baryon masses, at least up to 2.5 GeV.

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.

This means that there is a need for higher precision data, not only with electromagnetic beams, but especially with hadronic ones

1.4. Status of Baryon 'Data'

The properties of a single, non-strange, excited state $\Delta(1232)$ are known to within 5%;

Properties of a few excited states, the lowest state in each partial wave (the **** states), are known to $\approx \pm$ 30%;

Properties of other 'known' states have much larger uncertainties.

$\Longrightarrow$ Higher precision information needed.

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

JLab is one of the two flagship facilities of the DOE Office of Nuclear Physics.

N* program of Hall B has been highly touted for its promise of providing new, high precision information in baryon spectroscopy

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

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

Statistical precision expected to be ≈ 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).

However, none of these channels can be analysed in isolation.

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:

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

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,

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

For pion photoproduction,

$$\left\langle \pi N \left| i\left(\mathcal{T}^\dagger - \mathcal{T}\right)\right| \gamma N \right\rangle = \left\langle \pi N \left|\mathcal{T}^\dagger\mathcal{T}\right| \gamma N \right\rangle. \tag{1}$$

Inserting a complete set of physically accessible states X leads to

$$\left\langle N\pi \left| i\left(\mathcal{T}^\dagger - \mathcal{T}\right)\right| \gamma N \right\rangle = \sum_X \left\langle N\pi \left|\mathcal{T}^\dagger\right| X \right\rangle \left\langle X \left|\mathcal{T}\right| \gamma N \right\rangle. \tag{2}$$

As a result of unitarity, amplitudes for a single process cannot be treated in isolation, but a coupled-channel T-matrix must be used from the outset. If a few of the channels that can be measured at JLab (or a pion beam facility) are included, the $\mathcal{T}$ matrix would look like

$$\mathcal{T} = \begin{pmatrix} \mathcal{T}_{\gamma N\to\gamma N} & \mathcal{T}_{\gamma N\to\pi N} & \mathcal{T}_{\gamma N\to\eta N} & \mathcal{T}_{\gamma N\to\Lambda K} & \mathcal{T}_{\gamma N\to\Sigma K} & \mathcal{T}_{\gamma N\to\pi\pi N} \\ \mathcal{T}_{\pi N\to\gamma N} & \mathcal{T}_{\pi N\to\pi N} & \mathcal{T}_{\pi N\to\eta N} & \mathcal{T}_{\pi N\to\Lambda K} & \mathcal{T}_{\pi N\to\Sigma K} & \mathcal{T}_{\pi N\to\pi\pi N} \\ \mathcal{T}_{\eta N\to\gamma N} & \mathcal{T}_{\eta N\to\pi N} & \mathcal{T}_{\eta N\to\eta N} & \mathcal{T}_{\eta N\to\Lambda K} & \mathcal{T}_{\eta N\to\Sigma K} & \mathcal{T}_{\eta N\to\pi\pi N} \\ \mathcal{T}_{\Lambda K\to\gamma N} & \mathcal{T}_{\Lambda K\to\pi N} & \mathcal{T}_{\Lambda K\to\eta N} & \mathcal{T}_{\Lambda K\to\Lambda K} & \mathcal{T}_{\Lambda K\to\Sigma K} & \mathcal{T}_{\Lambda K\to\pi\pi N} \\ \mathcal{T}_{\Sigma K\to\gamma N} & \mathcal{T}_{\Sigma K\to\pi N} & \mathcal{T}_{\Sigma K\to\eta N} & \mathcal{T}_{\Sigma K\to\Lambda K} & \mathcal{T}_{\Sigma K\to\Sigma K} & \mathcal{T}_{\Sigma K\to\pi\pi N} \\ \mathcal{T}_{\pi\pi N\to\gamma N} & \mathcal{T}_{\pi\pi N\to\pi N} & \mathcal{T}_{\pi\pi N\to\eta N} & \mathcal{T}_{\pi\pi N\to\Lambda K} & \mathcal{T}_{\pi\pi N\to\Sigma K} & \mathcal{T}_{\pi\pi N\to\pi\pi N} \end{pmatrix}. \qquad (3)$$

2. Experimental Considerations

- Beam momenta and beam line considerations:

  Nominally, beam momentum of 2.5 GeV/c with π/K separation is needed. This momentum corresponds to a resonance mass of 2.37 (2.43) Gev/c^2 in the $\pi p (Kp)$ system. At higher momenta a separated beam line may become impractical since the kaons already have a velocity of 0.98 c at 2.5 GeV/c.

  The resolution for determining the momentum of individual beam particles should be 1% or better (accomplished perhaps by placing wire chambers in the beam line). Typical momentum acceptances for secondary beam lines have $\Delta P/P \approx 5\%$, which is fine as long as the beam can be divided up into momentum bins.

  The beam channel should be designed to provide a focal point 3-5 meters downstream of the last beam magnet in order to have room to install 4π detectors and shielding to reduce backgrounds.

  Attention should be paid to keeping backgrounds low, particularly for neutral particle detectors. For example, primary beam dumps should not be just across a shielding wall from the experimental area.

- Detector characteristics:

  Large solid angle ($\approx 4\pi$) is essential to provide complete angular distributions, accommodate multi-particle final states, and to minimize systematic uncertainties due to edge effects. Movable, small-acceptance spectrometers have their place, but not in the experiments envisioned for light-baryon spectroscopy.

  Gamma detection with good angular ($\approx 2^\circ$) and energy ($\approx 2\%$ at 1 GeV) resolution is essential for measuring π^0, η, η', ω and other neutral mesons in the final state.

  A comprehensive program for charged-particle final states (elastic scattering and charged meson production) needs a CLAS-like detector (toroidal magnetic field, etc.) but with a larger acceptance for gamma rays (The recent program (E913/914/958) with the Crystal Ball at BNL measured only neutral final states: they were hoping to add a downstream end cap and a tracker for charged particles as they moved to higher momenta.)

- Other:

  Polarized targets will be needed;

  Recoil polarization measurements will be highly desirable.

3. Summary

Hadron spectroscopy experiments with hadronic beams will provide information essential to our efforts to understand nonperturbative QCD dynamics.

πN experiments up to $\sqrt{s} \approx 2.5$ GeV, and KN experiments up to $\sqrt{s} \approx 3.0$ GeV are needed for significant progress to be made in our understanding of how nonperturbative QCD gives rise to hadrons.

Higher energies required for spectrum of cascade baryons.