Nucleon Excitations

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5-th International Conference on Quarks and Nuclear Physics
QNP 2009, Beijing , September 21-26, 2009

1: How is the spectrum of nucleon resonances organized and what is their mass pattern?

- Three-body dynamics? — Constituent quark models
- Are baryons generated dynamically? — Chiral Lagrangians
- Are there chiral doublets? — Chiral symmetry restored at high masses?
- Are there (L, S) super-multiplets? — AdS/QCD

In this talk I will argue that

a) at high masses, only light-baryon resonances are observed that can be described by the quantum numbers $N, L, S, (J)$

In the quark model, you have: $n_1, n_2, l_1, l_2, s_1, s_2, j_1, j_2, L, S, J$

b) and their masses are given by

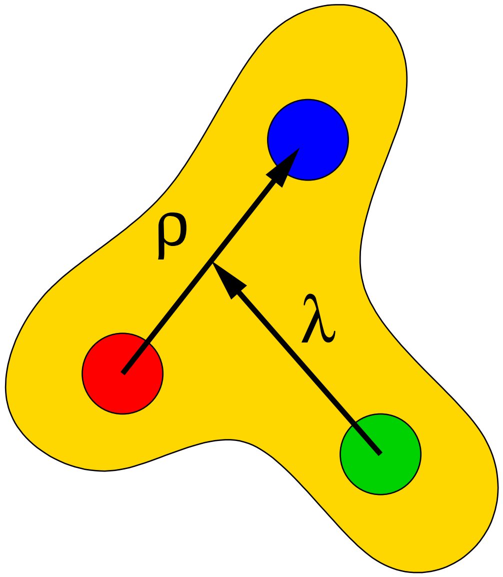
$$M^2 = 1.04(L + N + 3/2) - 1.46\alpha_D \quad [\mathrm{GeV}^2]$$

$\alpha_D = 0$ if there is a 'good' diquark with $I_{qq} = S_{qq} = 0$

2: Quark models:

In the quark model, there are two independent oscillators. Choosing harmonic oscillators (h.o.), the states are characterized by

$$(D, L^P_{\mathsf{N}})$$



D is the SU(3) dimensionality (56 or 70)
L the orbital angular momentum
P the parity
N the shell number

Note: In non-relativistic quark models $M^2 \propto \mathsf{N}$, bands with positive and negative parity alternate.

Two questions emerge ...

1. Can we relate these h.o. states with observed resonances?
2. Is there some systematic of the so-called missing resonances?
   Not all solutions of a Hamiltonian need to be realized dynamically!

... for which (speculative) answers will be given.

There are great successes of the quark model for baryon spectroscopy:

- **Interpretation of ground-state baryons in SU(3) multiplets**
- **Correct prediction of the multiplicity of low-mass negative-parity states in the first excitation band $(D, L^P_N) = (70, 1^-_1)$.**
- **Correct prediction of baryon properties like formfactors, magnetic moments, $\cdots$**

... but some problems remain:

- **The $N_{1/2^-}(1535) - N_{1/2^+}(1440)$ mass difference is**

  $+100\,$MeV experimentally

  - 80 MeV in quark models
- **There are more states predicted than found experimentally (missing resonance problem)**
- **There are no states in a 20-plet $(6 \otimes 6 \otimes 6) = (56 \oplus 2 \cdot 70 \oplus 20)$**
- **Conceptually, I do not expect that constituent quarks have a defined rest mass when going to high excitation energies.**

Quark model variants help ...

Five-quark states:

$$(q - qq) \quad (q\bar{q}qqq)$$

$$m \; N$$

P-wave S-wave

A P-wave excitation "costs" about 450 MeV. Adding a pseudoscalar $q\bar{q}$ pair in S-wave may be energetically favored.

Baryons like $N_{1/2^-}(1535)$ could be made up from five quarks.

B.S. Zou

Hybrid baryons:

The gluonic flux tube can be excited leading to a rich spectrum of hybrid baryons. Ph. Page

... but do not solve the problems

3: Dynamical generation of resonances:

1: **Classical example: $\Delta(1232)$: qqq or N ?** CHEW

2: **$N(1535)S_{11}$ as N -ΣK coupled-channel effect** KAISER, WEISE

3: **$\Lambda(1405)S_{01}$ (split into 2 states!)** OSET, MEISSNER

⇒ **Can all baryon resonances be constructed from their decay modes?** LUTZ

⇒ **Are these dual descriptions or lead qqq and molecular descriptions to different states (which may mix) leading to a larger number of states ?**

Quark model states need long-range corrections with higher Fock configurations. These are dominated by the meson–baryon interaction (and include four-quark and hybrid configurations).

Resonances described in a hadronic picture require short-range corrections. These lead back to interacting quarks and gluons.

Quark-model wave functions and meson–baryon states have a sizable overlap, possibly spanning the same Hilbert space!

$\mathcal{L}_{\text{full QCD}} \longrightarrow$	$\longrightarrow \mathcal{L}_{\chi\text{PT}}$		$\longrightarrow$ spectrum and w.f.
			$\longrightarrow$ spectrum and w.f.
	$\longrightarrow \mathcal{L}_{\text{Quark model}}$		$\longrightarrow$ spectrum and w.f.

Possibly, we should not add the red and the green spectrum !

1. **There is one $N(1535)S_{11}$ resonance, not a red and the green one.**
2. **$f_0(980), a_0(980)$ are both, molecules and $q\bar{q}$ states**
3. **The hidden charm X, Y, Z resonances are molecules and $q\bar{q}$ states**
4. **$\sigma(500)$ and $\kappa(700)$ are dynamically generated** — good basis
   and 1^3P_0 quark model states — bad basis

4 : Parity doublets

Baryon resonances exhibit an unexpected phenomenon: parity doublets, pairs of resonances with the same spin J but opposite parities. Often, these are quartets of N^* and Δ^* having the same J.

Resonances and star rating are taken from PDG. States not found in the recent SAID analysis are marked by [a].

$J=\frac{1}{2}$	$N_{1/2^+}(1710)^a$ **	$N_{1/2^-}(1650)$ ****	$\Delta_{1/2^+}(1750)^a$	$\Delta_{1/2^-}(1620)$ ****
$J=\frac{3}{2}$	$N_{3/2^+}(1720)$ ****	$N_{3/2^-}(1700)^a$ ***	$\Delta_{3/2^+}(1600)^a$ ***	$\Delta_{3/2^-}(1700)$ ****
$J=\frac{5}{2}$	$N_{5/2^+}(1680)$ ****	$N_{5/2^-}(1675)$ ****	no chiral partners	
$J=\frac{1}{2}$	$N_{1/2^+}(1880)^a$ **	$N_{1/2^-}(1905)^a$ *	$\Delta_{1/2^+}(1910)$ ****	$\Delta_{1/2^-}(1900)^a$ **
$J=\frac{3}{2}$	$N_{3/2^+}(1900)^a$ **	$N_{3/2^-}(1860)^a$ **	$\Delta_{3/2^+}(1920)^a$ ***	$\Delta_{3/2^-}(1940)^a$ **
$J=\frac{5}{2}$	no chiral partners		$\Delta_{5/2^+}(1905)$ ****	$\Delta_{5/2^-}(1930)^a$ ***
$J=\frac{7}{2}$	$N_{7/2^+}(1990)^a$ **	$N_{7/2^-}(2190)$ ****	$\Delta_{7/2^+}(1950)$ ****	$\Delta_{7/2^-}(2200)^a$ *
$J=\frac{9}{2}$	$N_{9/2^+}(2220)$ ****	$N_{9/2^-}(2250)$ ****	$\Delta_{9/2^+}(2300)^a$ **	$\Delta_{9/2^-}(2400)$ **

Is there a phase transition ? Glozman

5: Super-multiplets with defined quantum numbers

$\vec{L}$ and $\vec{S}$:

Relativity plays an important role in quark models. In relativistic models, only the total angular momentum J is defined. Experimentally, there are a few striking examples where the leading orbital angular momentum and the spin can be identified (small admixtures of other components are not excluded)

1. The negative-parity light-quark baryons form

   a N doublet, a N triplet, and a Δ doublet,

   well separated in mass from all other negative parity states.

$L;S$	$J^P = 1/2$	$J = 3/2$	$J = 5/2$
$L = 1; S = 1/2$	$N_{1/2^-}(1535)$	$N_{3/2^-}(1520)$	
$L = 1; S = 3/2$	$N_{1/2^-}(1650)$	$N_{3/2^-}(1700)$	$N_{5/2^-}(1675)$
$L = 1; S = 1/2$	$\Delta_{1/2^-}(1620)$	$\Delta_{3/2^-}(1700)$	

2. **The positive parity states form isolated**

N^* **doublet**, N^* **quartet**, Δ^* **quartet**

$L; S$	$J^P = 1/2^+$	$3/2^+$	$5/2^+$	$7/2^+$
$L = 2; S = 1/2$		$N_{3/2^+}(1720)$	$N_{5/2^+}(1680)$	
$L = 2; S = 3/2$	$N_{1/2^+}(1880)$	$N_{3/2^+}(1900)$	$N_{5/2^+}(2000)$	$N_{7/2^+}(1990)$
$L = 2; S = 3/2$	$\Delta_{1/2^+}(1910)$	$\Delta_{3/2^+}(1920)$	$\Delta_{5/2^+}(1905)$	$\Delta_{7/2^+}(1950)$

3. **At higher mass there is are mass degenerate negative-parity**

Δ **triplet** Δ **doublet**

	$J^P = 1/2$	$3/2$	$5/2$	$7/2$
$L = 1; S = 3/2$	$\Delta_{1/2^-}(1900)$	$\Delta_{3/2^-}(1940)$	$\Delta_{5/2^-}(1930)$	**No state!**
$L = 3; S = 1/2$			**2233 53**[a]	$\Delta_{7/2^-}(2200)$

[a] **from Arndt, 2006.**

Conclusion: L, S **supermultiplets are an important organizing principle for baryon spectroscopy!**

The radial excitation quantum number N

Caution: Shell number N and radial excitation number N are related by $\mathsf{N} = L + 2N$;

The Roper-like resonances (lowest mass states with ground-state q.n.):

	N, Δ	Λ	Σ, Σ	Ξ, Ξ	N=0
56, 8; 1/2	$N_{1/2^+}(1440)$	$\Lambda_{1/2^+}(1600)$	$\Sigma_{1/2^+}(1660)$	$\Xi_{1/2^+}(1690)$	
δM^2	1.19±0.11	1.31±0.11	1.34±0.11	1.13±0.03	N=1
56, 10; 3/2	$\Delta_{3/2^+}(1600)$		$\Sigma_{3/2^+}(1840)$	x	
δM^2	1.04 ± 0.15		1.47 ± 0.44		
70, 8; 1/2	$N_{1/2^+}(1710)$	$\Lambda_{1/2^+}(1810)$	$\Sigma_{1/2^+}(1770)$	x	Possibly
δM^2	2.04±0.15	2.03± 0.15	1.72 ± 0.16		N=2
70, 10; 1/2	$\Delta_{1/2^+}(1750)$		$\Sigma_{1/2^+}(1880)$	x	
δM^2	1.54 ± 0.16		2.12±0.11		

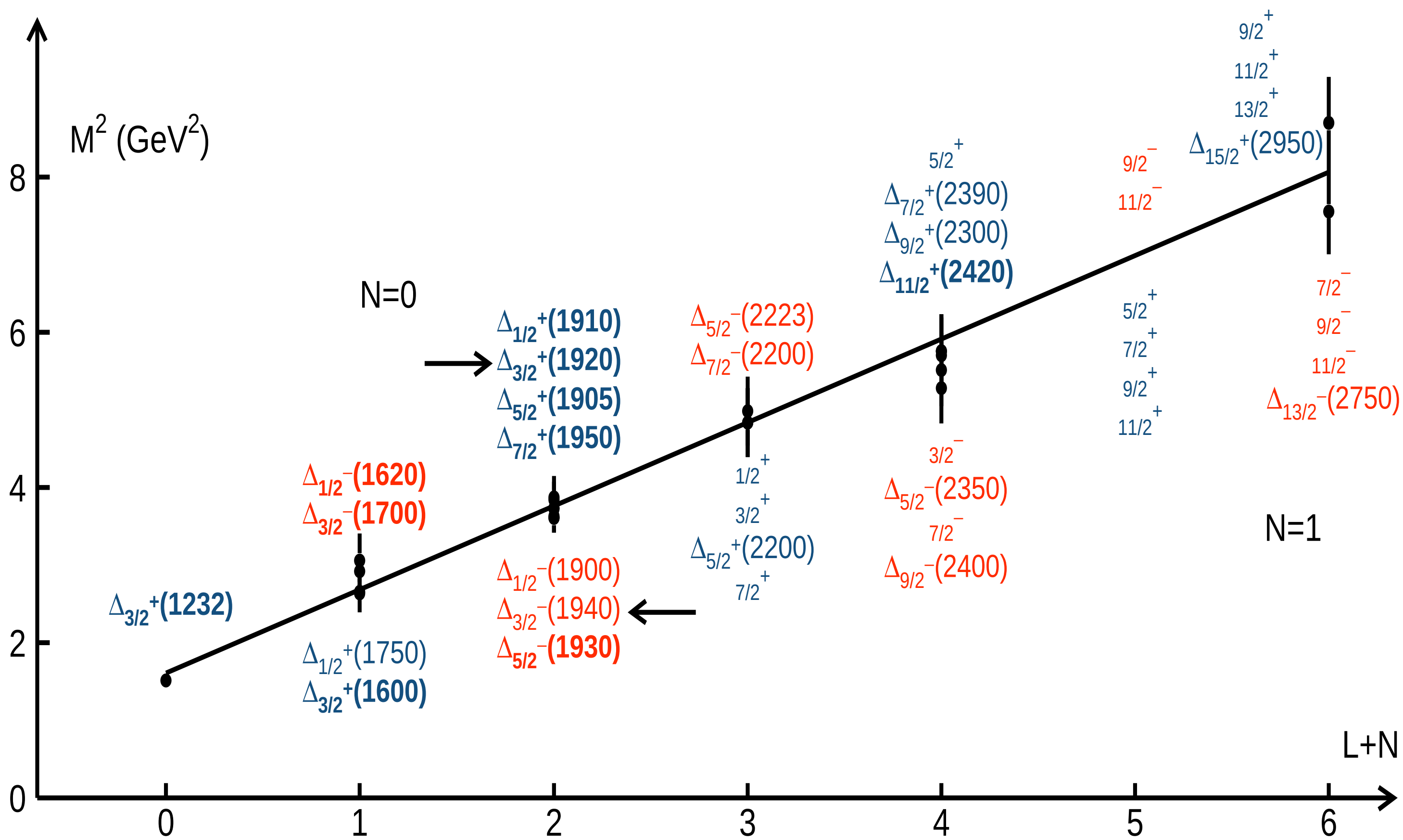
The states in the 70-plet require both oscillators to be excited !

6 : What are the masses as functions of L, S and N ?

ADS/QCD predicts for Δ resonances: **Brodsky, Teramond**

$$M^2 = a(L + N + 3/2)$$

The constant a is related to a soft cut-off at large distances. The full Δ is given by confinement only !



H. Forkel, M. Beyer and T. Frederico, JHEP 0707, 077 (2007);
E. K., EPJ A38, 187 (2008). [hep-ph]. **Mass is given by size !**

Including nucleons : $M^2 = 1.04 \cdot (L + N + 3/2) - 1.46\,\alpha_D$ $\left[\mathrm{GeV}^2\right]$

L, N	a_D	Resonance					Pred.
0,0	$\frac{1}{2}$	$N(940)$				input:	0.94
0,0	0	$\Delta(1232)$					1.27
0,1	$\frac{1}{2}$	$N(1440)$					1.40
1,0	$\frac{1}{4}$	$N(1535)$	$N(1520)$				1.53
1,0	0	$N(1650)$	$N(1700)$	$N(1675)$			1.64
1,0	0	$\Delta(1620)$	$\Delta(1700)$		L, N=0,1:	$\Delta(1600)$	1.64
2,0	$\frac{1}{2}$	$N(1720)$	$N(1680)$		L, N=0,2:	$N(1710)$	1.72
2,0	0	$N(1900)$	$N(1990)$	$N(2000)$	$\Delta(1910)$	$\Delta(1920)$	1.92
2,0	0	$\Delta(1905)$	$\Delta(1950)$	$\Delta(1900)^*$	$\Delta(1940)^*$	$\Delta(1930)^*$	1.92
0,3	$\frac{1}{2}$	$N(2100)$					2.03
3,0	$\frac{1}{4}$	$N(2070)$	$N(2190)$	L, N=1,2:	$N(2080)$	$N(2090)$	2.12
3,0	0	$N(2200)$	$N(2250)$	$\Delta(2223)$	$\Delta(2200)$	L, N=1,2:	2.20
4,0	$\frac{1}{2}$	$N(2220)$				$\Delta(2150)$	2.27
4,0	0	$\Delta(2390)$	$\Delta(2300)$	$\Delta(2420)$	L, N=3,1:	$\Delta(2400)$	2.43
5,0	$\frac{1}{4}$	$N(2600)$				$\Delta(2350)$	2.57
6,0	$\frac{1}{2}$	$N(2700)$					2.71
6,0	0	$\Delta(2950)$			L, N=5,1:	$\Delta(2750)$	2.84

*: L, N=1,1.

H. Forkel and E. K., Phys. Lett. B 679, 77 (2009).

Excellent agreement with 2 parameters !

7 : Which states are observed and which ones not?

a: Ground states: N, Δ with $56 = {}^4\mathbf{10} + {}^2\mathbf{8}$

b: The first excitation band: $(D, L^P_{\mathsf{N}}) = (70, 1^-_1)$

$$70 = {}^2\mathbf{10} + {}^4\mathbf{8} + {}^2\mathbf{8} + {}^2\mathbf{1}$$

$L; S$	$J = 1/2$	$J = 3/2$	$J = 5/2$
$L = 1; S = 1/2$	$N_{1/2^-}(1535)$	$N_{3/2^-}(1520)$	
$L = 1; S = 3/2$	$N_{1/2^-}(1650)$	$N_{3/2^-}(1700)$	$N_{5/2^-}(1675)$
$70, 10; 1/2$	$\Delta_{1/2^-}(1620)$	$\Delta_{3/2^-}(1700)$	

This is in agreement with quark model expectations.

c: The second excitation band:

$$(D, L_N^P) = \underline{(56, 0_2^+)}, \quad \underline{(70, 0_2^+)}, \quad \text{perhaps seen}: N(1710), \Delta(1750)$$

$$(D, L_N^P) = \quad (20, 1_2^+), \quad \text{not seen}$$

$$(D, L_N^P) = \underline{(56, 2_2^+)}, \quad \underline{(70, 2_2^+)}, \quad \text{partly seen}$$

D; s; L	$J = 1/2$	$J = 3/2$	$J = 5/2$	$J = 7/2$
56, 8; 1/2; 0	$N_{1/2^+}(1440)$			
56, 8; 1/2; 2		$N_{3/2^+}(1720)$	$N_{5/2^+}(1680)$	
56,10; 3/2; 0		$\Delta_{3/2^+}(1600)$		
56,10; 3/2; 2	$\Delta_{1/2^+}(1910)$	$\Delta_{3/2^+}(1920)$	$\Delta_{5/2^+}(1905)$	$\Delta_{7/2^+}(1950)$
70, 8; 1/2; 0	$N_{1/2^+}(1710)$			
70, 8; 3/2; 2	$N_{1/2^+}(1880)$	$N_{3/2^+}(1900)$	$N_{5/2^+}(2000)$	$N_{7/2^+}(1990)$
70, 8; 1/2; 2		x	x	
70,10; 3/2; 0	$\Delta_{1/2^+}(1750)$			
70,10; 1/2; 2		x	x	
20, 8; 1/2; 2	x	x		

d: The third excitation band:

$$(D, L^P_{\mathsf{N}}) \;=\; \underline{(56, 1_3\ )},\ 2\,(70, 1_3\ ), (20, 1_3\ ),$$

$$(D, L^P_{\mathsf{N}}) \;=\; (70, 2_3\ ),$$

$$(D, L^P_{\mathsf{N}}) \;=\; (56, 3_3\ ),\ \underline{(70, 3_3\ )},\ (20, 3_3\ ),$$

D; s		$J = 1/2$	$J = 3/2$	$J = 5/2$
$56, 8; 1/2$		$N_{1/2^-}(1846)$	$N_{3/2^-}(1875)$	
$56, 10; 3/2$		$\Delta_{1/2^-}(1900)$	$\Delta_{3/2^-}(1940)$	$\Delta_{5/2^-}(1930)$

D; s	$J = 3/2$	$J = 5/2$	$J = 7/2$	$J = 9/2$
$70, 8; 1/2$		$N_{5/2^-}(2070)$	$N_{7/2^-}(2190)$	
$70, 8; 3/2$	x	$N_{5/2^-}(2200)$	x	$N_{9/2^-}(2250)$
$70, 10; 1/2$		x	$\Delta_{7/2^-}(2200)$	

Some multiplets are (nearly) completely filled, others are empty.

Conjecture: permutation symmetry is relaxed for large separation. Only scalar isoscalar diquarks survive at large excitation energy. In the transition region, also vector isovector diquarks are important.

8: Conclusions and Outlook

1. **Quantum numbers**
   In contrast to the general believe, the leading orbital angular momentum of baryons can be identified. Also, the radial excitation quantum numbers seems to be an identifiable number.

2. **Mass values**
   A simple AdS/QCD-based mass formula reproduces the full baryon spectrum (Δ: 1 parameter, nucleon: 2nd parameter, strange and cascades: 3 parameter)
   The first two parameters are related to the size of the resonance. “Good diquarks”, qq pairs with $S = 0$ and $I = 0$, are more compact than other pairs (like $S = 1$ and $I = 1$).

3. **Occupation**
   The first excitation shell is completely full, the second partly, the third has completely filled multiplets and completely empty multiplets. There seems to be a dynamical selection rule. The observed states match the predictions of AdS/QCD.