Nucleon excitations *

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Abstract The mass pattern of nucleon and Δ resonances is compared with predictions based on quark models, the Skyrme model, AdS/QCD, and the conjecture of chiral symmetry restoration.

Key words Baryon resonances, AdS/QCD, quark models, chiral symmetry

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1 Introduction

The driving force behind the intense efforts to clarify the spectrum of meson and baryon resonances is the aim to improve the understanding of the confinement mechanism and of the dynamics of quarks and gluons in the non-perturbative region of QCD. Different approaches have been developed.

The systematics of the baryon ground states were constitutive for the development of quark models. For excited states, different quark model variants are capable of reproducing the main features of the data but the models fail in important details: the number of expected states is considerably larger than confirmed experimentally, and the masses of radial excitations are mostly predicted at too high masses.

Resonances fall into a mass range where the usefulness of quarks and gluons can be debated; there are attempts to generate resonances dynamically from ground-state mesons (pseudoscalar and vector) and ground-state baryons (octet and decuplet). Possibly, this is an alternative approach to the resonance spectrum; the mechanism may however also be the source of additional resonances which come atop of the quark model states.

In the harmonic oscillator (h.o.) approximation, the quark model predicts a ladder of meson and baryon resonances with equidistant squared masses, alternating with positive and negative parity, and this pattern survives in more realistic potentials. Experimentally, positive and negative parity states are often degenerate in mass. This fact is the basis for the conjecture that chiral symmetry might be restored when resonances are excited into the high-mass region.

AdS/CFT is a new approach to describe QCD phenomena in an analytically solvable model over a wide range of interaction energies. The calculations include the meson and baryon mass spectrum. In the case of mesons, most masses (except those for scalar and pseudoscalar mesons) are well reproduced; for baryons the numerical success is amazing.

Finally, there was the claim at this conference that the Skyrme model does as well as AdS/QCD in reproducing the mass spectrum. Hence the comparison, predictions versus experiment, will be done for predictions of AdS/QCD, of the Skyrme model, and of three different quark model variants. The main focus of the talk will be on baryon resonances; mesons will be mentioned briefly in a few cases.

2 Quark models

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

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

where D is the SU(3) dimensionality (56 or 70), L the orbital angular momentum, P the parity, N the shell number. Two questions emerge. First, can we relate these h.o. states with observed resonances? Second, is there some systematic of the so-called missing resonances? We remind the reader that not all solutions of a Hamiltonian need to be realized dynamically.

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The observed states *and* the missing states may hence contain an important message how QCD arranges a three-quark system at large excitation energies.

There are great successes of the quark model for baryon spectroscopy: these include the interpretation of ground-state baryons in SU(3) multiplets, the correct prediction of the multiplicity of low-mass negative-parity states in the first excitation band $(D, L^P_{\rm N}) = (70, 1^-_1)$, and the correct prediction of baryon properties like formfactors, magnetic moments. But some problems remain

- The $N_{1/2^-}(1535)$ – $N_{1/2^+}(1440)^*$ mass difference is +100 MeV experimentally, and - 80 MeV in most quark models.
- There are more states predicted than found experimentally (missing resonance problem).
- There are no states in a 20-plet, expected from the SU(6) decomposition $6{\otimes}6{\otimes}6 = 56{\oplus}2{\cdot}70{\oplus}20$.
- Conceptually, one may ask if constituent quarks should have a defined rest mass when going to high excitation energies.

Quark model variants help to improve some details. The gluonic flux tube can be excited leading to a rich spectrum of hybrid baryons but this possibility aggravates the problem of the missing resonances. Five-quark components in the wave functions can be justified since a P-wave excitation in $(q-qq)$ "costs" about 450 MeV, and adding a pseudoscalar $q\bar{q}$ pair in S-wave in $(q\bar{q}qqq)$ may be energetically favored. Baryons like $N_{1/2^-}(1535)$ could thus be made up from five quarks. If these cluster into a qqq and a $q\bar{q}$ color singlet, these states are not necessarily due to multiquark chemistry but rather meson-nucleon molecules.

3 Dynamically generated resonances

The classical example for a dynamically generated resonance is the $\Delta(1232)$ which is represented as qqq state in quark models while Chew explained it as resonance in the $N\pi$ system[1]. In the modern concept, nucleon and $\Delta(1232)$ are considered as fundamental particles from which higher-mass resonances are constructed. An often discussed state is $N_{1/2^-}(1535)$ which can be very successfully described as $N\eta$-ΣK coupled-channel effect[2] or $\Lambda_{1/2^-}(1405)$ coupling strongly to $\Sigma\pi$ and NK. Possibly, the latter resonance is split into two states[3]. Open is the question if all baryon resonances can be constructed from their decay modes. And it is also unclear if the generation of resonances provides a dual description of the same baryons as the quark model or if qqq and molecular descriptions lead to different states which could co-exist (and may mix) leading to a larger number of states than predicted by quark models alone.

Here it must be mentioned that 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. Hence quark-model wave functions and meson–baryon states have a sizable overlap and possibly, they span the same Hilbert space. Finally, both chiral Lagrangians and quark-model Lagrangians are approximations of the same underlying theory, of QCD. The resulting spectra should not be just added.

This view has far reaching consequences. It is easy to accept that there is one $N_{1/2^-}(1535)$ resonance, not a quark model state and a dynamically generated one. If $f_0(980)$ and $a_0(980)$, and the hidden charm resonances X, Y, Z, are both molecules and $q\bar{q}$, this is a controversially debated question. $\sigma(500)$ and $\kappa(700)$ are certainly dynamically generated and not 1^3P_0 quark model states. A different question is what happens when the current quark mass could be changed continuously from the b-quark mass to light quarks. It is possible that this gedanken experiment would connect the $\chi_{b0}(1P)$ to the σ. The response of QCD certainly depends critically on the mass when a $q\bar{q}$ pair is created in the vacuum. In the light quark sector, σ is the lowest mass state, in the bottomonium sector it is $\chi_{b0}(1P)$, hence σ may deserve the notation and interpretation as $f_0(1P)$ state.

4 Chiral multiplets

Baryon resonances exhibit an unexpected phenomenon: parity doublets, pairs of resonances with the same spin J but opposite parities[4]. Often, these are quartets of N^* and Δ^* having the same J, see Table 1. Resonances and star rating are taken from PDG[5]. If only those states are included which survived the latest GWU analysis[6], no quartet and only few parity doublets remain. The chiral multiplets are interpreted as indication that chiral symmetry may be restored at large excitation energy.

*We give spin and parity of a resonance explicitly and not the $N\pi$ partial wave.

Table 1. Chiral multiplets for $J=1/2$, 3/2, 5/2 (first three lines) and for $J=1/2,\cdots,7/2$ (last four lines) for nucleon and Δ resonances.

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

5 Super-multiplets with defined quantum numbers

5.1 $\vec{L}$ 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, collected in the first data block of Table 2, form a N^* doublet, a N^* triplet, and a Δ^* doublet, well separated in mass from all other negative parity states.
2. The positive parity states (second block) form an isolated N^* doublet, a N^* quartet, and a Δ^* quartet.
3. At higher mass there is a mass degenerate negative-parity Δ^* triplet and a Δ^* doublet (third block).
These multiplets are separated by 200 MeV from other states having the same quantum numbers. Of course, mixing of states having identical quantum numbers is possible; but there is no visible effect of mixing on the masses.

Frequently a statement is made that L and S cannot be good quantum numbers. Quarks, even constituent quarks, are supposed to move with relativistic velocities. And in relativity, only J is defined. But we should admit that we do not know the dynamical origin of the mass of a resonance. The nucleon mass is predominantly due to field energy. Why should the mass of the $\Delta_{7/2^+}(1950)$ not be predominantly due to field energy? As long as we have no deep understanding of the mechanism leading to the excited states, we should take phenomenology serious. And phenomenologically, L, S supermultiplets are an important organizing principle for baryon spectroscopy.

5.2 The radial excitation quantum number N

In the harmonic oscillator approximation, a shell number N is defined which gives - to first order - the masses of baryon resonances. We use, instead, the

Table 2. Supermultiplets in L and S for N and Δ excitations (upper part). The lower part of the table shows the mass square splitting of states within a given partial wave.

$L;S$	$J^P=1/2^-$	$J=3/2^-$	$J=5/2^-$		
$L=1;S=1/2$	$N_{1/2^-}(1535)$	$N_{3/2^-}(1520)$			
$L=1;S=3/2$	$N_{1/2^-}(1650)$	$N_{3/2^-}(1700)$	$N_{5/2^-}(1675)$		
$L=1;S=1/2$	$\Delta_{1/2^-}(1620)$	$\Delta_{3/2^-}(1700)$			
$L;S$	$J^P=1/2^+$	$3/2^+$	$5/2^+$	$7/2^+$	
$L=2;S=1/2$		$N_{3/2^+}(1720)$	$N_{5/2^+}(1680)$		
$L=2;S=3/2$	$N_{1/2^+}(1880)$	$N_{3/2^+}(1900)$	$N_{5/2^+}(2000)$	$N_{7/2^+}(1990)$	
$L=2;S=3/2$	$\Delta_{1/2^+}(1910)$	$\Delta_{3/2^+}(1920)$	$\Delta_{5/2^+}(1905)$	$\Delta_{7/2^+}(1950)$	
	$J^P=1/2^-$	$3/2^-$	$5/2^-$	$7/2^-$	
$L=1;S=3/2$	$\Delta_{1/2^-}(1900)$	$\Delta_{3/2^-}(1940)$	$\Delta_{5/2^-}(1930)$	No state!	
$L=3;S=1/2$			$\Delta_{5/2^-}(2233)$	$\Delta_{7/2^-}(2200)$	
	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	
56, 10; 3/2	$\Delta_{3/2^+}(1600)$		$\Sigma_{3/2^+}(1840)$	x	N=1
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	
δM^2	2.04±0.15	2.03± 0.15	1.72±0.16		Possibly 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		

radial excitation number N. N and N are related by $\mathsf{N} = L+2N$. To make contact with models, we define $N=0$ for the lowest-mass state. The Roper-like resonances (lowest mass states with ground-state q.n.: $N_{1/2^+}(1440)$, $\Delta_{3/2^+}(1600)$, $\Lambda_{1/2^+}(1600)$, $\Sigma_{1/2^+}(1660)$, $\Xi_{1/2^+}(1690)$) are given in the forth data block in Table 2. The spacings are all compatible with the spacing, per unit of angular momentum, of the leading (meson or) baryon trajectory (which is $1.14\,\mathrm{GeV}^2$).

The last (fifth) data block gives the third state in a given partial wave. For the second radial excitation, the expected spacing w.r.t. the ground state would be $2.28\,\mathrm{GeV}^2$. In the quark model, the states would belong to the fifth excitation band and the expected spacing would be in the order of $5.5\,\mathrm{GeV}^2$. The quark model suggests, however, states in which the two intrinsic harmonic oscillators are orbitally excited to $l_1=l_2=1$ and that $\vec{L}=\vec{l}_1+\vec{l}_2$ vanishes. In this case, the states belong to a 70-plet in SU(6). In this interpretation, also two states with $\vec{L}=\vec{l}_1+\vec{l}_2$ and $L=1$, i.e. with $J=1/2^+$ and $J=3/2^+$ should be observed. Since $L=2$ gives $\approx$1930 MeV, $L=0$ $\approx$1730 MeV, we may expect such a doublet at about 1830 MeV. Since both oscillators are excited, they may decouple from single-pion emission and could be observable in a cascade only, e.g. via $N_{3/2^-}(1520)\pi$.

5.3 Can all these data be used?

The recent analysis of the GWU group has shed doubts on the existence of many of the states reported in the Karlsruhe-Helsinki and Carnegie Mellon analyses [7, 8]. Of course, it is an open question if the old analyses are right or if many states listed in the Review of Particle Properties [5] are fake. In the BnGa partial wave analysis [9] many resonances, not seen in the GWU analysis, do show up in inelastic reactions. For the time being, the evidence for a failure of the old analysis is not convincing, and the full spectrum listed in [5] is used for the discussion presented here.

6 AdS/QCD

The AdS/CFT correspondence provides an analytically solvable approximation to QCD in the regime where the QCD coupling is large. It has led to important insights into the properties of quantum chromodynamics and can be used to calculate the hadronic spectrum of light-quark meson and baryon resonances[10]. The dynamics is controlled by a variable ζ which is suggested[10] to be related to the mean distance between the constituents. In the hard-wall approximation, ζ is constrained to $\zeta \le \zeta_{\max} = 1/\Lambda_{\mathrm{QCD}}$. In the soft wall approximation[11], a dilaton background field proportional to ζ^2 is introduced which limits the mean distance between the constituents softly. The results on the baryon excitation spectrum shown below refer to solutions with a soft wall.

6.1 Δ resonances

Applied to Δ resonances, a very simple formula can be derived[12] which reads

$$M^2 = 1.04 \cdot (L+N+3/2)\ [\mathrm{Ge}V^2]\,. \qquad (1)$$

Replacing 3/2 by 1/2 and with a small readjustment of numerical constant by less than 10%[12], the meson mass spectrum is reproduced qualitatively, except for scalar and pseudoscalar mesons (see Fig. 57 in ref.[13]). For the Δ excitation spectrum, the agreement is excellent as visualized in Fig. 1. To Δ reso-

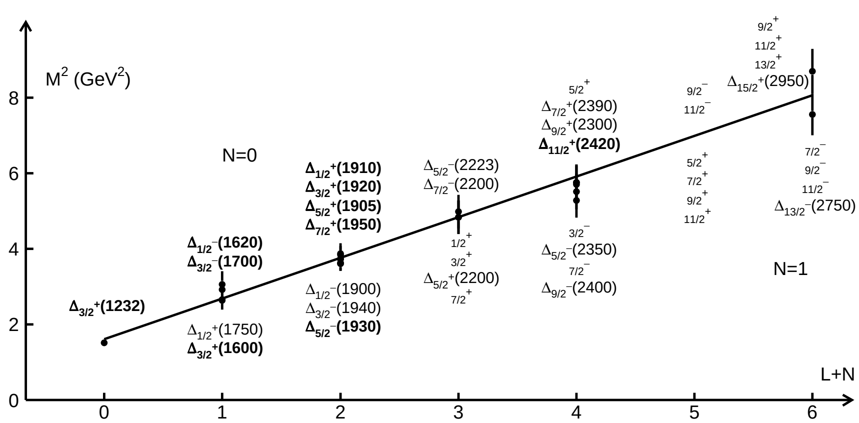

Fig. 1. Masses of positive and negative parity Δ resonances as a function of $L+\mathsf{N}$. The masses are three- and four-star resonances are bold, the others are classified as one-star or two-star resonances. The so-called $\Delta_{5/2^+}(2000)$ has entries at 1750 MeV and at 2200 MeV. We retain the 2200 MeV entry only.

nances with even angular momenta, we assigned the quantum numbers (L, $N=0$, $S=3/2$) or (L, $N=1$, $S=3/2$). Δ resonances with odd angular momenta, quantum numbers (L, $N=0$, $S=1/2$) or (L, $N=1$, $S=3/2$) are assigned, with a strict correlation between N and S.

6.2 Masses of nucleon resonances

Masses of nucleon resonances depend not only on L and N but also on S: the mass of the $L=1, S=1/2$ doublet - $N_{1/2^-}(1535)$ and $N_{3/2^-}(1520)$ - is smaller than that of the $L=1, S=3/2$ triplet comprising $N_{1/2^-}(1650)$, $N_{3/2^-}(1700)$, and $N_{1/2^-}(1675)$. The triplet is mass-degenerate with the negative-parity Δ doublet. The mass of the spin doublet $N_{3/2^+}(1720)$, $N_{5/2^-}(1680)$ with $L=2, S=1/2$ is smaller than that of the quartet with $L=2, S=3/2$ which is formed by $N_{1/2^+}(1880)$, $N_{3/2^+}(1900)$, $N_{5/2^+}(1870)$, $N_{7/2^+}(1990)$. The latter quartet is mass-degenerate with the positive-parity quartet of Δ states having the same L and S. More examples can be found. Nucleon resonances with intrinsic spin 1/2 have a mass which is smaller than their $S=3/2$ partners. We assign a reduction in mass to those baryons which have a scalar isoscalar diquark, a *good diquark*, as part of their wave function. Δ resonances never have *good diquarks*, nor nucleons with $S=3/2$. The nucleon has a wave function for which the probability to find a good diquark α_D is equal to 1/2. For the two states $N_{1/2^-}(1535)$, $N_{3/2^-}(1520)$, $\alpha_D=1/4$, and the squared mass difference to the spin or isospin 3/2-states is half the Δ–N mass square difference. These observations can be condensed into a surprisingly simple formula given by Forkel and Klempt[14]

$$M^2 = a\cdot(L+N+3/2) - b\cdot\alpha_D \;[\mathrm{GeV}^2] \qquad (2)$$

with $a=1.04\,\mathrm{GeV}^2$ and $b=1.46\,\mathrm{GeV}^2$. Eq. (2) reproduces very well the full light-quark baryon mass spectrum.

6.3 Other approaches

It is instructive to compare the precision with which the different models reproduce the baryon mass spectrum (Table 3). All resonances from PDG[5] are listed, 1-star to 4-star but for resonances which are observed neither by Arndt[6], nor by Höhler[7] nor by Cutkovsky[8], no mass is given here. Four new states, suggested by BnGa and GWU analyses, are included. Predictions based on AdS/QCD, on the quark model of Capstick-Isgur model[15] and on two variants of the Bonn model[16] - differing in the choice of the Lorentz structure of the confinement potential - are listed. For quark models, the comparison is not fully straightforward, due to the multitude of predicted states. The

Table 3. Masses of N and Δ resonances, experiment versus calculated masses. Mass values and errors are taken from a recent review [18]. FK: AdS/QCD model, eq. (2), CI: Capstick and Isgur[15], BnA and BnB Bonn model[16], MK: Skyrme model of Karliner and Mattis[17].

Resonance	Mass	FK	CI	Bn-A	Bn-B	MK
N_{param}		2	10	7	7	2
$N(940)$	940	943	960	939	939	1190
$\Delta(1232)$	1232 ± 1	1261	1230	1231	1261	1435
$N_{1/2^+}(1440)$	1450 ± 32	1396	1540	1698	1540	
$N_{1/2^-}(1535)$	1538 ± 10	1516	1460	1435	1470	1478
$N_{3/2^-}(1520)$	1522 ± 4	1516	1495	1476	1485	1715
$N_{1/2^-}(1650)$	1660 ± 18	1628	1535	1660	1767	
$N_{3/2^-}(1700)$	1725 ± 50	1628	1625	1606	1631	
$N_{5/2^-}(1675)$	1675 ± 5	1628	1630	1655	1622	1744
$\Delta_{1/2^-}(1620)$	1626 ± 23	1628	1555	1654	1625	1478
$\Delta_{3/2^-}(1700)$	1720 ± 50	1628	1620	1628	1633	1737
$\Delta_{3/2^+}(1600)$	1615 ± 80	1628	1795	1810	1923	1435
$N_{3/2^+}(1720)$	1730 ± 30	1735	1795	1688	1762	1982
$N_{5/2^+}(1680)$	1683 ± 3	1735	1770	1723	1718	1823
$N_{1/2^+}(1710)$	1713 ± 12	1735	1770	1729	1778	1427
$\Delta_{1/2^+}(1750)$		-	1835	1866	1901	
$N_{1/2^-}(1905)$	1905 ± 50	1833	1945	1910	1971	
$N_{3/2^-}(1860)$	1850 ± 40	1833	1960	1940	1949	
$N_{1/2^+}(1880)^a$	1890 ± 50	1926	1880	1973	1974	
$N_{3/2^+}(1900)$	1940 ± 50	1926	1870	1899	1904	
$N_{5/2^+}(1870)^a$	1870 ± 40	1926	1770	1934	1943	
$N_{7/2^+}(1990)$	2020 ± 60	1926	2000	1989	1941	2011
$\Delta_{1/2^-}(1900)$	1910 ± 50	1926	2035	2100	2169	2035
$\Delta_{3/2^-}(1940)$	1995 ± 60	1926	2080	2122	2161	
$\Delta_{5/2^-}(1930)$	1930 ± 30	1926	2155	2170	2152	1730
$\Delta_{1/2^+}(1910)$	1935 ± 90	1926	1835	1906	1928	1982
$\Delta_{3/2^+}(1920)$	1950 ± 70	1926	1915	1910	1955	1946
$\Delta_{5/2^+}(1905)$	1885 ± 25	1926	1910	1940	1932	1831
$\Delta_{7/2^+}(1950)$	1930 ± 16	1926	1940	1956	1912	1816
$N_{1/2^+}(2100)$	2090 ± 100	2017	1975	2127	2177	
$N_{1/2^-}(2090)$		2102	2135	2200	2180	
$N_{3/2^-}(2080)$	2100 ± 55	2102	2125	2079	2095	
$N_{5/2^-}(2060)^a$	2065 ± 25	2102	2155	1970	2026	
$N_{7/2^-}(2190)$	2150 ± 30	2102	2090	2093	2100	2075
$N_{5/2^-}(2200)$	2160 ± 85	2102	2234	2185	2217	
$N_{9/2^-}(2250)$	2255 ± 55	2184	2234	2212	2170	2234
$\Delta_{1/2^-}(2150)$		2184	2140	2171	2217	
$\Delta_{5/2^-}(2223)^b$	2223 ± 53	2184	2155	2170	2179	
$\Delta_{7/2^-}(2200)$	2230 ± 50	2184	2090	2210	2200	2162
$N_{9/2^+}(2220)$	2360 ± 125	2265	2327	2221	2221	2327
$\Delta_{7/2^+}(2390)$	2390 ± 100	2415	2032	2340	2343	
$\Delta_{9/2^+}(2300)$	2360 ± 125	2415	2407	2453	2421	2407
$\Delta_{11/2^+}(2420)$	2462 ± 120	2415	2450	2442	2388	2327
$\Delta_{9/2^-}(2400)$	2400 ± 190	2415	2083	2280	2207	
$\Delta_{3/2^-}(2350)$	2310 ± 85	2415	2145	2216	2234	
$N_{11/2^-}(2600)$	2630 ± 120	2557	2327	2628	2610	2558
$N_{13/2^+}(2800)$	2800 ± 160	2693	2558	2616	2619	2882
$\Delta_{13/2^-}(2750)$	2720 ± 100	2820		2685	2604	2579
$\Delta_{15/2^+}(2950)$	2920 ± 100	2820		2824	2768	2810

^{a}: BnGa; ^{b}: GWU

Bonn model[16] predicts, e.g., for the $1/2^-$ sector two low mass states which are readily identified, and then seven further states with masses, which are found to be (1901, 1918); (2153, 2185, 2194, 2232, 2242) in model $\mathcal{A}$, and (1971); (2082, 2180, 2203, 2261, 2270, 2345) in model $\mathcal{B}$. We compare the experimental masses with the center of gravity of a group of states. The groups were suggested by the authors. At the conference there was the claim that an equally good description of the data was obtained in a Skyrme model[17], also with just two parameters. This claim is tested as well. From Table 3 we determine the mean relative difference between calculated and measured mass for the five models:

$$(\delta M/M)_{\rm FK} = 2.5\%\ (2p);\ (\delta M/M)_{\rm CI} = 5.6\%\ (9p)$$
$$(\delta M/M)_{\rm BnA} = 5.1\%\ (7p);\ (\delta M/M)_{\rm BnB} = 5.4\%\ (7p)$$
$$(\delta M/M)_{\rm MK} = 9.1\%\ (2p).$$

The number of parameters adjusted to achieve good agreement with data is given in parentheses. At 2 GeV mass, AdS/QCD agrees on average within 50 MeV, the quark models to about 110 MeV, and the Skyrme model to about 190 MeV. Compared to the quark models, AdS/QCD requires substantially fewer parameters. The Skyrme models fails to predict a large number of resonances, including some well-established resonances, and gives the worst description of the experimental mass spectrum.

6.4 Interpretation

Why is the mass formula derived from AdS/QCD - and suggested on a phenomenological basis a few years earlier [19] - so successful? Two aspects are remarkable. First, in AdS/QCD the coefficient a is related to the hadron size, and the reduction in mass of nucleons with good-diquark content is interpreted by a smaller size of good diquarks compared to diquarks have spin or isospin 3/2. Second, baryon resonances form super-multiplets with defined L and S. This is not the organization principle for the dynamics of a highly relativistic three-quark system. Most physicist prefer to stay with the highly relativistic three-quark system and to abandon phenomenology. However, as mentioned in the introduction, the nucleon mass is not understood as arising from the motion of relativistic quarks but rather as effect of the breaking of chiral symmetry of nearly massless quarks. Possibly, chiral symmetry breaking is also the primary source for the masses of excited baryons, but chiral symmetry is broken in an extended volume. A physical picture emerges which assigns the largest fraction of the masses of light-quark baryons to a volume in which field energy is stored. Centrifugal forces expand the size as suggested a long time ago by Nambu[20]. The string-like behavior is the reason why AdS/QFT works so nicely. Isoscalar scalar diquarks are more tightly bound, their volume is smaller. The fraction of the isoscalar scalar diquarks is smaller for odd angular momenta that in case of even L.

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