Do parity doublets in the baryon spectrum reflect restoration of chiral symmetry ?

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Abstract: We discuss the mass spectrum of highly-excited nucleon and Δ^* resonances. The spectrum exhibits parity doublets, pairs of resonances of identical total angular momentum J but of opposite parity. It has been proposed that the parity doublets evidence restoration of chiral symmetry at large baryon excitation energies. We compare this conjecture with the possibility that high-mass states are organized into (L, S)-multiplets with defined intrinsic quark spins and orbital angular momenta. The latter interpretation results in a better description of the data. There is however a small trend possibly indicating the onset of chiral symmetry restoration.

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1 Introduction

The observation of parity doublets in high-mass excitations of the nucleon and of the Δ has stimulated a discussion if this effect signals restoration of chiral symmetry [1]-[5]. At high masses, resonances can be grouped into doublets of states having the same total angular momentum J but opposite parities. At lower masses, chiral symmetry is broken, and the mass of the chiral partner of the nucleon, the N(1535)S_{11}, differs from the nucleon mass substantially. In this letter, we will denote resonances like the N(1535)S_{11} as $\mathrm{N}_{1/2^-}(1535)$ where spin and parity are given explicitely.

Chiral symmetry allows for separate parity doublets in the nucleon and the Δ sector even though it supports also a higher symmetry in which N* and Δ^* resonances of a given J and opposite in parity are all degenerate in mass. Data seem to support this higher symmetry. This interpretation is however not uncontested: in a relativistic quark model with instanton induced forces, nucleonic parity doublets arise naturally [6]-[9]. However, none of the present quark model calculations reproduces the parity doublets in the Δ^* mass spectrum [10]-[12]. The interpretation of the parity doublets as evidence for chiral symmetry restoration seems thus unavoidable.

In this letter we suggest a different interpretation of parity doublets. We show that parity doublets develop naturally when spin orbit forces are neglected. The symmetry leading to the occurence of parity doublets is thus identified as absence of spin-orbit forces.

Table 1, adapted from Cohen and Glozman [4], shows N^* and Δ^* masses above 1.9 GeV, for states with positive and negative parity. In many cases, the effect of parity doubling is striking: states with identical J but opposite parity often have very similar masses. This does of course not imply that chiral symmetry restoration is the reason for the occurence of parity doublets.

Consider e.g. the first six Δ states in Table 1 with $J = 1/2, 3/2$ and $5/2$, and with positive and negative parities [13]. The masses are clearly degenerate; they form three parity doublets. The $\Delta_{7/2^+}(1950)$ and the $\Delta_{7/2^-}(2200)$ should also form a parity doublet but the $\Delta_{7/2^+}(1950)$ has a mass which is very close to the other three positive-parity resonances; the four positive-parity resonances rather seem to belong to a spin quartet of states with intrinsic orbital angular momentum $L = 2$ and intrinsic spin $S = 3/2$ coupling to $J = 1/2, .., 7/2$. The question arises if the parity doublets are really due to restoration of chiral symmetry or if the parity doublets reflect a symmetry of the underlying quark dynamics.

Cohen and Glozman [4] emphasize that the scheme requires the existence of a $\Delta_{11/2^-}$ and a $N_{11/2^+}$ at about 2500 MeV, of a $\Delta_{13/2^-}$ and a $N_{13/2^-}$ at 2750 MeV, and of three additional states at 2950 MeV. The existence of these states is a compelling prediction of chiral symmetry restoration. Experimental searches for these states are being carried out at ELSA in Bonn [14]. Also at Jlab [15], GRAAL [16], and at Spring8 [17] the high-mass baryon spectrum is studied.

$J = \frac{1}{2}$	1	$N_{1/2^+}(2100)$	$N_{1/2^-}(2090)$	a	$\Delta_{1/2^+}(1910)$	$\Delta_{1/2^-}(1900)$
$J = \frac{3}{2}$	2	$N_{3/2^+}(1900)$	$N_{3/2^-}(2080)$	b	$\Delta_{3/2^+}(1920)$	$\Delta_{3/2^-}(1940)$
$J = \frac{5}{2}$	3	$N_{5/2^+}(2000)$	$N_{5/2^-}(2200)$	c	$\Delta_{5/2^+}(1905)$	$\Delta_{5/2^-}(1930)$
$J = \frac{7}{2}$	4	$N_{7/2^+}(1990)$	$N_{7/2^-}(2190)$	d	$\Delta_{7/2^+}(1950)$	$\Delta_{7/2^-}(2200)$
$J = \frac{9}{2}$	5	$N_{9/2^+}(2220)$	$N_{9/2^-}(2250)$	e	$\Delta_{9/2^+}(2300)$	$\Delta_{9/2^-}(2400)$
$J = \frac{11}{2}$	6	$\mathbf{N_{11/2^+}}$	$N_{11/2^-}(2600)$	f	$\Delta_{11/2^+}(2420)$	$\boldsymbol{\Delta_{11/2^-}}$ (*)
$J = \frac{13}{2}$	7	$N_{13/2^+}(2700)$	$\mathbf{N_{13/2^-}}$	g	$\boldsymbol{\Delta_{13/2^+}}$	$\Delta_{13/2^-}(2750)$
$J = \frac{15}{2}$	8	$\mathbf{N_{15/2^+}}$	$\mathbf{N_{15/2^-}}$	h	$\Delta_{15/2^+}(2950)$	$\boldsymbol{\Delta_{15/2^-}}$ (*)

Table 1: Parity doublets of N^* and Δ^* resonances of high mass, after [4]. The states in boldface are predicted to have the same mass as their chiral partner when chiral symmetry is restored in the high-mass excitation spectrum of baryon resonances. We suggest that the states marked with a (*) should have considerably higher masses than their chiral partners while the other three states in boldface should be degenerate in mass with corresponding states of opposite parity.

2 N^* and Δ^* resonances

The discussion of which resonances one should expect, and at which masses, seems to require an understanding of how three valence quarks interact to form baryons and baryon resonances. This we do not have. Instead, we emphasize regularities in the mass spectra which can be used to identify leading quantum numbers.

A baryon resonance can be characterized by its flavor structure, by its spin J and parity P. In addition, there are quantum numbers which are not directly accessible: the total spin $\vec{J}$ can be decomposed into its orbital and spin angular momentum; the total orbital angular momentum $\vec{L}$ is a sum of two orbital angular momenta $\vec{l}_\rho$ and $\vec{l}_\lambda$ of the two oscillators allowed in a three-body system, $\vec{S}$ the sum of the three quark spins. In a relativistic situation, $\vec{l}_\rho$, $\vec{l}_\lambda$, $\vec{L}$, and $\vec{S}$ are not observable. Further, a flavor-octet resonance may have a symmetric or mixed-symmetry spacial wave function, and the spacial wave functions can have n_ρ and n_λ nodes, the baryon could be radially excited. The multitude of dynamical degrees of freedom leads to a rich spectrum. This is the problem of the *missing resonances*: quark models predict a much larger number of states than observed.

An alternative was proposed by Lichtenberg who suggested that baryons should be considered as quark-diquark excitations where two quarks are frozen into a quasi-stable subsystem [18]. This possibility was never scrutinized in a dynamical model; however, resonances like the $\mathrm{N}_{7/2^+}(1990)$ and $\Lambda_{7/2^+}(2020)$ are not easily accomodated in a diquark model.

We conjecture that the solution of the missing resonances might be found in a different interpretation of diquark configurations. Quark models expand the wave functions into harmonic oscillator wave functions $|(l_\rho, n_\rho); (l_\lambda, n_\lambda)\rangle$. It is plausible that baryon resonances are formed with one oscillator excited in the scattering process. Since it is not known which one is hit, there is a coherent superposition of $|(l_\rho, n_\rho) \neq 0; (l_\lambda, n_\lambda) = 0\rangle$ and $|(l_\rho, n_\rho) = 0; (l_\lambda, n_\lambda) \neq 0\rangle$ wave functions. No baryon is excited to a $|(l_\rho, n_\rho) \neq 0; (l_\lambda, n_\lambda) \neq 0\rangle$ component of a wave function, at the moment the resonance is formed. For these states, the initial l_ρ or l_λ (only one is non-zero) can be identified with the total orbital angular momentum L and the initial n_ρ or n_λ with $N = n_\rho + n_\lambda$ (which we define as radial quantum number). The wave functions constructed in this way are in general no energy eigenfunctions but should form a wave packet of energy eigenfunctions with a defined phase of the rotation or vibration.

This constraint leads to a large reduction in the number of expected states. We leave open the question if the 'missing' states do not exist or if they decouple from the πN system. Since most of the N* and Δ^* resonances were found in πN elastic scattering, they could have escaped detection so far. They should uncover themselves in photoproduction experiments of complex final states [19] which allow to study cascades of high-mass resonances. Two-oscillator excitations could be populated via pion emission from a high-mass resonance.

We now show that the leading quantum numbers, L, S, J, N of the known N* and Δ^* resonances can be identified in most cases, and that mixing between different internal configurations is small. This is an old observation stressed, e.g., by Feynman, Pakvasa and Tuan [20].

Table 2 shows all known N* and Δ^* resonances except the 1-star $\Delta_{1/2^+}(1750)$ and $\Delta_{5/2^+}(2000)$. The ground states N and Δ are known to be members of a SU(6) 56-plet which decomposes into a spin-1/2 octet and a spin-3/2 decuplet with $L = 0$. Likely, there is a small contribution of $L = 2$ in the wave function [21] but this effect does not prevent us from identifying $L = 0$ as leading component. In any case, the spatial wave function of these ground-state baryons is symmetric, and their spin-flavor wave function must be symmetric, too. The antisymmetry of the wave function w.r.t. the exchange of two quarks as required by the Pauli principle is guaranteed by the three colors.

In the first two rows of Table 2 there are two series' of states having the same quantum numbers as the ground state baryons, with mass square differences of $a \sim 1.1\,\mathrm{GeV}^2$. The Roper $\mathrm{N}_{1/2^+}(1440)$ and the analogous state $\Delta_{3/2^+}(1600)$ are supposed to be first radial excitations of the respective ground states; the $\mathrm{N}_{1/2^+}(1710)$ and $\mathrm{N}_{1/2^+}(2100)$ the second and third radial excitation. The $\Delta_{3/2^+}(1920)$ could be a radial excitation even though the assignment of intrinsic orbital angular momentum $L = 2$ and quark spin $S = 3/2$ is possible as well and perhaps more likely. Also the $\mathrm{N}_{1/2^+}(2100)$ could belong to a quartet of states with $L = 2$ and $S = 3/2$, yet its mass is rather high in comparison to the other positive parity N* states assigned to $L = 2$. We prefer to reserve this entry for the $\mathrm{N}_{1/2^+}(1986)$ proposed by the SAPHIR collaboration [22].

D	S	L	N					Mass (1)
56	1/2	0	0,1,2,3	$\mathrm{N}_{1/2^+}(939)$	$\mathrm{N}_{1/2^+}(1440)$	$\mathrm{N}_{1/2^+}(1710)$	$^{1}\mathrm{N}_{1/2^+}(2100)$	939 MeV
	3/2	0	0,1,2,3	$\Delta_{3/2^+}(1232)$	$\Delta_{3/2^+}(1600)$	$\Delta_{3/2^+}(1920)$		1232 MeV
70	1/2	1	0		$\mathrm{N}_{1/2^-}(1535)$	$\mathrm{N}_{3/2^-}(1520)$		1530 MeV
	3/2	1	0		$\mathrm{N}_{1/2^-}(1650)$	$\mathrm{N}_{3/2^-}(1700)$	$\mathrm{N}_{5/2^-}(1675)$	1631 MeV
	1/2	1	0		$\Delta_{1/2^-}(1620)$	$\Delta_{3/2^-}(1700)$		1631 MeV
56	1/2	1	1		$\mathrm{N}_{1/2^-}$	$\mathrm{N}_{3/2^-}$		1779 MeV
	3/2	1	1		$^{a}\Delta_{1/2^-}(1900)$	$^{b}\Delta_{3/2^-}(1940)$	$^{c}\Delta_{5/2^-}(1930)$	1950 MeV
70	1/2	1	1		$^{1}\mathrm{N}_{1/2^-}(2090)$	$^{2}\mathrm{N}_{3/2^-}(2080)$		2151 MeV
	3/2	1	1		$\mathrm{N}_{1/2^-}$	$\mathrm{N}_{3/2^-}$	$\mathrm{N}_{5/2^-}$	2223 MeV
	1/2	1	1		$\Delta_{1/2^-}(2150)$	$\Delta_{3/2^-}$		2223 MeV
56	1/2	2	0		$\mathrm{N}_{3/2^+}(1720)$	$\mathrm{N}_{5/2^+}(1680)$		1779 MeV
	3/2	2	0	$^{a}\Delta_{1/2^+}(1910)$	$^{b}\Delta_{3/2^+}(1920)$	$^{c}\Delta_{5/2^+}(1905)$	$^{d}\Delta_{7/2^+}(1950)$	1950 MeV
70	1/2	2	0		$\mathrm{N}_{3/2^+}$	$\mathrm{N}_{5/2^+}$		1866 MeV
	3/2	2	0	$\mathrm{N}_{1/2^+}$	$^{2}\mathrm{N}_{3/2^+}(1900)$	$^{3}\mathrm{N}_{5/2^+}(2000)$	$^{4}\mathrm{N}_{7/2^+}(1990)$	1950 MeV
	1/2	2	0		$\Delta_{3/2^+}$	$\Delta_{5/2^+}$		1950 MeV
70	1/2	3	0		$^{3}\mathrm{N}_{5/2^-}(2200)$	$^{4}\mathrm{N}_{7/2^-}(2190)$		2151 MeV
	3/2	3	0	$\mathrm{N}_{3/2^-}$	$\mathrm{N}_{5/2^-}$	$\mathrm{N}_{7/2^-}$	$^{5}\mathrm{N}_{9/2^-}(2250)$	2223 MeV
	1/2	3	0		$\Delta_{5/2^-}$	$^{d}\Delta_{7/2^-}(2200)$		2223 MeV
56	1/2	3	1		$\mathrm{N}_{5/2^-}$	$\mathrm{N}_{7/2^-}$		2334 MeV
	3/2	3	1	$\Delta_{3/2^-}$	$\Delta_{5/2^-}(2350)$	$\Delta_{7/2^-}$	$^{e}\Delta_{9/2^-}(2400)$	2467 MeV
56	1/2	4	0		$\mathrm{N}_{7/2^+}$	$^{5}\mathrm{N}_{9/2^+}(2220)$		2334 MeV
	3/2	4	0	$\Delta_{5/2^+}$	$\Delta_{7/2^+}(2390)$	$^{e}\Delta_{9/2^+}(2300)$	$^{f}\Delta_{11/2^+}(2420)$	2467 MeV
70	1/2	5	0		$\mathrm{N}_{9/2^-}$	$^{6}\mathrm{N}_{11/2^-}(2600)$		2629 MeV
56	3/2	5	1	$\Delta_{7/2^-}$	$\Delta_{9/2^-}$	$^{f}\Delta_{11/2^-}$	$^{g}\Delta_{13/2^-}(2750)$	2893 MeV
56	1/2	6	0		$^{6}\mathrm{N}_{11/2^+}$	$^{7}\mathrm{N}_{13/2^+}(2700)$		2781 MeV
	3/2	6	0	$\Delta_{9/2^+}$	$\Delta_{11/2^+}$	$^{g}\Delta_{13/2^+}$	$^{h}\Delta_{15/2^+}(2950)$	2893 MeV
70	1/2	7	0		$^{7}\mathrm{N}_{13/2^-}$	$^{8}\mathrm{N}_{15/2^-}$		3032 MeV
56	3/2	7	1	$\Delta_{11/2^-}$	$\Delta_{13/2^-}$	$^{h}\Delta_{15/2^-}$	$^{i}\Delta_{17/2^-}$	3264 MeV
56	1/2	8	0		$^{8}\mathrm{N}_{15/2^+}$	$\mathrm{N}_{17/2^+}$		3165 MeV
	3/2	8	0	$\Delta_{13/2^+}$	$\Delta_{15/2^+}$	$^{i}\Delta_{17/2^+}$	$\Delta_{19/2^+}$	3264 MeV

Table 2: Nucleon and Δ^* resonances and the quantum numbers assigned to them. More resonances are expected from quark models than shown here (see text for a discussion). D is the dimensionality of the SU(6) representation, S, L are intrinsic spin and orbital angular momenta assigned to a given resonance; N represents a radial excitation quantum number. The masses in the right-hand column are calculated using eq. (1). Pairs of nucleon resonances marked $^1, ^2, ^3, ..$ and Δ resonances $^a, ^b, ^c, ..$ are interpreted as parity doublets in [4].

In many cases, quantum numbers can be assigned to groups of states on the basis of an evident multiplet structure. The low-mass negative parity resonances with $L = 1$ cannot have a completely symmetric spatial wave function, hence they cannot be assigned to a 56-plet and must be in a SU(6) 70-plet. The latter decomposes into a N^* spin doublet, a N^* spin quartet and a Δ^* spin doublet, in accordance with the experimental findings. These states are listed in rows 3-5 in Table 2.

In line 7, we find a triplet of negative-parity Δ^* resonances at about 1930 MeV. We are tempted to assign $L = 1, S = 3/2$ to these states; however spin $S = 3/2$ and isospin $I = 3/2$ require a symmetric spatial wave function. This can only be achieved if not only the angular momentum is excited (to $L = 1$), also the radial wave function needs to have a node. The only way to avoid this conclusion would be to assign $L = 3, S = 1/2$ to the $\Delta_{5/2^-}(1930)$ and $L = 1, S = 1/2$ to the $\Delta_{1/2^-}(1900)$ and $\Delta_{3/2^-}(1940)$. We prefer to consider these three states as a triplet. The gap in mass square to the negative-parity doublet is $\sim 1.1\,\mathrm{GeV}^2$ and we assign one unit of radial excitation energy ($N = 1$) to these states.

We may expect e.g. also resonances in a SU(6) 70-plet with ($N = 1, L = 1, S = 1/2$). The 70-plet would contain a N^* spin doublet $1/2^-, 3/2^-$ at 1866 MeV, a N^* spin quartet $1/2^-, 3/2^-, 5/2^-$ at 1950 MeV and a Δ^* doublet $1/2^-, 3/2^-$ also at 1950 MeV. There are no entries for these states in the Review of Particle Properties even though there are two resonances proposed by SAPHIR, a $N_{1/2^-}(1897)$ [22] observed in the $N\eta'$ decay mode and a $N_{3/2^-}(1895)$ [23] decaying into $K^+\Lambda$. These are good candidates for the ($N = 1, L = 1, S = 1/2$) multiplet.

In rows 8-10 we list further negative-parity resonances. Their assignment as $L = 1, N = 2$ states is an educated guess.

Positive-parity baryons with $L = 2$ are possible as $\frac{1}{\sqrt{2}}\,|(2,0);(0,0) \pm (0,0);(2,0)\rangle$ configurations building a 56-plet and a 70-plet. The next rows (11-12) list a doublet of N^*'s and a quartet of Δ^*'s belonging to the 56-plet. The N^* quartet at 1950 MeV (row 14) is part of the 70-plet. All these resonances could have partners with radial excitation N but no candidates are known. (Except perhaps the $\Delta_{5/2^+}(2000)$ for which two mass values, 1752 and 2200 MeV, are listed by the Particle Data Group. The larger value would allow a $L = 2, N = 1$ assignment.)

For $L = 3$ and $L = 4$ we should expect a repetition of the pattern observed for $L = 1$ and for $L = 2$. Indeed, the known states can be mapped onto the predicted pattern.

The quantum numbers of high-mass resonances can best be identified when they are 'stretched' states, with their spin and orbital angular momentum aligned. Their observation can be used to assign quantum numbers to states where only one resonance of a spin multiplet is observed. For $L = 4$ there is no state which would need to be assigned to a 70-plet. In particular, there is no $N_{11/2^+}$. For large excitation energies, the largest total angular momenta J in a given mass range is often given by $J = L + S$ with $S = 1/2$ for N^* and $S = 3/2$ for Δ^*: spin and isospin are locked.

The most straightforward assignment for nucleon resonances in the mass range above 2.5 GeV is $(L, S) = (5, 1/2)$ for the $N_{11/2^-}(2600)$, and $(L, S) = (6, 1/2)$ for the $N_{13/2^+}(2700)$. To the $\Delta_{13/2^-}(2750)$ we assign ($L = 5, S = 3/2$) and $N = 1$ since for $N = 0$, a one-oscillator excitation to $L = 5$ cannot be fully symmetric. The $\Delta_{15/2^+}(2950)$ should have ($L = 6, S = 3/2$). These two states are expected here to have the same mass. This expectation is not really supported by the data but also not falsified, due to the large experimental errors.

3 Baryon masses

The regularity of the excitation energies suggests a baryon mass formula [24] which is discussed in this section. The mass formula reproduces with good χ^2 the masses of all but one baryons with known spin and parity. The baryon mass formula reads

$$\mathrm{M}^2 = \mathrm{M}_\Delta^2 + \frac{\mathrm{n_s}}{3} \cdot \left(\mathrm{M}_\Omega^2 - \mathrm{M}_\Delta^2\right) + a \cdot (L+N) - I_{sym} \cdot \left(\mathrm{M}_\Delta^2 - \mathrm{M}_\mathrm{N}^2\right). \quad (1)$$

$\mathrm{M_N}, \mathrm{M}_\Delta, \mathrm{M}_\Omega$ are input parameters taken from [25], $a = 1.142\,\mathrm{GeV}^2$ is the Regge slope determined from the series of light (isoscalar and isovector) mesons with quantum numbers $J^{\mathrm{PC}} = 1^{--}, 2^{++}, 3^{--}, 4^{++}, 5^{--}, 6^{++}$. There is no adjustable parameter in the mass formula.

The first two terms define the offset masses of Regge trajectories with n_s strange quarks in the baryon. Regge trajectories are usually drawn as functions of J. They can, however, also be drawn as functions of L. The squared masses then increase linearly with L, with good consistency. A motivation for this dependence was given by Nambu [28]. Note that the physical picture behind the mass formula is radically different from present quark models for baryon resonances. Here, the baryonic mass-gain with L is assigned to an increasing mass of the flux tube connecting (nearly massless) quarks. In quark models, the mass gain with L is due to an increase of kinetic and potential energy of the constituent quarks.

N is the radial excitation quantum number. There are 17 cases in which baryon resonances are observed which are higher in mass but have the same quantum numbers as a lower-mass state (see Table II in [24]) the Roper $\mathrm{N}_{1/2^+}(1440)$ being the best known example. The spacings in mass square are nearly the same as those for consecutive values of L. These facts require the $L+N$ dependence of the baryon masses while $L+2N$ gives the harmonic-oscillator band. This observation has also been made by Bijker, Iachello and Leviatan [26, 27]. They proposed a baryon mass formula which is based on a spectrum-generating algebra. The Hamiltonian is bilinear in six vector boson operators constructed for the two oscillators, plus one scalar boson operator. Excitations of n_ρ, n_λ are described as phonon vibrational excitations; calculated masses reproduce well experimental values.

The total angular momentum J does not enter the formula. The spin orbit or $\vec{L}\cdot\vec{S}$ coupling is supposed to vanish or to be small.

The spin S enters only through the last symmetry term which is defined to reproduce the N-Δ mass difference. It acts only on octet and singlet particles having spin 1/2; N*'s with spin 3/2 and Δ^*'s are predicted to be degenerate in mass. $\mathrm{I_{sym}}$ is the fraction of the harmonic-oscillator wave function (normalized to the nucleon wave function) which is antisymmetric in spin and flavor. It is given by

$$\begin{array}{llll} \mathrm{I_{sym}} = & 1 & \text{for } S=1/2 & \text{octet particles in a 56-plet;} \\ \mathrm{I_{sym}} = & 1/2 & \text{for } S=1/2 & \text{octet particles in a 70-plet;} \\ \mathrm{I_{sym}} = & 3/2 & \text{for } S=1/2 & \text{singlet particles;} \\ \mathrm{I_{sym}} = & 0 & \text{otherwise.} & \end{array} \quad (2)$$

Instantons and anti-instantons induce interactions in quark pairs when they are antisymmetric in both, in spin and in flavor. The data require, through the term $\mathrm{I_{sym}}$, a mass contribution proportional to this fraction in the wave function. It is this peculiar pattern of (2) which leads us to conclude that deviations from the leading Regge trajectory originate from instanton-induced interactions. In particular the N-Δ mass splitting is thus assigned to instanton-induced interactions and not to magnetic spin-spin interactions due to one-gluon exchange. The numerical agreement between predicted and observed baryon masses is quite good. For 44 the N* and Δ^* resonances listed in [25] the χ^2 is 40. With the same errors, the one-gluon exchange model results in $\chi^2 = 82$ calculated for the 32 resonances for which a mass is given in [10]; the one-boson exchange model [11] yields a χ^2 of 8 but uses only the 14 resonances below 1700 MeV. The number of parameters used for the mass formula is 4, in the one-gluon-exchange model 10 and in the one-boson exchange model 5.

It may be useful to exploit the predictive power of the mass formula also for some states which are not related to the question of parity doublets. We have included in Table 2 baryon resonances which are unobserved so far, and masses predicted by eq. (1). In particular a negative-parity doublet at 1779 MeV and a positive-parity doublet at 1866 MeV is expected. Not listed are resonances with a (L, S, N) assignment for which no state is known. In the subsequent discussion we use only the lowest and second lowest mass baryon in a given partial wave. Thus uncertainties due to the problem of missing resonances are mostly avoided.

4 Chiral parity doublets versus SU(6) multiplets

The mass formula predicts parity doublets, either of identical or of approximately equal masses. The origin of the mass doublets is different for N* and Δ^* resonances. We begin with a discussion of Δ^* resonances.

The three Δ^* resonances $\Delta_{5/2^-}(1930)$, $\Delta_{9/2^-}(2400)$, and $\Delta_{13/2^-}(2750)$ are unlikely to have intrinsic $L = 3, 5, 7$, respectively, but rather $L = 1, 3, 5$. The $\Delta_{5/2^-}(1930)$ is nearly degenerate in mass with two other negative-parity states, the $\Delta_{9/2^-}(2400)$ with the $\Delta_{5/2^-}(2350)$, suggesting that they all belong to a spin quartet (see Table 2), that they have $S = 3/2$. Hence their wave function is symmetric in spin and in flavor. The Pauli principle now requires a symmetric spatial wave function but negative parity states can have a symmetric wave function only when they are also excited radially.

Figure 1 (left) shows the multiplet structure of Δ^* resonances. According to eq. (1) the masses depend on $L+N$, hence positive-parity Δ^*'s with L even and $N = 0$ are mass degenerate with negative-parity Δ^*'s with orbital angular momentum $L - 1$ and $N = 1$. In absence of spin-orbit forces, the four positive-parity Δ^*'s with $J = L-3/2, ..., L+3/2$ have the same mass, and so have the four negative-parity states. But the L values differ by one unit, the quartet of positive-parity Δ^*'s is shifted to the right. Only six states form parity doublets, two states remain 'solitaires', the negative-parity state with $J = L - 1 - 3/2$ and the positive-parity state with $J = L+3/2$. This effect is visualized in Fig. 1 for $(L+N, P) = 2\pm$, $4\pm$, $6\pm$. The solitaire states are separated from their parity partners by one spacing $a = 1.142\,\text{GeV}^2$. The spacing is even larger ($2a$) when high-mass Δ^* resonances all have intrinsic spin 3/2 as we suggested above.

We predict that the $\Delta_{11/2^+}(2420)$ and $\Delta_{15/2^+}(2950)$ should remain solitaires, should not have close-by chiral partners, in contrast to the prediction of [4]. On the contrary, a $\Delta_{13/2^+}$ should exist at about 2893 MeV, about mass-degenerate with the $\Delta_{13/2^-}(2750)$, in this case in agreement with the prediction of [4].

The nucleon mass spectrum is more complicated, as shown in Fig. 1 (right). Nearly mass-degenerate chiral doublets develop due to the I_{sym} term in eq. (1). For positive-parity baryons with spin $S = 1/2, I_{sym} = 1$; for negative parity baryons with $S = 3/2, I_{sym} = 0$. A positive-parity baryon with orbital angular momentum L thus undergoes a shift downwards (in mass square equal to the Δ-N mass separation) and is thus found at a mass not too far from negative-

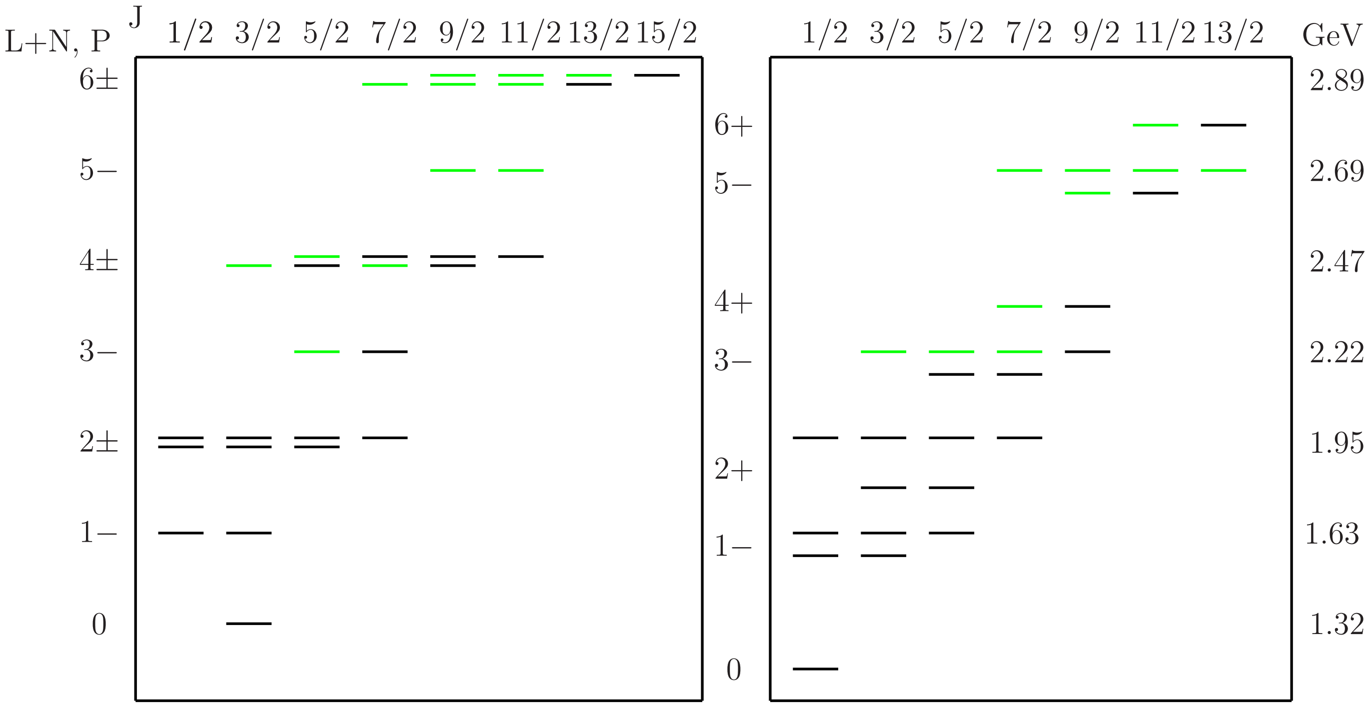

Figure 1: Schematic diagram of the energy levels of Δ^* (left) and N^* (right) resonances. The vertical axis is linear in squared baryon masses, mass values are given on the right axis. In case of mass degenerate states, negative-parity states are drawn below those with positive parity. Observed states are denoted by dark lines, expected ones by grey lines.

parity N^* resonances having orbital angular momentum $L-1$ and $S = 3/2$. Mass degeneracy is thus expected but only approximately. The predicted mass splitting is small enough that data may mimic parity doublets. Striking differences are only expected for negative-parity states with $J = L - 3/2$. These states are difficult to establish experimentally but they are true solitaires.

A decision if nucleonic resonances form parity doublets requires a quantitative analysis which is presented next. First we notice that according to eq. (1) the mass difference between two resonances with consecutive L and otherwise identical quantum numbers vanishes asymptotically: $M_{L+1}^2 - M_L^2 = (M_{L+1} - M_L)(M_{L+1} + M_L) = a$ and hence $M_{L+1} - M_L = a/(M_{L+1} + M_L)$. Asymptotically, all mass separations vanish with $1/M$ and chiral symmetry is trivially restored.

We now look for an effect of chiral symmetry beyond this trivial asymptotic behavior. We do so by comparing the consistency of the data with the assumption of parity doublets and, alternatively, with their consistency with (L,S) multiplets with vanishing $\vec{L}\cdot\vec{S}$ coupling.

First we calculate the mean mass deviation of baryon resonances when they are interpreted as parity doublets:

$$\sigma_{parity\ doublets} = \sqrt{\frac{1}{10}\sum_{i=1,20}(M_i - M_\pm)^2} = 97\ \text{MeV} \tag{3}$$

where $M_\pm$ are the mean masses of positive- and negative-parity resonances paired to one parity doublet (see Table 1). The sum extends over 20 resonances; there are 10 degrees of freedom.

We now determine the deviation of baryon masses from the mean value of a (L, S)-multiplet:

$$\sigma_{spin\ multiplets} = \sqrt{\frac{1}{13}\sum_{i=1,20}(M_i - M_{cg})^2} = 39 \text{ MeV} \tag{4}$$

where the M_{cg} are the mean values (center of gravity) of the 7 multiplets involved. 13 is number of degrees of freedom.

The comparison of the two hypotheses reveals that evidence for parity doublets in the high-mass spectrum is weak, at most. The data are better described in terms of (L, S)-multiplets embracing SU(6) multiplets of different J but having the same intrinsic orbital and spin angular momenta. The symmetry leading to parity doublets is the vanishing of spin-orbit forces and not a phase transition to chiral dynamics.

Finally we examine the possibility that chiral symmetry is not yet fully restored but does already influence the mass spectrum. We do so by testing the hypothesis that the solitaire states could be slightly 'attracted' by its nearest chiral partner (even thought the solitaire state remains within its (L, S) multiplet).

Indeed, the mass of the $\Delta_{7/2^+}(1950)$ is larger than the mean of its three partners of lower J, possibly it is 'attracted' by the $\Delta_{7/2^-}(2200)$. The same effect is found for the $L = 2$ states $N_{5/2^+}(2000)$and $N_{7/2^+}(1990)$ having masses which are larger than the $N_{3/2^+}(1900)$ and thus closer to the masses of the $N_{5/2^-}(2200)$ and $N_{7/2^-}(2190)$ (which have $L = 3$). The $N_{9/2^-}(2250)$ (with an assigned $L = 3$) is even slightly above the $(L = 4)$ $N_{9/2^+}(2220)$. (In this case, we do not have a neighbor state to quantify an attraction). If we normalize for these resonances the mass difference to be zero at the masses at the center of gravity of a multiplet (1921 MeV for the four positive parity Δ^* with $L = 2$) and 1 at the mass of the chiral partner (2200 MeV), we find a attraction factor γ_{attr} of the $\Delta_{7/2^+}(1950)$ of $\gamma_{attr} = 0.10 \pm 0.14$. The error is derived assuming errors as given in (4). The mean attraction factor for the three cases, $\Delta_{7/2^+}(1950)$, $N_{5/2^+}(2000)$ and $N_{5/2^+}(1990)$, in which γ_{attr} can be defined is $\gamma_{attr} = 0.13 \pm 0.09$. There is thus a hint that the solitaire states are attracted by their parity-doublet partner, even though chiral symmetry breaking effects still dominate the interaction. Optimistically, the non-zero value $\gamma_{attr} = 0.13 \pm 0.09$ can be seen as onset of a regime in which chiral symmetry is restored.

5 Conclusions

We have studied the question if parity doubling observed in high-mass N^* and Δ^* resonances can be interpreted as evidence for chiral symmetry restoration in baryon excitation. We find that the appearance of parity doublets does not reflect chiral symmetry but rather the vanishing of spin-orbit forces in quark-quark interactions in baryons. This new interpretation of the parity doublets gives predictions for masses of high-mass baryon resonances which differ distinctively from those based on the hypothesis of chiral symmetry restoration.

We have searched for indications that chiral symmetry might lead to a weak attraction between chiral partners. We find a positive 1.4σ effect. Clearly, more precise data are required to establish an onset of chiral symmetry restoration in the baryon mass spectrum.

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