Interpretation of N(1440), N(1535) and N(1520)

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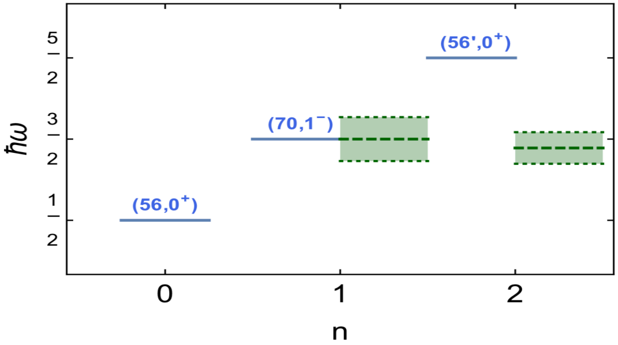
- Works on the Way

Nucleon Resonances below 2 GeV

Resonance	Status	J^P	M_{BW}^{exp} MeV	Γ_{BW}^{exp} MeV
$N(1440)$	****	$\frac{1}{2}^+$	1410-1470	250-450
$N(1680)$	****	$\frac{5}{2}^+$	1665-1680	115-130
$N(1710)$	****	$\frac{1}{2}^+$	1680-1740	80-200
$N(1720)$	****	$\frac{3}{2}^+$	1680-1750	150-400
$N(1860)$	**	$\frac{5}{2}^+$	1800-1980	220-410
$N(1880)$	***	$\frac{1}{2}^+$	1830-1930	200-400
$N(1900)$	****	$\frac{3}{2}^+$	1890-1950	100-320
$N(1990)$	**	$\frac{7}{2}^+$	1950-2100	200-400
$N(2000)$	**	$\frac{5}{2}^+$	2030-2090	335-445
$N(1520)$	****	$\frac{3}{2}^-$	1510-1520	100-120
$N(1535)$	****	$\frac{1}{2}^-$	1525-1545	125-175
$N(1650)$	****	$\frac{1}{2}^-$	1645-1670	100-150
$N(1675)$	****	$\frac{5}{2}^-$	1670-1680	130-160
$N(1685)$	*	$\frac{1}{2}^-?$	1665-1675	15-45
$N(1700)$	***	$\frac{3}{2}^-$	1650-1750	100-300
$N(1875)$	***	$\frac{3}{2}^-$	1850-1920	120-250
$N(1895)$	****	$\frac{1}{2}^-$	1870-1920	80-200

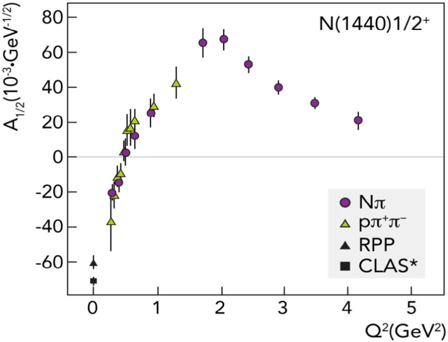
Mass Ordering Problem



- In the traditional q^3 picture, the Roper $N_{1/2+}(1440)$ usually gets a mass ~ 100 MeV above the $N_{3/2-}(1520)$ and $N_{1/2-}(1535)$.
- $N(1440)$ is usually blamed sitting at a wrong place or intruding the q^3 spectrum. It could be $q^4\bar{q}$ pentaquark, q^3g hybird, $q^3(q\bar{q})$ resonace ...

Data of Helicity Transtion Amplitude of $N_{1/2+}(1440)$

Transverse helicity amplitudes for $N(1440)$ electroproduction. Circles - analysis of single-pion final states; Triangles - analysis of $ep \to e^{'}\pi^{+}\pi^{-}p^{'}$; Square- CLAS Collaboration result $\gamma^{*}p \to N(1440)$.



- The sign change in the helicity amplitude may suggest a node in the wave function, and hence mainly the first radial excitation state.

On $N_{3/2^-}(1520)$ and $N_{1/2-}(1535)$

$N_{3/2^-}(1520)$ and $N_{1/2-}(1535)$ are a pair of $l = 1$ excited states and expected to have similar properties. However,

- In $N_{3/2-}(1520)$ decay modes, branching ratio of $\Gamma_{\eta N}/\Gamma_{tot}$ is almost zero.
- In $N_{1/2-}(1535)$ decay modes, the branching ratio of $N(1535) \to N\eta$ process is as large as the one of $N(1535) \to N\pi$.

One may propose tentatively

- $N_{3/2-}(1520)$ may contain a large ground-state $(l = 0)$ non-strange pentaquark component.
- $N_{1/2-}(1535)$ may contain a large ground-state $(l = 0)$ $uuds\bar{s}$ component.

Constituent Quark Model with Cornell-like Potential

- Realistic Hamiltonian for a N-quark system:

$$
\begin{aligned}
H &= H_0 + H_{hyp}^{OGE}, \\
H_0 &= \sum_{k=1}^{N}(m_k + \frac{p_k^2}{2m_k}) + \sum_{i<j}^{N}(-\frac{3}{8}\lambda_i^C \cdot \lambda_j^C)(A_{ij}r_{ij} - \frac{B_{ij}}{r_{ij}}), \\
H_{hyp}^{OGE} &= -C_{OGE}\sum_{i<j}\frac{\lambda_i^C \cdot \lambda_j^C}{m_i m_j}\vec{\sigma}_i \cdot \vec{\sigma}_j,
\end{aligned} \tag{1}
$$

- The bases constructed from H.O. WF, considering permutation symmetries,

$$
\begin{aligned}
\Psi_{NLM}^{\mathrm{o}} &= \sum_{n_\lambda, n_\rho, n_\eta, n_\xi, l_\lambda, l_\rho, l_\eta, l_\xi} A(n_\lambda, n_\rho, n_\eta, n_\xi, l_\lambda, l_\rho, l_\eta, l_\xi) \\
&\cdot \Psi_{n_\lambda l_\lambda m_\lambda}(\vec{\lambda})\Psi_{n_\rho l_\rho m_\rho}(\vec{\rho})\Psi_{n_\eta l_\eta m_\eta}(\vec{\eta})\Psi_{n_\xi l_\xi m_\xi}(\vec{\xi}) \\
&\cdot C(l_\lambda, l_\rho, m_\lambda, m_\rho, l_{\lambda\rho}, m_{\lambda\rho}) \\
&\cdot C(l_{\lambda\rho}, l_\eta, m_{\lambda\rho}, m_\eta, l_{\lambda\rho\eta}, m_{\lambda\rho\eta}) \\
&\cdot C(l_{\lambda\rho\eta}, l_\xi, m_{\lambda\rho\eta}, m_\xi, LM)
\end{aligned} \tag{2}
$$

Baryons Masses in the Constituent Quark Model

$(\Gamma, {}^{2s+1}D, N, L^P)$	Status	J^P	M^{exp}(MeV)	M^{cal}(MeV)
$N(56, {}^2 8, 0, 0^+)$	****	$\frac{1}{2}^+$	939	939
$N(56, {}^2 8, 2, 0^+)$	****	$\frac{1}{2}^+$	N(1440)	1499
$N(56, {}^2 8, 2, 2^+)$	****	$\frac{5}{2}^+$	N(1720)	1655
$N(56, {}^2 8, 2, 2^+)$	****	$\frac{3}{2}^+$	N(1680)	1655
$N(20, {}^2 1, 2, 1^+)$	***	$\frac{1}{2}^+$	N(1880)	1749
$N(20, {}^4 1, 2, 1^+)$	-	$\frac{3}{2}^+$	missing	1749
$N(70, {}^2 10, 2, 0^+)$	****	$\frac{1}{2}^+$	N(1710)	1631
$N(70, {}^4 10, 2, 0^+)$	****	$\frac{3}{2}^+$	N(1900)	1924
$N(70, {}^2 10, 2, 2^+)$	-	$\frac{3}{2}^+$	missing	1702
$N(70, {}^2 10, 2, 2^+)$	**	$\frac{5}{2}^+$	N(1860)	1702
$N(70, {}^4 10, 2, 2^+)$	***	$\frac{1}{2}^+$	N(2100)	1994
$N(70, {}^4 10, 2, 2^+)$	*	$\frac{3}{2}^+$	N(2040)	1994
$N(70, {}^4 10, 2, 2^+)$	**	$\frac{5}{2}^+$	N(2000)	1994
$N(70, {}^4 10, 2, 2^+)$	**	$\frac{7}{2}^+$	N(1990)	1994

$(\Gamma, {}^{2s+1}D, N, L^P)$	Status	J^P	M^{exp}(MeV)	M^{cal}(MeV)
$N(70, {}^2 10, 1, 1^-)$	****	$\frac{3}{2}^-$	N(1520)	1380
$N(70, {}^2 10, 1, 1^-)$	****	$\frac{1}{2}^-$	N(1535)	1380
$N(70, {}^4 10, 1, 1^-)$	****	$\frac{1}{2}^-$	N(1650)	1672
$N(70, {}^4 10, 1, 1^-)$	****	$\frac{5}{2}^-$	N(1675)	1672
$N(70, {}^4 10, 1, 1^-)$	***	$\frac{3}{2}^-$	N(1700)	1672
$\Delta(70, {}^2 10, 1, 1^-)$	****	$\frac{1}{2}^-$	Δ(1620)	1380
$\Delta(70, {}^2 10, 1, 1^-)$	****	$\frac{3}{2}^-$	Δ(1700)	1380

- All the ground state baryons are well reproduced.
- $N(1520)$, $N(1535)$, $\Delta(1620)$ and $\Delta(1700)$ are poorly described.
- No room for $N(1685)$ in the q^3 negative party spectrum.

Ground State Pentaquark Mass Spectra

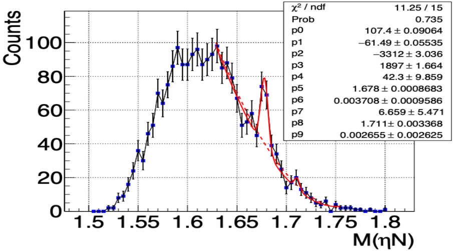
$q^4\bar{q}$ configurations	J^P	$M(q^4\bar{q})$ (MeV)	$M(q^3s\bar{s})$ (MeV)
$\Psi^{csf}_{[211]_C[31]_{FS}[4]_F[31]_S}$	$\frac{1}{2}^-, \frac{3}{2}^-$	2562, 2269	2762, 2586
$\Psi^{csf}_{[211]_C[31]_{FS}[31]_F[4]_S}$	$\frac{3}{2}^-, \frac{5}{2}^-$	2025, 2269	2420, 2546
$\Psi^{csf}_{[211]_C[31]_{FS}[31]_F[31]_S}$	$\frac{1}{2}^-, \frac{3}{2}^-$	2123, 2049	2448, 2414
$\Psi^{csf}_{[211]_C[31]_{FS}[31]_F[22]_S}$	$\frac{1}{2}^-$	2025	2393
$\Psi^{csf}_{[211]_C[31]_{FS}[22]_F[31]_S}$	$\frac{1}{2}^-, \frac{3}{2}^-$	1683, 2049	2135, 2354
$\Psi^{csf}_{[211]_C[31]_{FS}[211]_F[22]_S}$	$\frac{1}{2}^-$	–	2165
$\Psi^{csf}_{[211]_C[31]_{FS}[211]_F[31]_S}$	$\frac{1}{2}^-, \frac{3}{2}^-$	–	2032, 2243

A Surprising Byproduct:

- The $q^4\bar{q}$ pentaquark state with the $[31]_{FS}[22]_F[31]_S$ configuration and the quantum numbers $I(J^P) = \frac{1}{2}(\frac{1}{2}^-)$ is predicted to have the lowest mass, 1683 MeV.
- A bold guess: The $N^+(1685)$ resonance could be the lowest pentaquark state.

$N(1685)$

- $N(1685)$ was firstly reported in the photoproduction of η meson off the quasi-free neutron. Its Breit-Wigner (BW) width is less than $30\ \mathrm{MeV}$, much less than the width of other low-lying nucleon resonances [PLB**647**: 23-29 (2007)].
- $N(1685)$ was listed in PDG as an one-star isospin $1/2$ resonance in 2012 after the observation of a narrow enhancement at $W \sim 1.68$ in the $\gamma n \to \eta n$ excitation function at GRAAL, CBELSA/TAPS, LNS, and A2@MAMI.



Though removed from the PDG listing in 2016, the new date on the invariant mass spectra of $\gamma N \to \pi\eta N$ reactions from GRAAL still reveal the N(1685) resonance.[JETP Letters **106**: 693-699(2017)]

Possible Mixtures of q^3 and $q^4\,\bar{q}$ States

- We expect to derive the right mass for $N(1520)$, $N(1535)$, $\Delta(1620)$ and $\Delta(1700)$ by mixing the q^3 states with $q^4\,\bar{q}$ components.
- All four q^3 states take the same mass, $1380\ \mathrm{MeV}$. As examples, we take the lowest pentaquark states (except the 1683 MeV state) to mix with the four q^3 states.

J^P	ψ_1 State	ψ_2 State	q^3	$q^4\bar{q}$ config.	$q^4\bar{q}$ Mass
$\frac{1}{2}^-$	1530	1882	1380	$q^3 s\bar{s}_{[211]_F[31]_S}$	2032
$\frac{3}{2}^-$	1515	1895	1380	$q^4\bar{q}_{[31]_F[4]_S}$	2025
$\frac{1}{2}^-$	1610	1893	1380	$q^4\bar{q}_{[31]_F[31]_S}$	2123
$\frac{3}{2}^-$	1700	1923	1380	$q^3 s\bar{s}_{[22]_F[31]_S}$	2243

- $N(1520)3/2^-$ and $N(1875)3/2^-$ as well as $\Delta(1620)1/2^-$ and $\Delta(1900)1/2^-$ with non-strange components, $q^4\bar{q}$.
- $N(1535)1/2^-$ and $N(1895)1/2^-$ as well as $\Delta(1700)3/2^-$ and $\Delta(1940)3/2^-$ with hidden strange components, $q^3 s\bar{s}$.

Negative Parity Baryon States Below 2 GeV

Resonance	Status	J^P	M^{exp} (MeV)	M^{cal} (MeV)
$N(1520)$	****	$\frac{3}{2}^-$	1510-1520	1515
$N(1535)$	****	$\frac{1}{2}^-$	1515-1545	1530
$N(1650)$	****	$\frac{1}{2}^-$	1645-1670	1672
$N(1675)$	****	$\frac{5}{2}^-$	1670-1680	1672
$N(1685)$	*	$\frac{1}{2}^-?$	1665-1675	1683
$N(1700)$	***	$\frac{3}{2}^-$	1650-1750	1672
$N(1875)$	***	$\frac{3}{2}^-$	1850-1920	1895
$N(1895)$	****	$\frac{1}{2}^-$	1870-1920	1882
$\Delta(1620)$	****	$\frac{1}{2}^-$	1590-1630	1610
$\Delta(1700)$	****	$\frac{3}{2}^-$	1690-1730	1700
$\Delta(1900)$	***	$\frac{1}{2}^-$	1840-1920	1893
$\Delta(1940)$	**	$\frac{3}{2}^-$	1940-2060	1923

A possible interpretation:

- $N(1440)$ is mainly the first radial excitation while $N(1520)$, $N(1535)$, $\Delta(1620)$, and $\Delta(1700)$ may have sizable pentaquark components.
- $N(1895)1/2^-$, $N(1875)3/2^-$, $\Delta(1900)1/2^-$, and $\Delta(1940)3/2^-$ states may have large pentaquark components.

Form Factor and Helicity Transition Amplitudes

- We calculate the proton electric form factor G_E, and $N(1440)$, $N(1535)$ and $N(1520)$ helicity transition amplitudes in the q^3 picture to figure out how far the q^3 picture may go and how important other components may play.

N* rest frame $P_i = (E_N, 0, 0, -|\boldsymbol{k}|), \quad P_f = (M_{N^*}, 0, 0, 0), \quad k = (\omega, 0, 0, |\boldsymbol{k}|)$

$$\omega = \frac{M_{N^*}^2 - M_N^2 - Q^2}{2M_{N^*}} \qquad |\boldsymbol{k}| = \left[Q^2 + \left(\frac{M_{N^*}^2 - M_N^2 - Q^2}{2M_{N^*}}\right)^2\right]^{\frac{1}{2}} \qquad Q^2 = -k^2$$

$$A_{1/2} = \frac{1}{\sqrt{2K}} \left\langle N^*, S_z' = \frac{1}{2} \middle| q_1' q_2' q_3' \right\rangle T^{+}_{s's}(q_1 q_2 q_3 \to q_1' q_2' q_3') \left\langle q_1 q_2 q_3 \middle| N, S_z = -\frac{1}{2} \right\rangle,$$

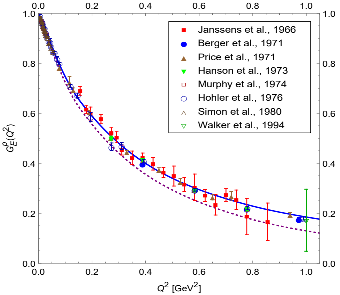
$$A_{3/2} = \frac{1}{\sqrt{2K}} \left\langle N^*, S_z' = \frac{3}{2} \middle| q_1' q_2' q_3' \right\rangle T^{+}_{s's}(q_1 q_2 q_3 \to q_1' q_2' q_3') \left\langle q_1 q_2 q_3 \middle| N, S_z = \frac{1}{2} \right\rangle,$$

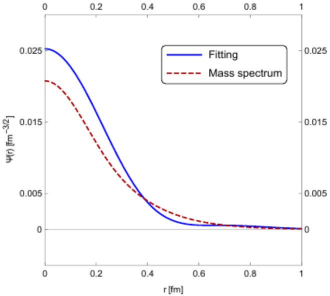
$$S_{1/2} = \frac{1}{\sqrt{2K}} \left\langle N^*, S_z' = \frac{1}{2} \middle| q_1' q_2' q_3' \right\rangle T^{0}_{s's}(q_1 q_2 q_3 \to q_1' q_2' q_3') \left\langle q_1 q_2 q_3 \middle| N, S_z = \frac{1}{2} \right\rangle \frac{|\boldsymbol{k}|}{Q}$$

$$K = \frac{M_{N^*}^2 - M_N^2}{2M_{N^*}}$$

Proton Form Factor and Quark Distribution

- Dashed Curves: Proton spatial wave function is imported from the mass spectrum calculations
- Solid Curves: Proton spatial wave function is fitted to experimental data.





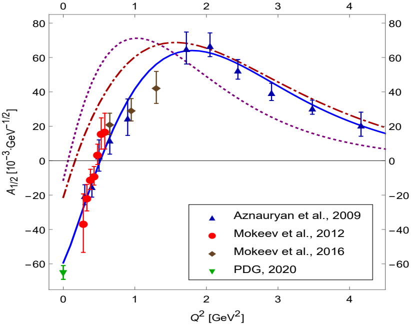
One may conclude:

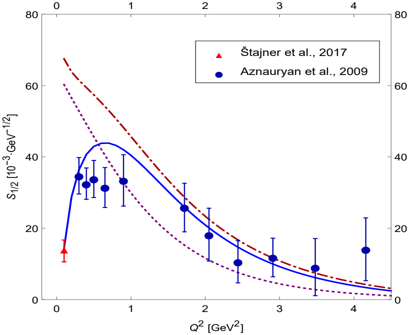
- Impulse approximation makes sense.
- The three-quark core dominantly contribute to the proton electric form factor.
- Meson cloud contribution is negligible.

Helicity Transition Amplitudes of $N(1440)$

The $A_{1/2}$ and $S_{1/2}$ of the $N(1440)$ resonance are investigated in three cases:

- Spatial wave function imported from mass spectrum studies as the first radial excitation of the nucleon
- $N(1440)$ is a general radial excitation of the nucleon.
- $N(1440)$ is just a q^3 state with positive parity.

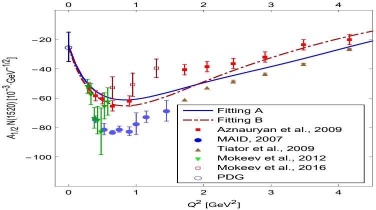


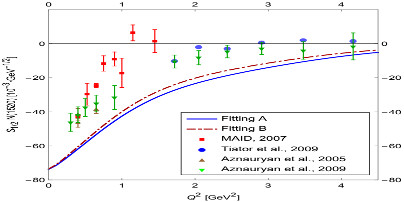


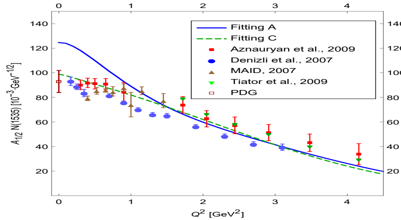
- $N(1440)$ is likely a q^3 dominant state.

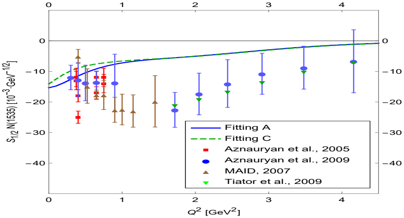
Helicity Transitions Amplitude of $N(1520)$ and $N(1535)$

- Fitting A: $N(1520)$ and $N(1535)$ take the same spatial wave function as $l = 1$ excitations of the nucleon.
- Fitting B (C): $N(1520)$ ($N(1535)$) fitted alone as nucleon $l = 1$ excitation.









- $N(1520)$ and $N(1535)$ may have considerable other components beside q^3.

Works on the Way

- Calculate meson cloud contributions to nucleon form factors in dispersion relation approach, using as inputs experimental data of π electromagnetic form factor and $\pi\pi \to N\bar{N}$ amplitudes.

- Study Δ transition amplitudes in dispersion relation approach and quark model.

- Study $N(1440)$, $N(1520)$ and $N(1535)$ helicity transition amplitudes,
  1. considering meson cloud contributions in effective field theory
  2. including two-body currents to improve the impulse approximation
  3. including pentaquark components, $q^4\bar{q}$.

Beer Time

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