Excited baryons in the large N_c limit

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May 19, 2011

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Motivation

- Traditional issues to study **baryons**: **effective theories** and **constituent quark models**
- The $1/N_c$ expansion is a **new theoretical method** (1993)
  - Systematic
  - Valid for the whole energy region
  - Model independent
  - Predictive
  - Gives support to constituent quark models
  - Used to study baryon masses, magnetic moments, axial currents, decay widths

Large N_c QCD

- 't Hooft suggested to **generalize QCD** to N_c **colors** [1] in the limit $\frac{g}{\sqrt{N_c}} \to 0, \; g \text{ fixed when } N_c \to \infty$

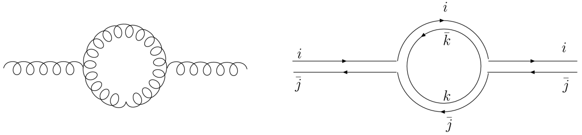


Diagram of order $\mathcal{O}(1)$

- **Witten : Large N_c power counting rules for Feynman diagrams [2]**
  The leading Feynman diagrams are planar and contain a minimum number of quark loops

[1] G. 't Hooft, Nucl. Phys. **72**, 461 (1974).

[2] E. Witten, Nucl. Phys. **B160**, 57 (1979).

Mesons in large N_c QCD

$$|1\rangle_c = \frac{1}{\sqrt{N_c}} \underbrace{(\bar{l}l + \bar{m}m + \ldots + \bar{n}n)}_{N_c \text{ terms}}$$

Large N_c mesons are stable and non-interacting

Baryons in large N_c QCD

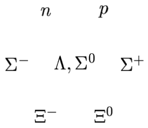
$$\varepsilon_{i_1 i_2 i_3 \cdots i_{N_c}} q^{i_1} q^{i_2} q^{i_3} \cdots q^{i_{N_c}}$$

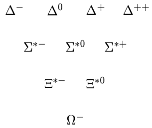
bound states of N_c **valence quarks completely antisymmetric in color** because baryons are colorless

Baryon mass grows with N_c

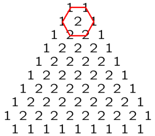
Baryon weight diagrams

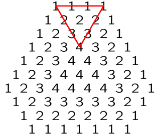
For $N_c = 3$





For large N_c





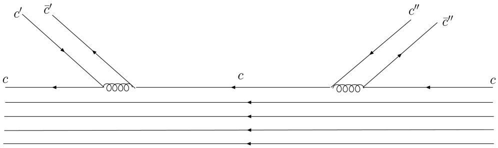
Familiar $N_c = 3$ baryons can be **identified** with **states at the top of the flavor representations**

Exact SU$_f(3)$: all particles in **each weight diagram** have the **same mass** when $m_u = m_d = m_s$

Exact SU(6) : **all the particles** have the **same mass**

Baryon-meson scattering amplitude

baryon + meson $\rightarrow$ baryon + meson $\sim \mathcal{O}(1)$



$[X_0^{ia}, X_0^{jb}] = 0$, **consistency condition for unitarity**

$\Rightarrow$ SU($2N_f$) contracted is an exact symmetry in $N_c \rightarrow \infty$ limit [3,4]

$\Rightarrow$ Infinite tower of degenerate baryon states

SU$(2N_f)_c$ symmetry realized at $N_c \rightarrow \infty$ by **Skyrme model** and **non-relativistic quark model**

[3] J.-L. Gervais and B. Sakita, Phys. Rev. Lett. **52**, 87 (1984); Phys. Rev. **D30**, 1795 (1984).
[4] R. Dashen and A. V. Manohar, Phys. Lett. **B315**, 425 (1993).

SU(6) symmetry of non-relativistic quark model **exact in the large N_c limit** for ground state baryons

Assumed SU(6)×O(3) for excited states to include $\ell \neq 0$

SU($2N_f$) generators

$$\begin{aligned} S^i &= q^\dagger (S^i \otimes 1\!\!1) q \quad (3,1) \\ T^a &= q^\dagger (1\!\!1 \otimes T^a) q \quad (1,\mathrm{adj}) \\ G^{ia} &= q^\dagger (S^i \otimes T^a) q \quad (3,\mathrm{adj}) \end{aligned}$$

SO(3) generators (excited states)

$$\ell^i = q^\dagger \ell^i q \quad (3)$$

$1/N_c$ Expansion of a QCD 1-body operator [5]

(a)

(b)

$1/N_c$ **expansion** of **a static QCD 1-body operator** (**baryon mass**, axial vector current, magnetic moment) transforming according to a given SU(2)×SU(N_f) representation

$$\mathcal{O}^{1-\mathrm{body}}_{\mathrm{QCD}} = \sum_n \frac{1}{N_c^{n-1}} c_n O^n, \quad O^n = O_\ell \cdot O_{SF}$$

where O_ℓ and O_{SF} are expressed in terms of products of **SO(3)** and **SU($2N_f$)** generators

[5] R. Dashen, E. Jenkins and A. V. Manohar, Phys. Rev. **D51**, 3697 (1995).

The Baryon Structure

The **total wave function of baryons** Ψ

$$\Psi = \psi_{lm}\, \chi\, \phi\, C$$

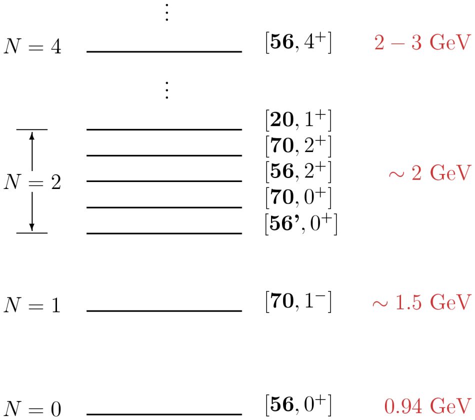
ψ_{lm}, χ, ϕ and C are the orbital, spin, flavor and color parts

Steps in forming SU(6) $\times$ O(3) symmetric wave functions for low excitations and $N_c = 3$

SU(3)		SU(2)	SU(6)		O(3)	SU(6) $\times$ O(3)
					2^+_2 S	$[\mathbf{56}, 2^+]$
10	$\times$	$\frac{3}{2}$				
			56	$\times$	0^+_2 S	$[\mathbf{56}', 0^+]$
8	$\times$	$\frac{1}{2}$				
					0^+_0 S	$[\mathbf{56}, 0^+]$
10	$\times$	$\frac{1}{2}$				
8	$\times$	$\frac{3}{2}$			2^+_2 M	$[\mathbf{70}, 2^+]$
8	$\times$	$\frac{1}{2}$	70	$\times$	0^+_2 M	$[\mathbf{70}, 0^+]$
1	$\times$	$\frac{1}{2}$			1^-_1 M	$[\mathbf{70}, 1^-]$
8	$\times$	$\frac{1}{2}$	20	$\times$	1^+_2 A	$[\mathbf{20}, 1^+]$
1	$\times$	$\frac{3}{2}$				

Baryon spectrum

SU(6) notation: $[\mathbf{X}, l^P]$, $N_c = 3$



Excited States I

First approach [6]

- Witten's suggestion: **Hartree approximation in $N_c \to \infty$ limit**
    - Each quark moves in an **average potential** generated by the other $N_c - 1$ quarks
    - Total potential experienced by **each quark** is of order $\mathcal{O}(1)$
    - Interaction between **any given pair of quarks** of order $\mathcal{O}(1/N_c)$
- Low excitations: baryons composed of $\mathcal{O}(N_c)$ **ground-state quarks** (the core) and $\mathcal{O}(1)$ **excited quarks**
- The core quarks are described by **symmetric wave functions in both orbital and spin-flavor parts** as ground-state baryons
- **Excited quark** coupled to **a symmetric ground state core**

[6] J.L. Goity, Phys. Lett. **B414**, 140 (1997).

Extensively applied to $[70, 1^-]$ baryon :
ground state core made of $N_c - 1$ quarks + **one excited quark** (2 flavors [7], 3 flavors [8])

$$S^i = s^i + S_c^i;\; T^a = t^a + T_c^a;\; G^{ia} = g^{ia} + G_c^{ia}$$

Wave function :

$$\begin{aligned}
|\ell S; JJ_3; (\lambda\mu)YII_3\rangle = & \sum_{\substack{m_\ell, S_3, m_1, m_2,\\ Y_c, I_c, I_{c_3}, y, i, i_3}} \left(\begin{array}{cc|c} \ell & S & J \\ m & S_3 & J_3 \end{array} \right) \\
\times & \sum_{pp'} c^{[N_c-1,1]}_{pp'}(S) \left(\begin{array}{cc|c} S_c & \frac{1}{2} & S \\ m_1 & m_2 & S_3 \end{array} \right) \left(\begin{array}{cc|c} (\lambda_c\mu_c) & (10) & (\lambda\mu) \\ Y_c I_c I_{c_3} & yii_3 & YII_3 \end{array} \right) \\
\times & |S_c m_1\rangle |1/2 m_2\rangle |(\lambda_c\mu_c) Y_c I_c I_{c_3}\rangle |(10) yii_3\rangle |\ell m\rangle
\end{aligned}$$

$c^{[\mathrm{N_c}-1,1]}_{pp'}(S)$ **are isoscalar factors of S_{N_c}**

[7] C.E. Carlson, C.D. Carone, J.L. Goity and R.F. Lebed, Phys. Rev. **D59**, 114008 (1999).
[8] J.L. Goity, C.L. Schat and N.N. Scoccola, Phys. Rev. **D66**, 114014 (2002).

Has also been applied to $[\mathbf{70}, \ell^+]$ $(\ell = 0, 2)$ [9]

Mass operator

$$M_{[\mathbf{70},\ell^+]} = \sum_{i=1}^{6} c_i O_i + \sum_{j=1}^{4} d_j B_j$$

Operator	Fitted coef. (MeV)			
$O_1 = N_c \mathbb{1}$	$c_1 =$	556	$\pm$	11
$O_2 = \ell_q^i s^i$	$c_2 =$	-43	$\pm$	47
$O_3 = \frac{3}{N_c} \ell_q^{(2)ij} g^{ia} G_c^{ja}$	$c_3 =$	-85	$\pm$	72
$O_4 = \frac{4}{N_c+1} \ell^i t^a G_c^{ia}$				
$O_5 = \frac{1}{N_c}(S_c^i S_c^i + s^i S_c^i)$	$c_5 =$	253	$\pm$	57
$O_6 = \frac{1}{N_c} t^a T_c^a$	$c_6 =$	-25	$\pm$	86
$B_1 = t^8 - \frac{1}{2\sqrt{3}N_c} O_1$	$d_1 =$	365	$\pm$	169
$B_2 = T_c^8 - \frac{N_c-1}{2\sqrt{3}N_c} O_1$	$d_2 =$	-293	$\pm$	54
$B_4 = 3\ell_q^i g^{i8} - \frac{\sqrt{3}}{2} O_2$				

$$\chi^2_{\text{dof}} = 1.0$$

[9] N. Matagne and Fl. Stancu, Phys. Rev. **D74**, 034014 (2006)

$[70, 1^-]$ non-strange baryons : the three towers of states [10], [11]

For $N_c \geq 5, I \leqslant 3/2$, 13 states :

$N_{1/2}, N'_{1/2}, N_{3/2}, N'_{3/2}, N_{5/2}, \Delta_{1/2}, \Delta'_{1/2}, \Delta_{3/2}, \Delta'_{3/2}, \Delta''_{3/2}, \Delta'_{5/2}, \Delta''_{5/2}, \Delta''_{7/2}$

Considering H of order up to $\mathcal{O}(N_c^0)$,

$$H = c_1 N_c + c_2 \ell \cdot s + \frac{1}{N_c} \ell^{(2)} \cdot g \cdot G_c$$

Diagonalize it in the basis of the 13 states

$\Rightarrow$ **Observe a pattern of denegeracy**

$$N_{1/2}, \Delta_{3/2} \quad (m_0)$$
$$N'_{1/2}, \Delta_{1/2}, N_{3/2}, \Delta'_{3/2}, \Delta_{5/2} \quad (m_1)$$
$$\Delta'_{1/2}, N'_{3/2}, \Delta''_{3/2}, N_{5/2}, \Delta'_{5/2}, \Delta''_{7/2} \quad (m_2)$$

according to $|I - J| \leqslant K$

[10] T. Cohen and R.F. Lebed, Phys. Rev. **D67**, 096008 (2003).

[11] D. Pirjol and C. Schat, Phys. Rev. **D67**, 096009 (2003).

Excited States II

Second approach

- A totally symmetric orbital-spin-flavor state

$$\Phi_S = \frac{1}{\sqrt{N_c - 1}} \sum_Y |[N_c - 1, 1]Y\rangle_O |[N_c - 1, 1]Y\rangle_{SF}$$

Illustration for $N_c = 5$ ($[\mathbf{70}, 1^-]$)

$$\ytableaushort{12345} = \frac{1}{\sqrt{4}} \left(\ytableaushort{1234,5}\ \ytableaushort{1234,5} + \ytableaushort{1235,4}\ \ytableaushort{1235,4} + \ytableaushort{1245,3}\ \ytableaushort{1245,3} + \ytableaushort{1345,2}\ \ytableaushort{1345,2} \right)$$

Young tableau	Young-Yamanouchi basis vectors of [41]
$\ytableaushort{1234,5}$	$\frac{1}{\sqrt{20}}(\mathbf{4ssssp - sssps - sspss - spsss - pssss})$
$\ytableaushort{1235,4}$	$\frac{1}{\sqrt{12}}(3sssps - sspss - spsss - pssss)$
$\ytableaushort{1245,3}$	$\frac{1}{\sqrt{6}}(2sspss - spsss - pssss)$
$\ytableaushort{1345,2}$	$\frac{1}{\sqrt{2}}(spsss - pssss)$

- As $S_c = I_c$, in the decoupling picture, information on isospin is lost

Matrix elements of the spin-spin and isospin-isospin operators with the exact and the approximate wave function

	$\langle s \cdot S_c \rangle$		$\langle S_c^2 \rangle$	
	approx. w.f.	exact w.f.	approx. w.f.	exact w.f.
$^2 8$	$-\frac{N_c+3}{4N_c}$	$-\frac{3(N_c-1)}{4N_c}$	$\frac{N_c+3}{2N_c}$	$\frac{3(N_c-1)}{2N_c}$
$^4 8$	$\frac{1}{2}$	$-\frac{3(N_c-5)}{4N_c}$	2	$\frac{3(3N_c-5)}{2N_c}$
$^2 10$	-1	$-\frac{3(N_c-1)}{4N_c}$	2	$\frac{3(N_c-1)}{2N_c}$

	$\langle t \cdot T_c \rangle$		$\langle T_c^2 \rangle$	
	approx. w.f.	exact w.f.	approx. w.f.	exact w.f.
$^2 8$	$-\frac{N_c+3}{4N_c}$	$-\frac{3(N_c-1)}{4N_c}$	$\frac{N_c+3}{2N_c}$	$\frac{3(N_c-1)}{2N_c}$
$^4 8$	-1	$-\frac{3(N_c-1)}{4N_c}$	2	$\frac{3(N_c-1)}{2N_c}$
$^2 10$	$\frac{1}{2}$	$-\frac{3(N_c-5)}{4N_c}$	2	$\frac{3(3N_c-5)}{2N_c}$

Results of the fits (nonstrange baryons)

- Only with the **7 resonances**: $^2N_{1/2}(1538 \pm 18)$, $^4N_{1/2}(1660 \pm 20)$, $^2N_{3/2}(1523 \pm 8)$, $^4N_{3/2}(1700 \pm 50)$, $^4N_{5/2}(1678 \pm 8)$, $^2\Delta_{1/2}(1645 \pm 30)$ and $^2\Delta_{3/2}(1720 \pm 50)$

Fit 1

Operator		Approx. w.f. (MeV)	Exact w.f. (MeV)
$O_1 = N_c \mathbb{1}$	$c_1 =$	211 ± 23	299 ± 20
$O_2 = \ell^i s^i$	$c_2 =$	3 ± 15	3 ± 15
$O_3 = \frac{1}{N_c} s^i S_c^i$	$c_3 =$	-1486 ± 141	-1096 ± 125
$O_4 = \frac{1}{N_c} S_c^i S_c^i$	$c_4 =$	1182 ± 74	1545 ± 122
$O_5 = \frac{1}{N_c} t^a T_c^a$	$c_5 =$	-1508 ± 149	417 ± 79
$\chi^2_{\rm dof}$		1.56	1.56

Fit 2

Operator		Approx. w.f. (MeV)	Exact w.f. (MeV)
$O_1 = N_c \mathbb{1}$	$c_1 =$	484 ± 4	484 ± 4
$O_2 = \ell^i s^i$	$c_2 =$	3 ± 15	3 ± 15
$O_3' = \frac{1}{N_c}\left(2s^i S_c^i + S_c^i S_c^i + \frac{3}{4}\right)$	$c_3' =$	150 ± 11	150 ± 11
$O_5' = \frac{1}{N_c}\left(2t^a T_c^a + T_c^a T_c^a + \frac{3}{4}\right)$	$c_5' =$	139 ± 27	139 ± 27
χ^2_{dof}		1.04	1.04

$\Rightarrow$ No decoupling of the wave function and the operators S^i, T^a, G^{ia}

Wave function [12]

$$|\ell S(\lambda\mu)YII_3;JJ_3\rangle = \sum_{m_\ell,S_3} \left(\begin{array}{cc|c} \ell & S & J \\ m_\ell & S_3 & J_3 \end{array} \right) |[N_c-1,1]SS_3(\lambda\mu)YII_3\rangle|[N_c-1,1]\ell m_\ell\rangle$$

Generators : Wigner-Eckart theorem for SU(6)

$$\langle [N_c-1,1](\lambda'\mu')Y'I'I'_3S'S'_3|E^{ia}|[N_c-1,1](\lambda\mu)YII_3SS_3\rangle =$$
$$\sqrt{C^{[N_c-1,1]}(\mathrm{SU}(6))} \left(\begin{array}{cc|c} S & S^i & S' \\ S_3 & S^i_3 & S'_3 \end{array} \right) \left(\begin{array}{cc|c} I & I^a & I' \\ I_3 & I^a_3 & I'_3 \end{array} \right)$$
$$\times \sum_{\rho=1,2} \left(\begin{array}{cc||c} (\lambda\mu) & (\lambda^a\mu^a) & (\lambda'\mu') \\ YI & Y^aI^a & Y'I' \end{array} \right)_\rho \left(\begin{array}{cc||c} [N_c-1,1] & [21^4] & [N_c-1,1] \\ (\lambda\mu)S & (\lambda^a\mu^a)S^i & (\lambda'\mu')S' \end{array} \right)_\rho$$

where $C^{[N_c-1,1]}(\mathrm{SU}(6)) = N_c(5N_c+18)/12$ is the SU(6) Casimir operator for irrep $[N_c-1,1]$

$$E^i = \frac{S^i}{\sqrt{3}}; \quad E^a = \frac{T^a}{\sqrt{2}}; \quad E^{ia} = \sqrt{2}G^{ia}$$

[12] N. Matagne and F.L. Stancu, Phys. Rev. **D83**, 056007 (2011).

Isoscalar factors for the ^{48} states

$(\lambda_1\mu_1)S_1$	$(\lambda_2\mu_2)S_2$	ρ	$\left(\begin{array}{cc} [N_c-1,1] & [21^4] \\ (\lambda_1\mu_1)S_1 & (\lambda_2\mu_2)S_2 \end{array}\right\Vert\left.\begin{array}{c} [N_c-1,1] \\ (\lambda-2,\mu+1)S \end{array}\right)_\rho$
$(\lambda-2,\mu+1)S$	$(11)1$	1	$[N_c(4S-3)+6S]\sqrt{\frac{2(S+1)}{S[N_c(N_c+6)+12(S-1)S]N_c(5N_c+18)}}$
$(\lambda-2,\mu+1)S$	$(11)1$	2	$-\frac{N_c-2S}{S}\sqrt{\frac{3(S-1)(S+1)(N_c-2S+6)(N_c+2S)(N_c+2S+4)}{2(N_c-2S+2)[N_c(N_c+6)+12(S-1)S]N_c(5N_c+18)}}$
$(\lambda\mu)S+1$	$(11)1$	/	$-\sqrt{\frac{3}{2}}\sqrt{\frac{2S+3}{2S+1}}\sqrt{\frac{(N_c-2S)(N_c+2S+4)}{N_c(5N_c+18)}}$
$(\lambda\mu)S$	$(11)1$	/	$-\frac{1}{S}\sqrt{\frac{3}{2}}\sqrt{\frac{(N_c-2S)(N_c+2S+4)}{(N_c+2S+2)(5N_c+18)}}$
$(\lambda\mu)S-1$	$(11)1$	/	$\frac{N_c+4S^2}{S}\sqrt{\frac{3(N_c+2S+4)}{2(2S-1)(2S+1)(N_c+2S+2)N_c(5N_c+18)}}$
$(\lambda-2,\mu+1)S-1$	$(11)1$	1	$\frac{3\sqrt{2(S-1)(N_c+2S)}}{\sqrt{S[N_c(N_c+6)+12(S-1)S](5N_c+18)}}$
$(\lambda-2,\mu+1)S-1$	$(11)1$	2	$-\frac{N_c}{S}\sqrt{\frac{3(N_c-2S+6)(N_c+2S+4)}{2(N_c-2S+2)[N_c(N_c+6)+12(S-1)S](5N_c+18)}}$
$(\lambda-1,\mu-1)S$	$(11)1$	/	$-2\sqrt{\frac{3(S+1)(N_c-2S)(N_c+2S)}{S(N_c-2S+2)(N_c+2S+2)N_c(5N_c+18)}}$
$(\lambda-1,\mu-1)S-1$	$(11)1$	/	$2(S-1)\sqrt{\frac{3(N_c-2S)(N_c+2S)}{S(2S-1)(N_c-2S+2)(N_c+2S+2)N_c(5N_c+18)}}$
$(\lambda-3,\mu)S-1$	$(11)1$	/	$-2\sqrt{\frac{3(S-1)(N_c+2S-2)}{(2S-1)(N_c-2S+4)N_c(5N_c+18)}}$
$(\lambda-4,\mu+2)S-1$	$(11)1$	/	$-\sqrt{\frac{3}{2}}\sqrt{\frac{2S-3}{2S-1}}\sqrt{\frac{(N_c+2S)(N_c-2S+2)(N_c-2S+6)}{(N_c-2S+4)N_c(5N_c+18)}}$
$(\lambda-2,\mu+1)S$	$(11)0$	1	$\sqrt{\frac{N_c(N_c+6)+12(S-1)S}{2N_c(5N_c+18)}}$
$(\lambda-2,\mu+1)S$	$(11)0$	2	0
$(\lambda-2,\mu+1)S$	$(00)1$	/	$\sqrt{\frac{4S(S+1)}{N_c(5N_c+18)}}$

$$M_{[\mathbf{70},1^-]} = \sum_i c_i O_i + \sum_j d_j B_j$$

Operator	Fit 1 (MeV)	Fit 2 (MeV)	Fit 3 (MeV)
$O_1 = N_c \mathbb{1}$	489 ± 4	492 ± 4	492 ± 4
$O_2 = \ell^i s^i$	24 ± 6	6 ± 6	6 ± 5
$O_3 = \frac{1}{N_c} S^i S^i$	129 ± 10	123 ± 10	123 ± 10
$O_4 = \frac{1}{N_c} \left[T^a T^a - \frac{1}{12} N_c(N_c+6)\right]$	145 ± 16	134 ± 16	135 ± 16
$O_5 = \frac{3}{N_c} L^i T^a G^{ia}$	-19 ± 7	3 ± 7	4 ± 3
$O_6 = \frac{15}{N_c} L^{(2)ij} G^{ia} G^{ja}$	9 ± 1	9 ± 1	9 ± 1
$O_7 = \frac{1}{N_c^2} L^i G^{ja} \{S^j, G^{ia}\}$	129 ± 33	6 ± 33	
$B_1 = -\mathcal{S}$	138 ± 8	138 ± 8	137 ± 8
$B_2 = \frac{1}{N_c} \sum_{i=1}^{3} T^i T^i - O_4$	-59 ± 18	-40 ± 18	-40 ± 18
χ^2_{dof}	1.7	0.9	0.84

- **Fit 1 :** $M(\Lambda(1405)) = 1407$ MeV
- **Fit 2-3 :** $M(\Lambda(1405)) = 1500$ MeV
- Important role of O_7 in Fit 1 ($\chi^2_{dof} = 2.95$ without it)
- O_2 **and** O_7 contribute to the $\Lambda(1405) - \Lambda(1520)$ splitting
- **Spin operator** O_3 dominant for N
- **Flavor operator** O_4 dominant for Δ

Results for Fit 1

	Part. contrib. (MeV)									Total (MeV)	Exp. (MeV)	Name, status
	c_1O_1	c_2O_2	c_3O_3	c_4O_4	c_5O_5	c_6O_6	c_7O_7	d_1B_1	d_2B_2			
$N_{\frac{1}{2}}$	1467	-8	32	36	19	0	-31	0	0	1499 ± 10	1538 ± 18	$S_{11}(1535)$****
$\Lambda_{\frac{1}{2}}$								138	15	1668 ± 9	1670 ± 10	$S_{01}(1670)$****
$\Sigma_{\frac{1}{2}}$								138	-25	1628 ± 10		
$\Xi_{\frac{1}{2}}$								276	0	1791 ± 13		
$N_{\frac{3}{2}}$	1467	4	32	36	-10	0	16	0	0	1542 ± 10	1523 ± 8	$D_{13}(1520)$****
$\Lambda_{\frac{3}{2}}$								138	15	1698 ± 8	1690 ± 5	$D_{03}(1690)$****
$\Sigma_{\frac{3}{2}}$								138	-25	1658 ± 9	1675 ± 10	$D_{13}(1670)$****
$\Xi_{\frac{3}{2}}$								276	0	1821 ± 11	1823 ± 5	$D_{13}(1820)$***
$N'_{\frac{1}{2}}$	1467	-20	162	36	48	-18	42	0	0	1648 ± 11	1660 ± 20	$S_{11}(1650)$****
$\Lambda'_{\frac{1}{2}}$								138	15	1784 ± 16	1785 ± 65	$S_{01}(1800)$***
$\Sigma'_{\frac{1}{2}}$								138	-25	1745 ± 17	1765 ± 35	$S_{11}(1750)$***
$\Xi'_{\frac{1}{2}}$								276	0	1907 ± 20		
$N'_{\frac{3}{2}}$	1467	-8	162	36	19	15	-17	0	0	1675 ± 10	1700 ± 50	$D_{13}(1700)$***
$\Lambda'_{\frac{3}{2}}$								138	15	1826 ± 12		
$\Sigma'_{\frac{3}{2}}$								138	-25	1787 ± 13		
$\Xi'_{\frac{3}{2}}$								276	0	1949 ± 16		
$N_{\frac{5}{2}}$	1467	12	162	36	-29	-4	25	0	0	1669 ± 10	1678 ± 8	$D_{15}(1675)$****
$\Lambda_{\frac{5}{2}}$								138	15	1822 ± 10	1820 ± 10	$D_{05}(1830)$****
$\Sigma_{\frac{5}{2}}$								138	-25	1782 ± 11	1775 ± 5	$D_{15}(1775)$****
$\Xi_{\frac{5}{2}}$								276	0	1945 ± 14		

	Part. contrib. (MeV)									Total (MeV)	Exp. (MeV)	Name, status
	c_1O_1	c_2O_2	c_3O_3	c_4O_4	c_5O_5	c_6O_6	c_7O_7	d_1B_1	d_2B_2			
$\Delta_{\frac{1}{2}}$	1467	8	32	181	38	0	-24	0	0	1702 ± 18	1645 ± 30	$S_{31}(1620)$****
$\Sigma''_{\frac{1}{2}}$								138	34	1875 ± 16		
$\Xi''_{\frac{1}{2}}$								276	59	2037 ± 22		
$\Omega_{\frac{1}{2}}$								413	74	2190 ± 29		
$\Delta_{\frac{3}{2}}$	1467	-4	32	181	-19	0	12	0	0	1668 ± 20	1720 ± 50	$D_{33}(1700)$****
$\Sigma''_{\frac{3}{2}}$								138	34	1841 ± 16		
$\Xi''_{\frac{3}{2}}$								276	59	2003 ± 21		
$\Omega_{\frac{3}{2}}$								413	74	2156 ± 27		
$\Lambda''_{\frac{1}{2}}$	1467	-24	32	-108	0	0	-38	138	-44	1421 ± 14	1407 ± 4	$S_{01}(1405)$****
$\Lambda''_{\frac{3}{2}}$	1467	12	32	-108	0	0	19	138	-44	1515 ± 14	1520 ± 1	$D_{03}(1520)$****
$N_{1/2} - N'_{1/2}$	0	-8	0	0	-10	-55	18	0	0	-55		
$N_{3/2} - N'_{3/2}$	0	-12	0	0	-15	17	28	0	0	18		

Status of $\Lambda(1405)$

- Negative parity baryon resonance with $J = 1/2, I = 0, \mathcal{S} = -1$
- Difficult to be described by **constituent quark models** (mass too large, small mass difference with spin-orbit partner ($\Lambda(1520)$))
- Mass well described in the **first approach**, $S_c = 0$ contributions $\Rightarrow$ **Vanishing Spin-Spin** contributions
- Not so well described in **our picture**, $S_c = 1$ contributions also included
  $\Rightarrow$ **Nonvanishing Spin-Spin** contributions
- $\Lambda(1405)$, qqq state? Meson-Baryon "molecule" nature suggested by study of N_c dependence of decay widths [13]

[13] T. Hyodo, D. Jido, L. Roca, Phys. Rev. **D77**, 056010 (2008).

Conclusions

- $[\mathbf{70}, 1^-]$ baryon masses
- Two complementary approaches :
  - **Core + excited quark** ignores isospin terms
  - **Exact wave function** includes isospin term
    $\Rightarrow$ Contribution to Δ similar to that of spin terms in N
    $\Rightarrow$ Flavor dependent interactions are required
- Status of $\Lambda(1405)$ still **uncertain**
  $\Rightarrow$ more studies in large N_c
- Analysis of multiplets higher than $[\mathbf{70}, 1^-]$ is necessary (work in progress)