

The excited baryon mass spectrum : within chiral quark-soliton model

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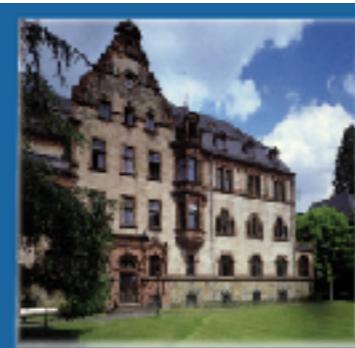
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WE-Heraeus Physics School

QCD – Old Challenges and
New Opportunities

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Motivation

- Puzzles in mass spectra of excited baryon :
Missing resonances & Mass ordering.
- Missing resonances problem : A large number of resonances are predicted but those are much larger than the observed resonances.
- Mass ordering problem : Discordant mass orderings from the observed resonances,
e.g. $N(1535, 1/2^-) > N(1520, 3/2^-)$ in observation
 $N(70, L=1, 1/2^-) < N(70, L=1, 3/2^-)$ in prediction.

[U. Löring et al, Eur. Phys. J. A10, 309, 2001]

[R. Edwards et al, Phys. Rev. D84, 074508, 2011]

Chiral quark-soliton model(CQSM)

- Basic concept : Baryons can be considered as N_c quarks are bound by the mesonic mean fields at large N_c (E. Witten, 1979)

$$\mathcal{S}_{\text{eff}} = -N_c \text{Tr} \ln [\partial_\tau + h(U) - i\gamma_4 \hat{m}]$$

$$h(U) = -\gamma_4 \gamma_k \partial^k - i\gamma_4 M U^{\gamma_5}$$

$$\hat{m} = \text{diag} [m_u, m_d, m_s]$$

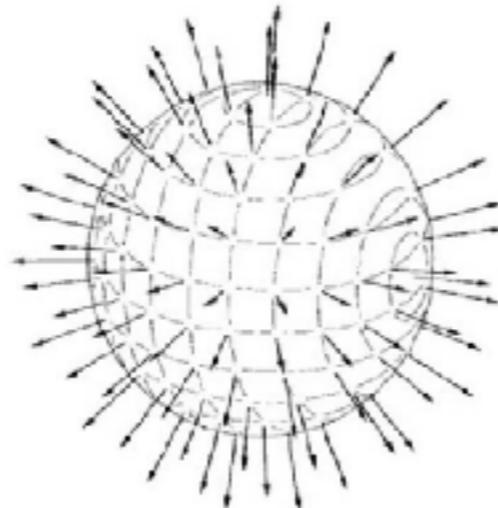
[E. Witten, Nucl. Phys. B160. 57, 1979]

[HCh. Kim et al. Prog. Part. Nucl. Phys. Vol.37, 91 (1996)]

Classical solitons

- Hedgehog Ansatz :

$$U_{SU(2)} = e^{i\boldsymbol{\tau} \cdot \mathbf{r}\pi(r)}$$



- Correlation function

$$\langle J_N^\dagger(\vec{x}, T) J_N(\vec{x}', -T) \rangle \sim \Pi_N(T) \sim e^{-[N_c E_{val} + E_{sea}]T}$$

- Classical mass

$$\frac{\partial}{\partial U} [N_c E_{val} + E_{sea}] = 0 \quad \rightarrow \quad M_{\text{cl}} = N_c E_{val}(U_c) + E_{sea}(U_c)$$

[HCh. Kim et al. Prog. Part. Nucl. Phys. Vol.37, 91 (1996)]

Hedgehog Ansatz and mean field

- Trivial embedding of the SU(2) field into the SU(3) field

$$U_{SU(3)} = \begin{bmatrix} e^{i\boldsymbol{\tau} \cdot \boldsymbol{r}\pi(r)} & 0 \\ 0 & 1 \end{bmatrix} \quad \text{SU(3)_f} \otimes \text{O(3)_{space}} \rightarrow \text{SU(2)<sub>iso+space

By hedgehog Ansatz</sub>$$

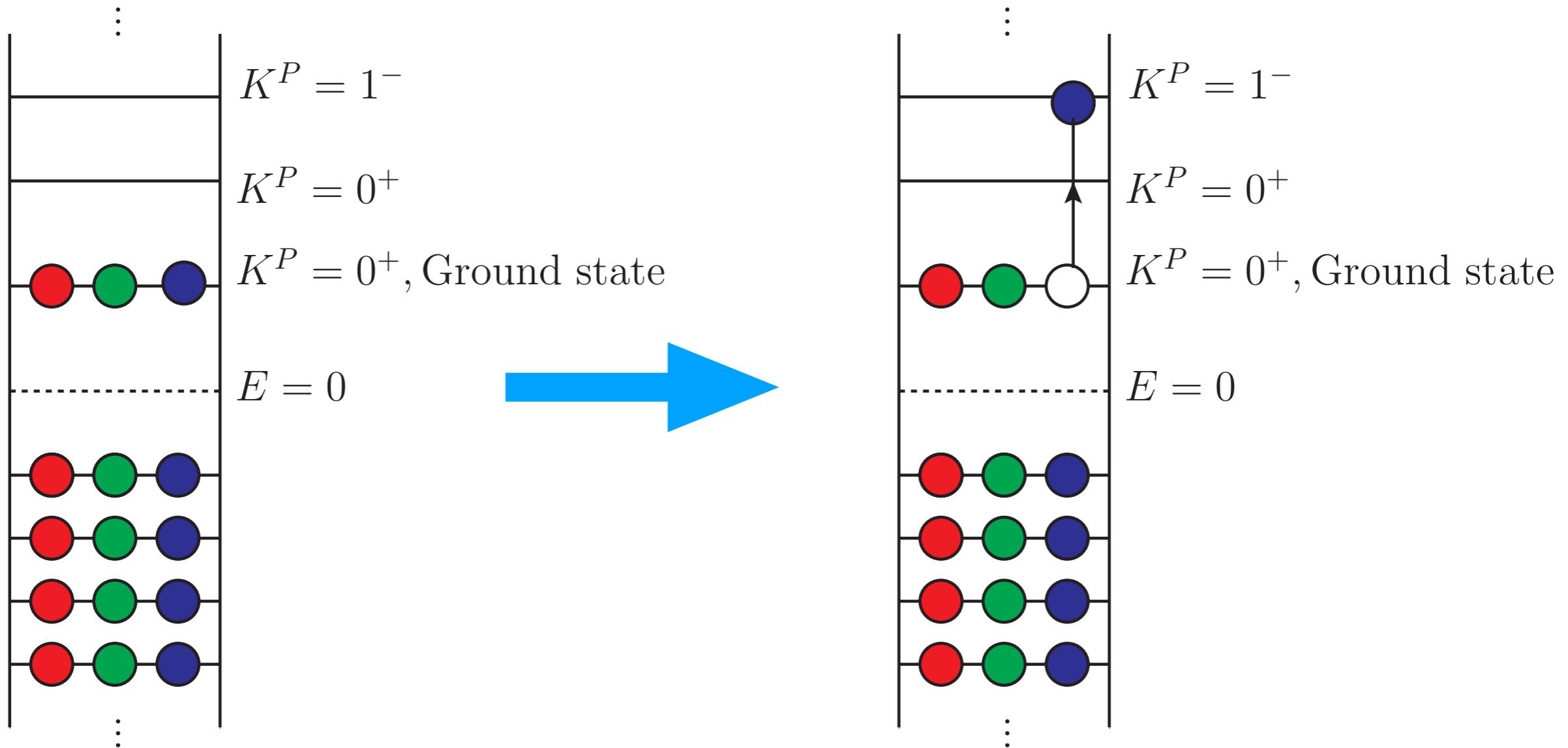
[E. Witten, Nucl. Phys. B223. 422, 1983]

- Breaking of this higher symmetry will reduce the number of baryon states
→ Missing resonances could be solved
- Collective(Zero-mode) quantization

$$U(\boldsymbol{x}, t) = R(t) U_c(\boldsymbol{x} - \boldsymbol{Z}(t)) R^\dagger(t)$$

$$\int D\boldsymbol{U} [\dots] \rightarrow \int DRD\boldsymbol{Z} [\dots]$$

Schematic pictures of the excited baryons



- Ground state of baryon
- Excited state of baryon

Collective Hamiltonians

- Hamiltonian for rotational energy

$$\mathcal{H}_{rot} = \frac{1}{2I_2} \sum_{a=4}^7 \tilde{T}_a^2 + \frac{(\tilde{\mathbf{T}} - a_K \hat{\mathbf{K}})^2}{2I_1}$$

Quantization rule :

$$\tilde{T} + \tilde{J} = \hat{K}, \quad \hat{Y} = \frac{N_c}{3}$$

- Hamiltonian for $SU(3)_f$ symmetry breaking

$$\mathcal{H}_{br} = \alpha \mathcal{D}_{88}^{(8)}(R) + \beta \hat{Y} - \frac{\gamma}{\sqrt{3}} \sum_{i=1}^3 \mathcal{D}_{8i}^{(8)}(R) \tilde{T}_i - \frac{\delta_K}{\sqrt{3}} \sum_{i=1}^3 \mathcal{D}_{8i}^{(8)}(R) \hat{K}_i$$

$$\alpha = -\frac{2}{3} \frac{m_s}{m_u + m_d} \Sigma_{\pi N} + m_s \frac{K_2}{I_2}, \quad \beta = -m_s \frac{K_2}{I_2}$$

**Additional terms
in the $K>0$ state**

$$\gamma = 2m_s \left(\frac{K_1}{I_1} - \frac{K_2}{I_2} \right), \quad \delta_K = 2m_s \left(d_K - \frac{K_1}{I_1} a_K \right)$$

[D. Diakonov, V. Petrov, and A. Vladimirov, Phys. Rev. D88, 074030 (2013)]

Model-Independent analysis

κ	J^P	N	Λ	Σ	Ξ
0,Ground	1/2+	939	1115	1192	1317
0	1/2+	1440	1600	1660	1690
	1/2-	1650	1800	1620	
1	1/2-	1535	1670	1560	
	3/2-	1520	1690	1670	1820
	1/2+	1710	1810	1880	1950
2	3/2+	1720	1890	1840	
	5/2+	1680	1820	1915	2030
	3/2-	1700		1940	
	5/2-	1675	1830	1775	

(MeV)

[V. Guzey, M. V. Polyakov, hep-ph/0512355 (2005)]

- The baryons are categorized according to quantization rule
- In octet, $\hat{Y} = 1$, $\tilde{T} = \frac{1}{2}$

$$J = |\tilde{T} - K|, \sim |\tilde{T} + K|$$
- $K=0, J=1/2$
- $K=1, J=(1/2, 3/2)$
- $K=2, J=(3/2, 5/2)$

Model-Independent analysis

K	J^P	Δ	Σ	Ξ	Ω
0, Ground	3/2+	1232	1385	1530	1672
0	3/2+	1600	1730		
	1/2-	1630	1750		
	3/2-	1700			
1	5/2-	1930			
	1/2+	1910			
	5/2+	2000			
	3/2+	1920	2080		2470
2	5/2+	1905	2070	2250	2380
	7/2+	1950	2030	2120	2250

(MeV)

[V. Guzey, M. V. Polyakov, hep-ph/0512355 (2005)]

- In decuplet, $\hat{Y} = 1, \tilde{T} = \frac{3}{2}$

$$J = |\tilde{T} - K|, \sim |\tilde{T} + K|$$
- K=0, J=3/2
- K=1, J=(1/2, 3/2, 5/2)
- K=2, J=(1/2, 3/2, 5/2, 7/2)

Model-Independent analysis

- Center mass

$$M_C = M_{cl} + \Delta\mathcal{E}(0^+ \rightarrow K^P) + \frac{C_2(SU(3)) - \tilde{T}(\tilde{T} + 1) - \frac{3}{4}\hat{Y}^2}{2I_2}$$

$$+ \frac{1}{2I_1} \left[a_K J(J + 1) + (1 - a_K)\tilde{T}(\tilde{T} + 1) - a_K(1 - a_K)K(K + 1) \right]$$

$$M_{cl}=781.0 \text{ MeV} \quad I_2^{-1}=415.3 \text{ MeV}$$

K^P	I_1^{-1}	a_K	$\Delta\epsilon$
Ground, 0^+	154.0	0	0
0^+	83.3	0	481.3
0^-			586.3
1^-	128.3	0.30	501.3
1^+			732.5
2^+	138.0	-0.05	717.9
2^-			664.3

(MeV)

Model-Independent analysis

- Center masses

Octet

K	JP	PDG	This work
0	1/2+	1605±27	1605
	1/2-	1710 ⁺³⁵ ₋₅₇	1710
1	1/2-	1615±13	1615
	3/2-	1673±5	1673
	1/2+	1846 ⁺⁶¹ ₋₄₉	1846
	3/2+	1865 ⁺¹⁰ ₋₃₀	1874
2	5/2+	1873 ⁺⁵⁵ ₋₆₀	1856
	3/2-		1820
	5/2-	1803 ⁺³ ₋₁₃	1803

(MeV)

Decuplet

K	JP	PDG	This work
0	3/2+	1730±63	1730
	1/2-	1750 ⁺⁵⁰ ₋₂₀	1750
	3/2-		1808
	5/2-		1903
	1/2+		1981
1	5/2+		2135
	3/2+	2097 ⁺⁴⁸ ₋₂₁	2092
	5/2+	2071 ⁺²⁰ ₋₄₄	2074
	7/2+	2038 ⁺¹⁸ ₋₂₂	2049

(MeV)

Model-Independent analysis

- Baryon mass

$$\begin{aligned} M_B &= M_C + \langle B | \mathcal{H}_{\text{br}} | B \rangle \\ &= M_C \end{aligned}$$

$$+ \langle B | \left[\alpha \mathcal{D}_{88}^{(8)}(R) + \beta \hat{Y} - \frac{\gamma}{\sqrt{3}} \sum_{i=1}^3 \mathcal{D}_{8i}^{(8)}(R) \tilde{T}_i - \frac{\delta_K}{\sqrt{3}} \sum_{i=1}^3 \mathcal{D}_{8i}^{(8)}(R) \hat{K}_i \right] | B \rangle$$

- Baryon wave function

$$|B\rangle = \sqrt{\frac{\dim(r)(2J+1)}{2K+1}} \sum_{\tilde{T}', \tilde{T}'_3, \tilde{J}'_3} C_{\tilde{T}' - \tilde{T}'_3 J \tilde{J}'_3}^{KK'_3} (-1)^{-\tilde{T}' - \tilde{T}'_3} \mathcal{D}_{(-\tilde{Y}\tilde{T}'\tilde{T}'_3)(YTT_3)}^{(r)}(R^\dagger) \mathcal{D}_{\tilde{J}'_3 J_3}^J(S^\dagger) \chi_{K'_3}$$

[D. Diakonov, V. Petrov, and A. Vladimirov, Phys. Rev. D88, 074030 (2013)]

Model-Independent analysis

α	β	γ
-255.03	-140.04	-101.08

(MeV)

[Ghil-Seok Yang, Hyun-Chul Kim, Prog. Theor. Phys. 128, 397 (2012)]

- K=0 case

8	$K(J^P)$	N	Λ	Σ	Ξ
PDG	0(1/2+)	1440^{+10}_{-30}	1600^{+100}_{-40}	1660 ± 30	1690 ± 10
This Work		1394	1564	1645	1776
PDG	0(1/2-)	1650^{+25}_{-5}	1800^{+50}_{-80}	1620^{+20}_{-35}	
This Work		1499	1669	1751	1881

10	$K(J^P)$	Δ	Σ	Ξ	Ω
PDG	0(1/2+)	1600 ± 100	1727 ± 27		
This Work		1590	1730	1870	2011

(MeV)

Model-Independent analysis

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This Work		1499	1669	1751	1881
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PDG	0(1/2+)	1600 ± 100	1727 ± 27		
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(MeV)

What are we more considering?

- Valence states of quark are changed in excited state of baryon.
- All parameters related with valence states can be changed also.
- Therefore, the value of α , β , γ can be changed at each K^P .

Model-Independent analysis

α	β	γ	δ
-167.51	-65.84	311.67	125.0

(MeV)

- K=1 case

(MeV)

8	K(J^P)	N	Λ	Σ	Ξ
PDG	1(1/2-)	1535±10	1670±10	1560 ⁺¹⁶ ₋₁₄	
This Work		1475	1670	1560	1810
PDG	1(3/2-)	1520 ₋₁₀	1690±5	1670 ⁺¹⁵ ₋₅	1823±5
This Work		1545	1690	1655	1818

8	K(J^P)	Δ	Σ	Ξ	Ω
PDG	1(1/2-)	1630±30	1750 ⁺⁵⁰ ₋₂₀		
This Work		1540	1750	1960	2170
PDG	1(3/2-)	1700 ⁺⁵⁰ ₋₃₀			
This Work		1613	1808	2002	2197

Summary & Outlook

- The excited baryons can be categorized according to the quantization rule in CQSM.
- We extract parameters from the experimental data and then we can obtain masses of excited baryons.
- We are investigating the $\alpha, \beta, \gamma, \delta$ values at each K^P .

Thank you for listening!!!!