Structure of $\Lambda(1405)$ and the $\Lambda(1405)$-Meson-Baryon couplings

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Outline

1. Introduction

2. Our Approach/Results
   - $\Lambda(1405)$ in the extended CQM
   - The $\Lambda(1405)$-Meson-Baryon Couplings

3. Conclusion and Outlook

Data From PDG. [C.Amsler et al., Phys. Lett. B **667** 1 (2008)]

$\Lambda(1405)$, S_{01}, $I(J^P) = 0(\frac{1}{2}^-)$, Status: $* * **$

- Mass: 1406.5 ± 4.0 MeV
- Total decay width: 50 ± 2 MeV

Table: $\Lambda(1405)$ Decays Data

Mode	Decay width (Γ_i (MeV))
$\Sigma\pi$	50 ± 2
$\Sigma\gamma$[1]	
$\Lambda\gamma$[1]	

[1] $\Gamma_{\Sigma\gamma} = 10 \pm 4$ *or* 23 ± 7 keV, and $\Gamma_{\Lambda\gamma} = 27 \pm 8$ keV, obtained by isobar model calculations, H. Burkhardt and J. Lowe, Phys. Rev. C **44**, 607 (1991).

Previous Works: Structure of $\Lambda(1405)$

- Hadronic level
  - S-channel Resonance: DeGrand and Jaffe, Ann. Phys. 100, 425 (1976)
  - Quasibound State:
    - R. H. Dalitz and S. F. Tuan, Ann. Phys. 10, 307 (1960).
    - J. Schnick and R. H. Landau, Phys. Rev. Lett. 58, 1719 (1987).
    - P. B. Siegel and B. Saghai, Phys. Rev. C 52, 392 (1995).
    - M. Kimura, T. Miyakawa, A. Suzuki, M. Takayama, K. Tanaka, and A. Hosaka, Phys. Rev. C 62, 015206 (2000).
  - Double Poles Structure: Oset et al., Nucl.Phys.A835:59-66,2010
    - $1390 - 66i$ MeV, $\Sigma\pi$
    - $1426 - 16i$ MeV, $\bar{K}N$
- Quark Model: *uds*, singlet, first orbitally excited state Koniuk and Isgur, Phys. Rev. D 21, 1868 (1980)

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Motivation of Our Work

- Strong decay width of $\Lambda(1405)$: result from CQM much smaller than data [Koniuk and Isgur, Phys. Rev. D 21, 1868 (1980)]
- Mixed structure of $\Lambda(1405)$ required by QCD Sum rule: [Nakamura et al., Phys. Lett. B 662, 132 (2008).]
- Extended CQM:
  - $N(1535)$:
    - Axial charge: [An and Riska, Eur. Phys. J. A **37**, 263 (2008)];
    - Helicity amplitude $A^p_{1/2}$: [An and Zou, Eur. Phys. J. A **39**, 195 (2009)].
  - $N(1440)$:
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    - Mass: [Julia-Diaz and Riska, Nucl. Phys. A **780**, 175 (2006)].

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Wave Function for Λ(1405) in ECQM.

Baryons in ECQM:

$$|B\rangle = A_{(B)3q}|qqq\rangle + A_{(B)5q}\sum_i A_i|qqqq_i\bar{q}_i\rangle + \cdots . \quad (1)$$

Configuration mixing [Koniuk and Isgur, Phys. Rev. D 21, 1868 (1980)]:

$$|\Lambda(1405)\rangle = 0.90|\Lambda_1^2 P_A\rangle - 0.43|\Lambda_8^2 P_M\rangle + 0.06|\Lambda_8^4 P_M\rangle , \quad (2)$$

qqq component:

$$|\Lambda(1405)_1^2 P_A, \frac{1}{2}^-\rangle = \frac{1}{\sqrt{6}}|\Lambda\rangle_a X_a \Phi_{\Lambda^*}(\vec{q}_\lambda, \vec{q}_\rho) , \quad (3)$$

$$|\Lambda(1405)_8^2 P_M, \frac{1}{2}^-\rangle = -\frac{1}{2\sqrt{3}}(|\Lambda\rangle_\lambda X_\lambda + |\Lambda\rangle_\rho X_\rho)\Phi_{\Lambda^*}(\vec{q}_\lambda, \vec{q}_\rho) , \quad (4)$$

$$|\Lambda(1405)_8^4 P_M, \frac{1}{2}^-\rangle = \frac{1}{2\sqrt{3}}(|\Lambda\rangle_\lambda X'_\lambda + |\Lambda\rangle_\rho X'_\rho)\Phi_{\Lambda^*}(\vec{q}_\lambda, \vec{q}_\rho) . \quad (5)$$

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General wave function for $qqqq\bar{q}$ components in $\frac{1}{2}^-$ baryons [An and Riska, Eur. Phys. J. A **37**, 263 (2008)]:

$$\psi^{(i)}_{t,s} = \sum_{a,b,c} \sum_{Y,y,T_z,t_z} \sum_{S_z,s_z} C^{[1^4]}_{[31]_a[211]_a} C^{[31]_a}_{[F^{(i)}]_b[S^{(i)}]_c} [4]_X[F^{(i)}]_{b,Y,T_z}[S^{(i)}]_{c,S_z}[211;C]_a(Y,T,T_z,y,\bar{t},t_z|1,1/2,t) (S,S_z,1/2,s_z|1/2,s)\bar{\chi}_{y,t_z}\bar{\xi}_{s_z}\varphi_{[5]} \,. \quad (6)$$

Four-quark XFSC configurations [An and Riska, Eur. Phys. J. A **37**, 263 (2008)]:

configuration	flavor-spin	C_{FS}	color-spin	C_{CS}
1	$[31]_{FS}[211]_F[22]_S$	-16	$[31]_{CS}[211]_C[22]_S$	-16
2	$[31]_{FS}[211]_F[31]_S$	$-40/3$	$[31]_{CS}[211]_C[31]_S$	$-40/3$
3	$[31]_{FS}[22]_F[31]_S$	$-28/3$	$[22]_{CS}[211]_C[31]_S$	$-16/3$
4	$[31]_{FS}[31]_F[22]_S$	-8	$[211]_{CS}[211]_C[22]_S$	0
5	$[31]_{FS}[31]_F[31]_S$	$-16/3$	$[211]_{CS}[211]_C[31]_S$	$+8/3$

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Five-quark components in $\Lambda(1405)$ the corresponding coefficients [An, Saghai, Yuan and He, Phys. Rev. C 81, 045203 (2010)]:

Baryon	Flavor-spin configuration	A_u	A_d	A_s
$\Lambda(1405)^2_1 P_A$	$[31]_{FS}[211]_F[22]_S$	$\sqrt{\frac{1}{3}}$	$\sqrt{\frac{1}{3}}$	$\sqrt{\frac{1}{3}}$
$\Lambda(1405)^2_8 P_M$	$[31]_{FS}[211]_F[22]_S$	$-\sqrt{\frac{1}{6}}$	$-\sqrt{\frac{1}{6}}$	$\sqrt{\frac{2}{3}}$
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$$|\Lambda(1405), s_z\rangle^{(i)}_{5q} = \sum_{abc} C^{[1^4]}_{[31]_a[211]_a} C^{[31]_a}_{[211]_b[22]_c} [4]_X[211]_F(b)[22]_S(c)[211]_C(a) \bar{\chi}_{s_z}\Psi(\vec{\kappa}_i) \quad (7)$$

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Formalism

Transition amplitude for $\Lambda(1405) \to MB$:

$$\begin{aligned} T^M &= \langle B|\hat{T}^M|\Lambda(1405)\rangle \\ &= \{A_{(B)3q}\langle qqq| + A_{(B)5q}\langle qqqq\bar{q}|\}\hat{T}^M\{A^*_{3q}|qqq\rangle^* + A^*_{5q}|qqqq\bar{q}\rangle^*\} \\ &= A_{(B)3q}A^*_3\langle qqq|\hat{T}^M_3|qqq\rangle^* + A_{(B)5q}A^*_5\langle qqqq\bar{q}|\hat{T}^M_5|qqqq\bar{q}\rangle^* \\ &\quad + A_{(B)3q}A^*_5\langle qqq|\hat{T}^M_{53}|qqqq\bar{q}\rangle^* + A_{(B)5q}A^*_3\langle qqqq\bar{q}|\hat{T}^M_{35}|qqq\rangle^* \\ &= \langle\hat{T}^M_d\rangle_3 + \langle\hat{T}^M_d\rangle_5 + \langle\hat{T}^M_{nd}\rangle \end{aligned} \tag{8}$$

Diagonal transition:

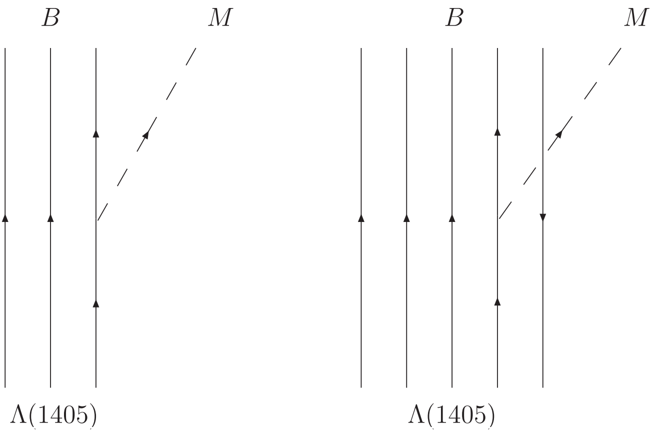
$$\begin{aligned} \langle\hat{T}^M_d\rangle_3 &= A_{(B)3q}A^*_3\langle qqq|\hat{T}^M_3|qqq\rangle^* \\ \langle\hat{T}^M_d\rangle_5 &= A_{(B)5q}A^*_3\langle qqqq\bar{q}|\hat{T}^M_5|qqqq\bar{q}\rangle^* \end{aligned} \tag{9}$$

Non-Diagonal transition:

$$\langle\hat{T}^M_{nd}\rangle = A_{(B)3q}A^*_5\langle qqq|\hat{T}^M_{53}|qqqq\bar{q}\rangle^* + A_{(B)5q}A^*_3\langle qqqq\bar{q}|\hat{T}^M_{35}|qqq\rangle^* \tag{10}$$

Formalism

Diagonal transition ($qqq \rightarrow qqqM$ and $qqqq\bar{q} \rightarrow qqqq\bar{q}M$):



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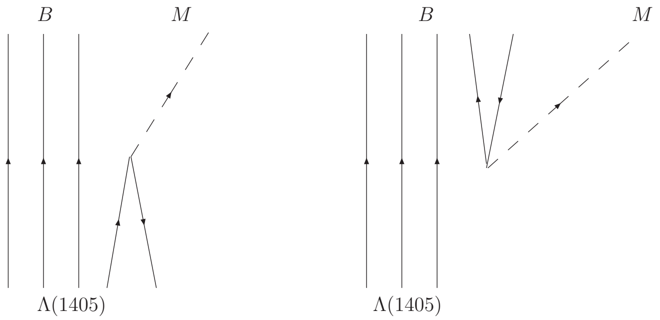

Formalism

Meson-Quark-Quark coupling [Riska and Brown, Nucl. Phys. A **679**, 577 (2001)]:

$$\mathcal{L}_{Mqq} = i\frac{g_A^q}{2f_M}\bar{\psi}_q\gamma_5\gamma_\mu\partial^\mu m_a\lambda_a\psi_q \,. \tag{11}$$

⇒ The following transition operators [An, Saghai et al., Phys. Rev. C **81** 045203 (2010)]:

$$\begin{aligned}
\hat{T}_d^M &= \sum_i^{nq}\frac{g_A^q}{2f_M}\phi_z^{i'\dagger}\begin{pmatrix} (1+\frac{k_0}{2m_f})k_M - \frac{k_0}{2\mu}q_{iz} & -\sqrt{2}\frac{k_0}{2\mu}q_{i-} \\ -\sqrt{2}\frac{k_0}{2\mu}q_{i+} & -(1+\frac{k_0}{2m_f})k_M + \frac{k_0}{2\mu}q_{iz} \end{pmatrix}\phi_z^i X_M^i \,, \\
\hat{T}_{53}^M &= -\sum_i^4\frac{g_A^q}{2f_M}(m_i+m_f)\phi_z^{\bar{q}\dagger}\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}\phi_z^i X_M^i \,, \\
\hat{T}_{35}^M &= -\sum_i^4\frac{g_A^q}{2f_M}(m_i+m_f)\phi_z^{i\dagger}\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}\phi_z^{\bar{q}} X_M^i .
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Formalism

Hadronic level:

$$\mathcal{L}_{\Lambda(1405)MB} = i\frac{f_{\Lambda(1405)MB}}{m_M}\bar{\psi}_B\gamma_\mu\partial^\mu\phi_M X_M\psi_{\Lambda(1405)} + h.c. \qquad (13)$$

$\Rightarrow$

$$T^M = \frac{f_{\Lambda(1405)MB}(M_{\Lambda(1405)} - m_B)}{m_M} \qquad (14)$$

$\Rightarrow$

$$f_{\Lambda(1405)MB} = \frac{m_M\langle B|[\hat{T}^M_d + \hat{T}^M_{35} + \hat{T}^M_{53}]|\Lambda(1405)\rangle}{M_{\Lambda(1405)-m_B}} \qquad (15)$$

or

$$g_{\Lambda(1405)MB} = \langle B|[\hat{T}^M_d + \hat{T}^M_{35} + \hat{T}^M_{53}]|\Lambda(1405)\rangle \qquad (16)$$

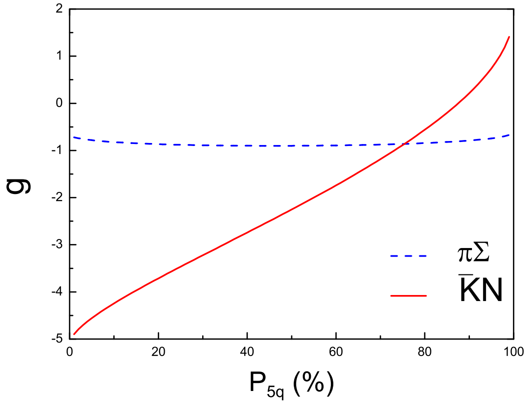
Results

Table: Results for the $\Sigma\pi$ decay width of $\Lambda(1405)$.

	A	B	C	D	E
P_{5q} (%)	0	25	45	75	100
$\Gamma_{\Sigma\pi}$ (MeV)	24	47	50	45	23

Results

The coupling constants $g_{\Lambda(1405)\Sigma\pi}$ and $g_{\Lambda(1405)\bar{K}N}$:



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$$P_{5q} = 0\% \Rightarrow g_{\Lambda(1405)\bar{K}N} = -5.3;$$

$$P_{5q} = 100\% \Rightarrow g_{\Lambda(1405)\bar{K}N} = 1.9$$

$|g_{\Lambda(1405)\bar{K}N}| = 3.2 \pm 0.6$ [Compilation of the coupling constants: O. Dumbrajs et al., Nucl. Phys. B **216**, 277 (1983)]

$\Rightarrow$ 1σ: $P_{5q} = 19 \sim 43\%$
$\Rightarrow$ 2σ: $P_{5q} = 7 \sim 55\%$

Lead to $\Rightarrow$ 1σ: $g_{\Lambda(1405)\pi\Sigma} = 0.86 \sim 0.90$
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$\Rightarrow 2\sigma$: $g_{\Lambda(1405)\pi\Sigma} = 0.80 \sim 0.90$

Results

$$P_{5q} = 0\% \Rightarrow g_{\Lambda(1405)\bar{K}N} = -5.3;$$

$$P_{5q} = 100\% \Rightarrow g_{\Lambda(1405)\bar{K}N} = 1.9$$

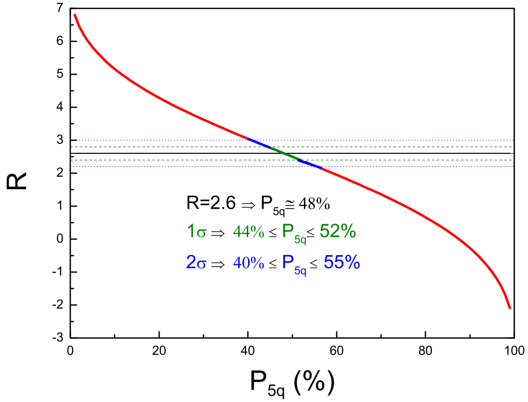
$|g_{\Lambda(1405)\bar{K}N}| = 3.2 \pm 0.6$ [Compilation of the coupling constants: O. Dumbrajs et al., Nucl. Phys. B **216**, 277 (1983)]

$\Rightarrow 1\sigma$: $P_{5q} = 19 \sim 43\%$
$\Rightarrow 2\sigma$: $P_{5q} = 7 \sim 55\%$

Lead to $\Rightarrow 1\sigma$: $g_{\Lambda(1405)\pi\Sigma} = 0.86 \sim 0.90$
$\Rightarrow 2\sigma$: $g_{\Lambda(1405)\pi\Sigma} = 0.80 \sim 0.90$

Results

The ratio $R = g_{\Lambda(1405)\bar{K}N}/g_{\Lambda(1405)\pi\Sigma}$ compare to the previous result [$R = 2.6 \pm 0.2$, J. K. Kim and F. V. hippel, Phys. Rev. **184** 1961 (1969)]:



Conclusion:

- $\Lambda(1405)$ favors a mixed structure of the qqq and $qqqq\bar{q}$ components;
- $40 \sim 55\%$ five-quark component in $\Lambda(1405)$ leads to reasonable values for the coupling constants $g_{\Lambda(1405)\bar{K}N}$ and ratio between $g_{\Lambda(1405)\bar{K}N}$ and $g_{\Lambda(1405)\pi\Sigma}$, and the $\pi\Sigma$ decay width.

Outlook:

- Taking into account the $qqqq\bar{q}$ components, we can give a new spectroscopy for the baryons;
- The effects of the $qqqq\bar{q}$ components in the meson hadron- and photo-production should be considered.

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Thank you very much for your attention!