Determination of $\bar{K}N$ compositeness of the $\Lambda(1405)$ resonance from its radiative decay

Takayasu SEKIHARA (RCNP, Osaka Univ.)

in collaboration with

Shunzo KUMANO (KEK)

Contents

1. Introduction
2. Compositeness
3. Formulation of $\Lambda(1405)$ radiative decay
4. Radiative decay width vs. compositeness
5. Summary
1. Introduction
1. Introduction

++ Hadrons ++

- Hadrons --- Interact with each other by strong interaction.

- They should be “color” singlet.

- Why we know that baryons (mesons) are composed of $qqq$ ($q\bar{q}$) ?
  - We can construct color singlet states minimally from $qqq$ and $q\bar{q}$.
  --- QCD, fundamental theory of strong interaction, restricts observables to be color singlet.

- Excellent successes of constituent quark models.

  --- Classifications with $qqq$ and $q\bar{q}$, mass spectra, magnetic moments, transition amplitudes, ...

  ( Parton distribution inside nucleons.  ... )
++ Exotic hadrons and their structure ++

- **Exotic hadrons** --- not same quark component as ordinary hadrons
  = not $qqq$ nor $q\bar{q}$. --- They should be "**color**" singlet as well.

--- Actually **some hadrons cannot be described by the quark model**.

- **Do they really exist?**
- If they do exist, **how are their properties?**
  --- Can we extend **constituent quarks to penta- and tetra-quarks?**
  --- How is the "**constituent**" gluons?
- If they do not exist, **what forbid their existence?**

<- We know very few about hadrons (and **dynamics of QCD**).
1. Introduction

++ Exotic hadrons and their structure ++

- Exotic hadrons --- not same quark component as ordinary hadrons
  = not $qqq$ nor $q\bar{q}$. --- They should be "color" singlet as well.
  --- Compact multi-quark systems, glueballs, hadronic molecules, ...

- Candidates: $\Lambda(1405)$, the lightest scalar mesons, $XYZ$, ...

- $\Lambda(1405)$ --- Mass = 1405.1 $^{+1.3}_{-1.0}$ MeV, width = 1/(life time) = 50 ± 2 MeV, decay to $\pi\Sigma$ (100 %), $I (J^P) = 0 (1/2^-)$.  

---

\[ \Lambda(1405) 1/2^- \]

\[ I(J^P) = 0(\frac{1}{2}^-) \]

\[
\begin{array}{ll}
\text{Mass} & m = 1405.1^{+1.3}_{-1.0} \text{ MeV} \\
\text{Full width} & \Gamma = 50 \pm 2 \text{ MeV} \\
\text{Below } & \overline{K}N \text{ threshold} \\
\hline
\Lambda(1405) \text{ DECAY MODES} & \frac{\Gamma_i}{\Gamma} & p \text{ (MeV/c)} \\
\Sigma \pi & 100 \% & 155
\end{array}
\]
1. Introduction

++ Exotic hadrons and their structure ++

- Exotic hadrons --- not same quark component as ordinary hadrons
  = not $qqq$ nor $q\bar{q}$. --- They should be “color” singlet as well.
- Compact multi-quark systems, glueballs, hadronic molecules, ...
  ◦ Candidates: $\Lambda(1405)$, the lightest scalar mesons, $XYZ$, ...

- $\Lambda(1405)$ --- Mass = 1405.1 $^{+1.3}_{-1.0}$ MeV, width = 1/(life time) = 50 $\pm$ 2 MeV,
  decay to $\pi\Sigma$ (100 %), $I (j^p) = 0$ (1/2--). Particle Data Group
- Why is $\Lambda(1405)$ the lightest excited baryon with $j^p = 1/2--$?
  --- $\Lambda(1405)$ contains a strange quark, which should be $\sim 100$ MeV
    heavier than up and down quarks.
  ◦ Strongly attractive $\bar{K}N$ interaction in the $I = 0$ channel.
  -- $\Lambda(1405)$ is a $\bar{K}N$ quasi-bound state ??? Dalitz and Tuan ('60), ...
1. Introduction

++ Dynamically generated $\Lambda(1405)$ ++

- The chiral unitary model (ChUM) reproduces low-energy Exp. data and dynamically generates $\Lambda(1405)$ in meson-baryon degrees of f.
  
  Kaiser-Siegel-Weise (’95), Oset-Ramos (’98), Oller-Meissner (’01), Jido et al. (’03), ...

\[ T_{ij}(s) = V_{ij} + \sum_{k} V_{ik} G_k T_{kj} \]

--- Spontaneous chiral symmetry breaking + Scattering unitarity.

$\Lambda(1405)$ in $KN-\pi\Sigma-\eta\Lambda-K\Xi$ coupled-channels.

- Prediction: Two poles for $\Lambda(1405)$ are dynamically generated.


--- One of the poles (around 1420 MeV) originates from $KN$ bound state.


1. Introduction

++ Determine hadron structures ++

- How can we determine the structure of hadrons in Exp.?

\[ |\Lambda(1405)\rangle = C_{uds} |uds\rangle + C_{\bar{K}N} |\bar{K}\rangle \otimes |N\rangle + C_{uud\bar{u}s} |uud\bar{u}s\rangle + \cdots \]

- **Spatial structure (= spatial size).**
  --- **Loosely bound hadronic molecules** will have large spatial size.


- **“Count” quarks inside hadron by using some special condition.**
  --- Scaling law for the quark counting rule in high energy scattering.


- **Compositeness** \(X\) = amount of two-body state inside system.
  cf. Deuteron is a proton-neutron bound state, not elementary.

2. Compositeness
2. Compositeness

++ Uniqueness of hadronic molecules ++

- Hadronic molecules seem to be unique, because they would have large spatial size compared to other (compact) hadrons.

- The uniqueness comes from the fact that hadronic molecules are composed of hadrons themselves, which are color singlet.

--> This fact leads to various quantitative and qualitative differences of hadronic molecules from other compact hadrons.

- Large spatial size.

- Theoretical prediction of existence around two-body threshold.

- Compositeness defined from two-body wave functions.
2. Compositeness

++ Physical meaning of compositeness ++

- **Compositeness** \( (X) \) = amount of the two-body components in a resonance as well as a bound state.

- **For \( \Lambda(1405) \):**

- Compositeness can be defined as the contribution of the two-body component to the normalization of the total wave function.

\[
\langle \Lambda(1405) | \Lambda(1405) \rangle = X_{KN} + X_{\pi\Sigma} + \cdots + Z = 1
\]

--- \( K, N \) are color singlet and hence observables, but quarks are not.

(Large composite \( \leftrightarrow X \sim 1 \))
2. Compositeness

++ Compositeness, model calculation ++

- Compositeness \( (X) \) = amount of the two-body components in a resonance as well as a bound state.

\[ X \sim 1 \quad \text{(Large composite } \leftrightarrow X \sim 1) \]

- Recently compositeness has been discussed in the context of the chiral unitary model.

--- **Elementariness**

\[ Z = 1 - \sum_i X_i \]

--- **i-channel compositeness** is expressed as:

\[ X_i = -g_i^2 \frac{dG_i}{d\sqrt{s}} (\sqrt{s} = W_{\text{pole}}) \]

- **Cut-off is not needed for** \( dG/d\sqrt{s} \).

\[ G_i(s) = i \int \frac{d^4q}{(2\pi)^4} \frac{1}{q^2 - m_k^2 + i\epsilon} \frac{1}{(P - q)^2 - m_k'^2 + i\epsilon} \]

2. Compositeness

++ Compositeness, model calculation ++

- Compositeness \( (X) \) = amount of the two-body components in a resonance as well as a bound state.

\[ X \sim 1 \text{ (Large composite } \leftrightarrow X \sim 1) \]

--- Elementariness

- Recently compositeness has been discussed in the context of the chiral unitary model.

--- \( i \)-channel compositeness is expressed as:

\[
X_i = -g_i^2 \frac{dG_i}{d\sqrt{s}} (\sqrt{s} = W_{\text{pole}})
\]

-- Compositeness can be determined from the coupling constant \( g_i \) and the pole position \( W_{\text{pole}} \).

---

Seminar @ ASRC, JAEA (May 21st, 2014)
2. Compositeness

++ Compositeness, model calculation ++

- Compositeness \((X)\) = amount of the two-body components in a resonance as well as a bound state.

\[
\text{(Large composite } \longleftrightarrow X \sim 1)\]

--- Elementariness

- Recently compositeness has been discussed in the context of the chiral unitary model.

--- \(i\)-channel compositeness is expressed as:

\[
X_i = -g_i^2 \frac{dG_i}{d\sqrt{s}} (\sqrt{s} = W_{\text{pole}})
\]

- Compositeness of \(\Lambda(1405)\) in the chiral unitary model:

--> Complex values, which cannot be interpreted as the probability.

<table>
<thead>
<tr>
<th>(\Lambda(1405)), lower pole</th>
<th>(\Lambda(1405)), higher pole</th>
</tr>
</thead>
<tbody>
<tr>
<td>(W_{\text{pole}})</td>
<td>(1391 - 66i) MeV</td>
</tr>
<tr>
<td>(X_{K^0 N^0})</td>
<td>(-0.21 - 0.13i)</td>
</tr>
<tr>
<td>(X_{\pi^0 \Sigma^0})</td>
<td>(0.37 + 0.53i)</td>
</tr>
<tr>
<td>(X_{\eta \Lambda})</td>
<td>(-0.01 + 0.00i)</td>
</tr>
<tr>
<td>(X_{K^0 \Xi})</td>
<td>(0.00 - 0.01i)</td>
</tr>
<tr>
<td>(Z)</td>
<td>(0.86 - 0.40i)</td>
</tr>
</tbody>
</table>


2. Compositeness

++ Compositeness, model calculation ++

- **Compositeness** \((X)\) = amount of the two-body components in a resonance as well as a bound state.

\[(\text{Large composite } \leftrightarrow X \sim 1)\]

--- Elementariness

- Recently compositeness has been discussed in the context of the chiral unitary model.

--- \(i\)-channel compositeness is expressed as:

\[X_i = -g_i^2 \frac{dG_i}{d \sqrt{s}} (\sqrt{s} = W_{\text{pole}})\]

- Compositeness of \(\Lambda(1405)\) in the chiral unitary model:

**\(\rightarrow\)** Large \(KN\) component for (higher) \(\Lambda(1405)\), since \(X_{KN}\) is almost unity.

---

\[Z = 1 - \sum_i X_i\]

<table>
<thead>
<tr>
<th>(\Lambda(1405)), lower pole</th>
<th>(\Lambda(1405)), higher pole</th>
</tr>
</thead>
<tbody>
<tr>
<td>(W_{\text{pole}})</td>
<td>1391 – 66i MeV</td>
</tr>
<tr>
<td>(X_{\bar{K}N})</td>
<td>-0.21 – 0.13i</td>
</tr>
<tr>
<td>(X_{\pi\Sigma})</td>
<td>0.37 + 0.53i</td>
</tr>
<tr>
<td>(X_{\eta\Lambda})</td>
<td>-0.01 + 0.00i</td>
</tr>
<tr>
<td>(X_{\bar{K}\Xi})</td>
<td>0.00 – 0.01i</td>
</tr>
<tr>
<td>(Z)</td>
<td>0.86 – 0.40i</td>
</tr>
</tbody>
</table>

2. Compositeness

++ Compositeness in experiments ++

- How can we determine compositeness of $\Lambda(1405)$ in experiments?

\[ X_i = -g_i^2 \frac{dG_i}{d\sqrt{s}} (\sqrt{s} = W_{\text{pole}}) \]

--- Compositeness can be evaluated from the coupling constant $g_i$ and the pole position $W_{\text{pole}}$.

- Exercise: $\pi\Sigma$ compositeness.
  - Pole position from PDG values:
    \[ W_{\text{pole}} = M_{\Lambda(1405)} -- i \Gamma_{\Lambda(1405)} / 2 \text{ with } M_{\Lambda(1405)} = 1405 \text{ MeV}, \Gamma_{\Lambda(1405)} = 50 \text{ MeV}. \]
  - Coupling constant $g_{\pi\Sigma}$ from $\Lambda(1405) \rightarrow \pi\Sigma$ decay width:
    \[ \Gamma_{\Lambda(1405)} = 3 \times \frac{p_{\text{cm}}M_{\Sigma}}{2\pi M_{\Lambda(1405)}} |g_{\pi\Sigma}|^2 = 50 \text{ MeV} \]
    \[ \rightarrow |g_{\pi\Sigma}| = 0.91. \]

---> From the compositeness formula, we obtain $|X_{\pi\Sigma}| = 0.19$.
--- Not small, but not large $\pi\Sigma$ component for $\Lambda(1405)$.

- Then, how is $\bar{K}N$ compositeness?
2. Compositeness

++ Compositeness in experiments ++

- How can we determine \( KN \) compositeness of \( \Lambda(1405) \) in Exp.?

- Pole position can be fixed from PDG values.

\[ X_i = -g_i^2 \frac{dG_i}{d\sqrt{s}} (\sqrt{s} = W_{\text{pole}}) \]

- Unfortunately, one cannot directly determine the \( KN \) coupling constant in Exp. in contrast to the \( \pi \Sigma \) coupling strength, because \( \Lambda(1405) \) exists just below the \( KN \) threshold (~1435 MeV).

- Furthermore, there are no direct model-independent relations between the \( KN \) compositeness and observables such as the \( K^- p \) scattering length, in contrast to the deuteron case.

--- The relation for deuteron is valid only for small \( B_E \).

---> Therefore, in order to determine the \( KN \) compositeness, we have to observe some reactions which are relevant to the \( KN \) coupling constant. --- Such as the \( \Lambda(1405) \) radiative decay!
3. Formulation of $\Lambda(1405)$ radiative decay
3. Formulation

++ Radiative decay of $\Lambda(1405)$ ++

- There is an “experimental” value of the $\Lambda(1405)$ radiative decay:
  \[
  \Gamma(\Lambda(1405) \rightarrow \Lambda\gamma) = 27 \pm 8 \text{ keV}, \quad \text{PDG; Burkhardt and Lowe, Phys. Rev. C44 (1991) 607.}
  \]
  \[
  \Gamma(\Lambda(1405) \rightarrow \Sigma^0\gamma) = 10 \pm 4 \text{ keV or } 23 \pm 7 \text{ keV.}
  \]

- There are also several theoretical studies on the radiative decay:

--- Structure of $\Lambda(1405)$ has been discussed in these models, but the $\overline{K}N$ compositeness for $\Lambda(1405)$ has not been discussed.

|-- Discuss the $\overline{K}N$ compositeness from the $\Lambda(1405)$ radiative decay! |
++ Formulation of radiative decay ++

- Radiative decay width can be evaluated from following diagrams:


- Photon emission from meson-baryon components inside $\Lambda(1405)$.

  --- Strictly, $qqq$ or $qqqqq$ systems should have finite spatial size, so we may have to take into account the following diagram:

  but we neglect this diagram.

  **The $qqq$ or $qqqqq$ component inside $\Lambda(1405)$ should be small** according to the failure of the quark model.
3. Formulation

++ Formulation of radiative decay ++

- Radiative decay width can be evaluated from following diagrams:

- Photon emission from *meson-baryon components* inside $\Lambda(1405)$.

--- Strictly, $qqq$ or $qqqqq$ systems should have finite spatial size, so we may have to take into account the following diagram:

but we neglect this diagram.

<-- The $qqq$ or $qqqqq$ component inside $\Lambda(1405)$ should be small according to the failure of the quark model.
3. Formulation

++ Formulation of radiative decay ++

- Radiative decay width can be evaluated from following diagrams:

- Each diagram diverges, but sum of the three diagrams converges due to the gauge symmetry.
  --- One can prove that the sum converges using the Ward identity.

- The radiative decay width can be expressed as follows:
  \[
  \Gamma_{Y^0 \gamma} = \frac{p'_{\text{cm}} M_{Y^0}}{\pi M_{\Lambda(1405)}} |W_{Y^0 \gamma}|^2
  \]
  with
  \[
  W_{Y^0 \gamma} \equiv e \sum_i g_i Q_{M_i} \tilde{V}_{iY^0} A_{iY^0}
  \]
  --- Sum of loop integrals $A_{iY^0}$ and meson charge $Q_{M_i}$.
  --- $\tilde{V}$: Fixed by flavor $SU(3)$ symmetry.
3. Formulation

++ Formulation of radiative decay ++

- Radiative decay width can be evaluated from following diagrams:

- Each diagram diverges, but sum of the three diagrams converges due to the gauge symmetry.
  --- One can prove that the sum converges using the Ward identity.

- The radiative decay width can be expressed as follows:
  \[
  \Gamma_{Y^0\gamma} = \frac{p'_{\text{cm}} M_{Y^0}}{\pi M_{\Lambda(1405)}} |W_{Y^0\gamma}|^2
  \]
  with
  \[
  W_{Y^0\gamma} \equiv e \sum_i g_i Q_i M_i V_{iY^0} A_{iY^0}
  \]
  --- Coupling constant \( g_i \) appears as a model parameter!

  --> Radiative decay is relevant to the \( K\bar{N} \) coupling!

- For \( \Lambda(1405) \), \( K^- p \), \( \pi^{\pm} \Sigma^\mp \), and \( K^+ \Xi^- \) are relevant channels.
3. Formulation

++ Radiative decay in chiral unitary model ++

- **Taken from the coupling constant** $g_i$ **from chiral unitary model**, one can evaluate **radiative decay width in chiral unitary model**.

### Table 3. The radiative decay widths of the $\Lambda(1405)$ predicted by different theoretical models, in units of keV. The values denoted by “$\chi PT$” are the results obtained in the present study. The widths calculated for the low-energy pole and high-energy pole are separated by a comma.

<table>
<thead>
<tr>
<th>Decay channel</th>
<th>$\chi PT$</th>
<th>$\Lambda(1405)$, lower pole</th>
<th>$\Lambda(1405)$, higher pole</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma \Lambda$</td>
<td>16.1, 64.8</td>
<td>$W_{\text{pole}} = 1391 - 66i$ MeV</td>
<td>$0.99 + 0.05i$</td>
</tr>
<tr>
<td>$\gamma \Sigma^0$</td>
<td>73.5, 33.5</td>
<td>$X_{KN} = -0.21 - 0.13i$</td>
<td>$0.99 + 0.05i$</td>
</tr>
<tr>
<td>$\gamma \Sigma^0$</td>
<td>60, 17</td>
<td>$X_{\pi \Sigma} = 0.37 + 0.53i$</td>
<td>$-0.05 - 0.15i$</td>
</tr>
<tr>
<td>$\gamma \Lambda$</td>
<td>18, 2.7</td>
<td>$X_{\eta \Lambda} = -0.01 + 0.00i$</td>
<td>$0.05 + 0.01i$</td>
</tr>
<tr>
<td>$\gamma \Sigma^0$</td>
<td>$X_{K \Xi} = 0.00 - 0.01i$</td>
<td>$0.00 + 0.00i$</td>
<td></td>
</tr>
<tr>
<td>$Z$</td>
<td>$0.86 - 0.40i$</td>
<td>$0.00 + 0.09i$</td>
<td></td>
</tr>
</tbody>
</table>

- **$\Lambda\gamma$ decay mode**: Dominated by the $\bar{K}N$ component.
  - Larger $K^-p\Lambda$ coupling strength:
  - Large $\pi\Sigma$ cancellation:

  \[
  \tilde{V}_{K^-p\Lambda} = -\frac{D + 3F}{2\sqrt{3}f} \approx -\frac{0.63}{f}
  \]

  with

  \[
  Q_{\pi^+} = -Q_{\pi^-} = 1
  \]
3. Formulation
++ Radiative decay in chiral unitary model ++

- Taken from the coupling constant $g_i$ from chiral unitary model, one can evaluate radiative decay width in chiral unitary model.

Table 3. The radiative decay widths of the $\Lambda(1405)$ predicted by different theoretical models, in units of keV. The values denoted by “UχPT” are the results obtained in the present study. The widths calculated for the low-energy pole and high-energy pole are separated by a comma.

<table>
<thead>
<tr>
<th>Decay channel</th>
<th>$\gamma\Lambda$</th>
<th>$\gamma\Sigma^0$</th>
<th>$\eta\Lambda$</th>
<th>$K\Sigma^0$</th>
<th>$\pi\Sigma$</th>
<th>$\pi K\Xi^0$</th>
<th>$Z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma\Lambda$</td>
<td>16.1, 64.8</td>
<td>18, 2.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\gamma\Sigma^0$</td>
<td>73.5, 33.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- $\Sigma^0\gamma$ decay mode: Dominated by the $\pi\Sigma$ component.

- Smaller $K^-p\Sigma^0$ coupling strength:

- **Constructive $\pi\Sigma$ contribution:**

$$\tilde{V}_{K^-p\Sigma^0} = \frac{D - F}{2f} \approx \frac{0.17}{f}$$

$$\tilde{V}_{\pi^+\Sigma^-\Sigma^0} = -\tilde{V}_{\pi^-\Sigma^+\Sigma^0} = \frac{F}{f} \approx \frac{0.47}{f}$$
+++ Our strategy +++

- We evaluate the $\Lambda(1405)$ radiative decay width $\Gamma_{\Lambda\gamma}$ and $\Gamma_{\Sigma^0\gamma}$ as a function of the absolute value of the $KN$ compositeness $|X_{KN}|$.

--- We can evaluate the $\Lambda(1405)$ radiative decay width when the $\Lambda(1405)$--meson-baryon coupling constant (model parameter) and the $\Lambda(1405)$ pole position are given.

--- $|X_{KN}|$ should contain information of the $\Lambda(1405)$ structure!

\[
\Gamma_{Y^0\gamma} = \frac{p'_{cm} M_{Y^0}}{\pi M_{\Lambda(1405)}} |W_{Y^0\gamma}|^2
\]

\[
W_{Y^0\gamma} \equiv e \sum_i g_i Q_{Mi} \tilde{V}_{iY^0} A_{iY^0}
\]
3. Formulation

++ Our strategy ++

- We evaluate the $\Lambda(1405)$ radiative decay width $\Gamma_{\Lambda\gamma}$ and $\Gamma_{\Sigma^0\gamma}$ as a function of the absolute value of the $\bar{K}N$ compositeness $|X_{\bar{K}N}|$.

--- We can evaluate the $\Lambda(1405)$ radiative decay width when the $\Lambda(1405)$-meson-baryon coupling constant (model parameter) and the $\Lambda(1405)$ pole position are given.

- $\Lambda(1405)$ pole position from PDG values:

  
  \[
  W_{\text{pole}} = M_{\Lambda(1405)} - i \frac{\Gamma_{\Lambda(1405)}}{2} \text{ with } M_{\Lambda(1405)} = 1405 \text{ MeV, } \Gamma_{\Lambda(1405)} = 50 \text{ MeV.}
  \]

- Assume isospin symmetry for the coupling constant $g_i$:

  \[
  g_{\bar{K}N} = g_{K-p} = g_{K^0_n}, \quad g_{\pi\Sigma} = g_{\pi^+\Sigma^-} = g_{\pi^-\Sigma^+} = g_{\pi^0\Sigma^0}
  \]

  and neglect $K\Xi$ component:

  \[
  g_{K+\Xi^-} = g_{K^0\Xi^0} = 0
  \]

- The coupling constant $g_{KN}$ as a function of $X_{KN}$ is determined from the compositeness relation:

  \[
  |X_{\bar{K}N}| = |g_{\bar{K}N}|^2 \left| \frac{dG_{K-p}}{d\sqrt{s}} + \frac{dG_{K^0_n}}{d\sqrt{s}} \right|_{\sqrt{s}=W_{\text{pole}}}
  \]
3. Formulation

++ Our strategy ++

- We evaluate the $\Lambda(1405)$ radiative decay width $\Gamma_{\Lambda\gamma}$ and $\Gamma_{\Sigma^0\gamma}$ as a function of the absolute value of the $KN$ compositeness $|X_{KN}|$.

--- We can evaluate the $\Lambda(1405)$ radiative decay width when the $\Lambda(1405)$--meson-baryon coupling constant (model parameter) and the $\Lambda(1405)$ pole position are given.

- Coupling constant $g_{\pi\Sigma}$ from $\Lambda(1405) \rightarrow \pi\Sigma$ decay width:

$$\Gamma_{\Lambda(1405)} = 3 \times \frac{p_{cm} M_{\Sigma}}{2\pi M_{\Lambda(1405)}} |g_{\pi\Sigma}|^2 = 50 \text{ MeV}$$

$$\Rightarrow |g_{\pi\Sigma}| = 0.91.$$  

- Interference between $KN$ and $\pi\Sigma$ components (= relative phase between $g_{KN}$ and $g_{\pi\Sigma}$) are not known.

$$\Rightarrow$$ We show allowed region of the decay width from maximally constructive / destructive interferences:

$$W^{\pm}_{Y^0\gamma} = e \left( |g_{\bar{K}N}| \times |\tilde{V}_{K-pY^0} A_{K-pY^0}| \pm |g_{\pi\Sigma}| \times |\tilde{V}_{\pi+\Sigma-Y^0} A_{\pi+\Sigma-Y^0} - \tilde{V}_{\pi-Y^0} A_{\pi-Y^0}| \right)$$

$$\Gamma_{Y^0\gamma} = \frac{p'_{cm} M_{Y^0}}{\pi M_{\Lambda(1405)}} |W_{Y^0\gamma}|^2$$
4. Radiative decay width vs. compositeness
4. Radiative decay vs. compositeness

++ $\Lambda(1405)$ radiative decay width ++
- We obtain allowed region of the $\Lambda(1405)$ radiative decay width as a function of the absolute value of the $\overline{KN}$ compositeness $|X_{KN}|$.

--- $\Lambda(1405)$ pole position dependence is small (discuss later).
4. Radiative decay vs. compositeness

++ $\Lambda(1405)$ radiative decay width ++

- $\Lambda\gamma$ decay mode:
  Dominated by the $\overline{K}N$ component.

--- Due to the large cancellation between $\pi^+\Sigma^-$ and $\pi^-\Sigma^+$,
  allowed region for $\Lambda\gamma$ is very small and
  is almost proportional to $|X_{\overline{K}N}|$ ($\propto |g_{\overline{K}N}|^2$).

--> **Large $\Lambda\gamma$ width**
  = large $|X_{\overline{K}N}|$.

- The $\Lambda(1405) \rightarrow \Lambda\gamma$ radiative decay mode is suited
  to observe the $\overline{K}N$ component inside $\Lambda(1405)$. 
4. Radiative decay vs. compositeness

++ $\Lambda(1405)$ radiative decay width ++

- $\Sigma^0\gamma$ decay mode:
  Dominated by the $\pi\Sigma$ component.

- $\Gamma_{\Sigma^0\gamma} \sim 23$ keV even for $|X_{KN}| = 0$.

- Very large allowed region for $\Gamma_{\Sigma^0\gamma}$.

- $\Gamma_{\Sigma^0\gamma}$ could be very large or very small for $|X_{KN}| \sim 1$. 
4. Radiative decay vs. compositeness

++ Compared with the “experimental” result ++

- There is an “experimental” value of the $\Lambda(1405)$ radiative decay:
  \[
  \Gamma(\Lambda(1405) \rightarrow \Lambda\gamma) = 27 \pm 8 \text{ keV},
  \]
  \[
  \Gamma(\Lambda(1405) \rightarrow \Sigma^0\gamma) = 10 \pm 4 \text{ keV} \text{ or } 23 \pm 7 \text{ keV}.
  \]
4. Radiative decay vs. compositeness

++ Compared with the “experimental” result ++

- There is an “experimental” value of the $\Lambda(1405)$ radiative decay:
  \[ \Gamma(\Lambda(1405) \rightarrow \Lambda\gamma) = 27 \pm 8 \text{ keV}, \quad \text{PDG; Burkhardt and Lowe, Phys. Rev. C44 (1991) 607.} \]
  \[ \Gamma(\Lambda(1405) \rightarrow \Sigma^0\gamma) = 10 \pm 4 \text{ keV or } 23 \pm 7 \text{ keV}. \]

- From $\Gamma(\Lambda(1405) \rightarrow \Lambda\gamma) = 27 \pm 8 \text{ keV}$: $|X_{KN}| = 0.5 \pm 0.2$.
  
  --- $KN$ seems to be the largest component inside $\Lambda(1405)$!
++ Compared with the “experimental” result ++

- There is an “experimental” value of the $\Lambda(1405)$ radiative decay:
  $\Gamma(\Lambda(1405) \rightarrow \Lambda \gamma) = 27 \pm 8$ keV, PDG; Burkhardt and Lowe, Phys. Rev. C44 (1991) 607.
  $\Gamma(\Lambda(1405) \rightarrow \Sigma^0 \gamma) = 10 \pm 4$ keV or $23 \pm 7$ keV.

- From $\Gamma(\Lambda(1405) \rightarrow \Sigma^0 \gamma) = 10 \pm 4$ keV: $|X_{KN}| > 0.5$.
  --- Consistent with the $\Lambda \gamma$ decay mode: large $\overline{K}N$ component!
++ Compared with the “experimental” result ++

- There is an “experimental” value of the $\Lambda(1405)$ radiative decay:
  \[ \Gamma(\Lambda(1405) \rightarrow \Lambda\gamma) = 27 \pm 8 \text{ keV}, \]
  \[ \Gamma(\Lambda(1405) \rightarrow \Sigma^0\gamma) = 10 \pm 4 \text{ keV} \text{ or } 23 \pm 7 \text{ keV}. \]

- From $\Gamma(\Lambda(1405) \rightarrow \Sigma^0\gamma) = 23 \pm 7 \text{ keV}$: $|X_{KN}|$ can be arbitrary.
4. Radiative decay vs. compositeness

++ Pole position dependence ++

- The $\Lambda(1405)$ pole position is **not well-determined** in Exp.

--- Two poles? 1420 MeV instead of nominal 1405 MeV?


$$|X_{\bar{K}N}| = |g_{\bar{K}N}|^2 \left| \frac{dG_{K^-p}}{d\sqrt{s}} + \frac{dG_{\bar{K}^0n}}{d\sqrt{s}} \right|_{\sqrt{s}=W_{\text{pole}}}$$

How the relation between $\Gamma_{\Lambda\gamma}$, $\Gamma_{\Sigma^0\gamma}$ and $|X_{\bar{K}N}|$ is changed if the pole position is shifted?

Pole position from PDG.
4. Radiative decay vs. compositeness

++ Pole position dependence ++

- The \( \Lambda(1405) \) pole position is not well-determined in Exp.

--- Two poles? 1420 MeV instead of nominal 1405 MeV?


--- Will be seen in, e.g.,

\[ K^- p^* \rightarrow \Lambda(1405) \] production.

\[ |X_{KN}| = |g_{KN}|^2 \left| \frac{dG_{K^-p}}{d\sqrt{s}} + \frac{dG_{K^0n}}{d\sqrt{s}} \right|_{\sqrt{s}=W_{\text{pole}}} \]

Higher \( \Lambda(1405) \) pole position.
4. Radiative decay vs. compositeness

++ Pole position dependence ++

- The $\Lambda(1405)$ pole position is not well-determined in Exp.

--- Two poles? 1420 MeV instead of nominal 1405 MeV? 


--- Will be seen in, e.g., $\pi^- p \rightarrow K^0 \Lambda(1405)$ production. Lower $\Lambda(1405)$ pole position.

$|X_{KN}| = |g_{KN}|^2 \left| \frac{dG_{Kp}}{d\sqrt{s}} + \frac{dG_{Kn}}{d\sqrt{s}} \right|_{\sqrt{s}=W_{pole}}$

$\Gamma_{\gamma\gamma}$, $M_{\Lambda(1405)} = 1381$ MeV

$\Sigma^0\gamma$, $M_{\Lambda(1405)} = 1381$ MeV
4. Radiative decay vs. compositeness

++ Pole position dependence ++

- Pole position dependence is not strong for the $\Lambda\gamma$ decay mode.
  --- Especially the result of $|X_{KN}|$ from the empirical value of the $\Lambda\gamma$ decay mode is almost same.

- Different branching ratio $\Lambda\gamma / \Sigma^0\gamma$.
  --> Could be evidence of two poles.
5. Summary
5. Summary

++ Summary ++

- We have investigated the $\Lambda(1405)$ radiative decay from the viewpoint of compositeness = amount of two-body state inside system.

$$X_i = -g_i^2 \frac{dG_i}{d\sqrt{s}} (\sqrt{s} = W_{\text{pole}})$$

- We have established a relation between the absolute value of the $\bar{K}N$ compositeness $|X_{\bar{K}N}|$ and the $\Lambda(1405)$ radiative decay width.

  - For the $\Lambda \gamma$ decay mode, $\bar{K}N$ component is dominant.
    --> Large $\Lambda \gamma$ width directly indicates large compositeness $|X_{\bar{K}N}|$.

  - For the $\Sigma^0 \gamma$ decay mode, $\pi \Sigma$ component is dominant.
    --> We could say $|X_{\bar{K}N}| \sim 1$ if $\Gamma_{\Sigma^0 \gamma}$ could be very large or very small.

- By using the “experimental” value for the $\Lambda(1405)$ decay width, we have estimated the $\bar{K}N$ compositeness as $|X_{\bar{K}N}| > 0.5$.

--- For more concrete conclusion, precise experiments are needed!
Thank you very much for your kind attention!
Appendix