Internal structure of resonant $\Lambda(1405)$ state in chiral dynamics

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1. Introduction

++ “Strange” baryon resonance $\Lambda(1405)$ ++

- $\Lambda(1405)$ --- Mass = $1406 \pm 4$ MeV, width = $50 \pm 2$ MeV,
  decay to $\pi\Sigma$ (100 %), $I (J^P) = 1 (1/2^-)$ (PDG).

- Why is $\Lambda(1405)$ the lightest excited baryon with $J^P = 1/2^-$?

--- $\Lambda(1405)$ is a $\bar{K}N$ quasi-bound state ??? Dalitz and Tuan ('60), ...

- One goal: confirmation of the meson-baryon molecule picture
  in experiments (as well as pole position etc.).

<-- “$\Lambda(1405)$ size” will be an important “observable”.

--- “$\Lambda(1405)$ size” is also important for, e.g., kaonic nuclei.
1. Introduction

++ Dynamically generated Λ(1405) ++

- Chiral unitary model (ChUM) dynamically generates Λ(1405) in mesons and baryons degrees of freedom.

  Kaiser-Siegel-Weise ('95), Oset-Ramos ('98), Oller-Meissner ('01), Jido et al. ('03), ...

\[ T\text{-matrix} = \]

--- Weinberg-Tomozawa Int. and higher ChPT terms in the kernel.

- In ChUM Λ(1405) is dynamically generated without explicit CDD poles. Hyodo et al. Phys. Rev. C78 025203.

  --- Λ(1405) in the meson-baryon interaction picture.

- Then, how about internal structure of Λ(1405) ?

  --> We probe internal structure of Λ(1405) in ChUM.
1. Introduction

++ How to probe the structure? ++

- **Usual approach:**
  Interaction $\rightarrow$ (NR or Rel.) potential $\rightarrow$ Schrödinger Eq. etc. $\rightarrow$ wave function $\rightarrow$ density distributions
e.g. Akaishi-Yamazaki ('02), Dote-Hyodo-Weise ('09).

- **Our approach:**
  Interaction $\rightarrow$ scattering amplitude (T-matrix) $\rightarrow$ form factors with respect to probe current $\rightarrow$ density distributions
  --- Direct probe of the form factors from T-matrix.
  • We keep analyticity for the scattering amplitudes.
  $\rightarrow$ $\Lambda(1405)$ form factors on the resonance pole (1426 - 17 i MeV).
2. Photon-coupled amplitudes

++ Matrix elements in scattering amplitude ++

- Define form factors as matrix elements of the resonance:

\[
\langle Z_R | J^\mu | Z_R \rangle_{\text{Breit}} = \left( F_E(Q^2), F_M(Q^2) \frac{i\sigma \times q}{2M_p} \right)
\]

- These matrix elements appear in the photon-coupled scattering amplitudes \( T_\gamma \) close to the pole position as:

\[
T_\gamma \approx \frac{g_i g_j}{\sqrt{s - Z_R}}
\]

- So the matrix elements can be extracted from residue of pole:

\[
\text{Res} \left[ -\frac{T_{\gamma ij}}{T_{ij}} \right]_{\text{Breit}} = \left( F_E(Q^2), F_M(Q^2) \frac{i\sigma \times q}{2M_p} \right)
\]

- Then, how \( T_\gamma \) (double pole !) is determined in ChUM ?
2. Photon-coupled amplitudes

++ Photon-coupled amplitudes in ChUM ++

- For $\Lambda(1405)$ in meson-baryon interaction picture, photon couples to the intermediate mesons, baryons, and WT vertices.

--> Double-pole diagrams, which contribute to $T_\gamma$ on the pole, are:

With this approach, we have Ward identity:

--> We have correct normalization:

$$F_E(Q^2 = 0) = Q_{EM}, \quad F_B(Q^2 = 0) = B, \quad F_S(Q^2 = 0) = S$$

Borasoy et al.
Phys. Rev. C72 065201;
3. Results

++ Each channel contribution to charges ++

- Let us see the resonant $\Lambda(1405)$ structure, dynamically generated on $1426 - 17$ i MeV [higher $\Lambda(1405)$ pole] in full coupled channel.
- In order to see which channel is important for the $\Lambda(1405)$ structure, we make channel decomposition to the baryon / strangeness number for $\Lambda(1405)$.

<table>
<thead>
<tr>
<th>Component</th>
<th>$F_B(0) = -F_S(0)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>1</td>
</tr>
<tr>
<td>$\bar{K}N$</td>
<td>$0.994 + 0.048i$</td>
</tr>
<tr>
<td>$\pi\Sigma$</td>
<td>$-0.047 - 0.151i$</td>
</tr>
<tr>
<td>$\eta\Lambda$</td>
<td>$0.052 + 0.012i$</td>
</tr>
<tr>
<td>$K\Xi$</td>
<td>$-0.002 + 0.002i$</td>
</tr>
<tr>
<td>Contact</td>
<td>$0.002 + 0.089i$</td>
</tr>
</tbody>
</table>

- The baryon / strangeness number is dominated by $\bar{K}N$.
- Consistent with the description of $\Lambda(1405)$ as a $\bar{K}N$ bound state.
3. Results

++ Structure of resonant $\Lambda(1405)$ state ++

- Let us see the resonant $\Lambda(1405)$ structure, dynamically generated on 1426 - 17 i MeV [higher $\Lambda(1405)$ pole] in full coupled channel.

- Complex form factors for the resonant $\Lambda(1405)$.

--- The imaginary parts are in smaller magnitude than the real parts reflecting relatively small imaginary part of the pole position.

3. Results

++ Structure of resonant \( \Lambda(1405) \) state ++

- Let us see the resonant \( \Lambda(1405) \) structure, dynamically generated on 1426 - 17 i MeV [higher \( \Lambda(1405) \) pole] in full coupled channel.

- Rapid increase / decrease of the EM form factors at small \( Q^2 \).

--> This implies characteristic structure of EM density for \( \Lambda(1405) \)!
3. Results

++ Structure of resonant $\Lambda(1405)$ state ++

- Fourier transformation --> charge density ($P = 4 \pi r^2 \rho$).

(radial coordinate in CM)
3. Results

++ Structure of resonant $\Lambda(1405)$ state ++

- Fourier transformation $\rightarrow$ charge density ($P = 4 \pi r^2 \rho$).

- Negative (positive) charge appears in outer (inner) region.

--- Interpreted as that the lighter $K^-$ surrounds the heavier $p$, recalling the large $\overline{K}N$ component for the conserved charge.
3. Results

++ Structure of resonant $\Lambda(1405)$ state ++

- Fourier transformation $\rightarrow$ magnetic moment density ($P = 4 \pi r^2 \rho$).

![Graph 1]

(radial coordinate in CM)

- **Spatially larger structure** of $\Lambda(1405)$.
- Magnetic moment distribution beyond $\sim 1$ fm.

![Graph 2]

$\langle r^2 \rangle_M = 1.138 - 0.343i$ fm$^2$

--- Large distribution of nucleon inside $\Lambda(1405)$.
3. Results

+++ Structure of resonant Λ(1405) state +++

- Channel decomposition shows component of structure.
- Electric $\bar{K}N$ component:

- Distribution is dominated by the $\bar{K}N$ component.

--> Indeed the lighter $K^-$ surrounds the heavier $p$, as expected.
3. Results

++ Structure of resonant $\Lambda(1405)$ state ++

- Channel decomposition shows component of structure.

--- Electric $\pi\Sigma$ component:

- $\pi\Sigma$ component shows dumping oscillation as decay channel.

--> Observe the decaying component in coordinate space, originating from that $\Lambda(1405)$ exists above the $\pi\Sigma$ threshold.
3. Results

+++ Structure of resonant $\Lambda(1405)$ state +++

- **Baryonic and strangeness structure for $\Lambda(1405)$:**

- We observe widely spread $\bar{K}$ around $N$, and both distributions are larger than the typical nucleon size $\sim 0.8$ fm.

- **Consistent with the EM structure.**

--- Small imaginary part and decaying $\pi\Sigma$ part (very tiny).
3. Results

++ Special case: $\bar{K}N$ bound state ++

- How good is our method to extract form factors? It works well?

--> we consider $\bar{K}N$ bound state as “$\Lambda(1405)$ w/o width”.

--- Weinberg-Tomozawa interaction only with $\bar{K}N$ channel

$x$ exclusion of explicit CDD poles in the Amp. Hyodo et al. ('08).

--> Dynamically generated $\bar{K}N$ bound state at 1424 MeV.

- Similar distributions compared to resonant $\Lambda(1405)$, due to small width and large $\bar{K}N$ coupling for resonant $\Lambda(1405)$. 
3. Results

++ Special case: $\bar{K}N$ bound state ++

- Changing binding energy of $\bar{K}N$ bound state, adjusting interaction strength of the model.

--> Mean squared radii:

- Spatial structure stretches as binding energy decreases, and vice versa.

--- Consistent with expectation from quantum mechanics.
3. Results

++ Special case: $\bar{K}N$ bound state ++

- Changing binding energy of $\bar{K}N$ bound state, adjusting interaction strength of the model.

--> Mean squared distance between $\bar{K}$ and $N$:

--- Compared with MSD evaluated from NR wave func.:

\[ \langle x^2 \rangle_{NR} = \frac{1}{4\mu B_E} \]

- Quite good agreement with MSD in quantum mechanics.

--> The form factor defined through the scattering amplitudes correctly reflects the structure of bound state.
3. Results

++ Exercise: meson-$N$ bound state ++

- Changing meson mass $m$ of meson-$N$ bound state, instead of physical kaon mass.
  --- With constraint $\mu B_E = \text{const.}$

--> meson-$N$ distance within hadronic interaction range.

- Correctly reflects the structure with respect to mass ratio.
  - Interchange of meson and $N$ distributions takes place above / below the $m = M_N$.
  - Almost flat mean squared distance with respect to $m$ due to the constraint $\mu B_E = \text{const.}$
4. Summary

++ Summary ++

- We calculate electromagnetic, baryonic, and strangeness form factors and internal density distributions of $\Lambda(1405)$ in chiral unitary approach, in which we have meson-baryon interaction picture based on chiral symmetry with Bethe-Salpeter equation.

--- Structure from our form factor is consistent with expectation from quantum mechanics.

- $\Lambda(1405)$ is composed of widely spread $K$ around $N$ (dominant) + escaping $\pi\Sigma$ oscillation component.

- Both $\bar{K}$ and $N$ distributions are larger than typical nucleon size $\sim$ 0.8 fm.

--- Our description of $\Lambda(1405)$ in chiral dynamics is consistent with meson-baryon interaction picture.
Thank you very much for your kind attention!
Appendix
Appendix

++ How to probe “Λ(1405) size” in Exp.? ++

- There is some possibility to obtain information of “Λ(1405) size” from heavy ion collisions.

--- Λ(1405) yields estimated by the coalescence model.

<-- Sensitive to the structure!

Sungtae Cho, T. S. et al.,