PHOTOPRODUCTION OF K^* AND THE STRUCTURE OF THE $\Lambda(1405)$ RESONANCE

T. HYODO AND A. HOSAKA

Research Center for Nuclear Physics (RCNP), Ibaraki, Osaka 567-0047, Japan
E-mail: hyodo@rcnp.osaka-u.ac.jp

M. J. VICENTE VACAS AND E. OSET

Departmento de Física Teórica and IFIC,
Centro Mixto Universidad de Valencia-CSIC,
Institutos de Investigación de Paterna, Aptd. 22085, 46071 Valencia, Spain

We study the structure of the $\Lambda(1405)$ resonance based on the chiral unitary model. In the photoproduction of K^* vector meson, we obtain a spectrum of $\Lambda(1405)$ which peaks at 1420 MeV and differs from the nominal shape. This is a consequence of the dominance of one of the two poles at around 1400 MeV, predicted by the chiral unitary model. The novel structure of the $\Lambda(1405)$ state would be revealed by an experimental study of the present reaction and other reactions, such as $\pi^- p \to K^0\pi\Sigma$, in which the other pole is favored.

The $\Lambda(1405)$ resonance has been one of the most interesting particles in baryon spectroscopy, because of the lightest mass in the low-lying negative parity states and the difficulty in describing it within a naive quark model. A successful approach based on the meson-baryon molecule picture[1] is revisited with the modern knowledge of chiral perturbation theory, and leads to the development of the chiral unitary approaches.[2,3,4]

The chiral unitary model reproduces the $S = -1$ meson-baryon scattering amplitude in good agreement with data, generating the $\Lambda(1405)$ dynamically. Interestingly, in the energy region of 1400 MeV, two poles are generated in the $I = 0$ scattering amplitude.[5,6,7,8,9,10,11,12] This double pole structure is qualitatively independent of the details of the models. It is worth noting that this structure was first reported within the cloudy bag model.[13] Also in a study of $1/2^-$ pentaquark states based on the correlated diquark picture[14], two Λ^* states were found in the relatively low energy region.

Table 1. Pole positions and coupling strengths $|g_i|$ to meson-baryon channels.

position [MeV]	$\pi\Sigma$	$\bar{K}N$	$\eta\Lambda$	$K\Xi$
$z_1 = 1390 - 66i$	2.9	2.1	0.77	0.61
$z_2 = 1426 - 16i$	1.5	2.7	1.4	0.35

These poles have been analyzed in Ref. 15 through the argument based on flavor $SU(3)$ symmetry. The positions of the poles and their coupling strengths to meson-baryon channels are shown in Table 1. As seen in the table, the pole z_1 couples dominantly to $\pi\Sigma$ channels, while z_2 couples dominantly to $\bar{K}N$ channels. This indicates that the spectra of $\Lambda(1405)$ seen in invariant mass distribution of $\pi\Sigma$ differ depending on the reactions to generate the resonance. In fact, such differences were seen in previous theoretical studies,[16,17] and it was found in Ref. 18 that the z_1 pole was favored in the $\pi^- p \to K^0\pi\Sigma$ reaction.[19]

In this paper, we study the threshold production of K^* and $\Lambda(1405)$ in order to isolate the z_2 pole.[20] This reaction has some advantages:

- With the polarized photon beam, the parity of the exchanged particle can be identified by the angular distribution of the final π^+K^0.
- In pseudoscalar K exchange, the pole z_2 will be favored, because only the $\bar{K}N$ channel couples to $\Lambda(1405)$ in the initial stage.

The scattering amplitude of this process (the upper panel of Fig. 1) can be divided into two parts,

$$-it = (-it_{\gamma\to K^- K\pi})\frac{i}{p_{K^-}^2 - m_{K^-}^2}(-it_{K^-p\to MB}) \ . \qquad (1)$$

The former part $(-it_{\gamma\to K^- K\pi})$, is derived from the effective Lagrangians,[20] and it evantually shows a clear correlation between the π^+K^0 distribution and the polarization of the initial photon. The amplitude $(-it_{K^-p\to MB})$ is constructed as

$$-it_{K^-p\to MB} = -it_{ChU} - it_{\Sigma^*} \ , \qquad (2)$$

as shown in the lower panel of Fig. 1. We denote $-it_{ChU}$ the meson-baryon scattering amplitude derived from the chiral unitary model, and $-it_{\Sigma^*}$ is the $\Sigma(1385)$ pole term. In the chiral unitary model,[6,9] t_{ChU} is obtained by

$$t_{ChU} = [1 - VG]^{-1}V \, , \qquad (3)$$

where G is the meson-baryon loop function and V is the kernel interaction derived from the Weinberg-Tomozawa term of the chiral Lagrangian. The

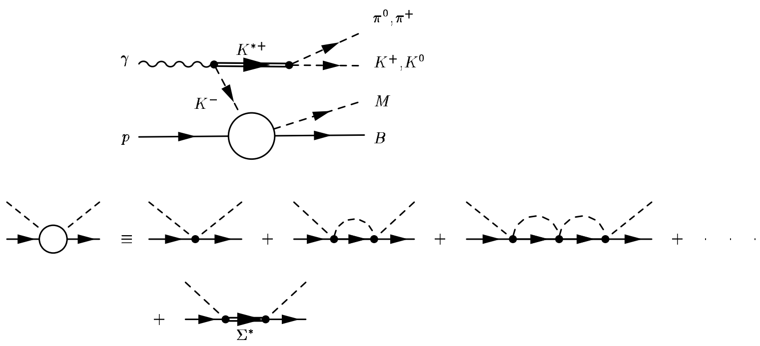

Figure 1. Feynman diagram for the reaction. M and B denote the meson and baryon of ten coupled channels of $S = -1$ meson-baryon scattering.

$-it_{\Sigma^*}$ term is introduced with the resonance propagator of the Breit-Wigner form and coupling constants deduced from the $\pi N\Delta$ coupling using $SU(6)$ symmetry. We have introduced a strong form factor of monopole type with cutoff $\Lambda = 1$ GeV, for the vertex $K^- p\Sigma^*$ in order to account for the finite size structure of the baryons.

The total cross sections of this reaction for final MB states $\pi\Sigma$ and $\pi\Lambda$ are of the order of a few hundred nano barn. Among them, the $\pi\Lambda(I = 1)$ channel gives the largest magnitude, which might disturb the $I = 0$ amplitude that we are interested in. However, below the threshold of the $\bar{K}N$ channel, it is possible to isolate the $\Lambda(1405)$ from $\Sigma(1385)$ contribution, using a proper combination of the final states. Neglecting the $I = 2$ component which is not relevant in the present study, the isospin decomposition of the $\pi\Sigma$ states is instructive,

$$\begin{aligned} \frac{d\sigma(\pi^{\pm}\Sigma^{\mp})}{dM_I} &\propto \frac{1}{3}|T^{(0)}|^2 + \frac{1}{2}|T^{(1)}|^2 \pm \frac{2}{\sqrt{6}}\mathrm{Re}(T^{(0)}T^{(1)*}) \ ; \\ \frac{d\sigma(\pi^{0}\Sigma^{0})}{dM_I} &\propto \frac{1}{3}|T^{(0)}|^2 \ , \end{aligned} \tag{4}$$

where $T^{(I)}$ is the amplitude with isospin I. It is seen that the charged channels ($\pi^{\pm}\Sigma^{\mp}$) couple to both $\Lambda(1405)(I = 0)$ and $\Sigma(1385)(I = 1)$, while the neutral channels couple to either one of the two; $\pi^0\Sigma^0$ is to $\Lambda(1405)$ and $\pi^0\Lambda$ is to $\Sigma(1385)$.

The invariant mass distributions for $\pi\Lambda$ and $\pi\Sigma$ final states are shown in Fig. 2. The photon energy is set as $E_\gamma = 2500$ MeV ($\sqrt{s} \sim 2350$ MeV), which is the threshold energy for $K^*\Lambda(1405)$ production. The neutral final states, $\pi^0\Sigma^0$ and $\pi^0\Lambda$ are pure $I = 0$ and $I = 1$, respectively, and we clearly

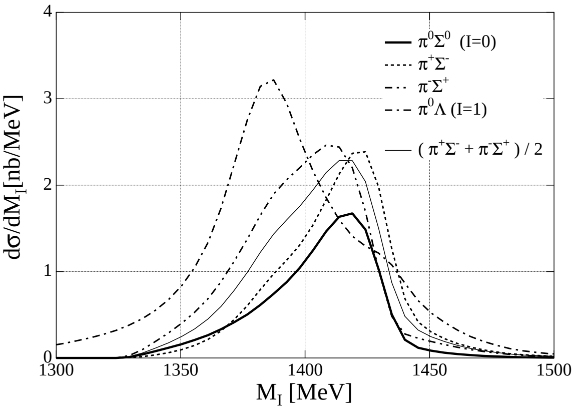

Figure 2. Invariant mass distributions of $\pi^0\Sigma^0$ (Thick solid), $\pi^+\Sigma^-$ (Dashed), $\pi^-\Sigma^+$ (Dash-dot-dotted), $\pi^0\Lambda$ (Dash-dotted) and $(\pi^+\Sigma^- + \pi^+\Sigma^-)/2$ (Thin solid) in units of [nb/MeV]. Initial photon energy in Lab. frame is 2500 MeV (threshold of $K^*\Lambda(1405)$).

see the separation of the $\Lambda(1405)$ and $\Sigma(1385)$. As expected, the peak position of the $I = 0$ spectrum is around 1420 MeV, which indicates the dominance of the z_2 pole. These neutral channels are helpful to distinguish the isospin states, although detection would be difficult experimentally.

The charged final states (dashed and dash-dot-dotted lines) are easier to observe in experiments. These spectrum shows similar structure as the Kaon photoproduction process,[16] which has been confirmed in experiments.[21] As seen in Eq. (4), the difference between $\pi^+\Sigma^-$ and $\pi^-\Sigma^+$ is originated from the interference term $\mathrm{Re}(T^{(0)}T^{(1)*})$, and it vanishes when we sum the two distributions. We show the average of the charged $\pi\Sigma$ channels by the thin solid line in Fig. 2. A peak of the spectrum is again seen at around 1420 MeV, showing the dominance of the z_2 pole. Compared to the $\pi^0\Sigma^0$ spectrum, the width of this distribution is slightly larger because of a finite contribution from the $\Sigma(1385)$.

In summary, we have studied the structure of the $\Lambda(1405)$ through the $\gamma p \to K^*\Lambda(1405) \to \pi^+K^0MB$ reaction, in which the use of a polarized photon makes the reaction mechanism simpler. In this reaction, we obtain an $I = 0$ spectrum which peaks at around 1420 MeV with a narrower width than the nominal $\Lambda(1405)$, reflecting the fact that the two poles are present in this energy region. Detailed analysis of this reaction and other processes dominated by the z_1 pole will reveal the novel structure of the $\Lambda(1405)$ resonance. The experimental confirmation of two Λ^* states would provide more information on hadron spectroscopy and non-perturbative dynamics of QCD.

Acknowledgments

This work is supported by the Japan-Europe (Spain) Research Cooperation Program of Japan Society for the Promotion of Science (JSPS) and Spanish Council for Scientific Research (CSIC), which enabled T. H. and A. H. to visit IFIC, Valencia and M. J. V. V. visit RCNP, Osaka. This work is also supported in part by DGICYT projects BFM2000-1326, and the EU network EURIDICE contract HPRN-CT-2002-00311.

References

1. R. H. Dalitz, T. C. Wong, and G. Rajasekaran, Phys. Rev. **153**, 1617 (1967).
2. N. Kaiser, P. B. Siegel, and W. Weise, Nucl. Phys. **A594**, 325 (1995).
3. E. Oset and A. Ramos, Nucl. Phys. **A635**, 99 (1998).
4. M. F. M. Lutz and E. E. Kolomeitsev, Nucl. Phys. **A700**, 193 (2002).
5. J. A. Oller and U. G. Meissner, Phys. Lett. **B500**, 263 (2001).
6. E. Oset, A. Ramos, and C. Bennhold, Phys. Lett. **B527**, 99 (2002).
7. D. Jido, A. Hosaka, J. C. Nacher, E. Oset, and A. Ramos, Phys. Rev. **C66**, 025203 (2002).
8. C. Garcia-Recio, J. Nieves, E. Ruiz Arriola, and M. J. Vicente Vacas, Phys. Rev. **D67**, 076009 (2003).
9. T. Hyodo, S. I. Nam, D. Jido, and A. Hosaka, Phys. Rev. **C68**, 018201 (2003).
10. T. Hyodo, S. I. Nam, D. Jido, and A. Hosaka, Prog. Theor. Phys. **112**, 73 (2004).
11. C. Garcia-Recio, M. F. M. Lutz, and J. Nieves, Phys. Lett. **B582**, 49 (2004).
12. S. I. Nam, H. -Ch. Kim, T. Hyodo, D. Jido, and A. Hosaka, hep-ph/0309017.
13. P. J. Fink Jr., G. He, R. H. Landau, and J. W. Schnick, Phys. Rev. **C41**, 2720 (1990).
14. A. Zhang *et al.*, hep-ph/0403210.
15. D. Jido, J. A. Oller, E. Oset, A. Ramos, and U. G. Meissner, Nucl. Phys. **A725**, 181 (2003).
16. J. C. Nacher, E. Oset, H. Toki, and A. Ramos, Phys. Lett. **B455**, 55 (1999).
17. J. C. Nacher, E. Oset, H. Toki, and A. Ramos, Phys. Lett. **B461**, 299 (1999).
18. T. Hyodo, A. Hosaka, E. Oset, A. Ramos, and M. J. Vicente Vacas, Phys. Rev. **C68**, 065203 (2003).
19. D. W. Thomas, A. Engler, H. E. Fisk, and R. W. Kraemer, Nucl. Phys. **B56**, 15 (1973).
20. T. Hyodo, A. Hosaka, M. J. Vicente Vacas, and E. Oset, Phys. Lett. **B593**, 75 (2004).
21. LEPS, J. K. Ahn, Nucl. Phys. **A721**, 715 (2003).