The WA3 data and the two $K_1(1270)$ resonances

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Abstract

Recent studies based on unitary chiral perturbation theory (U$\chi$PT) found that the low-lying axial vector mesons can be dynamically generated due to the interaction of the pseudoscalar octet of the pion and the vector nonet of the rho. In particular, two poles in the second Riemann sheet have been associated to the nominal $K_1(1270)$ resonance. In this talk, we present a recent analysis of the WA3 data on $K^-p \rightarrow K^-\pi^+\pi^-p$ at 63 GeV using the U$\chi$PT amplitudes, and show that it is in favor of the existence of two $K_1(1270)$'s [Phys. Rev. D 75, 014017 (2007)].

1 Introduction

The unitary extension of chiral perturbation theory, U$\chi$PT, has been successfully applied to study many meson-baryon and meson-meson interactions. More
recently, it has been used to study the lowest axial vector mesons $h_1(1235)$, $h_1(1170)$, $h_1(1380)$, $a_1(1260)$, $f_1(1285)$, $K_1(1270)$ and $K_1(1400)$ \cite{2} \cite{3}. Both works generate most of the low-lying axial vector mesons dynamically. However, there is a surprising discovery in Ref. \cite{3}, i.e., two poles are found in the second Riemann sheet in the $S = 1$ and $I = 1/2$ channel and both are attributed to the $K_1(1270)$.

Although the $K_1(1270)$ has been observed in various reactions, the most conclusive and high-statistics data of the $K_1(1270)$ come from the WA3 experiment at CERN that accumulated data on the reaction $K^-p \rightarrow K^-\pi^+\pi^-p$ at 63 GeV. These data were analyzed by the ACCMOR Collaboration \cite{4}. As will be shown in this paper, the two-peak structure, with a peak at lower energy depending drastically on the reaction channel investigated, can be easily explained in our model with two poles for the $K_1(1270)$ plus the $K_1(1400)$. With only one pole, as has been noted long time ago \cite{4} \cite{5}, there is always a discrepancy for the peak positions observed in the $K^*\pi$ and $\rho K$ invariant mass distributions.

2 Chiral unitary model and the two $K_1(1270)$’s

In the following, we briefly describe the chiral unitary approach, while detailed formalism can be found in Refs. \cite{1} \cite{3}. In the Bethe-Salpeter formulation of the unitary chiral perturbation theory \cite{3}, one has the following unitarized amplitude:

$$T = \left[1 + V \hat{G}\right]^{-1}\left(-V\right) \vec{\epsilon} \cdot \vec{\epsilon'},$$

(1)

where $\hat{G} = \left(1 + \frac{1}{3} \frac{q^2}{M_l^2}\right)G$ is a diagonal matrix with the $l$-th element, $G_l$, being the two meson loop function containing a vector and a pseudoscalar meson:

$$G_i(\sqrt{s}) = \frac{i}{(2\pi)^4} \int \frac{d^4q}{q^2} \frac{1}{(P - q)^2 - M_l^2 + i\epsilon} \frac{1}{q^2 - m_l^2 + i\epsilon},$$

(2)

with $P$ the total incident momentum, which in the center of mass frame is $(\sqrt{s},0,0,0)$. The loop function $G_l$ can be regularized either by a cutoff or by dimensional regularization. In the former case, one has cutoff values, whereas in the latter, one has subtraction constants as free parameters, which have to be fitted to the data.
Figure 1: The modulus squared of the coupled channel amplitudes multiplied by the corresponding loop functions in the $S = 1$ and $I = \frac{1}{2}$ channel.

The tree level amplitudes are calculated using the following interaction Lagrangian \( \mathcal{L}_I \):

\[
\mathcal{L}_I = -\frac{1}{4} \text{Tr} \left\{ (\nabla_\mu V_\nu - \nabla_\nu V_\mu) (\nabla'^\mu V'^\nu - \nabla'^\nu V'^\mu) \right\},
\]

(3)

where \( \text{Tr} \) means SU(3) trace and \( \nabla_\mu \) is the covariant derivative defined as

\[
\nabla_\mu V_\nu = \partial_\mu V_\nu + [\Gamma_\mu, V_\nu],
\]

(4)

where \([\cdot,\cdot]\) stands for commutator and \( \Gamma_\mu \) is the vector current \( \Gamma_\mu = \frac{1}{2} (u^\dagger \partial_\mu u + u \partial_\mu u^\dagger) \) with \( u^2 = U = e^{i\sqrt{2}fP} \). In the above equations \( f \) is the pion decay constant in the chiral limit and \( P \) and \( V \) are the SU(3) matrices containing the pseudoscalar octet of the pion and the vector nonet of the rho.

Fig. 1 shows the modulus squared of the $S = 1$, $I = \frac{1}{2}$ amplitudes multiplied by the corresponding loop functions obtained with $f = 115$ MeV, $a(\mu) = -1.85$ and $\mu = 900$ MeV. The pole positions and corresponding widths obtained with this set of parameters are shown in Table 1. From Fig. 1 the two poles are clearly seen: the higher pole manifests itself as one relatively narrower resonance around 1.28 GeV and the lower pole as a broader resonance at $\sim 1.20$ GeV.

The effective couplings for the coupled channels $\phi K$, $\omega K$, $\rho K$, $K^* \eta$ and $K^* \pi$, calculated from the residues of the amplitudes at the complex pole positions, are tabulated in Table 1 for both the lower pole and the higher pole,
Table 1: Effective couplings of the two poles of the $K_1(1270)$ to the five channels: $\phi K$, $\omega K$, $\rho K$, $K^*\eta$ and $K^*\pi$. All the units are in MeV.

| $\sqrt{s_{pp}}$ | $1195 - i123$ | $1284 - i73$ |
|-----------------|---------------|---------------|
| $g_i$           | $g_i$         | $g_i$         |
| $\phi K$        | 2096 $- i1208$ | 1166 $- i774$ | 1399 |
| $\omega K$      | $-2046 + i821$ | $-1051 + i620$ | 1220 |
| $\rho K$        | $-1671 + i599$ | 4804 $+ i395$ | 4821 |
| $K^*\eta$       | 72 $+ i197$   | 3486 $- i536$ | 3526 |
| $K^*\pi$        | 4747 $- i2874$ | 769 $- i1171$ | 1401 |

respectively. It is clearly seen that the lower pole couples dominantly to the $K^*\pi$ channel while the higher pole couples more strongly to the $\rho K$ channel. If different reaction mechanisms favor one or the other channel, they will see different shapes for the resonance. More importantly, it is to be noted that not only the two poles couple to different channels with different strengths, but also they manifest themselves in different final states. In other words, in the $\rho K$ final states, one favors a narrower resonance around 1.28 GeV, while in the $K^*\pi$ final states, one would favor a broader resonance at a smaller invariant mass.

3 Studying the WA3 data with the U\chi PT amplitudes

The reaction $K^-p \rightarrow K^-\pi^+\pi^-p$ can be analyzed by the isobar model as $K^-p \rightarrow (K^{*0}\pi^- or \rho^0K^-)p \rightarrow K^-\pi^+\pi^-p$. Therefore, one can construct the following amplitudes to simulate this process. Assuming $I = 1/2$ dominance for $K^{*0}\pi^-$ and $\rho^0K^-$ as suggested by the experiment one has

$$T_{K^{*}\pi} \equiv T_{K^{*0}\pi^-} = \sqrt{\frac{2}{3}}a + \sqrt{\frac{2}{3}}aG_{K^{*}\pi}t_{K^{*}\pi}K^{*}\pi + \sqrt{\frac{2}{3}}bG_{\rho K}t_{\rho K}K^{*}\pi,$$

$$T_{\rho K} \equiv T_{\rho^0K^-} = -\sqrt{\frac{1}{3}} - \sqrt{\frac{1}{3}}G_{K^{*}\pi}t_{K^{*}\pi}K^{*}\pi - \sqrt{\frac{1}{3}}bG_{\rho K}t_{\rho K}K^{*}\pi,$$ (5)

where $t_{ij}$ are the coupled channel amplitudes obtained in Section 2 and the Clebsch-Gordan coefficient $\sqrt{\frac{2}{3}}(-\sqrt{\frac{1}{3}})$ accounts for projecting the $I = 1/2$ $K^*\pi$
(\rho K) state into $\bar{K}^*\pi^-(\rho^0 K^-)$. The coefficients $a$ and $b$ are complex couplings.

To contrast our model with data, it is necessary to take into account the existence of the $K_1(1400)$, which is not dynamically generated in our approach. Therefore, we add to the amplitudes in Eq. (5) an explicit contribution of the $K_1(1400)$

$$
T_{K^*\pi} \rightarrow T_{K^*\pi} + \frac{g_{K^*\pi}}{s - M^2 + iM\Gamma(s)},
$$

$$
T_{\rho K} \rightarrow T_{\rho K} + \frac{g_{\rho K}}{s - M^2 + iM\Gamma(s)},
$$

(6)

where $g_{K^*\pi}$ and $g_{\rho K}$ are complex couplings, and $M$ and $\Gamma(s)$ are the mass and width of the $K_1(1400)$ with the $s$-wave width given by

$$
\Gamma(s) = \Gamma_0 \frac{q(s)}{q_{on}} \Theta(\sqrt{s} - M_{K^*} - M_\pi).
$$

(7)

$q(s)$ and $q_{on}$ are calculated by

$$
q(s) = \frac{\lambda^{1/2}(s, M_{\pi}^2, M_{K^*}^2)}{2\sqrt{s}} \quad \text{and} \quad q_{on} = \frac{\lambda^{1/2}(M^2, M_{\pi}^2, M_{K^*}^2)}{2M}.
$$

(8)

In our model, Eq. (6), we have the following adjustable parameters: $a$, $b$, $g_{K^*\pi}$, $g_{\rho K}$, $M$ and $\Gamma_0$. In principle, $f$ and $a(\mu)$ can also be taken as free parameters. One can then fix these parameters by fitting the WA3 data (see Ref. 1 for details). According to Ref. 8, for an $s$-wave resonance, the theoretical differential cross section can be calculated by

$$
\frac{d\sigma}{dM} = c|T|^2 q
$$

(9)

where $M$ is the invariant mass of the $K^*\pi$ or $\rho K$ systems, $c$ is a normalization constant, $T$ is the amplitude specified above for the $K^*\pi$ or $\rho K$ channels and $q$ is the center of mass three-momentum of $K^*\pi$ or $\rho K$. We have taken $c$ to be 1, or in other words, it has been absorbed into the coupling constants $a$, $b$, $g_{K^*\pi}$ and $g_{\rho K}$. The theoretical invariant mass distributions calculated with Eq. (9) are shown in Fig. 2 in comparison with the WA3 data.

From Fig. 2 it is clearly seen that our model can fit the data around the peaks very well. In Fig. 2 the dashed and dotted lines are the separate contributions of the $K_1(1270)$ and the $K_1(1400)$. One can easily see that the $K_1(1400)$ decays dominantly to $K^*\pi$, which is consistent with our present understanding of this resonance.
Figure 2: $K^*\pi$ and $\rho K$ invariant mass distributions. The data are from the WA3 reaction $K^- p \rightarrow K^- \pi^+ \pi^- p$ at 63 GeV [4]. Data in the upper panels are for $0 \leq |t'| \leq 0.05$ GeV$^2$ and those in the middle and bottom panels for $0.05 \leq |t'| \leq 0.7$ GeV$^2$, where $t'$ is the four momentum transfer squared to the recoiling proton. The data are further grouped by $J^P LM^\eta$ followed by the isobar and odd particle. $J$ is the total angular momentum, $P$ the parity, $L$ the orbital angular momentum of the odd particle. $M^\eta$ denotes the magnetic substate of the $K\pi\pi$ system and the naturality of the exchange.
It should be mentioned that in our model the lower peak observed in the invariant mass distribution of the $K^*\pi$ channel is due to the contribution of the two poles of the $K_1(1270)$. This is very different from the traditional interpretation. For example, the lower peak observed in the $K^*\pi$ invariant mass distributions of $K^\pm p \to K^\pm \pi^+\pi^- p$ at 13 GeV was interpreted as a pure Gaussian background by Carnegie et al. [9], which has a shape similar to the contribution of the $K_1(1270)$ as shown in Fig. 2. On the other hand, the K-Matrix approach was adopted to analyze the WA3 data [4] and the SLAC data [10]. In this latter approach, the lower peak mostly comes from the so-called Deck background, which after unitarization, also has a shape of resonance. As we mentioned in the introduction, even in the original WA3 paper [4], it was noted that their model failed to describe the $1^+ S1^+(K^*\pi)$ data, in the notation $J^P L M^\eta$ with $\eta$ the naturality of the exchange [4]. The predicted peak is 20 MeV higher than the data. If the fit were done only to the $K^*\pi$ data, the agreement was much better but then the predicted $K_1(1270)$ would be lower by 35 MeV than that obtained when other channels were also considered in the fit.

It is worth stressing that the $K_1(1270)$ peak seen in the upper-left panel of Fig. 2 is significantly broader than that in the upper-right panel. Furthermore the peak positions are also different in the two cases (1240 MeV and 1280 MeV respectively). Both features have a straightforward interpretation in our theoretical description since the first one is dominated by the low-energy (broader) $K_1(1270)$ state, while the second one is dominated by the higher-energy (narrower) $K_1(1270)$ state.

4 Summary and conclusion

Studies based on unitary chiral perturbation theory obtain two poles in the $I = 1/2$, $S = 1$, vector-pseudoscalar scattering amplitudes which can be assigned to two $K_1(1270)$ resonances. One pole is at $\sim 1200$ MeV with a width of $\sim 250$ MeV and the other is at $\sim 1280$ MeV with a width of $\sim 150$ MeV. The lower pole couples more to the $K^*\pi$ channel whereas the higher pole couples dominantly to the $\rho K$ channel. Different reaction mechanisms may prefer different channels and thus this explains the different invariant mass distributions seen in various experiments.

We have analyzed the WA3 data on the $K^- p \to K^- \pi^+\pi^- p$ reaction since
it is the most conclusive and high-statistics experiment quoted in the PDG on the \( K_1(1270) \) resonance. Our model obtains a good description of the WA3 data both for the \( K^*\pi \) and \( \rho K \) final state channels. In our model, the peak in the \( K\pi\pi \) mass distribution around the 1270 MeV region is a superposition of the two poles, but in the \( K^*\pi \) channel the lower pole dominates and in the \( \rho K \) channel the higher pole gives the biggest contribution.

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