Hadron resonances in three-body systems made of Kaons

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Introduction

- The study of systems made by mesons and baryons is one of the challenging issues in nuclear physics.
- The use of effective chiral Lagrangians has been very useful in understanding of the properties of several meson and baryon states.

\[ \bar{K} N \rightarrow \pi \Sigma \]
\[ \Lambda(1405) \]

\[ \pi \pi \rightarrow \bar{K} K \]
\[ \sigma(600), f_0(980), a_0(980) \]

Interest in few-body systems formed by one or more kaons

\[ \bar{K}N \quad \bar{K}N \]

Quasibound state
(20-70 MeV) with large width (70-100 MeV)

\[ \bar{K}K \quad \bar{K}K \]

New N* 1/2+ around 1910 MeV

\[ \bar{K}N \quad \bar{K}N \]

Very weakly bound state

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Most peculiars:

\[
\begin{align*}
\Lambda(1405) & \quad \rightarrow \quad \text{Double pole nature} \\
N^*(1910) & \quad \rightarrow \quad \text{Simultaneous presence of the } \Lambda(1405) \text{ and } a_0(980)
\end{align*}
\]

We have studied the following systems
The Model

We solve the Faddeev equations

\[ T = T^1 + T^2 + T^3 \]

\[ T^i = t^i + t^i G[T^j + T^k] \]
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\[ T = T^1 + T^2 + T^3 \]

\[ T^i = t^i + t^i G[T^j + T^k] \]

\[ t = V + V g t \]
We consider as coupled channels:

- $K \bar{K} N$, $K \pi \Sigma$, $K \pi \Lambda$
- $KK\bar{K}$, $K\pi\pi$, $K\pi\eta$
- $K\bar{K}\pi$, $\eta\pi\pi$

All the interactions are in s-wave.
I and subsystem and form a bound state. The energy for these two matrix elements with isospin 1, Bar, and less contribution from resonance in the subsystem. For the case in which the $K K$ interaction and coupled channel, we have also solved the variant mass of the system [22, 30], in which the state is generated by the PDG, around 250 MeV. Note, however, that the width of the resonance gets generated when the in the two-body dynamics as compared to the region where the $S = 0$ $(850)$ transition with a magnitude in the two-body channels have a smaller weight, even if these two-body channels have a smaller weight.

To understand further the structure of the resonance found in this work is much smaller than the two values listed by the PDG, around 250 MeV. Note, however, that the width is very similar, it does not mean that the fraction $K K$ with $I = 1$ and $T = 1$ is in isospin 1, with magnitude for these two matrix elements with isospin 1, $K K$ and $K K$.

In Fig. 2, we show the contour plots associated to the modulus of the three-body squared amplitude as functions of the total three-body energy, $E_{3b}$. The energy position as well as the opening of the three-body $K K N$ channel and we relate to the double pole structure of the resonance plays an important role to the region where the $K K$ resonance is around 1390 MeV, which couples strongly to the $K K N$. (Right) Dashed Lines: (Left) $K K$ and $K K$: there is a pole around 1390 MeV, which couples strongly to the $K K N$. (Right) Solid line: energy range used in the calculations. We consider the cases in which only the $K K$ transition with $I = 23$ is very similar, it does not mean that the fraction $K K$ with $I = 1$ and $T = 1$ is in isospin 1, with magnitude for these two matrix elements with isospin 1, $K K$ and $K K$.

The energy position as well as the opening of the three-body $K K N$ channel and we relate to the double pole structure of the resonance plays an important role to the region where the $K K$ resonance is around 1390 MeV, which couples strongly to the $K K N$. (Right) Dashed Lines: (Left) $K K$ and $K K$: there is a pole around 1390 MeV, which couples strongly to the $K K N$. (Right) Solid line: energy range used in the calculations. We consider the cases in which only the $K K$ transition with $I = 23$ is very similar, it does not mean that the fraction $K K$ with $I = 1$ and $T = 1$ is in isospin 1, with magnitude for these two matrix elements with isospin 1, $K K$ and $K K$.
Figure 2: (Left) Squared amplitude for the $\pi K\bar{K}$ channel for total isospin $I = 1$ with the $K\bar{K}$ subsystem in isospin zero. (Right) Contour plot as a function of the total energy, $\sqrt{s}$, and the invariant mass $\sqrt{s_{23}}$ of the $K\bar{K}$ subsystem, which is in isospin zero.

Experimental upper limit for this state, while the width is close to the lower experimental value, thus, our findings are compatible with the known data set. Surprisingly, for a better comparison one needs more experiments which could help in determining the properties of this state with more precision. The decay modes seen for this resonance are $\rho\pi$ and $\pi(\pi\pi)$ S-wave. The channel $\pi\pi\pi$ is at three-body channel which couples to $\pi K\bar{K}$ and $\pi\pi\eta$. However, the three pion threshold (around 410 MeV) is far away from the region in which the state is formed, thus, it naturally is not essential in the generation of the $\pi(1300)$. However, the inclusion of channels like $\pi\pi\pi$ or $\rho\pi$ could help in increasing the width found for the state within our approach, since there is more space for the $\pi(1300)$ to decay to these channels.

Finally, we would like to mention that apart from the $\pi K\bar{K}$, $\pi\pi\eta$ systems, we have also studied the $\eta K\bar{K}$, $\eta\pi\pi$ systems in S-wave to search for possible signals of the $\eta$ states listed in the PDB, $\eta(1295)$, $\eta(1405)$ and $\eta(1475)$, but we have not found any clear signal which could be related to any of them.

3.2 Study of the $f_0(980)\pi\pi$ and $f_0(980)K\bar{K}$ systems. The state found at 1400 MeV can be understood as a molecular resonance formed by a pion and the $f_0(980)$, which is dynamically generated in the $K\bar{K}$ interaction (see Fig. 3). As explained in Sec. 2.2, we can use the obtained $\pi(K\bar{K})I=0\rightarrow\pi(K\bar{K})I=0$ three-body $T$-matrix to determine the amplitude which describes the interaction between the pion and the $f_0(980)$, and use this latter one to study the $f_0(980)\pi\pi$ system. To do this, we first need to relate the amplitude of the $\pi(K\bar{K})$ system with the one of the $\pi f_0(980)$ system. For that, particularizing Eq. (15) for the $\pi-f_0(980)$ system, we get...
We can use now these amplitudes to study systems like $f_0(980)\pi\pi$, $f_0(980)K\bar{K}$

How to do this?

$$T_{P_1(P_2P_3)}(\sqrt{s}, \sqrt{s_{23}} \simeq M_{R_{23}}) = g_{R_{23}\to(P_2P_3)}G_{R_{23}} t_{P_1R_{23}}(\sqrt{s})G_{R_{23}} g_{R_{23}\to(P_2P_3)}$$

$$t_{(P_2P_3)}(\sqrt{s_{23}}) = \frac{g_{R_{23}\to(P_2P_3)}^2}{s_{23} - M_{R_{23}}^2 + iM_{R_{23}}\Gamma_{R_{23}}}$$

$$t_{P_1R_{23}}(\sqrt{s}) = \frac{iM_{R_{23}}\Gamma_{R_{23}}}{t_{(P_2P_3)}(\sqrt{s_{23}} = M_{R_{23}})} T_{P_1(P_2P_3)}(\sqrt{s}, \sqrt{s_{23}} = M_{R_{23}})$$
Figure 4: (Upper panel) Squared amplitude for the $f_0(980)$ channel for total isospin zero, thus, with the $\pi\pi$ subsystem in isospin zero. (Lower panel) Contour plots as a function of the invariant mass of the $\pi\pi$ system, $\sqrt{s}$, and the invariant mass of the $\pi\pi$ subsystem, $\sqrt{s_{23}}$, respectively (Left side) and as a function of the $\pi\pi$ and $f_0(980)\pi$ invariant masses, $\sqrt{s_{23}}$ and $\sqrt{s_{12}}$, respectively (Right side).

For higher values of the invariant mass of the $\pi\pi$ and $K\bar{K}$ subsystems, around the region of the $f_0(980)$ and $a_0(980)$, we do not find a clear structure which could be associated with higher scalar resonances, like $f_0(2000)$ or $f_0(2100)$.
Decay modes: \( \pi \pi, \pi \pi \pi \pi, \pi \pi K \bar{K} \)

\( f_0(1790) \) found by BES Collaboration.\(^6\)

We have solved the Faddeev equations using unitary chiral dynamics to determine the input two-body t-matrices.

We have studied several systems made of Kaons, like

\[ K\bar{K}N, KK\bar{K}, \pi\pi\bar{K}, f_0(980)\pi\pi \]

And we have found generation of several states

\[ N^*(1910)(1/2^+), K(1460), \pi(1300), f_0(1790) \]