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Chiral dynamics in the $pp \to dK^+\bar{K}^0$ and $pp \to d\pi^+\eta$ reactions

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Abstract. We perform a study of the final-state interactions of the $K^+\bar{K}^0$ and the $\bar{K}^0 d$ systems in the reactions $pp \to dK^+\bar{K}^0$ and $pp \to d\pi^+\eta$. The interactions of the mesons are accounted for by using chiral unitary techniques, which generate dynamically the $a_0(980)$-resonance, and the $\bar{K}^0 d$ interaction is also taken into account. The amount of $\pi^+\eta$ *versus* $K^+\bar{K}^0$ production is shown to depend critically on the primary mixture of the two mechanisms, with large interference effects due to final-state interactions

PACS. 12.39.Fe Chiral Lagrangians – 13.75.Lb Meson-meson interactions – 13.75.Cs Nucleon-nucleon interactions (including antinucleons, deuterons, etc.) – 13.75.Gx Pion-baryon interactions

1 Introduction

The reaction $pp \to dK^+\bar{K}^0$ is presently the subject of experimental study by the ANKE Collaboration at the Cooler Synchrotron COSY at Jülich with the aim (among others) of learning about the nature and properties of the $a_0(980)$-resonance [1]. The problem has attracted also the interest of theoretical groups [2,3] (see furthermore the contributed papers in [4]). The prospect of gaining novel information about the $a_0(980)$-resonance, which might help to shed further light from the experimental side on the disputed nature of this resonance, is one of the attractive features of this reaction. This controversy originates from the observation that there are several different models to deal with the isospin $I = 0$, 1 scalar sector, all of them reproducing the scattering data to some extent, but with different conclusions with respect to the origin of the underlying dynamics. In particular, in refs. [5–9] these resonances are considered as pre-existing ones (genuine quark model states), while in ref. [10] they appear as meson-meson resonances generated by a potential.

2 Basic reaction mechanisms

The reaction measured in [1] is

$$pp \to dK^+\bar{K}^0 \ . \tag{1}$$

We study it theoretically in connection with the accompanying process

$$pp \to d\pi^+\eta \ , \tag{2}$$

since the dynamics of coupled channels, which we use here, deals with both channels simultaneously. On the other hand, the energy of the ANKE experiment is fixed to $\sqrt{s} = 2912.88$ MeV just about 45 MeV above the $dK^+\bar{K}^0$ threshold.

Reaction (1) forces the $K^+\bar{K}^0$ system to be in an $I = 1$ state which, given the proximity of the $a_0(980)$-resonance, would have its rate of production and invariant-mass distributions very much influenced by the tail of that resonance. Reaction (2), which is also planned to be measured by the ANKE Collaboration, could see the actual shape of the $a_0(980)$-resonance through the mass distribution of the $\pi^+\eta$ system.

Due to total angular momentum and parity conservation as well as to the antisymmetry of the initial state, the two mesons cannot be simultaneously in intrinsic S-wave and in S-wave relative to the deuteron. At low energies they can only be in $\ell = 0$, $L = 1$ or $\ell = 1$, $L = 0$, where $\ell = 0$ is the orbital angular momentum of the CM motion of the two pseudoscalars PQ and the deuteron, and L the orbital angular momentum of the pseudoscalar mesons in their own CM frame, that we also call intrinsic angular momentum of the two mesons. These two possibilities lead

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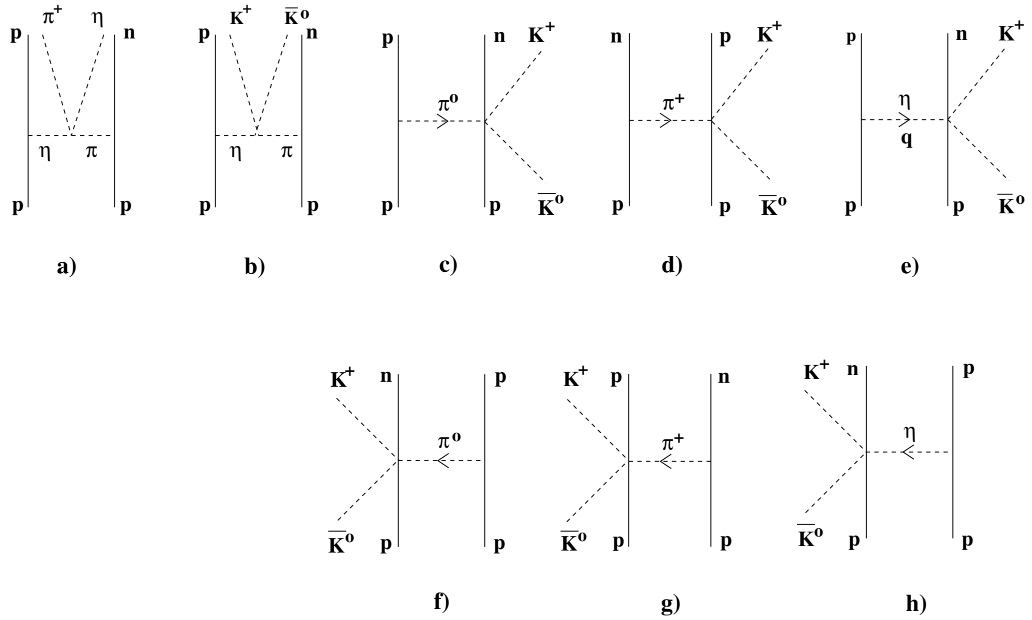

Fig. 1. Chiral model for the primary production used to extract the structures given in eq. (3).

to the following amplitudes for $K\bar{K}$ production:

$$
\begin{aligned}
&\text{I)}\ \boldsymbol{\sigma}^{(1)}\boldsymbol{p}_1\,\boldsymbol{\sigma}^{(2)}(\boldsymbol{p}_{K^+}-\boldsymbol{p}_{\bar{K}^0})+\boldsymbol{\sigma}^{(1)}(\boldsymbol{p}_{K^+}-\boldsymbol{p}_{\bar{K}^0})\,\boldsymbol{\sigma}^{(2)}\boldsymbol{p}_1\ ,\\
&\text{II)}\ -\boldsymbol{\sigma}^{(1)}\boldsymbol{p}_1\,\boldsymbol{\sigma}^{(2)}\boldsymbol{p}_d-\boldsymbol{\sigma}^{(1)}\boldsymbol{p}_d\,\boldsymbol{\sigma}^{(2)}\boldsymbol{p}_1\ .
\end{aligned}
\tag{3}
$$

Should the $K\bar{K}$ system be in an intrinsic S-wave, $L=0$, we would have eq. (3II) and the cross-section contains the factor $\boldsymbol{p}_d^2$, as correctly stated in ref. [11], which largely affects the shape of the $K\bar{K}$ invariant-mass distribution.

3 Final-state interactions

The $K^+\bar{K}^0$ system in $I=1$ will interact strongly and couple to the $\pi^+\eta$ system. In [12] the input of the lowest-order chiral Lagrangian was used as the kernel (potential) of the Bethe-Salpeter equation which produced exact unitarization in coupled channels. Diagrammatically it means that starting from the tree-level diagrams of fig. 1 we will have final production of $K^+\bar{K}^0$ and $\pi^+\eta$ from diagrams of fig. 1 which originally give rise to $\pi^+\eta$ and $K^+\bar{K}^0$, respectively. By calling G the loop function of the mesons, the sums in fig. 2 will dress the structure eq. (3II) containing the $\boldsymbol{p}_d$ vector corresponding to the case when the two mesons are in S-wave in their CM reference system, $L=0$. So we will have

$$
\begin{aligned}
\pi^+\eta:\ & f^S_{\pi\eta}|\boldsymbol{p}_1||\boldsymbol{p}_d|\mathrm{Y}_{1m}(\hat{p}_d)\to|\boldsymbol{p}_1||\boldsymbol{p}_d|\mathrm{Y}_{1m}(\hat{p}_d)\big(f^S_{\pi\eta}\\
&+f^S_{\pi\eta}G_{\pi\eta}t_{\pi\eta\to\pi\eta}+f^S_{K\bar{K}}G_{K\bar{K}}t_{K\bar{K}\to\pi\eta}\big)\ ,\\
K^+\bar{K}^0:\ & f^S_{K\bar{K}}|\boldsymbol{p}_1||\boldsymbol{p}_d|\mathrm{Y}_{1m}(\hat{p}_d)\to|\boldsymbol{p}_1||\boldsymbol{p}_d|\mathrm{Y}_{1m}(\hat{p}_d)\big(f^S_{K\bar{K}}\\
&+f^S_{K\bar{K}}G_{K\bar{K}}t_{K\bar{K}\to K\bar{K}}+f^S_{\pi\eta}G_{\pi\eta}t_{\pi\eta\to K\bar{K}}\big)\ .
\end{aligned}
\tag{4}
$$

Now we consider the FSI from the $\bar{K}d$ system. The interaction of the K^+ with the protons and neutrons is rather weak and we neglect it. However, this is not the case for the $\bar{K}^0 n$ interaction which is very strong close to threshold due to the $\Lambda(1405)$-resonance below the $\bar{K}^0 n$ threshold [13–16]. On the other hand what we need here is the $\bar{K}^0$ interaction with the deuteron that is quite strong close to the threshold due to extra reinforcement of the multiple scattering of the $\bar{K}$ in the deuteron as proved in multiple evaluations of this quantity using Faddeev equations [17–21]. A reanalysis of this quantity in the light of the new $\bar{K}N$ amplitudes generated in the chiral dynamical approach of [15] was done in [22] within the fixed scatterer approximation for the deuteron, which proves rather accurate comparing the results with those of the non-static calculation of [21]. A sizeable $\bar{K}d$ scattering length of about $(-1.6+i1.9)$ fm is obtained in [22]. In order to take into account this extra interaction we first extrapolate the results of the $\bar{K}d$ scattering amplitude at threshold of [22] to the small finite $\bar{K}$ energies of the ANKE experiment [1].

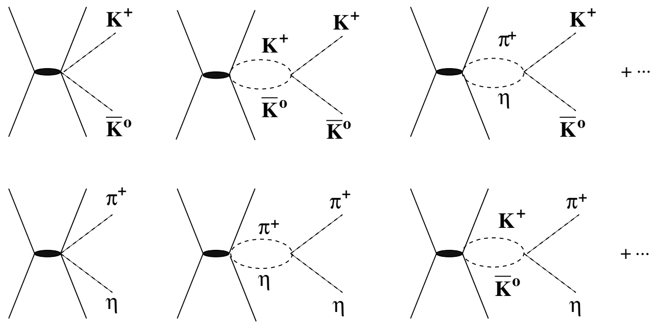

Fig. 2. Diagrams relevant to take into account the meson-meson FSI. The $a_0(980)$-resonance is dynamically generated through the iteration of the meson-meson bubbles. This iteration is indicated in the figure by the ellipses.

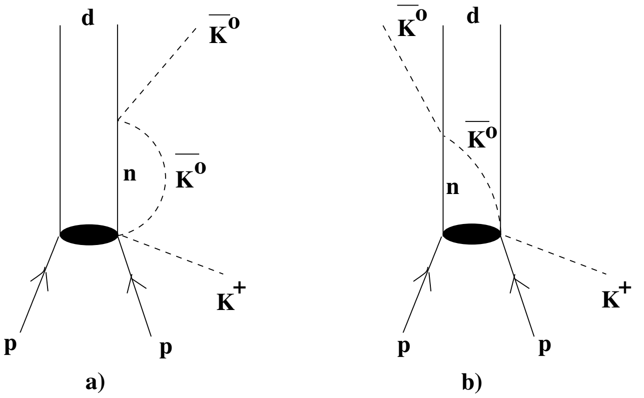

Fig. 3. Diagrams to take into account the $\bar{K}^0 d$ FSI.

The $\bar{K}d$ FSI are diagrammatically represented in fig. 3, and the corresponding terms are renormalized by changing them by

$$1 + G_d\, t_{\bar{K}d} \;, \tag{5}$$

where G_d is the meson-deuteron loop function for the $\bar{K}N$ interaction. Further details can be seen in ref. [23].

4 Results and discussion

Apart from the absolute normalization of the amplitudes, our chiral model for the primary production depends on two free parameters, θ and ϕ, such that

$$f^S_{K\bar{K}} = \cos\theta \,, \quad f^S_{\pi\eta} = \sin\theta\cos\phi \,, \quad f^P_{K\bar{K}} = \sin\theta\sin\phi \,, \tag{6}$$

where $f^p_{K\bar{K}}$ provides the strength for the amplitude of eq. (3I).

First, in order to show the relevance of the FSI, we take $\theta = \phi = 0$, implying $f^S_{\pi\eta} = 0$ and $f^P_{K\bar{K}} = 0$. In fig. 4 we display several curves corresponding to $\mathrm{d}\sigma_{K^+\bar{K}^0}/\mathrm{d}M_I$ neglecting either the two considered FSI and including either one or two of them. The distribution in the absence of any FSI (dotted line) peaks around $M_I = 1003$ MeV. If the $K^+\bar{K}^0$ interaction is switched on (dashed line) the strength is shifted considerably towards low invariant mass and the peak moves to about $M_I = 997$ MeV. This is an obvious consequence of the presence of the $a_0(980)$-resonance around 980 MeV and the $K^+\bar{K}^0$ distribution feels the tail of that resonance which increases the strength the closer one is to the resonance position, and hence to smaller values of the $K^+\bar{K}^0$ invariant mass. If one switches on only the $\bar{K}^0 d$ FSI (dash-dotted line) the distribution is rather broad and there is an accumulation of strength to higher values of the M_I. Finally, when all the interactions are considered (thick solid line) the peak of the distribution moves back to lower masses around 1 GeV, where the pure phase space peaks as well. The strength is furthermore increased by about a factor five due to the combined effects of both FSI.

We can see that the distributions are rather dependent on the values of the θ and ϕ and so are the angular distributions. This fact could be used to extract the optimal parameters from the data on $K^+\bar{K}^0$ mass distributions and angular distributions, assuming that a good fit is possible. Should this be the case, the theory would then predict absolute rates and mass distribution for the $\pi^+\eta$ production or other experimental yields, which would be a real prediction of the approach in spite of having started from two unknown parameters. The final results of the ANKE experiment are thus awaited to test the theoretical ideas exposed here.

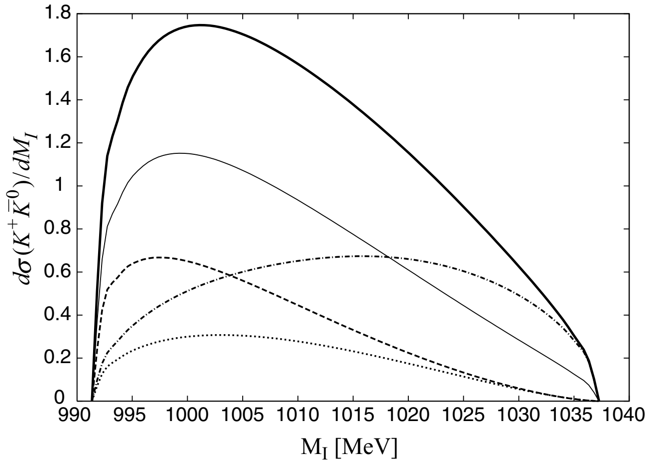

Fig. 4. $\mathrm{d}\sigma(K^+\bar{K}^0)/\mathrm{d}M_I$ for the whole range of available M_I in the reaction $pp \to dK^+\bar{K}^0$ with $\sqrt{s} = 2912.88$ MeV. The thick (thin) solid line is the full result with $a_{\bar{K}N} = -1.84\,(-1.34)$. The dashed line corresponds to including only meson-meson FSI, the dash-dotted one includes only $\bar{K}^0 d$ FSI and the dotted line includes no FSI with a $\boldsymbol{p}_d^2$ factor for the modulus squared of the amplitude.

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