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Phenomenological Studies of the Low Energy Dynamics in the ppK^+K^- System

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Abstract In this article we review studies of the near threshold $pp \to ppK^+K^-$ reaction done with the COSY-11 and ANKE detectors. We discuss phenomenological studies of the ppK^+K^- dynamics, in particular the recent investigations on the K^+K^- final state interaction are presented.

1 Introduction

The primary motivation for the near threshold $pp \to ppK^+K^-$ reaction studies was closely connected with understanding of the nature of scalar resonances $a_0(980)$ and $f_0(980)$, which properties suggest that they are not ordinary mesons. Besides the interpretation as $q\bar{q}$ mesons [1], these particles were also proposed to be $qq\bar{q}\bar{q}$ tetraquark states [2], hybrid $q\bar{q}$/meson-meson systems [3] or even quark-less gluonic hadrons [4]. Since both $f_0(980)$ and $a_0(980)$ masses are very close to the sum of the K^+ and K^- masses, they are considered also as $K\bar{K}$ bound states [5,6], which formation requires a strong $K\bar{K}$ interaction. Since kaon targets are still unavailable, the K^+K^- potential can be probed experimentally only in a multi-particle production reactions, like e.g. the $pp \to ppK^+K^-$ near threshold, where in the first order the S-wave interaction is relevant. Studies of the low energy $pp \to ppK^+K^-$ system gives opportunity to investigate also the pK^- final state interaction, very important in view of the nature of $\Lambda(1405)$ which is often considered as the $N-K^-$ molecule.

Measurements of the near threshold $pp \to ppK^+K^-$ reaction have been performed mainly at the cooler synchrotron COSY at the research center in Jülich, Germany [7]. COSY provides proton and deuteron beams with low emittance and small momentum spread. This allowed for precise determination of the proton–proton collision energy, in the order of fractions of MeV, and for dealing with the rapid growth of cross section at the threshold. First measurements of the $pp \to ppK^+K^-$ reaction were performed by the COSY-11 collaboration and they revealed that the total cross sections near threshold are relatively small (in the order of nanobarns) making the study difficult due to low statistics [8–10]. Moreover, a possible influence from the f_0 or a_0 mesons on the K^+K^- pair production appeared to be too weak to be distinguished from the direct production of these mesons based on the COSY-11 data [9]. However, the ratios of the differential cross sections as a function of the pK and the ppK invariant masses measured at excess energies Q = 10 and Q = 28 MeV:

$$R_{pK} = \frac{d\sigma/dM_{pK^-}}{d\sigma/dM_{pK^+}}, \quad R_{ppK} = \frac{d\sigma/dM_{ppK^-}}{d\sigma/dM_{ppK^+}},$$

showed a significant enhancement in the region of both the low pK^- invariant mass M_{pK^-} and the low ppK^- invariant mass M_{ppK^-} [10,11]. Since the pK^+ interaction is known to be very weak, this enhancement

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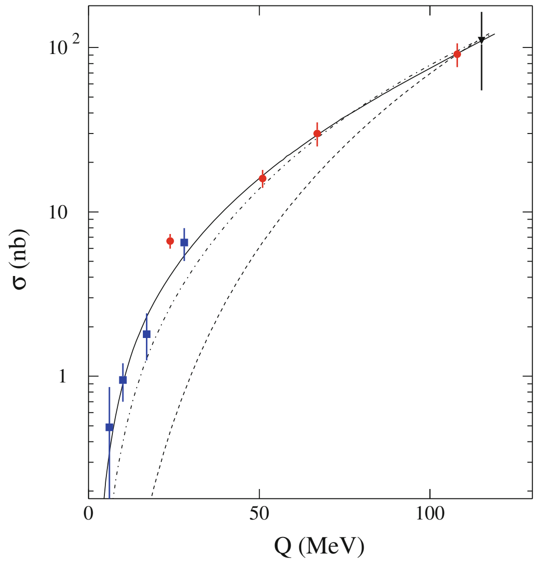

Fig. 1 Excitation function for the $pp \to ppK^+K^-$ reaction. *Triangle* and *circles* represent the DISTO and ANKE measurements, respectively [12,14,21]. The *squares* are results of the COSY–11 [8,9,11] measurements. The *dashed curve* represents the energy dependence obtained assuming that the phase space is homogeneously and isotropically populated, and there is no interaction between particles in the final state. Calculations taking into account the pp and pK^- FSIs are presented as the dashed–dotted curve. The dashed and dashed–dotted curves are normalized to the DISTO data point at Q = 114 MeV. *Solid curve* corresponds to the result obtained taking into account pp, pK, and K^+K^- interactions parametrized with the effective range approximation. These calculations were obtained using the quoted scattering length $a_{K^+K^-}$ and effective range $b_{K^+K^-}$ values. Figure adapted from [20]

indicates a strong influence of the pK^- final state interaction. This effect was confirmed by the ANKE collaboration at significantly higher energies [12–14]. Influence of the interaction in the low energy ppK^+K^- system manifests also in the shape of the $pp \to ppK^+K^-$ excitation function presented in Fig. 1, where one observes a strong deviation from the pure phase space expectations (dashed curve).

2 Description of the Dynamics in the Low Energy ppK^+K^- System

In the close-to-threshold region kaon pairs production requires large momentum transfer between the interacting nucleons, thus the complete transition matrix element of the $pp \to ppK^+K^-$ reaction may be factorized approximately as [15]:

$$\left|M_{pp\to ppK^+K^-}\right|^2 \approx |M_0|^2 \cdot |M_{FSI}|^2 , \tag{1}$$

where $|M_0|^2$ represents the total short range production amplitude, and $|M_{FSI}|^2$ denotes the final state interaction enhancement factor. Since exact calculations for the dynamics of four-body final states are still unavailable, the enhancement factor for the ppK^+K^- system was approximated assuming the factorization of M_{FSI} to the two-particle scattering amplitudes [16]:

$$M_{FSI} = F_{pp}(k_1) \times F_{p_1K^-}(k_2) \times F_{p_2K^-}(k_3), \tag{2}$$

where k_1, k_2 and k_3 denote the relative momentum of particles in the proton–proton and two proton-K^- subsystems. Here one assumes strong proton–proton and pK^- interactions neglecting the K^+ influence. Using this approximation the ANKE collaboration have described all the differential distributions measured at higher energies from the threshold using an effective scattering length $a_{pK^-} = i\,1.5\,\text{fm}$ [12]. This model, however, underestimates COSY-11 total cross sections near threshold, as one can see in Fig. 1 (dashed–dotted curve), which indicates that in the low energy region the influence of the K^+K^- final state interaction may be significant.

Motivated by this observation the COSY-11 collaboration has estimated the scattering length of the K^+K^- interaction based for the first time on the low energy $pp \to ppK^+K^-$ Goldhaber Plot distributions measured at excess energies of Q = 10 and 28 MeV [11]. The final state interaction model used in that analysis is was based on the factorization ansatz in Eq. 2, with an additional term describing the interaction of the K^+K^- pair. Factors describing the enhancement originating from the pK^- and K^+K^-–FSI were instead parametrized using the scattering length approximation:

$$F_{pK^-} = \frac{1}{1 - ika_{pK^-}}, \quad F_{K^+K^-} = \frac{1}{1 - ik_4 a_{K^+K^-}}, \tag{3}$$

where $a_{pK^-} = i$ 1.5|,fm and $a_{K^+K^-}$ is the scattering length of the K^+K^- interaction treated as a free parameter in the analysis. As a result of these studies $a_{K^+K^-}$ was estimated to be: $|Re(a_{K^+K^-})| = 0.5^{+4}_{-0.5}$ fm and $Im(a_{K^+K^-}) = 3 \pm 3$ fm.

Within this simple model any coupled channel effects, like e.g. the charge-exchange interaction allowing for the $K^0K^0 \rightleftharpoons K^+K^-$ transitions, were neglected. However, studies done by the ANKE collaboration showed that even with their high statistics data can be described well without introducing these effect [17].

3 Determination of the Effective Range of the K^+K^- Final State Interaction

Since the pK^- scattering length estimated by the ANKE group is rather an effective parameter [12], we have repeated the K^+K^- final state interaction studies using more realistic a_{pK^-} value estimated independently as a mean of all values summarized in ref. [18]: $a_{pK^-} = (-0.65 + 0.78i)$fm. Moreover, in the fit we have taken into account not only the differential cross sections measured by the COSY-11 collaboration, but also all the $pp \to ppK^+K^-$ total cross sections measured near threshold [19,20]. Since the energy range for the experimental excitation function is rather big the K^+K^- final state enhancement factor was approximated using the effective range expansion:

$$F_{K^+K^-} = \frac{1}{\frac{1}{a_{K^+K^-}} + \frac{b_{K^+K^-}k_4^2}{2} - ik_4}, \tag{4}$$

where $a_{K^+K^-}$ and $b_{K^+K^-}$ are the scattering length and the effective range of the K^+K^- interaction, respectively. Moreover, we have repeated the analysis for every a_{pK^-} value quoted in ref. [18] to check how their different values change the result. This allowed us also to estimate the systematic error due to the used pK^- scattering length used in the estimation of $a_{K^+K^-}$ and $b_{K^+K^-}$. The best fit to the experimental data corresponds to

$$\begin{aligned} \mathrm{Re}(b_{K^+K^-}) &= -0.1 \pm 0.4_{stat} \pm 0.3_{sys}\mathrm{fm} \\ \mathrm{Im}(b_{K^+K^-}) &= 1.2^{+0.1_{stat}+0.2_{sys}}_{-0.2_{stat}-0.0_{sys}}\mathrm{fm}, \\ |\mathrm{Re}(a_{K^+K^-})| &= 8.0^{+6.0_{stat}}_{-4.0_{stat}}\mathrm{fm} \\ \mathrm{Im}(a_{K^+K^-}) &= 0.0^{+20.0_{stat}}_{-5.0_{stat}}\mathrm{fm}, \end{aligned} \tag{5}$$

with a χ^2 per degree of freedom of: $\chi^2/ndof = 1.30$ [20]. The fit is in principle sensitive to both the scattering length and effective range, however, with the available low statistics data the sensitivity to the scattering length is very weak. Calculations with inclusion of the interaction in the K^+K^- system described in this section are shown as the solid curve in Fig. 1. One can see that the experimental data are described quite well over the whole energy range.

4 Summary and Outlook

Studies of the $pp \to ppK^+K^-$ reaction near threshold done with the COSY-11 and ANKE detectors suggest that the scalar resonances contribution to this reaction is negligible. The enhancement in the total cross sections may be explained introducing final state interaction, which manifests itself for example in the ratios of differential cross sections as a function of the pK and the ppK invariant masses. The influence of the pK^- interaction is seen in the broad range from very close to threshold energy up to Q = 108 MeV [11,12]. Dynamics in the

ppK^+K^- system produced near threshold was described within a simple model assuming factorization of the total final state interaction enhancement factor into two-particles interactions. Within this model we have estimated parameters of the K^+K^- interaction, in particular the effective range of this interaction.

However, the latest ANKE results obtained at Q = 24 MeV suggest that the interaction in the ppK^+K^- system is far more complex and one should use much more sophisticated model than the factorization anszatz [14]. Thus, the results of analysis quoted in this article should be considered rather as effective parameters. It seems that this reaction is driven by the $\Lambda(1405)$ production $pp \to K^+\Lambda(1405) \to ppK^+K^-$ rather than by the scalar mesons [17] with possible cusp effect generated by the $pK^- \rightleftharpoons n\overline{K}^0$ coupling.

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