Kaon pair production in pp, pd and dd collisions at COSY

M. Hartmann*, A. Dzyuba†, I. Keshelashvili**, Y. Maeda‡, A. Polyanskiy§,*, C. Wilkin¶ and X. Yuan‖

*Institut für Kernphysik and Jülich Centre for Hadron Physics, Forschungszentrum Jülich, D-52425 Jülich, Germany
†High Energy Physics Department, Petersburg Nuclear Physics Institute, RU-188350 Gatchina, Russia
**Department of Physics, University of Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerland
‡Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka 567-0047, Japan
§Institute for Theoretical and Experimental Physics, RU-117218 Moscow, Russia
¶Physics and Astronomy Department, UCL, London WC1E 6BT, United Kingdom
‖Institute of Modern Physics, Chinese Academy of Sciences, 730000 Lanzhou, PRC

Abstract. The near-threshold production of kaon-pairs has been investigated in proton-proton, proton-deuteron and deuteron-deuteron collisions at the Cooler Synchrotron COSY. The excitation function for the $pp \to ppK^+K^-$ reaction and the invariant K^-p, K^-pp, and K^+K^- mass distributions indicate the presence of both K^-p and K^+K^- final state interactions. Analogous final-state interactions of antikaons with deuterons has been found in the $pp \to dK^+\bar{K}^0$ reaction as well as in the $pn \to dK^+K^-$ reaction, measured in the quasi-free $pd \to p_{\rm sp}dK^+K^-$ process with a "spectator" proton ($p_{\rm sp}$). The existing COSY data on the $pd \to {}^3\text{He}K^+K^-$ reaction are not yet sufficient to study the $K^-{}^3\text{He}$ and K^+K^- final state interactions. A very small total cross section was found for the $dd \to {}^4\text{He}K^+K^-$ reaction.

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COSY is a Cooler Synchrotron designed to accelerate and store protons or deuterons, polarized and unpolarized, for momenta up to 3.7 GeV/*c*, corresponding to energies of 2.9 GeV for protons and 2.3 GeV for deuterons [1]. It is equipped with electron and stochastic cooling systems that can be used in the energy ranges of 40 – 183 MeV and 830 – 2830 MeV, respectively. Extensive measurements of kaon-pair production have been carried out at several COSY facilities over the last decade. Values of total and differential cross sections are now available for a variety of reactions, *cf.* Fig. 1.

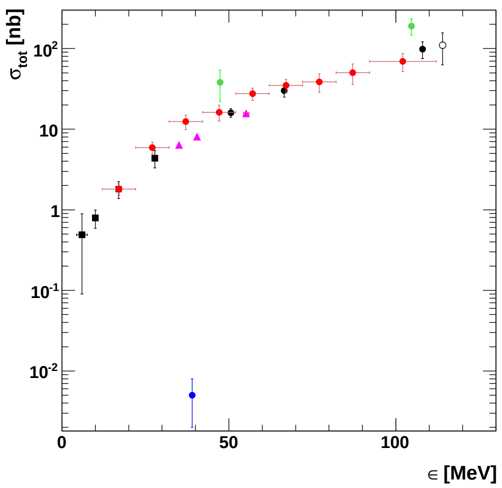

FIGURE 1. (color online) World data set on total cross sections for kaon-pair production as functions of excess energy. Closed symbols denote COSY results for $pp \to ppK^+K^-$ (black) [2, 3, 4, 5], $pp \to dK^+\bar{K}^0$ (green) [6, 7], $pn \to dK^+K^-$ (red) [8, 9], $pd \to {}^3\text{He}K^+K^-$(pink) [10], and $dd \to {}^4\text{He}K^+K^-$ (blue) [11] reactions. In addition there is a high energy $pp \to ppK^+K^-$ point from SATURNE (open circle) [12].

The $pp \to ppK^+K^-$ reaction has been studied by the COSY-11 [2, 3] and COSY-ANKE [4, 5] collaborations for excess energies ε ranging from 3 to 108 MeV. The closely related $dK^+\bar{K}^0$ exit channel has also been measured at ANKE for $\varepsilon = 47$ and 105 MeV [6, 7]. The $pn \to dK^+K^-$ reaction has been investigated at ANKE [8, 9] using a deuterium cluster-jet as an effective neutron target and measuring $pd \to p_{\rm sp}dK^+K^-$. The momentum of the non-observed proton spectator $p_{\rm sp}$, and thus the excess energy $\varepsilon_{K\bar{K}} = 17$–102 MeV, was then reconstructed from the four-momenta of the remaining detected particles.

These $pN \to (2N)K\bar{K}$ data have been analyzed in terms of the relevant final-state interactions (FSIs). It turns out that, in addition to the well known interaction of the two outgoing nucleons, there is a delicate interplay between the $K\bar{K}$ and $\bar{K}N$ FSIs, see *e.g.* Ref. [13]. The K^+N interaction is generally believed to be fairly weak and has been neglected in all analyses.

The $\bar{K}N$ systems produced may provide valuable information about the much debated antikaon-nucleon interaction strength and, possibly, about intermediate hyperon states such as the $\Lambda(1405)$. In all the $pp \to ppK^+K^-$ data one sees low mass enhancements compared to phase space in both the K^-p and K^-pp invariant mass distributions. These are not found in the analogous K^+p and K^+pp distributions. The effects can be made more explicit by evaluating the ratio of the differential cross sections $d\sigma/dM$, where M is the invariant mass of the $K^\pm p$ or $K^\pm pp$ system. This is done in Fig. 2 for data taken at 2.65 GeV [5]. It is remarkable that the ratio varies by an order of magnitude for a change in the Kp invariant mass of 50 MeV/c^2. What is equally remarkable is that, within the framework of a very simplified FSI treatment, both ratios can be described together using the same free parameter, which can be interpreted as an effective K^-p scattering length with a value of $a_{K^-p} = (0+1.5i)$ fm [5]. The formalism also describes well the ANKE data at the two higher excess energies and also the COSY-11 results in the vicinity of threshold [3].

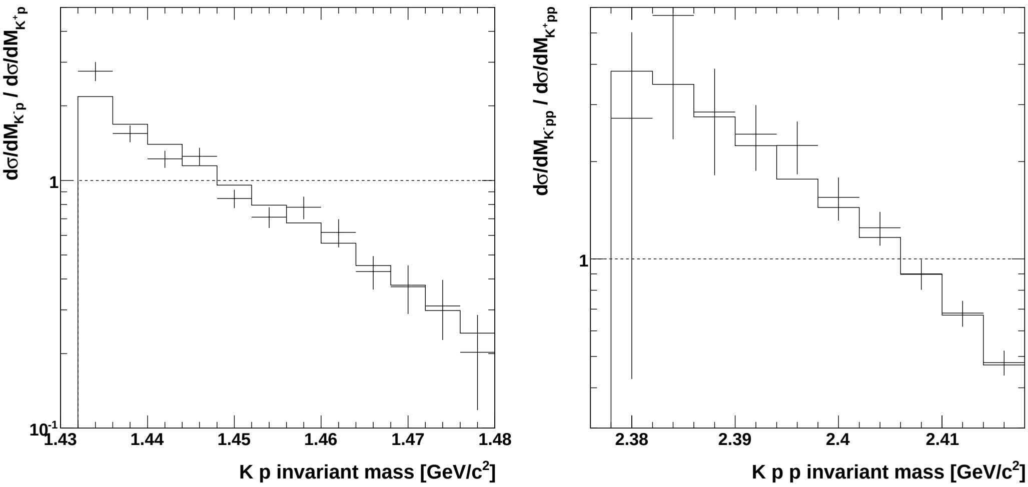

FIGURE 2. Ratio of the differential cross section for $pp \to ppK^+K^-$ in terms of the $K^\pm p$ (left) and $K^\pm pp$ (right) invariant masses. These 2.65 GeV data have been selected to come from the region $M(K^+K^-) < 1.01$ GeV/c^2, where there is only a very small ϕ contribution. The histograms include the effects of the pp and K^-p FSIs in a simplified treatment with an effective K^-p scattering length of $a_{K^-p} = (0+1.5i)$ fm [5]. Without the K^-p FSI the ratios are expects to be unity, as shown by the dashed lines.

Similar effects are observed in the $pp \to dK^+\bar{K}^0$ reaction, where the $\bar{K}^0d$ pairs are found preferentially at small invariant masses. Due to angular momentum and parity considerations, an overall s-wave final state is forbidden and a partial wave decomposition reveals that it is the $\bar{K}^0d$ pair that are dominantly in an s-wave and are enhanced compared to K^+d, which are mainly to be found in a p-wave [13]. The same low-mass enhancement is also evident in the K^-d distribution produced in the $pn \to dK^+K^-$ reaction [9]. These effects have been interpreted as evidence for a strong attractive $\bar{K}d$ FSI and all the main features are well described with a $\bar{K}d$ scattering length of $|a_{\bar{K}d}| = 1.5$ fm [13].

The most prominent feature of the ANKE $pp \to ppK^+K^-$ data is, of course, the production of the ϕ meson which shows up as a clear peak in the K^+K^- invariant-mass distribution illustrated in Fig. 3. The simulation that includes both ϕ and non-ϕ production with effects coming from pp and K^-p FSIs describes well the vast bulk of the data. However it underestimates the cross section for very low K^+K^- masses, *i.e.*, in the interval between the K^+K^- and $K^0\bar{K}^0$ thresholds. A similar underestimate is to be found in the same region of the $pn \to dK^+K^-$ data and is evidence for some $K\bar{K}$ FSI. In addition to elastic K^+K^- scattering in the final state, there is also the possibility of $K^+K^- \rightleftharpoons K^0\bar{K}^0$ charge-exchange scattering. This can give rise to interesting coupled-channel effects because of the

8 MeV/c^2 difference between the two thresholds. A combined analysis of the ANKE low K^+K^- mass $pp \to ppK^+K^-$ data sets at three energies [14] suggests that isospin-zero $K\bar{K}$ production is dominant, though the statistics in this region are quite low. The statistics are even lower for the COSY-11 $pp \to ppK^+K^-$ data and a recent reanalysis of these results puts only weak limits on the $K\bar{K}$ scattering length: $|Re(a_{K^+K^-})| = 0.5^{+4.0}_{-0.5}$ fm and $Im(a_{K^+K^-}) = 3.0 \pm 3.0$ fm [15]. To study the $K\bar{N}$ and the $K\bar{K}$ FSI in greater detail, new high statistics data were collected at ANKE at 25 and 108 MeV excess energy and these are currently under analysis [16].

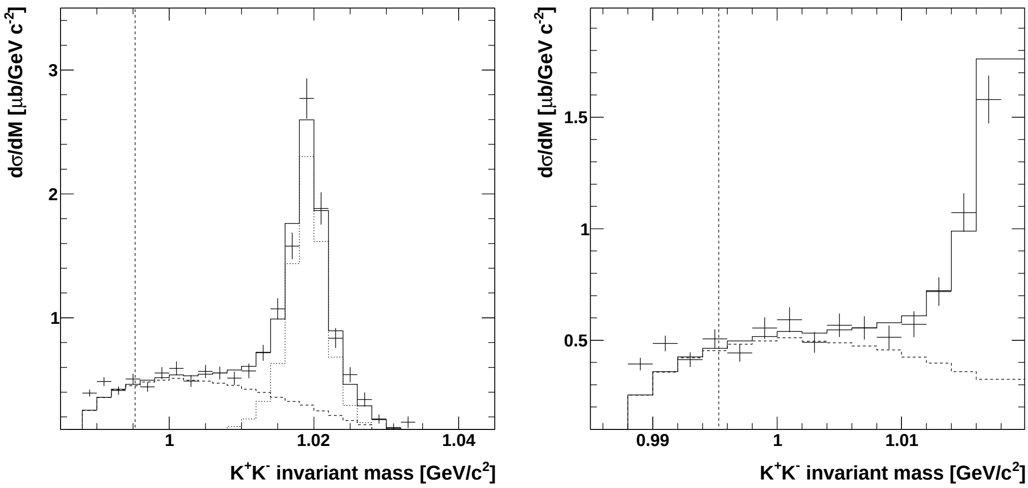

FIGURE 3. Differential cross section for the $pp \to ppK^+K^-$ reaction with respect to the K^+K^- invariant mass at 2.65 GeV. The dotted histogram and the dashed curve represent the simulations for the ϕ and non-ϕ contributions to the spectrum, with their sum being shown by the solid histogram. The left panel shows the full spectrum while the right panel illustrates the behavior near threshold. The simulations fail to reproduce the lowest mass points unless the $K\bar{K}$ FSI, including the $K^+K^- \rightleftharpoons K^0\bar{K}^0$ charge-exchange scattering, is taken into account [14]. The position of the $K^0\bar{K}^0$ threshold is indicated by the vertical dashed line.

Evidence of the relative importance of the different FSIs can also be gained from the study of the energy dependence of the $pp \to ppK^+K^-$ total cross section shown in Fig. 4. The influence of low mass enhancements in the final state is clearly more important at low energies because of the obvious total energy constraint. The pp FSI increases relatively the low energy predictions but this effect is much less than that induced by the K^-p, in part due to the fact there are two K^-p pairs. The influence of the K^+K^- FSI is comparatively small, which is consistent with the findings from the differential spectra.

The $K\bar{K}$ interaction near threshold is important, not merely because of the $\phi(1020)$, but also due to the influence of the light scalar (s-wave) mesons, $a_0/f_0(980)$. These lead to the large scattering lengths that are required to describe the K^+K^- data [14]. However these resonances have widths of about 50–100 MeV/c^2 and are therefore much harder to see in the $K\bar{K}$ mass distributions than the narrow ϕ, especially at COSY where the excess energy is limited to roughly 100 MeV. The difficulty is compounded by the strong competition coming from the kaon-nucleon interaction. As a consequence there is only indirect evidence for scalar-meson production from the partial-wave decompositions of the $pn \to dK^+K^-$ and $pp \to dK^+\bar{K}^0$ data. These reveal an s-wave dominance in the $K\bar{K}$ systems [6, 7, 4], which might be a sign of the influence of the a_0^0/f_0 and a_0^+ channels, respectively. On the other hand, it has to be stressed that, even if the production were mediated by the production of excited hyperons, there could still be FSIs in the $K\bar{K}$ channels.

The COSY-MOMO collaboration measured the $pd \to {}^3\mathrm{He}K^+K^-$ reaction at three excess energies, $\varepsilon = 35$, 41 and 55 MeV [10]. Although the ^{3}He ions were detected in a high resolution spectrograph, there was no magnetic analysis in the region of the vertex detector and so the signs of the charges of the kaons were not identified. This means that these data do not allow one to construct ratios of the $K^-{}^3\mathrm{He}/K^+{}^3\mathrm{He}$ invariant mass distributions of the type that were so illuminating in the $pp \to ppK^+K^-$ case. As a result the $K^-{}^3\mathrm{He}$ FSI could not be investigated cleanly. The angular distribution of the kaon pair in their rest frame with respect to the proton beam direction shows that the ϕ meson in $pd \to {}^3\mathrm{He}\,\phi$ is strongly polarized. This is in marked contrast to the ω meson in the analogous $pd \to {}^3\mathrm{He}\,\omega$ reaction where the polarization was shown to be consistent with zero [17]. Although there is a strong s-wave K^+K^- production in the $pd \to {}^3\mathrm{He}K^+K^-$ reaction, only upper limits of 25% and 10% could be determined for the $a_0(980)$ and $f_0(980)$ contributions [18].

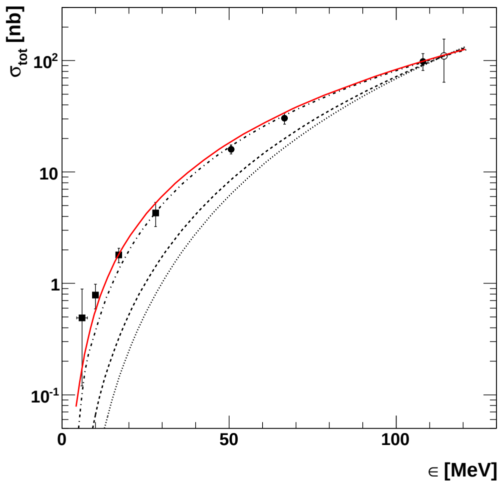

FIGURE 4. (color online) Measurements of the $pp \to ppK^+K^-$ total cross sections from COSY [2, 3, 4, 5] and SATURNE (open circle) [12] as a function of the excess energy ε. The doted curve represents the energy dependence expected from four-body phase space. The dashed curve includes the effects arising from the pp final state interaction whereas the dot-dashed curve contains in addition distortion from the K^-p FSI. The solid curve includes finally a contribution from the $K\bar{K}$ interaction, including the effects of charge-exchange scattering. All the curves are normalized on the SATURNE point.

The $dd \to {}^4\mathrm{He}X^0$ reaction is of particular interest since it selects isospin-zero states X^0 which, in the $dd \to {}^4\mathrm{He}K^+K^-$ case, could be sensitive to the production of the f_0 resonance. This reaction has also attracted interest because of the possibility of studying charge-symmetry breaking induced by f_0/a_0 mixing, which could be a large effect due to their similar masses. An investigation has been proposed at COSY-WASA through the study of $dd \to {}^4\mathrm{He}\,(f_0 \to \pi^0\eta)$ [19]. The total $dd \to {}^4\mathrm{He}K^+K^-$ cross section has been measured at ANKE [11] but, as is shown in Fig. 1, the total cross section is only about 5 pb, which is several orders below that of all other reactions. This is the rarest reaction so far measured at COSY, being about **eleven** orders of magnitude smaller than the dd total cross section. It brings into question the feasibility of studying f_0/a_0 mixing using the $dd \to {}^4\mathrm{He}\,\pi^0\eta$ reaction.

The dominant FSI in all the kaon pair production reactions studied at COSY seems to be that of the low energy antikaon with nucleons. It is tempting to ascribe this to the production of the high mass tail of the $\Lambda(1405)$ excited hyperon in $pp \to K^+p(\Lambda^* \to K^-p)$. Since the central mass value lies below the K^-p threshold, it is important to study the production of this hyperon more directly and this was possible at ANKE through the measurement of the $pp \to K^+p(\Lambda^* \to \Sigma^0\pi^0)$ channel at 2.83 GeV [20]. It should be noted that isospin forbids the decay of the $\Sigma(1385)$ into the $\Sigma^0\pi^0$ final state and the $\Sigma^0\pi^0$ invariant mass spectrum presented in the left panel of Fig. 5 shows the typical asymmetric shape that is to be associated with the opening of the K^-p channel at 1432 MeV/c^2.

In the right panel of Fig. 5 are the corresponding data for the K^+K^-pp channel, presented in terms of the K^-p invariant mass [5]. It is known that the K^-p and $(\Sigma\pi)^0$ channels are strongly coupled and this effect has been parameterized in terms of a separable potential [21] which allows one to estimate effects arising from the coupled $K^-p/\Sigma^0\pi^0$ FSI. Using this approach with kaon exchange, it is possible to reproduce simultaneously the shapes of the two spectra shown in Fig. 5 by the curves [22]. However, the model is still simplistic in that the pp FSI has been neglected, as has the antisymmetrization between the two protons, and the relative normalization disagrees with experiment by about a factor of three. Nevertheless, the similarity of the shapes with the measured spectra does suggest that the $\Lambda(1405)$ could indeed be playing a crucial role in the production of kaon pairs in nucleon-nucleon collisions.

To summarize, there is ample evidence that the antikaon is strongly attracted to the recoil nucleons in near-threshold kaon pair production in both pp and pn collisions. Only residual effects of the K^+K^- interaction are seen, including a possible cusp at the $K^0\bar{K}^0$ threshold. More information on this will soon be forthcoming from the high statistics data currently being analyzed at ANKE. Data for pd collisions are as yet inconclusive because of the lack of a positive identification of the kaon charge and this experiment will have to be repeated. The dd data are not meaningful because of the very low total cross section for K^+K^- production. The shapes of the K^-p and $\Sigma^0\pi^0$ invariant mass distributions in the $pp \to K^+p(K^-p)$ and $pp \to K^+p(\Sigma^0\pi^0)$ reactions are well reproduced using an empirical approach and a coupled channel final state interaction formalism. This suggests that they might share a common production

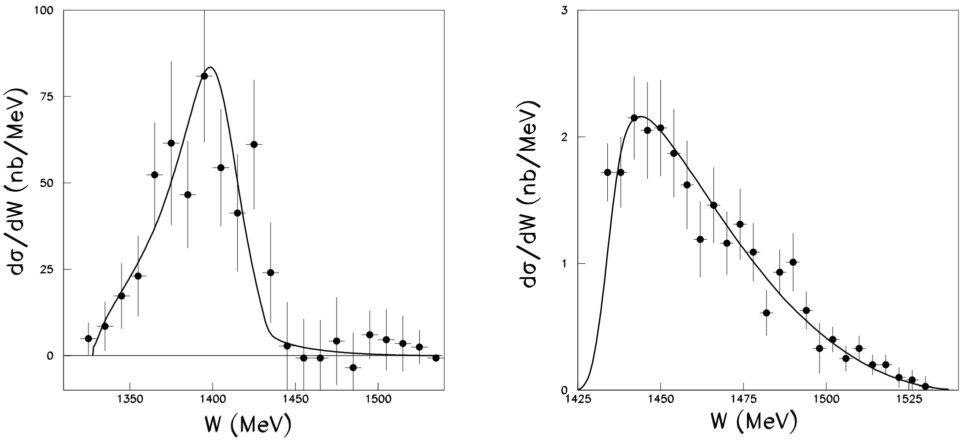

FIGURE 5. Left panel: Differential cross section for the $pp \to K^+ p \Sigma^0 \pi^0$ reaction at 2.83 GeV as a function of W, the $\Sigma^0\pi^0$ invariant mass [20]. Right panel: *idem* for $pp \to K^+ pK^- p$ where W is the $K^- p$ invariant mass [5]. The curves are predictions for the relative sizes assuming that the $\Lambda(1405)$ is excited through kaon exchange in the two cases [22].

mechanism involving the $\Lambda(1405)$. A more detailed microscopic model, where the two reactions are considered together, is still lacking.

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