Study of the hadronic production of kaon pairs below the threshold for the ϕ meson

P. Moskal[ab], M. Silarski[a], A. Budzanowski[c], E. Czerwiński[ab], R. Czyżykiewicz[a], D. Gil[a], D. Grzonka[b], M. Janusz[ab], L. Jarczyk[a], B. Kamys[a], A. Khoukaz[d], P. Klaja[ab], W. Oelert[b], C. Piskor-Ignatowicz[a], J. Przerwa[ab], B. Rejdych[a], J. Ritman[b], T. Sefzick[b], M. Siemaszko[e], J. Smyrski[a], A. Täschner[d], P. Winter[b], M. Wolke[b], P. Wüstner[b], M. J. Zieliński[a], W. Zipper[e], J. Zdebik[a]

[a]Institute of Physics, Jagiellonian University, PL-30-059 Cracow, Poland

[b]IKP & ZEL, Forschungszentrum Jülich, D-52425 Jülich, Germany

[c]Institute of Nuclear Physics, PL-31-342 Cracow, Poland

[d]IKP, Westfälische Wilhelms-Universität, D-48149 Münster, Germany

[e]Institute of Physics, University of Silesia, PL-40-007 Katowice, Poland

The near threshold production of K^+K^- pairs in proton-proton collisions has been investigated at the cooler synchrotron COSY below and above the threshold for the ϕ meson using the COSY-11 and ANKE facilities, respectively. The excitation function determined for the $pp \to ppK^+K^-$ reaction revealed a statistically significant enhancement close to the threshold which may plausibly be assigned to the influence of the K^-p interaction. In addition, observed consistently by both groups, a strong enhancement at low values of the ratio of the K^-p to K^+p invariant mass distributions shows that the proton interacts much stronger with K^- than with K^+. In this report we focus on the measurements performed by the COSY-11 collaboration. We explain the experimental method used and present main results of completed analyses as well as a new qualitative elaboration of the ppK^+K^- events population on the Goldhaber plot. We conclude with the observation that event densities increase at the region where the influence from the K^+K^- interaction is expected.

1. Introduction

A primary motivation for measuring cross sections for the $pp \to ppK^+K^-$ reaction near the kinematical threshold was the study of the hadronic interaction between K^+ and K^- mesons in order to understand the structure of the scalar resonances $f_0(980)$ and $a_0(980)$ [1]. Such measurements have been made possible by beams of low emittance and small momentum spread available at storage ring facilities and in particular at the cooler synchrotron COSY placed in Jülich, Germany [2]. A precise determination of the collision energy, in the order of fractions of MeV, permitted to deal with the rapid growth of cross sections [3] and thus to take advantage of threshold kinematics like e.g. full space phase coverage achievable with dipole magnetic spectrometers rather limited in geometrical acceptance. Early experiments on K^+K^- pair production at COSY conducted by the COSY-11 collaboration revealed, however, that the total cross section at threshold is by more than seven orders of magnitude smaller than the total proton-proton production cross section making the study difficult due to low statistics [4,5,6]. 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 [5]. Recent results obtained by the ANKE collaboration with much higher statistics can also be explained without the need of referring to the scalars f_0 or a_0 [7,8]. However, the systematic collection of data below [4,5,6] and above [7,9] the ϕ meson threshold combined together reveal a significant signal in the shape of the excitation function in which the K^-p and perhaps also the K^+K^- interaction manifests itself. These observations motivate us to search for a signal from the interaction between the K^+ and K^- in two dimensional invariant mass distributions. The analysis is based on generalizations of the Dalitz plot for four particles proposed by Goldhaber et al. [10,11]. The knowledge about the KK and KN interactions is important in many physical fields. In addition to the already mentioned studies of the nature of the scalar resonaces $a_0(980)$ and $f_0(980)$, in particular for their interpretation as $K\bar{K}$ molecules [12,13,14], it is also of importance in view of discussions on the structure of the excited hyperon $\Lambda(1405)$, since it is not clear whether it is a usual three quark system or whether it is a $\bar{K}N$ bound state [15]. Furthermore, an understanding of kaon and antikaon interactions with a nucleon is essential for studies of properties of strange particles immersed in dense baryonic matter [16] and in the determination of the structure of neutron stars [17,18].

2. Measurements of the $pp \to ppK^+K^-$ reaction at COSY-11

The measurements of the $pp \to ppK^+K^-$ reaction close to threshold have been conducted using the cooler synchrotron COSY [2] and the COSY-11 detection system [19] shown schematically in Fig. 1. The target, being a beam of H_2 molecules grouped inside clusters of up to 10^5 atoms [20], crosses perpendicularly the beam of protons circulating in the ring. If at the intersection point of the cluster target and COSY beam a collision of protons leads to the production of a K^+K^- meson pair, then the reaction products having smaller momenta than the circulating beam are directed by the magnetic dipole field towards the COSY-11 detection system and leave the vacuum chamber through a thin exit foils [19]. Tracks of positively charged particles, registered by drift chambers, are traced back through the magnetic field to the nominal interaction point leading to a momentum determination. Knowledge of the momentum combined with a simultaneous mea-

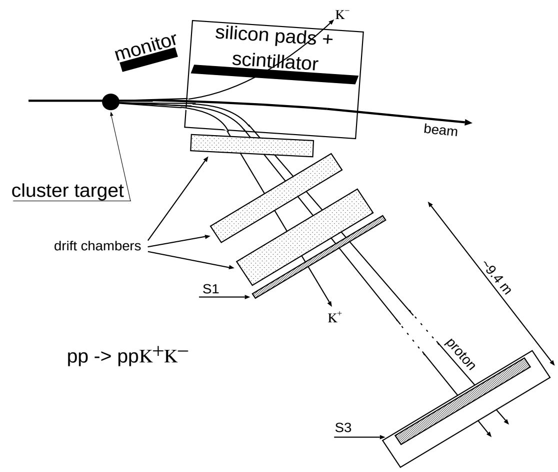

Figure 1. Schematic view of the COSY-11 detector with an exemplary event of the reaction channel $pp \to ppK^+K^-$. For the description see text.

surement of the velocity, performed by means of scintillation detectors S1 and S3, permits to identify the registered particle and to determine its four momentum vector. Since at threshold the center-of-mass momenta of the produced particles are small compared to the beam momentum, in the laboratory frame all ejectiles are moving with almost the same velocity. This means that the laboratory proton momenta are almost two times larger then the momenta of kaons. Therefore, in the dipole field protons experience a much larger Lorentz force than kaons. As a consequence, in case of the near threshold production, protons and kaons are registered in separate parts of the drift chambers. Therefore, as a first step in the reaction identification events with two protons registered in an appropriate part of the drift chambers are selected based on the time-of-flight between the S1 and S3 scintillation hodoscopes. The additional requirement that the mass of the third particle, registered at the far side of the chamber with respect to the circulating beam, corresponds to the mass of the kaon, allows to identify events with a $pp \to ppK^+X^-$ reaction [16]. Knowing both the four momenta of

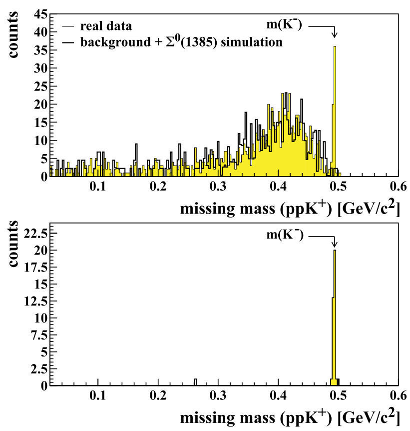

Figure 2. (Upper panel) Exemplary missing mass spectrum determined for the $pp \to ppK^+X^-$ reaction at an excess energy of Q = 17 MeV [5]; (Lower panel) Missing mass distribution from upper panel after additional requirement of the signal in the dipole detector as it is described in the text.

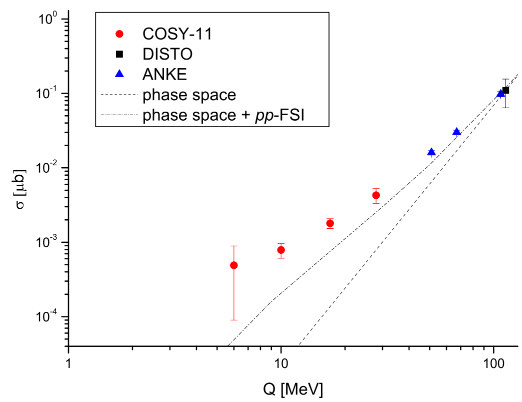

Figure 3. Total cross section as a function of the exess energy Q for the $pp \to ppK^+K^-$ reaction. The data are form references [4,5,6,7,9] and the meaning of the lines is described in the text.

positively charged ejectiles and the proton beam momentum one can calculate the mass of an unobserved system X^-. Figure 2 (upper panel) presents an example of the missing mass spectrum with respect to the identified ppK^+ subsystem. In the case of the $pp \to ppK^+K^-$ reaction this should correspond to the mass of the K^- meson, and indeed a pronounced signal can be clearly seen at this position. The additional broad structure seen in the upper panel of Fig. 2 is partly due to the $pp \to pp\pi^+X^-$ reaction, where the π^+ was misidentified as a K^+ meson, and in part due to the K^+ meson production associated with the hyperons $\Lambda(1405)$ or $\Sigma(1385)$ [5,6]. The background, however, can be completely reduced by demanding a signal in the silicon pad detectors (mounted inside the dipole) at the position where the K^- meson originating from the $pp \to ppK^+K^-$ reaction is expected (lower panel of Figure 2). This clear identification allows to select events originating from the $pp \to ppK^+K^-$ reaction and to determine the total and differential cross sections.

Figure 3 shows the excitation function for the $pp \to ppK^+K^-$ reaction established by the COSY-11 [4,5,6] group near the threshold and by ANKE [7] and DISTO [9] collaborations at higher energies. The dashed line shows the result of calculations under the assumption of a homogeneous phase space population, normalized to the DISTO data point (Q = 114 MeV). For the dashed–dotted line, the proton-proton final state interaction is included using parameterization known from the three body final state [21]. It is clearly seen that calculations neglecting the interaction of kaons underestimate the experimental results by a factor of five in the vicinity of the kinematical threshold. Therefore, the enhancement may be due to the influence of K^-p or K^+K^- interaction. And indeed, with a factorization ansatz for the pp and pK^- interaction, the ANKE collaboration described the excitation function much better [7,8], however still underestimating the two lowest data points by more than a factor of two. This could indicate that in this region the influence of the K^+K^- interaction is significant and cannot be neglected. This observation encouraged us to carry out the analysis of differencial cross sections for the low energy data at Q = 10 MeV (27 events) and Q = 28 MeV (30 events), in spite of the fact that the available statistics is quite low [6].

3. Goldhaber plot analysis: generalization of the Dalitz plot for four particle final state

Usage of the Dalitz plot for extracting information about the interaction among particles in the case of three body final states is well known. It was introduced by Dalitz in a nonrelativistic application [22] and then extended to the relativistic case by Fabri [23]. If the transition amplitude is constant over phase space and if additionally there is no final state interaction, the occupation of the Dalitz plot would be fully homogeneous because the creation in any phase space interval would be equally probable. Thus, final state interaction should show up as a modification of the event density in the Dalitz plot.

In the case of four particles in final state the analysis is more complex, because one needs five variables to fully describe a relative movement of particles. Nevertheless, there are many different types of generalization of the Dalitz plot for four-body final states. In this contribution we present a generalization proposed by Goldhaber [10,11], which we use further on for studying the interaction in the ppK^+K^- system. However, there exist many other approaches as described e.g. by Nyborg or Chodrow [24,25,26]. Consider a reaction yielding in the final state four particles with masses m_i and total energy $\sqrt{s}$ in the centre-of-mass frame. Assuming that the matrix element for the process M depends only on invariant masses of two- and three particle subsystems [24] the distribution of events can be expressed in some choice of five independent invariant masses e.g.: M_{12}^2, M_{34}^2, M_{14}^2, M_{124}^2, M_{134}^2. Assuming further that M depends at most on M_{12}^2, M_{34}^2, and M_{124}^2, which corresponds to the situation where only two two-particle or one three-particle resonances are present [24], one obtains the following distribution of events:

$$d^3P = \frac{\pi^3 \left|M\right|^2 g\left(M_{12}^2, m_1^2, m_2^2\right)}{8sM_{12}^2} dM_{12}^2 dM_{34}^2 dM_{124}^2 \quad (1)$$

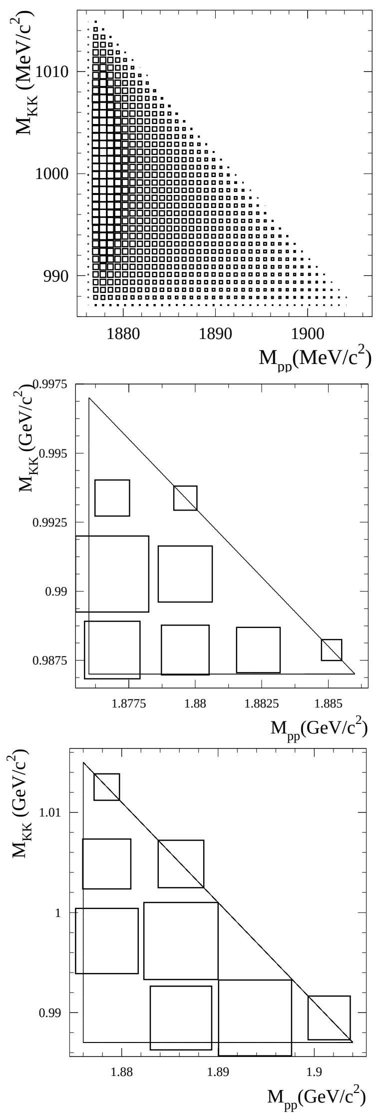

Figure 4. Goldhaber plots for the $pp \rightarrow ppK^+K^-$ reaction. (upper panel) Simulations at $Q = 28$ MeV for homogeneously populated phase space modified by proton-proton final state interaction taken into account as weights proportional to the inverse of a squared Jost-function of the Bonn potential [21,27]. (middle and lower panels) Experimental data obtained at Q = 10 MeV (middle), and Q = 28 MeV (lower).

where g is a simple analytical function of its variables [24]. The projection of the physical region on the (M_{12}, M_{34})-plane gives a right isosceles triangle in which the area is not proportional to the phase space volume. It is important to note that the event density in the Goldhaber plot is not homogeneous and goes to zero on the entire boundary of the plot given by the following equations: $M_{12}+M_{34}=\sqrt{s}$, $M_{12}=m_1+m_2$, $M_{34}=m_3+m_4$ [24].

Figure 4 (upper panel) presents the simulated distribution for the ppK^+K^- reaction determined taking into account only the pp–FSI. Experimental event distributions after acceptance corrections for both studied excess energies are shown in the middle and lower panels. Clearly the event densities in the experimental Goldhaber plots differ from the simulated spectrum. In particular data show an enhancement in the range of small K^+K^- invariant masses which may signify a signal from the kaon-antikaon interaction. A similar enhancement is seen by the ANKE group [7] below the ϕ meson mass in the K^+K^- invariant mass distributions. As a next step in the analysis we will compare experimental data to the results of Monte Carlo simulations generated with various parameters of the K^+K^- interaction taking into account the pK–FSI, as described in references [7,8].

4. Acknowledgements

We acknowledge the support by the European Community-Research Infrastructure Activity under the FP6 programme (Hadron Physics, RII3-CT-2004-506078), by the Polish Ministry of Science and Higher Education under the grants No. 3240/H03/2006/31 and 1202/DFG/2007/03, and by the German Research Foundation (DFG).

REFERENCES

1. W. Oelert, Proc. of the Workshop on Meson Production, Interaction and Decay, Cracow, World Scientific, Singapore (1991) 199.
2. D. Prasuhn et al., Nucl. Instr. & Meth. A 441 (2000) 167; R. Maier, Nucl. Instr. & Meth. A 390 (1997) 1.
3. P. Moskal, M. Wolke, A. Khoukaz, W. Oelert, Prog. Part. Nucl. Phys. 49 (2002) 1.
4. M. Wolke, Ph. D thesis, Rheinische Friedrich-Wilhelms-Universität Bonn (1997).
5. C. Quentmeier et al., Phys. Lett. B 515 (2001) 276.
6. P. Winter et al., Phys. Lett. B 635 (2006) 23.
7. Y. Maeda et al., Phys. Rev. C 77 (2008) 01524.
8. C. Wilkin, AIP Conf. Proc. 950 (2007) 23.
9. F. Balestra et al., Phys. Lett. B 468 (1999) 7.
10. W. Chinowsky, G. Goldhaber, S. Goldhaber, W. Lee, T. O'Halloran, Phys. Rev. Lett. 9 (1962) 330.
11. W. Chinowsky, G. Goldhaber, S. Goldhaber, W. Lee, T. O'Halloran, Phys. Rev. Lett. 6 (1963) 62.
12. C. Hanhart, Eur. Phys. J. A 31 (2007) 543.
13. J.D. Weinstein, N. Isgur, Phys. Rev. D 41 (1991) 2236.
14. D. Lohse et al., Nucl. Phys. A 516 (1990) 513.
15. N. Kaiser et al., Nucl. Phys. A 594 (1995) 325.
16. P. Moskal et al., J. Phys. G 28 (2002) 1777.
17. G.Q. Li et al., Nucl.Phys. A 625 (1997) 372.
18. G.E. Brown, H. Bethe, Astrophys. J. 423 (1994) 659.
19. S. Brauksiepe et al., Nucl. Instr. and Meth. A 376 (1996) 397; P. Klaja et al., AIP Conf. Proc. 796 (2005) 160; J. Smyrski et al., Nucl. Instr. and Meth. A 541 (2005) 574; P. Moskal et al., Nucl. Instr. & Meth. A 466 (2001) 448.
20. H. Dombrowski et al., Nucl. Instr. & Meth. A 386 (1997) 228.
21. P. Moskal et al., Phys. Lett. B 482 (2000) 356.
22. R.H. Dalitz, Phil. Mag. 44 (1953) 1068.
23. E. Fabri, Nuovo Cimento 11 (1954) 479.
24. P. Nyborg et al., Phys. Rev. 140 (1965) 914.
25. D. Chodrow, Nuovo Cimento **50**, 674 (1967).
26. M. Silarski, P. Moskal, AIP Conf. Proc. 950 (2007) 77.
27. B. L. Druzhinin et al., Z. Phys. A 359 (1997) 205.