Kaon-pair production in hadron-induced reactions

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Abstract. An experimental program has been initiated at the Cooler Synchrotron COSY-Jülich — a storage ring for (un-)polarized proton and deuteron beams up to 3.7 GeV/c — to investigate strangeness production in hadron-induced reactions. Besides studies of hyperon-production ($pN \to KYN$, where $Y = (\Lambda, \Sigma)$), measurements of the production of kaon pairs have also been conducted; these comprise: $pp \to ppK^+K^-$ below (COSY-11) and above (ANKE) the ϕ-threshold, $pp \to dK^+K^-$ to study a_0, f_0, ϕ-production on the neutron (ANKE), $pp \to dK^+\bar{K}^0$ for kaon-pair production in the a_0^+-channel (ANKE), $pd \to {}^3HeK^+K^-$ which is sensitive to ${}^3He\bar{K}$ final state interaction (MOMO), and $dd \to {}^4HeK^+K^-$ which filters kaon pairs in the f_0-channel (ANKE). ANKE, a magnetic spectrometer at an internal target position of COSY, is equipped with detector systems for positively and negatively charged particles. These can detect the kaons and one can reconstruct the intermediate $K\bar{K}$-states by their invariant mass. Alternatively, the K^+ and the two baryons or the nucleus in the final state are detected and the missing mass technique is applied to find the non-observed residuum. In this contribution, the recent ANKE results [1–4], as well as plans for future measurements are presented.

PACS. 25.10+s Nuclear reactions involving few-nucleon systems – 13.75-n Hadron-induced low- and intermediate-energy reactions and scattering energy (energy $\leq$ 10 GeV)

1 Introduction

Quantumchromodynamics (QCD) is the theory of strong interactions. The properties of QCD at low energies or large distances are yet poorly known and are among the few uncharted territories of the standard model. A better understanding of strong QCD can be achieved from the spectroscopy of strongly bound quark states (hadrons).

An outstanding example is the light scalar mesons $a_0(980)$ and $f_0(980)$. Up to now, more states with $J^P = 0^+$ have been observed, than it is necessary to form the scalar nonet. This initiated the discussion about the nature of the $a_0/f_0(980)$ resonances. The naive constituent quark model treats the scalar mesons as qq states (see *e.g.* [5]). However, a_0/f_0 can be also identified with $K\bar{K}$ molecules [6] or compact $qq - \bar{q}\bar{q}$ states [7]. The possible observation of the a_0/f_0-mixing [8,9] which can violate isospin conservation, is very interesting, because this symmetry plays an important role in QCD and such a measurement can provide a new observable which is sensitive to the yet unknown structure of the light scalar mesons.

Another interesting topic is the properties of light vector mesons ($J^P = 1^-$), ρ, ω and ϕ, such as their coupling constants, production mechanisms close to thresholds and in particular the so-called Okubo-Zweig-Iizuka (OZI) rule [10]. This rule states that processes with disconnected quark lines between initial and final states are suppressed. As a result, the production of ideally mixed ϕ-mesons (quark content $s\bar{s}$) in a reaction $AB \to \phi X$ is reduced compared to $AB \to \omega X$ (ω is a linear combination of $u\bar{u} + d\bar{d}$) under similar kinematical conditions. Calculations by Lipkin [11] predict ratio of single ϕ to ω production of $R_{\phi/\omega} = 4.2 \times 10^{-3} \equiv R_{OZI}$. However, $R_{\phi/\omega}$ is strongly enhanced, in particular in $p\bar{p}$ interactions [12].

In order to clarify such questions, an experimental program has been started at the Cooler Synchrotron COSY Jülich [13] aiming exclusive data on the $K\bar{K}$ production from pp, pn, pd and dd interactions close to the threshold. These experiments are also attractive for the investigation of the low energy $\bar{K}N$ and $\bar{K}\Lambda$ interactions [14].

At the COSY–11 spectrometer the total cross section of the reaction $pp \to ppK^+K^-$ has been measured below ϕ-meson threshold [15,16]. The data show a significant enhancement of the total cross section as compared to pure phase-space expectations or calculations within a one-boson exchange-model. The enhancement in K^-p low invariant-mass region significantly indicates FSI for this system [16]. At MOMO the reaction $pd \to {}^3HeK^+K^-$ has been studied at three different excess energies [17]. The total cross section for ϕ production and non-resonant K^+K^- production have been determined. The differential

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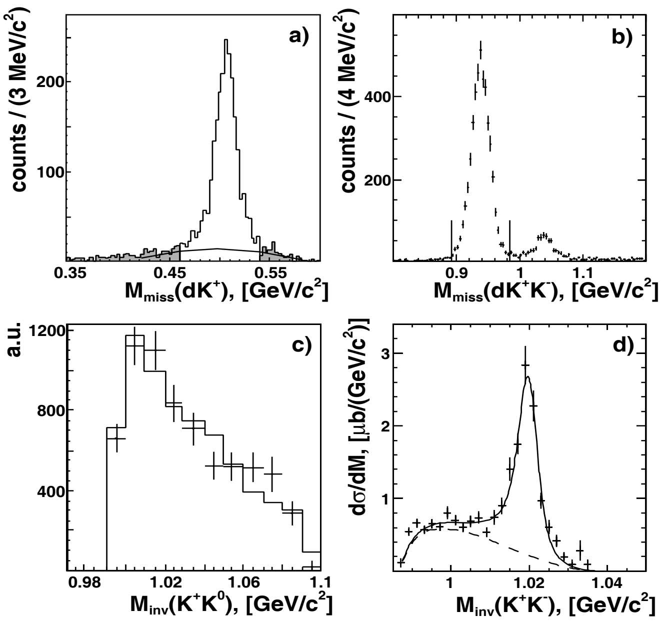

Fig. 1. a) Missing-mass $m(pp, dK^+)$ distribution of the $pp \to dK^+\bar{K}^0$ events for $T_{beam} = 2.83$ GeV. The line shows the background distribution (polynomial fit) and the shaded area indicate the events used for background subtraction [4]. b) Missing-mass $m(pd, dK^+K^-)$ distribution of the $pd \to dK^+\bar{K}^0X$ events with lines indicating the proton selection range [3]. c) $K^+\bar{K}^0$ invariant-mass distribution for the reaction $pp \to dK^+\bar{K}^0$ at $T_{beam} = 2.83$ GeV before acceptance correction. Line shows the best fit for lowest allowed partial wave assumption [4]. d) Cross section as a function of the K^+K^- invariant-mass for the reaction $pp \to ppK^+K^-$ at $T_{beam} = 2.65$ GeV. The dashed line shows the fit of non-ϕ contribution (based on four-body phase space). The solid line is the sum of ϕ and non-ϕ parts, includes also the smearing effect of the momentum resolution [1].

spectra – which are consistent with pure $K\bar{K}$ S-wave production outside the ϕ peak – show no evidence for a_0/f_0 production. Also there is no indication for strongly bound antikaonic states, [14]. In this paper, recent results obtained with the ANKE spectrometer, as well as plans for future measurements are presented.

2 ANKE spectrometer

The magnetic spectrometer ANKE [18] consists of three dipoles and detection systems for identification of charged particles. In our measurements an H_2/D_2 cluster jet target [19] which can provide aerial densities of up to $5 \cdot 10^{14}$ cm^{-2}s^{-1} has been used. Together with 10^{11} particles in the COSY ring, it corresponds to luminosities up to $3.5 \cdot 10^{-31}$ cm^{-2}s^{-1}.

K^+-mesons are detected in a detection system for positively charged particles, using time-of-flight (TOF) measurement between 23 scintillation start counters, which are placed near a side exit window of the spectrometer magnet and the range telescopes system (for $p_{K^+} = 390$ – 625 MeV/c) or a wall of scintillation counters ($p_{K^+} = 625$ – 1000 MeV/c). The momentum reconstruction algorithm uses the track information provided by two multiwire proportional chambers (MWPCs). This information as well as the kaon energy losses in the scintillators are used in order to suppress background.

High momentum particles (p, d or He) produced in coincidence with the kaons are detected by a forward detection system which consists of three MWPCs (used for momentum reconstruction) and two layers of scintillation counters. As a selection criteria, the energy loss of the particles and time difference between the hits in the side and forward systems are used.

K^--mesons are counted in a detection system for negatively charged particles containing layers of scintillation counters and two MWPCs, which also provides the possibility to use TOF, time difference between "negative" and "positive" detection systems and ΔE techniques and to reconstruct K^- momenta.

Since neutral particles (such as $\bar{K}^0$ or n) and spectator protons can not be detected directly at ANKE the missing-mass technique has been used for the final event identification (see Fig. 1). The widths (FWHM) of the missing-particle peaks are around 25 – 30 MeV/c^2 due to the ANKE momentum resolution, mainly that of the high momentum particles. The ϕ-peaks in the K^+K^- invariant mass spectra are narrower (several MeV/c^2).

3 Recent ANKE results

3.1 Search for the $a_0^+(980)$ in the reaction $pp \to dK^+\bar{K}^0$

Two experiments on $a_0^+(980)$ production have been performed in pp collisions at $T_p = 2.65$ GeV (2001) and $T_p = 2.83$ GeV (2002) (corresponding to 47.4 and 104.7 MeV excess energy (Q) with respect to the $K^+\bar{K}^0$ threshold). Contributions from misidentified events, which are of the order of 13%, have been subtracted in the differential spectra (Fig. 2). In order to improve the invariant-mass and angular resolutions a kinematical fit has been applied to the data. As a result of the fit, the $K\bar{K}$ invariant-mass resolution is less than 3 MeV/c^2 in the full range for $Q = 47.4$ MeV data and less then 10 MeV/c^2 for $Q = 104.7$ MeV.

Since the data have been obtained close to threshold, the analysis has been restricted to the lowest allowed partial waves, *i.e.* s-wave in the $K\bar{K}$ system accompanied by a p-wave of the deuteron with respect to the meson pair ("$a_0^+(980)$-channel"[1]), and p-wave $K\bar{K}$ production with an s-wave deuteron (non-resonant channel). Under this assumption the square of the spin-averaged transition matrix element can be written as:

$$|\bar{\mathcal{M}}|^2 = C_0^q q^2 + C_0^k k^2 + C_1(\hat{\boldsymbol{p}} \cdot \boldsymbol{k})^2 + C_2(\hat{\boldsymbol{p}} \cdot \boldsymbol{q})^2 + C_3(\boldsymbol{k} \cdot \boldsymbol{q}) + C_4(\hat{\boldsymbol{p}} \cdot \boldsymbol{k})(\hat{\boldsymbol{p}} \cdot \boldsymbol{q}) \ . \quad (1)$$

[1] Due to selection rules the $a_0^+(980)$ can contribute only to this channel.

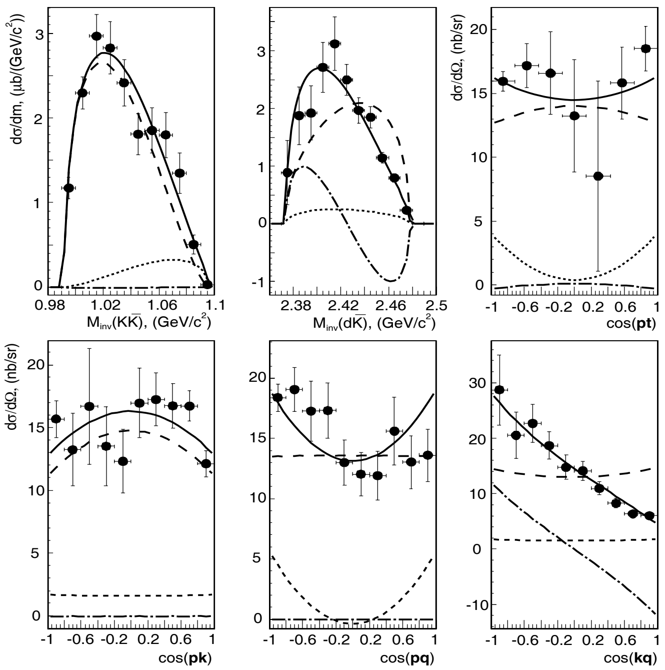

Fig. 2. Angular and invariant mass distributions for $T_p = 2.83$ GeV. The dashed (dotted) line corresponds to $K\bar{K}$ production in a relative s- (p-)wave, the dash-dotted to the interference term, and the solid line is the sum of these contributions [4].

Here $\boldsymbol{k}$ is the deuteron momentum in the overall c.m. system, $\boldsymbol{q}$ denotes the K^+ momentum in the $K\bar{K}$ system, and $\hat{\boldsymbol{p}}$ is the unit vector of the beam momentum. Only $K\bar{K}$ p-waves contribute to C_0^q and C_2, only $K\bar{K}$ s-waves to C_0^k and C_1, and only s-p interference terms to C_3 and C_4. The coefficients C_i can be determined from the data by a simultaneous fit of Eq.(1) to the six measured differential distributions, (two invariant-mass spectra and four angular distributions) which are not corrected for the ANKE acceptance. ANKE events uniformly distributed over reaction phase space and traced through GEANT model has been used for the fit.

The coefficients C_i can be directly related to the different partial waves. They contain even more information than a Dalitz plot, particularly for the interference of $[(K\bar{K})_s d]_p$ and $[(K\bar{K})_p d]_s$ contributions. In Fig. 1c) the fit for the $K^+\bar{K}^0$ invariant-mass is shown, demonstrating the dominance of the "a_0-channel" (around 90% of $[(K\bar{K})_s d]_p$ configuration).

The coefficients C_i define the initial differential distributions. These allow one to calculate the total acceptance and the total and differential cross sections (see Fig. 2). Values of $\sigma(pp \to dK^+\bar{K}^0) = (38 \pm 2_{\rm stat} \pm 14_{\rm syst})$ and $(190 \pm 4_{\rm stat} \pm 39_{\rm syst})$ nb have been obtained for 47.4 and 104.7 MeV excess energy [2,4]. The energy dependency of the total cross section can be described by phase space with the mentioned partial wave restrictions.

3.2 $\phi(1020)$-production on proton and neutron

The reaction $pp \to pp\phi$ has been measured at three beam energies 2.65, 2.70 and 2.83 GeV which correspond to 18.5, 34.5 and 75.9 MeV excess energies above ϕ-production threshold. At the K^+K^- invariant-mass spectra the peaks around ϕ-meson mass are clearly visible for the all data sets (*e.g.* at $\epsilon = 18.5$ MeV, see Fig 1d).

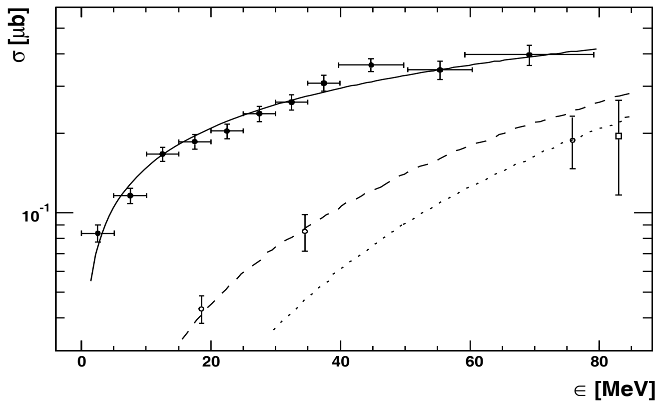

Fig. 3. Total cross section of the reactions $pn \to d\phi$ (filled circles [3]) and $pp \to pp\phi$ (open circles for ANKE [1] and open box for DISTO [21]) as a function of their excess energies. On-neutron ϕ-production can be described by 2-body ($\sim \sqrt{\epsilon}$) phase space (solid line). In pp case the pure 3-body $\sim \epsilon^2$ (dotted line) curve have been modified by a Jost-function, in order to include an effect of the protons FSI (dashed line).

In order to extract the ϕ-contribution a fit of the K^+K^- invariant-mass spectra has been performed for these three data samples. The distributions have been described by a Breit-Wigner function for ϕ and four-body phase-space for non-ϕ part.

Using the number of ϕ-mesons from the fit, the integral luminosity for the measurements, and the efficiencies and acceptances of the ANKE detectors, the total ϕ-meson production cross section has been deduced for the three energies, taking into account the branching ratio in ϕ decay $\Gamma_{K^+K^-}/\Gamma_{tot} = 0.491$ [20]. The results plotted in Fig 3 show a very good agreement with the DISTO data point [21] at $\epsilon = 83$ MeV.

The cross section for the two low energy data points is higher than predicted by a pure phase space extrapolation normalized to the 75.9 MeV point , but this enhancement can be explained by the final state interaction between the two protons in the $^1S_0$-state. The same effect is also visible in the differential spectra [1].

The measurement of the reaction $pn \to dK^+K^-$ at $T_{beam} = 2.65$ MeV has been performed on deuterons as an effective neutron target. Such measurements have the advantage that the c.m. excess energy of the neutron in deuteron varies due to the fermi-motion. Thus, even in an experiment with fixed beam momentum the energy dependency of the total cross section for a quite large ϵ region can be measured.

In order to confirm the spectator hypothesis, a Monte Carlo simulation has been performed where the momentum of neutron in the target deuteron has been derived from the Bonn potential [22]. The energy dependence of the $pn \to d\phi$ cross section is assumed to follow phase space which is consistent with the results to be shown later. Af-

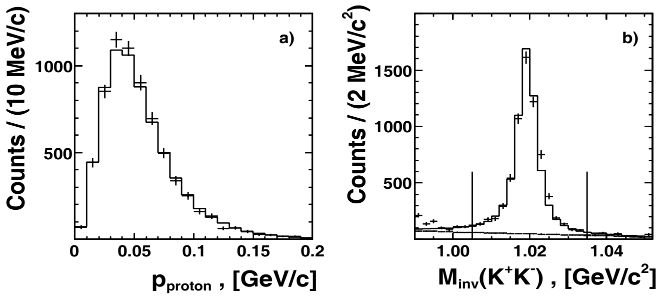

Fig. 4. a) momentum distribution for unobserved spectator protons compared with Monte-Carlo simulation based on the spectator model. b) K^+K^- invariant-mass distribution with lines showing the mass range of selected ϕ-mesons events [4].

ter including the detector response, the simulation fits the shape of the data for momenta very well (see Fig. 4a) at least up to 150 MeV/c.

In Fig. 4b the K^+K^- invariant mass spectrum for the 4500 events is shown. The distribution is dominated by the ϕ meson peak on top of a slowly varying background from direct K^+K^- production. This has been estimated by a three-body phase-space simulation (effected by deuteron wave-function) which, together with the ϕ contribution, is fitted to the overall spectra.

Data on $pp \to pp\omega$ [23,24] and $pn \to d\omega$ [25] production cross section have been used to determine $R_{\phi/\omega}$. One obtains $R_{\phi/\omega} = (3.3 \pm 0.6) \times 10^{-2} \approx 8 \times R_{OZI}$ in proton-proton and $R_{\phi/\omega} = (4.0 \pm 1.9) \times 10^{-2} \approx 9 \times R_{OZI}$ proton-neutron collision, indicating that the enhancement of the ratio is independent of isospin. It may be a signal for additional, and as yet non-understood, dynamical effects related to the role of strangeness in few-nucleon systems.

4 Current activities

We are currently working on a joint analysis of the reactions $pp \to ppK^+K^-$, $pn \to dK^+K^-$ and $pp \to dK^+\bar{K}^0$ in order to separate different isospin fractions and in particular search for contributions from $a_0/f_0(980)$ and K^-p FSI (observed in [16]). A measurement of the isoscalar $K\bar{K}$ production in the isospin selective reaction $dd \to {}^4HeK^+K^-$ has been performed in April 2006. In order to suppress the huge background from breakup protons the energy losses of the high momentum particles in the forward detector have been included into the online trigger. According to a first rough analysis we expect less than 100 $dd \to {}^4HeK^+K^-$ events in the data.

5 Summary

The total and differential cross section of the reaction $pp \to dK^+\bar{K}^0$ have been determined at excess energies of 47.4 and 104.7 MeV. A partial wave decomposition shows $K\bar{K}$ s-wave dominance ("a_0^+-channel").

The energy dependence ϕ production cross sections in the reaction $pp \to pp\phi$ and $pn \to d\phi$ in an energy range up to 80 MeV has been measured. Together with ω the data show almost one order of magnitude enhancement of $R_{\phi/\omega}$ in comparison with the OZI-rule prediction.

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References

1. M. Hartman *et al.*, Phys. Rev. Lett. **96**, (2006) 242301.
2. V. Kleber *et al.*, Phys. Rev. Lett. **91**, (2004) 172304-1.
3. Y. Maeda *et al.*, Phys. Rev. Lett. **97**, (2006) 142301.
4. A. Dzyuba *et al.*, Eur. Phys. J. A **29**, (2006) 245.
5. D. Morgan, Phys. Lett. B **51**, 71 (1974); K.L. Au, D. Morgan, and M.R. Pennington, Phys. Rev. D **35**, 1633 (1987); D. Morgan and M.R. Pennington, Phys. Lett. B **258**, 444 (1991); D. Morgan and M.R. Pennington, Phys. Rev. D **48**, 1185 (1993); A.V. Anisovich *et al.*, Eur. Phys. J. A **12**, 103 (2001); S. Narison, hep-ph/0012235.
6. J. Weinstein and N. Isgur, Phys. Rev. Lett. **48**, 659 (1982); Phys. Rev. D **27**, 588 (1983); Phys. Rev. D **41**, 2236 (1990); G. Janssen *et al.*, Phys. Rev. D **52**, 2690 (1995); J.A. Oller and E. Oset, Nucl. Phys. A **620**, 438 (1997) [Erratum-ibid. A **652**, 407 (1999)].
7. N.N. Achasov, hep-ph/0201299; R.J. Jaffe, Phys. Rev. D **15**, 267 (1977); J. Vijande *et al.*, Proc. Int. Workshop MESON 2002, May 24–28, 2002, Cracow, Poland, World Scientific Publishing, ISBN 981-238-160-0, p.501, hep-ph/0206263.
8. C. Hanhart, Phys. Rept. **397**, (2004) 155.
9. N.N. Achasov *et al.*, Phys. Lett. B **88**, (1979) 367.
10. S. Okubo, Phys. Lett. **5**, (1963) 165, G. Zweig, CERN report TH-401 (1964), J. Iizuka, Prog. Theor. Phys. Suppl. **38**, (1966) 21.
11. H.J. Lipkin, Phys. Lett. B **60**, (1976) 371.
12. V.P. Nomokonov and M.G. Sapozhnikov, Phys. Part Nucl. **34**, (2003) 94.; C.Amsler *et al.*, Rev. Mod. Phys. **70**, (1998) 1293.
13. R. Maier, Nucl. Instrum. Methods Phys. Res. A **390**, (1997) 1.
14. V.Yu. Grishina *et al.*, nucl-th/0608072;
15. C. Quentmeier *et al.*, Phys. Lett. B **515**, (2001) 276.
16. P. Winter *et al.*, Phys. Lett. B **635**, (2006) 23.
17. F. Bellemann *et al.*, nucl-ex/0608047;
18. S. Barsov *et al.*, Nucl. Instrum. Methods Phys. Res. A **462**, (2001) 364.
19. H. Dombrowski *et al.*, Nucl. Instrum. Methods Phys. Res. A **386**, (1997) 228.
20. S. Eidelmann *et al.*, Phys. Lett. B **592**, (2004) 1.
21. F. Balestra *et al.*, Phys. Rev. C **63**, (2001) 024004.
22. R. Machleidt *et al.*, Phys. Rep. **149**, (1987) 1.
23. F. Hibou *et al.*, Phys. Rev. Lett. **83**, (1999) 492.
24. S. Abd El-Samad *et al.*, Phys. Lett. B **522**, (2001) 16.
25. S. Barsov *et al.*, Eur. Phys. J. A **21**, (2004) 521.