

Strangeness Production in pp and pn Reactions at COSY

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The COoler SYnchrotron COSY-Jülich delivers phase-space cooled, polarized proton and deuteron beams with momenta up to $p=3.65$ GeV/c. Various experiments on hadron-induced strangeness production on proton, neutron and nuclear targets have been carried out. Here we report about recent results on associated strangeness production in $pp \rightarrow KYN$ ($Y=\Lambda, \Sigma$) reactions, on K^+ -production in pn collisions, and on $K\bar{K}$ -pair production in pp interactions. We also briefly discuss possible measurements to disentangle the parity of the recently discovered pentaquark state Θ^+ , the spin dependence of the YN interaction, as well as planned experiments which aim at the determination of the a_0 - f_0 mixing matrix element, a quantity which is believed to be sensitive to the nature of the light scalar mesons $a_0/f_0(980)$.

1. Experimental facilities at COSY

COSY-Jülich [1] provides electron or stochastically cooled, polarized proton and deuteron beams with momenta up to $p=3.65$ GeV/c, corresponding to beam energies of $T_p=2.83$ and $T_d=2.23$ GeV, respectively. Various experimental facilities at internal or external target positions can be used for the study of K -meson production in hadronic interactions.

In measurements with thin and windowless internal targets, secondary processes of the produced mesons can be neglected and, simultaneously, sufficiently high luminosities are obtained. For the pp and pn measurements at the ANKE and COSY-11 facilities a cluster-jet target [2] providing areal densities of up to $\sim 5 \times 10^{14}$ cm⁻² has been used (with H₂ or D₂ as target material). With proton beam intensities of a few 10^{10} luminosities of $\mathcal{L} \gtrsim 10^{31}$ cm⁻²s⁻¹ have been achieved.

The ANKE spectrometer [3] comprises three dipole magnets D1–D3 which separate forward-emitted charged reaction products from the circulating COSY beam and allow one to determine their emission angles and momenta. With a gap height of ~ 20 cm, the spectrometer dipole D2 provides a large angular acceptance of up to $\pm 7^\circ$ vertically and $\pm 12^\circ$ horizontally, which is particularly advantageous for correlation measurements with threshold kinematics. The layout of ANKE, including detectors and the DAQ system, has been optimized and used to study K^+ -spectra from pA collisions at beam energies down to $T_p=1.0$ GeV ($p=1.70$ GeV/c) [4–6], thus far below the free nucleon-nucleon threshold at $T_{NN}=1.58$ GeV. This is a very challenging task because of the small K^+ -production cross sections, *e.g.* 39 nb for pC collisions at 1.0 GeV. In subsequent experiments ANKE has been used to measure K^+ -mesons in coincidence with protons and deuterons from $pn \rightarrow pK^+ X$ (Sect. 4), $pp \rightarrow dK^+ \bar{K}^0$ (Sect. 5.1), and $p^{12}\text{C} \rightarrow p/d K^+ X$ [7] reactions.

The COSY-11 experiment [8] has been designed to study meson production processes very close to the corresponding production thresholds. Positively charged ejectiles leaving the interaction region at forward angles are separated from the circulating COSY beam and are momentum analyzed in one of the C-shaped ring dipole magnets downstream of the target region. The 4-momenta of protons and K^+ -mesons are measured, leaving the non-identified hyperon ($pp \rightarrow pK^+Y$ reactions [9–12]) or the K^- -meson ($pp \rightarrow ppK^+K^-$ [13]) to be identified by a missing mass analysis. In case of the ppK^+K^- final state (see Sect. 5.1) an additional silicon pad detector, mounted inside of the dipole magnet, has been utilized to measure the hit position of the K^- candidates and to further reduce the background from other reaction channels.

At the external target positions of COSY a liquid hydrogen (LH_2) or deuterium (LD_2) target is being used with a size of typically a few mm^3 . The diameter of the electron cooled and stochastically extracted beam can be less than 2 mm with a very small beam halo, while the momentum spread $\Delta p/p$ is less than 10^{-4} . The small interaction region permits to install vertex counters very close to the interaction point for precise track reconstruction of charged ejectiles.

The external experiment COSY-TOF [14] is a wide angle, non magnetic spectrometer with various start and stop detector components for time-of-flight measurements, combining high efficiency and acceptance with a moderate energy and momentum resolution. The system allows one to completely reconstruct the 4-vectors of all final particles from $pp \rightarrow KYN$ events including the determination of the delayed decay vertices of Λ - and Σ -hyperons as well of the K_S^0 . Associated strangeness production has been measured in the reactions $pp \rightarrow pK^+\Lambda$, $pK^+\Sigma^0$, $pK^0\Sigma^+$, and $nK^+\Sigma^+$ at beam momenta between 2.5 and 3.3 GeV/c (Sect. 2). First tests on the corresponding reactions in pn interactions have been performed with the LD_2 target.

The MOMO experiment [15] focuses on near threshold meson-pair production via the reactions $pd \rightarrow {}^3\text{He} \pi^+\pi^-/K^+K^-$ (Sect. 5.1). The setup comprises a scintillating-fiber meson detector near the external LD_2 target with a opening angle $\pm 45^\circ$, and the high resolution magnetic spectrometer BIG KARL which is used for ${}^3\text{He}$ identification.

For future double polarization experiments a frozen spin NH_3 target (TOF) [16] and a polarized internal H_2/D_2 gas target utilizing a storage cell (ANKE) [17] are presently being developed.

2. Associated strangeness production at COSY-11 and COSY-TOF

Investigation of associated strangeness production close to threshold may provide insight into the dynamics of the production processes, *e.g.* the role of N^* -resonances or the effect of hyperon-nucleon final-state interaction (FSI). Total $pp \rightarrow pKY$ cross sections from COSY-11 [12] and COSY-TOF [18] at excitation energies $Q < 150$ MeV have been described within various approaches, *e.g.* the K - π exchange models of Laget [19] and Sibirtsev [20] as well as resonance-model calculations of Dillig [21], Tsushima [22] and Shyam [23]. In order to discriminate between these models precise data, covering full phase space, are needed for different isospin channels. Spin observables should also be measured, in particular the polarization of the hyperon, which can be extracted via its self-analyzing weak decay.

2.1. Production mechanisms in pp collisions

Dalitz plot analyses of data from COSY-TOF are a powerful tool to investigate strangeness-production mechanisms. This is demonstrated in Fig. 1 where the data [24] are compared with calculations performed with a model of Sibirtsev [20], in which contributions from non-resonant meson exchanges are included coherently with those from the $N^*(1650)$, 1710 , 1720 -resonances and the $p\Lambda$ -FSI. The strength of each effect can be adjusted separately to find the best agreement between data and model.

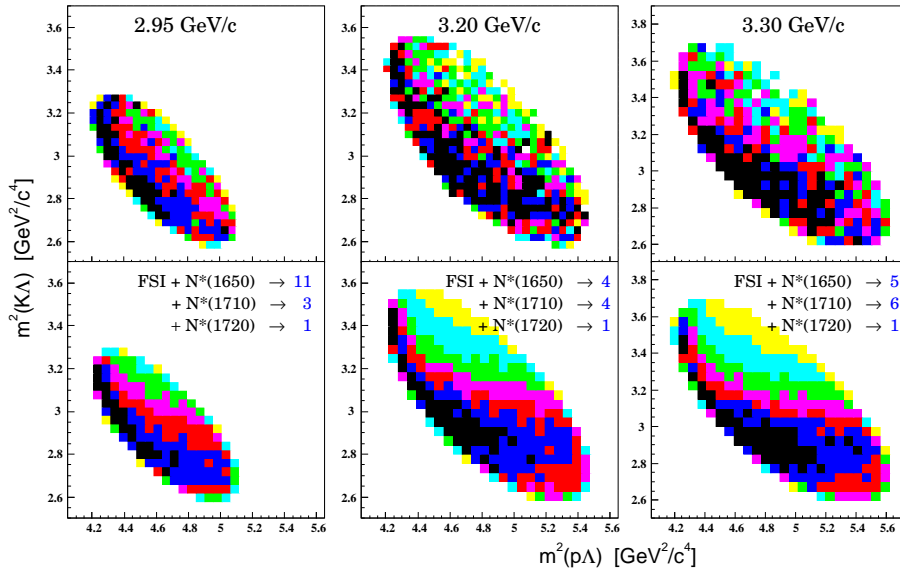


Figure 1. Dalitz plots measured at COSY-TOF for the reaction $pp \rightarrow pK^+\Lambda$ (upper) at beam momenta of 2.95 GeV/c, 3.20 GeV/c and 3.30 GeV/c [24]. The lower plots depict the results of calculations with the model of Sibirtsev [20] where the strengths of the amplitudes of the various resonances have been adjusted to the data as indicated.

Whereas at 2.85 GeV/c only the $N^*(1650)$ is relevant (not shown here), a significant contribution from the $N^*(1710)$ is needed at 2.95 GeV/c. At 3.20 GeV/c the amplitudes of both resonances are equal within the precision of the analysis, and at 3.30 GeV/c the $N^*(1710)$ becomes dominant. Since the excitation of N^* -resonances can only follow an exchange of a non-strange meson, it can be concluded that there is no dominant kaon exchange contributing to the reaction. Note that even at 3.30 GeV/c the $p\Lambda$ -FSI has a significant influence on particular regions of the measured Dalitz plots.

As a next step hyperon production in pn -reactions will be studied at COSY-TOF. First test measurements showed that events of the type $pn(p) \rightarrow K^0\Lambda p(p)$ can be identified (first results from ANKE on the reaction $pn \rightarrow K^+X$ are presented in Sect. 4). Moreover, the use of a polarized beam will allow one to extract polarization observables. In this context a special motivation comes from the DISTO experiment where in the reaction $\vec{p}p \rightarrow K^+\vec{\Lambda}p$ the polarization transfer coefficient D_{YY} has been measured to be strongly negative [25], pointing at a K -exchange dominance [19]. COSY-TOF allows one to study this quantity closer to threshold with full phase-space coverage.

2.2. ΛN final-state interaction

Although of very high interest, at present little is known about the strength of the hyperon-nucleon interaction (parameterized by the scattering length) at small energies not to speak of its spin dependence. The problem is due to the fact that it is practically impossible to perform low energy scattering experiments with unstable particles. Thus, in order to determine the scattering length of this reaction one has to rely on extrapolations from the data to threshold. A detailed analysis of the world data set for elastic Λp scattering gave $a_s = -1.8_{-4.2}^{+2.3}$ fm and $a_t = -1.6_{-0.8}^{+1.1}$ fm for the spin-singlet and spin-triplet scattering lengths, respectively, where the errors are strongly correlated [26].

An alternative are production experiments with a hyperon-nucleon pair in the final state. Then, the scattering parameters are to be determined from the impact of their FSI on the invariant mass spectra. In Ref. [27] a method has been proposed that allows one to extract the scattering lengths from the production data directly. In particular, an integral representation for the ΛN scattering lengths in terms of a differential cross section of reactions with large momentum transfer such as $pp \rightarrow K^+ p \Lambda$ or $\gamma d \rightarrow K^+ n \Lambda$ has been derived. This formula should enable the determination of the scattering lengths to a theoretical uncertainty of about 0.3 fm.

Up to date, all experiments for ΛN production in pp collisions were performed unpolarized and thus contain contributions from both spin triplet as well as spin singlet final states with an unknown ratio. However, polarization measurements will allow one to disentangle the different spin states, as is discussed in detail in Ref. [27]. The corresponding experiments can be performed at COSY.

3. A note on the Θ^+ pentaquark state

The recent discovery of the Θ^+ baryon with strangeness $S = +1$, mass $m_{\Theta^+} \sim 1.54$ GeV/ c^2 and width $\Gamma < 25$ MeV/ c^2 in various experiments (see *e.g.* Ref. [28] and references therein) has triggered an intensive investigation of exotic resonances (*i.e.* non $3q$ states). After the existence of Θ^+ seems to be confirmed experimentally its quantum numbers, like spin or parity, have to be determined.

At COSY the ANKE and COSY-TOF facilities can be used for measurements of Θ^+ -production in hadronic interactions. Since both cannot detect photons the relevant reaction channels are:

$$pp \rightarrow \Sigma^+ \Theta^+ \rightarrow \Sigma^+ [pK^0] \rightarrow \begin{pmatrix} p\pi^0 \\ n\pi^+ \end{pmatrix} [p(\pi^+\pi^-)] . \quad (1)$$

This implies K^0 identification by the $(\pi^+\pi^-)$ invariant mass and the Σ^+ by the $[p(\pi^+\pi^-)]$ missing mass and asking for an additional proton ($\Sigma^+ \rightarrow p\pi^0$) or an additional positive pion ($\Sigma^+ \rightarrow n\pi^+$). For the candidate events $\{\Sigma^+, K^0\}$ the invariant mass of the $[pK^0]$ subsystem has to be reconstructed.

At COSY-TOF an about 5σ signal in the $K^0 p$ invariant mass distribution has, in fact, been observed at a beam momentum of 2.95 GeV/ c . The very preliminary cross section estimate is of the order of a few hundred nb. The width of the peak is about 25 MeV/ c^2 , corresponding to the experimental resolution [29]. At ANKE a proposal [30] has been accepted to measure the reactions $pp \rightarrow K^0 p \Lambda \pi^+$, $pp \rightarrow K^0 p \Sigma^+$, and $pn \rightarrow K^0 p \Lambda$ at maximum COSY energy. These measurements will be carried out in spring 2004.

In recent papers, Thomas *et al.* [31] and Hanhart *et al.* [28] have emphasized that the parity of the Θ^+ can be determined from polarization observables of the reaction $\vec{p}\vec{p} \rightarrow \Sigma^+\Theta^+$ near the production threshold. In particular, the sign of the spin correlation coefficient A_{xx} yields the negative of the parity of the Θ^+ [28]. Such measurements can, in principle, be carried out at ANKE and COSY-TOF.

4. Investigation of K^+ -production on neutrons with ANKE

Data on the K^+ -production cross section from pn interactions in the close-to-threshold regime are not available yet. This quantity is, for example, crucial for the theoretical description of pA and AA data since it has to be used as an input parameter for corresponding model calculations. Predictions for the ratio σ_n/σ_p range from one to six, depending on the underlying model assumptions: Piroué and Smith [32] proposed that there is no difference between K^+ production on the neutron and proton, whereas the analysis by Tsushima *et al.* [33] yields $\sigma_n/\sigma_p \sim 2$ for the total production cross sections. Fäldt and Wilkin [34] draw an analogy between K^+ - and η -meson production and give a ratio of six for the ratio between production on the neutron and proton.

K^+ -production in pD interactions has been measured with ANKE $p=2.60$ and 2.83 GeV/c [6,35]. Figure 2 shows the K^+ -momentum spectrum for the higher beam momentum. Based on the assumption that the K^+ -production cross section is governed by the sum of the elementary pp and the pn cross sections, the spectra have been analyzed in a simple phase-space approach, assuming $\sigma_D = \sigma_p + \sigma_n$. In Fig. 2 the resulting momentum spectra are shown based on the approaches from Ref. [32] (dashed line labeled by “ $\sigma_n=\sigma_p$ ”) and Ref. [33] (dash-dotted line, “ $\sigma_n=2\sigma_p$ ”).

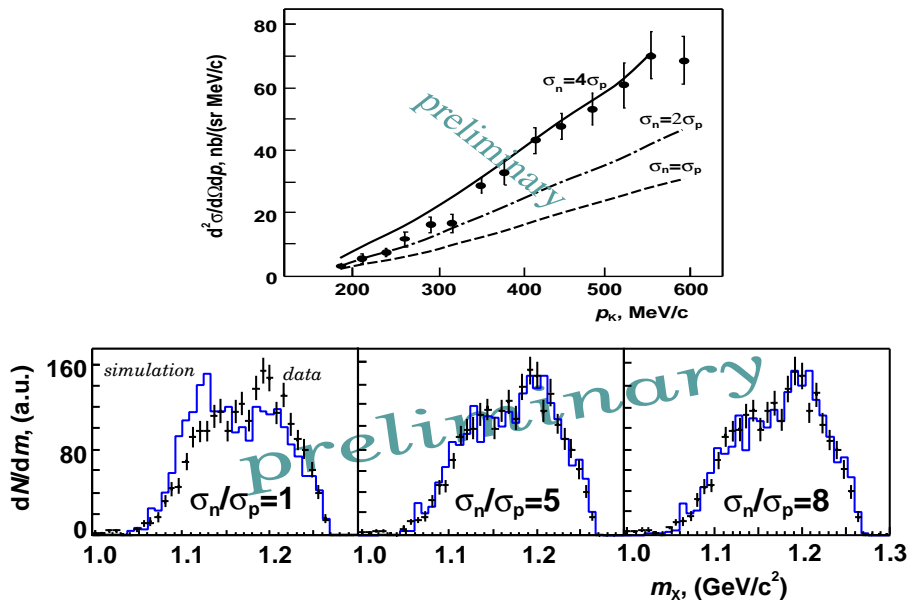


Figure 2. Upper: Double differential $pD \rightarrow K^+X$ cross section at 2.83 GeV/c in comparison with model calculations using different ratios σ_n/σ_p (lines) [6,35]. The overall systematic uncertainty from the luminosity normalization of 20% is not included in the error bars. Lower: Missing mass m_X for $pD \rightarrow K^+pX(p_s)$ events (with an undetected “spectator” proton p_s) at $p=2.83$ GeV/c in comparison with the phase-space calculations.

The apparent difference between the calculated and measured cross sections can be due to the fact that the ratio σ_n/σ_p differs from those given in Refs. [32,33]. Thus the simulations were also made keeping the relative weights of the individual pp and pn channels constant (as given by Ref. [33]) but treating the ratio of the sum of these two contributions, *i.e.* σ_n/σ_p , as a free parameter. The best agreement between data and calculations is obtained for $\sigma_n/\sigma_p \sim 3$ at 2.60 GeV/c and $\sigma_n/\sigma_p \sim 4$ at 2.83 GeV/c (solid line in upper part of Fig. 2).

The resulting large value of σ_n/σ_p from the inclusive spectra is supported by the analysis of missing-mass spectra from $pD \rightarrow K^+ pX(p_s)$ events collected during the same beam time. The spectrum for 2.83 GeV/c is also shown in Fig. 2 and is compared with the result of the Monte-Carlo simulations, again for different ratios σ_n/σ_p . The best agreement between data and simulations is obtained for $\sigma_n/\sigma_p \sim (4 - 5)$.

5. $K\bar{K}$ -pair production at ANKE, COSY-11 and MOMO

A primary goal of hadronic physics is to understand the structure of mesons and baryons, their production and decays, in terms of quarks and gluons. The non-perturbative character of the underlying theory — Quantum Chromo Dynamics (QCD) — hinders straight forward calculations. QCD can be treated explicitly in the low momentum-transfer regime using lattice techniques [36], which are, however, not yet in the position to make quantitative statements about light scalar states ($J^P=0^+$). Alternatively, QCD inspired models, which use effective degrees of freedom, are to be used. The constituent quark model is one of the most successful in this respect (see e.g. Ref. [37]). This approach treats the lightest scalar resonances $a_0/f_0(980)$ as conventional $q\bar{q}$ states. However, they have also been identified with $K\bar{K}$ molecules [38] or compact $qq\bar{q}\bar{q}$ states [39]. It has even been suggested that at masses below 1.0 GeV/c² a full nonet of 4-quark states might exist [40]. Such possible deviations from the minimal quark model have a parallel in the baryon sector, where the above mentioned Θ^+ state requires at least five quarks.

The existing data are insufficient to conclude on the structure of the light scalars and additional observables are urgently called for. In this context the charge-symmetry breaking (CSB) a_0 - f_0 mixing plays an exceptional role since it is sensitive to the overlap of the two wave functions. It should be stressed that, although predicted to be large long ago [41], this mixing has not been identified unambiguously in corresponding experiments.

5.1. First experimental results

An experimental program has been started at COSY which aims at exclusive data on a_0/f_0 production close to the $K\bar{K}$ threshold from pp [13,42], pn [43], pd [43,44] and dd [45,46] interactions — *i.e.* different isospin combinations in the initial state. The reactions $pp \rightarrow ppK^+K^-$ and $pd \rightarrow {}^3\text{He}K^+K^-$ have been measured at COSY-11 [13,47] and MOMO [44], respectively, at excitation energies up to $Q = 56$ MeV above the $K\bar{K}$ threshold. However, mainly due to the lack of precise angular distributions, the contribution of the a_0/f_0 to $K\bar{K}$ production remains unclear for these reactions.

At ANKE, the reaction $pp \rightarrow dK^+\bar{K}^0$ has been measured exclusively (by reconstructing the \bar{K}^0 from the measured dK^+ missing mass) at beam momenta of $p=3.46$ and 3.65 GeV/c ($Q=46$ and 103 MeV). These measurements crucially depend on the high luminosities achievable with internal targets, the large acceptance of ANKE for close-to-threshold

reactions, and the excellent kaon identification with the ANKE detectors. The obtained differential spectra for the lower beam momentum are shown in Fig. 3 [48].

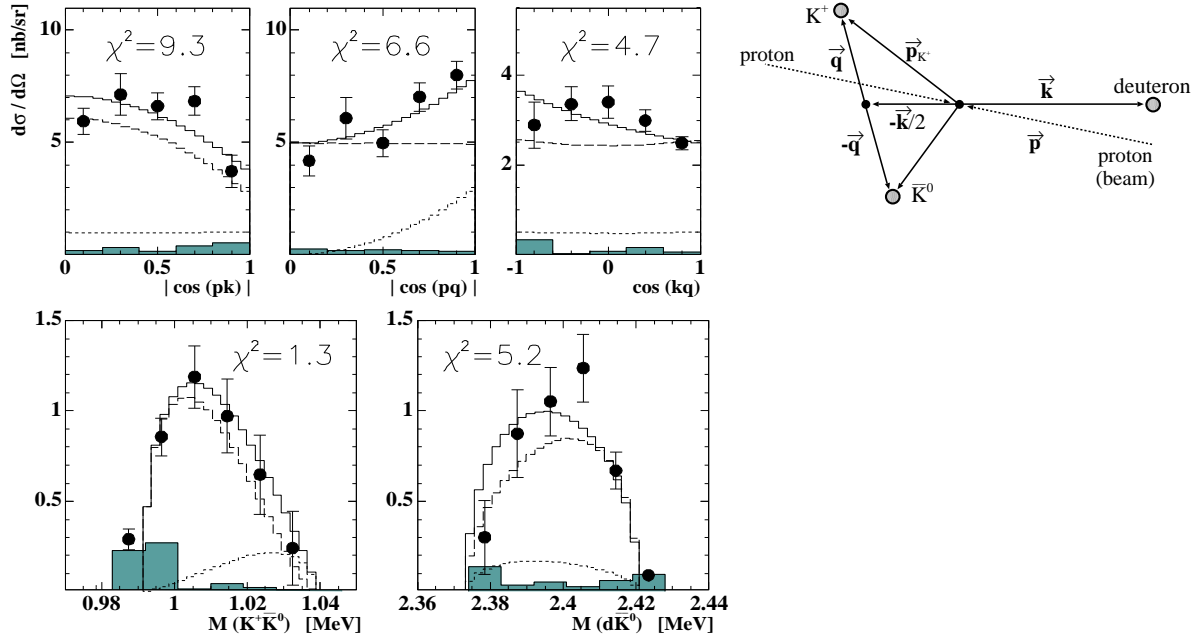


Figure 3. ANKE data for the reaction $p(3.46 \text{ GeV}/c)p \rightarrow dK^+\bar{K}^0$ [48]. The shaded areas correspond to the systematic uncertainties of the acceptance correction. The dashed (dotted) line corresponds to $K^+\bar{K}^0$ -production in a relative S -(P -) wave and the solid line is the sum of both contributions. For definition of the vectors p , q and k in the cms of the reaction $pp \rightarrow dK^+\bar{K}^0$ see right hand part of the figure. Angular distributions with respect to the beam direction \vec{p} have to be symmetric around 90° since the two protons in the entrance channel are indistinguishable.

The background of misidentified events in the spectra of Fig. 3 is less than 10% which is crucial for the partial-wave analysis. This analysis reveals that the $K^+\bar{K}^0$ pairs are mainly (83%) produced in a relative S -wave (dashed line in Fig. 3), which has been interpreted in terms of dominant a_0^+ -resonance production [48].

Data on the reaction $p(3.46 \text{ GeV}/c)p \rightarrow d\pi^+X$ have been obtained at ANKE in parallel to the kaon data. In contrast to the latter, where the spectra are almost background free, the $pp \rightarrow d\pi^+\eta$ signal is on top of a huge multi-pion background. This makes the analysis of this channel much more demanding and at present even model dependent [49]. A total cross section of $\sigma(pp \rightarrow d\pi^+\eta) \sim 4.6 \mu\text{b}$ has been extracted from the data with a resonant contribution of $\sigma(pp \rightarrow da_0^+ \rightarrow d\pi^+\eta) \sim 1.1 \mu\text{b}$ [49]. Together with the cross section for the $a_0^+ \rightarrow K^+\bar{K}^0$ channel this yields a branching ratio of $B.R.(KK/\pi\eta) \sim (0.029 \pm 0.005_{\text{stat}} \pm 0.02_{\text{syst}})$ which is in reasonable agreement with model calculations $B.R.(KK/\pi\eta) \sim 0.04$ [50]¹ for this beam momentum. This confirms the interpretation of dominant resonant $K^+\bar{K}^0$ production via the a_0^+ from above.

¹Note that the branching ratio at beam momenta close to the $K\bar{K}$ threshold strongly depends on the Q value of the reaction due to phase-space cuts at the upper edge of the mass distributions.

The data at $Q=103$ MeV are still being analyzed. As the next step a measurement of the reaction $pn \rightarrow dK^+K^-$ at $Q \sim 100$ MeV will be performed at ANKE in Feb. 2004. The results of a similar experiment on the reaction $pn \rightarrow K^+X$ — demonstrating the feasibility of such measurements with a D_2 target — are described in Sect. 4. According to our cross-section estimates a measurement of the reaction $dd \rightarrow \alpha K^+K^-$ should be feasible within few weeks of beam time and is foreseen for winter 2004/05 [45,46,51].

5.2. Planned investigations of light scalar mesons

The experimental results on a_0^+ production in pp interactions can also be regarded as a successful feasibility test for a long-term experimental program with the final goal to determine the charge-symmetry breaking a_0 - f_0 mixing amplitude. These measurements will require the use of a photon detector which is not yet available at COSY. However, it is planned to relocate the WASA detector [52] from its current location at CELSIUS/TSL to COSY in summer 2005, which will then make these experiments feasible.

Both, the a_0^0 - and the f_0 -resonances can decay into K^+K^- and $K_S K_S$, whereas in the non-strange sector the decays are into different final states according to their isospin, $a_0^\pm \rightarrow \pi^\pm \eta$, $a_0^0 \rightarrow \pi^0 \eta$ and $f_0 \rightarrow \pi^0 \pi^0$ or $\pi^+ \pi^-$. Thus, only the non-strange decay channels have defined isospin and allow one to discriminate between the two mesons. It is also only by measuring the non-strange decay channels that CSB can be investigated. Such measurements can be carried out with WASA at COSY for active π^0 - or η -meson identification, while the strange decay channels $a_0/f_0 \rightarrow K_S K_S$ should be measured in parallel.

Since it is possible to manipulate the initial isospin of purely hadronic reactions one can identify observables that vanish in the absence of CSB [53,54]. The idea behind the proposed experiments is the same as behind recent measurements of CSB effects in the reactions $np \rightarrow d\pi^0$ [55] and $dd \rightarrow \alpha\pi^0$ [56]. However, the interpretation of the signal from the scalar mesons is much simpler as compared to the pion case. Since the a_0 and the f_0 are rather narrow overlapping resonances, the a_0 - f_0 mixing in the final state is enhanced by more than an order of magnitude compared to CSB in the production operator (i.e. “direct” CSB violating $dd \rightarrow \alpha a_0$ production) and should, e.g., give the dominant contribution to the CSB effect via the reaction chain $dd \rightarrow \alpha f_0(I=0) \rightarrow \alpha a_0^0(I=1) \rightarrow \alpha(\pi^0 \eta)$ [57]. This reaction seems to be most promising for the extraction of CSB effects, since the initial deuterons and the α particle in the final state have isospin $I=0$ (“isospin filter”). Thus, any observation of $\pi^0 \eta$ production in this particular channel is a direct indication of CSB and can give information about the a_0 - f_0 mixing amplitude [57].

In analogy with the measurement of CSB effects in the reaction $np \rightarrow d\pi^0$, it has been predicted that the measurement of angular asymmetries (i.e. forward-backward asymmetry in the da_0 c.m.s.) can give information about the a_0 - f_0 mixing [58–60]. It was stressed in Ref. [59] that — in contrast to the $np \rightarrow d\pi^0$ experiment where the forward-backward asymmetry was found to be as small as 0.17% [55] — the reaction $pn \rightarrow d\pi^0 \eta$ is subject to a kinematical enhancement. As a consequence, the effect is predicted to be significantly larger in the a_0/f_0 case. The numbers range from some 10% [59] to factors of a few [58] and, thus, should easily be observable. It has been pointed out in Ref. [60] that the analyzing power of the reaction $\bar{p}n \rightarrow d\pi^0 \eta$ also carries information about the a_0 - f_0 mixing amplitude. This quantity can be measured at COSY as well.

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