First Results on $K^+$ Production in $pp$ and $pD$ Interactions from ANKE and Planned Experiments on the Light Scalar Resonances $a_0/f_0(980)$ at COSY∗

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ANKE is a magnetic spectrometer and detection system at an internal target position of COSY-Jülich optimized for charged kaon detection. Recent results from ANKE on kaon production in $pp$ and $pD$ interactions are reported. From the $pp$ data first absolutely normalized angular and invariant-mass spectra for the reaction $pp \rightarrow dK^+K^0$ have been obtained. A partial-wave decomposition reveals a strong contribution of $S$-wave $KK$-pairs with low relative energy, suggesting dominance of resonant kaon production via the $a_0^+(980)$. This indicates that systematic studies of the light scalar resonances $a_0/f_0(980)$ are possible at COSY. Final goal of these measurements — requiring a neutral-particle detector which is not yet available — is to obtain information about the charge-symmetry breaking $a_0$-$f_0$ mixing. From the analysis of the $pD$ data it is concluded that the $K^+$-production cross section on the neutron is significantly larger as compared to the proton. A cross-section ratio of $σ_n/σ_p \sim 4$ is deduced.

1. The ANKE spectrometer

The COoler SYnchrotron COSY-Jülich [1], which provides proton beams in the energy range $T_p = 0.04 – 2.83$ GeV, is well suited for the study of $K^+$-meson production in $pp$ and $pA$ reactions. 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 measurements described here, a cluster-jet target [2] with hydrogen or deuterium as target material has been used, providing

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areal densities of up to $\sim 5 \times 10^{14}$ cm$^{-2}$. With proton beam intensities of a few $10^{10}$ luminosities of $\mathcal{L} > 10^{31}$ cm$^{-2}$s$^{-1}$ have been achieved.

The ANKE spectrometer \[3, 4\] consists of three dipole magnets, which separate forward-emitted charged reaction products from the circulating proton beam and allow to determine their emission angles and momenta. $K^+$-mesons in the momentum range $p_K \sim 150–600$ MeV/c can be detected, the angular acceptance is $\pm 12^\circ$ horizontally and up to $\pm 7^\circ$ vertically.

Subthreshold $K^+$-production in $pA$ reactions has been the prime motivation for building ANKE and the detection system for $K^+$-mesons. This is a very demanding task because of the small $K^+$-production cross sections, e.g. 39 nb for $pC$ collisions at 1.0 GeV \[5\]. The results of these measurements have been published in Refs. \[6, 7, 8, 9, 10\]. In subsequent experiments ANKE has been used to study kaon production in more elementary (i.e. $pp$ and $pD$) reactions as well.

From the $pp$ data information about the production of the scalar resonance $a_0^+(980)$ close to the $KK$ threshold has been extracted, see Sect. \[2.2\] This experiment can also be regarded as a successful feasibility test for a longer experimental program which has the final goal to determine the charge-symmetry breaking $a_0-f_0$ mixing amplitude. These measurements are motivated in Sects. \[2.1\] and \[2.3\] and will require the use of a photon detector which is not available at COSY yet. In Sect. \[2.2\] first data from ANKE on $K^+$-production in $pD$ interactions are presented. These data show that deuterium can be used as an effective neutron target for meson-production studies like, e.g., for some of the planned measurements on $a_0/f_0$-production. The data also yield novel information about the $K^+$-production cross section in $pn$ interactions.

\section{Investigation of $a_0/f_0$-resonance production at COSY}

\subsection{Physics case}

One of the primary goals of hadronic physics is the understanding of the internal 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 straightforward calculations. QCD can be treated explicitly in the low momentum-transfer regime using lattice techniques \[11\], which are, however, not yet in the position to make quantitative statements about the light scalars. 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. \[12\]). 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 $KK$ molecules \[13\] or compact $qq-\bar{q}\bar{q}$ states \[14\]. It has even
been suggested that at masses below 1.0 GeV a complete nonet of 4-quark states might exist [15].

The existing data base is insufficient to conclude on the structure of the light scalar mesons 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 [16], this mixing has not unambiguously been identified yet in corresponding experiments.

2.2. Measurement of the strange decay channels with ANKE

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 \( pp [17, 18] \), \( pn, pd [19, 20] \) and \( dd [21, 22] \) interactions — i.e. different isospin combinations in the initial state. During the first experiment which has been made in this context at ANKE, the reaction \( pp\rightarrow dK^+K^0 \) has been measured exclusively at beam energies of \( T = 2.65 \) and 2.83 GeV, corresponding to excess energies \( Q = 46 \) and 106 MeV above the \( K\bar{K} \) threshold. 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 energy are shown in Fig. 1 [23].

The background of misidentified events in the spectra of Fig. 1 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. 1), which has been interpreted in terms of dominant \( a_0^+ \)-resonance production, corresponding to a total cross section of \( \sigma(pp\rightarrow dK^+K^0) = 83\% \cdot \sigma(pp\rightarrow dK^+\bar{K}^0) = 32 \text{ nb} \) [23]. Based on these data, which are in line with model predictions for different initial isospin configurations [24], it is concluded that the production cross section for the light scalar resonances in hadronic interactions is sufficiently large to permit systematic studies at COSY (during our first beam time \( \sim 1000 \) events have been collected within five days of beam time using a hydrogen target with an average luminosity of \( L = 2.7 \cdot 10^{31} \text{ cm}^{-2}\text{s}^{-1} \)).

The data from the second measurement at \( Q = 106 \text{ MeV} \) are still being analyzed. As the next step of the experimental program a measurement of the reaction \( pn \rightarrow dK^+K^- \) at \( Q \sim 100 \text{ MeV} \) will be performed in Feb. 2004 [20]. For these measurements deuterium will be used as target material serving as an effective neutron target. The results of a similar experiment on the reaction \( pn \rightarrow K^+X \) — demonstrating the feasibility of such experiments — are described in Sect. 3.2. According to our cross-section estimates a
Fig. 1. ANKE data for the reaction $p(2.65\text{ GeV})p \rightarrow dK^+\bar{K}^0$. 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 a definition of the angles $pk$, $pq$ and $kq$ see Fig. 2.

Fig. 2. Definition of the vectors $\vec{p}$, $\vec{k}$ and $\vec{q}$ in the cms of the reaction $pp\rightarrow dK^+\bar{K}^0$. Angular distributions with respect to the beam direction $\vec{p}$ have to be symmetric around $90^\circ$ since the two protons in the entrance channel are indistinguishable.
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 [21, 22].

2.3. Outline of future experiments using a photon detector

Both, the $a_0^0$- and the $f_0^0$-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, $a_0^+ \rightarrow \pi^+ \eta$, $a_0^0 \rightarrow \pi^0 \eta$ and $f_0 \rightarrow \pi^0 \pi^0$ or $\pi^+ \pi^-$. Thus, only the non-strange decay channels have defined isospin and allow to directly discriminate the two mesons. It is also only by measuring the non-strange decay channels that CSB can be investigated. As described in the following, these measurements require the use of a photon detector for active $\pi^0$- or $\eta$-meson identification. With such a detector the strange decay channels $a_0/f_0 \rightarrow K_S K_S$ should be measured in parallel and the results can be compared with those from ANKE for the charged kaons. Figure 3 shows the results from ANKE for the reaction $p(2.65 \text{GeV})p \rightarrow d\pi^+ X$. The measurements have been made in parallel to the ones for the decay channel $a_0^+ \rightarrow K^+ K^0$. In contrast to these data, where the spectra contain less than 10% of misidentified particles, the $pp \rightarrow d\pi^+ \eta$ signal is on top of a huge broad background stemming from multi-pion events (right spectrum in Fig. 3). This makes the analysis of this channel much more demanding and even model dependent [25]. 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 $\sigma(pp \rightarrow d a_0^0 \rightarrow d\pi^+ \eta) \sim 1.1 \mu\text{b}$.

Figure 3. ANKE data for the reaction $p(2.65 \text{GeV})p \rightarrow d\pi^+ X$ [24]. Left: missing mass $m(pp, d)$ which contains the Flatté distribution of the $a_0^+$ at a mass of $\sim 980$ MeV/c$^2$; right: the missing mass $m(pp, d\pi^+)$ reveals the $\eta$ signal on top of a huge multi-pion background.

The data from ANKE indicate that with better background suppression
(i.e. identification of the $\eta$ in the final state) the $a_0$-resonance can be studied at COSY in the non-strange decay channels as well. Thus, for the proposed measurements on the $a_0/f_0$ the detection of the photons from $\pi^0$ and $\eta$ decays is required. Due to the larger $Q$ values in the non-strange channels the angular acceptance of the corresponding photon detector should be as large as possible. Figure 4 shows the predicted invariant $\pi^0\eta$ mass spectrum for the reaction $pn \to d\pi^0_0\eta$ assuming an “ideal” experiment (i.e. perfect $\pi^0$ and $\eta$ identification and no background — comparable to the current conditions at ANKE for $K^+$-mesons, c.f. lower left spectrum in Fig. 1). The $a_0^0$-resonance is, in fact, visible on a broad background of non-resonant $\pi^0\eta$ events. Note that the calculated total cross sections for the resonant and non-resonant contributions from Ref. 26 are in accord with the above mentioned experimental values from ANKE.

![Fig. 4. Predicted invariant $\pi^0\eta$-mass spectrum](image)

Since it is possible to manipulate the initial isospin of purely hadronic reactions one can identify observables that vanish in the absence of CSB 27, 28. The idea behind the proposed experiments is the same as behind recent measurements of CSB effects in the reactions $np \to d\pi^0$ 29 and $dd \to \alpha\pi^0$ 30. However, the interpretation of the signal from the scalar mesons is largely simplified 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 $dd \to \alpha a_0$ production)
and should, e.g., give the dominant contribution to the CSB effect via the reaction chain \( dd \rightarrow \alpha f_0(I=0) \rightarrow \alpha a_0^0(I=1) \rightarrow \alpha(\pi^0\eta) \) \([31]\). This reaction seems to be most promising for the extraction of CSB effects, since the initial deuterons and the \( \alpha \) 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 \([31]\). According to our cross section estimates, it should be possible to collect sufficient statistics within a few weeks of beam time if a frozen-pellet target is used offering luminosities of more than \( 10^{32} \text{cm}^{-2}\text{s}^{-1} \) \([21,28]\).

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 \([26,32,33]\). It was stressed in Ref. \([32]\) 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% \([29]\) — 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\% \([32]\) to factors of a few \([26]\) and, thus, should easily be observable in an experiment with a large acceptance photon detector at COSY. It has been pointed out in Ref. \([33]\) that the analyzing power of the reaction \( \vec{p}n \rightarrow d\pi^0\eta \) also carries information about the \( a_0-f_0 \) mixing amplitude. This quantity can be measured at COSY as well, using the polarized proton beam and a azimuthally symmetric photon detector.

3. \( K^+ \)-meson production on neutrons

3.1. Physics case

Experimental 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, like transport codes. Predictions for the ratio \( \sigma_n/\sigma_p \) range from one to six, depending on the underlying model assumptions: in Ref. \([34]\) it has been proposed that there is no difference between \( K^+ \) production on the neutron and proton, whereas the analysis in Ref. \([35]\) yields \( \sigma_n/\sigma_p \sim 2 \) for the total production cross sections. The authors of Ref. \([36]\) draw an analogy between \( K^+ \)- and \( \eta \)-meson production and give a ratio of six for the ratio between production on the neutron and proton.
3.2. First results from ANKE

$K^+$-production in $pD$ interactions has been investigated with ANKE at two beam energies, $T_p = 1.83$ and 2.02 GeV. Figure 5 shows the $K^+$-momentum spectrum for the higher beam energy. 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 $\sigma_D = \sigma_p + \sigma_n$ with $\sigma_n/\sigma_p$ being a free parameter. The main results of this analysis are described below, however, for further details we refer to a forthcoming publication.

![Graph showing double differential $pD \rightarrow K^+X$ cross section at 2.02 GeV in comparison with our model calculations using different ratios $\sigma_n/\sigma_p$ (lines). The vertical and horizontal kaon emission angles have been restricted to $\vartheta < 4^\circ$ during the analysis. The overall systematic uncertainty from the luminosity normalization of 20% is not included in the error bars.]

In order to determine $\sigma_n/\sigma_p$, phase-space distributed $pp \rightarrow K^+X$ and $pn \rightarrow K^+X$ events have been generated with the PLUTO package \[37\] taking into account the intrinsic motion of the nucleons in the deuteron. The events have been generated for all reaction channels which may lead to $K^+$-production in $pN$ interactions at our beam energy and have been weighted according to the cross-section parameterizations from Ref. \[35\]. Each event subsequently has been tracked through the spectrometer and all detection efficiencies have been taken into account. In Fig. 5 we show the resulting momentum spectra based on the approaches from from Ref. \[34\] (dashed line labeled by “$\sigma_n=\sigma_p$”) and Ref. \[35\] (dash-dotted line labeled by “$\sigma_n=2\sigma_p$”).

The apparent difference between the calculated and measured cross sections can be due to the fact that the ratio $\sigma_n/\sigma_p$ is different than in Refs.
Thus we repeated the simulations keeping the relative weights of the individual $pp$ and $pn$ channels constant (as given by Ref. [35]) but treating the ratio of the sum of these two contributions, i.e. $\sigma_n/\sigma_p$, as a free parameter. The best agreement between data and calculations is obtained for $\sigma_n/\sigma_p \sim 3$ at 1.83 GeV and $\sigma_n/\sigma_p \sim 4$ at 2.02 GeV (solid line in Fig. 5).

The resulting large cross-section ratio $\sigma_n/\sigma_p$ from the inclusive spectra is supported by the analysis of missing-mass spectra from $pD \to K^+pX$ events recorded during the same beam time. The spectrum for $T = 2.02$ GeV is shown in Fig. 6 and is compared with the result of the Monte-Carlo simulations, again for different ratios $\sigma_n/\sigma_p$. In the simulations it has been taken into account that protons can either stem from the $K^+$ production processes (e.g. $pp \to pK^+\Lambda$ but not from $pn \to nK^+\Lambda$) or from the subsequent hyperon decay ($pp$ and $pn$). The best agreement between data and simulations is obtained for $\sigma_n/\sigma_p \sim (4 - 5)$.

![Fig. 6. Missing mass $m_X$ for $pD \to K^+pX$ events at $T = 2.02$ GeV in comparison with our model calculations using different ratios $\sigma_n/\sigma_p$ (lines).](preliminary.png)

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