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 $pp \to dK^+\bar{K}^0$ have been obtained. A partial-wave decomposition reveals a strong contribution of S-wave $K\bar{K}$-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 $\sigma_n/\sigma_p \sim 4$ is deduced.

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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

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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 areal densities of up to $\sim 5 \times 10^{14}$ cm^{-2}. With proton beam intensities of a few 10^{10} luminosities of $\mathcal{L} > 10^{31}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ 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. [6–10]. 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 $K\bar{K}$ threshold has been extracted, see Sec. 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 Sec. 2.1 and 2.3 and will require the use of a photon detector which is not available at COSY yet. In Sec. 3.2 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.

2. Investigation of a_0/f_0-resonance production at COSY

2.1. 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 straight forward 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 $K\bar{K}$ 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 $pp \to dK^+\bar{K}^0$ 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 $\sigma(pp \to da_0^+ \to dK^+\bar{K}^0) = 83\% \times \sigma(pp \to dK^+\bar{K}^0) = 32$ 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 ~ 1000 events have been collected within five days of beam time using a hydrogen target with an average luminosity of $L = 2.7 \times 10^{31}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$).

The data from the second measurement at $Q = 106$ MeV are still being analyzed. As the next step of the experimental program a measurement of the reaction $pn \to dK^+K^-$ at $Q \sim 100$ MeV will be performed

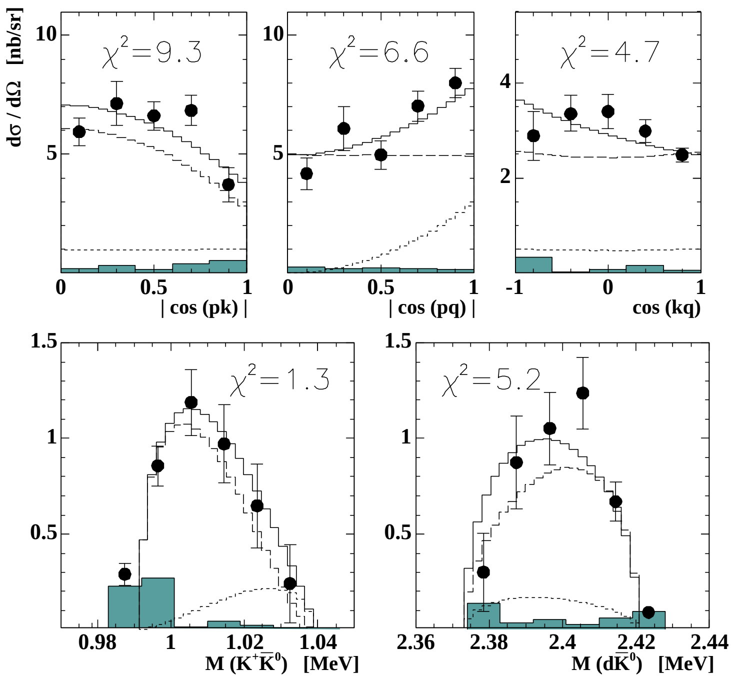

Fig. 1. ANKE data for the reaction $p(2.65\,\mathrm{GeV})p \to dK^+\bar{K}^0$ [23]. The shaded areas correspond to the systematic uncertainties of the acceptance correction. The dashed (dotted) line corresponds to $K^+\bar{K}^0$-production in a relative S- (P-) wave and the solid line is the sum of both contributions. For a definition of the angles pk, pq and kq see Fig. 2.

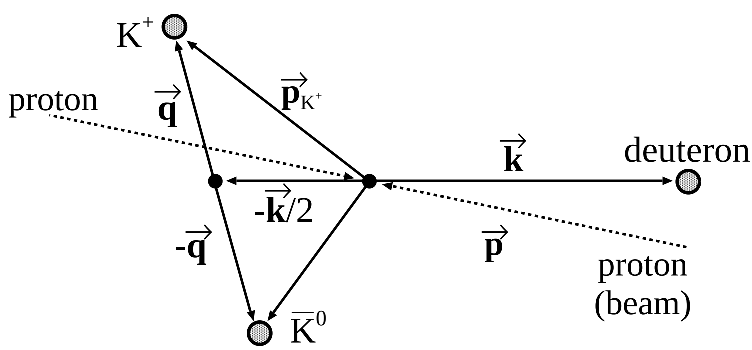

Fig. 2. Definition of the vectors $\vec{p}$, $\vec{k}$ and $\vec{q}$ in the cms of the reaction $pp \to dK^+\bar{K}^0$. Angular distributions with respect to the beam direction $\vec{p}$ have to be symmetric around 90° since the two protons in the entrance channel are indistinguishable.

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 $pn \to K^+X$ — demonstrating the feasibility of such experiments — are described in Sec. 3.2. According to our cross-section estimates a measurement of the reaction $dd \to \alpha K^+K^-$ 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-resonances can decay into K^+K^- and K_SK_S, whereas in the non-strange sector the decays are into different final states according to their isospin, $a_0^\pm \to \pi^\pm\eta$, $a_0^0 \to \pi^0\eta$ and $f_0 \to \pi^0\pi^0$ 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 π^0- or η-meson identification. With such a detector the strange decay channels $a_0/f_0 \to K_SK_S$ 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 $p(2.65\,\mathrm{GeV})p \to d\pi^+X$. The measurements have been made in parallel to the ones for the decay channel $a_0^+ \to K^+\bar{K}^0$. In contrast to these data, where the spectra contain less than 10% of misidentified particles, the $pp \to d\pi^+\eta$ 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 $\sigma(pp \to d\pi^+\eta) \sim 4.6\mu$b has been extracted from the data with a resonant contribution of $\sigma(pp \to da_0^+ \to d\pi^+\eta) \sim 1.1\mu$b.

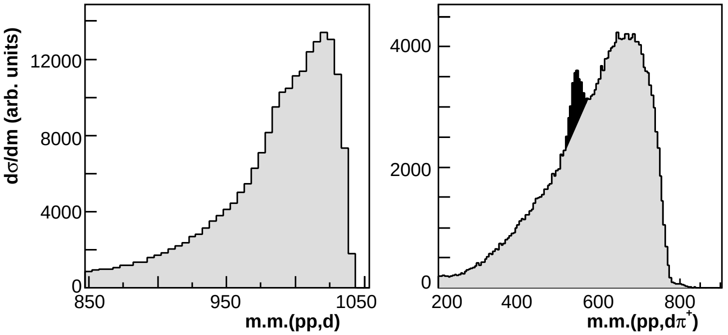

Fig. 3. ANKE data for the reaction $p(2.65\,\mathrm{GeV})p \to d\pi^+X$ [25]. Left: missing mass $m(pp,d)$ which contains the Flatté distribution of the a_0^+ at a mass of ~ 980 MeV$/c^2$; right: the missing mass $m(pp,d\pi^+)$ reveals the η signal on top of a huge multi-pion background.

The data from ANKE indicate that with better background suppression (*i.e.* identification of the η 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 π^0 and η 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 $pn \to da_0^0$ [26] assuming an "ideal" experiment (*i.e.* perfect π^0 and η identification and no background — comparable to the current conditions at ANKE for K^+-mesons, *cf.* 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.

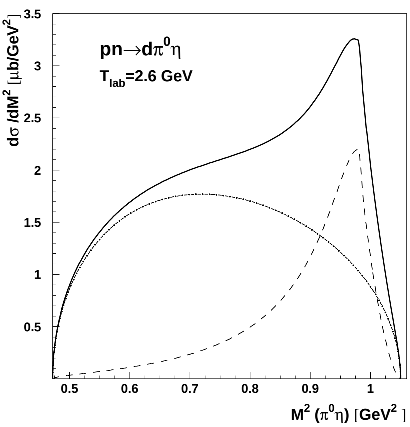

Fig. 4. Predicted invariant $\pi^0\eta$-mass spectrum [26] for the reaction $pn \to d\pi^0\eta$ taking into account resonant production via the a_0^0 (dashed line) as well as non-resonant production (dashed dotted). The shape of the a_0-resonance has been described by a Flatté distribution with: K-matrix pole at 999 MeV, $\Gamma_{a_0\to\pi\eta} =$ 70 MeV, $\Gamma_{KK}/\Gamma_{\pi\eta} = 0.23$.

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 $dd \to \alpha f_0(I=0) \to \alpha a_0^0(I=1) \to \alpha(\pi^0\eta)$ [31]. 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 [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 $10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ [21, 28].

In analogy with the measurement of CSB effects in the reaction $np \to d\pi^0$, 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 $np \to d\pi^0$ experiment where the forward–backward asymmetry was found to be as small as 0.17% [29] — the reaction $pn \to d\pi^0\eta$ 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 $\vec{p}n \to d\pi^0\eta$ 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 σ_n/σ_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 η-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 σ_n/σ_p being a free parameter. The main results of this analysis are described below, however, for further details we refer to a forthcoming publication.

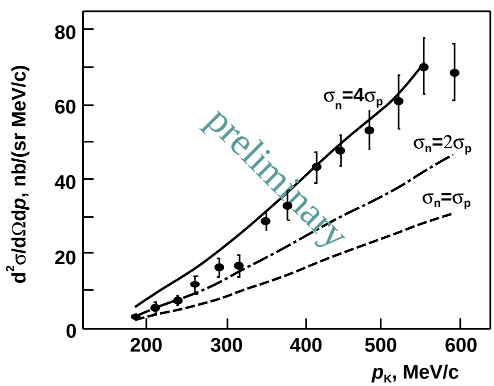

Fig. 5. Double differential $pD \to K^+X$ cross section at 2.02 GeV in comparison with our model calculations using different ratios σ_n/σ_p (lines). The vertical and horizontal kaon emission angles have been restricted to $\vartheta < 4°$ during the analysis. The overall systematic uncertainty from the luminosity normalization of 20% is not included in the error bars.

In order to determine σ_n/σ_p, phase-space distributed $pp \to K^+X$ and $pn \to K^+X$ 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 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 σ_n/σ_p is different than in Refs. [34,35]. 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.* 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 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 σ_n/σ_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 σ_n/σ_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 $\sigma_n/\sigma_p \sim (4–5)$.

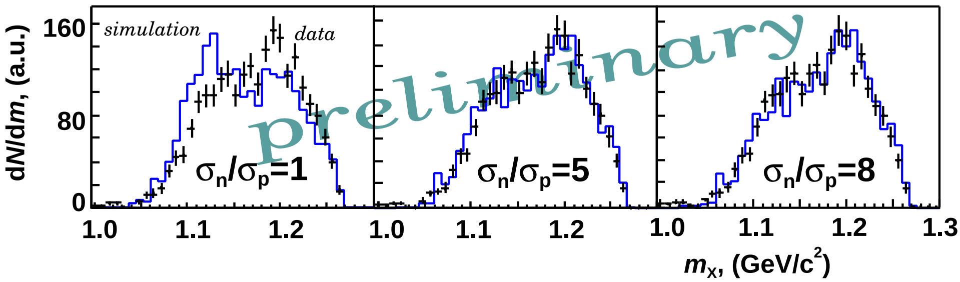

Fig. 6. Missing mass m_X for $pD \to K^+pX$ events at $T = 2.02$ GeV in comparison with our model calculations using different ratios σ_n/σ_p (lines).

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