STRANGENESS PRODUCTION IN HADRON-INDUCED REACTIONS

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After the experimental program "Subthreshold K^+ production in proton-nuclear interactions" has been successfully finished, a new 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 K and $\bar{K}$ mesons production in pp, pn and dd interactions. These are new studies of hyperon-production ($pN \to KYN$, where $Y = (\Lambda, \Sigma)$, in particular reaction $pp \to K^+n\Sigma^+$) as well as measurements of the production of kaon pairs in reactions: $pp \to ppK^+K^-$ above the ϕ-threshold, $pn \to dK^+K^-$ to study a_0, f_0, ϕ-production on the neutron, $pp \to dK^+\bar{K}^0$ for kaon-pair production in the "a_0^+-channel" and $dd \to {}^4\mathrm{He}K^+K^-$ which filters kaon pairs in the f_0-channel

ANKE, a magnetic spectrometer at an internal target position of COSY (Fig. 1), is equipped with detector systems which consist from scintillator counters and multiwire proportional chambers for registration positively and negatively charged particles. They can do spectroscopy of K^+, K^-, p, d, ^{3,4}He in the momentum range 200–2500 MeV/c with the momentum resolution (FWHM) about 1.5%, so that one can reconstruct the intermediate $K\bar{K}$-states by their invariant mass or find by the missing-mass technique not-detected particles such as neutral kaons and spectator protons. The missing-mass resolution (FWHM) is better than 10 MeV/c^2 and the resolution for kaon-pair invariant-mass spectrum is about 3 MeV/c^2.

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. However, a_0/f_0 can be also identified with $K\bar{K}$ molecules or compact $qq - \bar{q}\bar{q}$ states. The possible observation of the a_0/f_0-mixing (which can violate isospin conservation) is very interesting because this symmetry plays an important role in

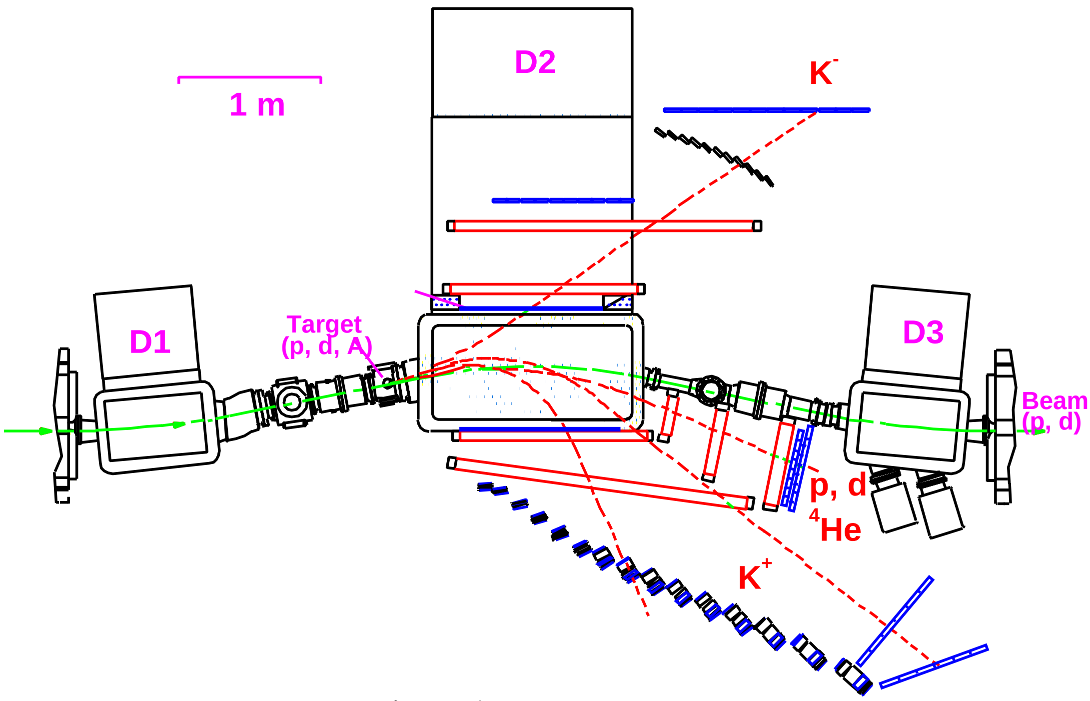

Fig. 1. ANKE spectrometer

QCD and such a measurement can provide a new observable which is sensitive to unknown structures of the light scalar mesons.

Two experiments on $a_0^+(980)$ production have been performed in pp collisions at $T_p = 2.65$ GeV [1] and $T_p = 2.83$ GeV [2] (corresponding to 47.4 and 104.7 MeV excess energy (Q) with respect to the $K^+\bar{K}^0$ threshold). The advantage of this reaction is that it contains no physical background (ϕ-meson). Contribution from background accidental 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 for $Q = 47.4$ MeV data and less than 10 MeV/c^2 for $Q = 104.7$ MeV. In the experiment both momentum and angular distributions of K^+ and d were measured.

Since the data have been obtained close to threshold, the model 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 s-wave deuteron (non-resonant channel). Under this assumption the square of the spin-averaged transition matrix element can be written as:

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

Here $\vec{k}$ is the deuteron momentum in the overall c.m. system, $\vec{q}$ denotes the K^+ momentum in the $K\bar{K}$ system, and $\hat{\vec{p}}$ 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 the GEANT simulation have 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. The fit for the $K^+\bar{K}^0$ invariant-mass spectrum demonstrates 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 $\sigma(pp \to dK^+\bar{K}^0) = (38 \pm 2_{\rm stat} \pm 14_{\rm syst})$ nb and $(190 \pm 4_{\rm stat} \pm 39_{\rm syst})$ nb have been obtained for 47.4 and 104.7 MeV excess energy. The energy dependence of the total cross section can be described by phase space with the above mentioned partial wave restrictions.

In principle, the contribution of the $a_0^+(980)$ resonance should be visible in the invariant mass distribution of the scalar $K\bar{K}$ channel. In Fig. 2a the $K\bar{K}$ invariant-mass distribution is shown for Q=104.7 MeV. A Flatte distribution is added to the $a_0^+(980)$-channel ($[(K\bar{K})_s d]_p$ partial wave configuration). The mass of the $a_0(980)$ meson has been taken as 984.7 MeV. From this figure one can see that in order to describe our experimental data a rather large width of $a_0(980)$ resonance is needed. Another possibility to explain experimental data is a mixture of a_0 with non-resonant production of kaon-pair in s-wave (α – fraction of resonance). One can conclude that either the $a_0^+(980)$ has a large width or it has a very week coupling to the scalar $K\bar{K}$ channel, at least for the investigated reaction.

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. 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 predict ratio of single ϕ to

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

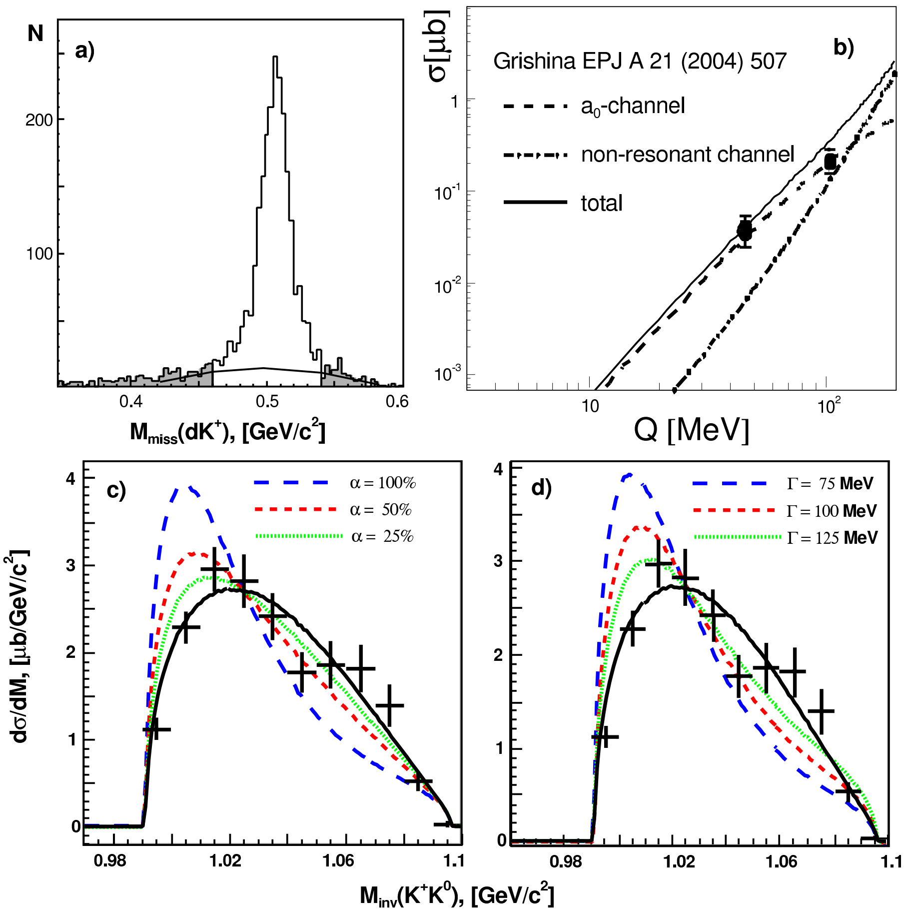

Fig. 2. a) Missing-mass $m(pp, dK^+)$ distribution of the $pp \to dK^+\bar{K}^0$ events for $T_{beam} = 2.83$ GeV. The line shows the background distribution (polynomial fit) and the shaded area indicates the events used for background subtraction. b) Total cross section for the reaction $pp \to dK^+\bar{K}^0$. Lines indicate theoretical predictions. c) $K^+\bar{K}^0$ invariant-mass spectrum and models with different fractions (α) of resonance contribution to kaons s-wave. d) Fit result plus Flatte distribution to the $[(K\bar{K})_s d]_p$ term with different widths of $a_0^+(980)$. Black solid line coresponds to our best fit result without a_0^+

ω production of $R_{\phi/\omega} = 4.2 \times 10^{-3} \equiv R_{OZI}$. However, experimentally measured $R_{\phi/\omega}$ is strongly enhanced in comparison with this prediction, for example in $p\bar{p}$ interactions where $R_{\phi/\omega}$ can be as large as $\sim 100 \times R_{OZI}$.

The reaction $pp \to pp\phi$ has been studied 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 (ϵ) [3]. At the K^+K^- invariant-mass spectra the peaks around ϕ-meson mass are clearly visible for the all data sets (see Fig. 3a-c). 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-meson decay $\Gamma_{K^+K^-}/\Gamma_{tot} = 0.491$. The results plotted in Fig. 3d show a good agreement with those obtained by the DISTO collaboration [Phys. Rev. C **63**, 024004 (2001)] data point at $\epsilon = 83$ MeV. The cross section for the two low energy data points is higher than predicted by a pure phase space extrapolation

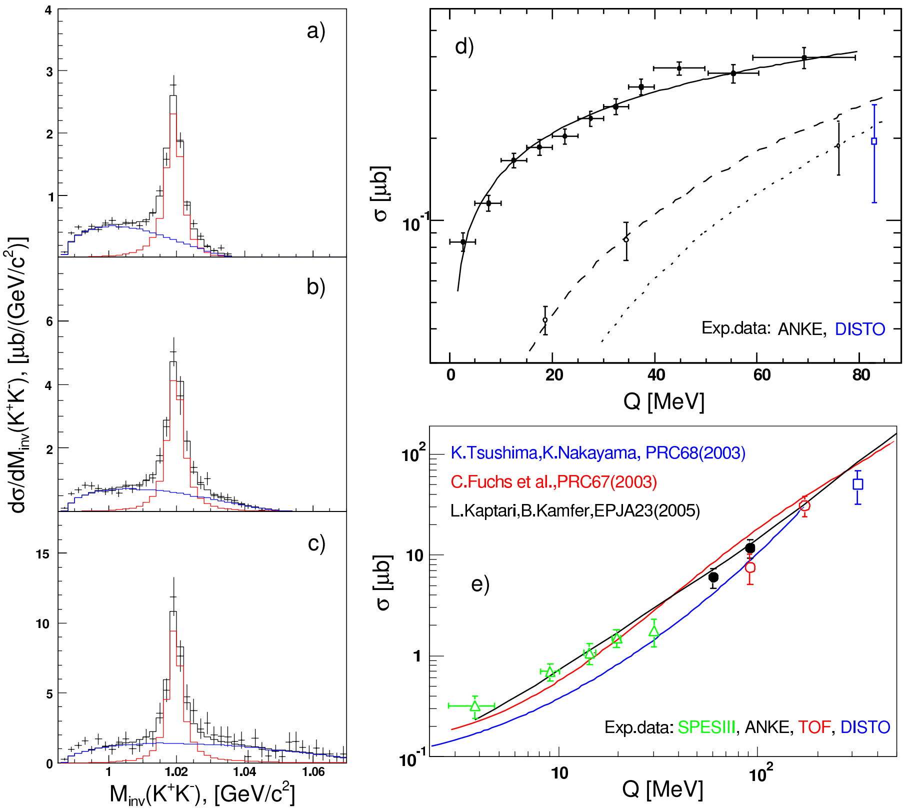

Fig. 3. a, b, c) Invariant-mass of K^+K^- pair for the reaction $pp \to ppK^+K^-$ at three beam energies 2.65 (a), 2.70 (b) and 2.83 GeV (c). Lines indicate ϕ and non-ϕ contributions. d) Total cross section of the reactions $pn \to d\phi$ (filled circles) and $pp \to pp\phi$ (open circles for ANKE and open box for DISTO) 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). e) Total cross section for the reaction $pp \to pp\omega$ and different theoretical predictions

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 [3].

The pilot measurement of cross sections of the reaction $pn \to dK^+K^-$ at $T_{beam} = 2.65$ MeV [4] has been performed on deuteron 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 dependence 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, in which the momentum of neutron in the target deuteron has been derived from the Bonn potential. The energy dependence of the $pn \to d\phi$ cross section is assumed to follow the phase space. This assumption is consistent with the results to be shown later – see Fig. 3d. After including the detector response, the simulation fits the shape of the data for momenta very well at least up to 150 MeV/c.

K^+K^- invariant-mass distribution is dominated by the ϕ-meson peak on the 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.

The world data on $pp \to pp\omega$ had a gap between 20 and 200 MeV excess energies. Our study of this reaction [5] has removed this uncertainty. The first measurement of the total cross section for the reaction $pn \to d\omega$ has been also performed at ANKE spectrometer [6]. These production cross sections have been used to determine $R_{\phi/\omega}$.

We have obtained $R_{\phi/\omega} = (33\pm6)\times10^{-3} \approx 8\times R_{OZI}$ in proton-proton and $R_{\phi/\omega} = (40\pm19)\times10^{-3} \approx 9 \times R_{OZI}$ in proton-neutron collisions 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.

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 to search for contributions from $a_0/f_0(980)$ and K^-p FSI.

A measurement of the isoscalar $K\bar{K}$ production in the isospin selective reaction $dd \to {}^4\text{He}K^+K^-$ 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 on-line trigger. According to a first rough analysis we expect less than 100 $dd \to {}^4\text{He}K^+K^-$ events in the data.

Another direction of PNPI group activity is the production of light hyperons in proton-proton collisions in the close-to-threshold region. Nowdays not much data about $pp \to K^+n\Sigma^+$ reaction are available, moreover existing information is very inconsistent.

A model independent estimate for $R(\Sigma^+/\Sigma^0)$ might be obtained from the isospin relation linking the different Σ-production channels, the amplitudes satisfy equation:

$$f(pp \to K^+n\Sigma^+) + f(pp \to K^0p\Sigma^+) + 2f(pp \to K^+p\Sigma^0) = 0. \qquad (2)$$

This leads to so-called triangle inequality between the total cross sections (Fig. 4). But recent experiments in the close-to-threshold region give surprisingly high total cross sections for this process and breaking this triangle inequality.

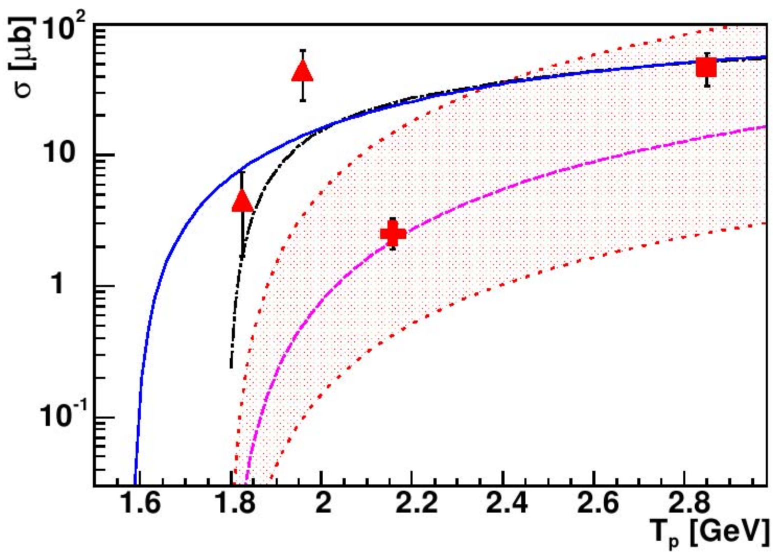

Fig. 4. Total cross section for the reaction $pp \to K^+n\Sigma^+$. Triangles shows data obtained by T. Rozek *et al.* [Phys. Lett. B **643**, 251 (2006)], cross – the value from Ref. [7], box – bubble-chamber data [Phys. Rev. **123**, 1465 (1961)]. Shaded area shows the region restricted by triangle inequality. Lines show the behaviors of total cross sections $pp \to pK^+\Lambda$ (solid), $pp \to pK^+\Sigma^0$ (dashed), $pp \to K^+n\Sigma^+$ (chain line)

Since one cannot *a priori* exclude an anomalous threshold behavior associated with $I = \frac{1}{2}$ K^+n-system, further experimental studies for this reaction are necessary in order to clarify the situation. We have obtained the total cross section at a proton beam energy of T_p =2.16 GeV which corresponds to 128 MeV excess energy [7].

Information about the Σ^+ production was determined from three simultaneously measured observables, *viz* the K^+ inclusive double differential cross section, and the K^+p and $K^+\pi^+$ correlation spectra. The most important is the last one because there is only one more physical source of K^+ and π^+ coincidence – reaction $pp \to K^+n\Lambda\pi^+$ which has much smaller total cross section. The accidental background contribution is also small.

The measured missing-mass spectrum of detected K^+p pairs as well as the inclusive K^+ double differential cross section also allow to fix strength (upper limit for total cross section) of $pp \to K^+n\Sigma^+$. For it they have been compared with multichannel model traced through the GEANT simulation program.

Obtained total cross section $\sigma(pp \to K^+n\Sigma^+) = (2.3{\pm}0.6_{\rm stat}{\pm}0.4_{\rm syst})$ μb is significantly smaller than that presented in [Phys. Lett. B **643**, 251 (2006)] at lower excess energy. The important point is that simultaneously measured total cross sections for $pp \to pK^+\Lambda$ and $pp \to pK^+\Sigma^0$ reactions are in good agreement with world data.

In order to confirm this result, a new experiment on Σ^+ production has been performed in September 2007. Data have been taken at four beam energies – 1.83, 1.92, 1.95 and 2.02 GeV. Data analysis is going on now.

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