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Kaon pair production in pp, pd, dd and pA collisions at COSY

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An overview of experiments at the Cooler Synchrotron COSY on kaon-pair production in pp, pd, dd collisions in the close-to-threshold regime is given. These include results on ϕ-meson production, where the meson is detected via its K^+K^- decay. The study of ϕ production on a range of heavier nuclear targets allows one to deduce a value of the ϕ width in nuclei and its variation with the ϕ momentum.

XLIX International Winter Meeting on Nuclear Physics, BORMIO2011
January 24-28, 2011
Bormio, Italy

1. Introduction

The cooler synchrotron COSY [1] at the Forschungszentrum Jülich in Germany can accelerate protons and deuterons up to about 3.7 GeV/c. Both polarized and unpolarized beams are available. Excellent beam quality is achieved with the help of electron and/or stochastic cooling. COSY can be used as an accelerator for external target experiments and as a storage ring for internal target experiments. Kaon pair production experiments have been performed at the internal spectrometer ANKE by the COSY-ANKE collaboration, at the internal COSY-11 spectrometer by the COSY-11 collaboration, and at the external BIG KARL spectrograph by the COSY-MOMO collaboration.

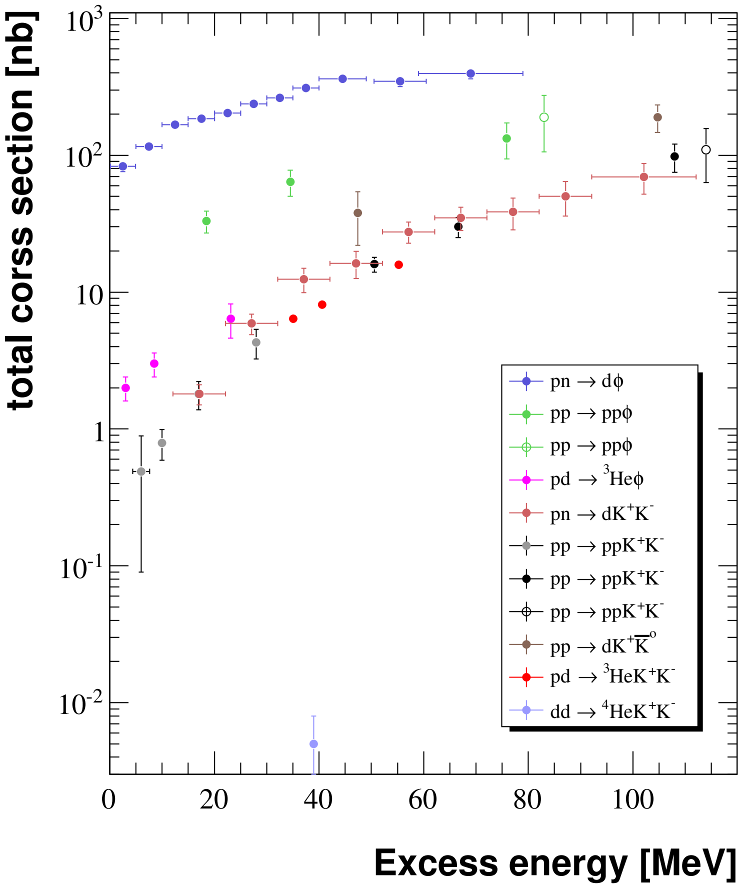

Figure 1: World data set on total cross sections for kaon-pair production in terms of the excess energy for each reaction. Closed symbols denote COSY results, which are $pp \to ppK^+K^-/\phi$ (black and green) [2, 3, 4, 5], $pp \to dK^+\bar{K}^0$ (brown) [6, 7], $pn \to dK^+K^-/\phi$ (light-red and blue) [8, 9], $pd \to {}^3\mathrm{He}\,K^+K^-/\phi$ (red and pink) [10], and $dd \to {}^4\mathrm{He}\,K^+K^-$ (light-blue) [11] reactions. In addition there are data on $pp \to ppK^+K^-$ and the corresponding $pp \to pp\phi$ reaction from SATURNE (open circles, black and green) [12].

2. Kaon-pair and ϕ meson production on hydrogen and deuterium targets

Extensive measurements of kaon-pair and ϕ-meson production have been carried out at several COSY facilities over the last decade. Values of total and differential cross sections are now available for a variety of reactions. The world data set of total cross sections for kaon pair production is shown in Fig. 1 as a function of the excess energy ε.

The $pp \to ppK^+K^-$ reaction (black and green symbols) has been studied by the COSY-11 [2, 3] and COSY-ANKE [4, 5] collaborations at excitation energies between 3 and 108 MeV. The closely related reaction $pp \to dK^+\bar{K}^0$ (brown), where the $K\bar{K}$ has isospin one, has also been investigated at COSY-ANKE [6, 7]. In addition, measurements of the $pn \to dK^+K^-$ reaction (blue and light-red) have been carried out at COSY-ANKE [8, 9] using a deuterium cluster-jet as an effective neutron target. The non-observed proton spectator was identified and its momentum and the excess energy ε reconstructed from the four-momenta of the detected deuteron and kaon pair.

The $pd \to {}^3\text{He}K^+K^-$ (red and pink) reaction has been measured by the COSY-MOMO collaboration [10]. Here the kaon pair may have isospin zero or one. However, the $dd \to {}^4\text{He}K^+K^-$ reaction studied by COSY-ANKE is an ideal isospin-zero filter which may be sensitive to the production of the scalar meson $f_0(980)$. In fact, the total cross section (light blue point) is only about 5 pb [11], which makes it of no practical use.

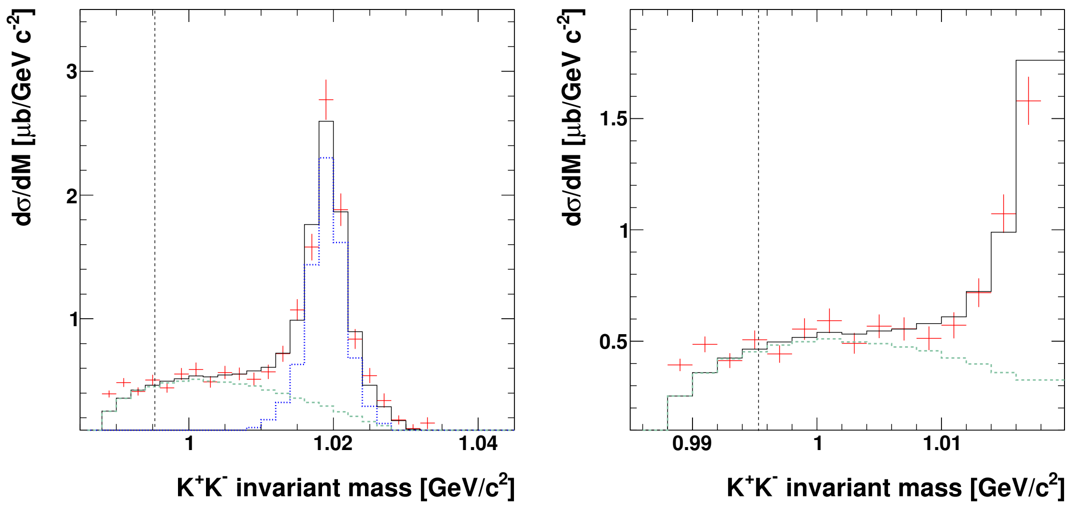

Figure 2: Differential cross section for the $pp \to ppK^+K^-$ reaction with respect to the K^+K^- invariant mass at 2.65 GeV. The blue-dotted histogram and the green-dashed curve represent the simulations for the ϕ and non-ϕ contributions to the spectrum, with their sum being shown by the black-solid histogram. The left panel shows the full spectrum while the right panel illustrates the behaviour near threshold. The simulations fail to reproduce the lowest mass points unless the $K\bar{K}$ FSI, including the $K^+K^- \rightleftharpoons K^0\bar{K}^0$ charge-exchange scattering, is taken into account [13]. The position of the $K^0\bar{K}^0$ threshold is indicated by the vertical dashed line.

The high energy $pp \to ppK^+K^-$ result (open circle) was obtained at SATURNE [12]. The invariant mass distribution of K^+K^- pairs in this reaction has been measured at COSY-ANKE [4] at three excess energies $\varepsilon = 51$, 67 and 108 MeV. The internal ANKE spectrometer detects simultaneously slow positive and negative particles in the side detectors and fast positive particles in the forward detector. The spectrum obtained at $\varepsilon = 51$ MeV ($T_p = 2.65$ GeV) is shown in Fig. 2. All three spectra show a strong peak associated with the production of the $\phi(1020)$ meson, which decays about 50% of the time into K^+K^-. The prompt K^+K^- spectrum is described by a four-body phase-space distribution, modified by the pp and K^-p final state interaction (FSI). However, the distributions at all three energies show a small low mass enhancement compared to the fitted curves. This enhancement has been discussed as a coupled channel effect; the threshold for the $K^0\bar{K}^0$ channel (dashed vertical line) is about 8 MeV above that for the K^+K^- system [13].

The important K^-p FSI has been investigated by comparing the invariant mass distributions of K^-p and K^+p [5, 14]. The ratio of K^-p to K^+p production changes by an order of magnitude within 50 MeV/c^2, as shown in Fig. 3 (left). The same holds true if one compares the ratios of K^-pp and K^+pp production, (right side). The K^-p FSI can be described by assuming an imaginary scattering length of 1.5 fm. New data with significant larger statistics have been collected at two excess energies of 25 MeV and 108 MeV at ANKE in order to study the K^-p FSI and the effects between the two kaons in greater detail. These data are currently under analysis.

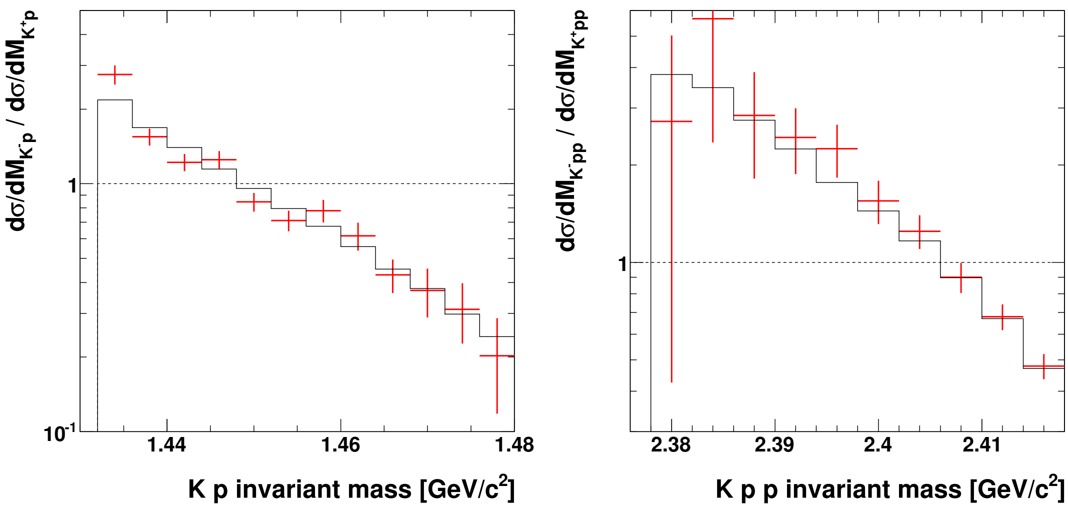

Figure 3: Ratio of the differential cross section for $pp \to ppK^+K^-$ in terms of the $K^\pm p$ (left) and $K^\pm pp$ (right) invariant masses. These 2.65 GeV data have been selected to come from the region $M(K^+K^-) < 1.01$ GeV/c^2, where there is only a very small ϕ contribution. The histograms include the effects of the pp and K^-p FSIs in a simplified treatment with an effective K^-p scattering length of $a_{K^-p} = (0+1.5i)$ fm [5]. Without the K^-p FSI the ratios are expected to be unity, as shown by the dashed lines.

The final state interactions also influence significantly the energy dependence of the $pp \to ppK^+K^-$ total cross section illustrated in Fig. 4. A strongly attractive threshold FSI enhances the cross section at low ε because the region of attraction then represents a larger fraction of the available phase space. It is here the combination of the K^-p, pp and, to a lesser extent, K^-K^+ FSIs that leads to an acceptable description.

In addition to measuring kaon pair production, the $\Lambda(1405)$ has been investigated at ANKE through the study of the $pp \to K^+p\Sigma^0\pi^0$ reaction [15]. Although the dominant decay of this

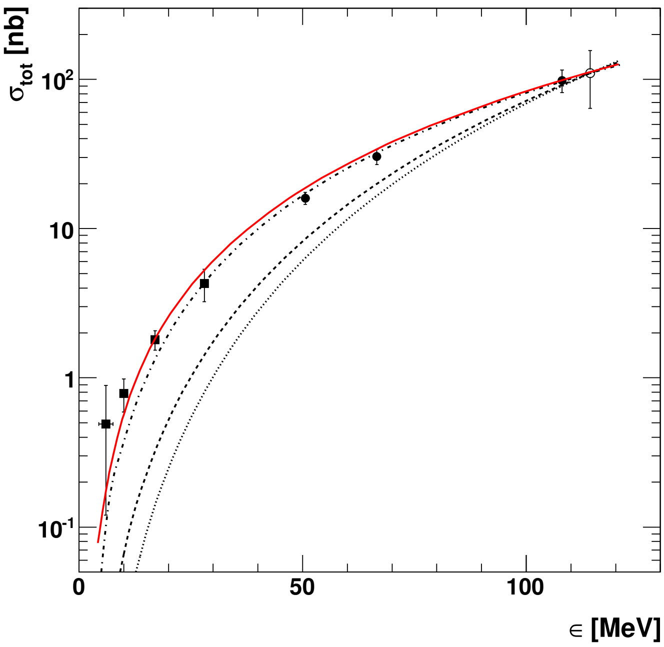

Figure 4: (color online) Measurements of the $pp \to ppK^+K^-$ total cross sections from COSY [2, 3, 4, 5] and SATURNE (open circle) [12] as a function of the excess energy ε. The doted curve represents the energy dependence expected from four-body phase space. The dashed curve includes the effects arising from the pp final state interaction whereas the dot-dashed curve contains in addition distortion from the K^-p FSI. The solid curve includes finally a contribution from the $K\bar{K}$ interaction, including the effects of charge-exchange scattering. All the curves are normalized on the SATURNE point.

hyperon is $\Lambda(1405) \to \Sigma\pi$, there is a significant branching ratio for $\Lambda(1405) \to K^-p$, even though the central mass value is below the K^-p threshold. Indeed, the opening of this threshold distorts significantly the $\Sigma^0\pi^0$ spectrum. The shapes of the two spectra and the relative strengths of the production cross sections suggest strongly that much of the prompt kaon pair production in pp collisions actually proceeds through the excitation and decay of the $\Lambda(1405)$ in the form $pp \to K^+p\{\Lambda(1405) \to K^-p\}$, rather than through the production of K^+K^- pairs associated with the scalar resonances [16].

Similar FSI effects are observed in the $pp \to dK^+\bar{K}^0$ reaction, where the $\bar{K}^0d$ pairs are found preferentially at small invariant masses. Due to angular momentum and parity considerations, an overall s-wave final state is forbidden and a partial wave decomposition reveals that it is the $\bar{K}^0d$ pair that is dominantly in an s-wave and is enhanced compared to K^+d, which is found more in a p-wave [13]. The same low-mass enhancement is also evident in the K^-d distribution produced in the $pn \to dK^+K^-$ reaction [9]. These effects have been interpreted as evidence for a strongly attractive $\bar{K}d$ FSI and all the main features of the data are well described with an effective $\bar{K}d$ scattering length of strength $|a_{\bar{K}d}| = 1.5$ fm [13].

Another important result on ϕ production in proton-proton collisions is the angular distribution of the $\phi \to K^+K^-$ decay at $\varepsilon = 18.5$ MeV, which is essentially a pure $\sin^2\theta$ distribution in the

Jackson frame. Thus, the ϕ meson is tensor polarized with $|m| \approx 1$ along the beam axis, as expected near threshold due to conservation laws [4]. The comparison of the total cross sections for ϕ and ω-production at the same excess energies [4, 5, 17] yields a ratio $R_{\phi\omega}$ that is about seven times larger than the prediction $R_{\mathrm{OZI}} = 4.2 \times 10^{-3}$ [18] based on the Okubo-Zweig-Iizuka (OZI) rule. A similarly enhanced value of $R_{\phi/\omega}$ was found in the ANKE studies of the quasi-free $pn \to d\phi$ and $pn \to d\omega$ production. However, the precision achieved for the ratio was limited by the large uncertainties in the ω measurement. A more precise study of the $pn \to d\omega$ reaction, including angular distributions, is expected soon from ANKE.

The production of prompt kaon pairs as well as ϕ mesons decaying into K^+K^- was also studied by the COSY-MOMO collaboration at the magnetic spectrograph BIG KARL using the $pd \to ^3\mathrm{He}\,K^+K^-$ reaction [10]. The invariant mass distributions of prompt pairs measured at three excess energies, 35, 40 and 55 MeV, can be described by pure phase-space distributions. Effects due to a possible K^{-3}He FSI are not visible, due the inability to distinguish between the two charged kaons in this experiment. In comparison to the $pp\phi$ reaction [4], the ϕ peak is less pronounced. The unexpected result of the $pd \to ^3\mathrm{He}\,\phi$ study is that the ϕ meson is strongly tensor polarized, with $m \approx 0$ along the beam axis [10]. In contrast, the ω meson is unpolarized in the corresponding $pd \to ^3\mathrm{He}\,\omega$ reaction [19]. Such a difference is a clear violation of the OZI rule. Furthermore, the ratio $R_{\phi/\omega}$ of the total cross sections for $pd \to ^3\mathrm{He}\,\phi$ and $pd \to ^3\mathrm{He}\,\omega$ at the same excess energy is about a factor twenty larger [10] than predicted by the OZI-rule [18].

3. ϕ-meson production and the in-medium ϕ-width in nuclear matter

The properties of light vector mesons are expected to change in dense nuclear matter [21, 22, 25, 23, 24, 26]. The cleanest place where to test these ideas is in the case of the $\phi(1020)$ meson, where the narrow vacuum line-shape ($\Gamma = 4.3$ MeV/c^2) allows one to investigate small modifications of the in–medium width. Rather than studying the width directly, at COSY-ANKE the variation of the ϕ production cross section in proton-nucleus collisions with atomic number A has been measured [27]. The production rate depends on the attenuation of the ϕ flux in a nuclear target which, in turn, is governed by the ϕ width. In the low-density approximation, this can be related to an effective ϕN total cross section. The big advantage of this method is that one can identify the ϕ meson through its large K^+K^- decay branch.

Protons of energy 2.83 GeV were incident on four nuclear targets, *viz.* C, Cu, Ag and Au. Positive kaons were first selected using a dedicated detection system that can identify a K^+ even if the π^+/p background is 10^5 more intense [28]. The coincident K^- was subsequently isolated using the time-of-flight difference between the stop counters in the ANKE negative and positive detector systems [29]. For all targets there was a clear ϕ peak sitting on a background of non-resonant K^+K^- production.

The relative luminosity for each target was obtained by measuring in parallel the production rate for positive pions [27]. Since the acceptance corrections in ANKE are essentially target-independent, the ratio of luminosity–normalised counts corresponds to the ratio of the cross sections for ϕ production in the ANKE acceptance window. The resulting so-called transparency ratios, relative to carbon, are presented in Fig. 5 in the form

$$R = 12\ \sigma_{pA\to\phi X'} \big/ A\ \sigma_{pC\to\phi X}\,.$$

The ratios shown correspond to ϕ production rates that follow the power law $\sigma(A) \propto A^{\alpha}$, with $\alpha = 0.56 \pm 0.03$.

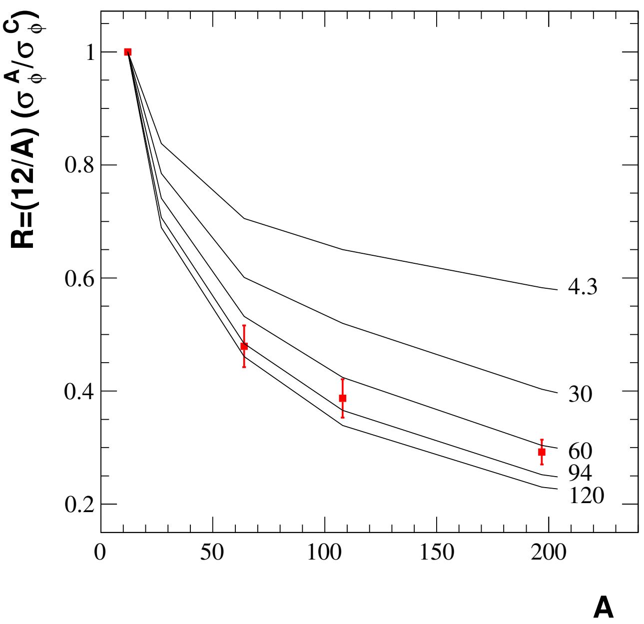

Figure 5: Comparison of the measured transparency ratio R as a function of atomic number A with predictions of model calculations for different ϕ widths in the meson rest system at normal nuclear density. Both statistical and systematics uncertainties are shown.

The interpretation of the obtained transparency ratios in terms of an in-medium ϕ width is model-dependent. The first results for the in-medium ϕ width extracted from the obtained ratios were presented and discussed in [30] (compare also [27]). As an example of the interpretations, the Paryev predictions [31] for the transparency ratios shown in Fig. 5 indicate a value of 73^{+14}_{-10} MeV/c^2 for the in-medium width of a ϕ meson in its rest frame at nuclear density $\rho_0 = 0.16$ fm^{-3}. This corresponds to ≈ 50 MeV/c^2 in the nuclear rest frame for a ϕ with a momentum of 1.1 GeV/c, which is typical for the ANKE conditions.

The transparency ratios measured in the photoproduction of the ϕ on various nuclei up to copper at the SPring-8 facility [32] have been interpreted in terms of a width of around 95 MeV/c^2 at a typical ϕ momentum of ≈ 1.8 GeV/c [33]. The difference with the published ANKE value might be an indication of a momentum dependence of the width. To test this possibility, the ANKE data have been binned in intervals of ϕ momenta and preliminary values of the transparency ratios evaluated in each. The corresponding widths as a function of p_ϕ, extracted using two reaction models, are shown in Fig. 6.

Although the width is model-dependent, the values obtained within the approaches of the two different groups both show a significant growth with p_ϕ and this might explain much of the difference between the ANKE and SPring-8 values. In fact, the ANKE results would display even

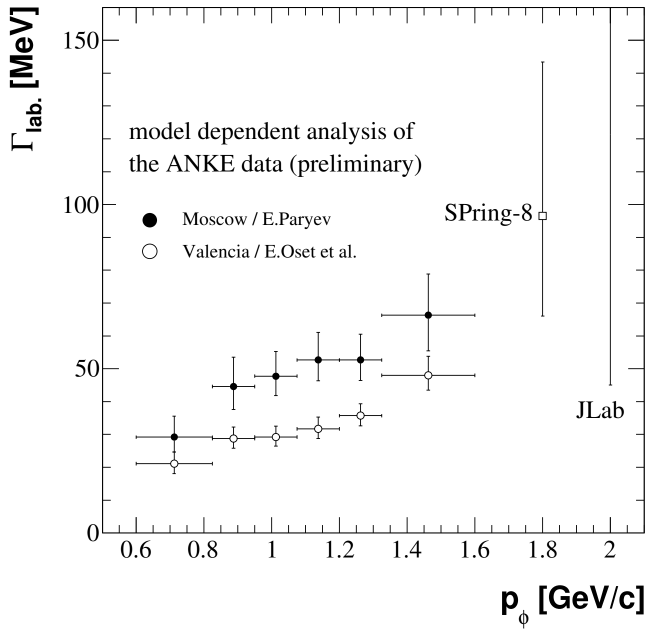

Figure 6: Preliminary values of the width Γ of the ϕ meson in nuclear matter at normal density $\rho_0 = 0.16\ \mathrm{fm}^{-3}$, as extracted from the ANKE transparency ratios, using two different reaction models. The strong p_ϕ momentum dependence observed might help to explain the apparent difference from the SPring-8 result at higher p_ϕ. For completeness, results from a JLab experiment are also shown [34].

a slightly steeper p_ϕ dependence if one considered nuclear targets only up to copper, as in the SPring-8 work.

As the next step in the ANKE analysis the momentum-dependent differential ϕ cross-sections will be extracted from the experimental data and compared with the values expected from the various calculations. This procedure will show whether the model calculations can describe simultaneously the momentum dependents of the measured cross sections and ratios. Only then could one draw more definite conclusions about the ϕ-width in nuclei and its momentum dependence.

4. Acknowledgments

The results presented here reflect the efforts of the COSY-ANKE, COSY-11, and COSY-MOMO collaborations and the COSY machine crew. Particular thanks are due to Colin Wilkin for help in the preparation of this contribution. The work was supported in part by the BMBF, DFG, COSY-FFE, RFBR and VI-QCD.

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