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Recent results on $pp \to pp\phi/K^+K^-$ production and the momentum dependence of ϕ-meson nuclear transparency

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Abstract. Kaon pair production by 2.83 GeV protons has been investigated in two experiments using the ANKE magnetic spectrometer at COSY-Jülich:
(1) Differential and total cross sections for the $pp \to ppK^+K^-$ reaction are separated into kaon pairs arising from the decay of the ϕ-meson and the remainder. The measurements show that higher partial waves represent the majority of the $pp \to pp\phi$ cross section at an excess energy of 76 MeV. Taken together with existing low energy ANKE data, the energy dependence of the results seem to suggest some S-wave ϕp enhancement near threshold. The non-ϕ K^+K^- data can be described in terms of the combined effects of two-body final state interactions, using the same effective scattering parameters already determined from lower energy ANKE data.
(2) The inclusive production of ϕ mesons on C, Cu, Ag, and Au targets has also been studied using the K^+K^- decay to detect the ϕ. The momentum dependence of the nuclear transparency ratio, the in-medium ϕ width, and the differential cross section for ϕ meson production at forward angles have been determined for these nuclei in the momentum range of 0.6 - 1.6 GeV/c. There are indications of a significant momentum dependence in the values extracted for the ϕ width, which on average exceed the free value by about an order of magnitude. The results are compared with data from other experiments at slightly higher momenta.

1 Introduction

The ANKE magnetic spectrometer [1,2] is placed at an internal target station of the COSY accelerator and storage ring of the Forschungszentrum Jülich. One of the outstanding capa-

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bilities of this facility is the system of telescopes that allows one to identify produced K^+ when the background from π^+ and protons is a factor of 10^5 or more higher than the kaon signal. By exploiting this advantage, it was possible to measure the cross sections for K^+K^- pair production in both proton-proton [3] and proton-nucleus collisions [4]. The good K^+K^- invariant mass resolution allowed the identification of the ϕ meson through its K^+K^- decay branch to be carried out reliably. How these measurements were carried out and analyzed are described in detail in these two papers. The results are also given there and so only the principal points are discussed here.

When a light vector meson is produced in a nuclear medium, its properties might change. The main modification in the ϕ case is expected to be a broadening of its spectral function with only a small shift in the mass. This broadening can be studied by examining the variation of the ϕ production cross section (or nuclear transparency ratio) with atomic number A. This was the approach adopted at ANKE, where the large K^+K^- branching ratio ($\approx 50\%$) was exploited. Only the main results of this work [4] are briefly sketched in section 3.

The modelling of proton-induced production in a nucleus will depend upon ϕ production in more elementary reactions such as $pp \to pp\phi$. We had previously studied this reaction close to threshold [5] where the S-waves dominate but, in order to identify the contributions from higher partial waves and study the energy dependence, we have also undertaken an experiment at an excess energy of 76 MeV [3] and some of the results are outlined in section 2.

Although there is a clear ϕ peak in the K^+K^- invariant mass produced in the $pp \to ppK^+K^-$ reaction [3], in order to subtract the non-ϕ background reliably one has to study this in some detail. The major effects seen here are the strong K^-p attraction, which might be linked to the $\Lambda(1405)$, and a much smaller K^+K^- final state interaction. Some of these phenomena are illustrated in section 2.

2 The production of K^+K^- pairs in proton-proton collisions at 2.83 GeV

The $pp \to ppK^+K^-$ reaction had already been studied at ANKE at excess energies with respect to the ϕ threshold of $\varepsilon_\phi = 18.5$, 34.5, 76 MeV [6]. Although the ϕ meson was well identified in these data, the limited statistics at the higher energies did not permit the investigation of the effects of higher partial waves. Much higher statistics data are now available at $\varepsilon_\phi = 76$ MeV [3] and the interested reader will find the full details in this reference. The results can also be compared to the DISTO data at $\varepsilon_\phi = 83$ MeV [8].

To deduce the $pp \to ppK^+K^-$ cross section, shown in Fig. 1 in terms of the K^+K^- invariant mass, parametrizations of both ϕ and non-ϕ contributions have to be fitted to various differential spectra in order to make acceptance corrections. For the ϕ this was done on the basis of a truncated partial wave decomposition [3], whereas for the non-ϕ our earlier ansatz of a product of final state interactions (FSI) in the K^-p, pp, and K^+K^- systems was employed [6, 7]. Using the same parameters that fitted the $\varepsilon_\phi = 18.5$ MeV data, the strong distortions in the non-ϕ spectra are well reproduced as seen, for example, in Fig. 2 for the ratio of the Kpp mass distributions.

Having reliable parametrizations of the background under the ϕ peak in Fig. 1, the differential distributions for the $pp \to pp\phi$ reaction could be safely extracted. As already noted by DISTO [8], the non-isotropy in the different angular distributions shown in Fig. 3 is a signal for the presence of higher partial waves. For example, the departure from a $\sin^2\theta$ dependence (dashed line) in the ϕ decay angle requires p-wave ϕ production, whereas the deviations from isotropy in the angle between the proton in the pp rest frame and the ϕ direction (the helicity angle) indicate the importance of P-waves in both the pp and $\phi\{pp\}$ systems. Higher partial waves are also necessary to explain the momentum distributions of the proton in the pp rest frame and the ϕ in the overall c.m. system.

The truncated partial-wave description of the $pp \to pp\phi$ spectra shows that the contribution from purely S-wave final states represents only a small fraction of the total cross section

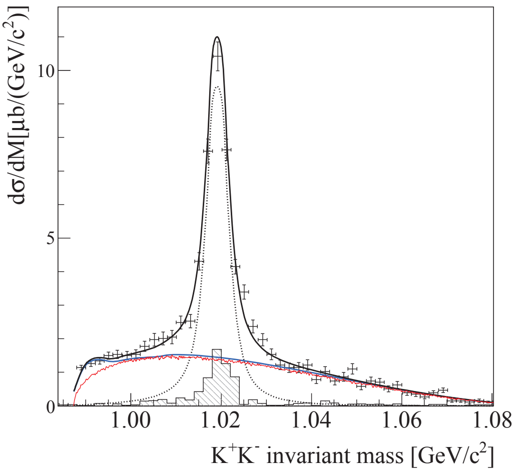

Fig. 1. (Color on-line) The $pp \to ppK^+K^-$ differential cross section in terms of the K^+K^- invariant mass. The solid line is the sum of ϕ (dotted line) and non-ϕ contributions (the red curve is phase space and the blue a parametrization based upon two-body final state interactions, cf. [3]). The error bars correspond only to the statistical uncertainties; systematic uncertainties are shown by the hatched histograms.

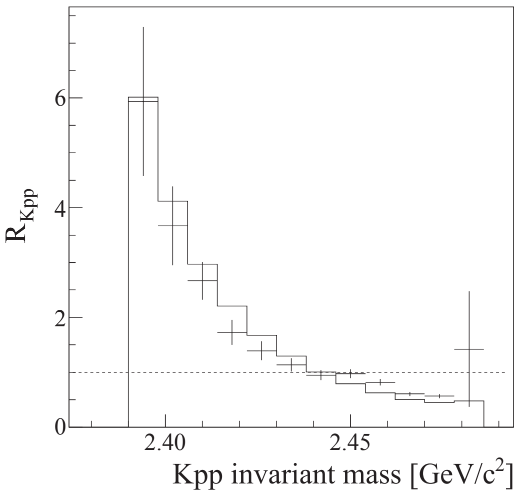

Fig. 2. Ratio of the $pp \to ppK^+K^-$ cross sections in terms of the K^-pp invariant mass divided by that using the K^+pp mass (cf. [3]). The histogram is the prediction within the FSI model, whereas the dashed line represents the four-body phase-space simulations.

at $\varepsilon_\phi = 76$ MeV. This explains why there is no evidence for the S-wave pp final state interaction in either these or the DISTO data (cf. [5]). However, the energy dependence of the $pp \to pp\phi$ total cross section then seems to indicate some low mass ϕp enhancement.

In general, ϕ-meson production on hydrogen with elementary probes is not completely understood at the energy of our experiment [9,10]. It might be interesting to note in this context that strangeness production in closely related channels might have some influence [11–13].

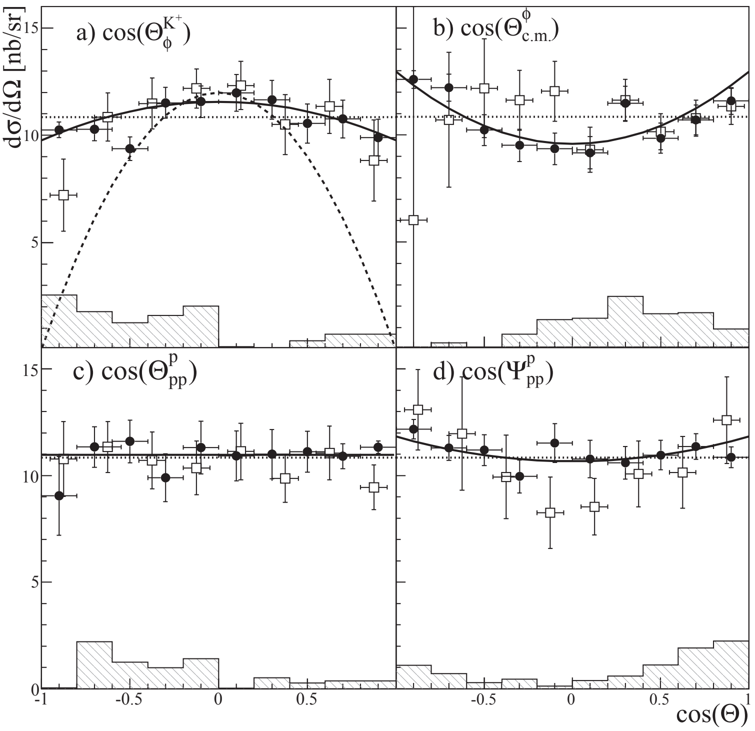

Fig. 3. Angular distributions measured for the $pp \to pp\phi$ reaction (black circles) compared with the scaled DISTO data (open squares). The solid curves show fits to the ANKE results for (a) the ϕ decay angle, (b) the ϕ c.m. angle, (c) the proton Jackson angle, and (d) the proton helicity angle. An extended description can be found in the full article [3].

Further evidence is found for structure in the K^+K^- invariant mass distribution at the $K^0\bar{K}^0$ threshold [7] and this region will also be investigated in data taken below the ϕ threshold that are currently being analyzed [14].

3 Momentum dependence of the ϕ-meson nuclear transparency

The production of the ϕ meson in proton collisions with C, Cu, Ag, and Au targets has been studied at the bombarding energy of 2.83 GeV by measuring its K^+K^- decay at ANKE in the angular cone $\theta_\phi < 8^\circ$. The analysis of such data yields information on the behaviour of the ϕ in a nuclear environment.

The nuclear transparency ratio, normalised to carbon, is defined as $R = (12/A)(\sigma^A/\sigma^C)$, where σ^A is the inclusive cross sections for ϕ production in pA collisions. The comparison of the values of R, averaged over the ϕ momentum range 0.6–1.6 GeV/c, with model calculations yields an in-medium ϕ width of $33 - 50$ MeV/c^2 in the nuclear rest frame at normal nuclear density [15].

The data have subsequently been put into six bins of ϕ momentum and Fig. 4 shows the momentum dependence of the measured transparency ratios for different nuclei. In order to extract information on the in-medium ϕ width, a reaction model is essential and three approaches have been considered.

Model 1: The Valencia eikonal approximation [16] uses the predicted ϕ self-energy [17,18] for

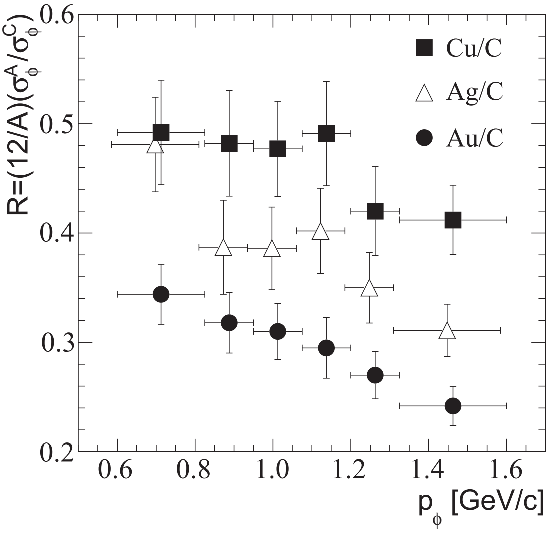

Fig. 4. Momentum dependence of the nuclear transparency ratio R, normalized to carbon, for Cu, Ag, and Au targets. The drawn error bars consider quadratically weighted statistical and systematic uncertainties. Further details in [4].

both single- and two-step production processes, with nucleon and Δ intermediate states.
Model 2: Paryev developed the spectral function technique for ϕ production in both the primary proton-nucleon and secondary pion-nucleon channels [19,20].
Model 3: The Rossendorf BUU transport calculation [21] includes a variety of secondary ϕ production processes. In contrast to Models 1 and 2, where ϕ absorption is governed by its width Γ_ϕ, Model 3 describes it in terms of an effective in-medium ϕN cross section $\sigma_{\phi N}$ that is related to Γ_ϕ in the low-density limit.

The in-medium ϕ widths in the nuclear rest frame at normal nuclear density, derived within these three models, are presented in Fig. 5. Similar behaviour is seen for all three approaches and the differences come mainly from the descriptions of secondary production processes.

The values extracted for the ϕ width are not in disagreement with the Spring-8 and JLab results that were determined at slightly higher momentum but it clearly exceeds the KEK result [22,23] [1].

In an attempt to understand further the model calculations, the double differential cross sections for ϕ production was evaluated within the ANKE acceptance window for different momentum bins. The experimental results for the four target nuclei are compared in Fig. 6 with the predictions of the Paryev and BUU calculations (Models 2 and 3) that used the extracted central values of the ϕ width shown in Fig. 5 as input.

The BUU calculation describes rather well the data at high momenta, where direct ϕ production dominates, but the models strongly underestimate ϕ production at low momenta. This suggests that some process, whose contribution to ϕ production increases for low ϕ momenta and with the size of the nucleus, is not included. A better understanding of both the production mechanism of the ϕ (cf. Sec. 2) and its propagation through nuclear matter is crucial. These are also important ingredients for investigations in heavy ions collisions.

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[1] In the ANKE publication of Ref. [4] it was assumed that the value of the in-medium ϕ width was extracted from the KEK data using only the low momentum part of ϕ-spectra [22]. We have since been informed by R. Muto [23] (cf. [24]) that the results were obtained through an overall fit to the momenta of all detected ϕ. These correspond to an average momentum of $< p_\phi >= 1.83$ GeV/c (cf. Fig. 5 and Fig. 4 of Ref. [4]).

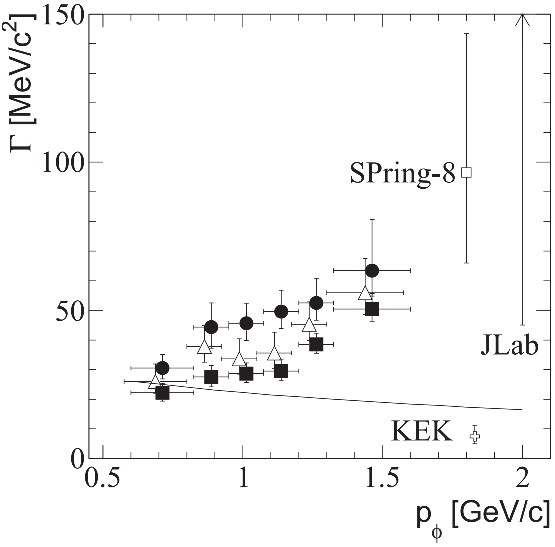

Fig. 5. In-medium ϕ width in the nuclear rest frame as a function of its momentum (cf. [4]). The points were evaluated by comparing the data of Fig. 4 with model calculations (1 – full squares, 2 – full circles, 3 – open triangles). Also shown are the results from other experiments [22,23,25,26]. The solid line represents the value of Γ_ϕ calculated from the predicted ϕ self-energy in nuclear matter [18].

4 Summary and Outlook

The clean identification of K^+K^- pairs at COSY-ANKE allows both the ϕ and non-ϕ production to be measured in proton-proton and proton-nucleus collisions. The $pp \to pp\phi$ differential cross sections at an excess energy of 76 MeV clearly show the influence of several higher partial waves and, as a result, the energy dependence of the total cross section can only be understood if S-wave production is enhanced near threshold. On the other hand, the non-ϕ data can all be described in terms of two-body final state interaction effects, with parameters determined from lower energy data. It is nevertheless surprising that this description is so effective at the higher energy reported here.

The production of ϕ-mesons has also been studied in proton interactions with four different nuclear targets as a function of the momentum p_ϕ of the meson. The comparison of the data with different reaction models shows that, although generally good, they predict too small cross sections for low p_ϕ. These models therefore clearly need further refinement.

The nuclear data also indicate that the A-dependence of non-ϕ kaon pair production is markedly different from that of the ϕ. These are now being analyzed in detail in order to extract the associated transparency ratios. These will be sensitive in the models to the K^+ and K^- potentials and the effects on the ratios might be expected to be even stronger than those evident in the $pp \to ppK^+K^-$ ratio data shown in Fig. 2.

New data are also being analyzed on the elementary $pp \to ppK^+K^-$ reaction at low energy, i.e. below the ϕ threshold. The high statistics over the more limited K^+K^- invariant mass range, combined with the better mass resolution, should allow us to study in greater depth possible structure at the $K^0\bar{K}^0$ threshold that arises through channel coupling [7]. The results should be available in late 2012.

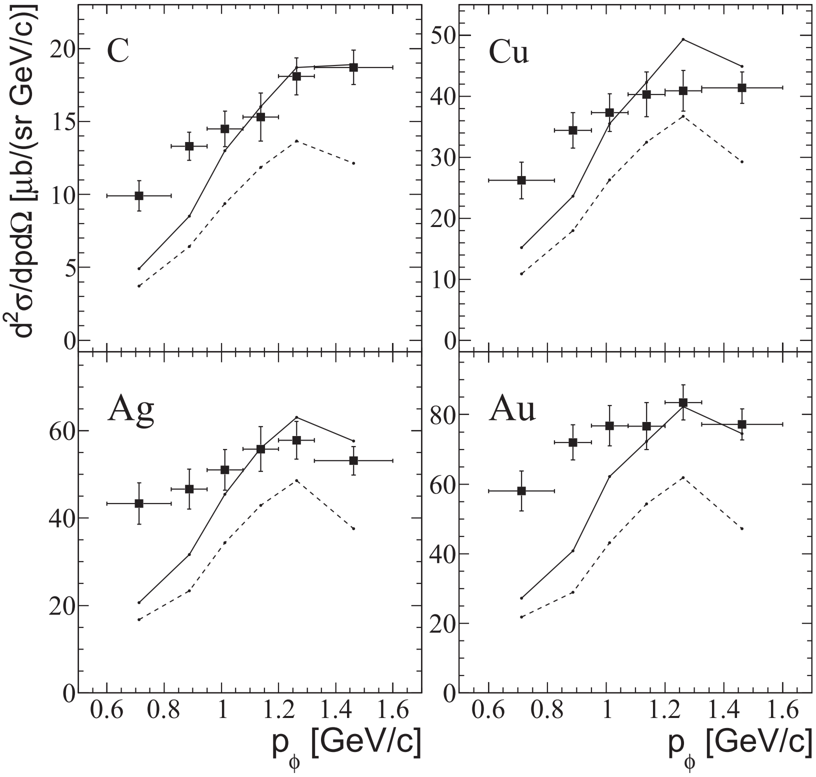

Fig. 6. Inclusive double-differential cross sections for ϕ production on C, Cu, Ag, and Au target, as functions of the ϕ momentum, compared with the predictions of Model 2 (dashed) and Model 3 (solid lines).

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