Determination of the in-medium ϕ-meson width from proton-nucleus collisions

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The production of ϕ mesons on C, Cu, Ag, and Au targets has been measured via the $\phi \to K^+K^-$ decay at an incident proton energy of 2.83 GeV with the ANKE spectrometer at COSY. From an analysis of the target mass dependence of the production cross section the in-medium ϕ width have been extracted in the momentum region of 0.6–1.6 GeV/c for normal nuclear density and compared with results of other experiments.

1 Introduction

The study of the effective masses and widths of light vector mesons in nuclear medium, through their production with hadron, heavy–ion and photon beams incident on nuclear targets, has received considerable attention in recent years [1,2]. The vacuum width of the $\phi(1020)$ meson is narrow compared to other nearby resonances. It is therefore the best place to test for medium modifications because small effects should be experimentally observable. The main modification of the ϕ in nuclear matter is expected to be a broadening of its spectral function, whereas its mass should be hardly changed.

Dileptons from $\phi \to e^+e^-/\mu^+\mu^-$ decays experience no strong final-state interactions in a nucleus. Broadening of the ϕ in the nucleus should be directly testable by examining $\ell^+\ell^-$ mass spectra. However, such a measurement is difficult due to the low branching ratios.

The KEK-PS-E325 collaboration measured e^+e^- invariant mass distributions in the ϕ region in proton-induced reactions on carbon and copper at 12 GeV and deduced a mass shift of

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3.4% and a width increase by a factor of 3.6 at normal nuclear density ρ_0 for ϕ momenta around 1 GeV/c [3]. This corresponds to an in-medium ϕ width of about 11 MeV in the nuclear rest frame for the average measured ϕ momentum.

An alternative way to determine the in-medium broadening of the ϕ meson has been adopted in [4,5]. The variation of the ϕ production cross section (or nuclear transparency ratio) with atomic number A has been studied both experimentally and theoretically. This A-variation depends on the attenuation of the ϕ flux in the nuclear target which, in turn, is governed by the imaginary part of the in-medium ϕ self-energy or width. In the low-density approximation, this width is related to an effective ϕN total cross section $\sigma_{\phi N}$ [2].

A large in-medium ϕN total cross section of about 35 mb was inferred by the LEPS collaboration from measurements of K^+K^- pairs photoproduced on Li, C, Al and Cu targets at SPring-8 for average ϕ momenta $\approx$ 1.8 GeV/c [4]. In the low-density approximation, this implies an in-medium ϕ width of about 97 MeV/c^2 in the nuclear rest frame at density ρ_0. The value of $\sigma_{\phi N}$ is significantly larger than the cross section in free space, viz. $\approx$ 10 mb.

The CLAS collaboration studied ϕ photoproduction on ^{2}H, C, Ti, Fe, Pb targets by measuring the e^+e^- decay [5]. From an analysis of the transparency ratios normalised to carbon within the Glauber model, values of $\sigma_{\phi N}$ in the range of 16–70 mb were extracted for an average ϕ momentum of $\approx$ 2 GeV/c, which is not inconsistent with the LEPS result.

Both the LEPS and CLAS results are larger than that obtained at KEK. One possible reason for the discrepancy could be the different ϕ momenta. A study of momentum dependence of the in-medium width could therefore provide useful information about the properties of the ϕ meson in a nucleus.

2 Experiment and Results

We have measured the production of ϕ mesons at small angles in the collisions of 2.83 GeV protons with C, Cu, Ag, and Au targets via the $\phi \to K^+K^-$ decay, using the ANKE-COSY magnetic spectrometer. The 2.83 GeV proton beam energy corresponds to an excess energy of about 76 MeV above the free NN threshold where few production channels are open. Secondary ϕ production processes are also expected to be less important at small angles.

As a first step, we have studied the nuclear transparency ratio normalised to carbon, $R = (12/A)(\sigma^A/\sigma^C)$, averaged over the ϕ momentum range 0.6–1.6 GeV/c [6,7]. Here σ^A and σ^C are inclusive cross sections for ϕ production in pA (A = Cu, Ag, Au) and pC collisions in the angular cone $\theta_\phi < 8^\circ$. The comparison of the ratio with model calculations [8,9] yields an in-medium ϕ width of $33 - 50$ MeV/c^2 in the nuclear rest frame for an average ϕ momentum of 1.1 GeV/c for normal nuclear density ρ_0=0.16 fm^{-3}.

The large number of reconstructed ϕ mesons for each target (7000–10000) allows the data to be put into six bins of approximately equal statistics in order to carry out more detailed studies. In Fig. 1 the preliminary results on the momentum dependence of the measured transparency ratios is shown for different nuclei. A decrease of the ratios with p_ϕ could be a signal of contributions of secondary ϕ production processes, especially for the lower momentum.

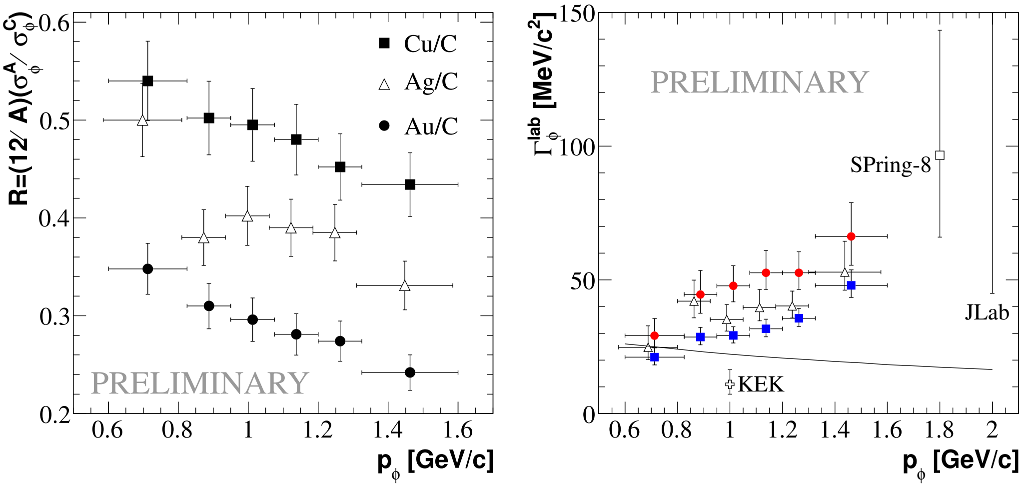

Figure 1: Left: Momentum dependence of the transparency ratios for the four nuclei studied. Right: Momentum dependence of the ϕ in-medium width for normal nuclear density exctracted using different models: Model 1 (blue squares), Model 2 (red circles) and Model 3 (open triangles). Experimental results by KEK-PS-E325 [3], Spring-8 [4] and JLab [5] are also plotted. The theoretical prediction of [10, 11] is shown by the solid line.

Any extraction of in-medium ϕ widths is model dependent; we consider three approaches.
Model 1: The eikonal approximation of the Valencia group [8] uses the predicted ϕ self-energy in nuclear medium [10, 11] both for the one-step ($pN \rightarrow pN\phi$) and for the two-step ϕ production processes, with nucleon and Δ intermediate states.
Model 2: Paryev [9] developed the spectral function approach for ϕ production in both the primary proton-nucleon and secondary pion-nucleon channels.
Model 3: The Rossendorf BUU transport calculation [12] 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 can be related to the ϕ width Γ_ϕ within the low-density approximation (LDA).

The in-medium ϕ width in the nuclear rest frame at normal nuclear density obtained in these models is presented in Fig. 1. Similar behaviour is seen for all three approaches and the differences come mainly from the divergent descriptions of the secondary production processes. The ϕ width extracted is in agreement with the Spring-8 [4] and JLab [5] results that have been measured for slightly higher momentum and exceeds the Valencia prediction [10, 11].

In order to understand further the model calculations, the double differential cross sections for ϕ production have been evaluated within the ANKE acceptance window for different momentum bins. The major systematic uncertainty arises from the evaluation of the integrated luminosity L^A_{int} for target A. For this purpose the flux of π^+ mesons with momentum ≈ 500 MeV$/c$ produced at small angles was measured. In order to estimate the double differential cross section for forward π^+ production at 2.83 GeV, the available experimental data [13, 14] have been combined (for details see Appendix A).

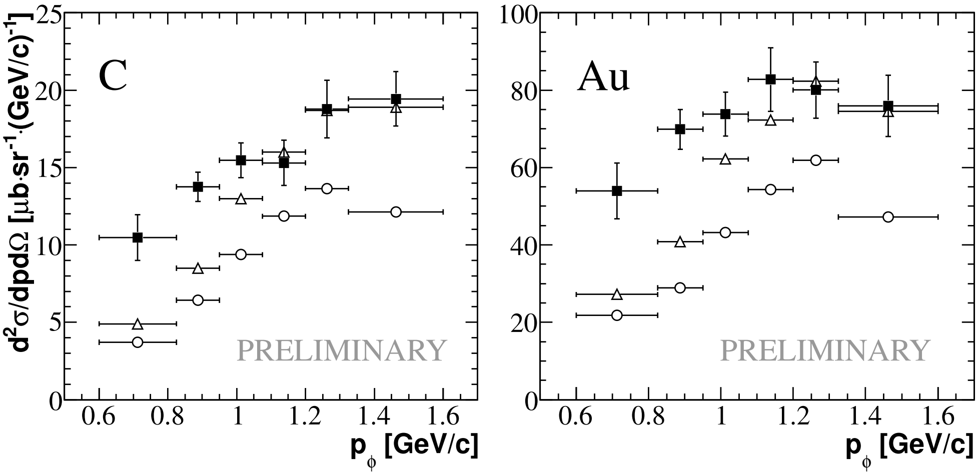

Figure 2: Comparison of the measured double differential cross section for ϕ production at small angles (full squares) for carbon (left) and gold (right) nuclei with the predictions of Models 2 (open circles) and 3 (open triangles).

The double differential cross sections for ϕ production were estimated in the Paryev and BUU calculations and in Fig. 2 the measured cross sections for carbon and gold nuclei are compared with the predictions in these models. The extracted values of the in-medium ϕ width or $\sigma_{\phi N}$ cross section have been used to estimate the ϕ production cross section within these models. The BUU calculation describes rather well the high momenta, where direct ϕ production dominates. Both models strongly underestimate ϕ production at low momenta. This suggests that some process, whose contribution to the ϕ production cross sections increases for low ϕ momenta and with the size of the nucleus, is not included in the models. Further theoretical studies of secondary production processes is therefore clearly needed to extract the maximum information from these experiments.

The results presented here would not have been possible without the efforts of the COSY machine crew and other members of the ANKE collaboration. The work was supported in part by the BMBF, DFG, COSY-FFE, RFBR and VI-QCD.

A Cross section for π^+ production at small angles at 2.83 GeV

There are no experimental data for π^+ production in pA collisions at 2.83 GeV and so estimates have been made on the basis of the available differential cross sections for forward π^+ and π^- production measured under closely related kinematic conditions [13,14].

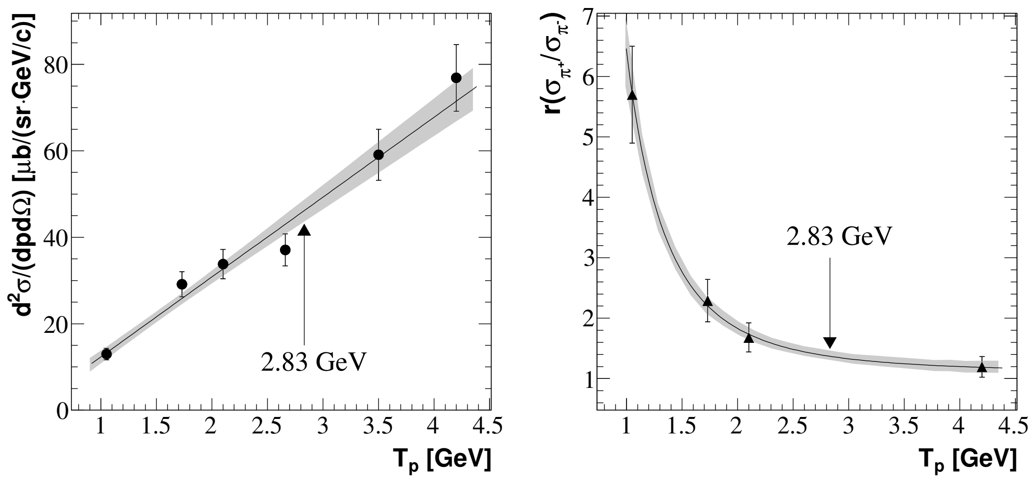

Figure 3: Left: Corrected double differential cross section for π^- production on carbon [14]. Right: Ratio of the double differential cross sections for π^+ and π^- production [14]. Errors of the fits are shown by the shaded bands ($cl = 67\%$). For explanations, see the text.

In Ref [13] a total systematic uncertainty of 6% was quoted, though the maximal beam energy used was only 1 GeV. Momentum spectra of π^+ and π^- at six higher energies were measured in the range 1–4.2 GeV [14] with an overall systematic uncertainty of 20% and a relative error between points of 10%.

A	$d^2\sigma^A_{\pi^+}/(dp\,d\Omega)$ mb/(sr GeV/c)
C	59.8 ± 7.2
Cu	113 ± 15
Ag	138 ± 19
Au	174 ± 24

Table 1: Cross sections assumed for the forward production of 500 MeV/c π^+ in the collision of 2.83 GeV protons with C, Cu, Ag, and Au targets. The errors include all statistical and systematic effects, as explained in the text.

A weighted average of the cross sections for the production of 500 MeV/c π^- from carbon at 1 GeV [13] and 1.05 GeV [14] was first determined and the π^- values obtained in [14] scaled to match this average at 1 GeV. The linear fit to the energy dependence of the scaled cross sections shown in Fig. 3 allows us to estimate the cross section at 2.83 GeV.

The dependence with beam energy of the ratio r(C) of the cross sections for 500 MeV/c π^+ and π^- production was then fitted by an exponential function to obtain a result at 2.83 GeV (Fig. 3). Finally, the differential cross section for forward π^+ production was derived from the values of $\sigma^C(\pi^-)$ and r(C). The cross sections for the other targets (Cu, Ag and Au) were determined assuming a $A^{\alpha_{\pi^+}}$ dependence with the exponent $\alpha_{\pi^+} = 0.38 \pm 0.02$ [6]. They are listed in Table 1.

To check this methodology, a similar procedure was carried out for the data from Cu and Pb targets [13, 14]. The results obtained agree with the values for Cu and Au listed in Table 1 within 2–3%. Since the statistical errors are small, the main contributions to the total uncertainties of the π^+ production cross sections are systematic. The resulting uncertainty for different nuclei is $\approx$ 12–14%.

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