In-medium ϕ meson width extracted from proton-nucleus collisions

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Abstract. The inclusive production of ϕ mesons at small angles in proton collisions with C, Cu, Ag, and Au targets has been measured at an incident energy of 2.83 GeV at the ANKE-COSY facility. The ϕ mesons were registered via the $\phi \to K^+K^-$ decay. The momentum dependence of the nuclear transparency ratio, the in-medium ϕ width, and the differential cross section for ϕ production have been determined in the momentum region $p_\phi = 0.6 - 1.6$ GeV/c. Comparison with different model calculations suggests a significant broadening of the in-medium ϕ width for normal nuclear density with evidence for a momentum dependence.

1 Introduction

The study of the properties of light vector mesons (ρ, ω, ϕ) in nuclear medium, through their production with photon, proton, and heavy-ion beams incident on nuclear targets, has been a very active research field for several years [1,2]. Changes in their in-medium properties are expected to be connected with the partial restoration of chiral symmetry in hot/dense nuclear matter. The vacuum width of the $\phi(1020)$ meson, $\Gamma_0 = 4.3$ MeV/c^2, is narrow compared to other nearby resonances. It is therefore a good probe 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 little shifted.

Dileptons from $\phi \to e^+e^-/\mu^+\mu^-$ decays experience no strong final-state interactions in a nucleus. Modification of the ϕ in the nucleus should therefore be directly testable by examining $\ell^+\ell^-$ mass spectra. However, such a measurement is difficult due to the low branching ratios ($\sim 10^{-4}$). 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 downward mass shift of 3.4% and a width increase by a factor of 3.6 at normal nuclear density $\rho_0 = 0.16$ fm^{-3} for average ϕ momenta $p_\phi \approx 1.8$ GeV/c [3,4]. This corresponds to an in-medium ϕ width of about 8 MeV/c^2 in the nuclear rest frame for this average ϕ momentum.

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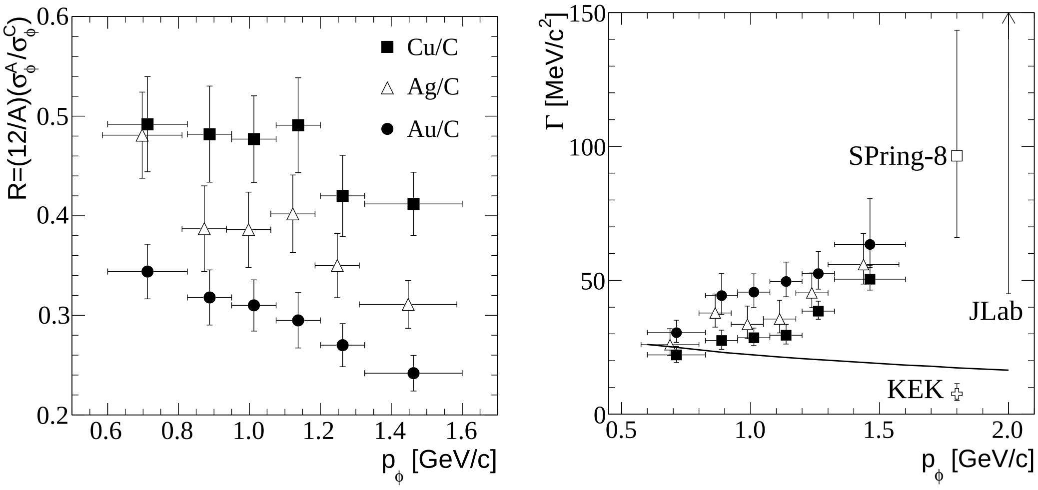

Fig. 1. Left: Momentum dependence of the transparency ratios for the four nuclei studied at ANKE. Right: Momentum dependence of the ϕ in-medium width for normal nuclear density extracted using different models (see text): Model 1 (full squares), Model 2 (full circles) and Model 3 (open triangles). Experimental results from KEK-PS-E325 [3], Spring-8 [5], and JLab [6] are also plotted. The theoretical prediction of [11, 12] is shown by the curve.

An alternative way to determine the in-medium broadening of the ϕ meson has been adopted in [5,6]. 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 [7], the width is related to an effective ϕN total cross section $\sigma_{\phi N}$, though this is less obvious at higher densities where two-nucleon effects might be significant. The main advantage of this approach is that one can use the dominant decay mode $\phi \to K^+K^-$ (BR $\approx$ 50%).

An in-medium ϕN total cross section of 35^{+17}_{-11} mb was inferred in a Glauber-type analysis by the LEPS collaboration from measurements of K^+K^- pairs photoproduced on Li, C, Al, and Cu targets at SPring-8 [5]. This is significantly larger than the cross section in free space, viz. $\approx$ 10 mb, and, in the low-density approximation, it implies an in-medium ϕ width of about 97 MeV/c^2 in the nuclear rest frame for $< p_\phi >\approx 1.8$ GeV/c at density ρ_0.

The CLAS collaboration studied ϕ photoproduction on ^{2}H, C, Ti, Fe, Pb targets by measuring the e^+e^- decay [6]. From an analysis within a Glauber model of the transparency ratios normalised to carbon, values of $\sigma_{\phi N}$ in the range of 16–70 mb were extracted for $< p_\phi >\approx 2$ GeV/c, which is not inconsistent with the LEPS result.

Both the LEPS and CLAS results are an order of magnitude larger than that obtained at KEK, despite all measurements being carried out at similar average ϕ momenta. In order to clarify this situation, further investigations are needed. In addition, a study of the momentum dependence of the in-medium width could 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. This 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.

We first 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 [8,9]. 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 $\theta_\phi < 8°$.

Any extraction of an in-medium ϕ width is model dependent; we consider three approaches. Model 1: The eikonal approximation of the Valencia group [10] uses the predicted ϕ self-energy in nuclear medium [11,12] both for the one-step ($pN \to pN\phi$) and the two-step ϕ production processes, with nucleon and Δ intermediate states.
Model 2: Paryev [13] 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 [14] 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 Γ_ϕ within the low-density approximation.

The comparison of the ratio R with the model calculations 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.

Large numbers of reconstructed ϕ mesons for each target (7000–10000) were accumulated over the course of the experiment. These allow the data to be put into six bins of approximately equal statistics in order to carry out more detailed studies [15]. In Fig. 1 the results on the momentum dependence of the measured transparency ratios are shown for the three combinations, Cu/C, Ag/C and Au/C. A decrease of the ratios with p_ϕ could be a signal of contributions of secondary ϕ production processes, especially for the lower momenta.

Figure 1 presents the in-medium ϕ width in the nuclear rest frame at normal nuclear density obtained in these models. Similar behaviour is seen for all three approaches and the differences come mainly from the divergent descriptions of the secondary production processes. The width extracted is in agreement with the Spring-8 [5] and JLab [6] results that have been measured for slightly higher momentum but exceeds the KEK-PS-E325 result [3] and the Valencia prediction [11,12].

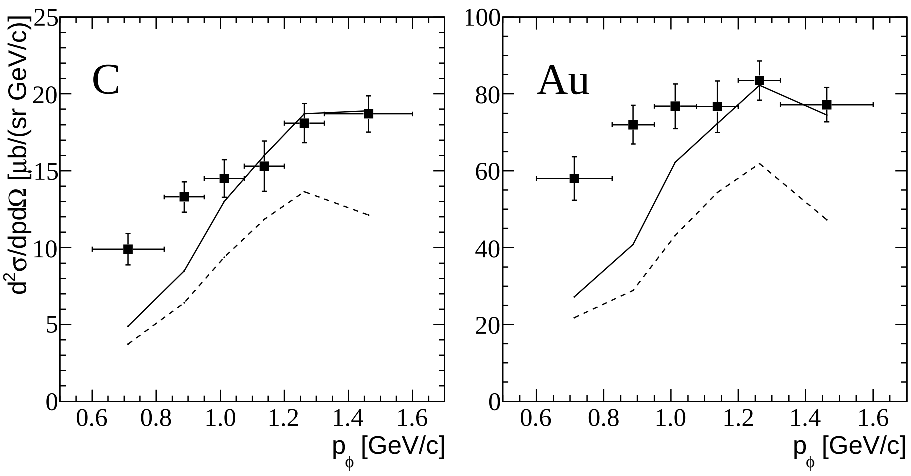

Fig. 2. Comparison of the measured double differential cross section for ϕ production at small angles (full squares) for carbon (left) and gold (right) nuclei with the predictions of Models 2 (dashed lines) and 3 (solid lines).

The double differential cross sections for ϕ production have also been evaluated within the ANKE acceptance window for different momentum bins, with the results being shown in Fig. 2. In order to estimate the integrated luminosity, the flux of π^+ mesons produced at small angles with momentum ≈ 500 MeV/c was measured. Double differential cross sections for forward π^+ production at 2.83 GeV have been determined by combining the available experimental data [16,17] (for details see [18]).

The ϕ production cross sections were also estimated in the Paryev and BUU calculations using the values of the in-medium ϕ width shown in Fig. 1. The measured cross sections for carbon and gold nuclei and the model predictions are compared in Fig. 2. The BUU calculation describes rather well the high momenta, where direct ϕ production dominates. Both models underestimate strongly ϕ production at low momenta. This suggests that some process, whose contribution to the ϕ production cross sections increases for low p_ϕ and with the size of the nucleus, is not included in the models. However, it seems that the transparency ratios are less sensitive to nuclear effects or secondary production processes than the production cross sections.

Taken together, our data show evidence for a momentum dependence of the in-medium ϕ meson width. The findings are not inconsistent with the results obtained at SPring-8 and JLab at slightly higher p_ϕ. As well as studying ϕ production, our data can also be used to investigate the transparency ratios for non-resonant kaon pair production, which are expected to be sensitive to the strengths of the K^+ and K^- interactions with the nucleus. The corresponding data analysis is in progress.

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