Noname manuscript No.
(will be inserted by the editor)

Momentum dependence of hadronic production of the ϕ-meson and its width in nuclear matter

M. Hartmann · **B. Kämpfer** ·
Yu. T. Kiselev · **V.K. Magas** ·
E. Ya. Paryev · **A. Polyanskiy** ·
L. Roca · **H. Schade** · **C. Wilkin**

Received: date / Accepted: date

Abstract Information on the properties of the ϕ meson in the nuclear environment has been derived from its production in proton collisions with C, Cu, Al, and Au nuclear targets. The experiment was carried out with 2.83 GeV protons at the Cooler Synchrotron COSY, with the ϕ being detected via its K^+K^- decay using the ANKE magnetic spectrometer. The measured dependence of the production cross section on the nuclear mass number has been compared

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M. Hartmann
Institut für Kernphysik and Jülich Centre for Hadron Physics, Forschungszentrum Jülich, D-52425 Jülich, Germany
E-mail: m.hartmann@fz-juelich.de

B. Kämpfer
Institut für Strahlenphysik, Helmholtz-Zentrum Dresden-Rossendorf, D-01314 Dresden, Germany

Yu. T. Kiselev
Institute for Theoretical and Experimental Physics, RU-117218 Moscow, Russia

V.K. Magas
Departament d'Estructura i Constituents de la Matèria and Institut de Ciències del Cosmos, Universitat de Barcelona, 08028 Barcelona, Spain

E. Ya. Paryev
Institute for Nuclear Research, Russian Academy of Science, RU-117312 Moscow, Russia

A. Polyanskiy
Institut für Kernphysik and Jülich Centre for Hadron Physics, Forschungszentrum Jülich, D-52425 Jülich, Germany; Institute for Theoretical and Experimental Physics, RU-117218 Moscow, Russia

L. Roca
Departamento de Fisica, Universidad de Murcia, E-30071 Murcia, Spain

H. Schade
Institut für Strahlenphysik, Helmholtz-Zentrum Dresden-Rossendorf, D-01314 Dresden, Germany; TU Dresden, Institut für Theoretische Physik, D-01062 Dresden, Germany

C. Wilkin
Physics and Astronomy Department, UCL, London WC1E 6BT, United Kingdom

with calculations within three different nuclear models. These suggest a significant broadening of the width of the ϕ in medium relative to its vacuum value. The ANKE results obtained in the momentum range $0.6 < p_\phi < 1.6$ GeV/c are compared with data from photoproduction experiments at slightly higher momenta.

Keywords ϕ meson production · nuclear medium effects

PACS 13.25.-k · 13.75.-n · 14.40.Cs

1 Introduction

The study of the effective masses and widths of light vector mesons in nuclear medium has received considerable attention in recent years [1,2]. Nuclear collisions of elementary particles (γ, π, p), in so-called cold static matter, can show changes in the properties [3–6] of these mesons. Compared to ultra-relativistic heavy-ion collisions (hot and dense matter), the theoretical treatment of such experimental data is more transparent and more closely related to the elementary processes.

The narrow vacuum width of the $\phi(1020)$ ($\Gamma = 4.3$ MeV/c^2) allows one to investigate small changes in its properties. The main modification in nuclear matter is expected to be a broadening of the ϕ spectral function while the mass should hardly shift. Such a broadening should be directly testable by examining the invariant mass spectra. Owing to the small final-state interactions, the dileptonic decay $\phi \to e^+e^-$ has been proposed but such measurements are made difficult by the low e^+e^- branching ratio of about 10^{-4}. The KEK-PS-E325 collaboration has investigated the e^+e^- mass spectra in proton-induced reactions at 12 GeV [7]. From the study of the spectral shape of production on copper relative to that on carbon they deduced a small mass reduction of 3.4% and a width increase by a factor of 3.6 at normal nuclear density ρ_0. This corresponds to an in-medium ϕ width of about 11 MeV in the nuclear rest frame for their average ϕ momentum of about 1 GeV/c.

A much larger in-medium broadening was reported by the LEPS collaboration in ϕ photoproduction on Li, C, Al and Cu targets when detecting the K^+K^- decay [8]. The variation of the production cross section with atomic number A depends on the attenuation of the ϕ flux in the nucleus. This is governed in turn by the imaginary part of the ϕ in-medium self-energy or width. In the low-density approximation (LDA), this width can be related to an effective ϕN total cross section [9], though this is less obvious at higher densities where two-nucleon mechanisms are important. The big advantage of this approach is that one can exploit the large K^+K^- branching ratio ($\approx 50\%$). The ϕN total cross section of about 35 mb deduced at LEPS is significantly bigger than that in free space, viz. ≈ 10 mb [10–12], and would correspond to an in-medium width of about 97 MeV/c^2 in the nuclear rest for $p_\phi \approx 1.8$ GeV/c.

The CLAS collaboration at JLab also studied the variation of ϕ photoproduction on different targets ^{2}H, C, Ti, Fe, Pb [13]. From an analysis of

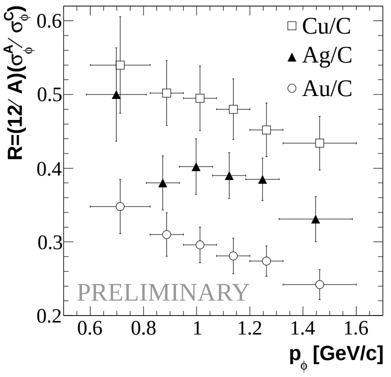

Fig. 1 Momentum dependence of the transparency ratios for the four nuclei studied.

the A-dependence, in the form of transparency ratios normalised to carbon (compare below), they extracted values of $\sigma_{\phi N}$ in the range of 16-70 mb for $p_{\phi} \approx 2$ GeV/c. The result is not inconsistent with the LEPS findings at slightly lower momenta, although the precision is limited due to the low statistics associated with the detected $e^{+}e^{-}$ decay.

2 Experiment and Results

The attenuation method was also used at COSY-ANKE but, in contrast to the photoproduction of LEPS and CLAS, the ϕ mesons were produced in proton-induced collisions at the Cooler Synchrotron of the Forschungszentrum Jülich. The beam energy of 2.83 GeV corresponds to an excess energy of about 76 MeV above the free NN threshold where few production channels are open. The magnetic spectrometer ANKE detected the ϕ-meson via its $K^{+}K^{-}$ decay in the angular cone $\theta_{\phi} < 8^{\circ}$, were secondary production processes are also expected to be less important.

In the initial stage we studied the nuclear transparency ratios normalised to carbon, $R = (12/A)(\sigma^{A}/\sigma^{C})$, averaged over the ϕ momentum range 0.6–1.6 GeV/c [14,15]. Here σ^{A} and σ^{C} are inclusive cross sections for ϕ production in pA ($A =$ Cu, Ag, Au) and pC collisions. The comparison of the ratios with model calculations [16,17] yields an in-medium ϕ width of $33 - 50$ MeV/c^{2} in the nuclear rest frame at 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 momentum 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 are shown for different nuclei. However, to extract information on the in-medium ϕ width, a reaction model is essential and we consider here three approaches to the problem.

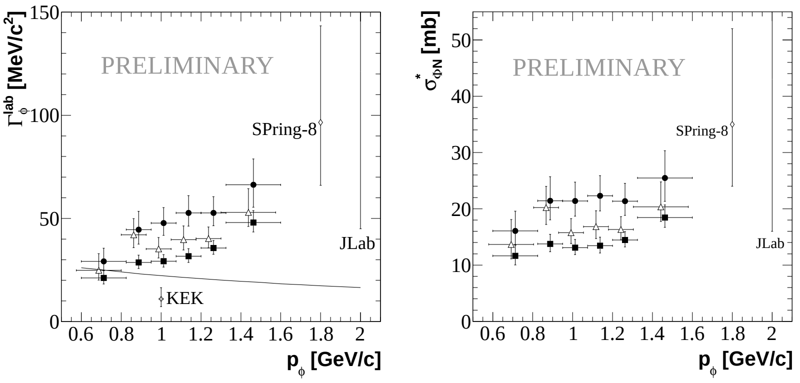

Fig. 2 Left: Momentum dependence of the in-medium ϕ width for normal nuclear density extracted using different models: Model 1 (squares), Model 2 (circles) and Model 3 (triangles). Experimental results from KEK-PS-E325 [7], Spring-8 [8] and JLab [13] are also plotted. The theoretical prediction of [18,19] is shown by the solid line. Right: The effective ϕN total cross section deduced from the in-medium ϕ widths within the low-density approximation (see text).

Model 1: The eikonal approximation of the Valencia group [16] uses the predicted ϕ self-energy [18,19] for both one-step ($pN \to pN\phi$) and two-step production processes, with nucleon and Δ intermediate states.
Model 2: Paryev [17] 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 [20] 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 by using the standard low-density relation $\Gamma_0(p) = \rho_0 \sigma_0^*(p) p/E_\phi$.

The in-medium ϕ width in the nuclear rest frame at normal nuclear density obtained in these models is presented in Fig. 2. Similar behaviour is seen for all three approaches and the differences come mainly from the choices in the descriptions of secondary production processes. The ϕ width extracted is not in disagreement with the Spring-8 [8] and JLab [13] results that have been determined at slightly higher momentum but it exceeds the Valencia prediction [18,19].

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 (compare [15,21]). The experimental results for carbon and gold nuclei are compared in Fig. 3 with the predictions of the Paryev and BUU calculations that used the extracted values of the in-medium ϕ width or $\sigma_{\phi N}$ cross section as input.

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

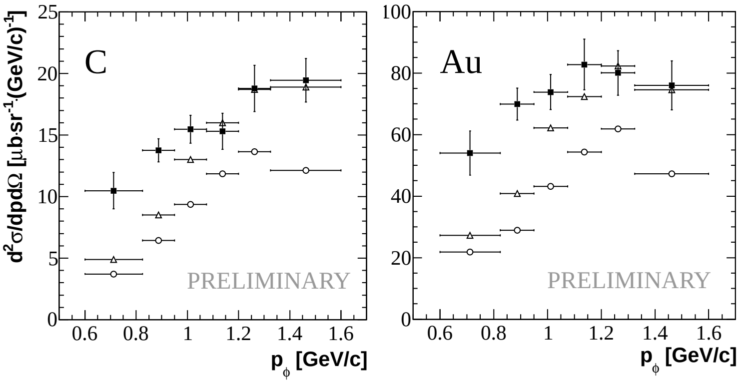

Fig. 3 Comparison of the measured double differential cross section for ϕ production at small angles (full squares) for carbon (left) and gold (right) nuclei with the predictions of Models 2 (open circles) and 3 (open triangles).

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.

Acknowledgements We wish to thank the COSY machine crew and other members of the ANKE collaboration for their help during the preparation and running of the experiments reported here. The work was supported in part by the BMBF, DFG, COSY-FFE and RFBR.

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