ϕ-meson production and the in-medium ϕ-width in proton-nucleus collisions

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Abstract. The production of ϕ-mesons in collisions of 2.83 GeV protons with C, Cu, Al, and Au targets has been measured with the ANKE magnetic spectrometer at the Cooler Synchrotron COSY. The ϕ-mesons were detected at small angles via their K^+K^- decay. The measured target mass dependence of the production cross section can be related to the in-medium ϕ width. First comparisons with model calculations suggest a significant broadening of the ϕ-width relative to its vacuum value of 4.3 MeV/c^2.

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The properties of light vector mesons are expected to change in hot and dense nuclear matter as created in ultrarelativistic heavy-ion collisions. Investigations with elementary (γ,π,p) probes in nuclear collisions, in so-called cold static matter, can cause comparable changes in the properties [1, 2, 3, 4]. Current overviews of this active research field are to be found in Refs. [5, 6].

The narrow vacuum line-shape ($\Gamma = 4.3$ MeV/c^2) of the $\phi(1020)$ meson allows one to investigate small modifications of its width in medium. The KEK-PS-E325 collaboration measured e^+e^- production in proton-induced reactions on carbon and copper at 12 GeV and studied the invariant mass spectra in the vicinity of the ϕ-meson peak. From this they deduced an increase in the width by a factor 3.6 at normal nuclear density [7]. A much larger in-medium broadening was reported by SPring-8 [8] (compare also [9, 10]) and the very recent JLab [11] measurements. Both these experiments studied the variation of the ϕ production cross section with the atomic number A. The production depends on attenuation of the ϕ flux in a nuclear target which, in turn, is governed by the imaginary part of the ϕ in-medium self-energy or width. In the low-density approximation [12], this width can be related to an effective ϕN total cross section, though this is less obvious at higher densities where two-nucleon mechanisms are important (compare [9, 13, 14, 15, 16, 17]). The big advantage of this method is that one can exploit the large K^+K^- branching ratio ($\approx$ 50%) in order to identify the ϕ meson.

The attenuation method was also used at COSY-ANKE but, in contrast to the photoproduction of SPring-8 and JLab, the ϕ mesons were produced in proton-induced collisions at the COSY Cooler Synchrotron of the Forschungszentrum Jülich. The circulating

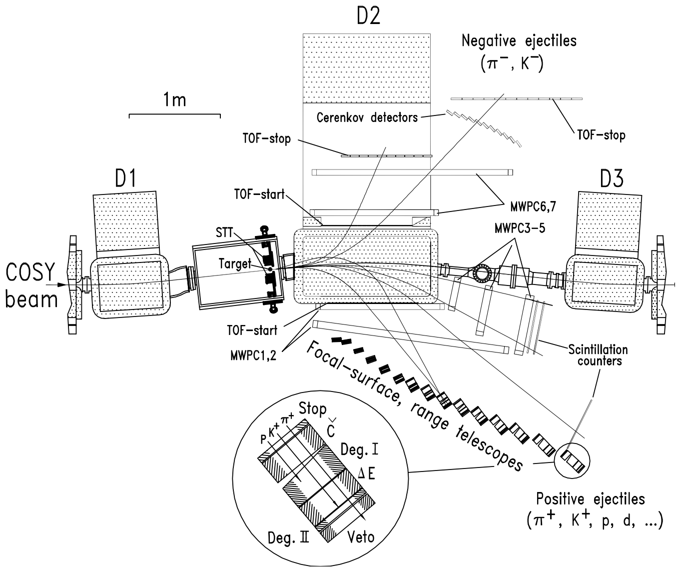

FIGURE 1. Top view of the ANKE spectrometer and detectors [18, 19]. The spectrometer contains three dipole magnets D1, D2, and D3, which guide the circulating COSY beam through a chicane. The central C-shaped spectrometer dipole D2, placed downstream of the target, separates the reaction products from the beam. The ANKE detection system, comprising range telescopes, scintillation counters and multi-wire proportional chambers, registers simultaneously negatively and positively charged particles and measures their momenta. The silicon tracking telescopes (STT) placed in the target chamber are used to measure low energy recoils from the target.

protons of 2.83 GeV (76 MeV above the free NN threshold) interacted with thin and narrow internal C, Cu, Ag and Au targets placed in front of the main spectrometer magnet D2 of the ANKE system, as shown in Fig. 1.

The ANKE spectrometer [18, 19] has detection systems placed to the right and left of the beam to register positively and negatively charged ejectiles, i.e., K^+ and K^- in the case of inclusive ϕ-meson production. Although not used in the present analysis, forward-going particles such as protons can also be detected in coincidence. The positive kaons were first selected using a dedicated detection system that can identify a K^+ against a π^+/p background that is 10^5 more intense (compare Fig. 2 and Refs. [19, 20]). The coincident K^- was subsequently identified from the time-of-flight difference between the stop counters in the negative and positive detector systems.

The K^+K^- invariant mass spectra measured in the $pA \to K^+K^-X$ reaction look similar for the four targets and the results for the C and Au target are presented in Fig. 3. In all cases there is a clear ϕ peak sitting on a background of non-resonant K^+K^- production together with a relatively small number of misidentified events.

The relative luminosity for each target was derived by measuring simultaneously the fluxes of π^+ mesons with momenta between 475 and 525 MeV/c in the angular cone $\theta_\pi < 4^\circ$. Since the double-differential cross section for π^+ production has not been measured at 2.83 GeV, we parametrized the available data [21] at seven proton energies in the range 1–5.6 GeV in the form

$$\sigma_A = \sigma_0 A^\alpha. \tag{1}$$

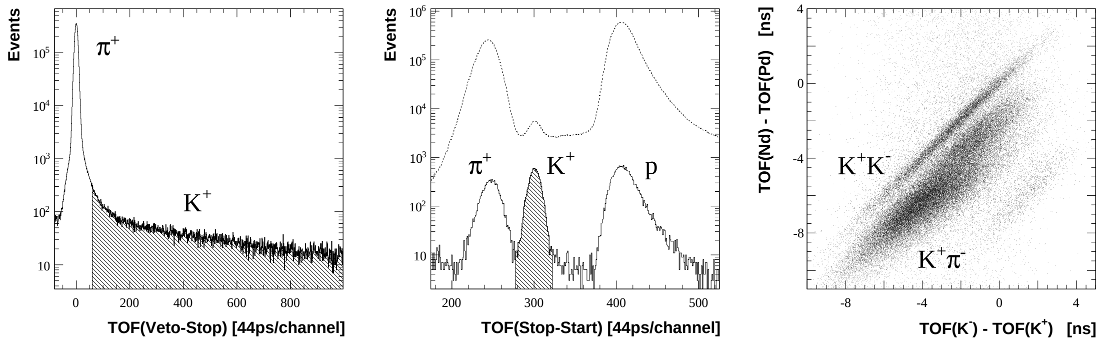

FIGURE 2. (Left panel) The decay products of stopped K^+ -mesons give rise to delayed time signals in the ANKE particle range hodoscopes relative to the prompt pion signal [20]. (Middle panel) The time-of-flight spectrum for positive ejectiles before (upper) and after (lower) using the delayed-decay information. The hatched areas indicate the K^+ selections for the subsequent analysis of K^+K^- correlations shown in the right panel. (Right panel) Absolute time difference between negative and positive STOP counters compared with the time difference reconstructed from the particle momenta [19].

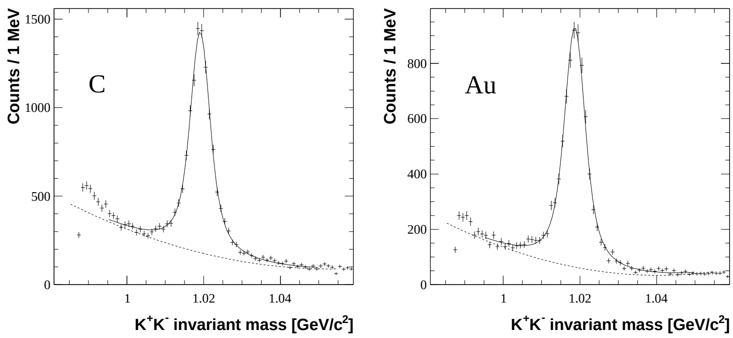

FIGURE 3. Invariant mass distributions for K^+K^- pairs produced in pC and pAu collisions. The vast majority of events in the peak come from ϕ mesons that decay outside the nucleus.

The interpolation of these fits to 2.83 GeV yielded an exponent $\alpha_{\pi^+} = 0.38 \pm 0.02$ (see Fig. 4, left panel), and this allowed us to normalize the ratios of the numbers of measured ϕ mesons.

Since the acceptance corrections in ANKE are essentially target-independent, the ratio of the counts corresponds to the ratio of the cross sections for ϕ production in the ANKE acceptance window. The resulting so-called transparency ratios, normalized to carbon, are presented in the right panel of Fig. 4 in the form

$$R = \frac{12\ \sigma_{pA\to\phi X'}}{A\ \sigma_{p\mathrm{C}\to\phi X}}\,. \tag{2}$$

The ratios shown correspond to ϕ production rates that follow the power law of Eq. (1) with $\alpha_\phi = 0.56 \pm 0.03$.

The interpretation of the obtained transparency ratios in terms of the in-medium ϕ width has to rely on a detailed theoretical treatment. As an example, the calculations

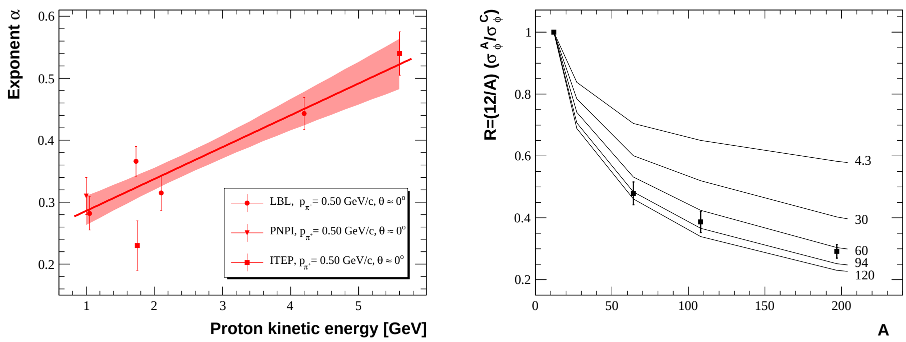

FIGURE 4. (Left panel) The π^+ production scaling factor α of Eq. (1) as a function of proton beam energy [21]. The dependence of the confidence interval ($cl = 67\%$) is shown by the colored band. (Right panel) Comparison of the measured transparency ratio R as a function of atomic number A with predictions of model calculations [17] for different ϕ widths in its rest system at normal nuclear density. The experimental uncertainties reflect both statistical and systematics effects.

of Paryev [17] for different in-medium widths are compared in Fig. 4 with the ANKE data. The model considers primary proton-nucleon as well as secondary pion-nucleon ($\pi N \to \phi N$) processes in the proton-nucleus calculations. It uses the new measurements of the $pp \to pp\phi$ and $pn \to d\phi$ reactions [22, 23] and estimates of the cross section difference between $pn \to pn\phi$ and $pp \to pp\phi$ [24]. The calculations were done in the limited ANKE acceptance of $0.6\ \mathrm{GeV}/c < p_\phi < 1.6\ \mathrm{GeV}/c$, $0^\circ < \theta_\phi < 8^\circ$. Fitting the data with the model yields a value of $73^{+14}_{-10}\ \mathrm{MeV}/c^2$ for the in-medium width of a ϕ meson in its rest frame at nuclear density $\rho_0 = 0.16\ \mathrm{fm}^{-3}$. This corresponds to $\approx 50\ \mathrm{MeV}/c^2$ in the nuclear rest frame for a ϕ with momentum of 1.1 GeV/c, which is typical for the ANKE conditions.

The comparison of the ratios with the work of the Valencia group [2, 14, 15] results in an about 1.6 times smaller in-medium broadening of the ϕ compared to the findings using the Paryev model. In between those two models lie the first results from the ongoing Rossendorf Boltzmann-Uehling-Uhlenbeck (BUU) calculations [25]. A more detailed discussion of the ANKE data within all available model calculations is given in A. Polyanskiy *et al.* [26].

Combining the three approaches [14, 17, 25], the width of about (33-50) MeV/c^2 for a momentum of 1.1 GeV/c at ANKE can be compared with the results obtained at KEK, SPring-8 and JLab, in the following all at normal nuclear density. In the low density approximation [12], $\Gamma^{lab}_{coll} = \rho(p/E)\sigma^*_{\phi N}$. In this limit the ϕN total cross section of $\sigma^*_{\phi N} = 35^{+17}_{-11}$ mb determined by SPring-8 [8] at momenta around $p_\phi = 1.7\ \mathrm{GeV}/c$ corresponds to an in-medium width of about $\approx 95\ \mathrm{MeV}/c^2$. The recent JLab result [11] in the range $46 - 200\ \mathrm{MeV}/c^2$ at 2 GeV/c overlaps the SPring-8 measurements. The ANKE value looks somewhat smaller in comparison, but not inconsistent given all the uncertainties in the experiments and the models applied. The KEK result [7] at comparable momenta to ANKE ($p_\phi < 1.25\ \mathrm{GeV}/c$) appears lower in comparison.

A momentum-dependent increase of the ϕ in-medium broadening, as suggested by Wood *et al.* [11], and shown for the collisional part of the broadening by Mühlich *et* *al.* [9], might partly explain the different results, but this has certainly not been unambiguously proven so far. The high statistics of 7000-10000 ϕ per target provided by the existing ANKE data allows us to search for such a possible variation in the momentum range of $0.6\ \mathrm{GeV}/c < p_\phi < 1.6\ \mathrm{GeV}/c$, and an investigation of this is in progress.

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