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Author(s)	Sakuma, F; Chiba, J; En'yo, H; Fukao, Y; Funahashi, H; Hamagaki, H; Ieiri, M; Ishino, M; Kanda, H; Kitaguchi, M; Mihara, S; Miwa, K; Miyashita, T; Murakami, T; Muto, R; Nakura, T; Naruki, M; Ozawa, K; Sasaki, O; Sekimoto, M; Tabaru, T; Tanaka, KH; Togawa, M; Yamada, S; Yokkaichi, S; Yoshimura, Y
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## Nuclear-Matter Modification of Decay Widths in the $\phi \rightarrow e^+e^-$ and $\phi \rightarrow K^+K^-$ Channels

F. Sakuma,<sup>1,\*</sup> J. Chiba,<sup>2,†</sup> H. En'yo,<sup>3</sup> Y. Fukao,<sup>1</sup> H. Funahashi,<sup>1</sup> H. Hamagaki,<sup>4</sup> M. Ieiri,<sup>2</sup> M. Ishino,<sup>1,‡</sup> H. Kanda,<sup>1,§</sup> M. Kitaguchi,<sup>1</sup> S. Mihara,<sup>1,‡</sup> K. Miwa,<sup>1</sup> T. Miyashita,<sup>1</sup> T. Murakami,<sup>1</sup> R. Muto,<sup>3</sup> T. Nakura,<sup>1</sup> M. Naruki,<sup>3</sup> K. Ozawa,<sup>4,||</sup> O. Sasaki,<sup>2</sup> M. Sekimoto,<sup>2</sup> T. Tabaru,<sup>3</sup> K. H. Tanaka,<sup>2</sup> M. Togawa,<sup>1</sup> S. Yamada,<sup>1</sup> S. Yokkaichi,<sup>3</sup> and Y. Yoshimura<sup>1</sup>

(KEK-PS E325 Collaboration)

<sup>1</sup>Department of Physics, Kyoto University, Kitashirakawa Sakyo-ku, Kyoto 606-8502, Japan

<sup>2</sup>Institute of Particle and Nuclear Studies, KEK, 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan

<sup>3</sup>RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan

<sup>4</sup>Center for Nuclear Study, Graduate School of Science, University of Tokyo, 7-3-1 Hongo, Tokyo 113-0033, Japan

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The invariant mass spectra of  $\phi \rightarrow K^+K^-$  are measured in 12 GeV  $p + A$  reactions in order to search for the in-medium modification of  $\phi$  mesons. The observed  $K^+K^-$  spectra are well reproduced by the relativistic Breit-Wigner function with a combinatorial background shape in three  $\beta\gamma$  regions between 1.0 and 3.5. The nuclear mass number dependence of the yields of the  $K^+K^-$  decay channel is compared to the simultaneously measured  $e^+e^-$  decay channel for carbon and copper targets. We parameterize the production yields as  $\sigma(A) = \sigma_0 A^\alpha$  and obtain  $\alpha_{\phi \rightarrow K^+K^-} - \alpha_{\phi \rightarrow e^+e^-}$  to be  $0.14 \pm 0.12$ . Limits are obtained for the partial decay widths of the  $\phi$  mesons in nuclear matter.

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The properties of hadrons, such as mass, decay width, and branching ratio, have been extensively studied and well established in the history of particle physics. Recent interests have been extended to understanding how these properties are modified in hot or dense matter. This issue is of fundamental importance since such modifications can be related to the basic nature of QCD, spontaneous chiral symmetry breaking, i.e., the mechanism that creates most of the hadron masses. Inspired by many theoretical works related to this subject, several experiments including ours have been carried out.

Amongst the many types of hadrons, the  $\phi$  meson, which is a vector meson ( $1^{--}$ ) of an almost pure  $s\bar{s}$  state, has very attractive features for use as a probe to detect the possible changes in its properties. Its natural width is narrow ( $\Gamma_\phi = 4.26 \text{ MeV}/c^2$ ) [1] without any nearby resonance; therefore, we may be able to clearly detect the possible mass modification. Theoretically, various models predict the in-medium mass modification of the  $\phi$  meson both in dense and hot matter [2–9]. The predicted decrease in mass at normal nuclear density is up to  $40 \text{ MeV}/c^2$  and the width broadening is up to  $45 \text{ MeV}/c^2$ . Moreover, since  $m_\phi$  is only  $32(24) \text{ MeV}/c^2$  greater than  $2m_{K^\pm}$  ( $2m_{K^0}$ ), the partial decay width  $\Gamma_{\phi \rightarrow K\bar{K}}$  is sensitive even to a small change in the spectral function of the  $\phi$  meson and/or kaon. Several theoretical models point out the possible change in the branching ratio  $\Gamma_{\phi \rightarrow K\bar{K}}/\Gamma_{\phi \rightarrow l^+l^-}$  in a nuclear medium [6,7,10].

There are few experimental reports on the search for the in-medium modification of the  $\phi$  meson. With regard to the ratio of the partial decay width  $\Gamma_{\phi \rightarrow K\bar{K}}/\Gamma_{\phi \rightarrow l^+l^-}$ , the experiments NA49 and NA50 at the CERN-SPS reported

$\phi$ -meson yields in the  $K^+K^-$  and  $\mu^+\mu^-$  channels, respectively. There are discrepancies by factors ranging from 2 to 4 between these measurements [11–13]. Recently, the CERES experiment at the CERN-SPS reported new results in the  $\phi \rightarrow e^+e^-$  and  $\phi \rightarrow K^+K^-$  measurements [14]. The results in the  $K^+K^-$  channels are in agreement with those of NA49, and both decay channels are consistent with each other.

The present experiment E325, performed using the KEK 12 GeV proton synchrotron, recently reported the spectral modification of the  $\phi$  meson in nuclear matter measured in the  $e^+e^-$  decay channel for the first time [15]. We also reported the modification of  $\rho$  and/or  $\omega$  mesons in Refs. [16,17]. In the present study, new results are reported on the shape analysis for the  $\phi \rightarrow K^+K^-$  invariant mass spectra, and the nuclear mass number dependence of  $\phi$ -meson production is compared between the  $e^+e^-$  and  $K^+K^-$  decay channels to determine whether the ratio of the partial decay width  $\Gamma_{\phi \rightarrow K^+K^-}/\Gamma_{\phi \rightarrow e^+e^-}$  depends on the nuclear size. This work is an advanced study over Ref. [18], where we reported the production cross sections and their rapidity and transverse momentum dependences of the  $\omega$  and  $\phi$  mesons measured in the present experiment.

The cross section for a nuclear target of mass number  $A$  is parameterized as  $\sigma(A) = \sigma_0 A^\alpha$ . When the  $\phi$  meson and/or kaon is modified in a medium and  $\Gamma_{\phi \rightarrow K^+K^-}/\Gamma_{\phi \rightarrow e^+e^-}$  changes, the ratio of the  $\phi$ -meson yield  $R = N_{\phi \rightarrow K^+K^-}/N_{\phi \rightarrow e^+e^-}$  becomes dependent on the mass number since a larger number of  $\phi$  mesons are to be modified in a larger nucleus. Consequently, by using two different nuclear targets  $A_1$  and  $A_2$ , the difference in the  $\alpha$  parameter

between  $\phi \rightarrow e^+e^-$  ( $\alpha_{\phi \rightarrow e^+e^-}$ ) and  $\phi \rightarrow K^+K^-$  ( $\alpha_{\phi \rightarrow K^+K^-}$ ) can be related to  $R$  as follows:

$$\begin{aligned} \Delta\alpha &= \alpha_{\phi \rightarrow K^+K^-} - \alpha_{\phi \rightarrow e^+e^-} \\ &= \frac{\ln\left[\frac{N_{\phi \rightarrow K^+K^-}(A_1)}{N_{\phi \rightarrow K^+K^-}(A_2)}\right] - \ln\left[\frac{N_{\phi \rightarrow e^+e^-}(A_1)}{N_{\phi \rightarrow e^+e^-}(A_2)}\right]}{\ln(A_1/A_2)} \\ &= \ln[R(A_1)/R(A_2)]/\ln(A_1/A_2). \end{aligned} \quad (1)$$

It is important that most of the experimental effects are canceled in obtaining  $\alpha$ .

The details of the experiment can be found elsewhere [19]. A primary proton beam of 12 GeV with a typical intensity of  $10^9$  protons per 1.8-s spill was focused on carbon and copper targets, and the spectrometer detected  $e^+e^-$  and  $K^+K^-$  pairs simultaneously. In this Letter, we used the  $e^+e^-$ -triggered data collected in 2001 and 2002 and the  $K^+K^-$ -triggered data collected in 2001. In 2001, one carbon (0.092 g/cm<sup>2</sup>) and two copper targets (0.073 g/cm<sup>2</sup> each) were used, while in 2002, one carbon (0.184 g/cm<sup>2</sup>) and four copper targets (0.073 g/cm<sup>2</sup> each) were used. The targets were aligned in a line so that the same beam normalization could be used for all the targets.

The invariant mass distributions of the  $K^+K^-$  pairs are shown in Fig. 1. To examine the modification in the mass shape as a function of  $\beta\gamma (= p/m)$ , the data were divided into three  $\beta\gamma$  regions. Each mass spectrum was fitted with a combinatorial background shape [20] and a resonance shape of  $\phi \rightarrow K^+K^-$  in the mass range between  $2m_{K^\pm}$  and 1.15 GeV/ $c^2$ . The fits were performed by using the maximum likelihood method [21]; the ‘‘likelihood chi-square  $\chi_\lambda^2$ ’’ is shown in Fig. 1. The combinatorial background shape was evaluated by the event-mixing method. For the  $\phi$ -meson resonance shape, the relativistic Breit-Wigner (RBW) distribution with the natural mass ( $m_0$ ) and decay width ( $\Gamma_0$ ) was used after taking the spectrometer performance into account. The RBW distribution is given by

$$\frac{d\sigma}{dm} = \frac{mm_0\Gamma(m)}{(m^2 - m_0^2)^2 + [m_0\Gamma(m)]^2}, \quad (2)$$

where  $\Gamma(m) = \Gamma_0(q/q_0)^3(m_0/m)$ ,  $q = (m^2/4 - m_{K^\pm}^2)^{1/2}$ , and  $q_0 = (m_0^2/4 - m_{K^\pm}^2)^{1/2}$  [22].

The spectrometer performance was examined by a detailed detector simulation using the GEANT4 toolkit [23]. The kinematical distributions of the  $\phi$  mesons used in the simulation were obtained from the nuclear cascade code JAM [24], which reproduced our measured distributions fairly well [18]. From the data, we obtained the peak position  $m = 1019.43 \pm 0.21(\text{stat}) \pm 0.04(\text{syst})$  MeV/ $c^2$  and the mass resolution  $\sigma = 1.91 \pm 0.29(\text{stat}) \pm 0.23(\text{syst})$  MeV/ $c^2$  for the copper targets, while the simulation gave  $m = 1019.49$  MeV/ $c^2$  and  $\sigma = 2.24$  MeV/ $c^2$ . The agreements are significantly remarkable, and we have used the simulated mass shape for the fits in Fig. 1.

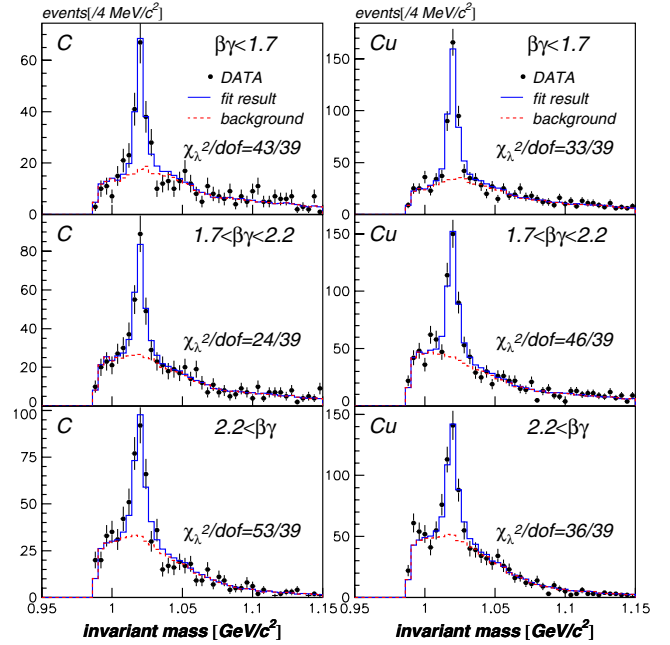


FIG. 1 (color online). Invariant mass distributions of  $K^+K^-$  pairs. The closed circles represent the observed distributions, and the solid lines represent the fit results with the expected  $\phi \rightarrow K^+K^-$  shape on the combinatorial background shown with dashed lines.

The observed  $K^+K^-$  spectra are well reproduced by the fit in all the  $\beta\gamma$  bins. Therefore, the changes in mass spectra are not statistically significant in the  $\phi \rightarrow K^+K^-$  channel. Indeed, we have observed a mass shape modification in the  $\phi \rightarrow e^+e^-$  channel [15] in the very low  $\beta\gamma$  region ( $\beta\gamma < 1.25$ ) for the copper target data. In Fig. 2, we compare the acceptances of the  $K^+K^-$  and  $e^+e^-$  channels. In the region  $\beta\gamma < 1.25$ , we have very limited statistics for  $\phi \rightarrow K^+K^-$ , and we cannot obtain a reasonable fit for the  $K^+K^-$  data. Thus, it is impossible to compare the  $\phi \rightarrow K^+K^-$  shape directly with the modified shape observed in the  $e^+e^-$  channel. It can be concluded that in the region  $\beta\gamma > 1.25$ , both  $\phi \rightarrow K^+K^-$  and  $\phi \rightarrow e^+e^-$  do not show signs of shape modification.

We obtained the  $\phi$ -meson yields for three bins for  $K^+K^-$  and four bins for  $e^+e^-$  as functions of  $\beta\gamma$ . For the  $K^+K^-$  decay channel, the  $\phi$ -meson yields were obtained by integrating from  $2m_{K^\pm}$  to 1.07 GeV/ $c^2$  after subtracting the background described before. To obtain the  $\phi$ -meson yields for the  $e^+e^-$  decay channel, we employed the same procedure as used in Ref. [15]; in that study, the spectra were fitted with a simulated  $\phi$  resonance shape and a quadratic background curve. The  $\phi$ -meson yields were then obtained by integrating the data in the mass range between 0.9 and 1.1 GeV/ $c^2$  after subtracting the background. Thus, the excess yield observed in Ref. [15] must also be counted as  $\phi$  mesons.

Table I summarizes the yields for both decay channels with the systematic errors containing the contributions

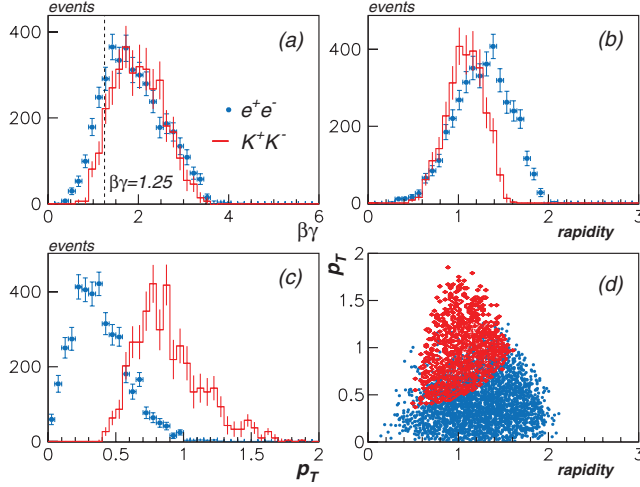


FIG. 2 (color). Observed kinematical distributions of  $\phi \rightarrow e^+e^-$  and  $\phi \rightarrow K^+K^-$ . Distributions of (a)  $\beta\gamma$ , (b) rapidity, (c)  $p_T$ , and (d)  $p_T$  and rapidity. The points represent  $\phi \rightarrow e^+e^-$ , and the lines represent  $\phi \rightarrow K^+K^-$ . The histograms for  $\phi \rightarrow K^+K^-$  are scaled by a factor of  $\sim 3$ .

from the uncertainty in the background estimation [25]. In Table I, the  $\alpha$  parameters are corrected for the target dependence of the experimental efficiencies. The most significant correction was the difference in the geometrical acceptance for each target position. The effect was estimated by the JAM simulation, and  $\alpha$  changed by a maximum of 0.04. The other corrections due to the trigger, tracking, and analysis were estimated to be small and were included in the systematic errors together with those from the background estimations. In the analysis thereafter, the errors in  $\alpha$  are the quadratic sums of the statistical and systematic errors.

The observed  $\alpha$  parameters are plotted as functions of  $\beta\gamma$  in Fig. 3(a) and as functions of the rapidity ( $y$ ) and transverse momentum ( $p_T$ ) in (b) and (c). The  $e^+e^-$  and  $K^+K^-$  decay channels cannot be compared directly because of the difference in the detector acceptance between the  $e^+e^-$  and  $K^+K^-$  decay channels, as shown in Fig. 2. Therefore, we determined  $\alpha_{\phi \rightarrow e^+e^-}$  two dimensionally on

the  $y$ - $p_T$  plane under the assumption that  $\alpha_{\phi \rightarrow e^+e^-}$  is linearly dependent on  $y$  and  $p_T$ , and estimated the values corresponding to the kaon acceptance windows [26]. To determine the plane  $\alpha_{\phi \rightarrow e^+e^-}(y, p_T)$ , the  $e^+e^-$  data were divided into  $3 \times 3$  bins in the  $y$ - $p_T$  plane, and they were fitted with the function  $\alpha(y, p_T) = ay + bp_T + c$ . We obtained  $a = -0.32 \pm 0.11$ ,  $b = 0.13 \pm 0.17$ ,  $c = 1.24 \pm 0.15$ , and  $\chi^2/\text{dof} = 4.2/6$ , indicating that the above assumption is statistically acceptable.

In Fig. 3(a), we show the estimated values of  $\alpha_{\phi \rightarrow e^+e^-}(\beta\gamma)$  in the kaon acceptance window as a hatched band; this can be compared to the measured value of  $\alpha_{\phi \rightarrow K^+K^-}$ . The difference  $\Delta\alpha$  in the kaon acceptance is plotted in Fig. 3(d). We expect that  $\Delta\alpha$  should be zero when  $\Gamma_{\phi \rightarrow K^+K^-}/\Gamma_{\phi \rightarrow e^+e^-}$  does not change in nuclear media. Although it is interesting to observe that  $\Delta\alpha$  increases when  $\beta\gamma$  decreases,  $\Delta\alpha$  at the lowest  $\beta\gamma$  bin is only  $0.33 \pm 0.17$ ; the average value is  $0.14 \pm 0.12$ . Therefore,  $\alpha_{\phi \rightarrow e^+e^-}$  and  $\alpha_{\phi \rightarrow K^+K^-}$  are statistically the same in the measured kinematic region.

On the basis of these results, the possible modification of the decay widths is discussed below. In a medium, we expect the total and partial decay widths  $\Gamma$  to change to  $\Gamma^*$  according to the relation

$$\begin{aligned} \Gamma_{\phi}^*/\Gamma_{\phi}^0 &= 1 + k_{\text{tot}}(\rho/\rho_0), \\ \Gamma_{\phi \rightarrow K^+K^-}^*/\Gamma_{\phi \rightarrow K^+K^-}^0 &= 1 + k_K(\rho/\rho_0), \\ \Gamma_{\phi \rightarrow e^+e^-}^*/\Gamma_{\phi \rightarrow e^+e^-}^0 &= 1 + k_e(\rho/\rho_0), \end{aligned} \quad (3)$$

where  $\Gamma^0$  is the value in vacuum and  $\rho_0$  is the normal nuclear density [27]. We expect  $k_{\text{tot}} \simeq k_K$  since the  $\phi$  meson mainly decays into  $K\bar{K}$  as long as such decays are kinematically allowed.

To estimate the relation between  $\Delta\alpha$ ,  $k_K$ , and  $k_e$ , we performed the Monte Carlo calculation described in Ref. [15], where  $\phi$  mesons were uniformly produced in a nucleus and decayed according to the values of  $k_K$  and  $k_e$ . In the plane of  $k_K$  and  $k_e$ , the expected values of  $\Delta\alpha$  were obtained. The results are shown in Fig. 4 as a colored

TABLE I.  $\phi$ -meson yields and the  $\alpha$  parameters for the  $e^+e^-$  and  $K^+K^-$  decay channels evaluated by the fits. The first errors are statistical and the second are systematic.

$\beta\gamma$	$N_{\phi}$ (C)	$N_{\phi}$ (Cu)	$\alpha$
$\phi \rightarrow e^+e^-$			
0–1.25	$331 \pm 32 \pm 6$	$703 \pm 50 \pm 26$	$1.18 \pm 0.07 \pm 0.02$
1.25–1.75	$702 \pm 51 \pm 9$	$899 \pm 63 \pm 4$	$0.87 \pm 0.06 \pm 0.02$
1.75–2.5	$945 \pm 62 \pm 14$	$1096 \pm 71 \pm 12$	$0.81 \pm 0.06 \pm 0.01$
2.5–3.5	$579 \pm 52 \pm 4$	$626 \pm 56 \pm 5$	$0.77 \pm 0.08 \pm 0.01$
$\phi \rightarrow K^+K^-$			
1–1.7	$99 \pm 20 \pm 18$	$285 \pm 29 \pm 27$	$1.38 \pm 0.13 \pm 0.07$
1.7–2.2	$143 \pm 24 \pm 19$	$279 \pm 32 \pm 30$	$1.14 \pm 0.12 \pm 0.03$
2.2–3.5	$177 \pm 26 \pm 11$	$269 \pm 33 \pm 21$	$0.99 \pm 0.12 \pm 0.03$

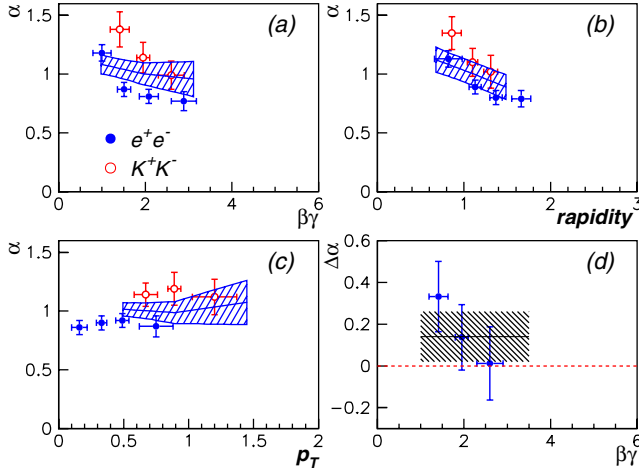


FIG. 3 (color online).  $\alpha$  parameters of  $\phi \rightarrow e^+e^-$  (closed circles) and  $\phi \rightarrow K^+K^-$  (open circles) as functions of (a)  $\beta\gamma$ , (b) rapidity, and (c)  $p_T$ . The horizontal error bars are the rms values of the horizontal bins. The hatched bands show corrected  $\alpha_{\phi \rightarrow e^+e^-}$  to be compared with  $\alpha_{\phi \rightarrow K^+K^-}$  (see text). In (d), the differences between  $\alpha_{\phi \rightarrow K^+K^-}$  and  $\alpha_{\phi \rightarrow e^+e^-}$  in the kaon acceptance window are shown. The average value and error are also plotted as a hatched band.

contour, where the measured  $\Delta\alpha$  and its error provide the 90% confidence limit.

Next, we have investigated how the  $K^+K^-$  spectra could provide constraints for  $k_K$ . Since we observed a significant excess on the low-mass side of the  $\phi$ -meson peak in the  $\phi \rightarrow e^+e^-$  channel [15], we consider that a similar excess can exist in the  $\phi \rightarrow K^+K^-$  spectra. We thus reanalyzed the  $\phi \rightarrow K^+K^-$  spectra with the same fitting procedure as described earlier, except that the mass range from  $2m_{K^\pm}$  to  $1.01 \text{ GeV}/c^2$  ( $0.01 \text{ GeV}/c^2$  below the  $\phi$  peak) was excluded from the fit. Because of the statistical limitation, we combined all the kinematical bins into one.

This procedure gives the amount of excess  $N_{\text{ex}}$  as a surplus over the  $\phi$ -meson peak and the background. Since the  $K^+K^-$  acceptance is a function of the invariant mass, we corrected  $N_{\text{ex}}/N_\phi$  and obtained  $0.044 \pm 0.037(\text{stat}) \pm 0.058(\text{syst})$  and  $0.076 \pm 0.025(\text{stat}) \pm 0.043(\text{syst})$  for carbon and copper targets, respectively. Although these surpluses are close to zero, they statistically limit the number of modified  $\phi$  mesons in the  $K^+K^-$  spectra. The ratio  $N_{\text{ex}}/N_\phi$  can be considered as the ratio of the number of  $\phi$  mesons decayed inside the nucleus to that outside it, i.e.,  $N_{\text{ex}}/N_\phi = N_\phi^{\text{in}}/N_\phi^{\text{out}}$ .

The relation between  $N_\phi^{\text{in}}/N_\phi^{\text{out}}$  and  $k_K$  was also obtained by the Monte Carlo calculation. We assumed that the decays inside the half-density radius of the Woods-Saxon distribution contribute to  $N_\phi^{\text{in}}$ . By using the calculated relation,  $k_K$  was obtained as  $1.4 \pm 1.1(\text{stat}) \pm 2.1(\text{syst})$ ; this was the average value for carbon and copper targets. This result is plotted in Fig. 4, together with the upper-limit value, 6.0, at the 90% confidence limit.

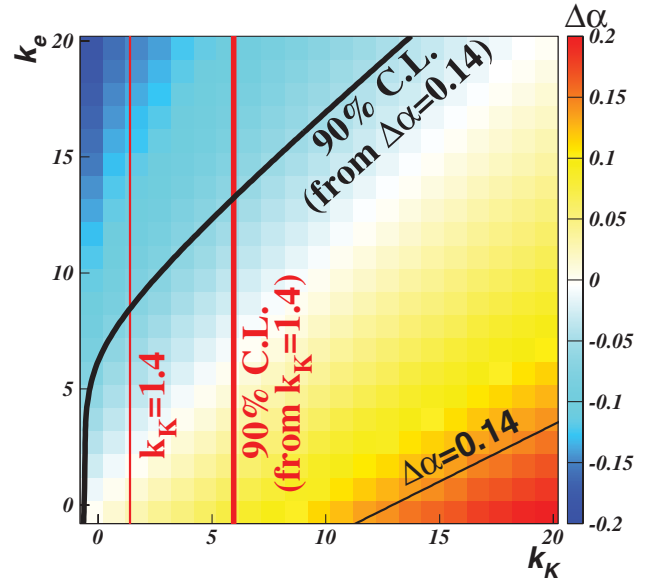


FIG. 4 (color). The obtained constraints on the in-medium modification of the partial decay widths of  $\phi \rightarrow K^+K^-$  and  $\phi \rightarrow e^+e^-$  (see text).

The two constraints shown in Fig. 4 are the first experimental limits assigned to the in-media broadening of the partial widths of the  $\phi$  meson. To obtain the limits, we have renormalized the probability distribution functions by eliminating an unphysical region corresponding to  $\Gamma^*/\Gamma^0 < 0$ .

To conclude, the experiment KEK-PS E325 measured the  $\phi$ -meson production via the  $e^+e^-$  and  $K^+K^-$  decay channels in 12 GeV  $p + A$  reactions. The observed  $K^+K^-$  spectra are well reproduced by the relativistic Breit-Wigner distribution with a combinatorial background shape. The nuclear mass number dependences of  $\phi \rightarrow e^+e^-$  and  $\phi \rightarrow K^+K^-$  are consistent. We have obtained the limits on the in-media decay widths for both the decay channels.

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\*Electronic address: sakuma@nh.scphys.kyoto-u.ac.jp

†Present address: Faculty of Science and Technology, Tokyo University of Science, 2641 Yamazaki, Noda, Chiba 278-8510, Japan.

‡Present Address: ICEPP, University of Tokyo, 7-3-1 Hongo, Tokyo 113-0033, Japan.

§Present Address: Physics Department, Graduate School of Science, Tohoku University, Sendai 980-8578, Japan.

||Present Address: Department of Physics, University of Tokyo, 7-3-1 Hongo, Tokyo 113-0033, Japan.



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- [26] Indeed, in our detector acceptances, JAM predicts such a dependence of the  $\alpha$  parameter in the  $y$ - $p_T$  plane.
- [27] This linear assumption is consistent with the theoretical calculation in Fig. 4 of Ref. [4] at the  $\phi$  mass (1020 MeV/ $c^2$ ).