

## Evidence for In-Medium Modification of the $\phi$ Meson at Normal Nuclear Density

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Invariant mass spectra of  $e^+e^-$  pairs have been measured in 12 GeV  $p + A$  reactions to detect possible in-medium modification of vector mesons. Copper and carbon targets are used to study the nuclear-size dependence of  $e^+e^-$  invariant mass distributions. A significant excess on the low-mass side of the  $\phi$  meson peak is observed in the low  $\beta\gamma(= \beta/\sqrt{1-\beta^2})$  region of  $\phi$  mesons ( $\beta\gamma < 1.25$ ) with copper targets. However, in the high  $\beta\gamma$  region ( $\beta\gamma > 1.25$ ), spectral shapes of  $\phi$  mesons are well described by the Breit-Wigner shape when experimental effects are considered. Thus, in addition to our earlier publications on  $\rho/\omega$  modification, this study has experimentally verified vector meson mass modification at normal nuclear density.

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The properties of hadrons, which are composite particles of quarks and gluons, have been measured and determined in the past in many experimental studies. These properties, such as mass and decay width, represent vacuum expectation values. Therefore, in principle, they can differ when the vacuum itself changes, i.e., when they are in hot and/or dense matter.

A possible and interesting experimental approach to the in-medium properties of hadrons is to measure the dileptons from the decays of hadrons in hot or dense nuclear matter, in which the chiral symmetry could be restored leading to changes in those properties. The present experiment, KEK-PS E325, was conducted at the KEK 12-GeV Proton-Synchrotron, in order to search for in-medium mass modifications of vector mesons in the reaction 12 GeV  $p + A \rightarrow \rho, \omega, \phi + X \rightarrow e^+e^- + X'$ . In our earlier publications [1,2], we reported the mass modification of  $\rho$  and  $\omega$  mesons in a nuclear medium. In the present Letter, we report new results of the  $\phi$  meson.

In the case of the  $\rho$  and  $\omega$  mesons, it is very difficult to distinguish between matter effects affecting only one of the two mesons, or both, due to the overlapping of two peaks with different widths [1,2]. The natural width of the  $\phi$  meson is narrow (4.26 MeV/ $c^2$ ) without other resonances in the vicinity; therefore, we can examine the possible mass modification more clearly. When the properties are modified by the medium, the observed spectrum contains two components: in-vacuum decays with a normal mass distribution and in-medium decays with a modified mass distribution. The latter component can cause an excess around the  $\phi$  meson peak in the invariant mass spectra.

Theoretically, the possibility of the decrease in the mass of light vector mesons in a nuclear medium was first pointed out by Brown and Rho [3]. Thereafter, many theoretical studies were conducted. Hatsuda and Lee calculated the density dependence of the  $\phi$  meson mass based on QCD sum rules [4]. According to their calculation, the expected mass decrease for the  $\phi$  meson at normal nuclear density is 20–40 MeV/ $c^2$ . As for the decay width of the  $\phi$  meson, some theoretical calculations predict the broadening of the width by a factor between 5 or 6 [5,6] and 10 [7], at normal nuclear density. When the width of the  $\phi$  meson broadens by a factor of 10, the lifetime of a  $\phi$  meson,  $c\tau_\phi$ , in a nucleus is reduced from 46 to 5 fm and the probability of in-medium decay increases, thereby reflecting the in-medium properties.

Although several experimental reports on the in-medium modification of  $\rho$  and  $\omega$  mesons exist, including our reports [1,2,8–11] (recently, the GSI S236 Collaboration reported an enhancement of the pion-nucleus potential in a deeply bound pionic  $^{115}119^{123}\text{Sn}$  nuclei as a possible signature of chiral symmetry restoration [12]), experimental information on the  $\phi$  meson modification is very limited. The CERES/NA45 experiment measured dielectron spectra in high-energy heavy-ion collisions [8]; the HADES experiment measured dielectron spectra in 2 GeV A C-C collisions [13]. However, in both experiments, the mass resolution and/or statistics for the  $\phi$  mesons were not sufficient to draw a definite conclusion regarding the  $\phi$  meson mass modification. The NA60 Collaboration measured the dimuon spectra in 158 GeV A In-In collisions [11], and the PHENIX experiment at RHIC reported the

$\phi \rightarrow e^+e^-$  spectrum in Au + Au collisions at  $\sqrt{s_{NN}} = 200$  GeV [14]. Recently, the LEPS Collaboration reported a possible  $\sigma_{\phi N}$  modification in-medium by measuring the  $A$  dependence of the  $\phi$  photoproduction yields in the  $K^+K^-$  decay mode [15]. Thus far, no clear evidence for the modification of the  $\phi$  meson mass has been observed in the above experiments. The result described in the present Letter is the first positive signal of the  $\phi$  meson modification.

Detector elements relevant to our analysis are briefly described as follows. For further details of the E325 spectrometer, see [16]. It comprises two arms with electron ID counters and kaon ID counters that share a dipole magnet and tracking devices. The typical acceptance in the laboratory frame was  $0.5 < \text{rapidity} < 2.0$  and  $1 < \beta\gamma < 3$  for  $e^+e^-$  pairs. In the present Letter, we report analysis results with  $e^+e^-$ -triggered data collected in 2001 and 2002. A primary proton beam with a typical intensity of  $9\ (7) \times 10^8$  per 1.8-sec spill in 2001 (2002) was delivered to targets located at the center of the magnet. In order to observe the nucleus-size dependence, we accumulated data by using two types of targets, carbon and copper. In 2001, one carbon and two copper targets were used simultaneously, while in 2002, one carbon and four copper targets were used simultaneously. The thickness of each copper target was  $73\ \text{mg}/\text{cm}^2$  and that of the carbon target was  $92\ (184)\ \text{mg}/\text{cm}^2$  in 2001 (2002). They were aligned along the beam axis and separated typically by  $46\ (23)\ \text{mm}$  in 2001 (2002).

To reproduce the observed invariant mass spectra, we performed a detailed detector simulation using GEANT4 [17]. All the experimental effects that affect the invariant mass spectrum, such as multiple scattering and energy loss including the external Bremsstrahlung of particles, tracking performance with chamber resolution, and misalignment of tracking devices, were considered. The effect of internal radiative corrections was also taken into account according to [18]. The mass resolution of  $\phi \rightarrow e^+e^-$  was estimated to be  $10.7\ \text{MeV}/c^2$ .

We reconstructed the masses of the  $\phi$  mesons from the measured momenta of the  $e^+$  and  $e^-$ . Figure 1 shows the obtained invariant mass distributions. We divided the data into three parts based on the  $\beta\gamma$  values of the observed  $e^+e^-$  pairs,  $\beta\gamma < 1.25$ ,  $1.25 < \beta\gamma < 1.75$ , and  $1.75 < \beta\gamma$ . We fitted each mass spectrum with a resonance shape of  $\phi \rightarrow e^+e^-$  and a quadratic background curve. For the  $\phi$  meson resonance shape, we used the Breit-Wigner curve  $M_\phi(m) \propto 1/[(m - m_0)^2 + (\Gamma_0/2)^2]$  with pole mass  $m_0 = 1019.456\ \text{MeV}/c^2$  and decay width  $\Gamma_0 = 4.26\ \text{MeV}/c^2$  convoluted over the detector response in the simulation according to the kinematical distributions of the  $\phi$  mesons in each  $\beta\gamma$  region. The kinematical distributions of the  $\phi$  meson were obtained by the nuclear cascade code JAM [19], which reproduced well the observed distributions as shown in Fig. 2. The relative abundance of the  $\phi$  mesons  $N_\phi$ , and the parameters of the quadratic background were

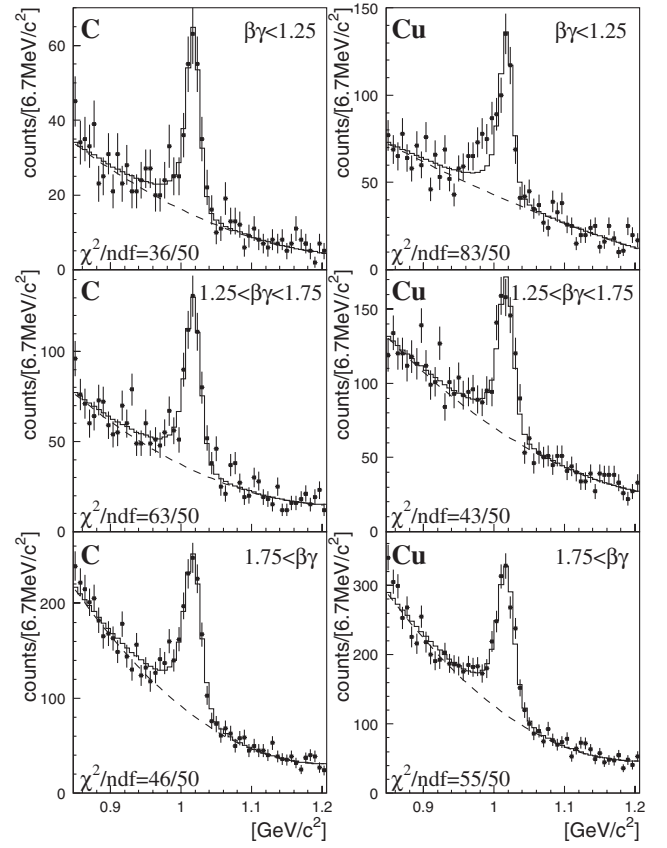


FIG. 1. Obtained  $e^+e^-$  distributions with the fit results. The target and  $\beta\gamma$  region are shown in each panel. The points with error bars represent the data. The solid lines represent the fit results with an expected  $\phi \rightarrow e^+e^-$  shape and a quadratic background. The dashed lines represent the background.

obtained from the fit. The fit region was from  $0.85$  to  $1.2\ \text{GeV}/c^2$ . The carbon data were well reproduced by the fit in all the  $\beta\gamma$  regions. On the other hand, the copper data in the lowest  $\beta\gamma$  region contradicted the applied

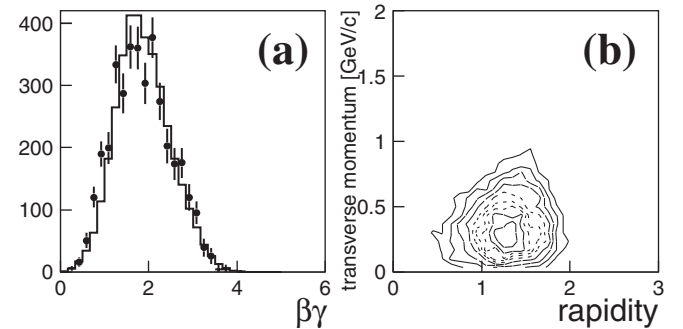


FIG. 2. Kinematical distributions of  $e^+e^-$  pairs in the mass region  $0.95 < M_{ee} < 1.05\ \text{GeV}/c^2$ . Acceptance was not corrected. Distributions of (a)  $\beta\gamma$  and (b) contours in transverse momentum and rapidity. In the plot (a), points represent data and the line represents simulation result using the nuclear cascade code, JAM [19].

TABLE I. The fit  $\chi^2/ndf$  values (a) including and (b) excluding the excess region: 0.95–1.01 GeV/ $c^2$ .

	$\beta\gamma$ range	$\chi^2/ndf$ (a)	$\chi^2/ndf$ (b)
C	<1.25	36/50	31/41
	1.25–1.75	63/50	54/41
	1.75<	46/50	37/41
Cu	<1.25	83/50	57/41
	1.25–1.75	43/50	38/41
	1.75<	55/50	53/41

resonance shape at 99% C.L. due to the visible excess on the low-mass side of the  $\phi$  meson peak.

To evaluate the amount of excess  $N_{\text{ex}}$ , we repeated the same fit procedure except that the mass region from 0.95 to 1.01 GeV/ $c^2$ , where the excess is observed, was excluded from the fit. The obtained  $\chi^2/ndf$ 's including and excluding the excess region are shown in Table I. We obtained  $N_{\text{ex}}$  by subtracting the integral of the fit results from that of the data in the mass region from 0.95 to 1.01 GeV/ $c^2$ . To evaluate systematic errors, we varied the fit region, binning, mass resolution, and mass scale, changed the background curve from quadratic to cubic, changed the Breit-Wigner shape from the nonrelativistic one to the relativistic one, and modified the kinematical distribution of  $\phi$  mesons in the simulation. Then we averaged the obtained values of  $N_{\text{ex}}$  and  $N_{\phi}$  to obtain the listed values in Table II. The systematic errors represent the maximum deviations from the averaged values. For the statistical errors we selected the largest values in above fit conditions. The excess is statistically significant for the copper target data in the lowest  $\beta\gamma$  bin, whereas it is marginal for the carbon target data. This excess is considered to be the signal of the mass modification of the  $\phi$  mesons in a target nucleus because such an effect should be visible only for slow  $\phi$  mesons produced in a large target nucleus.

In the mass region of the  $\rho$  meson the excess was observed both in C and Cu targets [2], but in the case of the  $\phi$  meson we observed the excess only in Cu targets data with small  $\beta\gamma$ . The  $\rho$ -meson lifetime ( $c\tau \sim 1.3$  fm) is shorter than the typical nuclear size and a significant

TABLE II. Numbers of  $\phi$  mesons [ $N_{\phi}$ ] and excess [ $N_{\text{ex}}$ ] evaluated by the fits (see text). Error values shown are statistic (first) and systematic (second).

	$\beta\gamma$ range	$N_{\text{ex}}$	$N_{\phi}$	$N_{\text{ex}}/(N_{\text{ex}} + N_{\phi})$
C	<1.25	$6 \pm 17^{+7}_{-6}$	$257 \pm 26^{+6}_{-7}$	$0.02 \pm 0.06^{+0.02}_{-0.01}$
	1.25–1.75	$-4 \pm 26^{+10}_{-12}$	$547 \pm 41^{+13}_{-15}$	$-0.01 \pm 0.05^{+0.02}_{-0.01}$
	1.75<	$39 \pm 42^{+22}_{-25}$	$1076 \pm 64^{+12}_{-15}$	$0.04 \pm 0.04^{+0.02}_{-0.01}$
Cu	<1.25	$133 \pm 28^{+5}_{-12}$	$464 \pm 38^{+6}_{-5}$	$0.22 \pm 0.04^{+0.01}_{-0.01}$
	1.25–1.75	$35 \pm 33^{+9}_{-12}$	$588 \pm 47^{+14}_{-8}$	$0.06 \pm 0.05^{+0.01}_{-0.01}$
	1.75<	$21 \pm 48^{+25}_{-29}$	$1367 \pm 72^{+24}_{-27}$	$0.02 \pm 0.03^{+0.02}_{-0.01}$

portion of  $\rho$  mesons should decay in both C and Cu nuclei. However, the  $\phi$ -meson lifetime ( $c\tau \sim 46$  fm) is much longer, so even if it is modified in nuclear medium, such an effect should only be visible for a larger nucleus and for  $\phi$ 's with small  $\beta\gamma$ .

We attempted to reproduce the observed mass spectra with a Monte Carlo-type model calculation that includes an in-medium mass modification of the  $\phi$  mesons based on the theoretical predictions of [4–7]. We assumed the density dependence of the  $\phi$  meson mass as  $m_{\phi}(\rho)/m_{\phi}(0) = 1 - k_1(\rho/\rho_0)$ , where  $\rho_0$  is the normal nuclear density [4]. To reproduce the large amount of excess in our data (22% for slow  $\phi$  in the copper target data), it is necessary to introduce a broadening of the total width of the  $\phi$  ( $\Gamma_{\phi}^{\text{tot}}$ ), or at least of the partial width for the  $\phi \rightarrow e^+e^-$  decay ( $\Gamma_{\phi}^{ee}$ ). When no broadening is introduced, the expected rate of in-nucleus decay is just 6% for the  $\phi$  mesons produced in copper nuclei with  $\beta\gamma < 1.25$ . For the density dependence of the total width broadening, we assumed  $\Gamma_{\phi}^{\text{tot}}(\rho)/\Gamma_{\phi}^{\text{tot}}(0) = 1 + k_2^{\text{tot}}(\rho/\rho_0)$ ;  $k_2^{\text{tot}} \geq 0$ . For  $\Gamma_{\phi}^{ee}$  we assumed  $\Gamma_{\phi}^{ee}(\rho)/\Gamma_{\phi}^{ee}(0) = 1 + k_2^{ee}(\rho/\rho_0)$ , and examined following two cases: (i) the branching ratio  $\Gamma_{\phi}^{ee}/\Gamma_{\phi}^{\text{tot}}$  remains unchanged in the medium ( $k_2^{ee} = k_2^{\text{tot}}$ ), and (ii)  $\Gamma_{\phi}^{ee}$  does not increase in the medium ( $k_2^{ee} = 0$ ). It should be noted that the ratio  $N_{\phi \rightarrow ee}^{\text{in}}/N_{\phi \rightarrow ee}^{\text{out}}$  increases with  $\Gamma_{\phi}^{\text{tot}}$  even in the case (ii). Here,  $N_{\phi \rightarrow ee}^{\text{in}}$  ( $N_{\phi \rightarrow ee}^{\text{out}}$ ) denotes the number of in-medium (in-vacuum)  $\phi \rightarrow e^+e^-$  decays. This is because both  $N_{\phi \rightarrow ee}^{\text{in}}$  and  $N_{\phi \rightarrow ee}^{\text{out}}$  decrease but the latter decreases faster.

We considered that  $\phi$  mesons were generated in the target nucleus according to the nuclear density profile. This is because we measured the mass-number dependence of the  $\phi$  meson production cross section as  $\sigma(A) \propto A^1$  [20]. Generated  $\phi$  mesons were traced until the decay point with the modified pole mass and decay width according to the nuclear density. The decay probability increases in the medium due to the width broadening. We used the Woods-Saxon distribution for the nuclear density profile:  $\rho/\rho_0 \propto (1 + \exp[(r - R)/\tau])^{-1}$ , where  $R = 4.1$  (2.3) fm, and  $\tau = 0.50$  (0.57) fm for the copper (carbon) target.

We modified the resonance shape of the  $\phi$  meson with the parameters  $k_1$  and  $k_2^{\text{tot}}$ , then fitted again the observed mass spectra with the same procedure as before. For  $k_2^{ee}$  we examined the two cases as described above. The best-fit results in both cases are shown in Fig. 3. The modification parameters  $k_1$ ,  $k_2^{\text{tot}}$ , and  $k_2^{ee}$ , are common to the six spectra. Figure 4 shows the confidence ellipsoids for the variation of  $\chi^2$  with  $k_1$  and  $k_2^{\text{tot}}$  in cases (i) and (ii). In case (i), obtained best-fit parameters are  $k_1 = 0.034^{+0.006}_{-0.007}$ ,  $k_2^{\text{tot}} = 2.6^{+1.8}_{-1.2}$ , and the minimum  $\chi^2$  ( $\chi_{\text{min}}^2$ ) is 316.4. In case (ii), best-fit parameters are  $k_1 = 0.033^{+0.011}_{-0.008}$ ,  $k_2^{\text{tot}} = 0^{+5.6}_{-0}$ , and the  $\chi_{\text{min}}^2$  is 320.8. In both cases the  $\chi_{\text{min}}^2$  was obtained with parameter  $k_1 \simeq 0.034$ , meaning the pole mass of the  $\phi$  meson decreases by 3.4% at normal nuclear density. The  $\chi_{\text{min}}^2$  in case (ii) (=320.8) is larger than that in

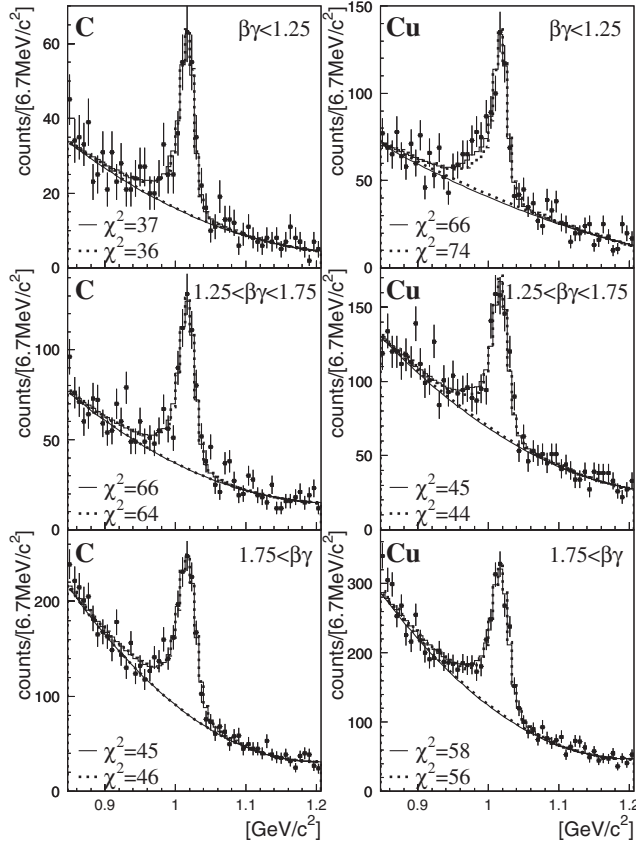


FIG. 3. The best-fit results in cases (i) (solid line) and (ii) (dotted line). The shift parameter  $k_1$ , and broadening parameters  $k_2^{\text{tot}}$  and  $k_2^e$ , are common to the six spectra. The values of  $\chi^2$ s are the sum of the squares of the deviations over 54 data points in each panel.

case (i) ( $=316.4$ ) by 4.4. When we fitted only the Cu data in the lowest  $\beta\gamma$  region, where the major discrepancy occurs, case (ii) was rejected at 99% C.L. and the best-fit parameters of  $k_1$  and  $k_2^{\text{tot}}$  do not change, while case (i) was

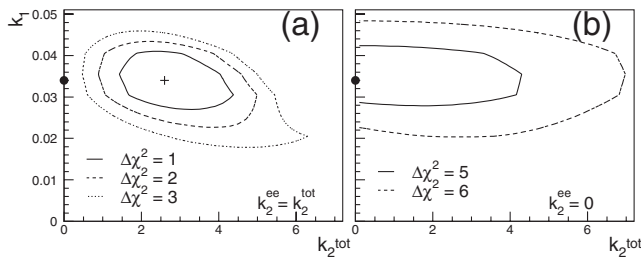


FIG. 4. Confidence ellipsoids for the modification parameters  $k_1$  and  $k_2^{\text{tot}}$  in cases (i) in (a) and (ii) in (b). The values of  $\Delta\chi^2$ 's in both panels are the differences from the  $\chi^2_{\text{min}} (= 316.4)$  at the best-fit point in case (i) which is shown by the cross in the panel (a). The best-fit point in case (ii) is shown by the closed circle in the panel (b), and also in (a) since the ordinates are common to the both cases in the parameter space.

not rejected. The data thus favor an increase of  $\Gamma_{\phi}^{ee}$  by a factor of 3.6 at normal nuclear density.

In summary, we investigated the mass modification of the  $\phi$  mesons by studying the  $e^+e^-$  invariant mass distributions obtained in 12 GeV  $p + A$  reactions. The data obtained with a copper target revealed a significant excess on the low-mass side of the  $\phi$  meson peak in the  $\beta\gamma_{\phi} < 1.25$  region. This observation is consistent with the picture of the  $\phi$  modification in the nucleus. Thus, we conclude that in addition to our earlier publication on  $\rho/\omega$  modification [1,2], this study experimentally verified vector meson mass modification at normal nuclear density.

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