Observation of meson modification in nuclear matter at KEK–PS

S. Yokkaichi*, J. Chiba†, H. En'yo*, H. Funahashi**, H. Hamagaki‡, M. Ieiri†, M. Ishino§, H. Kanda¶, M. Kitaguchi**, S. Mihara[1]**, T. Miyashita[2]**, T. Murakami**, R. Muto**, M. Naruki**, M. Nomachi[3]†, K. Ozawa‡, F. Sakuma**, O. Sasaki†, H. D. Sato**, M. Sekimoto†, T. Tabaru*, K.H. Tanaka†, S. Yamada** and Y. Yoshimura[4]**

*RIKEN (The Institute of Physical and Chemical Research) 2-1 Hirosawa, Wako, Saitama, 351-0198, Japan
†Institute of Particle and Nuclear Studies, KEK, 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan
**Department of Physics, Kyoto University, Kitashirakawa Sakyo-Ku, Kyoto 606-8502, Japan
‡Center for Nuclear Study, Graduate School of Science, University of Tokyo, 7-3-1 Hongo, Tokyo 113-0033, Japan
§ICEPP, University of Tokyo, 7-3-1 Hongo, Tokyo 113-0033, Japan
¶Physics Department, Graduate School of Science, Tohoku University, Sendai 980-8578, Japan

Abstract. We have measured invariant mass spectra of e^+e^- pairs and K^+K^- pairs in 12-GeV p+A interactions at KEK 12-GeV Proton-Synchrotron (PS). The aim of the present experiment is to detect in-medium modification of vector mesons, which is theoretically predicted as a consequence of a partial restoration of the chiral symmetry in nuclear matter. We have observed clear peaks of $\phi \to K^+K^-$, $\omega \to e^+e^-$ and $\phi \to e^+e^-$ in the invariant mass spectra. The $\phi \to K^+K^-$ invariant mass spectra have been well described with known physical processes. The nuclear mass-number dependence of the production cross section of $\phi \to K^+K^-$ follows A^α (α=1.01±0.09). In the e^+e^- invariant mass spectra, we have observed a statistically significant excess for the copper target below the ω peak over the known physical processes. The excess indicates that the spectral shape of meson is modified at the normal nuclear matter density.

INTRODUCTION

In recent years, studies of the chiral property of QCD in hot (T$\neq$ 0) or dense ($\rho \neq 0$) matter is one of the most interesting topics in the field of hadronic physics. There are many theoretical works and predictions about the nature of hadrons in such matter [1, 2, 3]. They suggest that spectral modification of vector mesons can be a good signature of restoration of the chiral symmetry in hot/dense matter. The observed excess in low mass electron pairs by the CERES/NA45 collaboration may hint the chiral symmetry restoration in hot matter [4]. In the dense matter case, Hatsuda and Lee [2] predicted that the chiral symmetry is partially restored at the normal nuclear density and the mass modification of vector mesons is expected. Although the TAGX collaboration reported the observation of the modified ρ meson in ^{3}He(γ, $\pi^+\pi^-$)X interactions [5], further data, especially in the leptonic decay modes which are free from final state interactions, are awaited. The present experiment is one of several experimental efforts [6] to investigate such a property of hadrons.

1 Present Address:ICEPP, University of Tokyo, 7-3-1 Hongo, Tokyo 113-0033, Japan
2 Present Address: Fujitsu Corporation, 4-1-1, Kamikodanaka, Nakahara, Kawasaki, Kanagawa 211-8588, Japan
3 Present Address: Department of Physics, Osaka University, 1-1 Machikaneyama, Toyonaka, Osaka 560-0043 , Japan
4 Present Address: Xaxon Corporation,1-3-19, Tanimachi, Chu-ou, Osaka, Japan

EXPERIMENT

The present experiment, KEK–PS E325, was designed to investigate chiral property of vector mesons at the normal nuclear matter density (ρ=ρ_0). Vector mesons were generated in 12-GeV p+A reactions and decays of the mesons in the modes of $\rho/\omega \to e^+e^-$, $\phi \to e^+e^-$ and $\phi \to K^+K^-$ were measured. We have constructed a large acceptance spectrometer in a dedicated primary beam line EP1B at KEK 12-GeV Proton-Synchrotron. The spectrometer was designed to be able to detect the slowly moving mesons which have a larger probability to decay inside a target nucleus. The layout of experimental setup is shown in FIGURE 1 schematically. The spectrometer had two electron arms and two kaon arms, which shares the dipole magnet and the tracking devices. The electron arms covered from $\pm 12°$ to $\pm 90°$ horizontally and $\pm 22°$ vertically. The kaon arms covered from $\pm 12°$ to $\pm 54°$ horizontally and $\pm 6°$ vertically. Primary proton beam (typical intensity is 5×10^8 Hz) was delivered to the targets located at the center of magnet. Three kinds of targets were used at the same time, aligned in-line along the beam axis, separated each other by 45 mm typically. Total interaction length of the three targets was about 0.1 $\sim$ 0.2 %. The Magnetic field at the center of the magnet was 0.71 T and the field integral was 0.81 T·m from the center to the radius of 1600 mm, where the last tracking devices BDC were located.

The mass scale and the resolution were evaluated through a comparison of the observed spectra of known resonances with the Monte Carlo simulation by taking into account the chamber resolution and the multiple scattering. The observed peak width of $\Lambda \to p\pi^-$ and $K_s \to \pi^+\pi^-$ decays were well reproduced with the simulation and the mass resolutions for $\omega \to e^+e^-$, $\phi \to e^+e^-$ and $\phi \to K^+K^-$ were estimated to be 9.6, 12.0 and 2.4 MeV/c^2 respectively [7, 8].

We started the construction of the spectrometer in 1996. The data taking is started in 1997 for K^+K^- channel and 1998 for e^+e^- channel. In next section, spectral shape of K^+K^- invariant mass for the data taken in 1999 [7] and e^+e^- mass for the data taken in 1998 [8] are discussed. The nuclear mass-number dependence of the production cross section of ϕ mesons is discussed for the K^+K^- data of 1997 [9] /1999[7]. Preliminary result for the mass number dependence of ω and ϕ meson production in e^+e^- channel for the 1999 data[10] is also presented.

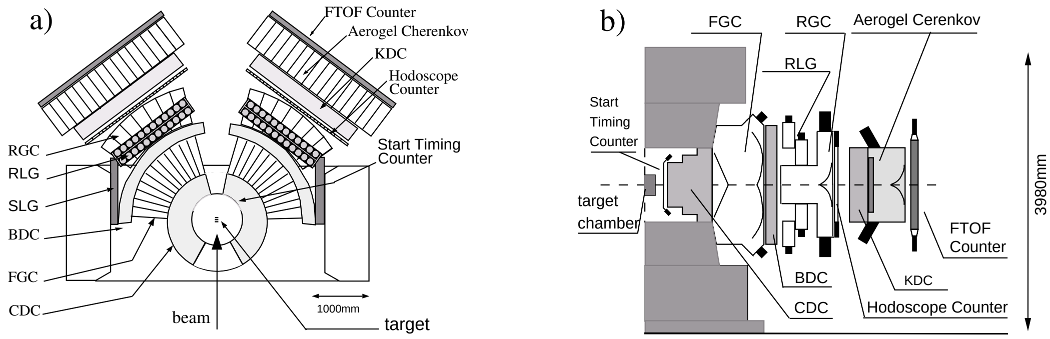

FIGURE 1.
Schematic view of the E325 spectrometer. a) is a top view and b) is a vertical cross section along the 33 degree line from the beam line, which is the center of the kaon arm (see text).

RESULT AND DISCUSSION

Spectral shape of K^+K^- . The invariant mass spectra of K^+K^- pairs detected in a single arm are shown in FIGURE 2 [7]. Clear peaks of $\phi \to K^+K^-$ decays are seen. We have reproduced the spectra with use of the nuclear cascade code, JAM [11] by taking following source in account: $\phi \to K^+K^-$ decays, $a_0/f_0 \to K^+K^-$ decays, non-resonant K^+K^- pairs and the background due to the miss-identified particle. The shape, used in fitting, of the last one is estimated using the event mixing methods and others were evaluated with JAM output events by taking into account the experimental mass acceptance and by smearing with the achieved mass resolution. The ratio of the amount of non-resonant K^+K^- pairs to that of $\phi \to K^+K^-$ was fixed at the JAM results. The amounts of the miss-identified particles were determined experimentally and were about 10% of the total number of K^+K^- pairs. Thus free parameters in the fitting we applied are only two, the over all normalization and the relative strength of $a_0/f_0 \to K^+K^-$ to $\phi \to K^+K^-$.

The observed spectra were well reproduced both for the light nuclear targets (C and CH_2) and for the heavy targets (Cu and Gd) with these four components by scaling down the yields of $a_0/f_0 \rightarrow K^+K^-$ from the JAM prediction to 17.7% and 18.4% respectivly. Such a scale down is validated since the production and decay of a_0/f_0 mesons are not well measured so far and JAM is not tuned well in this aspect. The determined ratios of $a_0/f_0 \rightarrow K^+K^-$ to $\phi \rightarrow K^+K^-$ were statistically the same for both the light and heavy cases. It means that the two spectra are statistically identical. Thus we did not observe a signature of in-medium modification of ϕ meson, which should appears as a significant mass-number dependence of the spectral shape.

It should be noted that the obtained kinematic distributions of the ϕ mesons are also well reproduced by JAM. Moreover, the nuclear mass-number dependence of the production cross section is also well reproduced by JAM, as described later.

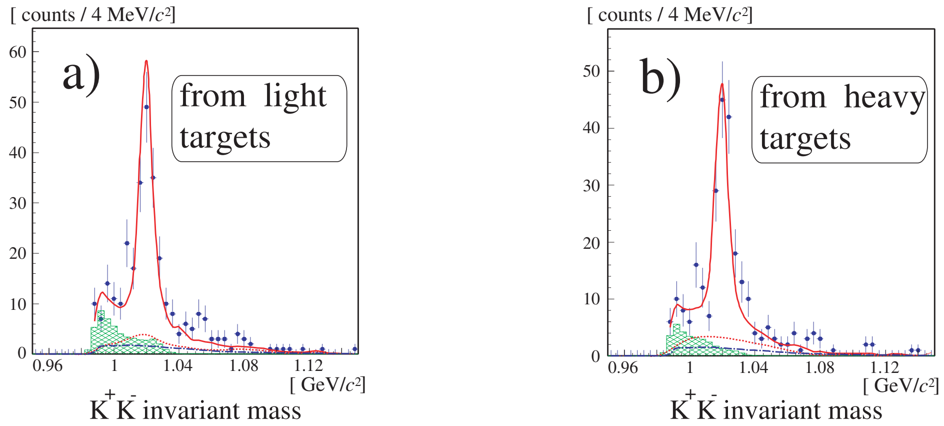

FIGURE 2.
Invariant mass spectra of K^+K^- pair. a) is for C and CH_2 targets and b) is for Cu and Gd targets. The solid lines are the best fit results. The hatched histograms denote the $a_0/f_0 \rightarrow K^+K^-$ decays. The dotted lines indicate the non-resonant K^+K^- pairs. The dot-dashed lines indicate the background due to the particle miss-identification [7].

Spectral shape of e^+e^- . As shown in FIGURE 3, we have observed a significant difference in the invariant mass spectra of e^+e^- below the ω meson peak between p+C and p+Cu interactions [8]. These histograms depict the events when the electron and the positron were detected in the different arms, so that the low-mass part of the spectra was largely suppressed.

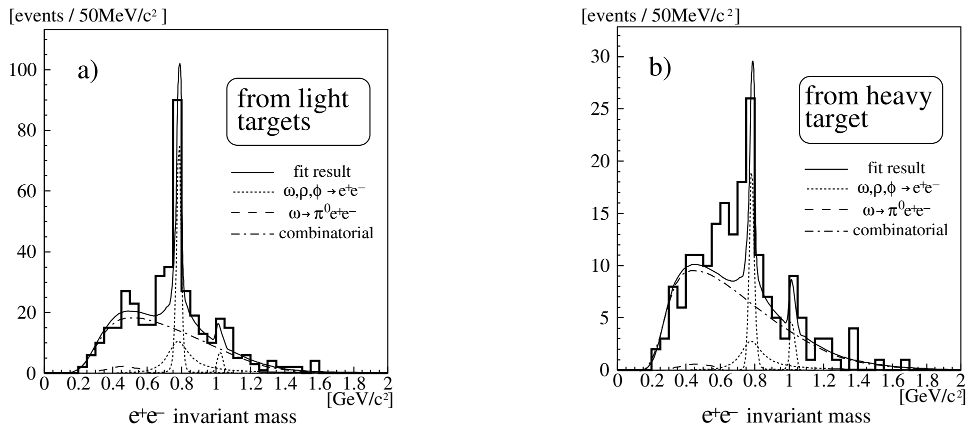

FIGURE 3.
Invariant mass spectrum of e^+e^- pair. (a) is for C and CH_2 targets and (b) is for Cu target. The solid lines show the best-fit results of the known hadronic sources with the combinatorial background. The dotted lines indicate the contributions from ρ, ω and ϕ decays. The dashed lines indicate $\omega \rightarrow \pi^0 ee$ decays and the dot-dashed lines indicate the combinatorial background. For the heavier target, an enhancement is seen below the ω mass region. This enhancement indicates the mass modification effect in nuclear matter.[8]

We tried to reproduce the shape of the histogram by taking into account the combinatorial background and the known hadronic sources. As hadronic sources, $\rho \to e^+e^-$, $\omega \to e^+e^-$, $\phi \to e^+e^-$, $\eta \to e^+e^-\gamma$, and $\omega \to e^+e^-\pi^0$ were considered. The mass shapes of the ρ, ω and ϕ mesons were given as the Breit-Wigner function with the natural width, which were smeared with the estimated mass resolution. The shapes of the e^+e^- invariant mass spectra from the Dalitz decays were taken from the reference [12]. To obtain the mass shape of the known sources in the observed spectra, we evaluated the experimental mass acceptance using the JAM output. The distribution of the combinatorial background was obtained by the event-mixing method. The relative abundances of the known sources and the background were obtained through the fitting. We assumed that the production cross section of ρ is equal to that of ω following the data obtained at the same energy [13].

The contributions of each source were determined by the fit and are shown in FIGURE 3 and TABLE 1. The contribution of $\eta \to e^+e^-\gamma$ turned out to be negligible. The excess in the mass region from 550 MeV/c^2 to 750 MeV/c^2 shown in the TABLE was estimated by subtracting the fit function from the data. The excess is statistically significant for the copper target data. This indicates the spectral shape of mesons is modified at the normal nuclear density. The mass range of this excess is consistent with the expected shift predicted by Hatsuda and Lee [2] or Brown and Rho [3].

TABLE 1.
Yield of mesons and excess between 550MeV/c^2 $\sim$ 750 MeV/c^2 obtained as fit results of the e^+e^- invariant mass spectra.

	ω	ϕ	excess
light targets(C and CH_2)	75.5 ± 9.0	7.4 ± 5.8	19.6 ± 11.7
heavy target (Cu)	20.0 ± 4.8	5.2 ± 2.7	29.5 ± 8.7

Nuclear mass-number dependence. We analyzed the nuclear mass-number dependence of the production cross section of the mesons using the standard parametrization: $\sigma(A) = \sigma(A{=}1)\times A^{\alpha}$. For ϕ meson in the K^+K^- channel, we obtained α=1.01$\pm$0.09 over the four targets: H, C, Cu and Pb [7, 9]. For $\omega \to e^+e^-$, we obtained α=0.67$\pm$0.12 [8] over the C and Cu targets. New preliminary results from the e^+e^- data taken in 1999 are α=0.67$\pm$0.08 for ω and α=1.10$\pm$0.13 for ϕ, both over the H, C and Cu targets [10]. These new results are statistically consistent with old results. In any case, the data for H were obtained by the subtraction as $\sigma(H) = \{\sigma(CH_2) - \sigma(C)\}/2$. These results are shown in FIGURE 4 and TABLE 2.

These results give the information about the production mechanism of mesons in p + A interaction. The value of α=2/3 for the ω meson indicates that ω is produced through the fragmentation from the first collision taking place at the nuclear surface. The stronger dependence, $\alpha \simeq 1$ for the ϕ meson suggests that ϕ is mainly produced in the secondary collisions of particles which are generated at the first collision. The JAM simulation results support this picture as shown in FIGURE 4. The ϕ meson production in JAM is dominated by the secondary process and α parameter calculated over the C and Cu targets is about 1.11, while the ω production is dominated by the primary fragmentation and calculated α is 0.78. In each case the values of α are calculated over C and Cu targets and are statistically consistent with our experimental results.

TABLE 2.
The α parameter of the production cross sections for ω and ϕ mesons. The JAM predictions for them are also shown.

	K^+K^- channel	e^+e^- channel(preliminary)	JAM
ω	–	0.67 ± 0.08	0.78
ϕ	1.01 ± 0.09	1.10 ± 0.13	1.11

SUMMARY AND OUTLOOK

We have constructed a large acceptance spectrometer at KEK-PS to detect the meson modification in the nuclear matter. Invariant mass spectra of K^+K^- and e^+e^- were measured. In the K^+K^- invariant mass spectra, spectral shape around ϕ meson can be explained with known hadronic sources. Nuclear mass-number dependence of ϕ meson production cross section measured in K^+K^- channel follows A^{α} (α=1.01$\pm$0.09), and the preliminary result in the e^+e^- channel is statistically consistent with it. This strong dependence suggests that ϕ mesons are produced mainly in

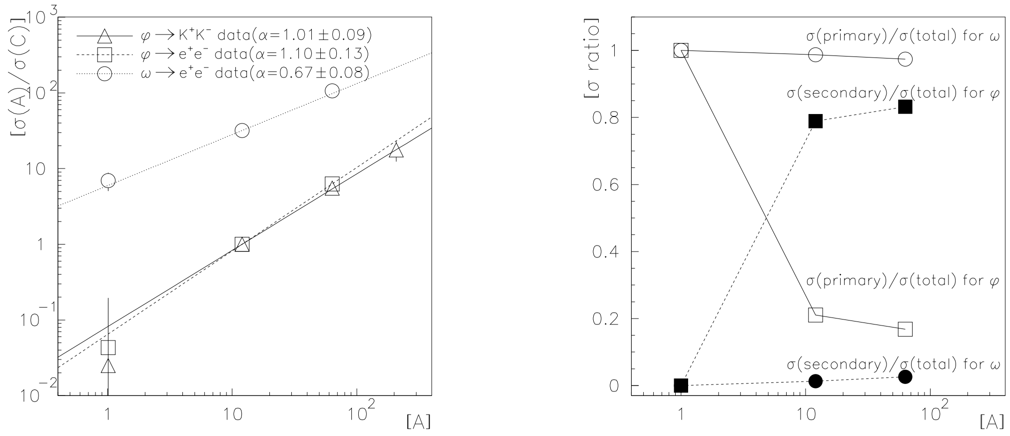

FIGURE 4.
Nuclear mass-number dependence of the meson production cross section. Left figure describes obtained data in $\phi \to K^+K^-$ (triangle), $\phi \to e^+e^-$ (square) and $\omega \to e^+e^-$ (circle). The ϕ meson production cross section of each target is normarized with the cross section for the carbon target. The ω meson's are normarized with the cross section of the ϕ for the carbon target [9, 7, 10]. Right figure describes the production cross section for each origin when the meson is produced in JAM simulation, for the ω and ϕ mesons. Cross sections are normarized with a total production cross section for each mesons. Open circle denotes the ω meson generated in the primary fragmentation and solid circle denotes ω generated in the secondary collisions. Open and solid square are primary and secondary for the ϕ meson respectively. Lines are just for eye-guide [10].

secondary collisions in p+A interaction. In the e^+e^- invariant mass spectra, a significant difference of spectral shape between carbon and copper targets is observed around the ρ/ω region. It indicates that the spectal shapes of mesons are modified at the normal nuclear matter density. Data taking and analysis are still ongoing and several times of more statistics will be accumulated in the end of 2001.

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REFERENCES

1. T. Hatsuda and T. Kunihiro, Phys. Rep. **247** (1994) 221, G.E. Brown and M. Rho, Phys. Rep. **269** (1996) 333, W.S. Chung, C.M. Ko, G.Q.Li, Nucl. Phys. **A641** (1998) 357 and references therein.
2. T. Hatsuda and S. H. Lee, Phys. Rev. **C46** (1992) R24.
3. G.E. Brown and M. Rho, Phys. Rev. Lett. **66** (1991) 2720.
4. G. Agakichiev *et al.*, Phys. Lett. **B422** (1998) 405
5. G.J. Lolos *et al.*, Phys. Rev. Lett. **80**, 241 (1998), M.A. Kagarlis *et al.*, Phys. Rev. **C60**, 025203 (1999).
6. W. Schoen *et al.* (HADES Collaboration), Acta Phys. Polon. **B27**:2959-2963 (1996).
   GSI/SIS proposal S214, Search for bound η- and ω- nuclear states using the recoilless $(d,{}^3He)$ reaction.
   T. Nakano *et al.*, Nucl. Phys. **A629**, 559c (1998).
   KEK-PS E325 proposal (http://www.pn.scphys.kyoto-u.ac.jp/phi/E325_project.html).
7. M. Ishino, Memoirs of the Faculty of Science, Kyoto Univ., Series of Physics, Astrohysics, Geophysics and Chemistry, Vol. 42, No.1, Article 1(2001) (doctor thesis), M. Ishino *et al.*, to be submitted to Phys. Rev. Lett.
8. K. Ozawa *et al.*, Phys. Rev. Lett. **86**, 5019 (2001), K. Ozawa, thesis for Kyoto University.
9. S. Yokkaichi, Memoirs of the Faculty of Science, Kyoto Univ., Series of Physics, Astrohysics, Geophysics and Chemistry, Vol. 41, No.1, Article 3(2001)(doctor thesis)
10. T. Tabaru, thesis for Kyoto University.
11. Y. Nara *et al.*, Phys. Rev. **C61**:024901 (1999).
12. A. Faessler, C. Fuchs and M. I. Krivoruchenko, Phys. Rev. **C61**:035206 (2000).
13. V. Blobel *et al.*, Phys. Lett. **B48**, 73 (1974).