Nuclear production of ϕ meson at KEK

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We have observed $\phi \to K^+K^-$ decays in 12–GeV $p + A$ interaction for three different targets, polyethylene, carbon and lead. The experiment E325 is being performed at the primary beam-line EP1B at the KEK Proton Synchrotron. The data from the first physics run in 1997 are reported. The kinematical region of the observed ϕ mesons covers 1 to 3 in $\beta\gamma_{lab}$ where modification of ϕ meson in nuclear matter is expected to be visible. The shape of the invariant mass spectra of the observed ϕ mesons are consistent with that observed in free space within the statistics which are presently available. The observed mass-number dependence of the production cross section follows A^α (α=0.98$\pm$0.10). No significant p_T dependence has been observed on the α parameter.

1. Introduction

In QCD, hadrons are described as a bound state of confined valence quarks which obtained the effective mass due to the spontaneous breaking of the chiral symmetry. This mechnism determines the properties of hadrons in free space, such as the mass and the decay width. If the vacuum structure was changed from that in free space, those properties should also change.

The quark condensate $\langle\bar{q}q\rangle$ is the order parameter of the chiral symmetry which is subject to change in hot (T$\neq$ 0) or dense ($\rho \neq 0$) matter providing a vacuum structure different from that in free space. Although $\langle\bar{q}q\rangle$ is not an observable, the mass of vector mesons can provide a good measure of the mass of valence quarks[1]. An experimental observation of in-medium modifications of vector mesons is thus desirable to study the nature of QCD in the non-perturbative region.

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In hot matter, $\langle\bar{q}q\rangle$ as a function of temperature is expected to decrease rapidly to zero around the critical temperature T_c where the QCD phase transition will occur and the chiral symmetry will be restored. The observed excess in lepton pairs by the CERN heavy-ion experiments may already hint a precursor of the symmetry restoration[2].

On the other hand, in dense matter, linear decrease of $\langle\bar{q}q\rangle$ is expected theoretically [1]. Several experimental efforts, including this work, have been started to investigate effects of the partially-restored chiral symmetry at normal nuclear-matter density.

Table 1
Experiments to study nuclear density effect on vector mesons

place	channel	status	Ref.
KEK(Tanashi)-ES	$\gamma + A \to \rho + X$ $(\rho \to \pi^+\pi^-)$	Published	[3]
KEK-PS	$p + A \to \phi + X(\phi \to K^+K^-/e^+e^-)$	Running (this work)	[4]
SPring-8	$\gamma + A \to \phi + X$ $(\phi \to K^+K^-)$	Ready to run	[5]
GSI/HADES	$\pi + A \to \omega + X$ $(\omega \to e^+e^-)$	Preparation	[6]
GSI/FRS	$d + A \to^3 He + A^*$(bound)	Ready to run	[7]

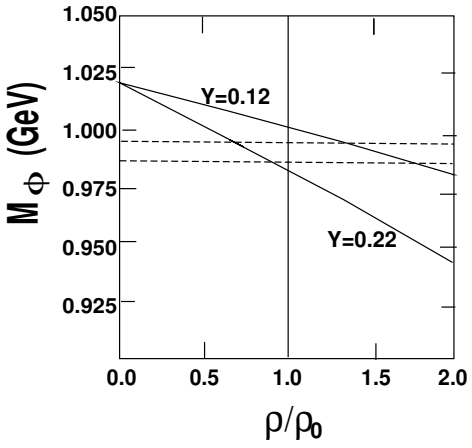

Figure 1. Hatsuda and Lee's predictions for the density dependence of the mass of ϕ meson. Dashed lines are the threshold of the $K\bar{K}$ channels. The two solid lines represent the range of the strange-quark condensate expected from the experimental observation (Y=$2\langle s\bar{s}\rangle/(\langle u\bar{u}\rangle + \langle d\bar{d}\rangle)$).

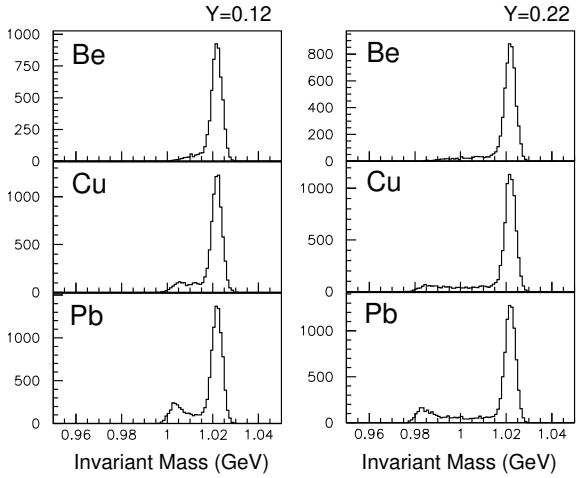

Figure 2. Expected signals for 3 different targets and for the different assumptions of the strangeness condensate as of Fig.1.

Table 1 lists those experiments. The present work, KEK-PS E325, is characterized

by the simultaneous measurements of the hadronic and the leptonic decay modes of the ϕ. Based on the QCD sum rule, Hatsuda and Lee predicted[1] that the ϕ-meson mass decreases as shown in Figure 1. According to this model, the mass decrease of ϕ meson is in the range of 20 to 40 MeV at normal nuclear density ρ_0.

Figure 2 shows the expected invariant mass spectra of the ϕ for beryllium, copper and lead nuclei, according to the predictions of the mass shift in Fig.1. The Woods-Saxon type nuclear density distribution is employed in the Monte Carlo calculation which treats the ϕ with $\beta\gamma_{lab} \sim 1$. The dispersion of mass in media, which is experimentally measurable, is neglected in the calculation.

In copper case, about 10% of ϕ mesons are expected to decay inside the nucleus when any in-medium modification is absent. And in the invariant mass spectra, they make the second peak on the left side of the main peak which consists of the ϕ mesons decayed outside the nucleus. It should be noted that in the K^+K^- channel, the invariant mass spectra could be deformed due to rescattering and modification of kaons in nucleus. Measurements in the e^+e^- channel are thus more desirable.

The decay branching ratios are sensitive to the mass shift of ϕ meson and kaon because of the small Q-value, 32MeV, in the K^+K^- channel. Even if the kaon mass shifted and the ϕ mass was unchanged, the effect would result in a change of the branching ratios. If the kaon mass were not modified and the ϕ-meson mass decreased more than 32 MeV , the decay to K^+K^- would be forbidden in nucleus.

Recently, Klingl *et al.*[8] calculated the in–medium modification of ϕ meson being at rest in nucleus. They obtained the mass shift of ϕ meson being consistent with the results of Hatsuda and Lee, with significant broadening of the width as large as 45 MeV/c^2, 10 times larger than in free space. Their calculations was done for the ϕ at rest, and the dispersion, i.e. the width change as a function of the momentum of ϕ meson is yet to be worked out. This calculation, however, implies a significant increase of the decay rate in nucleus for ϕ mesons in flight and a modification of the invariant mass shape in the $\phi \rightarrow K^+K^-$ channel.

Experimentally a detection of ϕ mesons at rest is nearly impossible since the daughter kaons decay immediately. Nevertheless with the slower ϕ mesons, the larger decay probability inside a nucleus and the lager nuclear matter effect are expected.

It should be noted that the production of ϕ meson with a nuclear target is not well studied so far. The cross section of particle productions with a nuclear target normally follows the relation, $\sigma(A) = \sigma(1) \times A^{\alpha}$, where A is the nuclear mass number. In the production of the J/ψ and the Drell–Yan lepton–pairs, α is close to unity in high energy, as measured in the $\mu^+\mu^-$ pairs by Binkley *et al.* in 300–GeV/c $n + A$ interaction[9]. To produce those particles it requires partonic interactions like $g + g \rightarrow J/\psi + g$ or $q + \bar{q} \rightarrow \gamma^*$, i.e. the production is supposed to be perturbative and all the nucleons in a nucleus contribute equally to the production. In the production of π, ρ and ω mesons α is almost 2/3, which corresponds to the projective surface area of nucleus. Those particles, consisting of light $u(\bar{u})$ and $d(\bar{d})$ quarks, are produced in the fragmentation, and the yield is supposed to be governed by the first collision of an incident proton whose mean free path in nucleus is much shorter than a typical nuclear radius. On the production of ϕ meson Binkley *et al.* showed α to be 0.66 ± 0.03, close to 2/3, although their identification of the ϕ meson was not perfect due to the poor mass resolution. Bailey *et al.* measured the

mass number dependence of the ϕ production in the K^+K^- channel in 120–GeV/c $p+A$ interaction and obtained $\alpha = 0.86 \pm 0.02$ [10]. Aleev *et al.* measured $\phi \rightarrow K^+K^-$ decays in 70–GeV $n+A$ interaction and obtained $\alpha = 0.81 \pm 0.06$ [11]. All the ϕ productions mentioned above were measured in the kinematical region of $0 \leq x_F \leq 0.3$ and $0 \leq p_T \leq 1$ GeV/c. No measurement of the target mass dependence of the ϕ meson production had been performed in the region of $x_F \leq 0$, close to the target rapidity.

The simultaneous measurements of $\phi \rightarrow K^+K^-$ and $\phi \rightarrow e^+e^-$ channels being planned in the present experiment can cancel the effect of unknown production mechanism by taking the ratio of the A–dependence between the both channels, and the media effect on the produced ϕ mesons can be extracted. It is, however, very important and interesting to study of the nuclear dependence of the production itself, to understand how the nature of the ϕ reveals in nuclear interaction.

The experiment E325 has been designed to explore the physics discussed above. The spectrometer newly built for the experiment is located at the primary beam line of KEK 12–GeV Proton Synchrotron. The special emphases are put on the detection of slowly moving ϕ mesons ($\beta\gamma_{lab} \leq 2$) which have a larger probability to decay inside nucleus, and the simultaneous measurements of $\phi \rightarrow K^+K^-$ and $\phi \rightarrow e^+e^-$ decays in the same apparatus. It should be noted that high quality primary beam on thin targets is needed to suppress the background from γ-conversion in the e^+e^- channel.

We started the construction of the spectrometer on June 1996. The engineering run was performed on November 1996, and the first physics run was executed in June 1997, focusing on the $\phi \rightarrow K^+K^-$ decay channel. The results from the run in 1997 are reported in this manuscript.

2. EXPERIMENT E325 AT KEK-PS

Figure 3 and 4 show a schematic layout of the experiment. Beam protons were delivered to three targets (carbon, lead, and polyethylene) placed in-line at the center of the spectrometer magnet.

The spectrometer has two arms for kaon and electron detection, sharing the magnet and the tracking devices as common. The kaon arms cover from $\pm 12°$ to $\pm 54°$ horizontally and $\pm 6°$ vertically, where the horizontal angle was measured from the beam line and the vertical angle was measured from the horizontal plane. The electron arms have a much larger acceptance covering from $\pm 12°$ to $\pm 90°$ horizontally and $\pm 22°$ vertically.

The trajectories and momenta of K^+K^- pairs and e^+e^- pairs from ϕ-meson decays were determined with the Cylindrical Drift Chamber (CDC) and the Barrel Drift Chambers (BDC). Kaons were identified with the Time–Of–Flight (TOF) method using the Start Timing Counters (STC) and the Forward TOF Counters (FTOF) in the off-line analysis. The Aerogel Čerenkov counters (AC) and the Hodoscope Counters (HC) were used with FTOF for the on–line trigger to select kaons. Electron identification was performed with the segmented Gas Čerenkov counters (FrontGC / RearGC) and the lead glass EM Calorimeters (SideEMC / RearEMC). Details of the experiment can be found elsewhere[4].

To evaluate the achieved tracking performance, $\Lambda \rightarrow p\pi^-$ decays were studied. In Figure 5, the invariant mass spectrum of $p\pi^-$ pairs are plotted. We required the decay

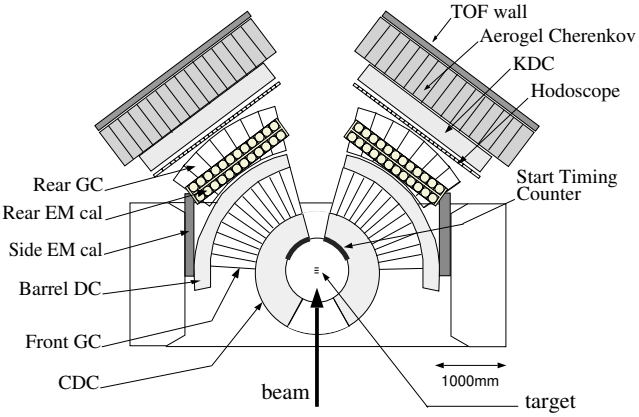

Figure 3. Top view of the E325 setup

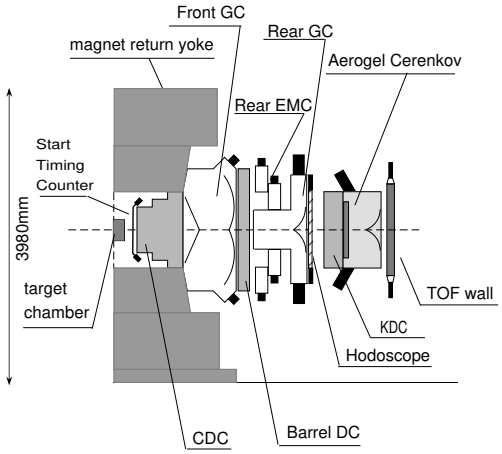

Figure 4. Side view of the E325 setup

points are more than 20 mm apart from the target. The clear resonance peak of Λ shows the mass resolution of 2.2 MeV/c^2.

By rescaling this mass resolution by taking account of the differences in the Coulomb scattering effects and in the momentum distributions of protons, pions, and kaons, we evaluated the mass resolution of the $\phi \to K^+K^-$ invariant mass to be 1.2 MeV/c^2, which is good enough for the present analysis. The peak value of the Gaussian fit is 1115.11 MeV/c^2, which is consistent with the mass of Λ in the literature[12], 1115.68 MeV/c^2.

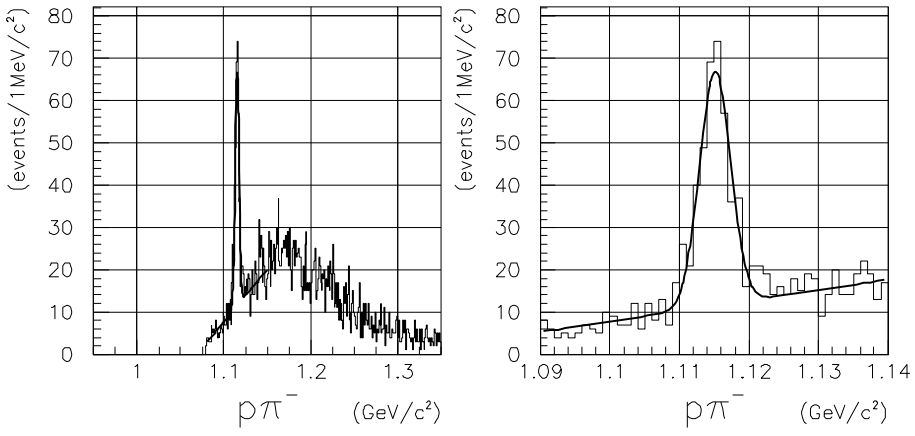

Figure 5. The pπ^- invariant mass spectra. The line is the best fit result of a Gaussian with a linear background. Λ is seen at 1115.11 MeV/c^2 with a resolution of 2.2 MeV/c^2.

3. Results and Discussion

The invariant mass spectra of the K^+K^- pairs are shown in Figure 6 for three different targets, polyethylene, carbon and lead. Clear resonance peaks corresponding to $\phi \rightarrow K^+K^-$ decays are observed.

To evaluate the shape of the background, the event–mixing method was applied. We have assumed that the background is due to an uncorrelated pair of particles so that the two tracks from different events should have the same distribution as the background shape. The hatched areas in the Figure 6 are the shape obtained by the event mixing.

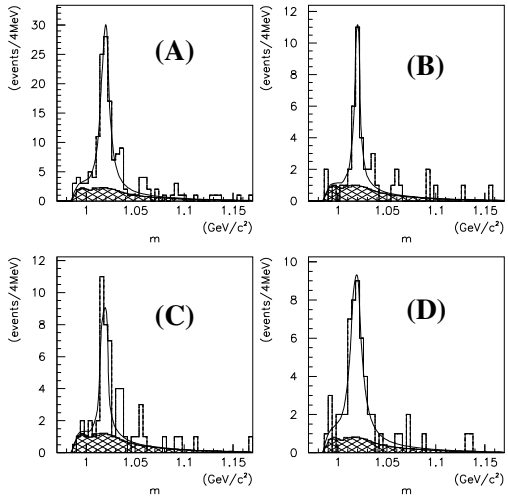

Figure 6. The invariant K^+K^- spectra. In (A) we include all the three targets. The spectra (B),(C) and (D) are corresponding to polyethylene, carbon and lead targets respectively. The hatched areas are the backgrounds evaluated by the event–mixing method.

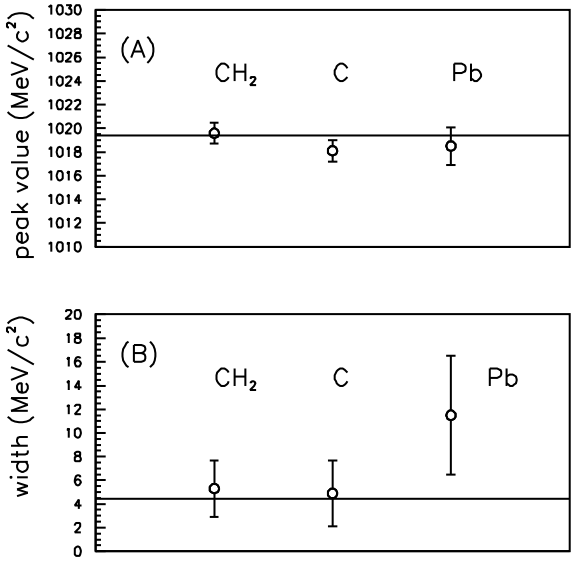

Figure 7. The resonance position (A) and width (B) of the observed ϕ mesons. The line is drawn at the values in free space.

The spectra were fit with the sum of the Breit-Wigner function and the background shape. The resonance positions and the widths are plotted in Figure 7. The resonance positions obtained by the present work are consistent with the known value of 1019.4 MeV/c^2. The widths of ϕ meson from the polyethylene and the carbon target are also consistent with the natural width of ϕ meson, 4.43$\pm$0.05 MeV/c^2[12]. For the lead target case, the width looks larger but the present statistical significance is not enough to conclude the difference.

We analyzed the mass number dependence of the production of ϕ meson using the standard parametrization, $\sigma(A) = \sigma(A = 1) \times A^{\alpha}$, where A is the atomic mass number

of the target nucleus. The results are plotted in Figure 8 together with the best fit line.

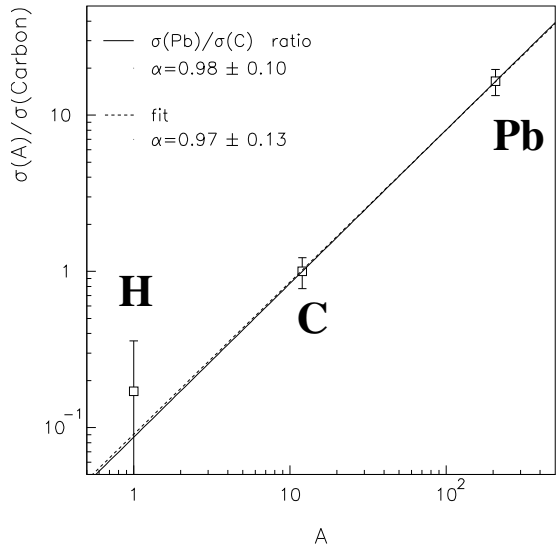

Figure 8. Mass number dependence of the cross section. The solid line is obtained by the ratio of the lead to the carbon data. The dashed line is the best fit over the three points. The data point for hydrogen is obtained by the CH_2–C subtraction.

The obtained α parameter is plotted in Figure 9 together with other available data[10, 11] as a function of x_F of observed ϕ mesons. In spite of the large difference in incident energies and in kinematical coverages, the obtained α is consistent with those of other experiments.

Table 2 summarized those α parameters. The region of the transverse momentum p_T is higher in the present experiment than in others. One has to consider that the Cronin effect[13], characterized by the increase of α as a function of p_T, can be the origin of the large α value obtained in the present experiment.

In the upper part of the Figure 10 we plot, the p_T dependence of α parameter of the present measurement, together with the α measurements in the 4.3–GeV/c $p+A \rightarrow \pi^+ + X$ interactions[14].

In the pion measurements, the increase of α above $p_T = 0.6$ is attributed to the Cronin effect. We did not observe any increase of α in the ϕ-meson production in the present data. The origin of the Cronin effect is not well understood so far. One of possible explanations is the change of the production mechanism from non–perturbative interaction to perturbative one. If we assume the α value is determined with the Q^2 involved in the interaction, the plot of p_T dependence of α mentioned above should be re–plotted as a function of transverse mass, m_T, as is shown in the lower part of the Figure 10. The α value of the present data, then, is reasonably understood together with the α increase seen in the pion data.

Table 2
Comparison of the α parameters and the kinematic regions.

	$\sqrt{s}$ (GeV)	α	p_T (GeV/c)	x_F
12GeV $p + Pb/C$(present work)	5.1	0.98±0.10	0.4< p_T <1.5	−0.8< x_F <0.3
120GeV/c $p + Ta/Be$[10]	15.1	0.86±0.02	0< p_T <1	0< x_F <0.3
100GeV/c $p + Be/p$[10]	14.2	0.96±0.04	0< p_T <1	0.11< x_F <0.24
70GeV $n + A$ [11]	11.6	0.81±0.06	0< p_T <1	0< x_F

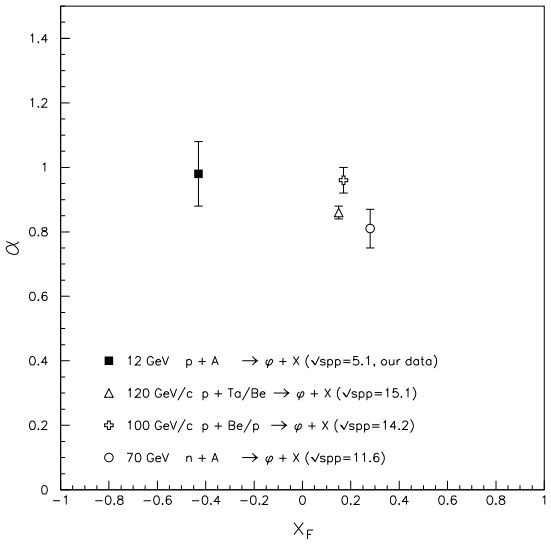

Figure 9. The x_F dependence of the α parameter

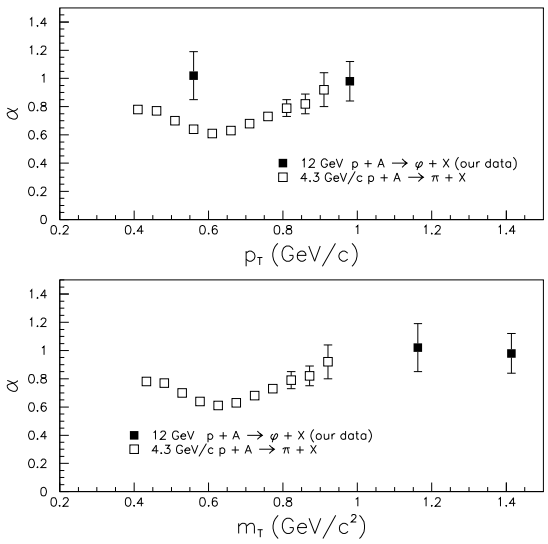

Figure 10. The p_T and m_T dependence of the α parameter.

The fact that the α parameter is close to unity at this energy region ($\sqrt{s} = 5.1$ GeV) is surprising. It is generally believed that incident energy of 12GeV is dissipated rapidly and the nucleons in the back half of the nucleus can not contributed to the particle production. The present results suggests that the production mechanism of ϕ mesons is similar to that of J/ψ at higher energy, which is visible because the production from the fragmentation is largely suppressed due to the significant heavy mass of the $s\bar{s}$ and the OZI suppression.

The result that the α is close to unity suggests that the ϕ mesons are generated at anywhere in the lead nuclei. And the average $\beta\gamma_{lab}$ of the observed ϕ mesons from the lead target is 1.8. The in-medium decay probability can then be deduced with an assumption of in-medium width of ϕ meson. If we take the width 45 MeV from the theoretical

calculation of Klingl *et al.*[8], The in-medium decay probability becomes as large as 40%, and the resonance peak shape should deformed consequently. The present observation is not consistent with such a picture.

As was explained in the Section 1, their calculation was made for the ϕ at rest, and the decay width is subject to change as the momentum of the ϕ increases. Their calculation should be considered as the maximum broadening of the ϕ meson in nuclear media, because the major mechanisms of the broadening is attributed to the K^--nucleon interactions in nucleus and the interactions gets weaker as the kaon momentum increases.

Further data accumulation and data analysis of the present experiment will enable us to determine the in-medium decay rate and in-medium decay width simultaniousely.

4. Conclusion and Outlook

The present experiment is the first attempt to measure the production and the decay of ϕ mesons in the kinematical region where the effect of nuclear media should play an important role. The experiment is on going at KEK with protons of 12–GeV incident energy, which is the lowest $\sqrt{s}$ amongst the ϕ–meson measurements in the hadron induced nuclear reactions.

The data from the first physics run in 1997 were reported. The K^+K^- invariant mass spectra for three different targets, carbon, polyethylene and lead, have been obtained. The widths of the resonance are 4.9±2.8 MeV for carbon and 11.5±5.0 for lead, for the ϕ mesons with $\beta\gamma_{lab}$ in the region from 1 to 3. The widths as well as the resonance positions are consistent with those in free space, and any significant resonance–shape modification, which is expected from the in–medium modification of hadrons, was not seen in the statistical accuracy which is presently available.

The mass number dependence of the production cross sections in the $\phi \rightarrow K^+K^-$ channel has been also obtained using carbon and lead targets. The parameter α is found to be 0.98 ± 0.10, very close to unity. This value is consistent with the ones measured at higher incident energies from 70 to 120 GeV using hadron induced nuclear reaction. The present measurement has firstly covered the region of $x_F < 0$ closer to the target rapidity, while other measurements covered only $x_F > 0$. No significant p_T dependence has been observed on the α parameter. In other words, the steepness of the A–dependence of the ϕ production at this energy is not likely from the Cronin effect.

We have the data being analyzed from the runs in 1998 and 1999. Further data accumulation is scheduled in 2000. The better statistics in the $\phi \rightarrow K^+K^-$ decay mode as well as the new information from the $\phi \rightarrow e^+e^-$ decay mode will soon be available.

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