PROPOSAL for LEPS Experiment in SPring-8

TITLE:

Influence of nucleus potential on kaon and antikaon pairs decayed from short lived particles in a nucleus

FROM:

Name:	C.J. Yoon (RCNP, Osaka University : Research Associate)
Address:	10-1 Mihogaoka, Ibaraki, Osaka Univ., Osaka 567-0047, Japan
Phone number:	+81-(0)90-3269-4607
FAX number:	+81-(0)791-58-0802
E-mail:	cjyoon@rcnp.osaka-u.ac.jp

COLLABORATION MEMBERS:

Name	Affiliation	Position
T. Nakano	RCNP, Osaka University, Japan	Professor
M. Yosoi	RCNP, Osaka University, Japan	Associate Professor
H. Noumi	RCNP, Osaka University, Japan	Professor
S. Ajimura	RCNP, Osaka University, Japan	Associate Professor
T. Hotta	RCNP, Osaka University, Japan	Assistant Professor
N. Muramatsu	RCNP, Osaka University, Japan	Assistant Professor
Y. Sugaya	RCNP, Osaka University, Japan	Assistant Professor
T. Yorita	RCNP, Osaka University, Japan	Assistant Professor
M. Miyabe	RCNP, Osaka University, Japan	Research Associate
Y. Morino	RCNP, Osaka University, Japan	Research Associate
C.J. Yoon	RCNP, Osaka University, Japan	Research Associate
D.S. Ahn	RCNP, Osaka University, Japan	Research Assistant
Y. Kato	RCNP, Osaka University, Japan	Research Assistant
T. Sawada	RCNP, Osaka University, Japan	Research Assistant
M. Oka	RCNP, Osaka University, Japan	Research Assistant
Y. Kon	RCNP, Osaka University, Japan	Graduate Student
S.Y. Ryu	RCNP, Osaka University, Japan	Graduate Student
Y. Kasamatsu	RCNP, Osaka University, Japan	Graduate Student
T. Ishikawa	LNS, Tohoku University, Japan	Assistant Professor
Y. Ohashi	JASRI, Japan	Research Staff
S. Daté	JASRI, Japan	Research Staff
M. Niiyama	Department of Physics, Kyoto University, Japan	Assistant Professor
Y. Nozawa	Department of Physics, Kyoto University, Japan	Graduate Student
N. Tomida	Department of Physics, Kyoto University, Japan	Graduate Student
M. Sumihama	Physics Department, Gifu University, Japan	Associate Professor
J.K. Ahn	Department of Physics, Pusan National Univ., Korea	Professor
S.H. Hwang	Department of Physics, Pusan National Univ., Korea	Graduate Student
J. Pochodazalla	Inst. of Nuclear Physics, Mainz U., Germany	Professor
K. Hicks	Department of Physics, Ohio University, USA	Professor
W.C. Chang	Institute of Physics, Academia Sinica, Taiwan	Professor
J.Y. Chen	Institute of Physics, Academia Sinica, Taiwan	Research Associate
C.Y. Hsieh	Institute of Physics, Academia Sinica, Taiwan	Graduate Student
M. Uchida	Department of Physics, Tokyo Institute of Technology, Japan	Associate Professor
H. Kawai	Department of Physics, Chiba University, Japan	Professor
E.A. Strokovsky	JINR, Dubna, Russia	Professor

REQUESTING RUNNING TIME:

312 hours (39 shifts; 13 days) for data taking.

BRIEF SCHEDULE:

We will use a standard experimental apparatus of LEPS spectrometer, and three plates of lead targets with thickness of 0.5 mm which corresponds to 0.27 radiation length in total. We believe the experiment is ready for the beam by the middle of October 2011 when the beam is scheduled to be delivered.

TYPE OF BEAM:

Linearly polarized tagged photon beam for the energy region of 1.5 $\sim$2.4 GeV, and 2.0 $\times$ 10^6/sec beam intensity; high intensity, low photon beam energy is preferred.

MAIN APPARATUS:

LEPS standard spectrometer; drift chambers, dipole magnet, Aerogel Cherenkov counters, plastic scintillating counters, photon beam tagging counter, electronics and DAQ system.

Influence of nucleus potential on kaon and antikaon pairs decayed from short lived particles in a nucleus

C. J. Yoon, for LEPS Collaboration,
Research Center for Nuclear Physics, Osaka University, 567-0047, Japan

Keywords: Kaonic potential, ϕ photo-production
PACS: 8723Kg, 25.30.Rw

Abstract

We propose an experiment to probe the interactions of kaon- and antikaon-nucleus by measuring K^+K^- pairs decayed from $\phi(1020)$ meson in a nuclear target. The K^+K^- pairs emerged from nuclei can be affected by hadronic potentials and the difference of kaon- and antikaon-nucleus potential maybe modify invariant masses of K^+K^- decayed from ϕ mesons. The ϕ mesons will be produced with a lead target for the energy region 1.5$\sim$2.4 GeV at LEPS facility in Super Photon Ring 8-GeV (SPring-8). By comparing results of Monte Carlo calculation with experimental data, we will measure kaon-, and antikaon-nucleus potential.

1. INTRODUCTION

Properties of hadrons embedded in medium are expected to reflect both the spontaneous breaking of the chiral symmetry as well as hadronic many-body effects. In particular, ϕ meson is the lowest bound state of $\bar{s}s$, its properties in nuclei are directly connected to the way kaon and anti-kaons are modified in a nuclear medium. The ϕ meson decaying in medium can be studied by using e^+e^- as well as K^+K^- channel. Since the kaons strongly interact inside nuclei while electron not interact with the nuclear medium, studying K^+K^- decay channel under nuclei may allows us to probe kaons-nucleus interaction [1].

The kaons-nucleus interaction is related to the kaon condensation which is regarded to be appeared in a high-dense matters such as a core of neutron star. Based on the analysis of K^--atomic levels [2], the K^-N interaction near threshold is strongly attractive with $-(150 \sim 200)$ MeV. Consistently, data from a KEK-PS experiment [3] of (K^-,n), and (K^-,p) reactions from ^{12}C, were interpreted by using K^-N potential with range of $-(160 \sim 190)$ MeV. However, a coupled channel calculations which fits the low-energy $K^{-}p$ interaction data, and $\pi\Sigma$ invariant mass shape from the $\Lambda(1405)$ resonance gives -100 MeV [4], and -80 MeV was obtained from analysis of proton-nucleus collision experiments [5][6]. The K^{-}N potential, therefore, has large uncertainty in theoretical and experimental sides. In this proposal, we demonstrate how the kaon (antikaon)-nucleus potentials modify invariant mass of $K^{+}K^{-}$ from decaying ϕ mesons in nuclei, and we will discuss a possible way to measure kaon (antikaon)-nucleus potentials, finally, estimation of running time together with a result of test experiment will be given.

2. METHOD AND GOAL

Let us consider a hadron is embedded in a nuclear matter, then the momentum of the hadron is governed by a relation of [7] [8]

$$(E-V)^2 = (M_0+S)^2 + \mathbf{P_{in}}^2. \tag{1}$$

Here V and S denote vector, and scalar potential of the hadron. M_0, mass of the hadron in a vacuum, E and $\mathbf{P_{in}}$, total energy of hadron in a vacuum, and a momentum in the medium, respectively. For the vacuum system, since the energy-momentum relation is expressed by

$$E^2 = M_0^2 + \mathbf{P_{out}}^2, \tag{2}$$

the momentum of the outgoing particle from inside of the nucleus can be derived by

$$\mathbf{P_{out}}^2 + M_0^2 = (\sqrt{(M_0+S)^2 + \mathbf{P_{in}}^2} + V)^2. \tag{3}$$

If we rely on the Quark Meson Coupling (QMC) model, the vector (V), and scalar potential (S) of the hadron can be calculated by using a light quark number scaling rule [9] as described by V=$41.8 \cdot (n_q - n_{\bar{q}})(\rho_B/\rho_0)$ MeV, and S= $m_h^* - m_h \simeq -184.5 \cdot (n_q + n_{\bar{q}}) \cdot (1/3)$ MeV, where the symbol ρ_0 denotes normal nuclear density given by 0.15 fm^{-3}, and ρ_B, a density of nuclear medium, n_q, and $n_{\bar{q}}$ denote number of light quarks, and antiquarks for the hadron. The symbol ${m_h}^*$, and m_h denotes hadron mass in a medium and in a vacuum, respectively. The vector and scalar potential for the kaon can be calculated by $\mathrm{V}_{K^+} = +41.8$ MeV, $\mathrm{S}_{K^+} = -63.3$ MeV. And for the antikaon, the values are calculated by $\mathrm{V}_{K^-} = -41.8$ MeV, $\mathrm{S}_{K^-} = -63.3$ MeV. The sums of vector and scalar potentials correspond to real parts of the optical potentials. Because experimentally measured invariant masses (M^*) can be expressed as a function of vector and scalar potential described by:

$$M^{*2} = \sum_i (E_i)^2 - \sum_i (\mathbf{P_{out}}_i)^2, \tag{4}$$

the effect of kaon- and antikaon-nucleus potential to be appeared in the K^+K^- effective mass spectrum, and the issue for the *how the invariant mass is modified,* is depends on its production-, decay-kinematics, and their potentials [10].

In order to investigate feasibility of this measurement at LEPS experiment in SPring-8, we performed a schematic Monte Carlo calculation. We produced ϕ meson by using two-body kinematics for the reaction of $\gamma(p) \to \phi p$ with a lead target, where '(p)' denote a proton in a target nucleus. Photon beams were generated for the energy region of 1.5∼2.4 GeV referred to a beam profile of the experimental data of the LEPS. Because the effect of nucleus potential occurs only if the produced ϕ meson decays inside of the target nucleus, kaon potentials were applied when the individual survival probability of the simulated ϕ-meson is larger than a quantity of $\exp(-(M_\phi/P_\phi)(R/\Gamma_\phi))$. Here M_ϕ denotes mass of ϕ, and P_ϕ, momentum of ϕ meson. We assumed radius of nucleus as R= $1.2A^{1/3}$ fm, where the symbol A denote mass number of nucleus target, and Γ_ϕ is given by 4.26 fm, we used the masses of the ϕ and kaon (antikaon) as the same ones in a vacuum. Instead, momentum dependent nucleus potential of ϕ meson was taken into account as an initial scalar potential of -30 MeV which reduce the effective mass of ϕ meson about 3% for the momentum region less than 400 MeV/c, and 1.5% for the momentum region larger than 400 MeV/c.

The simulated ϕ-mesons in a nucleus were decayed into the K^+K^- pairs satisfying a dispersion relation of Eq.(1), and they were propagated to the outside of the nucleus following to Eq.(3). For the decay process of ϕ meson, azimuthal angle of decaying K^+K^- were isotropically generated for the decay angle region of $0 \sim 180^\circ$ in the center of mass system, and the polar angle was generated for the region of $0 \sim 360^\circ$. Once the momentum of particle is increase, the vector and scalar potentials are expected to be decrease, we have soften the corresponding potentials by multiplying a scaling factor following to Ref. [11],

$$1/(1+\alpha(P_K/P_F)^\beta). \tag{5}$$

Here, P_F denote Fermi momentum of target nucleus which was generated by using an harmonic oscillator model, where the optimum values of the parameters α, and β are 0.5, which are taken from a study of heavy ion collisions experiment for the energy region of 1 GeV/nucleon. Figure 1 shows kaon (antikaon)-nucleus potential with respect to the momentum of kaon (antikaon) decayed from simulated ϕ mesons.

The events were generated by using GEANT3 package with a full geometry of the LEPS spectrometer. A top view of this spectrometer is shown in Fig. 2. The LEPS spectrometer consists of a dipole magnet with a magnetic field strength of 0.7 Tesla, and it has a start counter (SC), a silicon strip detector (SSD) array, three drift chambers, and time-of flight (TOF) counters, and Aerogel Cherenkov counters (AC). Maximum opening angle to accept outgoing pair of charged particles in this spectrometer is 50°.

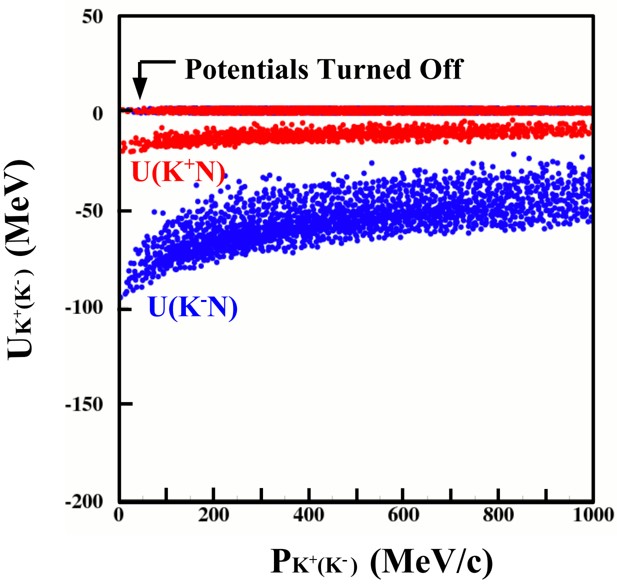

FIGURE 1. (Color online) Applied kaon-, antikaon-nucleus potentials with respect to the momenta of the decaying K^+K^- pairs from the simulated ϕ mesons. The red points denote K^+N potentials, and blue points denote K^-N potentials with respect to the momentum of kaon (antikaon). Data points at zero potentials correspond to the kaons (antikaon) decayed outside of nucleus.

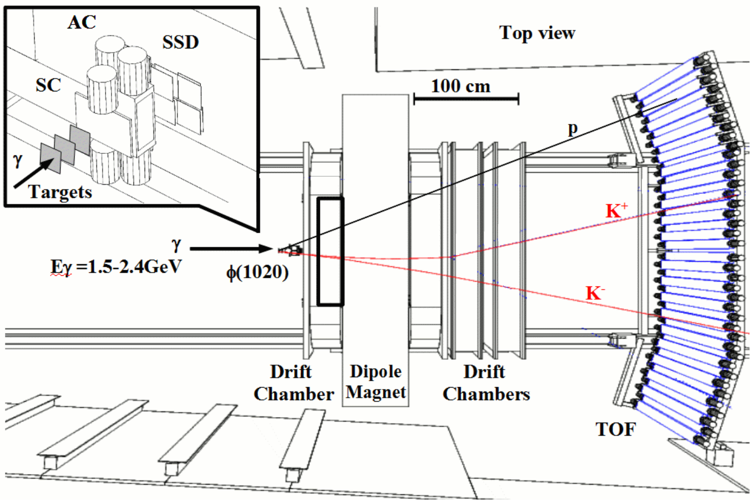

FIGURE 2. (Colors online) Top view of LEPS spectrometer which consists of a dipole magnet with a magnetic field of 0.7 Tesla, silicon strip detectors, aerogel Cherenkov counters, three drift chambers, time of flight hodoscope counters.

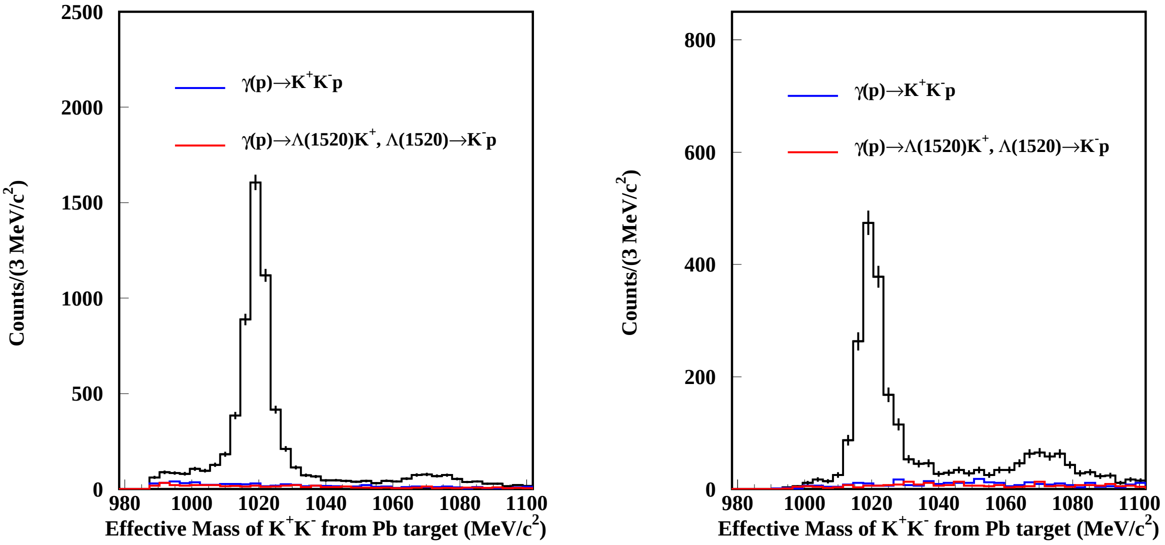

FIGURE 3. (Color online) Left: Reconstructed effective mass of K^+K^- decayed from ϕ meson produced by a lead target in which vector potentials $+42$ MeV (for K^+), -42 MeV (for K^-), and scalar potentials -63 MeV (for both) were assumed. Here red line presents data from the reaction of $\gamma(p) \to K^+K^-p$, and blue line presents data from the reaction of $\gamma(p) \to \Lambda(1520)K^+; \Lambda(1520) \to K^-p$. The solid line denotes sum of these two spectra with K^+K^- decayed from ϕ mesons, where the quoted error bars present statistical uncertainty. Right: Same data set of the left figure, however the opening angles of K^+K^- were required to be larger than 17°.

Here, we considered detector responses, in-flight decay of kaons, nuclear reactions, and multiple scattering in the spectrometer materials.

Left panel in Fig 3 shows reconstructed effective mass of K^+K^- pairs decayed from the simulated ϕ mesons with a lead target. Main background in this mass region can be considered as two component: (1) non-resonant K^+K^-, and (2) $\Lambda(1520)$ associated K^+K^-. These events were generated by using phase space of $\gamma(p) \to K^+K^-p$ reaction, and $\gamma(p) \to \Lambda(1520)K^+$ reaction followed by decay of $\Lambda(1520) \to K^-p$. Generated background events were mixed into the simulated data of ϕ mesons as individual fractions to be 8% (for non-resonance K^+K^-)[12], and 5% (for $\Lambda(1520)$ associated K^+K^-) [13] with respect to the events of ϕ meson for the mass region 995∼1045 MeV/c^2. The mixed events were analyzed with the same way of the analysis of the ϕ meson. As shown in this figure, levels of the K^+K^- background are very small. Right panel in Fig3 displays same data of the left panel, however we required opening angle of K^+K^- to be larger than 17°. A bump arised from kaons-nucleus potentials is clearly seen at 1070 MeV/c^2.

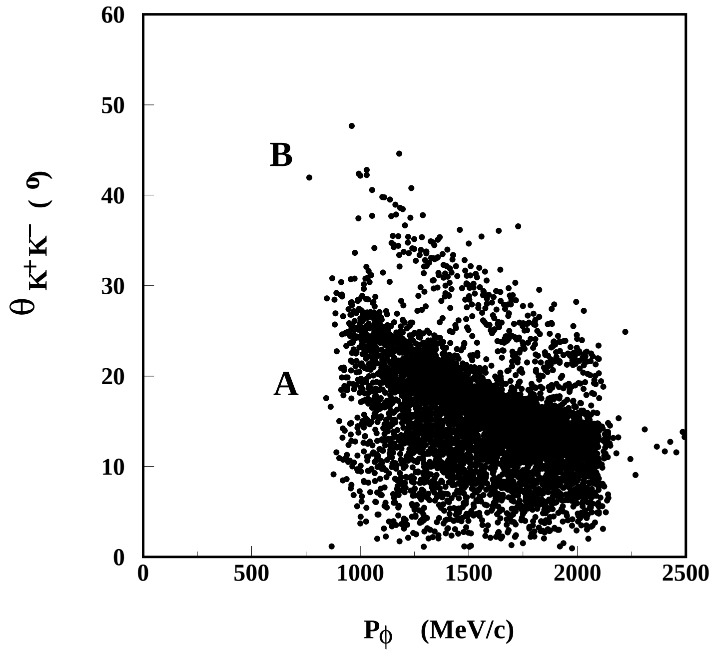

FIGURE 4. (Color online) Opening angle of K^+K^- with respect to the measured momentum of the ϕ meson, where 'A' corresponds to in-vacuum decay, while 'B' corresponds to in-medium decay. Dashed line denotes opening angle 17 °.

One may doubt that the requirement of the opening angle may produce a faked signal. However one has to keep in mind that acceptance of the high mass region (larger than 1040 MeV/c^2) does not change significantly. In figure 4, we display opening angle of K^+K^- with respect to the momentum of ϕ-meson. The data points 'A' correspond to the K^+K^- pairs decayed in a vacuum, while data points 'B' correspond to ones from inside of nucleus. By requiring opening angle of the K^+K^- to be larger than 17°, we can selectively take K^+K^- pairs decayed from inside of nucleus. Furthermore, we studied a behavior of the position of the bump by changing magnitude of the potentials, and found that the position of the bump is linearly depends on a magnitude of the kaon- and antikaon-nucleus potential as demonstrated in Fig5. By using this property, we will measure kaons-nucleus potential.

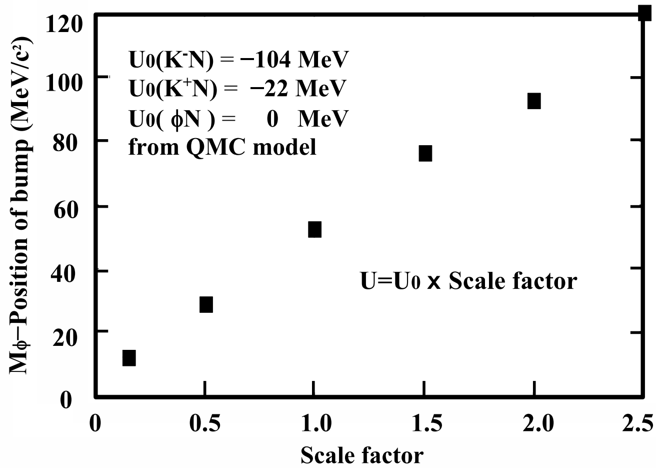

FIGURE 5. Relation between secondary bump positions with respect to the scale factor which multiplies to the antikaon (kaon)-nucleus potential obtained by the Quark Meson Coupling (QMC) model in which ϕN potential was set to be zero. In case ϕN potential is involved, these data points go down as much as magnitude of scalar potential of ϕ meson.

3. ESTIMATION OF YIELD AND RUNNING TIME

The yield of K^+K^- pairs decayed from ϕ meson in a nucleus was calculated by using following relation:

$$Y_{\phi_{in}\to K^-K^+} = N_\gamma T_\gamma \eta_K^2 \eta_{eff} \eta_{\phi_{in}} Br(\phi \to K^+K^-)\rho t(\frac{N_a}{A})(\frac{d\sigma}{d\Omega})^A \Delta\Omega\Delta T. \tag{6}$$

Here, N_γ is a number of tagged photon beam in a second, T_γ, transmission rate of tagged photon, η_K^2, survival probability of K^+K^- pair for the flight length of 4 m (target $\sim$TOF). Here momenta of kaons were assumed 1 GeV/c. The quantity η_{eff} express an overall efficiency for DAQ and reconstruction of K^+K^- pairs. The quantity $\eta_{\phi_{in}}$ denotes in-medium decay rate for the produced ϕ meson in a nucleus, $Br(\phi \to K^+K^-)$, branching ratio of K^+K^- decay mode for the ϕ meson. The quantity ρ, density of target material, t, thickness of target material. The quantity N_a denotes Avogadro number, A, mass number of target, $(\frac{d\sigma}{d\Omega})^A$, differential production cross section of ϕ meson with a nucleus, which is expressed by:

$$(\frac{d\sigma}{d\Omega})^A = A^{0.72}\left[Z(\frac{d\sigma}{d\Omega})^p + N(\frac{d\sigma}{d\Omega})^n\right], \tag{7}$$

where, $(\frac{d\sigma}{d\Omega})^p$, and $(\frac{d\sigma}{d\Omega})^n$ is a cross section on proton, and on neutron, respectively. These values are assumed as 0.010 μb/sr. A similar value was reported in Ref. [14]. Here the quantities Z, and N express atomic number, and neutron number $(N = A - Z)$ of target material. A quoted value, 0.72, expresses mass number (A) dependence of the cross section, which was taken from a result of previous LEPS experiment [15]. The $\Delta\Omega$, solid angle of LEPS spectrometer. The quantity ΔT, requested running time for data taking.

Given values described below, expected number of K^+K^- pairs decayed from ϕ meson with a 1.5 mm thick lead target is found to be 5,549 events, where 166 events are from in-medium decay. Since the K^+K^- background levels are very small, and shape of the background is expected to be not significantly changes, we can easily observe a bump in the K^+K^- effective mass spectrum as displayed right panel in Fig 3.

- $N_\gamma = 2.0 \times 10^6$/sec (Beam intensity)
- $T_\gamma = 0.5$ (Transmission rate for the tagged photon)
- $\eta_{eff} = 0.7$ (Overall efficiency)
- $\eta_{\phi^{in}} = 0.03$ (Escaping rate of K^+K^- pair from in-medium decaying ϕ meson)
- ρ =11.35 g/cm^3 (Density of lead target)
- $t = 0.15$ cm (Thickness of target)
- $(\frac{d\sigma}{d\Omega})^{A=207}$ =47 nb/sr (Differential production cross section of ϕ meson with a lead target, where differential cross section on proton, neutron was assumed as 10 nb/sr.)
- $\Delta\Omega$ =1.03 (Acceptance of LEPS spectrometer; $\pm$ 15 $^\circ$ for horizontal, $\pm$ 10 $^\circ$ for vertical direction)
- η_K^2 =0.36 (Survival probability of two kaons for 1 GeV/c region at 4 m distance)
- Δt=1.15 $\times$ 10^6 sec (Running time, 13 days)

4. RESULT OF TEST EXPERIMENT

In order to study feasibility of this measurement, we have performed a test experiment. Figure 6 shows a target system which consists of three pieces of lead plates with individual thickness of 0.5 mm. These are mounted on a foamed styrol, and it was attached on an existing liquid target vessel. Figure 7 shows a vertex distributions for z-direction, three separated individual targets are clearly identified together with a start counter. Data presented in here correspond to 42 hours-running time with tagged photon beam intensity of 0.16 $\times$ 10^6/sec.

Figure 8 displays distribution of a squared-momentum with respect to the squared-mass of the outgoing particles [16], where three clusters indicating pions, kaons, and protons.

Figure 9 shows invariant mass spectrum of K^+ and K^- pairs. A signal of ϕ meson at 1020 MeV/c^2 is clearly observed. Indicated two lines corresponds to three-standard

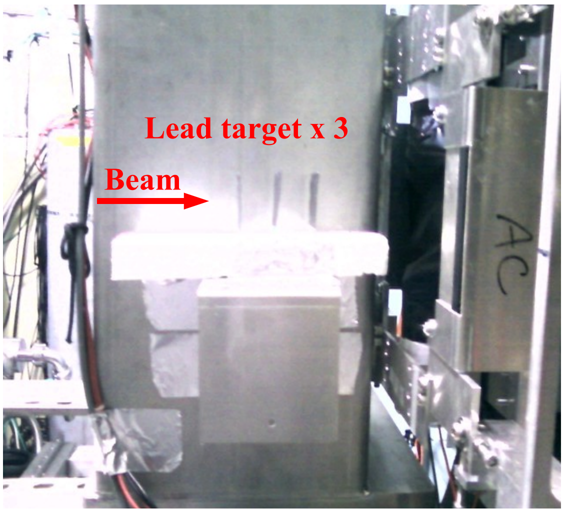

FIGURE 6. (Color online) A target consists of three pieces of leads plates with individual thickness of 0.5 mm. These are mounted on a form styroal, and it was put on a vessel of liquid target container.

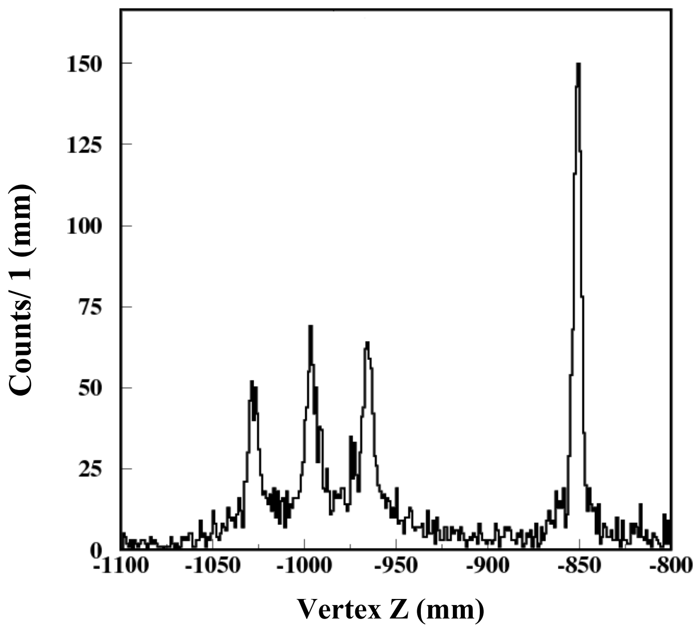

FIGURE 7. Vertex distribution of kaons, a set of three peaks corresponds to separated lead plate target while the fourth peak corresponds to start counter [16].

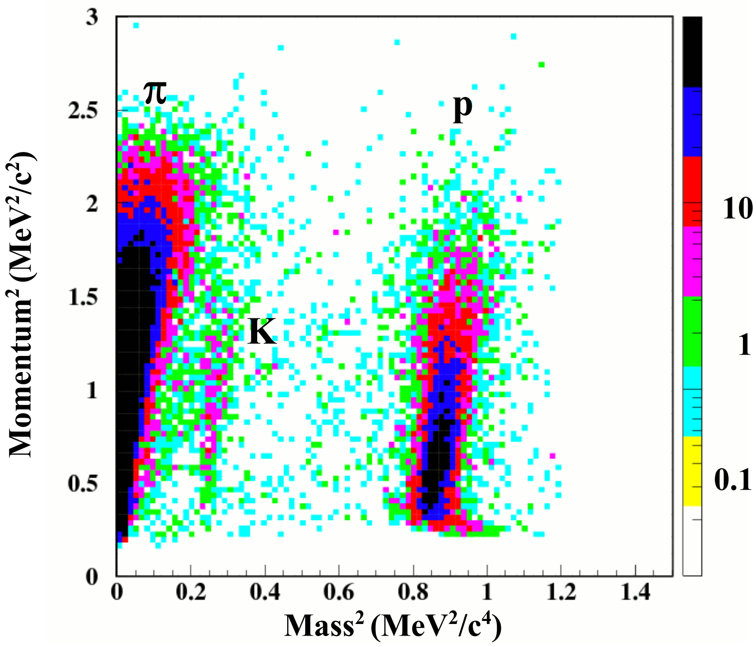

FIGURE 8. (Color online) Distribution of the squared-momentum with respect to the squared-mass of the outgoing particles [16].

deviations of the width of the ϕ-meson. We have estimated a number of signal events by counting events which are distributed inside of the boundaries. Resulting counting rate 54 signal events for the 42 hours running time (1.2 events/hour) consistent with the expected yield 5,549 events with 13 days running time (17.3 events/hour) under a 12.5 times higher beam intensity of the test experiment.

5. SUMMARY AND CONCLUSION

We have shown that how the kaon- and antikaon-nucleus potentials modify invariant mass of ϕ meson in a nucleus target by using a relativistic mean field approach. The ϕ mesons will be produced with a lead target for the energy region 1.5$\sim$2.4 GeV at LEPS facility in Super Photon Ring 8-GeV (SPring-8). The K^+K^- pairs decayed from ϕ mesons in nuclei may be affected by hadronic potentials and the difference of kaon- and antikaon-nucleus potential maybe modify invariant masses of ϕ mesons. As a result, a bump will be seen in the K^+K^- invariant mass spectrum, and the position of bump is linearly depends on the depths of kaonic potentials. By using this property, we will measure kaons (antikaons)-nucleus potentials.

We estimated yield of ϕ meson with a standard experimental setup of LEPS facility.

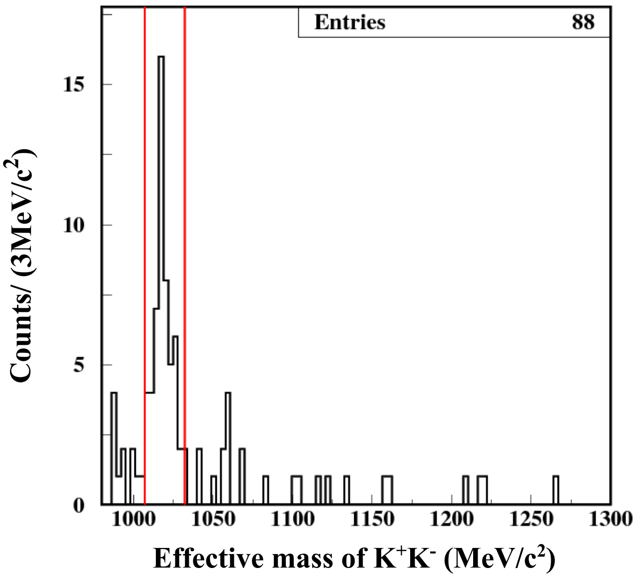

FIGURE 9. (Color online) Reconstructed K^+K^- invariant mass spectrum [16]. Indicated two lines correspond to three standard deviations bands of width of ϕ meson. Number of signal events was estimated by counting events inside of this window.

Obtained a rate of 1.2 events per hour with beam intensity 0.16 $\times 10^6$/sec exhibits that with a running time of 13 days under the requested beam condition 2.0 $\times 10^6$/sec 166 events of the available data on in-medium decay of ϕ meson can be obtained. Thus, the measurement of kaon (antikaon)-nucleus potentials by using in-medium decays for the first time via K^+K^- channels in a nucleus seems to be feasible.

REFERENCES

1. H. Markel, et al., *Coherent ϕ-meson electro-production on nucleus targets*, A proposal at MAMI-C, (2009); http://wwwa1.kph.uni-mainz.de/A1/publications/proposals/MAMI-A1-3-09.pdf.
2. E. Friedman, A. Gal, and C.J. Batty, *Density dependent K^- nuclear optical potentials from kaonic atoms*, Nucl. Phys. A 579, 518 (1994).
3. T. Kishimoto, et al., *Kaon-nucleus interaction studied through the in-flight (K^-,N) reactions*, Nucl. Phys. A 827, 321c (2009).
4. A. Gal, *Overview of strangeness nuclear physics*, in: K. Maeda, S. Nakamura, H. Tamura, and O. Hashimoto (Eds), Proceedings of the Sendai International Symposium on Strangeness in Nuclear and Hadronic Systm, SENDAI08, World Scientific, 2008, p.9–21.
5. W. Scheinast, et al., *In-medium effects on phase space distributions of antikaons measured in proton-nucleus collisions*, Phys. Rev. Lett. 96, 072301 (2006).
6. H. W. Barz and L. Naumann, *Contribution of the nucleon-hyperon reaction channels to K^- production in proton-nucleus collisions*, Phys. Rev. C 68, 041901 (2003).

7. T. Yamazaki, and Y. Akaishi, *Nuclear medium effects on invariant mass spectra of hadrons decaying in nuclei*, Phys. Lett. B453, 1 (1999).
8. J. Pochodazalla, *Exploring the potential of antihyperons in nuclei with antiprotons*, Phys. Lett. B669, 306 (2008); J. Pochodazalla, *Exploring the nuclear potential of antihyperons with antiproton at $\overline{P}ANDA$*, Hyperfine Interact 194, 255 (2009); J. Pochodazalla, and S. Pomp, *Exploring the potential of antilambdas in nuclei with antiproton*, in: K. Maeda, S. Nakamura, H. Tamura, and O. Hashimoto (Eds), Proceedings of the Sendai International Symposium on Strangeness in Nuclear and Hadronic System, SENDAI08, World Scientific, 2008, p.358–363.
9. K. Saito, K. Tsushima, and A. W. Thomas, *Nucleon and hadron structure changes in the nuclear medium and the impact on observables*, Prog. Part. Nucl. Phys. 58, 1 (2007).
10. P. Mülich, et al, *Photoproduction of phi mesons from nuclei*, Phys. Rev. C 67, 024605 (2003).
11. C. H. Lee, et al., *Momentum dependence of single particle potential in Dirac Brueckner approach*, Phys. Lett. B412, 235 (1997).
12. T. Ishikawa, *ϕ photo-production from Li, C, Al and Cu nuclei at $E_\gamma = 1.5 - 2.4$ GeV*, Ph.D thesis at Kyoto University, 139 (2005).
13. T. Ishikawa, *ϕ photo-production from Li, C, Al and Cu nuclei at $E_\gamma = 1.5 - 2.4$ GeV*, Ph.D thesis at Kyoto University, 131 (2005).
14. H. J. Besch, et al., *Photoproduction of ϕ mesons on protons at 2.0 GeV*, Nucl. Phys. B70, 257 (1974).
15. T. Ishikawa, et al., *ϕ photo-production from Li, C, Al and Cu nuclei at $E_\gamma = 1.5 - 2.4$ GeV*, Phys. Lett. B608, 215 (2005).
16. M. Sumihama, *Quick analysis of a test experiment*, (private communication).