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Performance test of a lead-glass counter for the J-PARC E36 experiment

Y. Miyazaki [a], S. Shimizu [b,*], S. Bianchin [c], C. Djalali [d], D. Gill [c], J. Jiang [e], M. Hasinoff [f], K. Horie [b], Y. Igarashi [g], J. Imazato [g], A. Ivashkin [h], M. Kohl [i], R. Narikawa [j], R. Pywell [k], S. Strauch [e], M. Tabata [l,m], A. Toyoda [g], H. Yamazaki [n], T. Yoshioka [a]

[a] *Department of Physics, Kyushu University, Fukuoka 812-0053, Japan*
[b] *Department of Physics, Osaka University, Osaka 560-0043, Japan*
[c] *TRIUMF, Vancouver, Canada, V6T 2A3*
[d] *Department of Physics and Astronomy, University of Iowa, Iowa City, IA 52242, USA*
[e] *Department of Physics and Astronomy, University of South Carolina, Columbia, SC 29208, USA*
[f] *Department of Physics and Astronomy, University of British Columbia, Vancouver, Canada, V6T 1Z1*
[g] *High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801, Japan*
[h] *Institute for Nuclear Research, Moscow 117312, Russia*
[i] *Physics Department, Hampton University, Hampton, VA 23668, USA*
[j] *Department of Physics, Rikkyo University, Toshima 171-8501, Japan*
[k] *Department of Physics, University of Saskatchewan, Saskatoon, Canada, S7N 5A2*
[l] *Institute of Space and Astronautical Science (ISAS), Japan Aerospace Exploration Agency (JAXA), Sagamihara 252-5210, Japan*
[m] *Department of Physics, Chiba University, Chiba 263-8522, Japan*
[n] *Research Center for Electron Photon Science, Tohoku University, Sendai 982-0826, Japan*

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A B S T R A C T

The J-PARC E36 experiment will search for a violation of lepton universality by a precise measurement of the ratio of the kaon decay widths $R_K = \Gamma(\mathrm{K}^+ \to \mathrm{e}^+\nu)/\Gamma(\mathrm{K}^+ \to \mu^+\nu)$. Charged particles will be identified by the combination of three independent systems: a lead-glass Cherenkov counter, an aerogel Cherenkov counter, and a time-of-flight measurement. The performance of the lead-glass Cherenkov counter was investigated with e^+, μ^+, and π^+ beams in the relevant momentum region from the K^+ decays. By using a polyethylene degrader to slow down the beam momentum in front of the lead-glass block, we succeeded in reducing the muon mis-identification probability down to 5% while maintaining a high e^+ detection efficiency of 98%.

1. Introduction

The $\mathrm{K}^+ \to \mathrm{l}^+\nu_l$ (K_{l2}) decay is one of the best channels to perform a lepton universality test [1]. The ratio of the decay width, R_K, of $\mathrm{K}^+ \to \mathrm{e}^+\nu$ (K_{e2}) and $\mathrm{K}^+ \to \mu^+\nu$ ($K_{\mu2}$) can be predicted in the framework of the Standard Model (SM) under the assumption of μ–e universality as

$$R_K^{SM} = \frac{\Gamma(K_{e2})}{\Gamma(K_{\mu2})} = (2.477 \pm 0.001) \times 10^{-5}. \quad (1)$$

Any deviation of the experimentally measured R_K from the SM value points to a μ–e universality violation indicates the existence of New Physics beyond the SM [1].

The J-PARC E36 experiment is aiming for a precision R_K determination by measuring the ratio of the K_{e2} and $K_{\mu2}$ branching ratios. The experiment will be performed using a stopped K^+ beam with the TREK detector system [2], which is based on a 12-sector superconducting iron-core toroidal spectrometer and a CsI(Tl) calorimeter, as shown in Fig. 1. Because of the huge difference in the K_{e2} ($P_{e^+} = 247$ MeV/c) and $K_{\mu2}$ ($P_{\mu^+} = 236$ MeV/c) branching ratios, a reliable determination of K_{e2} is very important to remove any $K_{\mu2}$ admixture, and thus the simultaneous use of a lead-glass Cherenkov counter (PGC), an aerogel Cherenkov counter (AC), and a time-of-flight measurement (TOF) between TOF1 and TOF2 counters has been adopted in the E36 experiment.

2. Lead-glass Cherenkov counter for E36

The lead-glass modules used in the TOPAZ experiment at KEK TRISTAN [4] have been adopted as the PGC for use in the J-PARC E36 experiment. The module mass is 26.7 kg, and the size is 122 mm (7.2 radiation length) in thickness and 340 mm in length. The top surface

* Corresponding author.
E-mail address: suguru@phys.sci.osaka-u.ac.jp (S. Shimizu).

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of each module is tilted at an angle of 3.72° so that the height of a module increases linearly from 113 to 135 mm. The lead-glass material is SF6W; the chemical composition and physical properties are summarized in Ref. [4]. They will be assembled with 7 modules stacked in a radial direction behind the TOF2 counters. The lead-glass surfaces were mirror-polished, and a HAMAMATSU R1652 [5] phototube was attached to the block for the Cherenkov photon detection. This configuration will allow us to construct a compact detector with enough thickness to contain most of the shower energy generated by the e^+s from K_{e2} decay.

In E36 it will be necessary to optimize the μ^+/e^+ separation near 240 MeV/c to obtain the most accurate R_K ratio. Cherenkov photons generated by the e^+ from K_{e2} decay can be produced from multiple e^+ and e^- particles created by an electromagnetic shower in the PGC; however the μ^+ from $K_{\mu 2}$ almost does not radiate. Therefore, the total Cherenkov photon yield from an e^+ is expected to be much larger than that from a μ^+, and we can separate e^+ from μ^+ by using this difference. In addition, we consider a new detection scheme which takes advantage of a non-linear effect above the threshold energy of the Cherenkov effect in the lead-glass material. The number of

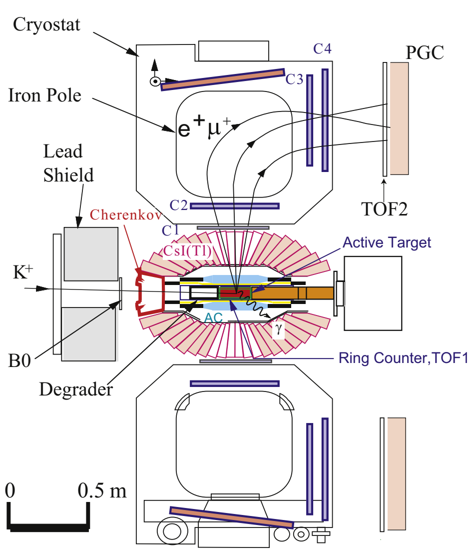

Fig. 1. Cross-sectional side views of the setup for the J-PARC E36 experiment [2,3]. The momentum vectors of charged particles and photons are determined by the toroidal spectrometer and the CsI(Tl) calorimeter, respectively. The spectrometer has 12 identical gaps and a rotational symmetry of 30°. Charged particles will be discriminated by a combination of measurements from the PGC, AC, and TOF detectors. The PGC is located at the end of the detector system.

Cherenkov photons, Y, depends on β as

$$Y \propto 1 - \frac{1}{n^2 \beta^2} \tag{2}$$

where the refractive index (n) of lead glass is 1.8. During the slowing down process, the μ^+ velocity changes strongly around the μ^+ threshold momentum for Cherenkov light production ($P_{\mathrm{thr}}^{\mu^+} \sim 70$ MeV/c), and the μ^+ Cherenkov yield is steeply decreasing as the momentum decreases near the threshold energy. On the other hand, the e^+ velocity is nearly constant ($v_e \sim c$), and the Cherenkov yield should be proportional to total path length of e^+ and e^- generated in a shower, namely to the initial e^+ energy. Therefore, we can expect the PGC performance for the μ^+/e^+ separation to be drastically improved by reducing the e^+ and μ^+ momenta from the K_{e2} and K_{e2} decays towards the threshold.

In order to estimate the Cherenkov photon yield from μ^+, the average μ^+ momentum inside the lead-glass block was calculated using the Bethe–Bloch energy loss formula taking into account the lead-glass material properties. A perpendicularly incident beam was assumed and the incident beam momentum was varied from 100 to 240 MeV/c. The Cherenkov photon yield $Y(x)$ at the distance (x) from the detector entrance face can be described by using the local beam velocity $\beta(x)$ as

$$Y(x)\,dx \propto \left\{1 - \frac{1}{n^2 \beta(x)^2}\right\} dx. \tag{3}$$

Fig. 2(a) shows the $Y(x)$ distribution assuming an initial muon momentum of 180 MeV/c. The total yield (Y_t) is obtained by integrating over the energy region above the threshold energy as

$$Y_t = \int_0^{x_c} Y(x)\,dx \propto \int_0^{x_c} \left\{1 - \frac{1}{n^2 \beta(x)^2}\right\} dx \tag{4}$$

where x_c is the critical position corresponding to the threshold energy. Fig. 2(b) shows the Y_t dependence on the initial beam momentum. A clear dependence of the total Cherenkov photon yield on the momentum was obtained. In particular, a steep change above the threshold energy for Cherenkov light production can be seen. Also, the number of Cherenkov photons from π^+ was calculated to compare it with that from μ^+, because π^+ should have a similar behavior ($P_{\mathrm{thr}}^{\pi^+} \sim$ 92 MeV/c). Here, it is to be noted that the relative size of the total Cherenkov photon yields was only taken into account in the calculation and the photon propagation effect to the photon detector was neglected, and therefore, the vertical axis of Fig. 2 is arbitrary.

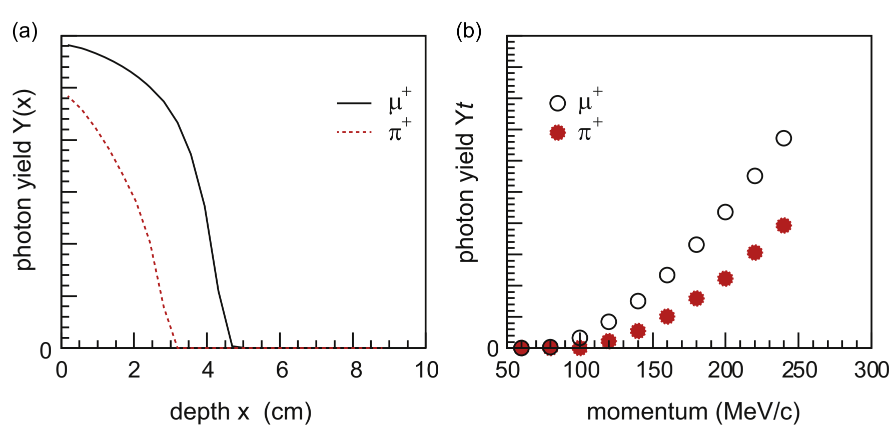

Fig. 2. The solid (black) and dotted (red) plots are calculation results of the Cherenkov photon yields for μ^+ and π^+, respectively. (a) Cherenkov photon yield $Y(x)$ at position x, assuming a beam momentum of 180 MeV/c. (b) Total Cherenkov photon yield as a function of the initial beam momentum, which is obtained from Eq. (4) using the calculation results of the energy loss inside a lead-glass module. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

3. Results of beam test

In order to check the lead-glass performance as the PGC in the E36 experiment and to establish the μ^+/e^+ separation scheme mentioned above, we conducted a test experiment using the TRIUMF M11 beam [6]. A schematic view of the experimental configuration is shown in Fig. 3. We injected a mixture of e^+, μ^+, and π^+ beams with the beam momentum from 100 to 240 MeV/c in 20 MeV/c steps. The lead-glass detector was placed at the end of the beam line. The beam hits the center of the lead-glass block and a shower leakage was negligibly small. In addition, a TOF system and an AC counter were placed upstream of the lead-glass blocks. They were used for particle identification in the analysis, as shown in Fig. 4(d). The beam size was defined to be 5×5 mm^2 by a plastic scintillation counter SC4 located in front of the lead-glass blocks.

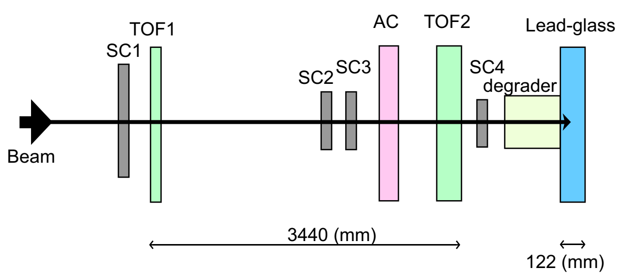

Fig. 3. A schematic view of the beam test setup at TRIUMF M11. We injected a mixture of e^+, μ^+, and π^+ beams with momentum from 100 to 240 MeV/c. The TOF system and the AC counter placed upstream of the lead-glass blocks were used for particle identification in the analysis. The polyethylene degraders were placed in front of the lead-glass blocks to decrease the beam momentum.

Fig. 4 shows typical (a) e^+, (b) μ^+, and (c) π^+ ADC spectra obtained by selecting events using the TOF and the AC with nearly 100% purity. Since the ADC spectrum for μ^+ and π^+ had an

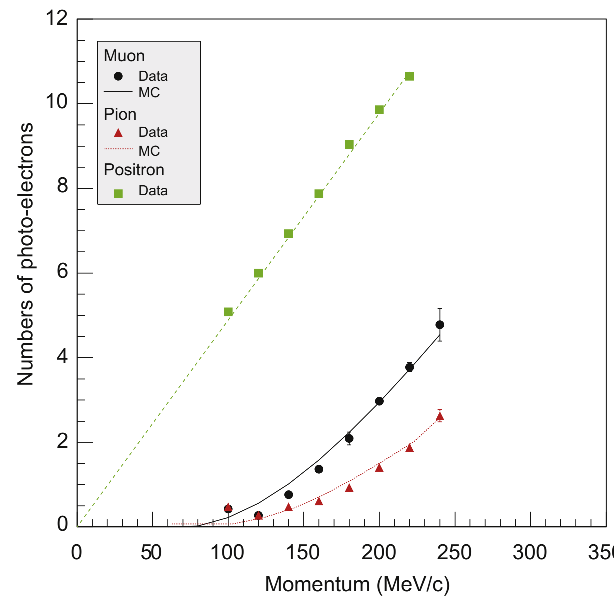

Fig. 5. The numbers of photo-electrons obtained from the ADC spectra of μ^+ (circle), π^+ (triangle) and e^+ (square) events. The ADC spectrum for μ^+ and π^+ was fitted by a gamma function convoluted with a Gaussian, and that for e^+ was fitted by a Gaussian function. The vertical axis of the μ^+ and π^+ theoretical calculations is adjusted to reproduce the experimental results. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

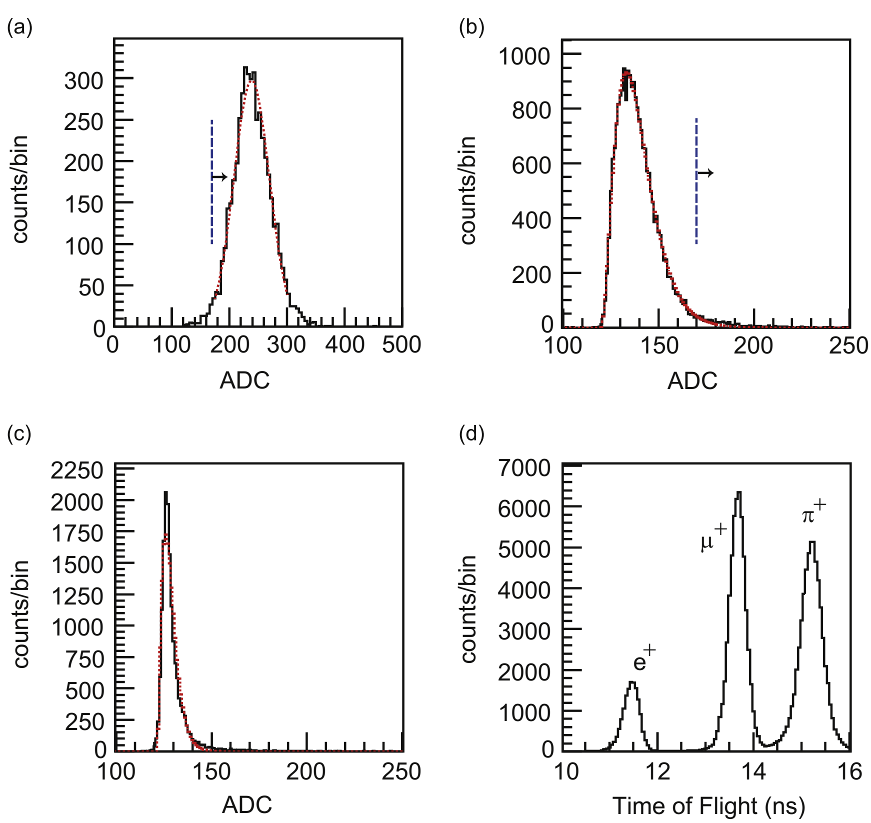

Fig. 4. The ADC spectrum for the initial beam of 180 MeV/c for (a) e^+, (b) μ^+, (c) π^+. (d) is the TOF spectrum for the charged particle selection. The dotted (red) curve in each ADC spectrum is the fitting result. The p_{eff} and p_{mis} values were determined from the fraction of the e^+ events and the μ^+ contamination over a certain threshold (dashed line), respectively. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

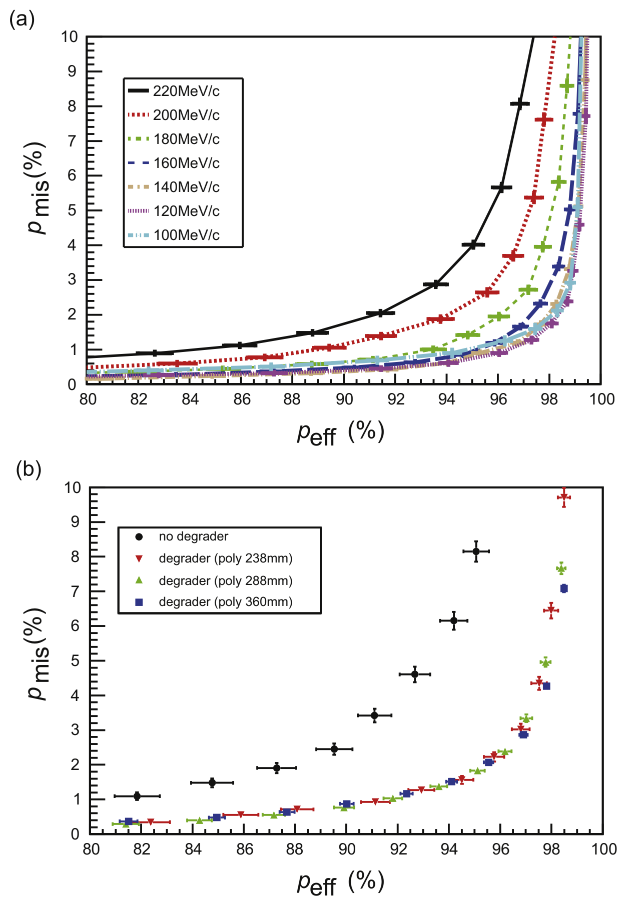

Fig. 6. Correlation plots of μ^+ mis-identification probability and e^+ efficiency obtained by changing (a) the initial beam momentum and (b) the degrader thickness using a 240 MeV/c incident beam. The detector performance is highly improved by decreasing the incident beam momentum. Using a polyethylene degrader, we succeeded in reducing the muon mis-identification probability down to 5% with keeping the high e^+ efficiency of 98%.

asymmetric structure due to the low photon yield, it was fitted by a gamma function with a Gaussian convolution, which can be parameterized by an average photo-electron number. On the other hand, the e^+ ADC spectrum was just fitted by a Gaussian function. The results are shown as the dotted (red) curves in Fig. 4. The number of photo-electrons obtained from these fits is plotted as a function of the beam momentum in Fig. 5. The μ^+ and π^+ calculation results obtained from Eq. (4) are also shown, where the vertical axis is adjusted to reproduce the data. Comparing the experimental data with the calculation, the behavior of the μ^+ and π^+ data is understandable as a threshold effect of the Cherenkov light production. The number of photo-electrons detected by the phototube is nearly proportional to the total number of generated photons in the lead-glass block, regardless of their spatial distribution, detailed structure of the block, light propagation properties, etc. In contrast to the μ^+ and π^+ data, the observed e^+ mean values are nearly proportional to the incident beam momentum, as shown in Fig. 5 by the dotted green line.

The e^+ efficiency (p_{eff}) and μ^+ mis-identification probability (p_{mis}) were determined as the fraction of the e^+ events and μ^+ events above a certain threshold, respectively as

$$p_{\text{eff}} = \frac{N[(V_{\text{ADC}} > V_{\text{th}}) \otimes \text{AC}(e^+) \otimes \text{TOF}(e^+)]}{N[\text{AC}(e^+) \otimes \text{TOF}(e^+)]} \tag{5}$$

$$p_{\text{mis}} = \frac{N[(V_{\text{ADC}} > V_{\text{th}}) \otimes \text{AC}(\mu^+) \otimes \text{TOF}(\mu^+)]}{N[\text{AC}(\mu^+) \otimes \text{TOF}(\mu^+)]} \tag{6}$$

where V_{ADC} is the ADC value of the lead-glass counter and V_{th} is the threshold level, as shown in Fig. 4 by the dashed lines. Fig. 6(a) shows the experimental results of the ($p_{\text{eff}}, p_{\text{mis}}$) correlation curves obtained by varying the V_{th} level at each initial beam momentum. The lead-glass performance for the μ^+/e^+ separation was found to be significantly improved by decreasing the beam momentum, indicating a clear validation of the measuring procedure using the threshold effect of the Cherenkov photon production.

Then, fixing the initial beam momentum to 240 MeV/c, which simulates the actual charged particles from the K_{e2} and $K_{\mu 2}$ decays, we placed a polyethylene degrader in front of the lead-glass counter to slow down the beam momentum. The degrader material was required to have a low Z number in order to suppress the electromagnetic shower generation by e^+s. The degrader thicknesses of 23.8, 28.8, and 36.0 cm were chosen to control the beam momentum, which corresponds to the average beam momenta of 180, 167, and 145 MeV/c, respectively. The results with the degraders are almost consistent with that with a 180 MeV/c beam.

Fig. 6(b) shows p_{mis} and p_{eff} correlation obtained by using these degraders. We succeeded in reducing the muon mis-identification probability down to 5% while keeping a high e^+ efficiency of 98%. On the other hand, it was found that the results are nearly the same independent of the degrader thickness, although the proper dependence had been expected from the preceding measurement to study the momentum dependence. This feature might be due to shower fluctuation in the degrader, which degrades the μ^+/e^+ separation from broadening the beam profile and momentum width.

4. Summary

The J-PARC E36 experiment aims to search for lepton universality violation by precisely measuring the ratio of the decay widths R_K. The charged particles will be identified by a combination of the PGC, aerogel Cherenkov counter, and time-of-flight system. The TOPAZ lead-glass performance as the PGC in E36 was investigated using e^+, μ^+, and π^+ beams by changing the beam momentum. The threshold effect of the Cherenkov photon production was clearly observed. Then, fixing the initial beam momentum at 240 MeV/c, we placed a polyethylene degrader in front of the lead-glass counters to decrease the beam momentum. A detailed analysis of the beam incident position and angle dependence taking into account the light propagation in the lead-glass material is now underway using a GEANT4 code. The overall particle identification capabilities in the E36 experiment will be confirmed after optimizing the AC and TOF performance.

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