Progress on Cherenkov Reconstruction in MICE

Daniel M. Kaplan, Michael Drews, Durga Rajaram, and Miles Winter
Illinois Institute of Technology, Chicago, Illinois 60616, USA

Lucien Cremaldi, David Sanders, and Don Summers
University of Mississippi, Oxford, Mississippi 38677, USA

(Dated: January 28, 2016)
Abstract

Two beamline Cherenkov detectors (Ckov-a,-b) support particle identification in the MICE beamline. Electrons and high-momentum muons and pions can be identified with good efficiency. We report on the Ckov-a,-b performance in detecting pions and muons with MICE Step I data and derive an upper limit on the pion contamination in the standard MICE muon beam.

INTRODUCTION

The international Muon Ionization Cooling Experiment (MICE) \cite{1} is designed to measure muon ionization cooling \cite{2}. Cooling is needed for neutrino factories based on muon decay \( (\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu \) and \( (\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu) \) in storage rings \cite{3} and for muon colliders \cite{4}.

Two high-density aerogel threshold Cherenkov counters \cite{5}, located just after the first Time of Flight counter (TOF0) in the MICE beamline, are used in support of muon and pion particle identification. The measured \cite{6} refractive indices of the aerogels in the counters are \( n_a = 1.069 \pm 0.003 \) in Ckov-a and \( n_b = 1.112 \pm 0.004 \) in Ckov-b. The corresponding momentum thresholds for muons (pions) are at 280.5 (367.9) and 217.9 (285.8) MeV/c, respectively. Light is collected in each counter by four 9354KB eight-inch UV-enhanced phototubes and recorded by CAEN V1731 500 MS/s flash ADCs (FADCs).

EVENT HANDLING AND CALIBRATION

A charge-integration algorithm identifies charge clusters \( q_i, i = 1–8 \) in the FADCs where the ADC value crosses a threshold, marking times \( t_1 \) and \( t_2 \) at the threshold crossings, approximating the pulse beginning and end times. The time \( t_{\text{max}} \) at the cluster signal maximum is found. The charges are converted to a photoelectron count \( p_e, \) by subtracting a pedestal \( q_0 \) and then normalizing by the single photoelectron charge \( q_1 \) for each phototube.

For all \( q_i > 0, \) the total charge, arrival time, \( t_1, \) and \( t_{\text{max}} \) are stored per event.

The asymptotic \( \beta=1 \) light yield \( N_{\beta=1} \) in each counter is measured using the electron peak in MICE calibration-beam runs, giving 25 and 16 photoelectrons (pe’s) in Ckov-b and Ckov-a, respectively, for a nominal run. The photoelectron yields versus momentum are displayed in Fig. 1. The observed muon thresholds, \( 213 \pm 4 \) and \( 272 \pm 3 \) MeV/c, are in reasonable agreement with the expectations given above. The average number of photoelectrons for normal incidence in the counters can be predicted from the Cherenkov angle \( \cos \theta_c = 1/n\beta, \) and, near threshold \( \beta_{\text{th}} = 1/n, \)

\[
N_{p_e} = N_{\beta=1} \times \sin^2 \theta_c = N_{\beta=1} \times \left(1 - (p_{\text{th}}/p)^2\right).
\]  

As seen in Fig. 2 the photoelectron spectra for \( \mu, \pi \) are observed to be Poisson-like with tails from electromagnetic showers and delta rays produced as the particle traverses TOF0 and the aerogel radiator. Secondary electrons from these processes above about 1 MeV/c produce Cherenkov light 5–6% of the time for each particle passage. For small-\( N_{p_e} \) signals, the measured spectra contain more zero-particle passage. For small-\( N_{p_e} \) signals, the measured spectra contain more zero-particle events than expected from pure Poisson-like behavior \( P_0(x) = e^{-x}, \) \( x = \langle N_{p_e} \rangle. \)
FIG. 1: Photoelectron ($N_{pe}$) curves versus momentum for muons in (left) Ckov-b and (right) Ckov-a. The $N_{\beta=1}$ values are about 75% of the values predicted from the asymptotic photoelectron spectrum of $\beta = 1$ electrons (labeled at right)---not unexpected since for electrons TOF0 acts effectively as a “preshower” radiator.

BEAM PARTICLE SPECTRA

The “D1” and “D2” dipoles in the MICE beamline [1] predominantly control the beam momentum and particle types transmitted into the MICE spectrometer. In the $p_{tgt} \approx p_{D1} \approx p_{D2}$ setting (calibration mode), the beamline transports a mixture of decay/conversion electrons, decay muons, and primary pions. For $p_{tgt} \approx p_{D1} \approx 0.5p_{D2}$, backward muon decays from the decay solenoid (DS) are selected. G4beamline [7] Monte Carlo runs indicate that a small leakage of primary pions through the D2 selection magnet can occur at the $\sim 1\%$ level [8]. Both these high-momentum pions and their decay muons should be observable in both Ckov-a and Ckov-b. Ckov-a can be used effectively to select the high-momentum $\pi, \mu$ events that are just over threshold [9].

FIG. 2: Typical photoelectron spectrum seen for muons or pions above threshold in Ckov-b (solid histogram), together with model fit components: Poisson (dashed), delta-ray tail (dot-dashed), and anomalous low-$N_{pe}$ component (dotted).
FIG. 3: Time-of-flight spectrum from TOF0 to TOF1 with (left) pea > 2 cut (solid) and peb > 8 cut (dot-dash), with shape of muon spectrum superimposed (dashed); and (right) pea > 2 and peb > 10 cuts. The peb requirements greatly reduce the delta-ray contribution. Fast $\pi$-$\mu$ are identified as the satellite peak centered at 27.6 ns.

ANALYSIS

Unambiguous identification of particle species using the Cherenkov detectors (measuring velocity) would require a momentum measurement from the MICE tracker, which was not available in Step I data. Muons and pions are thus indistinguishable here by the Cherenkov effect. In the following analysis we look for high-momentum $\pi$ or $\mu$ that trigger Ckov-a. An additional cut on the number of photoelectrons in Ckov-b serves to suppress the $\approx 6\%$ of slow “background” events that pass the Ckov-a cut due to delta-ray emission.

We analyzed 120k Step I muon events with $p_{tgt} = 400$ MeV/c and $p_{D2} = 237$ MeV/c (the “standard” muon beam settings). We also analyzed 35k muon events with $p_{tgt} = 500$ MeV/c and $p_{D2} = 294$ MeV/c. In Fig. 3 we cut away the electron signal (by requiring tof > 26.4 ns) and also make a Ckov-a $N_{pe} > 2$ cut. The shoulder centered at 27.6 ns is made up of fast muons and pions triggering in Ckov-a and at TOF1. The background events centered approximately at tof = 28 ns are from particles with momenta below threshold in Ckov-a, but giving $N_{pe} > 2$ Ckov-a light by delta-ray emission. This background is consistent with the expected 6% contamination level. The tof = 27.6 ns peak corresponds to $p_{\mu} = 277$ MeV/c or $p_{\pi} = 363$ MeV/c, both above threshold in Ckov-a.

Fast muons and pions will leave considerable light in Ckov-b. According to Eq. 1 about 10 pe will be produced in Ckov-b at $p_{\mu} = 270$ MeV/c. The probability for simultaneous delta-ray detection in both Ckov-a and Ckov-b will be about $0.06^2 = 3.6 \times 10^{-3}$. In Fig. 3 (right) we add a Ckov-b $N_{pe} > 10$ cut. The delta-ray background is substantially reduced.
to about 500 events. A fit to Gaussian signal and phase-space background of the form \( f = N(\sqrt{2\pi}\sigma)^{-1}e^{-(x-x^2)/2\sigma^2} + B (x-x_{lo})^\alpha(x_{hi}-x)^\beta \) gives 539 ± 34 signal events. When corrected for efficiency [9] we obtain \( N = 1002 \pm 56 \) events. By varying the fitting parameters we find a ±101-event systematic (syst) uncertainty [9]. The fast \( \pi-\mu \) fraction is thus 

\[
R_{\mu\pi} = \frac{1002 \pm 56 \pm 101}{118,793} = 0.84 \pm 0.05 \text{ (stat)} \pm 0.09 \text{ (syst)} \%
\]

If we assume pessimistically that all fast \( \pi-\mu \) are pions, we can obtain upper limits on the pion fraction: \( R_{\mu\pi} < 0.97\% \) (90\% CL) and \( R_{\mu\pi} < 1.00\% \) (95\% CL). Any Bayesian model would require some prior knowledge of the pion-to-muon ratio in the beam. Estimating this (based on the G4beamline simulation) to be about 1/20 (or about 50 pions) allows us to estimate the fraction of pions in the beam to be \( \pi/\mu \approx \frac{50}{118,793} = 0.04\% \) — indeed very small, surpassing the MICE design requirements.

*Presented at NuFact15, 10-15 Aug 2015, Rio de Janeiro, Brazil [C15-08-10.2]; work supported by U.S. DOE via the MAP Collaboration.
†Electronic address: kaplan@iit.edu; presenter

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