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Progress on Cherenkov Reconstruction in MICE*

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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) [1] is designed to measure muon ionization cooling [2]. Cooling is needed for neutrino factories based on muon decay ($\mu^- \to e^- \overline{\nu}_e \nu_\mu$ and $\mu^+ \to e^+ \nu_e \overline{\nu}_\mu$) in storage rings [3] and for muon colliders [4].

Two high-density aerogel threshold Cherenkov counters [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 [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_{max} at the cluster signal maximum is found. The charges are converted to a photoelectron count pe_i, by subtracting a pedestal q_{0i} and then normalizing by the single photoelectron charge q_{1i} for each phototube. For all $q_i > 0$, the total charge, arrival time, t_1, and t_{max} are stored per event.

The asymptotic β=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 ± 4 and 272 ± 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 $\beta_{th} = 1/n$,

$$N_{pe} = N_{\beta=1} \times \sin^2\theta_c = N_{\beta=1} \times (1 - (p_{th}/p)^2)\,. \quad (1)$$

As seen in Fig. 2, the photoelectron spectra for μ, π 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_{pe} signals, the measured spectra contain more zero-pe events than expected from pure Poisson-like behavior $P_0(x) = e^{-x}$, $x = \langle N_{pe}\rangle$.

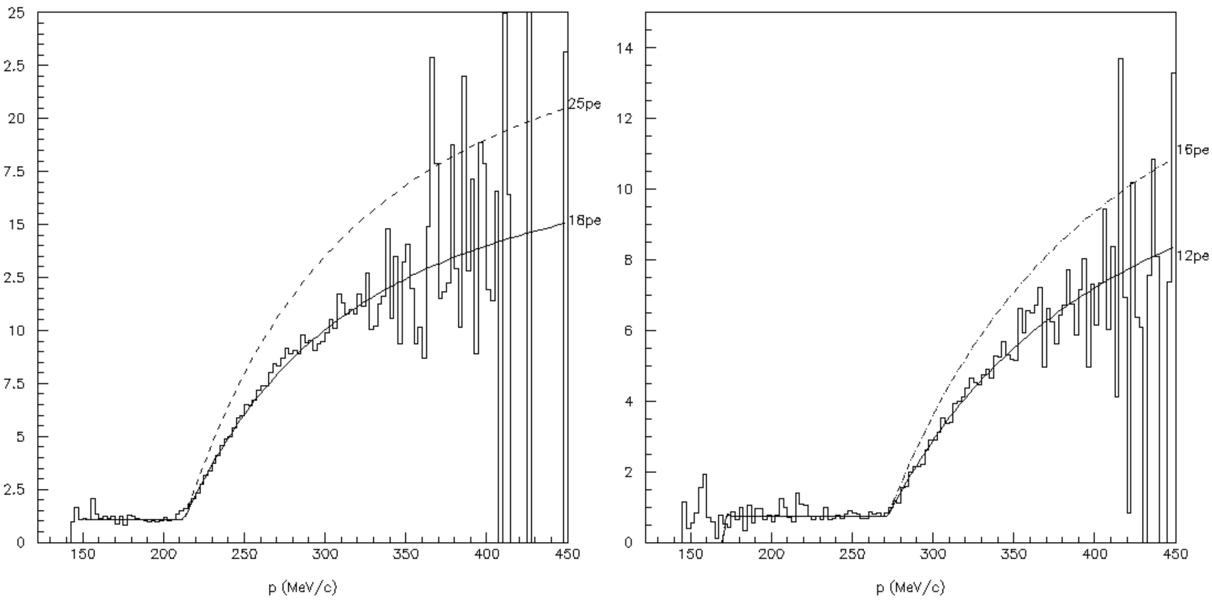

FIG. 1: Photoelectron (N_{pe}) curves versus momentum for muons in (left) Ckov-b and (right) Ckov-a. The $N_{\beta=1}$ values are about 75% of the values predicted from the asymptotic photoelectron spectrum of $\beta = 1$ electrons (labeled at right) — not unexpected since for electrons TOF0 acts effectively 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 π, μ events that are just over threshold [9].

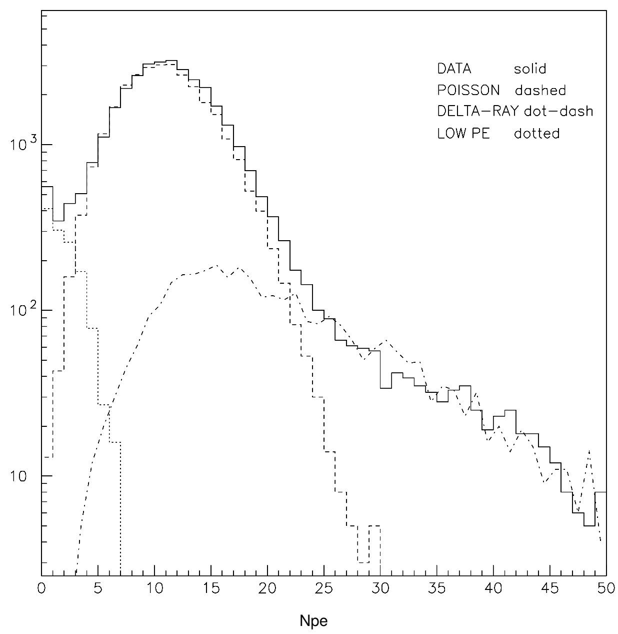

FIG. 2: Typical photoelectron spectrum seen for muons or pions above threshold in Ckov-b (solid histogram), together with model fit components: Poisson (dashed), delta-ray tail (dot-dashed), and anomalous low-N_{pe} component (dotted).

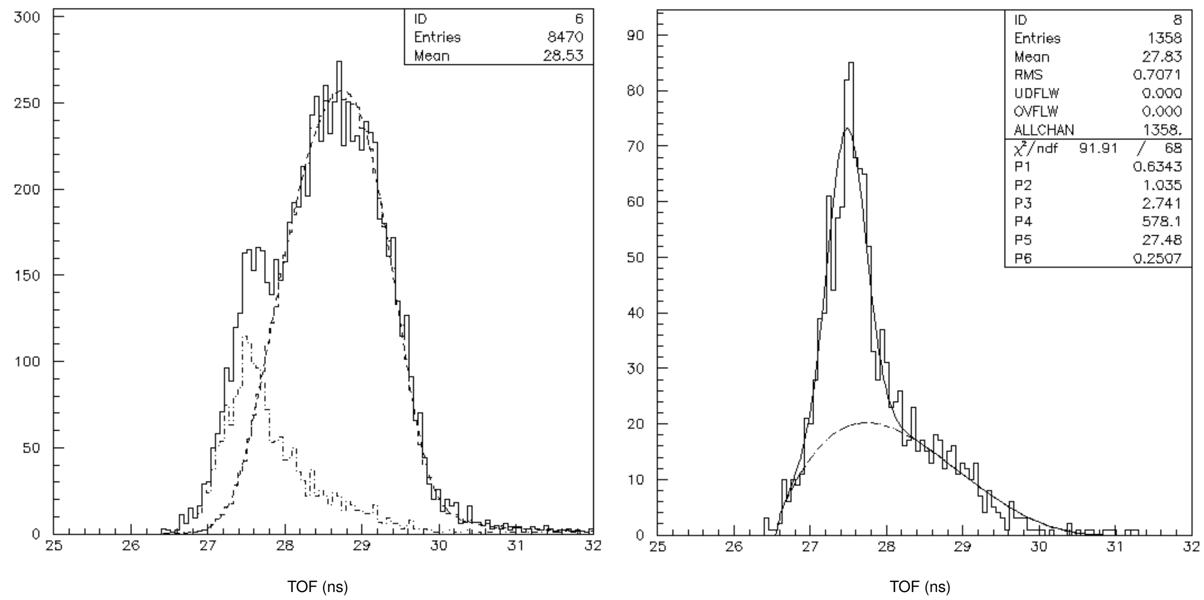

FIG. 3: Time-of-flight spectrum from TOF0 to TOF1 with (left) pea >2 cut (solid) and peb >8 cut (dot-dash), with shape of muon spectrum superimposed (dashed); and (right) pea >2 and peb >10 cuts. The peb requirements greatly reduce the delta-ray contribution. Fast π-μ are identified as the satellite 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 π or μ 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 ($x \equiv$ time of flight) $f = N(\sqrt{2\pi}\sigma)^{-1}e^{-(x-\bar{x}^2)/2\sigma^2} + B\ (x - x_{lo})^\alpha(x_{hi} - x)^\beta$ 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 π-μ fraction is thus $R_{\mu\pi} = (1002 \pm 56 \pm 101)/118,793 = [0.84 \pm 0.05\,(\text{stat}) \pm 0.09\,(\text{syst})]\%$.

If we assume pessimistically that all fast π-μ 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 $\pi/\mu \simeq 50/119,000 = 0.04\%$ — indeed very small, surpassing the MICE design requirements.

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[8] Pions leaking through D2 produce high-momentum decay muons in the MICE beam — a different production mechanism than that of the nominal MICE beam, which comes from pion decays *upstream* of D2.

[9] More details of the analysis may be found in L. Cremaldi *et al.*, MICE Note 473 (2015), `http://mice.iit.edu/micenotes/public/pdf/MICE0473/MICE0473.pdf`.