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A study on the e/μ identification capability of a water Čerenkov detector and the atmospheric neutrino problem

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Abstract

We carried out an experimental test of various characteristics of a water Čerenkov detector, especially the particle identification capability, using the 12-GeV proton synchrotron at KEK, Japan. The detector characteristics so far studied are well reproduced by the Monte Carlo simulation. Especially it is able to identify electrons and muons with mis-identification probabilities less than a few percent in the momentum range of 250–1000 MeV/c except the particle positions in the extreme edge of the detector volume. Based on the present results, the deficiency of μ-neutrinos in the atmospheric neutrinos is not an artifact caused by some peculiar detector characteristics.

Experiments with accelerator and reactor neutrinos have so far shown no clear evidence for neutrino oscillations [1]. However, there are two observational signals which may have resulted from neutrino oscillations: the deficiency of solar neutrinos, observed by four experiments (Homestake [2], Kamiokande [3], SAGE [4] and GALLEX [5]), and the possible deficiency of atmospheric μ-neutrinos, observed by the Kamiokande experiment [6,7], and later confirmed by the IMB [8] and Soudan-II collaborations [9].

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The observed deficiency of atmospheric μ-neutrinos can be summarized as follows:
The ratio ν_μ/ν_e is about 1.2 in the momentum range of $0.1 < p_e < 1.33$ GeV/c and $0.2 < p_\mu < 1.5$ GeV/c (visible energy: $E_{\rm vis} < 1.33$ GeV), while it should be close to 2.0, since most pions are produced at high altitude and decay into $\mu + \nu_\mu$ before they interact, and the produced muons subsequently decay into $e + \nu_e + \nu_\mu$ before hitting the ground, ending up with two ν_μ and one ν_e. In the high energy region ($E_{\rm vis} > 1.33$ GeV), a possible zenith angle dependence has been observed, i.e. the ratio ν_μ/ν_e or the

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observed ratio μ/e is close to the expected value for downward-going neutrinos, while it is strongly suppressed for upward-going neutrinos.

These results strongly indicate the existence of either $\nu_\mu \rightarrow \nu_\tau$ or $\nu_\mu \rightarrow \nu_e$ oscillations. However, the above results critically depend on the ability to reliably distinguish between electrons and muons in the Kamiokande detector. The particle identification (ID) capability of the Kamiokande detector has been checked using cosmic ray stopping muons and Michel electrons observed in the detector. However the momentum and vertex region of these studies did not cover the entire region used for the analysis [10].

Since the experimental test of the particle ID capability is of utmost importance, we carried out a detailed measurement of various characteristics of a water Čerenkov detector, especially the particle ID, using electron, pion and muon beams having momenta between 100 and 1000 MeV/c produced by the 12-GeV proton synchrotron at KEK. Data were taken in March and May 1994.

Here, we report the first results on the muon(μ)-electron(e) identification capability in the momentum regions of 250 MeV/c – 1 GeV/c for μ^- and of 100 MeV/c – 1 GeV/c for e^-, respectively.

A 1000 ton water Čerenkov detector was constructed at KEK, which was one third in volume and had the same photo cathode coverage as the present Kamiokande detector. A cross-sectional view of the detector is shown in Fig. 1. The water tank was cylindrical (about 10 m high and 10 m in diameter) and its inner surface was equipped with 380 20"-photomultiplier tubes (PMT's). The distance to the PMT planes measured from the center of the detector was 4.5 m for the top and bottom planes and 4.8 m for the side plane, respectively. Each PMT detected Čerenkov light and the corresponding charge and timing were read out. The beam was guided through four evacuated stainless steel pipes, which were inserted to the specified positions. A plastic scintillation counter (8 cmϕ) was placed at the exit of each beam pipe for the trigger.

The beam line consisted of a production target, magnets, a gas Čerenkov counter, TOF counters and a trigger counter. Particles, which were injected in the water Čerenkov detector, were identified with both the gas Čerenkov counter and the TOF counters. The distance of the two TOF counters was 29.6 m. Based on the

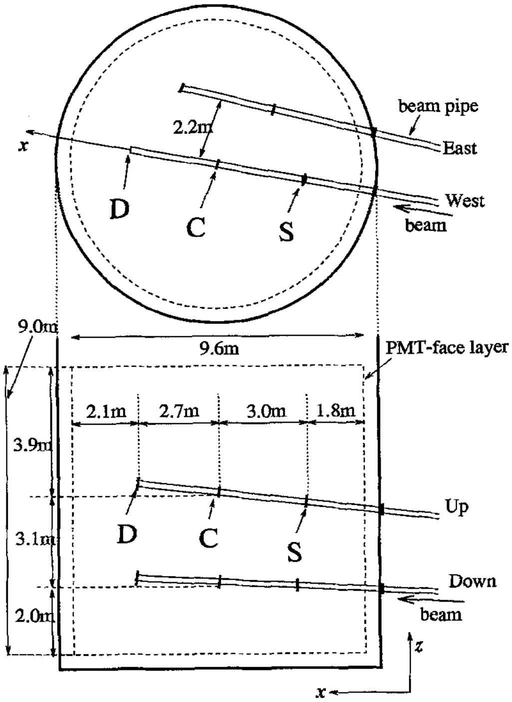

Fig. 1. A cross-sectional view of the water tank and the positions of the particle incidence. The results from the data at the positions C, S and D are presented in this paper.

electron data, the timing resolution of the TOF system was found to be 210 psec.

Electrons over the entire momentum range of 100 MeV/c – 1000 MeV/c were clearly separated from other particles by means of the gas Čerenkov and TOF counters. The long flight path and precise timing of the TOF counters enabled us to separate muons from pions below 500 MeV/c with negligible contamination. In order to obtain clean particle samples, the TOF values were restricted to be within $\pm 2\sigma$ from the respective peak.

Since the TOF system became inefficient above 600 MeV/c for separating muons from pions, we used the following technique to obtain a pure muon beam: First, pions were momentum-analyzed with the first magnet close to the target, say the momentum (p). Then, the second and third downstream magnets were set in such a way that they select those muons that are produced in the extreme backward direction in the pion rest system. Those muons have momenta about 0.57 p for $p >> m_\pi$. The second magnet system ef-

Table 1
Characteristics of the data samples. (a) events having a PMT whose signal exceeds 200 p.e.'s. These events are excluded from further analyses as the Kamiokande analysis applied this selection cut.

Beam	Particle	Momentum (MeV/c)	Number of scanned events	Number of single-ring events	Number of events with accidental particles	Number of punch-through events [(a)]
C	μ	250	100	100	0	0
		400	100	100	0	0
		500	100	100	0	0
		600	100	100	0	0
		700	100	100	0	0
		800	101	100	1	0
		900	102	100	1	1
	e	100	102	100	2	0
		200	101	100	1	0
		300	100	100	0	0
		400	101	100	1	0
		500	103	100	1	2
		600	101	100	1	0
		700	102	100	1	1
S	μ	300	101	100	1	0
		400	102	100	2	0
		500	102	100	2	0
		600	100	100	0	0
		800	101	100	1	0
		1000	100	100	0	0
	e	100	100	100	0	0
		200	101	100	1	0
		300	102	100	2	0
		400	100	100	0	0
		500	101	100	1	0
		600	101	100	1	0
		700	100	100	0	0
		800	100	100	0	0
D	μ	300	101	100	1	0
		400	100	100	0	0
	e	100	100	100	0	0
		200	102	100	1	1
		300	112	100	0	12

ficiently removed the parent pions, and thus produced a clean muon beam. The TOF system was also used to reject any remaining electrons and pions.

The estimated contamination of other particles in each sample is as follows: less than 0.1% for electrons of the full momentum range and for muons with $p_\mu < 500$ MeV/c, 1% for muons with $p_\mu = 600$ and 800 MeV/c, 2% for 900 MeV/c muons and less than 1% for 1000 MeV/c muons, where the TOF values were further required to be in the lower half of the $\pm 2\sigma$ range. These contaminated particles are pions, since pions dominate over muons at higher momenta.

The TOF system is sufficiently accurate to even measure the absolute momentum values and spreads. The momentum spread was estimated at each momentum by subtracting the intrinsic TOF resolution (210 psec) from the observed TOF width. The results were: 1.7±0.5% for pions, 3.1±0.8% for muons with

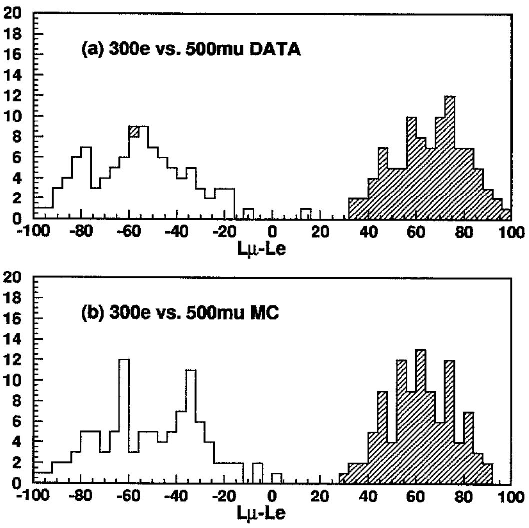

Fig. 2. The $[L_\mu - L_e]$ distribution of (a) data and (b) Monte Carlo samples for e (300 MeV/c) and μ (500 MeV/c) at the position S. The two data samples have about the same total-p.e.'s.

$p_\mu < 500$ MeV/c and 3.8±0.7% for muons with $p_\mu > 600$ MeV/c (backward decay beam). The momentum spread for muons was large as they were produced by in-flight decay of pions in the upstream beam line. The momentum spread of the backward decay muon beam was estimated for these data with $p_\mu < 700$ MeV/c, assuming that it did not change at high energies. The momentum spread of electrons should be much larger than that of pions, since they suffer radiative energy losses in the beam line. Nevertheless we assumed in our Monte Carlo calculations that the electron beam had the same momentum spread as pions, since it could not be determined by the TOF system.

Here, we present the first results obtained from the data which were taken at the three injection points (C, S and D, as shown in Fig. 1) using one of the beam pipes, in the period of March 1994.

Events were analyzed along the following chain of analyses, which are identical with what has been used in the Kamiokande experiment:
(i) About 100 events within 2σ from the peak of the total-photoelectron (total-p.e.) distribution are selected to avoid those that lost sizable energies in the beam line. (Events having a total-p.e. below the 2σ cut were later analyzed in order to check a possible bias caused by the 2σ cut. It was found that they were correctly identified as electrons or muons having momenta corresponding to their total-p.e.) (ii) A scanner selects single Čerenkov ring events and records the PMT's which detected Čerenkov light close to the ring edge. Table 1 summarizes some of the characteristics of the scan. (iii) Based on the relative timing of each PMT and hit pattern, the vertex and direction of the event are determined. (iv) Based on the total-p.e.'s detected in the event, the momentum is calculated. (v) Based on (iii) and (iv), i.e. the given vertex, direction and momentum, the expected number of p.e.'s in each PMT is calculated under the assumption that the particle is either a muon or an electron. (vi) The two likelihood functions L_μ and L_e are now defined corresponding to electron and muon likeliness [10]. First define the probability ($P(N, N_0)$) that a PMT observes N photoelectrons for the expected mean number of p.e. (N_0). Note that P is wider than the Poissonian due to an additional fluctuation in the PMT. For $N_0 < 10$ p.e. we take the empirical distribution for P. For $N_0 \geq 10$ p.e., P can be approximated as

$$P(N, N_0) = \frac{1}{\sqrt{2\pi}\sigma} \exp(-\frac{(N - N_0)^2}{2\sigma^2}), \quad (1)$$

$$\sigma^2 = 1.2^2 N + (0.1N)^2, \quad (2)$$

where the factor 1.2 comes from the actual PMT resolution and the second term in σ takes into account the 10% uncertainty in the relative PMT gain.

We now calculate the two expected numbers of p.e. in the ith PMT (N_i^e, N_i^μ) for the same total-p.e., the same vertex position and the same direction of an event, assuming that the event is either an electron or a muon. For the electron assumption, N_i^e is calculated by referring to a database of the mean angular distribution of the Čerenkov radiation, which was made by a Monte Carlo method taking into account electromagnetic showers in water. For the muon assumption, it is numerically calculated by considering the ionization energy loss of the muon [10]. Selecting the PMT's inside a cone with a half opening angle of $1.5 \times \theta_c$ from the reconstructed particle direction, θ_c being the Čerenkov angle, we finally define the following logarithmic functions for e-likeness or μ-likeness:

$$L_e = \log_{10}[\prod_{\theta_i < 1.5\theta_c} P(N_i, N_i^e)], \quad (3)$$

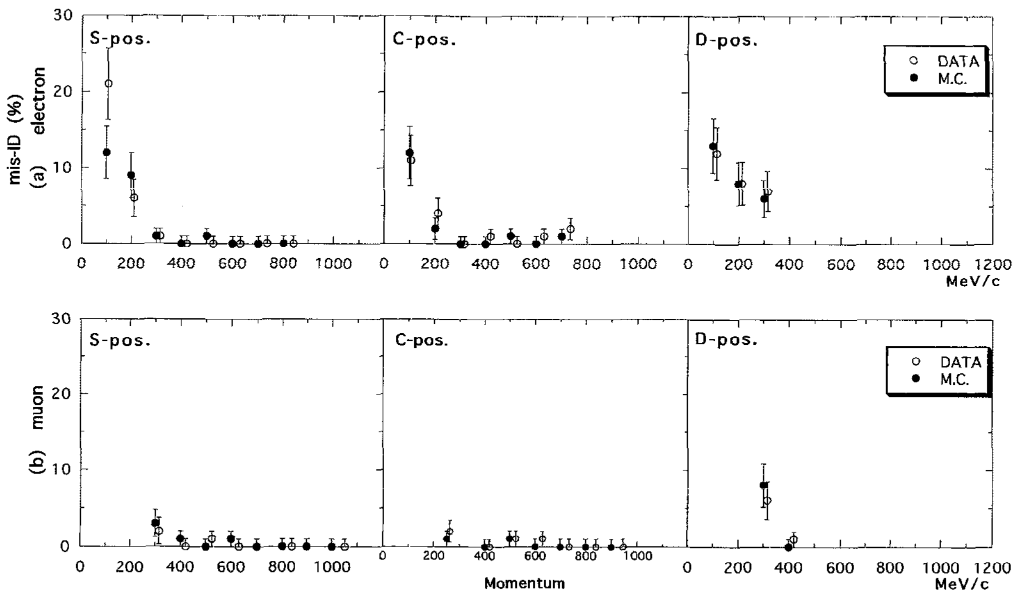

Fig. 3. The mis-identification probabilities for (a) electrons and (b) muons at the three points of beam incidence, compared with the Monte Carlo estimates.

$$L_\mu = \log_{10}[\prod_{\theta_i<1.5\theta_c} P(N_i, N_i^\mu)] . \quad (4)$$

An event is more e-like than μ-like if $L_e > L_\mu$, and vice versa.

As an example we show the L_μ–L_e distributions of typical data samples in Fig. 2. The hatched histograms correspond to the events identified as muons in the TOF system, while the open histograms are for the electron events.

Fig. 3 shows the resultant mis-identification probabilities as a function of momenta which are compared with the Monte Carlo estimates. These results clearly demonstrate that the water Čerenkov detector is capable of identifying electrons and muons with momenta larger than 250 MeV/c with a mis-identification probability less than a few percent except for the beam incidence at the detector edge (point D). The large mis-identification probability observed at point D is obviously due to a very short distance of the particle inlet to the PMT wall, which results in the small number of hit PMT's. Note that the point D corresponds to the extreme edge of the Kamiokande fiducial volume. More importantly, the measured mis-identification probabilities are well reproduced by the Monte Carlo calculations. Thus, the deficiency of μ-neutrinos in the atmospheric neutrinos is not an artifact caused by some peculiar detector characteristics.

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