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Anomalously Low Atmospheric ν_μ/ν_e Ratio as manifestation of $p \to e^+\nu\nu$ [1]

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W.A. Mann, T. Kafka and W. Leeson
Department of Physics, Tufts University
Medford, MA 02155, USA

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ABSTRACT

Recently we showed that, in a scenario in which absolute fluxes of low energy atmospheric neutrinos are below expectations of most calculations, the observed small ν_μ/ν_e ratio can be interpreted as evidence for proton decay $p \to e^+\nu\nu$ occuring in the water or iron media of underground detectors. A new analysis method is presented here which does not depend on neutrino flux calculations. In the Kamiokande 6.18 kiloton-year exposure, the rate of single-ring e-like events with lepton momenta of 100 - 500 MeV/c appears to be enhanced; this event excess is compatible with $\tau/B \sim 4 \times 10^{31}$ years.

The flux of atmospheric neutrinos gives rise to contained events in massive underground detectors. Event samples accumulated by the Kamiokande[1,2] and IMB[3,4] water Cherenkov experiments continue to show an effect which suggests an anomaly in the neutrino flavor content of the atmospheric flux. The observation concerns relative rates among subsamples of contained events whose images appear either as single, sharply-defined rings (muon-like), or as single, diffuse rings (electron-like). The majority of single-ring events are supposedly quasi-elastic charged current interactions. We assume the ratio of μ-like to e-like single-ring event rates $N_1(\mu)$ and $N_1(e)$ to measure R_ν, the muon neutrino flux $N(\nu_\mu + \bar{\nu}_\mu)$ divided by the electron neutrino flux $N(\nu_e + \bar{\nu}_e)$. From the decay chains of mesons and muons in cosmic ray showers, it is expected that R_ν should be nearly 2.0. This expectation is borne out in all detailed calculations of the atmospheric neutrino flux to date.[5] However, in the most recent reports by Kamiokande and IMB-3 the observed ratio is about 1.2. Since the measured value is nearly four standard deviations below the R_ν expectation for either experiment, the discrepancy is worthy of consideration as a harbinger of new physics. The new R_ν measurement obtained with the Soudan-2 fine-grained iron tracking calorimeter,[6] supports the view that R_ν is anomalous and does not represent an instrumentation effect with the water Cherenkov experiments.

To interpret the low R_ν value, one needs to know whether the μ-like events of the numerator are too few, whether e-like events of the denominator are too numerous, or whether a combination of both circumstances is actually the case. Two points of view have been expressed in the recent literature. According to one view (Refs. 1,2), there is an apparent dearth of muon-neutrino events (accompanied perhaps by a mild excess of electron-neutrino events (Refs. 3,4)), which is interpreted as evidence that neutrino oscillations deplete the muon-neutrino flux over

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distances of 10 to 10,000 kilometers. A different view, formulated by us in Ref. 7, assumes that the expected number of ν_μ events has been detected, and that there is an excess of electron-like events that requires interpretation. The situation could be clarified if the absolute fluxes for all neutrino flavors $(\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e)$ were accurately known, which is, however, not the case. The interpretation of Refs. 1,2 is based on absolute neutrino fluxes calculated by Gaisser et al. (Refs. 8), which happen to be the highest in the literature. In formulating our view in Ref. 7, we utilized absolute atmospheric neutrino fluxes calculated by Bugaev and Naumov,[9] which are lower than the Gaisser et al. fluxes. In this paper we reformulate the argument of Ref. 7 in a way which does not rely on any neutrino flux calculation. We assume that no atmospheric muon neutrinos are lost due to oscillations or other processes.

In Fig. 1a we show the distribution of lepton momentum for all contained, muon-like single-ring events in the 6.18 kty exposure of Kamiokande. The detection efficiency for these events is shown superimposed. The corresponding distribution for electron-like single ring events is shown in Fig. 1b. The Cherenkov threshold for detection of muons in water precludes direct observation of events with muon momenta 100 - 200 MeV/c. For this bin we have inferred a counting rate by extrapolating plausible distribution shapes. The shapes were calculated using muon quasi-elastic events and were fitted to the observed distribution of μ-like events. We regard the μ-like event sample to be free of any "new physics". Also, we assume that neutrino cross-sections are nearly the same for corresponding ν_μ, ν_e charged current channels. Then we can use the number of μ-like events in each momentum bin, together with the experimental detection efficiencies and the e-like to μ-like event ratio 1:2, to predict the number e-like events to be observed in the absence of new physics. The expected e-like event rates are depicted by the open triangles in Fig. 1b. We observe in Fig. 1b that there is an excess of e-like events over and above the expectation inferred from the μ-like event distribution and conventional ν fluxes. We note that the excess is significant only in the interval 100 - 500 MeV/c. We now consider nucleon decay processes as candidate sources for this apparent localized excess of single-ring e-like events.

The data restricts the number of viable nucleon decay modes in two ways:
(*i*) Topology constraint: Single $e^\pm$ showers are detected; any accompanying particles leave no signal in a water Cherenkov detector.
(*ii*) Momentum spectrum constraint: Single $e^\pm$ showers are detected with significant rate in the momentum interval from 100 MeV/c to 500 MeV/c.

We find that there is no two-body or four-body nucleon decay mode which, alone, can satisfy the $e^\pm$ spectrum constraint.[7] With three-body modes, there is only one which satisfies both the momentum spectrum constraint and the topology constraint. The mode is

$$p \to e^+ \nu \nu \tag{1}$$

To examine the extent to which mode (1) satisfies the positron spectrum constraint (*ii*), we subtract bin-by-bin the rate expectation for the e-like events which is based on the observed distribution of single-ring μ-like events. The excess of e-like events thus obtained is plotted in Fig. 1c. Superimposed on the histogrammed data is the phase space momentum distribution for positrons originating with decay (1) in a water medium (dashed line). The shape of the positron momentum spectrum of proton decay mode (1) is observed to describe the excess event distribution rather well.

We conclude that there is one nucleon decay mode which satisfies criteria (*i*) and (*ii*); that mode is process (1). If we suppose that proton decay via this mode gives rise to an excess of single-ring e-like events which accounts for the anomaly in the atmospheric ν_μ/ν_e ratio, then we infer from Fig. 1c that 51 ± 16 instances of proton decay have occurred in the 6.18 kty exposure of Kamiokande. The lifetime over branching ratio thus implied is $(\tau/B) = 3.7^{+1.7}_{-1.0} \times 10^{31}$years.

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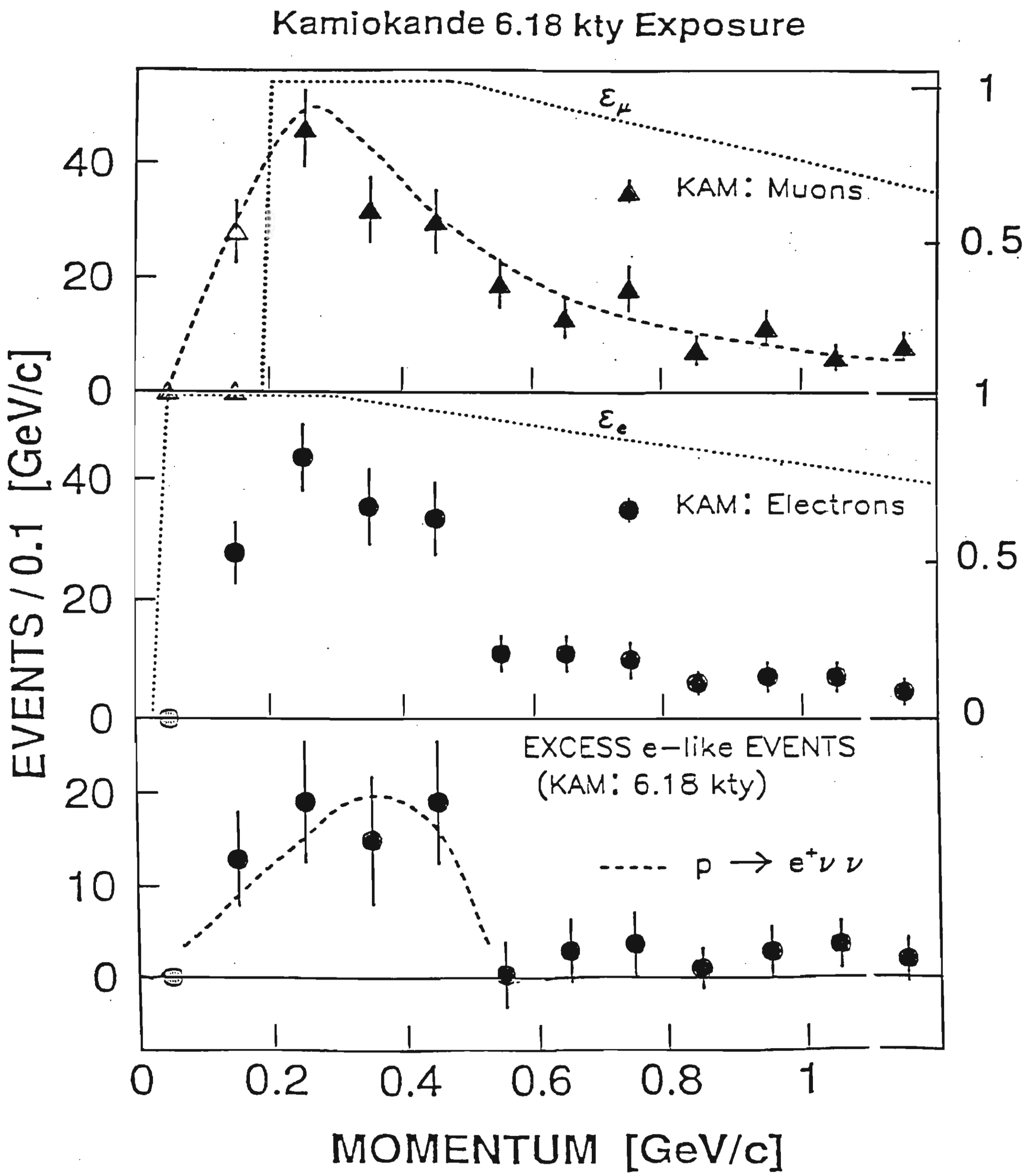
Figure Caption

Fig. 1

Momentum distributions of single-ring (a) μ-like and (b) e-like events from the 6.118 kty exposure of Kamiokande. Detection efficiencies are shown superimposed (dotted). The dashed curve in (a) depicts the distribution shape expected for quasielastic events. It is used to infer the event rate in the lowest momentum bin (open triangle).


Kamiokande 6.18 kty Exposure
ε_μ
KAM: Muons
ε_e
KAM: Electrons
EXCESS e-like EVENTS
(KAM: 6.18 kty)
p → $e^+\nu\nu$
EVENTS / 0.1 [GeV/c]
MOMENTUM [GeV/c]
0
20
40
10
0.2
0.4
0.6
0.8
1
0.5