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Study of Neutron Background in the Atmospheric Neutrino Sample in Kamiokande

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Abstract

Neutron background in the atmospheric neutrino sample was studied based on the vertex position distribution of the fully contained π^0 events. No evidence for the background contamination was observed. The neutron contamination in the sub-GeV e-like sample was less than 1.2% at 90% C.L..

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In recent years, the atmospheric ν_μ/ν_e ratio has been studied extensively. Kamiokande [1] [2], IMB-3 [3] and Soudan-2(preliminary) [4] observed that the atmospheric ν_μ/ν_e ratio was significantly smaller than that expected from Monte Carlo estimates based on standard calculations of atmospheric neutrino flux. Kamiokande also observed that, in the multi-GeV energy range, the ν_μ/ν_e ratio depended on the zenith-angle [2]. These results could be interpreted as evidence for neutrino oscillations. On the other hand, the Frejus [5] and the NUSEX [6] experiments, which were operated deeper underground, did not observe the small ν_μ/ν_e ratio within their statistics.

Recently, it was pointed out [7][8] that the small ν_μ/ν_e ratio could be explained by isolated neutron interactions in the detector: The isolated neutrons, produced by interactions of cosmic-ray muons, enter into a detector, produce π^0's via nN $\rightarrow \pi^0 X$, and the π^0's be misidentified as e-like events which are normally caused by charged-current ν_e interactions.

In this report, we study the neutron contribution to the atmospheric ν_μ/ν_e measurement in Kamiokande-II-III(Kam-II-III)[5].

The Kam-II-III detector is a 4.5-kton water Cerenkov detector located at a depth of 2700 meters water equivalent(m.w.e.) in the Kamioka mine in Japan. It consists of two layers of water. The inner volume of water, surrounded by 948 PMTs, 13.1 m in height, 14.4 m in diameter and 2.14 kton in mass, constitutes an inner-detector. The outer layer surrounds the inner-detector constituting a 4π solid-angle anti-counter. Standard rock surrounds the side and bottom anti-counter sections. Above the top anti-counter, there is a space of a hemispherical shape with the maximum gap of 7 m between the top anti-counter and the rock. The thickness of the anti-counter is 1.2 m, 1.7 m, and $\sim$2.3 m for the top, bottom and side regions, respectively. Muons pass through the inner-detector with a rate of 0.37/sec. The fiducial regions for fully-contained sub-GeV and multi-GeV events are 1.5 m and 1.0 m inside from the surface of the inner-PMT-layers, respectively. Therefore, the fiducial volume for the sub-GeV data is shielded by 2.7 m, 3.2 m and $\sim$3.8 m of water for the top, bottom and side regions, respectively.

If we take the number from Ref. [7], the isolated neutron flux at 2700 m.w.e. underground with T_n >200MeV, where T_n is the kinetic energy of neutrons, is 65 $m^{-2} yr^{-1}$. This number corresponds to 6.7×10^5 entering neutrons during the total runtime of Kam-II-III (6.8 *years*).

We estimated the number of neutrons entering the fiducial volume and producing pions. GEANT [9] was used to study the characteristic of the neutron interactions in Kamiokande. We assumed that the energy spectrum to be dT_n/T_n^2(T_n >200MeV) as in Ref. [7], the entering position of the neutrons to be uniformly distributed over the entire surface area, and

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[5] In this report we do not include the Kam-I data because (i) the detector configuration in Kam-I was different from that of Kam-II-III, and (ii) there was only 16% and no contribution to the total exposure for the sub- and multi-GeV data sample, respectively.

the direction of the entering neutrons to be uniformly distributed within the 2π solid-angle. The number of simulated neutron events was 5.5×10^5 which was equivalent to 5.6 years of the detector exposure assuming the neutron flux of Ref. [7]. About 1% of the simulated neutrons interacted in the inner-detector via nN $\rightarrow n\pi$X($n \geq$1) without any visible particles in the anti-counter region. These events were passed through the standard procedure of the atmospheric neutrino analysis. Since the interaction length of neutrons is less than 1 m, most of the events had their vertex position near the surface of the inner-detector volume.

Now, we study the properties of the background events in the sub-GeV region. Table 1 summarizes the observed number of events in the fiducial volume and compares them with the atmospheric-neutrino Monte Carlo events with the flux of Ref. [10] and with the neutron Monte Carlo events with the flux of Ref. [7]. If the adopted neutron flux [7] were indeed true, most of the observed events would have been produced by neutrons and the contribution of atmospheric neutrinos should be much smaller than what would be expected from the calculated flux of Ref. [10]. However, this is clearly not the case which is seen in the characteristics of the neutron events. For example, the fraction of multi-ring events in the sub-GeV sample is 0.28±0.02(stat.) and 0.30 for the data and neutrino MC, respectively. On the other hand, the same fraction is 0.82±0.02(stat.) for the neutron events.

For further study, we do not argue based on the absolute numbers predicted by the neutron MC because of the ambiguity in the neutron interaction. Instead, we study the vertex position distribution of single π^0's observed in the detector. The Kamiokande detector is capable of identifying two γ's with a high efficiency, and hence we should see an excess of single π^0 events near the surface of the fiducial volume, if neutrons indeed made a sizable contribution to the e-like events.

"π^0"-like events are selected according to the following criteria; (1) visible two Cerenkov rings should exist, (2) both of them should be inconsistent with μ-like, and (3) the invariant mass, assuming that both of them are γ's, should be between 90 and 180 MeV/c^2. Fig. 1 shows the invariant mass distribution for the observed events which satisfy the above criteria (1) and (2). One can clearly see the excess of events at around 135 MeV/c^2.

Fig. 2 shows the event rate of the π^0-like events as a function of D_{wall}, the distance to the nearest PMT-plane from the reconstructed vertex position of the events. The thick histogram in the figure shows the MC atmospheric-neutrino distribution normalized to the data. One sees that the shape of the above distribution agrees well between the data and the MC. One can estimate the number of neutron events from the difference in the D_{wall} distribution between the neutron and neutrino events. Shown in the same figure, by the shaded area, is the 90% C.L. upper limit on the neutron events, which corresponds to 13 events. (The best fit number of the neutron events is −3±9(stat.).) π^0's produced by atmospheric-neutrino interactions in this energy region are identified as π^0-like, e-like and the other types of events, and the Monte Carlo study shows that their fractions averaged over the sub-GeV energy region are 77%, 17% and 6%, respectively. Therefore, 90% C.L. upper limit on the number of background events to the π^0-like events, 13, can be translated to an upper limit on the background to the e-like events by using the above numbers, namely 13×(17%/77%)=2.8 events. We note that the total number of e-like events in the Kam-II-III data is 226. Therefore, a possible contamination of the neutron events to the e-like data sample is less than 1.2% at 90% C.L.. Even if we neglect the background to the μ-like events (which, according to Table 1, should be the similar number to the one to the e-like events), the above value is more than a factor of 30 too small to account for the small $(\mu/\mathrm{e})_{data}/(\mu/\mathrm{e})_{MC}$ value, 0.61±0.06(stat.)±0.06(syst.) (Kam-II-III). This value does not change significantly if we include the Kam-I data, $0.62^{+0.06}_{-0.05}$(stat.)±0.06(syst.) (Kam-I-II-III).

In order to further confirm that the single-ring e- and μ-like events have no significant neutron contamination, we show, in Fig. 3, the D_{wall} distribution for the (a) e-like and (b) μ-like events. The histograms in the figure show the MC atmospheric-neutrino distributions normalized to the data. No evidence for the excess of events near the surface of the fiducial volume is seen. The best-fit numbers of neutron events are 27±21(stat) and 17±23(stat) for the e-like and μ-like events, respectively.

According to Table 1 and because of the negligible neutron contamination to the sub-GeV data, the neutron contamination to the multi-GeV region should also be negligible. Here we cannot apply the same method as above to the multi-GeV data, because the efficiency of π^0 identification rapidly deteriorates at higher energies. However, it is still possible to independently estimate an upper limit on the neutron background in this energy region from the vertex and momentum-vector information. The Monte Carlo study shows that the total momentum vector of a neutron event points to the direction of the neutron within $\Delta\theta \sim 10^o$, and hence the entrance position of neutrons (or neutrinos) into the inner detector can be estimated using the information of the vertex position and the total momentum vector. Fig. 4 shows the distribution of the distance from the estimated entrance position to the reconstructed vertex position. One sees that the shape of the distribution of the data agrees well with the one expected from the sole neutrino origin. The 90% C.L. upper limit on the number of neutron events is 15, which corresponds to 14% of the total number of multi-GeV e-like events. (The best fit number of the neutron background events is 2±7(stat.).) This limit is weaker than that obtained for the sub-GeV e-like events, but is still too small to account for the observed small μ/e ratio in the multi-GeV data.

The discrepancy between the present results and the estimate in Ref.[7] should be sought in the flux of 'isolated' neutrons. Here the definition of an isolated neutron is that the observed neutron does not accompany any other particles[7]. Therefore, the flux of isolated neutrons should depend on various parameters such as the detector size and the spacing between the detector and the surrounding rock. It is possible that the flux of isolated neutrons in Kam-II-III is indeed much smaller than that estimated in Ref. [7]. The reasons are as follows: First, the size of the Kam-II-III detector, 16 m in height and 19 m in diameter, is much larger than the detector, 5.4 m in height and 5.6 m in diameter, that measured the isolated neutron flux[11]. Accordingly, both a neutron and a parent muon have a larger chance to be observed in Kam-II-III than in a smaller detector. Second, we note that a neutron can be produced by an interaction of a cosmic-ray muon in the rock, and that the probability of detecting only the neutron should increase with increasing spacing between the detector and the surrounding rock. In Kam-II-III there is no space between the anti-counter water and the surrounding rock except for the top section. On the other hand, the detector[11] which measured the isolated neutron flux had a space between the detector and the surrounding rock for the side and top sections.

In summary, we estimated the contamination of neutrons in the sub-GeV e-like data sample using the vertex-position distribution of the π^0-like events. No evidence for the background contamination was observed. The possible contamination of neutrons in the sub-GeV e-like sample was less than 1.2% at 90% C.L.. For the multi-GeV data, the background contamination was estimated using the information of the vertex position and the total momentum vector of the e-like events. We did not observe any evidence for the background contamination. The possible neutron contamination in the e-like sample was less than 14% at 90% C.L.. These numbers, especially the one for the sub-GeV data, were too small to account for the small (μ/e) ratio of the atmospheric neutrino data.

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Figure captions

Fig.1. Invariant mass distribution for the data and the Monte Carlo generated atmospheric-neutrino events. The events are selected according to the criteria (1) and (2) described in the text. The Monte Carlo events are normalized to the data at 135±45 MeV/c^2.

Fig.2 Event rate as a function of D_{wall}, the distance to the nearest PMT-plane from the event vertex for the sub-GeV π^0-like events. The thick histogram shows the MC atmospheric neutrino events normalized to the data. The thin one shows the 90% C.L. upper limit on the neutron events plus atmospheric neutrino events, and the shaded area shows the contribution of the neutron events to the upper-limit histogram.

Fig.3 Event rate as a function of D_{wall} for the sub-GeV (a)e-like and (b) μ-like events, respectively. The thick histograms show the MC atmospheric neutrino events normalized to the data.

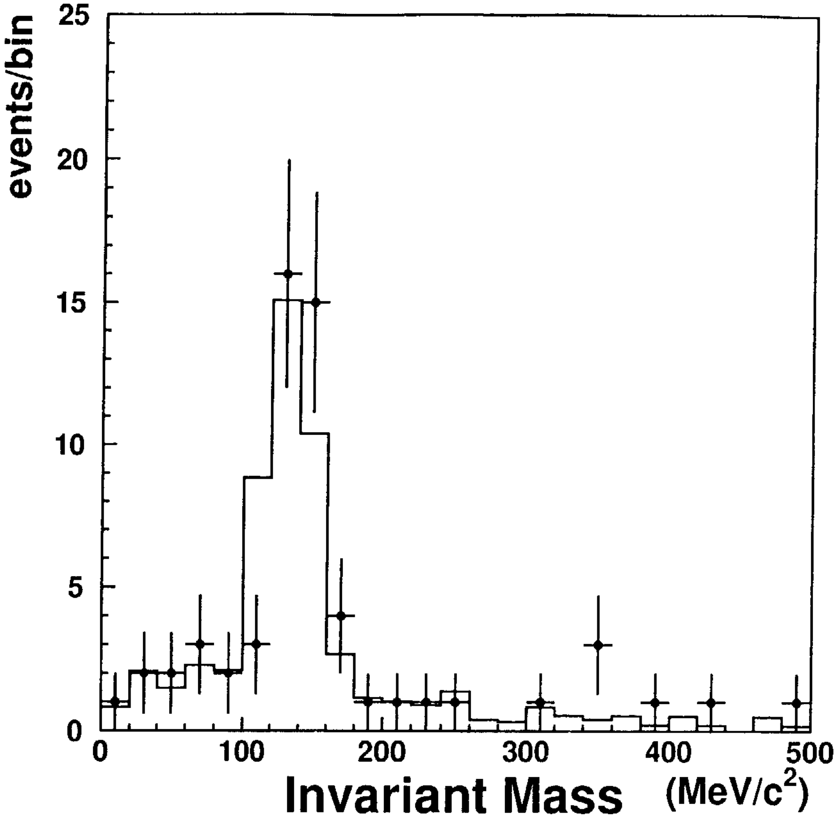
Fig.4 Distribution of D, the distance from the estimated entrance position to the reconstructed vertex position, for the multi-GeV e-like events. The thick histogram shows the MC atmospheric neutrino events normalized to the data. The thin one shows the 90% C.L. upper limit on the neutron events plus atmospheric neutrino events, and the shaded area shows the contribution of the neutron events to the upper-limit histogram.

Table 1. Summary of the number of events in the fiducial volume for the data, atmospheric neutrino Monte Carlo simulation and neutron Monte Carlo simulation assuming the neutron flux of Ref. [7] during the 6.8 years of the exposure of the Kam-II-III detector.

	Data	ν MC$^{(*)}$	neutron MC
Sub-GeV			
total	607	767.3	577±27$^{(**)}$
single-ring			
μ-like	209	322.7	51±8
e-like	226	211.7	51±8
multi-ring	172	232.9	475±25
Multi-GeV fully-contained events			
total	207	203.9	214±24
μ-like	31	42.2	5±4
e-like	105	76.5	57±12

(*)Based on the neutrino flux of Ref. [10].

(**)Error bars are statistical only.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Invariant Mass
(MeV/c^2)

Fig.1

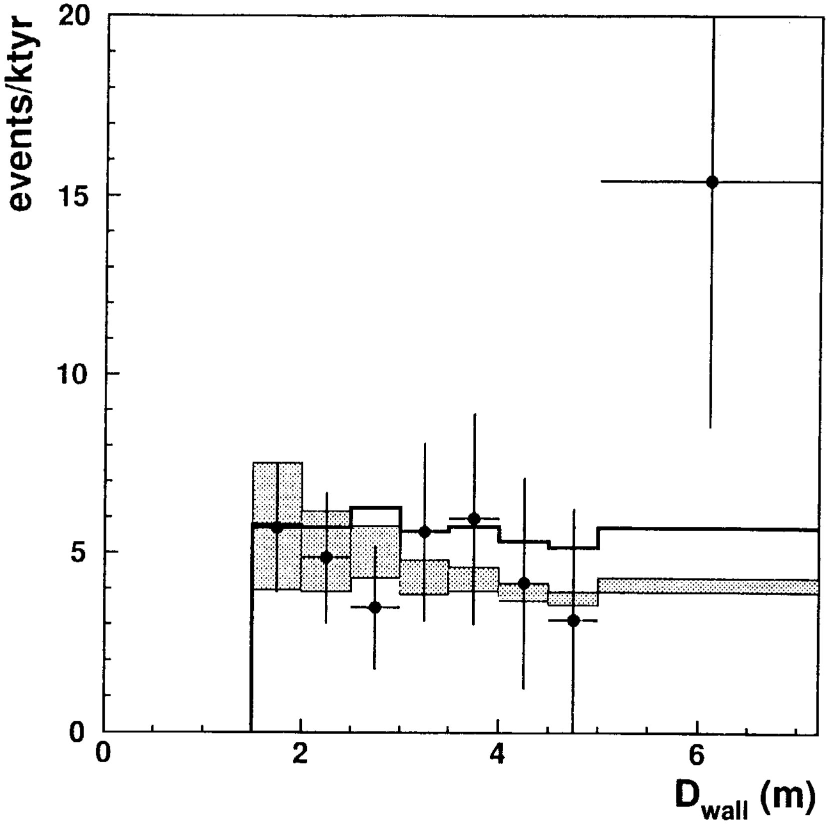
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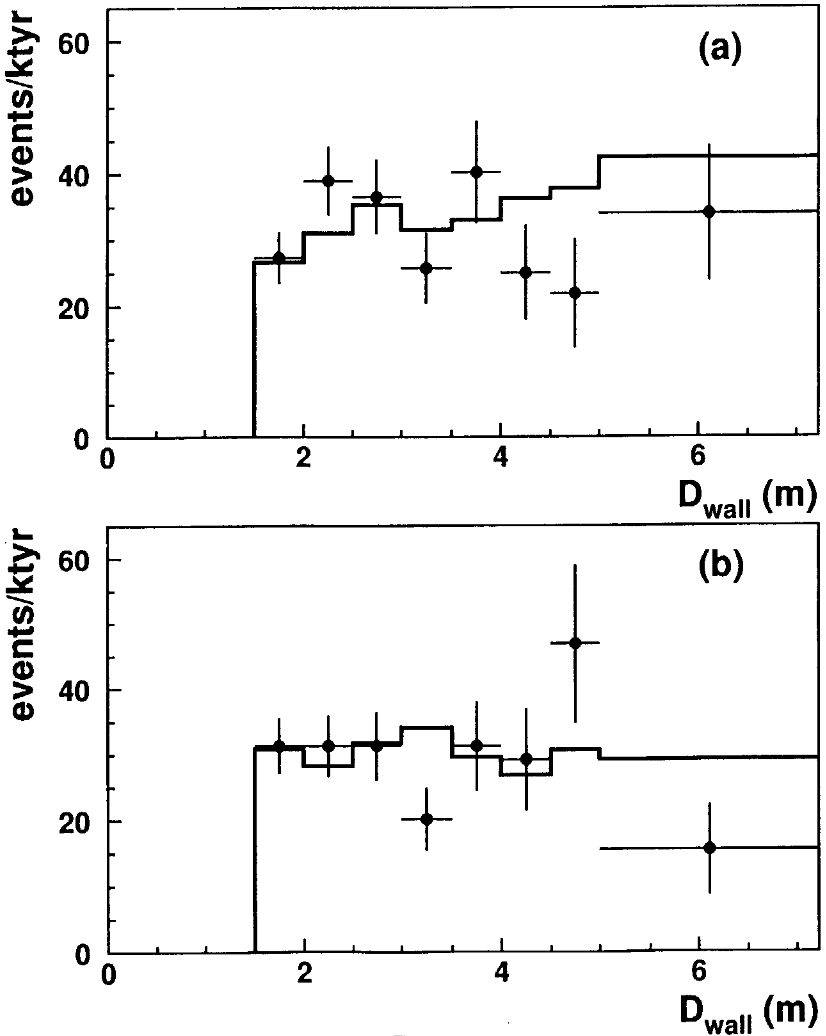
Fig.2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(b)
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2
4
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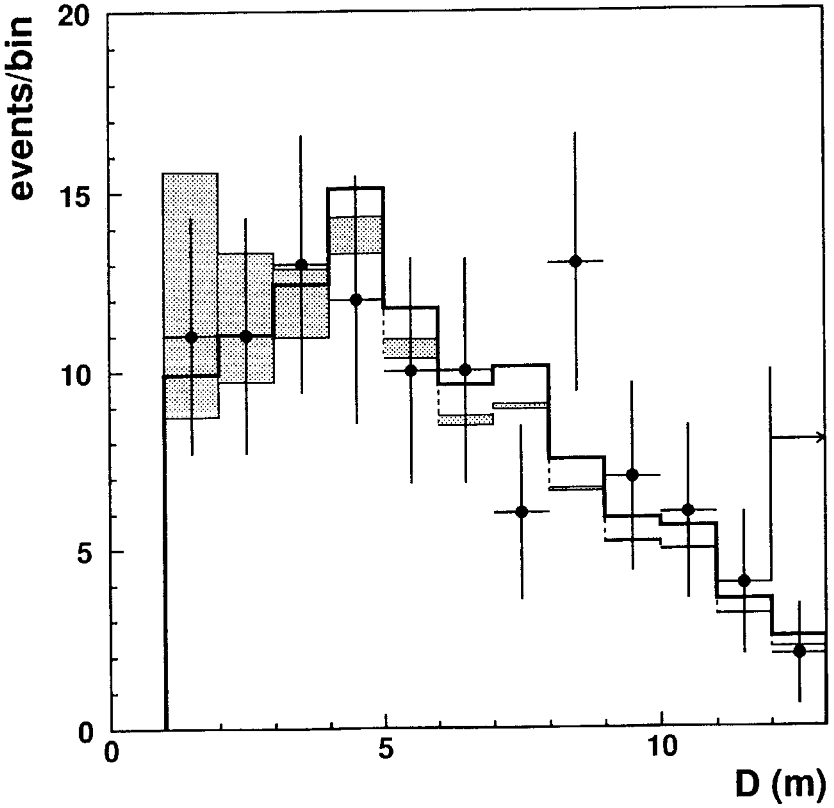
D$_{wall}$ (m)
D$_{wall}$ (m)

Fig.3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10
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5
10
D (m)

Fig.4