Comment on an interpretation of measurements of the flux of atmospheric neutrinos by the Kamiokande detector

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The spatial distribution of events detected by the Kamiokande detector in an experiment to measure the flux of atmospheric neutrinos is analyzed. It is shown that electron-like events near the boundaries of the working volume consist of a mixture of interactions of ν_e's with nucleons and of neutrons with O^{16} nuclei. Neutrons are produced in showers generated by muons in the earth. The ratio ν_μ/ν_e in the central volume of the detector, at a distance of about 3 m from the plane of the photomultipliers, is approximately as expected.

The background caused by isolated neutrons in Čerenkov detectors which radiate atmospheric neutrinos was discussed in Ref. 1. Neutrons are produced in showers generated by muons in the walls. Some of the high-energy neutrons may move far away from the core of the shower and pass through the inner volume of the detector without causing a visible signal in the anticoincidence shielding, giving rise to electron-like events as a result of the reaction $nA \rightarrow \pi X^0$. Estimate show that this background is substantial at depths to 5000 meters of water equivalent (mwe).

In a recent paper by the Kamiokande collaboration,[2] the authors presented the spatial distribution of points of interactions of electron- and muon-like events for energies above 1.33 GeV (see Fig. 1 of the present letter; the square of the detector radius is plotted along the abscissa, while the height of the detector is plotted along the ordinate). An event is "fully contained" (FC) if the interaction point lies within the working volume and if there is no visible energy in the anticoincidence system. A "partially contained" (PC) event can have a visible energy, corresponding to the passage of one particle, in the anticoincidence shielding, but the fact that the interaction point is in the working volume is solidly established. By definition, partially contained events must be muon-like events. The FC events are both muon-like (the open circles in Fig. 1) and electron-like (the filled circles). The total number of muon-like FC events is 31, and that of electron-like events is 98.

How well does the distribution in Fig. 1 correspond to the hypothesis that all detected events are neutrino interactions?

In the absence of an edge effect, the neutrino interaction points should be distributed uniformly. This is the correct distribution for the sum of FC and PC events. An edge effect should cause the density of FC neutrino events to fall off from the center toward the periphery. The density of events due to the neutron background should be higher in

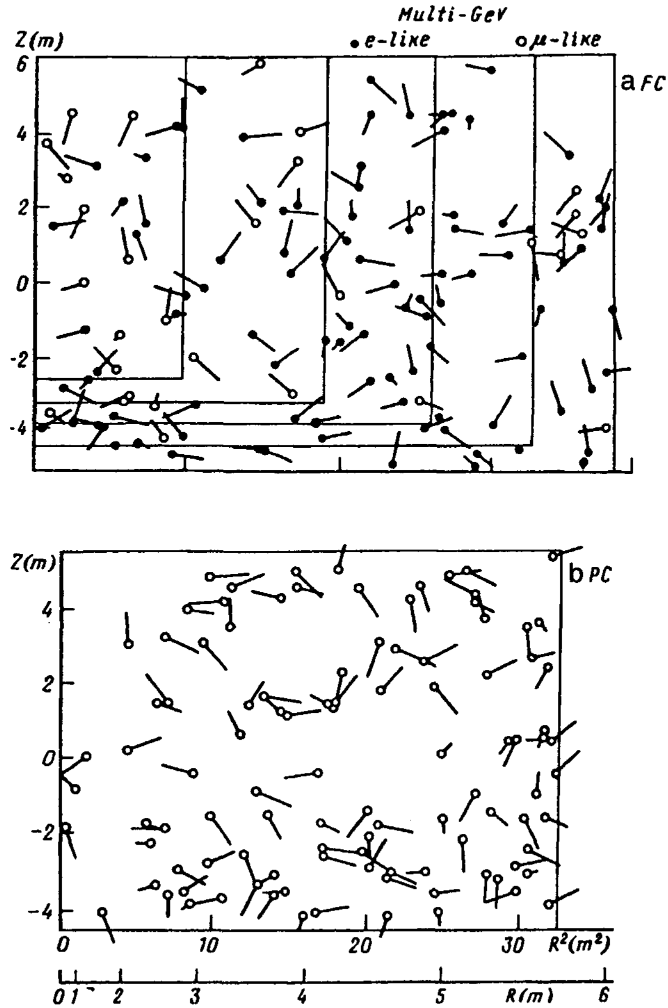

FIG. 1. Two-dimensional R^2–Z distribution of the interaction points and momentum directions for events detected by the Kamiokande detector. a) Fully contained (FC) events; b) partially contained (PC) events. Z—Vertical axis; R—distance along the radius of the cylindrical working volume; filled circles—interaction points for electron-like events; open circles—the same, for muon-like events. The vertical and horizontal lines are the boundaries of identical volumes (see the text proper).

the outer layers, since the neutron source is outside the detector. Because of the edge effect, the number of events associated with neutrons will fall off more slowly than $\exp(-r/\lambda)$ toward the center, where λ is the neutron range with respect to pion production.

Neutrons generated by muons in the rock reach the detectors primarily through the lateral walls and from below. The probability for a neutron produced in a shower above the apparatus to reach the detector without a charged-particle accompaniment is ex-

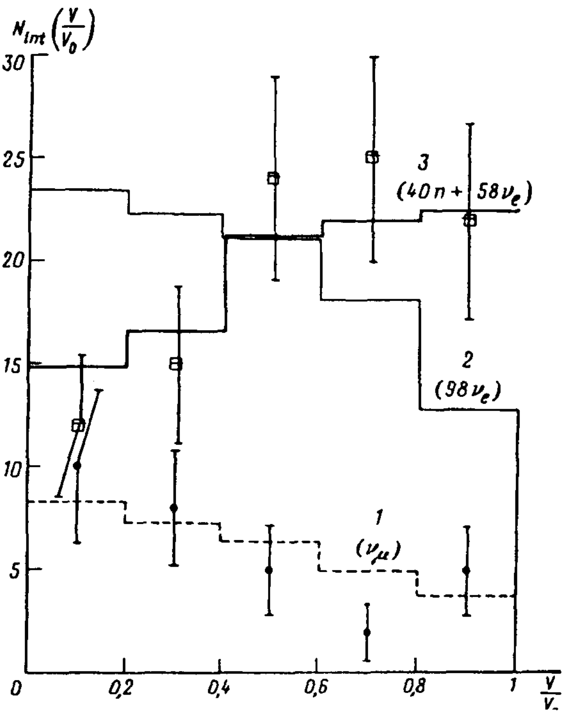

FIG. 2. Distribution of events detected by Kamiokande in identical fractions of the working volume (V/V_0), from the center to the periphery. Circles—Muon-like events; squares—electron-like events. Expected distributions: 1) For muon-like neutrino events; 2) the same, for electron-like events caused by neutrinos; 3) for a mixture of interactions of electron neutrinos and a background caused by high-energy neutrons.

tremely small. We divide the detector into five identical volumes, as shown in Fig. 1. The vertical lines are the intersections with cylindrical surfaces at distances of 0.5λ, 1.1λ, 2.1λ, and 3.3λ from the boundary of the working volume. The horizontal lines are cross sections of a cylinder at distances of 0.7λ, 1.4λ, 2.1λ, and 2.8λ from the bottom.

Figure 2 shows the distribution of the events detected experimentally over the volume of the detector, from the center to the periphery. The quantity plotted along the abscissa is the fraction of the volume, while that plotted along the ordinate is the number of events detected in the given volume. Histogram 1 is the expected distribution of interaction points of muon neutrinos for FC events; the points are experimental data. The curve and the points agree well. This agreement supports the hypothesis that the muon-like events are interactions of muon neutrinos.

Histogram 2 shows the distribution of interaction points which would be expected if all the electron-like events were caused by neutrinos. We see that the distribution of electron-like events found experimentally differs from the expected histogram and also from the distribution of muon-like events. Histogram 3 was calculated under the assumption that 58 events of the total number (98) detected are due to neutrino interactions, while 40 represent the detection of π^0 mesons produced in $nO^{16} \rightarrow \pi^0 X$ reactions, as was found in Ref. 1. The agreement between the experimental data and this histogram is completely satisfactory.

It can be concluded from Fig. 2 that the neutron background in the 40% of the working volume bounded by the 2.1λ positions on the bottom and the sides is small. We estimate it to be less than 20% of the number of events detected. Consequently, this volume can be used to determine the ratio ν_μ/ν_e. It turns out to be $(N_\mu^{FC}+N_\mu^{PC})/N_e^{FC}=59/27=2.2\pm0.4$, which is approximately what was expected.

This analysis shows that a working volume at least 5λ away from the walls must be selected for experiments to detect atmospheric neutrinos which interact inside a detector at depths of about 3000 mwe. This requirement becomes less stringent as the depth increases, but even at 5000 mwe one should still use anticoincidence shielding (1–2)λ thick.

It follows from the figures shown here that, if the dimensions of the inner volume of the detector are less than (4–6)λ, then the spatial distribution of events will be approximately uniform (see the last three points on histogram 3 in Fig. 2). This circumstance may make it difficult to distinguish the effect from background.

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