Super-Kamiokande data and atmospheric neutrino decay

G. L. Fogli, E. Lisi, A. Marrone, and G. Scioscia
Dipartimento di Fisica and Sezione INFN di Bari, Via Amendola 173, I-70126 Bari, Italy
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Neutrino decay has been proposed as a possible solution to the atmospheric neutrino anomaly, in light of recent data from the Super-Kamiokande experiment. We investigate this hypothesis by means of a quantitative analysis of the zenith angle distributions of neutrino events in Super-Kamiokande, including the latest (45 kTy) data. We find that the neutrino decay hypothesis fails to reproduce the observed distributions of muons. [S0556-2821(99)01713-0]

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The Super-Kamiokande (SK) experiment has confirmed, with high statistical significance, the anomalous flavor composition of the atmospheric neutrino flux. Such an anomaly is found in all SK data samples, including (in order of increasing energy) sub-GeV e-like and μ-like events (SGe and SGμ) [1], multi-GeV e-like and μ-like events (MGe and MGμ) [2], and upward through-going muons (UPμ) [3]. In particular, all muon event samples (SGμ, MGμ, and UPμ) show significant distortions of the observed zenith angle distributions, as compared with standard expectations. The recent muon data from the MACRO [4] and Soudan-2 [5] experiments, as well as from the finalized Kamiokande sample [6], are also consistent with the Super-Kamiokande data.

The observed dependence of the muon deficit on both energy and direction can be beautifully explained via neutrino flavor oscillations in the $\nu_\mu \rightarrow \nu_\tau$ channel [7]. Transitions into sterile states are also consistent with the data [8,9], as well as subdominant oscillations in the $\nu_\mu \rightarrow \nu_e$ channel [10]. Determining the flavor(s) of the oscillating partner(s) of the muon neutrino will represent a crucial test of such explanation(s). In the meantime, it is useful to challenge the oscillation hypothesis and to investigate possible alternative scenarios [11].

Neutrino decay has been recently proposed [12] as a possible solution to the atmospheric neutrino anomaly. In a nutshell, the muon neutrino ν_μ is assumed to have an unstable (decaying) component ν_d,

$$\cos \xi \equiv \langle \nu_\mu | \nu_d \rangle \neq 0, \tag{1}$$

with mass and lifetime m_d and τ_d, respectively. In the parameter range of interest, the ν_μ survival probability reads [12]

$$P_{\mu\mu} \simeq \sin^4 \xi + \cos^4 \xi \exp(-\alpha L/E), \tag{2}$$

where $\alpha = m_d/\tau_d$, and L/E is the ratio between the neutrino path length and energy. The possible unstable component of ν_e is experimentally constrained to be very small [12,13]; so one can take $P_{ee} \simeq 1$.

For large values of $\cos \xi$ and for $\alpha \sim O(D_\oplus / 1\ \text{GeV})$ ($D_\oplus = 12\,800$ km), the exponential term in Eq. (2) can produce a detectable modulation of the muon-like event distributions [12]. In particular, the expected modulation seems to be roughly in agreement [12] with the reconstructed L/E distribution of contained SK events [7]. However, the L/E distribution is not really suited to quantitative tests, since it is affected by relatively large uncertainties, implicit in backtracking the (unobservable) parent neutrino momentum vector from the (observed) final lepton momentum. Moreover, the L/E distribution includes only a fraction of the data (the fully contained events), and mixes low-energy and high-energy events, making it difficult to judge how the separate data samples (SG, MG, and UP) are fitted by the decay solution. Therefore, we think it worthwhile to test the neutrino decay hypothesis in a more convincing and quantitative way, by using observable quantities (the zenith distributions of the observed leptons) rather than unobservable, indirect parameters such as L/E.

To this purpose we use, as described in [10], five zenith-angle distributions of neutrino-induced lepton events in Super-Kamiokande, namely, SGe and SGμ (5+5 bins), MGe and MGμ (5+5 bins), and UPμ (10 bins), for a total of 30 data points. The data refer to the preliminary 45 kt y sample of Super-Kamiokande, as taken from [8,9]. The theoretical calculations are performed with the same technique as in [10], but the flavor survival probability refers now to ν decay [Eq. (2)] rather than ν oscillations. As in [10], conservative errors are assumed not only for the overall normalization of the expected distributions, but also for their shape distortions. The (dis)agreement between data and theory is quantified through a χ^2 statistic, which takes into account the strong correlations between systematics.

Figure 1 shows the results of our χ^2 analysis in the plane $(\cos \xi, \alpha)$, with α given in unit of GeV/$D_\oplus$. The regions at 90% and 99% C.L. are defined by $\chi^2 - \chi^2_{\text{min}} = 4.61$ and 9.21, respectively. As qualitatively expected, the data prefer $\alpha \simeq 1$ and large $\cos \xi$, in order to produce a large suppression of ν_μ's coming from below. However, the absolute χ^2 is always much higher than the number of degrees of freedom, $N_{\text{DF}} = 28$ (30 data points $-$ 2 free parameters). In fact, it is $\chi^2_{\text{min}} = 86.2$ at the best-fit point [reached for $(\cos \xi, \alpha) = (0.95, 0.90)$]. The very poor global fit indicates that the zenith distributions cannot be accounted for by neutrino decay, contrarily to the claim of [12], which was based on reduced and indirect data (the L/E distribution). This situation should be contrasted with the $\nu_\mu \leftrightarrow \nu_\tau$ oscillation hy-

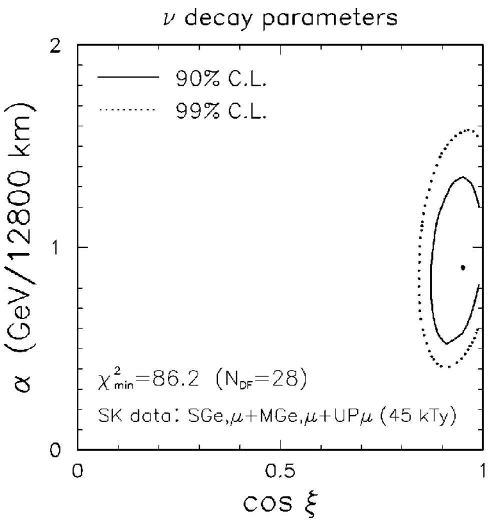

FIG. 1. Fit to the Super-Kamiokande data (45 kTy, 30 data points) in the plane of the neutrino decay parameters $\cos\xi = \langle\nu_\mu|\nu_d\rangle$ and $\alpha = m_d/\tau_d$. The solid and dotted lines are defined by $\chi^2 - \chi^2_{\rm min}$=4.61 and 9.21, corresponding to 90% and 99% C.L. for two variables. The analysis favors $\alpha \sim 1$ GeV/$D_\oplus$ and large $\cos\xi$. However, even at the best fit point there is poor agreement between data and theory ($\chi^2_{\rm min}/N_{\rm DF} = 86.2/28 = 3.1$), indicating that ν decay is not a viable explanation of the Super-Kamiokande observations.

pothesis, which gives $\chi^2_{\rm min}/N_{\rm DF} \sim 1$ both in two-flavor [7] and three-flavor scenarios [10]. Even using ''older'' Super-Kamiokande data (i.e., the published 33 kTy sample [1–3]), we get $\chi^2_{\rm min} \sim 65$ for the ν decay fit, still much higher than $N_{\rm DF}$.

Basically, neutrino decay fails to reproduce the SK zenith distributions for the following reason: The lower the energy, the faster the decay, the stronger the muon deficit—a pattern not supported by the data. This can be better appreciated in Fig. 2, which shows the SK data (45 kTy) and the expectations (at the ''best-fit'' point) for the five zenith angle (θ) distributions considered in our analysis. In each bin, both the observed and the expected lepton rates R are normalized to the standard values in the absence of decay R_0, so that ''no decay'' corresponds to $R/R_0 = 1$. The data are shown as dots with 1σ error bars, while the decay predictions are shown as solid lines. The predictions are affected by strongly correlated errors (not shown), as discussed in Appendix B of [10].

In Fig. 2, the muon data show significant deviations from the reference baseline $R/R_0 = 1$, most notably for MGμ events. The ν decay predictions also show some (milder) deviations, but their agreement with the data is poor, both in normalization and in shape. Neutrino decay implies a muon deficit decreasing with energy, at variance with the fact that the overall (θ-averaged) deficit is about the same for both SGμ's and MGμ's (-30%). The shape distortions of the muon zenith distributions are also expected to be exponentially weaker at higher energies (i.e., for slower neutrino decay). This makes it impossible to fit at the same time the distorted muon distributions observed at low energy (SGμ) and at high energy (UPμ), and to get a strong up-down asymmetry at intermediate energy (MGμ) as well. Notice in Fig. 2 that, although the predicted *shape* of the zenith distribution appears to be in qualitative agreement with the data pattern for SGμ's, it is not sufficiently up-down asymmetric for MGμ's, and it is definitely too flat for UPμ's, where the muon suppression reaches the plateau $P_{\mu\mu} \simeq c^4_\xi + s^4_\xi$, in disagreement with the observed $\cos\theta$ modulation [9]. Finally, we remark that the electron neutrinos, despite being ''spectators'' in the ν decay scenario (flat SGe and MGe distributions in Fig. 2), play a role in the fit through the constraints on their overall rate normalization, as in the $\nu_\mu \to \nu_\tau$ oscillation case [10].

In conclusion, we have shown quantitatively that the neutrino decay hypothesis, although intriguing, fails to reproduce the zenith angle distributions of the Super-Kamiokande sub-GeV, multi-GeV, and upgoing muon data for any value of the decay parameters α and $\cos\xi$. Even at the ''best fit'' point, data and expectations differ both in total rates and in zenith distribution shapes. Therefore, neutrino decay (at least in its simplest form [12]) is not a viable explanation of the Super-Kamiokande observations. The strong disagreement between data and theory was not apparent in [12], presumably because the experimental information used there was rather reduced and indirect.

Note added. When this work was being completed, our attention was brought to the recent paper [14], where several

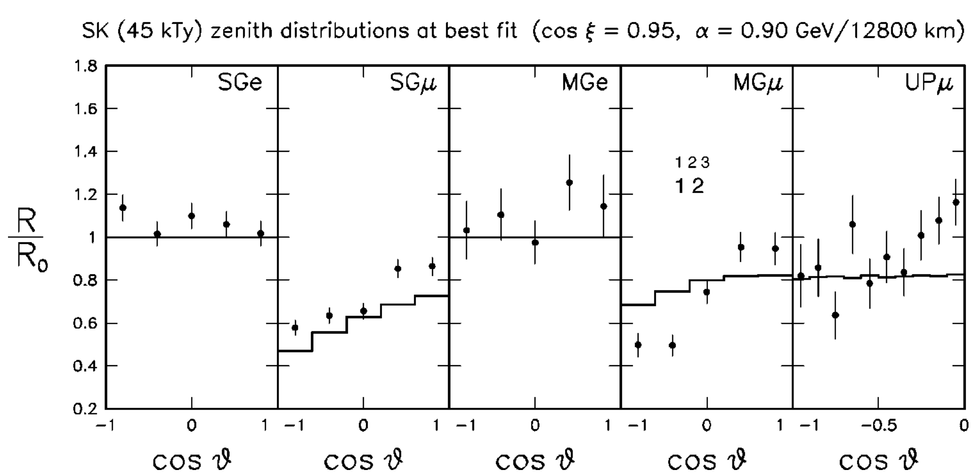

FIG. 2. Zenith angle distributions of Super-Kamiokande sub-GeV e-like and μ-like events (SGe and SGμ), multi-GeV e-like and μ-like events (MGe and MGμ), and upward-going muons (UPμ). Data: dots with $\pm 1\sigma$ statistical error bars. Theory (ν decay best fit): solid curves. In each bin, both theoretical and experimental rates R are normalized to their standard (no decay) expectations R_0. The solid curves do not appear to reproduce the muon data pattern.

scenarios—alternative to neutrino oscillations—are considered, including neutrino decay (for cos $\xi=1$). The authors of [14] find that neutrino decay provides a very poor fit to the Super-Kamiokande data, consistently with our conclusions. As far as the neutrino decay hypothesis is concerned, our work has the advantage of being more general (cos ξ unconstrained), more refined in the statistical approach, and updated with latest SK data (45 kTy) [8,9].

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