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Limits on the neutrino lifetime

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By using a distributed source of atmospheric neutrinos we have carried out a long baseline neutrino experiment. The flight times of the neutrinos are up to $\frac{1}{30}$ s. By looking for an attenuation with distance we can set mode-independent limits on the lifetime. The mean momentum for the neutrinos involved in our study is 940 MeV. Our limit is about $\tau p/m > 0.1$ s at 90% confidence level.

The issue of a nonzero neutrino mass has recently become a major experimental and theoretical question. A nonzero mass brings with it the possibility of neutrino decay. Many authors[1] have considered radiative decays of the neutrino. Nondiagonal interactions of the type needed for neutrino oscillations also introduce the possibility of nonradiative neutrino decay to very weakly interacting states.[2] These latter decay modes would be very difficult to observe except through the attenuation of a neutrino beam with distance. Very-long-base line experiments with well-understood neutrino fluxes are sensitive tests for these models.

Atmospheric neutrinos are produced by the decay of secondaries created by primary cosmic-ray interactions in the atmosphere. These neutrinos are incident from all directions with at most a 20% modulation[3] in the flux. This modulation is due to geomagnetic effects on the primary cosmic-ray flux and to path length effects on the secondary pion and muon decays. The rate expected is about 120 neutrino interactions per year in a 1000-metric-ton detector. The energy spectrum is peaked well below 1 GeV but triggering requirements and a long tail to higher energies restrict our sample to lie between approximately 400 MeV and 2 GeV. The mean energy for measured events[4] is 940 MeV. The source is a mixture of electron and muon neutrinos and antineutrinos. For the electron neutrinos the threshold is about 200 MeV.

We employ the 401-contained-event IMB data sample[4] collected in an exposure of 3.8 kiloton yr to search for evidence for a distance-dependent attenuation. This sample of atmospheric neutrino interactions is discussed in greater detail elsewhere.[5] Upward-going neutrinos have a path length in excess of 10^7 m and hence a flight time in excess of $\frac{1}{30}$ of a second. Since we have collected data at all zenith angles we can make a fit to data from large distances and extract a limit on $\tau p/m$. One cannot extract a mass-independent result from these data. We fit the data rate to the form

$$N(t)=N(t=0)e^{-(L/c)/(\tau p/m)} .$$

The angular error between the reconstructed single-track direction and the actual neutrino direction for this event sample[5] is about 30°. This has been determined by comparison of the reconstructed direction with the neutrino direction for Monte Carlo–simulated neutrino interactions. The very nature of the exponential function being fitted makes our result insensitive to modest angular errors.

TABLE I. Data used in the analysis. The lines marked with an asterisk have been used in the fit.

Distance (10^6 m)	Mean cosine	Number of events	Number of muon decays	Number of upward-going μ
10.6*	0.833	55	9	41
10.1	0.792	57	8	46
9.6	0.750	55	9	43
9.0	0.708	52	9	47
8.5	0.667	44	6	47
8.0	0.625	49	6	52
7.4	0.583	48	6	57
6.9	0.542	46	5	61
6.4*	0.500	47	5	67
5.9	0.458	44	6	67
5.3	0.417	45	7	69
4.8	0.375	48	9	71
4.3	0.333	51	10	77
3.8	0.292	46	10	76
3.2	0.250	46	10	75
2.7	0.208	43	11	74
2.2*	0.167	43	12	78
0.0	−1.000	51	8	

Because of the angular error and to maintain relatively large numbers of events we have selected regions of $\frac{1}{6}$ of the total solid angle. Only the projection of the angular error in the vertical direction would effect our sample. To maintain a large lever arm we have restricted our events to come from below the horizon. We have removed all multitrack events in which the direction may be ambiguous. This leaves us with 310 single-prong events. These are divided into 17 overlapping regions for the upward going samples. These will be compared with the 51 events coming in from above which travel a relatively very short distance and will not have decayed significantly yet.

We have not conducted a search for "radiative" neutrino decay[1,6] in which we would expect a significant rate increase in the detector due to the passage of photons coming from neutrino decay. Our detector is surrounded by solid rock and any produced photons would be promptly attenuated. Beyond that we make a 2-m fiducial cut (5.5 radiation lengths) to remove any entering particles and such events would have been removed. Accelerator and reactor experiments have a significantly higher integrated neutrino flux and are more sensitive to radiative decays. Since our detector dimensions of about 22 m are much smaller than the flight paths under consideration here, the probability of neutrino decay in flight in our detector is small unless we see evidence of a very rapid decay rate for the upward sample. That is not the case.

Table I lists the data used in our analysis. We have studied all neutrinos regardless of type and we have also studied only events with a muon-decay signature. These later events are muon-neutrino induced while the total sample is a mixture of neutrino types.

In addition to the contained events we have collected a sample of 187 upward-going muons from ν_μ interactions in the rock around the detector. These neutrinos have a comparable path length but a mean energy of 180 GeV.

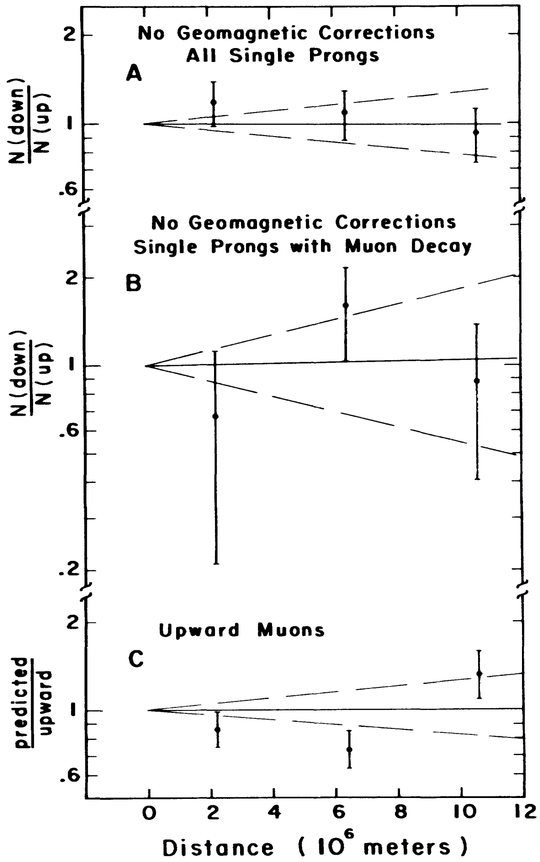

FIG. 1. The ratio of events expected over events observed as a function of the distance traveled. The dashed lines are bounds on the fit. The fit is the solid center line. A is all contained interactions with no corrections. B is all contained interactions with a muon decay signature with no corrections. C is the upward muon sample.

TABLE II. Summary of neutrino lifetime results.

Data sample		$\frac{m}{p\tau}$ best value (s^{-1})	$\frac{p\tau}{m}$ 90% C.L. (s)	Geomagnetic correction applied?	$c\tau\beta\gamma$[a] (10^7 m)
Contained single-prong events	All	0.016 ± 7.09	0.110	No	3.30
		-1.05 ± 7.09	0.125	Yes	1.29
	Muon decay	-0.147 ± 18.1	0.043	No	3.75
		-1.18 ± 18.1	0.045	Yes	1.35
Through-going muons		-0.549 ± 6.32	0.133	Yes	3.99

[a] Lower limit on the neutrino decay length.

The total reconstruction and scattering angular error for this sample is about 7°. Large solid-angle bins are still used to maintain relatively large numbers of events per bin. These data potentially contain interactions such as ν_τ charged currents not found in the contained events. Since we have no downward sample to compare with we have compared the rate to an absolute rate Monte Carlo calculation. The calculation uses a much-higher-energy neutrino spectrum[7] and contains the expected $\sec(\theta)$ (zenith angle) modulation of the flux.

To avoid problems of correlated errors from overlapping data sets we have used in our fit only the three nonoverlapping regions labeled with an asterisk in Table I. The table lists all regions to show the smoothness of the distribution.

In Fig. 1 we plot the data used in the fitted slope and the one standard deviation envelope on the fit. These data should have a small distance-dependent effect due to geomagnetic modulation. We have presented the raw data since calculations of the geomagnetic effect may still be improved. We take the calculation[8] of Gaisser *et al.* as representative and use it to correct our data and refit.

Our results for $m/p\tau$ in inverse seconds are given in the second column of Table II. Errors are statistical only. Systematic errors, if present, will be less than the geomagnetic corrections considered here. As can be seen by comparing the fits with and without geomagnetic corrections systematic effects are negligible. All limits are consistent with a stable neutrino. The contained event limits depend on comparison with the 51 events from above, 8 of which have a muon-decay signature.

Our results may be quoted as a 90%-confidence limit on the neutrino lifetime. For $p\tau/m$ we have obtained values shown in the third column of Table II, together with lower limits on the neutrino decay length, $c\tau\beta\gamma$, in the fourth column.

Our result may be compared with results on solar neutrinos.[9] If we assume that the observed rate of 2.1 ± 0.3 SNU (solar-neutrino units) come from the Sun when 7.0 ± 3.0 SNU are expected,[10] then we calculate a lifetime limit of > 278 s at 90% confidence level at a much lower energy than atmospheric neutrinos. The electron neutrino is effectively stable.

If the solar-neutrino results imply that the electron neutrino is effectively stable then our results may be interpreted as a limit on the muon neutrino lifetime. Since the electron-to-muon ratio[11] is about 0.31, 24% (the electron-neutrino-induced fraction) of the total contained sample will not vary with distance. All variation in the total contained sample may be assigned to the ν_μ fraction. Our results on all neutrinos gives these limits (90% C.L.) for the ν_μ lifetime:

0.096 s, no geomagnetic correction, $c\tau\beta\gamma \geq 2.88 \times 10^7$ m;

0.107 s, geomagnetic correction, $c\tau\beta\gamma \geq 3.21 \times 10^7$ m.

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