Volume 245, number 2 PHYSICS LETTERS B 9 August 1990

A study of atmospheric neutrino oscillations in the Fréjus experiment

Fréjus Collaboration

Ch. Berger, M. Fröhlich, H. Mönch, R. Nisius, F. Raupach
I. Physikalisches Institut der RWTH Aachen [1]*, D-5100 Aachen, FRG*

D. Blum, C. Bourdarios, B. Dudelzak, P. Eschstruth, S. Jullian, D. Lalanne, F. Laplanche, C. Longuemare [2], C. Paulot [3], O. Perdereau, Ph. Roy, G. Szklarz
Laboratoire de l'Accélérateur Linéaire, Centre d'Orsay, Bâtiment 200, F-91405 Orsay, France

L. Behr, B. Degrange, U. Nguyen-Khac, S. Tisserant
LPNHE - Ecole Polytechnique, Route de Saclay, F-91128 Palaiseau, France

C. Arpesella [4], P. Bareyre, R. Barloutaud, A. Borg, G. Chardin, J. Ernwein, J.F. Glicenstein, L. Mosca, L. Moscoso
DPhPE, CEN-Saclay, F-91191 Gif-sur-Yvette Cedex, France

J. Becker, K.H. Becker, H.J. Daum, B. Jacobi, B. Kuznik, H. Meyer, R. Möller, M. Schubnell and Y. Wei
Universität-Gesamthochschule Wuppertal [5]*, D-5600 Wuppertal 1, FRG*

Received 19 April 1990

Atmospheric neutrino interactions have been studied with the Fréjus proton decay detector using a total fiducial sensitivity of 1.56 kT yr. The atmospheric neutrino interaction sample has been compared to a Monte Carlo simulation which includes neutrino oscillations. The $\nu_e(\bar{\nu}_e)\leftrightarrow\nu_\mu(\bar{\nu}_\mu)$, $\nu_e(\bar{\nu}_e)\leftrightarrow\nu_\tau(\bar{\nu}_\tau)$ and $\nu_\mu(\bar{\nu}_\mu)\leftrightarrow\nu_\tau(\bar{\nu}_\tau)$ oscillations channels have been studied using the ratio of electron to muon charged current events. Three independent analyses have been performed and no evidence for neutrino oscillations has been found. The resulting limits on Δm^2 for maximal mixing are more restrictive by more than one order of magnitude with respect to earlier measurements.

1. Introduction

Neutrinos have the unique feature of being chargeless fermions which interact with other particles only through the weak interaction. There are no theoretical arguments which require neutrinos to be massless. Neutrino masses, although non-standard, arise in a number of theories and models. Experimentally, only upper limits on neutrino masses have been determined, either by direct measurements or by cosmological arguments.

The study of neutrino oscillations is one way to improve our knowledge of neutrino physics. Oscilla-

---

[1] Supported by the BMFT, FRG, under contract number 55AC14P.

[2] Present address: LPC, University of Caen, F-14021 Caen, France.

[3] Present address: Laboratoire GANIL, F-14021 Caen, France.

[4] Present address: Istituto di Fisica, Università di Milano, I-20133 Milan, Italy.

[5] Supported by the BMFT, FRG, under contract number 55WT84P.

tions have been searched for in various experiments, using reactor induced $\bar{\nu}_e$ fluxes [1] or high energy accelerator $\nu_\mu/\bar{\nu}_\mu$ beams [2].

If neutrinos are massive, in the most general situation the weak eigenstates ν_ℓ ($\ell = e, \mu, \tau$) are mixed in the mass term of the lagrangian. In the two-flavor hypothesis the mixing matrix is a 2×2 rotation matrix, parametrized by the mixing angle θ. Let m_1 and m_2 be the two mass eigenvalues. Considering a relativistic neutrino ν_ℓ (energy E_ν), after a flight distance D in vacuum the oscillation probability is [3]

$$P(\nu_\ell \rightarrow \nu_{\ell'}) = \sin^2 2\theta \sin^2(\pi D/L_o). \qquad (1)$$

The "oscillation length", L_o, is given by

$$L_o = 4\pi E_\nu/\Delta m^2$$
$$\approx 2.5(\text{km})\cdot E_\nu(\text{GeV})/\Delta m^2(\text{eV}^2), \qquad (2)$$

where $\Delta m^2 = m_2^2 - m_1^2$. The oscillation length determines the visibility of oscillations in an experiment: to detect oscillations, the distance between the neutrino source and the detector must be at least of order L_o.

The presence of matter in the path of the neutrinos modifies this simple picture. Due to $W^\pm$ exchange with atomic electrons, electron neutrinos have a different index of refraction in matter than other flavors. As shown by Mikheyev and Smirnov [4], and Wolfenstein [5], this can lead to a resonant amplification or suppression of the vacuum oscillations.

Cosmic ray interactions with atmospheric nuclei produce neutrinos, which have been detected in underground experiments [6–11]. The energy spectrum of atmospheric neutrinos detected in underground proton decay experiments peaks at about 1 GeV. In principle atmospheric neutrinos provide a unique opportunity to study neutrino oscillations with low Δm^2. With the large possible flight distances, Δm^2 as low as 10^{-4} eV^2 could be measured. The accessible range in $\sin^2 2\theta$ is mainly limited by statistics.

In this paper analyses of data taken by the Fréjus experiment are reported. the Fréjus proton decay detector, a fine grain calorimeter, has been described in details elsewhere [12]. It was located in the Laboratoire Souterrain de Modane in the Alps and consisted of flash tubes for tracking and Geiger tubes for triggering. Planes of tubes were sandwiched by 3 mm iron absorber plates. This detector provided two orthogonal views of each event. It had been calibrated by exposing prototype detectors in beam of electrons and pions at CERN, Bonn and DESY.

In order to study systematic uncertainties, three independent analyses have been performed. The common statistical treatment of the problem is presented. In each analysis, a comparison between data and simulation enables one to exclude a domain of values for the oscillation parameters.

2. Atmospheric neutrinos

Primary cosmic rays interacting with atmospheric nuclei (N) produce complex hadronic showers. In the decays of the unstable secondaries, neutrinos are generated. The basic scheme for atmospheric neutrino production is:

$$p + N \rightarrow n\pi/K + \dots$$
$$\pi/K \rightarrow \mu^+(\mu^-) + \nu_\mu(\bar{\nu}_\mu)$$
$$\mu^+(\mu^-) \rightarrow e^+(e^-) + \nu_e(\bar{\nu}_e) + \bar{\nu}_\mu(\nu_\mu)\,.$$

From this decay chain, the expected flavor ratio in the atmospheric neutrino flux can be simply estimated: one expects about twice as many muon neutrinos as electron neutrinos, and as many neutrinos as antineutrinos. At the detector, the neutrino flux is approximately isotropic, except at low energy (below 1 GeV) where geomagnetic effects become important. Thus atmospheric neutrinos are produced at every latitude and longitude, and may therefore have flight distances ranging from about 10 km up to about 13 000 km.

The atmospheric muon and electron neutrino fluxes have been computed by many authors [13–15], using different methods. Due to uncertainties on the primary flux and to an incomplete knowledge of the details of primary interactions with atmospheric nuclei, the expected neutrino fluxes have large systematic errors.

The neutrino flux used in our analyses has been calculated by Gaisser et al. [16], using a Monte Carlo simulation of the atmospheric showers. This procedure has also been applied to compute the atmospheric muon flux, the results being in excellent agreement with measurements [14]. The simulation used in ref. [16] is an updated version which takes into account the muon polarization in pion decay. The error on the overall normalisation is estimated to be ±20% [13–15]. The error on the ratio between the ν_e and ν_μ fluxes is estimated to be ±5% from the variation of this ratio with respect to the secondary pion spectrum index given in ref. [17]. For the two calculations of refs. [15,16] the ratios of the integrated ν_e to ν_μ fluxes agree within about 1%, whereas the fluxes themselves differ by about 18%.

3. Effects of neutrino oscillations on the atmospheric fluxes

Assuming neutrino oscillations exist, the apparent atmospheric neutrino fluxes could differ from the above calculations in three ways. Firstly, oscillations would change the flavor composition of the flux. Secondly, if the oscillation length is much longer than the height of the atmosphere but smaller than the diameter of the earth, only neutrinos coming from the opposite side of the earth have a significant oscillation probability. Therefore the angular distribution of the detected neutrinos would be distorted. Finally, if for some subsample of the data, the oscillation length was of the order of the flight distance, oscillations would modulate the visible energy distribution for a given flavor.

The detection of these manifestations of neutrino oscillations depends differently on the accumulated statistics and the angular and energy resolutions of the detector. As shown previously [11], the Fréjus detector provides good identification efficiencies of the incoming neutrino flavors for charged current interactions. However with low statistics (less than 200 events) and limited energy and angular resolutions, it is not possible to sensitively test for oscillations using only the visible energy or angular distributions.

Thus the only reliable information for studying neutrino oscillations in our experiment is the flux flavor composition. This information is contained in the e/μ ratio, defined as the ratio between the number of electron-like (CCe) and muon-like (CCμ) events. For oscillations into tau neutrinos, direct observation is not possible since about 90% of the atmospheric neutrino flux is below the threshold for the ν_τ charged current interaction. Thus a measured e/μ ratio which is smaller than expected could be interpreted as $\nu_e(\bar{\nu}_e)\leftrightarrow\nu_\tau(\bar{\nu}_\tau)$ oscillations, whereas a larger ratio could be explained as by either $\nu_\mu(\bar{\nu}_\mu)\leftrightarrow\nu_e(\bar{\nu}_e)$ or $\nu_\mu(\bar{\nu}_\mu)\leftrightarrow\nu_\tau(\bar{\nu}_\tau)$ oscillations.

4. Data and Monte Carlo analysis

In the three approaches which were developed, the e/μ ratio has been measured from the data and estimated by Monte Carlo simulation. Events with a primary vertex in a fiducial volume were selected, both contained and uncontained events being taken into account. The total exposure is 1.56 kT yr. The neutrino interaction simulations used in the three approaches are similar. They include a simulation of the nuclear reinteractions of secondary particles based on cascade models. In the last two methods particular attention was given to the simulation of low energy electromagnetic showers. In all analyses, topological cuts are used to reject the background induced by stopping muons, which could result from cosmic-ray atmospheric showers or atmospheric neutrino interactions within the rock surrounding the detector. The three approaches differ mainly in the event analyses. They are briefly presented below, together with their main results.

Details of the first approach (i) have already been presented elsewhere [11]. The simulated sample corresponds to a 10 kT yr exposure. Both real and simulated events are measured and classified using the same procedure. Measurements are made by a physicist on a graphic terminal. Tracks and showers are defined by eye, and the events are then kinematically reconstructed. Events with a total visible energy lower than 200 MeV are removed from the analysed samples.

In the second approach (ii), the simulated sample corresponds to a sensitivity of 16 kT yr. As previously, data and Monte Carlo events are treated in the same way. In this approach, measurements are made by an automatic procedure based on a pattern recognition program, the vertex of the event having been visually determined on a graphic terminal. Track finding, association in the orthogonal views, particle identification and energy measurement are automatic. Track type, i.e. showering or non-showering, is determined using a maximum likelihood method test on the transverse profile and on the distribution of hits per plane. Electrons and photons are not distinguished.

Finally, in the third approach (iii), the simulated statistics amounts to 30 kT yr. The reconstruction of showers and tracks for these simulated events is done with an automatic program which uses information from the generation such as the vertex position, the correlation of the fired cells in the two projections and the information whether each particle is of a showering type (e, γ) or not (μ, π, p). The agreement between this method and manual measurements was checked by measuring by hand a subsample corresponding to a 5 kT yr fiducial sensitivity. However, the data are measured manually as in (i).

In each of the three methods, events are classified either as CCe or CCμ according to the final state lepton using topological criteria similar to those presented in ref. [11]. The events without any visible lepton are classified as neutral current (NC). The efficiencies of this classification are about 95% and 85% for ν_μ and ν_e charged current interactions respectively [11].

The expected and measured sample compositions are shown in table 1 together with their e/μ ratios. From table 1 one can see that, in each of the three analyses, the agreement between the measured and expected values without oscillations of the e/μ ratio is excellent. Thus the Fréjus data do not provide evidence for neutrino oscillations.

Finally, we want to obtain predictions for the e/μ ratio when oscillations are present. For each oscillation channel, a modified atmospheric neutrino flux is computed for any given value of $\sin^2 2\theta$ and Δm^2 as follows.

Neutrinos are assumed to be generated at a constant height of 20 km in method (i) and (iii). Method (ii) uses a more detailed model for the generation of neutrinos throughout the atmosphere, which has negligible effects on the resulting ratio. For neutrino propagation through the earth, matter effects are taken into account whenever $\overset{(-)}{\nu}_e$ are concerned. Methods (i) and (iii) described above use an electronic density model for the Earth based on data from ref. [18]. Method (ii) uses a constant density approximation. This difference is also found to be negligible.

Events of the simulated samples (in the three approaches) are weighted by the ratio of the fluxes with and without oscillations. The weighted sample is then used to compute a prediction for the e/μ ratio, in any oscillation hypothesis.

5. Derivation of the limits on the oscillations parameters

In order to determine the excluded (or allowed) values for Δm^2 and $\sin^2 2\theta$, limits on the e/μ ratio are used.

Uncertainties on this ratio which enter these analyses have different sources. The systematic error on the neutrino flux has been estimated to be 0.03. The Monte Carlo simulation of the neutrino interactions in the detector has an associated systematic error of about 0.06 [11]. Finally the differences between the three analyses enable us to estimate a systematic error on this ratio of 0.04, due to the measurement and identification methods. Combining these errors in quadrature leads to a total systematic error on e/μ of 0.08. This uncertainty is assumed to be independent of the oscillation hypothesis.

In order to exclude a region in the (Δm^2, $\sin^2 2\theta$) plane for a given confidence level, the following pro-

Table 1
Data and Monte Carlo sample compositions without oscillations and e/μ ratios obtained by the three analyses (in (i) only events with $E_\nu \geqslant 200$ MeV are used).

Analysis	CCe		CCμ		NC		e/μ ratios	
	data	MC	data	MC	data	MC	data	MC
(i)	57	70.6	108	125.8	20	15.3	0.53±0.09	0.56±0.08
(ii)	62	69.8	108	113.9	14	13.4	0.57±0.09	0.61±0.08
(iii)	61	69.5	109	123	5	11.2	0.56±0.09	0.57±0.08

cedure is applied. For each mixing channel the e/μ ratio generated by the Monte Carlo can take on a certain range of values (e.g. for $\nu_\mu(\bar{\nu}_\mu)\leftrightarrow\nu_\tau(\bar{\nu}_\tau)$, e/μ can lie between about 0.5 and about 1). Each value of the e/μ ratio traces a curve in the (Δm^2, $\sin^2 2\theta$) plane. For a given e/μ ratio one combines the statistical and systematic errors in quadrature and calculates the probability that the ratio could have fallen beyond the experimentally measured one. It is then renormalised to the total probability contained in the allowed region for e/μ given by the Monte Carlo, according to the method recommended by the Particle Data Group [19]. The bounds on the e/μ ratio at 90 and 95% confidence level (CL) are used to obtain limit curves in the (Δm^2, $\sin^2 2\theta$) plane.

In the three approaches the excluded areas in the usual (Δm^2, $\sin^2 2\theta$) diagram are found to be similar. For each case, the most conservative limit of the three analyses is given below. Figs. 1 and 2 show iso-e/μ curves in the (Δm^2, $\sin^2 2\theta$) diagram corresponding to 90% and 95% CL limits. The limits (90% CL) on Δm^2 and $\sin^2 2\theta$ obtained in this experiment can be summarized as follows:

$\nu_e(\bar{\nu}_e)\leftrightarrow\nu_\mu(\bar{\nu}_\mu)$:

$$\Delta m^2 \leqslant 1.5\times10^{-3}\ \mathrm{eV}^2 \quad \text{(for maximal mixing)}$$

or

$$\sin^2 2\theta \leqslant 0.47 \quad (\text{for } \Delta m^2 \geqslant 1\ \mathrm{eV}^2), \tag{3}$$

$\nu_\mu(\bar{\nu}_\mu)\leftrightarrow\nu_\tau(\bar{\nu}_\tau)$:

$$\Delta m^2 \leqslant 3.5\times10^{-3}\ \mathrm{eV}^2 \quad \text{(for maximal mixing)}$$

or

$$\sin^2 2\theta \leqslant 0.60 \quad (\text{for } \Delta m^2 \geqslant 1\ \mathrm{eV}^2). \tag{4}$$

In the third channel, $\nu_e(\bar{\nu}_e)\leftrightarrow\nu_\tau(\bar{\nu}_\tau)$, the low CCe statistics together with systematic uncertainties make it impossible to exclude any value of (Δm^2, $\sin^2 2\theta$) at 90% confidence level.

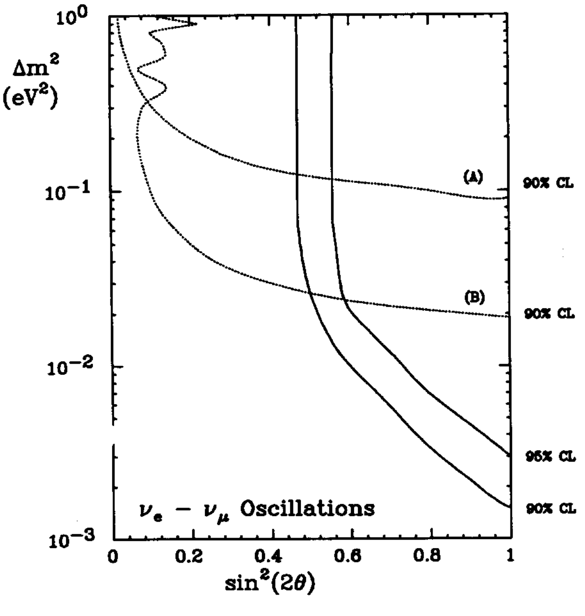

Fig. 1. (Δm^2, $\sin^2 2\theta$) diagram for $\nu_e(\bar{\nu}_e)\leftrightarrow\nu_\mu(\bar{\nu}_\mu)$ oscillations. The two e/μ=constant curves (plain line) correspond to 90% and 95% CL limits on the (e/μ) ratio respectively. (A) is the region excluded by accelerator appearance experiments [1] (90% CL). (B) is the region excluded by reactor disappearance experiments [2] (90% CL).

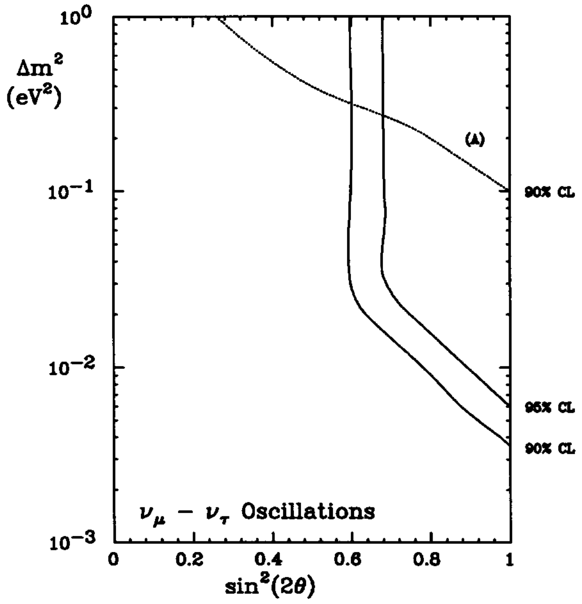

Fig. 2. (Δm^2, $\sin^2 2\theta$) diagram for $\nu_\mu(\bar{\nu}_\mu)\leftrightarrow\nu_\tau(\bar{\nu}_\tau)$ oscillations. The two e/μ=constant curves (plain line) correspond to the 90% and 95% CL limits on the e/μ ratio respectively. (A) is the region excluded by accelerator appearance experiments [2] (90% CL).

6. Conclusions

The study of atmospheric neutrino properties offers a unique opportunity to search for oscillations with low Δm^2. We have presented an analysis of the data taken with the Fréjus detector, corresponding to the final 1.56 kT yr sensitivity of the experiment. No evidence for neutrino oscillations was found in the data. The study outlined above leads to new excluded domains of the two flavor oscillation parameters. Existing limits are improved by about one order of magnitude in the $\nu_e(\bar{\nu}_e)\leftrightarrow\nu_\mu(\bar{\nu}_\mu)$ channel, and by about a factor of 30 in the $\nu_\mu(\bar{\nu}_\mu)\leftrightarrow\nu_\tau(\bar{\nu}_\tau)$ channel. However, these results are restricted to relatively large mixing angles.

Results from the Kamiokande collaboration [10] showed a deficit of muon type atmospheric neutrino events. Our data sample gives no evidence for such a deficit, in agreement with two other underground experiments IMB [9] and NUSEX [8]. Thus, our result does not require any interpretation in terms of evidence for neutrino oscillations as given in refs. [20–23].

References

[1] M. Talby, Proc. XXIVth Conf. on High energy physics (Münich, 1988), eds. R. Kotthaus and S.H. Kühn (Springer, Berlin, 1989) p. 1072.

[2] G. Bernardi, Proc. XXIVth Conf. on High energy physics (Münich, 1988), eds. R. Kotthaus and S.H. Kühn (Springer, Berlin, 1989) p. 1076.

[3] S.M. Bilenky and B. Pontecorvo, Phys. Rep. 42 (1978) 225; S.M. Bilenky and S.T. Petcov, Rev. Mod. Phys. 59 (1987) 671.

[4] S.P. Miheyev and A.Yu. Smirnov, Sov. J. Nucl. Phys. 42 (1985) 913; Nuovo Cimento 9C (1986) 17.

[5] L. Wolfenstein, Phys. Rev. D 17 (1978) 2369.

[6] M.F. Crouch et al., Phys. Rev. D 18 (1978) 2239.

[7] KGF Collab., M.R. Krishnaswamy et al., Proc. VIth Workshop on Grand unification (Minneapolis, MN, 1985), eds. S. Rudaz and T. Walsh (World Scientific, Singapore, 1986) p. 97.

[8] NUSEX Collab., M.A. Aglietta et al., Europhys. Lett. 8 (1989) 611.

[9] IMB Collab., R.M. Bionta et al., Phys. Rev. D 38 (1988) 768.

[10] Kamiokande Collab., H. Hirata et al., Phys. Lett. B 205 (1988) 416.

[11] Ch. Berger et al., Phys. Lett. B 227 (1989) 489.

[12] Ch. Berger et al., Nucl. Instrum. Methods A 261 (1987) 540.

[13] L.V. Volkova, Sov. J. Nucl. Phys. 31 (1980) 784.

[14] G. Barr, T.K. Gaisser and T. Stanev, Phys. Rev. D 38 (1988) 85, and references therein.

[15] E.V. Bugaev and V.A. Naumov, Phys. Lett. B 232 (1989) 391; and private communication (1989).

[16] G. Barr, T.K. Gaisser and T. Stanev, Phys. Rev. D 39 (1989) 3532.

[17] S. Barr et al., Phys. Lett. B 214 (1988) 147.

[18] F.D. Stacey, Physics of the Earth (Wiley, New York, 1969) p. 281.

[19] Particle Data Group, G.P. Yost et al., Review of particle properties, Phys. Lett. B 204 (1988) 80 (section II.E.2).

[20] M. Takita, Ph.D. Thesis, Tokyo University I.C.R. Report 1-86-89-3 (1989).

[21] J.G. Learned et al., Phys. Lett. B 207 (1988) 79.

[22] V. Barger and K. Whisnant, Phys. Lett. B 209 (1988) 365.

[23] K. Hidaka et al., Phys. Rev. Lett. 61 (1988) 1537.