

Search for $\nu_\mu \rightarrow \nu_e$ oscillations in the NOMAD experiment

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ABSTRACT: We present the results of a search for $\nu_\mu \rightarrow \nu_e$ neutrino oscillations in the NOMAD experiment at CERN. The experiment looked for the appearance of ν_e in a predominantly ν_μ wide-band neutrino beam at the CERN SPS. No evidence for oscillations was found. The 90% confidence limits obtained are $\Delta m^2 < 0.4 \text{ eV}^2$ for maximal mixing and $\sin^2(2\theta) < 1.2 \times 10^{-3}$ for large Δm^2 , excluding the LSND allowed region of oscillation parameters with $\Delta m^2 \gtrsim 10 \text{ eV}^2$.

1. Introduction

The NOMAD experiment was designed to search for ν_τ appearance from neutrino oscillations in the CERN wide-band neutrino beam produced by the 450 GeV proton synchrotron. The detector was optimised to efficiently identify electrons from $\tau^- \rightarrow e^- \nu_\tau \bar{\nu}_e$ decays and therefore could also be used to look for ν_e appearance in a predominantly ν_μ beam by detecting their charged current (CC) interactions $\nu_e N \rightarrow e^- X$. The main motivation for this search was the evidence for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ and $\nu_\mu \rightarrow \nu_e$ oscillations found by the LSND experiment [1]. In the case of $\nu_\mu \rightarrow \nu_e$ oscillations with $\Delta m^2 \gtrsim 10 \text{ eV}^2$ and with the probability of 2.6×10^{-3} observed by LSND, a signal should be seen in the NOMAD data.

Preliminary results of the search for $\nu_\mu \rightarrow \nu_e$ oscillations in NOMAD based on $\sim 15\%$ of the collected data were presented earlier [2]. In this paper we report the results of an improved analysis using the full NOMAD data sample and a “blind analysis” method.

2. NOMAD detector and data collection

The NOMAD detector [3] consisted of a large dipole magnet delivering a field of 0.4 T and housing several subdetectors, starting with an active target composed of 147 planes of drift

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chambers of 3 by 3 m². The walls of the chambers provided a low average density (0.1 g/cm³) target with a mass of 2.7 tons. The chambers were placed in front of a transition radiation detector (TRD) for electron-hadron discrimination which yielded a pion rejection factor of 1000 for an electron efficiency of 90%. A lead-glass electromagnetic calorimeter (ECAL) was used to improve electron identification and to measure the energies of electrons and photons with a resolution of $\sigma(E)/E = 3.2\%/\sqrt{E(\text{GeV})} \oplus 1\%$. A hadron calorimeter and two muon stations were located just behind the magnet coil.

NOMAD collected data from 1995 to 1998. Most of the running, a total exposure of 5.1×10^{19} protons on target (pot) corresponding to about 1.3×10^6 ν_μ CC interactions, was in neutrino mode. However, mostly to check the beam line simulation, some data, amounting to 0.44×10^{19} pot, were collected in antineutrino mode (reverse polarity on the horn and reflector) and some, 0.04×10^{19} pot, in zero-focusing mode (with the horn and reflector switched off).

3. Analysis principles

The $\nu_\mu \rightarrow \nu_e$ oscillation signal should manifest itself as an excess in the number of ν_e CC events over that expected for an intrinsic ν_e contamination in the beam (about 1% of ν_μ). Due to different energy and radial distributions of incident ν_e and ν_μ neutrinos, this excess would be particularly enhanced at low ν_e energies and small radii with respect to the beam axis. In order to reduce systematic uncertainties associated with the absolute flux predictions and selection efficiencies, we study the ratio $R_{e\mu}$ of the number of ν_e to ν_μ charged current interactions. The sensitivity of the search is increased by taking into account the $R_{e\mu}$ dependence on the neutrino energy E_ν and on the radial position of the neutrino interaction vertex r .

The presence or absence of $\nu_\mu \rightarrow \nu_e$ oscillations is established by comparing the measured $R_{e\mu}$ with the one expected in the absence of oscillations. In order to avoid biases, we adopted a “blind analysis” strategy: the comparison between the measured and predicted $R_{e\mu}$ is not made until the accuracy of the flux predictions and the robustness of the data analysis have been demonstrated and all selection criteria are fixed. A number of data samples (such as ν_μ CC, $\bar{\nu}_\mu$ CC and $\bar{\nu}_e$ CC events in neutrino mode, and charged current interactions of all four present in the beam neutrino species in antineutrino and zero-focusing modes) are used as control to verify the flux predictions.

4. Event selection

Charged current interactions of ν_μ are characterised by the presence of a primary muon in the final state which has to penetrate 13 interaction lengths of absorber material to reach both muon stations to be identified. In addition, in order to minimise the differences between selection efficiencies of ν_μ CC and ν_e CC events, we apply kinematic criteria identical to those used in the ν_e CC selection, although they are not needed for the background suppression. The resulting ν_μ CC data sample consists of about 750,000 events with negligible background contamination; the average selection efficiency is 60%.

PRHEP hep2001

The initial data sample for ν_e CC interactions is complementary to that used in the ν_μ CC selection, i.e. it includes only those events which have no muon (identified with looser criteria than in the ν_μ CC selection). We first require the presence of a track associated with the neutrino interaction vertex and identified as an electron in the TRD and ECAL. In addition to ν_e CC events, electrons are abundantly produced in ν_μ charged current and neutral current interactions (mostly in π^0 Dalitz decays and photon conversions). This background is greatly suppressed by a set of kinematic criteria requiring electron candidates to be kinematically isolated from the hadronic jet comprising all other particles in the event. The selected data sample contains about 8,000 events; the overall ν_e CC selection efficiency is estimated to be 44%. The remaining background contamination is evaluated from the sample of events failing kinematic cuts and found to be 2%.

Various sources of potential systematic errors, such as uncertainties in lepton identification and selection efficiencies, electron and hadron energy scales, etc., have been studied. Their contribution to the total systematic error was smaller than uncertainties in the neutrino flux prediction (discussed in the next section).

5. Prediction of neutrino fluxes

Since the oscillation search implies a direct comparison between the measured and expected $R_{e\mu}$, an accurate prediction of the neutrino fluxes and spectra is crucial. They are computed with a detailed Monte Carlo simulation of the neutrino beam line at CERN. This is implemented in three steps. First, the yields of the secondary particles from the interactions of 450 GeV protons with the Be target are calculated by a recent version of FLUKA [4], a generator of hadronic interactions. These yields are then modified in order to agree with all precise measurements presently available in the relevant energy and angular range, namely the SPY/NA56 [5] and NA20 [6] results. Finally, the propagation of the secondary particles up to the NOMAD detector is described by a simulation program based on GEANT which includes an accurate description of the magnetic field in the horn and reflector, and the modelling of reinteractions in the beam elements.

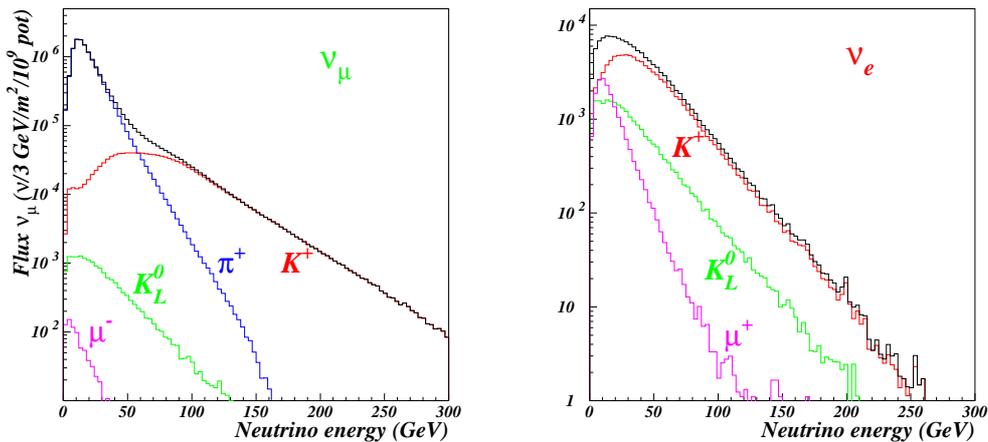


Figure 1: Composition of the ν_μ and ν_e spectra at NOMAD, within the transverse fiducial area of 260×260 cm², as predicted by the NOMAD simulation of the neutrino beam line.

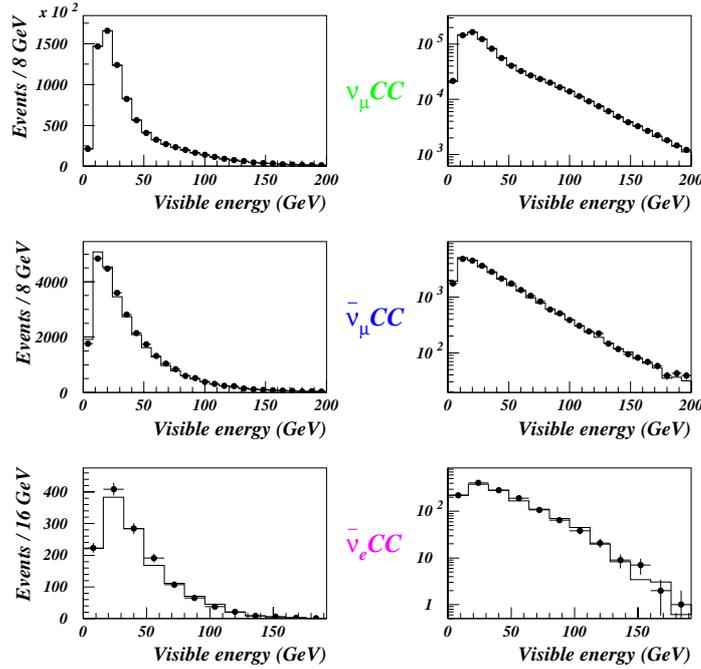


Figure 2: Neutrino energy spectra (shown in linear and logarithmic scale) for the data (points) and Monte Carlo prediction (histogram), for ν_μ CC (top), $\bar{\nu}_\mu$ CC (middle) and $\bar{\nu}_e$ CC (bottom) interactions in neutrino data-taking mode. The neutrino energy is approximated by the “visible energy”, defined as the sum of the energies of the charged lepton and of the hadrons observed in the final state.

The resulting neutrino energy spectra of ν_μ and ν_e , and their components, are shown in Figure 1. The bulk of the ν_e (ν_μ) flux comes from the decays of secondary K^+ (π^+), the yields of which were measured by SPY and NA20. However, the single largest uncertainty in the calculation of $R_{e\mu}$ is due to the limited number of experimental data points (especially at non-zero values of transverse momentum) measured by these experiments. This uncertainty is energy-dependent; its typical fractional value at low E_ν is 4%. The second largest systematic error of about 2.5% comes from a 15% uncertainty in the production of K_L^0 which accounts for 18% of the ν_e flux. Other potential sources of errors (such as tertiary particle yields, variations in the horn current, misalignments of the focusing devices and collimators, or inaccuracies in the simulation of the beam line elements) have also been investigated [7]; their cumulative contribution is smaller than 2%.

The calculated energy spectra and radial distributions of neutrinos are used to simulate their interactions in the NOMAD detector. The validity of the flux predictions, and of the proper Monte Carlo mix of deep inelastic, quasi-elastic and resonance interactions, are checked by comparing measured and simulated distributions for numerous control samples described in Section 3. Some examples of such comparisons are shown in Figure 2.

6. Results

The $R_{e\mu}$ distribution as a function of the visible energy for the data and Monte Carlo

prediction ($\pm 1\sigma$ uncertainty) is shown in Figure 3. We find a good agreement between the measured $R_{e\mu}$ and the one expected in the absence of oscillations: a χ^2 of 19.7/29 d.o.f. is obtained when the data are analysed in 10 energy and 3 radial bins (incorporating both statistical and systematic uncertainties). The best fit to $\nu_\mu \rightarrow \nu_e$ oscillations gives only a slightly better chi-squared value, $\chi_{\min}^2 = 18.6/27$ d.o.f.

We use a frequentist approach [8] to set a 90% confidence upper limit on the oscillation parameters shown in Figure 3. The values of $\Delta m^2 > 0.4 \text{ eV}^2$ for maximal mixing and $\sin^2(2\theta) > 1.2 \times 10^{-3}$ for large Δm^2 are excluded. This result rules out the interpretation of the LSND measurements in terms of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations with $\Delta m^2 \gtrsim 10 \text{ eV}^2$.

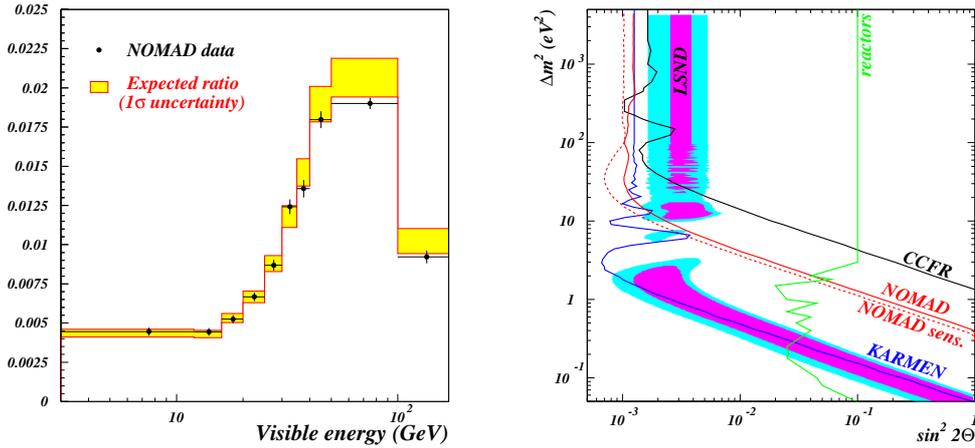


Figure 3: Left: $R_{e\mu}$ ratio as a function of the visible energy for the data (points); the filled band shows Monte Carlo prediction assuming no oscillations with 1σ systematic errors added in quadrature. Right: the 90% C.L. exclusion region in the $\Delta m^2 - \sin^2(2\theta)$ plane and the sensitivity [8] of this analysis, superimposed on the results of other experiments.

In conclusion, I would like to thank the organisers of the conference for a pleasant stay in Budapest. I am very grateful to Leslie Camilleri and Bob Cousins for their help.

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