The NOMAD $\nu_\mu \leftrightarrow \nu_\tau$ oscillations experiment

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Abstract

The CERN WA96 (NOMAD) experiment now at the building stage is aimed at detecting $\nu_\mu \leftrightarrow \nu_\tau$ oscillations with a sensitivity which should lower by one order of magnitude the present limit on the mixing parameter for high mass differences. Its originality resides in the τ identification method and the use of a light, high resolution, active target. The following article briefly reviews the motivations for the search, the basic ingredients of the method and describes the apparatus and its present stage of developpement.

1 The what's and why's in a nutshell.

1. Neutrino oscillations are reviewed at length in other papers in these proceedings. Here we only wish to remind the reader that one has to admit that neutrinos born in weak processes are mixtures of mass eigenstates. Since these acquire different phases during their propagation, the subsequent interaction of, say, a ν_μ -born neutrino has a certain probability to give rise to a lepton of another flavour (say, τ).
The probability of occurence of this phenomenon in a simplified two-flavour world where ν_μ and ν_τ would be linear combinations of two mass-eigenstates, is given by:

$$P(\nu_\mu \rightarrow \nu_\tau) = sin^2(2\theta)sin^2(\frac{\pi x}{L})$$

where:
1. θ is the mixing angle, that is $cos(\theta)$ is the amplitude of the lighter mass-eigenstate in the state $|\nu_\mu >$.
2. x is the distance from the production point to the interaction point.
3. $L = 4\pi p/\Delta m^2 = 2.48E(GeV)/(|m_2^2 - m_3^2|(eV^2))\ km$ where m_2 and m_3 are the two mass-eigenvalues.
From this one sees that for given θ the upper limit on Δm^2 an experiment can possibly set varies as E/x and that one has to go to large distances to probe small mass differences, whilst the upper limit on $\sin^2(2\theta)$ depends on the accumulated statistics only. However for 'high' Δm^2, the oscillating factor is washed out by the experimental spreads in E and x and averages to 1/2, yielding a constant limit on the mixing.

2. Why $\nu_\mu \leftrightarrow \nu_\tau$ oscillations ?
By analogy with the quark sector, one expects that
1. the τ - associated neutrino is dominated by the amplitude of the heaviest mass state.
2. mixing is stronger with ν_μ (associated to the next lower-mass charged lepton, the so-called 'adjacent generation') than with ν_e .
Most models based on the 'see-saw' mechanism have this kind of association built-in. On the other hand, it is known that the Universe embodies a large amount of non- shining mass. Recent results (COBE) on the microwave background fluctuations favour a 30-70 % mixing of 'hot' and 'cold' dark matter. Since neutrinos were abundantly produced during the Big Bang, they are a natural candidate for the former, if they have masses in the region of a few $10's\ eV$. However, LEP results show that there are only three light neutrino species, and upon interpreting the solar neutrino deficit as due to an oscillation, one suspects very low masses for ν_e and ν_μ .
All this strengthens the likelihood of a ν_τ dominated by a few $10's\ eV$ mass state, and therefore the possibility of detecting $\nu_\mu \leftrightarrow \nu_\tau$ oscillations in terrestrial experiments with a short ($\sim 1\ km$) baseline. The present limit on the mixing is $sin^2(2\theta) \leq 5.10^{-3}$ [2]. The above quark analogy argument encourages strongly going an order of magnitude lower [1].

2 The problem in a wallnut shell.

Detecting ν_τ 's means 'seeing' the τ 's they generate in Charged Current (C.C.) weak interactions on nuclei. τ 's lifetime is $\sim 3.10^{-13} sec.$, meaning a track length of $100\mu m$ to $1mm$ at S.P.S. energies. This can only be imaged using very high resolution techniques, like nuclear emulsions [3] or holographic bubble chambers. An alternate possibility choosen by the NOMAD collaboration is to forsake visualisation and identify τ 's by the kinematics of their decay products. The backgrounds to be fought are due to ordinary neutrino (ν_e , ν_μ) interactions, direct ν_τ production being very low ($\sim 10^{-6}$) at S.P.S. energies. Given that ν_e represents but $\sim 1\%$ of the beam, the cleanest decay channel w.r.t. C.C. interaction backgrounds is *a priori* $\tau \rightarrow e^- \nu_\tau \overline{\nu}_e$.

3 The kinematical method

1. Leptonic τ decays. To reject the ν_e C.C. background , we take advantage of the effect of the two escaping ν's from τ decays on the event's kinematics in the plane transverse to the beam. Let p_T^h, p_T^{miss}, p_T^e be the transverse components of, respectively, the total hadronic, $e^{-'}s$ and missing momenta; let $\phi_{mh} = \angle(p_T^{miss}, p_T^h)$ and $\phi_{lh} = \angle(p_T^e, p_T^h)$. For well-reconstructed ν_e events one expects a small ϕ_{mh} and $\phi_{lh} \approx \pi$, whilst for ν_τ events ϕ_{mh} can be large since p_T^{miss} essentially stems from the two escaping ν's. The difference shows clearly on a scatter plot where the ν_e sample exhibits a depletion in the high ϕ_{mh} region which does not exist in the ν_τ sample [4, 5]. The cut used in this region reduces the ν_e background by a factor $2-3\ 10^{-3}$, while keeping 40% of the τ events. Another requirement is to demand that the transverse mass computed from p_T^{miss} and p_T^e be less than a τ mass.
Other potential sources of $e^{-'}s$ are: asymetrical photon conversions or π^0 and η Dalitz decays, Compton electrons, μ^- and K_{e_3} decays in flight. Knock-on $e^{-'}s$ and π_{e2} decays proved innocuous because of the low rate for the later and the visible recoil hadron for the former. All the others, with the exception of in-flight μ decays, have their origin in the hadronic shower. Hence, the underlying principle of the cuts against these is to demand the electron to be somehow isolated from the hadrons (angle,relative p_T,mass(e^-,γ) against Dalitz decays).
The μ decay channel has also been considered. It does not suffer of many backgrounds which affect the e^- channel, but requires strengthening of the angle-plot cut and some isolation cuts because of the huge ν_μ background and the sizeable π to μ decay rate.

2. Semi-leptonic τ decays. Three channels have been studied: $\nu_\tau\ \pi^-$, $\nu_\tau\ \rho^-$, $\nu_\tau\ a_1^-$. The background here is mainly Neutral Current interactions, and the selection of τ 's against them is based on the following facts:
1. In a true τ event, the most energetic hadron originates most of the time from the decay of the τ .
2. The genuine τ decay hadron is separated from the rest of the hadronic shower.
More details can be found in [4, 6, 7].

4 The experimental set-up

The method just outlined requires clear electron identification and measurement. These are fulfilled by the use of Transition Radiation detectors, an electro-magnetic calorimeter and a preshower. The good spatial resolution of the system also allows proper reconstruction of the $p_T^{\prime}s$ of hadrons decaying into $\gamma's$ and helps identify the electron through its bremsstrahlung photons and its preshower signature. High precision on the p_T's from charged hadrons and $e^{-'}s$ implies a low Z target material to minimize multiple scattering and keep b'strahlung moderate, together with a number of high-resolution measuring planes. Compromising between often contradictory requirements,

the following design was arrived at : (see fig.)
1. The detector will be housed in the former UA1 horizontal field dipole magnet set at .4 Tesla and moved to the location of the old BEBC. It has an inner volume of about 3 by 3 m in cross-section and 6 m long.
2. The target is made of 44 3-by-3 meter drift chambers built with a self-supporting structure of composite materials (C and H nuclei), making up a fiducial mass of 2.97 tons. Each d.c. represents $\sim$ 2% of a radiation length; it has three planes of sense wires at $-5°, 0°, +5°$ w.r.t. the magnetic field, which should give a precision of $200\mu m$ per wire in the bending plane (y) and $2mm$ per chamber parallel to the beam. The maximum drift distance is 3.6 cm . Tests of a prototype actually yielded $\sigma_y = 160\mu m$.
3. 10 T.R. Detectors follow the target. They are made of a radiator of 400 polypropylene foils 20 μm thick spaced by 250 μm and an X-ray detector consisting of vertical straw tubes of $\emptyset 1.6cm$. These are made of aluminized mylar $25\mu m$ thick and filled with a mixture of 70% Xe and 30% CH_4 at atmospheric pressure. Extrapolation of the results of a prototype test forecasts a 90% efficiency for $e^{-'}s$ and a π/e rejection of 10^{-3}. To increase the lever arm, each couple of T.R. detectors will be followed by a D.C. of the type described above.
4. The preshower is made of 1.5 X_0 of Pb followed by two orthogonal planes of extruded aluminium tubes 1 by 1 cm in cross-section. Tests of a prototype reveal a $5-10$ π/e rejection factor, depending on the energy.
5. The calorimeter is made of 1100, 10.6 by 8 cm lead-glass blocs, 20 X_0 in depth, read by tetrodes with their axes at 45° w.r.t. the B field. Zero field tests of a 3 by 3 blocs prototype stack give $\sigma(E)/E = 5\%/\sqrt{E\ (GeV)}$. Taken together, the preshower-calorimeter system gives a π/e rejection of $\sim 10^{-3}$ for 90% efficiency to $e^{-'}s$. With the T.R. detector rejection one is thus well above what is needed to eliminate the $\sim$ 18500 $\pi^{-'}s$ predicted to go through the cuts.
6. Muons are identified by large drift chambers separated by a Fe filter downstream of the magnet, which serves itself as a first filter.

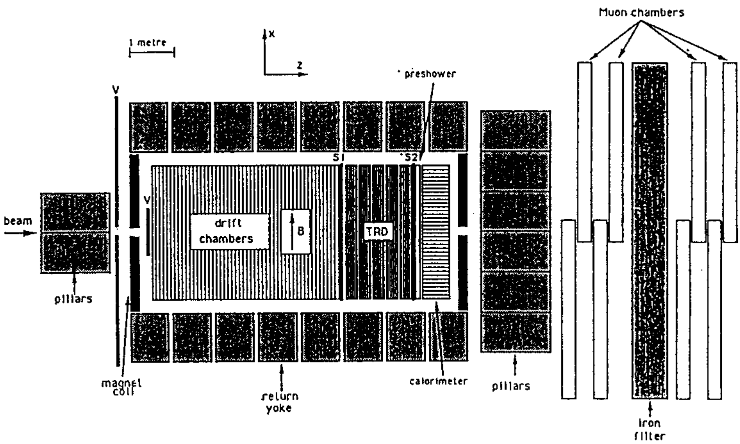
5 Expected sensitivity

Monte Carlo simulations of the experiment were performed with the previous characteristics to define different sets of cuts for the decay channels which have been mentionned above. Assuming two years of exposure in the CERN-SPS wide-band neutrino beams, 1.1 10^6 ν_μ C.C. events together with 3.7 10^5 N.C. and 13200 ν_e C.C are expected in the fiducial volume. The following table summarizes the estimated efficiencies, expected backgrounds and sensitivities with these statistics.

τ decay mode	Fraction	Efficiency	Predicted background	Limit on ν_τ / ν_μ
$\tau^- \rightarrow e^- \nu_\tau \bar{\nu}_e$	.178	.12	4.6	3.5 10^{-4}
$\tau^- \rightarrow \mu^- \nu_\tau \bar{\nu}_\mu$	.178	.039	2.2	8.4 10^{-4}
$\tau^- \rightarrow \pi^- \nu_\tau$	.108	.014	l.t. 2	2.2 10^{-4}
$\tau^- \rightarrow \rho^- \nu_\tau$	.227	.023	l.t. 2	6.6 10^{-4}
$\tau^- \rightarrow 3\pi^\pm \nu_\tau$	.138	.087	l.t. 2	2.9 10^{-4}

Merging these results, a negative search would yield a limit $sin^2 2\theta \leq 3.8\ 10^{-4}$ at the 90% c.l.

We conclude by noting that 83 % of the τ width is probed in 5 different channels, which will allow conclusive consistency checks in case a signal is observed and that backgrounds can be estimated from the data themselves (ν_e and ν_μ C.C. events share the same production dynamics, and N.C. backgrounds are charge-symmetric.)



The NOMAD experimental set-up.

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